Beam Instrumentation and Diagnostics (Lecture 1)

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Dr. Rhodri Jones

Head of the CERN Beam Instrumentation Group
Introduction

• What do we mean by beam instrumentation?
  – The “eyes” of the machine operators
    • i.e. the instruments that observe beam behaviour
    • An accelerator can never be better than the instruments measuring its performance!

• What does work in beam instrumentation entail?
  – Design, construction & operation of instruments to observe particle beams
  – R&D to find new or improve existing techniques to fulfill new requirements
  – A combination of the following disciplines
    • Applied & Accelerator Physics; Mechanical, Electronic & Software Engineering

• What beam parameters do we measure?
  – Beam Position
    • Horizontal and vertical throughout the accelerator
    • At a specific location for tune, coupling & chromaticity measurements
  – Beam Intensity (& lifetime measurement for a storage ring/collider)
    • Bunch-by-bunch charge and total circulating current
  – Beam Loss
    • Especially important for high brightness and superconducting machines
  – Beam profiles
    • Transverse and longitudinal distribution
What is meant by Beam Diagnostics?

- Beam Diagnostics
  - Making use of beam instrumentation

What do we consider as beam diagnostics?

- Operating the accelerators
  - Using instrumentation to measure and correct standard parameters
    - Orbit, tune, chromaticity control etc.
  
- Improving the performance of the accelerators
  - Understanding current performance to allow future improvements
  - Requires the measurement of performance indicators
    - Luminosity, brilliance (intensity and size) etc.

- Understanding accelerator limitations
  - Beam loss, instabilities, emittance growth etc.

- Detecting equipment faults
  - Aperture restrictions, polarity inversions, wrong settings etc.
How do we Qualify Beam Measurements?

- **Accuracy, Precision, Resolution**
  - Very often confused in day-to-day language
    - **Accuracy** – also known as the trueness of a measurement
    - **Precision** – how well a measurement can be reproduced
    - **Resolution** – the smallest possible difference measurable

<table>
<thead>
<tr>
<th>Accurate</th>
<th>Inaccurate (systematic error)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precise</td>
<td></td>
</tr>
<tr>
<td>Imprecise (reproducibility error)</td>
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- **Example for a BPM**
  - Mechanical & electrical offsets and gain factors influence accuracy
  - Various noise sources or timing jitter influence the precision
  - Number of bits in the ADC will limit the resolution
Beam Position Systems
Measuring Beam Position – The Principle

[Diagram showing beam particles and detector elements]
Wall Current Monitor – The Principle
Wall Current Monitor – Beam Response

\[ f_H = \frac{1}{2\pi RC} \]

\[ f_L = \frac{R}{2\pi L} \]
Electrostatic Monitor – The Principle
Electrostatic Monitor – Beam Response

\[ f_L = \frac{1}{2\pi RC} \]

Response (V) vs. Frequency (Hz) graph

Diagram showing a circuit with a capacitor (C) and resistor (R) connected to a voltage source \( V_B \) and an output voltage \( V \).
Electrostatic Beam Position Monitor
Electrostatic Monitor – The Principle
Electrostatic Pick-up – Button

✓ Low cost ⇒ most popular
× Non-linear
  • requires correction algorithm when beam is off-centre

For Button with Capacitance $C_e$ & Characteristic Impedance $R_0$

Transfer Impedance:

$$Z_T(f >> f_c) = \frac{A}{(2\pi r) \times c \times C_e}$$

Lower Corner Frequency:

$$f_L = \frac{1}{2\pi R_0 C_e}$$
Normalising the Position Reading

- To make it independent of intensity
- 3 main methods: \( V_A \propto I \times P_A \) and \( V_B \propto I \times P_B \)
  - Difference/Sum: \( \frac{(V_A - V_B)}{(V_A + V_B)} = \frac{\Delta}{\Sigma} = \frac{(P_A - P_B)}{(P_A + P_B)} = \frac{\Delta P}{Aperture} \)
  - Phase: \( \text{ArcTan} \left( \frac{V_A}{V_B} \right) = \text{ArcTan} \left( \frac{P_A}{P_B} \right) \)
  - Logarithm: \( \log \left( \frac{V_A}{V_B} \right) = \log \left( \frac{P_A}{P_B} \right) = \log(V_A) - \log(V_B) \)
• BPM electrodes typically give “intensity signals” with some position dependence!
  – Need to remove intensity content to get to the position
  – Difficult to do electronically without some intensity information leaking through
    • When looking for small differences this leakage can dominate the measurement

• Solution – cavity BPM allowing sub micron resolution
  – Design the detector to collect only the difference signal
    • Dipole Mode \( \text{TM}_{11} \) proportional to POSITION OFFSET (& intensity)
    • Shifted in frequency with respect to intensity dependent Monopole Mode \( \text{TM}_{01} \)
Cavity Beam Position Monitors

Obtain signal using waveguides that only couple to dipole mode for further Monopole Suppression

Courtesy of D. Lipka, DESY, Hamburg
Today’s State of the Art BPMs

- **Prototype BPM for ILC Final Focus**
  - Required resolution of 2nm (yes nano!) in a $6 \times 12$mm diameter beam pipe
  - Achieved World Record (so far!) resolution of 8.7nm at ATF2 (KEK, Japan)

![Prototype BPM Image](image1)

![Prototype BPM Image](image2)

![Histogram Image](image3)
Comparison of BPM Resolution

- **XFEL Data from 2017 Commissioning**
  - Standard Button BPMs: 78 mm & 40.5 mm aperture (RED)
  - Re-entrant cavity BPMs: 78 mm aperture (GREEN)
  - Cavity BPMs: 40.5 mm and 10 mm aperture (BLUE)
Processing System Families

**Legend:**
- `/` = Single channel
- `Wide Band`
- `Narrow band`

- **Normaliser Processor**
- **Active Circuitry**

- **Electrodes A, B**
  - Multiplexed
  - Hybrid $\Delta / \Sigma$
  - Individual Treatment
  - Passive Normalisation

- **Automatic Gain Control on $\Sigma$**

- **Functional Blocks:**
  - Heterodyne
  - Synchronous Detection
  - Homodyne Detection
  - Down Conversion
  - Direct Digitisation
  - Logarithmic Amplifiers
  - Differential Amplifier
  - Amplitude to Time
  - Limiter, $\Delta t$ to Ampl.
  - Limiter, $\phi$ to Ampl.
  - Amplitude to Phase

- **DIGITISER**
  - POS = (A-B)
  - No turn by turn
  - POS = $\Delta / \Sigma$

  | POS = $\Delta / \Sigma$ |
  | POS = $\Delta / \Sigma$ |
  | POS = $[\log(A/B)]$ |
  | POS = $[\log(A) - \log(B)]$ |
  | POS = $[A/B]$ |
  | POS = $[\text{ATN}(A/B)]$ |

- **Turn by turn**

**All rely on normalisation**
- Making the position signal independent of intensity
Modern BPM Read-out Electronics

• Based on the individual treatment of the electrode signals
  – Use of frequency domain signal processing techniques
    • Developed for telecommunications market
  – Rely on high frequency & high resolution analogue to digital converters
    • Minimising analogue circuitry
    • Frequency down-conversion used if necessary to adapt to ADC sampling rate
    • All further processing carried out in the subsequent digital electronics

A-Electrode Analogue Conditioning

B, C, D Channels treated the same as A
Diagnostics using Beam Position Systems
Initial Commissioning

- Threading the first pilot bunch round the LHC
  - One beam at a time, one hour per beam
  - Collimators used to intercept the beam
  - Correct trajectory, open collimator and move on

Courtesy of CMS

L1Calo Stream

first beam event seen in ATLAS

Courtesy of ATLAS
The Machine $\beta$-Function

$\beta (m)$

$\text{Beam Size} \propto \sqrt{\beta}$
The Machine $\beta$-Function

$\beta (m)$

$\pi$

$\theta$

$-\pi$

Oscillation Amplitude and Beam Size $\propto \sqrt{\beta}$
The Machine $\beta$-Function

$$\beta_{\text{measured}} = \beta_{\text{model}} \left( \frac{\cot \varphi_{12} - \cot \varphi_{13}}{\cot \varphi_{12} - \cot \varphi_{13}} \right)_{\text{measured}}$$

BPM 1  BPM 2  BPM 3
Analysis of BPM Data

- On line analysis of BPM Data
  - Polarity errors easily identified with 45° BPM sampling
  - Quick indication of phase advance errors
  - Used to verify optics functions
    - e.g. matching from transfer lines into ring
Beam Intensity Monitors
AC (Fast) Current Transformers

Image Current

Core of high relative permeability

Ceramic Gap

Image Current

Beam

CoFe based amorphous alloy
Vitrovac: $\mu_r = 10^5$
AC (Fast) Current Transformers

\[ I_{BCT} \]

\[ V_{BCT} \]

Beam

\( B_B \)
AC (Fast) Transformer Response

- **Low cut-off**
  - Impedance of secondary winding decreases at low frequency
  - Results in signal droop and baseline shift
  - Mitigated by baseline restoration techniques (analogue or digital)
The DC transformer

- AC transformers can be extended to very low frequency but not to DC (no $\text{d}I/\text{d}t!$)
- DC measurement is required in storage rings
- To do this:
  - Take advantage of non-linear magnetisation curve
  - Use 2 identical cores modulated with opposite polarities
DCCT Principle – Case 1: no beam

Hysteresis loop of modulator cores

Modulation Current - Core 1
Modulation Current - Core 2
DCCT Principle – Case 1: no beam

\[ V \propto \frac{dB}{dt} \]

\[ dB/dt \text{ - Core 1 (V1)} \]
\[ dB/dt \text{ - Core 2 (V2)} \]

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 ($V_1$)
- $dB/dt$ - Core 2 ($V_2$)
- Output voltage = $V_1 - V_2$
Zero Flux DCCT Schematic

\[ V = R \times I_{\text{beam}} \]

Compensation current \( I_{\text{feedback}} = -I_{\text{beam}} \)
Diagnostics using Beam Intensity Monitors
Monitoring Electron Cloud Activity

- **Secondary Emission Yield [SEY]**
  - SEY > Threshold \(\Rightarrow\) avalanche effect (multipacting)

- **Possible consequences:**
  - Instabilities, emittance growth, vacuum degradation, background
  - Energy deposition in cryogenic surfaces

- **Electron bombardment can reduce SEY of a material**
  - A function of the delivered electron dose
  - This technique of “scrubbing” can suppress electron cloud build-up
**Electron Cloud in LHC**
- Electron cloud creates instability in tail of bunch trains
- Increases the size of the bunches towards the end of each bunch train
- Leads to losses for these bunches
- Adjustments made to counter this effect
  - Chromaticity
  - Transverse feedback
  - Beam scrubbing

**Diagnostics**
- LHC fast BCT
  - Allows bunch by bunch intensity measurement
- LHC Synchrotron Light Monitor
  - Gated intensified Camera
  - Allows bunch by bunch profile measurement
Bad RF Capture of a single LHC Batch in the SPS (72 bunches)
Beam Loss Monitors
Beam Loss Detectors

• **Role of a BLM system:**
  – Protect the machine from damage
  – Dump the beam to avoid magnet quenches (for superconducting magnets)
  – Diagnostic tool to improve the performance of the accelerator

• **E.g. LHC**

<table>
<thead>
<tr>
<th>Stored Energy</th>
<th>Quench and Damage at 7 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam 7 TeV</td>
<td>2 x 362 MJ</td>
</tr>
<tr>
<td></td>
<td>Quench level: ( \approx 1 \text{mJ/cm}^3 )</td>
</tr>
<tr>
<td></td>
<td>Damage level: ( \approx 1 \text{ J/cm}^3 )</td>
</tr>
</tbody>
</table>

- **SPS incident**
  – June 2008
  – 2 MJ beam lost at 400GeV
Beam Loss Detectors

• Common types of monitor
  – Long ionisation chamber (charge detection)
    • Up to several km of gas filled hollow coaxial cables
    • Position sensitivity achieved by comparing direct & reflected pulse
      – e.g. SLAC – 8m position resolution (30ns) over 3.5km cable length
    • Dynamic range of up to $10^4$
  
  – Fibre optic monitors
    • Electrical signals replaced by light produced through Cerenkov effect
Beam Loss Detectors

- **Common types of monitor**
  - Ionisation chambers
  - Dynamic range of $< 10^8$
  - Slow response ($\mu$s) due to ion drift time

![Visualisation of ion chamber operation](image)
Beam Loss Detectors

• Common types of monitor
  – PIN photodiode (solid state ionisation chamber)
    • Detect coincidence of ionising particle crossing photodiodes
    • Count rate proportional to beam loss with speed limited by integration time
    • Can distinguish between X-rays & ionising particles
    • Dynamic range of up to $10^9$
Beam Loss Detectors – New Materials

• **Diamond Detectors**
  - Fast & sensitive
  - Used in LHC to distinguish bunch by bunch losses
  - Investigations now ongoing to see if they can work in cryogenic conditions

Courtesy of E. Griesmayer
Diagnostics using Beam Loss Monitors
Example from Last LHC Run

- Beam continually lost due to losses
  - What is going on?

<table>
<thead>
<tr>
<th>24-Aug-2017 17:41:44</th>
<th>Fill #: 6128</th>
<th>Energy: 59 GeV</th>
<th>$l(B1): 0.00e+00$</th>
<th>$l(B2): 0.00e+00$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experiment Status</td>
<td>ATLAS</td>
<td>ALICE</td>
<td>CMS</td>
<td>LHCb</td>
</tr>
<tr>
<td>Instantaneous Lumi ($ub.s^{-1}$)</td>
<td>-0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>BRAN Luminosity ($ub.s^{-1}$)</td>
<td>0.6</td>
<td>0.0</td>
<td>2.3</td>
<td>0.0</td>
</tr>
<tr>
<td>Fill Luminosity (nb)$^{-1}$</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>540.173</td>
</tr>
<tr>
<td>Beam 1 BKGD</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>Beam 2 BKGD</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
</tbody>
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LHCb VELO Position: **OUT**   Gap: -0.0 mm

Performance over the last 24 Hrs

Dump #1
5.9 TeV
RF issue

Dump #2
7 TeV

Dump #3
0.9 TeV

Dump #4
0.8 TeV
16L2 – First Event

• First beam dump event – as seen by the BLMs
  – Local aperture measurements did not reveal evident aperture restriction
  – Clear signature of losses from both beams
    • Both beams interacting with nuclei
BLM Diagnostics

- Time evolution of Losses

![BLM Diagnostics Graph](image-url)
Looking for constant losses

- Installation of additional BLMs!
  - Factor 15 improvement in sensitivity
BLM Diagnostics

- **Localisation**
  - BLM Spatial patterns clearly show losses originate from one specific interconnection
    - MQ16L2 (Cell 16 left of LHC Point 2)
    - Localisation possible to within 1m comparing with simulation
  - Losses can be on either beam
Additional Observations

- Beam not always dumped by BLMs in 16L2
  - Often dumped by BLMs near primary collimators
  - Indicating development of transverse instability

Losses at BLM

12 ms

Bunch by bunch position

Intra-bunch position
Head-Tail Instability Monitor

- Clearly shows instability in tail of bunch
  - Allowed simulations to try and re-create similar instability
  - Achieved when considering a large density of electrons over a short distance
    - Compatible with an ionised gas cloud

Measurement from head-tail monitor

Simulation
16L2 - Hypothesis

- **Something went wrong during vacuum pumpdown**
  - Air trapped on beam screen & cold bore of both beams
    - Solid nitrogen & oxygen formed
  - Falls into the beam & immediately vaporised
    - Creates local pressure rise with beam interaction producing ionized gas cloud
    - Leads to losses & beam instability
Summary of Lecture 1

• Today concentrated on beam position, intensity & loss monitors
  – Went into details of how they worked
  – Gave examples of their use as diagnostic tools

• Tomorrow we’ll continue with a look at
  – Beam profile monitoring & diagnostics
  – Tune, Coupling & Chromaticity measurement & feedback

For those that want to know more then I hope you’ve joined the Beam Instrumentation Afternoon Course!

• 3 Sessions on BPM design
  – Simulation software & “hands-on” laboratory measurements

• 1 Session on Tune Measurement
  – Simulate your own tune measurement system

• 2 Sessions on Profile Measurements
  – “Hands-on” laboratory measurements of transverse & longitudinal profile

• Final Session
  – Group presentation of your BI proposals for an accelerator