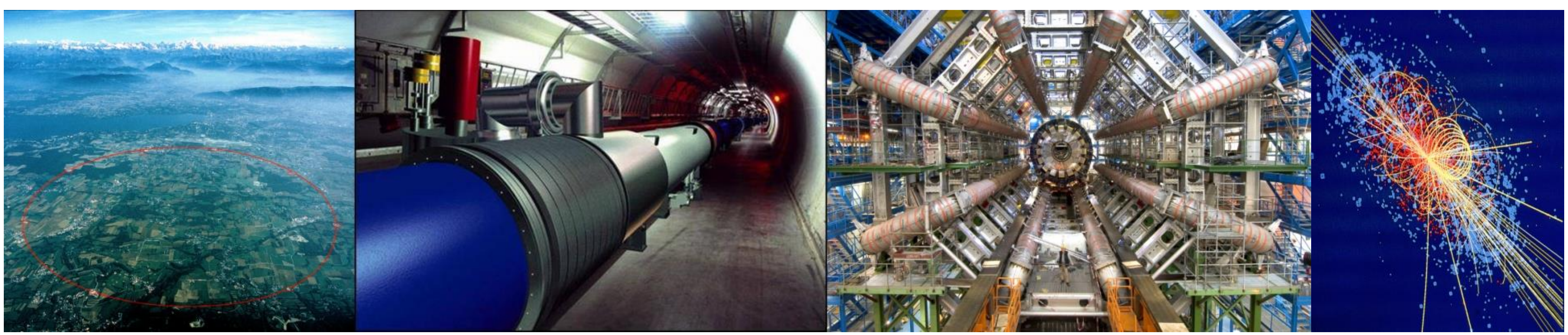
The CERN Accelerator School

Beam Instrumentation

T. Lefevre
CERN



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A big thanks to H. Schmickler and R. Jones who provided materials for this lecture !

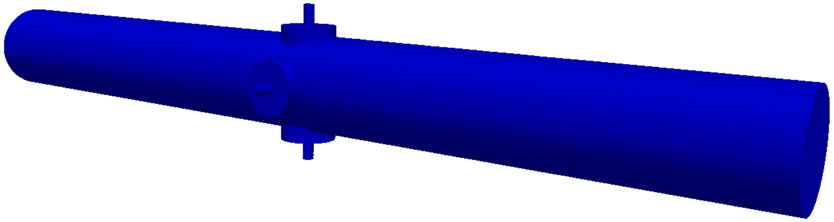
Introduction

- **Why is beam instrumentation important ?**

The “eyes”

Imaging photons emitted by the beam

The “ears”



Detecting electro-magnetic field propagating along with moving charged particles

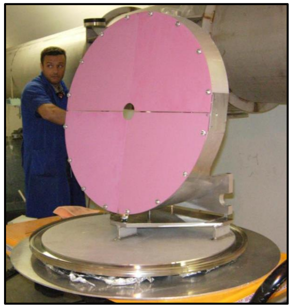
The “hands”

Intercepting particles with fixed or moving objects

An accelerator can never be better than the instruments measuring its performance !

Introduction

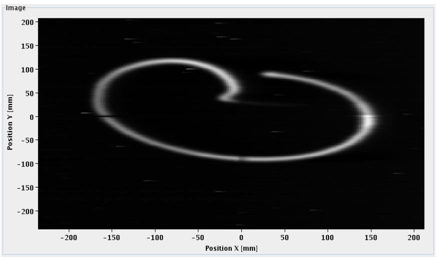
- **What does an instrumentation look like ?**



Based on 3 main components

- A sensor generating a beam-induced signal
  - Physic, Mechanic, Optic,..

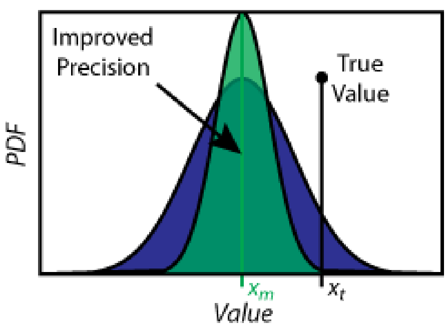
- An electronic acquisition chain
  - Analog and digital systems

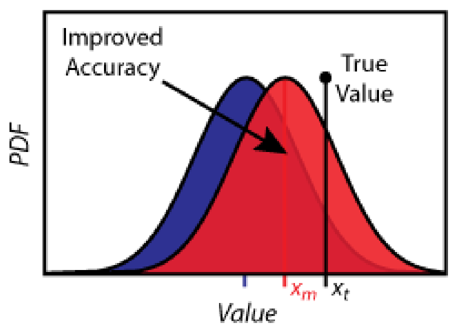


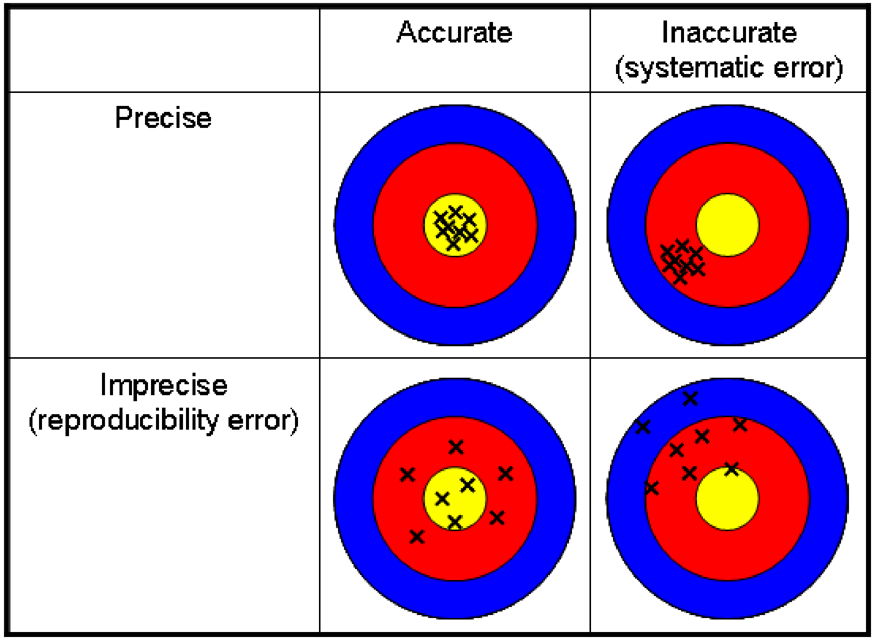
- Digital processing system (FW and SW) that computes, saves and displays the beam parameters
  - FirmWare (FPGA) & SoftWare
  - Data analysis, feedback systems

Introduction

- What is a good instrument ?
  - Accuracy – is it True or False?
  - Precision – is it reproducible?
  - Resolution – What is the smallest change I can measure ?







Introduction

- What beam parameters do we measure?
  - Beam Intensity (& lifetime measurement for a storage ring/collider)
    - Bunch-by-bunch charge and total circulating current
  - Beam Position
    - Horizontal and vertical throughout the accelerator
  - Beam profiles
    - Transverse and longitudinal distribution
  - Beam Loss
    - Especially important for high brightness and superconducting machines
  - And more but not discussed here..
    - Luminosity, Particle identification, Time of flight, Beam arrival monitors

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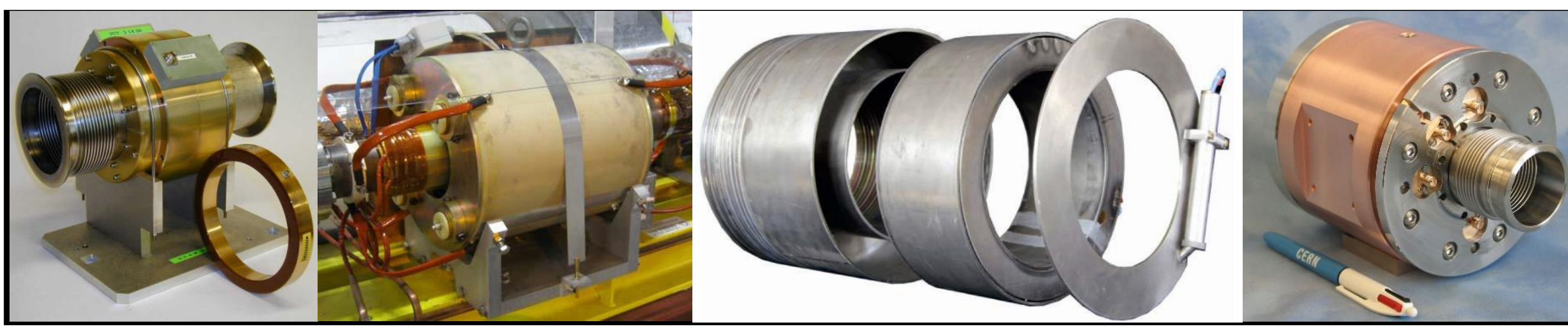
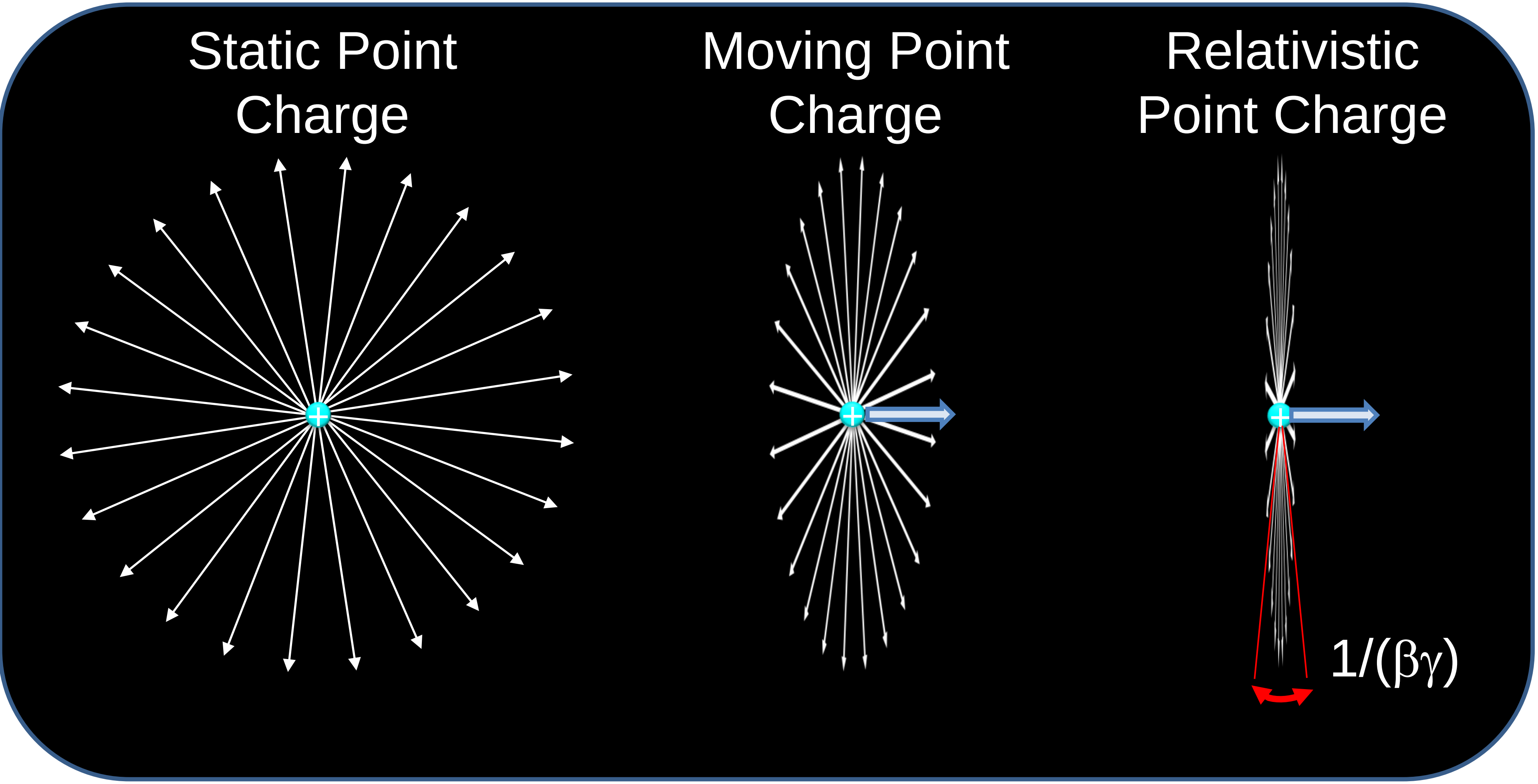
Beam Intensity Monitors



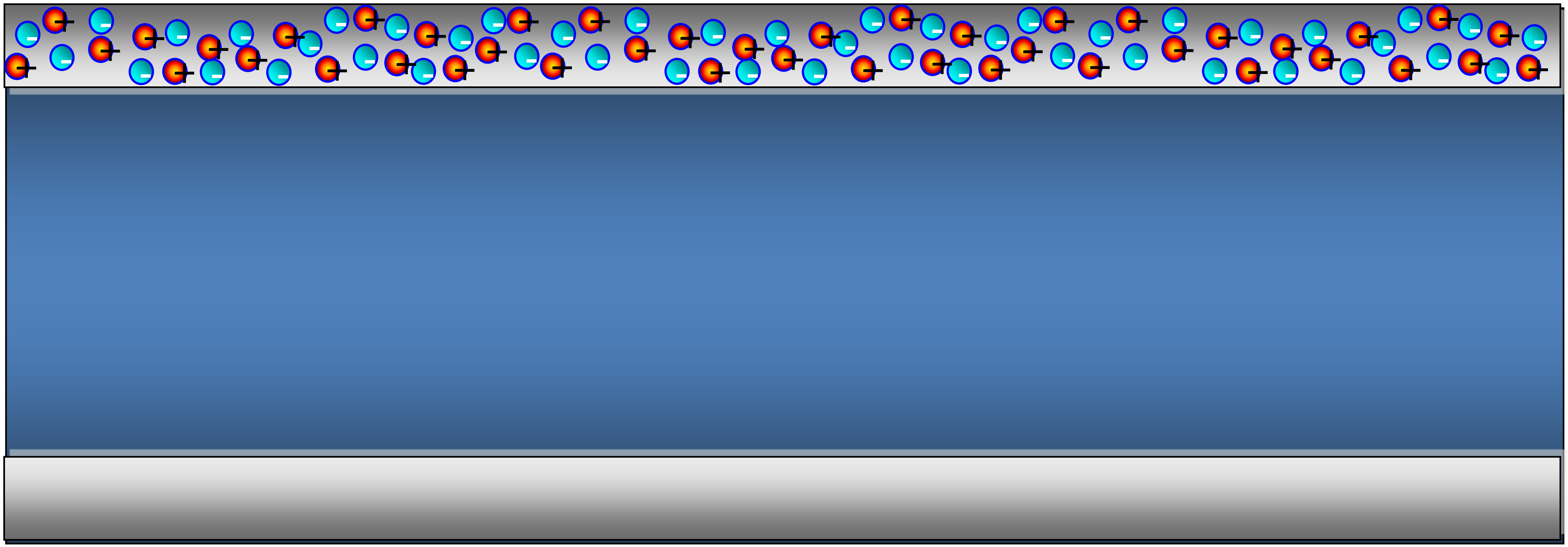
Beam Intensity Monitors

from electromagnetic fields and relativity



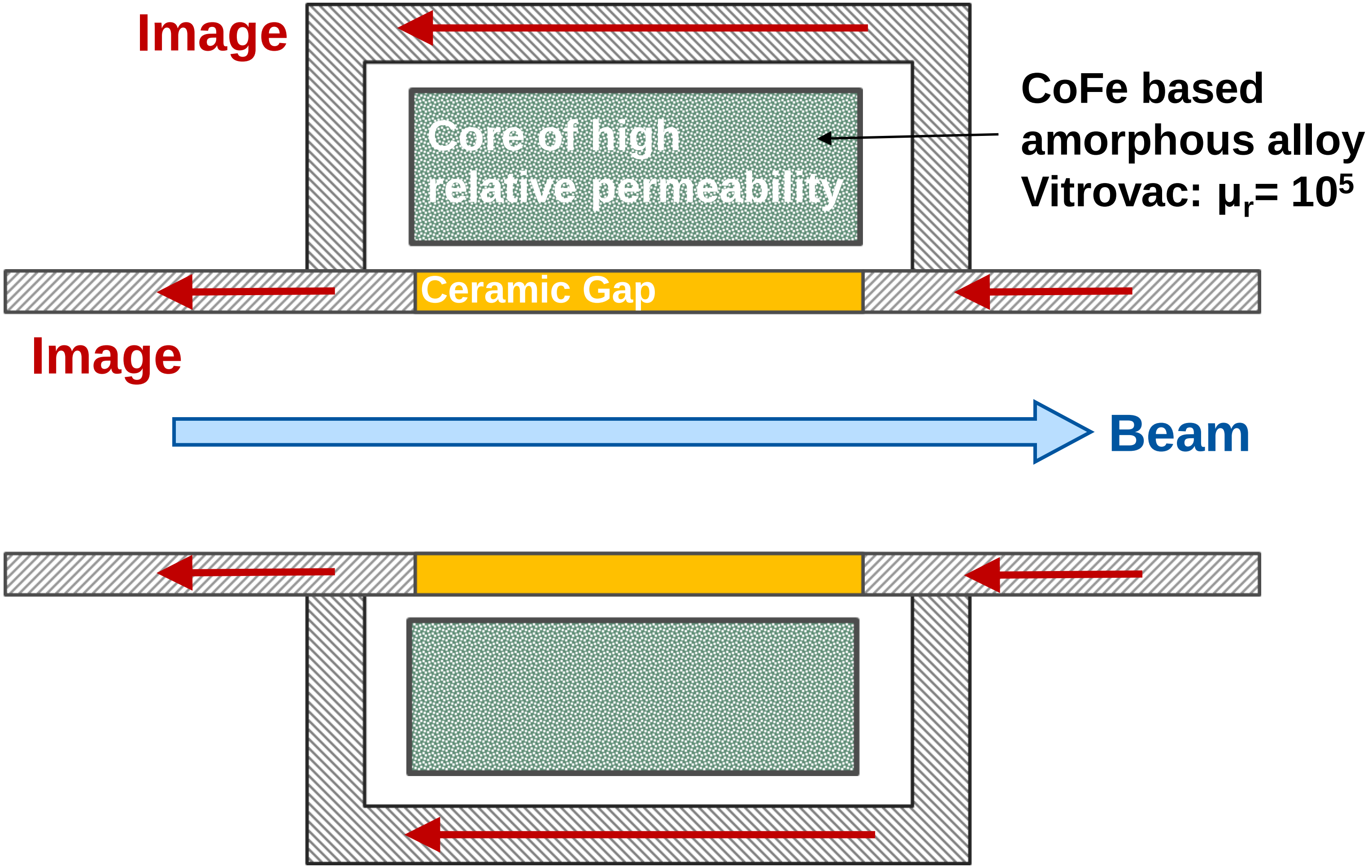
Beam Intensity Monitors

Beam image 'wall' current induced on a metallic beam pipe



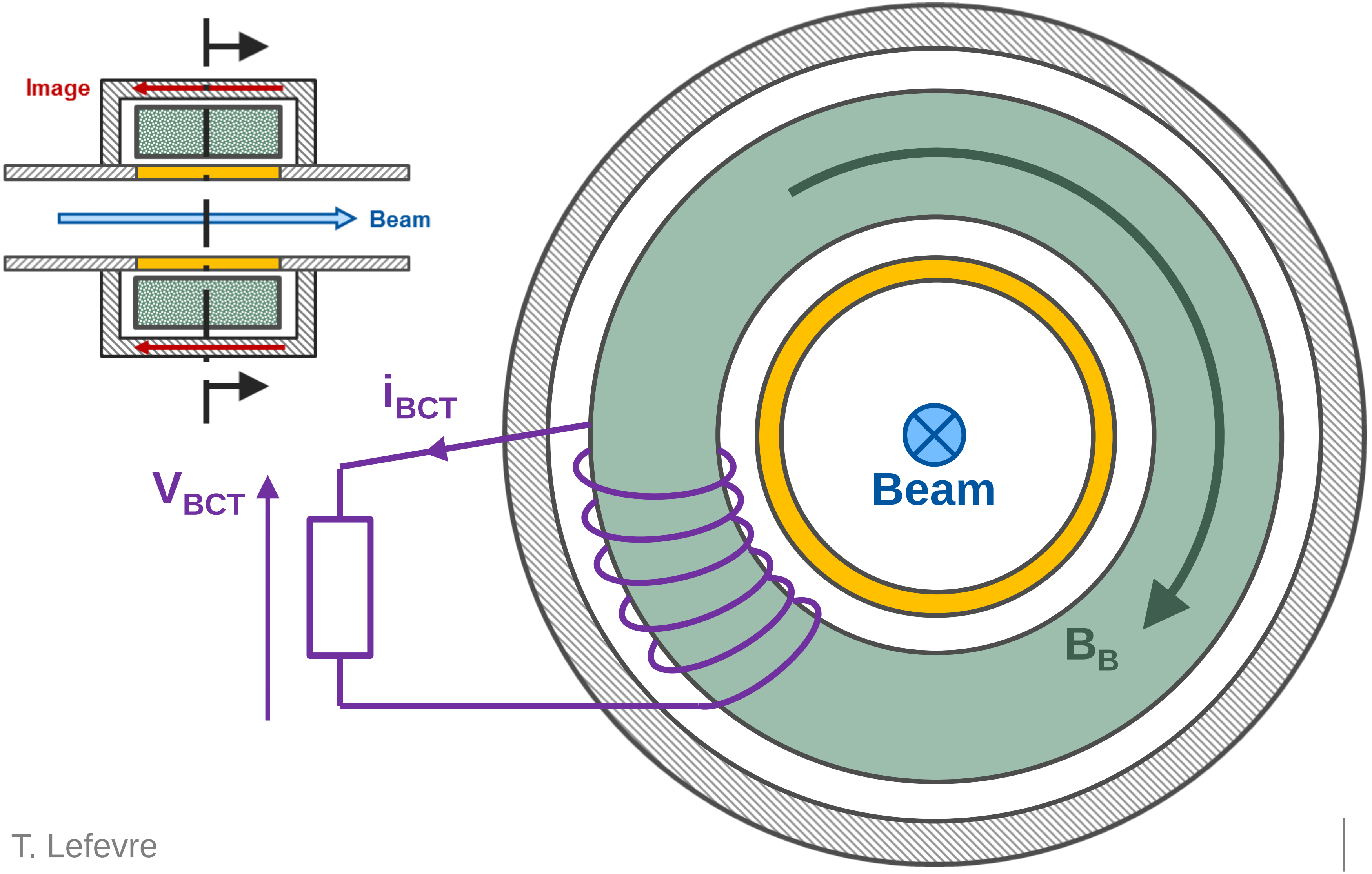
Beam Intensity Monitors

'The principle of an AC Current Tranformer'



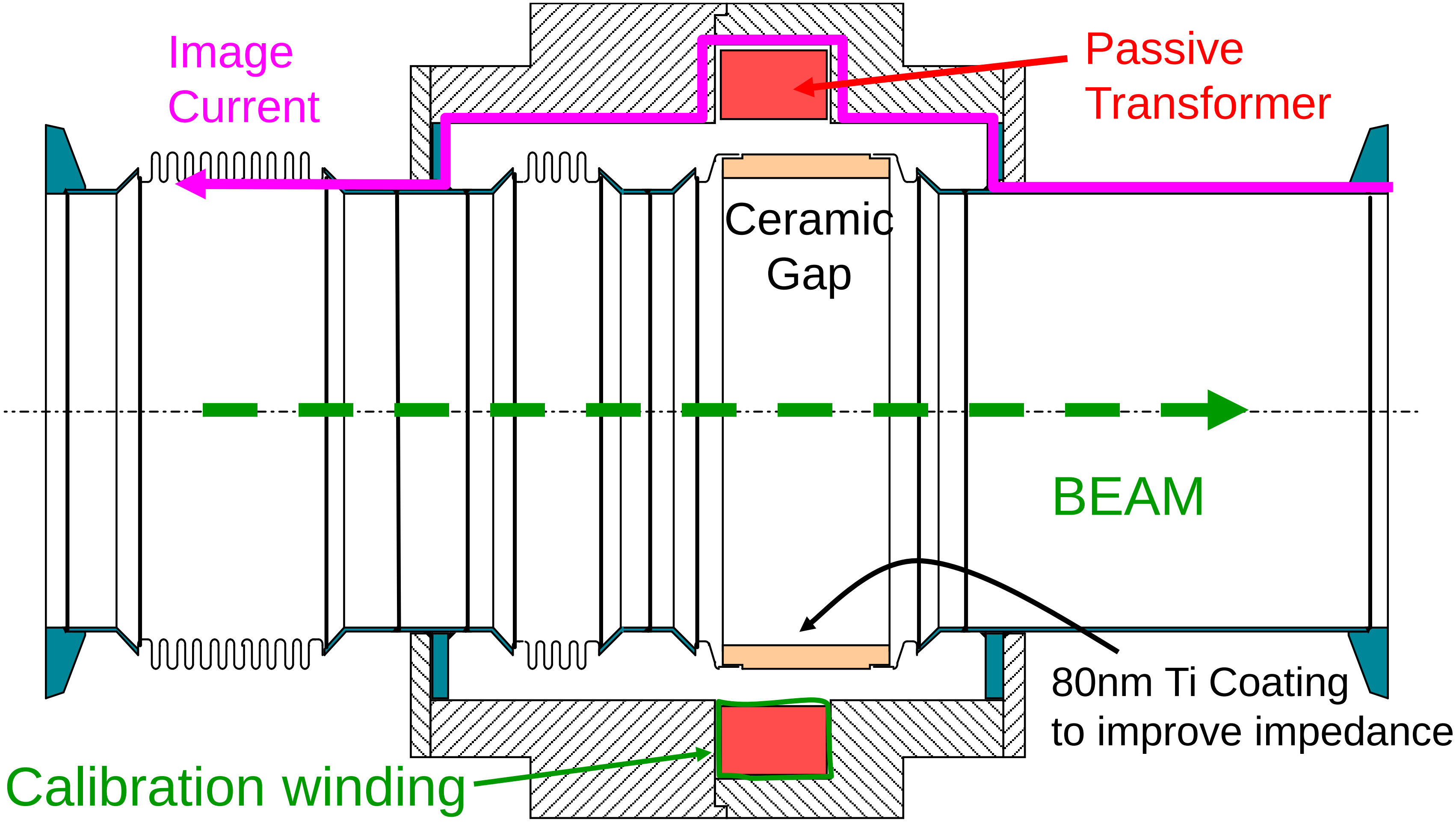
Beam Intensity Monitors

‘The principle of an AC Current Tranformer’



Beam Intensity Monitors

'The principle of an AC Current Tranformer'

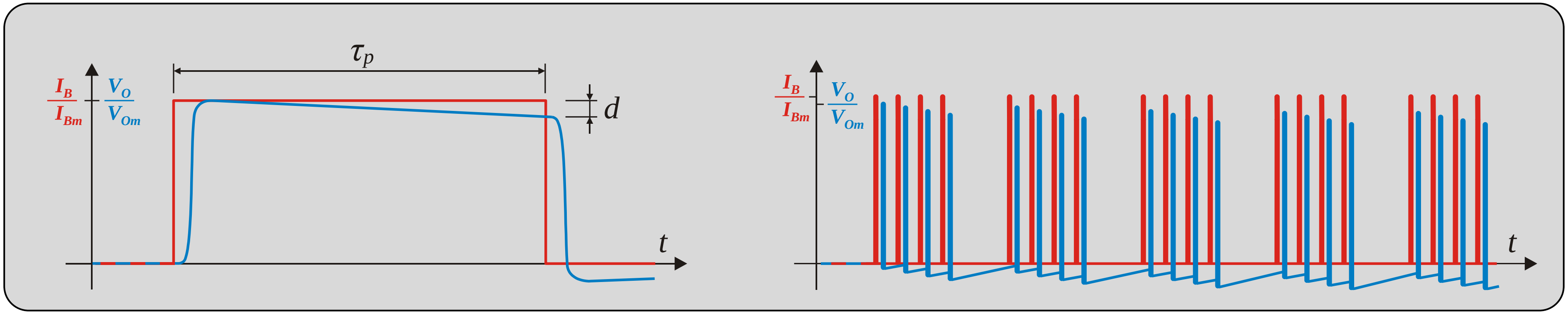


Beam Intensity Monitors

'The principle of an AC Current Tranformer'

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)

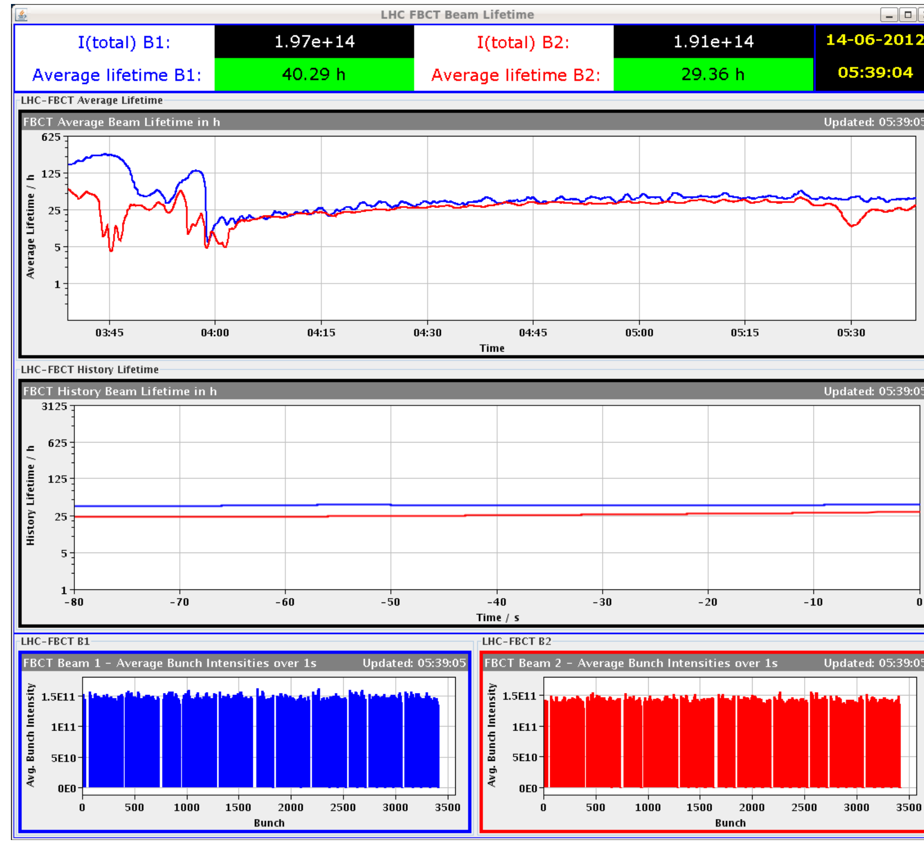


fBCT @ LHC

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

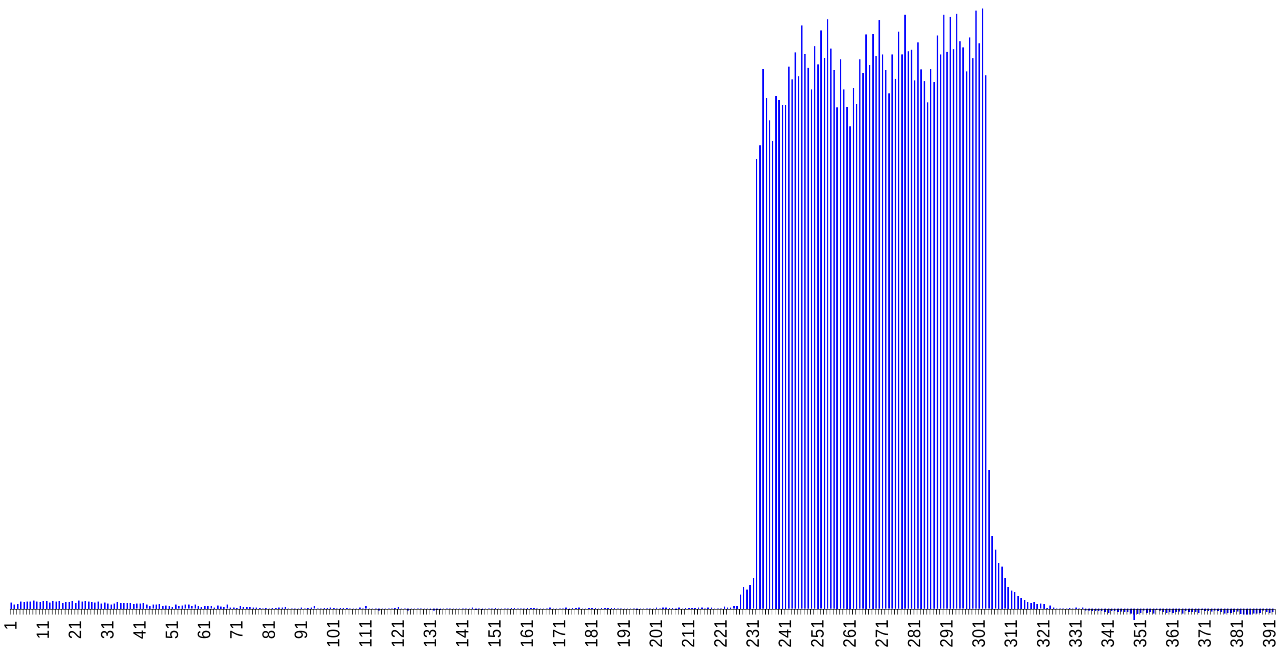
Beam Intensity Monitors

‘BCT @ LHC’



Beam Intensity Monitors

‘BCT @ SPS injection’



Example of a ‘*bad*’ RF capture

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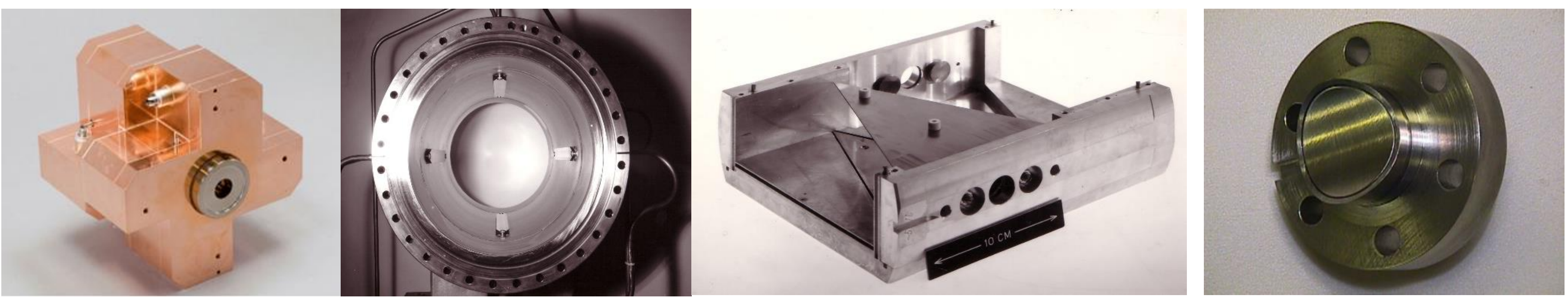
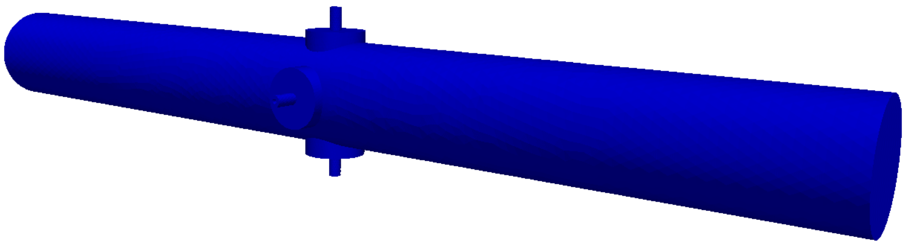
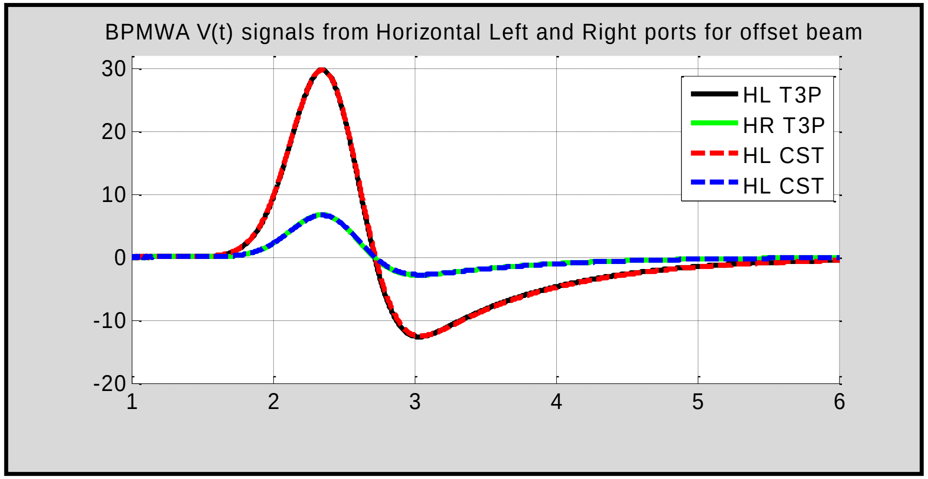
Beam Position Monitors

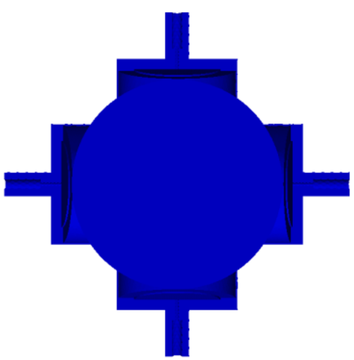


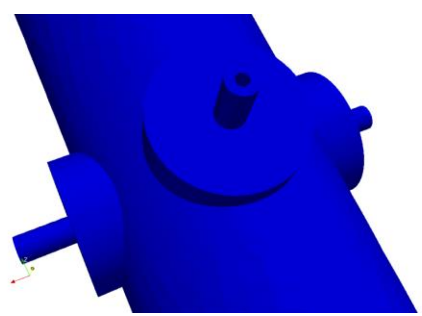
Electrostatic BPM

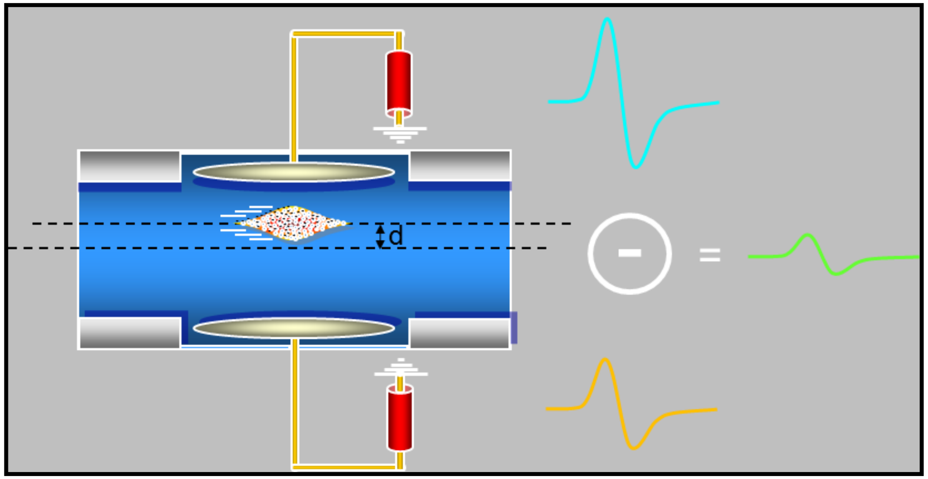
Amplitude of the signal depends on bunch intensity and position











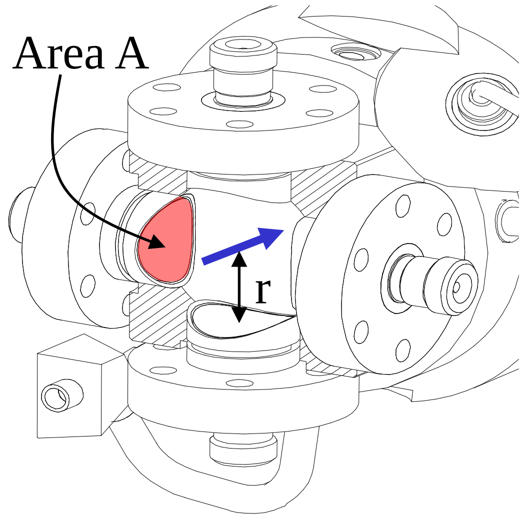
To make the measurement independent of beam intensity

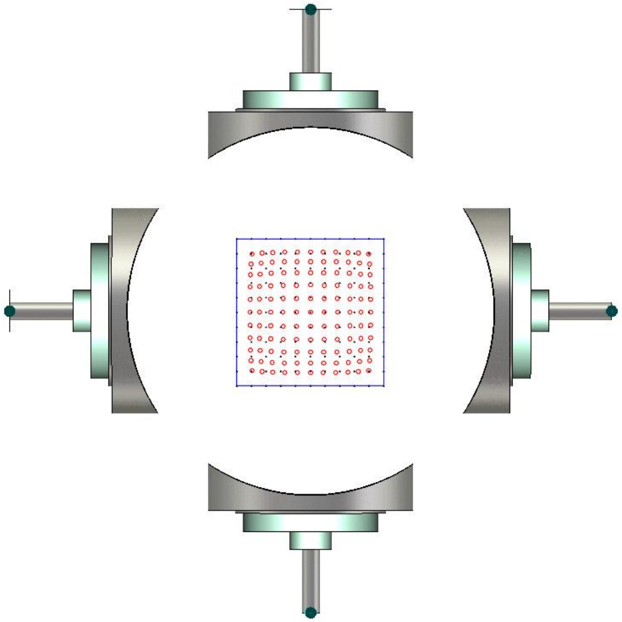
Difference/Sum : $(V_A - V_B) / (V_A + V_B) = \Delta / \Sigma$

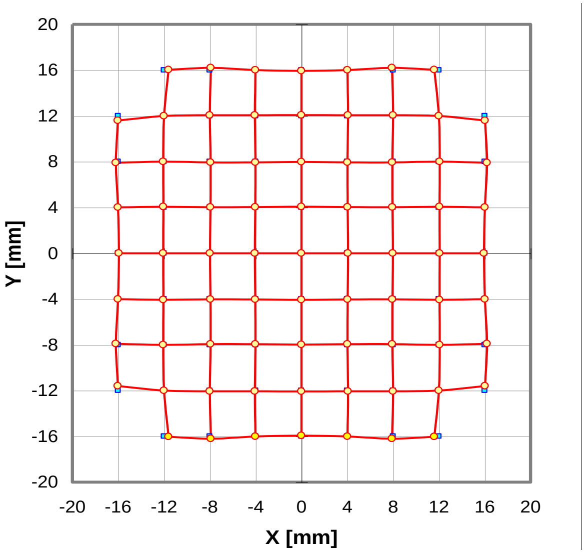
Beam Position Monitors

Electrostatic BPM

due to their finite size, buttons have a non-linear response to the beam position..

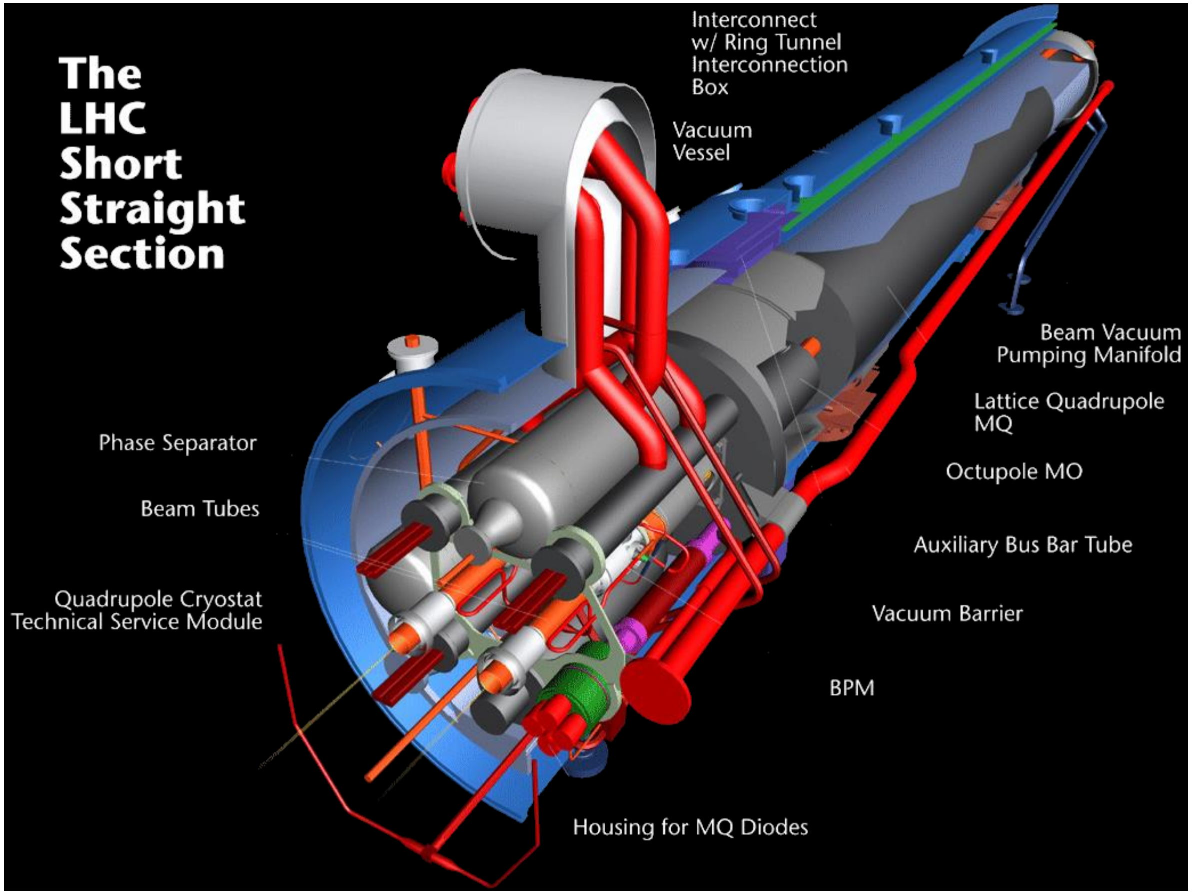


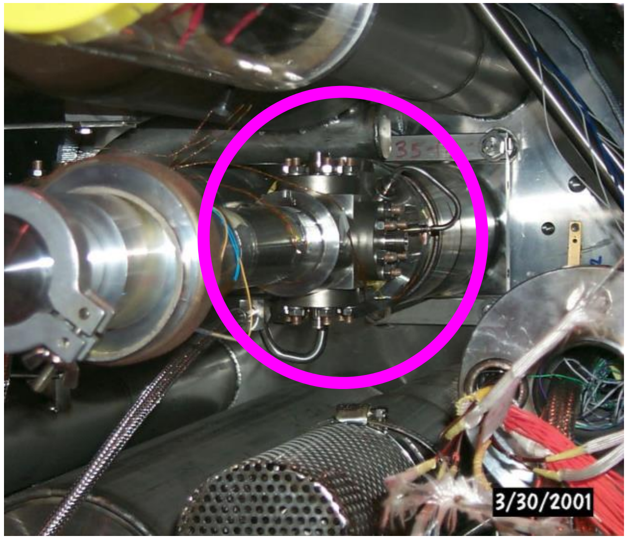




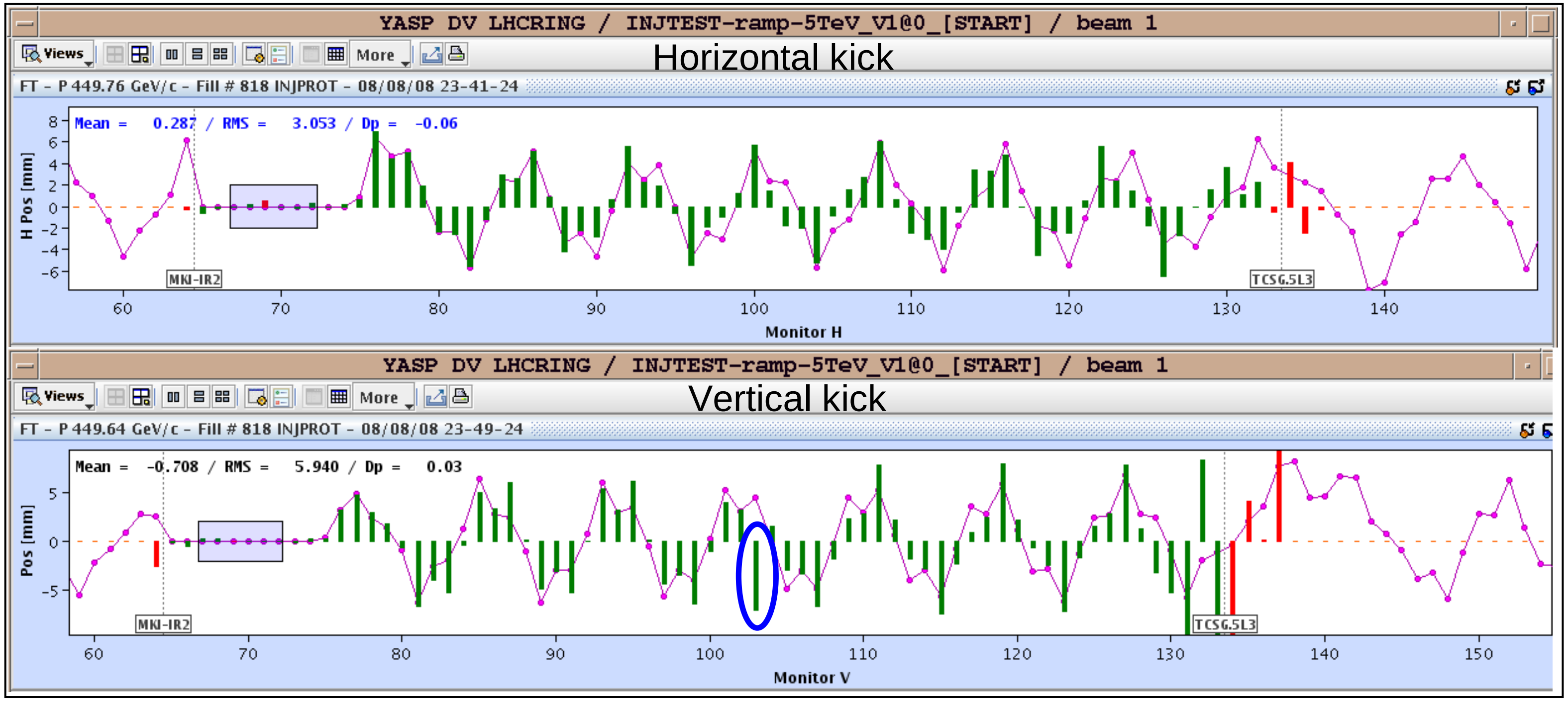
… that can be simulated and corrected mathematically

Beam Position Monitors





Beam Position Monitors



Wrong steering

BPM polarity error

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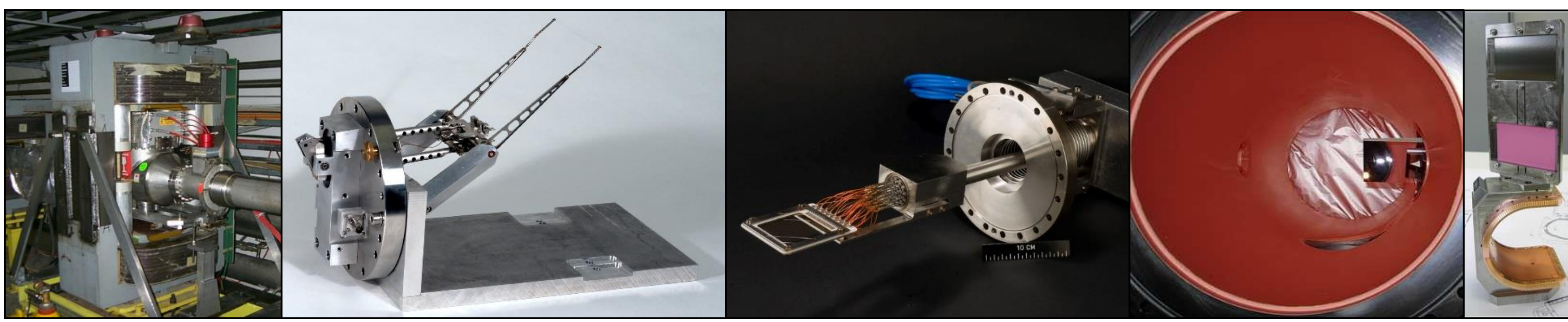
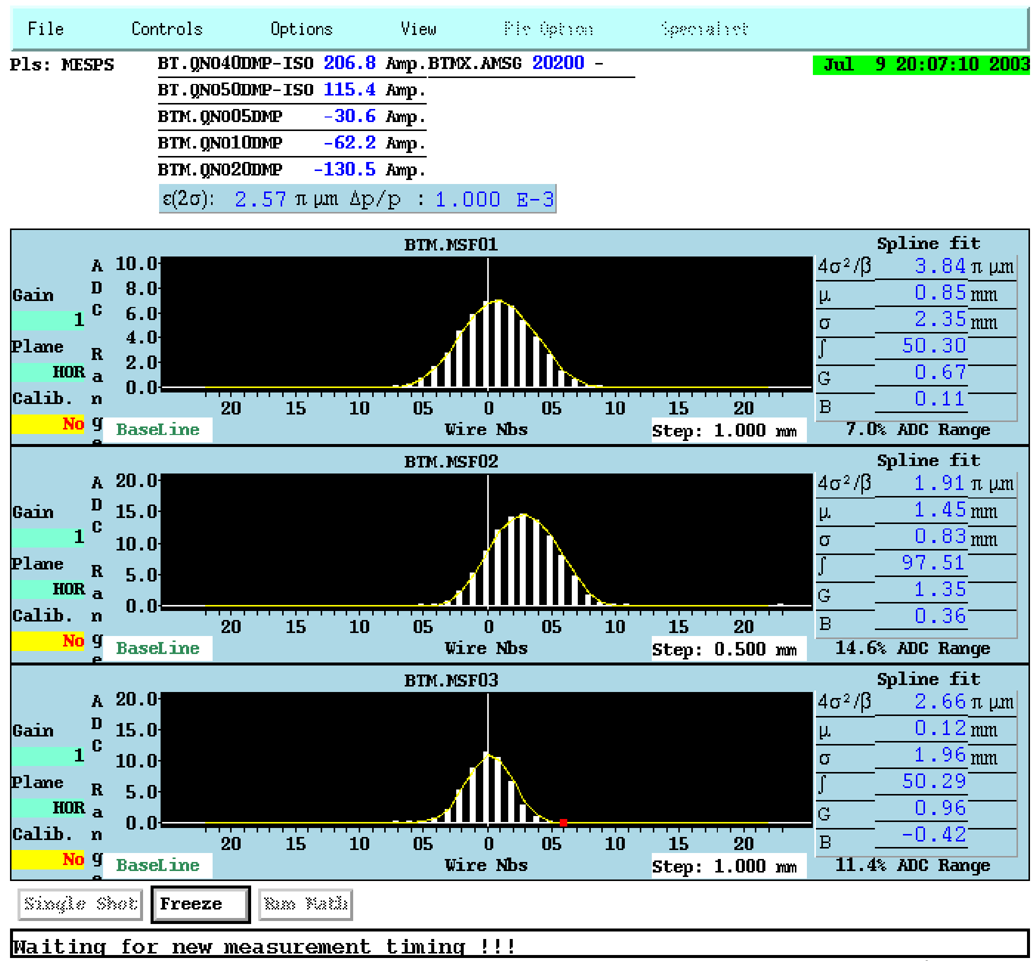
Transverse Beam Size Monitors



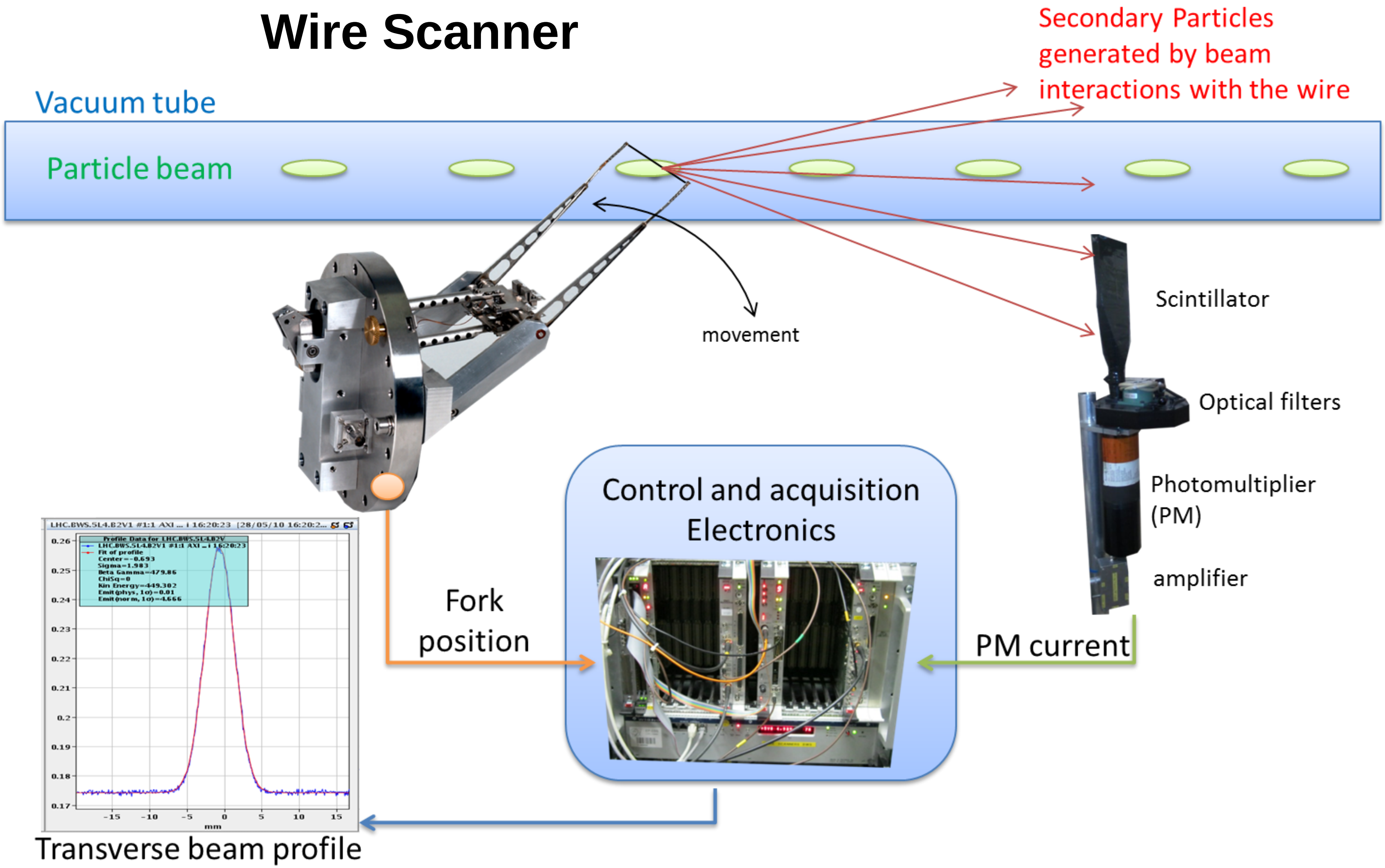
Transverse Beam Size Monitors

Secondary electron emission grids, aka SEMgrids



Transverse Beam Size Monitors

Wire Scanner



Transverse Beam Size Monitors

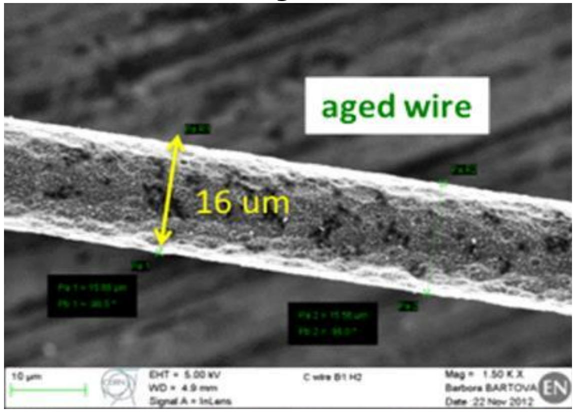
Wire Scanner

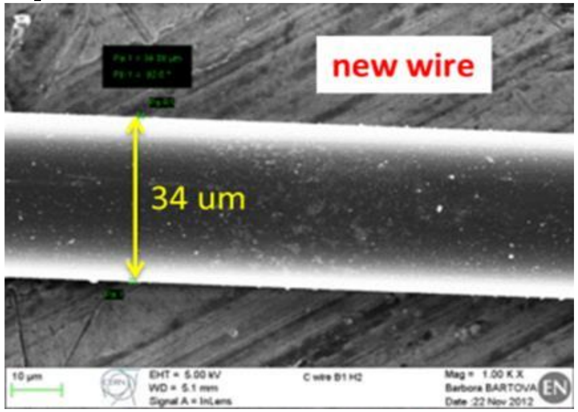
- Linear scanner operating at a speed of 1 ms^{-1}
- Rotational wire scanner operating at speed up to 20 ms^{-1}
- Provides absolute measurements & cross calibration to others instruments

Transverse Beam Size Monitors

Limitations of LHC Wire scanners scanning at 1m.s-1

- Limit defined by wire sublimation process



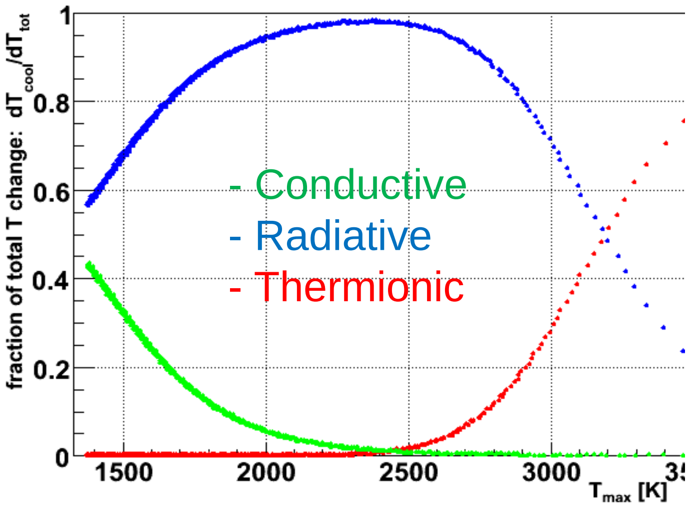


- At 450 GeV limit at 2.7×10^{13} protons
  - One injected SPS batch of 144 bunches @ 50ns OK
  - One injected SPS batch of 288 bunches @ 25ns NOT OK
- At 6.5 TeV limit at 2.7×10^{12} protons
  - ~20 main bunches
- Rotating Wire Scanner at 20 ms^{-1} would allow scanning all bunches at injection but with reduced resolution to measure smaller beams at top energy

Limitations 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 proton beam or beam induced RF heating

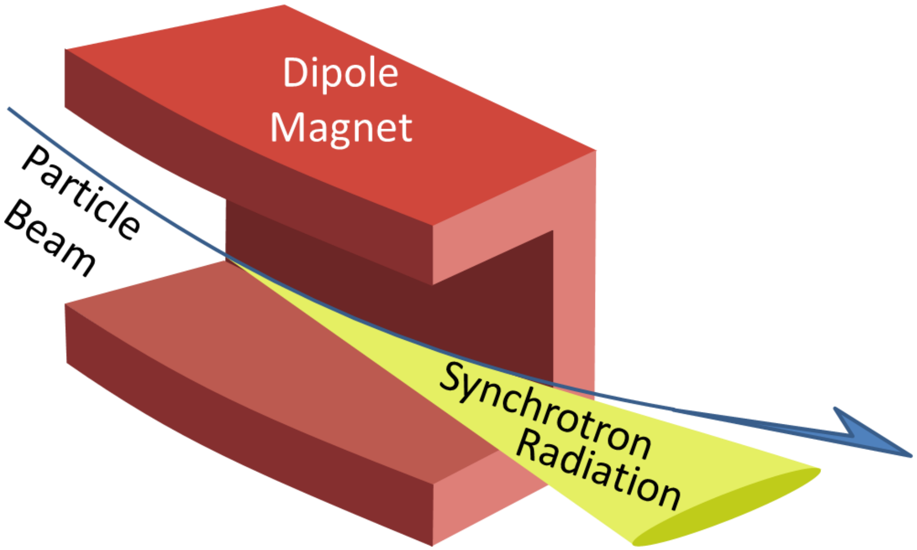
- Temperature evolution depends on
  - Heat capacity, which increases with temperature!
  - Cooling
    - Conductive
    - Radiative
    - Thermionic

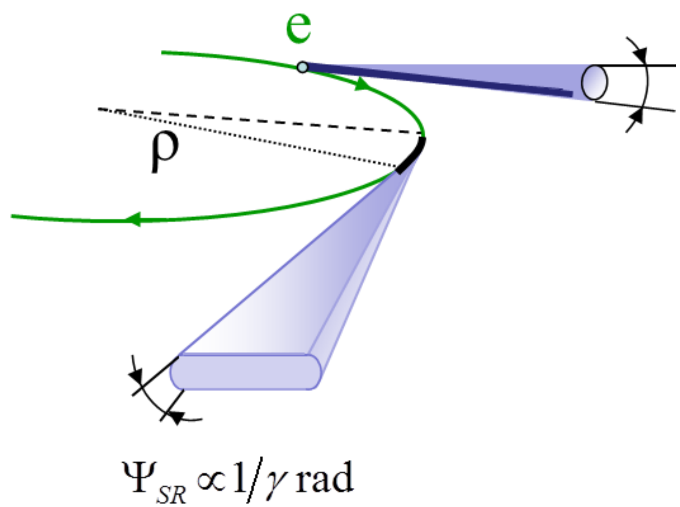


- Wire Choice
  - Carbon (tens of microns thick)
    - Good mechanical properties
    - Sublimates at 3915K
  - R&D on low density materials

Transverse Beam Size Monitors

‘Let There Be Light’





‘Synchrotron light monitor’, a natural source of photons

A great opportunity for beam instrumentation and beam imaging systems

Widely used for Electrons in rings

Transverse Beam Size Monitors

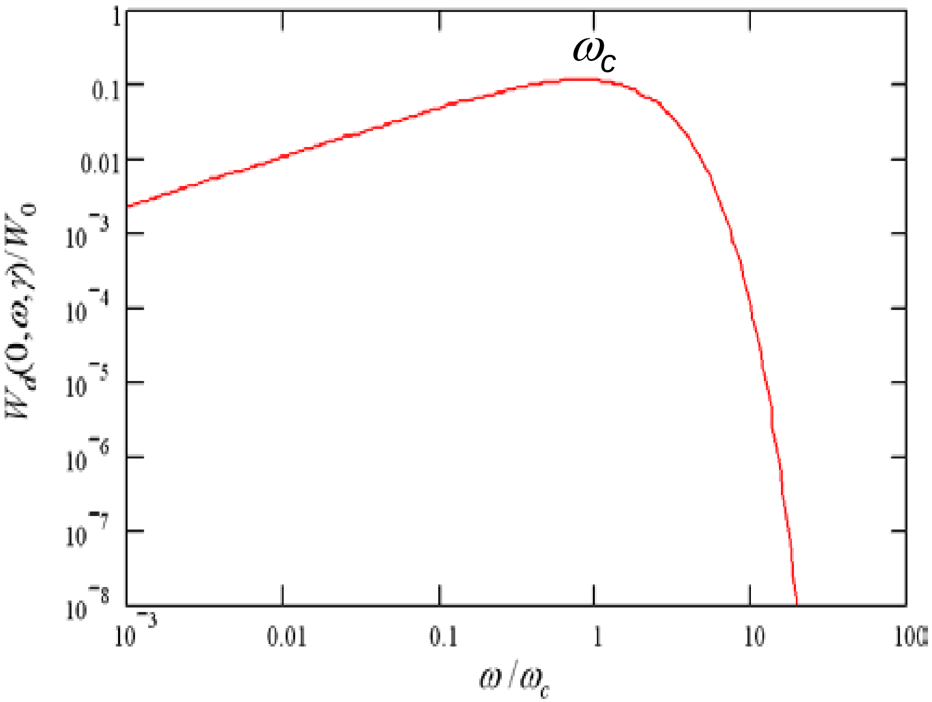
- **SR Power :**

$$P_\gamma = \frac{1}{6\pi\varepsilon_0} \frac{q^2 c}{\rho^2} \gamma^4$$

- **SR Critical Frequency :**

$$\omega_c = 3\gamma^3 \frac{c}{2\rho}$$

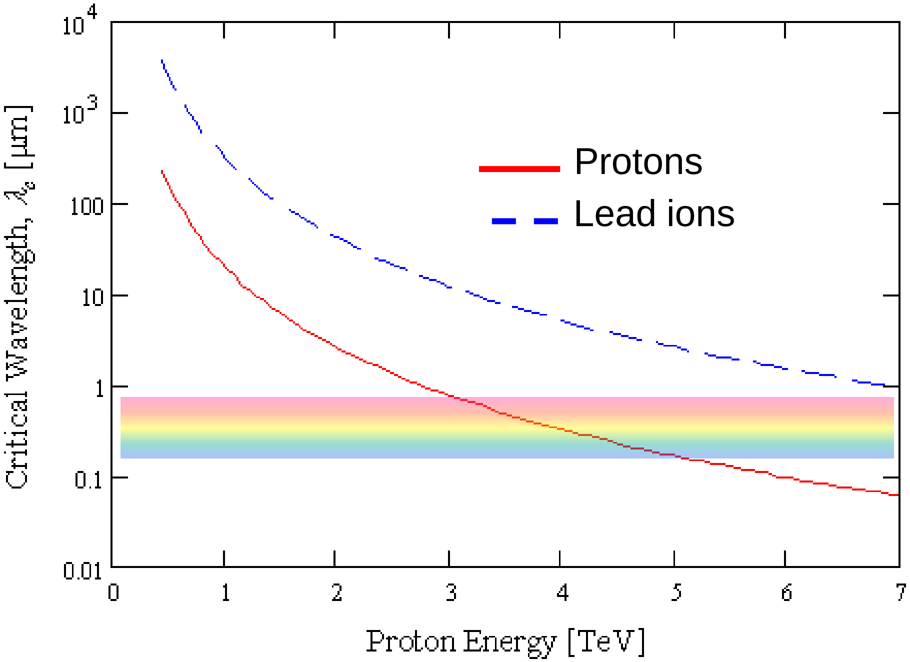
- γ charged particle Lorentz-factor
- ρ the bending radius



SR Intensity drops off sharply after critical wavelength

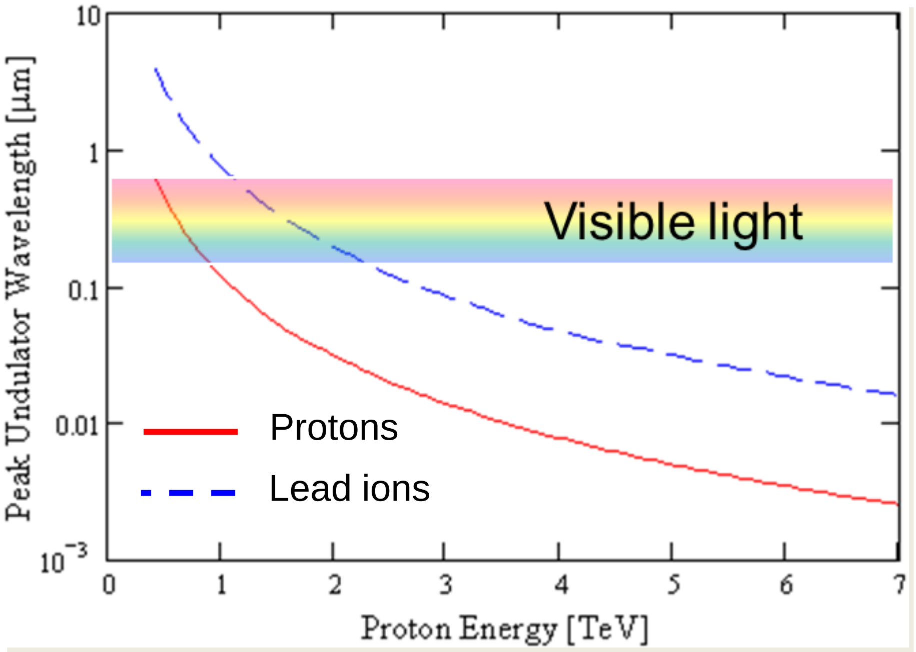
Transverse Beam Size Monitors

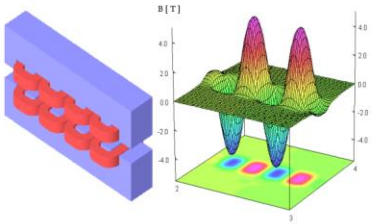
At LHC – Dipole radiation



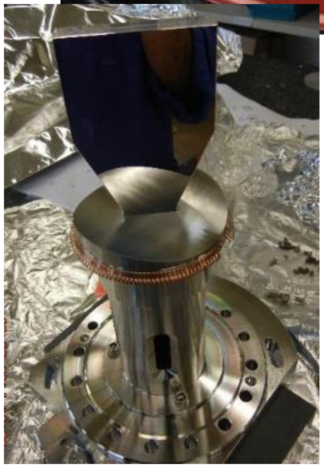
Little visible light at injection energy

At LHC – Undulator radiation

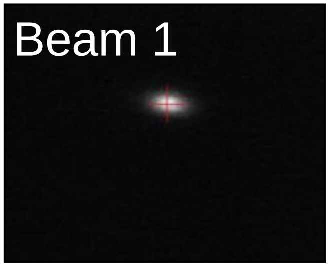


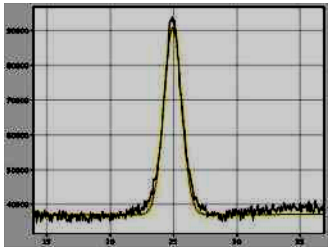


Transverse Beam Size Monitors

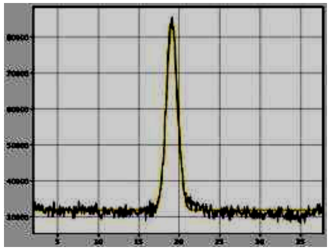


- Extraction mirror
- Table with Optics and Cameras

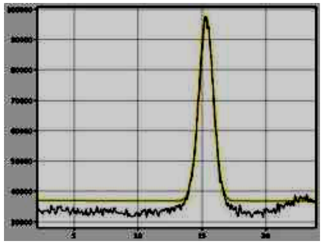




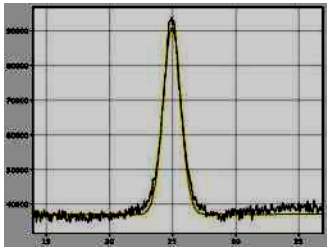
σ_h = 0.68mm



σ_h = 0.70mm



σ_v = 0.56mm

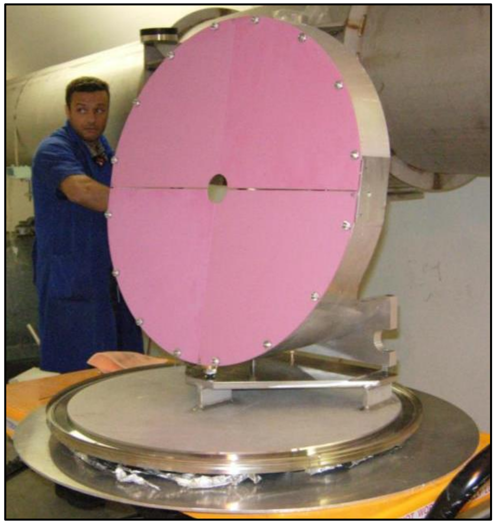


σ_v = 1.05mm

Transverse Beam Size Monitors

'Beam Imaging with Screens'

- Scintillating screens (Al_2O_3) widely used for large beams and low intensity and low energy beams



60cm wide screen

Beam imaging in the LHC dump lines

Camera

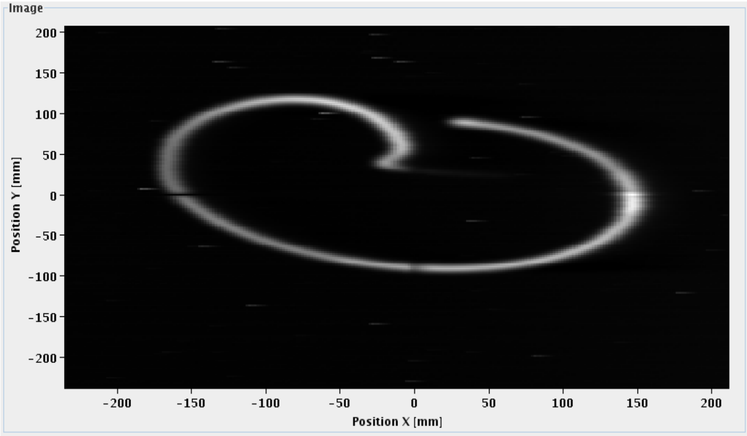


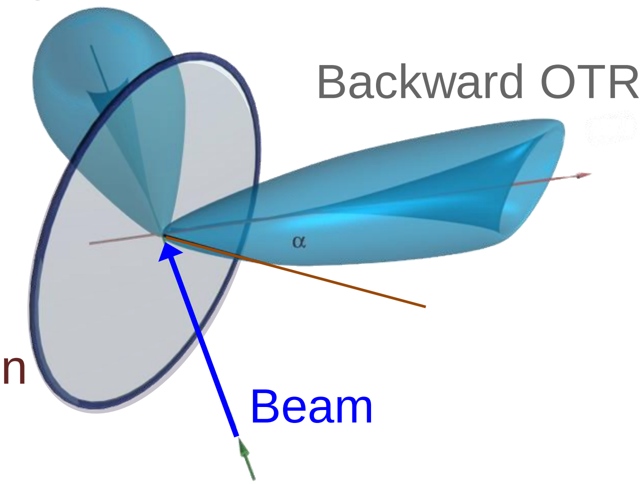
Image of a beam dilution just before the dump

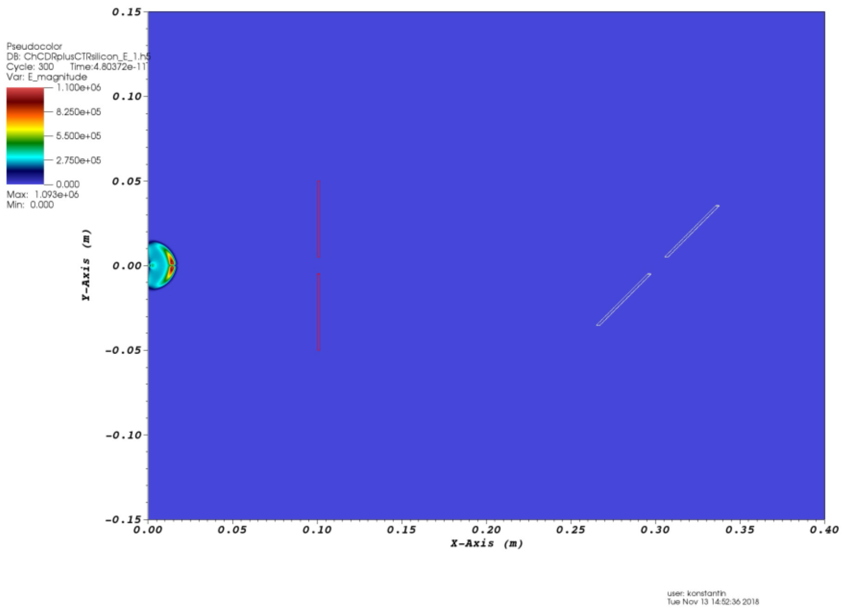
Transverse Beam Size Monitors

‘Beam Imaging with Screens’

- Optical transition radiation screens for high energy-higher intensity beams

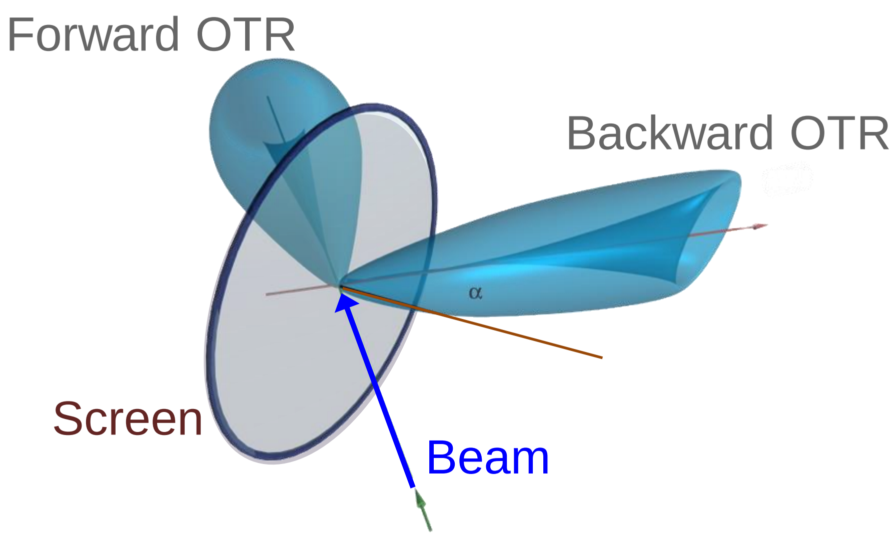
*As predicted in 1946 by Frank and Ginzburg, **Transition Radiation** is a broadband electromagnetic field emitted by a relativistic charged particle when it crosses boundary between two mediums of different dielectric constants.*





Transverse Beam Size Monitors

‘Beam Imaging with Screens’



- Using good reflecting material – highly polished surface
- The thermal limit for ‘best’ screens (C, Be) is ~ 1. 10^6 nC/cm^2

Number of OTR photons per charge particle

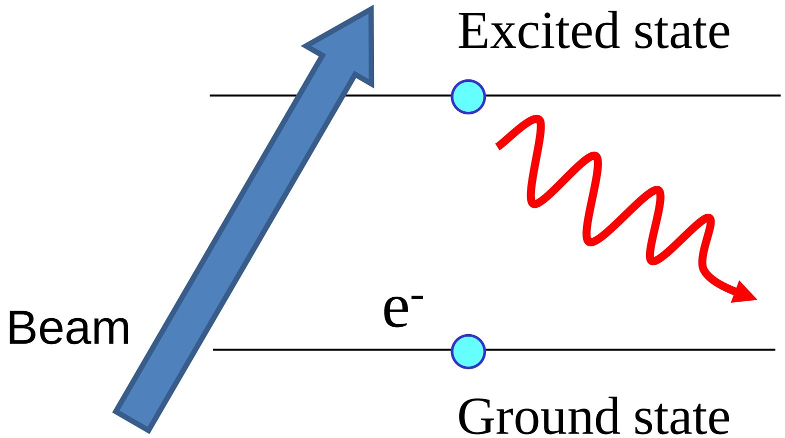
$$N_{ph} = \frac{2\alpha}{\pi} \cdot \ln\left(\frac{\lambda_b}{\lambda_a}\right)\left(\ln(2\gamma) - \frac{1}{2}\right)$$

~ 5 10^{-3} in [400-600]nm per particle

Radiation wavelengths

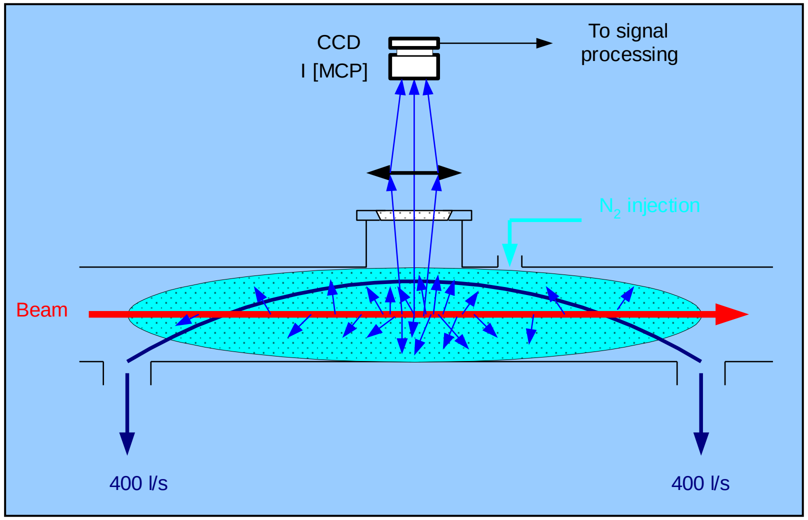
Beam energy

'Beam imaging with no screen'



A screen made out of gas

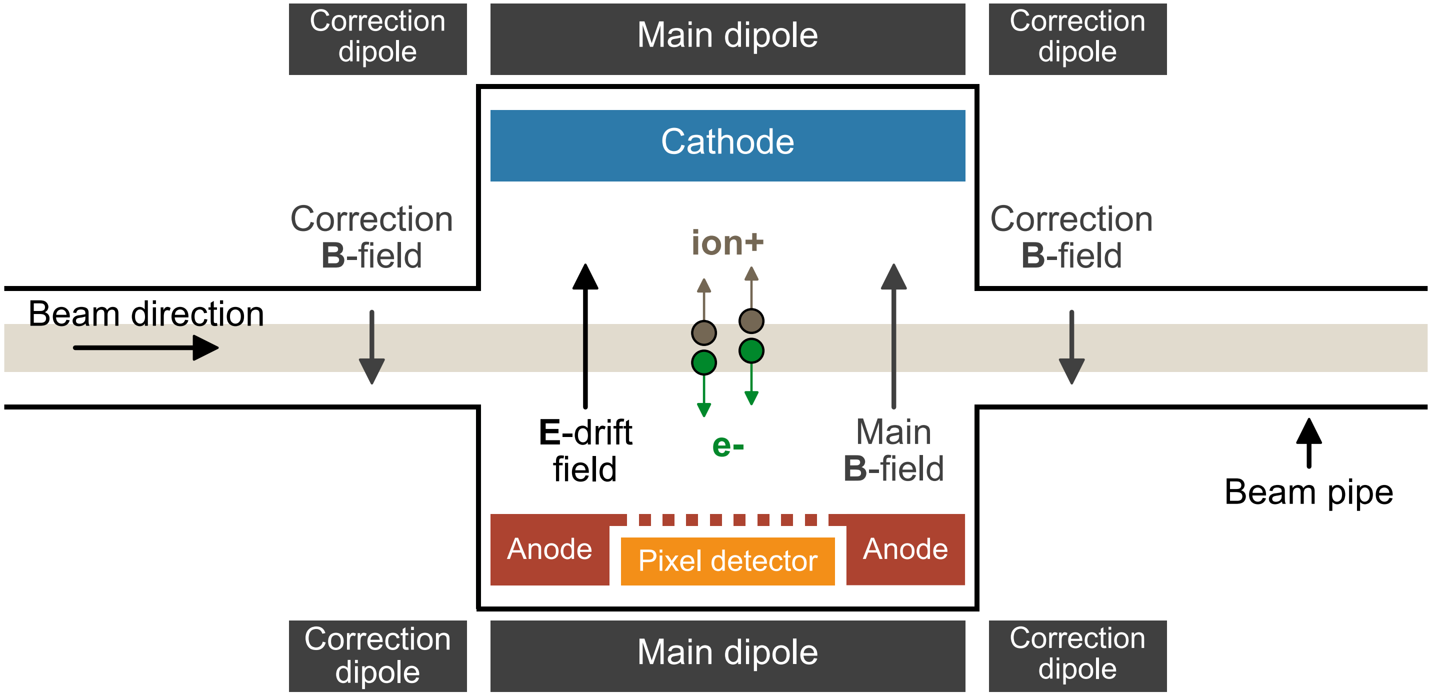
- Beam exciting gas molecules
- Emitting light as it decays to ground state



Rather low luminescence cross-section ($<10^{-9}$ ph/part depending on gas density and species) which limits its use of high-intensity beams

Transverse Beam Size Monitors

‘Gas ionization monitors’

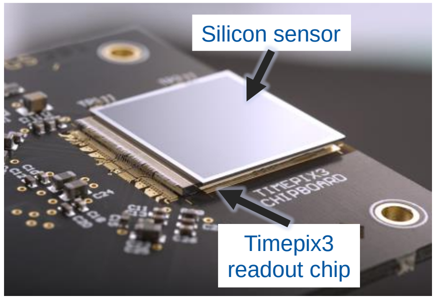


- *Charged particle ionises the gas*
- *Magnet used to guide electrons towards the detector*
- *Ionization probability proportional to the gas pressure (typically 10^{-7}-10^{-10}Torr) and almost constant for beam energy above 1GeV*

Transverse Beam Size Monitors

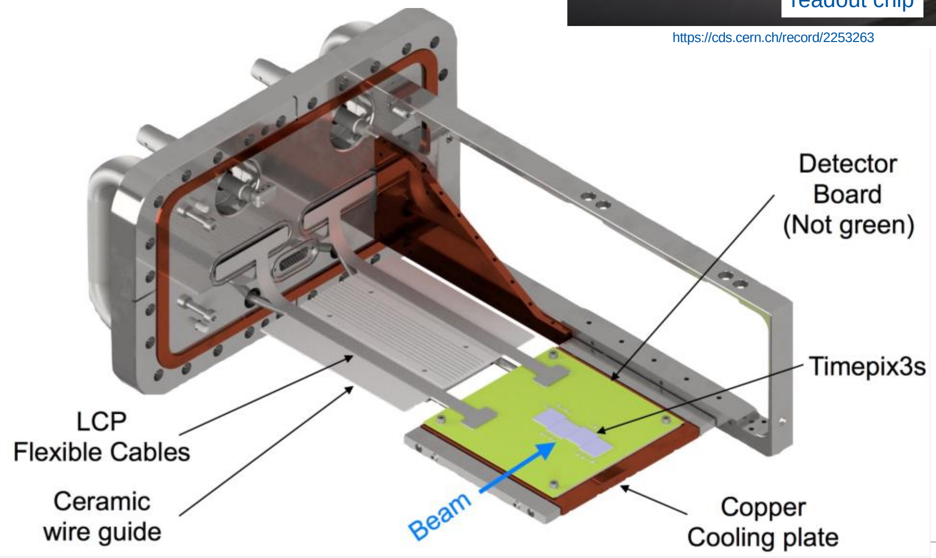
‘Gas ionization monitors’

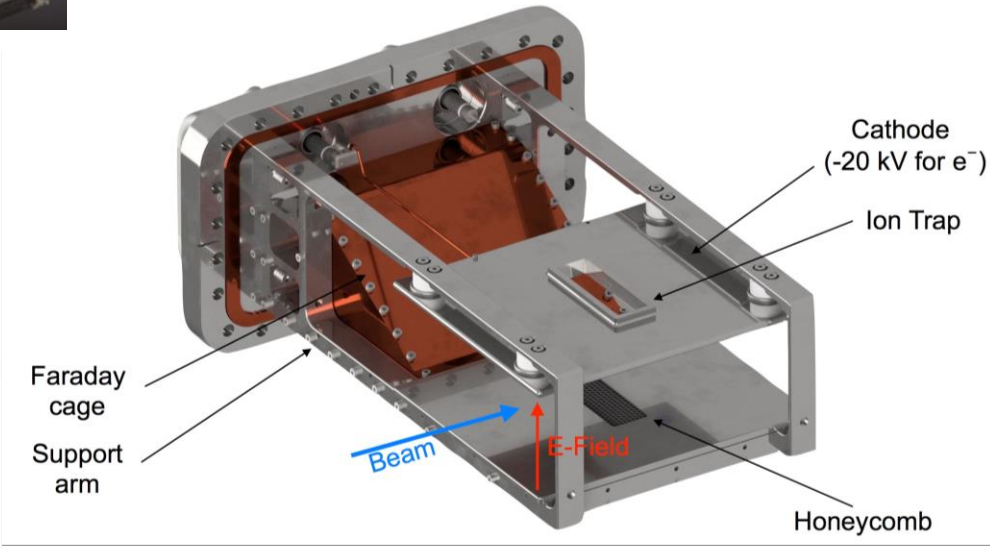
Using hybrid pixel detector technologies developed at CERN



https://cds.cern.ch/record/2253263

- 256x256 pixels
- 55um size
- 1.5625ns temporal resolution

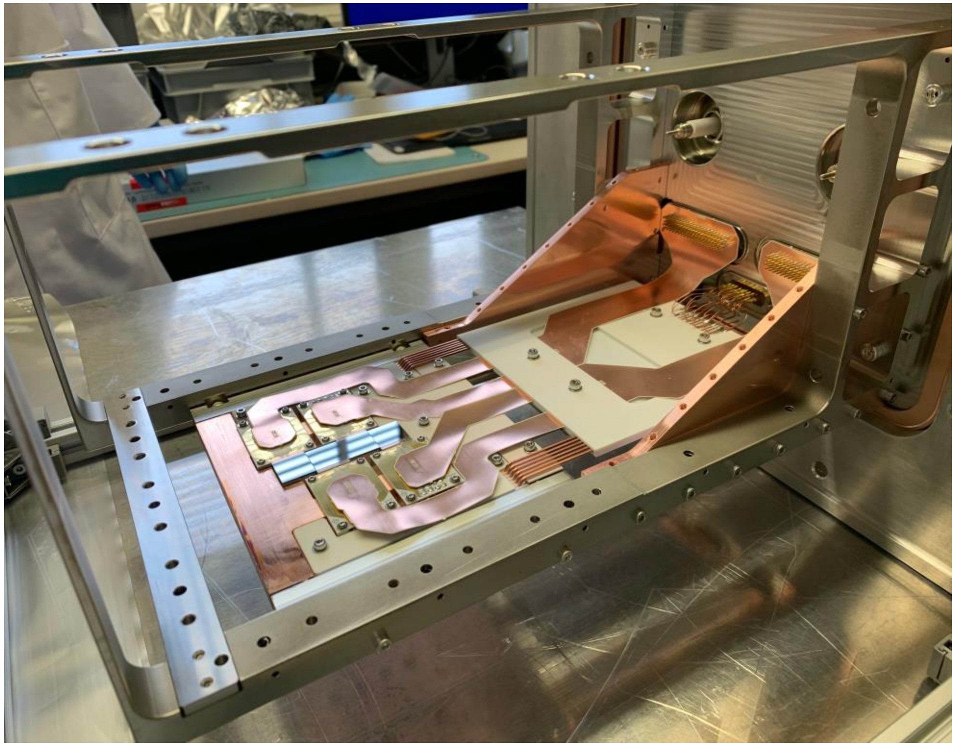




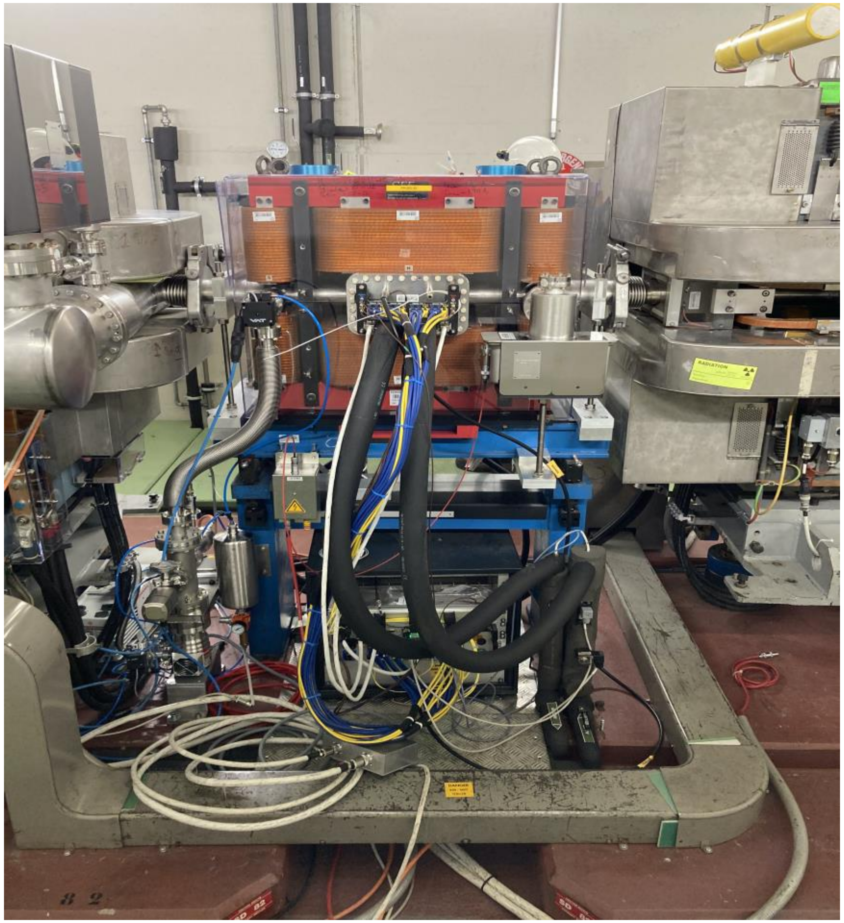
https://medipix.web.cern.ch/technology-chip/timepix3-chip
http://bgi-web.web.cern.ch/bgi-web/

Transverse Beam Size Monitors

‘Gas ionization monitors’



In vacuum flange

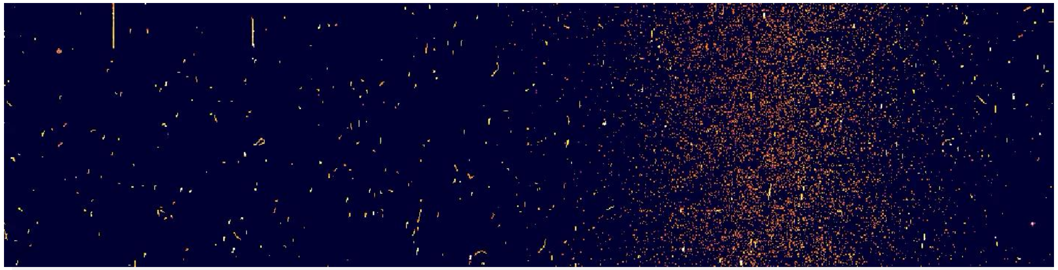


Monitor in PS ring

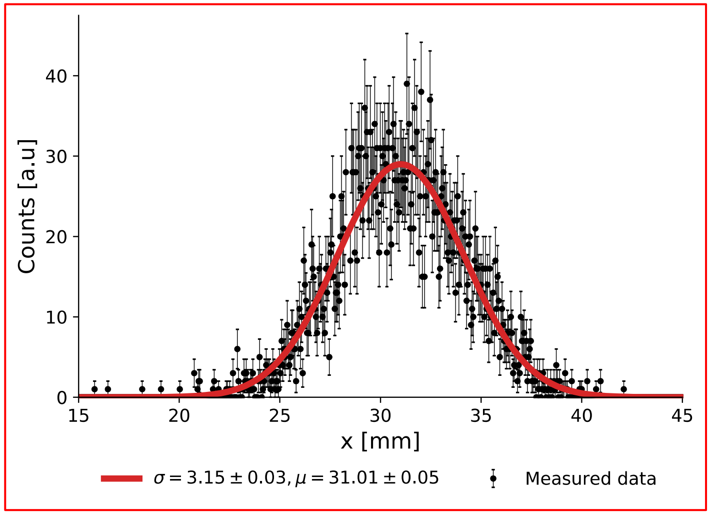
Transverse Beam Size Monitors

‘Gas ionization monitors’

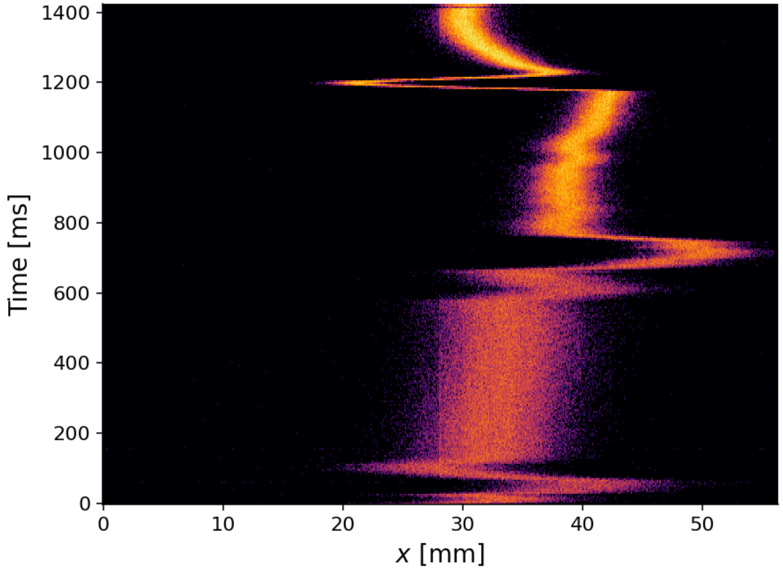
Continuous measurements during a PS cycle



- 1.5s in real time – slowdown for presentation
- Each image corresponds to 10ms integration time



Position and profile during a PS cycle



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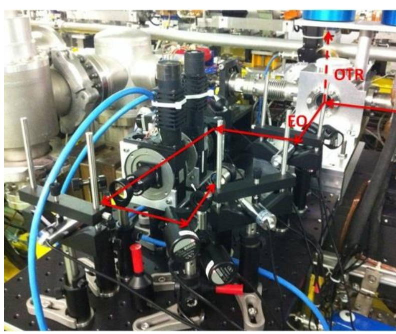
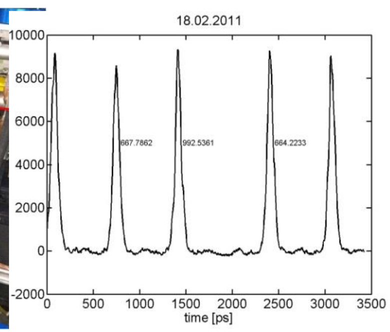
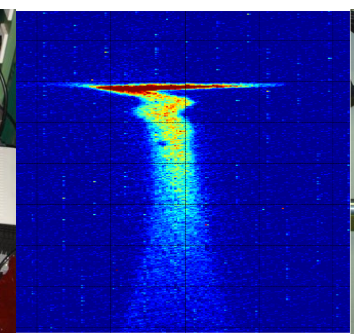
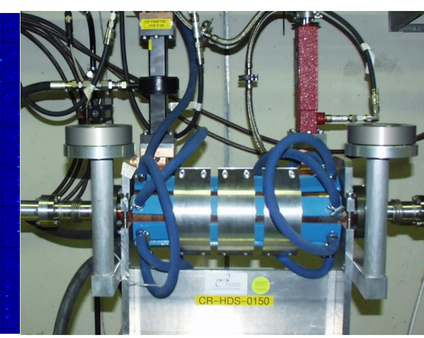
Longitudinal Beam Size Monitors





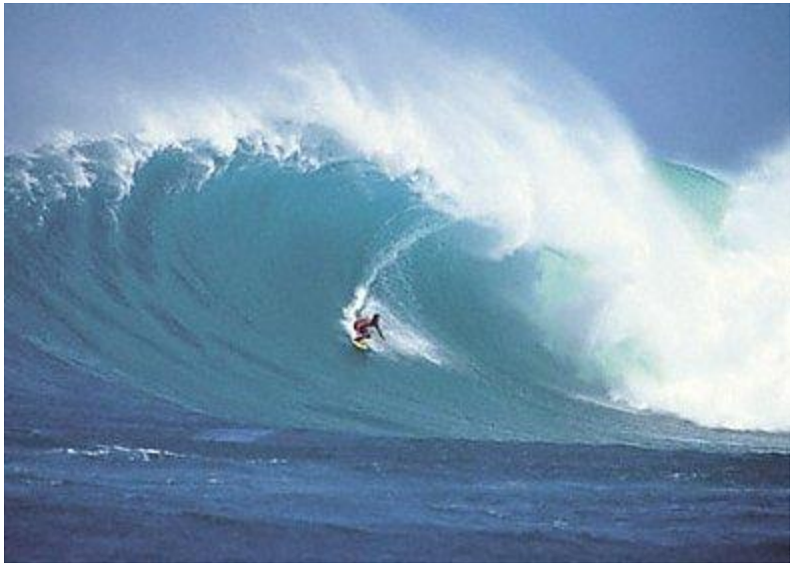




Longitudinal Beam Size Monitors

How short is a bunch of particle ?

Radiofrequency accelerating cavities



Synchronising the particle with the crest of the wave

Longitudinal Beam Size Monitors

How short is a bunch of particle ?

Interval between Ocean'swaves

~ 10-20seconds

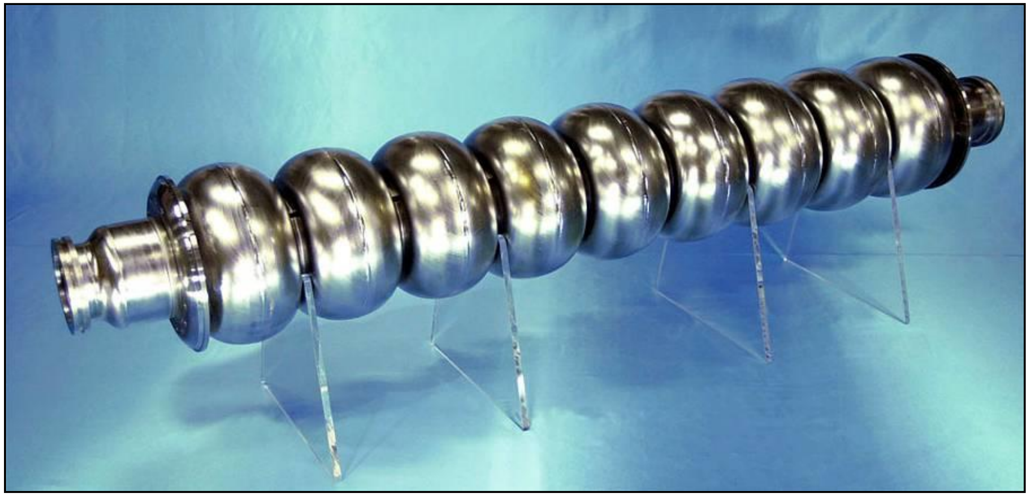
Longitudinal Beam Size Monitors

How short is a bunch of particle ?

Interval between Ocean'swaves

~ 10-20seconds

Interval between electromagnetic waves



At 400MHz – 25ns
At 3GHz – 333ps

To keep the particle of the crest of the wave, the bunch duration is typically a small fraction of that (~ 1%)

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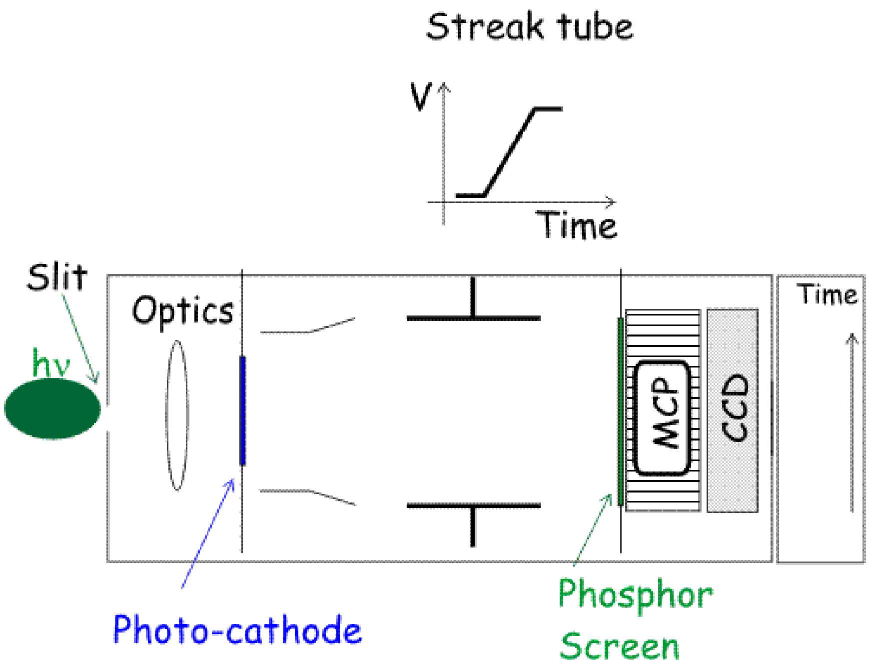
Longitudinal Beam Size Monitors

How short is a bunch of particle ?

p^+ @ LHC	250ps
H^- @ SNS	100ps
e^- @ ILC	500fs
e^- @ CLIC	130fs
e^- @ XFEL	80fs
e^- @ LCLS	<75fs

Longitudinal Beam Size Monitors

Particles producing photons detected using a Streak camera

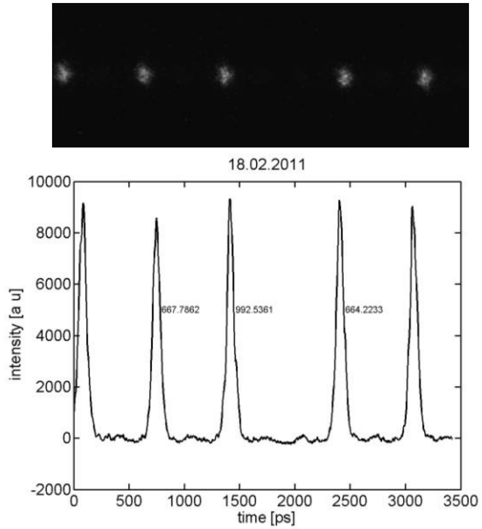


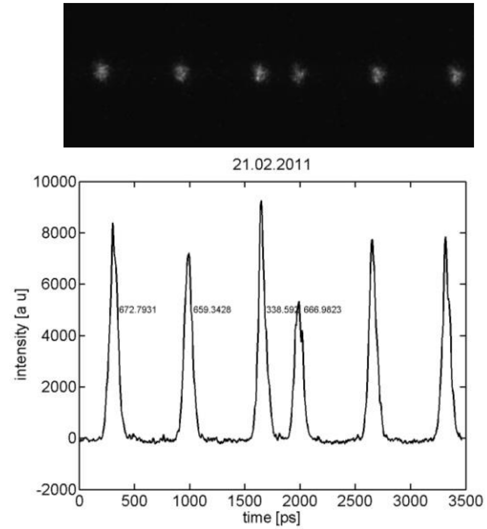
'Streak cameras uses a time dependent deflecting electric field to convert time information in spatial information on a CCD'

Fastest time resolution ~ 200fs

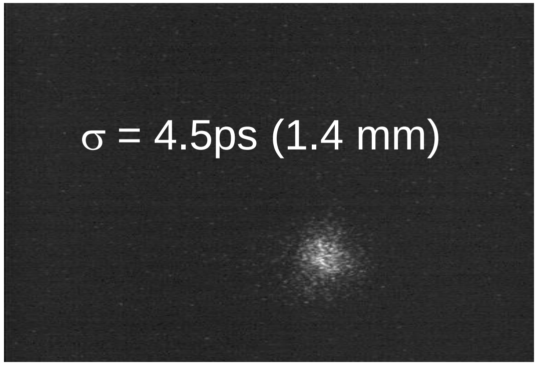
Longitudinal Beam Size Monitors

Observation of 5MeV electron bunch train using Cherenkov radiation at CLEAR
Sweep speed of 250ps/mm

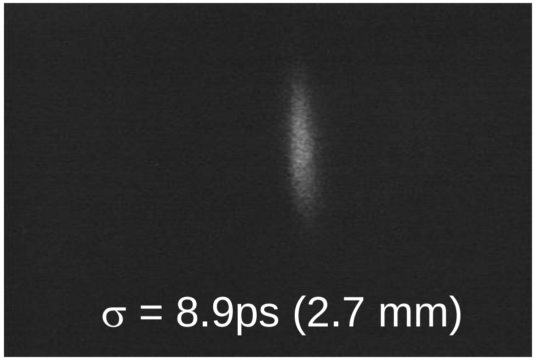




Measurement of bunch length using OTR and OSR at CTF3@CERN

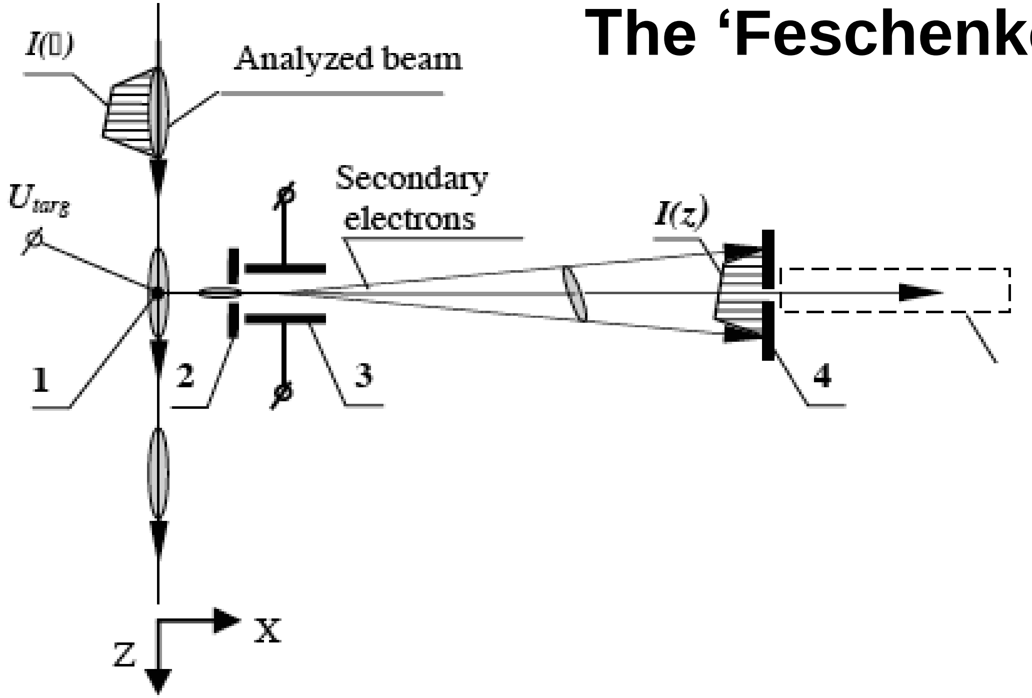


Sweep speed of 10ps/mm



Longitudinal Beam Size Monitors

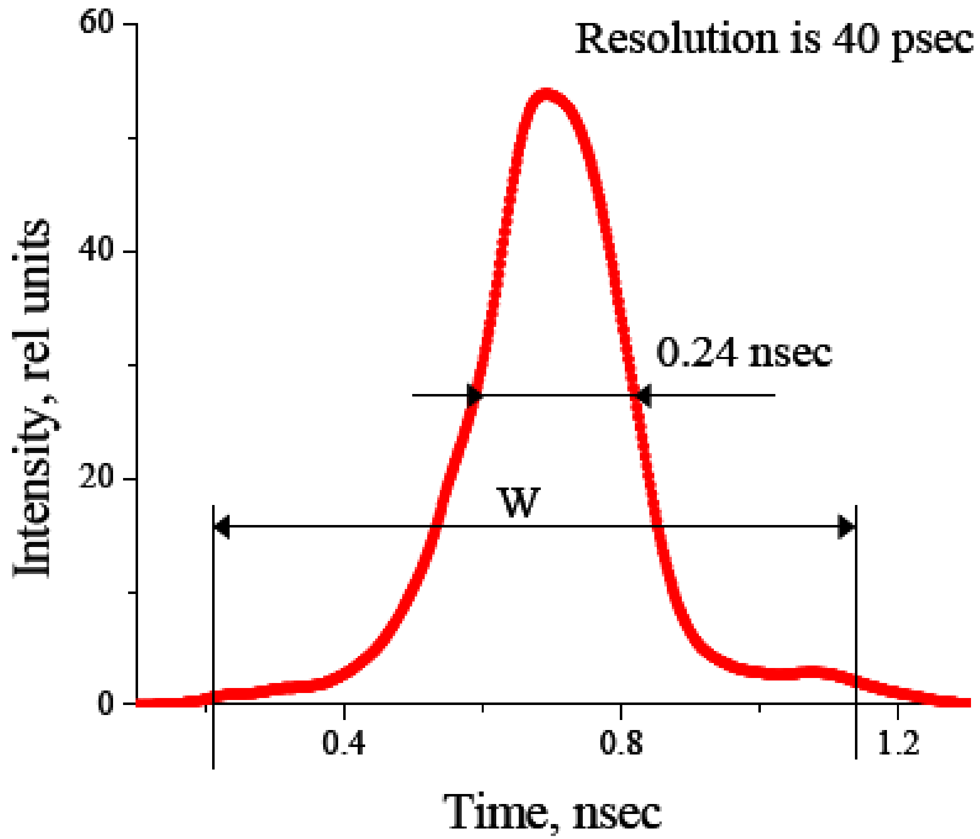
The 'Feschenko monitor'



1 - Target (wire, screen, laser for H^-) : Source of secondary electrons
2 - Input collimator
3 - RF deflector (100MHz, 10kV) combined with electrostatic lens
4 - Electron Beam detector (electron multiplier, ..)

Longitudinal Beam Size Monitors

The ‘Feschenko monitor’

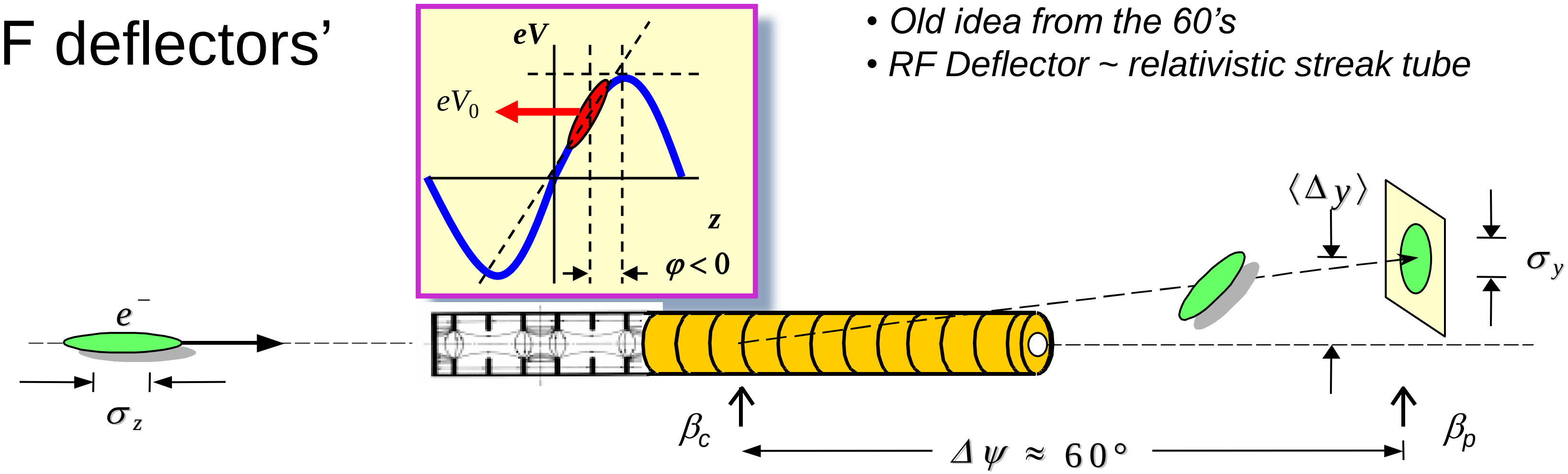


Longitudinal Bunch profile @ L4

Longitudinal Beam Size Monitors

'RF deflectors'

- *Old idea from the 60's*
- *RF Deflector ~ relativistic streak tube*



Beam profile RF on

$$\sigma_y = \sqrt{\sigma_{y_0}^2 + \sigma_z^2 \beta_c \beta_p \left(\frac{2\pi}{\lambda} \frac{eV_0}{E_0} \sin(\Delta\Psi)\cos(\varphi) \right)^2}$$

- Beam profile RF off: σ_{y_0}
- Deflecting Voltage: eV_0
- Bunch length: σ_z
- Beta function at cavity and profile monitor: $\beta_c \beta_p$
- RF deflector wavelength: λ
- Beam energy: E_0
- Betatron phase advance (cavity-profile monitor): $\Delta\Psi$

$\sin\Delta\psi = 1$, β_p small
Make β_c large

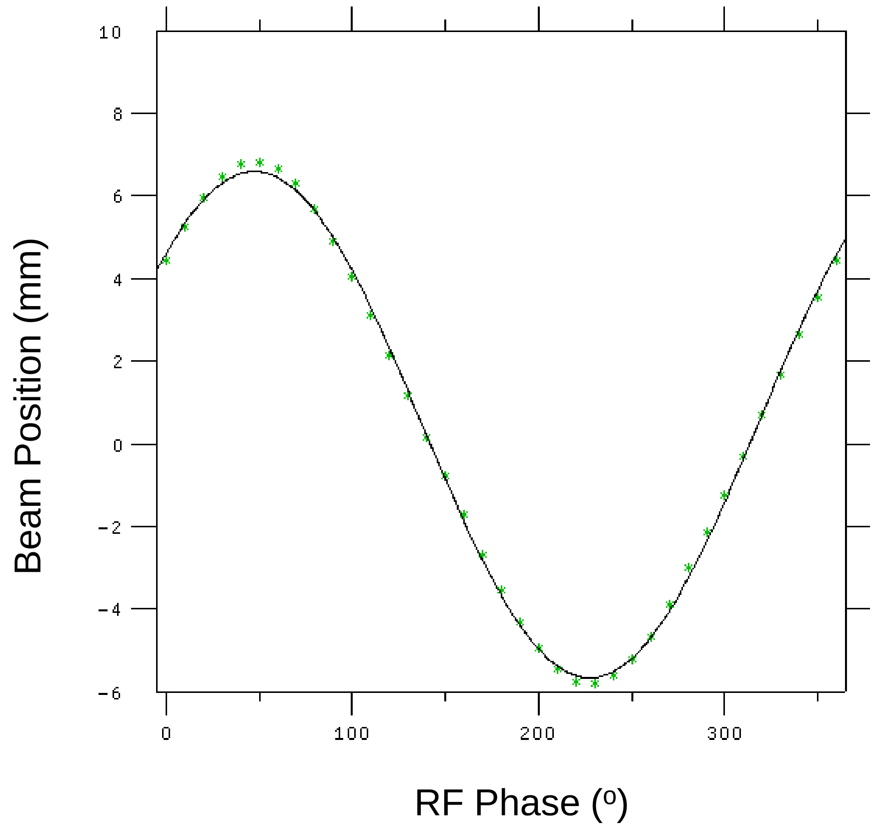
P. Emma et al, LCLS note LCLS-TN-00-12, (2000)

Longitudinal Beam Size Monitors

Calibration of RF Deflector

ΔX(mm) → Δφ(°) ΔT(ps)

Monitor the Beam Position on (or close to) the Profile monitor to calibrate the deflection angle



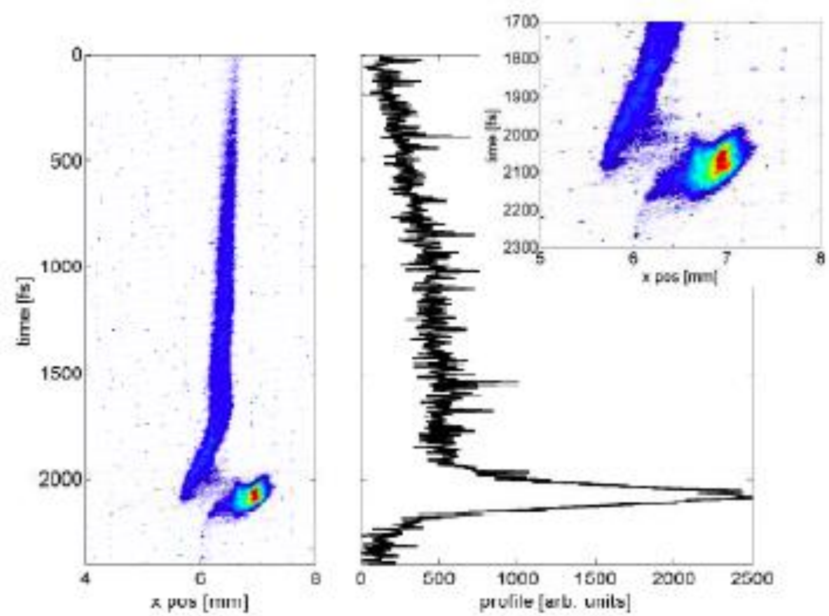
Beam offset on the screen

$$\Delta y(z) \approx \frac{eV_0}{E_0} \cdot \sqrt{\beta_c \beta_p}\, \sin(\Delta\Psi)\left(\frac{2\pi}{\lambda} - z\cos(\varphi) + \sin(\varphi)\right)$$

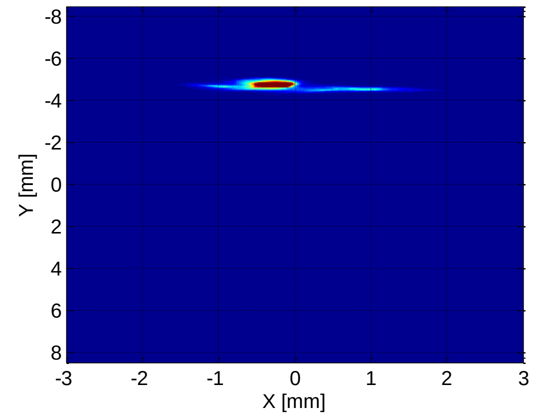
RF deflector phase

Longitudinal Beam Size Monitors

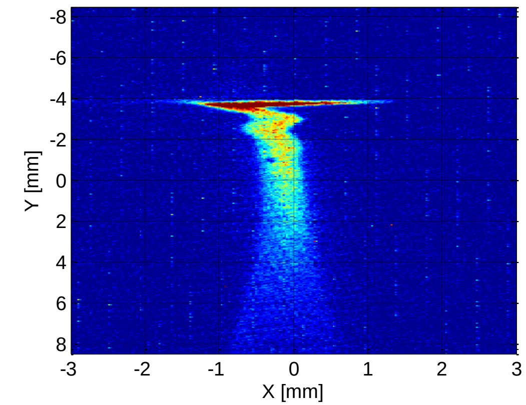
Bunch length measurement using LOLA @ Flash



LOLA off:



LOLA on:



→ Resolution of 4fs/pixels

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Beam Loss Monitors

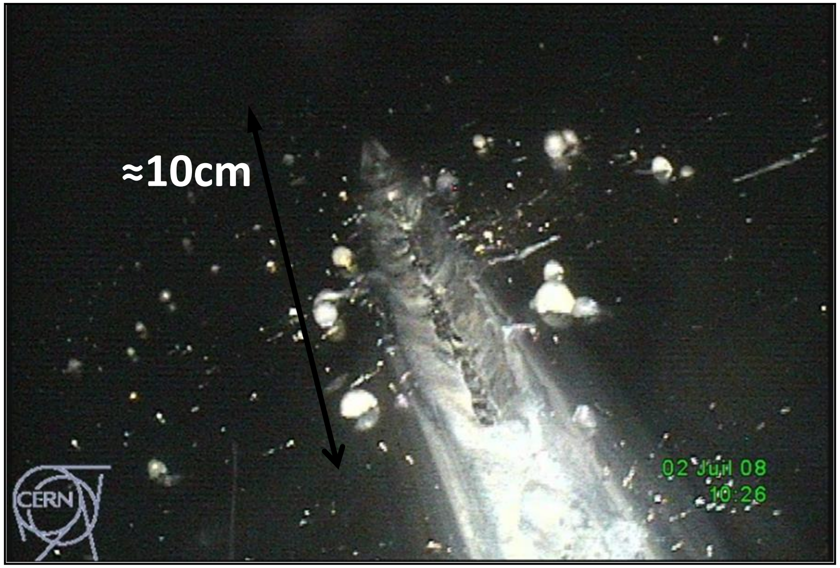
Beam Loss Monitors

- Role of a BLM system:
  - Protect the machine from beam damage
  - Dump the beam to avoid magnet quenches in Supra-conducting 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

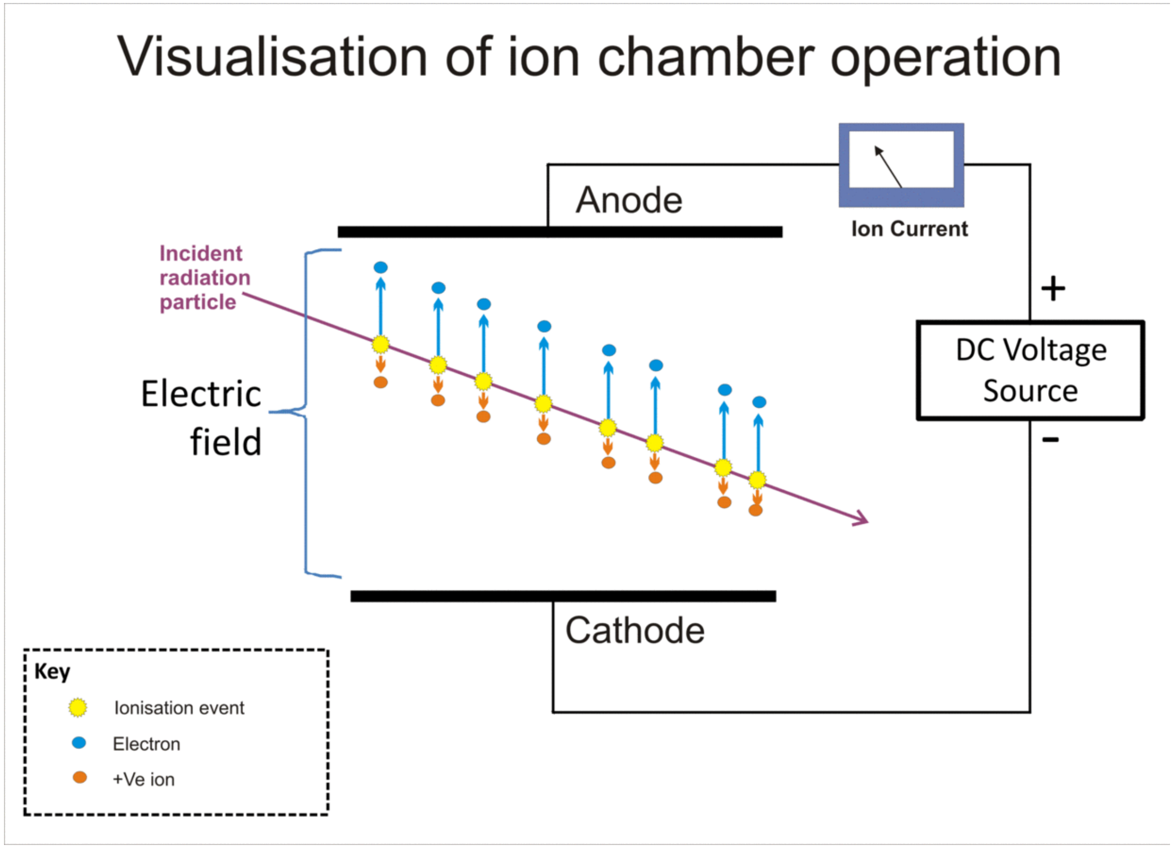
Quench and Damage at 7 TeV	
Quench level	≈ 1mJ/cm^3
Damage level	≈ 1 J/cm^3



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

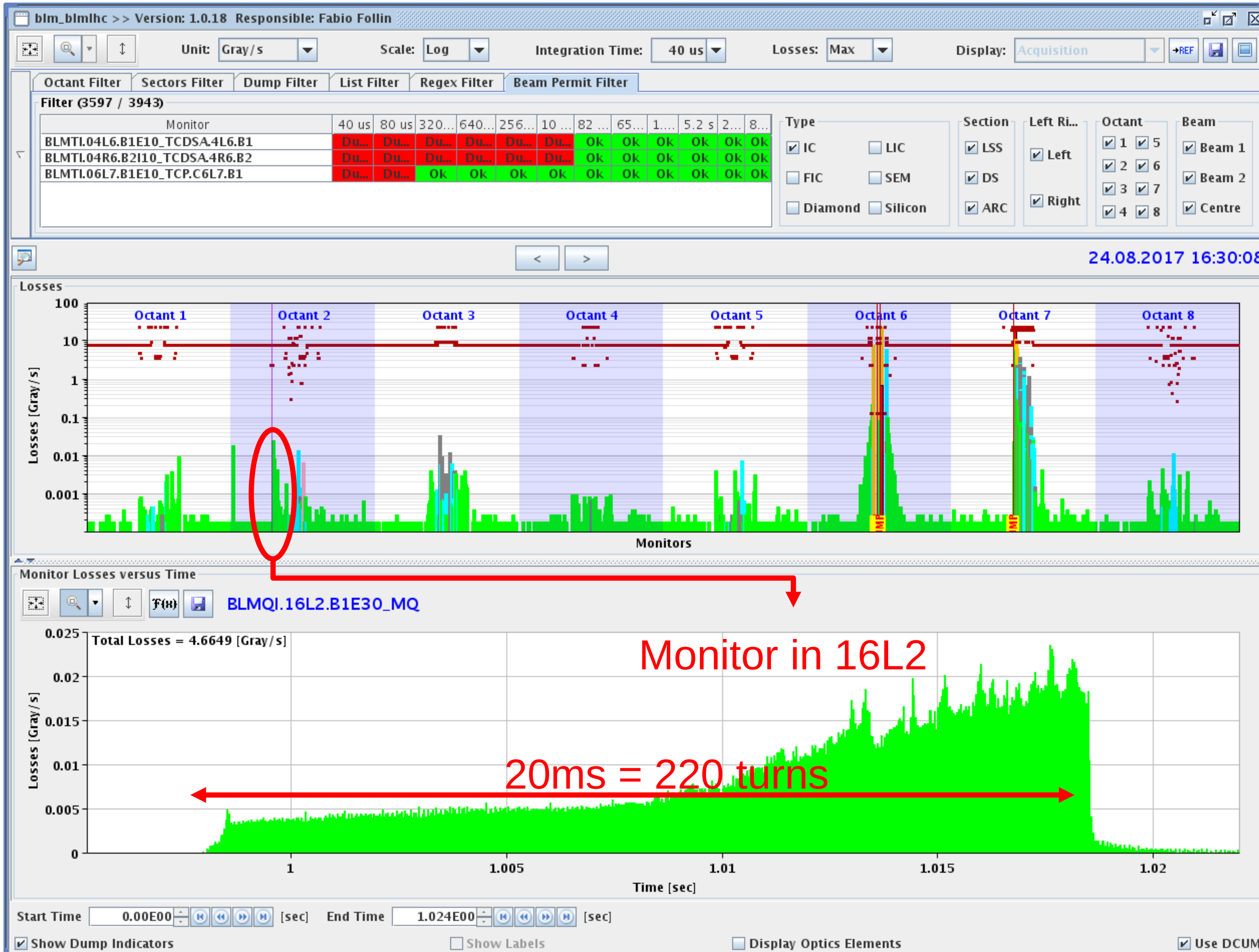
Beam Loss Monitors

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



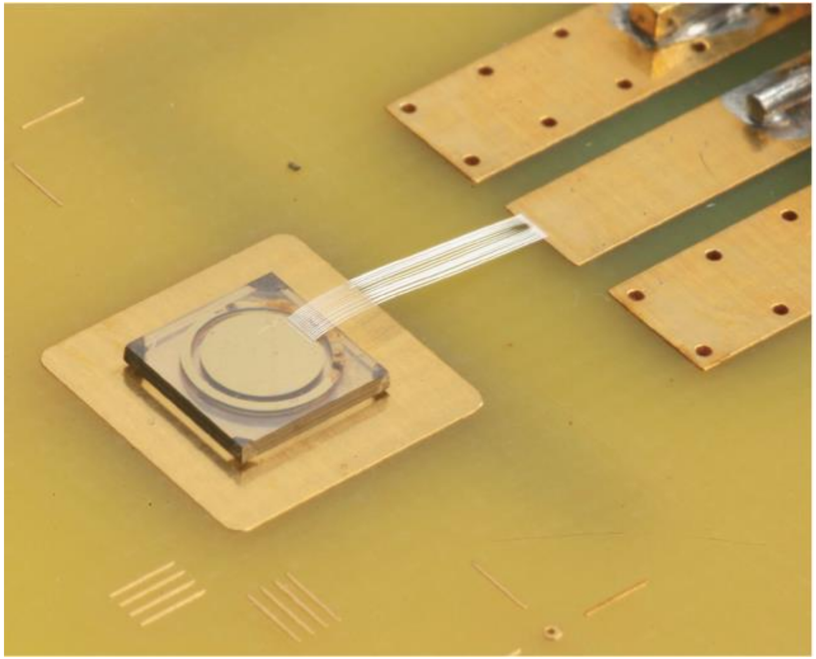
Beam Loss Monitors

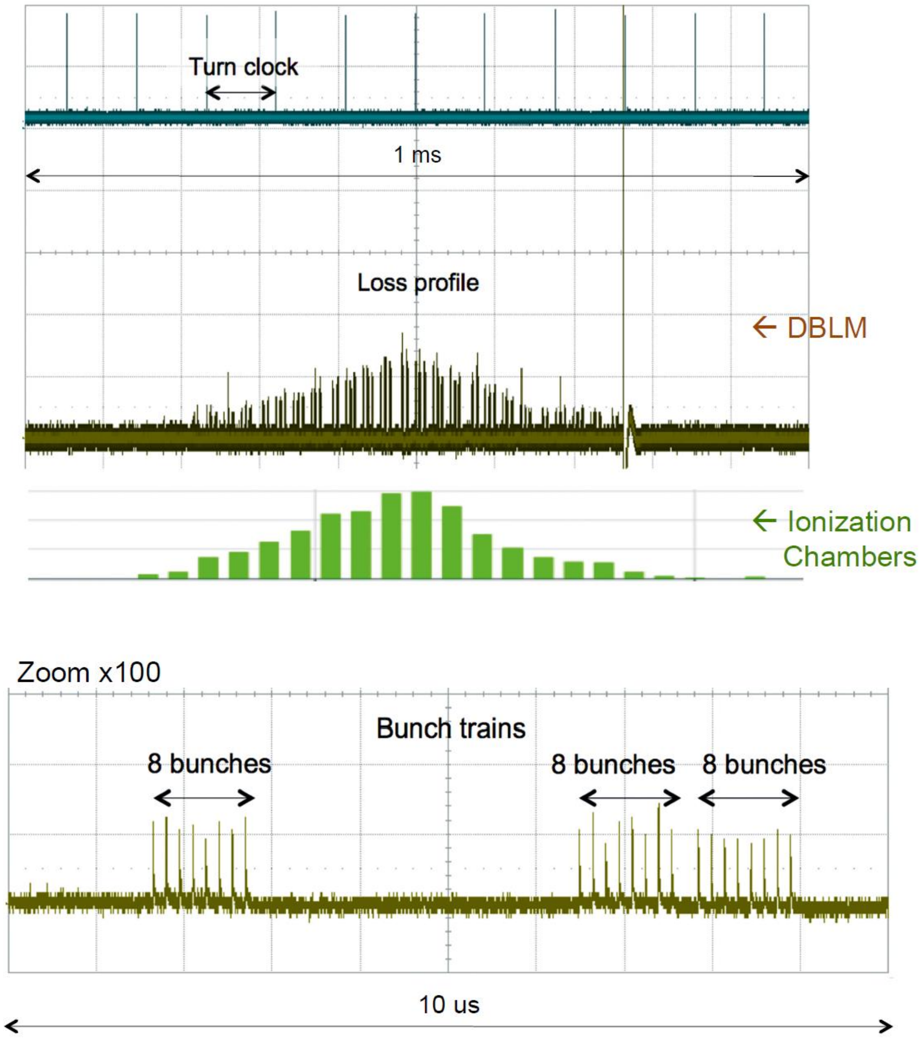
>4000 Ionisation Chambers in LHC



Beam Loss Monitors

- Diamond Detectors
  - Fast & sensitive
  - Used in LHC to distinguish bunch by bunch losses





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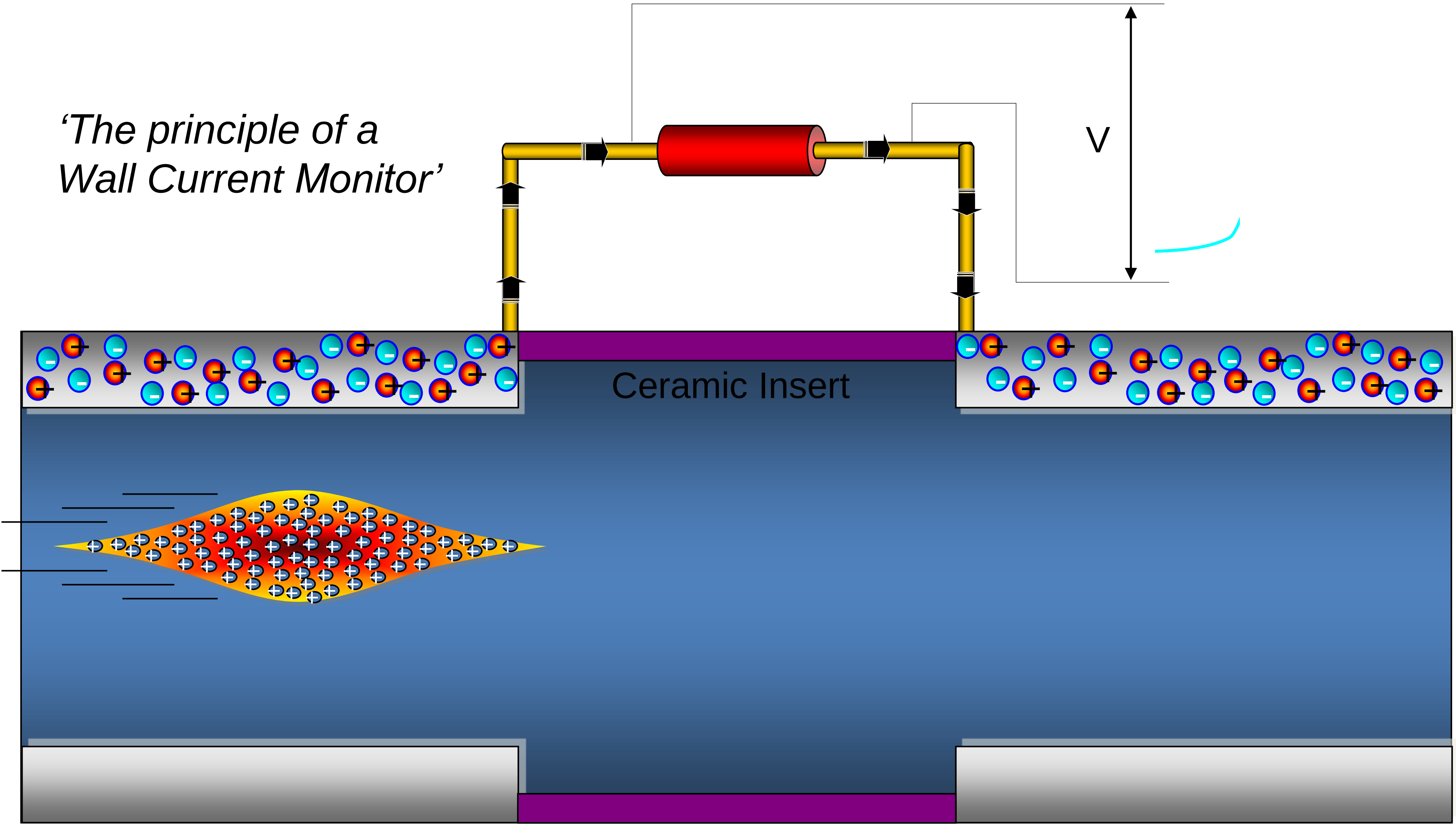
Thanks a lot for your attention

https://sy-dep-bi.web.cern.ch/

Extra slides

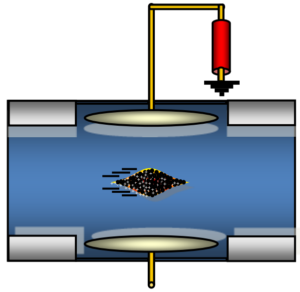
Beam Intensity Monitors

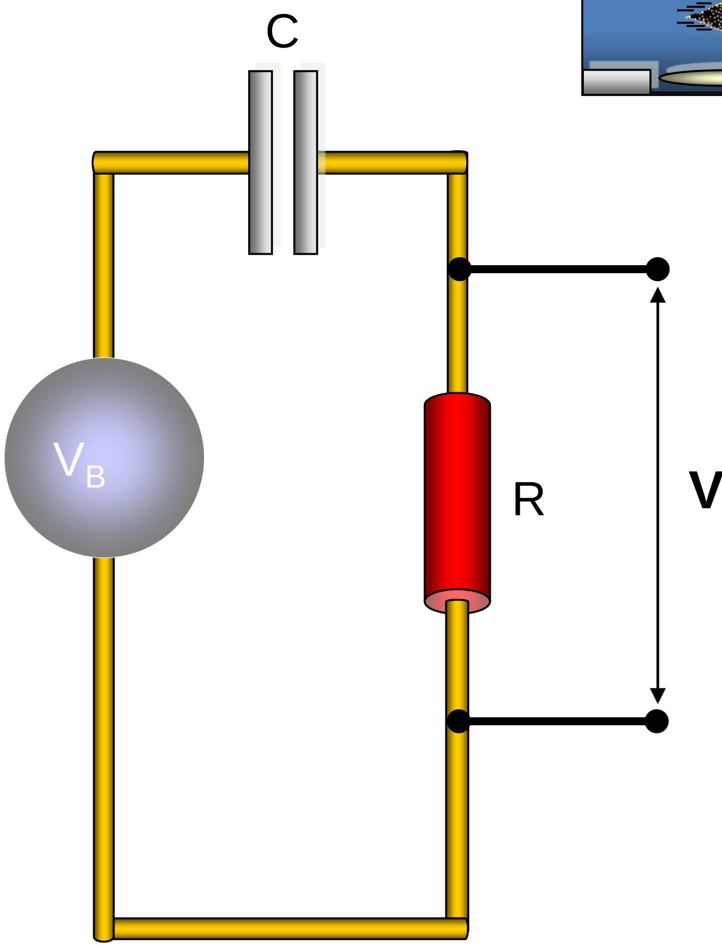
'The principle of a Wall Current Monitor'

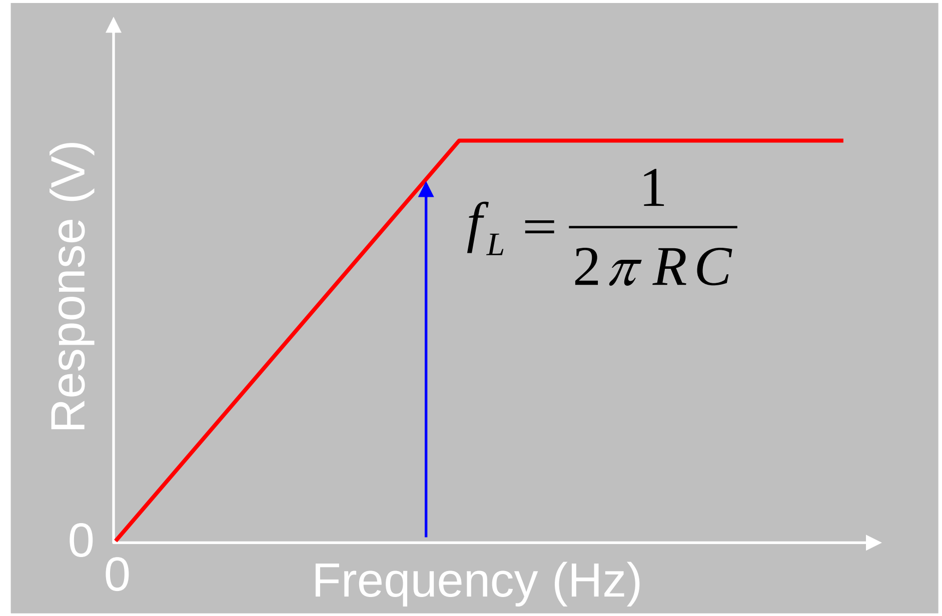


Beam Position Monitors

Electrostatic Button



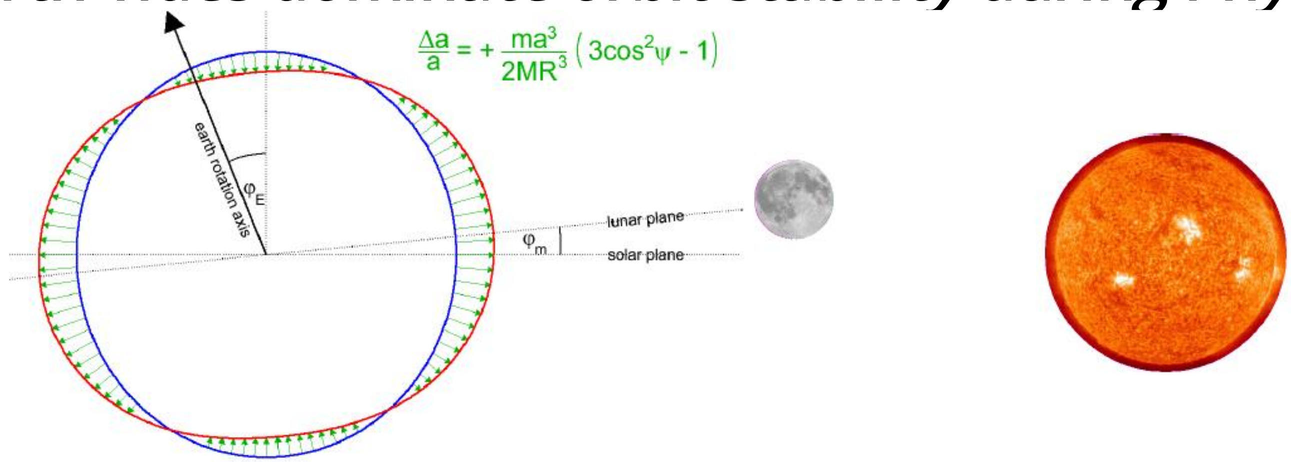


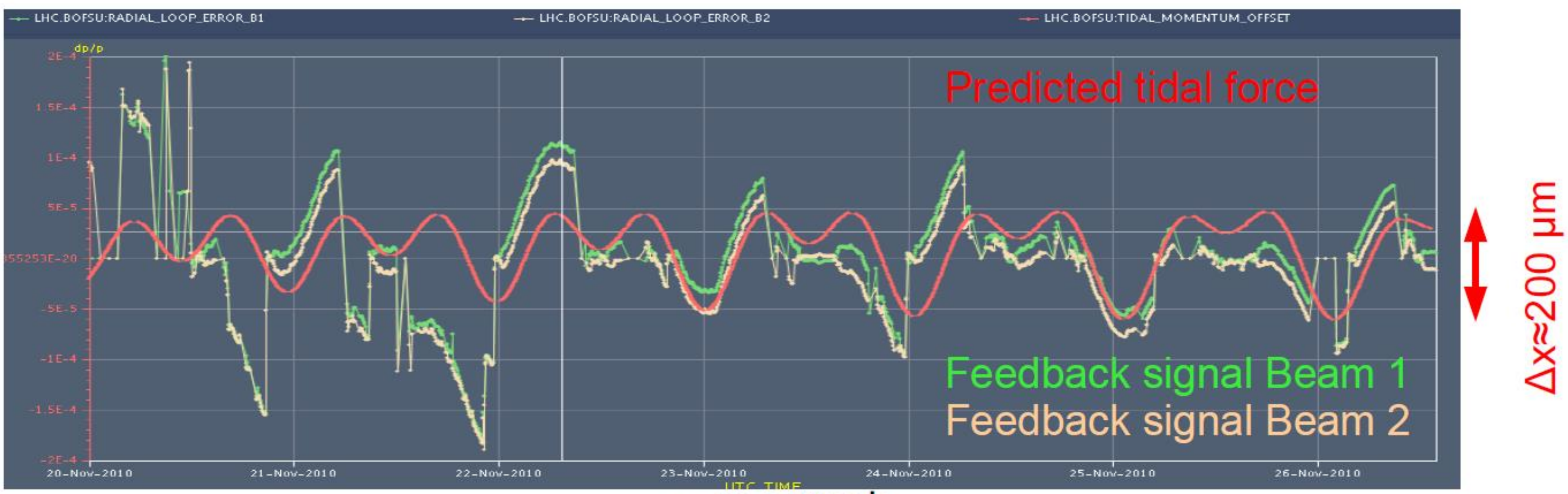


$$Z_{T(f>>f_c)} = \frac{A}{(2\pi r)\times c\times C_e}$$

Beam Position Monitors

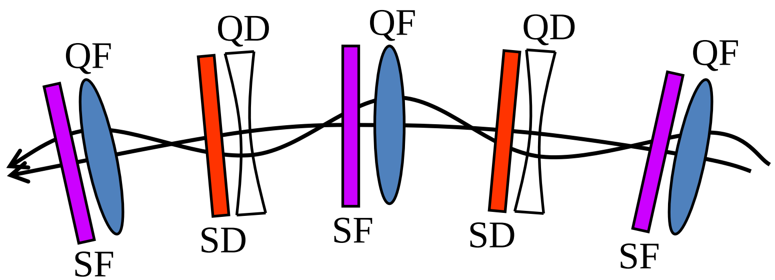
Earth Tides dominate orbit stability during Physics





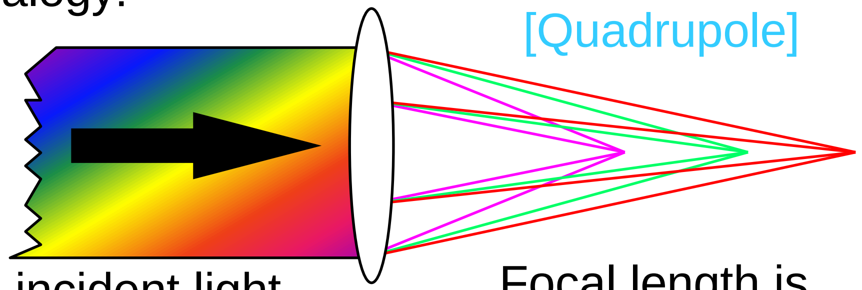
~ one week

- It can also measure Machine parameters?
  - Machine Tune



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

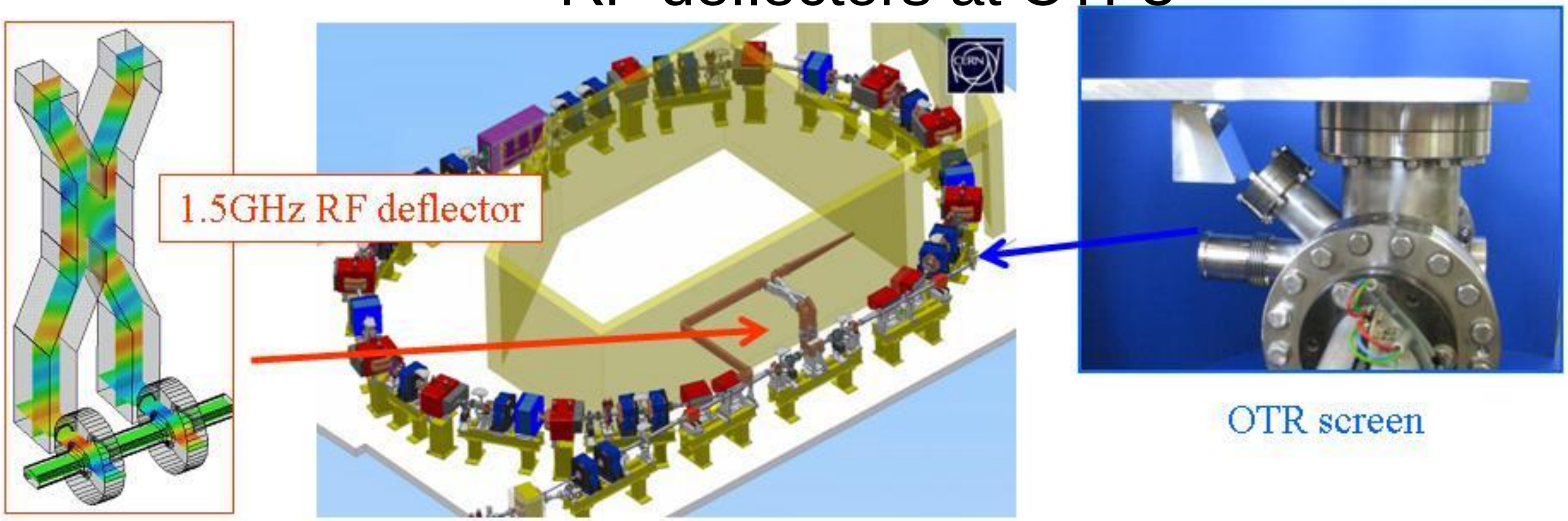
  - Machine Chromaticity

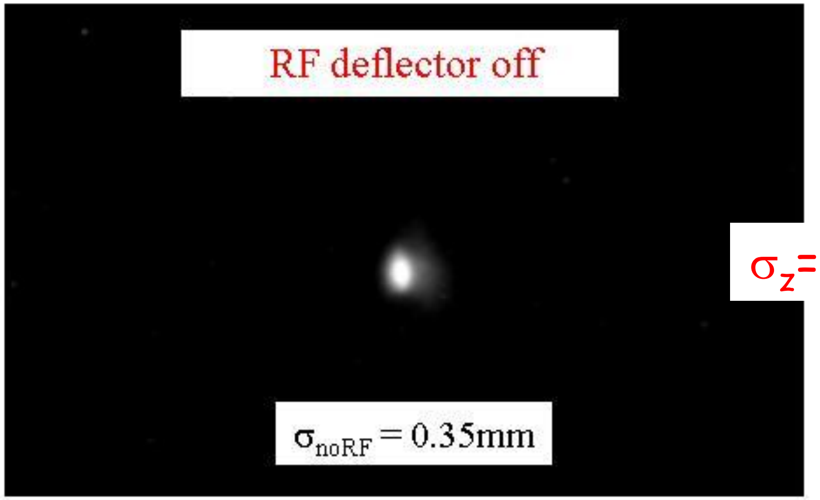


Spread in the Machine Tune due to Particle Energy Spread
Controlled by Sextupole magnets

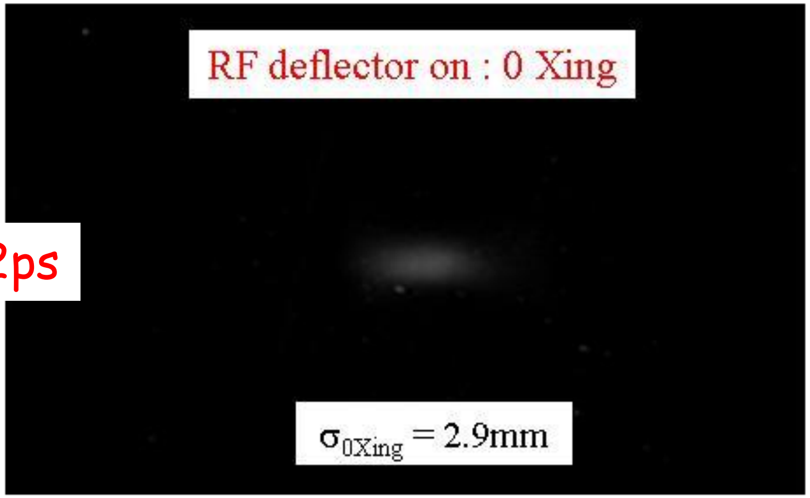
Longitudinal Beam Size Monitors

'RF deflectors at CTF3





σ_z=2ps

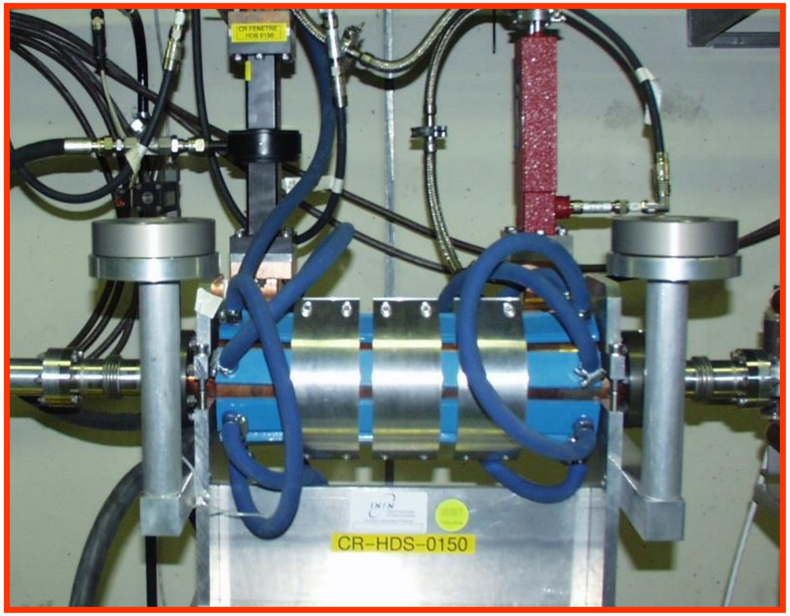


Longitudinal Beam Size Monitors

‘RF deflectors’

LOLA @ Flash

CLEAR@CERN



Beam Loss Monitors

- 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 or scintillation