Introduction to Beam Diagnostics

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(Beam Instrumentation)
A few depicted examples

- **Introduction**
- **Beam presence**: Scintillating screens (LHC)
- **Intensity measurement**, Faraday Cup and Transformer (Linac-4)
- **Transverse Profile** measurement, wire scanner & wire grids (PSB & PS)
- **Emittance** measurement
  - Slit and Grid (Linac-4, 3 MeV line)
  - Emittance measurement line (Linac-2)
  - Longitudinal Emittance measurement (Linac-2)
- **Trajectory** measurement (LHC and PS) using Beam Position Monitors (BPMs)
- **Longitudinal phase space**: Tomoscope (PS) using a wall current monitor
- **Tune** measurement (SPS) using BPMs
- **Losses**: Beam Loss Monitors (BLMs) (LHC)
An accelerator can never be better than the instruments measuring its performance!
## Diagnostic devices and quantity measured

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A beam parameter measurement
Beam Presence
Scintillating Screens

Method already applied in cosmic ray experiments
- Very simple
- Very convincing

Needed:
- Scintillating Material
- TV camera
- In/out mechanism

Problems:
- Radiation resistance of TV camera
- Heating of screen (absorption of beam energy)
- Evacuation of electric charges

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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 Intensity
Layout of a Faraday Cup

- Electrode: 1 mm stainless steel
- Only low energy particles can be measured
- Very low intensities (down to 1 pA) can be measured
- Creation of secondary electrons of low energy (below 20 eV)
- Repelling electrode with some 100 V polarisation voltage pushes secondary electrons back onto the electrode

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Faraday Cup
In order to keep secondary electrons with the cup a repelling voltage is applied to the polarization electrode.

Since the electrons have energies of less than 20 eV some 100V repelling voltage is sufficient.
Energy of secondary emission electrons

- With increasing repelling voltage the electrons do not escape the Faraday Cup any more and the current measured stays stable.
- At 40V and above no decrease in the Cup current is observed any more.

\[ I(\mu A) \] vs. \[ V \]

\[ \text{I}_{\text{total}} \text{ vs. eV} \]

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Intensity
Principle of a fast current transformer

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

Diagram by H. Jakob

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Magnetic shielding

- Shield should extend along the vacuum chamber length > diameter of opening
- Shield should be symmetrical to the beam axis
- Air gaps must be avoided especially along the beam axis
- Shield should have highest $\mu$ possible but should not saturate

Transformer steel ($\mu_2$)

Soft iron ($\mu_1$)

Permalloy ($\mu_3$)
Calibration of AC current transformers

- The transformer is calibrated with a very precise current source
- The calibration signal is injected into a separate calibration winding
- A calibration procedure executed before the running period
- A calibration pulse after the beam pulse measured with the beam signal
Profile measurements

• Secondary emission grids (SEM grids)

When the beam passes secondary electrons are ejected from the wires

The current flowing back onto the wires is measured

The ejected electrons are taken away by polarization voltage
Profiles from SEMgrids

- Projection of charge density projected to x or y axis is Measured
- One amplifier/ADC per wire
- Large dynamic range
- Resolution is given by wire distance
- Used only in transfer lines
Wire Scanners

A thin wire is quickly moved across the beam
Secondary particle shower is detected outside the vacuum chamber on a scintillator/photo-multiplier assembly
Position and photo-multiplier signal are recorded simultaneously
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
Emittance measurements

A beam is made of many, many particles, each one of these particles is moving with a given velocity. Most of the velocity vector of a single particle is parallel to the direction of the beam as a whole \((s)\). There is however a smaller component of the particles velocity which is perpendicular to it \((x\) or \(y)\).

\[
\vec{v}_{\text{particle}} = v_s \hat{u}_s + v_x \hat{u}_x + v_y \hat{u}_y
\]
Emittance measurements

• If for each beam particle we plot its position and its transverse angle we get a particle distribution whose boundary is an usually ellipse.
• The projection onto the x axis is the beam size
The slit and grid method

- If we place a slit into the beam we cut out a small vertical slice of phase space.
- Converting the angles into position through a drift space allows to reconstruct the angular distribution at the position defined by the slit.
Transforming angular distribution to profile

- When moving through a **drift space** the angles don’t change (horizontal move in phase space)
- When moving through a **quadrupole** the position does not change but the angle does (vertical move in phase space)

Influence of a drift space

Influence of a quadrupole

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The Slit Method
Emittance Meter

- SEM grid read-out 250kHz
- Stepping motors to allow coarse + fine position tuning
Transverse Emittance Measurement

Slit and grid phase space scanner

L-shaped 0.1mm slit moves under 45 degrees

Slit and grids move independently
Positioning precision: 50 µm
Movement PLC controlled

Slit and grids mounted in 2 independent vacuum boxes which can be separated

Horizontal and vertical SEMGrid
• wire distance .75 mm
• 30 signal wires
• readout with home built 36 channel 250 kHz ADC
• time resolved profiles

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Emittance plot Solenoid

- H3+
- H0
- H2+

Protons

X [mm]
Y [mm]

Emittance Plot
- Entries: 19890
- Mean x: -3.067
- Mean y: 4.603
- RMS x: 14.14
- RMS y: 49.27
Single pulse emittance measurement

Every 100 ns
a new profile

Kickers

slit

Quadrupole

Quadrupole

SEMgrid

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Transformation in Phase Space

Kicker → Kicker → Quadrupole → Quadrupole → SEMGrid

at slit  first drift space  first quadrupole  second drift space  Second quadrupole

X'  X'  X'  X'  X'

X  X  X  X  X
Result of single pulse emittance measurement

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Longitudinal Emittance measurement

- Spectrometer produces image of slit on second slit
- Second slit selects energy slice
- First kicker sweep phase space over all energies
- Buncher rotates energy slice in phase space
- At second spectrometer the phase distribution is transformed into an energy distribution analyzed by the second spectrometer
- Second kicker corrects for first kick

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Measure the particle position of each bunch as it travels around the ring.
The PS, a universal machine

All beams pass through the PS
Different particle types
Different beam characteristics
Concept of a super cycle
The Supercycle

This afternoon, no beam during 4 hours injection kicker intervention as soon as LHC is filled.

Comments
(23-Oct-2012 11:34:12)
BPM signals sampled at 120 MHz

Red: The sum signal  
Green: The difference signal

Procedure:
Produce integration gates and baseline signals  
Baseline correct both signals  
Integrate sum and difference signals and store results in memory  
Take external timing events into account e.g. harmonic number change, γ-transition etc.
Baseline restoration

Low pass filter the signal to get an estimate of the base line
Add this to the original signal
Trajectory measurements in circular machines

Needs integration gate
Can be rather tricky
Distance between bunches changes with acceleration
Number of bunches may change
Beams in the PS
RF Gymnastics

- Bunch splitting or recombination
  One RF frequency is gradually decreased while the other one is increased
- The gate generator must be synchronized

Example of generated gate around 2nd injection

Idem, during bunch splitting
Trajectory readout electronics

- **ADC**
- **BASELINE RESTORER**
- **INTEGRATOR**
- **MEMORY CONTROLLER**
- **DDR II SDRAM MEMORY**

- **CLOCK DISTRIBUTION**
- **ETHERNET INTERFACE**
- **ARM SINGLE BOARD COMPUTER**

- **FILTER**
- **PHASE TABLE**
- **POINTER MEMORY & Synchronisation**

- **LOCAL BUS REGISTER**
- **Synchrotron Timing**
- **CERN Timing**
- **HC Timing**
- **INJ Timing**
- **ST Timing**

- **EMBEDDED SIGNAL ANALYSES**
- **CHIPSOCPE ANALYSER**
- **JTAG**
Tune measurements

- When the beam is displaced (e.g. at injection or with a deliberate kick, it starts to oscillate around its nominal orbit (betatron oscillations)
- Measure the trajectory
- Fit a sine curve to it
- Follow it during one revolution
The Sensors

The kicker

Shoebox pick-up with linear cut

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Kicker + 1 pick-up

- Measures only non-integral part of Q
- Measure a beam position at each revolution
- Fourier transform BPM signal
- Search peak in Fourier Spectrum

Fourier transform of pick-up signal
Q-Measurement Results
Direct Diode Detection Base Band Q measurement

Diode Detectors convert spikes to saw-tooth waveform

Signal is connected to differential amplifier to cut out DC level

Filter eliminates most of the revolution frequency content

Output amplifier brings the signal level to amplitudes suitable for long distance transmission
BBQ Results from CERN SPS

Results from Sampling

After Fourier Transform

Amplitude / FS

Time [s]

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Tune feedback at the LHC

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Computed Tomography (CT)

Principle of Tomography:
• Take many 2-dimensional Images at different angles
• Reconstruct a 3-dimensional picture using mathematical techniques (Algebraic Reconstruction Technique, ART)
The reconstruction

Produce many projections of the object to be reconstructed.

Back project and overlay the “projection rays”.

Project the back-projected object and calculate the difference.

Iteratively back-project the differences to reconstruct the original object.

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Some CT results
Computed Tomography and Accelerators

RF voltage

Restoring force for non-synchronous particle

Longitudinal phase space

Projection onto $\Phi$ axis corresponds to bunch profile

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Reconstructed Longitudinal Phase Space

Courtesy S. Hancock

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Bunch Splitting
Stored Beam Energies

(Based on graph from R. Schmidt)

Energy stored in the beam [MJ]

Momentum [GeV/c]

Quench Levels | Units | Tevatron | RHIC | HERA | LHC
---|---|---|---|---|---
Instant loss (0.01 - 10 ms) | [J/cm³] | $4.5 \times 10^{-3}$ | $1.8 \times 10^{-2}$ | $2.1 \times 10^{-3}$ - $6.6 \times 10^{-3}$ | $8.7 \times 10^{-4}$
Steady loss (> 100 s) | [W/cm³] | $7.5 \times 10^{-2}$ | $7.5 \times 10^{-2}$ | | $5.3 \times 10^{-3}$
Beam power in the LHC

The Linac beam (160 mA, 200μs, 50 MeV, 1Hz) is enough to burn a hole into the vacuum chamber.

What about the LHC beam: 2808 bunches of $15 \times 10^{11}$ particles at 7 TeV?

1 bunch corresponds to a 5 kg bullet at 800 km/h.
Beam Loss Monitor Types

- Design criteria: Signal speed and robustness
- Dynamic range (> $10^9$) limited by leakage current through insulator ceramics (lower) and saturation due to space charge (upper limit).

**Secondary Emission Monitor (SEM):**
- Length 10 cm
- $P < 10^{-7}$ bar
- ~ 30000 times smaller gain

**Ionization chamber:**
- $N_2$ gas filling at 100 mbar over-pressure
- Length 50 cm
- Sensitive volume 1.5 l
- Ion collection time 85 $\mu$s

- Both monitors:
  - Parallel electrodes (Al, SEM: Ti) separated by 0.5 cm
  - Low pass filter at the HV input
  - Voltage 1.5 kV

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Quench levels
Industrial production of chambers

Beam loss must be measured all around the ring
=> 4000 sensors!
Conclusions

• Beam diagnostics is a very wide field where many different competences are needed
  – Machine physics
  – Electronics
  – Computing
  – Mechanics
• The instruments are the eyes with which we observe the beam
• The beam can never be adjusted with higher precision than what can be measured