Introduction to Beam Instrumentation

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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 of 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
    - A fascinating field of work!

- What beam parameters do we measure?
  - Beam Position
    - Horizontal and vertical throughout the accelerator
  - Beam Intensity (& lifetime measurement for a storage ring/collider)
    - Bunch-by-bunch charge and total circulating current
  - Beam Loss
    - Especially important for superconducting machines
  - Beam profiles
    - Transverse and longitudinal distribution
  - Collision rate / Luminosity (for colliders)
    - Measure of how well the beams are overlapped at the collision point
More Measurements

- **Machine Tune**
  
  Characteristic Frequency of the Magnet Lattice
  
  Given by the strength of the Quadrupole magnets

- **Machine Chromaticity**
  
  Spread in the Machine Tune due to Particle Energy Spread
  
  Controlled by Sextupole magnets

The Typical Instruments

- **Beam Position**
  
  electrostatic or electromagnetic pick-ups and related electronics

- **Beam Intensity**
  
  beam current transformers

- **Beam Profile**
  
  secondary emission grids and screens
  
  wire scanners
  
  synchrotron light monitors
  
  ionisation and luminescence monitors
  
  femtosecond diagnostics for ultra short bunches (afternoon course)

- **Beam Loss**
  
  ionisation chambers or pin diodes

- **Machine Tune and Chromaticity**
  
  in diagnostics section of tomorrow

- **Luminosity**
  
  in diagnostics section of tomorrow
Wall Current Monitor – The Principle

Wall Current Monitor – Beam Response

\[ f_L = \frac{R}{2\pi L} \]

\[ f_H = \frac{1}{2\pi RC} \]
Electrostatic Monitor – The Principle

Electrostatic Monitor – Beam Response

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

$$Z_{T(f \gg f_c)} = \frac{A}{(2\pi r) \times c \times C_e}$$

Lower Corner Frequency:

$$f_L = \frac{1}{2\pi R_0 C_e}$$

A Real Example – The LHC Button

$$f_L = \frac{1}{2\pi RC} = \frac{1}{2\pi \times 50\Omega \times 8pF} = 400\text{MHz}$$

$$Z_{R\Phi} = \frac{A}{(2\pi r) \times c \times C_e} = \frac{\pi \times (12\text{mm})^2}{(2\pi \times 24.5\text{mm}) \times c \times (8pF)} = 1.2\Omega$$

$$I_B = \frac{N_{pilot} e}{t} = \frac{5 \times 10^9 \times 1.6 \times 10^{-19}}{1 \times 10^{-9}} = 0.8A_{\text{peak}} \Rightarrow V_{f=\infty} = 0.8 \times 1.2 = 1V_{\text{peak}}$$

$$= \frac{N_{nom} e}{t} = \frac{1 \times 10^{11} \times 1.6 \times 10^{-19}}{1 \times 10^{-9}} = 16A_{\text{peak}} \Rightarrow V_{f=\infty} = 16 \times 1.2 = 20V_{\text{peak}}$$
Improving the Precision for Next Generation Accelerators

- Standard BPMs give intensity signals which need to be subtracted to obtain a difference which is then proportional to position
  - Difficult to do electronically without some of the intensity information leaking through
    - When looking for small differences this leakage can dominate the measurement
    - Typically 40-80dB (100 to 10000 in V) rejection \(\Rightarrow\) tens micron resolution for typical apertures

- Solution – cavity BPMs allowing sub micron resolution
  - Design the detector to collect only the difference signal
    - Dipole Mode TM_{11} proportional to position & shifted in frequency with respect to monopole mode

Today’s State of the Art BPMs

- Obtain signal using waveguides that only couple to dipole mode
  - Further suppression of monopole mode

- Prototype BPM for ILC Final Focus
  - Required resolution of 2nm (yes nano!) in a 6×12mm diameter beam pipe
  - Achieved World Record (so far!) resolution of 8.7nm at ATF2 (KEK, Japan)
Criteria for Electronics Choice - so called “Processor Electronics”

- Accuracy
  - mechanical and electromagnetic errors
  - electronic components
- Resolution
- Stability over time
- Sensitivity and Dynamic Range
- Acquisition Time
  - measurement time
  - repetition time
- Linearity
  - aperture & intensity
- Radiation tolerance

Processing System Families

Legend:
- / Single channel
- Wide Band
- Narrow band
- Normalizer
- Active Circuitry

Courtesy of G.Vismara
LINEARITY Comparison

[Graph showing transfer functions with normalized position (U) on the x-axis and transfer function values on the y-axis, comparing Δ/Σ, Atn(a/b), and loga-logb.

Amplitude to Time Normalisation

[Graph showing amplitude to time normalisation with time in nanoseconds on the x-axis and amplitude on the y-axis, showing waveforms A and B with and without delay lines.]

Diagram of beam splitter delay lines combiner and pick-up system.]

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Amplitude to Time Normalisation

\[ A + (B + 1.5\text{ns}) \]

\[ B + (A + 1.5\text{ns}) \]

\( \Delta t \) depends on position

BPM Acquisition Electronics

**Amplitude to Time Normaliser**

**Advantages**
- Fast normalisation (< 25ns)
  - bunch to bunch measurement
- Signal dynamic independent of the number of bunches
  - Input dynamic range \( \sim 45 \text{ dB} \)
  - No need for gain selection
- Reduced number of channels
  - normalisation at the front-end
- \(~10 \text{ dB} \) compression of the position dynamic due to the recombination of signals
- Independent of external timing
- Time encoding allows fibre optic transmission to be used

**Limitations**
- Currently reserved for beams with empty RF buckets between bunches e.g.
  - LHC 400MHz RF but 25ns spacing
  - 1 bunch every 10 buckets filled
- Tight time adjustment required
- No Intensity information
- Propagation delay stability and switching time uncertainty are the limiting performance factors
What one can do with such a System

Used in the CERN-SPS for electron cloud & instability studies.

The Typical Instruments

- Beam Position
  - electrostatic or electromagnetic pick-ups and related electronics

- Beam Intensity
  - beam current transformers

- Beam Profile
  - secondary emission grids and screens
  - wire scanners
  - synchrotron light monitors
  - ionisation and luminescence monitors
  - Femtosecond diagnostics for ultra short bunches (afternoon course)

- Beam Loss
  - ionisation chambers or pin diodes

- Machine Tunes and Chromacitities
  - in diagnostics section of tomorrow

- Luminosity
  - in diagnostics section of tomorrow
Current Transformers

Magnetic field

Fields are very low

Capture magnetic field lines with cores of high relative permeability

(CoFe based amorphous alloy Vitrovac: $\mu_r = 10^5$)

Beam current

$$I_{beam} = \frac{eN_q}{t} = \frac{eN_q \beta c}{w}$$

Transformer Inductance

$$L = \frac{\mu_0 \mu_r}{2\pi} w N^2 \ln \frac{r_0}{r_1}$$

The Active AC transformer

Winding of N turns and Inductance L

$$U = L \frac{dI_{beam}}{dt}$$

$$U(t) = \frac{I_{beam}(t)}{N} Re \frac{t}{\tau_{droop}}$$

Beam signal

Transformer output signal

$$\tau_{rise} = \sqrt{LC_s}$$

$$\tau_{droop} = \frac{L}{R_f + R_l} \approx \frac{L}{R_l}$$
**Fast Beam Current Transformer**

- 500MHz Bandwidth
- Low droop (< 0.2%/µs)

80nm Ti Coating ⇒ 20Ω to improve impedance

**Acquisition Electronics**

Data taken on LHC type beams at the CERN-SPS
What one can do with such a System

Bad RF Capture of a single LHC Batch in the SPS (72 bunches)

The DC current transformer

- AC current transformer can be extended to very long droop times but not to DC
- DC current measurement is required in storage rings
- To do this:
  - Take advantage of non-linear magnetisation curve
  - Apply a modulation frequency to 2 identical cores
DCCT Principle – Case 1: no beam

Hysteresis loop of modulator cores

\[ B \quad I \]

Modulation Current - Core 1
Modulation Current - Core 2

\[ I_M \quad t \]

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

$\frac{dB}{dt}$ - Core 1 ($V_1$)
$\frac{dB}{dt}$ - Core 2 ($V_2$)
Output voltage = $V_1 - V_2$

Zero Flux DCCT Schematic

Compensation current $I_{\text{feedback}} = -I_{\text{beam}}$
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Secondary Emission (SEM) Grids

- When the beam passes through secondary electrons are ejected from the wires
- The current flowing back onto the wires is measured
- The liberated electrons are removed using a polarisation voltage
- One amplifier/ADC chain is used for each wire
Profiles from SEM grids

- Charge density measured from each wire gives a projection of the beam profile in either horizontal or vertical plane.
- Resolution is given by distance between wires.
- Used only in transfer lines as heating is too great for circulating beams.

Wire Scanners

- For circulating beams a thin wire is moved across the beam.
  - Has to move fast to avoid excessive heating of the wire.
- Detection:
  - Secondary particle shower detected outside the vacuum chamber using a scintillator/photo-multiplier assembly.
  - Secondary emission current detected as for SEM grids.
- Correlating wire position with detected signal gives the beam profile.
More Exotic Measurement Results

- Wire Scanners used in the optimisation of Multi-Turn Extraction in the CERN PS
  - Clever use of Octupolar and Sextupolar fields splits the beam into 3 beamlets
  - These are separated in phase space by changing the tune and crossing the $1/3^{rd}$ resonance
  - Once separated these individual beamlets can be extracted with minimal losses

Beam Profile Monitoring using Screens

- Screen Types
  - Luminescence Screens
    - destructive (thick) but work during setting-up with low intensities
  - Optical Transition Radiation (OTR) screens
    - much less destructive (thin) but require higher intensity

Sensitivities measured with protons with previous screen holder, normalised for 7 px/$\sigma$

<table>
<thead>
<tr>
<th>Type</th>
<th>Material</th>
<th>Activator</th>
<th>Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminesc</td>
<td>CeI</td>
<td>Tl</td>
<td>$6 \times 10^5$</td>
</tr>
<tr>
<td></td>
<td>Al$_2$O$_3$</td>
<td>0.7%Sr</td>
<td>$3 \times 10^7$</td>
</tr>
<tr>
<td></td>
<td>Glass</td>
<td>Cs</td>
<td>$3 \times 10^9$</td>
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<tr>
<td></td>
<td>Quartz</td>
<td>none</td>
<td>$6 \times 10^9$</td>
</tr>
<tr>
<td>OTR [bw]</td>
<td>Al</td>
<td></td>
<td>$2 \times 10^{10}$</td>
</tr>
<tr>
<td></td>
<td>Tl</td>
<td></td>
<td>$2 \times 10^{11}$</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td></td>
<td>$2 \times 10^{12}$</td>
</tr>
<tr>
<td>Luminesc</td>
<td>GdI$_2$Te$_2$O$_7$</td>
<td>Tl</td>
<td>$2 \times 10^7$</td>
</tr>
</tbody>
</table>
OTR – The Principle

- Radiation emitted when a charged particle beam goes through the interface of 2 media with different dielectric constants
  - surface phenomenon allows the use of very thin screens (~10\(\mu\)m)

![Diagram of OTR Screen setup]

Beam Profile Monitoring using Screens

- Usual configuration
  - Combine several screens in one housing e.g.
    - \(\text{Al}_2\text{O}_3\) luminescent screen for setting-up with low intensity
    - Thin (~10\(\mu\)m) Ti OTR screen for high intensity measurements
    - Carbon OTR screen for very high intensity operation

- Advantages compared to SEM grids
  - allows analogue camera or CCD acquisition
  - gives two dimensional information
  - high resolution: \(~400 \times 300 = 120'000\) pixels for a standard CCD
  - more economical
    - Simpler mechanics & readout electronics
  - Time resolution depends on choice of image capture device
    - From CCD in video mode at 50Hz to Streak camera in the GHz range
Luminescence Profile Monitor

Beam size shrinks as beam is accelerated

CERN-SPS Measurements
- Profile Collected every 20ms
- Local Pressure at \( \sim 5 \times 10^{-7} \) Torr

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Beam Loss Detectors

- Role of a BLM system:
  1. Protect the machine from damage
  2. Dump the beam to avoid magnet quenches (for SC magnets)
  3. Diagnostic tool to improve the performance of the accelerator
- 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 $10^4$
Common types of monitor (cont)

- 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 $10^8$

Beam Loss Detectors

- PIN photodiode (count detection)
  - Detect MIP crossing photodiodes
  - Count rate proportional to beam loss
  - Speed limited by integration time
  - Dynamic range of up to $10^9$
BLM Threshold Level Estimation

Summary

- I've tried to give you an overview of the common types of instruments that can be found in most accelerators
  - This is only a small subset of those currently in use or being developed with many exotic instruments tailored for specific accelerator needs

- Tomorrow you will see how to use these instruments to run and optimise accelerators
  - Introduction to Accelerator Beam Diagnostics (H. Schmickler)

- Afternoon course: Beam Instrumentation & Diagnostics
  - For an in-depth analysis of all these instruments and on their application in various accelerators