Beam Instrumentation and Diagnostics
Part 1

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CAS
Introductory level course on
Accelerator Physics

Resources and References

- Peter Forck*: Lecture on Beam Instrumentation and Diagnostics* at the Joint University Accelerator School (JUAS),
  see also the extended Bibliography
  http://www-bd.gsi.de/conf/juas/juas.html
- M.G. Minty and F. Zimmermann: *Measurement and Control of Charged Particle Beams*, Springer Verlag 2003, (book).
- Conference series: IBIC (International Beam Instrumentation Conference), IPAC (International Particle Accelerator Conference), historic: DIPAC (Workshop on Beam Diagnostics and Instrumentation for Particle Accelerators), BIW (Beam Instrumentation Workshop)
- CERN Accelerator Schools (CAS):
  http://cas.web.cern.ch/cas/CAS%20Welcome/Previous%20Schools.htm and
  http://cas.web.cern.ch/cas/CAS_Proceedings.html
  - Rhodri Jones et al.: *Introduction to Beam Instrumentation and Diagnostics*, CERN-2014-009.
  - Daniel Brandt (Ed.), 2008 CAS on *Beam Diagnostics for Accelerators*, Dourdan, CERN-2009-005 (2009).
  - Heribert Koziol*, Beam Diagnostic for Acclerators*, Univ. Jyväskylä, Finland, 1992, CERN 94-01, http://cas.web.cern.ch/cas/CAS%20Welcome/Previous%20Schools.htm
- Jacques Bosser (Ed.), *Beam Instrumentation*, CERN-PE-ED 001-92, Rev. 1994

Overview – Part 1

- Introduction
- Beam Position Monitors
- Beam Current Monitors
- Transverse Profile Monitors
- Beam Loss Measurement for Protection and Diagnostics

Introduction

Introduction

- Beam Instrumentation is a very wide subject; with a large range of technologies and fields involved, including:
- Accelerator physics
  - understand the beam parameters to be measured
  - distinguish beam effects from sensor effects
- Particle physics and detector physics
  - understand the interaction of the beam with the sensor
- RF technology
- Optics
- Mechanics
- Electronics
  - Analogue signal treatment
    - Low noise amplifiers
    - High frequency analogue electronics
  - Digital signal processing
  - Digital electronics for data readout
- Software engineering
  - Front-end and Application Software

Introduction, cont’d

- Aim: assist in commissioning, tuning and operating the accelerator and to improve performance

- In this presentation:
  - Explain working principles of some of the most important instruments
  - Give indication on achievable performance
  - Give selected examples from operating machines and current developments

Measured Quantities

- Beam intensity
- Ideally: 6D phase space of the beam
- Real measurements: mean values and 1D-projection, some 2D-projections
  - Transverse position (mean x, y) → trajectory and orbit
  - Transverse profile
  - Bunch length, bunch shape
  - Mean momentum and momentum spread
  - Emittance and 2D phase space reconstruction (transverse and longitudinal)
  - Beam halo measurements
- Tune, chromaticity, coupling, beta function, dispersion
- Beam Losses
- Polarisation
- Luminosity

Classifications and Selected Devices

- **Singe pass machine** (LINAC and transport lines, also dedicated measurement lines ↔ **multi pass machine** (synchrotron)
- **Total Beam Energy** (beam particles x particle energy) low ↔ high
- **Non-intercepting** ↔ **Intercepting / Perturbing** ↔ **Destructive.** Often depending on:
  - Beam quantitates (intensity, energy, particle type)
  - Single pass or multi pass

- Different devices (techniques) to measure the same quantity ↔ Same device to measure different quantities

PROPERTY MEASURED →	Intensity/charge	tr. Position	tr. Size/shape	tr. Emittance	Beam Halo	Beam Loss
Current transformers	●					
Faraday cup	●					
Pick-ups	•	●				
Secondary emission monitors	•	●	●	●		
Wire scanners		●	●	●	•	
Scintillator screens		●	●	•		
OTR screen		●	●			
Residual-gas profile monitors		●	●	●		
Beam loss monitors						●

- Different Accelerator Laboratories have different names for the same type of device!

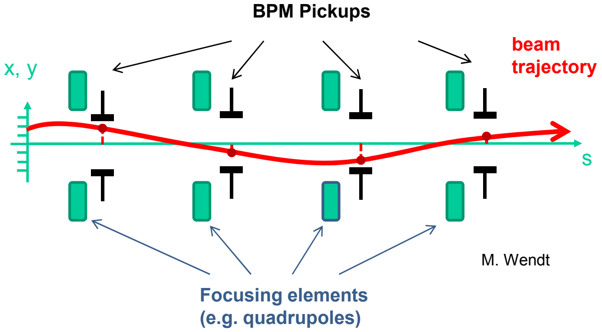
Harsh Environment

- Radiation (single event effects, radiation ageing, activation)
- Many sources of measurement noise and background
  - Place readout close to detector, but → radiation
- RF heating by the beam
- Accessibility and maintenance
- Sometimes: cryogenic temperatures
- Mostly: must operate in vacuum and be UHV compatible

Beam Position Monitors

Capacitive Pick-Ups for Bunched Beams

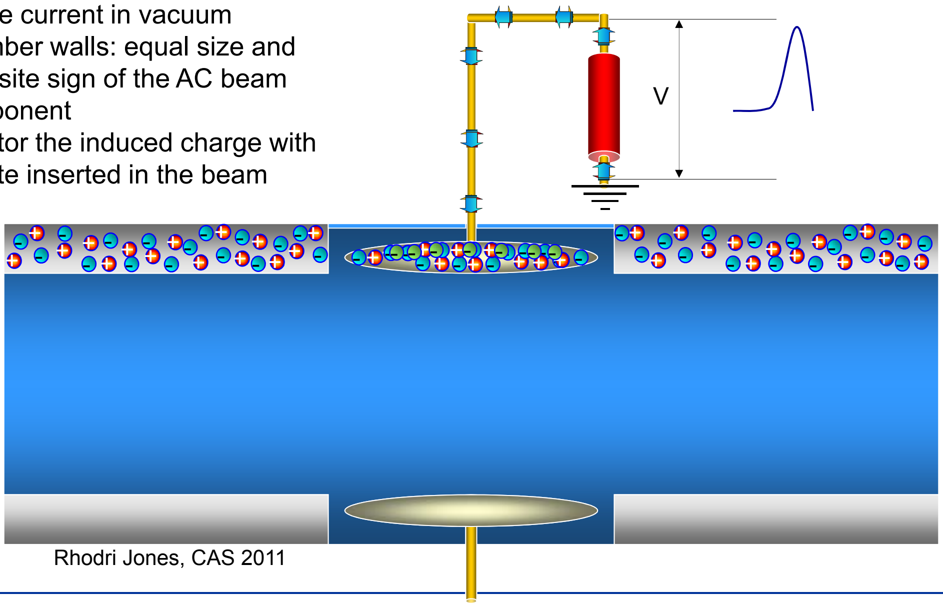
- Among the most numerous instruments
- Measurements:
  - Transverse beam position (typically next to focusing elements)
    - Beam trajectory or closed orbit
    - injection oscillations
  - Tune and lattice function in synchrotrons



M. Wendt

Capacitive Pick-Up – The Principle

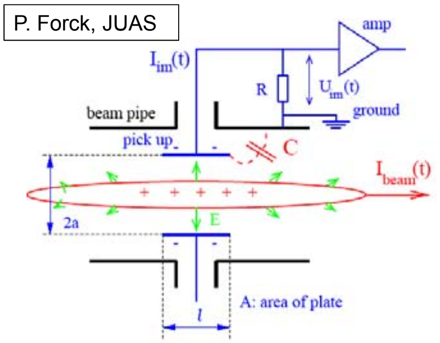
- Image current in vacuum chamber walls: equal size and opposite sign of the AC beam component
- Monitor the induced charge with a plate inserted in the beam pipe

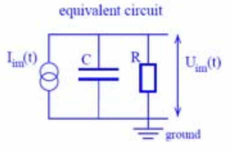


Rhodri Jones, CAS 2011

Schematics and Simplified Equivalent Circuit

P. Forck, JUAS





$$U_{im}(\omega) = \frac{R}{1 + i\omega RC} \cdot I_{im}(\omega)$$

$$I_{im} = \frac{A}{2\pi a l}\left(-\frac{l}{\beta c}\frac{dI_{beam}}{dt}\right) = \frac{A}{2\pi a l}\frac{1}{\beta c} i\omega I_{beam}(\omega)$$

frequency domain: $I_{beam} = I_0 e^{-i\omega t}$

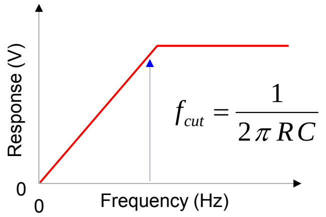
U_{im} … voltage measured due to image current
R … amplifier input resistor
ω … frequency
βc … beam velocity

$$U_{im}(\omega) = \frac{A}{2\pi a} \cdot \frac{1}{\beta c} \cdot \frac{1}{C} \cdot \frac{\mathbf{i\omega RC}}{\mathbf{1 + i\omega RC}} \cdot I_{beam}(\omega)$$

$\equiv Z_t(\omega, \beta) \cdot I_{beam}(\omega)$

Z_t … longitudinal transfer impedance

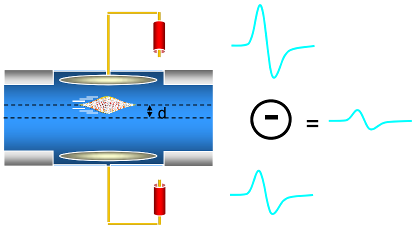
⇒ High pass characteristics with a cut-off frequency, f_{cut}



$$f_{cut} = \frac{1}{2\pi RC}$$

Beam Position

- Signal on each plate is proportional to the beam intensity
- The difference signal (ΔU), top - bottom, or left – right, is proportional to the position of the beam center of mass
- Normalization to the sum signal (ΣU) gives the **position:**
  - $\boldsymbol{x = \frac{1}{S_x(\omega,x,y)} \cdot \frac{\Delta U}{\Sigma U}}$ *(S_x … position sensitivity)*
- The difference signal (ΔU) is normally at least a factor 10 lower than the sum signal (ΣU)
- Difficult to do electronically without some of the intensity information leaking through
- When looking for small differences this leakage can dominate the measurement
- **Resolution** for typical apertures:
  - ≈ tens μm turn-by-turn
  - ≈ μm multi-turn resolution



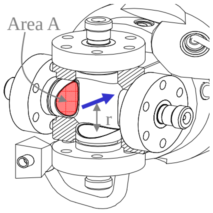
Example: Button Pick-up

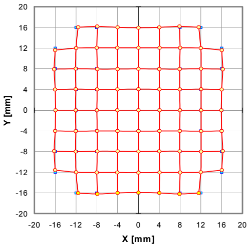
✓ Low cost ⇒ most popular

× Non-linear

- requires correction algorithm when beam is off-centre

$$X = 2.30\cdot10^{-5}X_1^{5} + 3.70\cdot10^{-5}X_1^{3} + 1.035X_1 +$$
$$7.53\cdot10^{-6}X_1^{3}Y_1^{2} + 1.53\cdot10^{-5}X_1Y_1^{4}$$



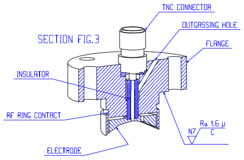


R. Jones, CAS

LHC buttons

$$f_{cut} = \frac{1}{2\pi RC} = \frac{1}{2\pi\times50\Omega\times8pF} = 400MHz$$

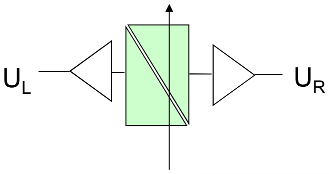
$$Z_{t\infty} = \frac{A}{(2\pi a)\times c\times C_e} = \frac{\pi\times(12mm)^2}{(2\pi\times24.5mm)\times c\times(8pF)} = 1.2\Omega$$

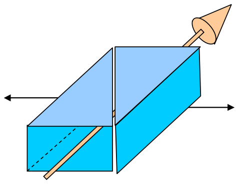


Shoebox Pick-up

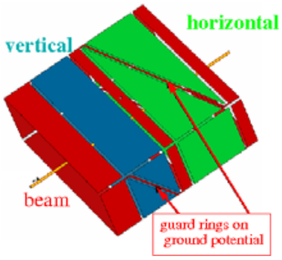
- ΔU gives linear position reading (no geometric correction)
- Condition: Linear cut: projection on the measurement plane must be linear:

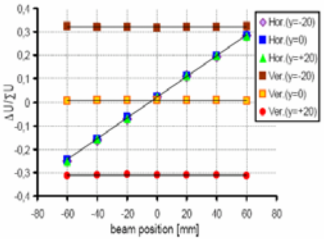
$$x \propto \frac{U_L - U_R}{U_L + U_R} = \frac{\Delta U}{\Sigma U}$$





- Various geometries have been built, example from GSI optimization study (P.Kowina et al., DIPAC 2005)



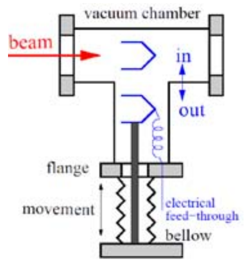


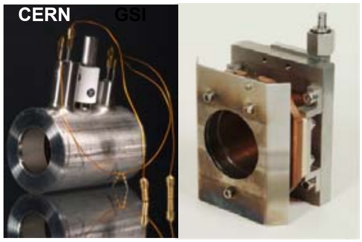
Beam Current

Faraday Cup

- Measurement of the beam’s **electrical charges**
  - Low energies only
  - Particles are stopped in the device → Destructive
  - Sensitive to low currents: down to 1 pA can be measured
  - Creation of secondary electrons of low energy (below 20 eV)
  - Repelling electrode with some 100 V polarization voltage pushes secondary electrons back onto the electrode
  - Absolute accuracy:
    - ≈ 1% (some monitors reach 0.1%)

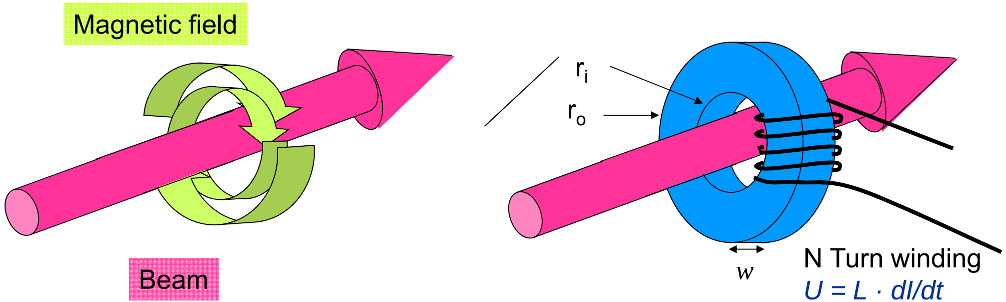
Faraday Cup at GSI LINAC, P. Forck, JUAS





Beam Current Transformer (BCT)

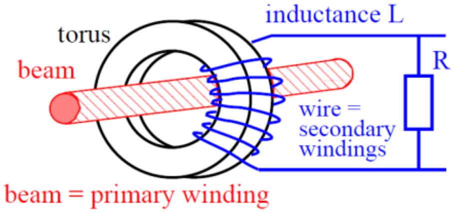
- Measurement of the **magnetic field** of the beam
- Non-interceptive
- Independent on beam energy
- Beam as primary winding of a transformer



U. Raich, CAS

Current Transformers

- Magnetic field of the beam is very low (Example: 1 μA, r = 10cm ⇒ 2 pT; compared to earth magnetic field of ≈50 μT)
- Aim of the Torus:
  - Capture magnetic field lines with cores of high relative permeability
  - Signal strength nearly independent of beam position.
  - CoFe based amorphous alloy Vitrovac: $\mu_r = 10^5$

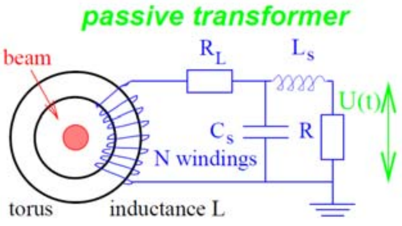


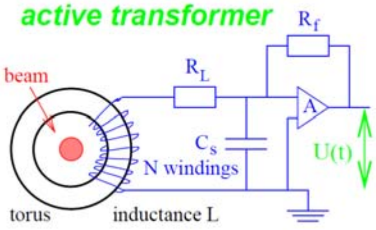
P. Forck, JUAS

Transformer Inductance

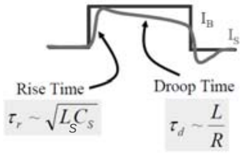
$$L = \frac{\mu_0 \mu_r}{2\pi} w N^2 \ln \frac{r_0}{r_i}$$

Adapt Droop Time with Active Transformer





P. Forck, JUAS



Bunch trains:

- Equal areas
- Baseline shift proportional to intensity

H. Koziol, CAS

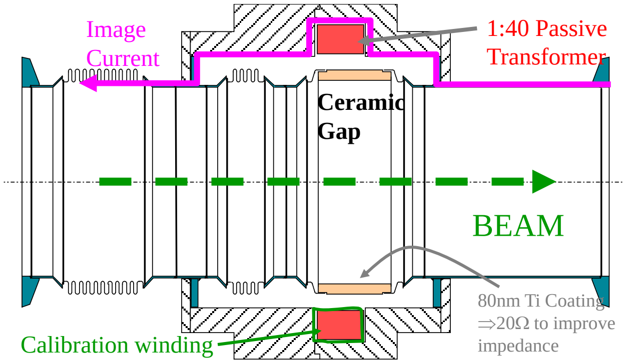
- Use a trans-impedance amplifier (current-to-voltage converter) for observation of beam pulses > 10 µs, e.g. at pulsed LINAC
- Droop time constants of up to 1s
- Longer rise times as well (to reduce high frequency noise of the amplifier

$$\tau_d = \frac{L}{R_f/A + R_L} \approx \frac{L}{R_L}$$

Transformer Housing

- Image current passing outside of the transformer torus
- High permeability material shields the transformer against external magnetic fields

CERN SPS Fast Beam Current Transformer (FBCT)

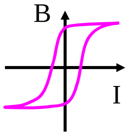


H. Jakob

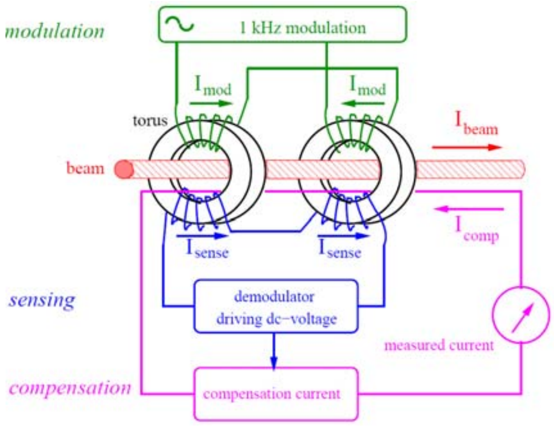
500 MHz Bandwidth; Low droop (< 0.2%/ms)

DCCT: DC Beam Current Transformer

- DC current dB/dt = 0 ⇒ no voltage induced
- Use two **identical** toroids
- Take advantage of non-linear magnetisation curve



- Modulation of opposite sign drives toroids into saturation
- Sense windings measure the modulation signal
  - Signals from the two toroids cancel each other as long as there is no beam

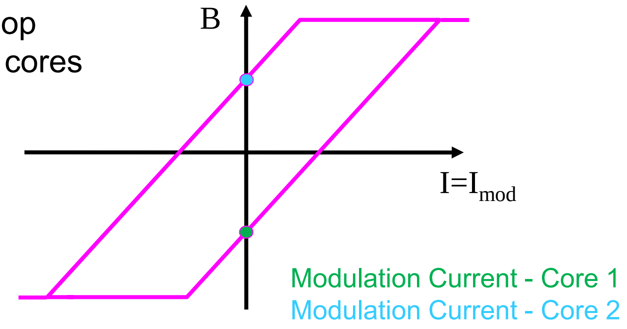


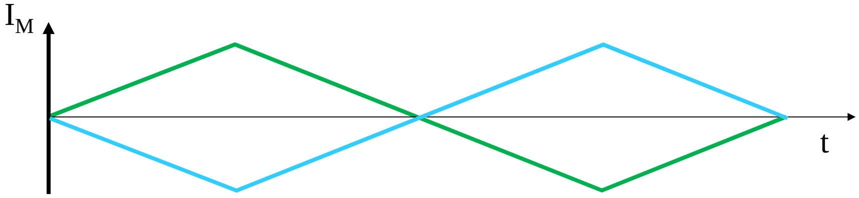
P. Forck, JUAS

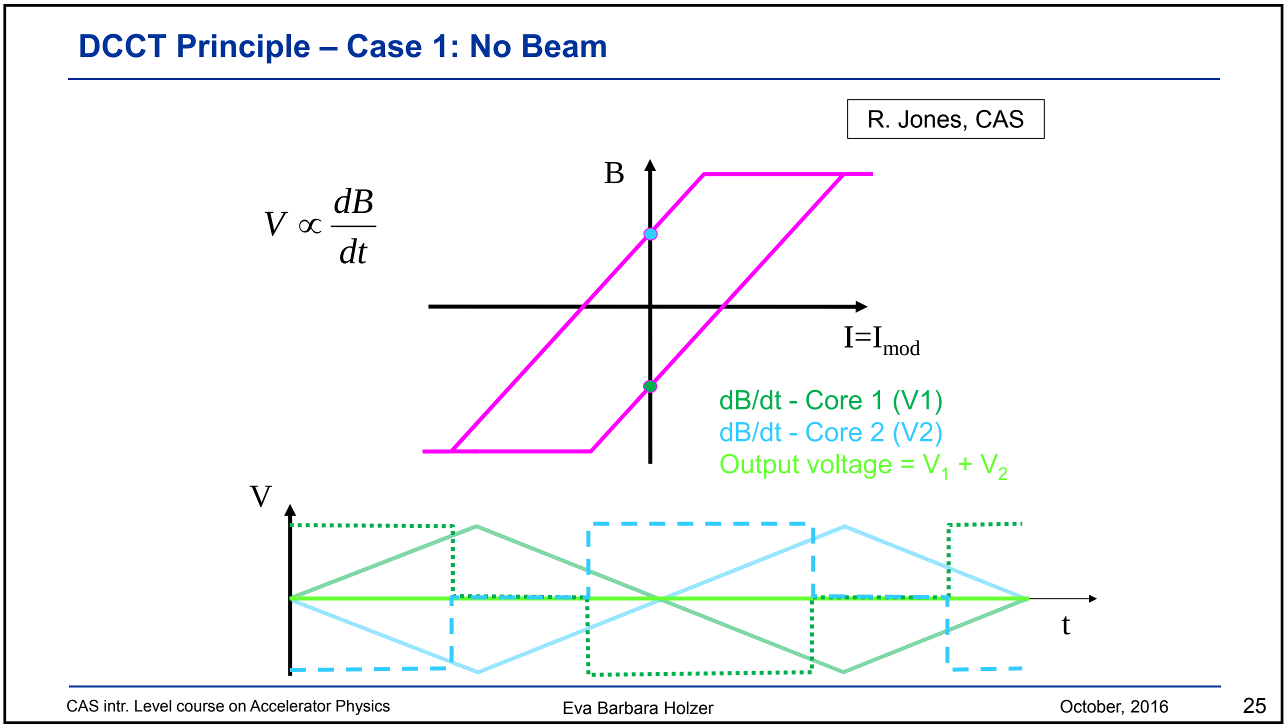
DCCT Principle – Case 1: No Beam

R. Jones, CAS

Hysteresis loop
of modulator cores







DCCT Principle – Case 1: No Beam

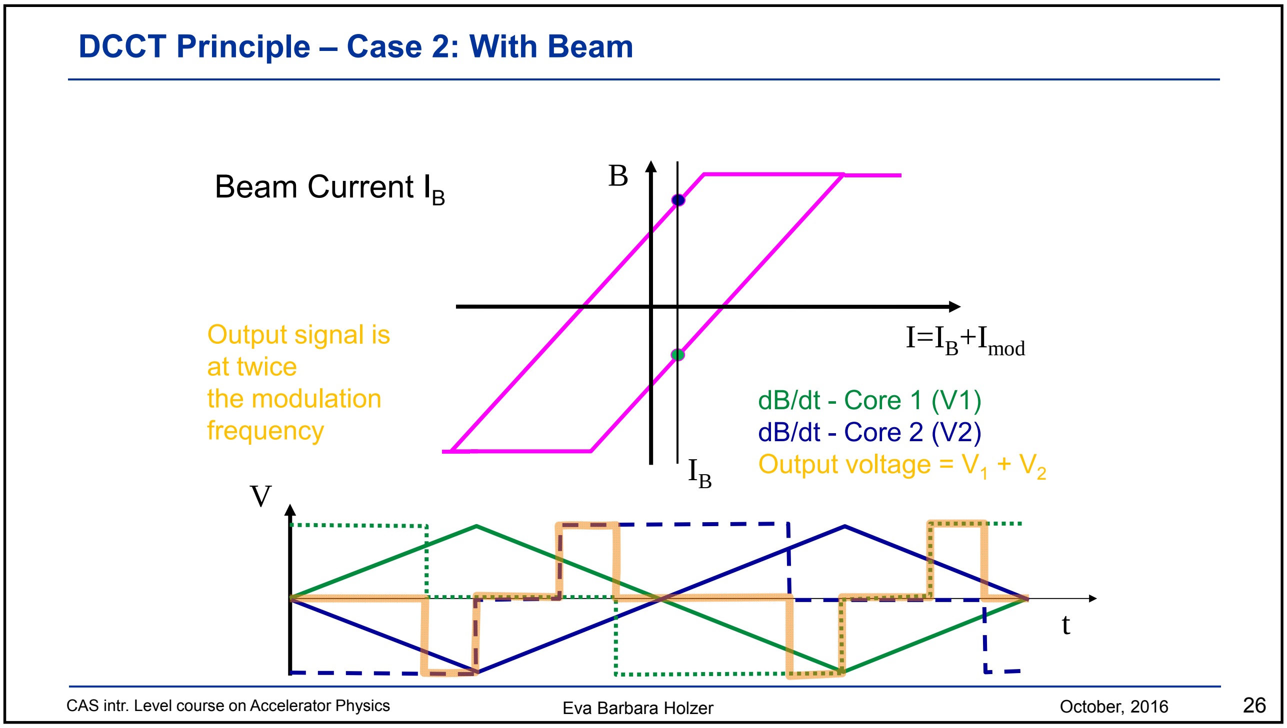
R. Jones, CAS

$$V \propto \frac{dB}{dt}$$

dB/dt - Core 1 (V1)

dB/dt - Core 2 (V2)

Output voltage = $V_1 + V_2$



DCCT Principle – Case 2: With Beam

Beam Current I_B

Output signal is at twice the modulation frequency

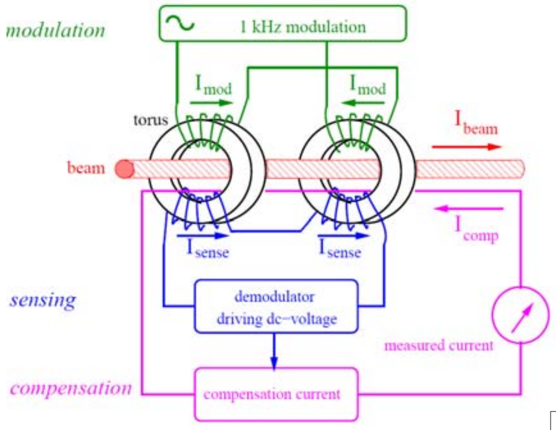
dB/dt - Core 1 (V1)

dB/dt - Core 2 (V2)

Output voltage = $V_1 + V_2$

DCCT in the “Zero Flux” Scheme

- The length of the pulses is a measure for the beam current
- Zero-flux scheme: compensate for the beam current and measure the magnitude of the compensation current



P. Forck, JUAS

Performance

- Achievable performance Fast Beam Current Transformers (FBCT):
  - Absolute accuracy: 1%
  - Reproducibility / relative precision: 0.1%
  - Dynamic range: 10^3 (10^4)

- Performance LHC DC Beam Current Transformers (DCCT):
  - Absolute accuracy: 0.2%
  - Noise floor 2 µA
  - Dynamic range 10^6 (µA – 1A)

Transverse Profile

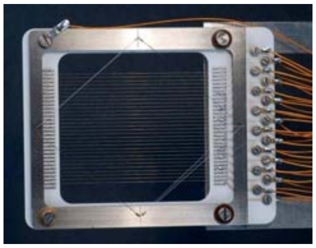
Overview - Beam Profile measurement

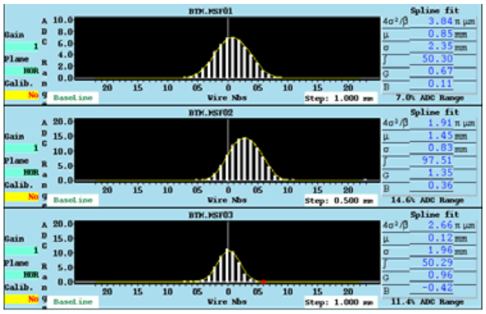
- Methods which intercept the beam with matter:
    - Secondary emission (SEM) grids
    - Screens
    - Wire scanners
  - more or less perturbing to the beam
  - Energies/intensity threshold for safe operation
    - Material damage (e.g. wire sublimation, breakage)
    - Radiation to other machine components (e.g. quenching of superconducting magnets)
- (Quasi) Non-Invasive Methods:
  - Synchrotron light monitors
  - Rest Gas Ionisation monitors
  - Luminescence monitors
  - Laser wire scanner
  - Electron beam scanner
  - Gas screen, gas pencil beams
  - Beam Gas Vertex Detector – designed for absolute measurement

SEM grids and wire scanners:
Used as reference measurement for the other methods

Secondary Emission (SEM) Grids

- When the beam passes through a wire, secondary electrons are emitted, proportional to beam intensity
- The current flowing back onto the wires is measured using one amplifier/ADC chain for each wire
- Clearing field removes liberated electrons
- Problem: thermal emission
- Very high sensitivity, semi-transparent
- Good absolute measurement
- Spatial resolution limited by wire spacing to <≈ 0.25mm
- Dynamic range: ≈ 10^6





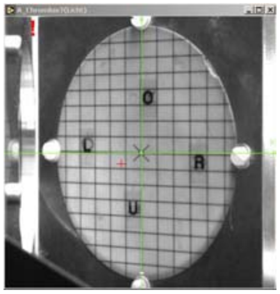
BTM.MSF01 — Step: 1.000 mm — Spline fit: $4\sigma^2/\beta$ 3.84 π µm; µ 0.85 mm; σ 2.35 mm; ∫ 50.30; G 0.67; B 0.11 — 7.0% ADC Range

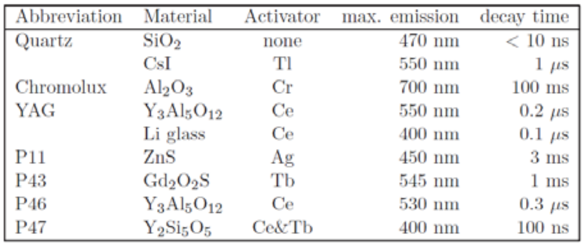
BTM.MSF02 — Step: 0.500 mm — Spline fit: $4\sigma^2/\beta$ 1.91 π µm; µ 1.45 mm; σ 0.83 mm; ∫ 97.51; G 1.35; B 0.36 — 14.6% ADC Range

BTM.MSF03 — Step: 1.000 mm — Spline fit: $4\sigma^2/\beta$ 2.66 π µm; µ 0.12 mm; σ 1.96 mm; ∫ 50.29; G 0.96; B -0.42 — 11.4% ADC Range

Scintillation Screens

- Typically for setting-up with low intensities, thick screens (mm) → emittance blow-up
- Workshop in 2011 at GSI to look at resolution possible with various screen materials: http://www-bd.gsi.de/ssabd/home.htm
- Sensitivities of different materials vary by orders of magnitudes





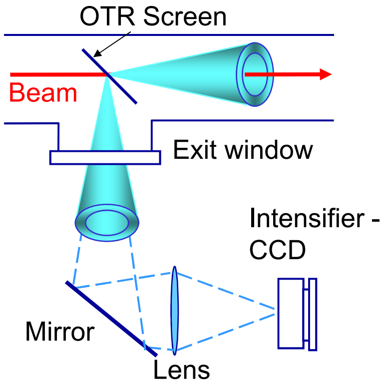
Abbreviation	Material	Activator	max. emission	decay time
Quartz	SiO_2	none	470 nm	< 10 ns
	CsI	Tl	550 nm	1 µs
Chromolux	Al_2O_3	Cr	700 nm	100 ms
YAG	$Y_3Al_5O_{12}$	Ce	550 nm	0.2 µs
	Li glass	Ce	400 nm	0.1 µs
P11	ZnS	Ag	450 nm	3 ms
P43	Gd_2O_2S	Tb	545 nm	1 ms
P46	$Y_3Al_5O_{12}$	Ce	530 nm	0.3 µs
P47	$Y_2Si_5O_5$	Ce&Tb	400 nm	100 ns

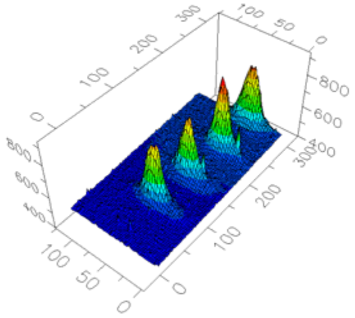
Approximate values for inorganic scintillators

P. Forck, JUAS

Optical Transition Radiation (OTR) Screens

- Radiation emitted when a charged particle beam goes through the interface of two media with different dielectric constants
- Surface phenomenon allows the use of very thin screens (≥ 0.25 μm)
- Much less intercepting, but requires higher intensity

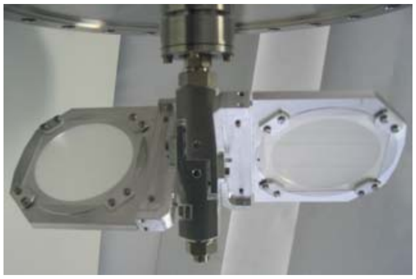


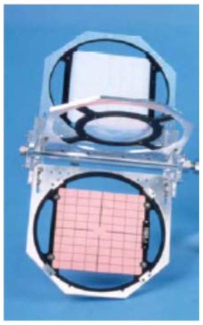


CERN SPS at injection

Beam Profile Monitoring Using Screens

- Combine several screens in one housing e.g.
  - Al_2O_3 scintillation screen for setting-up with low intensity
  - Thin (≈10μm) Ti OTR screen for high intensity measurements
  - Carbon OTR screen for very high intensity operation

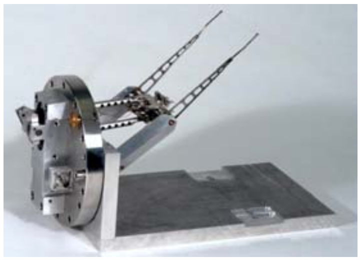


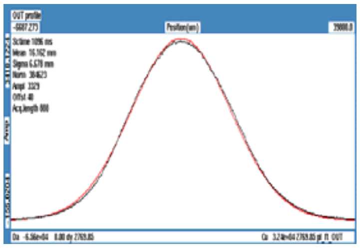


- Cameras:
  - CCD cameras are radiation sensitive
  - Analogue VIDICON camera can be used with high radiation

Wire Scanners

- A thin wire (down to 10 μm) is moved across the beam
  - Has to move fast to avoid excessive heating of the wire
  - Rotational scanner up to 10 m/s with special pneumatic mechanism (linear scanners slower)
- Detection
  - Secondary particle shower detected outside the vacuum chamber e.g. using a scintillator/photo-multiplier assembly
  - Secondary emission current detected as for SEM grids
- Correlating wire position with detected signal gives the beam profile
  - Wire vibrations limit position resolution
- Less invasive than screen or SEM grids



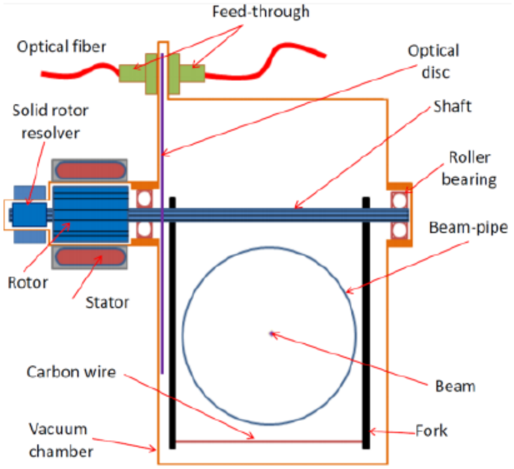


New Wire Scanner being developed at CERN

- Design specifications:

Wire speed	Wire position resolution
20 m/s	< 50 μm +- 2.5 μm

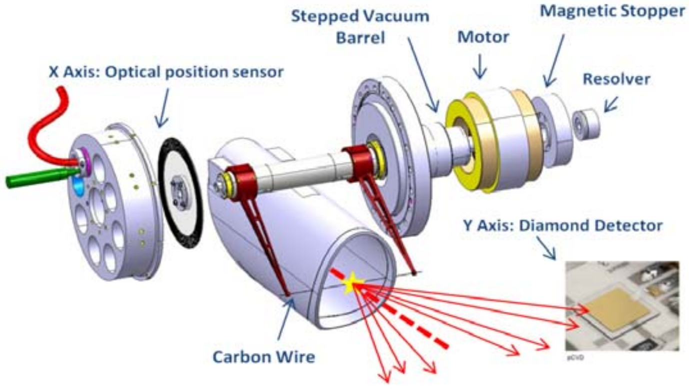
    - Using high resolution angular position sensor
  - Dynamic range: 10^5 - 10^6
    - Usage of sensor with large dynamic (e.g. diamond)
    - Automatic selection of gain range by the electronic
  - Minimize fork and wire deformations
    - Mechanical design (Study of dynamic behavior of fork/wire system)
    - Vibration mode optimized acceleration profile
  - Bunch by bunch measurements
    - 40 MHz digitalization of 25 ns integrated signal
    - Measurements synchronous with bunch clock (LHC and SP
  - 20 kGy over 20 years



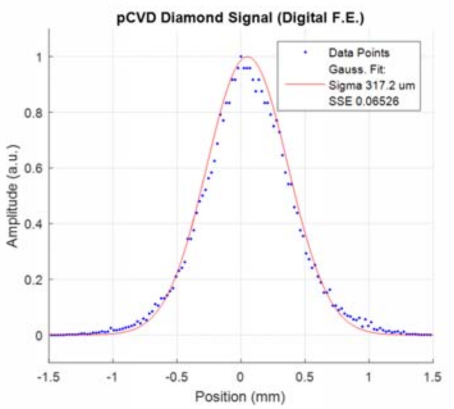
B. Dehning

- Current Wire Scanners at CERN:
  - Dynamic range 100; accuracy 5-10%; spatial resolution 50 μm (linear type) and 200 μm (rotational)

Mechanical Design and Profile Reconstruction



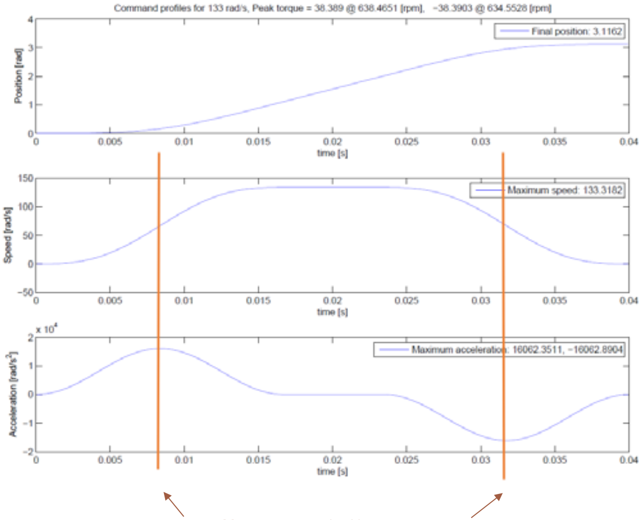
Beam profile measured with pCVD Diamond detector and upgraded acquisition electronics



Jose Luis Sirvent Blasco
https://twiki.cern.ch/twiki/bin/view/BWSUpgrade/SecondariesAcquisitionSystem

X axis: Optical position sensors (50 +- 2.5 μm)
Y axis: signal from diamond detector

Wire Motion Profile



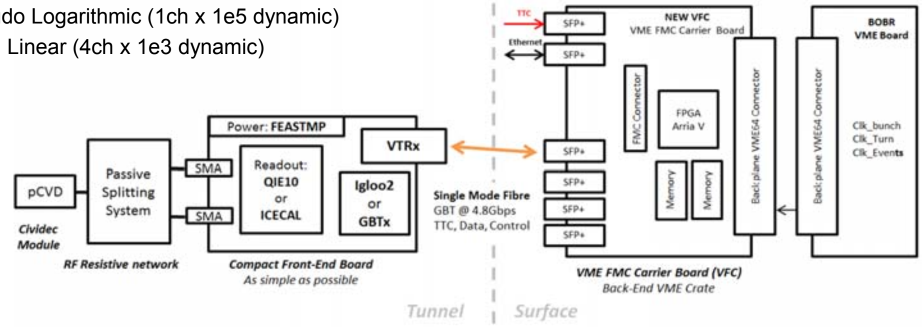
Max torque required here

J.Emery. Beam wire scanner control, monitoring and supplies part. Engineering specification. EDMS #1318827

Acquisition System

Jose Luis Sirvent Blasco
https://twiki.cern.ch/twiki/bin/view/BWSUpgrade/SecondariesAcquisitionSystem

- Radiation hard front-end close to wire scanner
- Optical transmission to surface back-end electronics (VME)
- CERN/BI standard components as much as possible (front-end motherboard (GEFE), Gigabit optical link with 4.8Gbps, back-end VME card (VFC), timing card (BOBR))
- Wire scanner specific components:
    - Front-end FPGA mezzanine card (FMC) holding radiation hard ASIC for Integration & Digitalization (two options investigated, developed at Fermilab for CMS/Atlas and University of Barcelona for LHCb respectively)
        - QIE10 → Pseudo Logarithmic (1ch x 1e5 dynamic)
        - ICECAL_V3 → Linear (4ch x 1e3 dynamic)

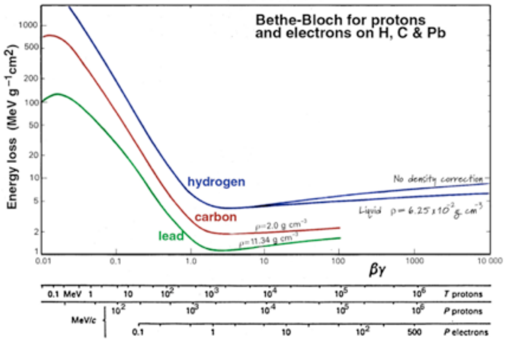


Beam Loss Measurement for Protection and Diagnostics

Detection Principles

- See *Review of Particle Physics*, J. Beringer et al. (Particle Data Group), Phys. Rev. D 86, 010001 (2012) for reference.
- **Ionization**
  - Energy loss by Ionization described by the Bethe-Bloch formula
  - Concept of Minimum Ionizing Particle
    - **dE/dx_{MIP} =**

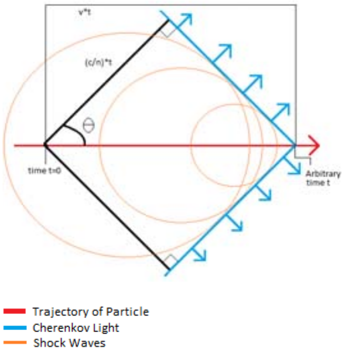
      (1-5) MeV cm^2 g^{-1}



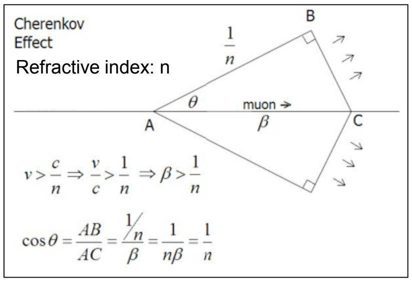
- **Scintillation**
  - Light produced by de-excitation of atom / molecule
  - Yield is proportional to the energy loss
    - **Y = dL/dx = R dE/dx**

Detection Principles cont'd

- **Cherenkov light**



Drawing: Bock and Vasilescu 1999



$$v > \frac{c}{n} \Rightarrow \frac{v}{c} > \frac{1}{n} \Rightarrow \beta > \frac{1}{n}$$

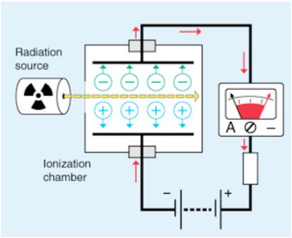
$$\cos\theta = \frac{AB}{AC} = \frac{1/n}{\beta} = \frac{1}{n\beta} = \frac{1}{n}$$

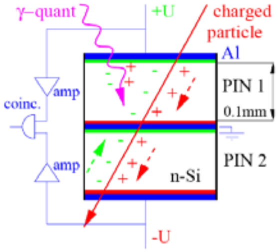
$$photon\ yield : \frac{dN}{dx} = 2 \cdot \pi \cdot \alpha \cdot \sin^2\Theta \cdot \left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2} \right)$$

$\cos\Theta = \frac{1}{\beta \cdot n}$ *with* $\beta > 1/n$; $\alpha = 1/137.036$ *and* $\lambda_{1,2} =$ wavelength interval

Common types of monitors

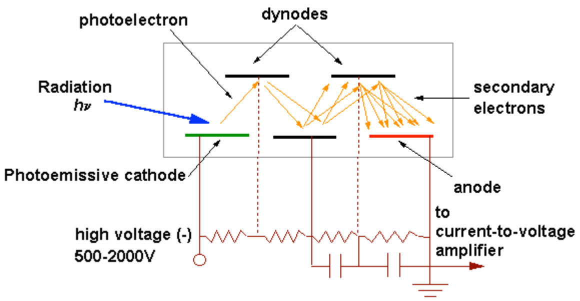
- Short ionisation chamber (charge detection)
  - Typically gas filled with many metallic electrodes and kV bias
  - Speed limited by ion collection time – tens of microseconds
  - Dynamic range of up to 10^8
- PIN photodiode (count detection)
  - Detect charged particle
  - Insensitive to photons from synchrotron radiation due to coincidence counting in two back-to-back mounted PIN diodes (K. Wittenburg, DESY)
  - Count rate proportional to beam loss
  - Speed limited by integration time
  - Dynamic range of up to 10^9





Common types of monitors cont'd

- Scintillator plus photo-multiplier
  - Types of scintillators
    - Inorganic crystals: NaI, CsI, ...
    - Organic (plastic, liquid)
  - Light directed (via waveguides) to photomultiplier tube



Common types of monitors cont’d

- Long ionisation chamber (charge detection)
    - Up to several km of gas filled hollow coaxial cables
    - Longitudinal position information by arrival time measurement
    - e.g. SLAC – 8m position resolution (30ns) over 3.5km cable length
    - Dynamic range of up to 10^4
- Cherenkov fibres
    - Time resolution 1 ns
    - Minimal space requirement
    - Insensitive to gamma background, E and B fields
    - Radiation hard (depending on type)
    - Combination fiber / readout can adapt to a wide dose range
    - Dynamic range 10^4 seems feasible

LHC BLM System

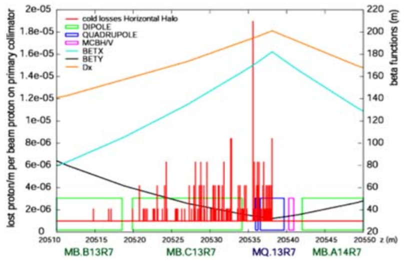
- Main purpose: **prevent damage and quench**
- 3600 Ionization chambers
- Beam abort thresholds:
    - 12 integration intervals: 40μs to 84s (32 energy levels)

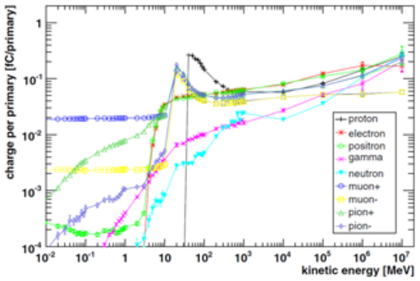
→ 1.5 Million threshold values

- Each monitor aborts beam
    - One of 12 integration intervals over threshold
    - Internal test failed
- Requirements and Challenges
    - High Dependability (Reliability, Availability, Safety)
    - Threshold precision (factor 2)
    - Reaction time 1-2 turns (100 – 200 μs)
    - Dynamic range: 10^8 (at 40μs 10^5 achieved – 10^6 planned)
    - Radiation hard: currently at CERN development of kGy radiation hard readout to avoid noise from long cables

Beam Abort Threshold Determination

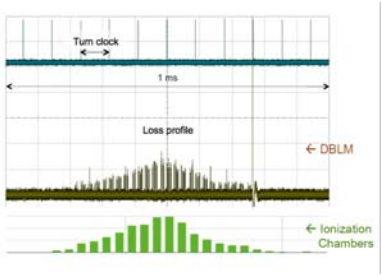
- Relate the BLM signal to the:
  - Number of locally lost beam particles
  - Deposited energy in the machine
  - Quench and damage levels
- Extensive simulations and experiments during system design and beam tests in the LHC
  - Proton loss locations (tracking codes: MAD-X, SIXTRACK)
  - Hadronic showers through magnets (GEANT, FLUKA)
  - Magnet quench levels as function of beam energy and loss duration
  - Chamber response to the mixed radiation field (GEANT, FLUKA, GARFIELD)

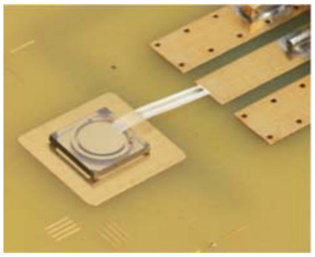


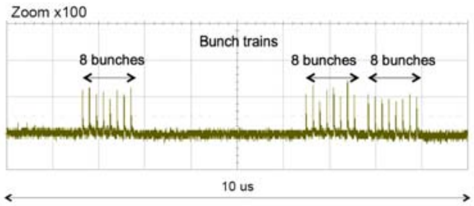


Diamond Detectors

- Fast and sensitive
- Small and radiation hard
- Used in LHC to distinguish bunch by bunch losses
- Dynamic range of monitor: 10^9
- Temporal resolution: few ns
- Test system installed in cryo magnet at LHC







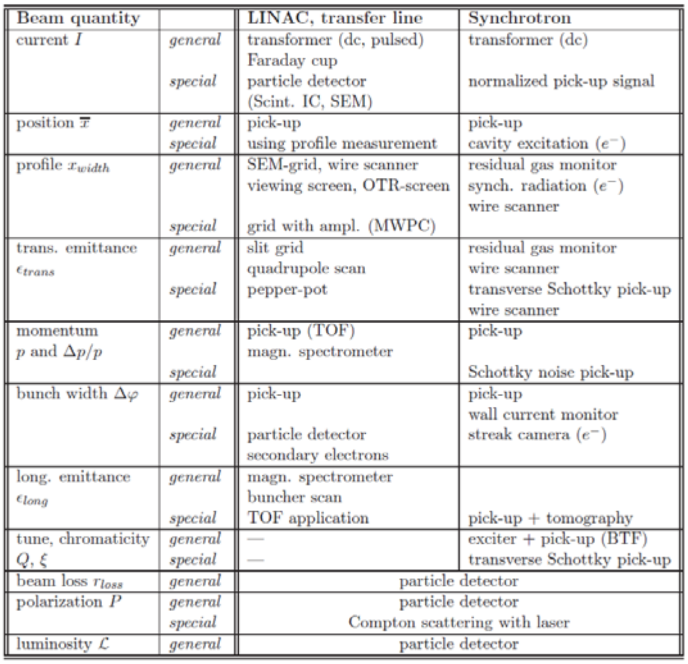
Thank you for your Attention

Glossary:

- GEFE : GBT Expandable Front-End
  - CERN/BI general purpose FPGA-based radiation tolerant front-end motherboard with optical signal transmission
  - Target Total Ionizing Dose (TID): up to 75 krad
- Igloo2 UMd Board
  - Another option for the front-end motherboard, equipped with a flash-based FPGA Igloo2, radiation tolerant components and a versatile link transceiver (VTRx) to drive the optical link with the GBT protocol.
- VFC board: VME FMC Carrier Board
  - CERN/BI general purpose FPGA-based back-end VME board
- *FMC: FPGA Mezzanine Card*
  - *https://en.wikipedia.org/wiki/FPGA_Mezzanine_Card*
  - Here: application specific Mezzanine card for the VFC board
- GBT: Gigabit Transceiver Link (4.8Gbps)
- QIE: Charge Integrator & Encoder

Overview of the most commonly used diagnostics devices for for the different beam parameters.

From: Peter Forck*: Lecture on Beam Instrumentation and Diagnostics* at the Joint University Accelerator School (JUAS)
http://www-bd.gsi.de/conf/juas/juas.html



Beam quantity		LINAC, transfer line	Synchrotron
current I	*general*	transformer (dc, pulsed) Faraday cup	transformer (dc)
	special	particle detector (Scint. IC, SEM)	normalized pick-up signal
position $\overline{x}$	*general*	pick-up	pick-up
	special	using profile measurement	cavity excitation (e^-)
profile x_{width}	*general*	SEM-grid, wire scanner viewing screen, OTR-screen	residual gas monitor synch. radiation (e^-) wire scanner
	special	grid with ampl. (MWPC)	
trans. emittance ϵ_{trans}	*general*	slit grid quadrupole scan	residual gas monitor wire scanner
	special	pepper-pot	transverse Schottky pick-up wire scanner
momentum p and $\Delta p/p$	*general*	pick-up (TOF) magn. spectrometer	pick-up
	special		Schottky noise pick-up
bunch width $\Delta\varphi$	*general*	pick-up	pick-up wall current monitor
	special	particle detector secondary electrons	streak camera (e^-)
long. emittance ϵ_{long}	*general*	magn. spectrometer buncher scan	
	special	TOF application	pick-up + tomography
tune, chromaticity Q, ξ	*general*	—	exciter + pick-up (BTF)
	special	—	transverse Schottky pick-up
beam loss r_{loss}	*general*	particle detector	
polarization P	*general*	particle detector	
	special	Compton scattering with laser	
luminosity $\mathcal{L}$	*general*	particle detector	