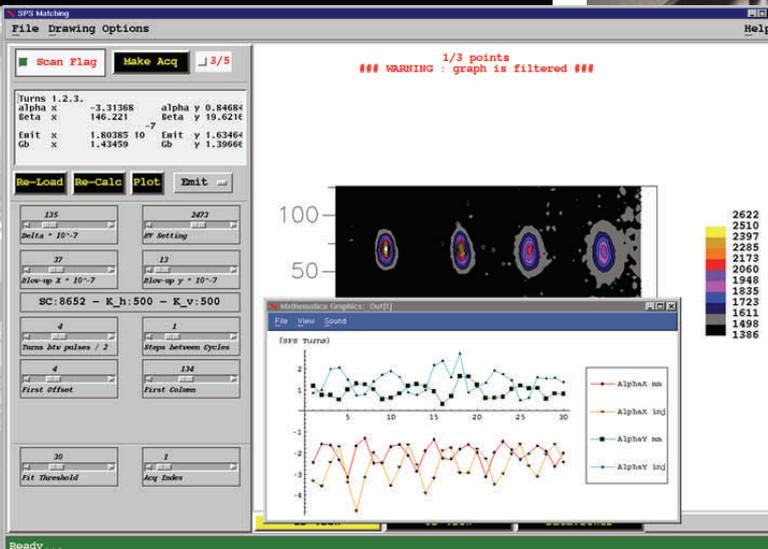
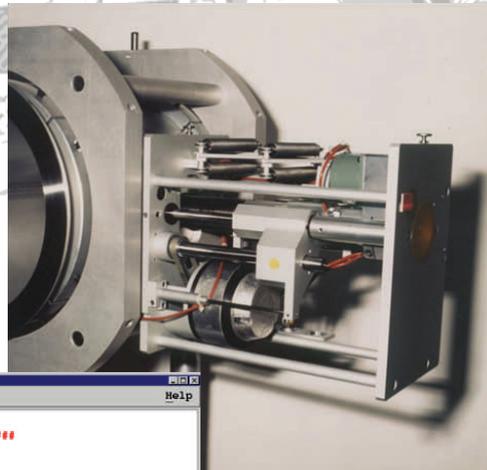
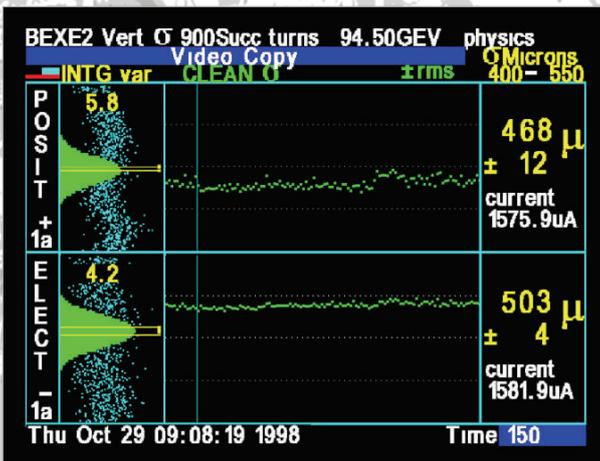


CAS 2011

Support Booklet for the Beam Instrumentation Course



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1. Beam position Monitors
2. Profile Monitors/Emittance
3. Tune and Phase Advance Measurements
4. Beam Loss Monitors
5. Bunch Length Measurements

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Chapter 1

Beam Position Monitors

P. Forck (GSI), R. Jones (CERN)

1.1 Problems to solve

1 Discussion on General Features of BPMs

Beam Position Monitors **BPM** are very frequently used at all accelerators. They are installed at very locations along transfer lines and synchrotrons with the main allocation to monitor the transverse beam center-of-mass.

1st discussion topic:

What are the main functional demands for a proper choice of BPMs? These demands depend on the beam properties; please specify them for the contribution to the discussion. The goal of this discussion is to collect the basic properties and define terms required for a BPM specification.

2nd discussion topic:

What types of BPMs do you know? For which type of beam they are used? What are advantages and disadvantages for the different types of BPM?

2 Numerical Examples for Signal Estimation of capacitive BPMs

The basic quantity for the signal estimation of a BPM is the transfer impedance $Z_t(f)$ in frequency domain defined as

$$U_{signal}(f) = Z_t(f) \cdot I_{beam}(f) .$$

It connects the beam current I_{beam} with the usable voltage U_{signal} at a given resistor. Please note that the given quantities are complex functions of the frequency f .

2.1 Estimation of Beam Spectrum

2.1.1 Assume a single bunch of Gaussian width $\sigma_t=100$ ns passing a BPM. Sketch the spectral beam current $I_{beam}(f)$ as a function of frequency! What are the corresponding values for $\sigma_t=10$ ns and $\sigma_t=1$ ns? Note: The Fourier transformation of a Gaussian beam of width σ_t is a half Gaussian function of width $\sigma_f=1/(2\pi\sigma_t)$.

2.1.2 How is the beam spectrum modified for multiple passes of bunches in a synchrotron? Sketch the beam spectrum as a function of frequency for the $\sigma_t=100$ ns bunch length and an acceleration frequency $f_{acc}=1$ MHz!

2.2 Estimation of Signal Voltage for a capacitive Shoe-box BPM

For capacitive BPMs the transfer impedance $Z_t(f)$ corresponds to a high pass characteristic with cut-off frequency $f_{cut}=1/(2\pi RC)$, here R denotes the resistor where the voltage is recorded and C the capacitance of the BPM plates with respect to the chamber wall plus the cable contribution.

2.2.1 Give the numerical value of f_{cut} for an $R=50 \Omega$ termination and a capacitance of $C=100$ pF! Sketch the transfer impedance $Z_t(f)$ for this case! (The capacitance is a typical value for shoe-box BPMs used at low energy proton synchrotrons, see Figure 1.)

2.2.2 What follows for the spectrum of the signal voltage $U_{signal}(f)$ for the cases of $\sigma_t=100$, 10 and 1 ns as discussed above? Sketch the signal shape in time domain for these cases! What is the type of algorithm required for the calculation of $U_{signal}(t)$?

2.2.3 Discuss the signal spectrum for the multiple passage of bunches in a synchrotron for the case of $\sigma_t=100$ ns bunch length and an acceleration frequency of $f_{acc}=1$ MHz. How is the signal spectrum modified if only part of the buckets is filled?

2.2.4 How is the signal voltage $U_{signal}(t)$ changed of a high impedance termination with $R=1$ M Ω ? What might be reasons for this choice?

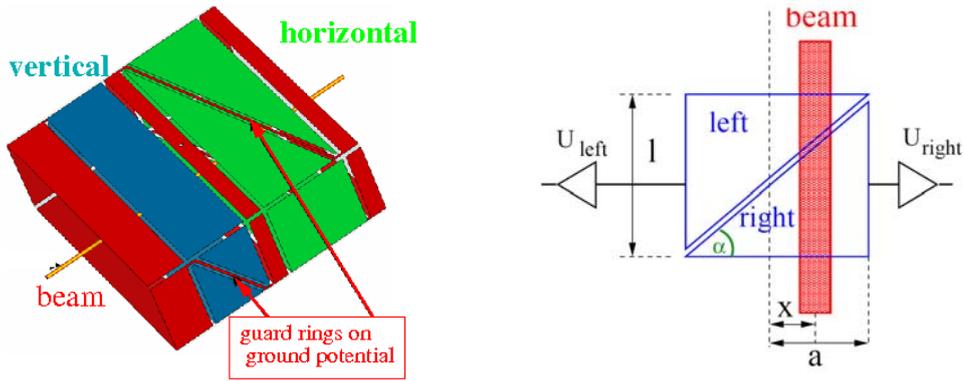


Figure 1: An example for a rectangular electrode arrangement of a shoe-box BPM and the scheme for position determination.

2.3 Estimation of Signal Voltage for capacitive Button BPM

2.3.1 Discuss qualitatively the same properties for a button BPM (see Figure 2) with typical capacitance of $C=5$ pF and shorter bunches as typically present at LINACs or electron synchrotrons with $\sigma_t=1$ ns, $\sigma_t=100$ ps and $\sigma_t=10$ ps! What is the expected signal shape $U_{signal}(t)$ in these cases?

2.3.2 A single bunch of 10^{10} electrons with a velocity $v \approx c$ in a bunch of $\sigma_t = 100$ ps length have to be detected by this BPM. The numerical value of the transfer impedance is typically $Z_t(f > f_{cut}) = 1 \Omega$. What is the numerical value of the signal voltage U_{signal} ? What might be technical problems related to a short bunch observation using button BPMs?

2.3.3 For the position measurement the difference voltage of opposite plates normalized to the sum voltage is used, i.e. for the horizontal reading it is $x = l/S \cdot (U_{right} - U_{left}) / (U_{right} + U_{left})$. A typical value for the position sensitivity is $S = 10\%/mm$. How precise should be the reading of the plate voltage to detect a $10 \mu m$ position offset? What is the numerical value of the difference voltage of this button BPM arrangement of the $\sigma_t = 1$ ns bunches? A general limitation of voltage measurements is given by the thermal noise contribution $U_{eff} = (4k_B \cdot T \cdot \Delta f \cdot R)^{1/2}$. Calculate the numerical value for a bandwidth of $\Delta f = 1$ GHz and room temperature $T = 300$ K; the value of the Boltzmann constant is $k_B = 1.4 \cdot 10^{-23}$ J/K. What is the signal-to-noise ratio for the button BPM case above? What is the minimal beam current to achieve a signal-to-noise ratio of 2:1? What is a method to improve the position reading?



Figure 2: Example for button BPMs at the LHC beam pipe of $\varnothing 50mm$ (from C. Boccard, CERN).

3 Signal Estimation of different BPM types

A single bunch of 10^{10} electrons with a velocity $v \approx c$ in a bunch of $\sigma_t = 100$ ps length have to be detected by a BPM. Compare qualitatively the signal shape for the following cases:

3.1 A button BPM having $f_{cut} = 640$ MHz and $Z_t(f > f_{cut}) = 1 \Omega$ (as done for exercise 2.3).

3.2 A stripline BPM of 30 cm length and an angular coverage of 10° , see Figure 3. The transfer impedance at the maximum is $Z_t = 1.5 \Omega$. Why does the shape of the time domain signal differ from the one of a button BPMs?

3.3 A cavity BPM (see Figure 4) having a resonance frequency of $f = 4$ GHz and a quality factor of $Q = 1000$. What influences the choice of the quality factor?

3.4 Discuss briefly reasons for an appropriate choice between these types!

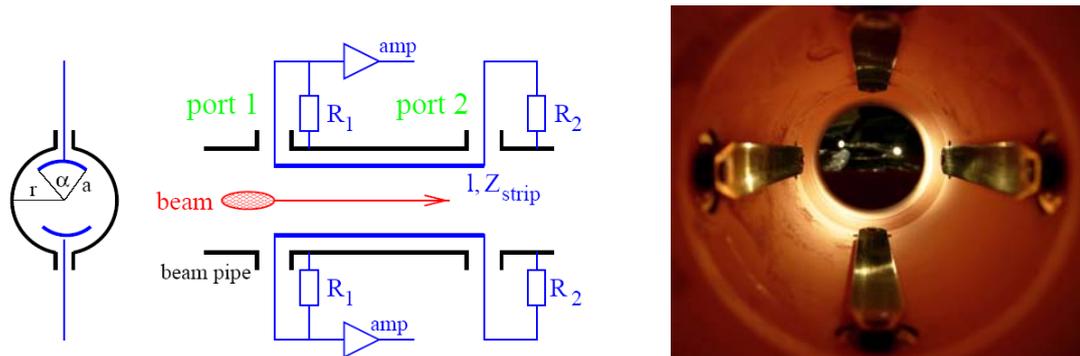


Figure 3: Scheme of a stripline BPM and photo of a 12 cm long realization at LHC (from C. Boccard, CERN).

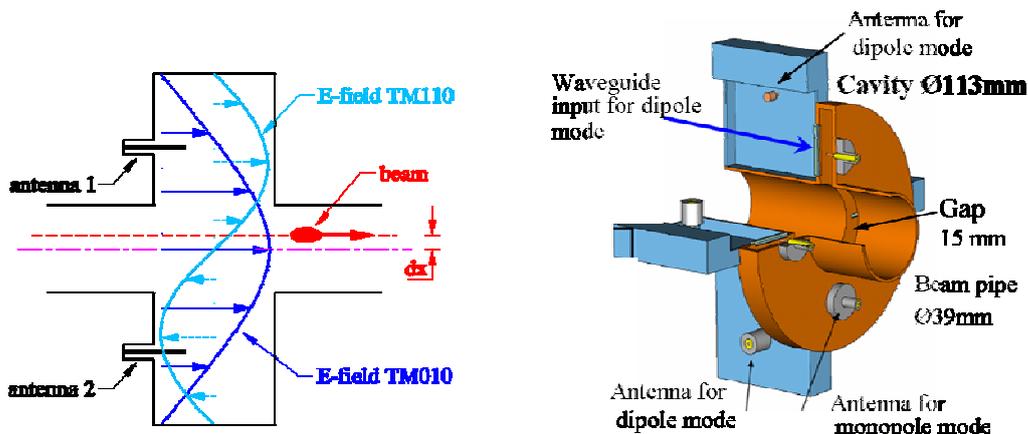


Figure 4: Scheme of a cavity BPM and technical drawing of a realization for ILC having a resonance frequency of 1.5 GHz (from M. Wendt, FNAL).

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1.2 Further Reading I:

Overview of Recent Trends and Developments for BPM Systems

M.Wendt, Proceedings of Beam Instrumentation Workshop DIPAC, DIPAC 2011

OVERVIEW OF RECENT TRENDS AND DEVELOPMENTS FOR BPM SYSTEMS*

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Abstract

Beam position monitoring (BPM) systems are the workhorse of beam diagnostics for almost any kind of charged particle accelerator: linear, circular or transport-lines, operating with leptons, hadrons or heavy ions. BPMs are essential for beam commissioning, accelerator fault analysis and trouble shooting, machine optics, as well as lattice measurements, and finally, for accelerator optimization, in order to achieve the ultimate beam quality.

This presentation summarizes the efforts of the beam instrumentation community on recent developments and advances on BPM technologies, i.e. BPM pickup monitors and front-end electronics (analog and digital). Principles, examples, and state-of-the-art status on various BPM techniques, serving hadron and heavy ion machines, sync light synchrotron's, as well as electron linacs for FEL or HEP applications are outlined.

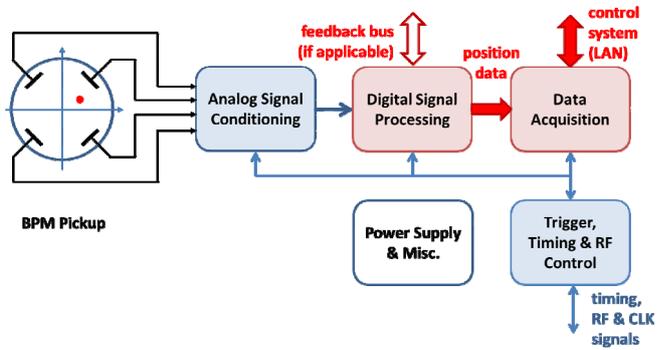


Figure 2: Schematics of a beam position monitor.

Each beam position monitor consists of a BPM pickup, with two or four symmetrically arranged electrodes, followed by a readout electronics system for signal conditioning and processing (Fig. 2). The pickup electrodes sense a part of the electromagnetic field of the passing beam and convert it to an electrical signal. The read-out electronics extract the beam position information out of the electrode signals by conditioning the analog signal, followed by digital signal processing techniques. The position data and other controls of the BPM read-out system are handled by a data acquisition interface, typically a CPU processor, which interfaces to the accelerator control system. The digital signal processing and data acquisition has to be supported by timing and clock signals, which are also used for time stamping, i.e. synchronizing BPM data across the entire system, as well as accelerator event and RF signals (for analog signal conditioning).

INTRODUCTION

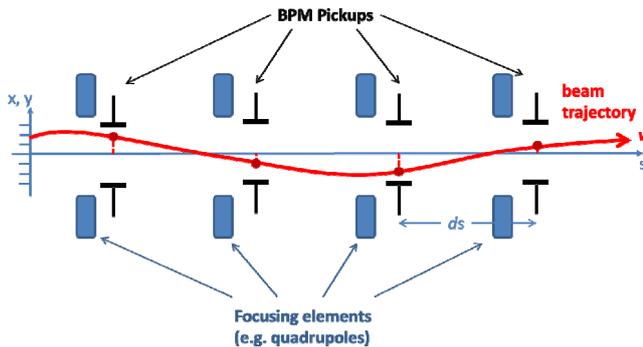


Figure 1: Measurement of the beam trajectory.

The observation of the beam trajectory

$$u(s) = A\sqrt{\beta} \sin(Q\varphi + \delta) \quad (1)$$

with $u = (x, y)$ as the transverse coordinates, A the amplitude of the oscillation, β the beta-function, Q the betatron tune, $\varphi = 0 \dots 2\pi$, and δ an initial condition, is one of the most fundamental beam measurements in any particle accelerator. A series of beam position monitors (BPM) are distributed along the beam-line, preferably near the focusing elements (e.g. quadrupole magnets), see Figure 1. The BPMs monitor the transverse beam displacement (x, y) at their locations s_n , knowing the distance ds between two monitors we may also get the slope (x', y') of the beam trajectory – if no optical elements are in-between.

* This work was supported by Fermi National Accelerator Laboratory, operated by Fermi Research Alliance, LLC under contract No. DE-AC02-07CH11359 with the United States Department of Energy
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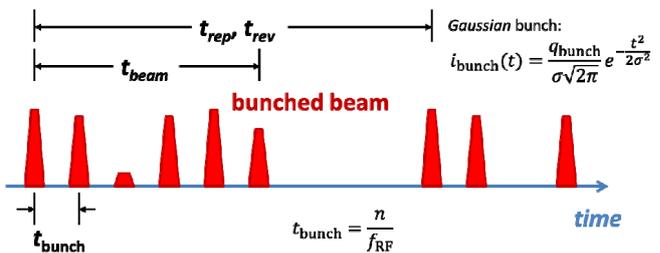


Figure 3: Beam structure.

The particle beam is a bunched stimulus signal for the BPM, with $t_{\text{bunch}} = n/f_{\text{RF}}$. As Figure 3 indicates, the beam bunches may have different intensities, sometimes even missing bunches. The beam structure spans t_{beam} , and typically repeats with t_{rep} in linacs and transport-lines, and t_{rev} in circular accelerators. Depending on the measurement or integration time of the BPM, we can resolve the beam position of single or all individual bunches, or the average over one or several beam pulses

or turns. Multipurpose accelerators, such as the CERN PS or the Fermilab Main Injector may accelerate different beam structures, apply sophisticated RF gymnastics and even use different particle species, which further complicates the operating conditions for the BPM system [1].

Some important characteristics of a BPM system are:

- *Measurement / integration time*, as described.
- *Position resolution*, i.e. the minimum beam displacement difference the BPM can resolve (typically depends a lot on the integration time).
- *Linearity and accuracy*, i.e. the absolute error of the reported beam position, over a part or the complete range of the beam pipe aperture.
- *x-y coupling*
- *Dynamic range*, in terms of beam intensity. The reported beam position has to be independent of the beam intensity, saturation or noise effects will appear at high / low beam intensities and compromise linearity and position resolution.
- *Reproducibility and long term stability* are important for storage rings and beam lattices which critically rely on references orbits.

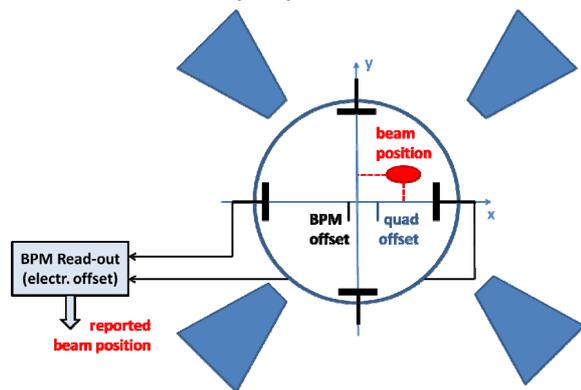


Figure 4: BPM and quadrupole offsets.

The zero-order effect of the linearity correction is the so-called *BPM-offset*. Fig. 4 illustrates the BPM and quadrupole offsets with respect to the vacuum pipe. A beam-based alignment (BBA) procedure can be performed to characterize the BPM-to-quadrupole offset and tilt, including the effects of the electronics [2], [3], [4].

Digital signal processing allows us to simultaneously output BPM data with different integration times, e.g. multiturn averaged position data, single pass / turn-by-turn, or even single bunch displacement information. This enables besides the beam orbit characterization, a large variety of direct and indirect beam measurements and observations, e.g. injection oscillations, betatron and synchrotron tunes, dispersion and beam energy, x-y coupling, beam optics, magnet alignment and errors, non-linear field effects, etc. [5]. For machine commissioning the processing of the beam intensity signal is of great value, while precise, RF derived clock signals also enable beam phase and time-of-flight measurements with today's BPM systems.

BPM PICKUP

The BPM pickup is an arrangement of electromagnetic antennas or a resonant device, and part of the accelerator vacuum system. In a simplistic view, for relativistic beams ($v \approx c_0$), the output signal of a BPM pickup can be expressed:

$$V_{\text{elec}}(x, y, \omega) = s(x, y) Z(\omega) I_{\text{beam}}(\omega) \quad (2a)$$

$$V_{\Delta}(x, y, \omega) = s(x, y, \omega) Z(\omega) I_{\text{beam}}(\omega) \quad (2b)$$

where V is the output signal for a broadband pickup electrode (2a) or a resonant cavity (2b), $Z(\omega)$ is the frequency dependent transfer function or shunt impedance of the pickup, and $s(x, y, \omega)$ is sensitive to the beam position (x, y) , and eventually also frequency dependent. The beam current $I_{\text{beam}}(\omega)$ can often be approximated by a Gaussian function for the bunch signal, with a repetition similar as shown in Fig. 3. Most BPM pickups can be classified as either broadband or resonant. Besides being an RF or microwave device, the BPM pickup has to be UHV certified, and in some superconducting cryogenic installations also must operate at cryogenic temperatures and meet special cleanroom requirements.

Broadband BPM Pickups

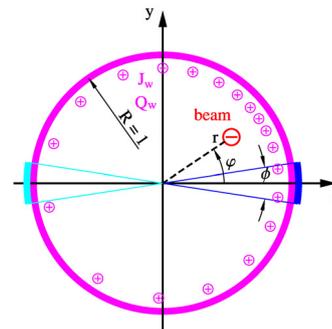


Figure 5: Beam and image currents.

For a broadband BPM pickup the sensitivity s in eq. (2a) is independent of ω . Broadband BPMs operate in terms of the image current model (Fig. 5), this *Laplace* problem was solved analytically for a beam pipe with circular or elliptical cross-section [6], [7], [8]:

$$J_w(R=1, \phi_w) = I_0 \frac{1 - \rho^2}{1 + \rho^2 - 2\rho \cos(\phi_w - \phi)} \quad (3)$$

Eq. (3) returns the image current density J_w at the surface of the beam pipe ($R=1, \phi_w$) for a beam position at $(\rho=r/R, \phi)$, where $I_0 = I_{\text{beam}}/2\pi$. Integrating ϕ_w over the range of the BPM electrode ϕ gives the electrode current I_{elec} , for which the geometric part is (note: cylindrical coordinates)

$$s(\rho, \phi) = \phi + 4 \sum_{n=1}^{\infty} \frac{\rho^n}{n} \cos(n\phi) \sin\left(\frac{n\phi}{2}\right) \quad (4)$$

Two symmetric arranged electrodes A, B (e.g. horizontal, as in Fig. 5) can now perform as BPM:

$$\text{beam pos.} = f\left(\frac{A-B}{A+B}\right) \text{ or } = f\left(20 \log_{10}\left(\frac{A}{B}\right)\right) \quad (5)$$

With typical pickup dimensions, e.g. $R=25$ mm, $\phi=30^\circ$, the sensitivity computes to 2.75 dB/mm around the beam pipe center. As eq. (2a) indicates, all broadband BPMs, suffer from a strong I_{beam} common mode term in the output signal, with a small amplitude modulation component due to the beam position (x,y) . The position sensitivity is basically fixed by the geometry and the related image current distribution, eq. (3), (4), (5).

Most prominent and widely applied member of the broadband BPM family is the electrostatic (capacitive) coupling so-called “button BPM” (different commercial button BPM feedthroughs are available). Also the stripline BPM (electromagnetic coupling) is popular, the length of the striplines, allows to match $Z(\omega)$ to the bunch spectrum $I_{\text{bunch}}(\omega)$. Circular split-plane (“shoe-box”) BPMs have an almost linear position dependence, which also can be achieved with large capacitive electrodes, spanning $\phi \approx 60^\circ$. [9] uses BPMs with magnetic coupling loop antennas for beam position monitoring near the dump, and [10] gives further theoretical background on magnetic BPMs, also for detection of the beam angle. [11] developed a inductive BPM with single pass capability and sub-micrometer resolution.

While all broadband BPMs basically follow with their position characteristics the image current model, they differ in their frequency behavior $Z(\omega)$, which is discussed extensively [12], [13], [14]. The numerical solution of the Laplace equation allows a more precise approach to evaluate $s(x,y)$, also for non-circular cross-sections of the beam pipe. The results can be fitted with 2-D polynomials or look-up tables, allowing a linearization in the post-processing of the BPM data.

The effect of non-relativistic beams to the sensitivity of different BPM electrode shapes has been studied in great detail with help of numerical methods [15].

Resonant BPM Pickups

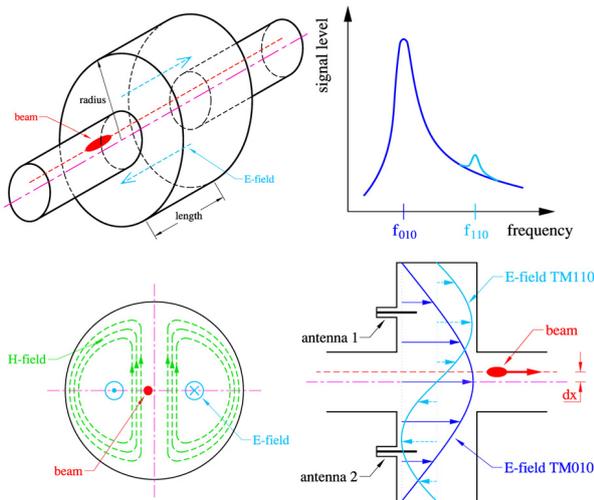


Figure 6: “Pillbox” cavity as BPM.

A cylindrical “pillbox” with conductive walls of length ℓ and radius R resonates at its eigenfrequencies

$$f_{mnp} = \frac{1}{2\pi\sqrt{\mu_0\epsilon_0}} \sqrt{\left(\frac{j_{mn}}{R}\right)^2 + \left(\frac{p\pi}{\ell}\right)^2} \quad (6)$$

This resonator can be utilized as passive, beam driven cavity BPM by providing beam pipe ports (Fig. 6). A subset of the eigenmodes eq. (6) is excited by the bunched beam, for the application as BPM the lowest transverse-magnetic dipole mode TM_{110} is of interest. Its

$$E_z = C J_1\left(\frac{j_{11}r}{R}\right) e^{i\alpha z} \cos\varphi \quad (7)$$

field component couples to the beam with an almost linear dependence to the beam displacement r , and vanishes when the beam is in the center ($r = 0$). Four symmetrically arranged pin antenna feedthroughs fix the polarization of TM_{110} to the horizontal and vertical axis, and provide the unnormalized difference signal $\Delta = f(x,y,I_{\text{beam}})$, the beam intensity is hidden in the constant C .

Resonant structures, e.g. “pill-box” or rectangular cavities, also coaxial resonators, and more complex waveguide-loaded resonators, became very popular to fulfil the high resolution, single-pass beam position monitoring demands of linear accelerators for the high luminosity final focus lattice [16], [17], or driving a SASE-FEL beam-line [18]. In [19] the operation of a simple cavity BPM inside a cryostat is presented. The discussion on the theoretical background was recently updated [20]. The x-y decoupling of the TM_{110} polarization is addressed in [21]. The high resolution potential of a BPM system with C-Band choke-mode resonators was demonstrated the first time at the SLAC final focus test beam, achieving 25 nm single-bunch, single-pass position resolution [22].

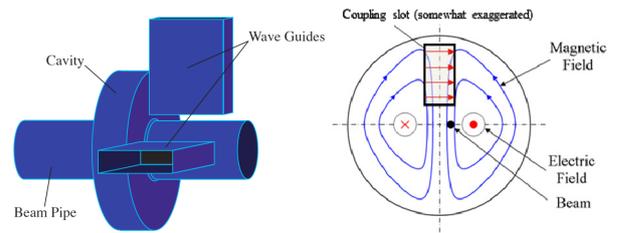


Figure 7: Waveguide-loaded cavity BPM.

The presence of the fundamental TM_{010} monopole mode adds a strong common mode component to the dipole-mode position signal, and even having a different frequency f_{010} , it limits the performance of the cavity BPM. A waveguide of width a , with a cut-off frequency

$$f_{010} < f_{10} = \frac{1}{2a\sqrt{\mu\epsilon}} < f_{110} \quad (8)$$

acts as very efficient, internal high-pass filter, and makes the cavity BPM quasi “common-mode free” (Fig. 7). The coupling slot between resonator and waveguide also helps to align the TM_{110} polarization planes, and minimizes the x-y coupling. However, the finite Q-value of the resonances still causes an unwanted leakage of the

monopole-mode at the frequency f_{110} of the dipole mode, thus limiting the resolution.

The first test of a system of three waveguide-loaded 14 GHz cavity BPMs was performed at BNL, demonstrating 150 nm beam position resolution [23]. Separate waveguide-loaded rectangular resonators (Fig. 8), operating at different C-Band frequencies achieved 8.7 nm resolution at the ATF2 final focus test beam-line [24].

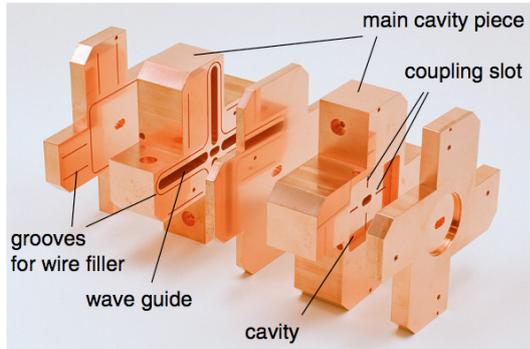


Figure 8: The ATF2 IP-BPM.

A magnetic waveguide-to-coaxial port coupling was introduced for the C-Band cavity BPMs at SPring-8 [25], a similar construction is tested for the XFEL [26]. The monopole-mode (TM_{010}) reference resonator, required to deliver beam intensity and phase reference signals to the read-out electronics, is also used as beam arrival time monitor, showing a 25 fsec temporal resolution performance. A low-Q, mass-producible X-Band cavity BPM for the CLIC main linac is under development, targeting <50 nm spatial resolution at <50 nsec integration time. Details on the effects of tolerances are discussed, as well as performance limitations due to mode leaking, and a comparison between single vs. multi-bunch beam stimulus [27].

Beam position monitoring based on TEM coaxial resonators, the so-called re-entrant cavity BPM, has also been studied, and is proposed to operate inside the cryomodule at the European XFEL project [28]. A waveguide-loaded version demonstrated sub-micron resolution, when tested under single-bunch, single-pass beam conditions [29].

Beam excited dipole mode signals from the HOM-couplers of standing wave accelerating structures have been studied at the FLASH FEL facility. An online SVD algorithm was used to orthogonalize the signals, thus make HOM signals usable as beam position monitor [30].

READ-OUT ELECTRONICS

The read-out system interfaces the BPM pickup to the accelerator data acquisition (control) system (Fig. 2). Signal conditioning, normalization and linearization of the position signals / data have to be provided for the time stamped beam position data. To achieve long term stability, calibration signals for gain-correction, or other correction methods are added to the system. The BPM data may also serve in beam orbit feedback systems, thus

a low latency of the signal processing is of important value.

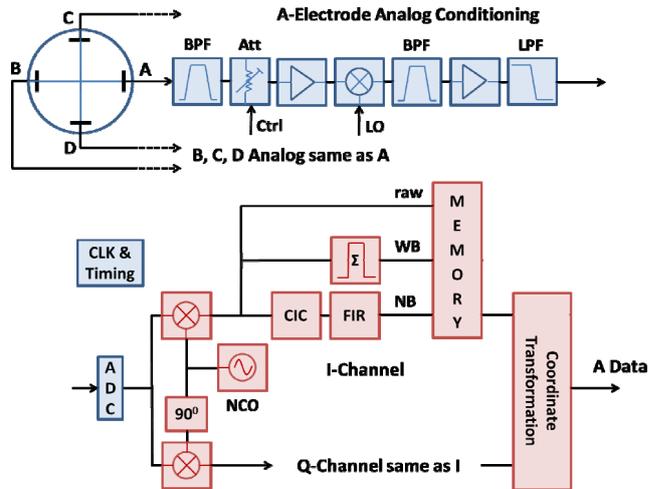


Figure 9: Key elements of the BPM read-out electronics.

An overview of “traditional” BPM read-out techniques was summarized in [31]. Today the BPM read-out electronics is typically based on frequency domain signal processing techniques, which were developed for the telecommunications market [32]. Bandpass filters in the analog section prepare the BPM pickup signals into sinewave-like burst signals, for waveform signal sampling and processing in the digital section. Microwave and RF analog components, 12-16 bit pipeline ADCs, FPGAs and clock distribution chips with sub-psec jitter are some of the key hardware elements. Figure 9 illustrates a typical electronics arrangement for a broad-band BPM pickup, 1-of-4 channels is shown. In some cases the analog down-mixer can be omitted, for cavity BPMs the schematics is similar, here the analog mixer is still required. The digital signal processing takes place in a FPGA, the I-Q down-conversion to baseband is required if the ADC clock is not locked to the accelerator RF.

As Figure 9 indicates, the measurement of the pickup electrodes signals (A, B, C, and D) is performed separately, normalization and linearization takes place in the FPGA or CPU. Drifts and aging effects have to be compensated by a calibration tone signal [33], or a channel switching scheme [34]. The effect of ADC clock jitter is discussed in various application notes [35], this becomes particularly critical in systems with heavy undersampling ($f_{\text{signal}} \gg f_{\text{CLK}}$). The digital data stream can be filtered and decimated in various ways, Fig. 8 indicates how narrow-band, wide-band and raw signals can be handled simultaneously. We usually down-convert $f_{\text{signal}} - f_{\text{NCO}}$ not exactly to DC, but to a low frequency with an integer number of oscillations over the measurement period, this avoids a crawling phase.

ACKNOWLEDGEMENTS

Thanks to all the colleagues of the beam instrumentation community for their great help and support in preparing this document!

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- 1.3 Further Reading II:**
Beam Position Monitoring
R. Shafer, Proceedings of Beam Instrumentation Workshop BIW89

BEAM POSITION MONITORING

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1. INTRODUCTION

The purpose of this paper is to review the topic of beam position monitoring as it applies to charged-particle beams in accelerators and beamlines. As this workshop is primarily to familiarize engineers with the subject, the emphasis will be on the engineering aspects of beam position measurement rather than on pedantic derivations of equations. The intent is not to present many specific solutions to specific problems, but to provide general guidelines on which specific designs can be based, with occasional examples. Some math must be included, however, to understand how pickup electrodes respond to beams and how various circuits process signals. The emphasis will be on calculating frequency dependence, power levels and beam-displacement sensitivities, and reviewing the advantages and disadvantages of a variety of electrode designs and signal-processing methods.

Beam instrumentation includes not only the electronics necessary to measure the properties of beams, but also the transducers that convert the beam signals into electrical signals. Processing electrical signals is a very well understood engineering field. The characteristics of the transducers that generate the electrical signals are not well documented, however. There is quite a bit of physics in beam transducers, and because the beam currents are not confined to wires, engineers sometimes have difficulty grasping the basic concepts in how particle beams couple to beam diagnostic devices and generate electrical signals. Therefore, this paper will concentrate on the beam-coupling mechanism, but will also discuss some of the signal-processing electronics.

First, the basic methods of noninterceptive beam position monitoring will be discussed. Then the basic characteristics of beams and beam position measuring systems will be reviewed. This is followed by several sections that discuss the signals from a variety of pickup electrode geometries. Several sections are then devoted to signal processing methods. Finally, several sections discuss the system aspects of beam position monitoring.

There have been several comprehensive survey articles on beam diagnostics stressing primarily the physics aspects of the subject.¹⁻⁶ These articles cover the broad range of particle beam diagnostics and are not restricted to position measurement.

2. BASIC METHODS OF BEAM POSITION MONITORING

The most common method of monitoring the position of a charged-particle beam is to couple to the electromagnetic field of the beam. The beam is a current, and it is therefore accompanied by both a magnetic field and an electric field. In the limit of very high beam energy, the fields are pure transverse electric and magnetic (TEM). If the beam is displaced from the center of a hollow

conducting enclosure, the magnetic and electric fields are modified accordingly. Detailed knowledge of how the magnetic and electric fields depend on the beam position allow accurate determination of the beam position.

Pickup electrodes, in general, cannot sense dc electric or magnetic fields (there are exceptions to this, of course, such as Hall probes and flux-gate magnetometers). The signals are induced by a time-varying component of the beam signal, usually beam current modulation. The carrier for the beam position information is the frequency (and harmonics) of the periodic beam bunches for a continuous train of bunches or the derivative of the instantaneous beam current for single bunches.

The conventional beam position pickup is a pair of electrodes (or two pair, if two beam position coordinates are being measured) on which the signals are induced. The ratio of the amplitudes of the induced signals at the carrier frequency is uniquely related to the beam position. Because the position information is contained in the amplitude variation of these signals, the information actually appears as AM (amplitude modulation) sidebands of the carrier. In synchrotrons, where the strong focusing forces cause the betatron oscillation frequency to be many times the revolution frequency, the sidebands are substantially displaced in frequency from the carrier signal.^{3,4}

A variant of the standard multielectrode beam position monitor is the wall-current monitor,⁷ which often is a gap in the beam pipe with a ceramic insert to maintain vacuum. A resistive path, often composed of many resistors in parallel, is connected across the gap to carry the wall currents. The azimuthal distribution of wall currents, determined by measuring the voltage drop across the resistors, can be used as a measurement of the beam position.

Another nearly noninterceptive method of measuring position is to intercept the beam with objects such as thin wires and to measure the response of the wire (induced currents) or ionizing radiation produced by the beam hitting the wire as the wire is moved through the beam.⁸ The wire, usually a low-Z material, may be either stepped through the beam or pushed through at a high velocity.⁸ In either case, some of the beam is lost or scattered out of the incident beam, causing some degradation of the beam quality. In addition, the wire is heated by the beam and, in many cases, is damaged by being overheated.

Still another method is to cause the beam itself to radiate energy. High-energy electrons, when they pass through large magnetic fields, will radiate visible, uv light or x-rays in narrow forward cones (synchrotron radiation). Detectors designed to intercept this synchrotron radiation can be used to determine the position of the source (i.e., the beam) in the magnetic field.⁹ This general technique is used in electron synchrotrons (synchrotron light sources) and in devices such as wigglers and undulators, which are specifically designed to make the electrons radiate.

Residual gas fluorescence¹⁰ or ionization¹¹ can be used to determine beam position. In the former, video-image processing of the visible light is used to determine the beam profile and position. In the latter, an electric field

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perpendicular to the beam is used to accelerate the liberated electrons or ions to a detector.

Finally, it is possible to probe the beam with another beam, and monitor the radiation produced by the two interacting beams. At the Stanford Linear Accelerator Center, for example, two very high energy beams (one an electron beam and the other a positron beam), are directed toward each other in the collision (final focus) area of the Stanford Linear Collider (SLC).^{12,13} The magnetic fields of each beam cause the other beam to be deflected and radiate (beamstrahlung). Measurement of the radiation yield as a function of the relative position of the two beams leads to a measurement of the relative beam positions.

In the case of negative-ion beams such as H^- (a proton with two electrons attached), a thin visible laser beam (photon energy about 2 eV) can be used to detach one of the electrons¹⁴ (the binding energy of the "extra" electron is about 0.75 eV). The result is that a narrow beam of neutral hydrogen atoms is produced. By monitoring the yield of the neutral hydrogen as a function of the position of the laser beam, the beam position can be determined. Laser beams may also be scattered off high-intensity electron beams as a probe.¹⁵

There are many ways of determining the beam position in a nearly noninterceptive way. The best one is determined by the type of beam being monitored, the conditions under which the monitoring is being done, and, finally, what specific measurements are required. Because the most common noninterceptive method is measuring the electric and magnetic fields, the remainder of the paper will discuss this method.

3. CHARACTERISTICS OF BEAMS AND POSITION MEASURING SYSTEMS

The purpose of this section is to discuss some of the beam and beam position measuring system characteristics that need to be considered when such a system is being designed. It is important to understand the range of the beam parameters to be expected and the requirements of the beam position monitoring system before undertaking a detailed design of the system. It is nearly always true that some compromises must be made in order to go from an ideal system design to a realizable one. These compromises may be due to time constraints, funding, space, or manpower resources. Hence, it is important to have a thorough understanding of how each parameter affects, or is affected by, the system design. With this understanding, it is usually possible to design a system that is simple, yet does not compromise the quality of the measurements.

Accuracy is the ability to determine the position of the beam relative to the device being used for measuring the beam position. This is limited by some combination of mechanical alignment errors, mechanical tolerances in the beam detection device, calibration errors in the electronics, attenuation and reflections in the cables connecting the pickup to the electronics, electromagnetic interference, and circuit noise (noise figure of the electronics). Signal processing

introduces additional inaccuracies such as granularity (least-significant-bit [LSB] errors) that is due to analog-to-digital conversion.

Resolution differs from accuracy in that it refers to the ability to measure small displacements of the beam, as opposed to its absolute position. Typically, the resolution of a system is much better than the accuracy. In many cases, good resolution is much more important than good accuracy. For example, it is often adequate to know the absolute beam position to a fraction of a millimeter, even though the beam motion (jitter) needs to be known to a few micrometers. In high-energy collider operation, for example, it is much more important to know the relative position of the two beams than to know the absolute position of either.

Bandwidth refers to the frequency range over which beam position can be measured. In some cases, a beam may have a fast transverse motion (jitter) that needs to be identified. In another case, the beam pulse may be very short (a picosecond, nanosecond, or a microsecond for example), and the measuring system must be able to acquire data in this time interval (acquisition bandwidth). Closely related is real-time bandwidth, which is the ability to generate a real-time analog signal proportional to the beam position in a limited time. This response is necessary if the signal is to be used in real-time, closed-loop control applications.

Beam current usually refers to the average (dc) beam current averaged over the microscopic bunch structure, but can also be used to refer to the instantaneous (intrabunch) beam current and to other temporal averages. For single bunches, the number of particles per bunch is often used as a measure of beam current. Closely related is beam intensity, which usually refers to the amplitude of a particular frequency harmonic of the beam-bunching frequency. Beam intensity differs from beam current in that intensity is a frequency-domain quantity, while current is a temporal-domain quantity.

Dynamic range refers to the range of beam intensities (or current or charge) over which the diagnostic system must respond. Often large dynamic range response is achieved by gain switching, but in addition, special methods of signal processing can provide a large dynamic range response and eliminate the need for gain switching.

Signal-to-noise ratio refers to the relative power levels of the wanted signal to unwanted noise. Noise may be true thermal noise, amplifier noise (noise figure), electromagnetic noise (EMI) such as silicon-controlled-rectifier (SCR) noise, or radio-frequency interference (RFI), which may be the same frequency as the beam position signals. In this application, shot noise (sometimes called Schottky noise) from the beam itself is actually a signal, because it can be used to determine the beam position. Signal-to-noise ratios place limits on the ultimate resolution of the system.

Beam bunching refers to the temporal characteristics of the beam current modulation. Usually the beam is in the form of short bunches with the same period as, or a multiple of, the period of the rf system being used to accelerate it. For example, at the Los Alamos Meson Physics Facility (LAMPF), the bunch

period is about 5 ns (201.25 MHz), while the rf period is 1.25 ns (805 MHz). The bunch length is usually quite short relative to the period and at some facilities is less than 30 ps. The bunch shape can be temporally symmetric such as Gaussian, parabolic, or cosine-squared, among others. It can also be nonsymmetric. The beam-bunching factor is typically the ratio of the bunching period to the beam bunch full length at half maximum (F LHM). Typically, this factor can be 10 or 20, often higher. This temporal profile creates many harmonics of the bunching frequency in the induced signals on the pickup electrodes. Beam bunching can change with time because of momentum spread in a nonisochronous beam-transport system, synchrotron oscillations in rf buckets, or by allowing a space-charge-dominated beam to coast in a beamline without longitudinal focusing forces.

4. BEAM CURRENT MODULATION IN THE TIME AND FREQUENCY DOMAINS

Beam bunches can have many shapes. Regardless of what the specific shape is, the beam-bunching frequency usually provides the carrier signal that is used for detecting the beam position. Because it is possible to make measurements in either the time or frequency domain, it is important to understand the interrelations between the two cases. A Gaussian bunch shape is used in the following calculations, although other shapes could just as easily have been used.

Consider a Gaussian-shaped beam bunch containing N particles of charge e in a bunch of rms temporal length σ (in time units) and with a bunching period T . The instantaneous beam current of a single bunch is given by

$$I_b(t) = \frac{eN}{\sqrt{2\pi}\sigma} \exp\left[\frac{-t^2}{2\sigma^2}\right] . \quad (4.1)$$

This is normalized so that the bunch area is the total charge eN independent of the rms bunch length σ . Assuming that the bunch is symmetric in time, centered at $t = 0$, and is in a pulse train with bunch spacing T , we can expand this in a cosine series with $\omega_0 = 2\pi/T$:

$$I_b(t) = \frac{eN}{T} + \sum_{m=1}^{\infty} I_m \cos(m\omega_0 t) , \quad (4.2)$$

where

$$I_m = \frac{2eN}{T} \exp\left[\frac{-m^2\omega_0^2\sigma^2}{2}\right] . \quad (4.3)$$

This may be rewritten

$$I_b(t) = \langle I_b \rangle + 2\langle I_b \rangle \sum_{m=1}^{\infty} A_m \cos(m\omega_0 t) , \quad (4.4)$$

where the average (dc) beam current is

$$\langle I_b \rangle = \frac{eN}{T} , \quad (4.5)$$

and the harmonic m amplitude factor is

$$A_m = \exp \left[\frac{-m^2 \omega_0^2 \sigma^2}{2} \right] . \quad (4.6)$$

The Fourier cosine series expansion of the beam current in Eq. (4.4) includes a dc component as well as many harmonics of the bunching frequency. The amplitude (intensity) of the various Fourier harmonics is determined by the factor A_m , which always approaches 1 for small harmonic numbers, regardless of the specific bunch shape. As the bunch shape approaches a δ function, the amplitude factor A_m approaches 1 for all harmonics. The peak amplitude of the low harmonics of the bunching frequency is about twice the dc current. Table 4.1 gives the amplitude factor A_m for a variety of pulse shapes.

Table 4.1. Amplitude factor A_m for a variety of bunch shapes. All expressions are normalized so that $A_m \rightarrow 1$ as the bunch length $\rightarrow 0$. In the table, T is the bunch spacing, W = full width at base of bunch, and $\omega_0 = 2\pi/T$.

Bunch Shape	A_m	Comment
δ function	1	For all harmonics
Gaussian	$\exp \left(\frac{-m^2 \omega_0^2 \sigma^2}{2} \right)$	σ is rms bunch length
Parabolic	$3 \left(\frac{\sin \alpha}{\alpha^3} - \frac{\cos \alpha}{\alpha^2} \right)$	$\alpha = m\pi W/T$
(cosine) ²	$\frac{\sin(\alpha - 2)\pi/2}{(\alpha - 2)\pi} + \frac{\sin \alpha\pi/2}{\alpha\pi/2} + \frac{\sin(\alpha + 2)\pi/2}{(\alpha + 2)\pi}$	$\alpha = 2mW/T$
Triangular	$\frac{2}{\alpha^2} - \frac{2 \cos \alpha}{\alpha^2}$	$\alpha = m\pi W/T$
Square	$\frac{\sin \alpha}{\alpha}$	$\alpha = m\pi W/T$

It should be noted that many bunch shapes can have zero values of A_m for certain harmonics m of the bunching frequency, depending on the bunch length. If a beam position system is being designed to operate at a harmonic of the bunching frequency, this must be taken into account. If the bunch shape is

variable, then the amplitude factor may vary and may even go to zero, depending on the specific bunch shape and length.

In summary, the currents associated with periodically spaced beam bunch may be considered either in the time domain or the frequency domain. Generally, if the signal processing is performed at harmonic $m = 1$ in the frequency domain, the amplitude factor A_1 is nearly 1, and the rms beam intensity at this frequency is $\sqrt{2}$ times the dc current.

An interesting alternate method to using the rf bunching modulation is the beam current modulation scheme being planned at CEBAF. A $1\text{-}\mu\text{A}$ rms beam current modulation at 10 MHz is placed on the $200\text{-}\mu\text{A}$ cw electron beam¹⁶ (rf frequency is 1497 MHz). Because the 10-MHz modulation can be turned on for less than one revolution around the recirculating linac (period about $4.2\ \mu\text{s}$), it is possible to measure the position of individual orbits while the machine is in operation. There are two other advantages to this method: First, the instrumentation is less expensive at 10 MHz, and second, the modulation scheme can be used without adversely affecting running experiments.

If a beam is centered in a circular, conducting beam pipe of radius b and has a velocity $v_b = \beta_b c$ (where c is the speed of light), then there is an electromagnetic field accompanying the beam and an equal magnitude, opposite charge, uniformly-distributed beam current density on the inner wall of the beam pipe. The field inside the beam pipe looks (nearly) like a transverse-electric-magnetic (TEM) wave propagating down the beam pipe at the beam velocity (this is exact only for $\beta_b = 1$). Beam position detectors sense these fields (or, equivalently, the corresponding wall current) and determine the beam position based on the relative amplitudes of the induced signals in two or more pickup electrodes. The instantaneous Fourier harmonic amplitudes of the wall currents (integrated over 2π), in this case, are the same as those for the beam itself. The wall current density is then, for a beam pipe with infinite conductivity, simply the beam current divided by the beam-pipe circumference:

$$i_w(t) = \frac{-I_b(t)}{2\pi b} \quad (4.7)$$

Some authors like to differentiate between pickups that detect the TEM fields and those that sense the wall currents. There is no difference. For a beam current $I_b(t)$ in the center of a conducting beam pipe of radius b , the azimuthal magnetic field accompanying it is $H_\theta(r, t) = I_b(t)/2\pi r$. Because $[\text{curl } \mathbf{H}(t)]_z = J_z(t)$, the discontinuity of $H_\theta(r, t)$ at $r = b$ requires that $J_z(b, t) = H_\theta(b, t)$, as long as the magnetic fields associated with the beam are confined to the region inside the beam pipe. For this reason, we can consider either the TEM wave or the wall current density as the excitation signal. For an rf-modulated cw beam in a metallic beam pipe, the magnetic field associated with the dc component of Eq. (4.4) will eventually appear outside the beam pipe, and the wall currents will then include only the ac components.

Circular beam pipes are the most common shape, and so the rest of this paper will deal exclusively with circular geometry. Other geometries for beam pipes

and beam pickup electrodes include rectangular, diamond, and elliptical, among others. All the calculations carried out in this paper can be done for these other geometries, with similar results.

5. SIGNALS FROM OFF-CENTER BEAMS

In the previous section, we considered a centered beam in a circular beam pipe. We now investigate what happens to the wall currents when the beam is displaced from the center.

LaPlace's equation can be solved in two dimensions to find the wall current density for a pencil beam current $I_b(t)$ at position r, θ inside a grounded, circular, conducting beam pipe of radius b .¹⁷ The wall current density i_w at b, ϕ_w is then

$$i_w(b, \phi_w, t) = \frac{-I_b(t)}{2\pi b} \left[1 + 2 \sum_{n=1}^{\infty} \left(\frac{r}{b}\right)^n \cos \left[n(\phi_w - \theta) \right] \right]. \quad (5.1)$$

An alternate way to obtain a solution is to use the method of images. In this case, the location of an image pencil beam is found such that the potential everywhere on the circle corresponding to the beam-pipe location (without the beam pipe) is zero. The wall current is then calculated using the differential form of Gauss's Law ($\text{div } \mathbf{E} = \rho/\epsilon_0$). The resultant expression for the wall current density i_w at b, ϕ_w is¹⁸

$$i_w(b, \phi_w, t) = \frac{-I_b(t)}{2\pi b} \left[\frac{b^2 - r^2}{b^2 + r^2 - 2br \cos(\phi_w - \theta)} \right]. \quad (5.2)$$

This closed-form expression, which is equivalent to the infinite series form in Eq. (5.1), is sometimes easier to deal with than the infinite series. However, when the expression must be integrated, the infinite series is often the preferred form. Note that the infinite series is of the form $r^n \cos n\theta$, indicative of solutions in cylindrical geometry.

If two electrodes (L and R for left and right) of angular width ϕ are placed at 0° and 180° , as shown in Fig. 5.1, the resultant currents flowing parallel to the beam on the inside surface of these electrodes are (assuming they are grounded and also at radius b)

$$I_R(t) = \frac{-I_b(t)\phi}{2\pi} \left\{ 1 + \frac{4}{\phi} \sum_{n=1}^{\infty} \frac{1}{n} \left(\frac{r}{b}\right)^n \cos(n\theta) \sin\left(\frac{n\phi}{2}\right) \right\}, \quad (5.3)$$

and

$$I_L(t) = \frac{-I_b(t)\phi}{2\pi} \left\{ 1 + \frac{4}{\phi} \sum_{n=1}^{\infty} \frac{1}{n} \left(\frac{r}{b}\right)^n \cos(n\theta) \sin\left[n\left(\pi + \frac{\phi}{2}\right)\right] \right\}. \quad (5.4)$$

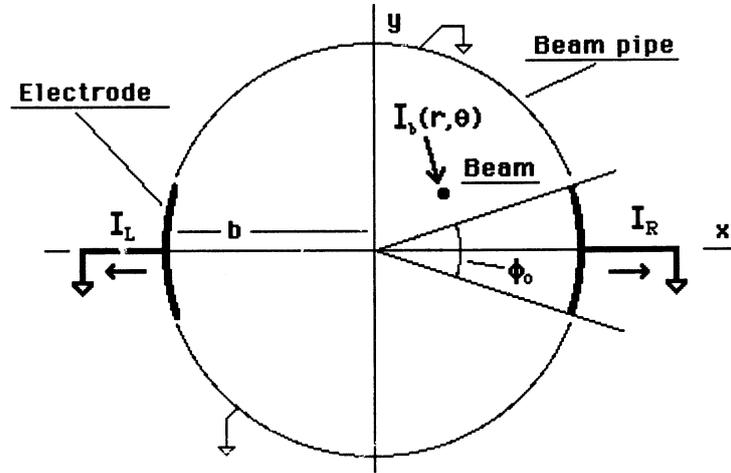


Fig. 5.1. Cross section of beam position monitor pickup model used for calculations.

$$\frac{R - L}{R + L} = \frac{4 \sin(\phi/2)}{\phi} \frac{x}{b} + \text{higher order terms} . \quad (5.5)$$

A more linear (in x) approximation in cylindrical geometry is to write the ratio of R/L in decibels (i.e., logarithmic form):

$$20 \text{ Log}_{10} \left(\frac{R}{L} \right) = x S_x = \frac{160 \sin(\phi/2)}{\text{Ln } 10} \frac{x}{\phi} \frac{1}{b} + \text{higher order terms} . \quad (5.6)$$

As an example, consider two opposing 36° ($\phi = 0.63$) electrodes in a 27.5-mm radius beam pipe. The calculated sensitivity S_x is 1.25 dB per millimeter of displacement. This sensitivity, multiplied by the displacement x , gives the decibel difference of the two signals. If the displacement is 10 mm, for example, the decibel difference is about 12.5 dB, corresponding to an amplitude ratio of 4.2 to 1.

In actuality, the electrodes are neither grounded nor at the same radius as the beam pipe. In practice, the best empirical results are obtained if the radius used in Eq. (5.6) is the average of the electrode and the beam pipe radius. As an example, consider the Deutches Electronen Synchrotron Laboratory (DESY) directional coupler beam position pickup,¹⁹ which has electrode dimensions corresponding to the above example and a ground plane radius of 32.5 mm.

The calculated sensitivity for a 30-mm effective-radius aperture is 1.14 dB per mm, which is close to the measured sensitivity of 1.18 dB per mm.

The actual measured response of the DESY pickup is a nonlinear function of displacement. Figure 5.2 shows the calculated response for a displaced beam in this geometry, using the decibel ratio of Eqs. (5.3) and (5.4). This curve agrees very well with the actual response.¹⁹

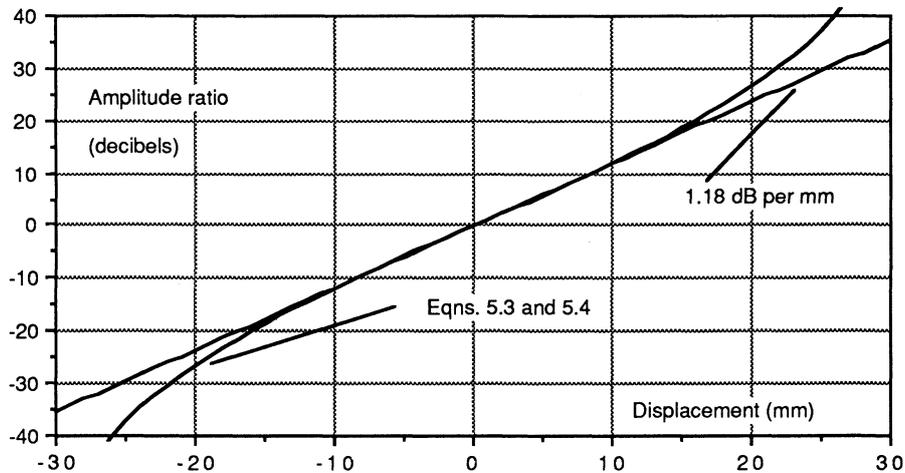


Fig. 5.2. Amplitude ratio response for a beam position monitor with a 60-mm-diam aperture and 36° electrodes. The calculated response using Eqs. (5.3) and (5.4) agrees closely with actual measurements.

Figure 5.3 shows the calculated integral linearity S_x (output amplitude divided by the x displacement) for this pickup for a vertically centered ($y = 0$), horizontally displaced beam and also for a beam displaced vertically by $y = \pm 10$ mm, using Eqs. (5.3) and (5.4). Due to the y -plane dependence, the variation of S_x inside a 20-mm-diam circle is about $\pm 7\%$.

In general, the pickup displacement sensitivity S_x is dependent on both the in-plane and orthogonal-plane displacements x and y . The in-plane nonlinearity can be corrected after the measurement using a software algorithm or look-up table. The orthogonal plane nonlinearity cannot be corrected, however, unless the y position is also measured.

Special electrode geometries can minimize this effect. As an example, Fig. 5.4 shows the calculated response for the above pickup with the electrode width increased to 75° . In this case, the y -plane nonlinearity is nearly zero, and S_x is flat within about $\pm 2\%$ inside a 20-mm-diam circle.

Both Eqs. (5.5) and (5.6) for the electrode response to a beam displacement have higher-order terms and therefore are nonlinear. The nature of the

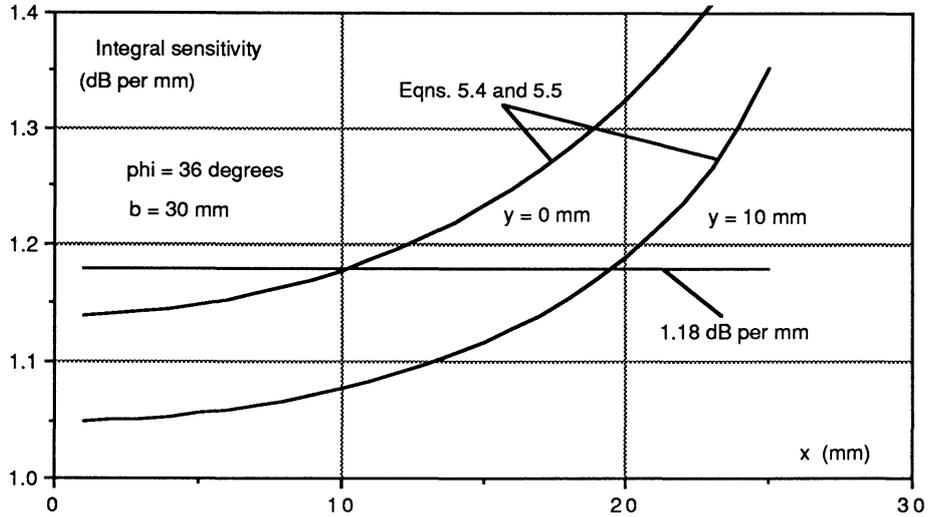


Fig. 5.3. Integral linearity plot for the pickup in Fig. 5.2 (60-mm-diam aperture with 36° electrodes). Note that the sensitivity for a vertically displaced beam ($y = \pm 10$ mm) is about 10% lower than for a vertically centered beam.

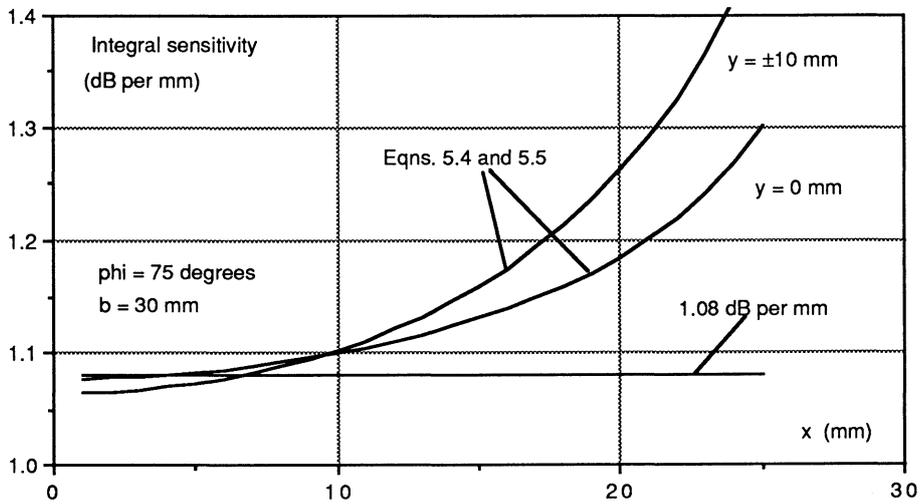


Fig. 5.4. Integral linearity plot for a pickup with a 60-mm-diam aperture and 75° electrodes. Note that the sensitivity for a vertically displaced beam ($y = \pm 10$ mm) is nearly the same as for a vertically centered beam.

nonlinearities are different for the two expressions, however, because Eq. (5.5) represents the normalized difference and Eq. (5.6) represents the logarithmic ratio. It is possible to design an electrode shape that is linear in the normalized difference, and this design will be discussed in a later section.

6. ELECTROSTATIC PICKUP ELECTRODES

We first consider the response of electrostatic (sometimes called capacitive) pickups. We consider specifically two opposing electrodes of length ℓ and azimuthal width ϕ in a beam pipe of radius b . If the current of a centered pencil beam is $I_b(t)$ and the beam has velocity $v_b = \beta_b c$, the charge density of the beam is

$$q_b(t) = \frac{I_b(t)}{\beta_b c} . \quad (6.1)$$

Equal magnitude, opposite-polarity charge appears on the inside surface of the electrodes. For an electrode of length ℓ and azimuthal width ϕ , this charge is

$$Q_s(t) = \frac{-\phi \ell I_b(t)}{2\pi \beta_b c} . \quad (6.2)$$

Assuming there is capacitance between the electrode and ground given by C , the signal current flowing onto the capacitance is equal to the time derivative of the charge on the electrode:

$$i_s(t) = \frac{-dQ_s(t)}{dt} = \frac{\phi \ell}{2\pi \beta_b c} \frac{dI_b(t)}{dt} . \quad (6.3)$$

Note that there is no dc component of charge on the capacitance. The capacitance integrates this current, yielding an output voltage

$$V_c(t) = \frac{\phi \ell}{2\pi C \beta_b c} I_b(t) - V_0 , \quad (6.4)$$

where V_0 is a constant of integration.

This capacitance may be directly between the electrode and the beam pipe, or it may be added externally. The equivalent circuit is shown in Fig. 6.1. It is important to note that the signal source is a current source, and that there is some inter-electrode capacitance. In addition, there is a bleeder resistor used to prevent excessive charge build-up in the circuit. The bleeder resistor causes the average voltage on the capacitor to be zero. Usually in electrostatic pickup circuits the shunt capacitance is the dominant conductance path at the important frequencies, and the voltage across it then represents the beam bunch temporal profile, as is seen in Eq. (6.4).

As an example, consider an electrostatic pickup electrode in the Proton Storage Ring (PSR) at the Los Alamos Meson Physics Facility (LAMPF). With a bunched 20-A peak current of 800-MeV protons ($\beta_b = 0.84$), an electrode of

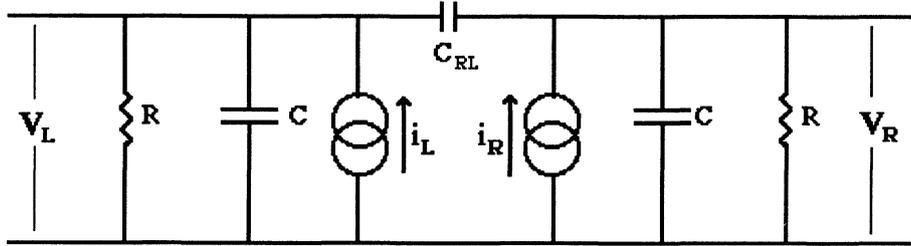


Fig. 6.1. Equivalent circuit for an electrostatic pickup. The signal sources are current generators with amplitudes specified in Eq. (6.3). Note that there is also an interelectrode coupling capacitance.

120° width and 10-cm length, and a capacitance-to-ground of 2 nF, the peak-to-peak output voltage is 1.3 V.

Usually these electrodes are coupled to the electronics by a short piece of transmission line. If neither end is properly terminated, then it is possible to excite standing waves in the cable. For this reason, special effort must be taken to damp the standing waves. The problem is most serious if the electronics is remote from the beam line, either because of the desire to have it outside the interlocked area, or to prevent radiation damage. Sometimes rad-hard electronics (in the form of a cathode follower²⁰) can overcome the radiation problem.

7. LINEAR RESPONSE PICKUP ELECTRODE DESIGN

We now consider a hollow tube with radius b and length $2L$ inside a grounded beam pipe. If the tube is cut diagonally to make two electrodes as shown in Fig. 7.1, the response to beam displacement is linear. This can be seen as follows.

If a beam of charge density q_b is displaced an amount r, θ from the axis of a cylinder whose length is given by $L(\phi) = L(1 + \cos \phi)$, the total charge on the inner surface of the cylinder is

$$Q_s = -q_b L \int_0^{2\pi} \frac{(1 + \cos \phi)(b^2 - r^2)}{b^2 + r^2 - 2br \cos(\phi - \theta)} d\phi . \quad (7.1)$$

Upon integration (with some difficulty), this becomes

$$Q_s = -q_b L \left(1 + \frac{r \cos \theta}{b} \right) = -q_b L \left(1 + \frac{x}{b} \right) , \quad (7.2)$$

which is linear in the beam displacement. The displacement sensitivity S_x is then given by

$$\frac{R - L}{R + L} = \frac{x}{b} , \quad (7.3)$$

which is only half the sensitivity of the electrodes in Eq. (5.5).

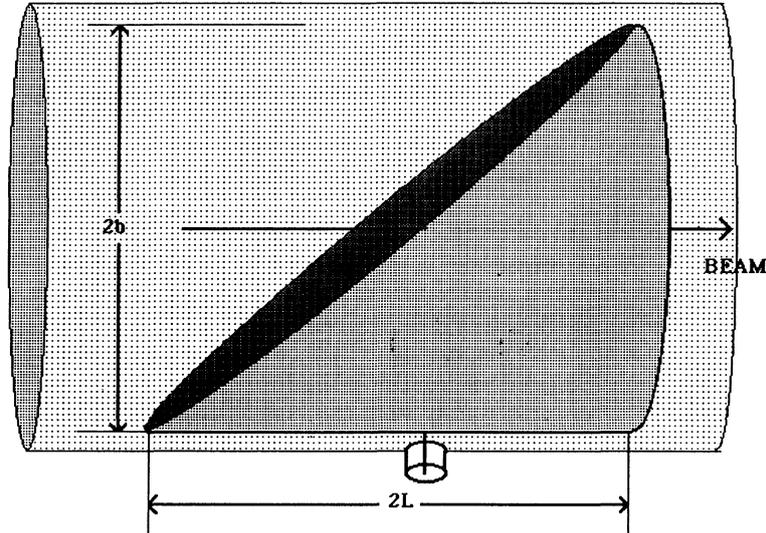


Fig. 7.1. Side view of a diagonally cut circular cross-section electrode that produces a linear response to a displaced beam. The displacement sensitivity (in decibels per unit displacement) is about 50% of a directional coupler with similar aperture.

8. BUTTON ELECTRODES

Button electrodes,²¹ in common use around electron synchrotrons and storage rings, are a variant of the electrostatic electrode. The electrodes are very small and usually circular. Unlike the electrostatic electrode, however, the transmission line carrying the output signal to the electronics is terminated in its characteristic impedance, thus giving a differentiated signal. Their equivalent circuit is essentially Fig. 6.1, but with R being the terminating resistance and C being very small. Using a radius b for the beam-pipe half-aperture, the voltage onto a termination of $R \Omega$ is, using Eq. (6.3):

$$V_B(t) = R i_s(t) = \frac{\phi \ell R}{2\pi \beta_b c} \frac{dI_b(t)}{dt} . \quad (8.1)$$

For circular electrodes, the factor $\phi \ell$ should be set equal to the electrode area divided by b .

It is useful to combine Eq. (8.1) with Eq. (4.1) to calculate the button-electrode response to a single Gaussian beam bunch containing N particles (for $\sigma > \ell/\beta_b c$):

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$$V_B(t) = \frac{-eN}{(2\pi)^{3/2}} \frac{\phi\ell R}{\beta_b c} \frac{t}{\sigma^3} \exp\left[\frac{-t^2}{2\sigma^2}\right]. \quad (8.2)$$

The peak output voltage of this bipolar doublet, which occurs at about $t = \pm\sigma$, is then given by

$$V_{\text{peak}} = \frac{eN}{(2\pi)^{3/2}} \frac{\phi\ell R}{\beta_b c} \frac{e^{-1/2}}{\sigma^2}. \quad (8.3)$$

This peak amplitude varies inversely as the square of the beam bunch length. For this reason, button electrodes are most useful around machines with very short bunches (i.e., electron accelerators and storage rings) and are not normally used around proton machines, which typically have longer bunch lengths (an exception to this is the PETRA ring at DESY, which will use button electrodes for monitoring both electron and proton beams).

If we use Eq. (8.1) in combination with the Fourier series expression as shown in Eq. (4.4), the rms output voltage for a beam intensity signal at frequency $\omega/2\pi$ is (where $A(\omega)$ is the amplitude factor Eq. (4.6) at frequency ω)

$$V_B(\omega) = \frac{\sqrt{2}\phi R}{\pi} \langle I_b \rangle A(\omega) \frac{\omega\ell}{2\beta_b c}. \quad (8.4)$$

This signal amplitude rises linearly with frequency for a given average beam current.

9. RESONANCES IN PICKUP ELECTRODES

We now consider a simple electrostatic electrode inside the beam pipe, as shown in Fig. 9.1. Assuming the only external connection to the electrode is at the center, both the upstream and downstream ends of the electrode are open (i.e., unterminated). Because the electrode forms a transmission line with the beam-pipe wall behind it and has a capacitance and an inductance per unit length, the electrode can resonate with current nodes at each end. Any resonance that has a voltage node at the external connection will resonate with a high Q , because no power can be coupled into the external circuit. The voltage induced by the passing beam thus remains on the electrode and, in some instances, can lead to beam instabilities. For this reason, electrostatic-type pickups of any shape should be avoided if possible. An exception is the button electrode, which is so short that the resonances are at very high frequencies (tens of GHz).

One way to couple to all the resonances in pickups is to make the external signal attachment at one end. In this way all resonances will couple to the external circuit. If, however, the transmission line used for the external circuit has a different characteristic impedance than the electrode itself, there will be a voltage-standing-wave ratio (VSWR) at the connection, and several reflections will be required for the power on the electrode to escape onto the transmission line. This will distort the temporal response of the electrode, which is a concern if the electrode is to be used at high frequencies.

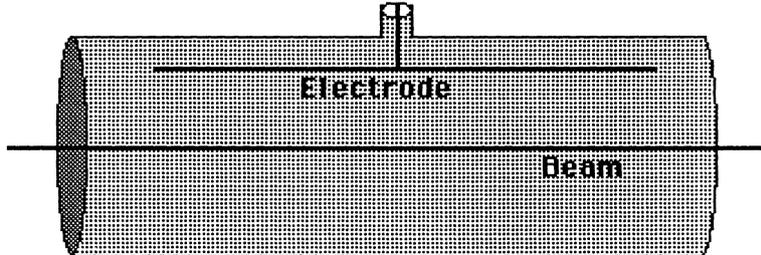


Fig. 9.1. Side view of an electrostatic pickup with the signal connection at the center. Because both ends are open, the beam can excite high-Q resonances in the electrode that have current nodes at the ends and a voltage node at the center.

The standard solution for minimizing the VSWR is to match the characteristic impedance of the electrode and the transmission line. In this case, the power induced on the electrode is transferred to the transmission line without any reflection and, therefore, appears immediately in the external circuit. This design is discussed in the following section.

10. DIRECTIONAL COUPLER PICKUP ELECTRODES

Directional coupler pickup electrodes (sometimes referred to as “stripline” or “microstrip” electrodes) are essentially transmission lines with a well-defined characteristic impedance and with a segment of the center conductor exposed to the beam.

We will examine the signal formation on this type of electrode in both the time and frequency domains. First, we consider the time domain.

Consider an electrode of azimuthal width ϕ , length ℓ , and characteristic impedance Z in a cylindrical beam pipe of radius b , as shown in Fig. 10.1. If the beam current is $I_b(t)$, the wall current intercepted by the electrode is $(\phi/2\pi) \cdot I_b(t)$ for a centered beam. This is the current that flows on the inner surface of the electrode exposed to the beam. When the beam pulse approaches the upstream end of the electrode, this wall current must cross the gap from the beam pipe wall to the electrode. Because the impedance of the gap is half the electrode’s characteristic impedance (the inducing current sees two transmission lines in parallel), the voltage induced across the gap is $V(t) = (\phi/2\pi) \cdot (Z/2) \cdot I_b(t)$. This voltage then launches TEM waves in two directions. One signal goes out the upstream port to the electronics. The other wave travels down the outside surface (primarily) of the electrode to the downstream port at a signal velocity $v_s = \beta_s c$ and out the downstream port. Because the impedance of the transmission line is Z , the current flowing in each direction is half the current flowing on the inside surface of the electrode. The beam travels down the beam pipe at a velocity $v_b = \beta_b c$ and induces a similar signal at the downstream gap,

with a delay given by $\ell/\beta_b c$ and with opposite polarity to the first one. The net result is that at the upstream port, we see a bipolar-doublet signal of the form

$$V_U(t) = \frac{\phi Z}{4\pi} \left[I_b(t) - I_b\left(t - \frac{\ell}{\beta_b c} - \frac{\ell}{\beta_s c}\right) \right] ; \quad (10.1)$$

while at the downstream port, the bipolar signal is given by

$$V_D(t) = \frac{\phi Z}{4\pi} \left[I_b\left(t - \frac{\ell}{\beta_s c}\right) - I_b\left(t - \frac{\ell}{\beta_b c}\right) \right] . \quad (10.2)$$

If $\beta_b c$ equals the TEM wave velocity $\beta_s c$ on the electrode, there is complete cancellation at the downstream port. Therefore this form of electrode structure can be highly directional. Directivities (the ratio of forward to reverse power) close to 40 dB have been obtained. This is quite useful in monitoring beams in collider-type storage rings that have counter-rotating beams.

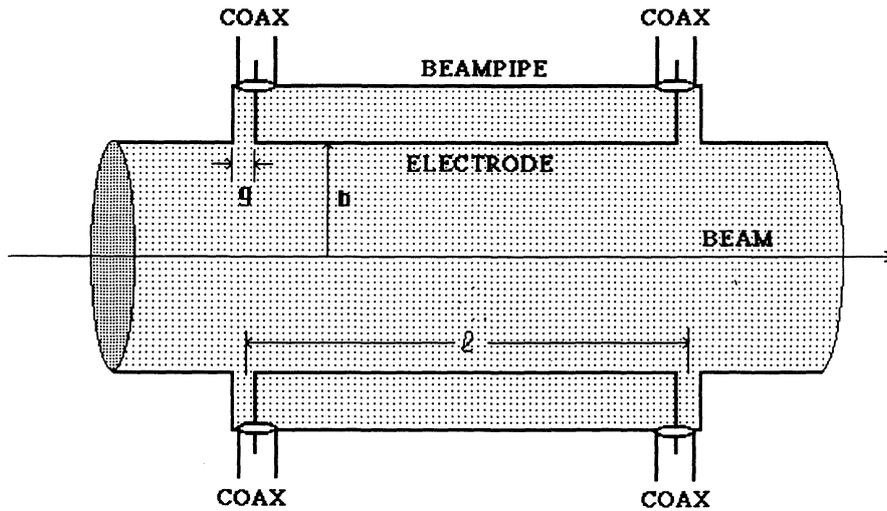


Fig. 10.1. Side view of a directional-coupler beam position electrode. The electrode is a section of an impedance-matched transmission line with the center conductor exposed to the image fields of the passing beam. Signals induced on the electrode exit through the upstream and downstream ports without reflection.

There are several variations of this geometry. In addition to terminating the downstream port in the characteristic impedance, the port may be either shorted to ground or left open. In these cases, the signal traveling down the

electrode to the downstream port is reflected, either inverted (shorted electrode) or noninverted (open electrode). In the latter case, a signal induced at the downstream port by the beam is twice the amplitude and the opposite polarity of the reflected signal. In all cases, the output signal at the upstream port is a bipolar doublet with zero net area.

For a Gaussian beam bunch shape, the bipolar doublet is of the form

$$V_U(t) = \frac{\phi Z}{4\pi} \left[\exp\left[\frac{-(t+\tau)^2}{2\sigma^2}\right] - \exp\left[\frac{-(t-\tau)^2}{2\sigma^2}\right] \right] I_b(t) , \quad (10.3)$$

$$\text{where } \tau = \frac{\ell}{2c} \left[\frac{1}{\beta_b} + \frac{1}{\beta_s} \right] . \quad (10.4)$$

This is plotted in Fig. 10.2 for a 10-cm-long electrode with several values of bunch length σ .

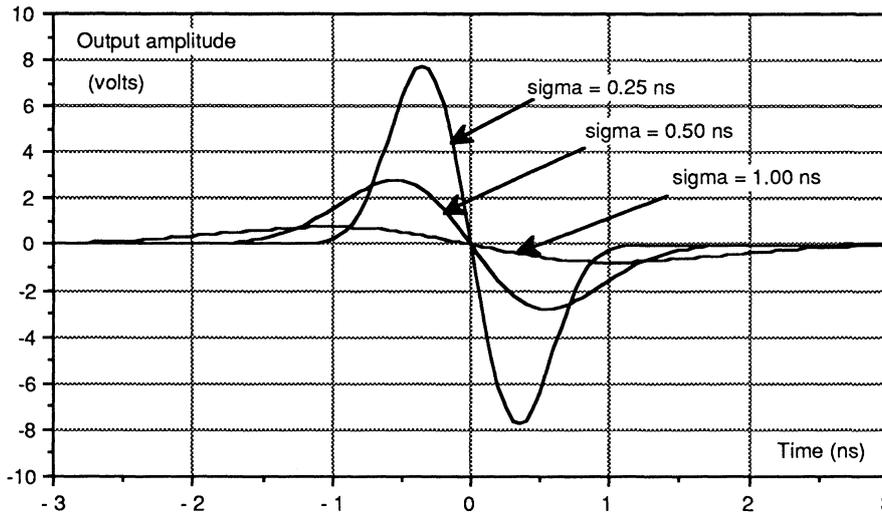


Fig. 10.2. Plot of the expected voltage waveform at the upstream port of a 10-cm-long, 45°-electrode 50 Ω directional-coupler pickup for 10^{10} protons with rms beam bunch lengths of 0.25, 0.5, and 1 ns.

The same analysis can be performed in the frequency domain using Eq. (4.4) for a beam current modulated at frequency $\omega/2\pi$. In this case the rms voltages at the upstream and downstream ports are

$$V_U(\omega) = \frac{\phi Z}{\sqrt{2\pi}} \langle I_b \rangle A(\omega) \sin \left[\frac{\omega \ell}{2c} \left(\frac{1}{\beta_s} + \frac{1}{\beta_b} \right) \right] \quad (10.5)$$

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and

$$V_D(\omega) = \frac{\phi Z}{\sqrt{2\pi}} \langle I_b \rangle A(\omega) \sin \left[\frac{\omega \ell}{2c} \left(\frac{1}{\beta_s} - \frac{1}{\beta_b} \right) \right] . \quad (10.6)$$

Note that there is a length of the electrode for which the argument of the sine function in Eq. (10.5) is $\pi/2$, and the output signal is maximized. This electrode is sometimes referred to as a “quarter wavelength” electrode, even though it is not quite quarter wavelength except when β_b and β_s are both equal to 1. Note also that there are periodic zeros in the response function when the argument is equal to $n\pi$. When this type of pickup is used as a wide-band pickup for looking at signals over a large frequency range, these dips in the response function are easily observed.

At low frequencies, the circular function in the expression for the signal amplitude at the upstream port can be replaced by its argument. The rms output voltage at low frequencies then becomes:

$$V_U(\omega) = \frac{\phi Z}{\sqrt{2\pi}} \langle I_b \rangle A(\omega) \frac{\omega \ell}{2\beta_b c} \left(1 + \frac{\beta_b}{\beta_s} \right) . \quad (10.7)$$

This approximation is valid if the electrode is substantially shorter than a quarter wavelength.

Comparing this approximation to Eq. (8.4) for the button electrode, we see that the two expressions are identical if the signal velocity β_s in Eq. (10.7) is set to infinity and R in Eq. (8.4) is set to $Z/2$. We have used two very different electrode designs in these calculations and two very different calculational methods. When a directional coupler electrode is very short, the output impedance does look like $Z/2$ (because it is terminated in Z at both ends), and we can also ignore the finite signal velocity on the electrode, so this equivalence is expected.

11. OTHER TYPES OF ELECTROMAGNETIC PICKUPS

There are several other types of electromagnetic position pickups that should be mentioned. Small loop couplers²² (often called B-dot loops, meaning dB/dt) are simply small shorted antennas that couple to the azimuthal magnetic field of the passing beam and can be quite directional.

A second type of position pickup that has been used in the past is the “window frame” pickup electrode.²³ In this design, a ferrite window frame is linked with a conductor so that off-center beams create a difference signal.

A third type is the so-called slot coupler (Faltin pickup²⁴) in which the beam fields couple to a nearby center conductor of a transmission line through holes or slots in the ground-plane wall, and induce signals that travel in the beam direction. One shortcoming of this design is that the slots make the transmission line dispersive, and the signal remains in synchronism with the beam for only a narrow frequency range.

A fourth type is a resonant rf cavity excited by a bunched beam in a TM mode that has a null for a centered beam. An off-center beam excites cavity resonances

whose amplitudes are proportional to the product of beam intensity \times beam displacement and whose phase is dependent on the direction of displacement.²⁵

12. HIGH-FREQUENCY EFFECTS

There are two high-frequency effects that the designer should consider when an electrode structure is being designed. These effects are the gap transit time and the Bessel factor.

If the gap g along the direction of the beam between the ground plane and the end of the electrode (see Fig. 10.1) is such that the transit time of the particle across the gap is a significant fraction of the period of the signal being measured, then the resultant signal amplitude is reduced by the transit time factor (TTF)

$$\text{TTF} = \frac{\sin \alpha}{\alpha} ; \alpha = \frac{\omega g}{2\beta_b c} . \quad (12.1)$$

The 3-dB point (TTF = 0.707) occurs when α in the above equation is about 1.4 radians (80°).

The Bessel factor arises from the fact that if the particle is not traveling at exactly the speed of light, the EM fields accompanying it are not TEM waves,²² but have a finite longitudinal extent. This can be seen as follows. Consider a charged particle at rest and centered in a hollow conducting tube. In this case, the field lines connecting the particle to the tube have a finite longitudinal extent (along the axis of the tube), as shown in Fig. 12.1. The longitudinal distribution of charge on the inner wall of the hollow cylinder extends over about $b/\sqrt{2}$ (rms length) where b is the tube radius. If we now transform into a rest frame in which the particle is moving with a velocity $v_b = \beta_b c$, this longitudinal distribution of fields, and the corresponding wall current, moves with it. Note that the wall current actually precedes the particle. For highly relativistic particles, this longitudinal distribution of fields and corresponding wall currents contracts (Lorentz contraction) into a disk, i.e., a TEM wave with no z components. At high frequencies, this finite longitudinal extent causes the signals of slow particles ($\beta_b < 1$) to roll off with the (Bessel) factor BF

$$\text{BF} = \frac{1}{I_0(\text{arg})} ; \text{arg} = \frac{\omega b}{\beta_b \gamma_b c} , \quad (12.2)$$

where $I_0(\text{arg})$ is the modified Bessel function of order zero. For $\text{arg} = 0$, the Bessel factor is 1. The 3-dB point occurs for $\text{arg} = 1.22$. Good design practice generally limits arg to less than about 1.

As an example, consider a 1-MeV ($\beta_b = 0.046$) proton beam in a pickup with a 1 cm half-aperture. The 3-dB point occurs at about 270 MHz.

13. SIGNAL-TO-NOISE AND RESOLUTION

The available thermal noise power in a bandwidth B at temperature T is given by $P_N = kTB$ where k is Boltzmann's constant, T is the temperature in kelvin, and B is the bandwidth in hertz. This is about -114 dBm per MHz

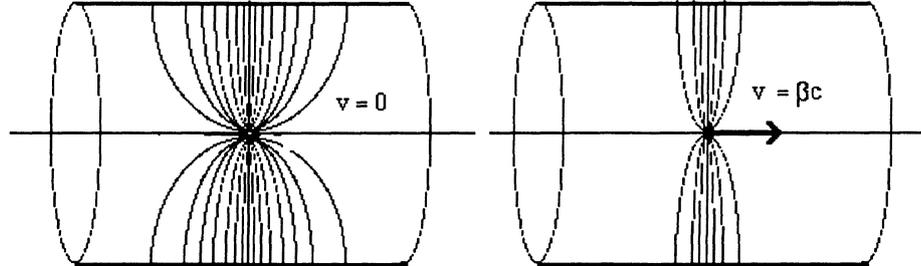


Fig. 12.1. The longitudinal field distribution of a static and moving charge ($\beta = 0.9$) in a grounded conducting cylinder. The longitudinal distribution contracts to a flat disk for highly relativistic particles. For slow particles, the field lines extend about $\pm b/\sqrt{2}$ longitudinally both in front of and behind the particle.

at room temperature. If we include the noise figure of the electronics, the noise power is often many decibels higher.

Resolution is sometimes limited by the noise power. We can use the relations developed in Eqs. (5.5) or (5.6) to estimate the resolution limit caused by thermal noise. The resolution limit is

$$\frac{\delta x}{b} = \frac{1}{4\sqrt{2}} \frac{\phi}{\sin(\phi/2)} \sqrt{\frac{P_N}{P_S}} \approx \frac{1}{2\sqrt{2}} \sqrt{\frac{P_N}{P_S}}, \quad (13.1)$$

where P_S is the signal power on a single electrode. Hence, a 40-dB signal-to-noise ratio (100:1 amplitude ratio) limits the resolution to about 0.35% of the half aperture.

As an example, consider a 1-mA beam in a quarter wavelength 45° ($\phi=0.79$ radian), 50- Ω pickup. The signal power P_S per electrode at the upstream port of a directional coupler is given by

$$P_S = 2 \left(\frac{\phi}{2\pi} \right)^2 Z (I_b)^2 A^2(\omega) \sin^2 \left[\frac{\omega \ell}{2c} \left(\frac{1}{\beta_b} + \frac{1}{\beta_s} \right) \right]. \quad (13.2)$$

Using the above parameters, $P_S = 1.56 \mu\text{W}$, which corresponds to -28 dBm. With a 10-MHz bandwidth and an electronic noise figure of 6 dB, the noise power P_N is -98 dBm. Thus the signal-to-noise ratio is about 70 dB, and the resolution limit is about $3 \mu\text{m}$ for a 50-mm-diam aperture.

Note that the signal power scales linearly with the characteristic impedance of the pickup, as is expected for current sources. Thus if signal-to-noise is a problem, raising the pickup impedance is a solution. Pickups with impedances exceeding 100 Ω have been used successfully. One way to accomplish this over a narrow band is to use a quarter-wave (transmission line) transformer at the

pickup to match the pickup to the cable. Resonant beam position monitors with effective electrode input impedances of approximately 5000Ω have been made for measuring the position of very small beam currents.²⁶

The RFI from accelerator rf systems can have serious effects on the accuracy and resolution if the shielding is not adequate. If the beam-bunching frequency is a subharmonic of the rf frequency, then operating the pickup at the lower frequency often eliminates the interference. EMI (electromagnetic interference) from pulsed and SCR power supplies is often a problem, and great care must be taken to eliminate ground loops that can pick up noise.

Shot noise is not a noise in the case of particle beams, but a signal. It relates specifically to fluctuations in the instantaneous beam current caused by the granularity of the individual particle charges. Because the fluctuations in beam current create a carrier signal, they allow detecting the beam position and therefore are sometimes called Schottky currents. The rms Schottky current for a coasting beam of average current $\langle I_b \rangle$ and bandwidth B is (for particles with charge $\pm e$)

$$I_{\text{shot}} = \sqrt{2e\langle I_b \rangle B} . \quad (13.3)$$

A specific example is that the Schottky current for a 1-A proton beam with a 1-MHz bandwidth is $0.6 \mu\text{A}$.

14. SIGNAL-PROCESSING METHODS

There are three general methods for deriving a normalized position signal from the raw pickup electrode signals. They are difference-over-sum (Δ/Σ) processing, amplitude-to-phase conversion (AM/PM) processing, and log-ratio processing. Each of these have certain advantages over the others. Specific advantages to look for are simplicity and cost, dynamic range (of beam signal intensity), linearity (of response vs displacement), and bandwidth (either acquisition or real-time).

Figure 14.1 shows the expected amplitude response using these three signal-processing methods for a 45° electrode width in a circular beam pipe. It is apparent that of the three processing methods, the log-ratio technique yields the response most linear in beam position.

15. DIFFERENCE-OVER-SUM PROCESSING

There are many variations of the difference-over-sum (Δ/Σ) method. We define shorthand notation as

$$\frac{\Delta}{\Sigma} = \frac{I_R - I_L}{I_R + I_L} \quad (15.1)$$

This ratio is “normalized,” because it is independent of the beam current.

The simplest approach to obtain Δ/Σ would be to detect the rf signals using diode detectors, homodyne detectors,²⁷ or demodulator chips,²⁸ and then to generate analog signals proportional to the rf envelope amplitudes. These signals

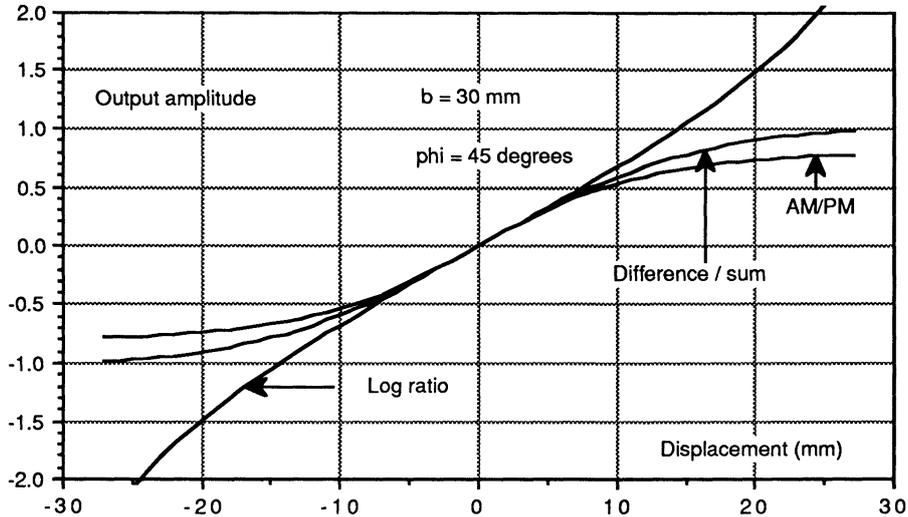


Fig. 14.1. Plot of the response of difference-over-sum, amplitude-to-phase conversion, and log-ratio processing methods to a displaced beam in a 60-mm-diam aperture with 45° directional-coupler electrodes. The log-ratio response is the most linear. All three curves have been normalized to the same slope at the center.

can then be digitized and then processed, or processed in analog circuits to achieve a Δ/Σ signal before digitization. Another common approach is to use 180° hybrid junctions to generate the Δ/Σ signal before rf detection. This latter method requires that the signals, and hence the signal cables, be properly phase-matched at the hybrid junction.

If the digitization is performed before the Δ/Σ function, the granularity of the ADC limits the dynamic range of the system. If the beam current varies over a 100 to 1 dynamic range (40 dB), the resolution with a 12-bit ADC is limited to about 2% of the half-aperture of the pickup at the low end. If the Δ/Σ function is performed in analog circuits, the analog-division process is slow and has a narrow dynamic range. An alternate process uses an automatic-gain-control (AGC) circuit as a normalizer.²⁹ This particular circuit also uses switching between electrodes at 40 kHz to eliminate possible gain differences between rf amplifier channels, which also limits the bandwidth.

One advantage to the Δ/Σ process is that it can also be carried out in the time domain by using a peak detector to capture the peak voltage in the bipolar signal from the individual electrodes.³⁰ A disadvantage of peak detection is that the peak voltage is very sensitive to the pulse shape, as is seen in Fig. 10.2. It is also very sensitive to cable attenuation and dispersion in long cables.³¹ Of all

the processing methods, Δ/Σ is perhaps the easiest to implement, and therefore is by far the most popular method.

16. AMPLITUDE-TO-PHASE CONVERSION

In the amplitude-modulation-to-phase-modulation (AM/PM) method,³² the two in-phase rf signals from the two pickup electrodes are split and re-combined in quadrature (i.e., with 90° relative phase shifts at the processing frequency) to convert the two signals of different amplitudes into two equal-amplitude signals whose phase difference is related to the amplitude difference of the two incoming signals. Figure 16.1 shows a block diagram of the basic conversion process, along with phasors indicating the signal processing. The transfer function is given by

$$\Delta\theta = 2 \tan^{-1} \left(\frac{R}{L} \right) - \frac{\pi}{2} \tag{16.1}$$

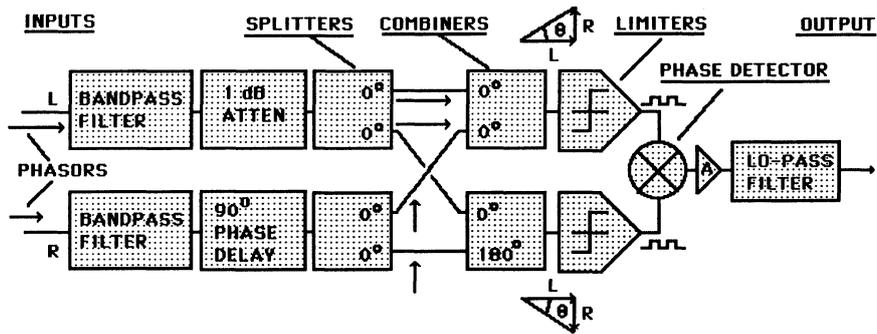


Fig. 16.1. Block diagram of the basic processing system for amplitude-to-phase conversion. After the two in-phase signals are filtered, they are split and recombined in quadrature using power splitters and combiners. At this point, the amplitude difference of the two input signals has been converted to a phase difference (6.6° per dB). The limiters remove the amplitude variation while preserving the phase information. The phase detector produces an analog signal proportional to the phase difference.

The conversion gain for these circuits is typically 6.6° of phase shift for each decibel of amplitude difference in the incoming signals. The quadrature phase shift can be accomplished by using either quarter-wavelength transmission lines (least expensive, but limited to a single frequency) or quadrature hybrids. The two signals are then clipped to a constant amplitude in a hard-limiter circuit that preserves the phase information within a fraction of a degree but removes all amplitude dependence, and then the phase difference is measured in a phase-detector circuit. The most common hard limiter presently in use is the 9685-type comparator, and the phase detectors are usually double-balanced mixers or exclusive ORs.

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The analog voltage output of the AM/PM processor is related to the amplitudes R and L of the two input signals by the relation

$$V_{\text{out}} = V_o \left[\tan^{-1} \left(\frac{R}{L} \right) - \frac{\pi}{4} \right] = V_o \tan^{-1} \left(\frac{R-L}{R+L} \right) . \quad (16.2)$$

Note the relationship to the Δ/Σ processing algorithm.

Hard limiters are usually the components that most restrict the system performance. Their dynamic range varies from 40 to over 60 dB depending on the operating frequency. They have been used at frequencies up to 100 MHz but perform best below about 20 MHz. To use hard limiters when the beam-current modulation is over 100 MHz, the rf signal is often heterodyned down to a lower frequency, typically 10 or 20 MHz. The real-time bandwidth is about 10% of the processing frequency and can be as high as 10 MHz.

AM/PM circuits using down conversion from 200 to 10 MHz and 425 to 20 MHz have been built at Los Alamos.³³ Fermilab has built approximately five hundred 53-MHz units and has built down-conversion units for both the 200-MHz proton linac and for the rapid-cycling Booster synchrotron.³⁴ This latter application is quite interesting in that the local oscillator used for the down-conversion tracks the Booster rf frequency from 30 to 53 MHz with a constant frequency offset, so that the IF frequency output to the AM/PM circuit is constant.

It is essential to keep the relative phase of the two signals entering the AM/PM processor within about $\pm 5^\circ$, otherwise Eq. (16.1) must be modified. Phase matching of the cables from the pickups to the electronics is therefore required.

The AM/PM circuits are specifically for frequency-domain signal processing and therefore function well for multibunch beam pulses. AM/PM processing has also been used for the measurement of the position of single, isolated beam bunches. In this application, a narrow-band filter is placed upstream of the AM/PM processor. The passage of a single bunch by the pickup electrode shock-excites the bandpass filter to ring for perhaps 10 cycles, which is sufficient time to complete the phase difference measurement.^{21, 32} These filters must be very carefully matched, with center frequencies equal within about $\pm 0.1\%$. Both lumped-component circuits and shorted coaxial transmission lines have been used in this application.

Real-time bandwidth is important if the signal is to be used in real-time control of the beam position. In this case, the processed beam position signal is fed back to a beam deflector electrode located upstream of the pickup, and the system is run in closed-loop fashion to reduce the transverse beam jitter. Because AM/PM system provides a normalized position signal, the position signal is independent of beam intensity. The jitter-control function can be accomplished more simply by using an unnormalized difference signal if the beam intensity variation is minimal. In this case, the closed-loop gain is proportional to the beam intensity.

Of the three basic types of position processors reviewed here, the AM/PM circuit is the most expensive and difficult to implement. However, the obtainable large dynamic range and high real-time bandwidth are very desirable features. Thus far, their application is limited to the Linac, Booster, Main Ring, and Tevatron³⁵ at Fermi National Accelerator Laboratory (FNAL); the Proton Storage Ring at Los Alamos National Laboratory;³⁶ and the LEP ring²¹ at CERN. The HERA-P ring at DESY also is planning to use a similar circuit. The SLAC SLC arcs³⁷ use Δ/Σ , however.

If ultimate resolution is the main objective, it is important to consider the effective noise figures obtainable with the various circuits. The effective noise figure for the electronics at the input of the hard limiter in AM/PM processing is in the 10- to 20-dB range and, in addition, there is noise downstream of the hard limiter that produces a resolution minimum independent of beam current.

17. LOG-RATIO PROCESSING

In the log-ratio method, the two signals are put into a discrete or hybrid circuit that produces an output signal proportional to the logarithm of the ratio of the two input signals. The log function is usually obtained by using an ideal forward-biased diode junction in the feedback circuit. There are several limitations to this method. First, commercial circuits are limited to a few hundred kilohertz of bandwidth because of the high dynamic resistance of the "diodes" (actually the base-emitter junctions of matched transistors) at low currents in combination with the distributed capacitance. A circuit designed for high-bandwidth operation possibly could achieve a bandwidth approaching 10 MHz. Second, the log-ratio circuit inputs are usually unipolar, so the signals must be the detected-envelope signals rather than the raw rf signals. Third, the output signal amplitude is proportional to the absolute temperature of the diode junction and should be temperature-compensated. The Analog Devices³⁸ AD538 is a commercially available log-ratio chip with temperature compensation. The Analog Devices AD540 chip uses controlled gain compression to emulate the log process and has bandwidths approaching 100 MHz.

The output of the log-ratio circuit is proportional to

$$V_{\text{out}} = V_o \ln\left(\frac{R}{L}\right) = 2V_o \tanh^{-1}\left(\frac{R-L}{R+L}\right) \quad (17.1)$$

Note the similarity to both the Δ/Σ and the AM/PM algorithm.

18. INTENSITY MEASUREMENT

Although the pickups and circuits discussed here are primarily designed for position measurement, they can be used to measure beam intensity as well. An example of this is the beam position system in the FNAL Tevatron, which has about 220 beam position monitors evenly distributed around the ring (mostly at 4 kelvin because the machine is superconducting) and only one beam current monitor. During the commissioning process, the ability to measure the beam

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intensity at every beam position monitor (using the sum of the electrode signal amplitudes) with a few percent accuracy was absolutely necessary to obtain the first full revolution of beam. Because the output power of the summed signal is slightly sensitive to both the beam bunch length and the beam position, the accuracy is limited.

19. ALIGNMENT, CALIBRATION, AND ON-LINE TESTING

The initial alignment and calibration can be separated into three main components: the pickup electrode assembly, the cabling, and the electronics.

After the pickup construction and assembly is complete, the electrode assembly is normally first “mapped” with an rf-excited taut wire stretched through the pickup at specific points to determine the electrical response for various displacement values of x and y , to determine both the electrical center and the displacement sensitivities, as well as the nonlinearities.¹⁹ The pickup is then installed and aligned mechanically with the other beamline components. An optional alternative is to place the taut wire along the magnetic axis of the beamline magnetic optics after the pickup is mechanically mounted, excite the wire with an rf signal, then measure the electrical offset (decibels of output signal unbalance) relative to the magnetic, rather than the mechanical, axis of the beam optics.³⁹ The electrical offset and the displacement sensitivity are then put into the computer database for correction to the beam position data as they are read out. The nonlinearities, as shown in Fig. 14.1, can be corrected in a look-up table at this time.

In the taut-wire measurement, the signal on the wire is by definition a TEM (principal) wave with no longitudinal electric or magnetic component, travels at the velocity of light, and emulates highly relativistic particles. The signals associated with slow particles, as discussed in Sec. 12 and illustrated in Fig. 12.1, are very difficult to generate on wires. As was shown in Secs. 6 through 10, the pickup response depends on the particle velocity, and this must be taken into account when calculating the pickup response.

The coax cables connecting the pickup electrode to the electronics must be checked for attenuation. If the signal processing is dependent on the relative phase delay in the cable pairs, their electrical length must be equalized as well.

The electronics can be separately calibrated for any electrical offset in output reading and in the voltage output vs decibel difference between the two inputs at a variety of fixed signal input power levels. Because the electronics is an active circuit, it can be expected to have nonlinearities. Therefore the electronics needs to be “aligned” before installation. The alignment process can be quite cumbersome if performed manually, so it is often performed using a computer-automated system. A common alignment circuit in use at both FNAL and LANL is an rf signal generator that uses electronic attenuators under computer control to step through a variety of input unbalances (-10 dB to $+10$ dB in 1-dB steps, and from -60 dBm to 0 dBm in total power output in 1-dB steps (a total of 1260 settings) in about 100 ms.³³ The electronic unit also provides a z axis and a horizontal axis signal (linear in total power dBm) to an x - y oscilloscope. The

analog output of the position-processing electronics provides the y -axis signal. The oscilloscope display is thus a real-time raster display with a 10-Hz refresh rate.

The overall calibration of assembled systems is of the order of 0.5% to 1% of the full aperture for center position accuracy and about $\pm 2\%$ on the displacement sensitivity S_x . Resolution can approach the signal-to-noise limit in Eq. (13.1).

Equally important is providing some way in which to monitor the performance and calibration of a system while it is in use. A method used at FNAL provides special test inputs into the rf input ports of the electronics that could perform these tests. A 10-mA dc current was put through a high-frequency inductor and onto the upstream side of a dc isolator in the rf circuitry. Because the pickup electrodes were back-terminated directional couplers, a measurement of the dc voltage at the point of current input determined the back-termination value within a few ohms and that continuity existed through the signal cable and the directional coupler (at 4 kelvin in the Tevatron) to the back terminations. The same test ports allowed injection of rf signals through a capacitive coupling into the signal-processing electronics with several decibel ratios to check proper operation of the electronics. All these tests, as well as the digitizers for collecting the measurement data, were under local microprocessor control, and the measured data was stored in RAM for subsequent readback by the host computer.

The degree of automation required depends on the size of the position measurement system, and the remoteness of the system components from the central computer. Because beam position measuring systems normally do not have redundancy, it is important to be aware of any channels that are not operating properly.

20. GENERAL HARDWARE SYSTEM ARCHITECTURE

More often than not, accelerator control systems, of which the beam diagnostics systems are an integral part, utilize distributed intelligence to control, read back, and perform a set of on-line tests on the systems that interface to the accelerator.

There are several advantages to using distributed intelligence. First, if a particular diagnostic subsystem performs a critical protection function on an accelerator component, the subsystem must remain operational even when the network to the host computer fails. Second, the microprocessor contains in its database the programs for performing the data collection tasks and the on-line calibration tasks, which can be initiated by the host and performed without host intervention.

In small, local systems, such complexity is not needed. An issue that always seems to arise in the design of small systems is whether the simultaneous measurement of beam position at many position pickups is required. It is certainly much less expensive to install multiplexers and sequentially process the signals from different pickups. However, if the accelerator has a very low duty cycle and a low repetition rate, data collection can be very slow with

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a multiplexed system. Also, if it is important to record betatron oscillations around the closed orbit in a synchrotron for “tune” or betatron phase advance information, a nonmultiplexed system is much preferable.

In terms of interconnections to the host, the following scheme was found to be quite efficient at the Tevatron.⁴⁰ A high-speed communication network (in this case serial CAMAC) was used as a point-to-point bidirectional link for downloading control parameters and reading back data asynchronously (not in real time but under the control of the host). A second single coaxial cable carried a 10-MHz bipolar clock signal with a set of superimposed diphase-encoded timing signals simultaneously to all microprocessors to synchronize them and to initiate sample-and-hold gating and digitization of beam position information or on-line system tests. The results were then stored in local memory until the host requested it. This minimized the traffic on the computer network.

21. SOFTWARE AND DISPLAYS

The effort put into developing software and displays always seems to be underestimated. Creative programmers never seem to have sufficient time to implement their plans. There is however, a minimum amount of software that is truly necessary. It usually is very unique to the specific application and cannot be specified adequately without a detailed knowledge of the system requirements.

Nevertheless, it is possible to say a few words about certain common aspects of software and displays. Automatic beamline control by closing the control loop from the position pickup to beam steering devices through the host computer is becoming more necessary as accelerators and beamlines become more complex. It simply is not possible to steer a beam through a long, complex beamline, or to minimize the orbit distortions in a large synchrotron, without the support of software algorithms.^{41,42} In some beamlines, it may be more accurate to measure the magnetic-lattice transfer matrices on-line than to compute them from beamline lattice designs.

In another area, the need for archiving measurement data for later recall in order to make comparisons is very important in locating malfunctioning accelerator components. For example, “cusps” in the orbit distortions that pinpoint the orbit perturbation are determined by subtracting archived data from new data for the same accelerator operating conditions. Another application is making specific measurements that require changing the accelerator operating conditions; (e.g., making measurements of the dispersion in the lattice⁴³). A third reason for archiving on a very short-term basis is to store a series of beam position measurements in FIFO memories thereby making available instant replays of accelerator performance just before unexpected equipment failures and subsequent beam loss. This of course represents a tremendous amount of data and certainly cannot be handled over a network. For this reason, such a capability must be built into the distributed intelligence, local to the beam position electronics.

Having the right software and displays available at turn-on is a tremendous asset in commissioning a facility. The software is usually one of the last

components to be "installed," and as often as not, it is written by a programmer who is unfamiliar with the accelerator and therefore does not write programs that provide the displays and other information in the most useful format for presentation. Furthermore, as distributed intelligence is becoming more common, the software "tree" is becoming multitiered in that specific control and data-processing functions are being separated into various locations, often with different operating systems, programming languages, and even programmers.

22. CONCLUSIONS

In designing a beam position measurement system, it is important to understand fully the characteristics of beam position diagnostics devices and the accelerator facility in which they are to be installed. It is possible to build a technically excellent piece of hardware that relies on the presence of beam modulation signals that are not always present, or does not take into account all the possible operating conditions of the accelerator, and therefore does not always provide the required measurements. In short, the designer must be knowledgeable in all aspects of the accelerator operation, the beam-coupling mechanism to the pickup electrodes, electronic instrumentation design, and in the applications software.

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- 1.4 Further Reading III:**
Signal Processing for Beam Position Monitors
G.Vismara, Proceedings of Beam Instrumentation Workshop BIW01

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SIGNAL PROCESSING FOR BEAM POSITION MONITORS

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Abstract

At the first sight the problem to determine the beam position from the ratio of the induced charges of the opposite electrodes of a beam monitor seems trivial, but up to now no unique solution has been found that fits the various demands of all particle accelerators. The purpose of this paper is to help “instrumentalists” to choose the best processing system for their particular application, depending on the machine size, the input dynamic range, the required resolution and the acquisition speed. After a general introduction and an analysis of the electrical signals to be treated (frequency and time domain), the definition of the electronic specifications will be reviewed. The tutorial will present the different families in which the processing systems can be grouped. A general description of the operating principles with relative advantages and disadvantages for the most employed processing systems is presented. Special emphasis will be put on recent technological developments based on telecommunication circuitry. In conclusion, an application example will show how to choose the correct solution for a particular case

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Signals processing for Beam Position Monitors

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Abstract. At the first sight the problem to determine the beam position from the ratio of the induced charges of the opposite electrodes of a beam monitor seems trivial, but up to now no unique solution has been found that fits the various demands of all particle accelerators. The purpose of this paper is to help “instrumentalists” to choose the best processing system for their particular application, depending on the machine size, the input dynamic range, the required resolution and the acquisition speed. After a general introduction and an analysis of the electrical signals to be treated (frequency and time domain), the definition of the electronic specifications will be reviewed. The tutorial will present the different families in which the processing systems can be grouped. A general description of the operating principles with relative advantages and disadvantages for the most employed processing systems is presented. Special emphasis will be put on recent technological developments based on telecommunication circuitry. In conclusion, an application example will show how to choose the correct solution for a particular case.

1. INTRODUCTION

The beam position monitor (BPM) can be found in every accelerator and is by far the most popular instrument, particularly useful for machine setting-up and developments.

The BPM has largely evolved since the early days, from the simple scope visualization of coaxial multiplexed P.U. signals into a very complex system. They are now capable of digitizing individual bunches separated by a few tenths of ns, with spatial resolution in the micron range, while the resulting orbit or trajectory collected from several hundred PUs can be displayed in a fraction of a second.

To obtain such a performance the processing electronics have to be optimized to the machine and beam parameters.

A unique solution capable of covering all the possible combinations with satisfactory results seems almost impossible to realize. This is the reason for the wide spectrum of signal processing in use today.

The BPM applications are not only limited to orbit and trajectory measurements, they can also perform static and dynamic beam parameter measurements by exploiting the large amount of data collected and stored in their memories¹.

By a “turn-by-turn” acquisition on a single monitor, it is possible to measure betatron oscillations, beam response and transfer function.

By a “turn-by-turn” acquisition using the whole monitoring system, it is possible to measure phase advance, local chromaticity, phase change versus beam current due to transverse reactive impedance and to perform optics checks.

By averaging over 1000 or more revolutions, high-resolution measurements can be obtained. The orbit response to local deflections is used for beam optics computing while machine impedance measurements are possible from the current dependence of the orbit.

A very recent application is energy calibration. In the LEP machine stable, polarized beam at 45 GeV is used to calibrate a spectrometer, which can then at >100 GeV measure the energy within a resolution of 10^{-4} . Three X and Y monitors on each side of the deflecting magnet, with very high resolution ($<1\mu\text{m}$) and long term and temperature stability, are required.

The BPM is also used for feedback applications to stabilize and align the beam; in this case, speed (loop bandwidth) is more important than linearity.

Another application (ESRF & SPS) for the BPM is the beam position interlock² which dump the beam when an excessive displacement is detected for a certain time.

These applications are much more performance demanding than for a simple position measurement. They require an excellent linearity over a large part of the chamber aperture, a high-resolution (μm) to avoid large beam excitation and good position stability versus beam intensity, time and temperature variation.

2. SIGNAL ANALYSIS

2.1. Signal Source

The reference parameter used to define the input signal in a processing system is the beam current circulating in the machine. The beam current depends on the injected charge and the revolution period. The relation between current and charge is:

$$I_b = Q_b * N_b / t_{\text{rev}}$$

Where Q_b is the charge per bunch in Coulombs, N_b is the number of bunches and t_{rev} is the revolution period.

The beam current is the correct parameter when defining the sensitivity of the processing system if it will integrate over one or more revolution cycles. When using wide-band processing systems, capable of resolving individual bunches, it is much more convenient to talk about charges per bunch.

Another parameter defining the input signal is the longitudinal charge density of a bunch. It can be assumed to be almost gaussian for leptons and cosine-square for protons, hence the induced signals at the PU's output will have almost the same shape. The bunch length depends on the voltage gradient and the beam energy.

It is also assumed that the transverse beam size is negligible relative to the PU aperture but for μm resolution it must be taken into account³.

In order to translate the I_b or Q_b , into the electrical voltage seen by the signal processing system, it is very convenient to define, in analogy to Ohm's law, the following relation:

$$V(t) = Z_t * I_b(t)$$

Where Z_t is called the transfer impedance of the PU.

2.2. Beam Structure

Particle accelerators can be filled with beam in various ways; these determine the signal spectral content that the processing electronics can exploit.

It is possible to define 4 major beam structures.

All rf buckets filled: Beam is trapped by the rf cavities in such a way that a particle bunch is present in all rf buckets. This situation is the easiest to be treated since the induced signal presents an almost monochromatic frequency spectrum. This is a typical condition for machines optimized for the maximum beam current (e.g. PEP II, LEP fixed target operation).

Few rf buckets filled: (with longitudinal symmetry): Beam bunches are only present in a regular structure over N possible buckets. The bunch density is the highest possible. The harmonics content shows the revolution frequency and all the multiple frequencies of [1 / bunch spacing] (e.g. LEP).

Variable buckets filled: In some particular cases the machine is filled with a particular structure, which is not longitudinally symmetric. A large spectral harmonic content is present (e.g. LHC).

Un-bunched beam: This situation can only be present in the absence of an rf signal, exclusively for proton or heavy ions machines (e.g. Cebaf recirculating linac). This is the most difficult structure to process, since an unstructured beam is almost impossible to treat by the processing systems discussed here.

Some authors summarize the above beam filling structures by introducing the notion of a beam-bunching factor. It is defined as the ratio between the bunch width and the bunch spacing.

2.3. Beam Position Monitors

Five PU families are nowadays employed: Electrostatic (Buttons, electrodes of various shapes,..), Electromagnetic (Couplers), Resonant cavity⁴ (specially suited for H.F. linacs), Magnetic and Resistive (wall current).

I will briefly describe the most commonly used.

2.3.1. Electrostatic (Capacitive)

Let us analyze the properties of buttons since they are the easiest and cheapest to build. The image current associated with a circulating beam will induce a charge directly proportional to the beam intensity and inversely proportional to the distance.

Their simplified equivalent circuit is the following:

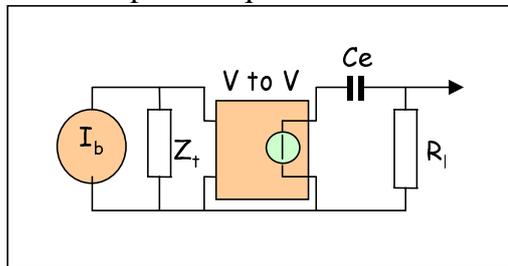


FIGURE 1. Simplified button's equivalent circuit

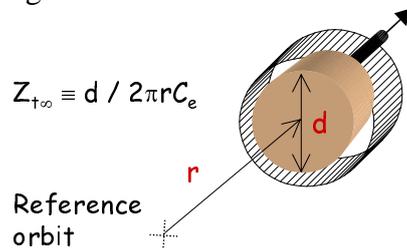


FIGURE 2. Button transfer impedance

where Z_t is the transfer impedance as defined above, C_e is the electrode capacitance and R_l is the load impedance.

The capacitive coupling is responsible for the low frequency cut-off, which depends on the PU time constant $T = R_l C_e$. Its value is in the hundreds of MHz range.

When designing button PUs special care should be taken to suppress unwanted parasitic signals due to the following phenomena:

- The button geometry determines a resonant cavity between the button and the body of the vacuum pipe; this resonator is usually tuned to GHz frequencies and can be excited by short bunches.
- The impedance variation on the transmission line from vacuum to air (ceramic or glass dielectric) will produce impedance mismatching, hence reflections, generating standing waves.

To attenuate these unwanted signals most processing systems have a front-end low-pass filter; in addition, the interconnection cables play a similar role as LP filters. The resulting global frequency response looks like a wide band-pass filter.

2.3.2. Electromagnetic (Strip Line Couplers)

Contrary to the electrostatic PU, here it is the electromagnetic field of the beam that induces a signal on the strip line:

$$Z_{t\infty} = 60 \ln[(r+h) / r] \equiv Z_0 [a / 2\pi(r+h)]$$

where Z_0 is the characteristic impedance and a, r, h are the mechanical dimensions.

The amount of obtainable signal depends on the azimuthal coverage and on the strip-line length if it is comparable to the bunch length (2σ).

The signal response versus frequency has a sinusoidal distribution and its maximum is obtained for a frequency corresponding to $f_0 = 1/4 * t$, where t is the electrical coupler length. On the other hand, for a frequency corresponding to $f_0 = 1/2 * t$ the induced signal will be a minimum. This distribution repeats for all multiples of the fundamental base-band frequency.

Each strip-line has two termination ports and the designer can choose the output signal polarity on the downstream port by putting either a short circuit or an open end on the upstream port. When the upstream port is loaded with its characteristic impedance, no signal will appear on the downstream port, if the transverse electro-magnetic (TEM) wave and the beam speed are identical. In this case, the coupler is directional and it is possible to separate the signals of two beams circulating in opposite directions.

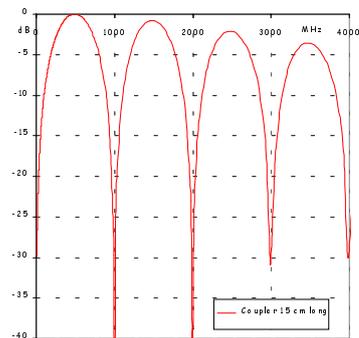


FIGURE 3. Coupler's frequency response

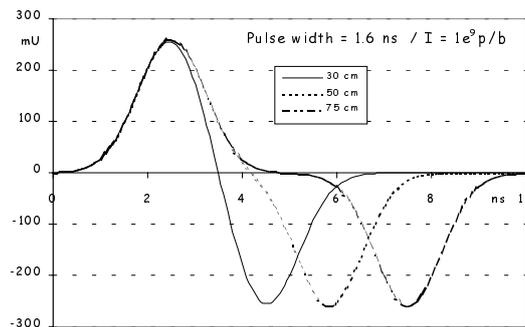


FIGURE 4. Coupler's time response

2.4. Beam position computing

The beam position is reconstructed from the signal difference of opposite PUs. The induced signals are intensity and position sensitive, hence the position can only be obtained by suppressing the intensity dependence; in other words, the signals should be normalized to the beam intensity:

$$\text{Position} = K_{x,y} * \Delta / \Sigma = K_{x,y} * N_p$$

where $K_{x,y}$ is a scaling coefficient, Δ the electrodes signal difference and Σ the beam intensity. For a BPM having a linear transfer function and the electrodes placed on a circular surface (of the vacuum pipe), $K_{x,y}$ corresponds to its radius (Figure 5).

2.4.1. Normalized Position (N_p)

In the above equation, N_p represents the normalized position. It is dimensionless and can vary from -1 unit (U) to $+1U$ passing through 0 for a centered beam.

$1U$ is called the “Normalized half aperture” (N_a). All parameters defining the performance of an analog signal processing system should be specified relative to N_a .

Button or coupler monitors have strongly nonlinear transfer functions, with higher sensitivity at the center. In this case the effective $K_{x,y}$ corresponds to the derivative at the center of the transfer function.

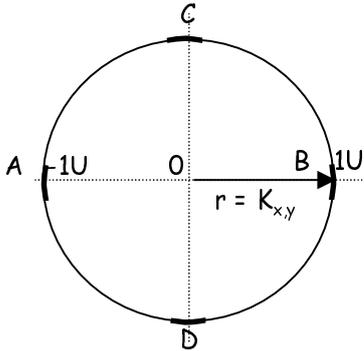


FIGURE 5. 4 PU's normalized representation

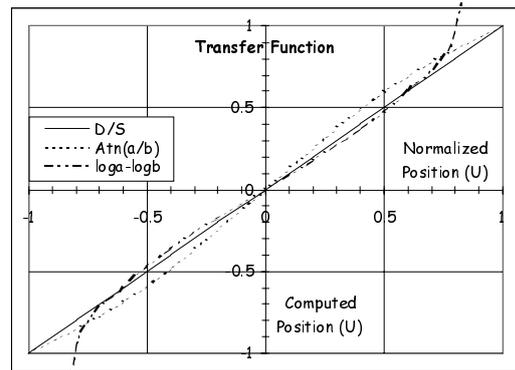


FIGURE 6. Normalized transfer functions

There are at least three methods to obtain a normalized signal.

2.4.2. Difference over Sum

As was explained above

$$N_p = (A-B)/(A+B)$$

where A, B are the induced voltage signals.

The difference and the sum can be obtained either in an analog way by the use of a $0^\circ/180^\circ$ passive hybrid, a differential amplifier, or simply computed by software.

2.4.3. Amplitude to phase conversion (AM/PM)

The two input signals are converted, by the use of a 90° passive hybrid, into two signals having identical amplitude but different phase. Their phase relation is

$$N_p = \phi = 2 * \text{Arctangent} (A/B)$$

The transfer function is not linear, and shows an S shape (Figure 6).
The slope at the center is higher, hence a large sensitivity or better S/N.

2.4.4. *Logarithmic ratio*

The two input signals are converted into their logarithmic equivalents and subtracted from each other, which is equivalent to the logarithm of their ratio.

This is a pure active analog process.

$$N_p = [\log (A) - \log (B)] = \log (A/B)$$

The transfer function is non-linear, and shows a reversed S shape (Figure 6).

There is a very large deviation when exceeding > 70 % of the N_a and the sensitivity around the center is ~1.5 times smaller compared to the AM/PM function.

3. DESIGN PARAMETER SPECIFICATIONS AND THEIR DEFINITION

When starting the design of analog signal processing electronics, one should first define all the parameter requirements indispensable to qualify the performance of the system.

Since engineers have adopted slightly different definitions according to the function of their systems, it is quite difficult to compare the performances of the different solutions.

In this chapter, I will try to define the way each fundamental parameter should be measured.

3.1. Accuracy

Accuracy is the ability to determine the absolute beam position.

This is limited by mechanical tolerances and alignment, the magnetic field distribution and the electronic errors. Beam based calibration techniques allow the global offset of a processing system to be determined for a particular condition, and so establish a reference point.

From here onwards it is the processing electronics that is responsible for the absolute position. The error sources are of various origin: the parasitic element on the PU itself (spurious resonances, impedance mismatching), interconnecting cables impedance mismatching and attenuation, electromagnetic interference and input stage noise, non-linearity and intensity dependence, gain difference between channels, calibration errors, and granularity errors on the digitizer.

3.2. Resolution

Resolution is the minimum position difference that can be resolved.

This parameter is particularly important in colliding machines, where luminosity depends on how accurately beams can be aligned.

Two resolutions can be defined:

3.2.1. Single shot resolution

This corresponds to the standard deviation (Stdev) of each individual position measurement. It applies to single beam passage (trajectory or transfer line) measurements.

3.2.2. Absolute resolution

This has the same definition as above but is obtained from the average over a certain time (e.g. 1 ms) when digitizing at the maximum acquisition rate. It applies to circulating or repetitive beam.

The measurements should be performed under conditions corresponding to a centered beam, at its nominal intensity.

The ADC resolution should be equal to or just below the rms. value of the output noise, measured within the input bandwidth of the digitizer.

At low input level, the absolute resolution depends on the input noise and the bandwidth of the analog processor. For large input signals, the limiting factor is mainly the ADC resolution (number of bits) and the uncertainty on electronic parameters such as the time jitter.

3.3. Stability

Stability is one of the most important parameters in a BPM since the main purpose of the system is to give a stable reference of the center. The uncertainty on the measurement stability will affect the global resolution of system.

The position measurement should be independent of the beam intensity, the bunch shape and the bucket filling.

Stability versus input signal: It is calculated as the Stdev from a series of digitized positions, measured over the whole dynamic range.

Reproducible intensity dependent errors can be compensated by the use of a polynomial fit when measuring the beam intensity.

The measurements should be averaged, in order to reduce the noise contribution to well below the error itself and are usually recorded for a centered position.

In addition, the position measurement should be stable with respect to the time and temperature at least during the time interval between two calibrations. This is extremely important for electron machines or in applications like energy calibration.

Long term position stability (LTPS): It is defined as the Stdev of the digitized values.

Position temperature coefficient: It is the slope of the position drift versus temperature.

The measurements should be done at the nominal input level, with all other parameters being fixed. The time interval for measuring the LTPS should range from at least one hour up to few days depending on the machine, with the temperature ranging from 0 to 40 C.

3.4. Non-conformity to the theoretical transfer function

This represents the measurement error relative to the theoretical transfer function.

Measurements on individual BPMs, high precision measurements (e.g. LEP spectrometer) and preservation of lepton beam spin polarization require processing systems with very low non-conformity.

Non-conformity is defined as the Stdev of the difference between the measured and the theoretical transfer function relative to $2N_a$ ($\pm 1U$). The reason for this choice is determined by the fact that it corresponds to the maximum possible excursion, which in turns equals the full scale of the ADC, in all the normalization process.

The measurement should be done at the nominal input level and for constant sum signals. Since the beam excursion never reaches the extremities, the measurement can in practice be limited to 80% of the full excursion.

3.5. Sensitivity

Sensitivity is the minimum input level at which beam position measurement still fulfills the accuracy specifications.

In order to be able to compare among different machines, the most adequate figure is the number of charges per bunch.

The present limit for standard orbit systems corresponds to a few 10^7 charges/bunch

3.6. Dynamic Range

The dynamic range determines the capability of the system to handle very different beam intensity conditions. Beam position measurements have to be possible, with reasonable accuracy, over the whole dynamic range.

During machine studies, circular machines are often filled with bunches of 1‰ (-60 dB) of the nominal intensity. The same is true for specific physics productions (e.g. Totem for LHC), and at the CERN anti-proton decelerating machine, where bunch intensity is reduced by 80 dB during the deceleration cycle. At GSI/Darmstadt bunch intensities can vary over several decades among proton and various ion beams.

The dynamic range is defined as the difference, expressed in dB, between the maximum input level before a large non-linearity on the output signal appears (saturation) and the minimum input level at which a pre-defined signal to noise ratio (S/N) is reached.

A practical figure to define when saturation is reached is a 1 dB signal compression (= 10% error in the position measurement) while a 20 dB S/N ratio could define the minimum input level.

Processors using a discrimination level will not be limited by the S/N ratio, the lower limit being determined by the discriminator's threshold.

3.7. Acquisition Time

This parameter defines the time required for the signal processor to store a full set of data into memory.

The importance of this parameter is related to the capability of resolving individual bunches and the absolute resolution of the processor, since the faster the system the larger the number of samples per time unit.

Some processor systems have the capability of digitizing individual bunches, others have turn by turn capability and finally some can only measure the integrated signal over several turns.

Several elements contribute to the acquisition time:

- ♣ The low-pass and band-pass filters selecting the useful frequency spectrum required for the signal processor.
- ♣ The switching and acquisition time of all channels (multiplexed signal treatment).
- ♣ The PLL time required to synchronize (synchronous detector).
- ♣ The set-up time for the automatic gain control AGC to stabilize (constant sum signal).
- ♣ The sample and hold circuit and the conversion time of the ADC.

4. PROCESSING SYSTEM FAMILIES

The various signal-processing systems can be grouped into different families according to the employed techniques. At least three different criteria can be used to group them.

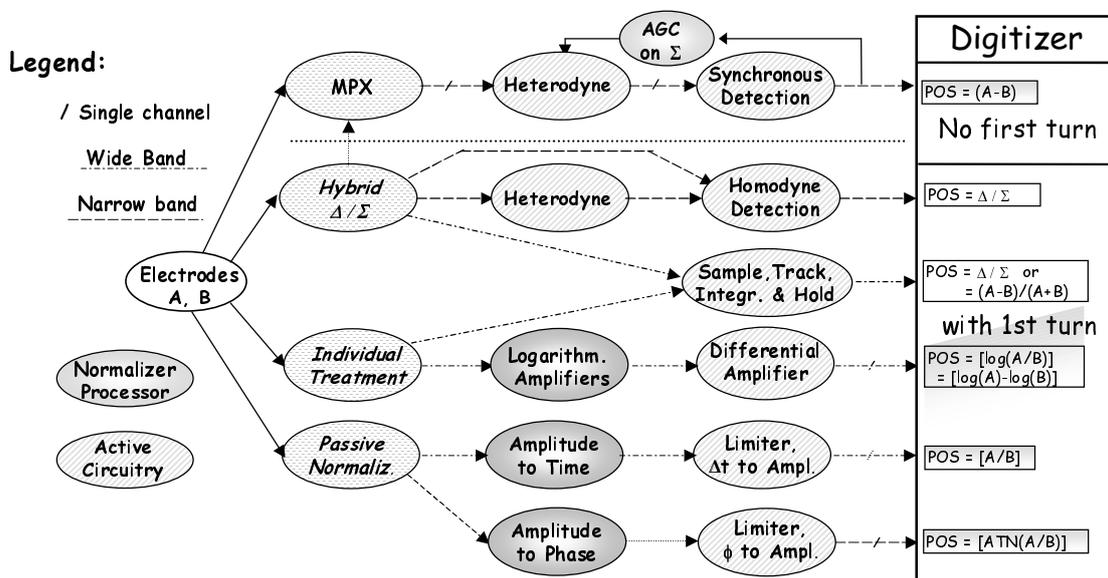


FIGURE 7. Schematic representation of the different families and their interconnections

4.1. Signal Recombination

Four main categories are nowadays employed:

- ◆ **Individual signal treatment:** The maximum signal information is still available, therefore a wide-band processing is the most suitable. Due to a very large Gain-Bandwidth, it offers a limited dynamic range.
- ◆ **Time MPX:** Electrode signals are sequentially time-multiplexed and processed by a single electronic system. It offers excellent long-term stability but cannot perform turn-by-turn measurements.
- ◆ **Δ/Σ :** The individual signals are immediately converted by the use of hybrids into Δ and Σ . This offers excellent center position stability but requires switchable gain amplifiers.
- ◆ **Passive Normalization:** The signal's amplitude ratio is converted into a phase or time difference. This is amplitude independent but the intensity information is lost.

4.2. Normalization Processes

Normalization is an analog process that will produce a signal proportional to the position information and independent of the input signal level.

Three conditions apply to all normalization processes: 1) The intensity information is lost. 2) The digitization requires a smaller number of bits. 3) No gain selection is required.

Two active and two passive techniques are actually employed.

- ◆ **Constant Sum:** The Normalization is obtained by keeping constant the sum of the two electrode signals using AGC amplifiers. This approach applies to the time MPX process, where the signals exploit the same amplification chain and the digital receiver, where a permanent calibration on all channels will guarantee identical gains.
- ◆ **Logarithmic Conversion:** Since the ratio of the logarithm of two signals is equal to the difference of the logarithm, the signals can be converted by logarithmic amplifiers to give the normalized signal as the difference of the outputs. It offers a large dynamic range, but limited linearity.
- ◆ **Amplitude to Time:** This is based on the sum of a direct and a delayed signal coming from the two electrodes. The zero crossing of the sum signal varies with time proportionally to the signal ratio, and hence to the position. It offers large bandwidth but is limited to bunched beams.
- ◆ **Amplitude to Phase:** Is a similar process where time is replaced by phase and a single period by multiple oscillations. It is a simple solution but requires accurate phase matching (Filters).

All other processes that require computing software to extract the position information from the recorded data are known as un-normalized processes.

4.3. Acquisition Time

This is the time required for the BPM to supply a full set of data to the digital processor. Three categories can be created:

- ◆ **Wide-band:** It groups all processing systems capable of measuring individual bunches separated by >10 ns down to a single bunch. The bandwidth can be as high as 100 MHz. Systems that belong to this group include: Sample/Track & Hold, Logarithmic amplifiers, Amplitude to Time normalizers.
- ◆ **Narrow-band:** It groups all processing systems capable of resolving one machine revolution period and in some cases can measure individual bunches separated by >100 ns. The bandwidth ranges from a few 100 kHz up to a few MHz. The Heterodyne and Amplitude to Phase processors belong to this group.
- ◆ **Slow acquisition:** A special class is reserved for the Time MPX processing which, while having an equivalent bandwidth relative to other heterodyne systems, is penalized in the acquisition rate by the time multiplexing.

5. PROCESSING SYSTEM DESCRIPTIONS

5.1. Time Multiplexed Processor ⁵

The processor is conceived for closed orbit measurement of stable stored beams.

The input MPX is usually built with a multiple configuration of Ga-As switches; the channel isolation should be >50 dB for frequencies up to 1 GHz.

A band-pass filter is used to select the largest line of the signal spectrum; its selectivity is not critical.

The essential element is the pre-amplifier which should handle a very large dynamic range (>75 dB) and compress it by >50 dB. Its input admittance should be kept stable as a function of the gain to avoid a zero offset drift. The global noise figure is increased by different insertion losses and should be optimized for the largest gain.

An active mixer, making use of a frequency synthesizer to reduce the noise contribution, is used to down convert the signal to a standard intermediate frequency (IF usually 10.7 MHz or a multiple). The IF amplifier and the demodulator are usually integrated telecom circuits. The IF bandwidth is selective enough to suppress side bands at the revolution frequency (multiple bunches) but sufficiently wide to allow for

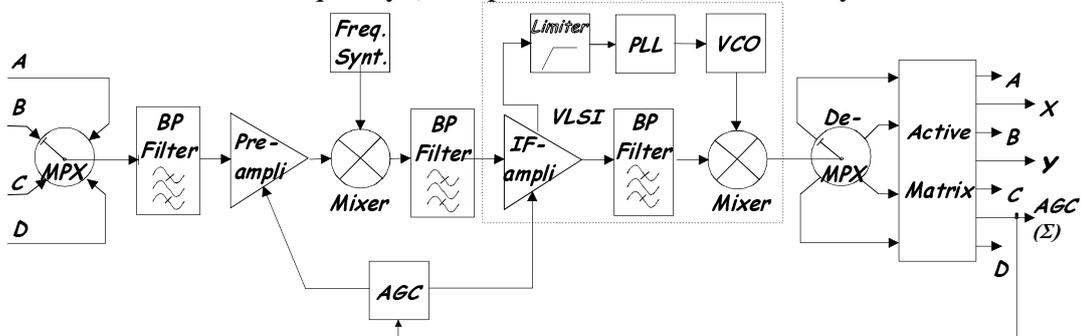


FIGURE 8. Block diagram of the time MPX processor.

fast switching among channels ($100 \text{ kHz} > \text{BW} < 1\text{MHz}$). Synchronous detection is obtained by comparing the phase of a sample of the carrier frequency with a reference signal and driving a VCO in a phase locked loop. Synchronous detection offers a clean detected DC signal but it slows down the MPX switching time since the PLL has to relock after each switching (even with accurate phase adjustment).

The last part of the chain is composed of an output de-multiplexer, four track & hold amplifiers and an active matrix of video amplifiers to produce the AGC sum and X, Y positions ⁶.

TABLE 1: Time Multiplexed processor

Advantages	Limitations
Normalization process	Requires a stable beam during the scanning
Reduced number of channels (x4)	No turn by turn acquisition
Identical gain for all the channels	Slow acquisition rate (MPX)
Large dynamic range (>80dB)	Reduced Noise Figure (gain matching & MPX insertion losses, AGC pre-ampli.)
Excellent position stability	Reduced linearity, for non-linear PU's since the Σ is not constant
No temperature dependence and component aging	Complex engineering

5.2. Δ / Σ Processor

When using this approach it is convenient to convert the input signals into their equivalent difference and sum at the earliest possible stage. This is done by a simple and reliable passive element called the “180° hybrid”. The input signals should be in-phase, which means tight tolerances on the interconnection cables. Since the hybrid is radiation resistant, it can be connected directly to the electrodes.

Wide-band: The LP filters will just stretch the pulses. The pre-amplifiers have a large BW and programmable gain but a limited dynamic range. For long bunches, the S & H circuits are suppressed and FADCs (1 GS/s) digitize the signal directly ⁷.

Narrow Band: In most of the cases, the hardware is similar to that of the time MPX. In some applications, the heterodyne conversion is suppressed. The pre-amplifiers have low noise figure ($\text{NF} < 2\text{dB}$), programmable gain through pin diodes switches, and will absorb a large input dynamic range (> 90 dB). A fraction of the Σ signal is limited and used as a local oscillator in a homodyne detector. The Δ & Σ signals are digitized by a track and hold circuit and externally triggered ADCs. This scheme is

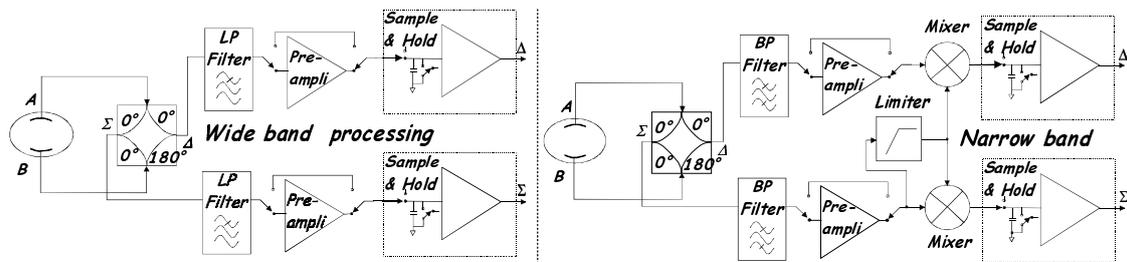


FIGURE 9. Block diagram of the Δ / Σ processors

also used for single bunch measurement in complex injector machines (SPS)⁸, where the bunch excites the BP filter to resonate on its central frequency (see amplitude to phase normalizer). No hardware modifications are necessary but even tighter tolerances on the phase matching are required.

TABLE 2. Δ & Σ Processor

Advantages	Limitations
The central position is independent of input intensity	Programmable gain amplifiers
Intensity measurement is available	Multiple calibration coefficients
Excellent Noise Figure	The absolute position is $f(\text{gain})$
[Wide band allows measurements on multiple bunches ($\Delta t < 20$ ns)]	{ Tight phase matching (Δ, Σ) at all the gains required by the synchronous detection ($\pm 5^\circ$) }
{ Large dynamic range > 90 dB }	{ Pedestal error on Σ }

[W.B.] & {N.B.}

5.3. Logarithmic Amplifiers^{9, 10, 11}

The processor makes use of logarithmic amplifiers to compress each signal. The outputs are at first demodulated, filtered and applied to a differential amplifier.

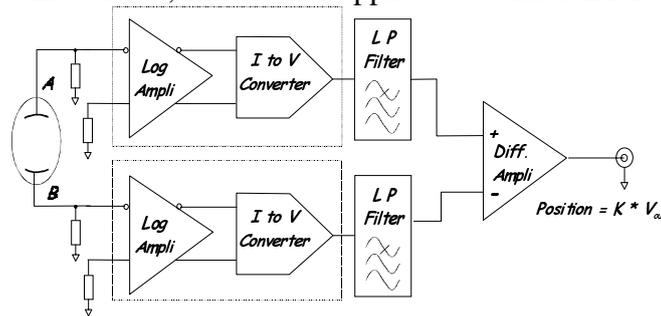


FIGURE 10. Block diagram of the logarithmic amplifier processor

The schematic is very simple but the hardware realization hides a very sophisticated electronic circuit in order to approach the ideal function. New generation circuits make use of several cascaded limiting amplifiers, with fixed gain and a wide bandwidth. Full wave rms. detectors are applied at each stage and by summing their output signals, a good approximation to a logarithmic transfer function is obtained.

TABLE 3. State of the art parameters for Logamp.

Input dynamic range	> 90	dB
Input noise	< 1.5	nV/ $\sqrt{\text{Hz}}$
Non conformance linearity	$< \pm 0.3$	dB
Limiter Bandwidth	D.C. to > 2	GHz
Video Bandwidth	D.C. to 30	MHz

The demand of the consumer market (primarily telecommunications) for these products has resulted in a wide variety of new circuits, each one optimized for a specific parameter.

TABLE 4. Logarithmic amplifiers.

Advantages	Limitations
Possible applications in the time and frequency domain (NB & WB)	State of the art performances are not simultaneously available
Very large dynamic range (>90 dB)	Poor position stability vs. input level, for peculiar conditions
Wide input bandwidth	Limited linearity (few % of the N_a)
No bunch shape dependency	Limited long term stability
Simultaneous digitization of + and - charges	Temperature dependence
Simple engineering	

5.4. Amplitude to Phase Normalization

This technique was first developed for RF signals working in the frequency domain and rapidly adapted to short pulses working in the time domain ¹².

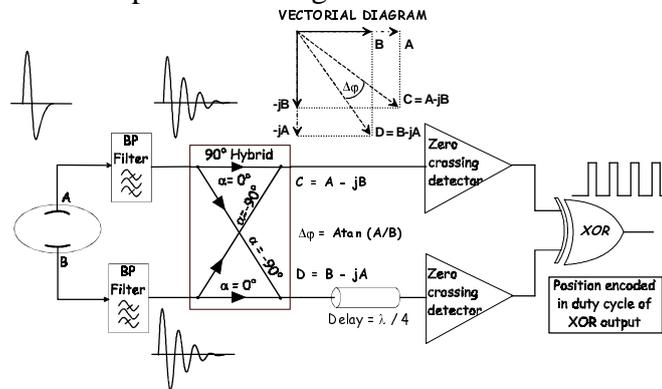


FIGURE 11. Block diagram of the amplitude to phase (AM/PM) processor

The two electrode signals are converted into a RF burst or a permanent RF signal, according to the beam shape, by the use of a BP filter. These in-phase signals are applied to the inputs of a “90° Hybrid”. Each signal is split into two branches; one of them is shifted by 90° and added to the opposite in-phase signal, and vice versa. The outputs are of equal amplitude and have a phase difference ($\Delta\phi$) proportional to the position.

$$\text{Position} \equiv \Delta\phi = 2 * \text{Arc-tangent} (A / B) - \pi/2$$

This relation is valid for both a continuous wave or for a burst after proper settling time, which depends on the bandwidth. To avoid an ambiguity in sign, one output is also delayed by 90° degrees.

The two signals are applied to comparators that suppress the amplitude dependence. The phase difference is reconverted into an amplitude variation by the use of XOR logic. The position information has a variable duty cycle at twice the filter frequency, and is digitized by an ADC driven by a LP filter and a video buffer.

Two cases should be distinguished:

Current modulated beam: The BP filters are tuned to the largest line in the frequency spectrum. Their selectivity (BW) should suppress all spurious frequencies (rejection > 40 dB) but be wide enough to accept the small frequency changes that may occur during an acceleration cycle. The BP filters are not critical elements and the phase shift needs only be matched to within a few percent.

Frequency down conversion¹³ : For frequencies above 150 MHz, comparators are less performant and the signal is therefore down converted using heterodyne conversion. The acquisition time is increased by the ratio f_{rf}/f_{if} .

Bunch modulated beams (single or multi bunches): The induced signals charge the BP filter, which in turn will start a free oscillation on its central frequency for a predetermined time. The pulse width should be shorter than the oscillation period ($W_{(fwhm)} < 1/4 * f_0$) to obtain the maximum signal. The bunch spacing should be larger than the damping time of the filter to allow for individual measurements. Acquisition rates up to a few MHz can be achieved, so that turn-by-turn and individual bunch acquisition is feasible. Since the BP filter selectivity is not critical, a single resonator can be employed. However, this results in a longer damping time and therefore requires a longer bunch separation¹⁴. Several BP filter parameters should be accurately matched in order to preserve the relative phase over several oscillation periods.

TABLE 5. Amplitude to Phase Normalization.

Advantages	Limitations
Normalization process	Upper frequency limit < 150 MHz
Reduced number of channels (x2)	Tight phase adjustment
Input dynamic range > 50 dB	[Minimum bunch spacing (> 100 ns)]
~10 dB reduction on the position dependent dynamic due to signal recombination (90° sum)	[Matched pair BP filters (tight tolerances)]
[Dynamic range is independent of the number of bunches]	Hardware; limited technological improvements foreseen
Simultaneous digitization of + and - charges	
Simple & Reliable	

{ Current modulated beams }, [Bunched beams]

5.5. Amplitude to Time Normalization

This new normalization idea is derived from the “Amplitude to phase” principle where “phase” is replaced by “time” and the applied signal has a single oscillation period. It applies to bunched beams and works in the time domain^{15, 16}.

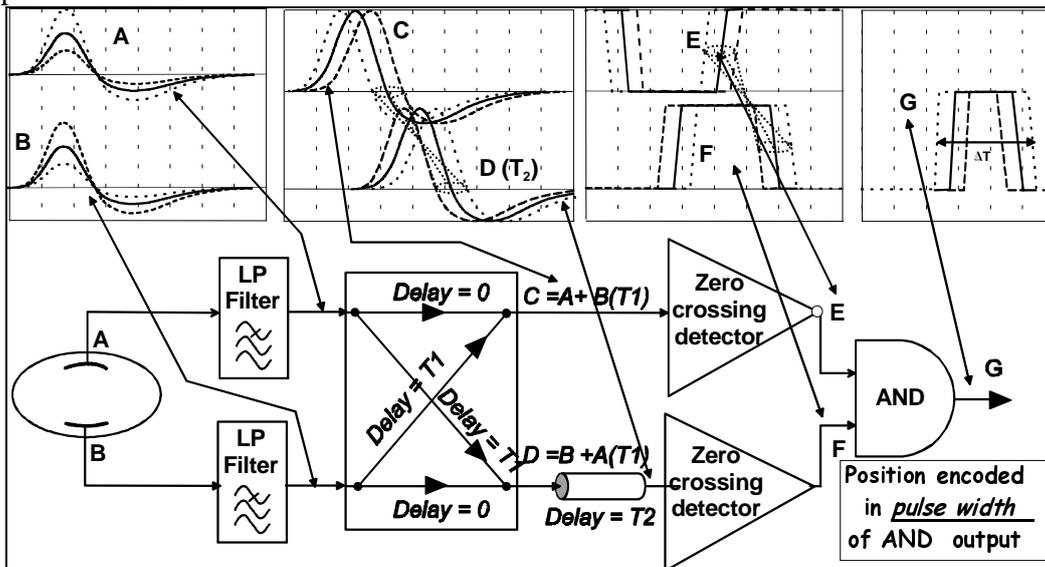


FIGURE 12. Block diagram of the amplitude to time processor

The LP filters produce the correct pulse shape. The signals from both electrodes are split in two and one branch is delayed by a time T_1 . The delayed signal of one channel is then added to the direct signal of the other channel, and vice versa. At C, the time of the zero crossing varies according to the signal ratio, up to a maximum of T_1 . At the output D, you have the same signal amplitude but the time variation has opposite sign.

The maximum time difference is therefore $2 * T_1$. The delay offset T_2 is required to avoid sign ambiguity and should always be larger than T_1 . The zero crossing is independent of amplitude and is easy to detect using fast comparator circuits. Their outputs drive an AND gate, which generates a pulse with a width proportional to the beam position.

$$\text{Position} \equiv \Delta t = 2 * T_1 * [(A - B) / (A + B)] + T_2$$

By integrating this pulse, the time variation is transformed into an amplitude that can be read by an ADC.

TABLE 6. Amplitude to Normalization.

Advantages	Limitations
Fastest normalization process (> 40 MS/s)	Can only be employed with bunched beams
Reduced number of channels (x2)	No Intensity information
Input dynamic > 50 dB	
~10 dB reduction on the position dependent dynamic due to signals recombination	Tight time adjustment
Dynamic is independent of the number of bunches	Propagation delay between comparators
Almost independent of the bunch length	

Remark: A specifically designed monolithic Ga-As chip would allow for a large speed breakthrough.

5.6. Digital Receiver ^{17,18}

The digital receiver is a new approach to the classical heterodyne receiver. This has become possible due to technological improvements in the telecommunication field.

In this new approach, the basic functionality is preserved but implementation is different. In fact, as processing and sampling technologies improve, digital moves from the baseband end (a) towards the pick-up sensor (b). The present situation allows the digital transition to take place just after the IF amplifier.

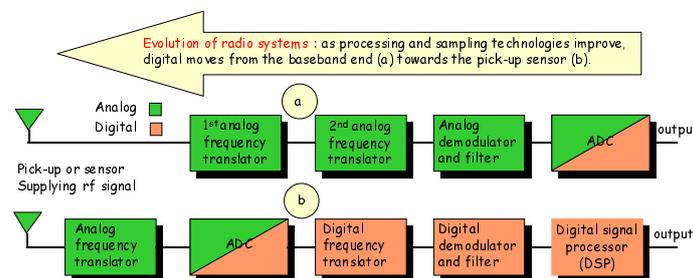


FIGURE 13. Block diagram of the evolution of the heterodyne receivers

The RF front-end circuit, while being identical to its analog counterpart, requires a specific design adapted to the digital world. A BP filter selects the useful signal while rejecting the image frequency and a Pin diode attenuator is used to avoid saturation.

A frequency down conversion then transposes the signal to the tens of MHz range (~36 MHz). A surface acoustic wave (SAW) filter with in-band flatness of ± 0.1 dB and a very linear amplifier with adjustable gain to ensure large dynamic range, are required.

The heart of the digital receiver is the analog to digital converter (ADC). Present performances for low cost ADC are: Input bandwidth (>100MHz); Sampling rate (> 40 MS/s); Resolution (12 bit); Linearity (<.5 LSB). The sampling rate should be chosen to be a few MHz below the IF frequency in such a way that the signal aliases down to the base band.

Once the IF signal is successfully digitized the next step is the data processing. This could be done by one or more digital signal processor (DSP), which implement the remaining functions (IF filtering, demodulation, data reduction). However, the total processing required in such a receiver may add up to several GFLOPS (giga floating operations per second), which is not a straightforward operation. For this reason specialized digital hardware, known as Digital Down-Converter (DDC) has been designed to perform these specific tasks.

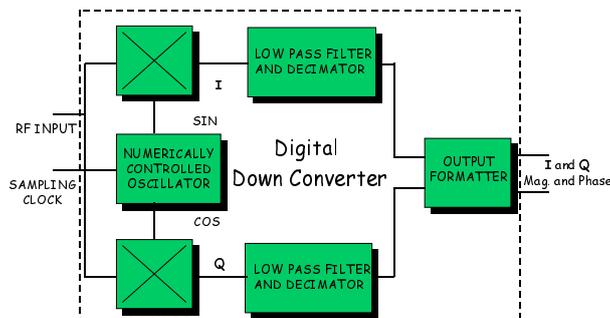


FIGURE 14. Block diagram of a digital down converter

The filtering action defines the processor bandwidth, which in turn affects the system resolution. Since the tuning frequency can easily be re-programmed, the same hardware allows for high speed / medium resolution and low speed high-resolution acquisition.

The data reduction (also called decimation) drastically reduces the downstream signal processing requirements.

The data flow is stored in a FIFO memory and accessed by a DSP that applies the correction factors, does additional filtering, calculates the position and the intensity and performs all other post-processing such as FFTs, etc.

Four identical channels are implemented, one for each electrode in the BPM block.

In order to guarantee an identical and stable gain in each channel, a pilot signal at a frequency shifted by -1.5 MHz and at a level of -10 to -20 dB relative to the beam signal is permanently injected via couplers.

By simply changing the tuning frequency of the digital IF filter, one can choose either the beam or the pilot signals. The digitized pilot signal is used to change the gain in the IF amplifier and keep the global four channel gain within the specified tolerance.

In the classical heterodyne receiver, the most critical parameter is the demodulator non-linearity. When using a digital processor, the demodulation action is done

digitally by the DDC, hence suppressing this error. Here it is mainly the ADC that defines the global non-linearity.

Another advantage of the digital receiver concerns the resolution. The signal to noise ratio is improved by the digital filtering and the over-sampling with respect to the base band. This factor corresponds to the square root of the ratio of the digital band-pass filter to the Nyquist bandwidth, expressed in dB.

TABLE 7. Digital receiver.

Advantages	Limitations
Programmability	No single shot measurement
Narrow & Wide band processing	No “plug and play” system
Identical gain for all channels due to possible permanent calibration	All problems related to a new inexperienced processing system
Resolution improved by over-sampling techniques	Complex engineering
Large dynamic range	
Excellent linearity (only limited by the ADC)	

6. APPLICATION EXAMPLE

The PS and SPS are versatile machines, capable of producing and accepting over 7 different types of beam. The transfer line between the two machines will be equipped with 20 BPMs, spread over 1.5 Km.

The purpose of this example is to choose the most suitable processing system.

6.1. Specifications

6.1.1. Beam parameters

TABLE 8. Beam parameters of the 4 most important cases for the PS to SPS transfer line

Beam	N° bunches	Spacing	Width	Intensity	Dynamic	Dynamic
Fixed target	2000	5	1.66	$1 \cdot 10^9$	30	42
LHC	1 to 84	25	2.1	$3 \cdot 10^9$	35	86
Special beam	1, 8, 16	131.2	4.8	$5 \cdot 10^9$	20	56
Heavy ions	16	131.2	6.2 / 15	$2.6 \cdot 10^8$	10	22
	N	ns	(fwhm) ns	Charge/bunch	(Bunch) dB	(Global) dB

Analysis of the beam parameters (Table 8) reveals the following difficulties:

- A very wide dynamic range (>86 dB), which comprises bunch intensity variation, variable number of bunches and 12 dB of position dynamic range.
- A variable bunch width, of an order of magnitude.
- Bunch spacing from 5 ns to a single bunch.

6.1.2. Processing system specifications

The required accuracy and linearity should be contained in 2% of the N_a for a nominal beam, while resolution and stability versus intensity should be $< 0.5\%$ of the N_a .

The PS extraction time is such that beam duty cycle is very low in the transfer line hence limiting the integrated radiation to an acceptable value.

Considering the long distances between the PUs and the electronics racks and taking into account the high frequency signal spectrum, it is advisable to place the processing electronics as near as possible to the PUs.

6.2. Pick-up choice

For a beam intensity of a few 10^8 p/b, the choice of a coupler offers a better sensitivity compared to buttons. The coupler length should be optimized to obtain a maximum response in the frequency range from a few MHz up to 200 MHz. This corresponds to a coupler length of 50 cm, with an azimuthal coverage of 24° and $Z_t = 7 \Omega$

6.3. Spectral analysis

The variable frequency signal spectral content makes it difficult to choose whether a wide or narrow band processor is most suited to this application.

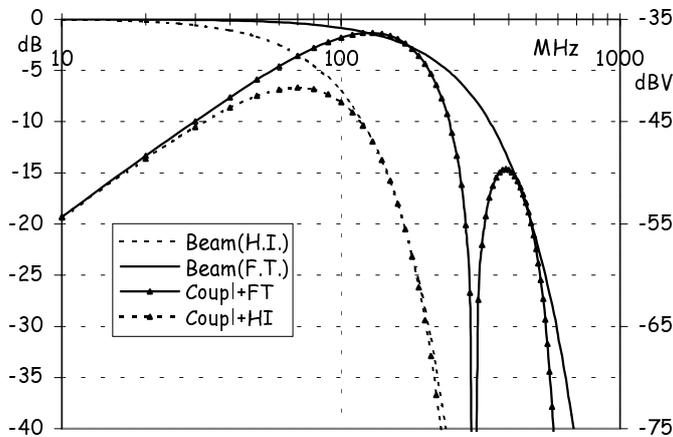


FIGURE 15. Beam and coupler signal frequency spectrum.

A “Spice” simulation of 3 particular cases (fixed target, LHC and single bucket filling) will help for a better understanding.

Let's take a wide-band system with a low-pass frequency of 200 MHz and a band-pass filter centered at 200 MHz, having a 12 MHz bandwidth. For a real narrow-band system (≈ 1 MHz) you can linearly scale down the results of the above-simulated BP filter.

Figures 16, 17 and 18 show the frequency contents and the time domain response.

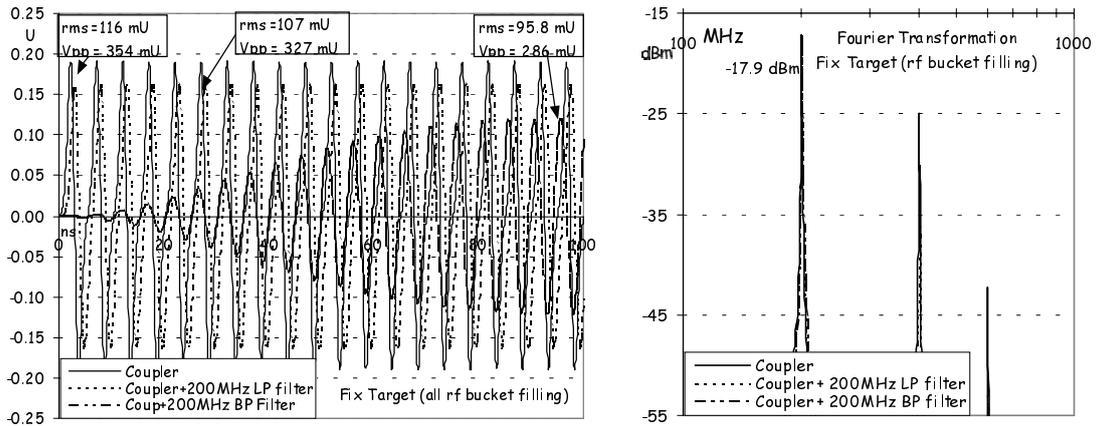


FIGURE 16. Fixed target (all rf buckets filled). Time response and spectral content

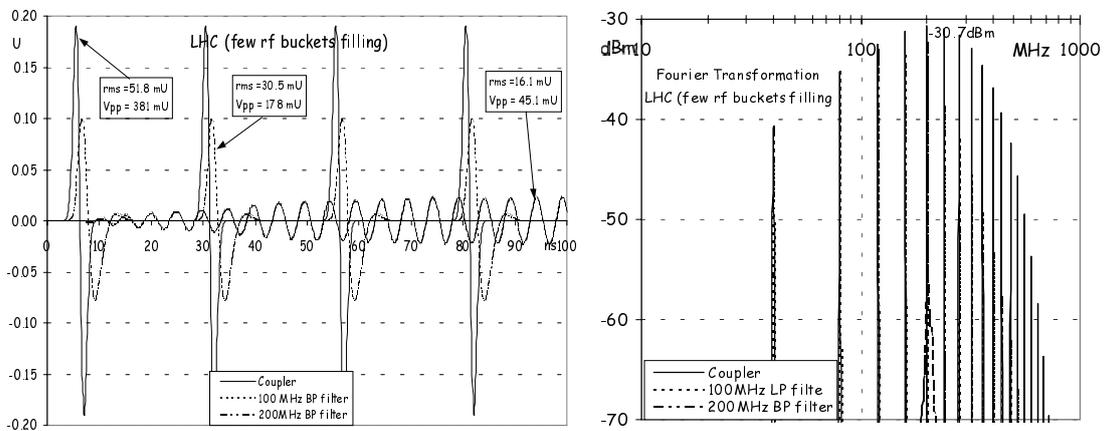


FIGURE 17. LHC (few rf buckets filling). Time response and spectral content

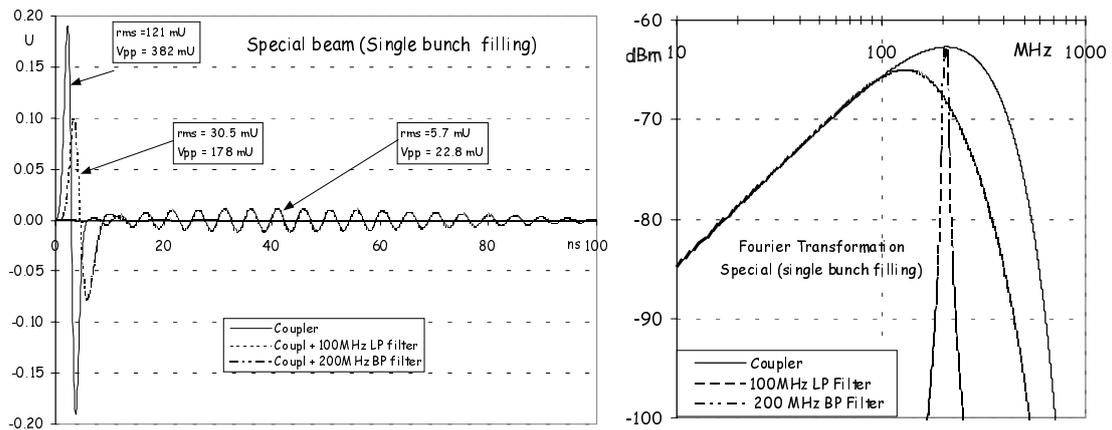


FIGURE 18. Single bunch. Time response and spectral content

6.4. Spectral content and time response.

Assuming an identical global input noise of $1.6 \mu\text{V}/\sqrt{\text{MHz}}$, the S/N ratio is indicated in the following table.

TABLE 9. S/N considerations

Processor	Wide-band	Narrow-band	
Band-width	200	12.0 (1.2)	MHz
Input noise	23.0	5.4 (1.7)	μ V (rms)
	S / N	S / N	
Fixed Target	76.8 [89.8]	86.4 (96.4)	dB
LHC	75.8 [82.6]	70.2 (80.2)	dB
Single (4.8ns)	67.1 [67.1]	39.8 (29.8)	dB

Values in [] correspond to the possible improvement one can obtain when averaging the collected data in a time interval equivalent to that required by a NB.

It should be noted that NB processing performs better for a limited frequency spectrum (Fixed Target) but as soon as the frequency spectrum becomes larger, WB processing becomes superior.

In the case of a single bunch, NB performance drops dramatically with the bunch length. The reason is that the first part of the bunch excites the filter but after half an oscillation period, the filter polarity changes and the input signal starts annihilating what has already been filled.

6.5. Processing system choice

TABLE 10. Processing system comparison

Processor type	Remarks	Solution =
MPX heterodyne	MPX, PLL and AGC don't work for single passage.	Unfeasible
NB Δ / Σ	200 MHz tune, cannot detect Heavy Ions at 7.6 or one of its harmonics.	Unfeasible
Phase Normalizer	200 MHz discriminator & logic is difficult to realize. Insufficient sensitivity for weak and long bunches.	Unfeasible
Time Normalizer	Not suitable for variable bunch widths. Electronics time jitter is too big relative to the possible time excursions.	Unfeasible
WB Δ / Σ	Requires several gain switching and scaling factors. Difficult to calibrate.	Feasible
Digital receiver	Easy switching from 200 down to 198.1 MHz tuning frequency. Adjustable BW. No AGC action, hence larger N° of bits	Feasible
Log-amplifier	Excellent dynamic range. Insensitive to bunch shape & length. Reduced N° of bits. Low cost. <i>Limited linearity</i>	Feasible

The above table collects the main advantages / disadvantages of the various processing systems. Three solutions appear to be feasible but just one offers almost no restrictions.

Since resolution and accuracy are not restrictive parameters for this application, the logarithmic processor is by far superior to all the others systems.

7. CONCLUSIONS

Experience has proved that every new machine requires a new approach to the same problem. This offers an excellent opportunity for new ideas.

Several different combinations among the currently available processing systems have still to be explored and this may provide solutions for particular cases.

The telecommunications field has similar needs and is expanding rapidly. Full advantage should be taken of its technological progress and of the reduced prices of components on the consumer market.

My personal feeling for the future is that two processing systems, capable of covering almost all possible applications, will coexist: the Amplitude to Time Normalizer and the Digital Receiver. Both have a bright future.

8. ACKNOWLEDGMENTS

I would like to thank Dr. Hermann Schmickler for his encouragement and precious advice for structuring this subject and my most faithful collaborator J.L. Pasquet who has built and tested most of the circuits described here.

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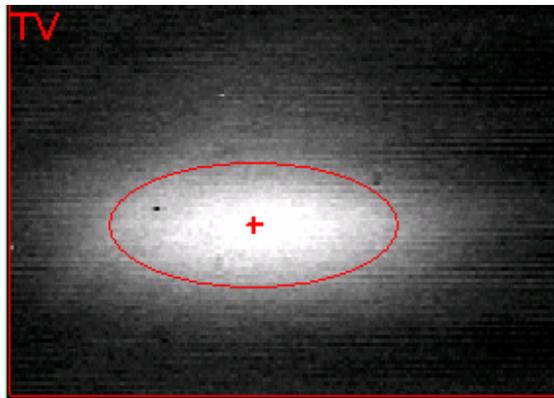
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Chapter 2

Profile Monitors / Emittance Measurements

2.1 Exercises and Literature: Profile Measurements

Synchrotron light profile monitor



Exercises

by Kay Wittenburg, -DESY-

Synchrotron light profile monitor

In electron accelerators the effect of synchrotron radiation (SR) can be used for beam size measurements. In this course we will focus on profile determination, but SR can also be used for bunch length measurements with e.g. streak cameras with a resolution of < 1 ps.

From classical electrodynamics the radiated power is given for a momentum change dp/dt and a particle with mass m_0 and charge e :

$$P_{SR} = \frac{e^2 c}{6\pi\epsilon_0 (m_0 c^2)} \left[\frac{dp}{dt} \right]^2$$

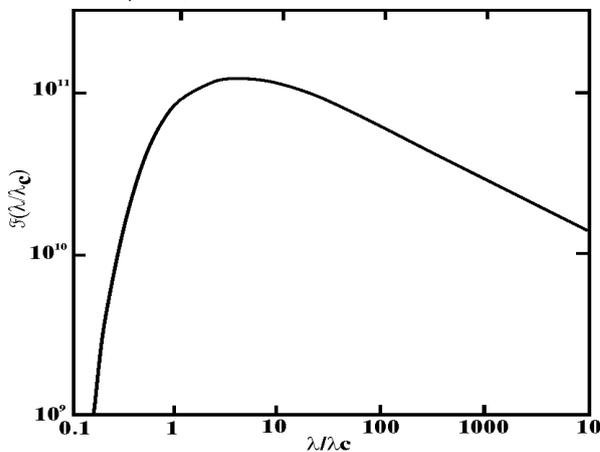
For linear accelerators $dp/dt = dW/dx$. For typical values of $dW/dx = 10 - 20$ MeV/m the SR is negligible. In circular machines an acceleration perpendicular to the velocity exists mainly in the dipole magnets (field B) with a bending radius $\rho = \beta\gamma m_0 c / (eB)$. The total power of N circulating particles with $\gamma = E/m_0 c^2$ is then

$$P_{tot} = \frac{e^2 c \gamma^4}{6\pi\epsilon_0 \rho^2} N$$

This expression is also valid for a ring having all magnets of the same strength and field-free sections in between.

The critical wavelength λ_c divides the Spectrum of SR in two parts of equal power:

$$\lambda_c = \frac{4\pi\rho}{3\gamma^3}$$



flux integrated over all ψ (Krisinsky *et al.* 1983).

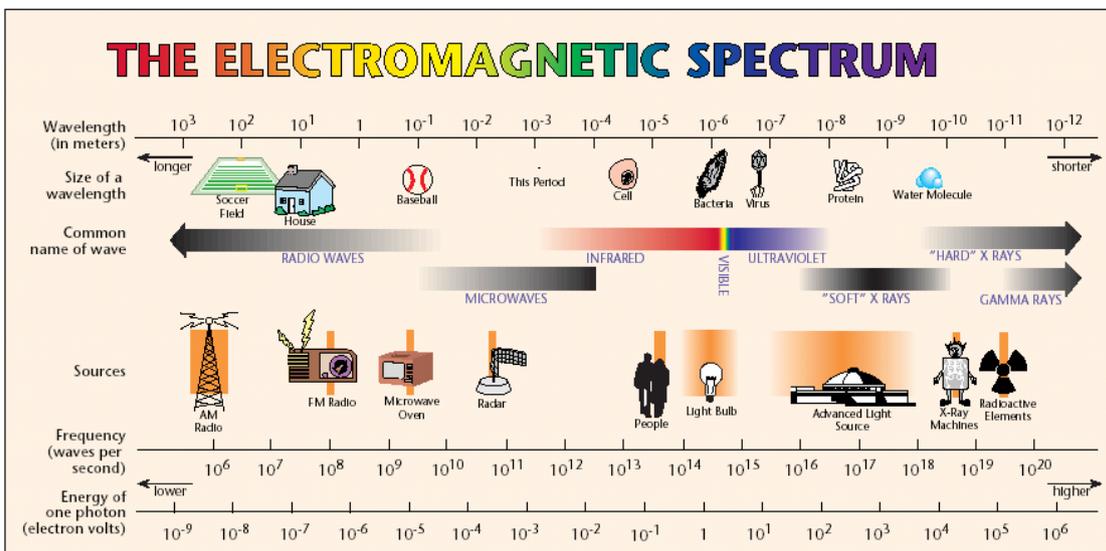
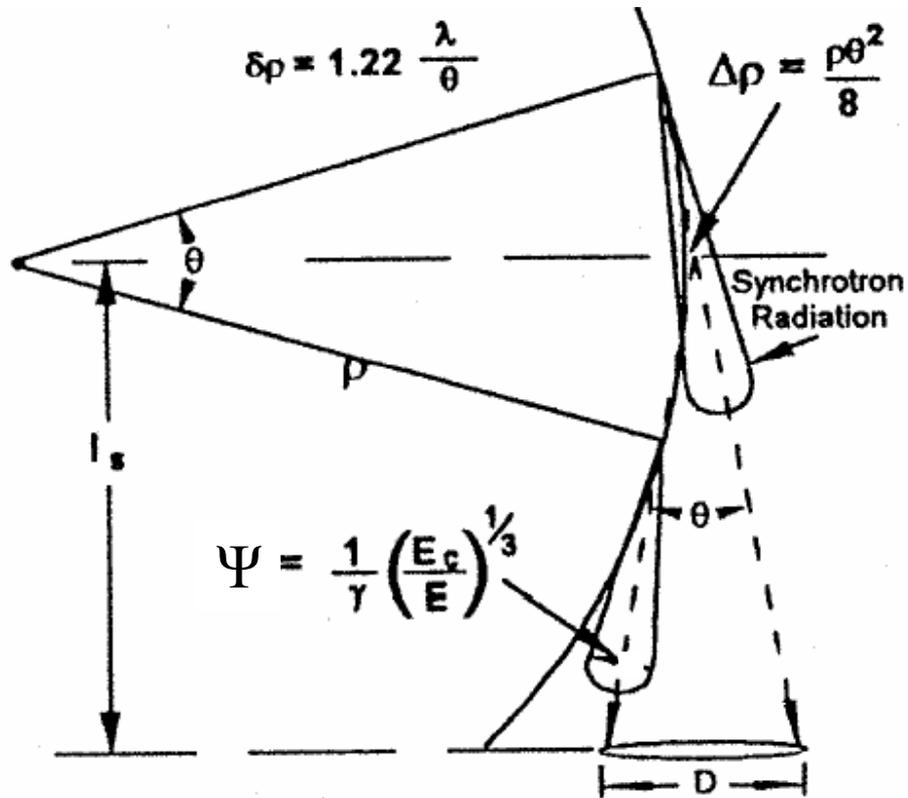
The opening angle Ψ of the SR (1/2 of cone!) for $\lambda \gg \lambda_c$:

$$\Psi = \frac{1}{\gamma} \left(\frac{\lambda}{\lambda_c} \right)^{1/3} = \left(\frac{3\lambda}{4\pi\rho} \right)^{1/3}$$

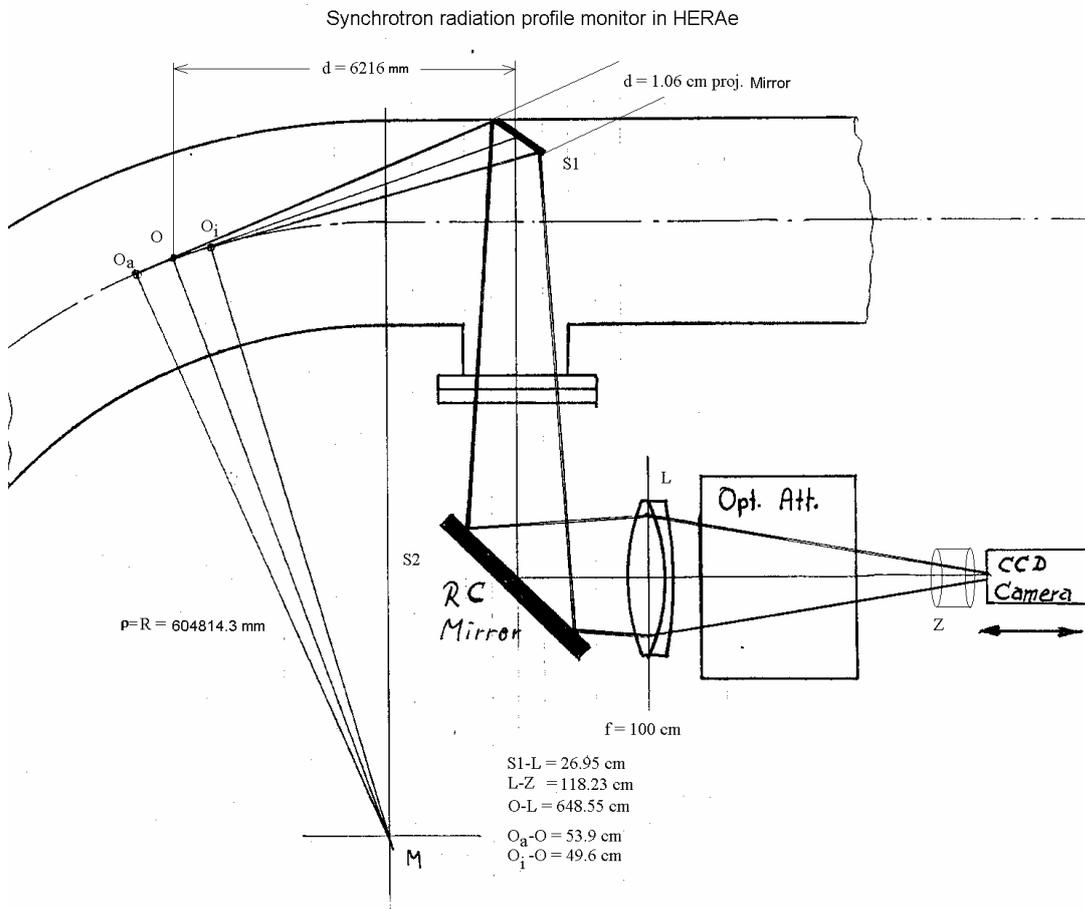
Path length s :

$$s = \rho\theta$$

ρ = Bending radius of Dipole



An Example: HERAe



$$R = \rho = 604814.3 \text{ mm}$$

$$G = O-L = 6485.5 \text{ mm}$$

$$B = L-Z = 1182.3 \text{ mm}$$

$$O-S1 = 6216 \text{ mm}$$

$$L = O_a-O_i = 1035 \text{ mm}$$

$$\text{opening angle (horizontal): } \tan\theta/2 = d/2/6216 \Rightarrow \theta/2 = \text{arc tan } d/2/6216 = \underline{0.85 \text{ mrad}}$$

$$\text{opening angle (vertikal): } \Psi(\lambda) = 1/\gamma (\lambda/\lambda_c)^{1/3}$$

with

$$\gamma = E/m_0c^2 = E [\text{MeV}]/0.511 = 23483 \text{ at } 12 \text{ GeV and } 52838 \text{ at } 27 \text{ GeV}$$

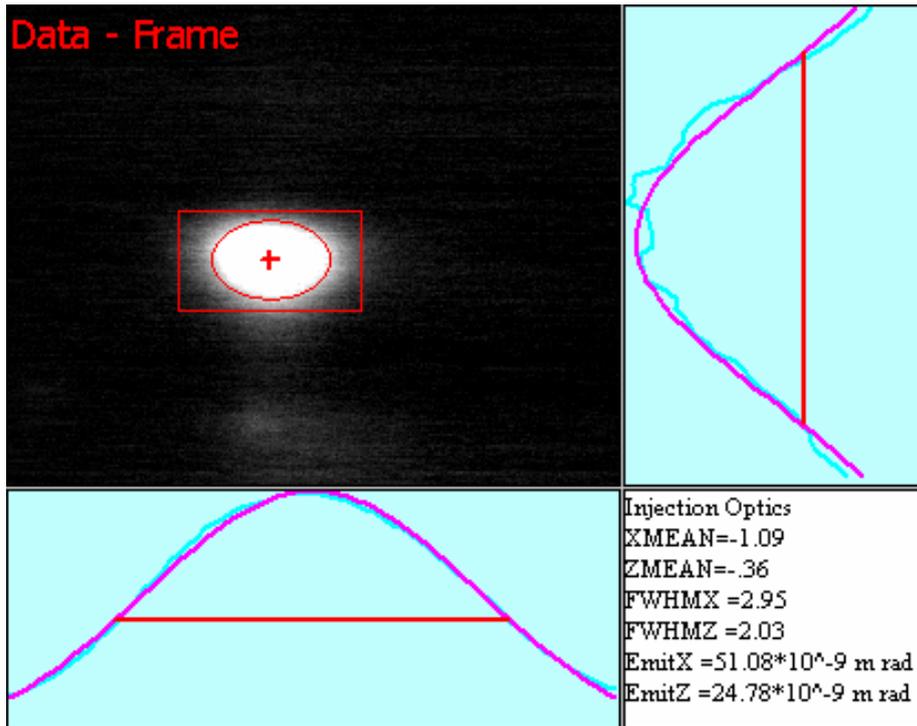
and

$$\lambda_c = \frac{4\pi\rho}{3\gamma^3} = 0.017 \text{ nm} < \lambda_c < 0.19 \text{ nm}$$

Exercise SR1: Which problems with the setup can be expected?:

Exercise SR2: What limits the spatial resolution?

Beam width $\sigma_{\text{beam}} = (\sigma_{\text{fit_measured}}^2 - \sigma_{\text{cor}}^2)^{1/2}$



Exercise SR3: Discuss possible improvements

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A Review of Optical Diagnostics Techniques for Beam Profile Measurements.

J A Clarke

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Synchrotron Radiation Profile Monitor for HERA Positron Beam

G. Kube, Rainer Fischer, Kay Wittenburg - Deutsches Elektronen Synchrotron DESY
[11th Beam Instrumentation Workshop](#), May 3-6 2004, Knoxville, Tennessee, USA

Detailed Resolution Studies of the Synchrotron Radiation Profile Monitor for HERAe

Gero Kube, Rainer Fischer, Kay Wittenburg (DESY, Hamburg)

Proc. DIPAC 2005 Lyon

A Review of Optical Diagnostics Techniques for Beam Profile Measurements.

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Abstract

The measurement of beam profiles using optical detectors is widespread. This paper reviews the various optical techniques employed in the community and points out the advantages and disadvantages for each one, illustrated by practical examples including experience with systems at the Daresbury SRS. Fundamental imaging limitations will be discussed together with calibration methods.

1. INTRODUCTION

In every particle accelerator the beam profile is an important parameter. Many methods exist for determining the beam profile, including several destructive techniques. This paper deals only with methods which rely on emitted visible synchrotron radiation from bending magnets as the diagnostic means. A review of the imaging resolution is given, followed by a discussion of optical detectors in use in the accelerator community. Possible calibration methods are also highlighted.

2. IMAGING RESOLUTION

The resolution of profile measurements by synchrotron radiation (SR) is strictly limited by fundamental effects. It is important that these effects are minimised so that the best resolution is obtained for the profile measurement. The horizontal and vertical cases are not the same; they are dealt with separately below.

2.1 Horizontal Case

2.1.1 Chromatic Error

In precise optical imaging of SR it is necessary to monochromate the light. This is most easily achieved with a bandpass filter. Typically a filter with a 500 nm centre wavelength and 30 nm bandwidth is used. However, as will be shown later, shorter wavelengths will improve the resolution.

2.1.2 Depth of Field Error

By its very nature the electron beam is a long source of light. This means that the imaging of the SR will produce a significant depth of field error, dependent upon the acceptance angle. For the simple case, illustrated in figure 1, the depth of field error is given by:

$$df = \frac{L}{2}\theta \quad (1)$$

where L is the length of the source and θ is the half-acceptance angle. Note that L is given by:

$$L = 2R(\theta + \theta_{SR}) \quad (2)$$

where R is the electron orbit radius and θ_{SR} , the natural opening angle of the photon beam, is given by:

$$\theta_{SR} = \frac{3\lambda}{4\pi R}^{1/3} \quad (3)$$

for the case where λ , the wavelength of the light, is much longer than the critical wavelength. This is usually the case for visible wavelengths. Note that θ_{SR} is the same in both planes.

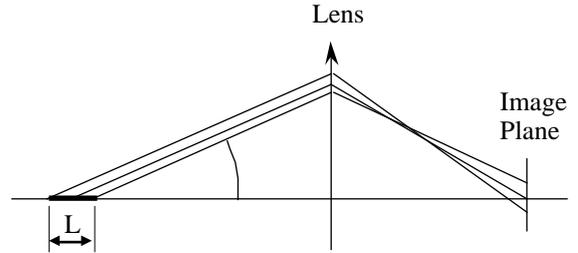


Figure 1. Depth of field error sketch.

2.1.3 Diffraction Error

Any imaging problem that involves apertures will inevitably have a diffraction error. Contrary to the depth of field error in the previous section, this error increases as the aperture is decreased. It is usual to restrict the aperture with either a circular iris or a vertical slit. The formulae for the diffraction resolution for these two cases are given below [1]. For an iris,

$$diff = 0.61 \frac{\lambda}{\theta} \quad (4)$$

and for a slit,

$$diff = 0.5 \frac{\lambda}{\theta} \quad (5)$$

Clearly, a vertical slit will give the better resolution.

2.1.4 Curvature Error

Due to the nature of the source, the curvature of the electron beam also contributes an error term that limits the horizontal resolution. From the geometry shown in figure 2 it is straightforward to derive the apparent width of the source as:

$$curv = \frac{R\theta^2}{2} \quad (6)$$

So, for a particular wavelength, the best resolution is found by minimising the sum of the squares of the three error terms described in equations (1), (5) and (6). For the SRS with $R = 5.5$ m, $\theta_{SR} = 2.8$ mrad and $\lambda = 500$ nm, the optimum value of θ is 2.6 mrad, defined by a vertical slit. This gives a combined value of 125 μ m for the apparent width of a negligible cross-section beam.

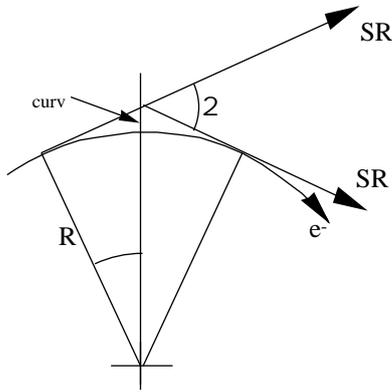


Figure 2. Curvature error sketch.

2.2 Vertical Case

For the vertical case the chromatic and depth of field errors are as for the horizontal. However, in the horizontal case the relevant diffraction effect and the depth of field error were both in the same plane. This is not true for the vertical case. Here the depth of field is again determined by the horizontal acceptance, but the diffraction is now only of consequence in the vertical plane. This means that the horizontal acceptance must be set to limit the depth of field and that any vertical acceptance limit will introduce unnecessary broadening due to diffraction. Therefore, in the vertical plane it is most advantageous to use a vertical slit instead of a circular iris. The minimum diffraction error is determined by the natural opening angle of the source. The diffraction limited resolution in the vertical plane can be estimated by replacing θ by θ_{SR} in equation (5). The difference between using a slit and an iris is illustrated in figure 3 for the SRS.

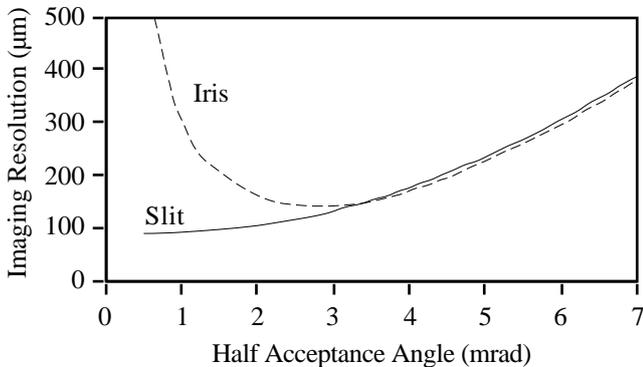


Figure 3. Apparent vertical width of a beam of narrow cross-section vs half acceptance angle for a slit and a circular iris.

Clearly the best vertical resolution is found by using a narrow vertical slit. However, since it is common to measure the profile of both planes with the same detector (eg a CCD camera) this is not always practical. Generally a compromise must be found between the resolution of the two planes in setting the horizontal acceptance, but since the vertical source size is usually much smaller than the horizontal it is normal to sacrifice some horizontal resolution in favour of the vertical. In fact, in modern 3rd generation light sources the vertical beam size may be significantly less than the diffraction limited resolution. In this case accurate profile measurements

can best be made with light of a significantly shorter wavelength.

3. CHARGE COUPLED DEVICES

The most common detector used for measuring beam profiles is the Charge Coupled Device (CCD). Such a device is a solid state detector that essentially consists of an array of discrete potential wells (known as pixels) that store accumulated charge. The charge, induced by incident photons, is read out sequentially. A complete description of CCDs is given in ref [2]. The CCD chip has a well defined geometry, which makes them ideal for metrology, with typical pixel sizes of $20 \mu\text{m} \times 20 \mu\text{m}$. Each chip will contain something like 512×512 pixels.

CCDs can have two geometries, Frame Transfer and Inter-Line Transfer (figure 4). Both of these can be used for profile measurements. The difference between the two types relates to the method used for reading out the accumulated charge. Each CCD has a memory area that is light insensitive to which all of the stored charges are transferred after a fixed integration time. The Frame Transfer type has a better horizontal spatial resolution but the Inter-Line type has a faster image to memory shift [3].

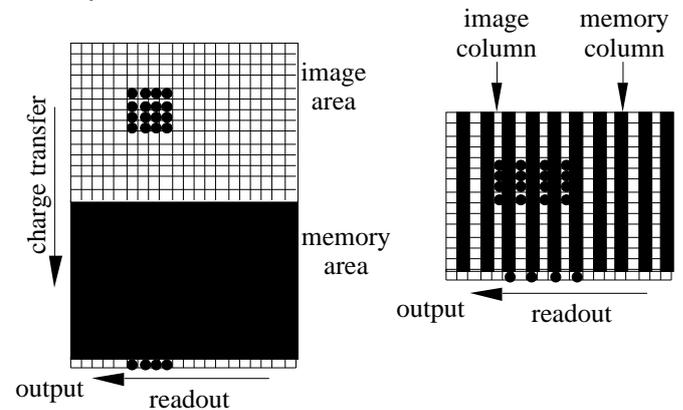


Figure 4. The two types of CCD detector. Frame Transfer on the left and Inter-Line Transfer on the right.

In order to use these devices for profile measurements it is necessary to connect the CCD camera to a framegrabber. A framegrabber is a device that interrogates the CCD and stores the reading for each pixel in buffer memory. It essentially consists of an Analogue to Digital Converter and some RAM (eg for an 8 bit ADC and 512×512 pixel array, 256 kbytes are required).

The CCD and framegrabber each have their own internal clocks for controlling timing functions. To achieve the best resolution it is necessary to synchronise these internal clocks [4] although for most applications this would only prevent a small error.

The framegrabber is usually a plug-in computer card. The values in the framegrabber memory can be manipulated by the computer to find the beam profiles. Although the framegrabber generally comes with some commercial software, this is not normally sufficient. It is not uncommon to have to write software for controlling the framegrabber and for determining the beam profiles. This software will have to determine the

centre of the beam using some peak detection algorithm, and then select the appropriate pixels for each plane. This is not straightforward and may need to be optimised for each particular application. For example, at Elettra this has been resolved by averaging and smoothing [5].

It is important to remember when using CCD cameras that the output is not necessarily linear with light intensity. It is common for camera manufacturers to apply a so-called 'gamma correction' to the CCD output to compensate for the fact that TV monitors have a non-linear response. Although the optical detector itself is inherently linear, the electronics in most cameras applies a logarithmic scaling to the output. If this correction factor is not removed either by adjusting the camera hardware or software then the CCD will not give accurate beam profile measurements [6].

It is often desirable to measure several beam profiles rapidly, over a few ms say, to investigate beam damping or instability. Unfortunately CCDs are relatively slow, running at TV refresh rate speeds. By screening off 90% of the optical detector (Frame Transfer type) and using it as a memory area it has been shown that it is possible to measure a short burst of profiles at around 10 kHz [7].

It is also useful to be able to monitor beam profiles from linacs or synchrotrons at their repetition rates of typically 50Hz. This can best be achieved by using fast shutters locked to the beam cycle. Mechanical shutters are possible but electro-optical ones are preferred. These are a sandwich of a photocathode, micro-channel plate and phosphor screen. The shutter is controlled by gating the accelerating potential across the micro-channel plate. Such a shutter has been used to monitor profiles stroboscopically turn-by-turn in the SLC damping rings [8].

4. PHOTODIODE ARRAYS

An alternative detector that can be used for measuring profiles is the Photodiode Array (PDA) [9]. This is a one dimensional strip of photodiodes (typically 25 μm long) that have an output that is linearly dependent upon the light intensity. This is a purely analogue device, unlike the CCD and framegrabber. The photodiodes are read sequentially and the output can be observed on a scope.

Of course, since the arrays are one dimensional the profile of only one plane can be observed. Therefore two arrays are required to measure both horizontal and vertical profiles simultaneously. This does however have the advantage of allowing the optical system to be optimised for each plane unlike the two dimensional CCD. The other advantage of the one dimensional array is that the need to find the centre of gravity of the beam is removed, greatly simplifying the measurement procedure.

Unlike the CCD the PDA does not lend itself easily to computer control. One method of overcoming this is to control the scope observing the PDA output. This has been successfully demonstrated at Daresbury where the scope is controlled over the GPIB interface [10]. Here, the scope trace is captured by the computer and the profile determined.

Typical integration times for PDAs are 25 ms, so like the CCD they are not ideally suited to rapid profile measurements.

However the fast shutter that was mentioned in the previous section could equally well be applied to the PDA.

5. CALIBRATION

An important requirement that must not be overlooked is proper calibration of the detector. In many cases the accuracy of the final measurement is limited by calibration error rather than by imaging resolution. Calibration here refers to the determination of the magnification of the optical system employed and so relates the measured profile width in the laboratory to the actual width in the storage ring.

Of course, if the focal lengths of the lenses used is well known then a theoretical calibration can be predicted. However it is always desirable to check this by experiment. This can best be achieved by moving the electron beam by a known amount and measuring how far the focussed image moves. The electron beam can be moved with local bumps or by varying the RF frequency, so long as the change in position of the beam is accurately known.

6. SUMMARY

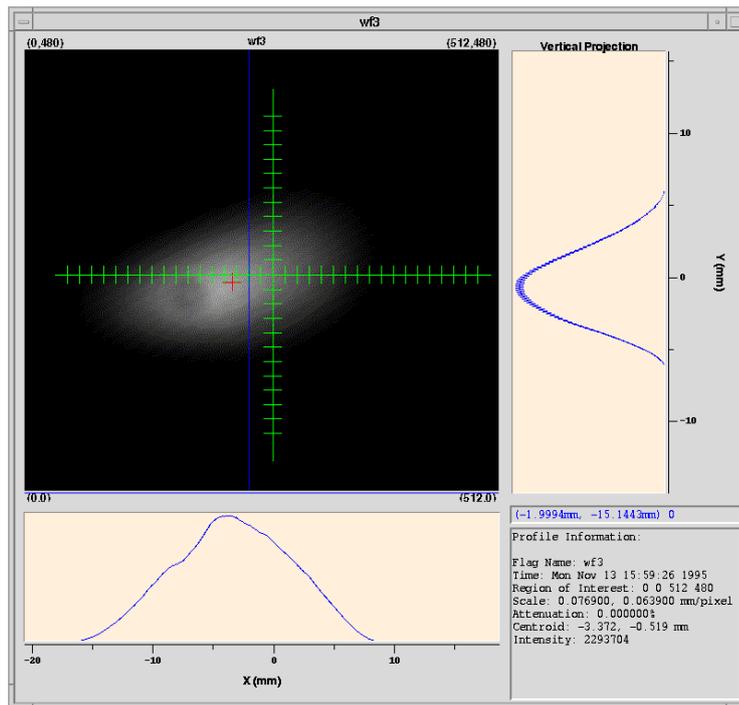
Measurement of beam profiles with synchrotron radiation is now commonplace. A review has been given of the points that need to be considered when deciding upon a particular technique. The simplest method to use is based upon a photodiode array detector. However, the most common method employed is with a CCD camera and framegrabber. This may take longer to commission because of software requirements but the final product has greater potential.

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Exercises:

LINACS/Transport Lines Emittance Measurement



by Kay Wittenburg, -DESY-

LINACS/Transport Lines Emittance Measurement

In a transfer line (or Linac), the beam passes once and the shape of the emittance ellipse at the entry to the line determines its shape at the exit. Exactly the *same* transfer line injected first with one emittance ellipse and then different ellipses has to be accredited with *different* α and β , γ functions to describe the cases. Thus α and β , γ depend on the input beam and their propagation depends on the structure. Any change in the structure will only change the α and β , γ values downstream of that point. ... The input ellipse must be chosen by the designer and should describe the configuration of all the particles in the beam.

1) Explain ways of measuring the emittance of a charged particle beam in a Linear accelerator or a transport line without knowing the beam optic parameters a, b, g.

- a) Exercise L1: Which one is the preferable method for a high energy proton transport line ($p > 5$ GeV/c)?
- b) Exercise L2: Assuming that the geometry between the measurement stations and the transport matrices M of the transport line are well defined (including magnetic elements), describe a way to get the emittance using the σ -matrix.

$$\mathbf{s} = \begin{pmatrix} \mathbf{s}_{11} & \mathbf{s}_{12} \\ \mathbf{s}_{21} & \mathbf{s}_{22} \end{pmatrix} = \begin{pmatrix} \mathbf{s}_y^2 & \mathbf{s}_{yy} \\ \mathbf{s}_{yy} & \mathbf{s}_y^2 \end{pmatrix} = \mathbf{e}_{rms} \begin{pmatrix} \mathbf{b} & -\mathbf{a} \\ -\mathbf{a} & \mathbf{g} \end{pmatrix} = \mathbf{s} \text{ matrix}$$

- c) Exercise L3: In a transport line for $p = 7.5$ GeV/c protons are two measurement stations. The first is located exactly in the waist of the beam and shows a beam width of $\sigma_y = 3$ mm, the second at a distance of $s = 10$ m shows a width of $\sigma_y = 9$ mm. Assuming no optical elements in this part, calculate the emittance and the normalized emittance of the beam.

References

S.Y. Lee, Accelerator Physics, World Scientific, pp 54-55 is attached

Emittance Measurements at the Bates Linac

K.D. Jacobs, J.B. Flanz, T. Russ

http://accelconf.web.cern.ch/accelconf/p89/PDF/PAC1989_1529.PDF

attached

Basic accelerator course, like Schmüser and Rossbach in previous CAS CERN 94-01 v 1

<http://doc.cern.ch/cgi-bin/tiff2pdf?/archive/cernrep/1994/94-01/p17.tif>

Beam-line instruments/ [Raich, U](#) ;

In: Joint US-CERN-Japan-Russia Particle Accelerators School on Beam

Measurement, Montreux, Switzerland, 11-20 May 1998 - World Sci., Singapore,

1999. - pp.263-276

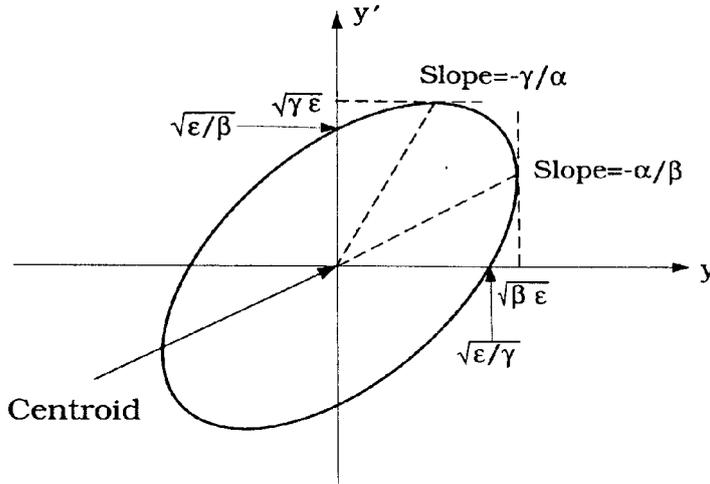


Figure 2.8: The Courant–Snyder invariant ellipse. The area enclosed by the ellipse is equal to $\pi\epsilon$, where ϵ is twice the betatron action; α, β and γ are betatron amplitude functions.

A. The emittance of a beam

A beam is usually composed of particles distributed in the phase space. Depending on the initial beam preparation, we approximate a realistic beam distribution function by some simple analytic formula. Neglecting dissipation and diffusion processes, each particle in the distribution function has its invariant Courant–Snyder ellipse.

Given a normalized distribution function $\rho(y, y')$ with $\int \rho(y, y') dy dy' = 1$, the moments of the beam distribution are

$$\langle y \rangle = \int y \rho(y, y') dy dy', \quad \langle y' \rangle = \int y' \rho(y, y') dy dy', \quad (2.94)$$

$$\sigma_y^2 = \int (y - \langle y \rangle)^2 \rho(y, y') dy dy', \quad \sigma_{y'}^2 = \int (y' - \langle y' \rangle)^2 \rho(y, y') dy dy', \quad (2.95)$$

$$\sigma_{yy'} = \int (y - \langle y \rangle)(y' - \langle y' \rangle) \rho(y, y') dy dy' = r \sigma_y \sigma_{y'}, \quad (2.96)$$

where σ_y and $\sigma_{y'}$ are the rms beam widths, $\sigma_{yy'}$ is the correlation, and r is the correlation coefficient. The rms beam emittance is then defined as

$$\epsilon_{\text{rms}} = \sqrt{\sigma_y^2 \sigma_{y'}^2 - \sigma_{yy'}^2} = \sigma_y \sigma_{y'} \sqrt{1 - r^2}. \quad (2.97)$$

If the accelerator is composed of linear elements such as dipoles and quadrupoles, the emittance defined in Eq. (2.97) is invariant. The rms emittance is equal to the phase-space area enclosed by the Courant–Snyder ellipse of the rms particle (see Exercise 2.2.16).

Although incorrect, the term “emittance” is often loosely used as twice the action variable of betatron oscillations. The betatron oscillations of “a particle” with an “emittance” ϵ is

$$y(s) = \sqrt{\frac{\beta\epsilon}{\pi}} \cos[\nu\phi(s) + \delta]. \quad (2.98)$$

Figure 2.8 shows a Courant–Snyder invariant ellipse for a given emittance of a beam. For a beam with rms emittance ϵ , the rms beam width is $\sqrt{\beta(s)}\epsilon$, and the beam rms divergence y' is $\sqrt{\gamma(s)}\epsilon$. Since $\gamma = (1 + \alpha^2)/\beta$, the transverse beam divergence is smaller at a location with a large $\beta(s)$ value, i.e. all particles travel in parallel paths. In accelerator design, a proper $\beta(s)$ value is therefore important for achieving many desirable properties.

B. The σ -matrix

The σ -matrix of a beam distribution is defined as

$$\sigma = \begin{pmatrix} \sigma_{11} & \sigma_{12} \\ \sigma_{12} & \sigma_{22} \end{pmatrix} = \begin{pmatrix} \sigma_y^2 & \sigma_{yy'} \\ \sigma_{yy'} & \sigma_{y'}^2 \end{pmatrix} = \langle (\mathbf{y} - \langle \mathbf{y} \rangle)(\mathbf{y} - \langle \mathbf{y} \rangle)^\dagger \rangle, \quad (2.99)$$

where \mathbf{y} is the betatron state matrix of Eq. (2.36), $\mathbf{y}^\dagger = (y, y')$ is the transpose of \mathbf{y} , and $\langle \mathbf{y} \rangle$ is the first moment. The rms emittance becomes (see also Exercise 2.2.14)

$$\epsilon_{\text{rms}} = \sqrt{\det \sigma} = \sqrt{\sigma_{11}\sigma_{22} - \sigma_{12}^2}. \quad (2.97)$$

Using the transfer matrix, we obtain

$$\sigma_2 = M_{21}\sigma_1 M_{21}^\dagger. \quad (2.100)$$

It is easy to verify that $\mathbf{y}^\dagger \sigma^{-1} \mathbf{y}$ is invariant under linear betatron motion, thus the beam distribution is

$$\rho(y, y') = \rho(\mathbf{y}^\dagger \sigma^{-1} \mathbf{y}). \quad (2.101)$$

C. Emittance measurement

The emittance can be obtained by measuring the σ -matrix. The beam profile of protons and ions is usually measured by using wire scanners or ionization profile monitors. Synchrotron light monitors are commonly used in electron storage rings. More recently, laser light has been used to measure electron beam size in the sub-micron range. Using the rms beam size and Courant-Snyder parameters, we can deduce the emittance of the beam.

EMITTANCE MEASUREMENTS AT THE BATES LINAC*

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Abstract

An emittance measuring system has been installed at the Bates Linear Accelerator Center. The system consists of three wire scanners used to measure the electron beam profile, plus a microcomputer for data acquisition and processing. The scanners are located in a drift space on a beam line. Each scanner measures the horizontal and vertical beam size with a possible resolution of $25\ \mu\text{m}$. The horizontal and vertical beam phase spaces can then be determined. Results of measurements are presented here. Calculations relating the theoretical accuracy of the emittance measurements with the distance separating the scanners, and the location and size of the beam waist, are also presented.

Another technique for measuring emittance has also been employed. This technique involves using a wire scanner to measure the beam size at a fixed location, as a function of the strength of an upstream quadrupole.¹

Introduction

The transverse phase space of a particle beam can be characterized by three parameters. For example, knowing the extent of the beam phase ellipse in distance and in angle, plus the orientation of the ellipse, will fully determine the phase space. An equivalent set of parameters is the location of a beam waist, the waist radius, and the maximum particle divergence at the waist. Various techniques can be used to measure these parameters. Measuring the beam size at three different locations, with fixed machine optics, will determine the phase space,² as will measuring the beam size at one location for three different optics configurations.

In this paper, we describe the technique for measuring the beam phase space by using the measurements of the beam sizes at three different locations. Calculations regarding the precision of this technique are presented, as are results of experimental measurements of the beam phase space at the Bates Linac.

Measurement Technique

Consider a beam in a field free region (drift space). If x_0 is the horizontal beam size at a waist located at axial position z_0 , and θ_0 is the maximum horizontal divergence angle any particle makes with the beam axis at the waist, then the beam size x at location z is given by

$$x^2 = x_0^2 + (z - z_0)^2 \theta_0^2 \quad (1)$$

To measure the beam phase space, we measure the beam size using three profile monitors, equally spaced by the distance L . Defining the origin to be at the center profile monitor, so that $z_1 = -L$, $z_2 = 0$, and $z_3 = +L$, the beam sizes x_i at the monitors are given by

$$\begin{aligned} x_1^2 &= x_0^2 + (L + z_0)^2 \theta_0^2 \\ x_2^2 &= x_0^2 + z_0^2 \theta_0^2 \\ x_3^2 &= x_0^2 + (L - z_0)^2 \theta_0^2 \end{aligned} \quad (2)$$

Thus, knowing the beam sizes x_i and the profile monitor separation L , we can calculate the waist size

$$x_0 = \left\{ x_2^2 - \frac{1}{8} \left(\frac{x_1^2 - x_3^2}{x_1^2 - 2x_2^2 + x_3^2} \right) \right\}^{1/2}, \quad (3)$$

the divergence at the waist

$$\theta_0 = \frac{1}{\sqrt{2}L} (x_1^2 - 2x_2^2 + x_3^2)^{1/2}, \quad (4)$$

and the location of the waist

$$z_0 = \frac{L}{2} \left(\frac{x_1^2 - x_3^2}{x_1^2 - 2x_2^2 + x_3^2} \right). \quad (5)$$

The particle beam emittance ϵ is given by the product $x_0 \theta_0$,

$$\epsilon = \frac{1}{4L} [8x_2^2(x_1^2 - 2x_2^2 + x_3^2) - (x_1^2 - x_3^2)^2]^{1/2}. \quad (6)$$

A similar set of calculations holds in the vertical dimension.

These calculations are for the case of equally spaced profile monitors in a drift space. They can be extended to include unequal monitor spacing and the presence of intervening optical components.

Measurement Error Analysis

In order to make meaningful emittance measurements using beam profile monitors of realistic resolution, it may be necessary to set up the beam and the profile monitors in a particular manner. The precision of the measurements depends on L , x_0 , and z_0 . (For a beam of fixed emittance, $\theta_0 \propto x_0^{-1}$, and is not an independent variable.) In general, the precision of an emittance measurement increases with increasing L , and when the waist is located closer to the center profile monitor.

To quantitatively determine the uncertainty in the phase space measurements, standard propagation of error calculations have been made. In making these calculations, it has been assumed that the uncertainty in the measured beam sizes σ_{x_i} dominate, and that L is known to greater precision. The results are

$$\begin{aligned} \frac{\sigma_{x_0}}{x_0} &= \left\{ \sigma_{x_1}^2 x_1^2 (x_1^2 - x_3^2)^2 (x_1^2 - 4x_2^2 + 3x_3^2)^2 \right. \\ &\quad + 4\sigma_{x_2}^2 x_2^2 [4(x_1^2 - 2x_2^2 + x_3^2)^2 - (x_1^2 - x_3^2)^2]^2 \\ &\quad \left. + \sigma_{x_3}^2 x_3^2 (x_1^2 - x_3^2)^2 (3x_1^2 - 4x_2^2 + x_3^2)^2 \right\}^{1/2} \\ &\quad / 4\sqrt{2}x_0^2 (x_1^2 - 2x_2^2 + x_3^2)^2, \end{aligned} \quad (7)$$

$$\frac{\sigma_{\theta_0}}{\theta_0} = \sqrt{2} \frac{(\sigma_{x_1}^2 x_1^2 + 4\sigma_{x_2}^2 x_2^2 + \sigma_{x_3}^2 x_3^2)^{1/2}}{(x_1^2 - 2x_2^2 + x_3^2)}, \quad (8)$$

$$\begin{aligned} \sigma_{z_0} &= \frac{2L}{(x_1^2 - 2x_2^2 + x_3^2)^2} [\sigma_{x_1}^2 x_1^2 (x_2^2 - x_3^2)^2 \\ &\quad + \sigma_{x_2}^2 x_2^2 (x_1^2 - x_3^2)^2 + \sigma_{x_3}^2 x_3^2 (x_1^2 - x_2^2)^2]^{1/2}, \end{aligned} \quad (9)$$

* Work supported by the U.S. Department of Energy

and

$$\frac{\sigma_\epsilon}{\epsilon} = \frac{4}{\sqrt{2}[8x_2^2(x_1^2 - 2x_2^2 + x_3^2) - (x_1^2 - x_3^2)^2]} \times [\sigma_{x_1}^2 x_1^2 (x_1^2 - 4x_2^2 - x_3^2)^2 + 16\sigma_{x_2}^2 x_2^2 (x_1^2 - 4x_2^2 + x_3^2)^2 + \sigma_{x_3}^2 x_3^2 (x_1^2 + 4x_2^2 - x_3^2)^2]^{1/2}. \quad (10)$$

Using Eq. (10), the beam configuration for making optimum emittance measurements can be found. For example, the effect of moving the location of the beam waist is shown in Fig. 1, for fixed monitor separation and different waist sizes.

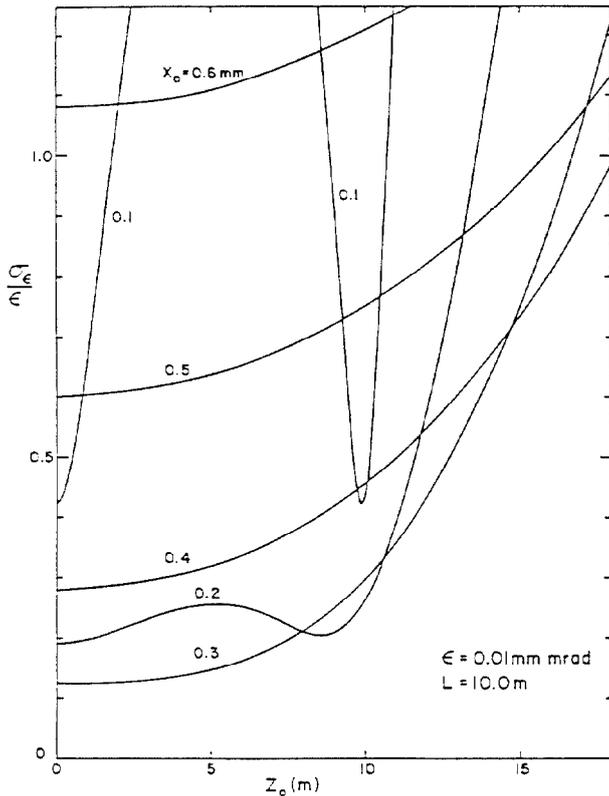


Fig. 1: Precision of emittance measurement σ_ϵ vs. location of waist z_0 , for different waist sizes x_0 . Here $L = 10$ m and $\epsilon = 0.01$ mm · mrad. The precision of the beam width at each profile monitor is taken to be $\sigma_{x_i} = 25$ μ m.

As can be seen, it is always best to have the waist near the center monitor ($z = 0$), although for some x_0 this requirement is not as critical. (When $z_0 \approx 0$, the precision of x_0 is improved, which leads to a decrease in σ_ϵ .) Figure 1 also indicates that for fixed z_0 , there is a dependency of σ_ϵ on x_0 . This is shown explicitly in Fig. 2, which plots σ_ϵ as a function of x_0 for $z_0 = 0$, and several different L . The optimum value of x_0 as a function of L is shown in Fig. 3. Finally, with x_0 at its optimum value and $z_0 = 0$, the obtainable σ_ϵ is shown as a function of L in Fig. 4. Here we see that the obtainable fractional precision σ_ϵ/ϵ scales as $L^{-1/2}$.

Experimental Results

Emittance measurements at Bates, based on the above analysis, are made with an automatic emittance measuring system. The beam profiles are determined using high resolution wire scanners.³ Data from the scanners are digitized, acquired,

and processed by the Linac Control System. The processing is done on a MicroVAX by programs written in a high level language, and includes fitting a Gaussian to the profile data to determine the beam size. Once the size is known at each scanner, the emittance, beam waist size and location, and beam divergence are calculated, along with estimates of their uncertainties.

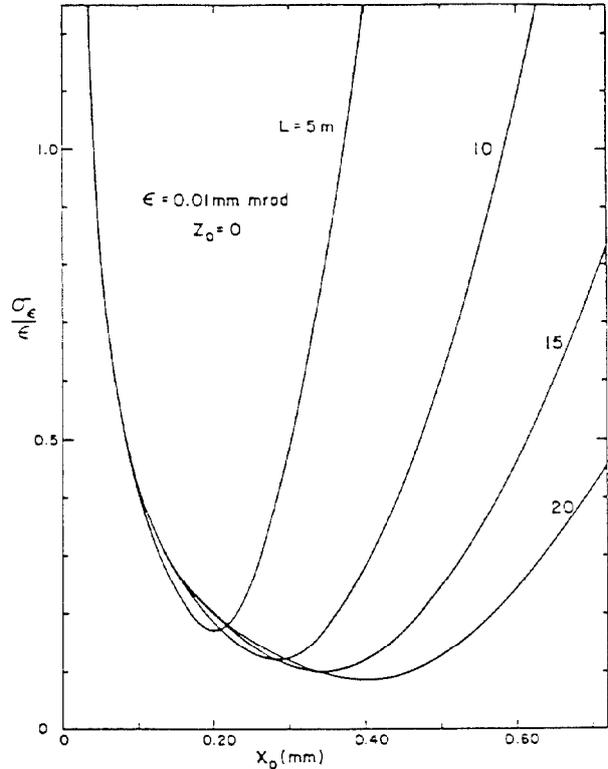


Fig. 2: Precision of emittance measurement σ_ϵ vs. waist size x_0 , for different profile monitor separations L . The waist is located at the center monitor ($z_0 = 0$), and $\epsilon = 0.01$ mm · mrad. The precision of the beam width at each profile monitor is taken to be $\sigma_{x_i} = 25$ μ m.

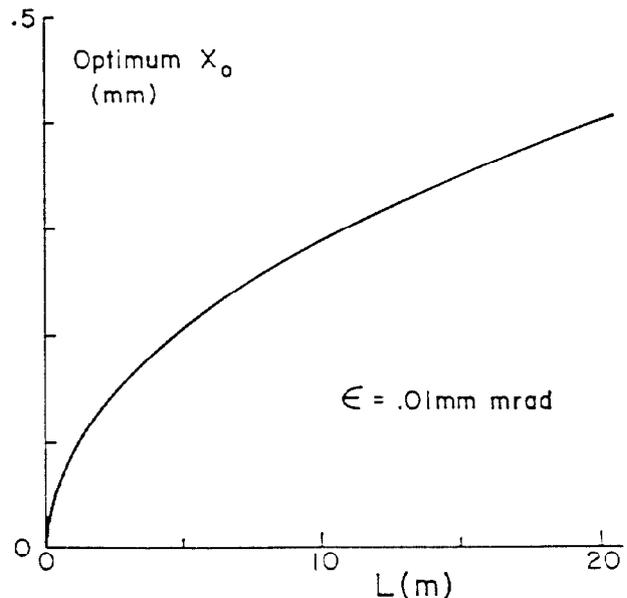


Fig. 3: Waist size x_0 for optimum emittance measurement vs. profile monitor separation L , for $\epsilon = 0.01$ mm · mrad.

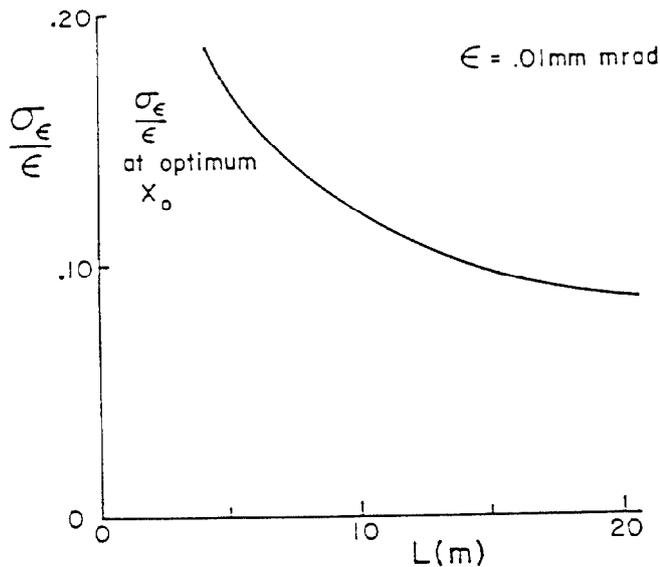


Fig. 4: Precision of emittance measurement σ_ϵ at optimum x_0 and z_0 vs. monitor separation L , for $\epsilon = 0.01 \text{ mm} \cdot \text{mrad}$. The precision of the beam width at each profile monitor is taken to be $\sigma_{z_i} = 25 \mu\text{m}$.

All data acquired and calculated are displayed on the MicroVAX workstation. These include plots of the raw data from the wire scanners, along with the fitted profiles. Finally, the beam phase space ellipse at the center scanner is calculated and displayed. Figure 5 shows a sample display. The time needed to acquire a complete set of data depends primarily on the speed of the wire scanners, with the data analysis taking much less time. The scanner speed is a function of several parameters such as the beam repetition rate and the range of scanner motion. Under typical conditions, an emittance measurement is completed in less than one minute.

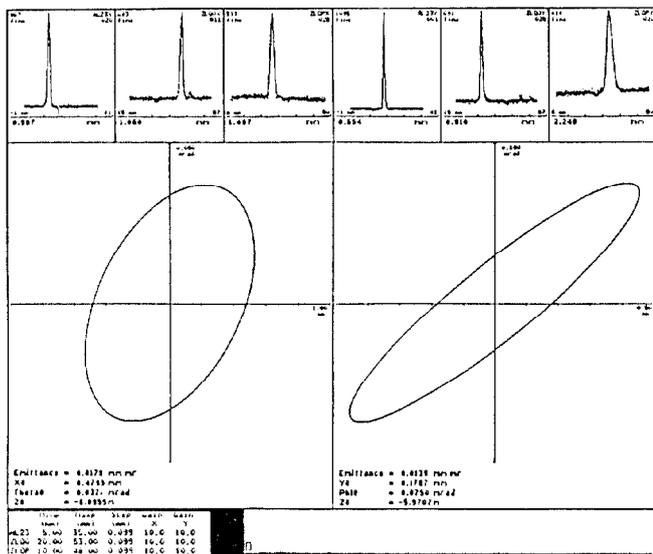


Fig. 5: Sample emittance measuring system display. The horizontal and vertical data are shown on the left and right halves, respectively. The small boxes at the top show beam profile data. The larger boxes show the calculated beam phase space ellipses.

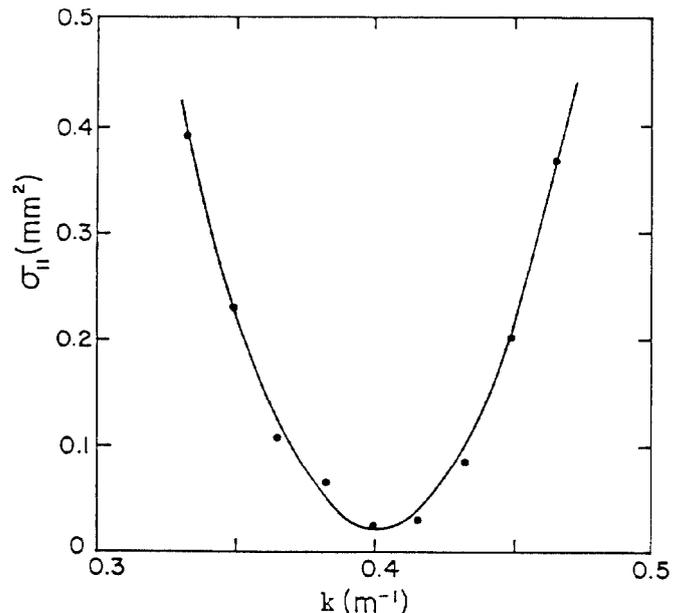


Fig. 6: Square of the horizontal beam size σ_{11} vs. strength k of a quadrupole singlet 8.03 m upstream from the measurement point. The points are experimental data, and the curve is the best fit parabola.

Preliminary results have been obtained with this system. The three wire scanners are located in a drift space where the beam emerges from the linac. The measured value of the horizontal emittance is $0.04 \text{ mm} \cdot \text{mrad}$ at a beam energy of 175 MeV, and $0.02 \text{ mm} \cdot \text{mrad}$ at 250 MeV. This is in good agreement with the expected value of $10/\gamma \text{ mm} \cdot \text{mrad}$. In addition, varying the strength of a quadrupole upstream from the emittance measuring system produces the expected rotation of the measured phase space ellipse. Similar results have been obtained in the vertical dimension. The uncertainties in these measurements, both statistical and systematic, are presently under study.

The emittance of the beam has also been measured using a different method.¹ In this technique, the size of the beam is measured at one location, as a function of the strength of an upstream quadrupole. The square of the beam size should have a parabolic dependence on quadrupole strength. Results of such a measurement in the horizontal dimension are shown in Fig. 6. From the parameters of the parabola fit to the data, shown in Fig. 6, the emittance is determined to be $0.02 \text{ mm} \cdot \text{mrad}$ at 250 MeV, in agreement with the emittance measured using the three scanner technique.

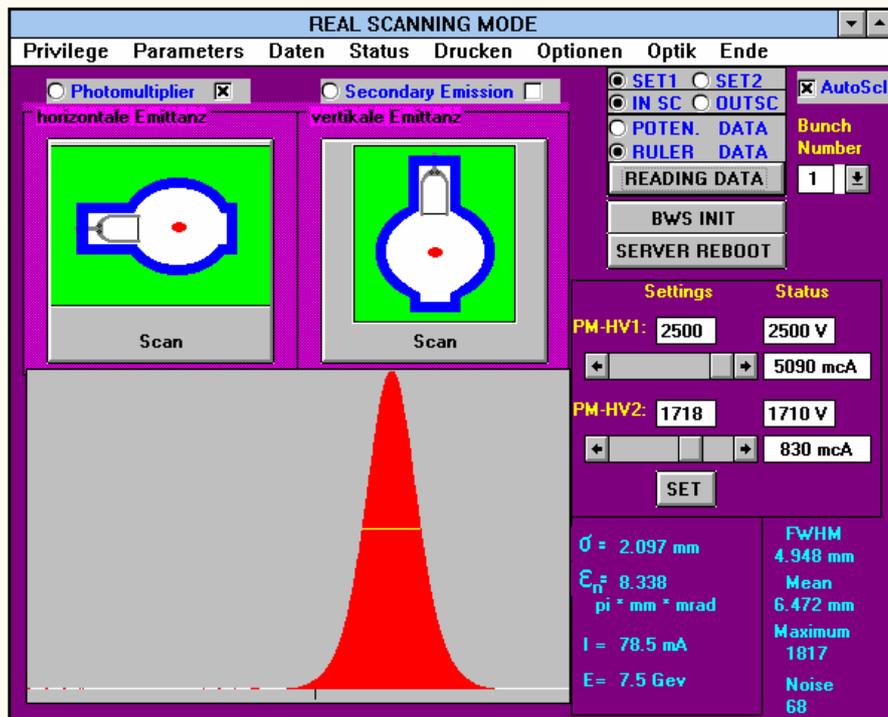
Summary

Emittance measurements have been made at Bates using an automatic emittance measuring system, consisting of three beam profile monitors equally spaced in a drift region. The results obtained are in good agreement with the values expected at Bates. Measurement of the emittance by an independent technique has yielded similar results.

References

- [1] M. C. Ross, *et al.*, SLAC-PUB-4278, March 1987.
- [2] R. I. Cutler, J. Owen, and J. Whittaker, Proc. of the 1987 IEEE Particle Accelerator Conference, p. 625, March 1987.
- [3] K. D. Jacobs, *et al.*, "The Beam Profile Measuring System at the Bates Linac," these proceedings.

Wire Scanners



by Kay Wittenburg, -DESY-

I. Introduction

Conventional wire scanners with thin solid wires (conventional compared with new techniques using, for example, Lasers) are widely used for beam size measurements in particle accelerators. The interaction of the wire with the beam generates a number of different interactions which can be used for the profile determination.

- ❖ Secondary emission current
- ❖ Bremsstrahlung, detection by Scintillators
- ❖ Scattering of beam particles, detection by Scintillators etc.
- ❖ creation of electromagnetic/hadronic showers, detection by shower counters.

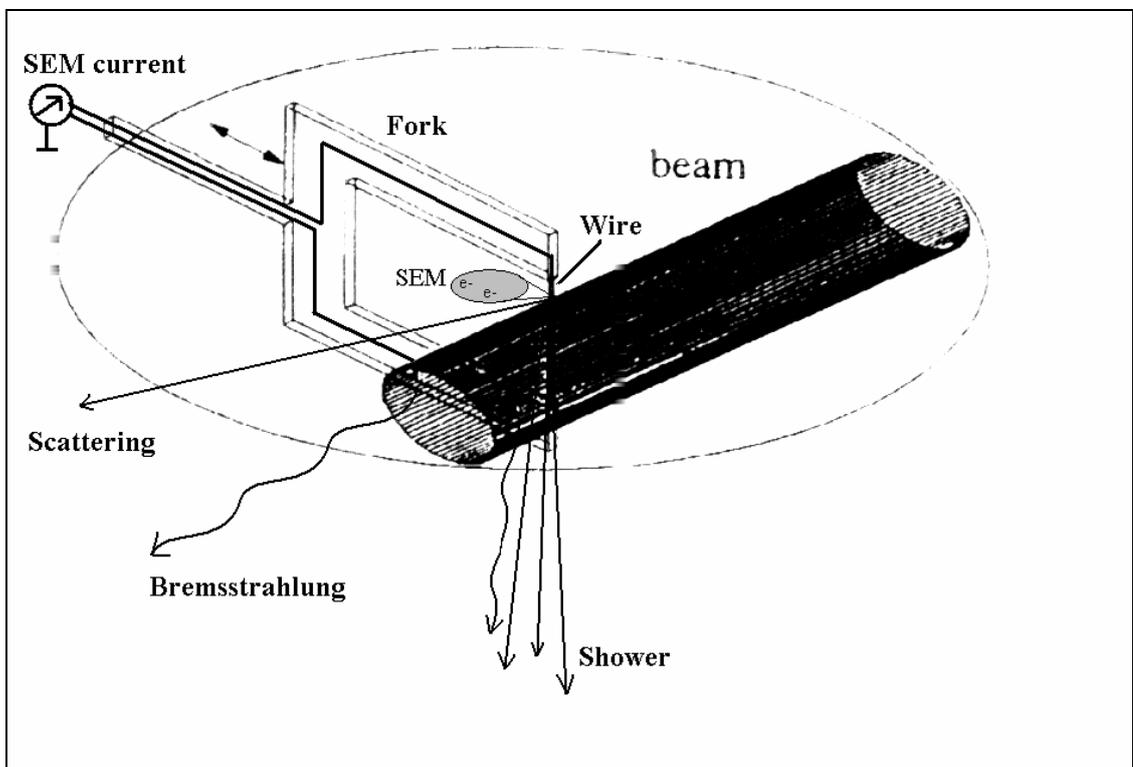


Figure WIRE1: Beam wire interactions

Exercise WIRE: Discuss where one should locate the Scintillator in case of a proton and an electron accelerator? Do you expect any difference?

Known limitations of wire scanners are:

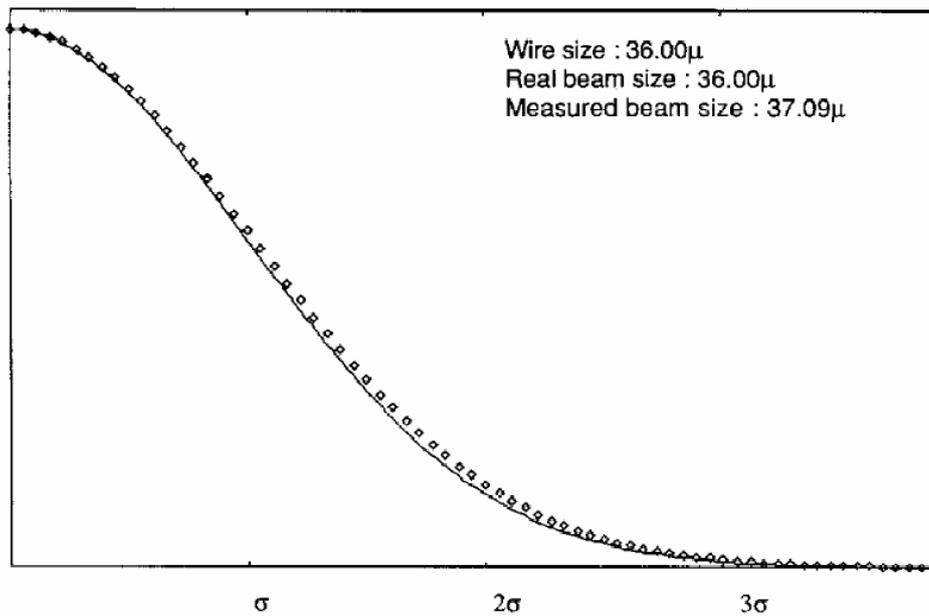
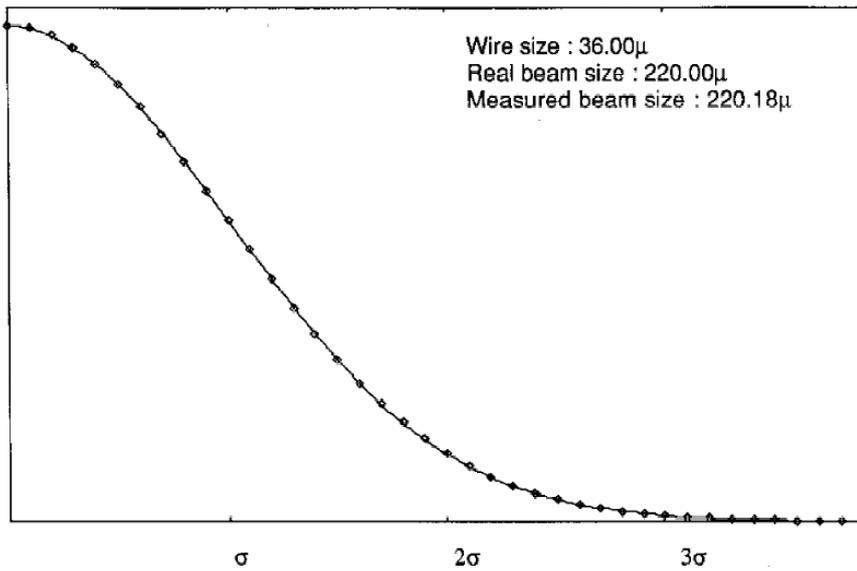
1. The smallest measurable beam size is limited by the finite wire diameter of a few microns.
2. Higher Order Modes may couple to conductive wires and can destroy them.
3. High beam intensities combined with small beam sizes will destroy the wire due to the high heat load.
4. Emittance blow up.

In the following the limitations will be discussed in detail:

II. Limitations:

1. Beam size

The smallest achievable wires have a diameter of about 5-6 μm . This limits the use of wire scanners to beam sizes of a few microns. An example of the error in the beam width determination is shown in the next figures for a 36 μm wire.



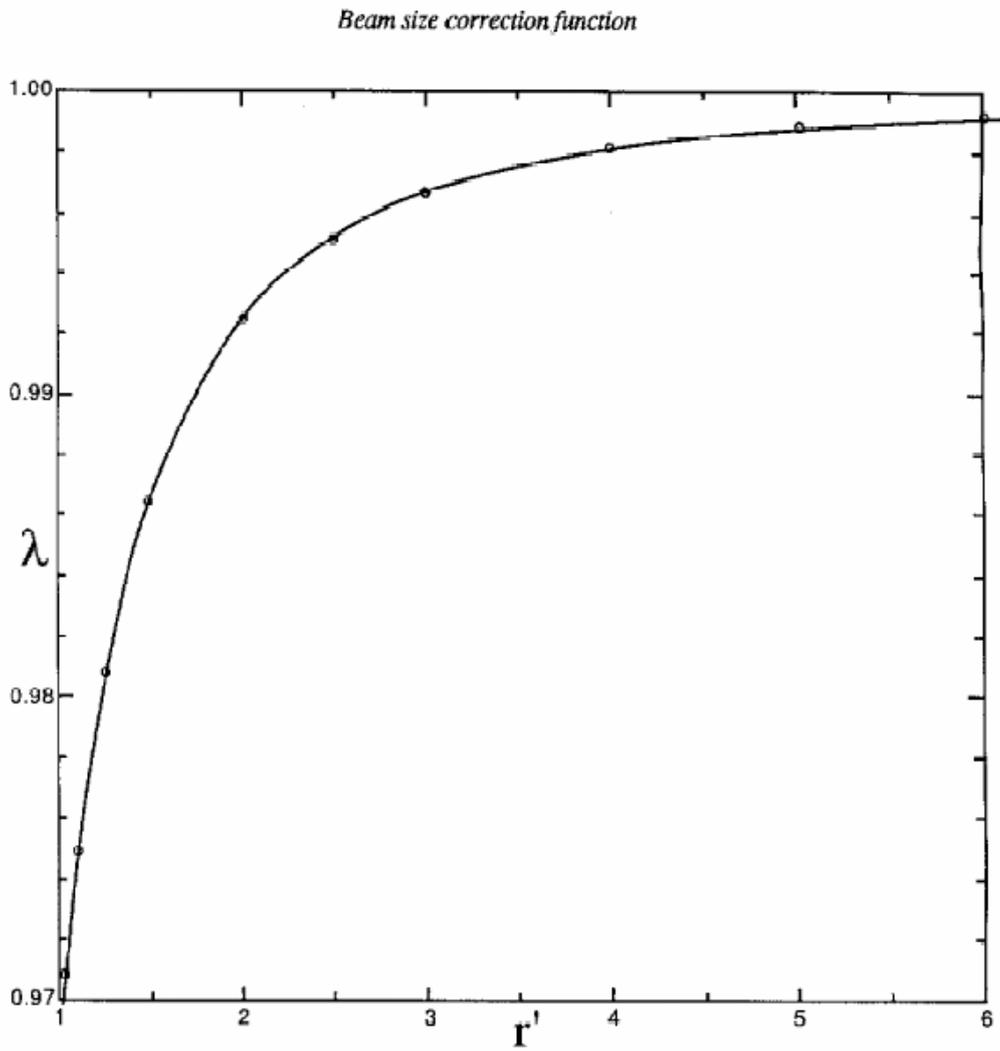


Figure WIRE 3 a-c: Influence of the wire diameter on the measured beam width (All figures from: Q. King; [Analysis of the Influence of Fibre Diameter on WireScanner Beam Profile Measurements](#), SPS-ABM-TM/Note/8802 (1988))

2. Higher Order Modes

An early observation (1972 DORIS) with wire scanners in electron accelerators was, that the wire was always broken, even without moving the scanner into the beam. An explanation was Higher Order Modes coupling into the cavity of the vacuum chamber extension housing the wire scanner fork. The wire absorbs part of the RF which led to strong RF heating.

Exercise WIRE1: Discuss methods of proving this behavior. What are possible solutions against the RF coupling?

3. Wire heat load

According to Bethe-Blochs formula, a fraction of energy dE/dx of high energy particles crossing the wire is deposit in the wire. dE/dx depends mainly on the material of the wire and its diameter, in the following we will assume dE/dx for minimum ionizing particles.

For simplification, a rectangular wire with a mean diameter of d' will be used in the calculation:

$$area = \frac{\pi d^2}{4} = d'^2 \Rightarrow d' = d / 2 \cdot \sqrt{\pi}$$

The following table shows parameters which can be used for some temperature estimations:

Wire Parameters

Parameter	Symbol	Unit	wire material				
			AL	W	Carbon	Beryllium	Quartz (SiO ₂)
wire diameter	d $= 7 \cdot 10^{-4}$	cm					
mean wire diameter	$d' = d/2 \cdot \sqrt{\pi}$ $= 5.5 \cdot 10^{-4}$	cm					
Conversion	0.239	cal/Joule					
Conversion factor	$C = 3.8 \cdot 10^{-14}$	cal/MeV					
Speed of wire	$v = 100$	cm/s					
specific heat capacity*	c_p	cal / g / °C	0.21	0.036	0.42 (>400°C) 0.17 (< 400°C)	0.43	0.18
Energy loss of min. ion. part. (MIPs)	dE/dx	MeV cm ² / g	1.62	1.82	2.3	1.78	2.33
	dE/dx_m	MeV/cm	4.37	35.13	5.3	3.3	5.3
density	ρ	g/cm ³	2.7	19.3	2.3	1.85	2.29
melting temp.	T_m	°C	650	3400	ca. 3500	1200	1700
Heat conductivity	l	W/(m K)	230	100-160	30-3000	200	1.2-1.4
Radiation length	l_{rad}	cm	8.9	0.35	18.8	34.7	12.3
Nuclear coll length	l_{nuc}	cm	26	9.6	34	30	25.4

Table WIRE1: Parameters of wire materials. * > 500 °C

Beam Parameters

The beam parameters used in this exercise are shown in the following table:

Parameter	Symbol	Unit	Value
circumference of accel.	circ.	m	300
particle		Proton	
Beam particle momentum	p	GeV/c	0.3-7
Beta function	$\beta_h = \beta_v$	m	11.8
Emittance	$\epsilon_h = \epsilon_v$	π mm mrad	15
revolution Frequency	f_{rev}	MHz	0.93
Bunch spacing	t_{bunch} f_{bunch}	ns MHz	98 10.2
Number of bunches in accel.	NB		11
Bunch charge	n_{bunch}	1/e	$1.1 \cdot 10^{11}$
Beam width measurement ¹	σ_h	mm	1.5
Beam width perpendicular to meas. ¹	σ_v	mm	1

Table WIRE2: Parameters of Beam

Each beam particle which crosses the wire deposits energy inside the wire. The energy loss is defined by dE/dx (minimum ionization loss) and is taken to be that for a minimum ionizing particle. In this case the temperature increase of the wire can be calculated by:

$$T = C \cdot dE / dx_m \cdot d' \cdot N \cdot \frac{1}{c_p \cdot G} \quad [^{\circ}C],$$

where N is the number of particles hitting the wire during one scan, d' is the thickness of a quadratic wire with the same area as a round one and G [g] is the mass of the part of the wire interacting with the beam. The mass G is defined by the beam dimension in the direction of the wire (perpendicular to the measuring direction).

Exercise WIRE2: Which kind of wire Material you will prefer for a wire scanner in this accelerator? Estimate the wire temperature after one scan with a speed v (assume no cooling mechanisms).

Exercise WIRE2a: Discuss cooling mechanisms which will cool the wire.

¹ Gaussian shape of width σ

4. Emittance blow up

Exercise WIRE3: Calculate the emittance blowup of the proton beam after one scan at a position with $\beta = 11.8$ m for $p = 0.3$ and 7 GeV/c (Carbon wire):

Assume a position of the wire scanner very close to a quadrupole ($\alpha=0$)

For small deflection angles a good approximation for average root mean square scattering angle is given by:

$$\delta \Theta = \frac{0.014 \text{ GeV}}{pc} \cdot \sqrt{\frac{d'}{L_{rad}}} \cdot \left(1 + 1/9 \cdot \log_{10} \frac{d'}{L_{rad}} \right)$$

High Resolution Measurements of Lepton Beam Transverse Distributions with the LEP Wire Scanners.

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Abstract

A large number of improvements were carried-out on the LEP Wire-Scanners in preparation for the 1992 running period. They include modifications of the monitors mechanics to decrease the vibrations and the heating of the wire by the beam generated electromagnetic fields, improvements of the detector chain and a software re-organization at the various levels for better noise rejection, improved user interface and "off-line" data analysis capabilities. It is now also possible to acquire the profiles of each of the sixteen circulating bunches, electrons and positrons, during the same sweep. As a consequence of these actions the quality of the collected data is much improved. The results are presented and discussed.

I. INTRODUCTION

Four wire-scanners are installed in LEP straight section 1 [1] to provide transverse distributions in both horizontal and vertical planes. Figure 1 gives the lay-out of the monitors together with their associated detectors.

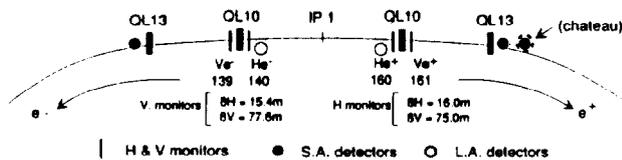


Fig 1: The LEP Wire-Scanners arrangement and Optics Parameters

One horizontal and one vertical monitor are symmetrically installed and are each associated with two detectors:

- a scintillator located behind a thin window, 75 meters downstream of the wire, receives the Bremsstrahlung resulting from the beam-wire interaction emitted at small angles (S.A.). It acquires the scan of the associated beam (i.e. e- profile from the monitors located on the e- injection side).

- a scintillator installed against the vacuum chamber near to the horizontal monitor collects the emission at large angles (L.A.) during the passage of the counter-rotating beam.

The signal received by the S.A. scintillators [1] is attenuated by 4 orders of magnitude before transmission to a photo-multiplier which has a gain 100 times smaller than that of the L.A. detectors.

II. THERMAL AND MECHANICAL OBSERVATIONS

Fourteen wires have been destroyed from 1989 to 1992, most of them in 1989 and 1990. With the exception of two 50 μm Beryllium wires, they were 36 μm thick carbon wires. The Be wires showed clearly [1] that the wire had melted over its full length, excluding beam energy deposition as the only destruction mechanism. This is confirmed by previous measurements at the SPS where the wires survived higher intensities at comparable speeds. Moreover, permanent wire average temperature monitoring has shown several interesting features (Figure 2):

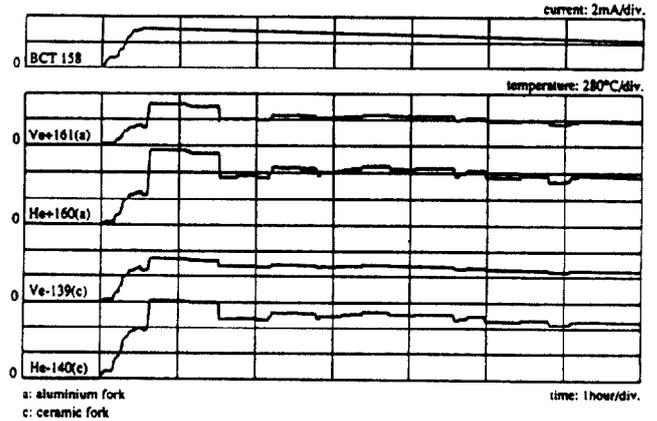


Fig. 2: Long term recording of wire resistance (temperature) and beam current with wires retracted in the parking position

The temperature of the wires increase with the stored current and the vertical wires temperature increases less than that of the horizontal ones. This indicates that the heating is of electromagnetic origin, due to the wake fields generated in the wire scanner tanks. The vertical wires heat up less because they are retracted in a rectangular tube functioning as a waveguide below cut-off. The second evidence in favour of electromagnetic heating is the fact that the wire temperature changes when beam manipulations modifying the bunch length take place at constant circulating beam intensity. Finally wire temperature recordings during scans provide other evidence of heating by electromagnetic coupling (Figure 3).

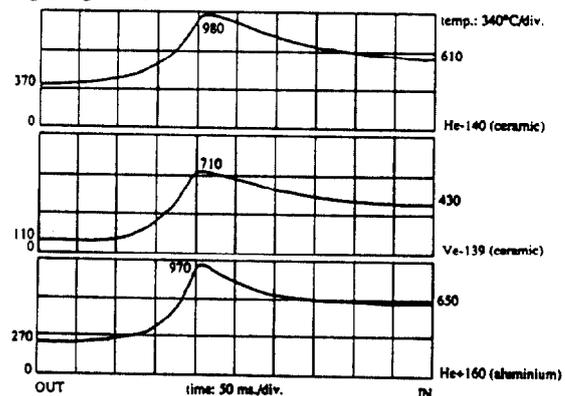


Fig. 3: Wire resistance change during scans of 300 μA on 300 μA circulating beams. Calculated temperatures are indicated.

As the wire approaches the beam, a temperature increase starts at approximately 40 mm from the beam centre, mainly due to coupling to the electric field. A steady state temperature is reached again when the wire is far from the beam. This results mainly from the magnetic field created by the beam passing in the loop formed by the wire and the supporting fork. The temperature increase of the

horizontal and vertical wires is inconsistent, the latter being too low compared to the former. Laboratory tests have shown that thermoemission starts at around 1000°C and shifts the resistance measurement towards lower equivalent temperatures. Electromagnetic heating of the wire being established, the fork construction was analysed for possible improvements. A coupling capacitance of a few pF was found between the wire and the fork; this was created between the aluminium arm, the wire supporting aluminium piece and the ceramic insulator (Figure 4). Two different types of supporting forks were installed in early 1991. The first design had a modified wire support piece and ceramic transition pieces to decrease the coupling capacitance (Figure 4).

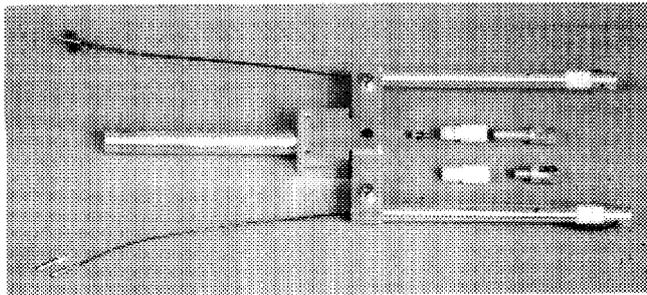


Fig. 4: Wire supporting fork with original (top) and modified (bottom) wire holding and ceramic isolating pieces.

A second design was implemented with the whole supporting tubes made of ceramic. In 1992, the wire length of the combined aluminium/ceramic forks was reduced from 55 to 29 mm. The vertical wire with this design broke twice in 1992. The temperature recording of the first incident showed that it happened at a circulating current of 2.8 mA; the temperature reached was 1280°C, uncorrected for thermoemission. For 1993, a 30 μm quartz wire has been installed in place of the broken wire. The quartz wire will definitely break any current loop leading to heating but it may experience high voltage breakthroughs when passing through the beam. Since 1991, no wires with full ceramic arms were broken.

Scans taken in 1991 and 1992 are affected by a shift of the beam centre of charge between the IN and OUT directions of the order of 100 μm . Laboratory tests have shown that it is due to an inertia induced movement of the driving screw [1]. This effect could be reduced in the laboratory from 70 to 10 μm by using a counter-pin pushing on the free end of the driving shaft. This modification could not be implemented for the 1993 LEP start-up.

III. LOW LEVEL AND APPLICATION SOFTWARE

The basic software design used in 1992 was unchanged from 1991. Amongst the various data structures exchanged between the local equipment server and the application, the PROFILE structures (one per profile) hold all the signals relative to a given bunch received from the photo-multiplier. If their initial analysis (sigma processing within the server) is successful, these data are trimmed to ± 4 sigmas; otherwise the entire profile is stored for more detailed "off-line" analysis. An analysis failure usually occurs when all signals are hidden within the noise. However, even with a good signal level the fit results (mainly the standard deviation) are noise dependent. In order to cope with this, two different methods have been tested :

- a simple rms calculation over the whole profile followed by a second iteration over a limited window
- a more refined gaussian fit providing a chi-squared minimization on all data above 10% of the maximum amplitude.

The later technique is less noise sensitive but is also less accurate when the distribution is not gaussian. For the future runs the results of both the rms processing and the gaussian fit will be forwarded to the application for systematic comparisons.

The application interface has also been upgraded for 1993 owing to the availability of more powerful graphic tools. It will be possible to display simultaneously up to eight circulating bunch profiles (of the same beam or of the two e+/e- beams) and to display IN and OUT profiles relative to a given scan on the same plot. These modifications added to better "off-line" analysis facilities will ease the interpretation of results.

IV. RESULTS AND DISCUSSION

A scan is systematically performed in the IN (beam) and OUT (of beam) directions. As a result, two profiles are measured and can be compared each time a sweep is triggered in a given plane. The wire position (x axis) is in millimeters whereas the y scale unit is arbitrary and depends on the monitor gain setting.

HORIZONTAL PLANE:

In this plane the signal received by the S.A. detectors is excellent and provides good gaussian fits of the bunch profiles. This is illustrated on Figure 5 in the case of a positron bunch analysed with the monitor located on the positron side. Standard deviations from both scan directions are in agreement within $\pm 1.3\%$.

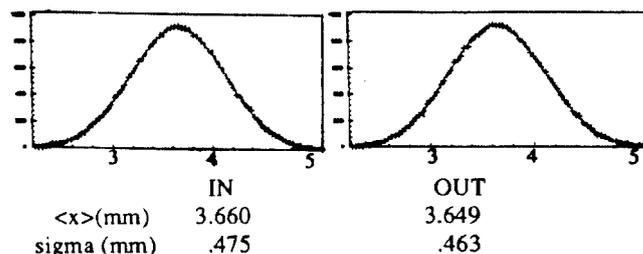


Fig 5: IN and OUT profiles and fit results of a positron bunch scanned with the He+ monitor and analysed with the S.A. detector at the window

Another S.A. detector (chateau) located fifteen meters downstream from the Bremsstrahlung radiation extraction window was also used in order to investigate eventual acceptance problems and effects of background close to the vacuum chamber. This detector was shifted radially which gave better shielding. Its response is given on Figure 6 for the same bunch .

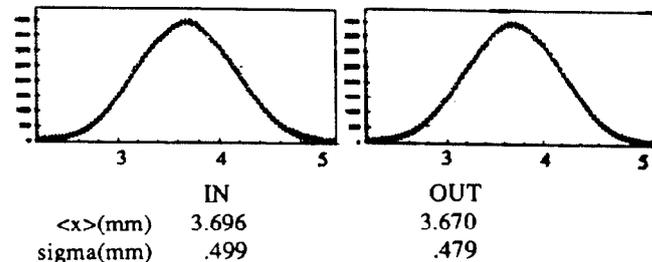


Fig 6: IN and OUT profiles and fit results of the same bunch from the S.A. detector located 15 meters downstream from the window

Between the IN and OUT directions the agreement is $\pm 2\%$ and both S.A. detectors give the same standard deviation within $\pm 2.1\%$

The response of the L.A. detectors is less good. The signal to noise ratio at large angle is less favourable and a compromise must be found between the shielding depth protecting the scintillator from background and the signal level to be analysed. In order to reduce the background noise 10 mm of Lead was necessary. However some saturation then started to affect the photomultiplier in the peak region (Figure 7)

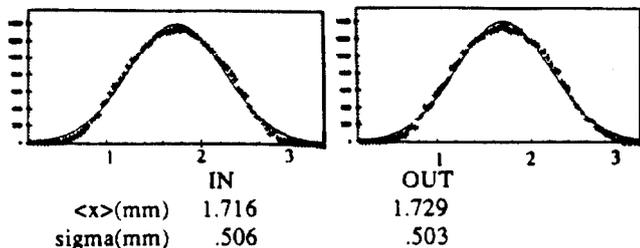


Fig 7: IN and OUT profiles and fit results of the same bunch scanned with the He- monitor and analysed with the L.A. detector.

The fit results provided by both directions agree very well but lead to standard deviations 5% higher than the S.A. detectors. The different average positions indicate that the beam trajectory is different at the e+ and at the e- monitors.

VERTICAL PLANE :

Typical profiles performed using the vertical monitors are shown on Figure 8 for the S.A. detectors.

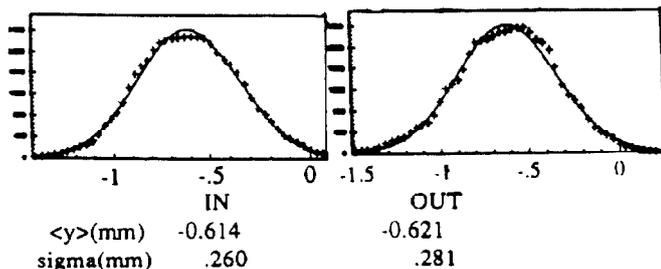


Fig 8: IN and OUT profiles and fit results of an electron bunch scanned with the Ve- monitor and analysed with the S.A. detector at the window.

Vertical profiles are usually affected by blow-up effects resulting from Coulomb Scattering of the beam through the wire. Taking the emittance ratio in LEP and the present monitor performances these effects can now be neglected in the horizontal plane at 46 GeV. They dilute mainly the second half of the vertical scan (positive and negative sides for respectively the IN and OUT directions) as can be seen on Figure 8. Hence, a direct gaussian fit provides a too pessimistic result. By modelling this effect and analysing the non-perturbed halves of the IN and OUT profiles [1], it is possible to reconstruct the initial distribution. An example of the results is given on Figure 9. A reduction of the rms value by 10% to 20% is then observed with respect to the fit of the entire measured distribution. However this method still suffers from the random mechanical effects (section II) and from timing imprecisions. Therefore it cannot be used systematically.

The L.A. detectors suffer from a lack of signal in the case of vertical profiles as they are located near to the H monitors (Figure 1) five meters downstream from the vertical ones.

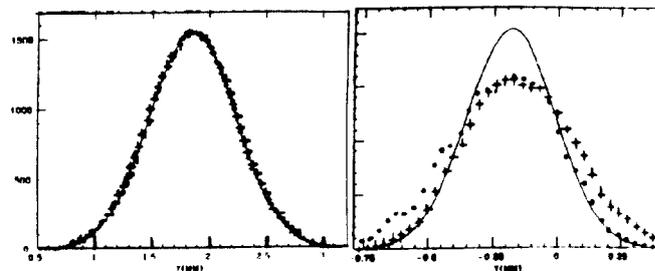


Fig 9: Initial distributions from IN and OUT profile analysis :
+ : IN direction , o : OUT direction , — : fitted profile .

The gaussian fits of profiles from the S.A. detectors provide emittance values of 0.9nm to 1 nm in the vertical plane and 14nm to 15 nm horizontally. The precision achieved is a few per cent in the horizontal plane. Vertically the results are not so accurate as long as blow-up effects are not properly eliminated.

V. COMPARISON WITH S.R. MONITORS

These figures, can be used to calibrate the U.V. telescopes [2]. The agreement between the two devices is disturbed by parasitic effects which must be considered; they are at locations in the machine where the optics are not the same and where beam dynamical effects are different (for example coupling). This can account for discrepancies of around 20%. Some 50Hz noise also disturbs the two devices differently as they have different modes of acquisition

VI. FUTURE UPGRADES AND CONCLUSION

Several steps will be taken to improve wire-scanner performances in addition to the ones discussed in section II. The mechanics will be modified to reduce the shift between the two directions. It has also been considered to add to each monitor a wire rotated by 45 degrees. This will allow a better evaluation of the tilt effects. The electric noise level will be reduced in the wire scanners environment by installing filters on adjacent motorised devices. These improvements are foreseen for the 1994 runs. Both the S.A. and L.A. detectors have been modified. The former will have a better acceptance in particular close to the vacuum chamber whereas the shape of the later has been reconsidered to increase its acceptance and hence have better signal to noise ratio.

Several software modifications will be implemented apart from the availability of the new application (section III). An interlock will prevent any scans above a given circulating beam current and temperatures will be systematically recorded during wire sweeps. The timing will be upgraded so as to lower the uncertainty in the absolute position reference between IN and OUT scans from 50 μ m down to 10 μ m (rms). The wire status will also be monitored in permanence.

Resulting from these modifications we expect to have the same level of performance in both the horizontal and vertical planes.

VIII. REFERENCES

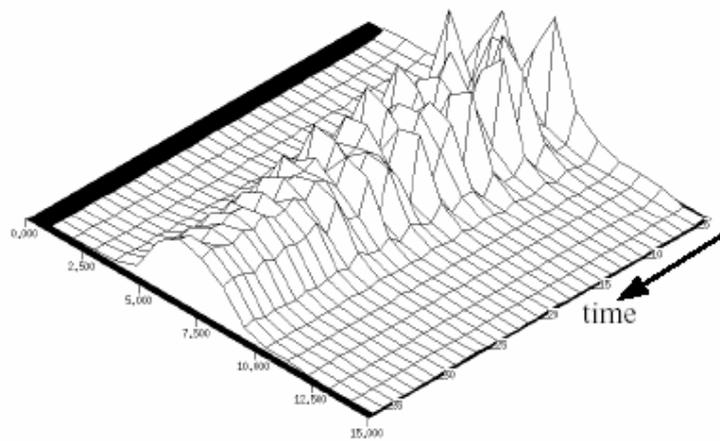
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2.2 EXERCISES AND LITERATURE: INJECTION MISMATCH

2.2 Exercises and Literature: Injection Mismatch

Advanced Instrumentation

Exercises: Injection mismatch



Exercises: Injection mismatch

As a rule, proton/ion accelerators need their full aperture at injection, thus avoiding mismatch allows a beam of larger normalized emittance ϵ^* and containing more Protons. In proton/ion ring accelerators any type of injection mismatch will lead to an emittance blowup. Off axis injection will lead to orbit oscillations. These oscillations can be detected easily by turn-by-turn BPMs in the ring (before Landau damping occurs). The orbit mismatch can be corrected by a proper setup of the steering magnets, kickers and septas. However, any mismatch of the optical parameters α , β (and therefore γ) will also lead to an emittance blowup (and beam losses) and is not detectable by BPMs.

Fig. 1a shows the phase ellipse at a certain location in a circular accelerator. The ellipse is defined by the optics of the accelerator with the emittance ϵ and the optical parameters $\beta =$ beta function, $\gamma = (1 + \alpha^2)/\beta$ and the slope of the beta function $\alpha = -\beta'/2$. Fig. 1b-d shows the process of filamentation after some turns.

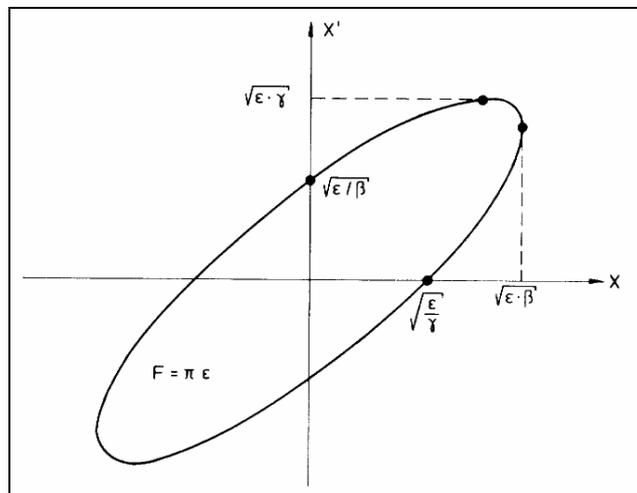


Fig 1a: A phase space ellipse of a circular accelerator, defined by α , β , γ , ϵ

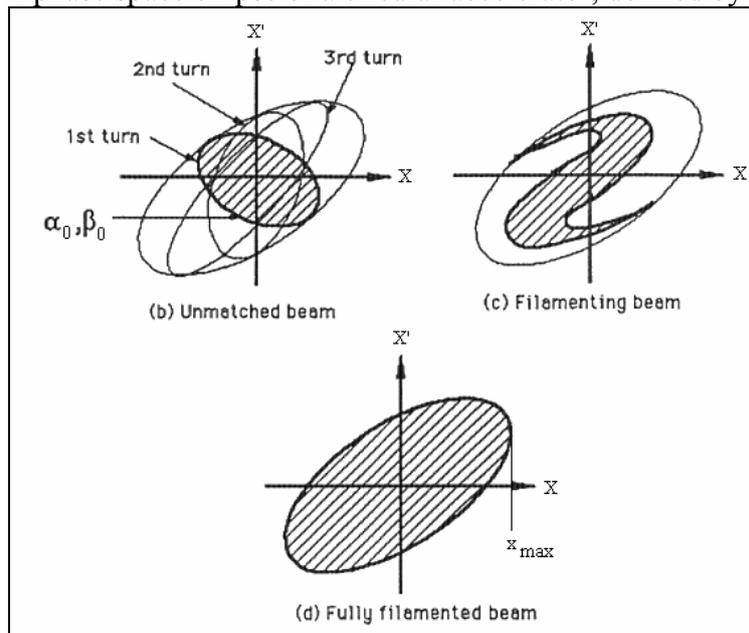


Fig. M1 b-d: Filamentation of an unmatched beam (from Ref. 2)

Assuming a beam is injected into the circular machine, defined by β_0 and α_0 (and therefore γ_0) with a given emittance ε_0 . For each turn i in the machine the three optical parameters will be transformed by

$$\begin{pmatrix} \beta_{i+1} \\ \alpha_{i+1} \\ \gamma_{i+1} \end{pmatrix} = \begin{pmatrix} C^2 & -2SC & S^2 \\ -CC' & SC'+S'C & -SS' \\ C'^2 & -2S'C' & S'^2 \end{pmatrix} \cdot \begin{pmatrix} \beta_i \\ \alpha_i \\ \gamma_i \end{pmatrix} \quad (\text{Starting with } i = 0)$$

where C and S are the elements of the Twiss matrix ($\mu = 2\pi q$, $q = \text{tune}$):

$$\begin{pmatrix} C & S \\ C' & S' \end{pmatrix} = \begin{pmatrix} \cos \mu + \alpha_0 \cdot \sin \mu & \beta_0 \cdot \sin \mu \\ -\gamma_0 \cdot \sin \mu & \cos \mu - \alpha_0 \cdot \sin \mu \end{pmatrix} \quad (1)$$

and $\gamma = (1 + \alpha^2)/\beta$

Without any mismatch, the three parameters will be constant while a mismatch will result in an oscillation of the parameters.

Some important machine parameters (here: HERAp)

Circumference $\text{circ} = 6.3 \text{ km}$, $f_{\text{rev}} = 47.3 \text{ kHz}$

Tune $q = 0.31$ or $f_{\text{tune}} = 14.6 \text{ kHz}$

Momentum $E_p = 40 \text{ GeV}/c$ at injection

Normalized emittance $\varepsilon_n = 20 \pi \text{ mm mrad}$, $\varepsilon_0 = 5 \cdot 10^{-7}$

$\beta_0 = 238 \text{ m}$, $\alpha_0 = -2.2$, $\Rightarrow \gamma_0 = 0.0245$ at the injection point ($\beta\gamma - \alpha^2 = 1$). \Rightarrow ring

$\beta = 214 \text{ m}$, $\alpha_0 = \alpha$, $\Rightarrow \gamma = 0.0272$ at the injection point. \Rightarrow injected beam

Exercise M1: Show the beta-oscillation for the mismatch. What is the oscillation frequency? What are typical amplitudes?

Discuss how to measure a 10% betatron mismatch at injection between a transport line and a storage ring, for example in the HERAp accelerator.

Exercise M2: How large is the emittance blow-up?

Exercise M2a: What kind of measurement will you propose to determine the β -mismatch? Which monitor do you propose for this measurement?

Exercise M2b: What is the effect of the proposed monitor(s) on the beam?

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Amplitude Function Mismatch

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Abstract

We develop the general equation of motion of an amplitude function mismatch in an accelerator lattice and look at its solution for some interesting cases. For a free β -wave oscillation the amplitude of the mismatch is written in terms of the determinant of a single matrix made up of the difference between the new Courant-Snyder parameters and their ideal values. Using this result, once one calculates the mismatch of the amplitude function and its slope at one point in the lattice (at the end of a *nearly* matched insertion, for example), then the maximum mismatch downstream can be easily computed. The formalism is also used to describe emittance growth in a hadron synchrotron caused by amplitude function mismatches at injection.

While most of the content of this paper is not new to the accelerator physics community, we thought it would be useful to place this important, basic information all in one place. Besides the classic work of Courant and Snyder, our sources include other papers, internal reports, and numerous discussions with our colleagues. More details may be found in a related paper.[1]

I. A STARTING POINT

The general solution for linear betatron oscillations in one transverse degree of freedom can be written as[2] $x(s) = A\sqrt{\beta(s)}\cos[\psi(s) + \delta]$ where A and δ are constants given by the particle's initial conditions. The phase advance $\psi(s)$ and the amplitude function $\beta(s)$ satisfy the differential equations $\psi' = \frac{1}{\beta}$, $2\beta\beta'' - \beta'^2 + 4\beta^2K = 4$, where $K = e(\partial B_y/\partial x)/p$, with $e =$ charge, $p =$ momentum, $\partial B_y/\partial x =$ magnetic field gradient, and $\beta' = d\beta/ds$, etc. When one considers the periodic solution of the amplitude function, the motion through a single repeat period can be described in terms of the Courant-Snyder parameters $\beta(s)$, $\alpha(s) \equiv -(d\beta(s)/ds)/2$, and $\gamma(s) \equiv (1 + \alpha^2)/\beta$, using the matrix

$$\begin{pmatrix} \cos \psi_C + \alpha \sin \psi_C & \beta \sin \psi_C \\ -\gamma \sin \psi_C & \cos \psi_C - \alpha \sin \psi_C \end{pmatrix} \quad (1)$$

which operates on the state vector X , with $X = (x, x')^T$. Here, the phase advance is $\psi_C = 2\pi\nu = \int_{s_0}^{s_0+C} \frac{ds}{\beta(s)}$, where

*Operated by the Universities Research Association, Inc., for the U.S. Department of Energy under Contract No. DE-AC35-89ER40486.

C is the repeat distance of the hardware, which may be the circumference of the accelerator, and ν is the *tune* of the synchrotron.

The matrix of Equation 1 is often written in compact form as $M = I \cos \psi_C + J \sin \psi_C$ where

$$J \equiv \begin{pmatrix} \alpha & \beta \\ -\gamma & -\alpha \end{pmatrix}. \quad (2)$$

The amplitude function and its slope propagate through an accelerator section according to

$$J_2 = M(s_1 \rightarrow s_2)J_1M(s_1 \rightarrow s_2)^{-1}, \quad (3)$$

where J_1 and J_2 contain Courant-Snyder parameters corresponding to points 1 and 2, and $M(s_1 \rightarrow s_2)$ is the transport matrix between these two points.

II. PROPAGATION OF A THIN GRADIENT ERROR

We wish to see how the amplitude function downstream of a thin gradient error is altered. If $J_0(s_0)$ is the matrix of unperturbed Courant-Snyder parameters at the location of the error and $J_0(s)$ contains the unperturbed parameters at a point downstream, then, using Equation 3,

$$\Delta J(s) = M(s_0 \rightarrow s)\Delta J(s_0)M(s_0 \rightarrow s)^{-1}, \quad (4)$$

where

$$\Delta J(s) = J(s) - J_0(s) = \begin{pmatrix} \alpha - \alpha_0 & \beta - \beta_0 \\ -(\gamma - \gamma_0) & -(\alpha - \alpha_0) \end{pmatrix}; \quad (5)$$

β is the new value of the amplitude function at s , β_0 is the unperturbed value, etc. Through a thin quad, $\Delta\alpha = q\beta_0$, $\Delta\beta = 0$, and $\Delta\gamma = 2\alpha q + \beta q^2$ and so

$$\frac{\Delta\beta(s)}{\beta_0(s)} = -(\beta_i q) \sin 2\psi_0(s - s_0) + \frac{1}{2}(\beta_i q)^2 [1 - \cos 2\psi_0(s - s_0)] \quad (6)$$

where $\psi_0(s - s_0)$ is the unperturbed phase advance between points s_0 and s and $\beta_i \equiv \beta_0(s_0)$. The amplitude function perturbation oscillates at twice the betatron frequency and for $(\beta_i q)$ sufficiently small, the perturbation describes simple harmonic motion. The change in α also propagates at

twice the betatron frequency, it being given by

$$\begin{aligned} \Delta\alpha(s) = & \beta_i q [\cos 2\psi_0(s - s_0) - \alpha_0(s) \sin 2\psi_0(s - s_0)] \\ & - \frac{1}{2}(\beta_i q)^2 [\sin 2\psi_0(s - s_0) \\ & - \alpha_0(s)(1 - \cos 2\psi_0(s - s_0))] . \end{aligned} \quad (7)$$

Introducing this quad error also changes the phase advance across the lattice. The new phase advance $\psi(s - s_0)$ across this section may be calculated using $\sin \psi(s - s_0) = \bar{M}(s_0 \rightarrow s)_{12} / \sqrt{\beta_i \beta(s)}$ where $\bar{M}(s_0 \rightarrow s)_{12}$ is the (1,2) element of the new ring matrix and $\beta(s)$ is the new amplitude function at s . Using Equation 6, we obtain

$$\begin{aligned} \sin \psi(s - s_0) = & [1 - \beta_i q \sin 2\psi_0(s - s_0) \\ & + (\beta_i q)^2 \sin^2 \psi_0(s - s_0)]^{-1/2} \sin \psi_0(s - s_0) . \end{aligned} \quad (8)$$

An explicit result for the change in the phase advance may be obtained perturbatively in orders of the quad error q from the above exact expression. To second order in q , we find that the change $\Delta\psi \equiv \psi(s - s_0) - \psi_0(s - s_0)$ is

$$\begin{aligned} \Delta\psi = & \beta_i q \sin^2 \psi_0(s - s_0) \\ & - (\beta_i q)^2 \sin 2\psi_0(s - s_0) \sin^2 \psi_0(s - s_0) + O(q^3) . \end{aligned} \quad (9)$$

To first order in q , at a point $\pi/2$ away from the location of the error, there is no change in the β function while the change in phase advance is at its maximum value of $\beta_i q$.

III. EQUATION OF MOTION OF β -WAVE

The equation of motion for an amplitude function mismatch is nonlinear when s is taken as the independent variable. A more congenial equation can be developed by using the reduced phase $\phi \equiv \psi/\nu$ as the independent variable. For betatron oscillations the Floquet transformation, where the other variable is $\zeta = x/\sqrt{\beta}$, produces the equation of motion $\frac{d^2\zeta}{d\phi^2} + \nu^2\zeta = 0$ which is pure simple harmonic motion with frequency (tune) ν . For the amplitude function mismatch, we need to define the reduced phase in terms of the unperturbed functions. That is, let $\phi \equiv \psi_0/\nu_0$, where $d\psi_0/ds = 1/\beta_0$, and ν_0 is the unperturbed tune. The equation of motion for $[\beta(\phi) - \beta_0(\phi)]/\beta_0(\phi) \equiv \Delta\beta/\beta_0$ in the absence of gradient errors is then

$$\begin{aligned} \frac{d^2}{d\phi^2} \frac{\Delta\beta}{\beta_0} + (2\nu_0)^2 \frac{\Delta\beta}{\beta_0} &= -2\nu_0^2 \det\Delta J \\ &= 2\nu_0^2 [\Delta\alpha^2 - \Delta\beta\Delta\gamma] \end{aligned} \quad (10)$$

where $\Delta\alpha = \alpha(\phi) - \alpha_0(\phi)$, etc. The quantity $\det\Delta J$ is an invariant in portions of the lattice without gradient perturbations as can be seen with the aid of Equation 3.

So, the free amplitude function distortion oscillates with twice the betatron tune and with a constant offset given by the determinant of the ΔJ matrix at any point. This offset must be there since $\beta > 0$ and hence $\Delta\beta/\beta$ must always be greater than -1 .

Rewritten in terms of the Courant-Snyder parameters,

$$\det\Delta J = - \frac{\left(\frac{\Delta\beta}{\beta_0}\right)^2 + \left(\Delta\alpha - \alpha_0 \frac{\Delta\beta}{\beta_0}\right)^2}{1 + \Delta\beta/\beta_0} < 0. \quad (11)$$

Thus, $|\det\Delta J|^{1/2}$ can be interpreted as the amplitude of the β mismatch for small perturbations.

The solution to Equation 10 is just simple harmonic motion with a constant term added:

$$\frac{\Delta\beta}{\beta_0}(\phi) = A \cos 2\nu_0\phi + B \sin 2\nu_0\phi + \frac{1}{2}|\det\Delta J|. \quad (12)$$

The constants A and B are found from the initial conditions:

$$A = \frac{\Delta\beta}{\beta_0}(0) - \frac{1}{2}|\det\Delta J|, \quad (13)$$

$$B = \alpha_0 \frac{\Delta\beta}{\beta_0}(0) - \Delta\alpha(0). \quad (14)$$

Thus, the maximum value of $\Delta\beta/\beta_0$ downstream of our starting point $\phi = 0$ is given by

$$\begin{aligned} \left(\frac{\Delta\beta}{\beta_0}\right)_{max} &= \sqrt{A^2 + B^2} + \frac{1}{2}|\det\Delta J| \\ &= \frac{|\det\Delta J|}{2} + \sqrt{|\det\Delta J| + \left(\frac{|\det\Delta J|}{2}\right)^2} \end{aligned} \quad (15)$$

where use has been made of Equation 11. The maxima occur at phases where

$$\tan 2\nu_0\phi = \left(\frac{\alpha_0 \frac{\Delta\beta}{\beta_0} - \Delta\alpha}{\frac{\Delta\beta}{\beta_0} - |\det\Delta J|/2} \right)_0 . \quad (16)$$

The usefulness of the above result is, of course, that once one calculates the mismatch of the amplitude function and its slope at one point in the lattice (at the end of a *nearly* matched insertion, for example), then the maximum mismatch downstream can be computed immediately.

If we look once again at the perturbation downstream of a thin quadrupole error, we see that just after the quad,

$$\det\Delta J = \begin{vmatrix} q\beta_i & 0 \\ -\Delta\gamma & -q\beta_i \end{vmatrix} = -(q\beta_i)^2 \quad (17)$$

where $\beta_i = \beta_0$ at the location of the quadrupole. Then,

$$\left(\frac{\Delta\beta}{\beta_0}\right)_{max} = q\beta_i \sqrt{1 + (q\beta_i)^2/4} + \frac{1}{2}(q\beta_i)^2 \quad (18)$$

$$\approx q\beta_i = \sqrt{|\det\Delta J|} \quad (19)$$

where the last line is valid for small perturbations.

IV. GENERAL EQUATION OF MOTION

To include the driving terms due to gradient errors in the equation of motion for $\Delta\beta/\beta_0$, we let β_0 satisfy the differential equation $K\beta_0 = \gamma_0 + \alpha'_0$, and let β satisfy $(K + k)\beta = \gamma + \alpha'$, where $\beta = \beta_0 + \Delta\beta$, etc. Then, the relative β error satisfies

$$\begin{aligned} & \frac{d^2}{d\phi^2} \frac{\Delta\beta}{\beta_0}(\phi) + (2\nu_0)^2 \frac{\Delta\beta}{\beta_0}(\phi) \\ &= -2\nu_0^2 \left[\beta_0^2(\phi) k(\phi) \left(1 + \frac{\Delta\beta}{\beta_0}(\phi) \right) + \det\Delta J(\phi) \right]. \end{aligned} \quad (20)$$

Here, in general, $\det\Delta J(\phi)$ is not invariant as it is altered by gradient perturbations:

$$\frac{d}{d\phi} \det\Delta J(\phi) = \beta_0^2 k \frac{d}{d\phi} \frac{\Delta\beta}{\beta_0} \quad (21)$$

For small perturbations we can drop quantities which are second order in the small quantities, e.g. $k\Delta\beta$. This reduces Equation 20 to

$$\frac{d^2}{d\phi^2} \frac{\Delta\beta}{\beta_0}(\phi) + (2\nu_0)^2 \frac{\Delta\beta}{\beta_0}(\phi) = -2\nu_0^2 \beta_0^2 k(\phi) \quad (22)$$

as appears in Courant and Snyder.[2]

Noting that $\Delta\alpha - \alpha_0(\Delta\beta/\beta_0) = -(1/2\nu_0)d(\Delta\beta/\beta_0)/d\phi$, one can easily exhibit Equation 20 entirely in terms of $\Delta\beta/\beta_0$ and its derivatives with respect to ϕ . Differentiating this resulting equation one obtains a *linear* differential equation for $\Delta\beta/\beta_0$:

$$\begin{aligned} & \frac{d^3}{d\phi^3} \frac{\Delta\beta}{\beta_0} + (2\nu_0)^2(1 + \beta_0^2 k) \frac{d}{d\phi} \frac{\Delta\beta}{\beta_0} \\ &+ 2\nu_0^2 \frac{d}{d\phi} [\beta_0^2 k] (1 + \frac{\Delta\beta}{\beta_0}) = 0. \end{aligned} \quad (23)$$

V. INJECTION MISMATCH

It is also of interest to look at the effects of mismatches of amplitude functions upon entrance to an accelerator. The treatment below may be followed in more detail in [3] and [4]. A beam which is described by Courant-Snyder parameters that are not the periodic parameters of the accelerator into which it is injected will tend to filament due to nonlinearities and hence have its emittance increased. Suppose β and α are the Courant-Snyder parameters as delivered by the beamline to a particular point in an accelerator, and β_0, α_0 are the periodic lattice functions of the ring at that point. A particle with trajectory (x, x') can be viewed in the $(x, \beta x' + \alpha x) \equiv (x, \eta)$ phase space corresponding to the beamline functions, or in the $(x, \beta_0 x' + \alpha_0 x) \equiv (x, \eta_0)$ phase space corresponding to the lattice functions of the ring. If the phase space motion lies on a circle in the beamline view, then the phase space motion will lie on an ellipse in the ring view. The equation of the ellipse in the "ring" system will be

$$\frac{(1 + \Delta\alpha_r^2)}{\beta_r} x^2 + 2\Delta\alpha_r x\eta_0 + \beta_r \eta_0^2 = \beta_0 A^2. \quad (24)$$

where $\beta_r \equiv \beta/\beta_0$ and $\Delta\alpha_r \equiv \alpha - \alpha_0(\beta/\beta_0)$.

If the phase space coordinate system were rotated so that the cross-term in the equation of the ellipse were eliminated, the ellipse would have the form $x_e^2/b_r + b_r \eta_{oe}^2 = \beta_0 A^2$ where $b_r \equiv F + \sqrt{F^2 - 1}$ and F is given by

$$F \equiv \frac{1}{2} [\beta_0 \gamma + \gamma_0 \beta - 2\alpha_0 \alpha]. \quad (25)$$

Note that if $\Delta\alpha_r = 0$, then $b_r = \beta_r$.

There is a physical significance to the quantity b_r ; it is the ratio of the areas of two circumscribed ellipses which have shapes and orientations given by the two sets of Courant-Snyder parameters found in the matrices J and J_0 . This might suggest that a beam contained within the smaller ellipse upon injection into the synchrotron (whose periodic functions give ellipses similar to the larger one) will have its emittance increased by a factor b_r . However, this would be an over-estimate of the increase of the average of the emittances of all the particles.

If in the beamline view the new phase space trajectory is $x^2 + \eta^2 = b_r R^2$, then in the synchrotron view, the equation of the ellipse would be $\frac{x^2}{b_r R^2} + \frac{\eta_0^2}{R^2/b_r} = 1$. A particle with initial phase space coordinates x_i and η_{oi} will commence describing a circular trajectory of radius a in phase space upon subsequent revolutions about the ring. The equilibrium distribution will have variance in the x coordinate

$$\sigma^2 = \langle x^2 \rangle = \frac{\langle a^2 \rangle}{2} = \frac{b_r^2 + 1}{2b_r} \sigma_0^2 = F \sigma_0^2, \quad (26)$$

where σ_0^2 is the variance in the absence of a mismatch. This expression can be rewritten in terms of $\det\Delta J$ which we found in Section III:

$$\frac{\sigma^2}{\sigma_0^2} = 1 + \frac{1}{2} |\det(\Delta J)|. \quad (27)$$

For the case where the slope of the amplitude function is matched and equal to zero, we have

$$\frac{\sigma^2}{\sigma_0^2} = 1 + \frac{1}{2} \left(\frac{\Delta\beta/\beta_0}{\sqrt{1 + \Delta\beta/\beta_0}} \right)^2. \quad (28)$$

This says that a 20% β mismatch at injection, for example, would cause only a 2% increase in the rms emittance.

VI. REFERENCES

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- [3] M. J. Syphers, "Injection Mismatch and Phase Space Dilution," Fermilab FN-458, June 1987.
- [4] D. A. Edwards and M. J. Syphers, *An Introduction to the Physics of High Energy Accelerators*, John Wiley, and Sons, New York, 1993.

Chapter 3

Tune and Chromaticity Diagnostics

3.1 Exercises I: Tune Measurements

Phase-Locked Loop (PLL) time resolved tracking of betatron tunes

Summary:

The students are confronted with the different ways of measuring betatron tunes. The importance of time resolved measurements is illustrated, which is best achieved with a PLL circuit. A simple analog model of a PLL circuit is developed. A realistic digital implementation is analyzed.

Problems to be solved:

Neglecting betatron oscillations after the injection process or beam instabilities we can assume that the particle beam will circulate on a stable closed orbit in the accelerator. In order to measure the betatron tune a transverse oscillation of the beam has to be excited and then observed with one or several position sensitive instruments. Depending on the choice of the excitation method and the observation instrument many different ways of measuring the tune with different qualities can be imagined. The following table gives a brief summary.

Beam Excitation Signal	Treatment of measured oscillation	Comments
Consecutive random noise kicks	Fourier transform	Work horse of operational tune measurement, precision 10 ⁻³ ...10 ⁻⁴
Single kick	Fourier transform, sliding Fourier transform, wavelet analysis	Observation of damped oscillation, large initial amplitude (emittance dilution in hadron machines after filamentation), access to non-linearities Precision depends on damping time
Sin wave excitation with slowly varying frequency (CHIRP)	Synchronous detection of beam motion	Measurement of full beam transfer function (network analyser) Precision only limited by beam stability and measurement time, precision typical typical 10 ⁻⁴
Continuous sin wave excitation on beam resonance	Phase locked loop (PLL) circuit keeps beam exciter on resonance	Best tool to trace tune changes during machine transitions (acceleration...) Information of full beam spectrum not available, precision depends on bandwidth of PLL. 10 ⁻⁶ can be
"AC-dipole"excitation Sin wave excitation OUTside frequencies of beam resonance	Fourier transform of beam motion	acts like a fast orbit changing dipole magnet, can create large amplitudes for diagnostics, no emittance blowup

Question 1)

Discuss the table with your tutor and draw the time envelope of the beam excitation signal and the beam response for the first 3 methods:

- a) broad band noise excitation and frequency analysis of the resulting oscillation.
- b) single kick stimulus and frequency analysis of resulting oscillation
- c) swept sine wave excitation and vector analysis of resulting oscillation

For a) What happens in case one does not use broad band (white) noise? Imagine the extreme case that the bandwidth of the “noise” spectrum is reduced to a single sinusoidal line.

Another way of looking at tune measurements is in frequency domain:

One considers the beam as a linear resonating oscillator, which responds to a stimulus like a filter. One can hence draw the spectral intensity of the beam exciter and the spectral density of the resulting beam oscillation. The ratio of both functions corresponds to the transfer function of the beam (as resonator) and the betatron tune can be measured as the maximum of this transfer function.

Question 2)

Repeat the discussion as in 1, but this time produce qualitative drawings in frequency domain for the input spectra and the output spectra. Indicate in the ratio of these spectra (i.e. in the “measured beam transfer functions”) the betatron tune.

We refer to the more rigorous mathematical treatment of a beam as damped harmonic oscillator as done for the transverse feedback.

Question 3)

Draw the transfer function of the beam as resonator as amplitude and phase as function of frequency. What physics parameters determine the resonance frequency and the width of these functions?

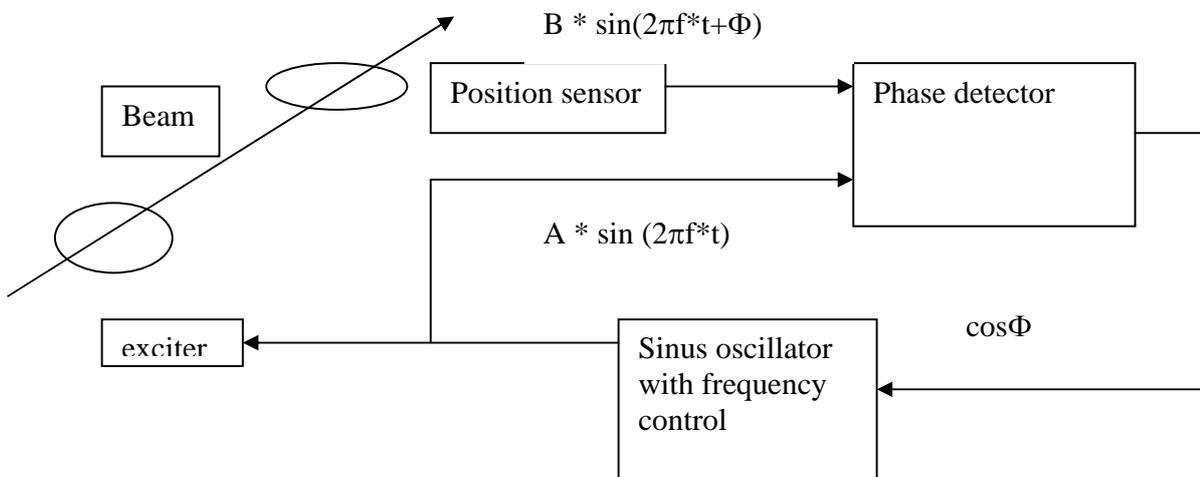
The following very simple electronic circuit (called **PLL** for **Phase Locked Loop**) excites the beam (via an electromagnetic deflection element) permanently with a sin-wave. In the return path the beam oscillation is measured with a position sensitive pickup. The phase detector measures the phase between beam exciter and beam response. The phase information is feed back to the frequency of the driving exciter, such that the circuit maintains an oscillation on the center of the resonance, even if this resonance changes as a function of time.

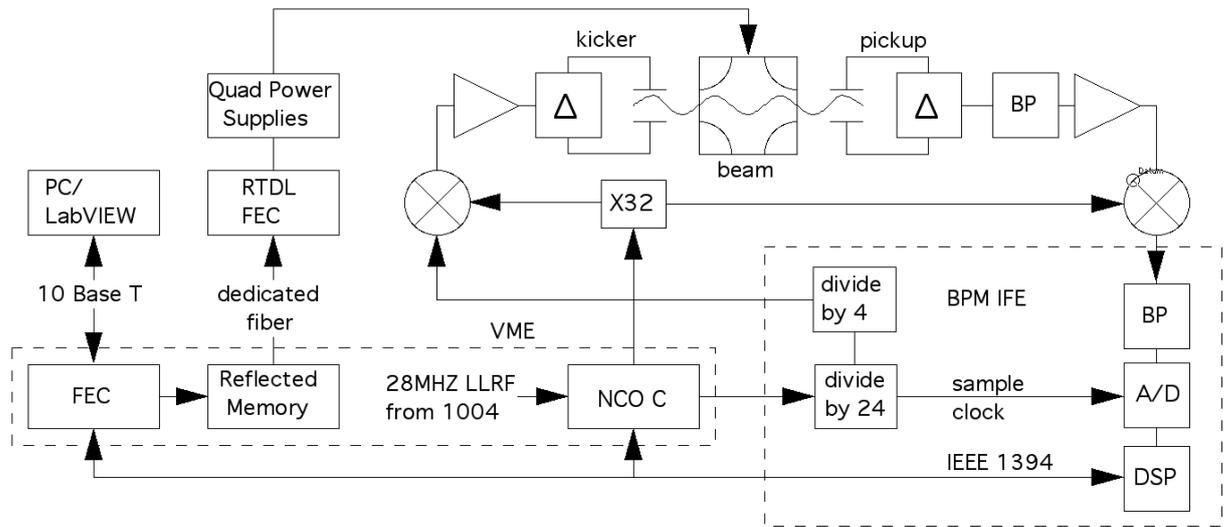
Question 4)

If the phase detector of the above circuit is made, such that its output is proportional to $\cos\Phi$, then there will be no action on the frequency of the oscillator for $\Phi=90$. Use the answer of question 3 to indicate to what frequency the PLL circuit will lock in this case. If you had to build such a phase detector, how would you do that?
By taking a second output of the controlled oscillator, which is 90 degrees shifted in phase (called a “quadrature oscillator” in the literature), one can construct another observable, which is proportional to $\sin\Phi$. This variable is at a maximum, in case the PLL has locked to the resonance.

Question 5)

Draw a sketch, how the signal proportional to $\sin\Phi$ could be used in order to regulate the amplitude of the beam exciting signal. Hint: Insert a 4-quadrant analog multiplier in to the output of the oscillator.



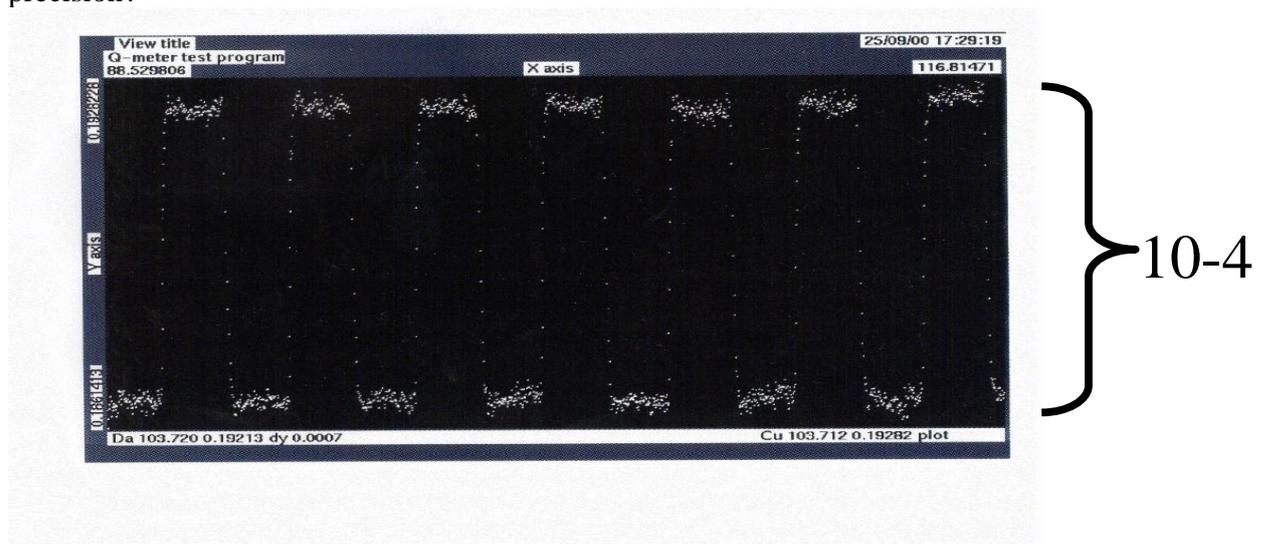


The circuit diagram above is taken from the most recent implementation of a PLL tune tracking system at RHIC (Brookhaven National Laboratory, Long Island US) (ref...)

Question 6) Discuss with your tutors the schematics and identify the building blocks, which have been explained before. The implementation of the PLL circuit happens in an entirely digital implementation in the block “DSP” = digital signal processing.

As closure of this exercise a measurement of the tunes in LEP during a rectangular current modulation in a LEP quadrupole.

Question7) Knowing the amount of current modulation in the quadrupole and the resulting tune change, what beam quantity is measured with this experiment? What precision does one need in the tune measurement, to measure the observable to 1% precision?



3.2 EXERCISES II: CHROMATICITY MEASUREMENTS

3.2 Exercises II: Chromaticity Measurements

Chromaticity measurements

Hermann Schmickler

Summary: The Students are introduced to different methods of measuring chromaticity. The methods based on PLL tune tracking are highlighted. The limitations of each individual measurement method are discussed based on specific measurement examples.

The “classical” method to measure chromaticity is the individual measurement of the betatron tune over a given range of beam momenta. The chromaticity is obtained from a linear fit to the data.

Problem 1: In practice people very often do not go through the problem of collecting the data for a linear fit; they just measure the difference of two tune readings for two beam momenta. Calculate the requirements on precision for the tune measurements for such a simple measurement, in case the beam momentum is varied by $\pm 10^{-3}$. The requested precision in chromaticity is half a unit.

By how much can in practice the beam momentum be varied?

Is the requested precision in tune measurements attainable with a single kick stimulus and a FFT analysis of the resulting beam oscillation?

The following list gives the keywords for other methods, which are used (have been used) for chromaticity diagnostics: Method a) has already been treated with the problem 1.

- a) Tune Difference for different beam momenta
- b) Width of tune peak or damping time
- c) amplitude ratio of synchrotron sidebands
- d) creation of periodic energy variations and PLL tune tracking

for advanced part (5th day)

- e) bunchspectrum variations during betatron oscillations
- f) Head-tail phase advance
(same as 5, but in time domain)

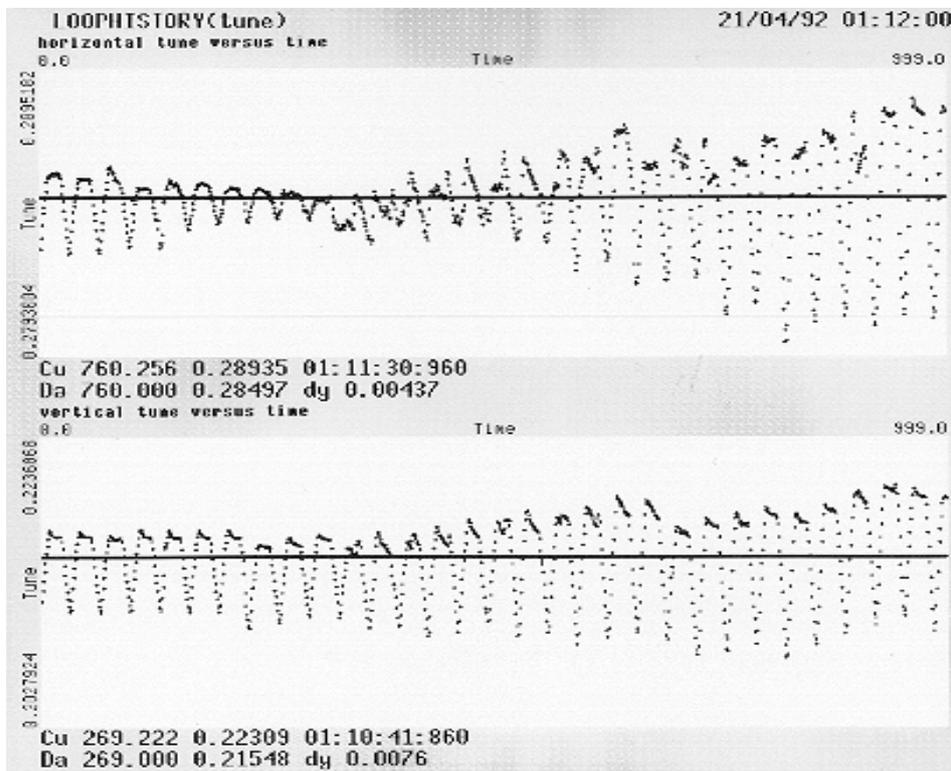
Problem 2: Discuss the above list with your tutors and try to understand the basic measurement principles.

Problem 3: The following figure shows a nice example of the chromaticities in LEP (top: horizontal, bottom: vertical) by a triangular modulation of the Rf-frequency.

The measurement shows the variation of the chromaticity during the beta squeeze of LEP.

- a) What is a beta squeeze? Recall what you have heard about low beta insertions.
- b) Calculate the minimum and maximum chromaticity during the shown beta-squeeze? Assume highly relativistic beams.

(The Rf-Frequency was 354 MHz, $\alpha = 3 \cdot 10^{-4}$, modulation depth 70 Hz, take as full scale of the vertical axis 0.004)



3.3 FURTHER READING I:

...

3.3 Further Reading I:

Diagnostics and Control of the Time Evolution of Beam parameters

H.Schmickler, Proceedings of Beam Instrumentation Workshop DIPAC, DIPAC 1997

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

European Laboratory for Particle Physics

CERN - SL DIVISION

CERN-SL-97-68 (BI)

**Diagnostics and Control of the
Time Evolution of Beam Parameters**

Hermann Schmickler

Abstract

Measurement tools for the betatron tunes, chromaticity and coupling exists in every circular accelerator. This article reviews diagnostic tools for the time evolution of these beam parameters in view of potential online feedbacks on magnetic elements in the LHC. For chromaticity measurements a new development made at CERN based on the detection of the phase difference between head and tail betatron oscillations is presented.

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Geneva, Switzerland
December, 1997

Diagnostics and Control of the Time Evolution of Beam Parameters

Hermann Schmickler, CERN, CH-1211 Geneva 23, (Switzerland)

Abstract: Measurement tools for the betatron tunes, chromaticity and coupling exists in every circular accelerator. This article reviews diagnostic tools for the time evolution of these beam parameters in view of potential online feedbacks on magnetic elements in the LHC. For chromaticity measurements a new development made at CERN based on the detection of the phase difference between head and tail betatron oscillations is presented.

Introduction: The following work has been stimulated by the participation in a working group called “*Dynamic Effects Working Group*” at CERN. In this working group various aspects of time varying magnetic fields and their control are studied for the LHC [1]. In particular at the beginning of the acceleration large variations of the betatron tunes, the chromaticities and coupling over a few seconds can be anticipated.

The author has collected experience from FNAL (Tevatron) , DESY (HERA-P), from older proton machines at CERN (SPS, ISR, PS) and from LEP on the subjects of measurement tools and eventual online feedback loops.

1. TUNE MEASUREMENTS

1.1 Fourier Transform (FFT) of beam motion:

The most common method for tune measurements is the excitation of a beam motion (in most cases broad band excitation with white noise) and the computation of the power density spectrum in frequency domain. The betatron tunes are determined as the frequency with the highest amplitude peak. The frequency resolution Δf is inversely proportional to the number of oscillation samples (Nsamp). One can write: $\Delta f = 2/N_{\text{samp}}$. So if for example one needs a tune resolution of 10^{-3} , at least 2000 samples have to be acquired. A modern computer can perform the time frequency transform (FFT) of 2048 samples in about 1 msec. For typical signal to noise ratios about a factor 4 can be gained in tune resolution by interpolation between the measured amplitude values [2]. If there is enough external excitation from other sources (ground motion, power supply ripple) or the beam is slightly unstable by itself the method also gives useful information without specific beam excitation. The signal to noise ratio can be improved by averaging several spectra into one measurement display.

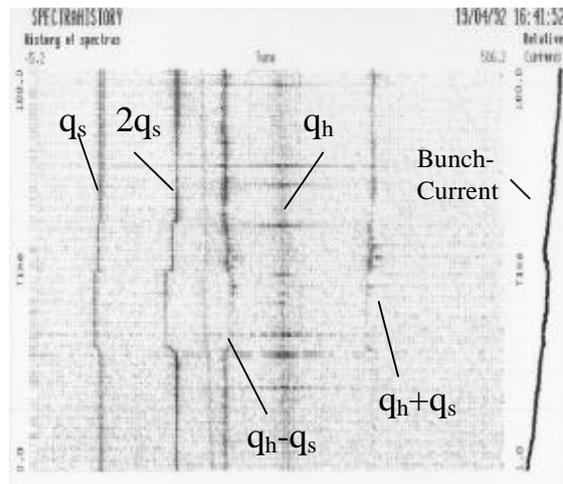


Fig.1: Accumulated spectra during LEP injection.

The time evolution of the tunes can be measured by accumulating many spectra and presenting them in a mountain range display. Figure 1 gives an example measured in LEP during injection. This figure nicely illustrates the diagnostic power of accumulated spectra. Apart from the horizontal tune multiples of the synchrotron tune and the synchrotron sidebands of the horizontal tune are visible. During a certain period two Rf-cavities had tripped (visible as shift in the synchrotron tunes). Such a tool is indispensable for machine set up and the study of many dynamic processes.

1.2 Chirp Excitation

As a variant of the previous method the beams are excited with a sine wave of time variable frequency. If one sends the excitation signal to a loudspeaker one gets the impression of a singing bird (at least at large machines!). For this reason the excitation is called “chirp” excitation. The chirp range is set around the expected betatron tunes and the length is taken corresponding to the requested time resolution and precision of the tune measurements. Data analysis of the resulting beam motion is either via sliding window Fourier transform or via a wavelet analysis [3]. The advantage of this method compared to noise excitation is that the phase information between excitation and beam motion is easier obtained and hence due to the better signal to noise ratio smaller excitation

amplitudes can be used. Figure 2 shows the result of a chirp measurement in the SPS. The sweep length is 20 msec and the repetition rate is 30 msec. In total 150 chirp measurements cover acceleration. More details can be found in [4].

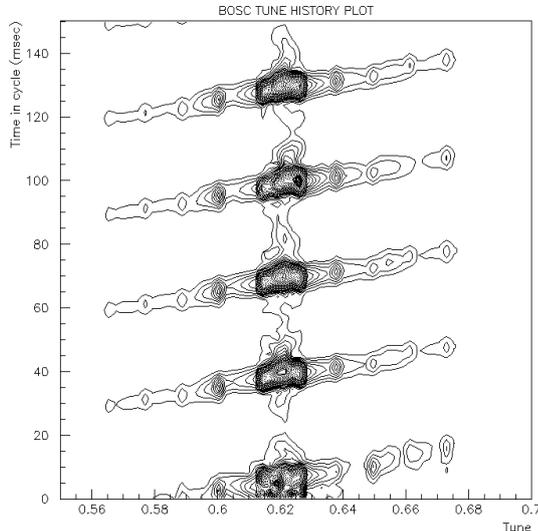


Fig. 2: Chirp tune measurement in the SPS. The horizontal scale is tune, the vertical scale is time (msec). The amplitude of the beam motion is encoded as grey scale.

1.3 Swept Frequency Analysis

For this method (often called “Network Analysis”) the beams are excited with a steady sinusoidal wave. Amplitude and Phase of the resulting oscillation are precisely determined by means of harmonic analysis. Thereafter the excitation frequency is increased in steps until the range of interest is covered. This represents a very precise measurement yielding the full information of the beam transfer function. The disadvantage is the long measurement time, which renders the method of little use for the study of dynamic phenomena. Details can be found in [5].

1.4 Phase Locked Loop Tune Tracker (PLL)

Most tune measurements use the amplitude peak of the beam oscillation as signal for tune measurements. This is somewhat odd, since the amplitude information with “0-slope” at its maximum suffers much more from noise than the phase information, which has its maximum slope at the tune resonance. Phase Locked Loop Circuits instead make use of the phase slope. The beams are excited with a continuous sine wave. By changing the frequency of the exciting oscillator an analog or digital circuit assures that the phase difference between excitation and beam motion is 90° . The tune measurement simply consists in a readout of the (filtered) frequency of the oscillator. In reality the design of such a PLL is more complicated, in particular the lock-in procedure and additional regulation circuits for constant amplitude of the beam oscillation. Many

details can be found in [6]. As the readout of the oscillator frequency can be made almost continuous a PLL circuit is the ideal tool for tracking the time evolution of the betatron tunes during machine transitions. Good measurement examples can be found in chapter 2.1 and 3.1 of this report.

1.5 Discussion

Common to all tune measurements is an exciter and an oscillation detector. The most natural approach is to implement the data treatment and the synthesis of the beam stimulus as a digital process of a system located “between” the monitor and the exciter. With the computing power of modern digital signal processors this should be a possible concept even for machines with revolution periods down to the microsecond. In that case the change in functionality is realised by a software reload.

The following functionalities are imported for the study of dynamic machine processes:

- Accumulated FFT spectra. Apart from the betatron tune lines other important spectral information is contained in the measurements. Beam excitation is done with random kicks or chirp signals.
- PLL tune tracking. In contrast to the previous method only the values of the betatron tunes are measured. With a good compromise in time resolution versus measurement noise a new tune reading is obtained every 100 machine turns.

The **Emittance Blowup** due to the beam excitation is of little importance for lepton machines, but this aspect is the key question for a proton machine. For machine studies and measurements during the setting up emittance blowup to a certain level can be tolerated, but on the operational beams for luminosity production one will only occasionally use a measurement with large (mm) oscillations. Accumulated or integrated spectra are very useful as they can be done without any excitation. In case the beams are quiet or kept quiet with a transverse feedback the use of chirp excitations can be considered, as the beam stimulus is centred around the region of interest. PLL tune tracking is on the first sight the worst one can do, as the beams are continuously excited on the resonance. On the other hand the very good signal to noise ratio of a PLL allows to work with sub micron beam oscillation amplitudes. Although not yet completely operational it has been shown at HERA-P that an online PLL tune measurement on two of the bunches of an operational beam was used for long periods without significant blowup [7].

2. Chromaticity Measurements

2.1 Variation of beam momentum

The commonly used method works by measuring directly the quantities involved in the definition of the chromaticity ξ . The definition is:

$$\Delta q = \alpha \cdot \frac{\Delta p}{p} = \alpha \cdot a \cdot \frac{\Delta f_{RF}}{f_{RF}} \quad (1)$$

(α = momentum compaction factor)

i.e. one measures the tune dependence Δq on beam momentum ($\Delta p/p$), which is very often done by varying the Rf-frequency ($\Delta f_{RF}/f_{RF}$).

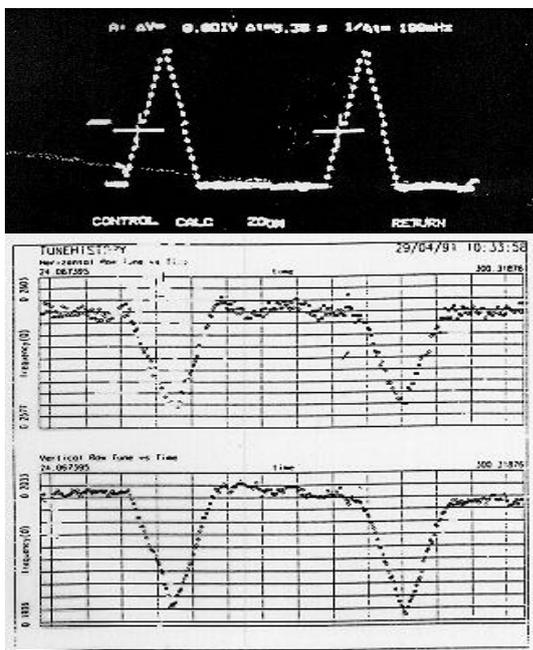


Fig. 3 Dynamic Chromaticity Measurement in LEP. Rf-frequency modulation measured on the tuning system (top trace) and tunes measured in PLL mode (bottom traces).

Figure 3 illustrates the measurement procedure implemented for LEP [8]. The tunes are measured in PLL mode (bottom traces) and the Rf-frequency is modulated in a three second long cycle with an asymmetric wave shape. The asymmetry of the modulation is important, as it allows to identify the sign of the chromaticities from the tune measurements. This is nicely visible in figure 4, which shows a chromaticity measurement during a beta squeeze of LEP. The top trace shows a diminishing horizontal chromaticity, which changes sign and then returns back to nominal sign and magnitude. The vertical chromaticity stays almost constant.

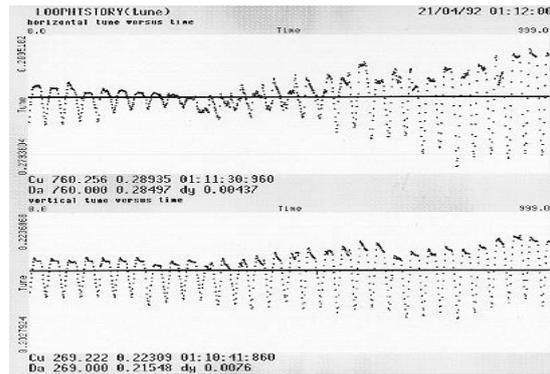


Fig.4: Horizontal (top trace) and vertical (bottom trace) chromaticity measurements during the beta squeeze in LEP.

2.2 Amplitude of Synchrotron Sidebands

The amplitude ratio of the betatron lines to their synchrotron side bands contains information on the chromaticity of the machine. This could well be used on accumulated tune spectra during machine transitions in order to get chromaticity information, but if the betatron tunes change a lot, it is not clear whether systematic lattice resonances influence the observed amplitude ratio. Studies have been made in LEP [9], but the issue has not been continued. In particular in proton machines the measurements are quite difficult, as the synchrotron tune is low and the signals of the side bands are often swamped in the spectral leakage of the main line.

2.3 Width of Tune Resonance

Using again equation (1) one can see that the momentum spread of the beam will result in a width of the betatron lines. Hence measuring the width of the resonance (best via swept frequency analysis (see chapter 1.3)) could be used as a measure of chromaticity. But there are other effects contributing to the line width (radiation damping, transverse feedbacks...), such that one normally looks only for variations in the width in order to deduce chromaticity changes. But in particular during acceleration this analysis is quite complicated, as the momentum spread changes during the measurement.

2.4 Frequency Shift in Bunch Spectrum

The longitudinal bunch profile generates a certain frequency spectrum in an electromagnetic coupler. If one excites betatron oscillations the longitudinal shape of the bunch changes depending on the chromaticity and hence will result in a different bunch spectrum. A detailed analysis yields that in frequency domain the measurable quantity is a shift in the peak of the bunch spectrum [10]. Experiments with this method are quite difficult and are at present not exploited for routine operation.

2.5 Phase of Head and Tail Betatron oscillations

This method is presently under development at CERN and has been stimulated by the ideas of the previous method. Rather than measuring in frequency domain the shift in bunch spectrum, the betatron oscillations of head and tail are individually sampled in time domain. The observable linked to the chromaticity is the phase difference between the head and tail oscillations. By the exciting kick this phase difference is initially forced to zero, evolving to a maximum after half a synchrotron period and then the oscillations rephase again after one complete synchrotron period. Figure 5 shows a computer simulation of the head tail motion for non zero chromaticity for illustration. The vertical axis is time (in [ns] along the longitudinal bunch profile), the horizontal axis is the revolution number after the kick stimulus and the amplitude of the betatron oscillation is encoded as grey scale. The head and tail oscillations are sampled in time slices indicated by the horizontal lines.

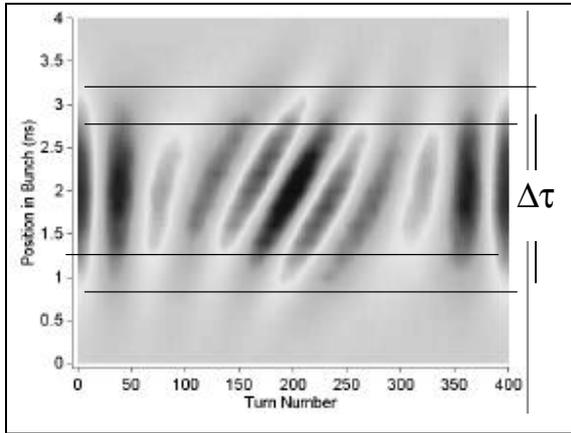


Fig. 5: Computer simulation of head-tail motion.

The chromaticity can be expressed as follows:

$$\chi = \frac{-h \cdot \Delta\Psi_i}{Q_0 \omega_0 \Delta t (\cos(2p \cdot i Q_s) - 1)} \quad (2)$$

with: $\eta=1/\gamma^2-\alpha$; Q_s = synchrotron tune, ω_0 = angular revolution frequency; $\Delta\Psi_i$ = head-tail phase difference, Δt = sampling time interval (see figure 6), Q_0 = betatron tune and i turn index since initial kick

Practically the measured chromaticity does not depend on the betatron tune, as Q_0 in equation 2 is the total tune of the machine. A first series of measurements have been performed in the SPS in order to validate the basic idea. The results are very good. For instance an agreement within 15% of the chromaticity measured via momentum change and the new method could be found over a wide

range of chromaticities. One dataset from these measurements is reported in figure 7. It shows the measured head-tail phase shift turn by turn for 3 different values of the sampling time interval Δt . As expected from equation 2 the dependence is linear. Any explanation of experimental details would leave the scope of this paper, but can be found in [11]

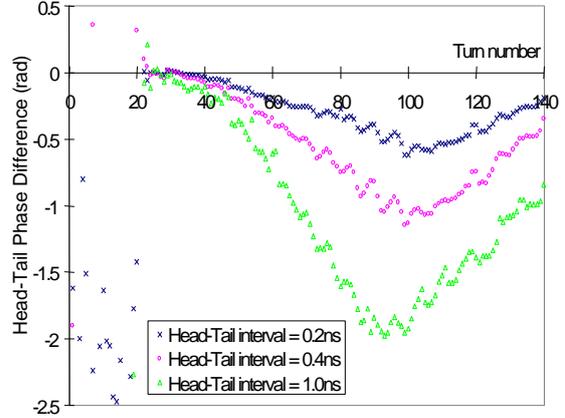


Fig. 6: Measured phase difference of head-tail betatron oscillations for 3 different sampling time intervals.

2.6 Discussion

By variation of the beam momentum and tune tracking a solid operational tool is available for dynamic chromaticity measurements. By extending the range of momentum variation even the non linear part of the chromaticity curve can be examined. But still the method has some limitations: The rate by which the beam momentum is changed can not made extremely short, for example in LEP the modulation cycle is limited to a 3 second interval. This is certainly too long for a chromaticity measurement during the start of acceleration, were a time resolution as short as 100 msec would be of interest. The LHC will require for the nominal beam currents tight control of the orbit, in particular in the collimation region. Periodic momentum changes and hence orbit changes in dispersive regions will be a problem. Secondly if one imagines the use of an online tune regulation loop a chromaticity measurement based on tune differences is very unfavourable. In that case the chromaticity would have to be deduced from the trims that the regulator has send to the quadrupoles in order to keep the tunes constant. With some sense for practical implementations one feels that this would not work!

For these reasons the development work on the head-tail sampling has been launched. The method provides a chromaticity reading independent of the betatron tunes and a measurement time of one synchrotron period (15 to 50 msec in case of the LHC). Further analysis will show the influence of octupolar fields, the limit in signal to noise ratio and consequently the amount of emittance growth that is linked with a single measurement.

3.4 FURTHER READING II:

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3.4 Further Reading II:

High Sensitivity Tune Measurement by Direct Diode Detection

M.Gasior (CERN), R.Jones (CERN), Proceedings of Beam Instrumentation Workshop DIPAC, DIPAC 2005

HIGH SENSITIVITY TUNE MEASUREMENT BY DIRECT DIODE DETECTION

M. Gasior, R. Jones, CERN, Geneva, Switzerland

Abstract

The fractional part of the betatron tune for a circular accelerator can be measured by observing beam oscillations on a position pick-up. In frequency domain the betatron frequency is seen as sidebands on either side of the revolution harmonics. Usually beam signal pulses from the pick-up are very short with respect to the revolution period, resulting in a broadband spectrum.

Classical tune measurement systems filter out just one of the betatron sidebands. As a consequence, most of the betatron energy is lost and only a very small fraction remains for further processing. This paper describes a new method, referred to as Direct Diode Detection (3D). It is based on the idea of time stretching beam pulses from the pick-up in order to increase the betatron frequency content in the baseband. The 3D method was recently tested in the CERN SPS and PS, BNL RHIC and FNAL Tevatron machines. Results from all these machines [1, 2, 3, 4] show that this method can increase the betatron signal level by orders of magnitude as compared to classical systems, making it possible to observe tunes with no explicit excitation. Frequency resolution in the order of 10⁻⁵ and amplitude sensitivity in the order of 10 nm has been achieved with this very simple hardware.

Presented at DIPAC'05 – 6/8 June 2005 – Lyon - FR

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The fractional part of the betatron tune for a circular accelerator can be measured by observing beam oscillations on a position pick-up. In frequency domain the betatron frequency is seen as sidebands on either side of the revolution harmonics. Usually beam signal pulses from the pick-up are very short with respect to the revolution period, resulting in a broadband spectrum. Classical tune measurement systems filter out just one of the betatron sidebands. As a consequence, most of the betatron energy is lost and only a very small fraction remains for further processing. This paper describes a new method, referred to as Direct Diode Detection (3D). It is based on the idea of time stretching beam pulses from the pick-up in order to increase the betatron frequency content in the baseband. The 3D method was recently tested in the CERN SPS and PS, BNL RHIC and FNAL Tevatron machines. Results from all these machines [1, 2, 3, 4] show that this method can increase the betatron signal level by orders of magnitude as compared to classical systems, making it possible to observe tunes with no explicit excitation. Frequency resolution in the order of 10^{-5} and amplitude sensitivity in the order of 10 nm has been achieved with this very simple hardware.

3D PRINCIPLE AND THE HARDWARE

The crucial part of a 3D-based tune measurement system is the peak detector. Two such detectors connected to opposing electrodes of a beam position pick-up (PU) (see Fig. 1) yield the amplitude modulation envelope of the beam signals. Such signals, depicted in Fig. 2, are superimposed on a DC voltage related to the bunch amplitude (revolution frequency content). The signal difference, shown in Fig. 3 for single bunch in the machine, contains almost the whole bunch modulation amplitude, with a DC component related to the beam offset from the centre of the pick-up. Since the DC content can be easily suppressed by series capacitors, most of the corresponding revolution frequency (f_r) background can be removed by the peak detectors before the first amplifying stage. In Fig. 4 the f_r attenuation characteristic is shown assuming single bunch in the machine, which is the most difficult case to deal with. For a detector time constant $\tau = R_f C_f$, which is larger than the machine revolution period $T = 1/f_r$, the suppression of the revolution line goes as $4\tau/T$ [1]. This makes it possible to obtain f_r attenuation in the order of 50 dB for $\tau \approx 100$, which is easily achievable in practice.

The 3D circuit in Fig. 1 can be also understood as two sample-and-hold blocks, sampling bunch signals close to their maxima at the bunch repetition rate, downmixing the wideband bunch spectrum into the baseband.

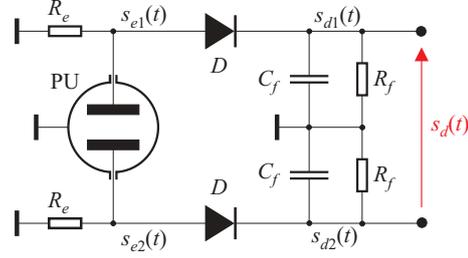


Figure 1: Direct Diode Detection principle.

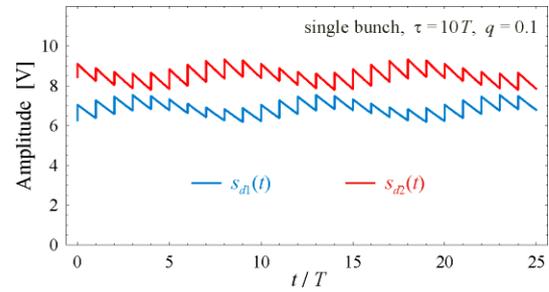


Figure 2: An example of peak detector voltages.

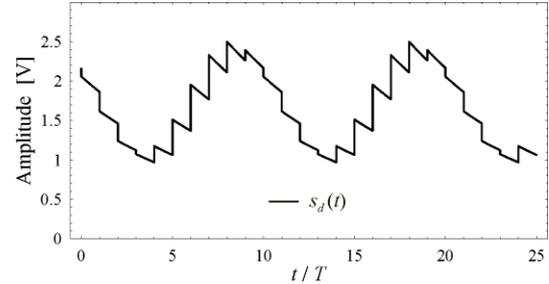


Figure 3: Difference of the signals in Fig. 2.

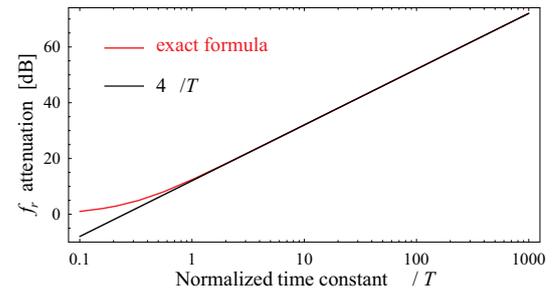


Figure 4: 3D circuitry revolution frequency attenuation.

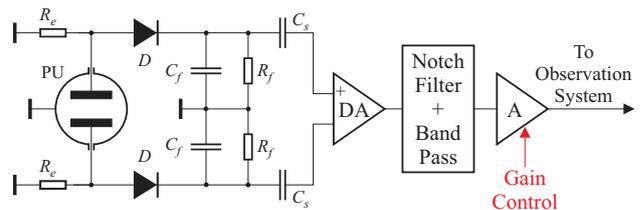


Figure 5: Block diagram of a 3D-BBQ system.

A block diagram of a 3D Base-Band Q (BBQ) measurement system is depicted in Fig. 5. The peak detector voltages with the DC content removed by the series capacitors are subtracted by the differential amplifier (DA), further increasing the suppression of f_r for beams close to the PU centre and improving the interference immunity. A notch filter attenuates f_r by another large factor, in the order of 100 dB [1]. The high cut-off frequency of the band pass filter is $0.5f_r$, as for all possible tune values one betatron sideband is always present in the band $(0, f_r/2)$. The typical low cut-off is $0.1f_r$, which means that the observation system only has to process frequencies between 0.1 and $0.5f_r$. For large machines, therefore, the 3D-BBQ output signal can be digitised with a 24-bit audio ADC at the revolution frequency, requiring relatively little processing power to yield a signal spectrum through an FFT, or to build a tune tracker based on a digital phase-locked loop (PLL) [2].

Notice that a 3D-BBQ system is ‘low frequency’ only after the detectors, due to the ‘time stretching’ of the short beam pulses. Before the detectors the processed bandwidth can easily be as high as a few hundred MHz. In the detection process the spectral content from this wide bandwidth is converted to the baseband, resulting in a very high sensitivity.

3D-BBQ prototypes according to the block diagram of Fig. 5 have been installed on four machines, namely SPS ($f_r \approx 43$ kHz), PS ($f_r \approx 477$ kHz), RHIC ($f_r \approx 78$ kHz) and Tevatron ($f_r \approx 48$ kHz) (chronological order). All prototypes were based on very similar hardware, with only the notch and band-pass filters adjusted for the machine f_r .

A detailed comparison of the 3D and classical tune measurement methods are given in [1], together with a quantitative estimate of the signal to noise improvement given by the 3D method operated on a machine with a single bunch. This factor is in the order of 30 dB for the PS, 40 dB for RHIC and Tevatron, 50 dB for the SPS, and 60 dB for the LHC.

RESULTS

All installed prototypes were sensitive enough to observe betatron oscillations with no explicit beam excitation. Such oscillations, with amplitudes in the μm range, were seen to be almost always present in the beam.

Examples of such measurements made with the SPS BBQ prototype and no intentional beam excitation are shown in Fig. 6 and 7. Figure 6 shows the horizontal tune path for the lowest intensity SPS beam of $\approx 5 \cdot 10^9$ protons in a single bunch at 26 GeV, during a programmed tune change of $\approx 5 \cdot 10^{-3}$. Figure 7 shows the SPS horizontal tune variations induced by the jaws of an LHC collimator prototype as it was cycled between a fully opened position and a gap of 1.96 mm. This measurement was performed with a single bunch at 270 GeV and formed part of a series used to evaluate impedance-induced tune changes introduced by LHC collimators [5]. Tune variations as small as a few Hz could be resolved in this

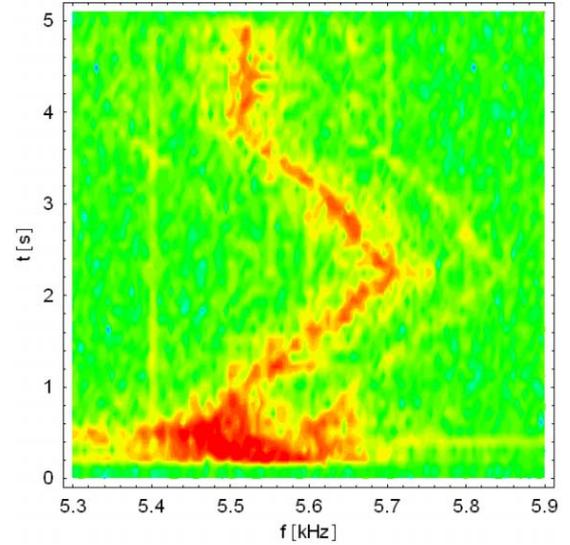


Figure 6: SPS, single bunch LHC pilot beam ($\approx 5 \cdot 10^9$ p⁺).

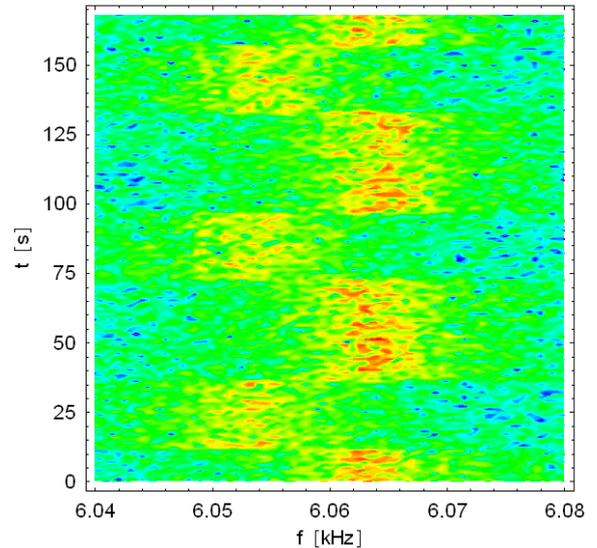


Figure 7: SPS, single bunch LHC beam ($\approx 10^{11}$ p⁺).

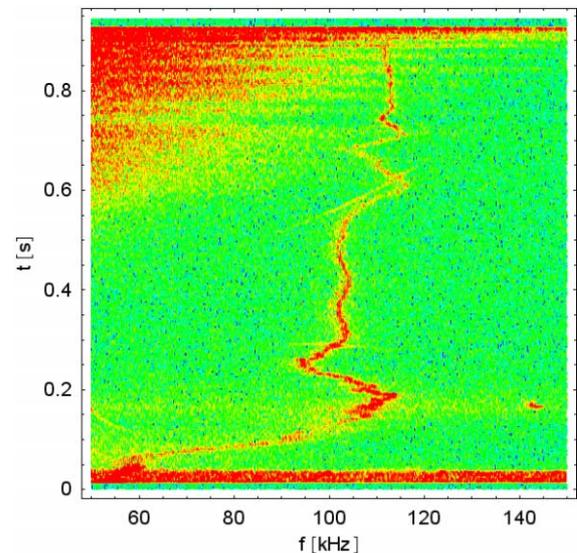


Figure 8: PS, AD beam (4 bunches, $\approx 4 \cdot 10^{12}$ p⁺/b).

way, with the tune resolution in the order of 10^{-5} . These SPS measurements were acquired using a low cost 24-bit PC sound card followed by off-line spectral analysis.

Figure 8 shows the horizontal tune evolution measured by the PS BBQ prototype with no explicit excitation for a beam destined for the Antiproton Decelerator (AD), and accelerated from 1.4 to 26 GeV. The noise-like components appearing from the middle of the record onwards result from the RF beam gymnastics performed for this type of PS beam.

Figure 9 shows a vertical plane time record from the RHIC 3D-BBQ prototype, with the corresponding frequency spectra shown in Figure 10. The largest amplitude signals correspond to beam oscillations caused by high voltage sweeps, related to the operation of an Ionization Profile Monitor (IPM). Each excitation consists of a burst of a hundred pulses, applied every 100th revolution. If either of the tunes happen to be a multiple of $f_r/100$, then these kicks resonantly excite the beam, as seen in the spectra for frequencies around 17.1 kHz ($0.22f_r$, close to the horizontal tune) and 17.9 kHz ($0.23f_r$, vicinity of the vertical tune).

Mains harmonics are clearly visible around the betatron tune paths throughout the RHIC acceleration cycle. These lines increase considerably once the main ramping power supplies are turned on around 26 s from the beginning of the record. The corresponding increase in the time domain signal can be seen in Figure 9. The presence of mains harmonics in the beam spectrum is reported in detail in [3] and is thought to be caused by magnetic field ripple in the main RHIC dipoles. Similar phenomenon was observed with the 3D-BBQs on the SPS, PS and Tevatron.

A comparison at RHIC between spectra from calibrated, million turn BPM data and that of the 3D-BBQ data has quantified the noise floor of the RHIC BBQ prototype at less than 10 nm. This is an order of magnitude better than most existing tune measurement systems.

CONCLUSIONS

This paper has introduced the principle of tune measurement using Direct Diode Detection. It has been shown to be highly sensitive while using simple, cheap and robust hardware. Prototypes recently installed on four machines, namely the CERN SPS and PS, BNL RHIC and FNAL Tevatron, have given very good results and are in the process of being converted into fully operational systems. Due to the many advantages of this method, 3D baseband tune measurement systems will be gradually introduced on all circular machines at CERN. This includes the LHC, where it is hoped to use the 3D-BBQ as part of a PLL tune tracking system, for the measurement of tune, chromaticity and coupling [5], with the ultimate aim of providing reliable tune feedback.

The 3D method is still under development and its full potential has probably not yet been fully realised. Extensive studies will therefore continue on this technique.

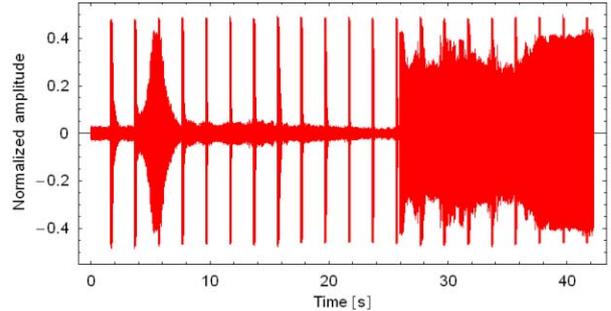


Figure 9: RHIC, a 3D-BBQ signal sound card record.

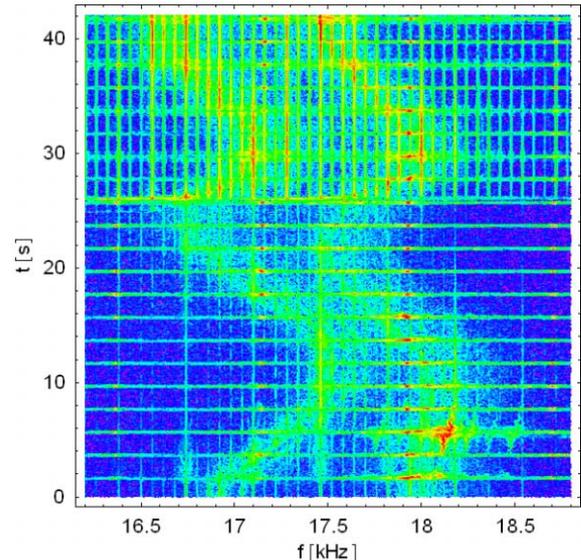


Figure 10: RHIC, spectra of the signal in Fig. 9.

ACKNOWLEDGMENTS

We would like to thank P. Cameron and J. Belleman for their help throughout the whole development as well as C.-Y. Tan for testing the BBQ prototype on the Tevatron.

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- [3] P. Cameron, M. Gasior, R. Jones, C.-Y. Tan, “The Effects and Possible Origins of Mains Ripple in the Vicinity of the Betatron Spectrum”, this proceedings.
- [4] C.-Y. Tan, “Novel Tune Diagnostics for the Tevatron”, PAC 2005.
- [5] H. Burkhardt et al., “Measurements of the LHC Collimator Impedance with Beam in the SPS”, PAC 2005.
- [6] P. Cameron, M. Gasior, R. Jones, Y. Luo, “Towards a Robust Phase Locked Loop Tune Feedback System - The Continuous Measurement of Global Betatron Coupling Using a Phase Locked Loop Tune Measurement System”, these proceedings.

3.5 Exercises III: Head-Tail Diagnostics

The Measurement of Chromaticity via a Head-Tail Phase Shift

SINGLE PARTICLE DYNAMICS IN A BUNCHED BEAM

The longitudinal motion of a particle within a bunch can be described in terms of the synchrotron frequency and the difference between the particle's momentum and the nominal momentum. This can be expressed as

$$\tau = \hat{\tau} \cos(\omega_s t + \phi)$$

where τ is the variation with time t of the particle from the bunch centre, ω_s is the angular synchrotron frequency and ϕ is the initial longitudinal phase of the particle (Fig. 1).

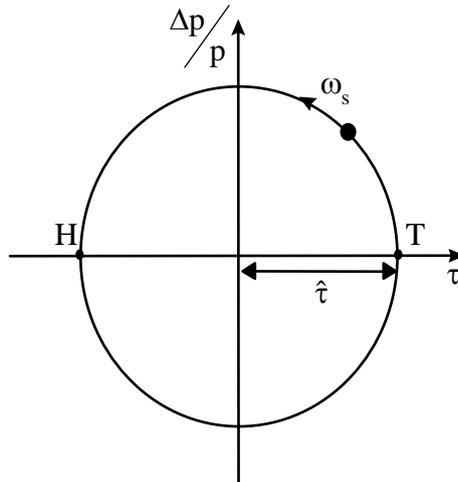


FIGURE 1. Longitudinal 'phase-space'.

If a single kick is applied to all particles within a given bunch, then during this longitudinal motion the particle will also undergo transverse motion, which can be described by the change in the betatron phase, $\theta(t)$, along the synchrotron orbit. The rate of change of this betatron phase is given by

$$\dot{\theta} = Q\omega = (Q_0 + \Delta Q)(\omega_0 + \Delta\omega) \quad (1)$$

where Q_0 is the nominal transverse tune, ΔQ is the change in tune due to the momentum spread, ω_0 is the nominal angular revolution frequency and $\Delta\omega$ is the change in this frequency due to the momentum spread.

Now
$$\frac{\Delta\omega}{\omega_0} = \eta \frac{\Delta p}{p} \quad , \quad \frac{\Delta Q}{Q_0} = \xi \frac{\Delta p}{p} \quad \text{and} \quad \dot{\tau} = -\frac{\Delta T}{T_{rev}} = \frac{\Delta\omega}{\omega_0}$$

where:

$$\begin{aligned}\xi &= \text{relative chromaticity (} Q'/Q_0 \text{ where } Q' \text{ is the chromaticity)} \\ \eta &= 1/(\gamma)^2 - \alpha \text{ (where } \alpha = 1/(\gamma_{tr})^2 \text{ is the momentum compaction factor)} \\ T_{\text{rev}} &= \text{revolution period}\end{aligned}$$

$$\text{Hence } \Delta Q = -\frac{\xi}{\eta} Q_0 \dot{\tau} \quad \text{and} \quad \Delta \omega = \omega_0 \dot{\tau}$$

Substitution into (1) gives:

$$\dot{\theta} = \left(Q_0 - \frac{\xi}{\eta} Q_0 \dot{\tau} \right) (\omega_0 + \omega_0 \dot{\tau}) = Q_0 \omega_0 \left(1 - \frac{\xi}{\eta} \dot{\tau} \right) (1 + \dot{\tau}) \approx Q_0 \omega_0 \left(1 + \dot{\tau} \left(1 - \frac{\xi}{\eta} \right) \right)$$

Integrating one obtains $\theta(t) \approx Q_0 \omega_0 (t + \tau) - \omega_\xi \tau + \theta_0$ where $\omega_\xi = Q_0 \omega_0 \frac{\xi}{\eta}$ and is known as the chromatic frequency. Since τ is usually much smaller than t , one can write:

$$\theta(t) \approx Q_0 \omega_0 t - \omega_\xi \hat{\tau} \cos(\omega_s t + \phi) + \theta_0$$

where θ_0 is the initial betatron phase of the particle.

Problems

HT1) Using this expression for $\theta(t)$ it can be shown that the amplitude of the oscillation at time t at any point X along the bunch ($X = 0$ in the centre of the bunch, X +ve towards the head and -ve towards the tail) is given by

$$y_X(t) = A \cos(Q_0 \omega_0 t - \omega_\xi X (\cos(-\omega_s t) - 1))$$

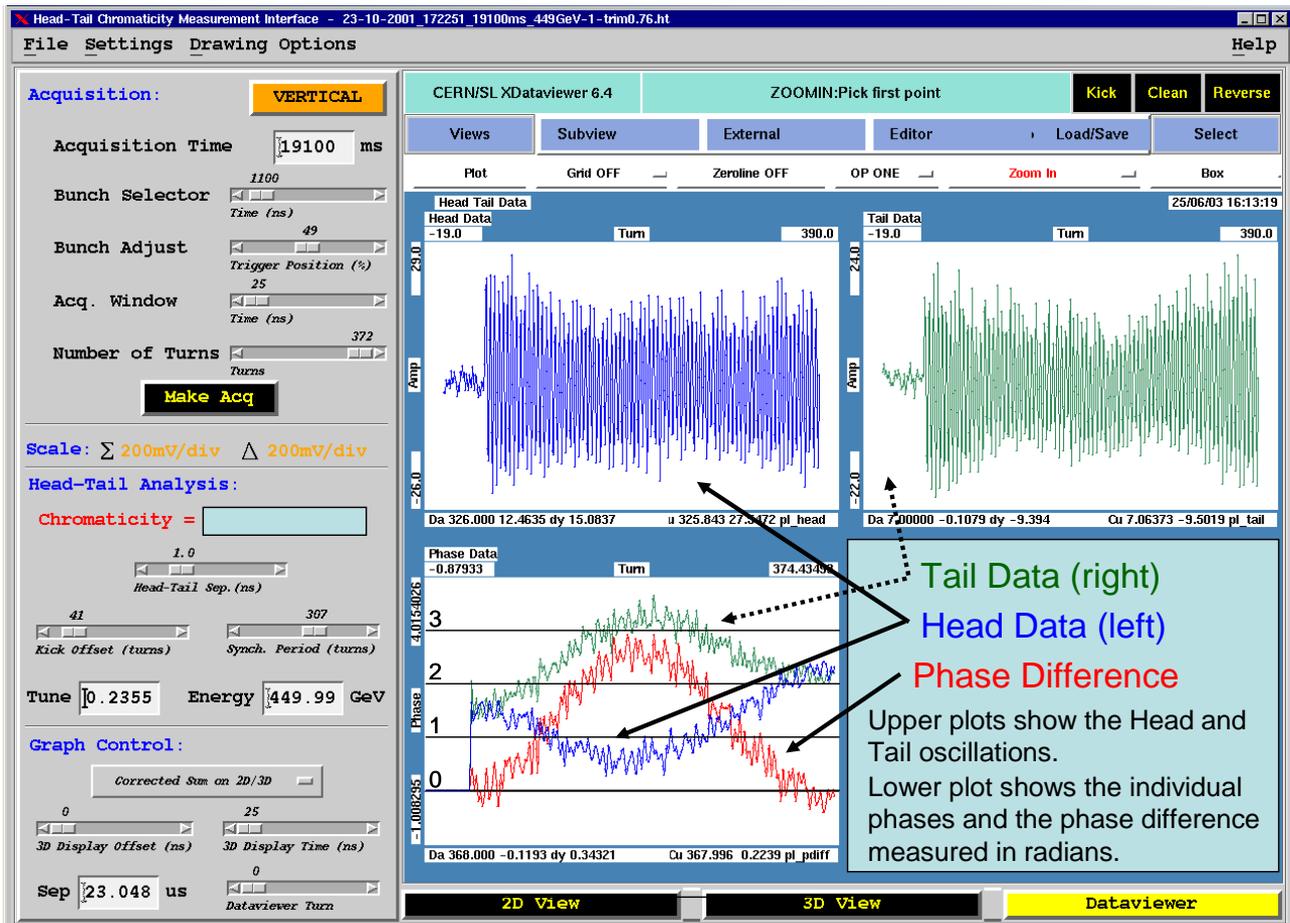
where $\omega_\xi = Q_0 \omega_0 \frac{\xi}{\eta}$ and is known as the chromatic frequency.

If one measurement is carried out on each turn at both the head (+X) and tail (-X) derive an expression for the phase difference observed on turn n between the head and tail, and hence the equation for the chromaticity.

(Note that the synchrotron tune, Q_s , is related to the revolution frequency with $\omega_s = Q_s \omega_0$)

HT2) When is the maximum phase difference obtained?

HT3) Shown below is an actual head-tail chromaticity measurement carried out at the CERN-SPS.



Knowing that the chromaticity is given by

$$Q' = \frac{\eta \Delta\psi(n)}{\omega_0(2X)(\cos(2\pi n Q_s) - 1)}$$

use the data shown in the plots along with the given parameters and information in the “head-tail analysis” panel to determine the value of the chromaticity.

Relevant parameters:

Proton rest mass, $E_0 = 0.938$ GeV

SPS revolution frequency, $f_0 = 43371$ Hz

SPS momentum compaction factor, $\alpha = 1.8539 \times 10^{-3}$

HT5) Propose a way, or ways, of measuring the betatron oscillations along the bunch.

3.6 Further Reading III:

The Measurement of Chromaticity via a Head-tail Phase Shift

D. Cocq et al.(CERN), Proceedings of Beam Instrumentation Workshop BIW, BIW98

The Measurement of Chromaticity via a Head-Tail Phase Shift

D. Cocq, O.R. Jones and H. Schmickler

Abstract

The most common method of measuring the chromaticities of a circular machine is to measure the betatron tune as a function of the beam energy and then to calculate the chromaticity from the resulting gradient. Even as a simple difference method between two machine energies this method does not allow instantaneous measurements, for instance during energy ramping or beta squeezing. In preparation for the LHC a new approach has been developed which uses the energy spread in the beams for a chromaticity measurement. Transverse oscillations are excited with a single kick and the chromaticity is calculated from the phase difference of the individually sampled head and tail motions of a single bunch. Using this method the chromaticity can be calculated using the data from only one synchrotron period (about 15-50 msec in the case of the LHC). This paper describes the theory behind this technique, two different experimental set-ups and the results of measurements carried out in the SPS.

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SLAC, USA
4-7 May 1998*

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D. Cocq, O.R. Jones and H. Schmickler

CERN, CH-1211 Geneva 23, Switzerland.

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INTRODUCTION

The tight tolerances on beam parameters required for successful LHC operation implies a good knowledge of the chromaticity throughout the cycle. However, many of the methods currently used to measure chromaticity in circular machines (see (1) and references therein) are likely to be incompatible with LHC high intensity running. For example, the most common method, of measuring the betatron tune as a function of beam energy, might be difficult to implement due to the tight tolerances imposed on the betatron tune itself. Chromaticity can also be calculated from the amplitude of the synchrotron sidebands observed in the transverse frequency spectrum. However, this method suffers from resonant behaviour not linked to chromaticity, and the fact that the low synchrotron tune of the LHC would make it difficult to distinguish these sidebands from the main betatron tune peak. The width of the betatron tune peak itself, or the phase response of the beam transfer function also give a measure of chromaticity, but require a knowledge of how the momentum spread in the beam changed with energy.

In this paper we describe a method that allows the chromaticity to be calculated from the turn-by-turn position data of a single bunch over one synchrotron period, after the application of a transverse kick. It will be shown that the chromaticity can be obtained by determining the evolution of the phase difference between two longitudinal positions within the bunch. This technique does not rely on an accurate knowledge of the fractional part of the betatron tune and, for a machine operating

well above transition, the calculated chromaticity is virtually independent of beam energy.

SINGLE PARTICLE DYNAMICS IN A BUNCHED BEAM

The longitudinal motion of a particle within a bunch can be described in terms of the synchrotron frequency and the difference between the particle's momentum and the nominal momentum. This can be expressed as

$$\tau = \hat{\tau} \cos(\omega_s t + \phi) \quad (1)$$

where τ is the variation with time t of the particle from the bunch centre, ω_s is the angular synchrotron frequency and ϕ is the initial longitudinal phase of the particle (Fig. 1).

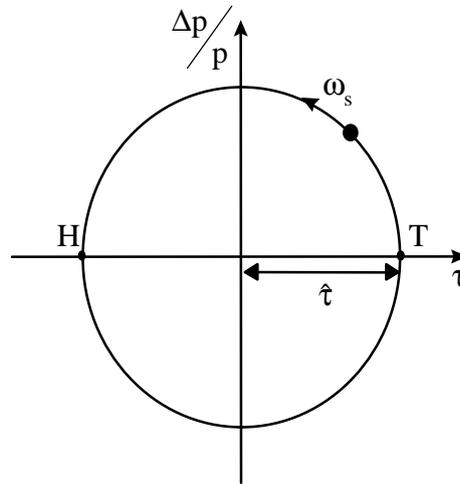


FIGURE 1. Longitudinal 'phase-space'.

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$$\text{Now} \quad \frac{\Delta\omega}{\omega_0} = -\eta \frac{\Delta p}{p} \quad , \quad \frac{\Delta Q}{Q_0} = \xi \frac{\Delta p}{p} \quad \text{and} \quad \hat{\tau} = -\frac{\Delta T}{T_{\text{rev}}} = \frac{\Delta\omega}{\omega_0}$$

where:

$$\xi = \text{relative chromaticity } (Q'/Q_0 \text{ where } Q' \text{ is the chromaticity})$$

$\eta = 1/(\gamma)^2 - \alpha$ (where $\alpha = 1/(\gamma_r)^2$ is the momentum compaction factor)

$T_{\text{rev}} =$ revolution period

Hence $\Delta Q = -\frac{\xi\tau}{\eta} Q_0 \dot{\tau}$ and $\Delta\omega = \omega_0 \dot{\tau}$, which on substitution into (1) gives

$$\dot{\theta} = \left(Q_0 - \frac{\xi\tau}{\eta} Q_0 \dot{\tau} \right) (\omega_0 + \omega_0 \dot{\tau}) = Q_0 \omega_0 \left(1 - \frac{\xi}{\eta} \dot{\tau} \right) (1 + \dot{\tau}) \approx Q_0 \omega_0 \left(1 + \dot{\tau} \left(1 - \frac{\xi}{\eta} \right) \right) \quad (3)$$

Integrating one obtains $\theta(t) \approx Q_0 \omega_0 (t + \tau) - \omega_\xi \tau + \theta_0$ where $\omega_\xi = Q_0 \omega_0 \frac{\xi}{\eta}$ and is known as the chromatic frequency. Since τ is usually much smaller than t , one can write:

$$\theta(t) \approx Q_0 \omega_0 t - \omega_\xi \hat{\tau} \cos(\omega_s t + \phi) + \theta_0 \quad (4)$$

where θ_0 is the initial betatron phase of the particle.

If we assume that the displacement due to the kick is much larger than the betatron oscillations performed by the particles in the unperturbed bunch, then the initial betatron phase can be set such that all the particles have the same initial position in the transverse plane; i.e. at $t = 0$ a particle with a longitudinal position described by $\hat{\tau}_i$ and θ_i will have an initial betatron phase given by

$$\theta_0 = \omega_\xi \hat{\tau}_i \cos(\phi_i) \quad (5)$$

Hence the position of a particle in the bunch, y_i , at any time t is given by

$$y_i(t) = A \cos(\theta(t)) \quad (6)$$

where A is the maximum amplitude of the betatron motion.

Extracting the chromaticity by considering head-tail evolution

Consider a system where the particles are distributed along a single synchrotron orbit, and where the particle position is measured as a function of time at the tail of the bunch (point T in Fig. 1). The initial synchrotron phase, ϕ_i , of the particle at the tail after a given time t , is given by $\phi_i = -\omega_s t$, and therefore the corresponding initial betatron phase, $(\theta_0)_i$, can be written as $(\theta_0)_i = \omega_\xi \hat{\tau}_i \cos(-\omega_s t)$. Hence the transverse amplitude at the tail evolves as

$$\begin{aligned} y_T(t) &= A \cos(Q_0 \omega_0 t - \omega_\xi \hat{\tau}_T \cos(\omega_s t + \phi) + \omega_\xi \hat{\tau}_T \cos(-\omega_s t)) \\ &= A \cos(Q_0 \omega_0 t + \omega_\xi \hat{\tau}_T (\cos(-\omega_s t) - 1)) \end{aligned} \quad (7)$$

Measurements are carried out turn by turn, which corresponds to time steps of $t=2\pi n/\omega_0$, where n is the turn number. Hence the signal at the tail of the bunch for a given turn, n , can be written as

$$y_T(n) = A \cos(2\pi n Q_0 + \omega_\xi \hat{\tau}_T (\cos(2\pi n Q_s) - 1)) \quad (8)$$

where Q_s is the synchrotron tune, with $\omega_s = Q_s \omega_0$. A similar expression can also be derived for the head of the bunch

$$y_H(n) = A \cos(2\pi n Q_0 - \omega_\xi \hat{\tau}_H (\cos(2\pi n Q_s) - 1)) \quad (9)$$

The phase difference between head and tail as a function of turn number is therefore given by

$$\Delta\psi(n) = -\omega_\xi (\hat{\tau}_H + \hat{\tau}_T) (\cos(2\pi n Q_s) - 1) \quad (10)$$

This equation is a maximum when $nQ_s = 1/2$, i.e. after half a synchrotron period, giving

$$\Delta\psi_{MAX} = -2\omega_\xi (\hat{\tau}_H + \hat{\tau}_T) = -2\omega_\xi \Delta\tau \quad (11)$$

The chromaticity can therefore be written as

$$\xi = \frac{-\eta \Delta\psi(n)}{Q_0 \omega_0 \Delta\tau (\cos(2\pi n Q_s) - 1)} \quad \text{or} \quad \xi = \frac{\eta \Delta\psi_{MAX}}{2Q_0 \omega_0 \Delta\tau} \quad (12)$$

Since the revolution frequency and total tune of the machine are known to a high degree of accuracy, and if one considers a machine operating well above transition, the chromaticity will depend only on the maximum phase difference attained between two regions of the same bunch separated longitudinally by a known time.

EXPERIMENTAL SET-UP

In order to illustrate the principle of this technique, head-tail phase measurements were performed on proton bunches in the SPS. Each acquisition involved the measurement of 100 to 200 turns of data (around one SPS synchrotron period) after the application of a single transverse kick. An exponential transverse coupler was used to provide the transverse position data as a function of the longitudinal position within the bunch. In the first experiments the signal from the coupler was analysed using two sample and hold amplifiers. This then provided information on the transverse position of two specific locations within the bunch (one positioned near the head of the bunch and the other near the tail). Later experiments relied on a digital oscilloscope with fast-frame capabilities, from which a single trace gave transverse position information for the whole bunch as a function of longitudinal position.

Head-Tail Phase Measurements using Head and Tail Samplers

The experiments using the head and tail samplers were performed on the Machine Development (MD) cycle of the SPS, which provided a single bunch of $\sim 2 \times 10^{10}$ protons at an energy of 26 GeV and with a length of ~ 3.8 ns.

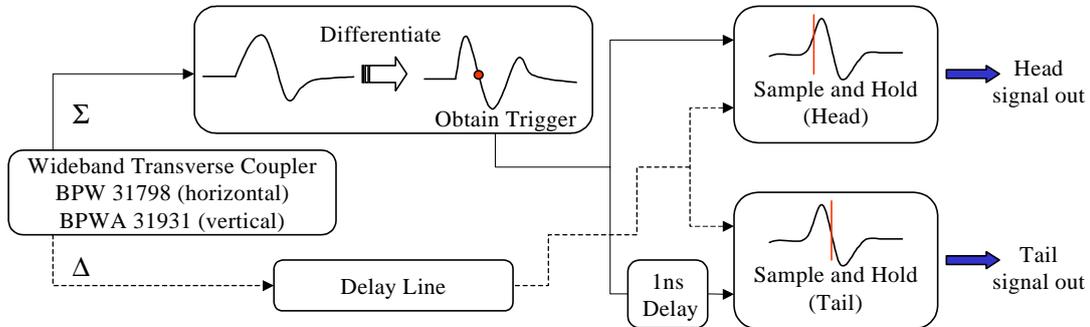


FIGURE 2. Sampler acquisition schematic.

Figure 2 shows a schematic of the acquisition system. The coupler sum signal was used to auto-trigger two Avtech AVS-105 variable gate width sample and hold amplifiers. The trigger of one sampler was delayed by ~ 1 ns with respect to that of the other, to allow the transverse bunch position to be sampled at two longitudinal positions separated in time by this delay. Each sampler had a gate width of ~ 200 ps and provided an output pulse of 500 ns duration with an amplitude proportional to the input amplitude. The output from both samplers was stored on a turn-by-turn basis on two channels of a Le-Croy 9354, 500 MHz, digital oscilloscope. Each acquisition, which consisted of around 200 turns of information, could then be transferred to a computer for analysis.

Head-Tail Phase Measurements using a Tektronix 784A Oscilloscope

By using a Tektronix 784A digital oscilloscope, with an analogue bandwidth of 1 GHz and a maximum sampling rate of 4 GS/s, the complete coupler signal of a single bunch could be reconstructed. Additionally, a fast-frame acquisition setting meant that the signal could be recorded on consecutive SPS machine turns. This removed the necessity of having individual sample and hold amplifiers. When using the Tektronix 784A the turn-by-turn acquisition was triggered directly from the SPS RF system.

Experiments using this acquisition system were again performed on the SPS MD cycle, this time with 20 bunches in the machine, with each bunch having the same characteristics as described previously. The internal memory of the oscilloscope provided enough space to record up to 160 turns of data, which could be transferred directly to a computer for further analysis.

RESULTS

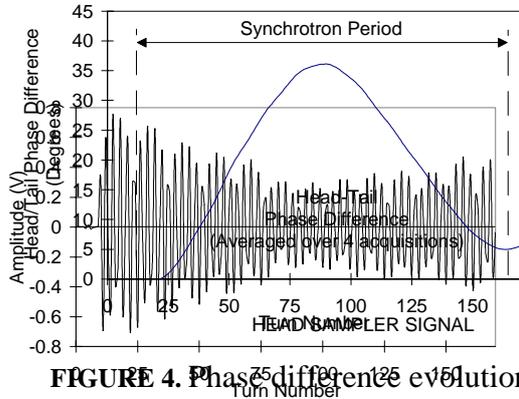


FIGURE 4. Phase difference evolution.

FIGURE 3(a). Head sampler signal.

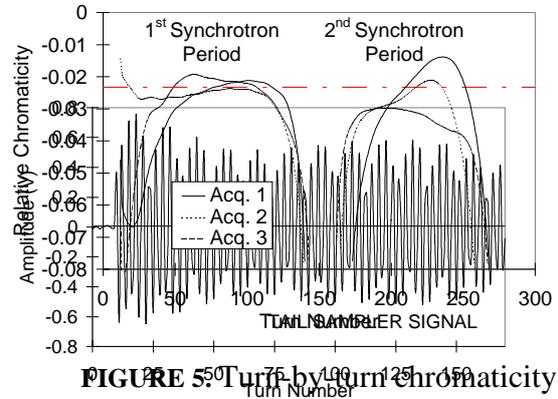


FIGURE 5. Turn-by-turn chromaticity.

FIGURE 3(b). Tail sampler signal.

The raw data obtained from the head-tail samplers result in graphs such as those of Figure 3(a & b). Here one sees the variation in the transverse position of two segments of the bunch separated by ~ 1 ns, after applying a kick to the beam.

In order to calculate the phase relationship between the head and tail signals, a sweeping harmonic analysis was performed. This involved working out the phase by harmonic analysis for each turn, using the current data point and 10 points either side. Since the same calculation was performed on both signals, the phase difference for each turn could be found by simply subtracting the individual phases. The results of such a harmonic analysis sweep is shown in Figure 4. Here one clearly sees the de-phasing and re-phasing of the two positions within the bunch during one synchrotron period, with the maximum phase difference occurring after half a synchrotron period.

Once the phase difference evolution is known, it is possible to calculate the chromaticity, using Equation (12), on a turn-by turn basis. The result of such a calculation is shown in Figure 5. Due to the cosine term in the denominator of Equation (12) the error in the calculation of the chromaticity is very large at the start and end of the synchrotron period, while it is a minimum at half the synchrotron period. In this particular case there was sufficient signal to enable the chromaticity to be calculated again during the second synchrotron period. The average value of the chromaticity in this particular case, indicated by the dashed horizontal line, was calculated from the 40 turns around the centre of both synchrotron periods.

A typical ‘mountain range’ display result obtained by capturing the coupler signal using the Tektronix 784A can be seen in Figure 6(a). The signal was sampled at 4Gs/s and automatically interpolated to give output data points every 20ps. The second, smaller, out of phase oscillation seen in the figure is the reflection of the main signal from the exponential coupler. In order to determine the chromaticity, we require knowledge of the phase difference evolution of two separate locations within the bunch. Hence two cuts in the longitudinal plane were performed to obtain the evolution of two points located either side of the bunch

centre (Fig. 6(b)). By performing a sweeping harmonic analysis on these two data sets, as previously described, the phase difference evolution and hence the chromaticity could be extracted on a turn-by-turn basis.

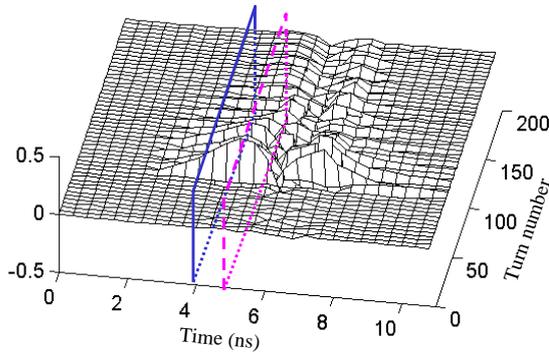


FIGURE 6(a). Tektronix 784A output.

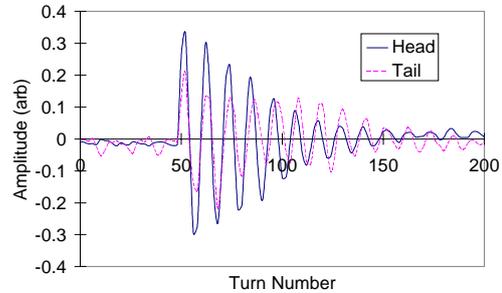


FIGURE 6(b). Extracted head and tail signals.

This phase difference evolution for two consecutive acquisitions is plotted in Figure 7. The measurements were found to be reproducible, with the calculated value for the chromaticity in agreement to within 10%.

Finally, Figure 8 shows the vertical chromaticity, calculated by the head-tail phase difference, as a function of the vertical chromaticity machine trim. The results are what one would expect, with a linear relationship found between the trim and chromaticity.

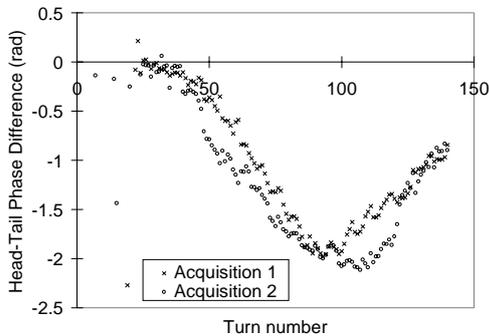


FIGURE 7. The time evolution of $\Delta\psi$.

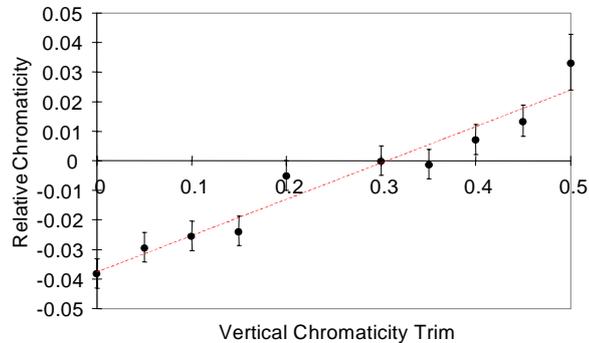


FIGURE 8. Variation of ξ with machine trim.

CONCLUSION

It has been demonstrated that the chromaticity of a circular machine can be calculated from the evolution of the phase difference between the head and tail of a single bunch after the application of a transverse kick. Using this technique a measure of chromaticity can be obtained from a single synchrotron period. The sensitivity of the head-tail method relies on the fact that a sufficiently large phase difference can be achieved between the head and tail signals. Since, for a given chromaticity, this phase difference is proportional to the head-tail separation, the

sensitivity is ultimately governed by the bunch length. Hence this technique should work in proton machines where the bunch lengths are relatively large, but may prove difficult to implement in lepton machines, where the small bunch lengths imply a very short maximum head-tail separation.

Further studies are planned to investigate the effect of higher order fields, such as octupolar fields, which will be of consequence for the LHC, and also to determine the signal to noise ratio required for accurate measurements. This latter point will ultimately determine the emittance blow-up caused by repeated measurements, which is again of great importance for any proton machines.

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Chapter 4

Beam Loss Monitoring (BLM)

4.1 Exercises and Literature

Beam Loss Monitors



by Kay Wittenburg, -DESY-

1 Introduction

Beam loss monitor systems are designed for measuring beam losses around an accelerator or storage ring. A detailed understanding of the loss mechanism, together with an appropriate design of the BLM-System and an appropriate location of the monitors enable a wide field of very useful beam diagnostics and machine protection possibilities.

Beam losses can be divided into two different classes:

1) Irregular losses.

sometimes called “fast or uncontrolled losses”: These losses may be distributed around the accelerator and not obviously on a collimation system. They are very often a result of a misaligned beam or a fault condition, e.g. operation failure, trip of the HF-system or of a magnet power supply. Losses should be avoided and should be kept to low levels.

Discuss why it should be avoided?

Sometimes such losses have to be tolerated even at a high level at low repetition rates during machine studies. However, a beam loss monitor system should define the allowed level of those losses. The better protection there is against these losses, the less likely is down time due to damage of components. A post mortem event analysis is most helpful to understand and analyse the faulty condition.

2) Regular losses.

sometimes called “slow” or “controlled” losses: Those losses are typically not avoidable and are localized on the collimator system or on other (hopefully known) aperture limits. They might occur continuously during operational running and correspond to the lifetime/transport efficiency of the beam in the accelerator. The lowest possible loss rate is defined by the theoretical beam lifetime limitation due to various effects.

Discuss which effects?

It is clearly advantageous to design a BLM-System which is able to deal with both loss modes.

In addition measurements of injection-, ejection- or collimator- efficiencies can be performed using BLMs or beam current monitors, as well as background measurements in the detectors. This survey concentrates on BLM systems which cover the entire accelerator.

1.1 Principles of loss detection

What should a Beam Loss Monitor monitor?

- In case of a beam loss, the BLM system has to establish the **number of lost particles** in a certain position and time interval.

- A typical BLM is mounted outside of the vacuum chamber, so that the monitor normally **observes the shower** caused by the lost particles interacting in the vacuum chamber walls or in the material of the magnets.
- The number of detected particles (amount of radiation, dose) and the signal from the BLM should be **proportional to the number of lost particles**. This proportionality depends on the position of the BLM in respect to the beam, type of the lost particles and the intervening material, but also on the momentum of the lost particles, which may vary by a large ratio during the acceleration cycle.
- Together with the specification for acceptable beam losses as a function of beam momentum, this defines a **minimum required sensitivity and dynamic range** for BLMs.
- Additional sensitivity combined with a larger dynamic range extends the utility of the system for **diagnostic work**.

Exercise BLM 1a:

Assuming a high energy accelerator, what is the main physical process in a BLM-detector to produce a useful signal?

Solution:

A nice list of “considerations in selecting a beam loss monitor” is discussed in [2]:

- Sensitivity
- Type of output (current or pulse)
- Ease of calibration (online)
- System end-to-end online tests
- Uniformity of calibration (unit to unit)
- Calibration drift due to aging, radiation damage, outgassing, etc.
- Radiation hardness (material)
- Reliability, Availability, Maintainability, Inspect ability, Robustness
- Cost (incl. Electronics)
- Shieldability from unwanted radiation (Synchrotron Radiation)
- Physical size
- Spatial uniformity of coverage (e.g. in long tunnel, directionality)
- Dynamic range (rads/sec and rads)
- Bandwidth (temporal resolution)
- Response to low duty cycle (pulsed) radiation
- Instantaneous dynamic range (vs. switched gain dynamic range)
- Response to excessively high radiation levels (graceful degradation)

Consideration of these parameters gives a good guide to find (or design) the best monitor type for a particular beam loss application.

Exercise BLM 1b:

Which type of particle detection / detector do you propose for beam loss detection? Why? How the signal creation works? (Discussion in auditorium)

Solution:

2 Measuring Beam Losses

2.1 Regular losses

Exercise BLM 2a:

HERAp is a proton storage ring (920 GeV/c) with 6.3 km circumference.

How many beam particles are lost within a second (N_{Lost}), assuming a proton beam current of $I_0=70$ mA and a lifetime of $\tau = 50$ hours?

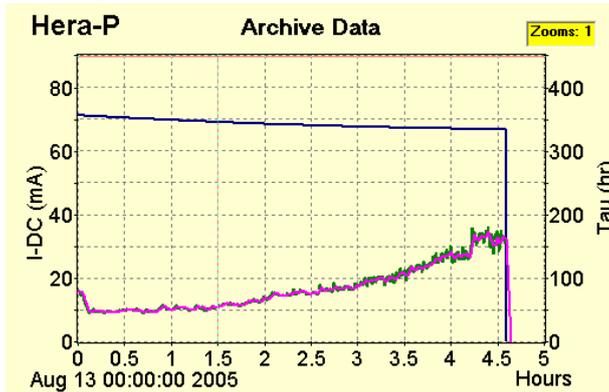


Fig. 1: Beam current [mA] vs time

Solution

Exercise BLM 2b:

Assuming all protons are lost in a 1 cm^3 block of iron (penetration length $L = 1 \text{ cm}$). Calculate the deposit power P [W] in the block ($1 \text{ J} = 6.241 \cdot 10^{18} \text{ eV}$):

Solution:

This number gives a macroscopic feeling of the measurable power due to beam losses during a bad luminosity run in HERAp with worse lifetime. Possible reasons for these losses are: Beam-beam kicks, transversal and longitudinal dispersion, residual gas scattering, halo scraping, instabilities... These losses can be used for beam diagnostics (see e.g. Ref. 3). But note that typically losses might not be concentrated at one location only!

Where to put the BLMs to measure beam losses?

Each BLM at different locations needs its special efficiency-calibration in terms of signal/lost particle. This calibration can be calculated by use of a Monte Carlo Program with the (more or less) exact geometry and materials between the beam and the BLM. For the simulation it might be important to understand the (beam-) dynamics of the losses and the loss mechanism.

Exercise BLM 2c:

At a certain location of a BLM in HERA (collimator), the efficiency to beam losses is about $\varepsilon = 0.1 \text{ MIP} / (\text{cm}^2 \cdot \text{lost proton})$ (at 300 GeV/c) at the BLM location.

Calculate the resulting current I_{ion} of a 1 litre air filled ionization chamber BLM. Assume that 1/10 of the losses above (Exercise BLM 2a) occur here. About $E_{\text{pair}} = 22 \text{ eV/pair}$ is needed to create an electron / ion pair in air.

Solution:

2.2 Quench Protection

A serious problem for high current and high brilliance accelerators is the high power density of the beam. A misaligned beam is able to destroy the beam pipe or collimators and may break the vacuum. This fact makes the BLM-System one of the primary diagnostic tools for beam tuning and equipment protection in these machines.

Superconducting accelerators need a dedicated BLM-system to prevent beam loss induced quenches. Such a system has to detect losses fast enough before they lead to a high energy deposition in the superconducting material.

Exercise BLM 2d:

Which design criteria are important for a BLM system to prevent beam loss induced quenches (Discussion in plenum)?

Solution:

Exercise BLM 2e:

What is a “critical loss rate”? How to define it

Discussion in plenum

Calculate from the following table and figure (note the time scale of the losses) the current I_{ion} in a 1 liter air filled ionization chamber at the critical loss rate at 40 and 820 GeV/c (at that particular location):

Momentum [GeV/c]	efficiency ε [MIP/cm ² /proton]
40	$3.25 \cdot 10^{-4}$
100	$4.47 \cdot 10^{-4}$
400	$1.53 \cdot 10^{-3}$
820	$2.20 \cdot 10^{-3}$

Tab. 1: Efficiency ε vs beam momentum for the BLMs at the superconducting magnets in HERA

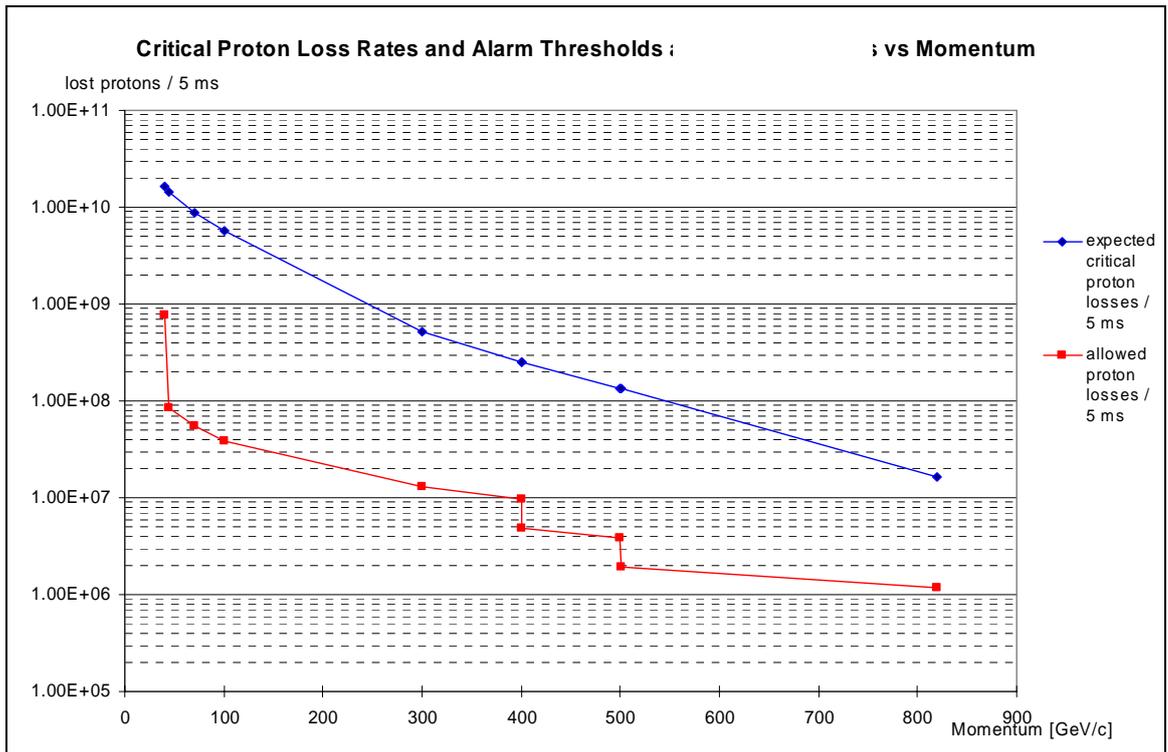


Fig. 2: Critical proton loss rate (above a quench occur) vs. momentum for the superconducting magnets in HERAp

Solution:

Exercise BLM 3a:

Calculate electron loss rate/bunch of 60pA/m at a bunch rate of 1 MHz

Solution:

Exercise BLM 3b:

Calculate electron loss rate/bunch of 1W/m loss-power at a bunch rate of 1 MHz

Solution:

Exercise BLM 3c:

What's the required dynamic range?

Solution:

Exercise BLM 3d:

Which type of BLM do you recommend for LINACs?

[Discussion in Plenum](#)

3 References

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6. ATOMIC AND NUCLEAR PROPERTIES OF MATERIALS

Table 6.1. Revised May 2002 by D.E. Groom (LBNL). Gases are evaluated at 20°C and 1 atm (in parentheses) or at STP [square brackets]. Densities and refractive indices without parentheses or brackets are for solids or liquids, or are for cryogenic liquids at the indicated boiling point (BP) at 1 atm. Refractive indices are evaluated at the sodium D line. Data for compounds and mixtures are from Refs. 1 and 2. Further materials and properties are given in Ref. 3 and at <http://pdg.lbl.gov/AtomicNuclearProperties>.

Material	Z	A	$\langle Z/A \rangle$	Nuclear collision length λ_T {g/cm ² }	Nuclear interaction length λ_I {g/cm ² }	$dE/dx _{\min}^b$ { $\frac{\text{MeV}}{\text{g/cm}^2}$ }	Radiation length ^c X_0 {g/cm ² } {cm}		Density {g/cm ³ } {g/ℓ} for gas	Liquid boiling point at 1 atm(K)	Refractive index n ($(n-1) \times 10^6$) for gas
H ₂ gas	1	1.00794	0.99212	43.3	50.8	(4.103)	61.28 ^d	(731000)	(0.0838)[0.0899]		[139.2]
H ₂ liquid	1	1.00794	0.99212	43.3	50.8	4.034	61.28 ^d	866	0.0708	20.39	1.112
D ₂	1	2.0140	0.49652	45.7	54.7	(2.052)	122.4	724	0.169[0.179]	23.65	1.128 [138]
He	2	4.002602	0.49968	49.9	65.1	(1.937)	94.32	756	0.1249[0.1786]	4.224	1.024 [34.9]
Li	3	6.941	0.43221	54.6	73.4	1.639	82.76	155	0.534		—
Be	4	9.012182	0.44384	55.8	75.2	1.594	65.19	35.28	1.848		—
C	6	12.011	0.49954	60.2	86.3	1.745	42.70	18.8	2.265 ^e		—
N ₂	7	14.00674	0.49976	61.4	87.8	(1.825)	37.99	47.1	0.8073[1.250]	77.36	1.205 [298]
O ₂	8	15.9994	0.50002	63.2	91.0	(1.801)	34.24	30.0	1.141[1.428]	90.18	1.22 [296]
F ₂	9	18.9984032	0.47372	65.5	95.3	(1.675)	32.93	21.85	1.507[1.696]	85.24	[195]
Ne	10	20.1797	0.49555	66.1	96.6	(1.724)	28.94	24.0	1.204[0.9005]	27.09	1.092 [67.1]
Al	13	26.981539	0.48181	70.6	106.4	1.615	24.01	8.9	2.70		—
Si	14	28.0855	0.49848	70.6	106.0	1.664	21.82	9.36	2.33		3.95
Ar	18	39.948	0.45059	76.4	117.2	(1.519)	19.55	14.0	1.396[1.782]	87.28	1.233 [283]
Ti	22	47.867	0.45948	79.9	124.9	1.476	16.17	3.56	4.54		—
Fe	26	55.845	0.46556	82.8	131.9	1.451	13.84	1.76	7.87		—
Cu	29	63.546	0.45636	85.6	134.9	1.403	12.86	1.43	8.96		—
Ge	32	72.61	0.44071	88.3	140.5	1.371	12.25	2.30	5.323		—
Sn	50	118.710	0.42120	100.2	163	1.264	8.82	1.21	7.31		—
Xe	54	131.29	0.41130	102.8	169	(1.255)	8.48	2.87	2.953[5.858]	165.1	[701]
W	74	183.84	0.40250	110.3	185	1.145	6.76	0.35	19.3		—
Pt	78	195.08	0.39984	113.3	189.7	1.129	6.54	0.305	21.45		—
Pb	82	207.2	0.39575	116.2	194	1.123	6.37	0.56	11.35		—
U	92	238.0289	0.38651	117.0	199	1.082	6.00	≈0.32	≈18.95		—
Air, (20°C, 1 atm.), [STP]			0.49919	62.0	90.0	(1.815)	36.66	[30420]	(1.205)[1.2931]	78.8	(273) [293]
H ₂ O			0.55509	60.1	83.6	1.991	36.08	36.1	1.00	373.15	1.33
CO ₂ gas			0.49989	62.4	89.7	(1.819)	36.2	[18310]	[1.977]		[410]
CO ₂ solid (dry ice)			0.49989	62.4	89.7	1.787	36.2	23.2	1.563	sublimes	—
Shielding concrete ^f			0.50274	67.4	99.9	1.711	26.7	10.7	2.5		—
SiO ₂ (fused quartz)			0.49926	66.5	97.4	1.699	27.05	12.3	2.20 ^g		1.458
Dimethyl ether, (CH ₃) ₂ O			0.54778	59.4	82.9	—	38.89	—	—	248.7	—
Methane, CH ₄			0.62333	54.8	73.4	(2.417)	46.22	[64850]	0.4224[0.717]	111.7	[444]
Ethane, C ₂ H ₆			0.59861	55.8	75.7	(2.304)	45.47	[34035]	0.509(1.356) ^h	184.5	(1.038) ^h
Propane, C ₃ H ₈			0.58962	56.2	76.5	(2.262)	45.20	—	(1.879)	231.1	—
Isobutane, (CH ₃) ₂ CHCH ₃			0.58496	56.4	77.0	(2.239)	45.07	[16930]	[2.67]	261.42	[1900]
Octane, liquid, CH ₃ (CH ₂) ₆ CH ₃			0.57778	56.7	77.7	2.123	44.86	63.8	0.703	398.8	1.397
Paraffin wax, CH ₃ (CH ₂) _{n≈23} CH ₃			0.57275	56.9	78.2	2.087	44.71	48.1	0.93		—
Nylon, type 6 ⁱ			0.54790	58.5	81.5	1.974	41.84	36.7	1.14		—
Polycarbonate (Lexan) ^j			0.52697	59.5	83.9	1.886	41.46	34.6	1.20		—
Polyethylene terephthalate (Mylar) ^k			0.52037	60.2	85.7	1.848	39.95	28.7	1.39		—
Polyethylene ^l			0.57034	57.0	78.4	2.076	44.64	≈47.9	0.92–0.95		—
Polyimide film (Kapton) ^m			0.51264	60.3	85.8	1.820	40.56	28.6	1.42		—
Lucite, Plexiglas ⁿ			0.53937	59.3	83.0	1.929	40.49	≈34.4	1.16–1.20		≈1.49
Polystyrene, scintillator ^o			0.53768	58.5	81.9	1.936	43.72	42.4	1.032		1.581
Polytetrafluoroethylene (Teflon) ^p			0.47992	64.2	93.0	1.671	34.84	15.8	2.20		—
Polyvinyltoluene, scintillator ^q			0.54155	58.3	81.5	1.956	43.83	42.5	1.032		—
Aluminum oxide (Al ₂ O ₃)			0.49038	67.0	98.9	1.647	27.94	7.04	3.97		1.761
Barium fluoride (BaF ₂)			0.42207	92.0	145	1.303	9.91	2.05	4.89		1.56
Bismuth germanate (BGO) ^r			0.42065	98.2	157	1.251	7.97	1.12	7.1		2.15
Cesium iodide (CsI)			0.41569	102	167	1.243	8.39	1.85	4.53		1.80
Lithium fluoride (LiF)			0.46262	62.2	88.2	1.614	39.25	14.91	2.632		1.392
Sodium fluoride (NaF)			0.47632	66.9	98.3	1.69	29.87	11.68	2.558		1.336
Sodium iodide (NaI)			0.42697	94.6	151	1.305	9.49	2.59	3.67		1.775
Silica Aerogel ^s			0.50093	66.3	96.9	1.740	27.25	136@ρ=0.2	0.04–0.6		1.0+0.21ρ
NEMA G10 plate ^t				62.6	90.2	1.87	33.0	19.4	1.7		—

Beam Loss Detection

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1 Abstract

A review of Beam Loss Monitor Systems (BLM systems) used in accelerators since about 1960 is given, with emphasis on systems suitable for measuring and localizing beam losses over an entire accelerator. Techniques presented include: Long and Short Ionization Chambers, Scintillation Counters, Electron Multipliers, Cryogenic Calorimeters and PIN Photodiodes.

2 Introduction

2.1 Uses of BLM systems

The usual goal of particle accelerators is to deliver high luminosity to experiments. The information from BLMs helps in the tuning of the machines for the high beam currents and long lifetimes necessary for improved luminosity.

Beam loss may result in damage to accelerator components or the experimental detectors. A task of the BLM system is to avoid such damage; in some accelerators it is an integral part of the protection system, signaling a beam abort system to fire if a certain loss rate is exceeded (Ref. 1, 2, 3). This is of vital importance to the Generation of superconducting accelerators, for which beam losses in the superconducting components may lead to a quench, resulting in a shut-down of accelerator operation during the quench recovery procedure, as well as possible damage to the components. Another task of BLM systems is to identify of the position (and time) of unacceptable losses. This often indicates the source of the problem in the machine. A BLM system provides a fast way to determine the position of aperture restrictions and semitransparent obstacles in the accelerator, and helps to keep the radiation level in the accelerator and its surroundings as low as possible.

2.2 Principles of loss detection

In case of a beam loss, the BLM system has to establish the number of lost particles in a certain position and time interval¹. All BLM systems discussed here are mounted outside of the vacuum chamber, so that the detector normally observes the shower caused by the lost particles interacting in the vacuum chamber walls or in the material of the magnets. The number of detected particles (amount of radiation, dose) and the signal from the BLM should be proportional to the number of lost particles. This proportionality depends on the position of the BLM in respect to the beam, type of the lost particles and the intervening material, but also on the momentum of the lost particles, which may vary by a large ratio during the acceleration cycle. Together with the specification for acceptable beam losses as a function of beam momentum, this defines a minimum required sensitivity and dynamic range for BLMs. Additional sensitivity combined with a larger dynamic range extend the utility of the system for diagnostic work.

One has to distinguish between two types of losses:

FAST LOSSES:

Total beam loss during one or very few turns. In most cases there is no need of a BLM system to localize the error in the machine. Often it is a easily detectable error like a closed vacuum valve, a broken power supply, a

¹ I exclude from my talk beam current monitors, which give the amount of losses but not the position

fired (or not fired) kicker, etc. Nevertheless it could be dangerous for accelerator components (especially superconducting components) and a BLM system may warn if an intolerable dose occurs.

SLOW LOSSES:

Partial beam loss over a time (circular machines) or distance (LINAC, transport lines) interval. In storage-rings, the lifetime is defined by slow losses. There are many reasons for these losses and a BLM system is very helpful for finding out what is happening in the machine. In superconducting accelerators a BLM system may prevent from beam loss induced quenches caused by slow losses.

In addition measurements of injection-, ejection- or collimator- efficiencies can be performed using BLMs (e.g. Ref. 4), as well as background measurements in the detectors (e.g. Ref. 27, 28). This survey concentrates on BLM systems which cover the entire accelerator.

3 Long Ionization-Chambers

In 1963, Panowsky (Ref. 5) proposed for SLAC a BLM system consisting of one long (3.5 km) hollow coaxial cable. It is an industrial RG-319/U cable with a diameter of 4.1 cm, filled with Ar (95%) + CO₂ (5%) and used as an ionization-chamber (Panowski's long ionisation chamber, PLIC). It is mounted on the ceiling along the LINAC, about 2 m from the beam.

Position sensitivity is achieved by reading out at one end the time delay between the direct pulse and the reflected pulse from the other end. The time resolution is about 30 ns (≈ 8 m), for shorter PLICs about 5 ns are achieved. This BLM system has been working for more than 20 years and was upgraded for the SLC (Ref. 6). Nearly the entire SLC is covered with a few PLICs

This principle of space resolution works for one-shot (-turn) accelerators (and transport lines) with a bunch train much shorter than the machine and with relativistic particles. For particles travelling significantly slower than the signal in the cable ($\approx 0.92c$) the resolution of multiple hits in the cable becomes difficult. In this case and for circular machines it is necessary to split the cable. Each segment has to be read out separately, with spatial resolution approximately equal to the length of the unit. This was done in the BNL 200 MeV LINAC, where 30 cables, each 7-9 m long, are used (Ref. 7). They are installed at 1.5 - 3 m from the beam.

In the AGS ring, Booster and transport lines about 200 monitors with a length of about 5 m are installed (Ref. 8, 9). To improve the sensitivity of the BLM system in the AGS ring for ion acceleration the cables were moved from a position below the magnets to the median plane on the open side of the magnets (Ref. 10). The dynamic range of the BLMs is about 10^3 .

In the KEK-PS 56 air-filled cables with a length of about 6 m are installed. Using amplifiers with a variable gain, a dynamic range of 10^4 is archived (Ref. 11).

4 Short Ionisation Chambers

Short ionization chambers are used in many accelerators. They are more or less equally spaced along the accelerator with additional units at special positions such as aperture restrictions, targets, collimators, etc. An early example of an Air filled Ionisation Chamber is the AIC proposed in 1966 in Ref. 12 (Fig. 1). 100 AICs were installed in the CERN-PS. Each chamber had a volume of about 8000 cm³ and used a multi-electrode layout to reduce the drift path, and hence the recombination probability, of the ions and electrons, with the goal of improved linearity. A dynamic range of 10^3 was obtained.

The idea of AIC was renewed in 1992 in Ref. 14. The authors propose an AIC with a 2π geometry around the beam pipe. The goal is to measure the loss in the vacuum wall independent of azimuth angle and with high sensitivity.

The TEVATRON relies on 216 Argon filled glass sealed coaxial ionization chambers to protect the superconducting magnets from beam loss induced quenches (Ref. 1). The volume of each chamber is 190 cm³ (Fig. 2). Most are positioned adjacent to each superconducting quadrupole. An Ar-filled chamber has the advantage of a better linearity because of a lower recombination rate than in AICs. A dynamic range of 10^4 has been reached.

A new idea is proposed in Ref. 15 for the UNK superconducting magnets. The ionization chamber is an integral part of the magnet and uses the liquid Helium as an ionization medium. A 2π geometry close to the beam pipe is foreseen, with predicted dynamic range of 10^5 , but additional investigations are necessary to determine the linearity in this range, which may be restricted by the recombination rate.

5 Scintillation counters

In case of losses in a machine without a BLM system, a temporary installation of plastic scintillator with photomultiplier readout is often made. These counters have a well known behavior but the strong radiation damage of the plastic scintillator restricts their long term use. Liquid scintillators avoid this damage and were installed in some accelerators, e.g. Ref. 16, 17. Fig. 3 shows the device at LAMPF with a dimension of 500 cm^3 . A photomultiplier (PM) inside a oil filled paint can detects the scintillation light from the oil. This BLM is very fast, the pulse rise time is about 10 ns and a dynamic range of 10^5 was obtained. The gain of the photomultipliers varies within a factor of 10. Therefore a careful intercalibration of the BLM sensitivities was necessary by adjusting the high voltage (HV). The drift of the gain is a well known behavior of PMs. A stabilized HV-source and continuous monitoring of the photomultiplier gain over the run period keep the calibration error small.

6 Aluminum Cathode Electron Multipliers

An enhanced sensitivity of photomultipliers to ionized radiation is achieved by replacing the photocathode by an aluminum foil. This foil works as secondary electron emitter when irradiated. A BLM system consisting of this Aluminum Cathode Electron Multipliers (ACEM) was proposed in Ref. 18 and installed in the CERN-PS (100 units) and in the PS-Booster (48 units). They are located on top of the magnets behind each straight section plus 32 additional positions for specific applications (PS). The dimensions of the tube are 4 cm in diameter and 9 cm length plus the adjacent HV-divider (Fig. 4). This BLM is very fast; the rise time of the signal is about 10 ns. For the dynamic range a value of 10^6 was exceeded by adjusting the HV. A careful selection of the ACEMs had led to gain variations of 10 %, but intercalibration and gain monitoring was performed nevertheless. This BLM system is rather expensive because the ACEM is not a standard tube of PM-suppliers (Ref. 20).

7 Cryogenic Microcalorimeters

A new system called the Cryogenic Microcalorimeter was proposed and tested in 1992 for LEP (Ref. 21). It is designed to detect beam loss induced quenches in the superconducting quadrupoles of LEP. This detector is different from all the other BLMs presented here because it does not make use of the charge created by the lost particles. A carbon resistor thermometer measures the temperature rise of the liquid Helium in the cryostat produced by beam losses. It is a very small device with dimensions of about $3 \times 3 \times 1.5\text{ mm}$ (see Fig. 5). Its position is restricted to the cryostat of superconducting magnets.

No values for the linearity and the dynamic range are available up to now but first measurements indicate an easily detectable signal with a rise time of about 20 ms in case of a beam induced quench. The signal occurs well before the quench and it should give enough time for the quench protection system to take action. The dynamic range is limited by the critical (quench-) temperature of the liquid Helium and by the noise of the monitor. One can expect that, with a known correlation between losses and temperature, this detector will work in a BLM system for superconducting accelerators. For quantitative loss measurements the temperature increase due to synchrotron radiation has to be taken into account.

8 PIN Photodiodes

Most of the existing BLM systems are installed in hadron accelerators or in Linacs. Circular electron accelerators emit hard synchrotron - radiation (SR). The radiation interacts with the BLMs and a separation between SR-background and the beam loss distributions using the traditional BLM techniques is practically impossible. HERA is an accelerator with an electron and a proton ring in the same tunnel, operating at the same time. Protection of the superconducting proton magnets from beam loss induced quenches must rely on a BLM

system which sees only the proton beam losses and not the SR-background. The (hadronic) shower created by beam losses includes a large number of charged particles, in contrast to the photons of the SR. The HERA BLM system consists of two PIN Photodiodes, mounted close together (face to face) and read out in coincidence (Ref. 22). Thus charged particles crossing through the diodes give a coincidence signal, while photons interact in only one diode do not.

In contrast to the charge detection of most other BLM systems, coincidences are counted, with the count rate is proportional to the loss rate so long as the number of overlapping coincidences is small.

The Photodiodes ($2 \times 2.5 \times 2.5 \text{ mm}^3$) and the preamplifier ($5 \times 5 \times 5 \text{ cm}^3$) are shielded by a hat of 3 cm of lead (Fig. 6). The overall reduction of SR signals is about 10^4 , resulting in a count rate of $\approx 1 \text{ Hz}$ with 25 mA current at 30 GeV/c in the electron ring (Ref. 23). The system has very low noise, with a dark count rate of less than 0.01 Hz. The pulse length is adapted to the 96 ns bunch spacing in HERA, so that the maximum count rate is 10.4 MHz. Therefore a dynamic range of more than 10^9 is available.

The radiation resistance of the BLMs is adequate for long term use in HERA. A dose of $5 \times 10^5 \text{ rad}$ leads to a small and tolerable reduction in gain (Ref. 24, 25), while the dose reaching the monitor below the lead shield will be about 10^4 rads/year . BLMs are mounted on top of each of the superconducting quadrupoles. At this position the showering of the lost protons give a count rate which is independent of the radial position of the loss, and, within 5 m, also of the longitudinal position (Ref. 23). Additional BLMs are mounted on collimators, and on some of the warm quadrupole magnets, for a total of 250 units.

The BLM system has been operating since the 1992 running period and their good performance is indicated by some measurements:

- 1) The loss rates calculated from lifetime and measured by the BLMs agree to within 25 % (Ref. 26)².
- 2) The counts are integrated over a time period of 5.2 ms to match the cryogenic time constant of the superconducting magnets (>20 ms). The predicted coincidence rate corresponding to the critical loss rate for a quench at 820 GeV/c is about 860 counts/5.2 ms. The only beam induced quench of a HERA quadrupole in 1992 showed a count rate of 1258 counts/5.2 ms for the quenched quadrupole. A nearby quadrupole which did not quench showed a rate of 893 counts/5.2 ms. The critical rate must be somewhere in between and is not far away from the predicted one. The critical rate was detected about 100 ms before the magnet quenched.
- 3) A lifetime problem in the HERA electron ring was solved using the BLMs. All monitors were moved from the proton ring to the electron ring to find the problematic section. A high count rate, inversely proportional to the beam lifetime, was measured in one of the straight sections. The problem vanished after a part of the vacuum-chamber in this section was replaced. This result demonstrates that the BLM system is also useful in high energy electron rings. It is planned to install about 250 additional monitors in the HERA electron ring.

9 Summary

Some Beam Loss Monitors techniques for measuring losses along an entire accelerator have been presented.

A long ionization chambers using a single coaxial cable works well for one-shot accelerators or transport lines. To achieve spatial resolution of losses along an entire accelerator two conditions must be fulfilled: 1) The machine must be much longer than the bunch train, and 2), the particles must be relativistic.

The most common BLM now in use is a short ionization chamber. Whether a simple air filled chamber is adequate, or an Argon or Helium filled chamber, with superior higher dynamic range, must be used, depends on the conditions of the particular accelerator. Ionisation chambers are radiation resistant but respond to synchrotron radiation.

A very sensitive system for measuring beam losses is an electron multiplier in combination with a photocathode and scintillator or with an Aluminum cathode acting as secondary electron emitter. Because of the adjustable gain the dynamic range can be large, but the calibration of each device must be adjusted and monitored over time. These systems are also sensitive to synchrotron radiation and relatively expensive.

The Cryogenic microcalorimeter measures the temperature rise of the liquid Helium in superconducting magnets resulting from beam loss. The temperature rise corresponding to beam loss sufficient to cause a quench

² Please note that the efficiency of the BLM to charged particles is about 20 time higher than previously assumed (Ref. 27). Correct the loss-rate in Ref. 26 by 1/20.

is readily observed. Some additional investigations must be made of the dynamic range and the linearity of this device but first measurements indicate its suitability for quench prevention and loss measurements. The temperature rise due to synchrotron radiation must be taken into account when using Cryogenic Microcalorimeters for loss diagnostics in electron machines. The application of the calorimeter is limited to superconducting magnets.

The combination of two PIN-Photodiodes in a coincidence counting results in a detector with very large dynamic range and extremely effective rejection of synchrotron radiation. The small dimensions permit simple shielding and easy installation at any position. The measured radiation resistance permits long term use also in high energy electron machines with a high radiation background. The monitor with its simple accompanying electronic is inexpensive, which may be of great importance in very big machines with a large number of loss monitors. A (present) limitation is the inability to distinguish overlapping counts, so that the response is linear only for losses for which there is significantly less than one count per coincidence interval.

Acknowledgements

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11 Figures

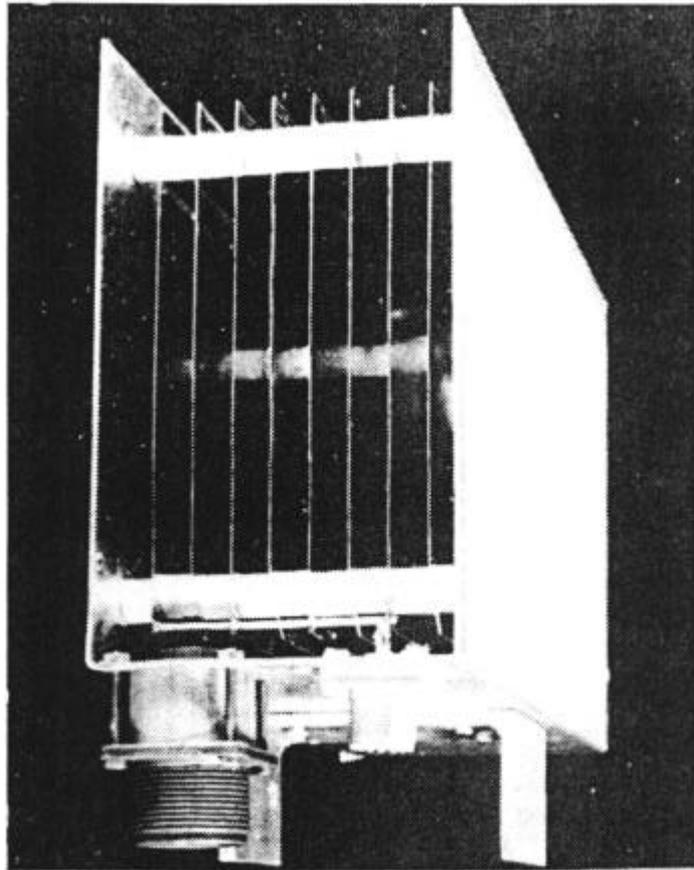


Figure 1: Air Ionisation Chamber at the PS (1968). The cover is removed (from Ref. 13).



Figure 2: The TEVATRON Argon filled Ionization Chamber (1983)

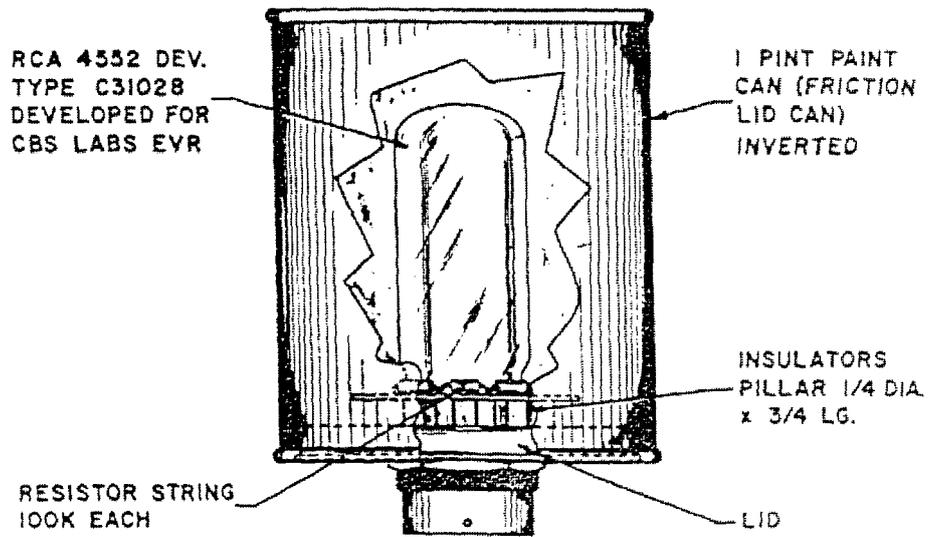


Figure 3: The Liquid Scintillator BLM at LAMPF (1971), (from Ref. 16)

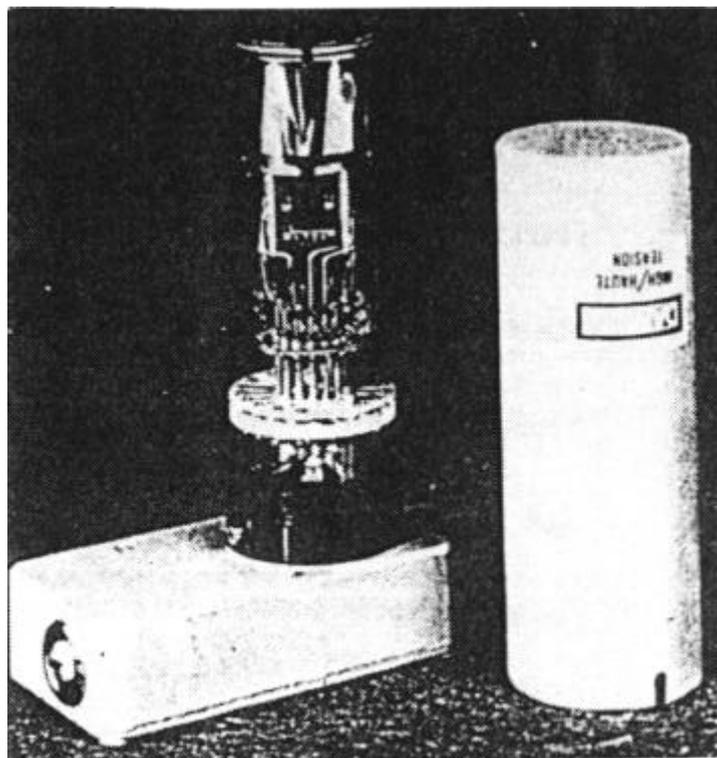


Figure 4: The Aluminum Electron Multiplier at CERN PS (1985), (from Ref. 19).

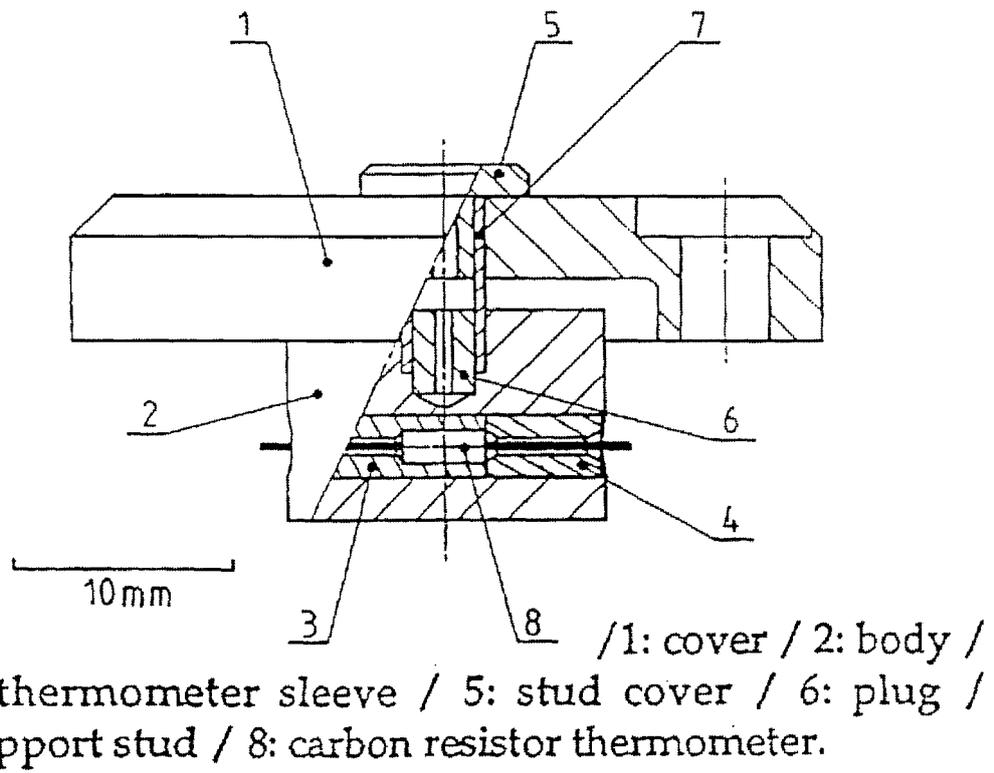


Figure 5: Cut-away view of the microcalorimeter (1992), (from Ref. 21).

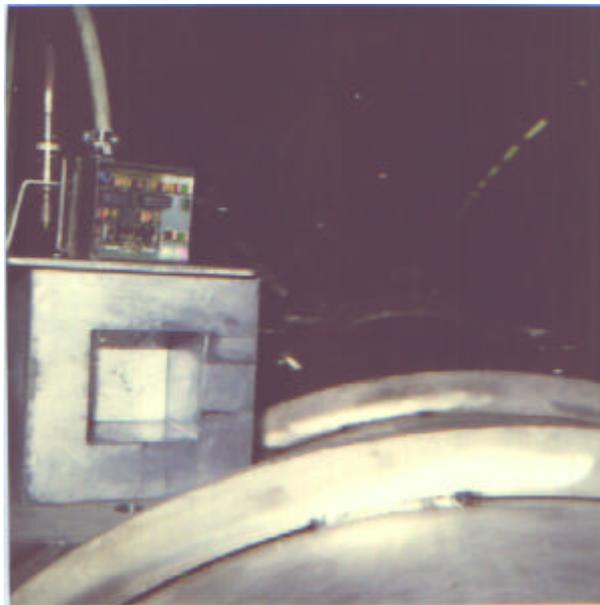
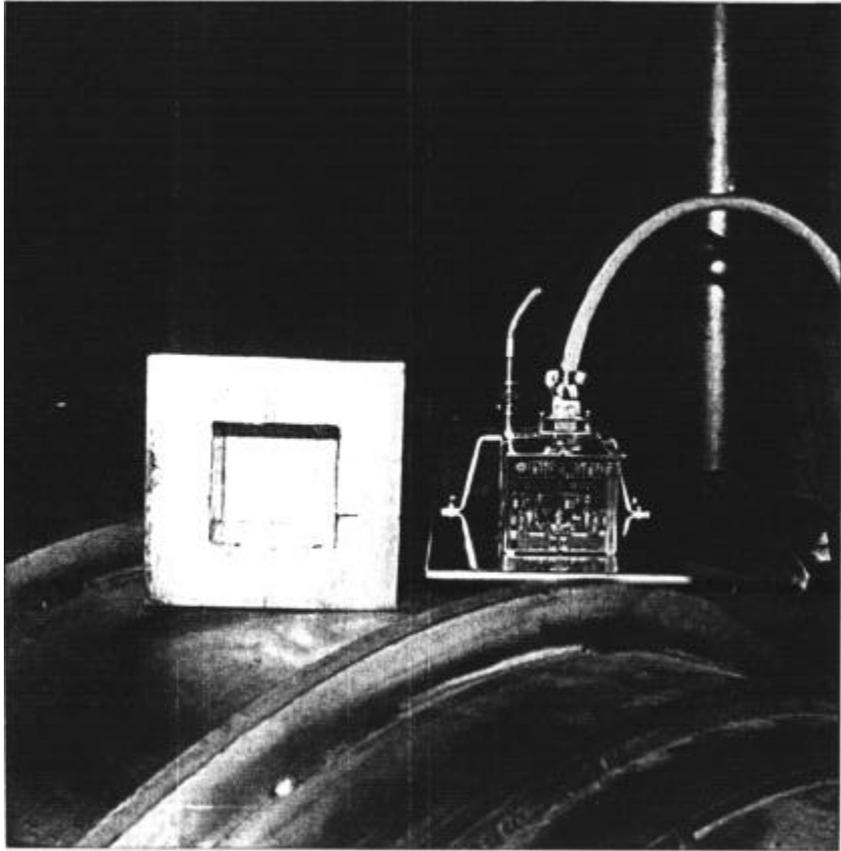


Figure 6: The PIN Photodiode BLM on top of a HERA magnet (1991). The lead hat is removed



BEAM LOSS MONITORING AND CONTROL

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Abstract

The use of Beam Loss Monitors (BLMs) as sensitive tools for various beam diagnostic applications will be discussed as well as their tasks in machine protection and loss location detection. Examples will illustrate that an appropriate design of a BLM-system and a proper understanding of loss events can improve machine performance.

1 INTRODUCTION

“You do not need a BLM-System as long as you have a perfect machine without any problems. However, you probably do not have such a nice machine, therefore you better install one.”

Beam loss monitor systems are designed for measuring beam losses around an accelerator or storage ring. A detailed understanding of the loss mechanism, together with an appropriate design of the BLM-System and an appropriate location of the monitors enable a wide field of very useful beam diagnostics and machine protection possibilities.

Beam losses can be divided into two different classes:

1) **Irregular losses**, sometimes called “fast or uncontrolled losses”: These losses may be distributed around the accelerator and not obviously on a collimation system. They are very often a result of a misaligned beam or a fault condition, e.g. operation failure, trip of the HF-system or of a magnet power supply. Losses should be avoided and should be kept to low levels

- to keep activation low enough for hands-on maintenance, personal safety and environmental protection,
- to protect machine parts from beam related (radiation) damage. This includes quench protection of superconducting magnets and acceleration structures and protection of detector components,
- to achieve long beam lifetimes or an efficient beam transport to get high integrated luminosity for the related experiments.

Sometimes such losses have to be tolerated even at a high level at low repetition rates during machine studies. However, a beam loss monitor system should define the allowed level of those losses. The better protection there is against these losses, the less likely is down time due to damage of components. A post mortem event analysis is most helpful to understand and analyse the faulty condition.

Some examples of such a functionality of beam loss monitor systems will be given in this paper.

2) **Regular losses**, sometimes called “slow” or “controlled” losses: Those losses are typically not avoidable and are localized on the collimator system or on other (hopefully known) aperture limits. They might occur continuously during operational running and correspond to the lifetime/transport efficiency of the beam in the accelerator. The lowest possible loss rate is defined by the theoretical beam lifetime limitation due to various effects, like residual gas, Touschek effect, etc.

Some examples will be discussed, where, with the help of a beam loss monitor system, the measurement of losses can be used for machine diagnostic purposes.

It is clearly advantageous to design a BLM-System which is able to deal with both loss modes.

2 SOME COMMON ASPECTS

There are some common aspects, which are valid for every beam loss monitor system:

- a) Type of loss monitor
- b) Positioning of the loss monitor

2.1 Type of Loss Monitor

Typical beam loss monitors detect beam losses by measurement of ionising radiation produced by lost beam in real-time and with a certain position resolution. Other systems, like differential beam current measurements, have a very rough position resolution, or have a very long time constant (e.g. dose measurements or activation) and are not the subject of this talk.

The produced radiation consists mainly of electromagnetic particles (electron-, positron- and gamma- shower), while the loss of a hadron (proton, ion) produces some hadronic particles (protons, neutrons), too. However, the signal source of beam loss monitors is mainly the ionizing capability of the charged shower particles.

Different types of such loss monitors exist and detailed descriptions of most types can be found in [1, 2]. Options for beam loss monitors might be: long and short Ion chambers, Photomultipliers with scintillators (incl. Optical Fibers), PIN Diodes, Secondary Emission Multiplier-Tubes, Microcalorimeters, Compton Diodes, etc. A nice list of “considerations in selecting a beam loss monitor” is discussed in [2]:

- Sensitivity
- Type of output (current or pulse)
- Ease of calibration (online)
- System end-to-end online tests
- Uniformity of calibration (unit to unit)
- Calibration drift due to aging, radiation damage, outgassing, etc.
- Radiation hardness (material)

- Reliability, Availability, Maintainability, Inspect ability, Robustness
- Cost (incl. Electronics)
- Shieldability from unwanted radiation (Synchrotron Radiation)
 - Physical size
 - Spatial uniformity of coverage (e.g. in long tunnel, directionality)
 - Dynamic range (rads/sec and rads)
 - Bandwidth (temporal resolution)
 - Response to low duty cycle (pulsed) radiation
 - Instantaneous dynamic range (vs. switched gain dynamic range)
 - Response to excessively high radiation levels (graceful degradation)

Consideration of these parameters gives a good guide to find (or design) the best monitor type for a particular beam loss application.

2.2 Positioning of the Loss Monitor

The loss of a high-energy particle in the wall of a beam pipe results in a shower of particles, which leak out of the pipe (Low energy beam particles, which do not create a shower leakage outside the vacuum pipe wall, will be hardly detectable by a loss monitor system). The signal of a loss detector will be highest, if it is located at the maximum of the shower. Refs. [3, 4, 5] are using Monte Carlo simulations to find the optimum locations for the monitors, as well as to calibrate the monitors in terms of ‘lost particles/signal’. The length of the shower depends on the energy of the lost particle and ranges from some meters for very high proton energies [4] to a few cm for medium electron energies [5]. Therefore the expected location of lost particles has to be studied in advance to locate the monitors at the right location, especially at electron accelerators. But this means, that an understanding of the loss mechanism and dynamics in the accelerator is necessary to predict the typical positions of losses. For example, Refs [5, 6] had done detailed particle tracking studies to follow the trajectory of an electron in the accelerator after an energy loss due to scattering on a residual gas molecule or on a microparticle.

There are many different reasons for beam losses and a complete beam loss system has to be carefully designed for a detection of a specific loss mechanism.

In the following, some examples for different loss mechanisms, their detection and their use for beam control and diagnoses will be presented.

3 SOME EXAMPLES FOR IRREGULAR, UNCONTROLLED LOSSES

3.1 Radiation Damage

A serious problem for high current and high brilliance accelerators is the high power density of the beam. A misaligned beam is able to destroy the beam pipe or collimators and may break the vacuum. This fact makes the BLM-System one of the primary diagnostic tools for

beam tuning and equipment protection in these machines. Such a system must have enough sensitivity and dynamic range to measure low-level losses at low current (test-) beams, as well as high local losses of short duration. Together with well-designed collimation and machine interlock systems, the BLM-System should prevent harmful accidents by switching off the beam in time in case that the loss rate exceeds a certain threshold at any position. But it should also serve as a sensitive diagnostic tool during the set-up periods of the accelerator to prevent high losses at nominal currents [7, 8]. This will help to prevent excessive activation of the environment and equipment damage. Especially for high-current proton and ion accelerators, this became a very important for hands-on maintenance as well as for ground water and air activation [9].

3.2 Obstructions

The set-up periods of a new accelerator or after a reconstruction of an existing machine are always associated with beam losses, before the machine goes into normal operation. Unexpected losses can be caused by a various number of reasons, and a BLM-System may help to find them. A ‘beautiful’ example is discussed in [10], where an RF-finger pointing in the beam line prevented the beam from circulating in Rhic. The loss pattern showed an apparent obstacle in the ring at a certain location. The losses there went away as the beam was steered locally around an obstacle after which the beam began circulating for thousands of turns.

Other obstacle-like obstructions are vacuum-crashes and trapped microparticles [11]. They caused in more or less sudden drops in the lifetime due to scattering of the electrons on the additional particles in the beam pipe. The lifetime is reduced because beam particles lose energy by bremsstrahlung both in the field of the atomic nuclei and in the macroscopic field of the highly charged microparticle or ‘dust’. The deviation of the electron orbit from the nominal orbit depends on the dispersion function in the accelerator and on the energy loss. Therefore the electrons may be lost behind the following bending magnet on the inside wall of the vacuum chamber. Beam loss monitors located at this location are sensitive to these effects and therefore can measure the vacuum-distribution, vacuum leaks (Fig. 1) and the existence, location and even the movement of microparticles [6, 12].

3.3 Quench Protection

Superconducting accelerators need a dedicated BLM-system to prevent beam loss induced quenches. Such a system has to detect losses fast enough before they lead to a high energy deposition in the superconducting material. A time constant of a few ms is adequate for the main loss system. HERA has shown, that the BLM-system is very often the last chance to recognize a doomed beam and to dump it before it is lost uncontrollably, possibly quenching magnets [3, 13]. Care has to be taken, to set-up

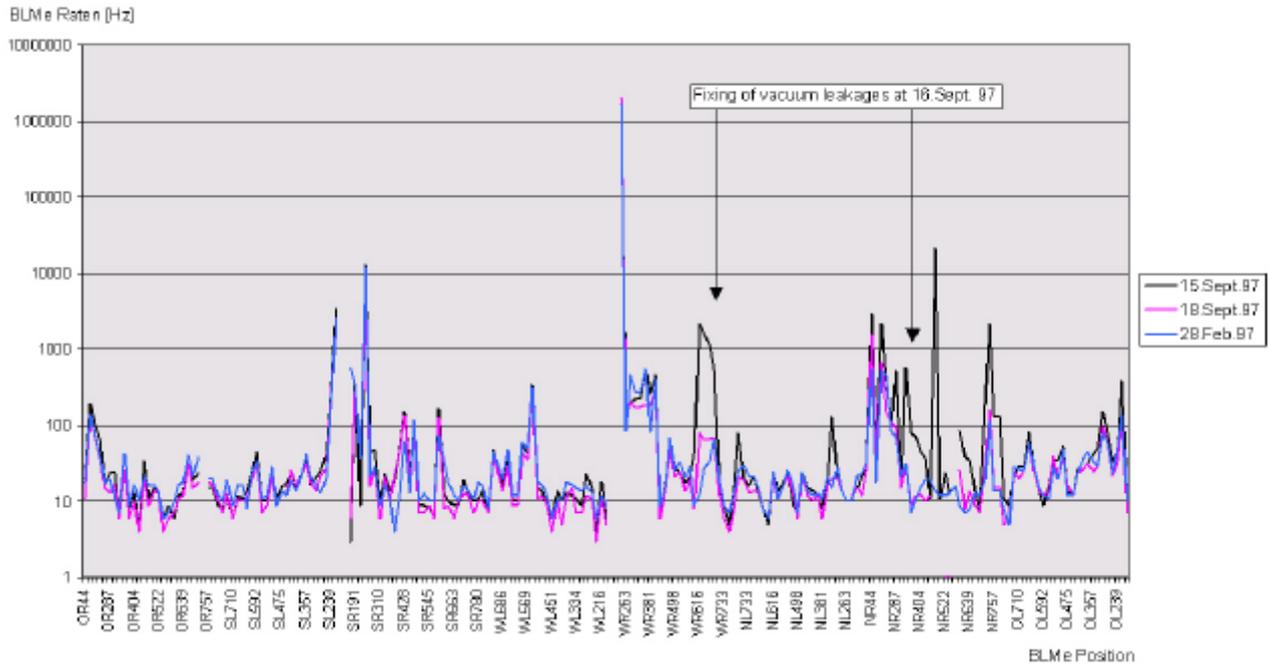


Figure 1: Beam loss monitor signals versus their location along HERAe at different dates during 1997. The two vacuum leaks on the 15.Sept. are clearly visible, as well as their repair on the next day. Note the reproducibility of the rates.

such a system properly, so that it is not overly active (dumping too often) and also not too relaxed, allowing dangerous loss rates. Typical locations for the protection system monitors are the quadrupoles of the accelerator, where the beam has its largest dimensions. The quadrupoles act as local aperture limits and therefore the chance for a loss is larger there. It might turn out, that some special locations are more sensitive to losses than others, e.g. global aperture limits and collimators. For such locations a special treatment of the alarm-threshold, timing constant (faster) and sensitivity is applicable. Even an additional type of monitor might be the right choice.

In all cases of fast beam losses, an event archive is most helpful for a post mortem analysis of the data, to find out the reason for the loss. Certainly this will improve the operational efficiency of the accelerator.

4 SOME EXAMPLES FOR REGULAR, CONTROLLED LOSSES

4.1 Injection Studies

The injection of beam into the next accelerator of a chain should work with the highest possible efficiency. Keeping the loss rate of adjacent BLMs as low as possible is a very simple way of tuning the injection schema. BLMs measure the loss directly and with better sensitivity and resolution than the differential beam current measurement. This became important, if low injection (test-) currents are required as a result of radiation safety issues. Additional, a distributed BLM-system shows the areas of losses during the injection process as well as the loss timing behaviour (Fig. 2). By placing BLMs at

betatron and dispersion aperture limits, one can distinguish between transversal mismatch (betatron oscillations) and energy mismatch (dispersion) at injection [15].

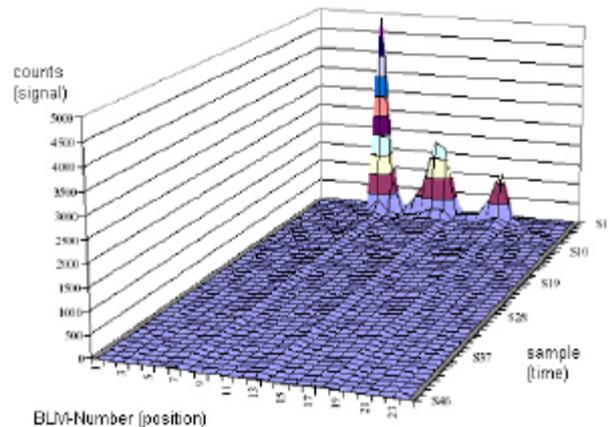


Figure 2: Surface plot of beam loss at injection and afterwards (from [14]).

4.2 Lifetime Limitations

Beside of unwanted conditions, there are unavoidable effects which limit the beam lifetime in an accelerator, e.g. vacuum lifetime (Coulomb scattering), Touschek effect, quantum lifetime, etc.:

Touschek Effect: Particles inside a bunch perform transverse oscillations around the closed orbit. If two particles scatter, they can transform their transverse momenta into longitudinal momenta. If the new momenta are outside the momentum aperture the particles are lost.

Good locations for the detection of Touschek scattered particles are in high dispersion sections following sections where a high particle density is reached. Since the two colliding particles lose and gain an equal amount of momentum, they will hit the in- and outside walls of the vacuum chamber. In principle the selectivity of the detection to Touschek events can be improved by counting losses at these locations in coincidence.

Coulomb Scattering etc.: Particles scatter elastically or inelastically with residual gas atoms or photons (Compton) or emit a high energy synchrotron radiation photon (Quantum). This leads to betatron or synchrotron oscillations and increases the population of the tails of the beam. If the amplitudes are outside the aperture the particles are lost. Losses from elastic scattering occur at aperture limits (small gap insertions, septum magnet, mechanical scrapers and other obstructions). If the energy carried away by the emitted photon is too large, the particle gets lost after the following bending magnet on the inside wall of the vacuum chamber.

A BLM-System with good selectivity to the different loss mechanisms is a very useful tool for various kinds of beam diagnostics, especially in Touschek limited (electron-) accelerators: The Touschek loss rate depends on the 3-dimensional electron density and on the spin of the scattering particles. Therefore any change of one or more of these parameters has an influence on the loss rates at the selected monitors. The BLM-System at BESSY was used to determine the (desired) vertical beam blow up due to a resonant head-tail mode excitation [16]. At ESRF the BLM-System was used to study the beam coupling between the transversal planes [17]. At ALS and BESSY the BLM-System was used to calibrate precisely the beam energy and observing its variation in time by using resonant depolarization of the beam [16, 18].

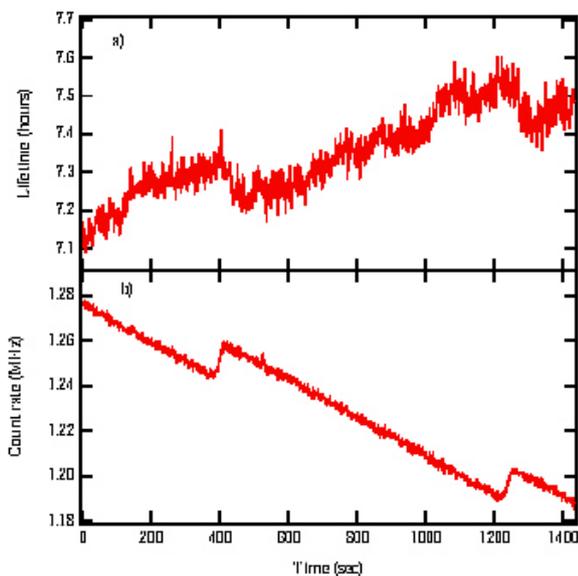


Figure 3: Beam lifetime derived from current monitor and count rate from beam loss monitor showing two partial spin depolarizations over a 25 minute period (from [18]). Note the much clearer signal from the BLM.

One useful applications of the energy measurement is the precise determination of the momentum compaction factor [18].

4.3 Tail Scans

Non-Gaussian tails in the transverse and longitudinal beam distribution produce lower beam lifetimes and background in experimental detectors. With beam profile monitoring, these tails are difficult to detect because of their small population in respect to the core of the beam. A combination of scrapers and BLMs is a good choice to measure the tail population and to get rid of it. Transverse tails are best measured at scraper positions with a large β -function and with no dispersion, while for longitudinal tail scraping scraper positions at small β -function and large dispersion are best. The measurement and scraping can be done by moving the scraper in small steps closer to the beam core measuring at each step the response of the adjacent BLM. This procedure does not affect the lifetime because the particles in the tails will get lost anyhow (as long as the scraper doesn't reach the beam core). Coulomb or Touschek scattering are the dominant processes for creating tails in lower energy electron rings, while at the very high energy ring LEP the dominant processes are Compton scattering on thermal photons (horizontal) and beam-beam bremsstrahlung (vertical) [19].

In the high-energy proton accelerator HERA, the lifetime limitation arises from proton diffusion due to beam-beam interaction and tune modulation due to ground motion. The ground motion frequencies can be measured with BLMs at the scrapers [20, 21]. The loss spectrum of a very stable machine corresponds very well with the ground motion spectrum. The diffusion parameters at different tune modulation settings are measured by retracting the scraper from the beam tail and observing the time constants of the adjacent loss rate decrease and slow increase afterwards [20].

4.4 Tune Scans

Any change of the 3-dimensional phase space of a particle beam will effect the loss rates. By observing these losses as a function of the tune, the phase space area of the lattice can be investigated, as well as the influence of insertion devices that may cause non-linearities [16, 22]. The examination of the tune area might be somewhat lengthy, when only measuring the small changes of the beam lifetime. With the help a BLM-System, this procedure can be done very fast because the change of the loss rate can be measured immediately. [23] had shown, that a combination of a collimator and a BLM is a very sensitive tool to make fast tune scans of the area around the working point even at very long lifetimes and very small lifetime-changes.

5 CONCLUSIONS

It has been shown, that a beam loss monitor system is a multi-faceted beam instrumentation tool, which opens a

wide field of applications. A precondition is a proper understanding of the physics of the beam loss to place the monitors at their adequate positions.

BLM-systems are frequently used to minimise irregular, uncontrolled losses to protect the environment and equipment of the accelerator from radiation damage; in superconducting accelerators also from beam loss induced quenches. They also serve as a sensitive tool to localise and study any kind of physical obstruction in the accelerator, from abominably RF-fingers down to different vacuum problems. Also a BLM-system helps to study and optimise the injection scheme of an accelerator. BLM-systems play an important role in investigating and optimising the beam lifetime, which is defined by different, but regular losses. A BLM-System with a good selectivity to the different loss mechanisms is a very useful tool for various kinds of beam diagnostics and beam control, e.g. controlled beam blow-up, coupling studies and tune scans. Even a precise energy calibration of the beam can be done with signals from a BLM-system. The combination of a scraper and a BLM offers additional useful applications for lifetime studies, e.g. ground motion observation, beam diffusion measurements and tail scans.

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Chapter 5

Bunch Length Measurements

5.1 Exercises



Excercises on Bunch Length Measurements

by T. Lefevre

Problem 1:

You have just been hired to work on a 5MeV electron gun – 4ps bunch length. Your first job is dedicated to the design of a bunch length monitor using Cherenkov radiation and a streak camera.

As a reminder, Cherenkov light is emitted when a charge particle travels inside a transparent medium with a velocity higher than the speed of light in this medium. The Cherenkov photons are emitted all along the material thickness

- Speed of light inside the material : $v = \frac{c}{n}$ with n is the index of refraction of the material
- β is the relative particle velocity
- γ is the particle relativistic factor : $\gamma = \frac{1}{\sqrt{1-\beta^2}}$
- d the thickness of the Cherenkov radiator

Questions:

- What is the minimum index of refraction of the given material so that Cherenkov effect occurs?
- Assuming that you will use fused silica as a Cherenkov radiator (index of refraction is 1.46), How thick must be the crystal to keep the time resolution below 1ps? You can neglect the effect of light dispersion and multiple scattering inside the radiator

Problem 2:

You have been promoted and are now in charge of the bunch length measurement at the end of the Linac for electrons energy of 50GeV (4ps bunch length). Your boss specifically asks for a non destructive method and you are considering Optical Diffraction Radiation.

ODR is a pure high relativistic phenomenon (contraction of length), where a charged particle emits radiation when it passes close to the edge of a dielectric medium. To produce ODR, there is a condition to fulfill between the distance from the edge to the beam (h), the beam energy (γ) and the wavelength (λ) of the radiation you like to produce.

$$h \leq \frac{\gamma\lambda}{2\pi}$$

Questions:

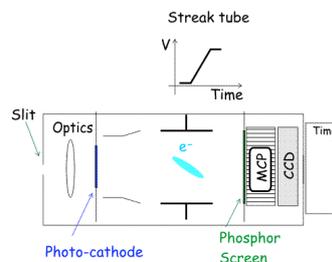
- What will be the required minimum distance from the edge of the slit to the beam in order to produce visible photons (550nm wavelength)
- Is that distance looks reasonable, Would you think it can be used at lower beam energies

Problem 3:

You are responsible for the purchase of the streak camera and you should define what the parameters of the streak camera to buy are. This is an expensive device and the performance of the camera should match precisely your needs. You were told that you need a minimum of 2points per sigma in order to clearly measure a Gaussian bunch length.

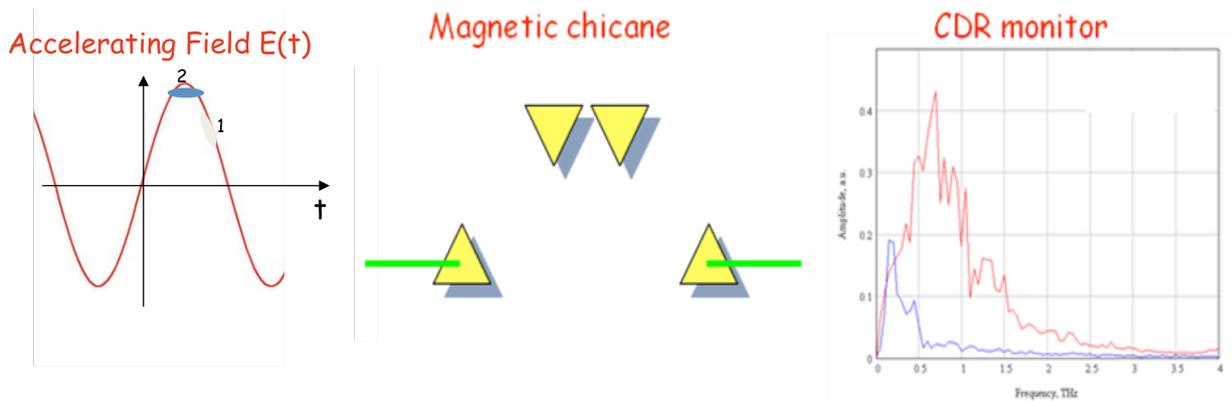
Questions:

- Assuming that your mcp-ccd system is 1cm wide in vertical and have 500pixels, what will be the minimum sweep speed (in ps/mm) of the streak tube in order to measure the 4ps bunch length in your linac



Problem 4:

You did so well for the bunch length measurement in the linac that you are asked to provide some support to operate of the bunch compressors. The bunch compression is done using an accelerating structure and a magnetic chicane. A coherent diffraction radiation monitor is measuring the bunch frequency spectrum just downstream of the chicane. Coherent radiation monitor relies on the fact that the shorter the bunch the broader the bunch frequency spectrum.

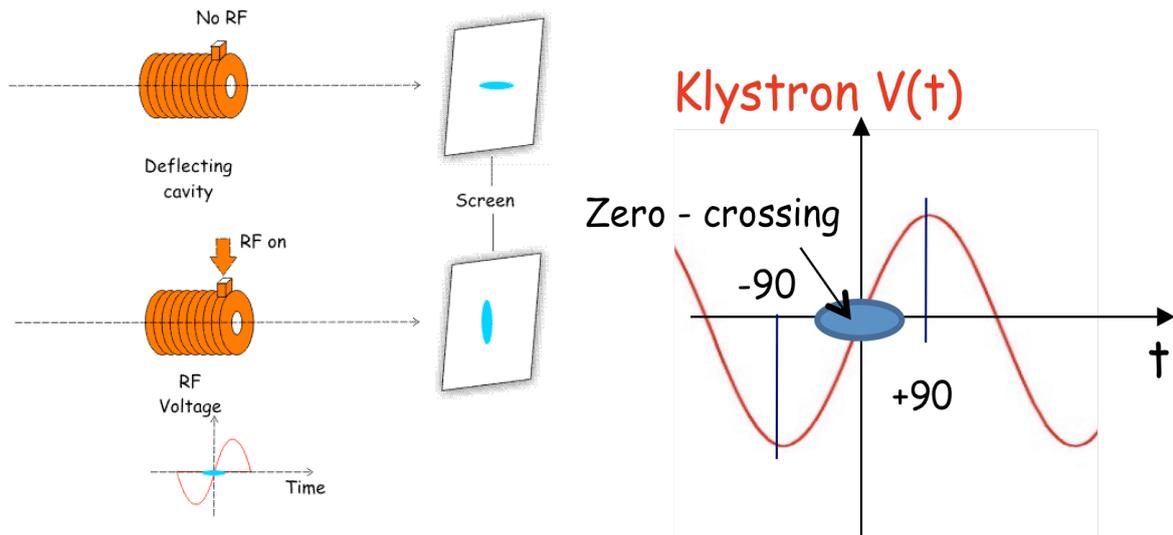


Questions:

- On the figure, there are two different settings of the klystron phase. For these two cases, draw what will be the trajectory of electrons sitting at the head and at the tail of the bunch for each case?
- On the CDR monitor, two different bunch frequency spectra have been measured. Choose which spectra corresponds to which phase settings
- Are you happy with the performance of the bunch compressor? if not what will you modify to have a better result

Problem 5:

With your new success, you really become a well recognized expert. In the meanwhile, the calibration of the RF deflector has changed during the replacement of a Klystron. You have been asked to calibrate the monitor. By changing the phase of your klystron with respect to the beam, the beam position changes on the screen. The RF deflector is working at 3GHz and for a maximum deflection ($\pm 90^\circ$ phase difference) the beam position on the screen changes by 5mm.



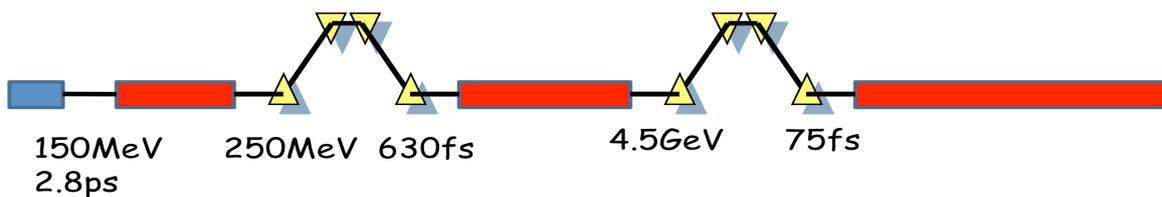
Questions:

- If the bunch is placed at the zero-crossing of the RF deflector. What happens to the beam position and to the beam size?
- If the natural beam size (no RF) on the screen is $10\mu\text{m}$, what will be approximately the size increase for zero-crossing if the bunch is 1ps long. The relation between the bunch length, the beam size on the screen with and without RF power is given by the following expression.

$$\sigma_y^2 = \sigma_{y_0}^2 + \sigma_z^2$$

Problem 6:

You are now working on the design of 4th generation light source and you have been asked to define the several techniques to measure bunch length all along the machine. The layout of the machine is presented here.



Questions:

Choose at least one location where the following detector could be used along the machine.

- ODR with a streak camera
- RF deflector
- Coherent diffraction radiation
- EO spatial decoding

5.2 Further Reading: Bunch Length Measurements



Lectures on Bunch Length Measurements

by T. Lefevre, CERN

Abstract

This lecture gives an introduction to the main techniques used to measure the longitudinal structure of particle beams. It is composed of two distinct parts. The first is a short introduction to the production of particle bunches, like we can observe them in most accelerators. The second part reviews the different techniques classically used to measure bunch length and presents their performances and limitations.

More..

In accelerators, the time structure of the beam is governed by the characteristic of the accelerating field. On one side of the present technology, electrostatic accelerators produce DC particle beams that have no variation in time. On the opposite side, Radio-Frequency (RF) accelerators generate beams with a time microstructure extremely well defined. The sinusoidal time behavior of the RF field only provides stable conditions for acceleration during a time that is small compared to the electric field period, noted T . Therefore, a typical beam accelerated in an RF cavity is composed of a succession of particle bunches, spaced by a time equal to T with a duration, called bunch length, equivalent to a fraction of T (Typically, $T/200$). Nowadays RF accelerators may have operating frequency up to tens of Gigahertz, which means that particle bunches can naturally be as short as few picoseconds. For some applications, like in Free Electron Lasers [1,2] or TeV Linear Colliders [3,4], the bunch length is even shorter, typically 10-100 femtoseconds long. In order to produce particle bunches as short, they have to be compressed. Two techniques, based on RF manipulations, have been developed, namely ballistic bunching [5] and magnetic compression [6]. Moreover, since the late 90's, the development of ultra-short intense laser pulses has contributed to the development of innovative acceleration schemes, i.e. Laser Plasma Wakefield Acceleration (LPWA) [7]. Here the accelerating field is generated by the interaction of a laser beam with a gas cell. The resulting plasma wave has a very high electric field that may oscillate at frequency up to Terahertz. The corresponding bunch length is of the order of femtoseconds.

In order to measure the longitudinal behavior of the particle beams, a lot of instruments have been developed during the last three decades. They can be regrouped in different categories: Direct Beam Observation, Detection of Coherent Radiation, Radio-Frequency Manipulation and Sampling Techniques.

Direct Beam Observation means that the longitudinal structure of the beam is directly measured by means of fast detectors. For example, the beam current can be measured using Wall Current Monitors [8] and then digitalized using a fast oscilloscope. Wall Current Monitors have already proven their performances up to 10GHz and state of the art oscilloscopes are improving their specifications every year with sampling rate as high as 20-50GSa/s. Another very popular method since 20years relies on the use of

Streak Cameras [9]. In this case an optical replica of the beam longitudinal distribution is first generated using an adequate technique like Synchrotron Radiation [9], Transition Radiation [9], Diffraction Radiation [10], Cherenkov Radiation [11], ... This light pulse is then analyzed by the Streak Camera, with time resolution down to 200fs.

The observation of Coherent Radiation can also provide information on the bunch length [12]. Let's consider a bunch, consisting of many particles, classically 10^9 to 10^{11} , that radiates light through one of the effect listed in the previous paragraph. For wavelength shorter than the bunch length, the particles radiate incoherently, not being affected by the radiation of the neighbors. And the power emitted is proportional to the number of particles. For wavelength longer or equal to the bunch length, every particle emits radiation in phase, in a coherent way and the emitted power scales with the number of particles squared. In this condition, the bunch length can be obtained by measuring the power spectrum of the beam radiation. This technique, applicable to any kind of radiation has in theory no resolution limit. In practice, the method is relatively simple to implement and has already demonstrated its performances for the measurement of extremely short bunches. One limitation resides in the fact that it cannot directly provide a profile but just an estimate of the bunch length.

In order to measure the longitudinal profile of the bunch, physicists have also conceived beam diagnostics based on Radio-Frequency manipulation. Here the main idea is to encode, using RF devices, longitudinal structure of the beam into spatial information, which is easier to measure. For example, one can use an RF deflecting cavity [13] that will kick the head of the bunch in one direction and the tail of the bunch in the opposite direction. By measuring the transverse beam size downstream, one can reconstruct the longitudinal bunch profile. A similar technique exists if using an RF accelerating structure combined with a profile monitor in a dispersive region. RF deflectors become a standard instrument for femtosecond bunches [14] with the only disadvantage that this is a destructive and expensive method.

The last category of instruments presented here are basing on sampling with very short laser pulses. Electro-optic sampling [15] is the most developed technique. It is based on the conversion of the coulomb field of the bunch into an optical intensity variation. An electro-optic crystal is placed close to the beam. The field of the particle induces a polarization change of the laser beam passing through the crystal at the same time. Other sampling techniques have been tested using different processes, like Compton scattering [16] or Laser photo-neutralization [17]. Whatever is the process involved, sampling techniques always need laser pulses shorter than the particle bunch length and extremely precise laser-beam synchronization.

Since few years, single shot electro-optic techniques have been proposed and tested and are becoming the reference for non-destructive short bunch length monitoring [18].

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² <http://lcls.slac.stanford.edu/>

³ <http://www.linearcollider.org/cms/>

⁴ <http://clic-study.web.cern.ch/CLIC-Study/>

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Silica aerogel radiators for bunch length measurements[☆]

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Abstract

Cherenkov radiators based on silica aerogel are used to measure the electron bunch length at the photo injector test facility at DESY Zeuthen (PITZ). The energy range of those electrons is 4–5 MeV. In this paper, the time resolution defined by the usage of aerogel is calculated analytically and Monte Carlo simulations are performed. It is shown that silica aerogel gives the possibility to reach a time resolution of about 0.1 ps for high photon intensities and a time resolution of about 0.02 ps can be obtained for thin silica aerogel radiators.

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Keywords: Silica aerogel; Bunch length; Time resolution; PITZ

1. Introduction

Successful optimization of the photo injector test facility at DESY Zeuthen (PITZ) requires beam diagnostics, allowing to measure electron beam properties with high resolution. To measure the temporal properties at electron energies of 4–5 MeV by optical means a radiation process is needed at which a photon bunch is produced with the same time properties as the electron bunch.

Optical transition radiation which is widely used for accelerator diagnostics produces a low number of photons per electron. In addition, those photons are produced with a wide angular distribution at these energies. Using Cherenkov radiation a significantly larger number of photons is obtained. In order to produce these photons in a Cherenkov cone with small opening angle, a material with small index of refraction is required. Therefore, silica aerogel is studied as alternative in this paper. For convenience of writing, only the short form aerogel is mainly used hereafter.

In the following section the basic properties of aerogels are summarized. In Section 3 analytical calculations on the expected degradation of the

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time resolution are presented. In Section 4 GEANT 4 simulations are compared with the analytical calculations. Finally, the results are summarized.

2. Aerogel radiators

2.1. Optical properties

The main optical properties of aerogel [1–8] are characterized by three parameters:

(1) Index of refraction n .

It is determined by the density ρ . The correct dependence [1] is $n = \sqrt{1 + \alpha\rho}$ where $\alpha = (0.438 \pm 0.001) (\text{g/cm}^3)^{-1}$ for a wavelength $\lambda = 400 \text{ nm}$. For low densities it is possible to use $n \approx 1 + k\rho$, where $k \approx 0.21 (\text{g/cm}^3)^{-1}$. The chemical composition of aerogel is SiO_2 , therefore the aerogel dispersion can be calculated from the quartz dispersion. Aerogels are produced in a range of index of refraction of 1.006–1.13 [1–3].

(2) Light scattering length L_{sc} .

This quantity is defined as the path length after which a fraction $1/e$ of the photons is not scattered. This effect is caused by Rayleigh scattering, for which $L_{\text{sc}} \sim \lambda^4$. Usually L_{sc} is cited at $\lambda = 400 \text{ nm}$. For good aerogels the scattering length is $L_{\text{sc}} = 1\text{--}2 \text{ cm}$, for best aerogels $L_{\text{sc}} = 4\text{--}5 \text{ cm}$. The dependence of L_{sc} on the refractive index n is weak [1,4].

(3) Light absorption length L_{ab} .

The light absorption length is defined as the path length after which a fraction $1/e$ of photons is not absorbed. It mainly depends on an admixture contained in the aerogel. The L_{ab} dependence on λ is a complicated relation [1,5]. For good aerogels $L_{\text{ab}} = 1 \text{ m}$ at $\lambda = 400 \text{ nm}$ and for best aerogels it reaches a value of 10 m .

2.2. Maximum thickness of aerogel

The maximum thickness of an aerogel sample is mainly limited by the scattering length L_{sc} . Let us

denote the number of Cherenkov photons per unit length of the electron path by $N_{\text{ph},1}$. The number of photons, which do not suffer from Rayleigh scattering, in dependence on the aerogel thickness, has the form

$$N_{\text{ph}} = N_{\text{ph},1} L_{\text{sc}} (1 - e^{-l/L_{\text{sc}}}). \quad (1)$$

The maximum number of photons $N_{\text{phmax}} = N_{\text{ph},1} L_{\text{sc}}$ is reached at $l \gg L_{\text{sc}}$. A good choice of aerogel thickness is $0.5 L_{\text{sc}}$. In that case about 80% of the produced photons will be collected and 20% will be scattered. The ratio of the background to the effect is around 0.25. Therefore, the maximum thickness used in this paper is $l_{\text{max}} \approx 2 \text{ cm}$.

2.3. Number of photoelectrons

It is convenient to express the number of Cherenkov photons per unit length of the particle path and per unit wavelength interval in the following form [9]

$$\frac{d^2 N_{\text{ph}}}{dl d\lambda} = 2\pi\alpha \frac{1}{\lambda^2} \left(1 - \frac{1}{n^2 \beta^2}\right), \quad (2)$$

where $\alpha = \frac{1}{137}$ and $\beta = v/c$.

Let us express the quantum efficiency of the photon detector in a form $Q(\lambda) = Q_0 f(\lambda)$, where Q_0 is the quantum efficiency at the maximum of the spectral distribution. Let us denote the collection efficiency of the Cherenkov photons on the photo cathode of the detector by $G(\lambda)$. Then the photo electron number can be written as

$$\begin{aligned} N_{\text{pe}} &= \left(1 - \frac{1}{n^2 \beta^2}\right) Q_0 l 2\pi\alpha \int \frac{1}{\lambda^2} f(\lambda) G(\lambda) d\lambda \\ &= \left(1 - \frac{1}{n^2 \beta^2}\right) Q_0 l B(\lambda), \end{aligned} \quad (3)$$

where $B(\lambda) = 2\pi\alpha \int \frac{1}{\lambda^2} f(\lambda) G(\lambda) d\lambda$.

Taking $f(\lambda)$ for a borosilicate glass window and a bialkali photo cathode [10] with $Q_0 = 20\%$ and $G = 1$, particles with $\beta = 1$ in matter with $n = 1.5$ gives $N_{\text{pe}} = 165$ photo electrons, where l is the path length in cm. In Table 1, the corresponding data are presented for electrons with $pc = 4.0 \text{ MeV}$ ($\beta = 0.9919$) and $pc = 4.5 \text{ MeV}$ ($\beta = 0.9936$).

2.4. Multiple scattering

The mean squared angle of the electron multiple scattering can be calculated using the Rossi formula including a correction [11]:

$$\theta_{MS} = \sqrt{\overline{\theta^2}} = \frac{21 \text{ MeV}}{p\beta c} \sqrt{\frac{l}{X_0}} \left(1.0 + 0.038 \ln \frac{l}{X_0} \right). \tag{4}$$

Aerogel is SiO₂, therefore $X_0 = 27 \text{ g/cm}^2$, the same as for quartz [2,11]. For refractive indices of $n = 1.01$, $n = 1.03$ and $n = 1.05$ the corresponding radiation length is $X_0 = 570 \text{ cm}$, $X_0 = 190 \text{ cm}$ and $X_0 = 115 \text{ cm}$, respectively.

In Table 2, the data for Cherenkov angle θ_C , radius of the Cherenkov cone at the exit of the aerogel plate $r_C = l \tan \theta_C$ and the multiple

scattering angle θ_{MS} are presented for different aerogels.

3. Time resolution

3.1. Reference plane

At PITZ, the Cherenkov light will be transmitted over 26 m to the entrance slit of the streak camera by an optical transmission line. In general, the optical system will have an influence on the time dispersion. This effect is not considered in this article. To analyze the influence of the radiator itself, the streak camera entrance slit is considered to be virtually back imaged near to the exit plane of the aerogel radiator.

In this article, we assume that this reference plane (RP) is located parallel to the exit plane of the aerogel (see Fig. 1). All the questions concerning the resolution discussed in this article are only considered up to this RP.

3.2. Thickness of aerogel

Besides the refractive index n also the thickness of the aerogel l is an important parameter for the time resolution. The optimal thickness in a real experiment has to be chosen as a compromise between two contradictory requirements. To improve the signal-to-noise ratio of the Cherenkov light detection taking into account light losses along the optical transmission line, the radiator

Table 1

Number of photo electrons per 1 cm path length of electrons with $p = 4.0 \text{ MeV}/c$ and $p = 4.5 \text{ MeV}/c$ in materials with different index of refraction

n	$p = 4.0 \text{ MeV}/c$	$p = 4.5 \text{ MeV}/c$
1.008	0.034	0.36
1.01	0.53	0.82
1.03	5.3	5.3
1.05	9.5	9.5
1.5	65	65

A bialkali photo cathode with $Q_0 = 20\%$ and a light collection efficiency of $G = 1$ was assumed.

Table 2

The parameters Cherenkov angle θ_C , Cherenkov cone radius r_C , angle of multiple scattering θ_{MS} , time difference because of path length differences Δ_{pl} , σ_{pl} of time difference, the time difference caused by multiple scattering $\Delta_{MS}(\delta)$ and the corresponding $\sigma_{MS}(\delta)$ for three aerogel radiators with $n = 1.01$, $n = 1.03$ and $n = 1.05$ and for two incident electron momenta at different thickness l

n	1.01	1.01	1.03	1.03	1.05	1.05	1.01	1.01
l (mm)	20	20	2	2	1	1	2	2
p (MeV/c)	4.0	4.5	4.0	4.5	4.0	4.5	4.0	4.5
θ_C (dg)	3.5	4.8	11.8	12.3	16.2	16.6	3.5	4.8
r_C (mm)	1.22	1.69	0.42	0.44	0.29	0.30	0.12	0.17
θ_{MS} (dg)	14.1	12.5	7.3	6.5	6.6	5.8	4.0	3.5
Δ_{pl} (ps)	0.25	0.48	0.30	0.32	0.29	0.30	0.025	0.048
σ_{pl} (ps)	0.072	0.14	0.085	0.092	0.082	0.086	0.0072	0.014
$\Delta_{MS}(\delta)$ (ps)	1.5	1.8	0.42	0.43	0.37	0.37	0.047	0.072
$\sigma_{MS}(\delta)$ (ps)	0.45	0.51	0.12	0.13	0.11	0.11	0.014	0.021

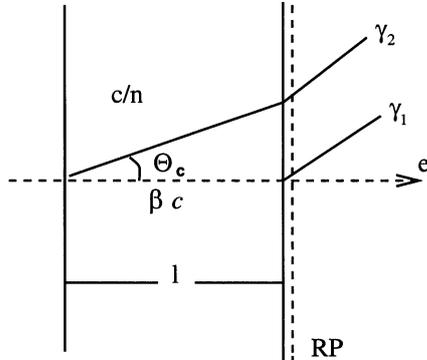


Fig. 1. Schematic view of the Cherenkov radiator system and the reference plane (RP, dashed line). The reference plane is meant to coincide with the downstream boundary of the Cherenkov radiator.

thickness has to be increased to produce more photons. But for improving the time resolution the radiator thickness is preferred to be small, as it will be shown in the next paragraphs. Two cases are considered:

- (A) Large thickness: for comparison of aerogel samples with different n , the thickness will be chosen such that the number of Cherenkov photons is equal. It means that

$$l \left(1 - \frac{1}{n^2 \beta^2} \right) = \text{const.} \quad (5)$$

Aerogels with $n = 1.01$, $n = 1.03$, $n = 1.05$ will be considered. For $n = 1.01$ the optimal thickness is chosen to be about $l = 20$ mm (see Section 2.2). According to Eq. (5) the rounded thickness for the other radiators was chosen accordingly: for $n = 1.03$ $l = 2$ mm and for $n = 1.05$ $l = 1$ mm.

- (B) Small thickness (for comparison): calculations for aerogel with $n = 1.01$ and $l = 2$ mm will be performed. The number of Cherenkov photons will be 10 times smaller in this case compared to case (A).

Modern technology allows to produce aerogel of such thicknesses.

3.3. Particle and light velocity

In Fig. 1 the electrons move perpendicular to the aerogel plate. The RP coincides with the second

boundary of the aerogel. The time interval between the arrival of the Cherenkov photons on the RP is

$$\Delta_{\text{pl}} = \frac{ln}{c \cos \theta_C} - \frac{l}{\beta c} = \frac{n^2 \beta}{c} \left(1 - \frac{1}{n^2 \beta^2} \right) l. \quad (6)$$

This effect is caused by the time difference of the particle and light arrival at the RP plane.

For $n = \text{const}$ Δ_{pl} is proportional to l . This means that one can improve the time resolution by decreasing the thickness.

The time distribution of the Cherenkov photon bunch has a rectangular shape (see Fig. 2, where $t_1 = l/\beta c$ and $t_2 = ln/c \cos \theta_C$), therefore the mean squared dispersion in time is $\sigma_{\text{pl}} = \Delta_{\text{pl}}/\sqrt{12}$.

The numerical values of the Δ_{pl} and σ_{pl} are summarized in Table 2.

3.4. Dispersion of refractive index

To study the dependence of the time resolution on the wavelength, it is convenient to write Eq. (6) in the form

$$\Delta_{\text{pl}} = \frac{\beta l}{c} \left(n^2 - \frac{1}{\beta^2} \right). \quad (7)$$

The relative change for two different wavelengths is given by

$$\delta(\lambda_1, \lambda_2) = \frac{\Delta_{\text{pl}}(\lambda_1) - \Delta_{\text{pl}}(\lambda_2)}{\Delta_{\text{pl}}(\lambda_1)} = \frac{n^2(\lambda_1) - n^2(\lambda_2)}{n^2(\lambda_1) - (1/\beta^2)}. \quad (8)$$

One can see that $\delta(\lambda_1, \lambda_2)$ does not depend on l . Some results of the calculation for aerogel with

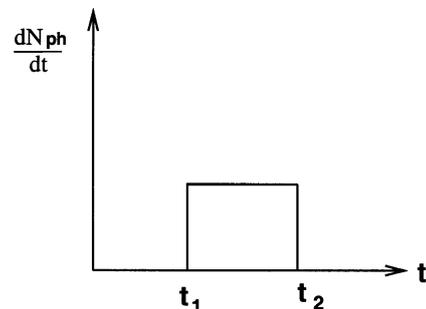


Fig. 2. Schematic view of the Cherenkov photon time distribution.

Table 3
 $\delta(\lambda_1, \lambda_2)$ in % is the relative change of Δ_{pl} as a result of the dispersion of n

λ_1 (nm)	λ_2 (nm)	β	n		
			1.05	1.03	1.01
300	550	1	7	7	7
		0.9936 ^a	8	9	18
		0.9919 ^b	8	9	30
200	700	1	20	20	20
		0.9936 ^a	23	25	40
		0.9919 ^b	23	26	50

^aFor $p = 4.5 \text{ MeV}/c$.

^bFor $p = 4.0 \text{ MeV}/c$.

Eq. (8) are presented in Table 3 basing on quartz data from [12]. If one works far from the threshold for Cherenkov radiation $\beta \gg 1/n$ and one uses

$$n^2 = 1 + \alpha\rho \quad (9)$$

one will obtain

$$\delta(\lambda_1, \lambda_2) = \frac{\alpha(\lambda_1) - \alpha(\lambda_2)}{\alpha(\lambda_1)}. \quad (10)$$

In this case one can see that $\delta(\lambda_1, \lambda_2)$ does not depend on n and l .

The region $\lambda = 300\text{--}550 \text{ nm}$ is the sensitive region of a bialkali photo cathode with borosilicate glass. It is seen that the dispersion is small enough for $n = 1.05$ and $n = 1.03$ but is 30% for $n = 1.01$, $p = 4.0 \text{ MeV}/c$.

The region of $200\text{--}700 \text{ nm}$ is presented for a dispersion estimation as an example for a photon detector with a wider sensitivity region.

3.5. Transverse dimensions and angular distribution of the electron beam

The arrival time of light on the chosen plane RP does not depend on the transverse coordinates of the electron, that is why there is no dispersion connected to the transverse size of the electron beam.

Two electrons e_1 and e_2 cross simultaneously the plane 1 (see Fig. 3). The electron e_1 is moving perpendicular to the aerogel plate and electron e_2 is moving at an angle α to it. In this case the time

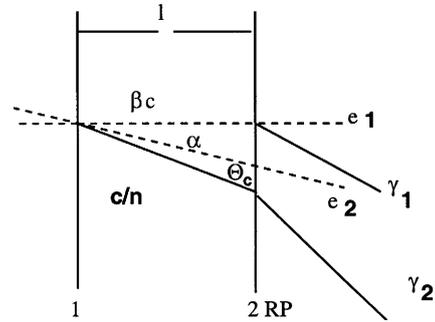


Fig. 3. Schematic view of the Cherenkov photon emission with different incident angles of the incoming electrons.

interval of the Cherenkov photons on the RP plane increases to

$$\Delta_x = \frac{l}{c} \left(\frac{n}{\cos(\alpha + \theta_C)} - \frac{1}{\beta} \right). \quad (11)$$

A typical value of α at the position where the Cherenkov radiator will be used at PITZ is 0.1° . The resulting contribution of α to the time resolution is negligibly small because $\alpha \ll \theta_C$.

3.6. Multiple scattering

Multiple scattering in aerogel creates an angular spread of the electron beam, therefore it leads to a time dispersion as given by the Eq. (11). The analytical calculation of this effect is complicated. One could put $\alpha = \theta_{MS}$ in Eq. (11). In this case, one will do an overestimation of the multiple scattering influence, because the angle θ_{MS} refers only to the electrons at the exit of the aerogel. The photons produced in the first part inside of the aerogel will have more narrow distribution than the photons produced in the last part.

The mean squared value of the trajectory shift is $r_{MS} = \frac{1}{\sqrt{3}}\theta_{MS}l$ [11] (see Fig. 4). Let us introduce an angle δ , so that $tg\delta = r_{MS}/l = \frac{1}{\sqrt{3}}\theta_{MS}$ and let us assume that $\alpha = \delta$. The value of $\Delta_{MS}(\delta) = l/c((n/\cos(\delta + \theta_C)) - (1/\beta))$ is presented in Table 2. It is seen that thin aerogel radiators and the use of aerogel with high index of refraction is preferred.

In Table 2 an estimation of $\sigma_{MS}(\delta)$ which is defined as $\sigma_{MS}(\delta) \approx \Delta_{MS}(\delta)/\sqrt{12}$ is included. For

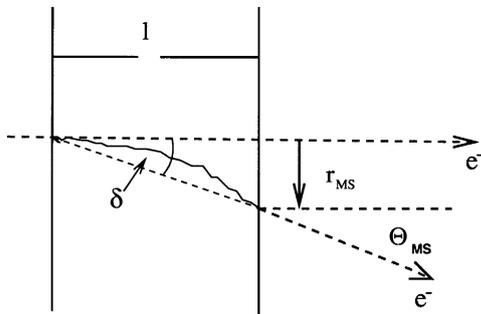


Fig. 4. Schematic view of the electron angular spread and shift due to multiple scattering.

$n = 1.05$, $n = 1.03$, and $n = 1.01$ with $l = 2$ mm the influence of multiple scattering is small, therefore the shape of the time spectrum is approximately rectangular. For $n = 1.01$ with $l = 20$ mm it is a rough estimation.

The data from Table 2 shows, that aerogel with $n = 1.01$, $l = 2$ mm gives the possibility to reach a time resolution $\sigma_{MS}(\delta) = 0.02$ ps. Aerogel with $n = 1.05$, $l = 1$ mm gives 10 times more photons and $\sigma_{MS}(\delta) = 0.1$ ps, whereas aerogel with $n = 1.05$, $l = 10$ mm would give 100 times more photons and $\sigma_{MS}(\delta) = 2$ ps.

3.7. Other effects

Rayleigh scattering of Cherenkov photons inside aerogel is not considered. The scattered photons would have a wide angular distribution and only a small part of them would be within the acceptance of an optical transmission line.

The effect of energy loss due to ionization and Bremsstrahlung is negligibly small. Compton scattering of Cherenkov photons is much smaller than Rayleigh scattering, therefore this effect gives a negligible contribution to the time resolution. Scattering of photons at the boundary of aerogel is not considered because the index of refraction is small.

In addition to the effects on the time resolution of the aerogel radiator itself, other important sources contribute to the time resolution of a bunch length measurement system which are not considered in this article, e.g. dispersion of the

optical transport system, streak camera resolution and time jitter of the facility.

4. Time resolution: Monte Carlo results

4.1. Simulation conditions

Simulations of the electron beam passage through aerogel for the PITZ set-up were performed using the GEANT 4 [13] code. The simulation setup consists of a vacuum tube with the electron beam, an aluminium entrance window, the aerogel piece and the corresponding RP (see Fig. 5). The thickness of the aerogel plate l is chosen as it is described in Section 3.2. Aerogel materials (SiO_2) with index of refraction of 1.01, 1.03 and 1.05 are investigated. In front of the aerogel a $20 \mu\text{m}$ thick aluminium window can be positioned. This window will be used in the experiment to protect the rest of the PITZ vacuum system from outgassing particles from aerogel. An ideal photon detector is placed behind the aerogel at the reference plane as described above (see Section 3.1).

Electrons produce Cherenkov photons inside the aerogel in a wavelength range of 350–800 nm. The GEANT program was configured to perform a Cherenkov light simulation without wavelength dependence of the refractive index and assuming a photon detection efficiency of 100 percent. The physical processes include Cherenkov effect, Rayleigh scattering, multiple scattering, ionization and Bremsstrahlung. These processes are switched on one after another. No absorption and reflection of

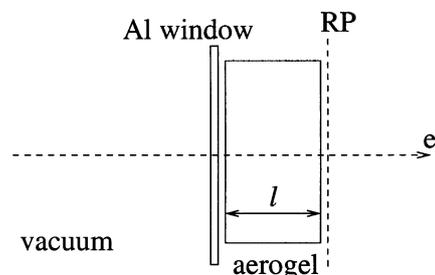


Fig. 5. Schematic view of the geometry of the GEANT 4 input.

the Cherenkov light at the boundaries of the aerogel were considered.

4.2. Acceptance model of the optical transmission line

To estimate the needed acceptance of the optical transmission line behind the aerogel plate, the transverse distribution of the photon emission points from the aerogel backplane and the angular distribution of the emitted photons are calculated for different processes. Both distributions are calculated with respect to the incident electron position and direction.

Fig. 6 shows the distribution of the photon output angle with respect to the incident electron direction for two examples: $n = 1.01$ and thickness $l = 20$ mm (figure top) and $n = 1.05$ and $l = 1$ mm (figure bottom) for an electron momentum of 4.5 MeV/ c . The processes described above are applied one after another. The Cherenkov effect alone results in an angle θ_C equally to that shown in Table 2. By adding Rayleigh scattering an almost constant background is produced, the peak at θ_C is still very clear. The electron scattering in the aerogel and the aluminium window causes smearing of the distribution and a strong increase of the tail of the distribution. The behavior is similar for aerogel of different refractive indices and thicknesses except that the Cherenkov angle peak occurs at different angles.

Fig. 7 shows the distribution of the photon output radius r with respect to the incident electron position for $n = 1.01$ and thickness $l = 20$ mm (upper figure) and $n = 1.05$ and $l = 1$ mm (lower figure) for an electron momentum of 4.5 MeV/ c . r is the distance between the exit point of photons in the aerogel exit plane relative to the incident electron beam position. In these figures different processes were added one after another. For the Cherenkov effect alone a radiation intensity edge occurs corresponding to r_C as shown in Table 2. Rayleigh scattering results in photons with larger radii but small intensities. By adding multiple scattering and the aluminium window the probability for larger radii increases and for smaller radii decreases. The effect of multiple

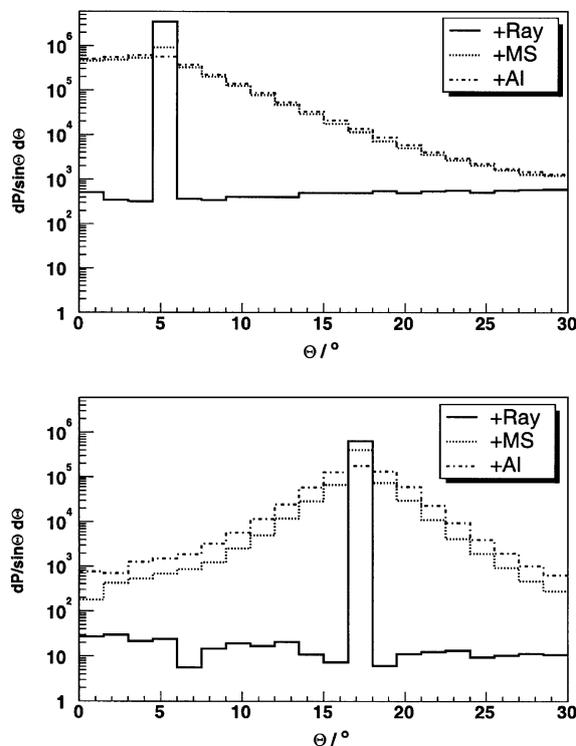


Fig. 6. Distribution of the Cherenkov photon bunches output angle with respect to the incident electron direction for $n = 1.01$ and thickness $l = 20$ mm (upper figure) and $n = 1.05$ and $l = 1$ mm (lower figure) for an electron momentum of 4.5 MeV/ c . +Ray means just considering the Cherenkov effect and Rayleigh scattering. +MS means the inclusion of multiple scattering and +Al that of the aluminium window. Here the processes are added one after another.

scattering is much stronger for aerogel with low index of refraction.

For a realistic experimental design an acceptance angle for the optical transmission line between radiator and streak camera has to be chosen. Adding θ_C and θ_{MS} for the first three cases in Table 2 leads to a choice of an acceptance angle of about 20° . In addition, all photons inside of a 5 mm radius around the initial electron direction are accepted, because the typical electron beam size at PITZ is smaller than this transverse size. This choice of cuts in angle and radius includes the peaks and edges seen in the Figs. 6 and 7, therefore most photons are collected. The following simulations are shown assuming these acceptance cuts.

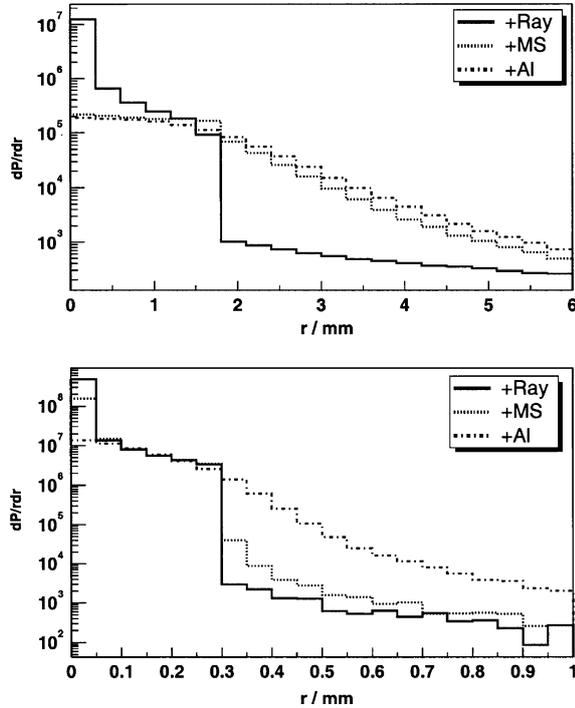


Fig. 7. Distribution of the Cherenkov photon bunches output radius with respect to the incident electron position for $n = 1.01$ and thickness $l = 20$ mm (upper figure) and $n = 1.05$ and $l = 1$ mm (lower figure) for an electron momentum of $4.5 \text{ MeV}/c$. Here the processes are added one after another. +Ray means the inclusion of Rayleigh scattering, +MS the inclusion of multiple scattering and +Al that of the aluminium window. The calculated values of r_C for pure Cherenkov effect are $r_C = 1.69$ mm and $r_C = 0.30$ mm respectively.

4.3. Particle and light velocity

To study the influence of different effects on the time resolution, simulations were performed step by step adding new phenomena to be considered in the simulation. The simplest case is when the bunch length is set to be zero and all electrons are assumed to have the same momentum, no aluminium window is in front of the aerogel and neglecting all electron interactions except the Cherenkov radiation. The electron incident angle is perpendicular to the aerogel plate.

Fig. 8 shows the time distribution of Cherenkov photons produced by electron bunches of $4.5 \text{ MeV}/c$ momentum and arriving at the photon

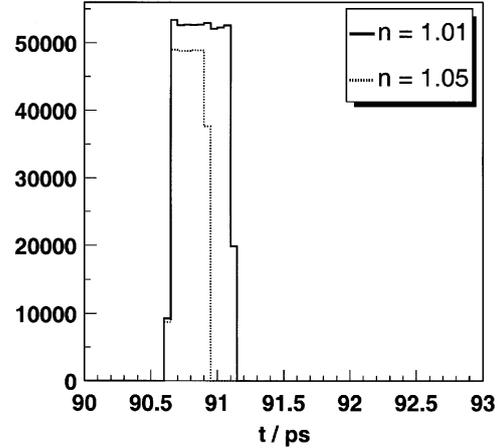


Fig. 8. Time distribution of Cherenkov photon bunches produced by electron bunches of $4.5 \text{ MeV}/c$ momentum, fixed electron direction and point-like source, no consideration of Rayleigh scattering, multiple scattering and aluminium window. The thickness of the aerogel samples is 20 mm for $n = 1.01$ and 1 mm for $n = 1.05$.

receiver plane for aerogels with $n = 1.01$ and $n = 1.05$ within the acceptance angle. The simulation time clock starts when the electrons start to move and ends when the photons, produced by the electrons, reach the photon receiver. This time distribution has a rectangular shape as expected from Fig. 2. The FWHM of these distributions is in agreement with the theoretical calculation of Δ_{PI} (see Table 2.). The simulated Cherenkov angle θ_C and cone radius r_C coincide with the expected values (see Figs. 6 and 7).

The integral of the distribution shown in Fig. 8 is proportional to the amount of emitted Cherenkov photons. These integrals are not equal for both distributions because the thickness was optimized for a momentum of $4 \text{ MeV}/c$.

4.4. Rayleigh scattering

To study the influence of Rayleigh scattering on the time resolution, a scattering length of 40 mm at 400 nm wavelength is assumed, using the proportionality mentioned in Section 2.1 (2). The resulting time distributions for an electron momentum of $4.5 \text{ MeV}/c$ are shown in Fig. 9. The FWHM does not change compared to Fig. 8. A small

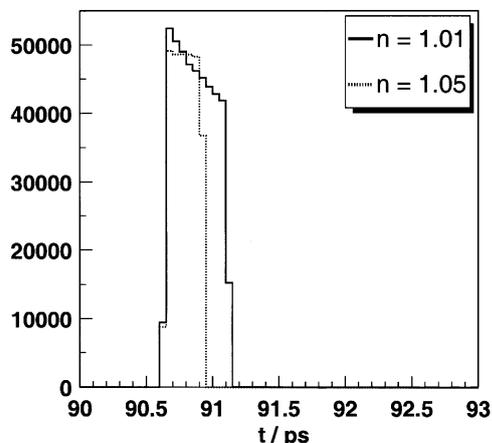


Fig. 9. Time distribution of Cherenkov photon bunches considering Rayleigh scattering produced by an electron bunch of $4.5 \text{ MeV}/c$ momentum, without multiple scattering and aluminium window. The thickness of the aerogel samples is 20 mm for $n = 1.01$ and 1 mm for $n = 1.05$.

decrease of intensity with time can be observed because of a longer way of the photons inside of the aerogel compared to photons which are produced near to the RP. The scattered photons have a large angle and radius (see Figs. 6 and 7) and therefore are mainly outside of the acceptance range.

4.5. Multiple scattering

To study the influence of multiple scattering, this process was included in the simulation. The processes ionization and Bremsstrahlung are added, too. Fig. 10 shows the time distributions of photons reaching the photon receiver for an electron momentum of $4.5 \text{ MeV}/c$. For a refractive index of $n = 1.01$ the shape of the distribution is changed completely compared to Fig. 9, it now has a long tail. The shape for $n = 1.05$ is mainly conserved, only for a logarithmic scale a small tail can be observed too. The reduction of the photon intensity at the beginning of the distribution compared to Fig. 9 is explained by the fact that due to multiple scattering the electron direction is changed. This results in a wider angular distribution of the emitted photons yielding longer path length.

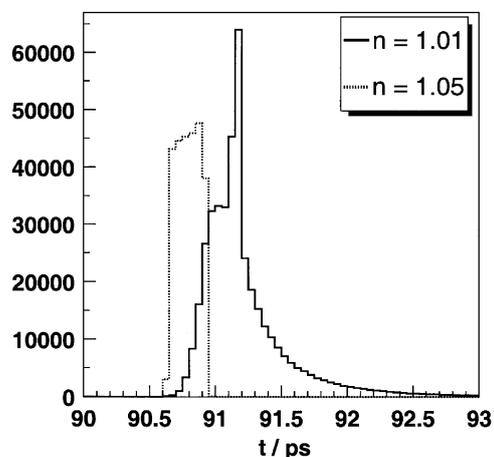


Fig. 10. Time distribution of Cherenkov photon bunches produced by electron bunches with a zero electron bunch length. Rayleigh and multiple scattering, ionization and Bremsstrahlung in aerogel are considered. No aluminium window is used, the momentum is $4.5 \text{ MeV}/c$. The thickness of the aerogel samples is 20 mm for $n = 1.01$ and 1 mm for $n = 1.05$.

4.6. Aluminium window

An aluminium window of $20 \mu\text{m}$ thickness is placed in front of the aerogel. This causes scattering of the electrons before they enter the aerogel. Fig. 11 shows the resulting time distributions for an electron momentum of $4.5 \text{ MeV}/c$. The tails are increased and longer. This is significant for $n = 1.01$. For $n = 1.05$ the tail is smaller by a factor of 10^3 . Therefore it is not visible in this linear plot.

4.7. Resolution

The described time distributions are calculated assuming a point-like electron source. The RMS time duration is a measure of the RMS time resolution of the system. These values are shown in Table 4. The RMS values are increased and decreased with adding one effect after another. The reason is that some photons can be scattered away out of the acceptance cone and give no contribution to the RMS value. The last line of Table 4 is comparable with $\sigma_{\text{MS}}(\delta)$ of Table 2.

The refractive index 1.01 is preferred for a small acceptance angle of an optical transmission line,

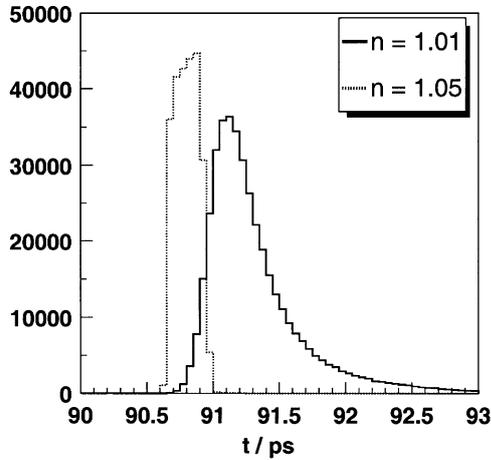


Fig. 11. Time distribution of Cherenkov photon bunches produced by electron bunches with zero electron bunch length. Rayleigh and multiple scattering, ionization and Bremsstrahlung and a 20 μm thick aluminium window are considered for an electron momentum of 4.5 MeV/c. The thickness of the aerogel samples is 20 mm for $n = 1.01$ and 1 mm for $n = 1.05$.

Table 4

RMS time resolution in ps for different refractive indices and different thicknesses of aerogel samples for an electron momentum of 4.5 MeV/c

l (mm)	$n = 1.01$	$n = 1.03$	$n = 1.05$	$n = 1.01$
	20	2	1	2
Cherenkov	0.14	0.092	0.086	0.014
+ Ray	0.60	0.104	0.090	0.014
+ MS	0.80	0.094	0.084	0.012
+ Al	0.58	0.110	0.091	0.017

From top to bottom the processes are added to each other.

but due to the large thickness of 20 mm to obtain the same photon yield a worse time resolution is caused by multiple scattering. By using a smaller thickness, as it is described in Section 3.2(B), the number of photons is decreased by a factor of 10. Fig. 12 shows the time distribution for different processes, the time range is much smaller than for the thicker aerogel with $n = 1.01$. The corresponding time resolutions are also shown in Table 4. One can see that aerogel gives the possibility to reach a time resolution of 0.02 ps. This time resolution can

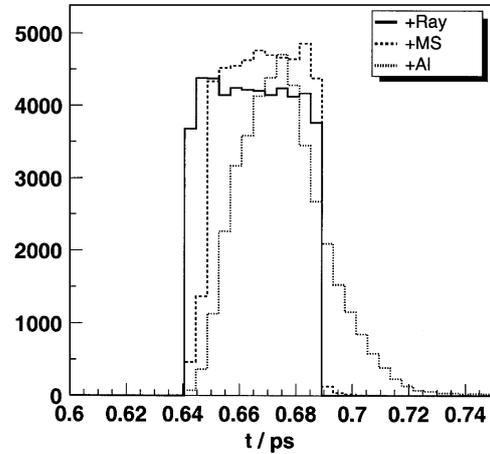


Fig. 12. Time distribution of Cherenkov photon bunches produced by electron bunches in aerogel with refractive index of 1.01 for a momentum of 4.5 MeV/c for different effects, the effects are added after another. The thickness of the aerogel sample is 2 mm.

be reached if the detector is able to detect the weak signal.

To determine how the proposed system will measure the bunch length distribution, an electron beam simulated with ASTRA [14] is used as input for the GEANT 4 simulation. The beam has a transverse size of $\text{RMS}_{x,y} = 2.3$ mm and an angle distribution of $\text{RMS}_{x',y'} = 1.6$ mrad with a mean momentum of 4.54 MeV/c and a momentum spread of 1.4%.

The example shown in Fig. 13 is for the worst case of time resolution for $n = 1.01$ and thickness $l = 20$ mm. The thick solid line represents the time distribution of the electron beam, the thin line shows the time distribution produced by Cherenkov photons in aerogel. Only small differences can be seen. The distributions for the other considered aerogels match even better the electron beam time distribution.

5. Summary

The time resolution of aerogel radiators used for the measurement of the electron bunch length at the PITZ facility is analytically calculated and simulated with GEANT 4. It was shown, that for

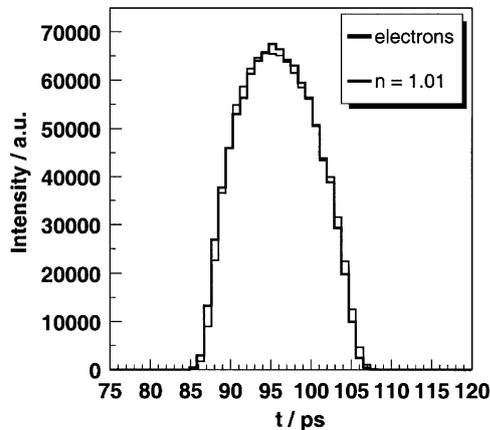


Fig. 13. Time distribution of a simulated electron beam and its corresponding Cherenkov photon beam produced in aerogel (refractive index $n = 1.01$, thickness 20 mm). The distributions are normalized to their areas.

aerogel of refraction index $n = 1.05$, 1 mm thickness and an aluminium window of $20 \mu\text{m}$ thickness, the time system response has a rectangular shape with the RMS resolution of ~ 0.1 ps. The tails are at the level of 10^{-3} . Such a radiator will allow to study the bunch structure of electrons. In addition, it is shown that with aerogel of $n = 1.01$ and 2 mm thickness a time resolution of ~ 0.02 ps could be reached if photon detectors with a corresponding time resolution and sensitivity would be available.

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COHERENT RADIATION DIAGNOSTICS FOR SHORT BUNCHES

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Abstract

Investigating the longitudinal charge distribution of electron bunches using coherent radiation has become an important diagnostic technique at many accelerators. The principle of the method and some example applications from the FLASH free-electron laser in Hamburg will be described in this article.

INTRODUCTION

The longitudinal charge distribution in an electron bunch is an important characteristic for many particle accelerators and storage rings: the gain length of a free-electron laser (FEL) depends on the peak current of the bunch, and thus, for a given charge, on the bunch length (a typical value is $15 \mu\text{m}/50 \text{fs}$); the slicing-technique for producing ultra-short x-ray pulses at third-generation light sources relies on producing and controlling a very short longitudinal structure in the bunch through interaction with a laser ($90 \mu\text{m}/300 \text{fs}$); high-energy physics machines need to achieve a sufficiently short bunch to avoid luminosity degradation due to the hourglass-effect ($600 \mu\text{m}/2 \text{ps}$).

Manipulating the bunch to get a desirable and short charge distribution is a complicated procedure and typically requires, for an FEL, several bunch compression steps involving complex longitudinal dynamics. Stable lasing is only achieved for a well-tuned machine. Measuring the longitudinal profiles, and thus guiding the tuning, is a very important ingredient for efficient machine running, as is the preservation of a once-found good machine setup using feedbacks.

Time-domain methods for measuring the longitudinal structure with resolutions in the 50 fs range exist, though typically require involved set-ups, for example high-power transverse deflecting cavities (that need special optics to attain maximum resolution and are thus not parasitic to normal machine operation), or techniques based on electro-optic principles. Coherent radiation diagnostics (CRD) allows a different approach to this measurement task by working in the frequency domain. No individual technique is currently giving all the information that is needed, and therefore several approaches to longitudinal diagnostics are often employed in parallel.

The notion that the bunch charge distribution affects the emission spectrum is known for a long time, though only starting around 1990 the application for beam diagnostics

has been investigated.¹ See [2] for further references on original works.

This article will give a brief introduction to the principle of the diagnostic technique, followed by an overview of some of the experimental arrangements that are currently employed. By no means a complete coverage is intended or possible. The focus will be on studies and results from the FLASH free-electron laser at DESY, Hamburg.

PRINCIPLE OF CRD

The basic relation of coherent radiation diagnostics connects the radiation emission spectrum of a bunch of electrons, $dU/d\lambda$, to that of a single-electron, $(dU/d\lambda)_1$, by

$$\frac{dU}{d\lambda} = \left(\frac{dU}{d\lambda} \right)_1 \left(N + N(N-1) |F(\lambda)|^2 \right). \quad (1)$$

N is the number of electrons in the bunch, $F(\lambda)$, the *form factor*, the Fourier transform of the normalized bunch charge distribution $S(z)$,

$$F(\lambda) = \int_{-\infty}^{\infty} S(z) e^{-2\pi i z/\lambda} dz. \quad (2)$$

Here, charge distribution and form factor are considered only for a line charge. A non-vanishing transverse extend influences the emission spectrum, although only weakly due to the strong collimation of the radiation for highly relativistic particles, unless the transverse extend is very large with respect to the wavelength. Transverse effects are studied in [3, 4].

The effect of coherent enhancement is illustrated in Fig. 1. For wavelengths comparable to the bunch length or larger, the spectral intensity is strongly amplified, as a large part of the bunch electrons emits coherently. The enhancement of the spectrum extends to shorter wavelengths for shorter bunches, and the shape of the spectrum depends on the shape of the charge distribution. Coherent radiation diagnostics uses this effect to deduce information about the bunch length or bunch shape. The derivations of the basic relations are given in detail in [5].

EXPERIMENTAL BASICS

Any setup that uses coherent radiation as a diagnostic tool includes as a minimum a source of some kind, some

¹The first description of coherent effects is made, to the authors knowledge, in an originally unpublished paper in 1945 by Schwinger within the context of synchrotron radiation, including also a discussion on shielding. The paper has been reissued in [1].

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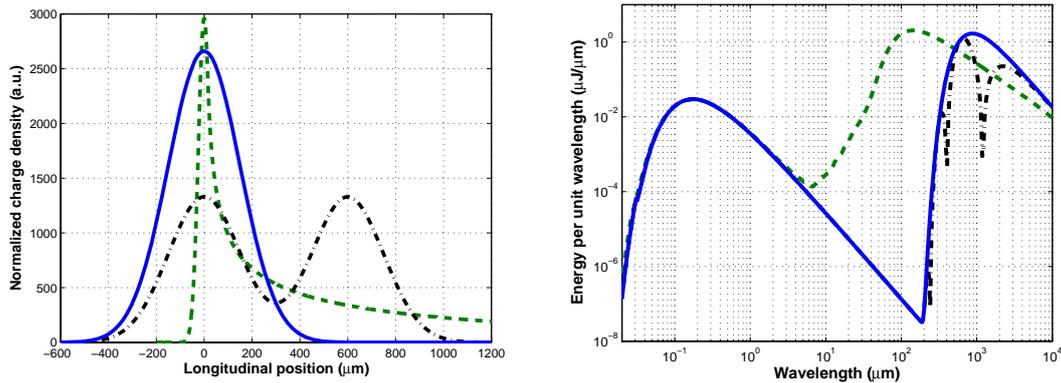


Figure 1: Example for coherent enhancement. On the left, three different bunch shapes are shown, on the right the effect on the emission spectrum after Eq. 1 for 1 nC bunch charge. As single-electron spectrum, synchrotron radiation for circular motion is taken.

beam line to transport the radiation, and a detector. Additional components for a more detailed analysis of the radiation, like spectrometers, are often added, some of which are mentioned in subsequent sections.

Radiation sources

All processes that result in the emission of radiation from an electron are in principle suitable for the purpose of CRD. At FLASH, for example, synchrotron, transition and diffraction radiation are used so far, and a dedicated tunable electromagnetic infrared undulator is currently being installed [6]. The choice of source depends very much on the desired application, as the spectral characteristics and the influence on accelerator operation vary.

A fully parasitic source, not influencing accelerator operation at all, is synchrotron radiation if taken from an existing bunch compressor or bending magnet. This source covers a wide wavelength range. The emission spectrum, especially at long wavelengths, is complicated, as the usual spectrum derived for circular motion in free space is not valid for the comparatively short bending magnets in a bunch compressor (edge effect) and the typically flat vacuum chambers (cut-off) [7, 8]. Also the coherent enhancement can be affected if a bunch only moves on an arc instead of a circle [9].

Transition radiation is significantly more intensive and can be reasonably well calculated for realistic geometries [10]. It is, however, destructive (even for a thin radiator, the emittance is degraded strongly). A fast kicker is used at FLASH to extract a single bunch for beam diagnostics with transition radiation, allowing quasi-parasitic operation if longer bunch trains are used.

Diffraction radiation is parasitic if the gap in the radiator is sufficiently wide to prevent wake fields from disturbing subsequent bunches. Due to the gap, however, short wavelengths are strongly suppressed [10], and this source is thus not suitable for investigations of short bunch structures.

Smith-Purcell radiation essentially combines the source

with a spectrometer [11], as the emitted frequency depends on the observation angle. It requires, similar to diffraction radiation, a radiator close by the beam, rising the question of wake fields and the emission of short wavelengths.

Undulator radiation is a narrow-band, high-intensity source, in principle rendering a spectrometer for analysing the radiation obsolete. Attention has to be paid to higher harmonics if a wiggler-like spectrum is obtained from a high-K device.

Radiation transport

The emitted radiation has inevitably to be coupled out from the accelerator vacuum into a measurement setup, requiring some form of radiation transport beam line. To avoid absorption from water vapour that is prominent in the infrared, evacuation of the whole setup is desirable, though only a fore vacuum on the order of 0.1 mbar is needed for distances up to several 10m. A window then has to separate the fore-vacuum from the ultra-high accelerator vacuum. Thin foils of polyethylene have a good wide-band transparency, though often are considered to be too fragile from a machine safety point-of-view. Other plastic materials, like for example TPX that has the advantage of being transparent in the visible, have also been used. Crystalline quartz (cut perpendicular to its optical axis to avoid birefringence) is frequently used, but its useful transmission range extends only down to 80μm. The only fully satisfactory material with almost constant transmission of 70% from the visible up to at least millimeter waves is diamond. It is also a strong material, so that 0.5 mm thick windows of 20 mm aperture withstand atmospheric pressure. To avoid etalon interference, such a window is typically wedged with an angle of up to 1°.

As the design of the beam line usually requires full attention to diffraction effects, Fourier optics codes (for example ZEMAX) are used. Although the application and working of such a code is in principle straightforward, care must be taken to implement the source correctly.

Detectors

Broad-band infrared detectors are bolometric, that is their primary detection mechanism is heating due to absorption of radiation. A subsequent effect then converts the temperature change into an electric signal.

Widespread use is made of pyroelectric detectors that use a change of polarization of certain materials like LiTaO_3 with temperature. Such a detector is essentially a capacitor of a few square millimeter area and a thickness between $30\ \mu\text{m}$ and $100\ \mu\text{m}$. Radiation enters through the transparent top electrode, is absorbed, and the resulting surface charge or voltage from the polarization change is detected. Etalon interferences due to the relatively weak absorption in the far infrared are pronounced, as shown in a measurement in Fig. 2. Wedged crystals could overcome this problem, but have so far not been made.

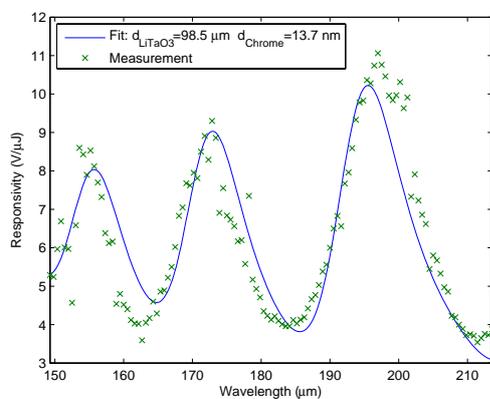


Figure 2: Response of a pyroelectric detector. The fit describes absorption in a stack of a thin Chrome top electrode, a LiTaO_3 crystal and a thick gold back electrode. The optical constant of LiTaO_3 are not known precisely, limiting the quality of the fit.

Pyroelectric detectors are intrinsically fast, and are used at FLASH with suitable read-out electronics to measure infrared radiation in long trains of up to 600 bunches with 1 MHz repetition rate. Response speeds exceeding 1 ns have been demonstrated elsewhere [12]. Since all pyroelectric crystals are also piezoelectric, mechanical vibrations excited by the absorption of short, intense infrared pulses result in ringing, typically at frequencies of several 100 kHz, depending on crystal geometry [12].

Another broad-band, room-temperature detector that is used frequently is the Golay cell, an opto-acoustic detector. The heating of a closed gas volume and subsequent pressure increase is detected optically via the flexing of a thin membrane. It is expected to have a much flatter response, showing no resonance structures like a pyroelectric detector, as the Golay cell has some similarity to a black body cavity. Measurements similar to those from Fig. 2 support this for the wavelength range $100\ \mu\text{m}$ to $160\ \mu\text{m}$, though indicate non-uniform response around $3\ \text{mm}$ [13].

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Orders of magnitude more sensitivity are possible with cooled bolometers, essentially due to the decreased heat capacity of materials at low temperatures (liquid Helium) and the fast change of resistivity with temperature in the transition region from normal to superconducting state. A superconducting hot-electron bolometer was shown in [14] to have a time constant faster than 25 ps. Wide bandwidth operation of such a detector into the mid-infrared is usually not possible due to the steeply increasing heat load from room-temperature black body radiation. Cold filters are employed to limit thermal radiation from reaching the detecting element.

BUNCH COMPRESSION MONITOR

The simplest application of coherent radiation diagnostics uses the frequency-integrated intensity as a relative measure of bunch length. An example from FLASH is shown in Fig. 3: Transition or diffraction radiation from a screen is coupled out through a crystalline quartz window and transported to a pyroelectric detector.

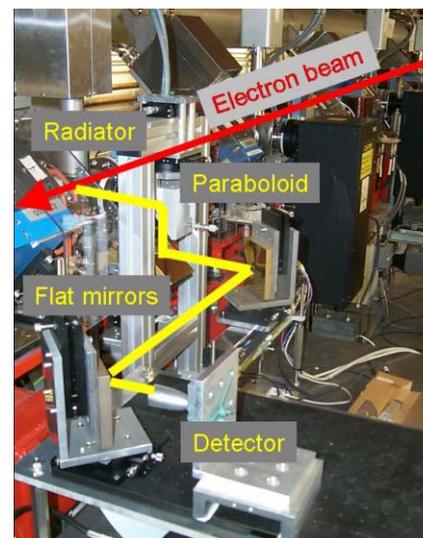


Figure 3: Bunch compression monitor setup at FLASH.

This compression monitor is installed after the first magnetic bunch compressor of FLASH. According to Fig. 1, the total radiation intensity increases with shorter bunches. The degree of bunch compression is adjusted by changing the acceleration phase of the acceleration module in front of the bunch compressor. A scan of this phase versus the intensity registered by the pyroelectric detector is shown in Fig. 4. Note that the curves obtained with synchrotron radiation from the last bunch compressor dipole magnet and with diffraction radiation from the set-up Fig. 3 are very similar except for the amplitude. Different pyroelectric detectors, different optics and only a simple alignment have been used, indicating the robustness of the method for determining maximum compression.

Such a scan, especially the deduced maximum compression phase, is used routinely at FLASH to establish the

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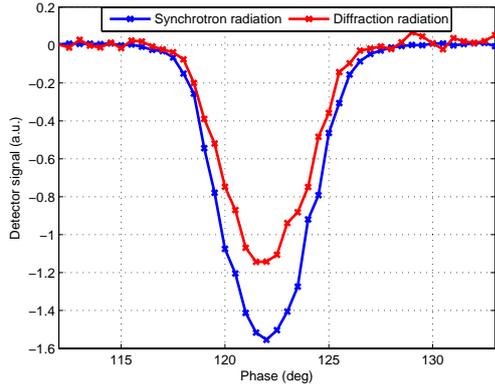


Figure 4: Phase scan with two bunch compression monitors at FLASH. The varied phase is that of the accelerating module in front of the bunch compressor.

per se arbitrary setpoint phase scale. A typical phase for SASE operation is several degrees away from maximum compression, thus allowing a simple feedback algorithm to stabilize the compression by regulating the module phase. This is an indispensable tool at FLASH to counteract drifts on the time-scale of some 10 seconds or longer. Despite the restricted wavelength range due to a crystalline quartz window, the phase found for maximum compression agrees well with the value expected from simulations.

A compression monitor based on using a ceramic gap as radiation source and diode detectors working up to several hundred GHz is proposed for the first bunch compressor of LCLS [15].

BUNCH SHAPE RECONSTRUCTION

By using the full spectral information instead of the frequency-integrated intensity, a more complete determination of the bunch profile is possible. Through knowledge of the single-electron spectrum and the bunch charge, at first the magnitude of the form factor $|F(\lambda)|$ can be deduced from (1). Inverting the Fourier transformation (2) to get the charge distribution is then possible if both amplitude and phase of the complex form factor are available. Although a strict solution of this phase-reconstruction problem is not possible, the Kramers-Kronig relation gives a handle to solve the problem from a practical point of view satisfactorily [2, 5, 16]. If the complex form factor is expressed as $F(\nu) = |F(\nu)| \exp(i\Theta(\nu))$, then

$$\Theta(\nu) = \frac{2\nu}{\pi} \int_0^\infty \frac{\ln(|F(\nu')|/|F(\nu)|)}{\nu'^2 - \nu^2} d\nu' \quad (3)$$

yields a phase, the so-called *minimal phase*, that is compatible with the measured form factor amplitude. Although this solution is not necessarily unique, in practice the requirement to extrapolate the measured data to zero and infinite frequency, and the measurement errors are a more

serious problem of the reconstruction process than the non-rigorous mathematics.

It is usually difficult to assess the single-electron spectrum precisely. It requires detailed knowledge of not only the radiation generation process in the actual experimental setup, but also of the distortions of the spectrum by the beam line and by the response of the instrument used to measure the spectrum. In some cases it has been possible to measure the incoherent spectrum over a certain wavelength range by assuring that the bunch is long enough to suppress coherent effects [17], but otherwise it is necessary to resort to simulations.

An example for a bunch shape reconstruction at FLASH is given in Fig. 5, taken from [18]. Here, synchrotron radiation from the first bunch compressor was transported to an experimental station outside of the accelerator tunnel, and the spectrum measured with a Martin-Puplett interferometer. The result is compared to a streak camera measurement using the visible part of the synchrotron radiation spectrum at the same beam line.

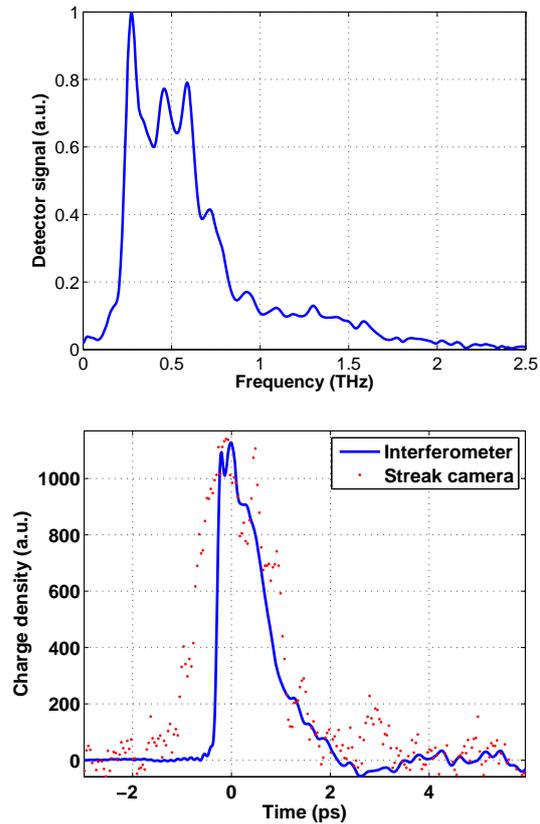


Figure 5: Example for a bunch shape reconstruction at FLASH. On top a measured synchrotron radiation spectrum, below the reconstructed charge distribution. The streak camera measurement has been made at the same synchrotron radiation beam line using visible light.

The streak camera resolution is limited to about 500 fs, the frequency-domain method mainly by the presence of a crystalline quartz window. Although an acceptable agree-

ment is found, the amount of work in correcting the measured spectrum and finding suitable extrapolations was significant, clearly indicating that full bunch shape reconstruction is still an experimental and not fully independent technique.

Another experimental result for full bunch reconstruction can be found in [19].

SINGLE-SHOT SPECTROMETER

A high variability of the SASE intensity on a shot-to-shot basis is found at FLASH. A thorough investigation using coherent radiation diagnostics requires thus equally fast spectral information, ruling out a scanning interferometer for this tasks. A single-shot spectrometer based on staged blazed gratings was developed at FLASH, allowing a wide wavelength coverage from $4\mu\text{m}$ up to some $500\mu\text{m}$. The details of the instrument are described in [20].

Measurements have been carried out at the FLASH transition radiation beamline which is located after the final bunch compression stage and equipped with a diamond window [21]. A phase scan with this instrument is reproduced in Fig. 6. Compared to the frequency-integrating scan from Fig. 4, it shows a much more complex behaviour, and especially a much stronger phase dependency (note that the phase scale in Fig. 4 has an arbitrary offset).

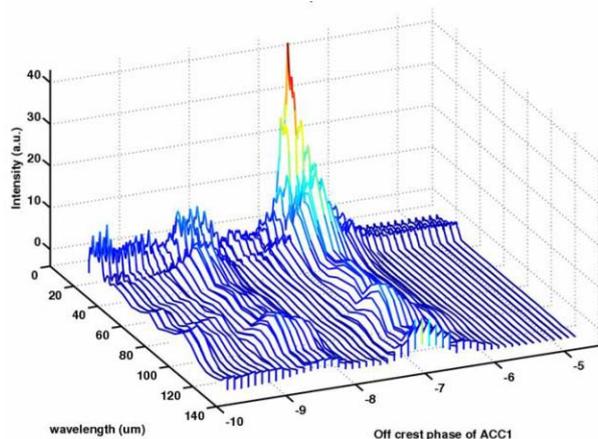


Figure 6: Phase scan with the single-shot spectrometer.

The narrow phase-band that shows high intensity at wavelengths around $30\mu\text{m}$ is typically also a good starting point for further machine optimization. SASE performance of FLASH is influenced by many parameters, thus no optimum setting can be suggested by such a measurement alone, but tuning has in several occasions been significantly shortened and improved by using CRD for the initial set-up.

CONCLUSION

Longitudinal bunch shape investigations using coherent radiation are by now a standard tool for nearly all machines
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operating with short bunches or short bunch features. The tools employed in routine machine operation are, however, invariably non-calibrated, thus giving only relative or empirical information to help setting up a machine. Full longitudinal charge profile reconstruction is still a specialist application, and typically requires significant, dedicated work.

From the experience gained at FLASH, there is a clear benefit from having a wide wavelength coverage with a single-shot resolving spectrometer, especially at the experimental level. With increased understanding of the measured spectra and their dependence on machine parameters, it will likely be possible to restrict the wavelength coverage at a later stage. The benefit, however, comes at the price of a significantly higher hardware complexity, requiring evacuated setups, diamond windows, and well designed optics.

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OBSERVATION OF FEMTOSECOND BUNCH LENGTH USING A TRANSVERSE DEFLECTING STRUCTURE

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 Josef Frisch, Douglas McCormick, Marc Ross, Tonee Smith (SLAC, Menlo Park, California),
 Jörg Rossbach (Universität Hamburg, Hamburg)

Abstract

The design of the VUV-FEL at DESY demands bunch lengths in the order of 50 fs and below. For the diagnostic of such very short bunches a transverse deflecting RF structure (LOLA) has been installed which streaks the beam according to the longitudinal distribution. Tests in the VUV-FEL yielded a rich substructure of the bunches. The most pronounced peak in the has a rms length of approximately 50 fs during FEL operation and below 20 fs FWHM at maximum compression. Depending on the transverse focusing a resolution well below 50 fs was achieved.

INTRODUCTION

To obtain enough gain for the SASE process it is necessary to produce peak currents in the order of 4 kA. With the present setup of the machine this can only be accomplished by compressing part of the bunch to 50 fs. Diagnosing such a short pulse poses a challenge to the beam instrumentation. Therefore a transversely deflecting structure is used to streak the beam.

For this purpose a structure formerly used for particle separation in secondary beams is utilized. It has been used before at SLAC under the name LOLA IV [1]. It is an S-band structure operating at a frequency of 2.856 GHz. Operating the structure close to the zero crossing of the field the bunches acquire no net deflection but are streaked vertically. Using a horizontally deflecting kicker one bunch per pulse is steered onto an OTR-screen. This way it is possible to diagnose parasitically one bunch out of a train of several hundred bunches. At SLAC this structure has been used for the same purpose [2,3,4]

SETUP

The setup of the VUV-FEL is depicted in figure 1. The electron bunches are created in an RF-gun and then

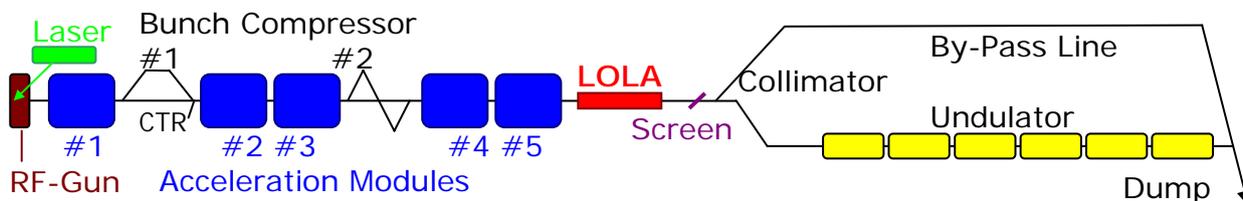


Figure 1: Schematic drawing of the VUV-FEL beam line. At the end of the accelerating section there is the transversely deflecting structure LOLA. It streaks the beam vertically so that on a downstream viewscreen the longitudinal profile of the bunches can be studied.

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accelerated in 5 superconducting modules up to presently 450 MeV. Behind the first and the third module there are two bunch compressors used to shape the longitudinal profile of the bunches. The initial bunch length is 7 ps (RMS) which is already long enough to probe the nonlinear rf curvature of the 1.3 GHz L-band cavities. This results in an incomplete compression in the first bunch compressor. The out coming bunch then has two main parts: A very short spike in the head and a tail which resembles the original distribution. The tail however still has an energy correlation imprinted in the first module and reshaped in the bunch compressor. Part of the tail is then compressed in the second bunch compressor to form a short spike with high peak current and good emittance. Depending on the exact phases in the modules #1-#3 the two bunch compressors produce a single or double spike at the exit of the linac. At the end of the acceleration sections, before the collimator system of the undulators, there is the transversely deflecting structure LOLA installed.

The structure is an S-band travelling wave structure. It operates in TE-TM-hybrid mode, so that a combination of electric and magnetic field produces a transverse kick. The maximum equivalent deflecting voltage is 20 MV over a structure length of 3.6 m. The fill-time is 680 ns, so that in a 1 MHz bunch train only one bunch is affected. A downstream OTR screen is utilized to analyse the streak. It is displaced from the centre of the beam pipe so that the beam can pass through. A kicker is used to steer only the bunch in question onto the screen.

To allow for a better synchronization with the master clock, LOLA is tuned to a frequency of 2.856059 GHz, which is an integer multiple of 1/11 of the master clock frequency of 9.027775 MHz. By means of an additional synchronization circuit it is guaranteed that the machine triggers always with a fixed phase relation to this reference [5]. At 9 MHz bunch rate this frequency offset

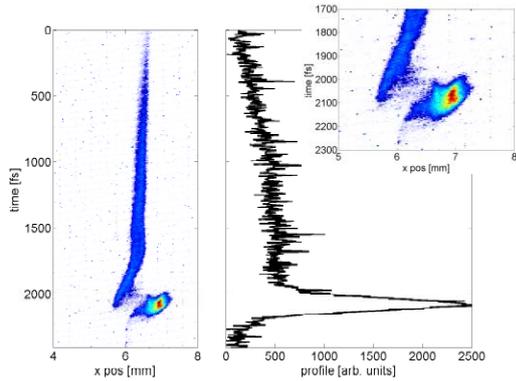


Figure 2: Image of the streaked bunch; inset: zoom on the spike at the head. The streak was approximately 4 fs/px.

results in a phase shift of 36° between neighbouring bunches. This way these bunches would miss the screen and not disturb the measurement.

Because an absolute calibration of the streak based on pure RF measurements did not seem precise enough, one power level was calibrated using the deflection of the beam. The calibration of the other power levels was then scaled according to the relative change of RF power. Relative power levels can be measured much more precisely than absolute levels, so that this method appeared accurate enough. For the calibration a relatively low power level was chosen, allowing for a phase shift of $\sim 7^\circ$ before the bunch misses the screen. In this way the influence of phase jitter on the calibration is reduced. A streak of 74 pixel/degree or 13.2 fs/pixel was measured. One pixel of the CCD corresponds to $26 \mu\text{m}$. A maximum possible streak of 1.8 fs/pixel can be achieved. The optical setup allows for a better resolution than $26 \mu\text{m}$.

The beam size at this location is larger, however. The standard beam optics foresee $200 \mu\text{m}$ spot size (RMS), which would then correspond to a resolution of approximately 15 fs. Unfortunately the spike is also the region of the largest energy spread in the bunch. An energy spread of $\sim 1 \text{ MeV}$ (RMS) is not uncommon. In

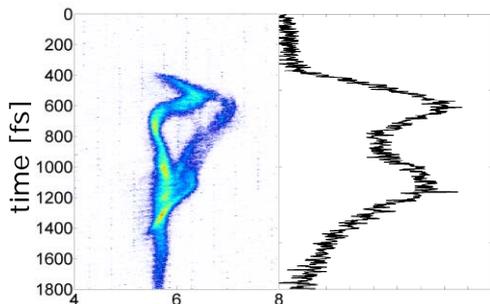


Figure 3: Bunch head with a double peak structure. There is a rich sub-structure of the bunch which shows not only longitudinally but transversely. Note that the streak is opposite to figure 2.

such a case each millimetre of vertical dispersion would contribute with 0.3 fs to above resolution.

RESULTS

The transverse deflecting structure LOLA has been used to measure the longitudinal bunch profile while the machine was setup for SASE operation. Two examples are given in the figures 2 and 3. While the performance of the FEL was quite similar in the two cases (approximately $1 \mu\text{J}$ photon pulse), the two profiles differ considerably. Both setups were started from a standard setting defined as follows: The acceleration in the first module was adjusted 6 degrees from the maximum compression phase, which is defined by the maximum of the coherent diffraction radiation at a station closely behind the first bunch compressor (see figure 1). The second and third module are adjusted for on-crest operation so that they do not add considerably to the longitudinal energy distribution. The second bunch compressor then creates the spike necessary for the high peak current at low emittance.

In the first case (figure 2) the module 1 phase was subsequently tuned for less compression, so that no strong peak was produced in the first bunch compressor but only in the second. This would also explain the relatively weak sub-structure of the bunch, because CSR would play a big role only after the second compression stage when it can not influence the longitudinal profile very much.

In the second case (figure 3) the phase was tuned to stronger compression in the first bunch compressor, so that both bunch compressors produce a spike. This results in the double peak structure that can be observed. At the same time there is even more structure to the bunch. This is probably due to wakefield and CSR effects in the first bunch compressor, which can then be translated into a longitudinal modulation in the second compressor stage.

In both cases the width of the peak in the projected profile is measured to be in the order of 120 fs (FWHM). This result however has to be considered preliminary because not all detrimental effects have been considered thoroughly yet. The true width will be smaller than that.

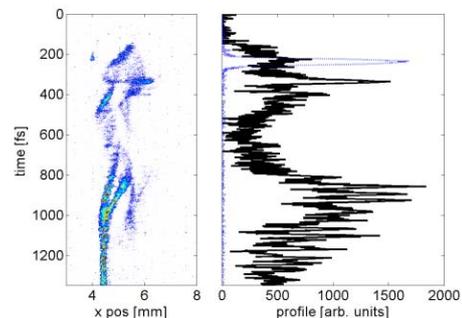


Figure 4: Bunch head with faster streak (2 fs/px) and optimized focusing. The dotted line in the right plot indicates the unstreaked beam size.

For the example in figure 4 the streak was increased and the unstreaked spot optimized for minimum vertical size. Consequently there was no lasing at that time, but the settings were somewhat close to the ones in figure 3. Exact consistency can not be guaranteed, particularly the compression might have been stronger. There is much more structure to be seen than in the previous cases. This appears in part enhanced by a lower intensity of the image which causes darker parts to vanish completely.

The effects that concern the most are the entanglement of the vertical and longitudinal structure of the bunch and the vertical dispersion. As can be seen from the figures 2 through 4 there is a strong variation of the horizontal profile along the bunch. This presumably has to be attributed to the two bunch compressors, which deflect horizontally. Nevertheless it can not be excluded that similar effects show vertically. Since the spike carries only a small fraction of the total bunch charge this can not be checked with the un-streaked beam. In this case the charge contained in the tail outshines the head.

A remedy to this problem might be a tomography in the z-y-plane. For this the voltage in the structure would have to be scanned while the change in profile would be recorded. This procedure is in preparation but is not finished yet. Likewise has the dispersion not been measured nor compensated yet.

The LOLA structure can also be used to monitor the jitter of the beam arrival time. This information is of special importance to pump-probe experiments to be

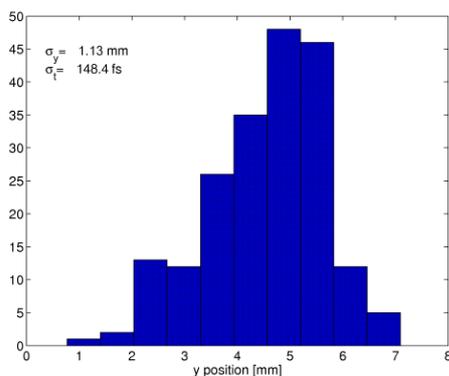


Figure 5: Phase jitter of the beam with respect to LOLA. The jitter due to the high power RF in LOLA is approx. 70 fs.

performed with external lasers synchronized to the master clock. The figure 5 shows the shot-by-shot jitter of the bunches measured with a BPM close to the viewscreen.

An RMS jitter of 145 fs (RMS) was measured. Note that this is the jitter of the beam with respect to the LOLA RF which can have a jitter by itself. The largest contribution will be the stability of the klystron, which was found to be in the order of 70 fs (RMS). A similar result for the beam jitter was found with electro-optical

sampling (EOS) at a nearby diagnostic station [6]. The main contribution to this timing jitter is expected to be the energy jitter in the first bunch compressor. Evaluation of this jitter delivered compatible results.

CONCLUSION AND OUTLOOK

A transversely deflecting structure has been successfully applied to the beam in the VUV-FEL at DESY. Although some important contributions to the measurement error are not fully controlled yet, the achieved resolution surpasses most other methods already and it can be used in normal operation of the accelerator.

There are plans to exploit more capabilities of this measurement method as well as measurements of slice-emittances. A first attempt has already been made [7], but for best results tomographic measurements are foreseen.

In view of higher bunch repetition rates at later times and in future projects, shorter structures with a shorter fill-time are being envisioned.

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FEMTOSECOND RESOLUTION BUNCH PROFILE MEASUREMENTS

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Abstract

The measurement of ultrashort longitudinal bunch profiles is of growing importance to accelerator development and operation. With requirements of ~ 10 fs time resolution, and a desire for non-destructive and real time diagnostics, the challenges for diagnostic development are significant. Alongside more established transverse deflecting cavity and CTR measurement techniques, new approaches arriving from the field of ultrafast lasers offer significant potential; Ultrafast electro-optic detection has now been demonstrated on several accelerators, and in many distinct forms, although challenges remain in getting to the desired time resolution. Proposed schemes combining ultrafast laser diagnostics with FEL interactions, such as the ‘‘optical replica’’ scheme also have considerable potential. Here, we discuss some of the recent developments in longitudinal diagnostics.

INTRODUCTION

Many different approaches to ultrafast characterization of electron bunches have been explored experimentally, and with the growing importance of such diagnostics to light source machines, more schemes are proposed to be tested in the near future. Here we discuss some of the leading longitudinal diagnostics techniques, with an emphasis on recent demonstrations of their sub-picosecond capabilities; this discussion is not intended to be an exhaustive review of the all the latest developments, but rather an examination of some of the experimental issues and challenges facing sub-ps longitudinal profile diagnostics. Furthermore, the longitudinal profile diagnostics are seen as distinct from approaches that aim to provide an empirical ‘bunch-length’ monitor, which only aims to inform on the first moments of the bunch profile, or on the presence of structure on a particular time scale of interest.

We discuss techniques through a sub-classification of i) spectral techniques, where the bunch profile is inferred from the spectral intensity of a radiated field, ii) electro-optic (EO) techniques where a Coulomb or radiated field is determined through sampling (possibly single shot) with an ultrafast laser, iii) direct electron bunch techniques, where an active change to the electron bunch properties is made in such a manner that the original longitudinal profile can be inferred from the bunch. Here we restrict ourselves to a brief discussion of transverse deflecting cavities, and proposed demonstrations of the ‘optical replica’ scheme.

SPECTRAL TECHNIQUES

Within spectral techniques we include the spectral measurements of coherent transition, diffraction and synchrotron radiation, and Smith-Purcell radiation (CTR, CDR, CSR and S-P, respectively). Such techniques have been applied to longitudinal bunch diagnostics in a considerable number of laboratories, and here we give selective examples to demonstrate the practical issues of their implementation and interpretation. These spectral techniques rely on causing the Coulomb field of the electron bunch to radiate in a controlled manner, and subsequently inferring the bunch profile from the emitted radiation spectrum. For femtosecond diagnostics it is important to address the temporal distinction in the Coulomb field and the electron bunch itself. At large distances from the bunch ($r \gg \sigma_z/\gamma$) the field will have a spreading angle of $\theta \sim 2/\gamma$, which corresponds to a temporal spreading in the field of $t \sim 2r/c\gamma$. Furthermore, the field strength will fall as $1/r$ at short distances from the electron bunch, and as $1/r^2$ at large distances. It therefore follows that the position of the radiating structure must be sufficiently close to the electron bunch both to retain the fast time structure and to ensure that the radiated field is sufficiently large for detection. As an example, for a $\gamma \sim 1000$ it follows that any measurements that wish to probe the bunch structure with a 10 fs resolution must be able to access the field distribution within a < 2 mm radius of the bunch (this requirement is also present in electro-optic techniques). For low energy machines this may be a deciding factor in the applicability of CDR or Smith-Purcell radiation techniques. A demonstration of the relative signal strength of CTR and CDR has been given by Delsim-Hashemi et al. [1, 2]. For a CTR or CDR screen inserted into the compressed bunch of FLASH, with $\gamma \sim 900$, the CDR energy is approximately two orders of magnitude reduced in power density with respect to the CTR radiation. The CDR screen is intercepting the Coulomb field at a radius of 5 mm from the bunch. They also observe a cut-off in the short wavelength emission for the diffraction radiation at $\lambda \approx 200 \mu\text{m}$, while the transition radiation has a cutoff at the much shorter wavelength of $\lambda \approx 50 \mu\text{m}$. In separate experiments, with a diffraction grating spectrometer they were able to observe CTR at wavelengths at short as $5 \mu\text{m}$, thus identifying the presence of extremely short time structure in the bunch [3]. At SLAC, CTR has also been used to characterize the extremely short bunches available at the FFTB

facility [4]. Using a Michelson-Morely interferometer the autocorrelation of the CTR radiation was measured, from which the power spectrum of the CTR radiation is determined. In that work, Muggli et al. comment that limitations in the accuracy of the diagnostic arise from the difficulties of transporting and detecting the full spectral range of the far-infrared radiation; these effects limited the ability to infer an actual bunch profile, although bunch lengths of 210fs FWHM were however able to be determined. At the Advanced Photon Source (APS), CTR and CSR diagnostics have been demonstrated for profile reconstruction of sub-picosecond 150 MeV bunches [5, 6]. The spectrum of the CTR/CSR was obtained from a Michelson-Morely interferometer. To determine the profile of the bunch, the phase of the radiation was retrieved from the intensity spectrum from applying a “minimal phase approximation”, a numerical process that is based on Kramers-Kronig relations. For the CTR measurements [5] the retrieved bunch profiles displayed FWHM durations as short as 290fs for leading spikes of the profile.

For Smith-Purcell radiation, the radiator is a periodic structure running parallel to the beamline. In such a structure the radiated power at a specific wavelength can be enhanced in proportion to the number of periods to the structure. It also has the property of acting as a wavelength dispersing element. Korby et al. [7] have determined bunch lengths using S-P radiation of a 15 MeV beam. Their S-P gratings had periods of either 6 mm or 10 mm, and a grating length of 100 mm. Through a moveable mirror directing the S-P radiation out of the beamline, they were able to determine the angular, and hence spectral, intensity of the radiation. Separately, Blakemore and Doucas [8, 9] have undertaken S-P experiments at the FELIX FEL facility in the Netherlands. In their experiments an array of 11 detectors arranged opposite the radiator were able to simultaneously collect the S-P radiation over a large angular range. They collect radiation in the range of $\lambda = 500 \mu\text{m}$ -3 mm, and determine a sub-ps bunch length. In both the above examples of S-P radiation, the bunch shape was not explicitly determined from the data; instead the experimental spectra were compared to calculated spectra based on trial bunch profiles.

In determining the bunch profile from the spectral content a number of issues must be accounted for. These issues can be summarized as i) the Coulomb field temporal profile at the radiator; ii) the propagation of the radiation to the detectors (Absorption, dispersion and diffraction); iii) the detector response, which may include the dispersive characteristics of the spectrometer. Finally, the net result is a power density measurement, and it therefore does not explicitly include information about the phase of the radiation (measurements of CTR or CSR by electro-optic techniques, which do measure the radiation phase, will be discussed separately below).

The propagation issue is one of the significant experimental challenges for spectral techniques. The long wavelength radiation is significantly affected by diffraction, and

there is always some long wavelength cutoff present. The design of transfer lines will usually be specific to the particular experimental conditions (e.g. transport distance from the beamline, available window aperture at the beamline, and the beam properties themselves). These issues, and the analysis of far-infrared (FIR) beamline propagation have been described in detail by Casalbuoni et al [10]; while focused particularly on the the CTR radiation transfer line at the 140m point of FLASH at DESY, the methods and many general results are equally applicable to other experimental situations.

Of a different character is the problem of missing phase information for the field. Lia and Sievers [11] have shown that the phase of the field can be determined from the field amplitude (i.e. the power spectrum) using Kramers-Kronig relation (KK). The KK relations relate the imaginary components of an analytic function through an integral function of the real components, with an integration range extending over the full spectral range of the signal. In the context of bunch diagnostics, a fundamental issue arises as to the validity of the KK phase retrieval in the absence of some spectral amplitude information. Grimm et al. [12] have discussed this issue with examples of sub-ps bunch profiles retrieved with different levels of missing data. Specifically, they show the importance of the long wavelength data in obtaining a faithful retrieval of the bunch shape. Earlier, Lai et al. also addressed this question of retrieval validity, and noted (as do Grimm et al.) that for some bunch profiles the underlying assumption of minimal phase employed in the retrieval may not always be appropriate; an example of a truncated Lorentzian with failed retrieval is given. The conclusion of Lai, Grimm, and others, however is that for “reasonable” bunch profiles, and with sufficient extent to the data, a meaningful bunch profile can indeed be obtained.

ELECTRO-OPTIC TECHNIQUES

Electro-optic techniques enable the ultrafast characterization of far-infrared (FIR) pulses directly in the time domain, and as such avoid the possible ambiguities associated with spectral techniques. In electron-bunch diagnostics, through carrying out the EO detection within the electron beamline, it is possible to measure the Coulomb field directly, avoiding the step of first causing the field to radiate; alternatively, the emitted CTR/CDR or CSR radiation can be measured with the EO detection outside the beamline. Unless otherwise stated, we will be referring to intra beamline measurements of the Coulomb field.

It is usual to describe the EO modulation as resulting from an electric field induced refractive index change within an EO material (such as appropriately orientated ZnTe or GaP crystals). This refractive index change can then be probed by optical means; the polarization components of a linearly polarised laser will experience a differing delay in propagating through the crystal, with the emerging pulse therefore becoming elliptically polarized.

This ellipticity can subsequently be converted into an intensity modulation by a suitable arrangement of polarisers. The net result is an intensity change in the optical probe as a function of the FIR field which is dependent on the particular arrangement of polarizers. In the two most commonly used arrangements, which we call “balanced detection” and “crossed polariser detection”, the intensity change is proportional to field or field squared, respectively.

An alternative perspective for describing the EO process has been derived by Jamison et al [13]; the ellipticity induced in the optical pulse is the result of sum and difference frequency mixing of the FIR and optical field. This is a rigorous description, and has the advantage of being a more appropriate formalism for describing the interaction with long duration (few ps) chirped optical pulses such as used in single shot EO techniques. In essence, they have shown that the optical field spectrum exiting the EO crystal, for a given polarisation component, is given by

$$\tilde{E}_{\text{out}}^{\text{opt}}(\omega) = \tilde{E}_{\text{in}}^{\text{opt}}(\omega) + i\omega a \tilde{E}_{\text{in}}^{\text{opt}}(\omega) * \left[\tilde{E}^{\text{Coul}}(\omega) \tilde{R}(\omega) \right] \quad (1)$$

where the coefficient a is dependent on the polarization geometry. $\tilde{R}(\omega)$ describes the material response due to the nonlinear coefficient and phase-matching. From Eqn. 1 it can be said that the far infrared spectrum of the Coulomb field is now ‘upconverted’ into the optical region. A FIR bandwidth of $\sim 100\%$ (if that can be assigned any rigorous meaning) is exchanged for an experimentally easier optical bandwidth of $\sim 5\%$. Importantly, if the EO frequency conversion is done directly on the Coulomb field within the beamline, the shift to optical frequencies allows the information from the DC component to propagate and be detected. Simple Fourier transformation of Equation 1 gives the equivalent expression for the optical field in the time domain,

$$E_{\text{out}}^{\text{opt}}(t) = E_{\text{in}}^{\text{opt}}(t) + a \left[E^{\text{Coul}}(t) * R(t) \right] \frac{d}{dt} E_{\text{in}}^{\text{opt}}(t) \quad (2)$$

We therefore see that the EO interaction has created a new optical pulse with pulse envelope described by the Coulomb field; in borrowing terminology from a quite distinct technique, we have created an “optical-replica” of the Coulomb field.

An important factor in the ultimate time resolution of EO techniques is the bandwidth of the response function, and the degree to which it is known. Fortunately, materials are available for which the response is approximately constant over the spectral region of interest. For the most commonly used crystal, ZnTe, $\tilde{R}(\omega)$ has an approximately flat spectrum from 0-2.5 THz. Sufficiently thin GaP crystals may have a cutoff as high as 8 THz ($\lambda \sim 37 \mu\text{m}$). Other EO materials with even broader response functions are known, although to date they have not been used in electron-bunch diagnostic experiments. In using materials with such a flat spectral response, time resolutions of < 150 fs can potentially be obtained without the need for explicit calibration of the response; this assertion has recently been examined

through EO benchmarking experiments (as discussed below).

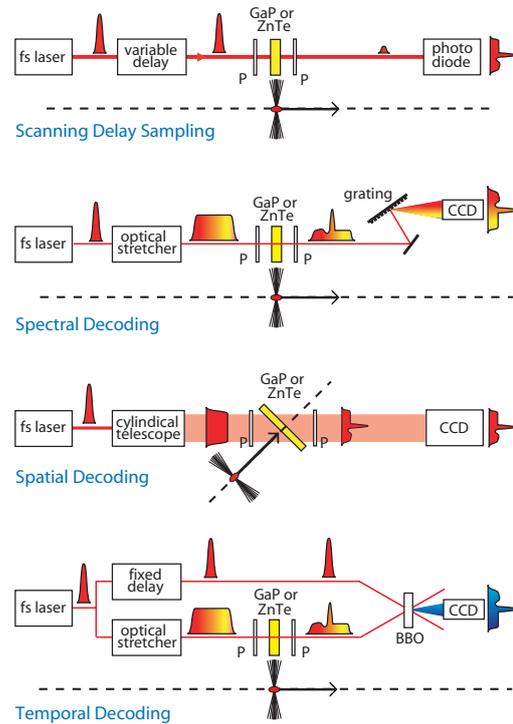


Figure 1: Schematic representations of the four EO detection techniques that have been demonstrated for detection of the bunch Coulomb field.

The above discussion describes the encoding of the Coulomb (or CTR/CSR) field into an optical pulse. The ellipticity introduced into the probe laser is converted into an intensity change with a suitable arrangement of polarisation optics. There are several demonstrated methods for observing this intensity change, each with particular merits. These methods, shown schematically in Fig. 1 are discussed in turn:

Scanning delay sampling: This is the simplest and first demonstrated example EO bunch diagnostics [14]. A short (sub-50fs) laser is used to sample fixed parts of the FIR pulse, and an integrated intensity change in the optical probe is measured. Scanning the relative delay between laser and electron bunch allows the build up of the profile. Multi shot measurements such as this do suffer from time jitter between the laser and electron bunch; however, in even the first demonstration, scanning rates of 2ps per μs were achieved, and over such short measurement periods very small timing jitter (< 50 fs) can be achieved. The time resolution is in the first instance determined by the sampling pulse duration, although for very short laser pulses (< 30 fs), group velocity dispersion of the optical pulse may become the dominating factor [15].

Spectral decoding (SD): The measurement of the optical spectrum can be used to directly infer the field temporal profile if a chirp is first applied to the optical pulse, so

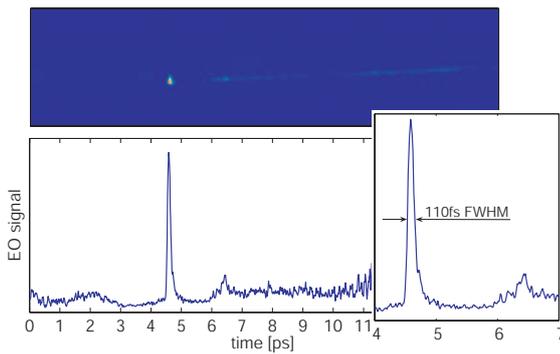


Figure 2: Single shot temporal decoding measurements at FLASH. These measurements are described further in Berden et al. [26].

that there is a known time-frequency relationship in the sampling laser pulse. A lower limit on the bunch duration for which this technique is suitable arises from the intrinsic connection between the temporal modulation of the chirped pulse, and the distortion of the initially known chirp (this limitation can also be shown to be a consequence of the convolution in Eqn. 1). For bunches shorter than this limitation, the measured bunch profile may contain significant artifacts, producing a misleading bunch profile. The limitation can be given approximately as $\tau_{\text{lim}} = 2.6\sqrt{T_c T_0}$, where T_c and T_0 are the FWHM of the chirped and transform limited optical pulse durations, respectively [16]. SD characterization of the in-beam-line Coulomb field has been demonstrated at several facilities, including FELIX [17], NSLS [19], and FLASH[20]. The technique has also been demonstrated for single shot characterisation of CSR [21, 22], and CTR [23].

Spatial encoding: This approach has many similarities to the scanning delay line approach, but instead allows for a single-shot measurement. By sampling the Coulomb field with an optical pulse obliquely incident to the EO crystal and the Coulomb field propagation direction, there is a spatial to temporal mapping introduced for the relative delay of the laser arrival time at the crystal. Imaging the EO crystal, and the intensity changes as a function of spatial position, therefore allows the determination of the field induced intensity changes as a function of relative arrival time at the crystal. An important requirement for spatial encoding is spatially uniform EO materials. The tolerances of this requirement can be difficult to satisfy, with even stress induced birefringence potentially adding significant experiential difficulty. This approach has been demonstrated at SLAC FFTB [24] and at DESY on FLASH [25]. At the FFTB EO signals of 270 fs FWHM were measured, while at FLASH ~ 300 fs FWHM signals have been obtained.

Temporal decoding (TD): Referring to the time domain description of Eqn. 2, it is apparent that for a long duration optical probe, an intensity modulation will be imposed only on portions of the the pulse envelope. TD temporally

resolves this intensity modulation through a process of optical second-harmonic generation, using a non-colinear geometry. Just as in spatial encoding, a time-space mapping is therefore achieved, although in TD this is purely with the optical fields, and is done outside the beamline. TD has been demonstrated at FELIX [18], and more recently at FLASH [26]. In these later experiments an electro-optic signals with FWHM duration of 110 fs were observed. An example of these ultrashort TD measurements is shown in Fig. 2

Benchmarking of Electro-Optic Signals

An important recent advance in electro-optic diagnostics has been the benchmarking of the measured signal with other diagnostics. In recent experiments at FLASH, a variety of longitudinal diagnostics were used to make concurrent measurements. The EO signal has been measured by Temporal Decoding, Spectral Decoding, and Spatial Encoding, together with simultaneously transverse deflecting cavity measurements of the electron bunch immediately following in the bunch train. CTR measurements were also made during the experiments, although not generally simultaneously. The Temporal decoding and transverse cavity measurements have in particular provided explicit confirmation of the exceptional time resolution achieved in the latest TD experiments, and in the faithful reproduction of the bunch profile.

DIRECT ELECTRON BUNCH TECHNIQUES

Direct electron bunch techniques rely on a change to the electron bunch phase space so that the longitudinal projection is converted to a more easily observed projection, such as transverse profile or energy.

Transverse Deflection Cavities: Lola

In RF transverse deflecting cavities, a transverse kick is applied to the bunch which is dependent on the relative phase of the RF with respect to the electron arrival time. Extremely fast temporal resolution can be obtained with a sufficiently rapidly varying deflecting force. Cavities capable of producing such a rapidly varying deflecting force were developed at SLAC in the 1960's, and were prosed for particle separates, as well as for fast bunch diagnostics.

More recently these original SLAC cavities have been installed and operated at the SPPS facility, and at FLASH. The transverse deflection cavity at FLASH, known as "Lola" after it original developers, is currently producing the highest time resolution of all the longitudinal diagnostics. Lola operates in a hybrid mode for which the net deflection produced by the combination of electric and magnetic fields is independent of the transverse position of the beam within the cavity (although the individual contributions from magnetic or electric fields does vary across the cavity aperture). The RF-bunch phase is operated at the

zero-deflection point, so that the longitudinal phase space of the bunch is streaked transversely, but does not have a mean deflection. At FLASH the Lola cavity is preceded by a kicker that adds an additional mean deflection, so that a single bunch can be deflected onto an off-axis OTR screen. An example of the Lola image, and the projected longitudinal profile is shown in Fig. 3. The temporal resolution of TDC is ultimately restricted by the unstreaked transverse beam size on the OTR screen; for Lola this is $\approx 200 \mu\text{m}$ in normal SASE operation conditions, and the maximum streak is 72 fs/mm , from which an ultimate resolution of 15 fs has been inferred [27].

Transverse deflecting cavities such as Lola are intrinsically destructive measurements. They also have large infrastructure requirements, and may require significant beamline space; the Lola cavity is 3.6 m in length, compared to the requirement of $\sim 10 \text{ cm}$ for CTR or electro-optic diagnostics. However, the added capability for measuring slice parameters, such as emittance, energy, or z-y correlations, makes them a more versatile diagnostic than longitudinal profiling by itself.

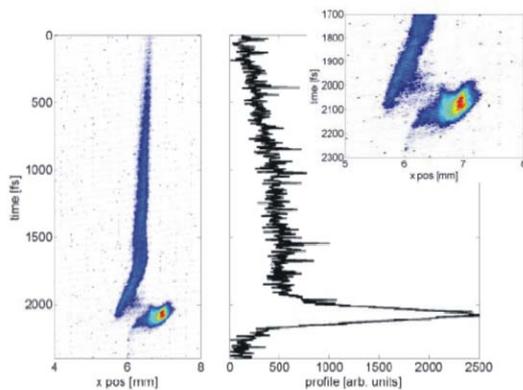


Figure 3: An example of a Lola transverse deflecting cavity measurement (from Hüning et al. [27]).

Optical Replicas

A new technique known as ‘optical replicas’ has been proposed as a means to obtain femtosecond resolution longitudinal profile diagnostics [28]. The basic concept of the scheme is to impose an optical wavelength density modulation on the electron bunch under investigation, and then cause the bunch to radiate optically by passing this modulated bunch through a resonant undulator.

The full scheme consists of i) an initial undulator resonant at $\lambda = 800 \text{ nm}$, which is synchronously seeded with an 800 nm Ti:S laser pulse. The interaction of the bunch with the seeded undulator will result in an energy modulation on the bunch with a period of 800 nm , or 2.7 fs . The bunch is taken through a drift space to allow the energy modulation to develop into a longitudinal density modulation, again with a period of 800 nm . This modulated bunch then

enters a second undulator also resonant at $\lambda = 800 \text{ nm}$. The pre-modulated bunch will therefore coherently radiate at 800 nm , with a radiated intensity dependent on the local charge density of the bunch. Simulations indicate that there will be sufficient intensity in the radiated optical pulse for it to be separately diagnosed with standard ultrafast laser diagnostics. An ultimate time resolution to this technique will be associated with the slippage length of the bunch with respect to the radiation field in the second undulator.

Experimental implementation of a demonstration of the optical replicas concept is currently underway [29]. The system will be installed on FLASH. With a proposed 5 period undulator the achievable time resolution will potentially be 5 cycles of the 800 nm resonant wavelength, or 13 fs .

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Chapter 6

Writeup of instrumentation and diagnostics lectures: CAS2009

6.1 Introduction to Beam Instrumentation and Diagnostics

INTRODUCTION TO BEAM INSTRUMENTATION AND DIAGNOSTICS

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Abstract

These lectures aim at describing instruments and methods used for measuring beam parameters in circular accelerators. Emphasis will be given to new detection and analysis techniques in each field of accelerator instrumentation. The clear distinction is made between “instrumentation”, i.e. the design and construction of the instruments themselves and “diagnostics”, the use of the data from these instruments for running and improving the performance of the accelerator.

INTRODUCTION

Beam instrumentation and diagnostics combines the disciplines of accelerator physics with mechanical, electronic and software engineering, making it an extremely interesting field in which to work. The aim of the beam instrumentation physicist or engineer is to design, build, maintain and improve the diagnostic equipment for the observation of particle beams with the precision required to tune, operate and improve the accelerators and their associated transfer lines.

This introduction is intended to give an overview of the instrumentation in use in modern synchrotrons. The choice available today is so vast that inevitably it will not be possible to cover them all. Many of the standard instruments have been covered in previous CAS schools (see for example Ref. [1] which also contains a comprehensive list of references) and will therefore be touched upon only briefly, with more emphasis being given to new and innovative measurement techniques and their use in beam diagnostics. The following subjects will be discussed:

1. Beam position measurement
2. Beam current measurement
3. Diagnostics of transverse beam motion (tune, chromaticity and coupling)
4. Emittance measurement
5. Beam loss monitoring
6. Luminosity measurement
7. Some examples of beam diagnostics

1. BEAM POSITION MEASUREMENT

The Beam Position Monitor (BPM) can be found in every accelerator. Its role is to provide information on the position of the beam in the vacuum chamber at the monitor location. For linacs and transfer lines the BPMs are used to measure and correct beam trajectories, while for synchrotrons such monitors are distributed around the ring and used to calculate the closed orbit. In circular machines, their location is usually chosen close to the main quadrupole magnets where the β -functions are largest and so any orbit distortion a maximum. For 90° lattices a typical layout involves placing horizontal monitors near the focusing quadrupoles (where the horizontal β -function is large) and the vertical monitors near the defocusing quadrupoles (where the vertical β -function is large). Apart from closed orbit measurements, the BPMs are also used for trajectory measurements (the first turn trajectory is particularly important for closing the orbit on itself) and for accelerator physics experiments, where turn-by-turn data, and even bunch-to-bunch data is often required.

In the early days a BPM monitoring system simply consisted of an oscilloscope linked directly to the pick-up signals. Since then, enormous advances in the acquisition and processing electronics have been made, turning beam position monitors into very complex systems. Modern BPMs are capable of digitising individual bunches separated by a few nanoseconds, with a spatial resolution in the micron range, while the resulting orbit or trajectory collected from several hundred pick-ups can be displayed in a fraction of a second.

1.1 Pick-ups

The measurement of beam position relies on processing the information from pick-up electrodes located in the beam pipe. Five pick-up families are commonly employed:

- Electrostatic – including so-called ‘button’ and ‘shoe-box’ pick-ups
- Electromagnetic – stripline couplers
- Resonant cavity – especially suited for high frequency linacs
- Resistive
- Magnetic

An excellent in depth analysis of most of these pick-ups is presented in Ref. [2]. Here we will briefly describe the two most commonly used, namely the electrostatic and electromagnetic pick-up.

1.1.2 Electrostatic (Capacitive)

The electrostatic or capacitive pick-up is the most widely used in circular accelerators. It consists of metallic electrodes situated on opposite sides of the vacuum chamber at the location where the beam is to be measured. As the beam passes through, electric charges are induced on the electrodes, with more induced on the side which is closer to the beam than the one furthest from the beam. By measuring the difference in the charge induced, the position can be calculated. Let us analyse the properties of button pick-ups (see Fig. 1) since they are the most popular due to their cheapness and ease of construction.

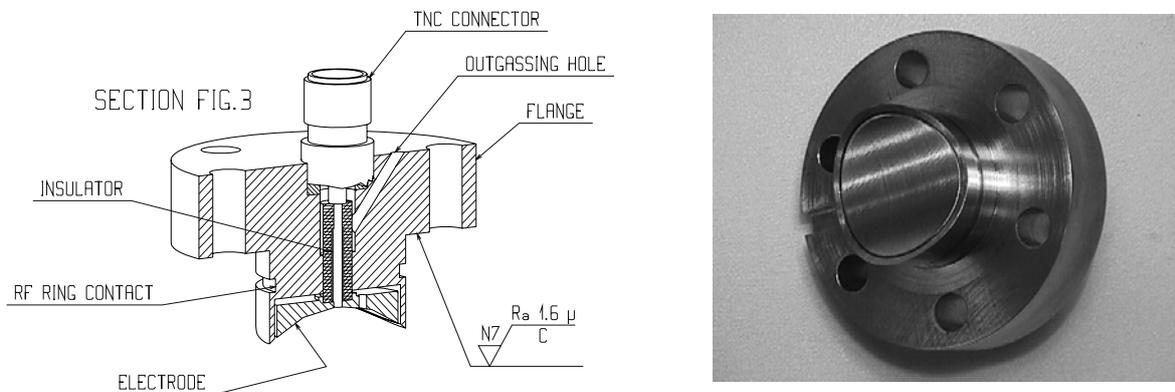


Fig. 1 Cross-section and photo of an LHC button electrode.

The image current associated with the beam will induce charges on the button which are proportional to the beam intensity and inversely proportional to the position of the beam from the electrode. A schematic representation is given in Fig. 2.

The figure of merit for any electrode is its transfer impedance (the ratio of the pick-up output voltage, V , to the beam current, I_B). For a capacitive pick-up the signal is proportional to the rate of change of beam current at low frequencies, while for high frequencies the capacitance ‘integrates’ the signal and the transfer impedance tends to its maximum. For the case of a button electrode of area A and capacitance C situated at a distance d from the beam the maximum transfer impedance (i.e. the

value it tends to at high frequency) can be approximated by:

$$Z_{T\infty} = \frac{A}{2\pi d(\beta c) C}$$

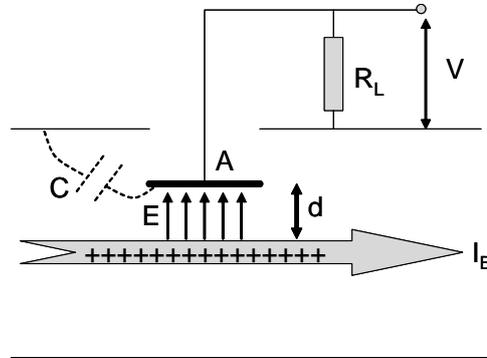


Fig. 2 Schematic of a capacitively coupled electrode.

Button electrode capacitances are typically in the 10pF range. Impedance transformation can be used to improve the low frequency response at the expense of that at high frequency. Figure 3(a) shows the frequency response of an 8pF button electrode for the matched 50Ω impedance case (1:1) and after two different impedance transformations. The time response of the button for different bunch lengths can be seen in Fig. 3(b).

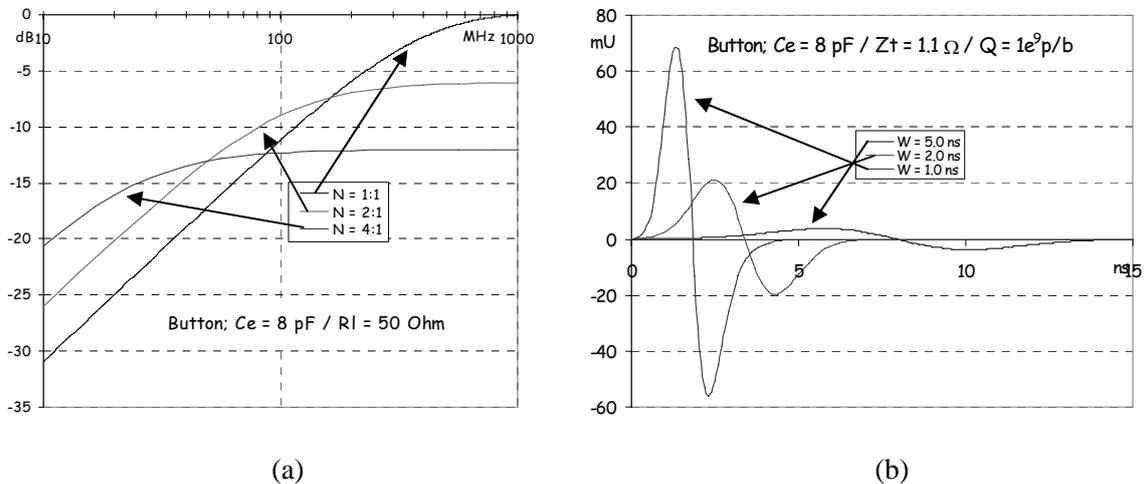


Fig. 3 Frequency (a) and time (b) response of a button electrode.

When designing such pick-ups care must be taken to limit the impedance variations when the transmission line used for signal extraction passes from the vacuum to a feedthrough or cable dielectric (such as ceramic, glass or air). Any such mismatch will produce unwanted reflections, often at high frequency, which could perturb the processing electronics. For this reason most processing chains introduce a low-pass filter on the button output. Special care must also be taken to pair the electrodes on opposite sides of the chamber to minimise offsets in the position reading. This pairing can be made less sensitive to capacitance variations if the high frequency cut-off for the processing electronics sits on the linear part of the button response, with the disadvantage that the overall signal amplitude is reduced.

1.1.3 Electromagnetic (stripline)

The electromagnetic pick-up is a transmission line (stripline) which couples to the transverse electromagnetic (TEM) field of the beam. The transmission line is formed between the stripline and the wall of the vacuum chamber and is excited by the beam only at the gaps on either end of the stripline where a longitudinal field occurs. Fig. 4 shows the layout of such an electromagnetic stripline electrode.

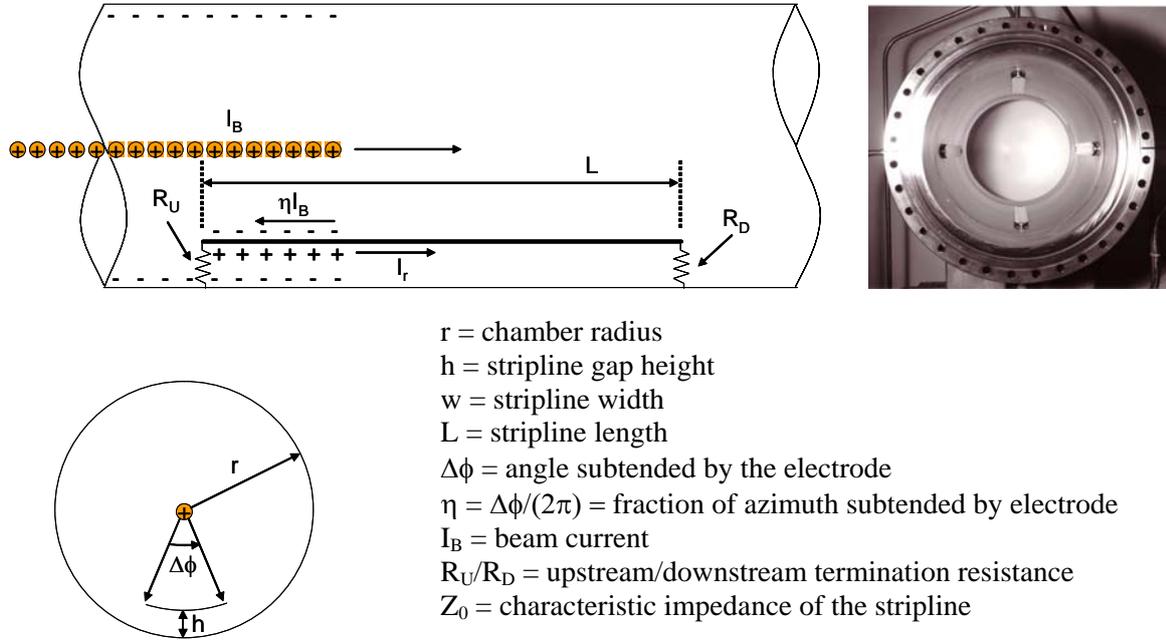


Fig. 4 Schematic and photo of an electromagnetic stripline pick-up.

Consider a bunch travelling from left to right (upstream to downstream). While it is over the upstream port there is a voltage V_r across R_U , causing a voltage wave of that amplitude to be launched to the right. The stripline forms a transmission line with the wall of the vacuum chamber of characteristic impedance Z_0 . The voltage wave is therefore accompanied by a right travelling current wave of amplitude $I_r = V_r / Z_0$. This current flows along the bottom surface of the electrode whilst an equal and opposite current flows along the chamber wall. In addition an image current of amplitude ηI_B travels along the top surface of the electrode. The voltage V_r across R_U can therefore be expressed as

$$V_r = (-I_r + \eta I_B) R_U = \eta I_B \frac{R_U Z_0}{R_U + Z_0} \Rightarrow V_r = \frac{1}{2} \eta I_B Z_0 \text{ for a matched stripline } (R_U = Z_0)$$

When the beam is over the downstream port it produces a voltage $-V_r = -\frac{1}{2} \eta I_B Z_0$ across R_D in the same way as it produced a voltage $+V_r$ across R_U . This launches a left-travelling wave of the same magnitude, but different sign to the right-travelling wave, which propagates along the transmission line formed by the stripline and the chamber wall and will produce an inverted signal upon arrival at the upstream port a time L/c later. The final signal observed at the upstream port will therefore be a bipolar pulse with the maxima separated by $2L/c$ (see Fig. 5(a)).

When the RF wavelength of the beam is equal to multiples of $2L$, the reflection and the signal from next bunch will cancel and there will be no net signal from the stripline. A maximum in the frequency response will be observed when L is a quarter of an RF period, and hence the stripline pick-

up length is usually chosen accordingly. The full frequency response of a 60cm long stripline is shown in Fig. 5(b) and has a lobe structure, with the minima located at multiples of $c/(2L)$.

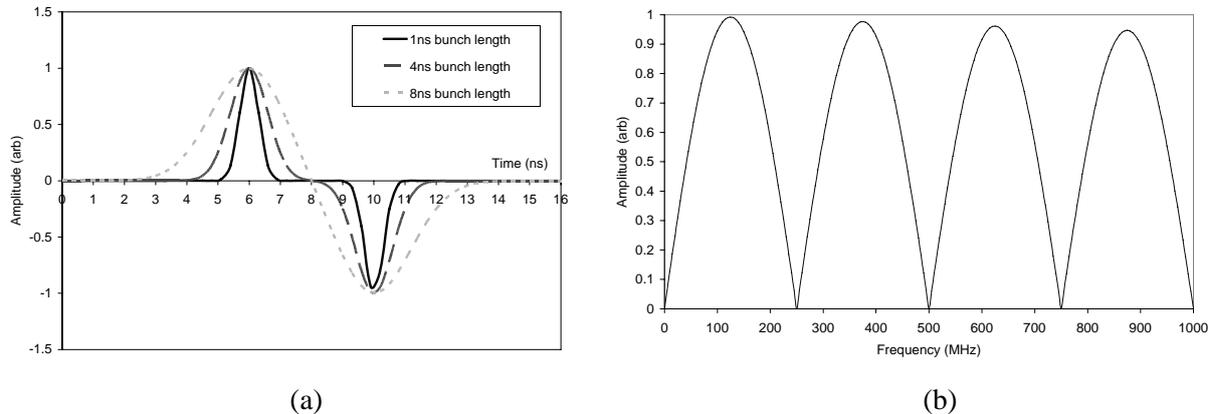


Fig. 5 Time (a) and frequency (b) response of a 60cm long electromagnetic stripline pick-up.

For a relativistic beam the voltage due to the beam passing the downstream port is produced at the same time as the right-travelling wave propagating between the stripline and the wall arrives at the downstream port. The two equal and opposite voltages therefore cancel producing no net signal at the downstream port. The electromagnetic stripline pick-up is therefore said to be “directional”, i.e. a signal is only observed on the upstream port with respect to the beam direction. These pick-ups are therefore used in all locations where there are two counter rotating beams in the same vacuum chamber. Due to the imperfections in the stripline and feedthrough impedance matching, the best directivity one can hope to obtain for a real stripline is generally around 25-30dB (i.e. the voltage signal of one beam with respect to the other is attenuated by a factor between 18-32).

1.2 Beam Position Acquisition Systems

Once the signals from the opposite electrodes of a pick-up have been obtained, the next step is to convert these signals into a meaningful beam position. The first thing to do is to normalise the position, i.e. to make it independent of the signal amplitude (or beam intensity). This is generally done using one of three algorithms, whose response curves can be seen in Fig. 6.

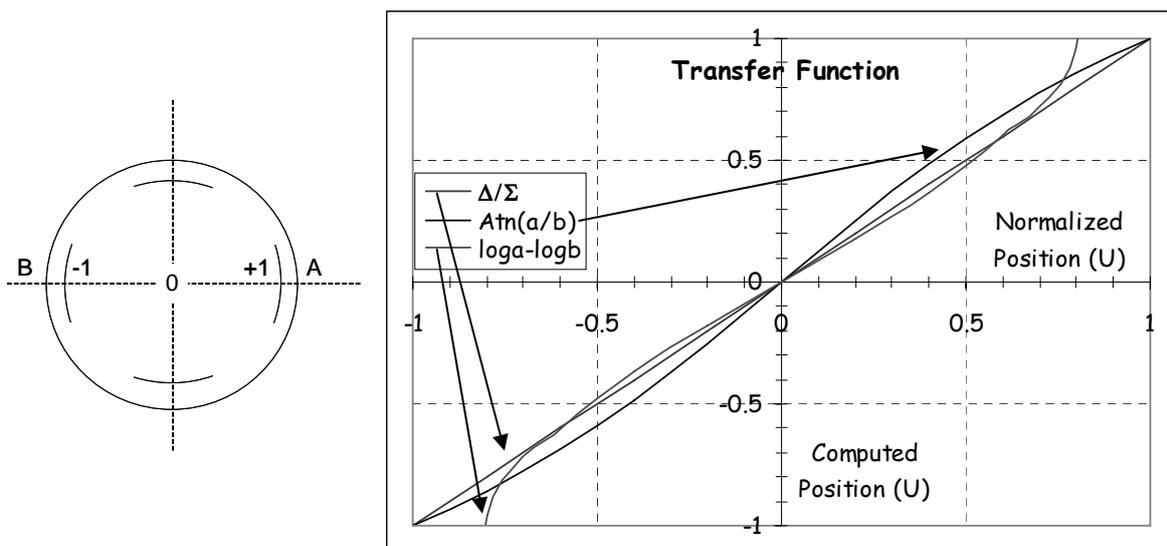


Fig. 6 Transfer functions for three commonly used position normalisation algorithms.

- **Difference over sum (Δ/Σ)** - The sum and difference can be obtained either using a $0^\circ/180^\circ$ passive hybrid, a differential amplifier or calculated by software (after digitising), to give:

$$\text{Normalised Position} = \frac{A - B}{A + B}$$

The transfer function of this algorithm can be seen to be highly linear.

- **Logarithmic ratio** - The two input signals are converted into their logarithmic counterparts and subtracted. In practice this is done using logarithmic amplifiers followed by a differential amplifier. This gives:

$$\text{Normalised Position} = \text{Log}(A) - \text{Log}(B) \left(= \text{Log} \left[\frac{A}{B} \right] \right)$$

whose response curve is seen to be an reversed S-shape, which becomes highly non-linear when exceeding 70% of the normalised aperture.

- **Amplitude to Phase** - The two input signals are converted by a 90° passive hybrid into signals of equal amplitude but varying phase, with the position dependence of this phase given by:

$$\text{Normalised Position} = \phi = 2 \times \text{ArcTan}(A/B)$$

Here the transfer function again deviates from the linear in an S form, but does not diverge for large excursions. In addition, the gradient is larger around zero, making it more sensitive towards the middle of the pick-up. A variation on the amplitude to phase algorithm is amplitude to time conversion, which will be discussed in more detail below.

The type of algorithm to be used will depend on the choice of processing electronics. In all cases the non-linearity is taken into account by calibration circuits and correction algorithms. A summary of commonly used beam position acquisition systems is given in Fig. 7.

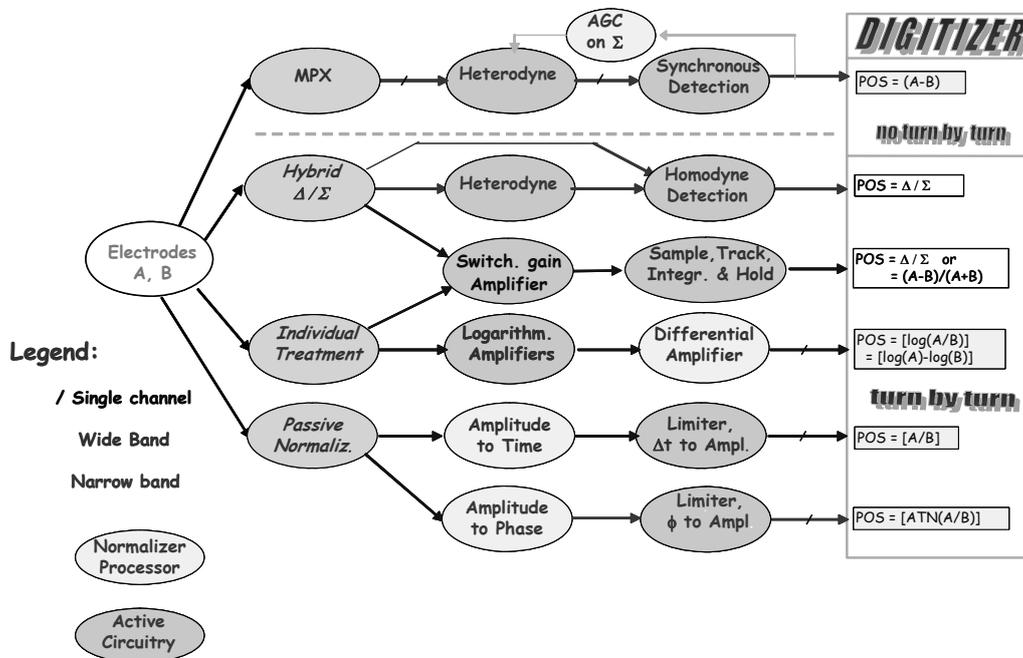


Fig. 7 Schematic representation of the various beam position processing families. (courtesy of G. Vismara, CERN)

Here we will only briefly mention the various families in passing, but detailed descriptions along with the advantages and disadvantages of each system can be found in ref [3].

MPX (multiplexed) – each of the BPM electrodes is multiplexed in turn onto the same, single acquisition electronics chain. This eliminates channel to channel variations, but since the switching is generally quite slow such an acquisition tends to be used in circulating machines where only the average orbit is of importance.

Hybrid (Sigma & Delta) – here a $0^\circ/180^\circ$ passive hybrid is usually used to give the sum (Σ) and difference (Δ) signal from the two electrodes. The position (or ratio of the sum and difference signals) can then be obtained in many ways including: direct digitisation, homodyne detection (mixing the sum and delta signals with the sum signal itself) or heterodyne detection (mixing sum and delta signals with an external reference).

Individual Treatment – in this case each electrode is treated separately, but in parallel. The acquisition can either consist of directly digitising each signal or using logarithmic amplifiers as outlined above. The disadvantage of this method is that it requires two (or four depending on the pick-up orientation) very well matched chains of electronics, since the combination of the signals to obtain a position is performed at the very end of the chain.

Passive Normalisation – here the amplitude difference (i.e. position information) in the input signals is directly converted into a phase or time. Intensity information is lost in this procedure, but the result is a varying phase or time which is directly proportional to the position.

1.2.1 Wide-Band Time Normalisation

The LHC beam position system will be based on a new concept of amplitude to time normalisation, so-called “wide-band time normalisation” or WBTN (see ref [4]). This was developed with two main aims in sight; to provide bunch by bunch beam position information (requiring one measurement every 25ns for the LHC) and to avoid the necessity of gain switching (requiring that one chain of electronics cope with a factor 40 difference in single bunch intensity). The principle of the WBTN technique is outlined in Fig. 8.

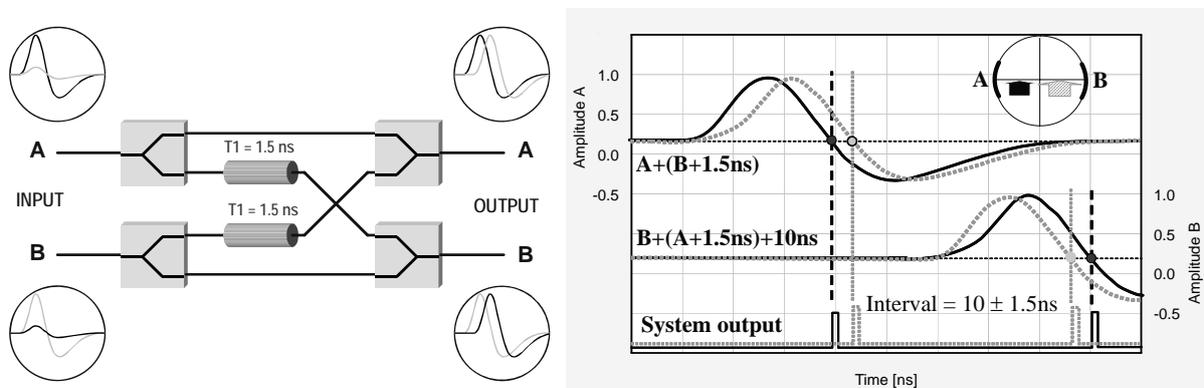


Fig. 8 The wide band time normalisation principle.

The signal from a single pick-up electrode is split and recombined with a delayed signal from the other electrode. This results in two signals where the relative zero crossing time depends on the position of the beam. In the case of the LHC the position information is converted into two pulses separated by $10 \pm 1.5 \text{ ns}$ (the position being encoded into the $\pm 1.5 \text{ ns}$). To obtain the required resolution and linearity using such a system requires precision high frequency electronic engineering. For example in order to achieve the 0.1% single shot resolution requested for the LHC ($50 \mu\text{m}$ on a 50mm diameter pick-up) a stability and reproducibility at the 3ps level is required. One advantage of this system is that once the position has been encoded into these two pulses, it can be transmitted in a digital manner over a fibre optic network. This is important for machines such as the LHC where the

amount of electronics in the tunnel, in particular digital electronics, has to be minimised due to radiation levels. Fibre-optic transmission allows all the digital processing electronics, which finally extract the position from the time difference, to be regrouped in surface buildings, where they are accessible and free from radiation concerns. The final implementation layout for the LHC WBTN system is shown in Fig 9.

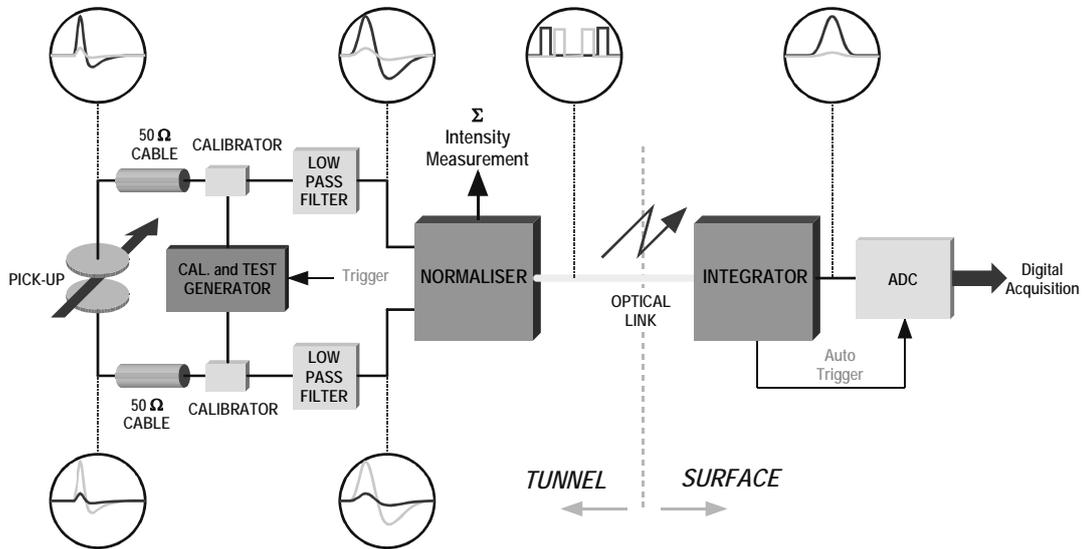


Fig. 9 Implementation of the Wide Band Time Normalisation electronics for the LHC. (courtesy of D. Cocq, CERN)

2. BEAM CURRENT AND INTENSITY MEASUREMENT

The measurement of beam current or bunch intensity is one of the most basic measurements performed at any accelerator. This is usually done by means of a “beam current transformer” or BCT. In order for the transformer to interact with the magnetic field of the beam it has to be placed over a ceramic gap in the vacuum chamber. To keep the impedance seen by the beam as low as possible an RF bypass (either a thin metallic coating or external capacitors on the ceramic) is required for the high frequency wall current components. In addition, to keep the vacuum chamber continuity, an Ohmic bypass external to the transformer is needed.

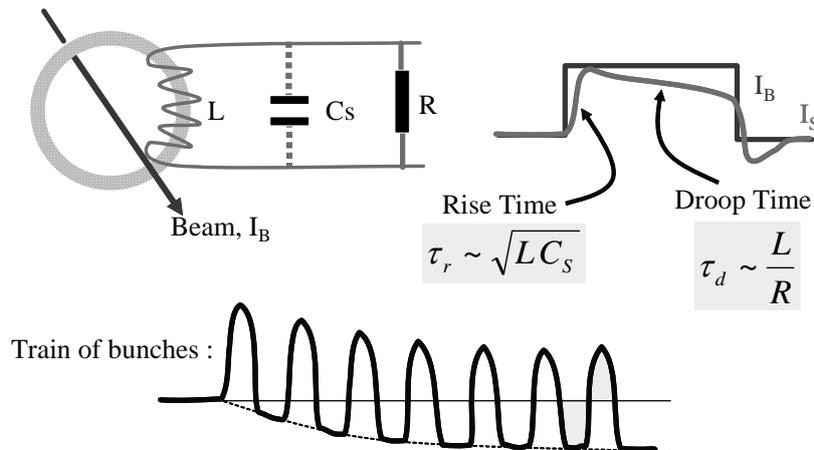


Fig. 10 The beam current transformer.

2.1 The Beam Current Transformer

The beam current, I_B , can be considered as the primary winding of the transformer, with the output voltage from the secondary windings given by $V = L \, dI_B/dt$. An ideal transformer would give a differentiated response, with the integrated charge being zero, which is not of much use as a measuring device. In reality the secondary windings have some stray capacitance, and are terminated by some finite resistance. This leads to signals of the form shown in Fig. 10. The transformer output now closely resembles the beam intensity distribution, with the added inconvenience of a DC offset due to the transformer droop. This DC offset can be corrected for either electronically or, in this modern era, by software treatment of directly digitised data.

A transformer with a bandwidth from 200Hz to 1GHz has recently been installed in the CERN-SPS [5]. Such a bandwidth is obtained by using a ferromagnetic core wound of high permeability metal tape to avoid eddy currents. With this instrument, operators can observe the bunch-by-bunch intensity evolution of beams destined for the LHC throughout the SPS acceleration cycle. In order to obtain the total charge in each bunch, fast integrators are required which are capable of working at repetition frequencies of up to 40MHz. Such an integrator chip has been developed by the Laboratoire de Physique Corpusculaire, Clermont-Ferrand, France, for capturing photomultiplier signals in the LHC-b experiment [6], and is now also used for bunch intensity measurements. A schematic of the integration principle and the resulting signals as measured in the CERN-SPS are shown in Fig. 11. The chip works using two integrators in parallel. As one integrates the other is discharged, with the output switched from one to the other on each clock cycle. The resulting integrated amplitude (voltage) is directly digitised, with all gain linearisation and DC offset subtraction performed by software.

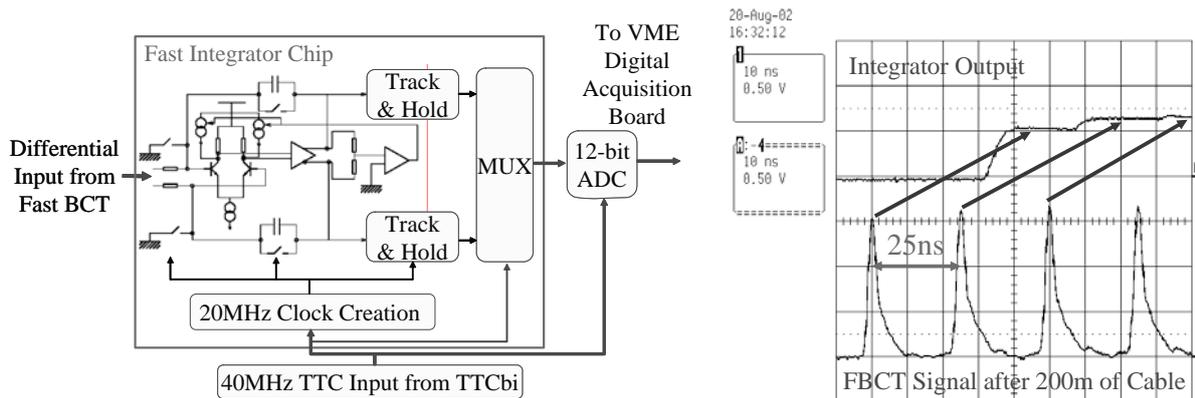


Fig. 11 The principle and measurement of the CERN-SPS fast beam current transformer.

2.2 The DC Beam Current Transformer

In storage rings and accelerators with cycle times of several seconds, a DC beam transformer can be used to measure the total current. Such an instrument was developed for the CERN-ISR (Intersecting Storage Rings), the first machine to sustain beams for hours [7]. A DC transformer is based on a pair of matched, toroidal, ferromagnetic cores, which are driven into saturation by a modulation current at frequencies of up to a few kHz. The principle of operation is shown in Fig. 12, and makes use of the hysteresis loop of the toroid. If an equal but opposite modulation current (the triangular waveforms in Fig. 12) is applied to both cores with the beam not present, then the voltage induced in the detection windings on each core will also be equal but opposite. When, however, there is a beam current I_B present, the starting point in the hysteresis loop for zero modulation current is offset due to the static magnetic field generated by the beam current. Since the modulation is opposite in each toroid, the time spent in saturation will be different for the two branches of the hysteresis loop. This results in the

generation of voltage pulses at twice the modulation frequency when the induced voltage in the detection windings on each core is combined. The demodulation of this signal gives a train of pulses, with the width of each pulse being a direct measure of the beam current, i.e. by how much the hysteresis curves are offset.

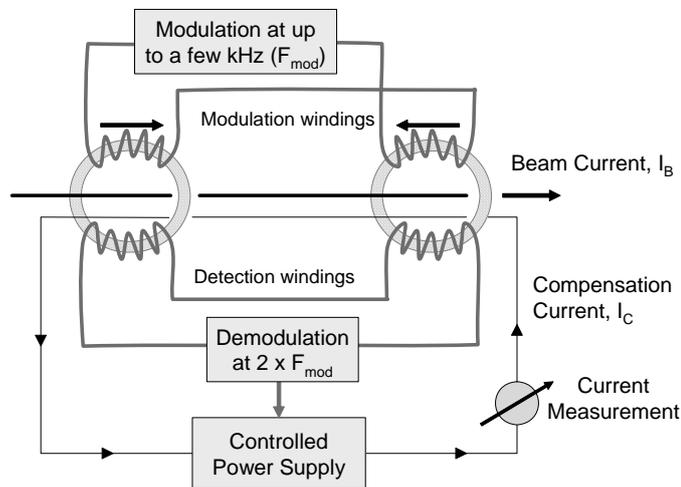
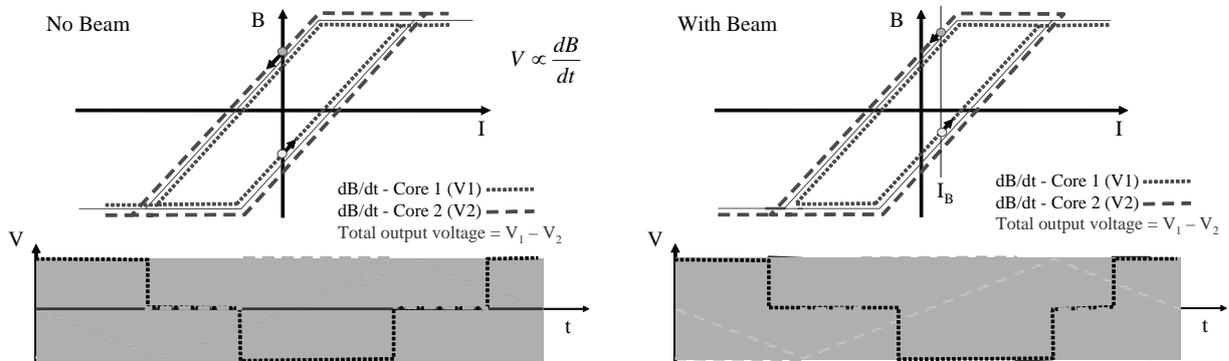


Fig. 12 The principle and schematic of a DC beam current transformer.

In the “zero flux detector” implementation of the DC beam transformer, the result of the demodulation is fed back into a compensating current loop (see Fig. 12). Once the compensation current and the beam current are identical the net static magnetic field seen by the toroids is zero (hence zero flux) and the output from the demodulator is also zero. The beam current can then be obtained by simply measuring the voltage produced by this compensation current across a know resistor.

For modern DC transformers such a zero flux detector is used to compensate the droop of the simple beam current transformer described in section 6.2. This significantly increases the bandwidth of the system, allowing measurement from DC to a few MHz.

3. DIAGNOSTICS OF TRANSVERSE BEAM MOTION

The instrumentation used to look at transverse beam motion is very important to the efficient operation of any circular accelerator [8]. There are three main parameters which can be measured using such diagnostics, namely the betatron tune, chromaticity and coupling, all of which are discussed in detail below.

3.1 Tune Measurement

All betatron tune measurements are based on applying a transverse excitation to the beam and looking at the resulting beam response. The most common methods of performing such measurements are presented in this section.

3.1.1 Fourier Transform (FFT) of beam motion

In the simplest case the beam is given a single kick using a powerful stripline or magnetic kicker, and allowed to oscillate freely (alternatively white noise can be injected onto the beam). The observation of the resulting beam motion is usually carried out using one of the types of position pick-ups covered in Section 1. Once the data has been recorded, the power density spectrum in frequency domain can be computed using a Fast Fourier Transform (FFT). The betatron tune is determined as the frequency which has the highest amplitude response. If there is enough external excitation from other sources (ground motion, power supply ripple etc) or the beam is slightly unstable by itself, the method also gives useful information without any specific beam excitation.

What is usually of most interest for particle colliders is to be able to track the tune evolution during the whole of the accelerator cycle. The simplest way of achieving this is to repeat the tune measurement outlined above at regular intervals. By displaying such data as a spectrograph (Fig. 13(a)) the complete history of the tune during the machine cycle can be tracked.

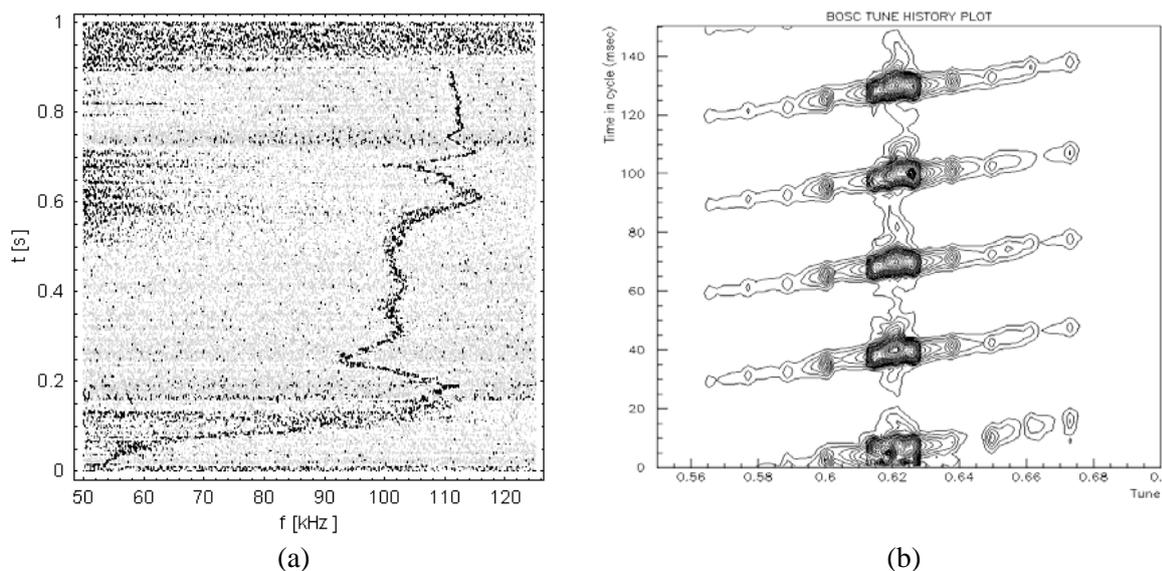


Fig. 13 (a) A spectrograph showing tune evolution in the CERN-PS.
(b) Chirped tune measurements from the CERN-SPS.

3.1.2 Chirp Excitation

In order to minimise the frequency range over which power is put into the beam, swept frequency or “chirp excitation” is often used (so-called because if listened to at audio frequencies such a signal sounds like the chirp of a bird). The chirp range is set around the expected betatron tunes and the sweep time is determined depending on the requested time resolution and precision of the tune measurement. The advantage of this technique is that in addition to an amplitude response it also gives phase information, as the phase difference between the observed motion and the applied sine wave is easily measured. This makes it more sensitive than the single kick method and so allows smaller excitation amplitudes to be used. Fig. 13(b) shows a result from the CERN-SPS where a chirp was

performed every 30ms. The sine wave can be seen to sweep from low to high frequency, with the main tune peak and the synchrotron satellites clearly visible.

3.1.3 Swept Frequency Analysis

For this method (often called “Network Analysis”) the beams are excited with a steady sinusoidal wave. The amplitude and phase of the resulting oscillation are precisely determined by means of harmonic analysis. Thereafter the excitation frequency is increased in steps until the range of interest is covered. This represents a very precise measurement yielding the full information of the beam transfer function. The disadvantage is the long measurement time, which renders the method of little use for the study of dynamic phenomena.

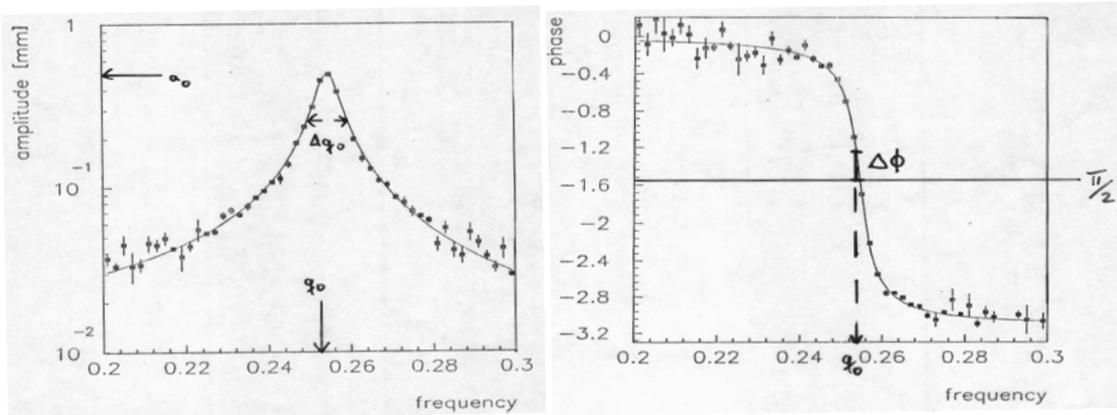


Fig. 14 Complete beam transfer function measured using swept frequency analysis in the CERN-LEP.

Such a complete beam transfer function is shown in Fig. 14. Notice how the phase jumps by 180° as the excitation sweeps across the betatron tune frequency. Such a response is typical of any harmonic oscillator. Since the rate of change of the phase change is a maximum at the peak of the amplitude response, measurements performed using the phase response of the beam are in general more sensitive than those relying on amplitude response.

3.1.4 Phase Locked Loop Tune Tracking

In order to have a fully continuous measurement of the tune a Phase Locked Loop (PLL) needs to be implemented. The basic principle of the PLL is sketched in Fig. 15. A voltage or numerically controlled oscillator (VCO or NCO) is used to put a sine wave excitation, $A \cdot \sin(\omega t)$, on the beam. The beam response to this signal is then observed using a pick-up, and will be of the form $B \cdot \sin(\omega t + \phi)$, where ϕ is the phase difference between the excitation and the observed signal. In the phase detector the excitation signal and the observed signal are multiplied together, resulting in a signal of the form $A \cdot B \cdot \sin(2\omega t + \phi) \cdot \cos(\phi)$, which is seen to have a DC component proportional to the cosine of the phase difference. This will therefore be zero when the phase difference is 90° which, as was seen above, is where the amplitude response is a maximum, i.e. at the tune frequency. The aim of the PLL is to “lock-in” to this 90° phase difference between excitation and observed signal by correcting the VCO frequency until the DC component of the phase detector output is zero. Since the PLL will always try to maintain this 90° phase difference, the VCO frequency will track any tune changes, so giving a continuous tune measurement.

In practice things are not quite as simple. Many parameters have to be optimised in order for the PLL to find, lock-in and subsequently track the tune peak. The beam spectra and dynamics also have to be well understood if the PLL is not to lock or jump to a spurious line, resonance, synchrotron sideband etc. In addition, for hadron machines, the continuous excitation will lead to emittance blow-up. In order for this to be kept to a minimum the applied excitation has to be small and therefore the

observation pick-up and following electronics very sensitive. This is less of a problem for lepton colliders where radiation damping takes care of any emittance blow-up caused by the excitation, making PLL systems much easier to implement on such machines.

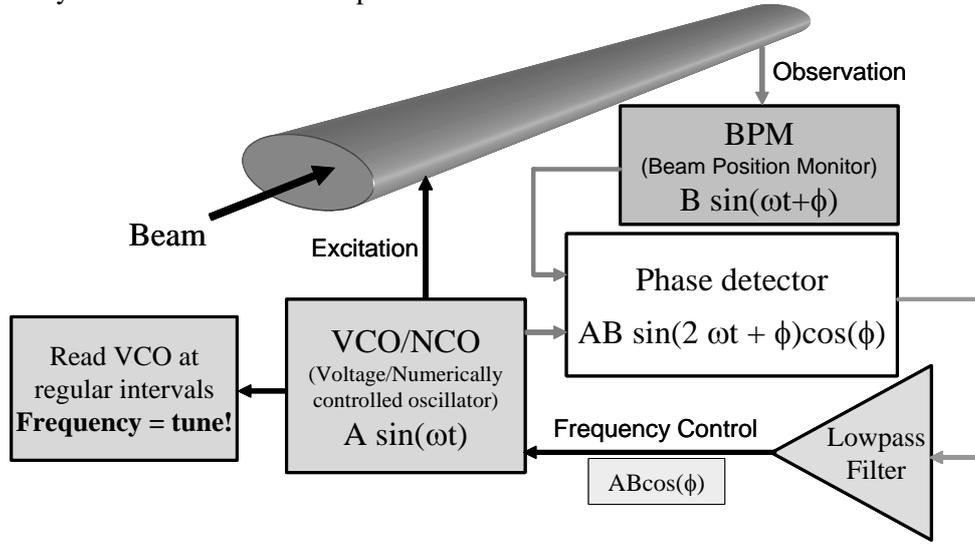


Fig. 15 Principle of a phase locked loop tune tracker.

3.2 Chromaticity Measurement

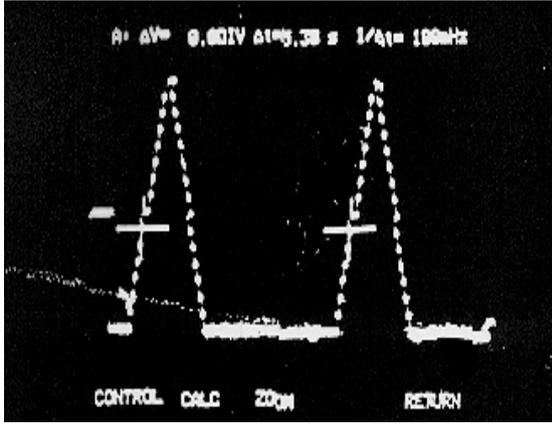
For any high energy synchrotron, the control of chromaticity is very important. If the chromaticity is of the wrong sign (corresponding to positive below the transition energy or negative above it) then the beam quickly becomes unstable due to the head-tail instability. If the chromaticity is too big then the tune spread becomes large and some particles are inevitably lost as they hit resonance lines in tune space. The most common method of measuring the chromaticity of a circular machine is to measure the betatron tune as a function of the beam energy and then to calculate the chromaticity from the resulting gradient. This is usually done by varying the RF frequency, keeping the magnetic field static. The equations of interest are:

$$\Delta Q = (\xi Q) \frac{\Delta p}{p} = Q' \frac{\Delta p}{p} = Q' \gamma_t^2 \frac{\Delta R}{R} = Q' \left(\frac{-\gamma_t^2 \gamma^2}{\gamma^2 - \gamma_t^2} \right) \frac{\Delta f}{f} \quad (3.1)$$

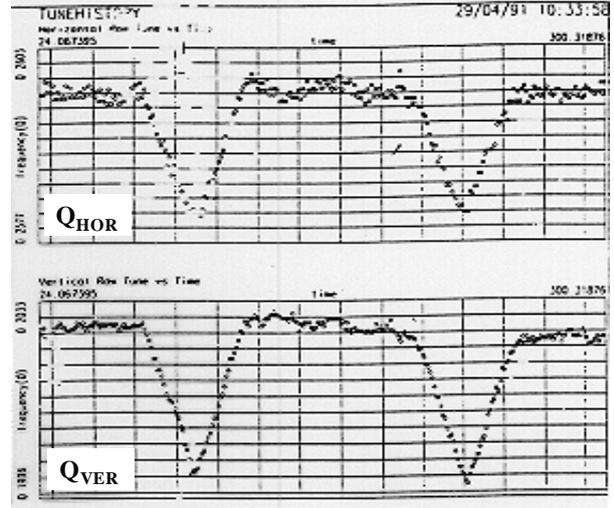
where ΔQ is the change in tune, $\Delta p/p$ the momentum spread (or relative change in momentum), $\Delta R/R$ the relative change in radius, $\Delta f/f$ the relative change in RF frequency and ξ the chromaticity. Please note that the chromaticity, ξ , is often expressed as $Q' = Q \xi$, where Q is the total betatron tune including the integer part.

In the CERN-SPS, for example, a chromaticity measurement consists of performing a tune measurement for three different RF frequency settings. Instead of noting the exact RF frequency, what is actually measured is the change in closed orbit, from which the relative change in radius can be calculated. These three points are then plotted, with the gradient giving the chromaticity.

In order to obtain continuous chromaticity measurements this technique of RF modulation is combined with the PLL tune measurement outlined in the previous section. The RF frequency is usually programmed with a small asymmetric function which periodically varies about the mean RF frequency. By tracking the tune during this time using the PLL and knowing the magnitude of the RF change, the chromaticity can be calculated and tracked. An example of such a measurement performed at the CERN-LEP is shown in Fig. 16.



(a)



(b)

Fig. 16 Example of a LEP chromaticity measurement. (a) shows the applied RF frequency shift and (b) shows the response of the horizontal and vertical betatron tunes measured by PLL tune tracking.

3.2.1 Head-Tail Chromaticity Measurement

The methods outlined above do not allow instantaneous chromaticity measurements, for instance during energy ramping or beta squeezing and are limited to repetition intervals in the Hz range. In preparation for the LHC a new approach has been developed which uses the energy spread in the beams for a chromaticity measurement. Transverse oscillations are excited with a single kick and the chromaticity is calculated from the phase difference of the individually sampled head and tail motions of a single bunch. Using this method the chromaticity can be calculated using the data from only one synchrotron period (about 15-50 milliseconds in the case of the LHC). In addition, this technique does not rely on an accurate knowledge of the fractional part of the betatron tune and, for a machine operating well above transition, the calculated chromaticity is virtually independent of beam energy.

Assuming longitudinal stability, a single particle will rotate in longitudinal phase-space at a frequency equal to the synchrotron frequency. During this longitudinal motion the particle also undergoes transverse motion. If the chromaticity is zero, then the particle will have the same tune wherever it is in the bucket. As soon as chromaticity is non-zero, however, the particle's tune will change depending on where it happens to be longitudinally. If a whole bunch of particles is kicked transversely, then the resulting transverse oscillations for a given longitudinal position within the bunch can be shown [9] to be given by

$$y(n) = A \cos(2\pi n Q_0 + \omega_\xi \hat{t} (\cos(2\pi n Q_s) - 1)) \quad (3.2)$$

where n is the number of turns since the kick, Q_0 is the betatron tune, Q_s is the synchrotron tune, \hat{t} is the longitudinal position with respect to the centre of the bunch and ω_ξ is the so-called chromatic frequency given by

$$\omega_\xi = Q' \omega_0 \frac{1}{\eta} \quad (3.3)$$

Here Q' is the chromaticity, ω_0 is the revolution frequency and $\eta = 1/\gamma^2 - 1/\gamma_{tr}^2$. If we now consider the evolution of two longitudinal positions within a single bunch separated in time by $\Delta\tau$, then from (3.1) it follows that the phase difference in the transverse oscillation of these two positions is given by

$$\Delta\psi(n) = -\omega_\xi \Delta\tau (\cos(2\pi n Q_s) - 1) \quad (3.4)$$

This phase difference is a maximum when $nQ_s = 1/2$, i.e. after half a synchrotron period, giving

$$\Delta\psi_{\max} = -2\omega_\xi \Delta\tau \quad (3.5)$$

The chromaticity can therefore be written as

$$Q' = \frac{-\eta \Delta\psi(n)}{\omega_0 \Delta\tau (\cos(2\pi n Q_s) - 1)} = \frac{\eta \Delta\psi_{\max}}{2\omega_0 \Delta\tau} \quad (3.6)$$

A schematic layout of the CERN-SPS Head-Tail monitor [10] set-up is shown in Fig. 17(a). A straight stripline coupler (see section 1.1.3) followed by a 180° hybrid is used to provide the sum and difference signals for a given measurement plane. These signals are fed into a fast-sampling (2GS/s on each channel), high bandwidth (2GHz) digital oscilloscope. A VME front-end acquisition crate then retrieves the data via a GPIB link and provides the bunch synchronous timing. Using the ‘‘Fast-Frame’’ capabilities of the oscilloscope the data from the same bunch can be captured over several hundred turns. Fig. 17(b) shows the result of such a head-tail chromaticity measurement. The top two plots show the transverse movement of the head and tail respectively of a single bunch after the beam is kicked. The lower left plot shows the evolution of the phase of the head and tail and the phase difference. It can be seen that the signals are re-phased after one synchrotron period, with the phase difference a maximum after $1/2$ a synchrotron period. The final plot (lower right) shows the calculated chromaticity (using equation 3.6) for all turns where the phase difference is well defined.

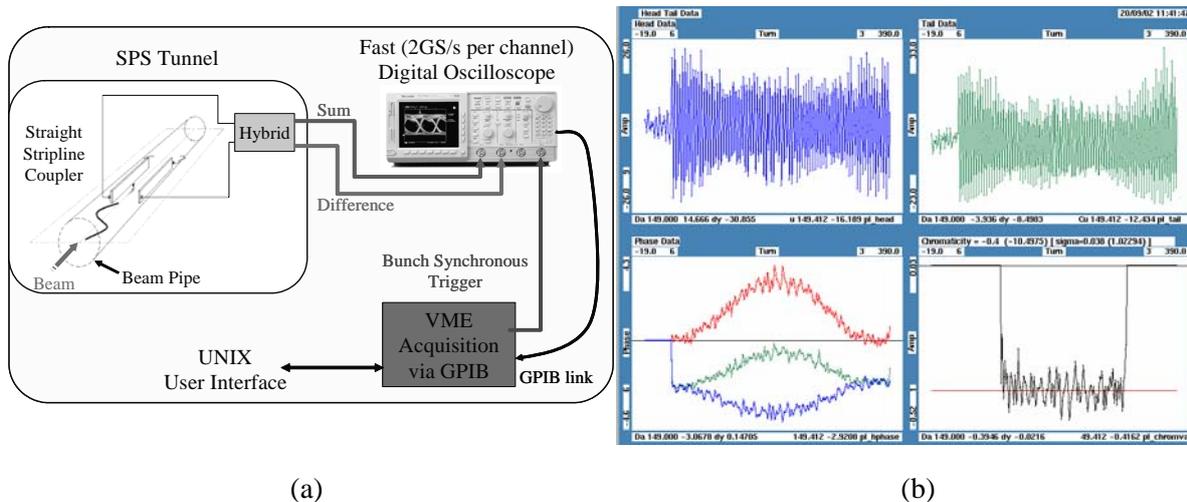


Fig. 17(a) Layout of the CERN-SPS head-tail monitor. (b) Head-tail monitor acquisition.

3.3 Coupling Measurement

The control of coupling (the degree to which horizontal and vertical betatron motion is linked) is also important for circular accelerators. Excessive coupling will make tune and chromaticity measurements almost impossible, as the information from both planes are mixed-up in the observed signal. A very good and comprehensive summary of linear betatron coupling can be found in [11].

3.3.1 Closest Tune Approach

For this method, both betatron tunes are measured during a linear quadrupole power converter ramp which crosses the values of the horizontal and vertical tunes. The remaining separation of the tune

traces is a direct measure for the total coupling coefficient $|c|$. A measurement example from the CERN-LEP, using a phase locked loop tune measurement is shown in Fig. 18. In order to ensure that the PLL keeps tracking both tunes, even when they approach each other, the measurements are performed on two different bunches.

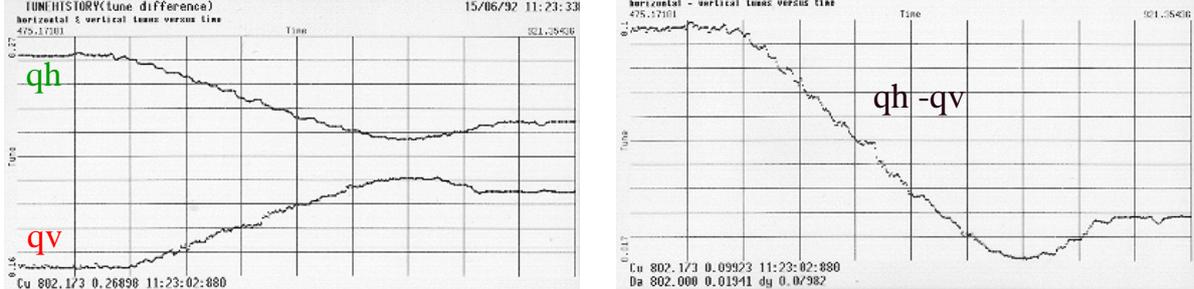


Fig. 18 LEP coupling measurement.

3.3.2 Kick Method

The above method does not allow for diagnostics during machine transitions. A better tool for the measurement of small coupling coefficients, although demanding quite large beam excitations, consists of applying a single kick in one plane and observing the time evolution of the betatron oscillations in both planes. This method is described in Ref [11].

4. EMITTANCE MEASUREMENT

The ultimate luminosity of any collider is inversely proportional to the transverse emittance of the colliding beams. Preservation of emittance and hence emittance measurements are of particular importance in the long chain of accelerators and storage rings of big hadron colliders as the emittance of a hadron bunch is not appreciably reduced through mechanisms such as the radiation damping associated with lepton machines. Good explanations of emittance can be found in Refs [12, 13].

The emittance which includes about 98 % of the beam-particles can be defined as

$$\varepsilon(98\%) = \frac{\text{beamwidth}^2 - \left(\frac{\Delta P}{P} \cdot D_m\right)^2}{\beta_m} = \frac{\text{FWHM}^2 - \left(\frac{\Delta P}{P} \cdot D_m\right)^2}{\beta_m} \quad (4.1)$$

where FWHM is the measured full width at half height (2.35σ) of the beam, $\Delta P/P$ the FWHM of the momentum spread, D_m the value of the dispersion-function and β_m the value of the beta-function at the monitor position.

From this equation one can immediately see that the measurement of emittance depends on many parameters. This limits the accuracy to which emittance can be calculated, which is generally with a precision no better than around 10%. A number of instruments are capable of measuring the beam profile quite precisely, but in calculating the emittance one also relies on knowledge of the beam optical parameters at the place of the instrument and these are often fraught with considerable uncertainties.

4.1 Scintillator and Optical Transition Radiation Screens

Scintillator screens have been used for nearly a century and are the simplest and most convincing device when one has to thread a beam through a transfer line and into and around an accelerator. The modern version consists of a doped alumina screen which is inserted into the beam and can stand high intensities and large amounts of integrated charge. In its simplest form a graticuled screen is observed using a TV-camera. It can deliver a wealth of information to the eye of an experienced observer, but only in a semi-quantitative way. Much can be done about that with modern means of rapid image treatment, but questions concerning the linearity of these screens at high beam densities remain.

Optical Transition Radiation (OTR) screens are a cheap substitute for scintillator screens. OTR radiation is generated when a charged-particle beam transits the interface of two media with different dielectric constants (e.g. vacuum to metal or vice versa) [14]. Since this is a surface phenomenon, the screens can be made of very thin foils which reduces beam scattering and minimises heat deposition. The radiation produced is emitted in two cones around the angle of reflection for backward (vacuum to metal) OTR so that if the foil is placed at 45° to the beam direction, the radiation produced is at 90° to the beam direction. In addition two cones of forward OTR (metal to vacuum) are produced around the beam direction (see Fig. 19). The angular distribution of the emitted radiation has a central hole and a peak located at $1/\gamma$. The higher the value of γ the sharper the peaks and the more light can be collected, which is why OTR is generally suited to lepton or high energy hadron machines.

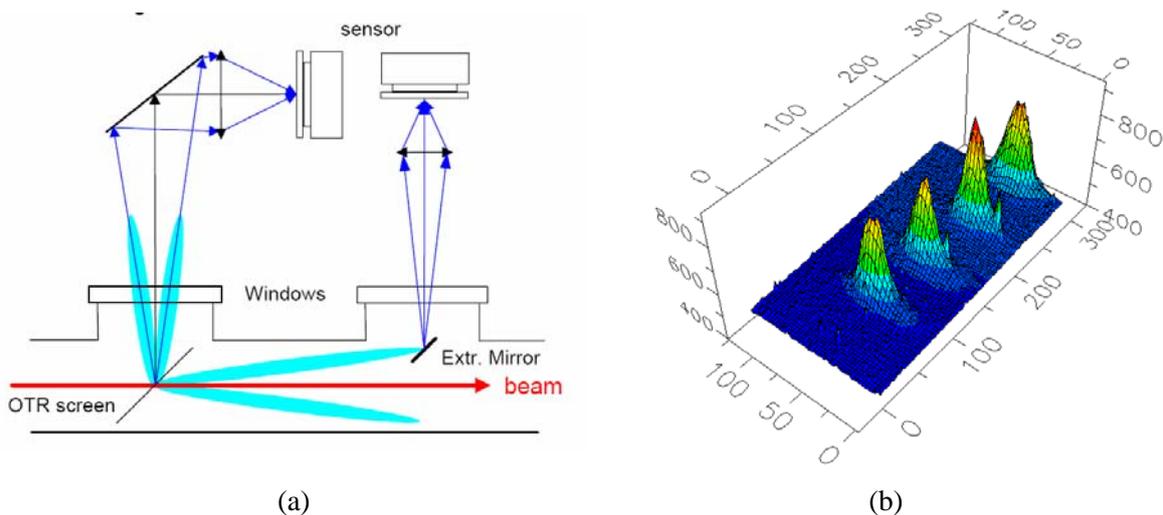


Fig. 19 (a) Backward and forward OTR patterns with their imaging schemes.
(b) Example of 2D OTR images taken every four turns at injection in the CERN-SPS.

4.2 SEM-Grids

Secondary Emission (SEM) Grids, also known as harps, consist of ribbons or wires which are placed in the beam. As the beam intercepts the grid, secondary emission occurs leading to a current in each strip which is proportional to the beam intensity at that location. By measuring this current for all strips a beam profile is obtained. SEM-grids are the most widely used means to measure the density profile of beams in transfer lines. In addition, sets of three, properly spaced (i.e. with the right phase advance between monitors), allow a determination of the emittance ellipse. What makes them popular is their simple and robust construction, the fact that there is little doubt about the measured distribution, and their high sensitivity, in particular at low energies and for ions. At higher energies they can be considered semi-transparent. Amongst their drawbacks are the limited spatial resolution (difficult to get the wire spacing much below 0.25mm) and the rather high cost for the mechanisms and electronics.

4.3 Wire Scanners

Of all the instruments used for measuring the emittance of circulating beams, wire-scanners are considered to be the most trustworthy. They come in two different types; rotative and linear. Rotative wire scanners consist of a thin wire (some tens of microns in diameter) mounted on a fork which is attached to a rotating motor (see Fig. 20), while linear scanners use motors which push/pull the wire across the beam. There are two ways of obtaining a beam profile with wire scanners; by measuring the secondary emission current as a function of wire position (similar to the SEM-grid acquisition mentioned above) or by measuring the flux of secondary particles created as the beam interacts with the wire. This latter technique is often used for high intensities, where the heating of the wire produces thermal emission which falsifies the secondary emission results. It relies on the use of radiation detectors, typically scintillators followed by photo-multipliers, placed downstream of the wire scanner to detect the γ -radiation and secondary particles produced when the wire intercepts the beam. To make the flux collected independent of the wire position may require the summation of the signals from two or more detectors positioned around the beam chamber.

Fast wire scanners are nearly non-destructive over a wide range of energies. Their spatial resolution can reach the micrometer range and, with fast gated electronics, the profiles of individual bunches can be observed. Their great sensitivity also allows them to be used for the study of beam halos.

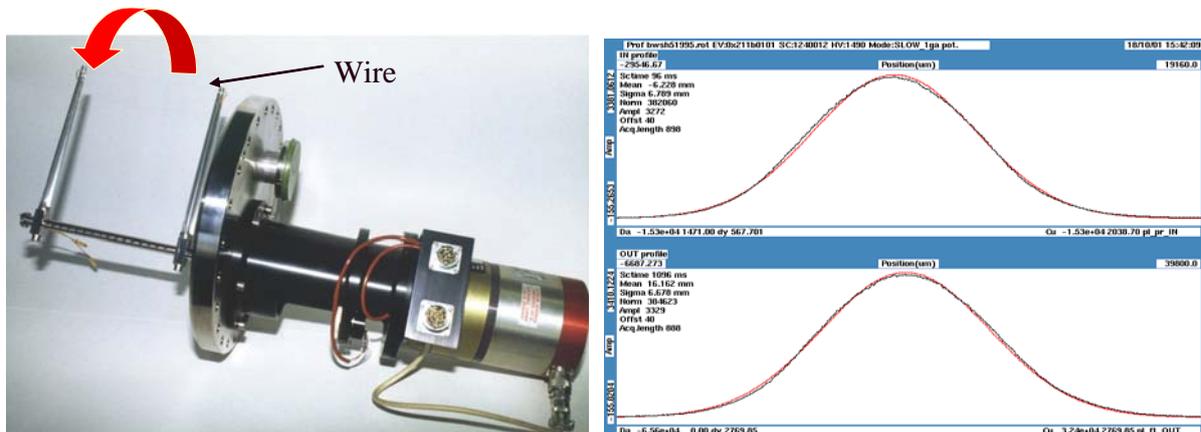


Fig. 20 Rotative wire scanner and an example of a wire scanner profile measurement.

4.4 Residual Gas and Luminescence Monitors

Rest gas monitors are used in many high energy accelerators in order to reconstruct transverse beam distributions (see e.g. Ref. [15]). The signal results from the collection of either the ions or the electrons produced by the beam ionising the small amount of residual gas in the vacuum chamber. These ions or electrons are accelerated using a bias voltage of several kilovolts and collected on a micro channel plate (MCP). The avalanche of electrons produced by the MCP then hits a phosphor screen, giving an image of the beam profile which can be monitored using a CCD camera (see Fig. 21). Due to their rigidity, ions are less sensitive to the distorting effects of the space charge from the circulating beam, but their slow drift time, even with high bias voltages, means that they spend a long time in this beam field, making it difficult to analyse rms beam dimensions smaller than one millimetre. In order to use electrons to produce an image, a transverse magnetic field needs to be added around which the electrons spiral on their way to the MCP. This eliminates, to a large extent, the space charge effects of the beam and allows sharper images to be produced than with ions. This additional magnetic field, however, is also seen by the beam and has to be compensated by two corrector magnets either side of the ionisation profile monitor.

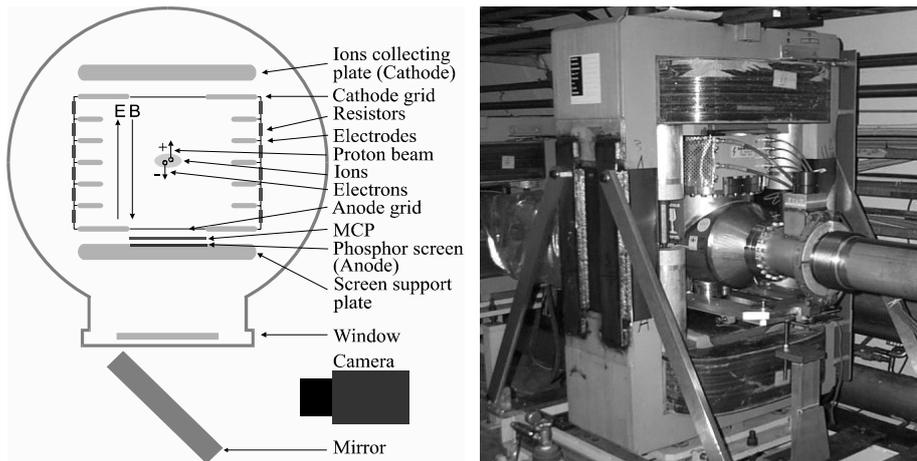


Fig. 21 Principle of a residual gas ionisation profile monitor and an example from the CERN-SPS.

Luminescence monitors (see e.g. Ref. [16]) also rely on the interaction of the beam with a gas in the vacuum chamber. In this case the gas of interest is nitrogen, in which electrons are excited from the ground state to a higher energy level by the passing beam. Once the beam has passed the electrons return to the ground state and emit photons. In the case of nitrogen the dominant photon wavelength is 391.3nm, corresponding to light at the lower end of the visible range, for which many detectors are available. In general, the residual gas alone does not produce enough photons for accurate imaging and hence a local pressure bump is usually created by injecting a small amount of nitrogen to enhance the photon production. The principle of luminescence monitoring and a schematic layout of such an instrument are shown in Fig. 22. Also shown in Fig. 22 is an example of a continuous measurement performed at the CERN-SPS, showing the ability of such an instrument to track the evolution of the beam size through the various acceleration stages with little effect on the beam.

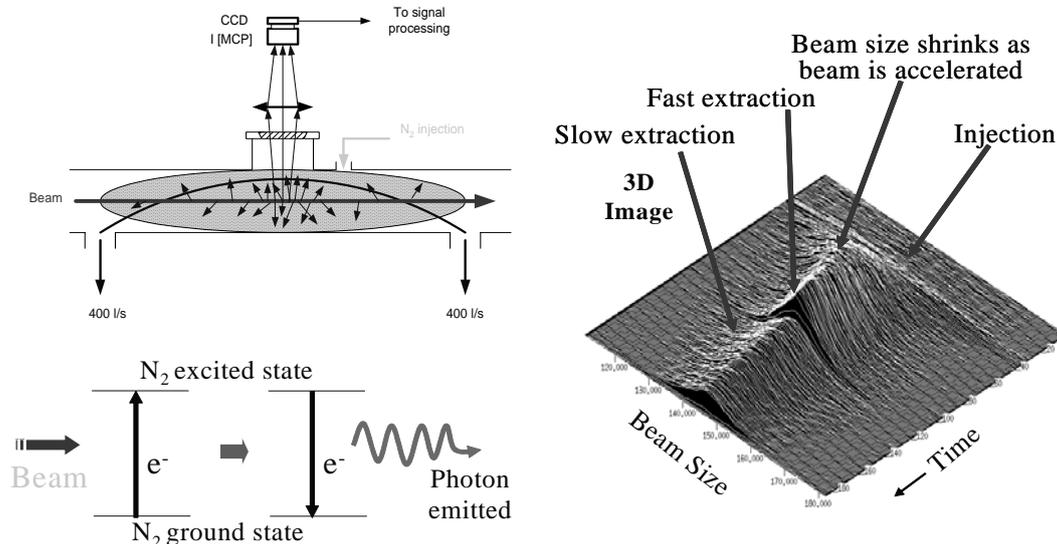


Fig. 22 Principle of luminescence monitoring and a beam measurement example from the CERN-SPS.

Most users consider both the residual gas ionisation and luminescence profile monitors to be semi-quantitative and not be relied upon for absolute emittance measurements, even after calibration

against some other instrument such as a wire scanner. Their virtual transparency for the beam, however, makes them useful for the continuous on-line tracking of beam size.

4.5 Synchrotron Radiation Monitors

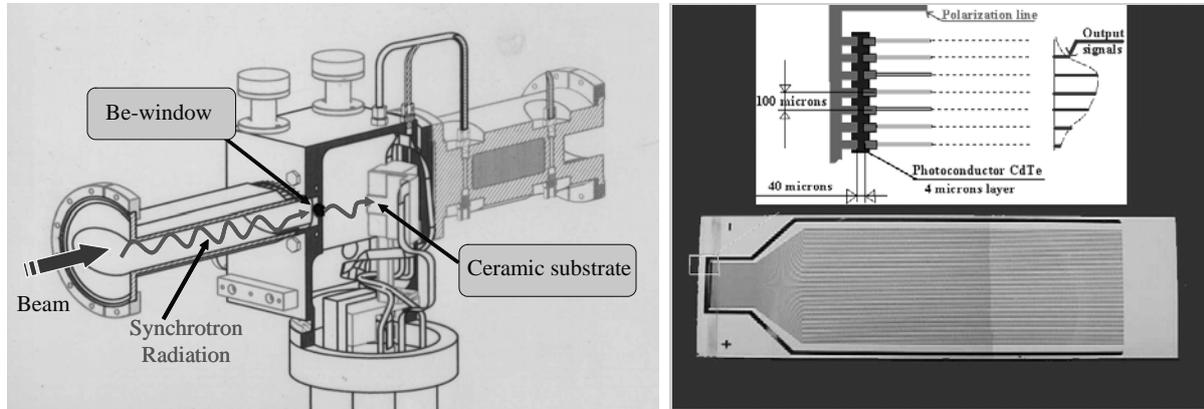


Fig. 23 The CERN-LEP BEXE detector based on cadmium telluride photo-conductors.

Synchrotron radiation monitors are limited to highly relativistic particles and offer a completely non-destructive and continuous measurement of the 2-dimensional density distribution of the beam. These monitors make use of the light produced when highly relativistic particles are deflected by a magnetic field. They are therefore usually positioned to make use of parasitic light produced by a dipole magnet in the machine or behind a purpose built “wiggler” magnet in which the beam is deflected several times to enhance the photon emission.

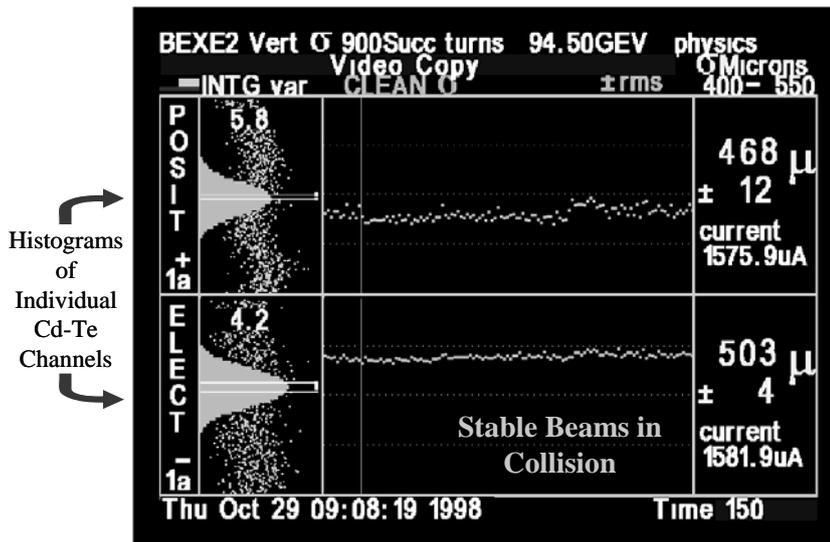


Fig. 24 Tracking vertical beam sizes with the BEXE detector during electron-position collisions.

The most common way of measuring the beam size with synchrotron radiation is to directly image the extracted light using traditional optics and a camera. The spatial resolution for such systems is usually limited by diffraction and depth-of-field effects. If the beam is sufficiently relativistic then the photon emission extends into the hard X-ray region of the spectrum and X-ray detectors can be used, for which diffraction effects can be completely disregarded. Such an instrument, based on

cadmium-telluride (CdTe) photo-conductors, was used at the CERN-LEP [17] to measure rms beam sizes down to 300 μm with a resolution of some 10 μm (see Fig. 23). The detector consisted of 64 voltage biased CdTe photo-conductors of 4 μm thickness and spaced by 100 μm on a ceramic substrate. Each photo-conductor was followed by its own individual charge amplifier. By reading out the signal from each cell the beam profile could be reconstructed. The interesting feature about such photo-conductors is that they allow real-time measurements with data acquisition rates up to 100kHz. In addition they are extremely radiation resistant, accepting doses beyond 10^{12} Grays. These detectors were heavily used towards the end of CERN-LEP operation to optimise the luminosity by tracking the electron and positron vertical beam size during collision (see Fig. 24).

5. BEAM LOSS MONITORING

Beam loss monitors (BLMs) have three main uses in particle accelerators:

- **Damage prevention** - Beam loss may result in damage to accelerator components or the experimental detectors. One task of any BLM system is to avoid such damage. In some accelerators it is an integral part of the protection system, signalling the beam abort system to fire if a certain loss rate is exceeded. This is of vital importance to the new generation of superconducting accelerators, for which even fairly small beam losses in the superconducting components can lead to magnet quenches.
- **Diagnostics** - Another task of BLM systems is to identify the position (and time) of unacceptable beam losses and to keep the radiation level in the accelerator and its surroundings as low as possible.
- **Luminosity optimisation** - BLMs can also help in the tuning of the machine in order to produce the long lifetimes necessary for improved luminosity.

The job of the BLM system is to establish the number of lost particles at a certain position within a specified time interval. Most BLM systems are mounted outside the vacuum chamber, so that the detector normally observes the shower caused by the lost particles interacting in the vacuum chamber walls or in the materials of the magnets. The number of detected particles and the signal from the BLM should be proportional to the number of lost particles. This proportionality depends on the position of the BLM with respect to the beam, the type of lost particles and the intervening material. It also, however, depends on the momentum of the lost particles, which may vary by a large amount during the acceleration cycle. One has to distinguish between two types of losses:

- **Fast losses** – where a large amount of beam is lost over a very few turns.
- **Slow losses** – where partial beam loss occurs over some time (circular machines) or distance (LINAC, transport lines). In storage-rings, the lifetime is defined by slow losses. There are many reasons for these losses and a BLM system is very helpful for finding out what is happening in the machine. In superconducting accelerators a BLM system can also prevent beam loss induced quenches caused by these slow losses.

The fact that BLM systems have to cover both of these cases means that they are required to function over a very large dynamic range, typically in the region of 10^4 to 10^6 .

5.1 Long Ionisation Chambers

In 1963, Panowsky [18] proposed a BLM system for SLAC which consisted of one long (3.5 km) hollow coaxial cable filled with Ar (95%) + CO₂ (5%), mounted on the ceiling along the LINAC, about 2m from the beam. When a beam loss occurs, an electrical signal is produced which propagates to both ends of the cable. Position sensitivity is achieved by comparing the time delay between the direct pulse from one end and the reflected pulse from the other. The time resolution is about 30ns (~ 8 m) which, for shorter versions, can be reduced to about 5ns. This principle of space resolution works for linear accelerators and transport lines with a bunch train much shorter than the machine and with relativistic particles. For particles travelling significantly slower than the signal in the cable the

resolution of multiple hits in the cable becomes difficult. In this case, and for circular machines, it is necessary to split the cable. Each segment has to be read out separately, with a spatial resolution which becomes approximately equal to their length.

5.2 Short Ionisation Chambers

Short ionisation chambers are used in many accelerators (see e.g. Ref. [19]). They are more or less equally spaced along the accelerator with additional units at special positions such as aperture restrictions, targets, collimators, etc. The chamber provides some medium with which the secondary particles created by the beam loss can interact, typically a gas such as nitrogen or argon. This interaction produces electron-ion pairs which are collected by a series of high voltage gaps along the length of the chamber. The resulting current is then measured and is proportional to the beam loss at the location of the monitor. An example of a CERN-SPS ionisation chamber is shown in Fig. 25.

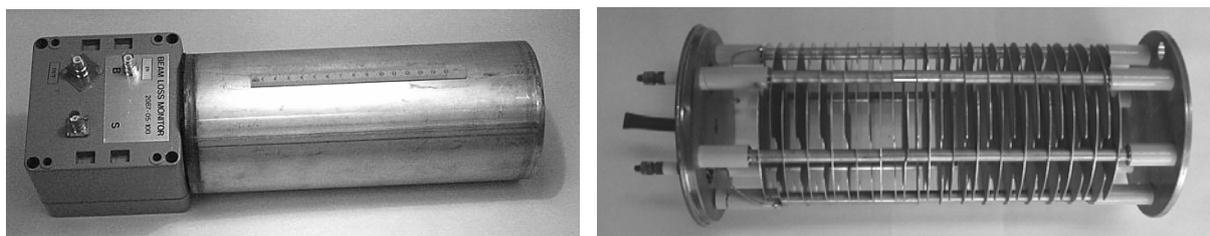


Fig. 25 A CERN-SPS ionisation chamber used for beam loss monitoring.

5.3 Scintillation Counters

In the case where losses occur in a machine without a full BLM system, a plastic scintillator with photomultiplier readout is often temporarily installed. Such systems have a well known behaviour, but the radiation damage of the plastic scintillator restricts their long term use. Liquid scintillators are not susceptible to such damage and have been installed in some accelerators [20, 21]. Such BLMs can be very fast, with pulse rise times of around 10ns, but suffer from drift in the photomultiplier gain.

5.4 Aluminum Cathode Electron Multipliers

In such detectors the sensitivity of photomultipliers to ionising radiation is increased by replacing the photocathode with an aluminium foil. This foil then works as a secondary electron emitter when irradiated. A BLM system consisting of Aluminum Cathode Electron Multipliers (ACEMs) is installed in the CERN-PS and PS-Booster [22]. It is very fast, with signal rise times in the order of 10ns, but is rather expensive since the ACEM is not a standard tube of photomultiplier manufacturers.

5.5 PIN Photodiodes

For circular electron accelerators which emit hard synchrotron radiation it is difficult to distinguish between the beam loss distributions and the synchrotron radiation background using traditional BLM techniques. In DESY-HERA, an electron-proton collider, the warm electron and a superconducting proton rings are in the same tunnel. Protection of the superconducting proton beam magnets from beam loss induced quenches must therefore rely on a BLM system which sees only the proton beam losses and not the synchrotron radiation background. In this case back to back PIN photodiodes are used to distinguish between the hadronic shower created by beam losses and the synchrotron radiation [23]. The charged particles will interact with both photodiodes, giving a coincidence signal, while the photons will be absorbed by the first diode. In contrast to the charge detection of most other BLM systems, PIN photodiode detection depends on counting coincidences, with the count rate proportional to the loss rate so long as the number of overlapping coincidences is small.

6. LUMINOSITY MONITORING

Luminosity Monitors are specific to colliders, since they measure the collision rate of the two counter-rotating particle beams. The following formulae define luminosity and related quantities:

Luminosity:
$$L = f_{rev} \frac{MN^2}{4\pi\sigma_*^2}$$

Normalized emittance:
$$\varepsilon_N = \gamma \frac{\sigma_*^2}{\beta_*}$$

Beam-beam tune shift:
$$\Delta\nu_{bb} = \frac{Nr_p}{4\pi\varepsilon_N}$$

where f_{rev} is the revolution frequency, M the number of bunches, N the number of particles per bunch, σ_* the rms beam size at the collision point, β_* the beta function at the collision point and r_p the particle radius.

Since the counting rates of the experiments are directly proportional to the luminosity, the aim of the accelerator operators is to maximise the luminosity. This can be done by having a large number of particles per bunch, many bunches and small beams sizes at the interaction point.

In this section, luminosity monitoring will be taken as an example of beam instrumentation engineering, i.e. the whole process from selecting an appropriate physics process to system design. The system presently under development for the LHC has been chosen for this case study, as all the documents and figures are easily at hand. The following steps will be treated:

- Functional requirements
- Choice of physics process
- Location of the sensor
- Choice of the sensor

6.1 Functional requirements of the LHC luminosity monitor

The monitor under discussion is aimed at giving a relative luminosity reading for machine optimisation, but it is not required to give the absolute luminosity (as defined above) for the calculation of the underlying cross-section of the experimental physics processes. Hence the system does not need an absolute calibration. In addition, the monitor is to be used to study the variation in luminosity between the individual bunches of the LHC. This means that the detector has to have the bandwidth of the individual bunch crossings, which is 40 MHz. The expected difference in luminosity between bunches is very small, so a resolution of 1% is required.

6.2 Choice of the physics process for the detector

Since any count-rate coming from the collision point of the beam particles can be used as a signal for luminosity monitoring there is a wide choice of physics processes that could be used for this measurement. Due to both cost and integration issues the detector has to be small in size, hence huge detector arrays covering a large solid angle of secondary particle production can be excluded. This eliminates all well identified physics processes producing particles with large transverse momenta. Diffractive beam particle interactions, for which at least one of the incoming protons dissociates into a leading (high energy) neutron plus other secondary particles have therefore been considered as a source for the luminosity signal. Due to the nature of this process, most of the secondary neutrons are emitted into a very small solid angle in the forward direction. The properties of this interaction are pretty well known from lower energies, so that the cross section can be assumed to within a 10% accuracy. This process has been chosen as the basis for LHC luminosity monitoring.

impossible. This, in addition to the other stringent requirement of a bandwidth of 40MHz meant that only two different detector technologies were retained and studied in detail:

1. A polycrystalline cadmium telluride (CdTe) detector array [24]
2. A pressurised ionisation chamber with continuous gas exchange [25]

The first option has the advantage of high bandwidth, but the radiation hardness is not completely demonstrated. The second option is believed to withstand the high radiation levels but, even after some years of optimisation, the bandwidth is still somewhat too low. Due to the high radiation doses expected, however, the most likely choice will be the ionisation chamber. Fig. 28 shows the design of the ionisation chamber presently used with test beams.

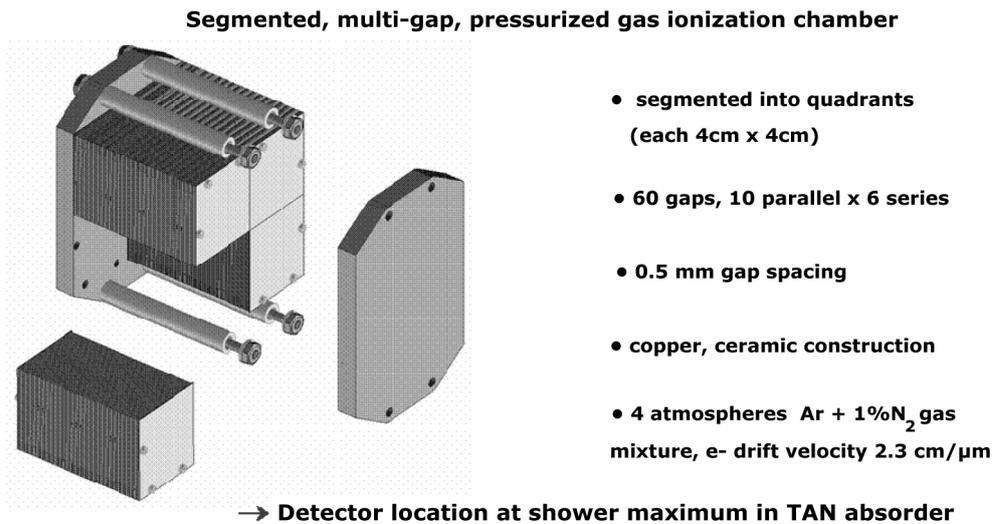


Fig. 28 Schematic of the ionisation chamber for LHC luminosity monitoring.

6.5 Electronics

The most critical element in the system is the detector itself, due to the requirements for bandwidth and radiation hardness. Once a signal is produced, it will be sent out of the TAN block via special radiation hard cables (stainless steel with a mineral insulator) to standard preamplifiers and digitising electronics. The signals will be recorded for each individual bunch crossing and averaged over many machine turns in order to produce the luminosity information for the control room.

7. SOME EXAMPLES OF BEAM DIAGNOSTICS

This section is meant to serve as general entertainment for those readers who have made it to here with their reading! Two examples from CERN-LEP operation have been selected, and show how difficult it can be to interpret primary measurements and decide on the right actions for solving a problem in an accelerator.

7.1 The CERN-LEP beam does not circulate!

The schedule for the CERN-LEP accelerator had a very regular structure. Every year LEP was used for about 8 months for physics beams followed by a 4 month maintenance and upgrade shutdown. During this shutdown major intervention work was sometimes carried out on the machine. At the next start-up it was therefore often expected that typical problems such as inverted magnet polarities would have to be overcome. One year, the start-up was particularly bad, with neither the electron beam nor the positron beam capable of being injected and made to circulate. Several hours were used to check all vacuum conditions, power supply currents, settings of the radio frequency system, injection deflectors

and so on, but nothing indicated a severe problem. Finally people started to look in detail at the measured beam trajectory from the injection point onwards. A typical example for the positron beam is shown in Fig. 29.

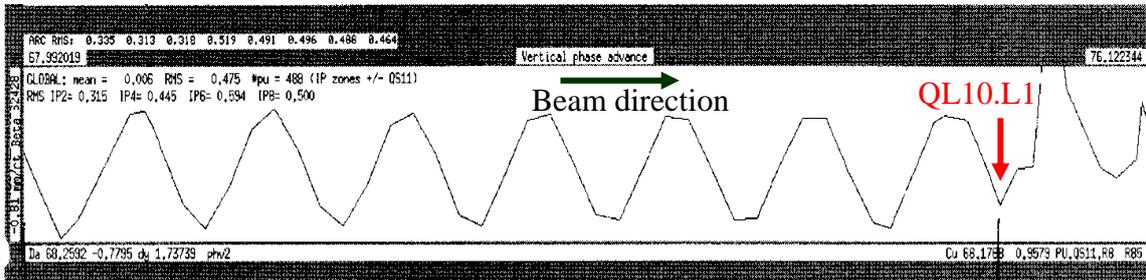


Fig. 29 Measurement of the LEP phase advance when beams did not circulate.

What is actually shown in Fig. 29 is the phase advance from one beam position monitor to the next, as calculated from the measured beam trajectory. At a particular quadrupole (QL10.L1) the regular pattern is distorted. Additional measurements also indicated that most of the beam was lost at this point. The first conclusion was to suspect a problem with this quadrupole. People went in, measured the current in the quadrupole, checked its polarity, inspected its coils, but could not find anything abnormal. The indications of the beam measurements, however, clearly pointed to a problem at this location. After many discussions and potential hypotheses it was decided to open the vacuum chamber. It should be noted that this was a major intervention, causing a stop of the accelerator for at least one day. One can understand the surprise of the intervention team when they looked into the open vacuum chamber and saw a beer bottle!!!

During the shutdown intervention, somebody had sabotaged the LEP accelerator and had inserted a beer bottle into the beam pipe (Fig. 30)! What had upset the operation team most at the time was the fact that it was a very unsocial form of sabotage - the bottle was empty!

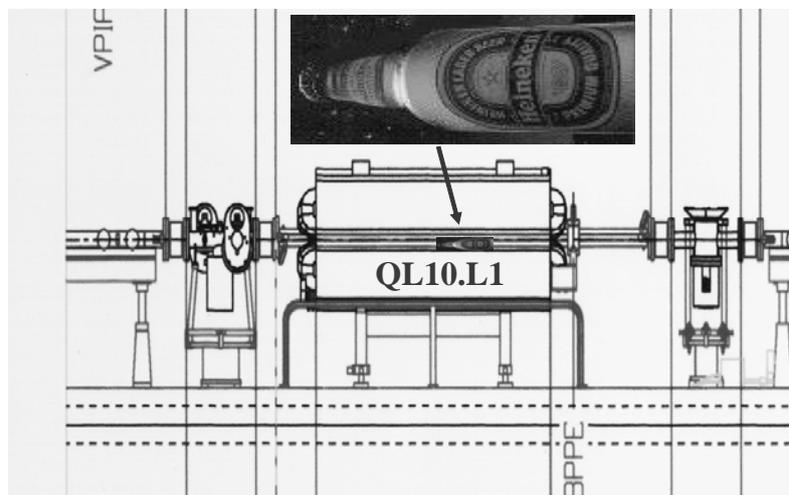


Fig. 30 The mystery of the beam circulation problem in LEP is solved!

7.2 The beam gets lost during the beta squeeze

This again is one of the stories from LEP operation which took several hours of beam diagnostics to solve. The problem in itself is pretty complex, and therefore requires some additional explanations beforehand.

The acceleration of the particle beams and the change of the lattice function in the insertion regions in order to get smaller values of the beta-function at the crossing point (hence higher luminosity) are so called “dynamic processes”. The presence of the beam requires that all actions are well synchronised. For example, the power converters of all relevant magnetic circuits have to be controlled such that beam parameters like the closed orbit, tunes and chromaticities stay within tolerance during the dynamic process. In order to achieve this, the behaviour of these beam parameters is periodically measured as a function of time and the corresponding power converter tables are updated.

During one period of LEP operation it was found that the beams were lost during the beta squeeze. Shortly before the total loss of the beams a significant beam loss was measured. As standard practice when encountering such problems, the engineer in charge (EIC) launched a new machine cycle with diagnostics facilities such as “tune history” (the measurement of the betatron tunes as a function of time – see Section 3) switched on. This indicated that the vertical tune moved out of tolerance during the beta squeeze. Fig. 31 shows an excerpt from the actual LEP logbook entry of this event.

01:40 Straight through to 98 GeV.
 At ~97-98 GeV e^- large vertical oscillation
 OPAL trigger. Maybe a bit too ambitious
 Tune history 01-12-40 fill 7065
 → nothing particularly nasty.
 Big radiation spikes in all expts.
 22 GeV 4Q50 Breakpoint at 93 GeV.
 640 μ A .234 / .164 5.27 mA
 93 GeV 4Q50 01-58-36 VEMS nic
 Tune history 01-50-25 fill 7066

Fig. 31 Excerpt from the LEP logbook when beams were lost during the beta squeeze.

As a result of this observation, the EIC launched another cycle, but inserted a breakpoint (to stop the accelerator cycle) just before the critical moment in the beta squeeze when the deviation in tune occurred. Having reached that breakpoint the tunes were measured statically and found to be perfectly within tolerance. The beta squeeze was then executed step by step, and to the big surprise of the operations crew, the tunes were found to be correct at all times. The beam had passed the beta squeeze like on an ordinary day! But on the next attempt, without a break in the cycle, the beam was again lost at the same moment, and several people scratched their heads to find an explanation.

Finally, the following measurement was made. The machine was prepared and a breakpoint again inserted just before the critical beam loss. Once this point was reached, the EIC requested the execution of one further step in the beta squeeze. The facility by which one could execute a single step in a dynamic process had the additional feature that one could specify the rate of current change of any machine element. This current rate limitation was changed from 25 A/s (nominal) down to 2.5 A/s on consecutive steps. The corresponding tune history (the result from the vertical plane is plotted on the lower graph) is shown in Fig. 32.

One can clearly see that a huge (negative) tune excursion occurred when the step was executed at the nominal rate. This observation led the EIC to the right conclusion, which was that one of the power supplies was able to deliver the demanded current statically, but not dynamically. When this

was discussed with experts from the power converter group, they indicated that the power supplies for the superconducting insertion quadrupoles were built as two blocks in series, each of them able to deliver the necessary current (each block typically 1000 A/10 V). Both of these blocks were required to have enough voltage margins to enforce a current change against the inductance of the quadrupole coil. This then explained the whole story. One of these blocks was faulty, but since the power converter could deliver its (static) current, it was not detected by an alarm or surveillance circuit. In the static case the working, single block could deliver the requested current. If the dynamic rate was too high, however, this single block could not provide enough current leading it to lose synchronism with the other power converters. This resulted in the large tune change observed and ultimately the total beam loss.

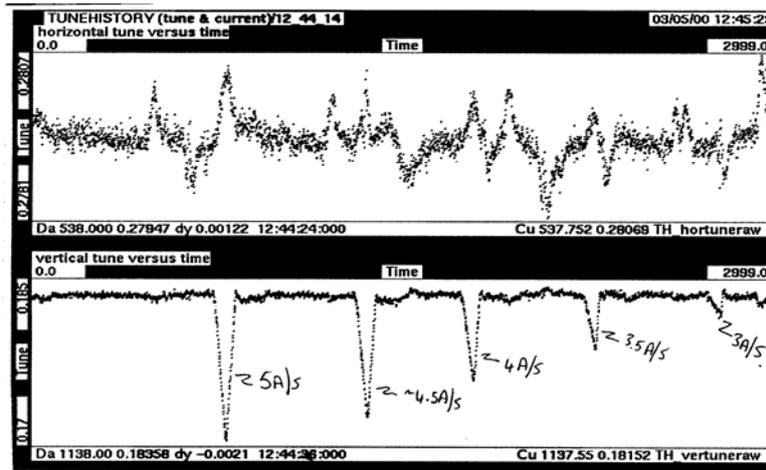


Fig. 32 The LEP tune history during the beta squeeze for various power converter ramp rates.

These two examples show the enormous potential of beam instrumentation if they are used in the right combination by intelligent people.

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