Beam Instrumentation
&
Beam Diagnostics

CAS 2005

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(CERN)
Instrumentation---Diagnostics

• Instrumentation: summary word for all the technologies needed to produce primary measurements of beam parameters.

• Diagnostics: making use of these instruments in order to
  - operate the accelerators  ex: orbit control
  - improve the performance of the accelerators  ex: tune feedback, emittance preservation
  - deduce further beam parameters or performance indicators of the machine by further data processing  ex: chromaticity measurements, betatron matching
  - detect equipment faults
Outline for Today

• Optimisation of Machine Performance (“the good days”)
  → Orbit measurement & correction
  → Luminosity: basics + luminosity tuning, betatron matching

• Diagnostics of transverse beam motion
  → Tune & chromaticity measurements
  → Dynamic effects: tune and chromaticity control
  → On-line $\beta$ measurements

• Trying to make the machine work (“the bad days”)
  → The beam does not circulate!
  → The beam gets lost, when changing the beta*
Orbit Acquisition

Horizontal

Vertical
Orbit Correction (Operator Panel)

**Screen Shot:**
- **Start Tasks**
- **Operation**
- **SPS Top10**
- **MDUMP Reset**
- **P2 Reset**
- **Active Tasks**

**SPS_orbit**
- **QUIT**
- **SPS XORBIT V9.01/2K+1**
- **Done**
- **Info**
- **Acquire**
- **Reference Orbit**
- **Reference Catalog**
- **Send Correction**
- **MON & COD**
- **no reference set**
- **no data**
- **Acquisition Time**
- **Load Orbit**
- **Difference**
- **Sum**
- **Cancel Correction**
- **Skeleton**
- **Closed Orbit**
- **dp/dq-offset shown**
- **Control Plane**
- **Hor**
- **Vert**
- **MD Specials**
- **MCADO**
- **Other Tools**

**Predicted Correction Results**
- **GLOBAL: mean = -0.006 RMS = 0.579 #pu = 113**
- **Cu 55.9562 - 1.0417 mon**
- **GLOBAL: mean = 0.023 RMS = 0.329 #pu = 113**
- **Cu 25.5858 6.04187 diff**

**Before Correction**
- **Da 56.0000 0.2709 dy -1.3117 BVP:3209**

**Difference**
- **Cu 55.9562 - 1.0417 mon**

**After Correction**
- **Da 26.0000 0.00381 dy 5.63786 BVP:21508**

**Cu 55.9562 6.04187 diff**

**Note:**
- Number of iterations required (max)
- Iterations = 5

**File Supercycle Help**
- Running SC 001
- Proton 1
- 0 - 90000 [BPP100]
Orbit Correction (Detail)
Luminosity & Beam-Beam Tune Shift

- Luminosity
- Normalized emittance
- Beam-beam tune shift

To maximize $L$ and minimize the stored energy, increase $N$ to the tune shift limit, choose a large number of bunches ($M$) and a small $\beta_*$.

\[ L = f_{\text{rev}} \frac{M N^2}{4\pi \sigma_*^2} \]

\[ \varepsilon_N = \gamma \frac{\sigma_*^2}{\beta_*} \]

\[ \Delta v_{bb} = \frac{N r_p}{4\pi \varepsilon_N} \leq 0.006 \text{ (LHC)} \]
Luminosity Measurement in the LHC:
Nominal locations of the neutral (TAN) absorbers

- The TAN absorbs forward neutral collision products (mostly neutrons and photons) and is placed in front of the outer beam separation dipole D2
- Ideal location to measure the forward flux of collision products
- The count rate is proportional to luminosity
• Peak power density of 1-10 W.kg$^{-1}$.m$^{-1}$ (location of luminosity detector)
• A 3m radiation hard cable will allow electronics to be located in a region with power density $< 10^{-5}$ W.kg$^{-1}$.m$^{-1}$ (100 Gy/year for nominal operation)
LHC Luminosity Measurement

Requirements:
- Capable of 40MHz acquisition
- Has to withstand high radiation dose: \(~10^8\) Gy/year
  - \(\rightarrow\) estimated \(10^{18}\) Neutrons/cm\(^2\) over its lifetime (20yrs LHC operation)
  - \(\rightarrow\) estimated \(10^{16}\) Protons/cm\(^2\) over its lifetime (20yrs LHC operation)
- No maintenance

Selected Technology:
- Pressurized Ionisation Chambers
  - developed by LBL (Berkeley, US)
    - Good radiation hardness
    - Meet 40 MHz bandwidth demand
Improving luminosity

1) Stronger focusing insertions
   → transition from high beta optics at injection to low beta optics at collision (so called beta squeeze):
   critical process with dynamic effects on orbit, tune and chromaticity

2) Smaller emittance and emittance preservation through the pre-injectors
   → measurements of beam size from low energy beams to high energy beams
   → betatron matching at injection

3) Higher intensity: sounds simple, but one needs diagnostics (and cures) for the onset of instabilities, real time longitudinal and transverse feedback, control of radiation issues, i.e. beam loss monitors.
Optical Transition Radiation Monitors

As Beam hits the 12μm Titanium foil 2 cones of radiation are emitted

Capturing emitted radiation on a CCD gives 2D beam distribution
β-Mismatch at injection seen as a beating in the beam profile

Next injection +1 turn

Very poor matching!!
Quadrupolar Pick-Up

- Position contribution can not be avoided, but can be measured and subtracted.

- Design suppresses the dominating intensity signal by coupling to the radial magnetic field component.

\[
A \propto i_b \left( 0 + 0.41 \left( \frac{\bar{x}}{r} - \frac{\bar{y}}{r} \right) + 1.23 \frac{\sigma_x^2 - \sigma_y^2 + \bar{x}^2 - \bar{y}^2}{r^2} + \ldots \right)
\]
Installation in the CERN-PS

SD03

Pick up
Wide Band
Resistive

Quadrupolar
Pick up

SS 03

22 m
12 m
3.2 m

SS 04

12 m
22 m
2.3 m

“One pick-up per plane”
Measurement of Matching

\[ \kappa \propto \sigma_x^2 - \sigma_y^2 = \epsilon_x(\beta_x + \frac{\Delta\beta_x}{2q_x}) - \epsilon_y(\beta_y + \frac{\Delta\beta_y}{2q_y}) + \sigma_p^2\left( D_x^2 + D_y^2 \right) \]

- Simultaneous fit to the two pick-up signals gives:
  - Injected emittances.
  - Betatron mismatches.
  - Horizontal dispersion mismatch.

- Input parameters
  - \( \beta_H, \beta_V, D_H \)
  - \( \Delta\mu_H, \Delta\mu_V \)
  - \( \sigma_p, q_h, q_v \)

- Most input parameters can be checked experimentally

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Outline for Today

- **Optimisation of Machine Performance**
  (“the good days”)
  → Orbit measurement & correction
  → Luminosity: basics + luminosity tuning, betatron matching

- **Diagnostics of transverse beam motion:**
  Important tools to stabilize performance at high levels
  → Tune & chromaticity measurements
  → Dynamic effects: tune and chromaticity control
  → On-line $\beta$ measurements

- **Trying to make the machine work**
  (“the bad days”)
  → The beam does not circulate!
  → The beam gets lost, when changing the beta*
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
**Principle of any Q-measurement**

Beam Diagnostics

**Beam Excitation Source for Transverse beam Oscillations**
- stripline kickers
- pulsed magnets

**Observation of Transverse beam Oscillations**
- E.M. pickup
- resonant BPM
- others

**G(\(\omega\)) H(\(\omega\))**

**BTF := H(\(\omega\))/G(\(\omega\))**

**Measurement of betatron tune Q:**
- Maximum of BTF
Simple example: FFT analysis

$G(\omega) = \text{flat}$
(i.e. excite all frequencies)

Made with random noise kicks

Measure beam position over many consecutives turns

apply FFT $\rightarrow H(\omega)$

$BTF = H(\omega)$
Network Analysis

1. Excite beams with a sinusoidal carrier

2. Measure beam response

3. Sweep excitation frequency slowly through beam response
Time Resolved Measurements

- To follow betatron tunes during machine transitions we need time resolved measurements. Simplest example:

  → repeated FFT spectra as before (spectrograms)
Principle of PLL tune measurements

This PLL system looks to the 90 deg. point of the BTF

Beam

Read VCO
Frequency = tune!
At regular Time intervals

VCO
Voltage controlled oscillator
A sin(ωt)

Phase detector
AB sin(2 ωt+φ)cos(φ)

Frequency control:
ABcos(φ)

BPM
B sin(ωt+φ)

Lowpass

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Illustration of PLL tune tracking

Single carrier PLL locks on 90° point of BTF;
Example of PLL tune measurement

In this case continuous tune tracking was used whilst crossing the horizontal and vertical tunes with a power converter ramp.

Closest tune approach is a measure of coupling.
Tune Measurement Systems

- Standard Tune Measurement (FFT) and PLL tune tracker will use a new BaseBand Tune (BBQ) system developed at CERN using Direct Diode Detection (3D)
### Advantages

- Sensitivity (noise floor measured at RHIC in the 10 nm range!!)
- Virtually impossible to saturate
  - → large Freq suppression already at the detectors + large dynamic range
- Simplicity and low cost
  - → no resonant PU, no movable PU, no hybrid, no mixers, it can work with any PU
- Base band operation
  - → excellent 24 bit audio ADCs available
- Signal conditioning / processing is easy
  - → powerful components for low frequencies
- Independence from the machine filling pattern guaranteed
- Flattening out the beam dynamic range (small sensitivity to number of bunches)

### Disadvantages

- Operation in the low frequency range
  - → More susceptible to EMC
- It is sensitive to the “bunch majority”
  - → gating needed to measure individual bunches
Results from the PS (AD cycle)

No explicit beam excitation

Q Kicker set to minimum

Beam Diagnostics
Measurement of Coupling using a PLL Tune Tracker

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

Fully coupled machine: $\Delta = |C^-|$
Measurement of Coupling using a PLL Tune Tracker

Tracking the vertical mode in the horizontal plane & vice-versa allows the coupling parameters to be calculated.

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Measurement of Coupling using a PLL Tune Tracker (RHIC Example)

Eigenmode 1

Eigenmode 2

Fully coupled

Tunes entirely defined by coupling

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β Function Measurement by k-Modulation

• **Purpose:**
  → measurement of \(< \beta >\) within a quadrupole
  → optics knowledge
  → emittance determination: \(\varepsilon = \sigma_{\text{rms}}^2 / \beta\)

• **Principle:**
  → a (small) strength variation \(\Delta k\) within a quadrupole induces a tune variation \(\Delta Q\)

\[
\Delta Q = \Delta k / 4\pi \int_{\text{Quad}} \beta(s) \, ds
\]

\[
< \beta_{H,V} > = (4\pi \Delta Q_{H,V} / L\Delta k) (1+\varepsilon(\Delta Q))
\]

- \(L\) is the quadrupole magnetic length
- \(\Delta Q\) is small enough to keep second order term contribution < 1%

• **\(\Delta k\) modulated using \(k\)-modulation facility in LEP to test:**
  → What is the smallest possible perturbation? (LHC emittance budget)
  → Can it work with beams colliding head ON?
β Measurement using k-Modulation in LEP

Effect of Q feedback loop speed (PLL mode)

→ $\Delta I = 1 \text{A}, 0.25 \text{ Hz}$

→ “fast” mode: 20 Hz

→ “normal” mode: 12 Hz
**β Measurement using k-Modulation in LEP**

Comparison between static $\Delta k$ , 1000 turns and k-modulation

**LEP:** 85GeV, 800mA, 4 bunches

- **1000 turns:**
  - $\beta_{\text{middle QUAD}} = 175.4$ m
  - $\beta$-beating: -9.2%
  - $<\beta> = 164.8$ m

- **k-modulation:**
  - $1A$ ($5 \times 10^{-4}$), 0.25 Hz
  - $<\beta> = 162.9$ m
Comparison between static $\Delta k$ and $k$-modulation with colliding beams in LEP

[103.3 GeV, 1860 $\mu$A on 1860 $\mu$A]

• Static $\Delta k$:
  → $I_0 + 0.5$ A : $\langle \beta \rangle = 383.9$ m
  → $I_0$
  → $I_0 - 0.5$ A : $\langle \beta \rangle = 392.8$ m

• $k$-modulation:
  → $I_0 + \Delta I$
  → $\Delta I = 1$A, 0.25 Hz
  → $\langle \beta \rangle = 389.4$ m
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]

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

$$\xi = \frac{Q'}{Q}$$
Chromaticity – Its Importance for the LHC?

• Change in $b_3$ during snap-back
  → Change in $Q'$ of ~150 units
• Nominal operation requires $\Delta Q' < 3$
• Correction by:
  → Feed-forward tables from magnet/chromaticity measurements
  → On-line feedback from $b_3$ measurements on reference magnets
  → Possible on-line feedback directly from chromaticity measurements
Chromaticity - What observable to choose?

<table>
<thead>
<tr>
<th>Tune Difference for different beam momenta</th>
<th>⇔</th>
<th>used at HERA, LEP, RHIC in combination with PLL tune tracking</th>
</tr>
</thead>
</table>

- Tune Difference for different beam momenta
- Width of tune peak or damping time
- Amplitude ratio of synchrotron sidebands
- Excitation of energy oscillations and PLL tune tracking
- Bunch spectrum variations during betatron oscillations
- Head-tail phase advance (same as above, but in time domain)

Difficult to measure

Very good results but requires kick ⇒ emittance growth!
Q’ Measurement via RF-frequency modulation (momentum modulation)

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

$q_h$

$q_v$
Chromaticity & Head-Tail Motion

Positive Chromaticity (Above Transition)

\[ Q > Q_0 \]

\[ \Delta \frac{p}{p} \]

\(-\omega_s \tau\)

\[ \hat{\tau} \]

\[ Q < Q_0 \]

Longitudinal Phase-Space
Chromaticity & Head-Tail Motion

Negative Chromaticity (Above Transition)

Longitudinal Phase-Space

\[ \Delta p/p \]

\[ Q < Q_0 \]

\[ Q > Q_0 \]

\[ -\omega_s \tau \]

Head

Tail

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Beam Diagnostics
Simulated Response

Simulated Bunch Evolution for Zero Chromaticity

Simulated Bunch Evolution for Positive Chromaticity

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Beam Diagnostics
The Head-Tail Measurement Principle

Chromaticity = 5

Phase difference between Head and Tail

Phase Difference ($\Delta \phi$)

Turn
Head-Tail System Set-up (SPS)

SPS Tunnel

Fast (2GS/s per channel)
Digital Oscilloscope

Sum

Difference

Bunch Synchronous Trigger

VME Acquisition via GPIB

UNIX User Interface

GPIB link
Measuring $Q'$ (Example 1: low $Q_s$)

$Q_s^{-1} = 310$ turns
Measuring $Q'$ (Example 2: high $Q_s$)

$Q_s^{-1} = 97$ turns
Measuring $Q'''$ and $Q''''$

Radial Position versus Chromaticity (115GeV)

Chromaticity ($\xi$)

Radial Position (mm)

- Radial Steering
- Scaled Head-Tail
Online measurement and feedback of $Q$ & $Q'$

• The aim for the LHC:
  → Permanent $Q$ & $Q'$ measurements with hard constraints on:
    • emittance preservation
    • insensitivity to machine-parameter changes (orbit, coupling…)
  → Online feedback to power supplies of quadrupole and sextupole magnets (bandwidth < 10 Hz)

• What has been done so far:
  → Early example from LEP → next slide
  → Present situation at DESY → following movie
Early example from LEP

Q - Feedback loop during energy ramping

$q_{ref H}$

$q_{ref V}$

$\Delta I_F = 0.93 \Delta Q_H + 0.32 \Delta Q_V (\frac{20}{GeV})$

$\Delta I_D = 0.33 \Delta Q_H + 0.97 \Delta Q_V (\frac{20}{GeV})$

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HERA-p solution:

- “Chirp” tune measurements
- Online display
- Operator “joystick” feedback to quadrupole and sextupole power-supplies
Online Q-display at HERA-p with “BLL” as control (brain locked loop)

HERA PROTON RAMP 40-920 GeV
Tunes qh green, qv magenta.
Excitation by 'Chirp' 10-20 kHz
(frev ~ 47.3 kHz)
The response depends on h/v coupling and chromaticities

39.69 GeV Sat Apr 20 17:24:00 2002
Outline for Today

- **Optimisation of Machine Performance** ("the good days")
  - Orbit measurement & correction
  - Luminosity: basics, profile and $\beta$ - measurements
- **Diagnostics of transverse beam motion**
  - Tune & chromaticity measurements
  - Dynamic effects: tune and chromaticity control
  - On-line $\beta$ measurements

- **Trying to make the machine work** ("the bad days")
  - The beam does not circulate!
  - The beam gets lost, when changing the beta*
LEP – No Circulating Beam
& 10 metres to the right …

Unsociable sabotage: both bottles were empty!!
**LEP Beams Lost During Beta Squeeze**

From LEP logbook

<table>
<thead>
<tr>
<th>Time</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>01:40</td>
<td>Straight through to 95 GeV.</td>
</tr>
<tr>
<td></td>
<td>At ~97-98 GeV e- large vertical oscillation</td>
</tr>
<tr>
<td></td>
<td>OPAL trigger. Maybe a bit too ambitious</td>
</tr>
<tr>
<td></td>
<td>Tunesistory 01-12-40 fill 7065</td>
</tr>
<tr>
<td></td>
<td>— nothing particularly nasty</td>
</tr>
<tr>
<td></td>
<td>Big radiation spikes in all sects.</td>
</tr>
</tbody>
</table>

- 22 GeV 4Q50. Breakpoint at 93 GeV.
- 640 µA 0.234 / 0.164 5.27 mA
- 93 GeV 4Q50 01-58-36 repms

Tunesistory 01-50-25 fill 7066
...and the corresponding diagnostics
In these two lectures we have seen how to build and use beam instrumentation to run and optimise accelerators.

Hopefully it has given you an insight into the field of accelerator instrumentation and the diverse nature of the measurements and technologies involved.