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 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
  – 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
More Measurements

- **Machine Tune**

  Characteristic Frequency of the Magnetic Lattice
  Given by the strength of the Quadrupole magnets

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

- **Machine Chromaticity**

  Optics Analogy:
  
  Achromatic incident light
  [Spread in particle energy]

  Lens [Quadrupole]

  Focal length is energy dependent
Not further treated:

• **Luminosity Measurements**  
  (dedicated arrangements close to the IP)

• **Direct Emittance Measurements**  
  (simultaneous measurement of size and divergence)

• **Particle identification, Time of flight**…  
  (relevant for secondary beam lines)

• **Synchronization, beam arrival time monitors**  
  …this needs a full course on its own
....in general...

• In every instrument we
  - intercept information of the particle beam
  - convert it to an electrical signal
  - digitize it and transmit it to the control room
  - display it, use it for the computation of corrections, use it in real-time feedback loops...
  - store it for further analysis

• What can we intercept?
  - the beam particles themselves
    (typical: beam screen, beam loss monitors...)
  - the electromagnetic field of the beam
    (most instruments, important: beam position monitors)
  - light emitted by the beam
    (typical: transverse and longitudinal profiles)
Accuracy, Precision, Resolution

- Very often confused in day-to-day language
- **Accuracy**: also called trueness of measurement
- **Precision**: how well can I reproduce my measurements
- **Resolution**: smallest possible difference in successive measurements

Ex: BPM: Mechanical and electrical offsets, gain factors influence the accuracy, various noise sources or timing jitter influence the precision, ADC resolution can limit the resolution.
The Typical Instruments

- **Beam Intensity**
  - beam current transformers

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

- **Beam Profile**
  - secondary emission grids and screens
  - wire scanners
  - synchrotron light monitors
  - ionization and luminescence monitors
  - femtosecond diagnostics for ultra short bunches

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

- **Machine Tune and Chromaticity** (derived quantities)
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Beam Image (wall) current– The Principle

\[ \gamma = 1 \quad \gamma \gg 1 \]

taken from w.Herr's lecture (Monday)
Wall Current Monitor – The Principle

Ceramic Insert

V
AC (Fast) Current Transformers

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

- Core of high relative permeability
AC (Fast) Current Transformers

Image

Beam

V_{BCT}

I_{BCT}

 Beam

B_B
Wall Current Monitor – Beam Response

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

\[ f_L = \frac{R}{2\pi L} \]
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)
What one can do with such a System

Bad RF Capture of a single LHC Batch in the SPS (72 bunches)
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Electrostatic Monitor – The Principle
Electrostatic Beam Position Monitor
**Principle of Beam Position Monitors**

- Intercept “beam image current” in the vacuum chamber on two isolated (capacitive) pickups.
- Other pickups (more involved): shoebox (linear) pickups, stripline directional couplers….
- Use high precision Rf electronics to shape the signals (short bunches deliver signals with high frequency content)
  - amplifiers
  - filters
  - down converters
- Digitize the individual pickup signals
- Eliminate the intensity information from the pickup signals (= “normalization”)
- Compute the position from the pickup-signal difference
- Linearize the pickup response
- Calibrate the system in metric units
Electrostatic Pick-up – Button

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

Position mapping with movable antenna

\[ X = 2.30 \cdot 10^{-5} X_1^5 + 3.70 \cdot 10^{-5} X_1^3 + 1.035 X_1 + 7.53 \cdot 10^{-6} X_1 Y_1^2 + 1.53 \cdot 10^{-5} X_1 Y_1^4 \]
Realization of Button BPM at LHC

Example LHC: $\varnothing$ 24 mm, half aperture $a=25$ mm, installed inside cryostat

Critically: $50 \, \Omega$ matching of button to standard feed-through.

Normalising the Position Reading

- To make it independent of intensity
- 3 main methods:
  - Difference/Sum: \( \frac{V_A - V_B}{V_A + V_B} = \Delta / \Sigma \)
  - Phase: \( \arctan \left( \frac{V_A}{V_B} \right) \)
  - Logarithm: \( \log(V_A) - \log(V_B) \)
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
Orbit Acquisition

This orbit excursion is too large!
Orbit Correction (Operator Panel)
Orbit Correction (Detail)
Beam Threading

- Threading the beam round the LHC ring (very first commissioning)
  - One beam at a time, one hour per beam.
  - Collimators were used to intercept the beam (1 bunch, $2 \times 10^9$ protons)
  - Beam through 1 sector (1/8 ring)
    - correct trajectory, open collimator and move on.

Beam 2 threading

BPM availability ~ 99%

Courtesy of CMS

L1Calo Stream

first beam event seen in ATLAS

Courtesy of ATLAS
Beam physics data derived from BPM rawdata:

Examples:

- Orbit difference for different beam momenta $\rightarrow$ dispersion
- Orbit difference for different beam intensities $\rightarrow$ Transverse impedance of vacuum chamber
- Turn by turn trajectory on each BPM; beam forced on constant oscillation $\rightarrow$ Beta function and phase advances
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- **Beam Loss**
  - ionization chambers or pin diodes

- **Machine Tune and Chromaticity** (derived quantities)
Beam Profile Monitoring using Screens

- **Screen Types**
  - Luminescence / Scintillating Screens
    - Destructive (thick) but work with low intensities
  - Optical Transition Radiation (OTR) screens
    - Much less destructive (thin) but require higher energy / intensity beam

- **OTR**
  - Radiation emitted when a charged particle goes through an interface with different dielectric constants
  - Surface phenomenon allows use of very thin screens (~10\(\mu\)m)
    - Can use multiple screens with single pass in transfer lines
    - Can leave it in for hundreds of turns e.g. for injection matching
Screen mechanism

- Screen with graticule
Results from TV Frame grabber

First full turn as seen by the BTV 10/9/2008

Un-captured beam sweeps through the dump line

- For further evaluation the video signal is digitized, read-out and treated by program
Beam Profile Monitoring using Wire-Scanners

- 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 vacuum chamber using scintillator/photo-multiplier
- Correlating wire position with detected signal gives the beam profile
Beam Profile Monitoring using Wire-Scanners

Vacuum tube

Particle beam

Secondary Particles generated by beam interactions with the wire

Control and acquisition Electronics

Graph showing beam profile with a peak at a certain distance.
Wire scanner profile

High speed needed because of heating.

Adiabatic damping

Current increase due to speed increase

Speeds of up to 20m/s => 200g acceleration
Limitation of WireScanners

- **Wire Breakage – why?**
  - Brittle or Plastic failure (error in motor control)
  - Melting/Sublimation (main intensity limit)
    - Due to energy deposition in wire by proton beam

- **Temperature evolution depends on**
  - Heat capacity, which increases with temperature!
  - Cooling (radiative, conductive, thermionic, sublimation)
    - Negligible during measurements (Typical scan 1 ms & cooling time constant ~10-15 ms)

- **Wire Choice**
  - Good mechanical properties, high heat capacity, high melting/sublimation point
  - E.g. Carbon which sublimates at 3915K
Synchrotron Light Monitors

- Synchrotron light
  - Emitted from a moving charge bent in a magnetic field
  - The main “raison d’être” for light sources
  - Also a very useful, non-invasive, powerful diagnostic tool
  - Can even be observed with protons & lead ions in the LHC
Synchrotron Light Image Acquisition

- **Using various cameras**
  - Standard CCD cameras for average beam size measurements
  - Gated intensified camera
    - For bunch by bunch diagnostics
  - Streak cameras
    - For short bunch diagnostics
• Proton Beam Example
  – LHC single bunch
    ~1.1e11p @ 3.5 TeV
  – Acquisition accumulated over 4 turns at 200Hz

• Limitations
  – Aberrations
    • Mitigated by careful design
  – Diffraction
    • Need to go to lower wavelengths as the beam size becomes smaller
Measuring Ultra Short Bunches

• Next Generation FELs & Linear Colliders
  – Use ultra short bunches to increase brightness or improve luminosity

• How do we measure such short bunches?
  – Direct Observation
    • Produce light & observe with dedicated instruments
    • Use of RF techniques
    • Use laser pulses and sampling techniques
  – Indirect Calculation
    • Reconstruct bunch length from frequency spectrum
      – Either directly from the bunch or through its radiation spectrum

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<table>
<thead>
<tr>
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<tbody>
<tr>
<td>p⁺ @ LHC</td>
<td>250ps</td>
<td></td>
</tr>
<tr>
<td>H⁻ @ SNS</td>
<td>100ps</td>
<td></td>
</tr>
<tr>
<td>e⁻ @ ILC</td>
<td>500fs</td>
<td></td>
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<tr>
<td>e⁻ @ CLIC</td>
<td>130fs</td>
<td></td>
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<tr>
<td>e⁻ @ XFEL</td>
<td>80fs</td>
<td></td>
</tr>
<tr>
<td>e⁻ @ LCLS</td>
<td>&lt;75fs</td>
<td></td>
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Measuring Ultra Short Bunches

- **RF Deflection**
  - Converts time information to spatial information
  - Coupled to spectrometer also provides energy information
  - Destructive technique
  - Resolution down to 1.3 fs
    - X-band RF cavity
    - Linac Coherent Light Source (SLAC)

\[
\begin{align*}
\langle \Delta y \rangle & \approx 60^\circ \\
\beta_c & \uparrow \\
\Delta \psi & \approx 60^\circ \\
\beta_p & \uparrow \\
\sigma_y & \\
\end{align*}
\]
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Beam Loss Detectors

- **Role of a BLM system:**
  - Protect the machine from damage
  - Dump the beam to avoid magnet quenches (for SC 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>
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<tbody>
<tr>
<td>Beam 7 TeV 2 x 362 MJ</td>
<td>Quench level ≈ 1mJ/cm³³</td>
</tr>
<tr>
<td>2011 Beam 3.5 TeV</td>
<td>Damage level ≈ 1 J/cm³³</td>
</tr>
</tbody>
</table>

- **SPS incident**
  - June 2008
  - 2 MJ beam lost at 400GeV
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
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
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Measurement of $Q$ (betatron tune)

- $Q$ – the eigenfrequency of betatron oscillations in a circular machine
  - One of the key parameters of machine operation
- Many measurement methods available:
  - different beam excitations
  - different observations of resulting beam oscillation
  - different data treatment

Characteristic Frequency of the Magnet Lattice
Produced by the strength of the Quadrupole magnets
Fourier analysis of turn by turn BPM measurements

1) Stimulate transverse beam oscillation with a kicker magnet (short dipole kick during one revolution period)
2) Measure turn-by-turn beam position
3) Fourier transform of data
4) Tune: = maximum of frequency spectrum
5) Resolution: \( \frac{dq}{q} = \frac{2}{N_{\text{samp}}} \)
6) Problems:
   - single shot measurement
   - oscillation has to last during measurement
   \( \rightarrow \) strong damping in some accelerators
   \( \rightarrow \) large initial excitation (emittance growth in case of hadron beams)
Time Resolved Measurements

- To follow betatron tunes during machine transitions we need time resolved measurements. Simplest example:
  - repeated FFT spectra as before (spectrograms)
Network Analysis

1. Excite beams with a sinusoidal carrier

2. Measure beam response

3. Sweep excitation frequency slowly through beam response
Chromaticity (Q’ or $\xi$)

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

Optics Analogy:
Achromatic incident light
[Spread in particle energy]

$$\Delta Q = Q' \frac{\Delta p}{p} = \left( \frac{1}{\gamma^2 - \alpha} \right)^{-1} Q' \frac{\Delta f}{f}$$

Focal length is energy dependent
Chromaticity Measurements...

Simply by using the definition:
- Measure betatron tune for different beam momenta;
- vary beam momentum by changing the Rf-frequency
Time resolved Q’ Measurement

Applied Frequency Shift
$\Delta F$ (RF)

Amplitude & sign of chromaticity calculated from continuous tune plot

$\Delta Q_h$

$\Delta Q_v$
Measurement Example during LEP $\beta$-squeeze

$q_h$

$q_v$
...a story from the good old days:

LEP after a technical stop
- no way to make the beam do one turn around the accelerator
- With BPM readings localize the problem to about 20 meters
- local check of equipment (quadrupole polarity…)
- radiography of beam pipe

- finally: cut beam pipe open
LEP – No Circulating Beam after a technical stop
Zoom on QL1
& 10 metres to the right …

Unsociable sabotage: both bottles were empty!!