Beam Instrumentation and Diagnostics (Lecture 1)

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Introduction

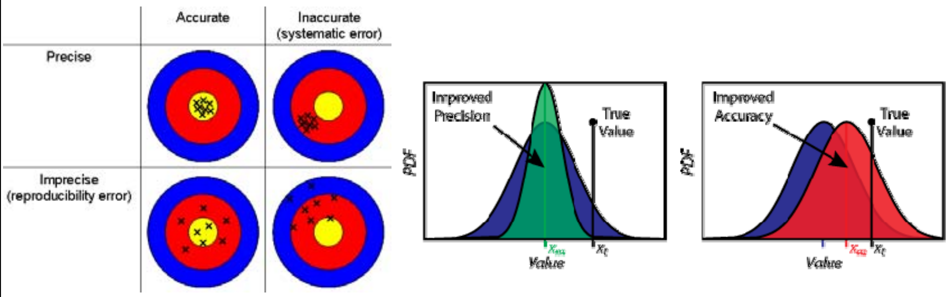
- What do we mean by beam instrumentation?
  - The “eyes” of the machine operators
    - i.e. the instruments that observe beam behaviour
    - An accelerator can never be better than the instruments measuring its performance!
- What does work in beam instrumentation entail?
  - Design, construction & 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
    - At a specific location for tune, coupling & chromaticity measurements
  - 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

What is meant by Beam Diagnostics?

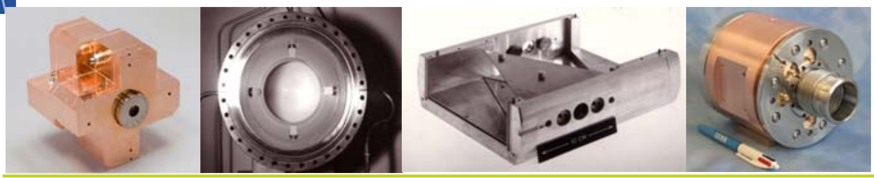
- Beam Diagnostics
  - Making use of beam instrumentation
- What do we consider as beam diagnostics?
  - Operating the accelerators
    - Using instrumentation to measure and correct standard parameters
      - Orbit, tune, chromaticity control etc.
  - Improving the performance of the accelerators
    - Understanding current performance to allow future improvements
    - Requires the measurement of performance indicators
      - Luminosity, brilliance (intensity and size) etc.
  - Understanding accelerator limitations
    - Beam loss, instabilities, emittance growth etc.
  - Detecting equipment faults
    - Aperture restrictions, polarity inversions, wrong settings etc.

How do we Qualify Beam Measurements?

- Accuracy, Precision, Resolution
  - Very often confused in day-to-day language
    - Accuracy – also known as the trueness of a measurement
    - Precision – how well a measurement can be reproduced
    - Resolution – the smallest possible difference measureable



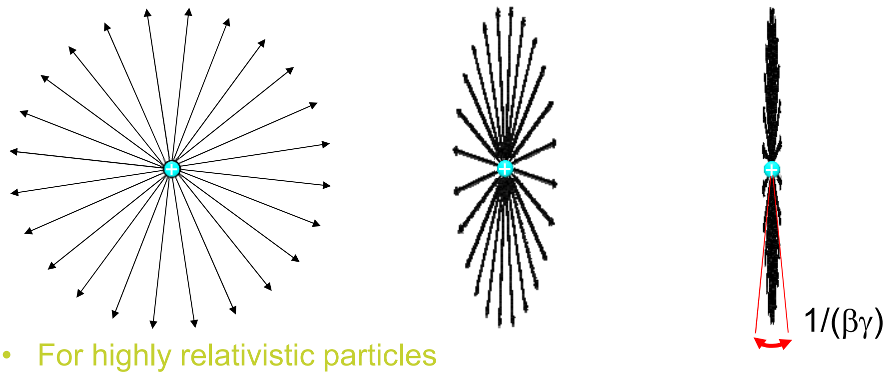
- Example for a BPM
  - Mechanical & electrical offsets and gain factors influence accuracy
  - Various noise sources or timing jitter influence the precision
  - Number of bits in the ADC will limit the resolution



Beam Position Systems

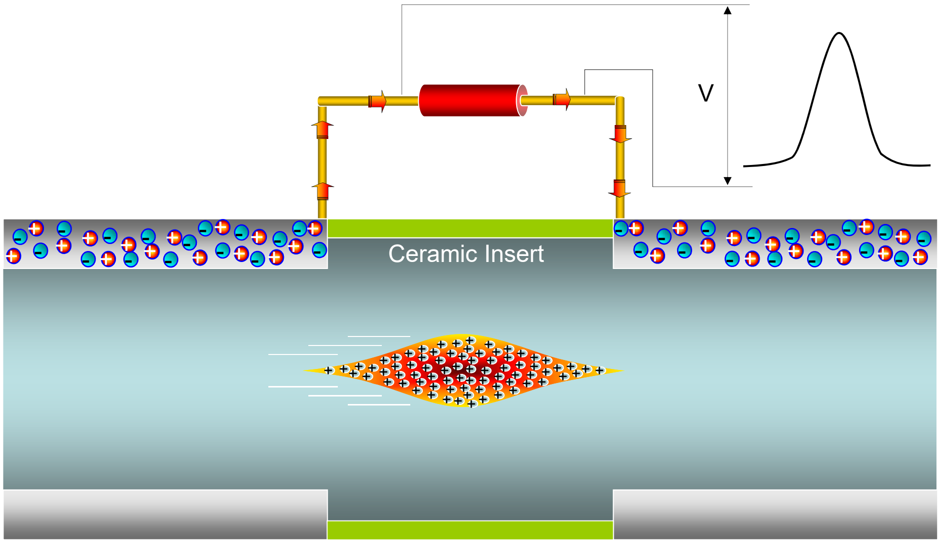
Electromagnetic Fields & Relativity

Static Point Charge | Moving Point Charge | Relativistic Point Charge

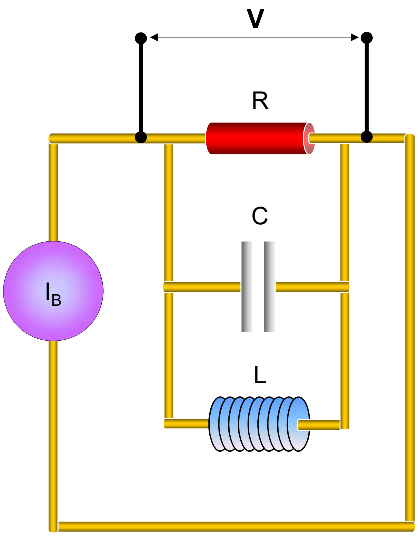


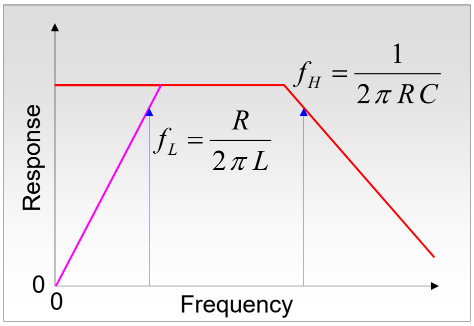
- For highly relativistic particles
  - Electric & magnetic fields transverse to the direction of motion
  - Can be considered as a Transverse EM (TEM) wave
- For non-relativistic particles
  - Need to take into account the finite longitudinal extent of the EM field

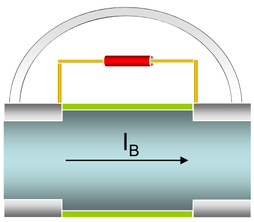
Wall Current Monitor – The Principle



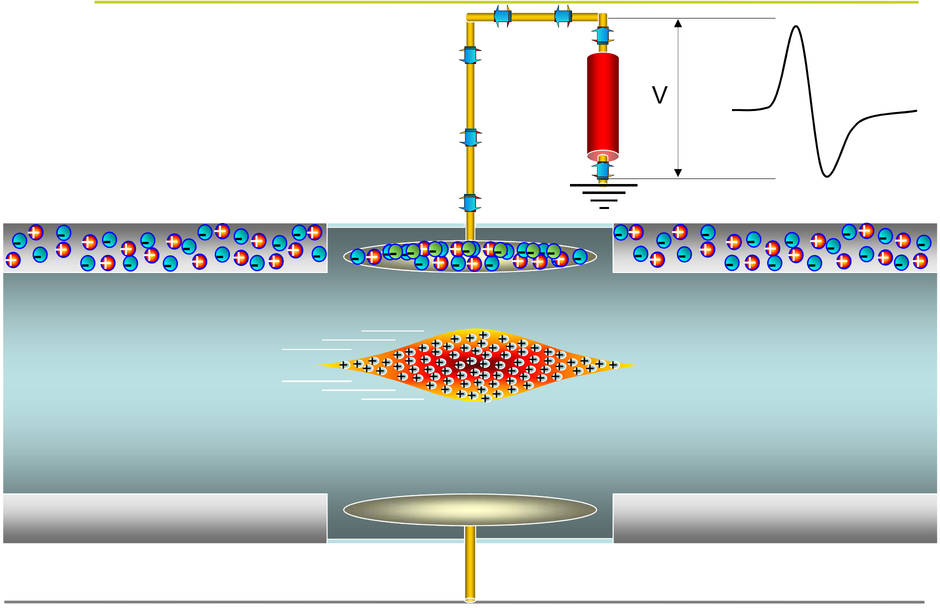
Wall Current Monitor – Beam Response



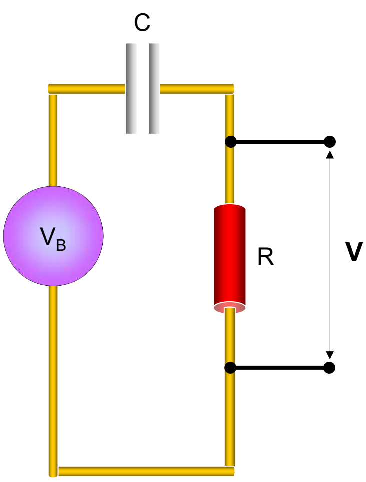


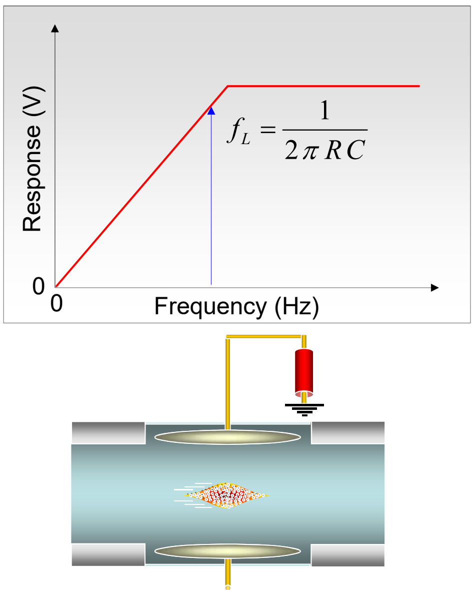


Electrostatic Monitor – The Principle



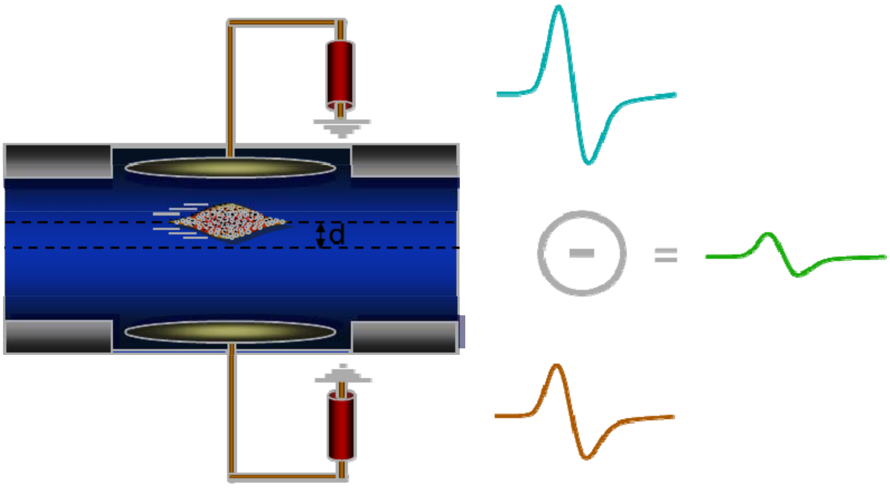
Electrostatic Monitor – Beam Response





Electrostatic Monitor – The Principle

Frequency (Hz)



Electrostatic Pick-up – Button

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

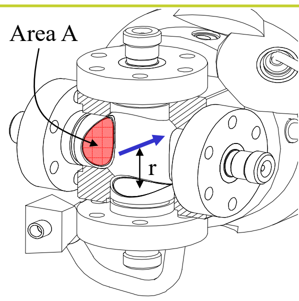
For Button with Capacitance C_e & Characteristic Impedance R_0

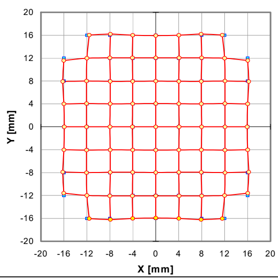
Transfer Impedance:

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

Lower Corner Frequency:

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

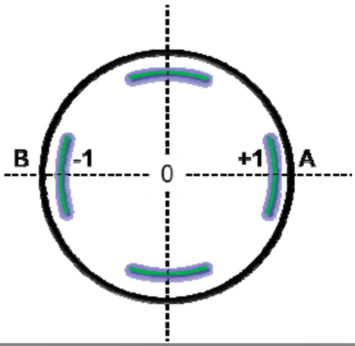


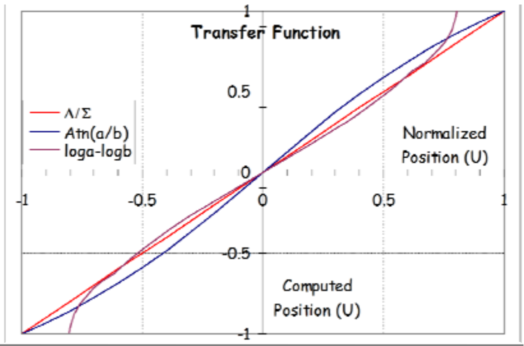


$$X = 2.30\cdot10^{-5}X_1^5 + 3.70\cdot10^{-5}X_1^3 + 1.035X_1 + 7.53\cdot10^{-6}X_1^3Y_1^2 + 1.53\cdot10^{-5}X_1Y_1^4$$

Normalising the Position Reading

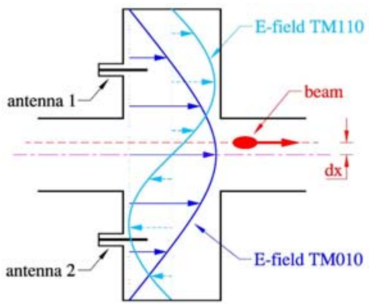
- To make it independent of intensity
- 3 main methods:
  - Difference/Sum : $(V_A - V_B) / (V_A + V_B) = \Delta / \Sigma$
  - Phase : $\text{Arctan}(V_A / V_B)$
  - Logarithm : $\text{Log}(V_A) - \text{Log}(V_B) = \frac{\text{Log}(V_A)}{\text{Log}(V_B)}$

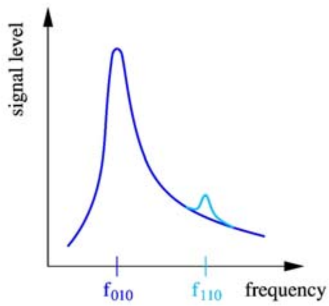




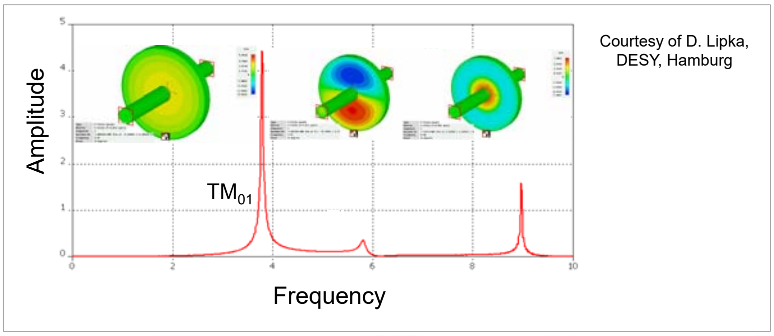
Improving Precision for Next Generation Accelerators

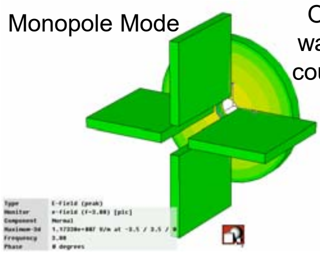
- BPM electrodes typically give “intensity signals” with some position dependence!
  - Need to remove intensity content to get to the position
  - Difficult to do electronically without some intensity information leaking through
    - When looking for small differences this leakage can dominate the measurement
- Solution – cavity BPM allowing sub micron resolution
  - Design the detector to collect only the difference signal
    - Dipole Mode TM_{11} proportional to POSITION OFFSET (& intensity)
    - Shifted in frequency with respect to intensity dependent Monopole Mode TM_{01}



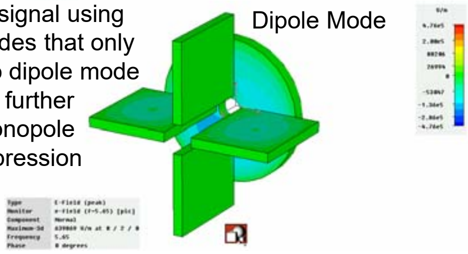


Cavity Beam Position Monitors





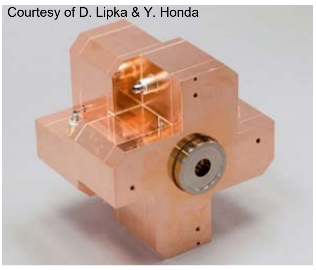
Obtain signal using waveguides that only couple to dipole mode for further Monopole Supression

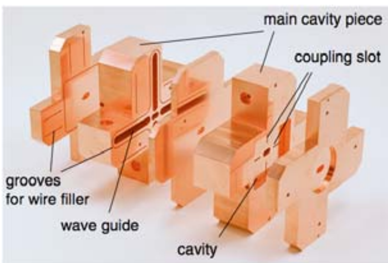


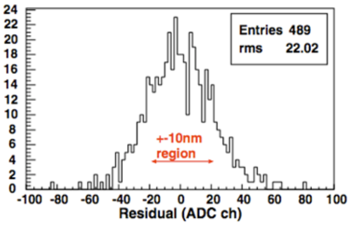
Today's State of the Art BPMs

- 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)

Courtesy of D. Lipka & Y. Honda

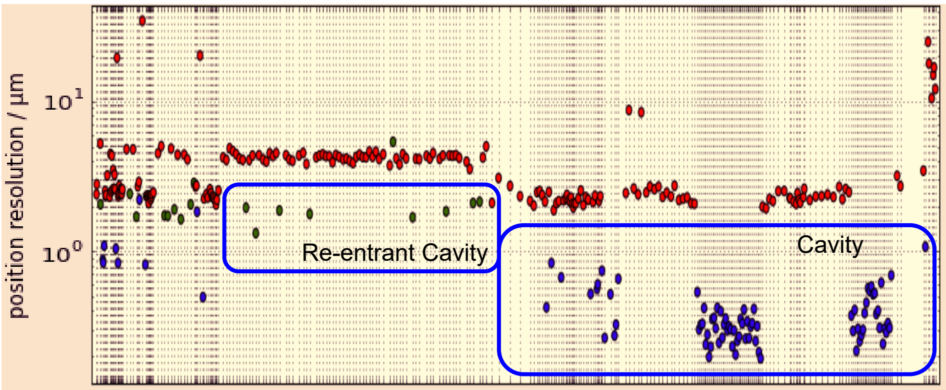




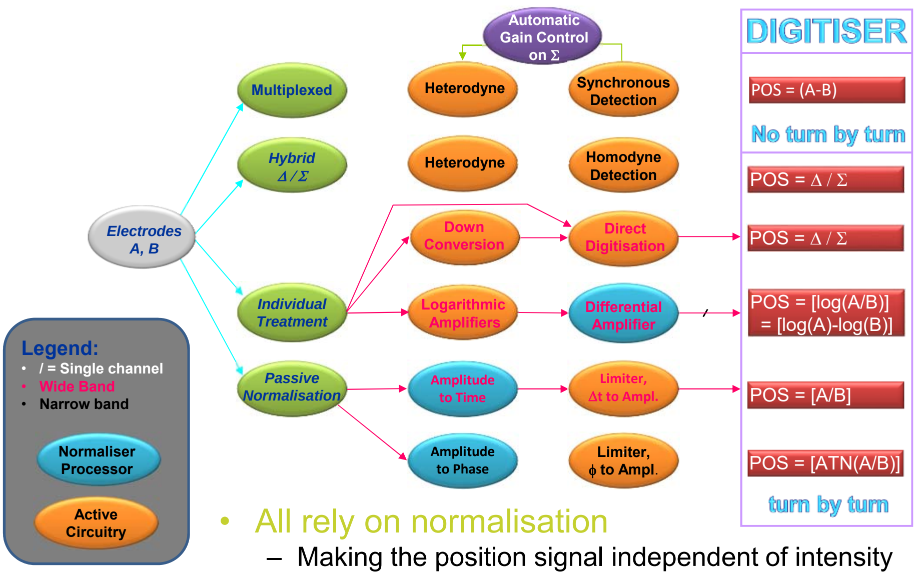


Comparison of BPM Resolution

- XFEL Data from 2017 Commissioning
  - Standard Button BPMs : 78 mm & 40.5 mm aperture (RED)
  - Re-entrant cavity BPMs : 78 mm aperture (GREEN)
  - Cavity BPMs : 40.5 mm and 10 mm aperture (BLUE)



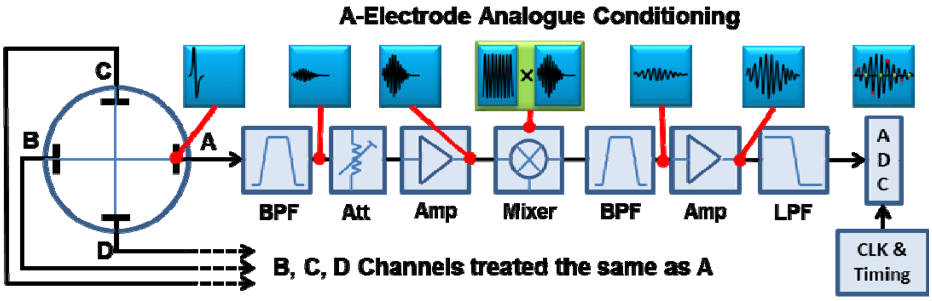
Processing System Families

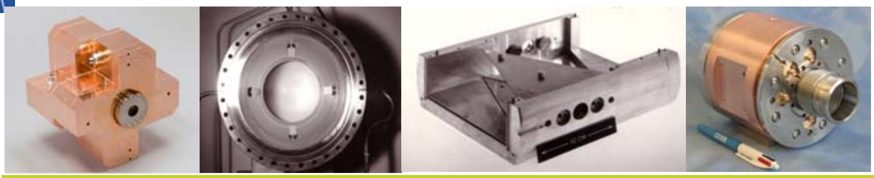


- All rely on normalisation
  - Making the position signal independent of intensity

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





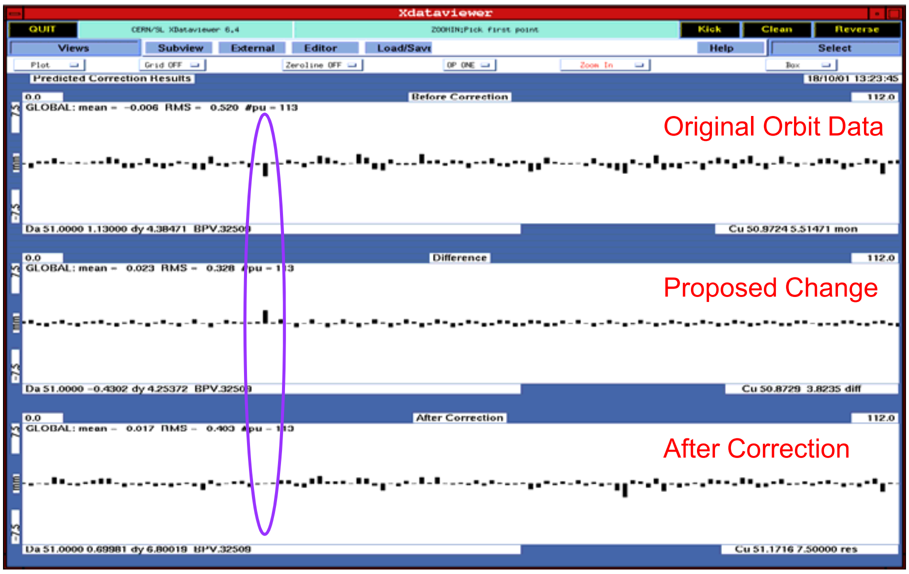
Diagnostics using Beam Position Systems

Orbit or Trajectory Acquisition

- Main use of BPM systems
  - Measure & correct orbit or trajectory

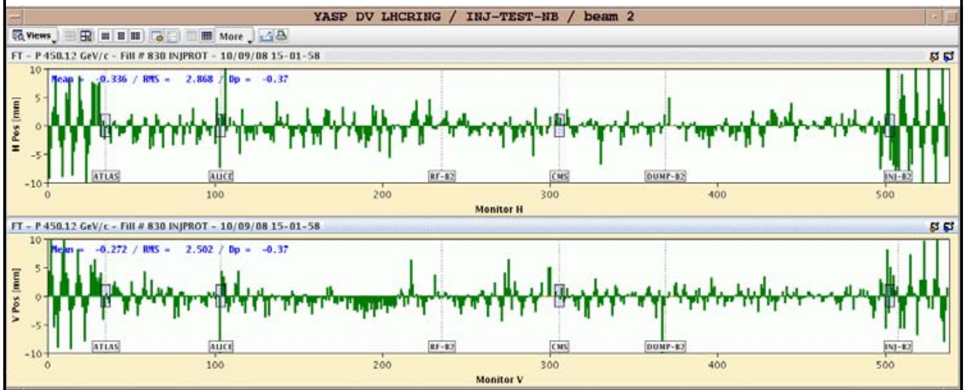
Orbit excursion too large ⇒ need to correct

Orbit or Trajectory Correction

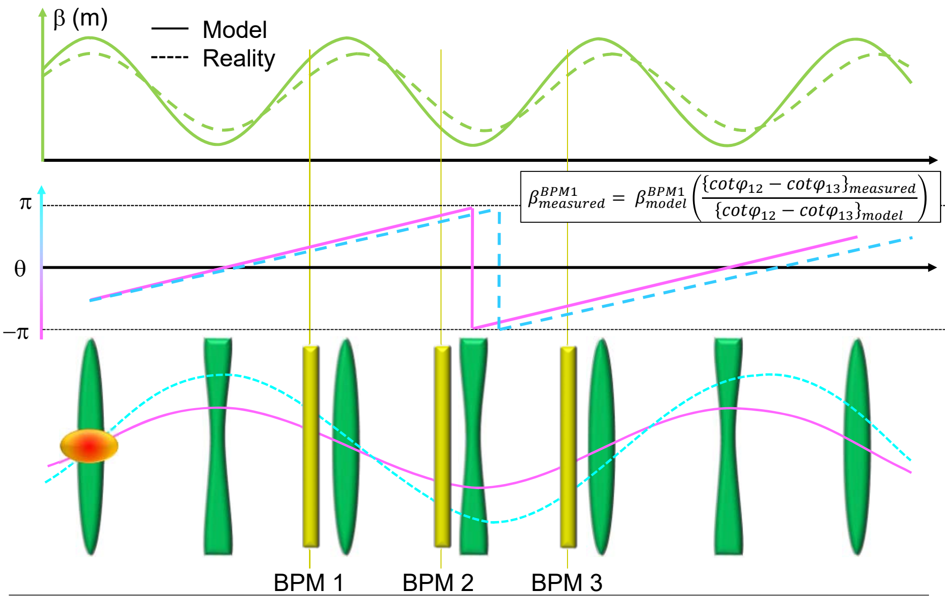


Initial Commissioning

- Threading the first pilot bunch round the LHC
  - One beam at a time, one hour per beam
  - Collimators used to intercept the beam
  - Correct trajectory, open collimator and move on

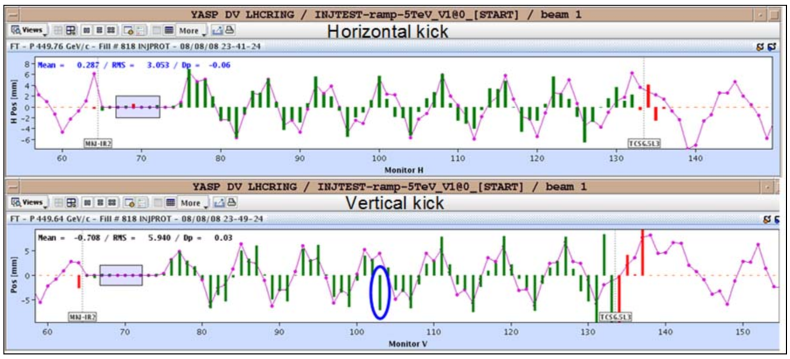


The Machine β-Function



Analysis of BPM Data

- On line analysis of BPM Data
  - Polarity errors easily identified with 45° BPM sampling
  - Quick indication of phase advance errors
  - Used to verify optics functions
    - e.g. matching from transfer lines into ring

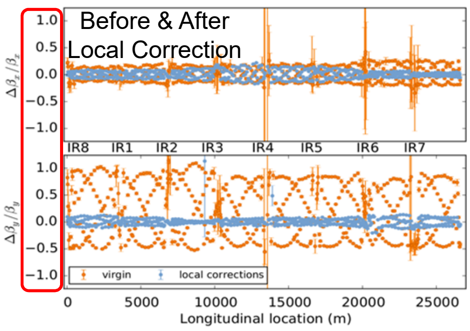


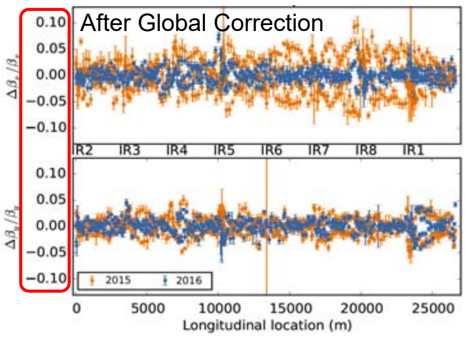
Optics phase error

BPM polarity error

Machine Optics Measurements

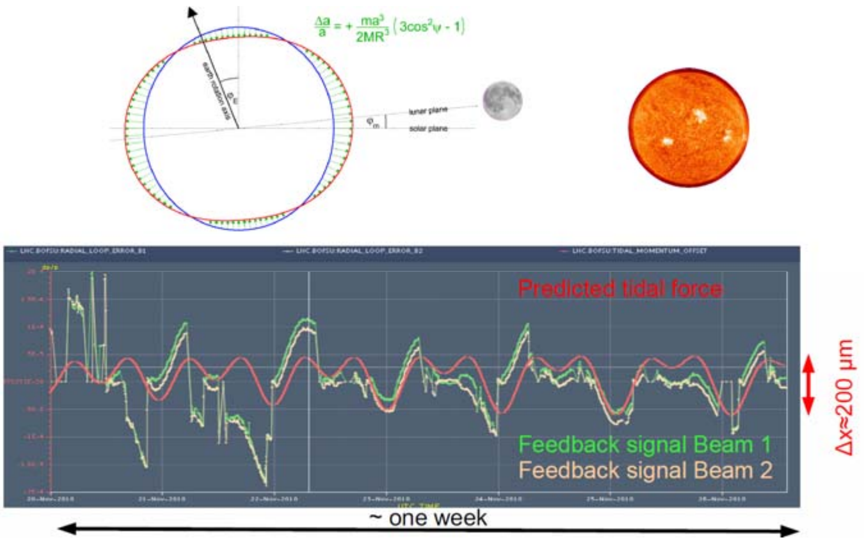
- Light Sources
  - Dominated by closed orbit techniques (Orbit Response Matrix - e.g. LOCO)
    - Activate one orbit corrector & observe change in orbit
    - SOLEIL & DIAMOND achieved 0.3 - 0.4% β-beating
  - Recently improved BPM electronics
    - Now allows turn-by-turn techniques to start competing with orbit response
- LHC
  - Only turn-by-turn technique feasible with correction < 2% achievable





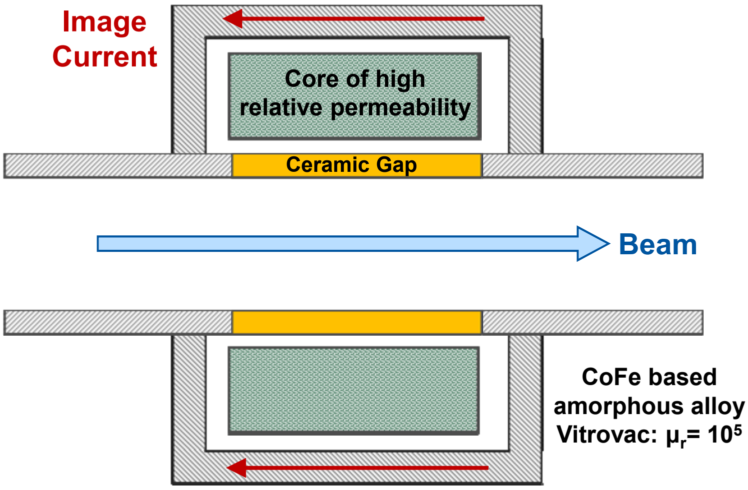
Maintaining Orbit Stability

- Earth Tides dominate during LHC Physics

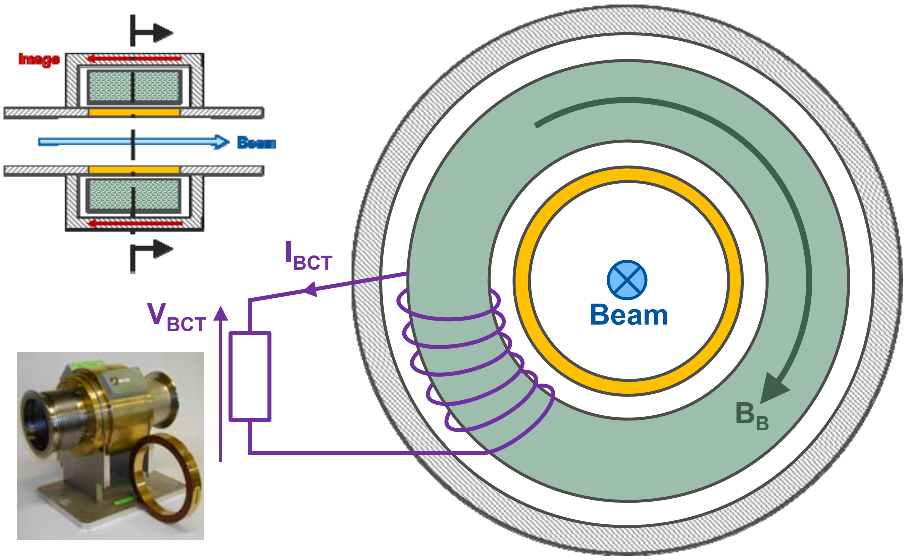


Beam Intensity Monitors

AC (Fast) Current Transformers

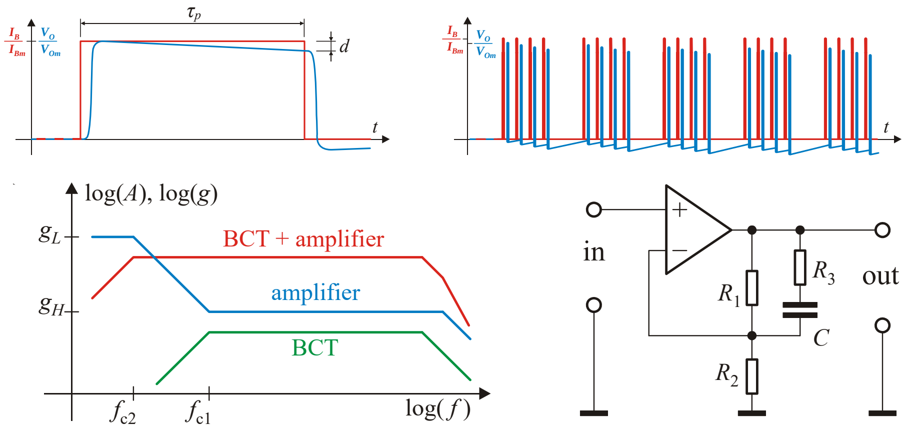


AC (Fast) Current Transformers



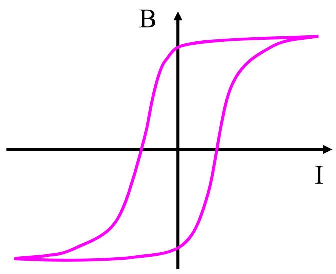
AC (Fast) Transformer Response

- 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)

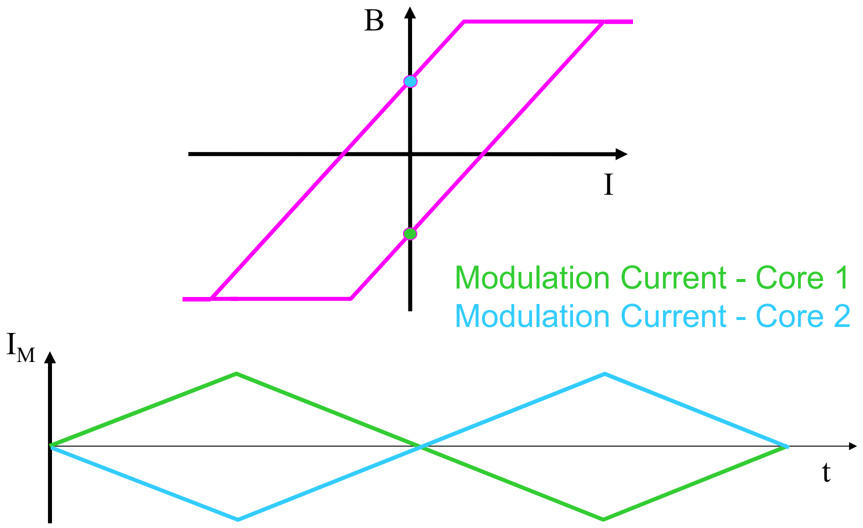


The DC transformer

- AC transformers can be extended to very low frequency but not to DC (no dI/dt !)
- DC measurement is required in storage rings
- To do this:
  - Take advantage of non-linear magnetisation curve
  - Use 2 identical cores modulated with opposite polarities

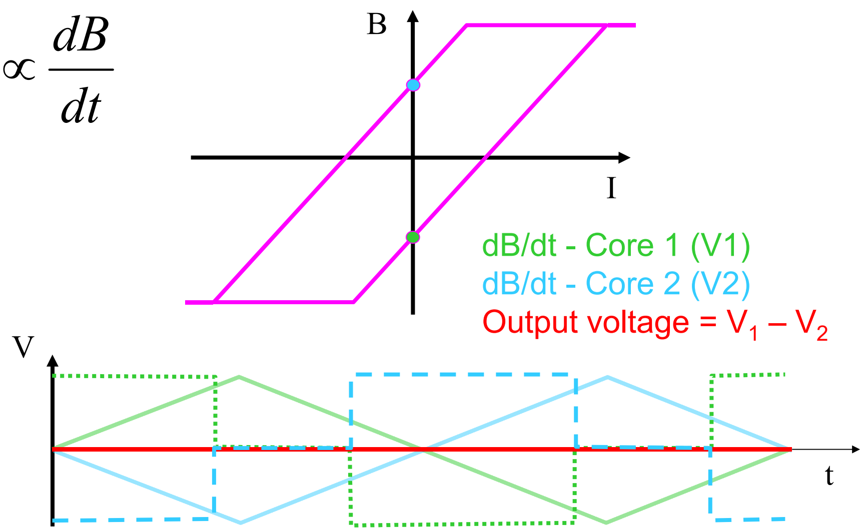


DCCT Principle – Case 1: no beam

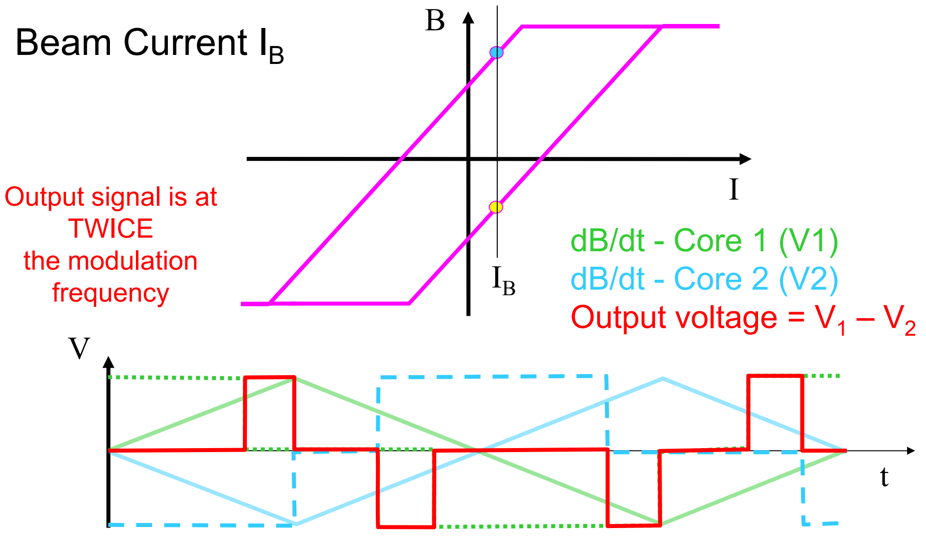


DCCT Principle – Case 1: no beam

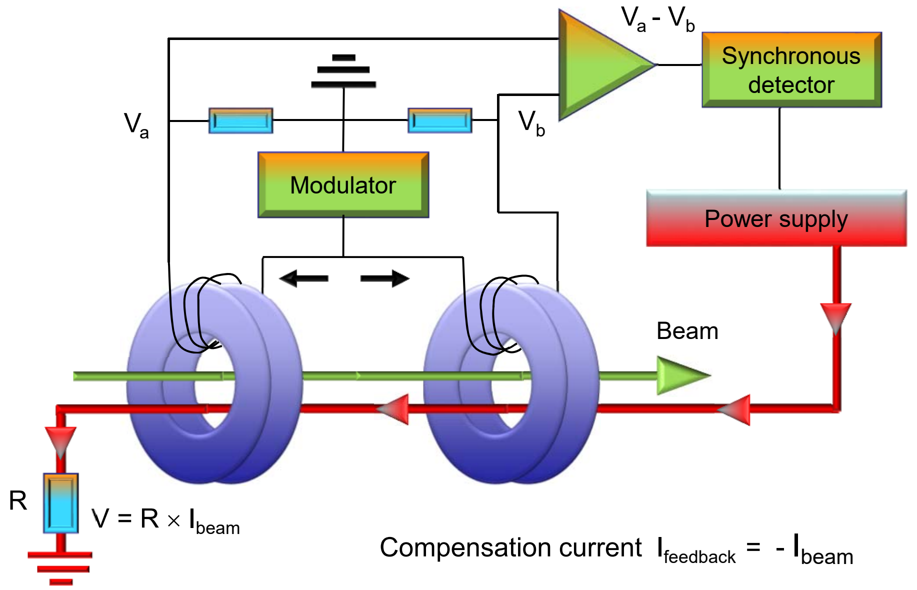
$$V \propto \frac{dB}{dt}$$



DCCT Principle – Case 2: with beam



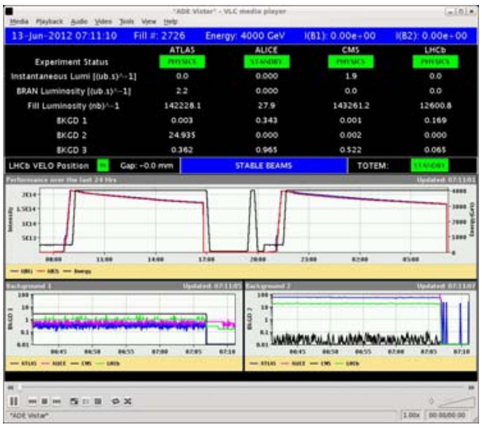
Zero Flux DCCT Schematic



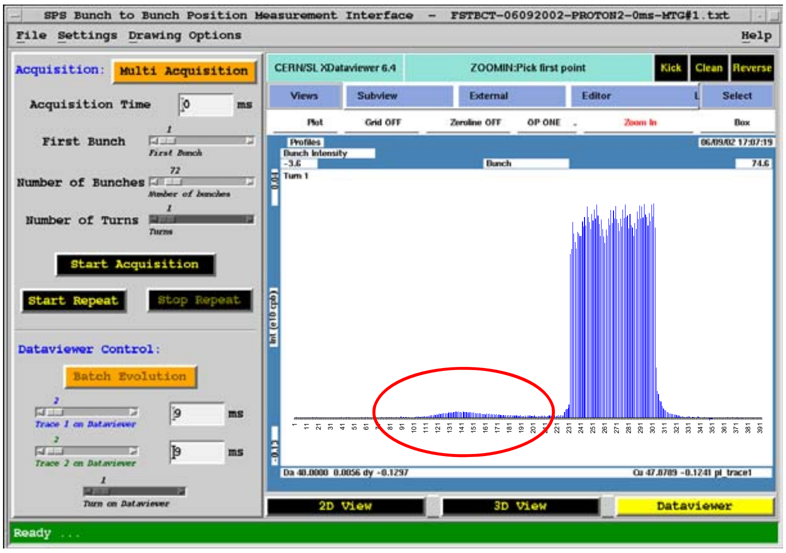
Diagnostics using Beam Intensity Monitors

BCTs in Operation

- Provide the general visual diagnostics for most accelerators
- LHC Operation Pages
  - Total intensity measurement
  - Lifetime calculation



Diagnostics using Fact BCTs



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

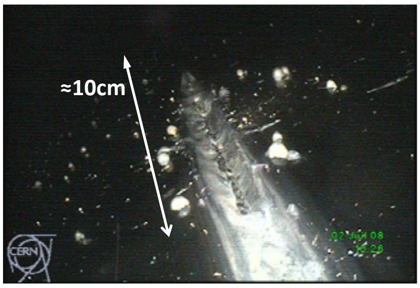
Beam Loss Monitors

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

Stored Energy	
Beam 7 TeV	2 x 362 MJ
2011 Beam 3.5 TeV	above 2 x 100 MJ

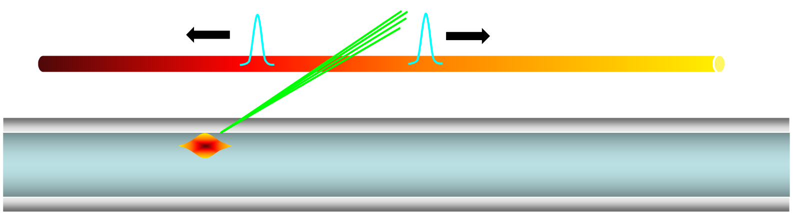
Quench and Damage at 7 TeV	
Quench level	≈ 1mJ/cm^3
Damage level	≈ 1 J/cm^3



- SPS incident
  - June 2008
  - 2 MJ beam lost at 400GeV

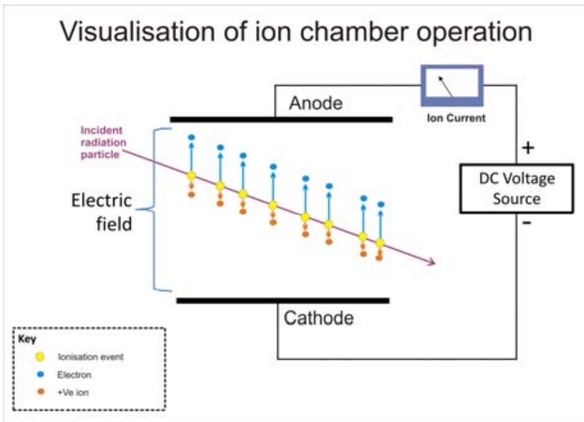
Beam Loss Detectors

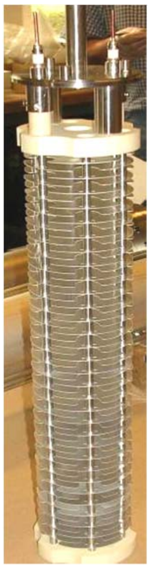
- Common types of monitor
  - Long ionisation chamber (charge detection)
    - Up to several km of gas filled hollow coaxial cables
    - Position sensitivity achieved by comparing direct & reflected pulse
      - e.g. SLAC – 8m position resolution (30ns) over 3.5km cable length
    - Dynamic range of up to 10^4
  - Fibre optic monitors
    - Electrical signals replaced by light produced through Cerenkov effect



Beam Loss Detectors

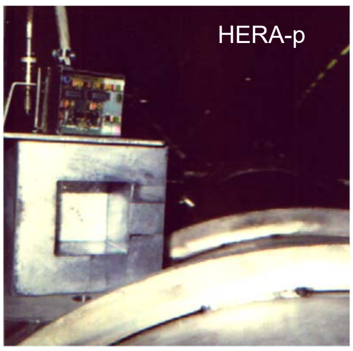
- Common types of monitor
  - Ionisation chambers
  - Dynamic range of < 10^8
  - Slow response (μs) due to ion drift time

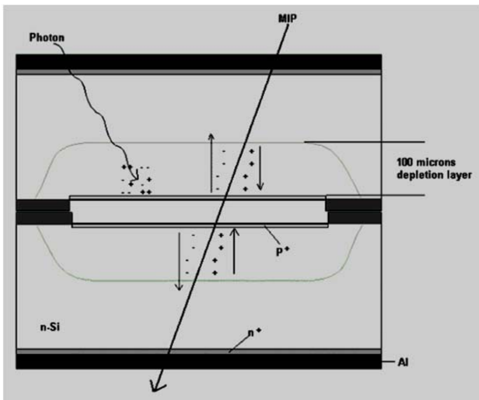




Beam Loss Detectors

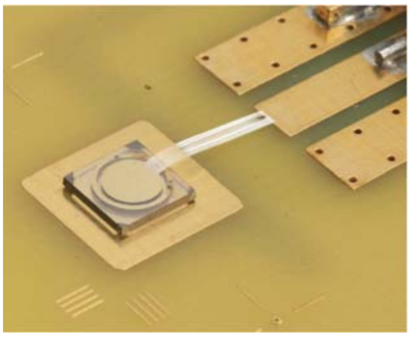
- Common types of monitor
  - PIN photodiode (solid state ionisation chamber)
    - Detect coincidence of ionising particle crossing photodiodes
    - Count rate proportional to beam loss with speed limited by integration time
    - Can distinguish between X-rays & ionising particles
    - Dynamic range of up to 10^9

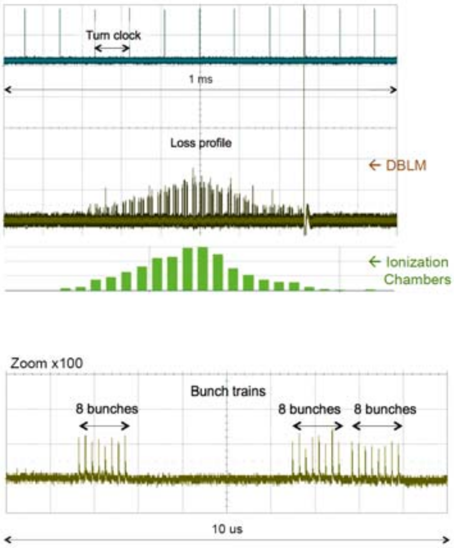




Beam Loss Detectors – New Materials

- 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



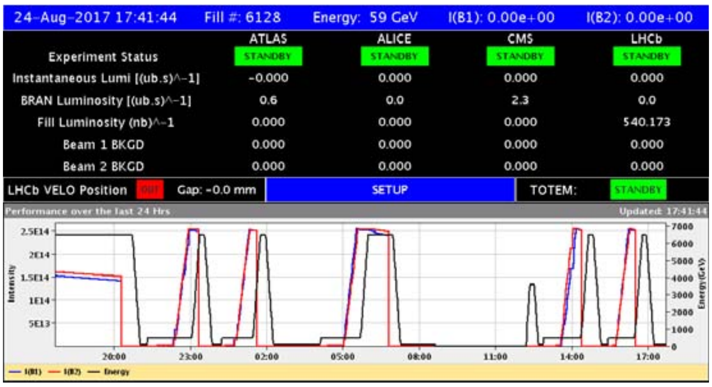


Courtesy of E. Griesmayer

Diagnostics using Beam Loss Monitors

Recent Example from LHC

- Beam continually lost due to losses
  - What is going on?

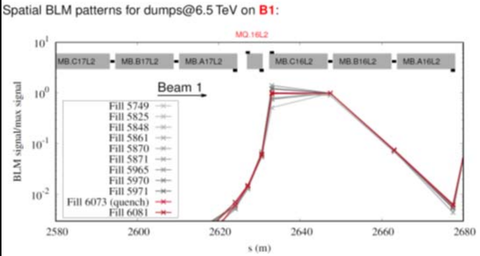


Dump #1 5.9TeV | RF issue | Dump #2 7TeV | Dump #3 0.9TeV | Dump #4 0.8TeV

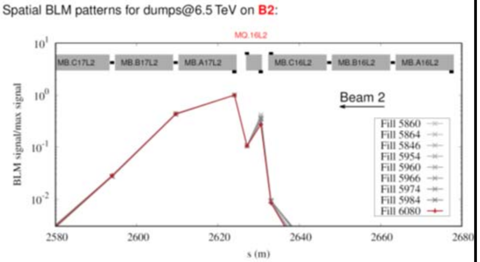
BLM Diagnostics

- Localisation
  - BLM Spatial patterns clearly show losses originate from one specific interconnection
    - MQ16L2 (Cell 16 left of LHC Point 2)
  - Losses can be on either beam

Spatial BLM patterns for dumps@6.5 TeV on B1:



Spatial BLM patterns for dumps@6.5 TeV on B2:

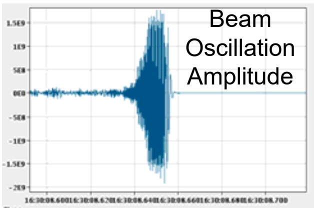


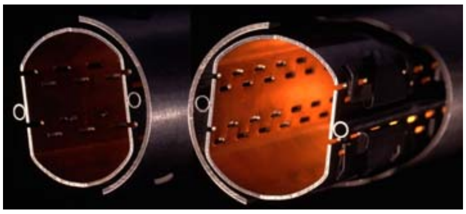
BLM Diagnostics

- Time evolution

Other Diagnostics & Hypothesis

- Additional observations
  - Beam not always dumped by BLMs in 16L2
  - Often dumped by BLMs near primary collimators
    - Development of transverse instability visible on tune measurement system





- Current Hypothesis
  - Something went wrong during vacuum pumpdown
  - Air trapped on beam screen & cold bore of both beams
    - Solid nitrogen & oxygen formed
  - Falls into the beam & immediately vaporised
    - Creates local pressure rise
    - Leads to losses & beam instability

Summary of Lecture 1

- Today concentrated on beam position, intensity & loss monitors
  - Went into details of how they worked
  - Gave examples of their use as diagnostic tools
- Tomorrow we'll continue with a look at
  - Beam profile monitoring & diagnostics
  - Tune, Coupling & Chromaticity measurement & feedback

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