Beam Instrumentation and Diagnostics (Lecture 2)

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Introduction

• **Yesterday was dedicated to**
  – Beam position measurement
  – Beam intensity measurement
  – Beam loss monitoring

• **Today we’ll continue with a look at**
  – Beam profile monitoring & diagnostics
  – Tune, Coupling & Chromaticity measurement & feedback
  – Making Accelerators work using beam instrumentation
Beam Profile Monitors
Profile Monitoring using Wires

- Secondary Emission Monitors (SEM or HARP)
  - Beam profile from secondary electrons emitted from wire grid on beam impact
  - Require many electronic channels for readout
Profile Monitoring using Wires

• **Wire-scanners**
  – Move thin wire across beam
  – Low energy: correlate wire position with secondary emission
  – High energy: correlate wire position with secondary shower
Limitation of Wire-Scanners

• **Wire Breakage – why?**
  - Brittle or Plastic failure (error in motor control)
  - Melting/Sublimation (main intensity limit)
    • Due to energy deposition in wire by particle 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
Profile Monitoring using Screens

- **Early Diagnostics**
  - Luminescence / Scintillating Screens
    - Destructive (thick) but work with low intensities

- **Advantages**
  - Allows use of CCD camera
    - gives 2D information

*First Beam in the LHC 8/8/2008*
Profile Monitoring using Screens

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

**• OTR screens**
- Less destructive than scintillation but requires higher energy / intensity beam
- Can be used for extremely high resolution measurements
Synchrotron Light Monitors

Visible light

Intensity drops off sharply after critical wavelength

• 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
  – X-ray pin hole cameras
    • For imaging small, high energy electron beams
  – Streak cameras
    • For short bunch diagnostics
Longitudinal Profile Measurement

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

• How do we measure such short bunches?
  – Direct Observation
    • Synchrotron radiation observed with dedicated instruments
      – Streak camera resolution ~200fs
    • 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

<table>
<thead>
<tr>
<th>Beam</th>
<th>Time (fs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>p⁺  @ LHC</td>
<td>250</td>
</tr>
<tr>
<td>H⁻ @ SNS</td>
<td>100</td>
</tr>
<tr>
<td>e⁻ @ ILC</td>
<td>500</td>
</tr>
<tr>
<td>e⁻ @ CLIC</td>
<td>130</td>
</tr>
<tr>
<td>e⁻ @ XFEL</td>
<td>80</td>
</tr>
<tr>
<td>e⁻ @ LCLS</td>
<td>&lt;75</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)

\[ eV \]
\[ eV_0 \]
\[ z \]
\[ \varphi < 0 \]

\[ \langle \Delta y \rangle \]
\[ \sigma_y \]
\[ \Delta \psi \approx 60^\circ \]
\[ \beta_c \]
\[ \beta_p \]
Measuring Ultra Short Bunches

• **Electro-Optic Sampling**
  – Birefringent crystal placed close to the beam
    • Non-destructive technique
  – Bunch passes simultaneous to chirped (time varying wavelength) laser pulse
  – Intensity of bunch electric field modifies polarisation of light in crystal
    • Longitudinal bunch distribution mapped to wavelength
  – Wavelength v. Intensity gives longitudinal bunch distribution
    • Can be done in a variety of ways (simplest example below)
    • Resolution down to 30 fs possible

Spectral Decoding

Limited to >250fs by laser bandwidth

![Diagram of Electro-Optic Sampling](image)
Diagnostics using Beam Profile Monitors
Optics Measurement in LINACs

3 Monitor Method
- Optics functions & initial emittance reconstructed using transport matrix

Measured Beam Profiles

rms ellipses
Optics Measurement in LINACs

Linear Mapping of measured beam size onto initial phase space

Measured Beam Profiles

rms ellipses
Optics Measurement in LINACs

- More advanced reconstruction
  - Linearly map measured profiles onto initial phase space
  - Use tomography to reconstruct particle density distribution

- Things get more complicated when you add space charge
Optics Measurement in LINACs

- Hybrid Phase Space Tomography in Linac4
  - Iteratively vary Twiss parameters
  - Track to the measurement locations including space-charge
  - Deduce new distribution of density in phase space from which particles fall on which wires
  - Generate new beam distribution & use for next iteration

Reconstructed & Measured profiles at last SEM grid
Measurements with Screens

- Injection matching measurements with OTR
  - Machine settings mismatch
  - Leads to filamentation
  - Results in emittance growth
Bunch by Bunch Diagnostics

LHC Synchrotron Light Diagnostics
- Gated intensified Camera
- Allows bunch by bunch profile measurement

Electron Cloud
- 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
Tune, Coupling & Chomaticity Measurement
Machine Tune

- **Machine Tune**

![Diagram of magnetic lattice with QF, QD, SF, and SD magnets]

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

- **Parameters per plane**
  - $Q$: Full betatron tune
  - $q$: Fractional tune (operating point)

- **Real life more complex**
  - horizontal & vertical oscillations couple
  - betatron motion at large amplitudes non-linear

$$Q = 11.25$$
$$q = 0.25$$

- Turn $n$
- Turn $n+1$
- Turn $n+2$
- Turn $n+3$
- Turn $n+4$
**Tune Measurement**

- **Integer tune**
  - can be seen in orbit response
  - H: 59, V: 64 for LHC

- **Fractional tune (q)**
  - Seen from turn-by-turn signal of single BPM if beam is given a kick
  - Fast Fourier Transform (FFT) of oscillation data gives resonant frequency (q)
Tune Measurement – the principle

- **Beam size**
  - defined by incoherent betatron motion of all particles

- **Particles have momentum spread**
  - gives spread in focussing by quadrupoles
  - gives rise to spread in the frequency of the betatron oscillations (chromaticity)
  - coherent oscillations will de-cohere

- **Hadrons do not forget!**
  - once hit they oscillate (practically) forever
  - any excitation must be kept very small
Tune Measurement – the principle

- Observable is typically turn-by-turn position from a BPM
- BPM electrode signal has temporal shape related to the temporal structure (intensity profile) of the passing beam
  - Most of the signal produced is linked to intensity
- On top we look for very small variations linked to position
  - Such signals are very difficult to simulate in the lab
Tune Measurement – the principle

- A typical perfect detection scheme

- Reality

- Dynamic range issues
  - Signals related to betatron oscillations are small with respect to beam offset signals
  - Even for centred beam leakage is of order 1-10% (of 100V!) for ns beam pulses
The LHC Tune Measurement System

• **Direct Diode Detection – the advantages**
  – Single RF Schottky diode can handle up to 50 V pulses
    • Higher with a few diodes in series (LHC detector has 6 diodes)
  – Betatron modulation downmixed to below the revolution frequency
    • Allows efficient signal processing with inexpensive, high resolution ADCs
  – Just AM receiver – so what’s new?
    • Slow discharge & use of low noise, high impedance amplifiers
    • Brutal filtering of revolution line & everything outside band of interest
LHC Tune System Performance

Sensitivity down to the 10 nanometre level
Enough to see residual beam oscillation without added excitation
Real-Time Tune Display

SPS Example:
Tune clearly visible from residual oscillations without additional excitation
• **Tune diagnostics throughout the ramp**
  – Early ramps had poor tune control
  – Beam loss observed every time tune crossed a resonance line
Tune Feedback in the LHC

- Routinely used to compensate fill-to-fill variations
  - Uses peak fit on FFT with 0.1..0.3 Hz bandwidth
  - Feedback on trim quadrupoles
Coupling Measurement

- Start with decoupled machine
  - Only horizontal tune shows up in horizontal FFT
- Gradually increase coupling
  - Vertical mode shows up & frequencies shift

FFT of Horizontal Acquisition Plane
Coupling & Tune Control

- **Measured tunes - the physical observables**
  - Often called the ‘normal modes’ or ‘eigenvalues’

- **Set tunes**
  - What tunes would be in absence of coupling
  - Can be calculated with knowledge of coupling

- **The coupling coefficient $C^-$**
  - Often called ‘minimum tune split’ or $\Delta Q_{\text{min}}$
  - ‘Forbidden zone’ in a system of coupled oscillators

- **Set tune split $\Delta$**
  - Difference between the set horizontal & vertical tunes

- **When $C^-$ greater than $\Delta$**
  - Conventional tune control no longer works
  - Magnet system applies correction to the wrong plane
  - Tune feedback becomes unstable

\[
Q_{x,0} = Q_1 + \frac{1}{2} \Delta - \frac{1}{2} \sqrt{\Delta^2 + |C^-|^2}
\]
Coupling & Tune Feedback

- Measurement from RHIC during acceleration cycle
  - At several points measured tune is defined by coupling
  - Tune feedback breaks down at these points
Coupling & Tune Feedback

- **Coupling Feedback at RHIC**
  - Measure coupling & feedback on skew quadrupole families
    - Maintains a decoupled machine
  - Coupling & Tune feedback ON
    - Easily tracks & corrects tune throughout acceleration cycle
**Chromaticity**

- **Machine Chromaticity**

**Optics Analogy:**

**Lens**

[Quadrupole]

Achromatic incident light

[Spread in particle energy]

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

**First Order**

\[
\Delta Q = Q' \frac{\Delta p}{p} = \left( \frac{1}{\gamma^2} - \alpha \right)^{-1} Q' \frac{\Delta f}{f} \\
\xi = \frac{Q'}{Q}
\]
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<td><strong>Head-tail phase advance (same as above, but in time domain)</strong></td>
<td>Good results on several machines but requires kick stimulus ⇒ emittance growth!</td>
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RF Momentum Modulation Techniques

- **Slow RF Variation**
  - Apply time varying RF modulation
  - Continuously measure the tune
    - Amplitude of tune variation proportional to chromaticity

**Example from the LHC**
- Sinusoidal RF modulation at 0.05Hz
- Tune continuously tracked in all planes of both beams
- Chromaticity calculated once acquisition complete
RF Momentum Modulation Techniques

• Slow RF Variation
  – Apply time varying RF modulation
  – Continuously measure the tune
    • Amplitude of tune variation proportional to chromaticity

Example from CERN-LEP
  – Triangular RF modulation
  – Allows sign of chromaticity to be easily determined

Applied Frequency Shift

$Q_h$ & $Q_v$ Variation
Example from LEP $\beta$-squeeze
Example from LHC Acceleration Ramp

- Dynamic Measurement Examples
  - LHC Ramp
    - RF continuously modulated
    - Tune measured continuously
    - Chromaticity calculated from tune modulation amplitude

\[
\Delta Q = Q' \frac{\Delta p}{p} = \left( \frac{1}{\gamma^2 - \alpha} \right)^{-1} Q' \frac{\Delta f}{f}
\]
Example from RHIC

- Chromaticity measurement with feedbacks on
  - RHIC Example
    - RF continuously modulated
    - Tune feedback maintains tunes constant
    - Chromaticity calculated from feedback corrections to tune

- Chromaticity still well computed with effects of other feedbacks taken into account
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Amplitude of Synchrotron Sidebands

- Recently demonstrated at DIAMOND
  - RF modulation changes orbit - not compatible with user operation
  - Looking for technique to measure chromaticity on-line
    - Measure Beam Transfer Function (BTF) on single bunch
      - Using transverse bunch by bunch feedback system
      - Emittance blow-up of single bunch irrelevant
Amplitude of Synchrotron Sidebands

- **Must be Careful with High Intensity Effects**
  - Modification of tune spectra by space charge & impedance
    - Measurements performed at GSI
  - Relative heights & mode structure given by chromaticity
    - Can be calculated with simplified analytical models
Diagnosing Machine Issues using Beam Instrumentation
LEP Beams Lost During $\beta$-Squeeze

- Extract from LEP logbook (when pen & paper still used!)
  - OK when stepping through the $\beta$-squeeze slowly
  - Beams lost when attempting to go straight through

- 

  Straight through to 95 GeV.
  At $\sim$ 97-98 GeV, large vertical oscillation.
  OPAL trigger. Maybe a bit too ambitious.
  Tunneling 01-12-40 fill 7065
  Nothing particularly nasty.
  Big radiation spikes in all spots.

- 

  01:40
  22 GeV 4050, Breakfast at 93 GeV.
  640 mA, 0.234 / 0.164 5.27 mA
  93 GeV 4050, 01-58-36 jems
  Tunneling 01-50-25 fill 7066
The Diagnostics

- **Tune Variation**
  - Tracked for different power converter ramp rates
The Explanation

- **Master-Slave Configuration for Power Converter**
  - Each converter can deliver full DC current
  - Slave converter not working
    - Slave only needed to give increased voltage for fast current changes

\[
U = IR + L \frac{dI}{dt}
\]
• No Circulating Beam after Technical Stop
  – Phase advance from BPMs show that optics no longer correct after specific quadrupole

QL10.L1

Positrons
The Explanation

- After many trials - open vacuum chamber in QL10.L1
  - & 10m to the right ....

- Unsociable sabotage
  - Both bottles were empty!!
Summary

• You now hopefully have a first impression of how to build and use beam instrumentation to run & optimise accelerators
• It should also be clear that there are two distinct types
  – “Bread & butter” instrumentation for standard operation
  – Innovative instrumentation to address specific requirements or new techniques to use traditional instrumentation in non-conventional ways

Want to know more?
Then Join the Beam Instrumentation Afternoon Course

• 3 Sessions on BPM design
  – Simulation software & “hands-on” laboratory measurements
• 1 Session on Tune Measurement
  – Program and measure using your own DSP
• 2 Sessions on Profile Measurements
  – “Hands-on” laboratory measurements
• Final Session
  – Group presentation of your BI proposals for an accelerator