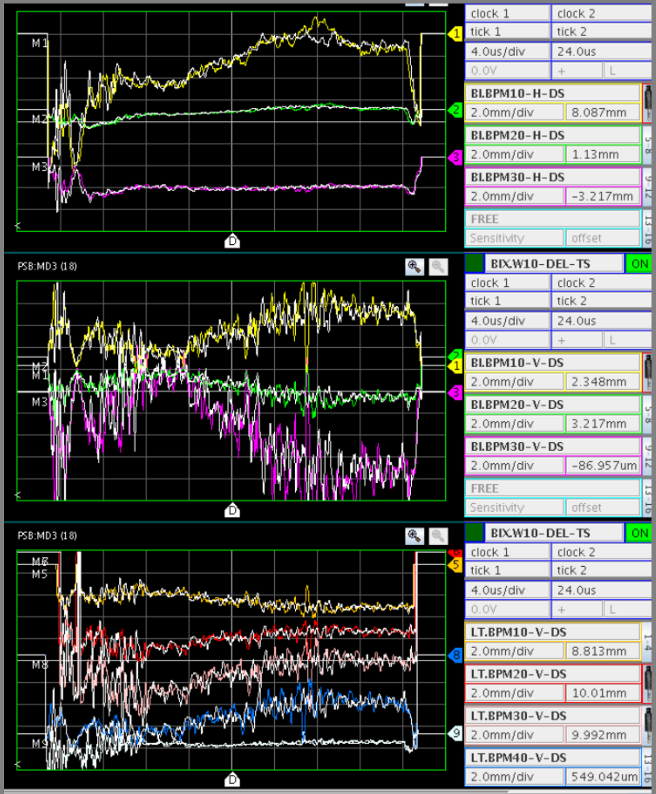
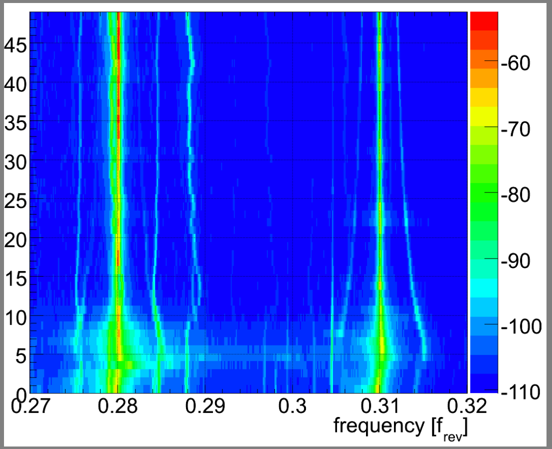




Beam Instrumentation

CAS@ESI Archamps October 2019

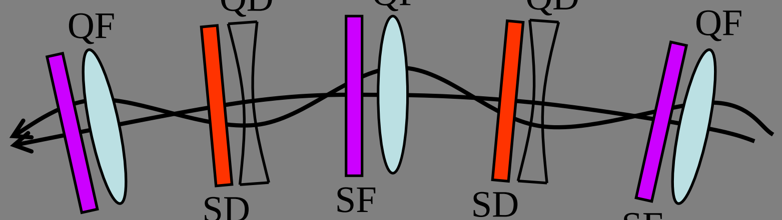
H.Schmickler, CERN

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
  - 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

More Measurements

- Machine Tune

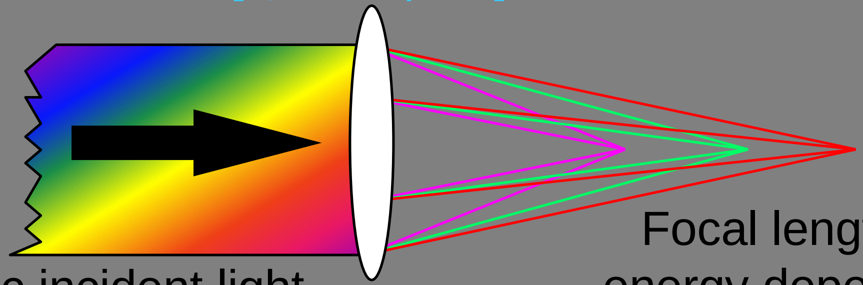


Characteristic Frequency of the Magnetic Lattice
Given by the strength of the Quadrupole magnets

- Machine Chromaticity

Optics Analogy:

Lens
[Quadrupole]



Achromatic incident light
[Spread in particle energy]

Focal length is energy dependent

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

Not further treated:

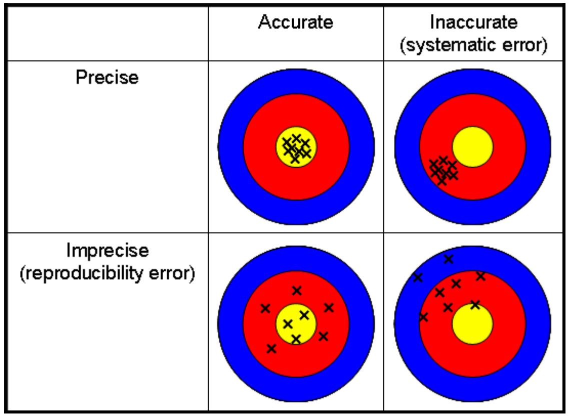
- Luminosity Measurements
  (dedicated arrangements close to the IP)
- Direct Emittance Measurements
  (simultaneous measurement of size and divergence)
- Particle identification, Time of flight…
  (relevant for secondary beam lines)
- Synchronization,
  beam arrival time monitors
  …this needs a full course on its own

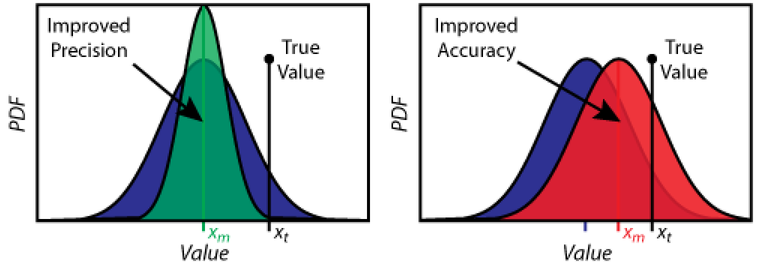
….in general…

- In every instrument we
  - intercept information of the particle beam
  - convert it to an electrical signal
  - digitize it and transmit it to the control room
  - display it, use it for the computation of corrections, use it in real-time feedback loops…
  - store it for further analysis
- What can we intercept?
  - the beam particles themselves (typical: beam screen, beam loss monitors…)
  - the electromagnetic field of the beam (most instruments, important: beam position monitors)
  - light emitted by the beam
  (typical: transverse and longitudinal profiles)

Accuracy, Precision, Resolution

- Very often confused in day-to-day language
- Accuracy:= also called trueness of measurement
- Precision:= how well can I reproduce my measurements
- Resolution:= smallest possible difference in successive measurements





Ex: BPM: Mechanical and electrical offsets, gain factors influence the accuracy, various noise sources or timing jitter influence the precision, ADC resolution can limit the resolution.

The Typical Instruments

- Beam Intensity
  - beam current transformers
- Beam Position
  - electrostatic or electromagnetic pick-ups and related electronics
- Beam Profile
  - secondary emission grids and screens
  - wire scanners
  - synchrotron light monitors
  - ionization and luminescence monitors
  - femtosecond diagnostics for ultra short bunches
- Beam Loss
  - ionization chambers or pin diodes
- Machine Tune and Chromaticity (derived quantities)

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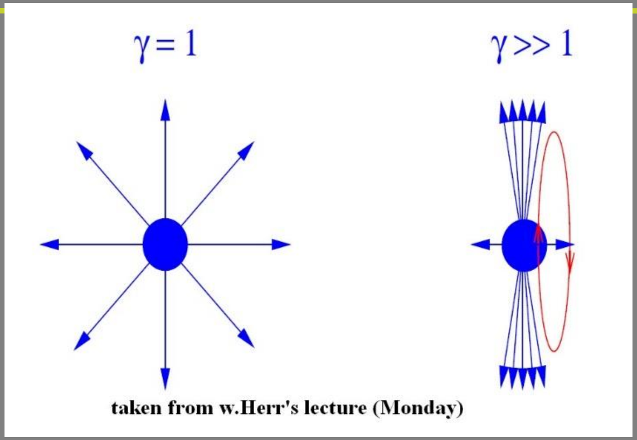
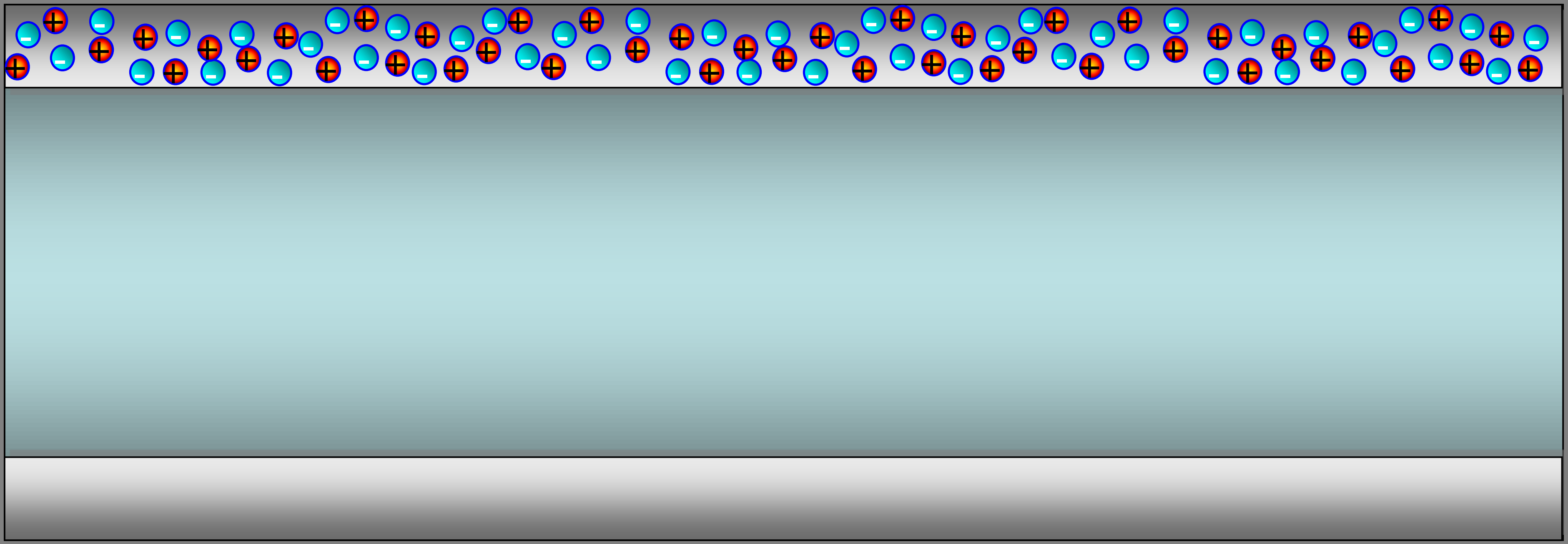
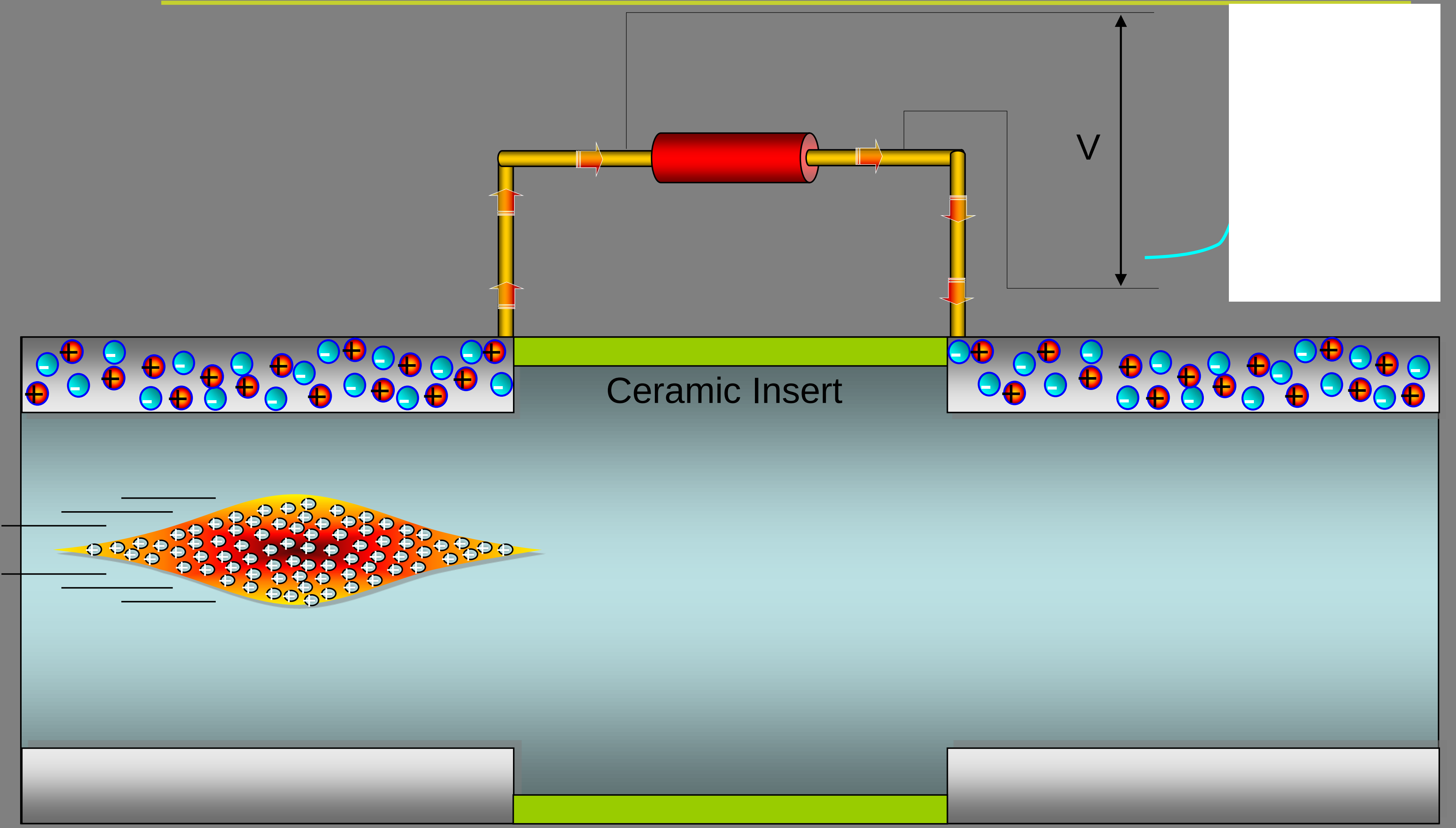
Beam Image (wall) current– The Principle

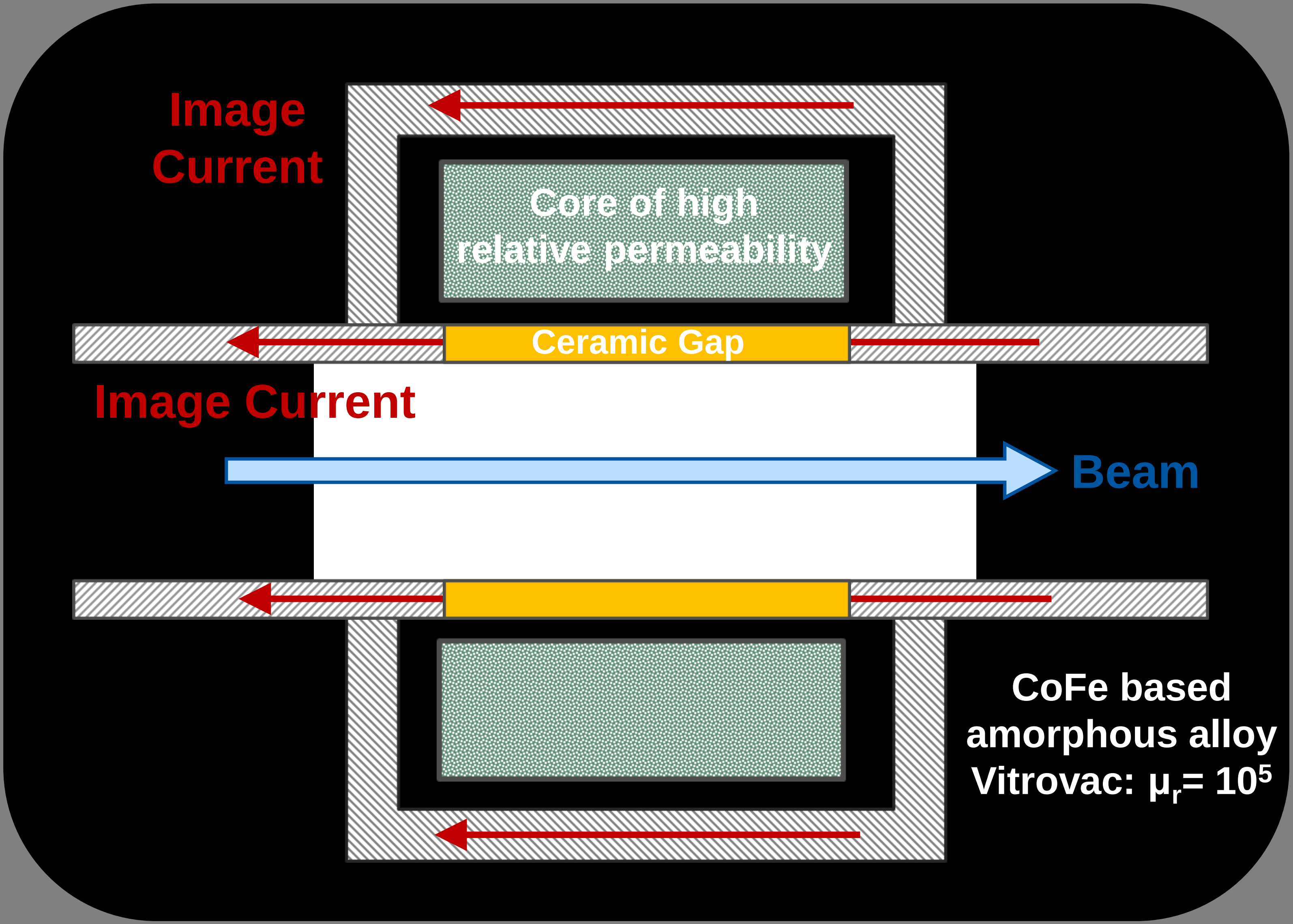




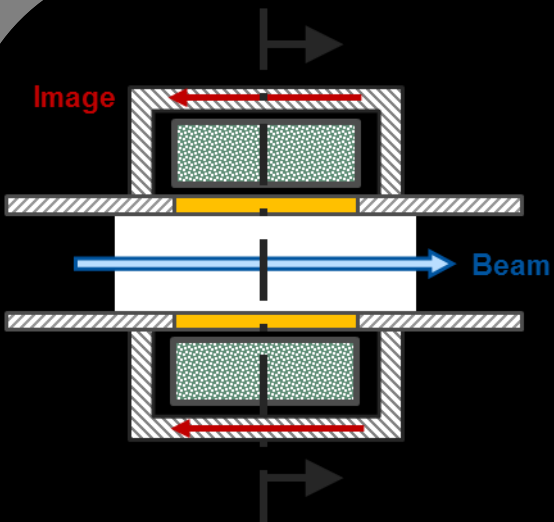
Wall Current Monitor – The Principle

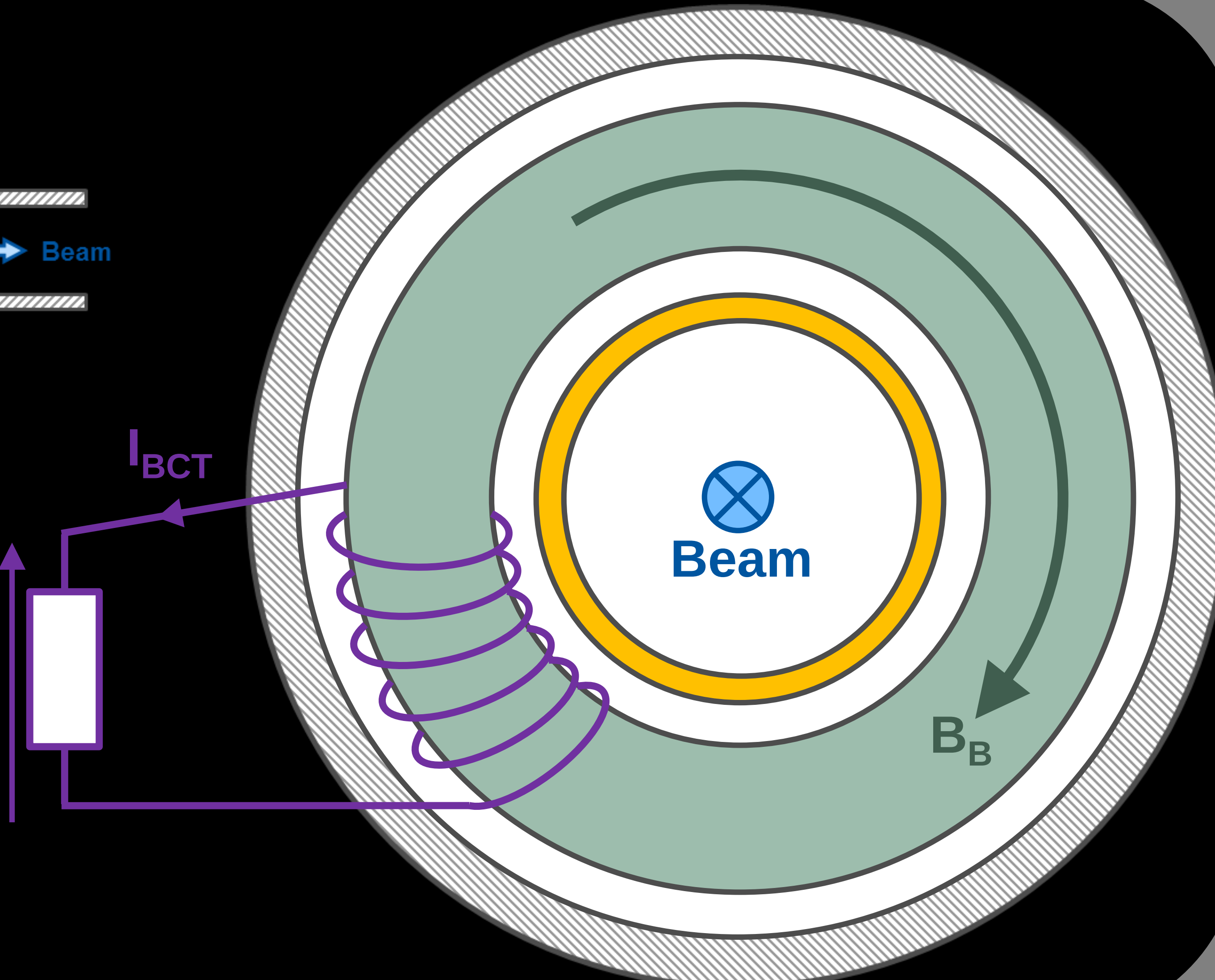


AC (Fast) Current Transformers

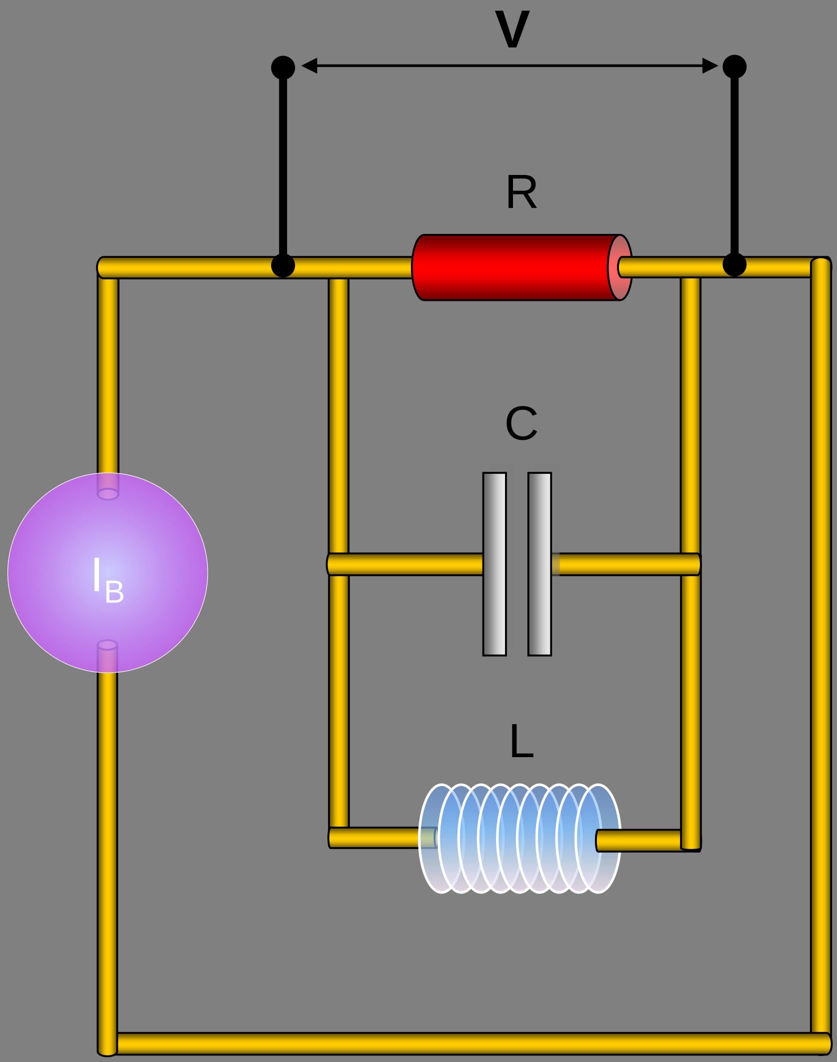


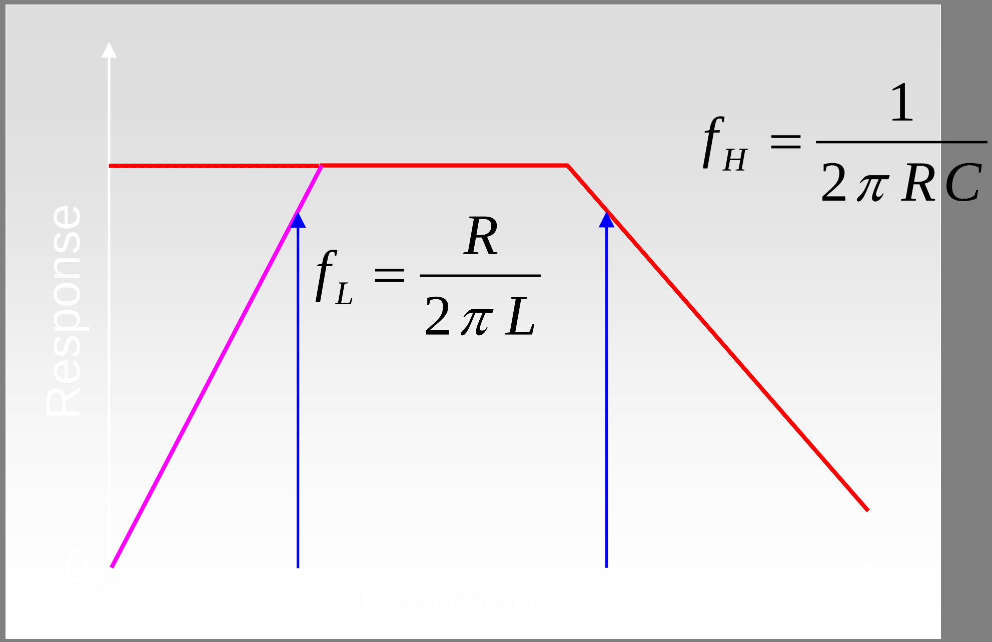
AC (Fast) Current Transformers

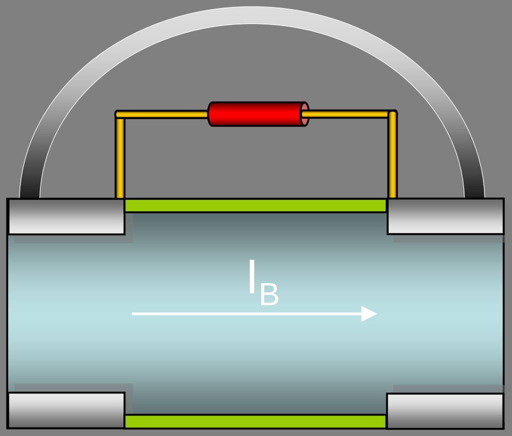




Wall Current Monitor – Beam Response

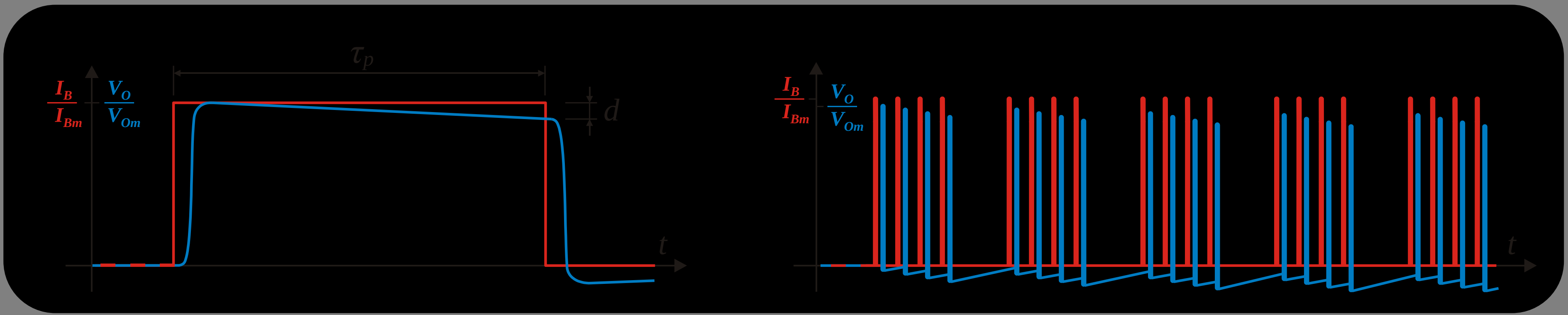


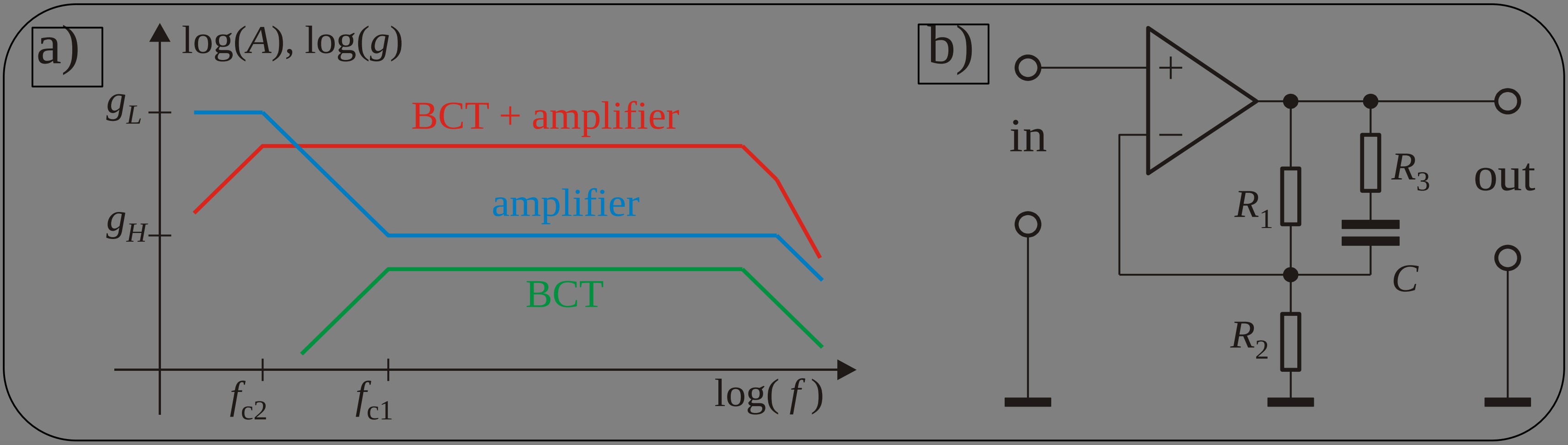




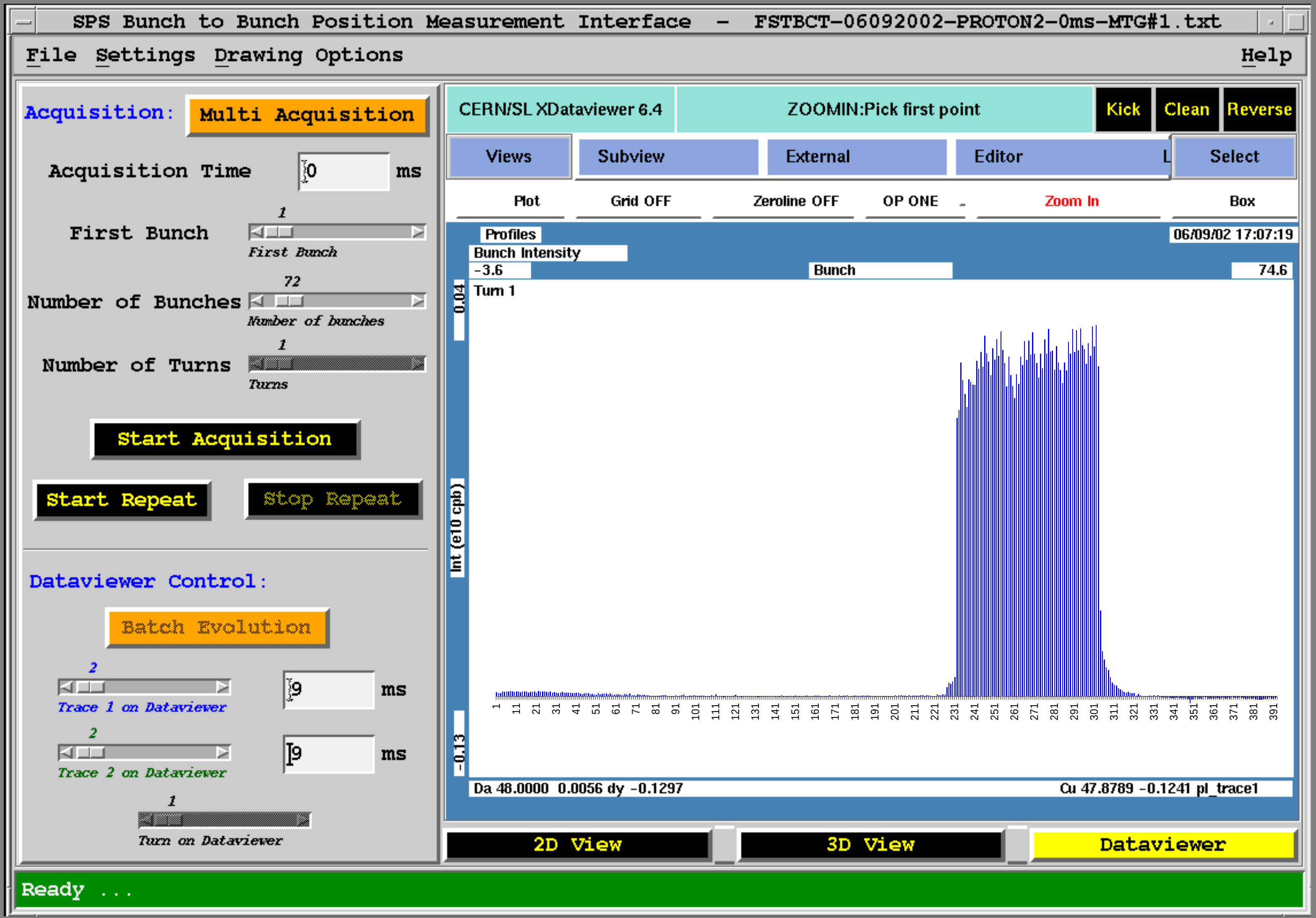
AC (Fast) Transformer Response

- 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)





What one can do with such a System

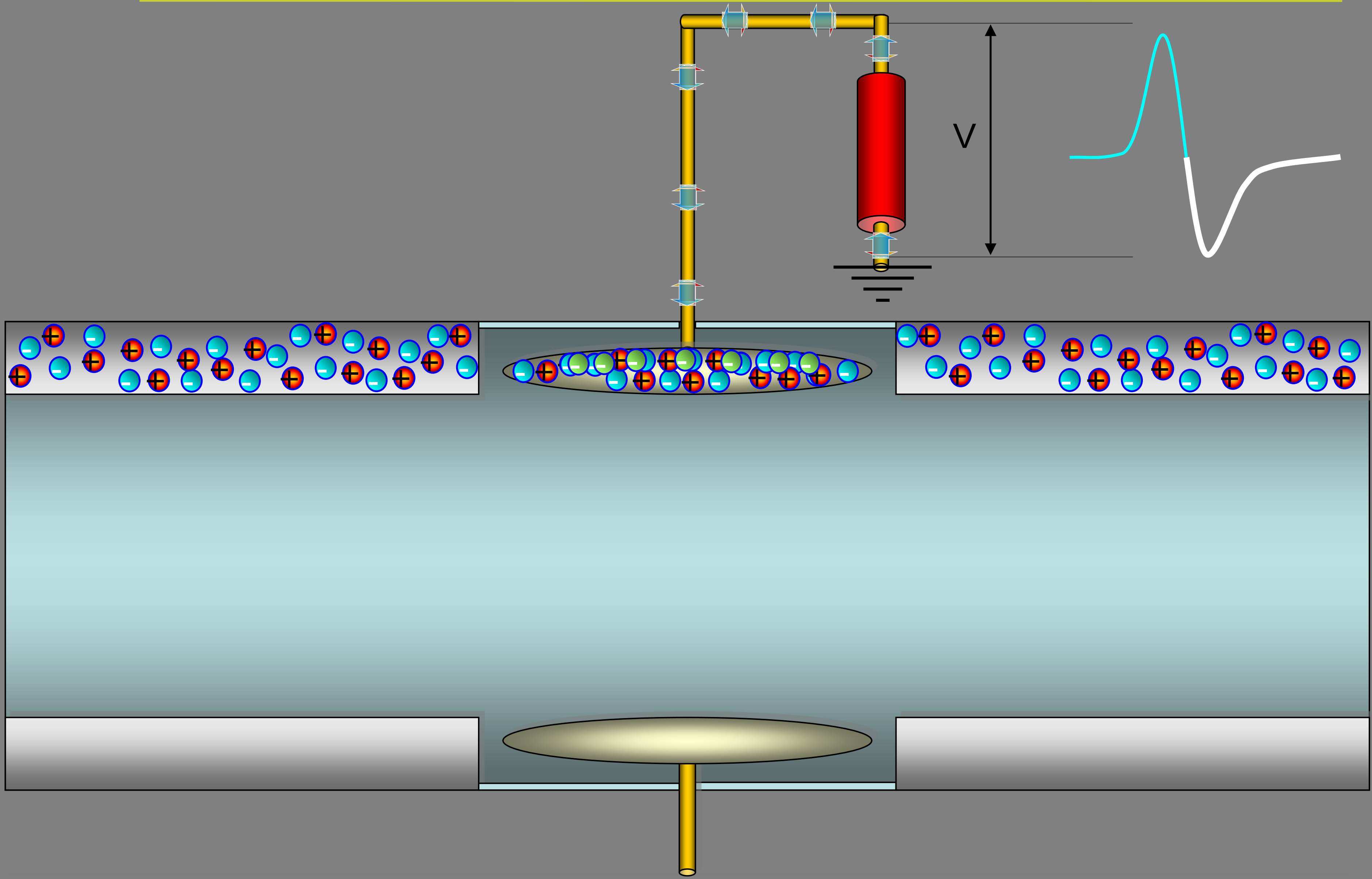


Bad RF Capture of a single LHC Batch in the SPS (72 bunches)

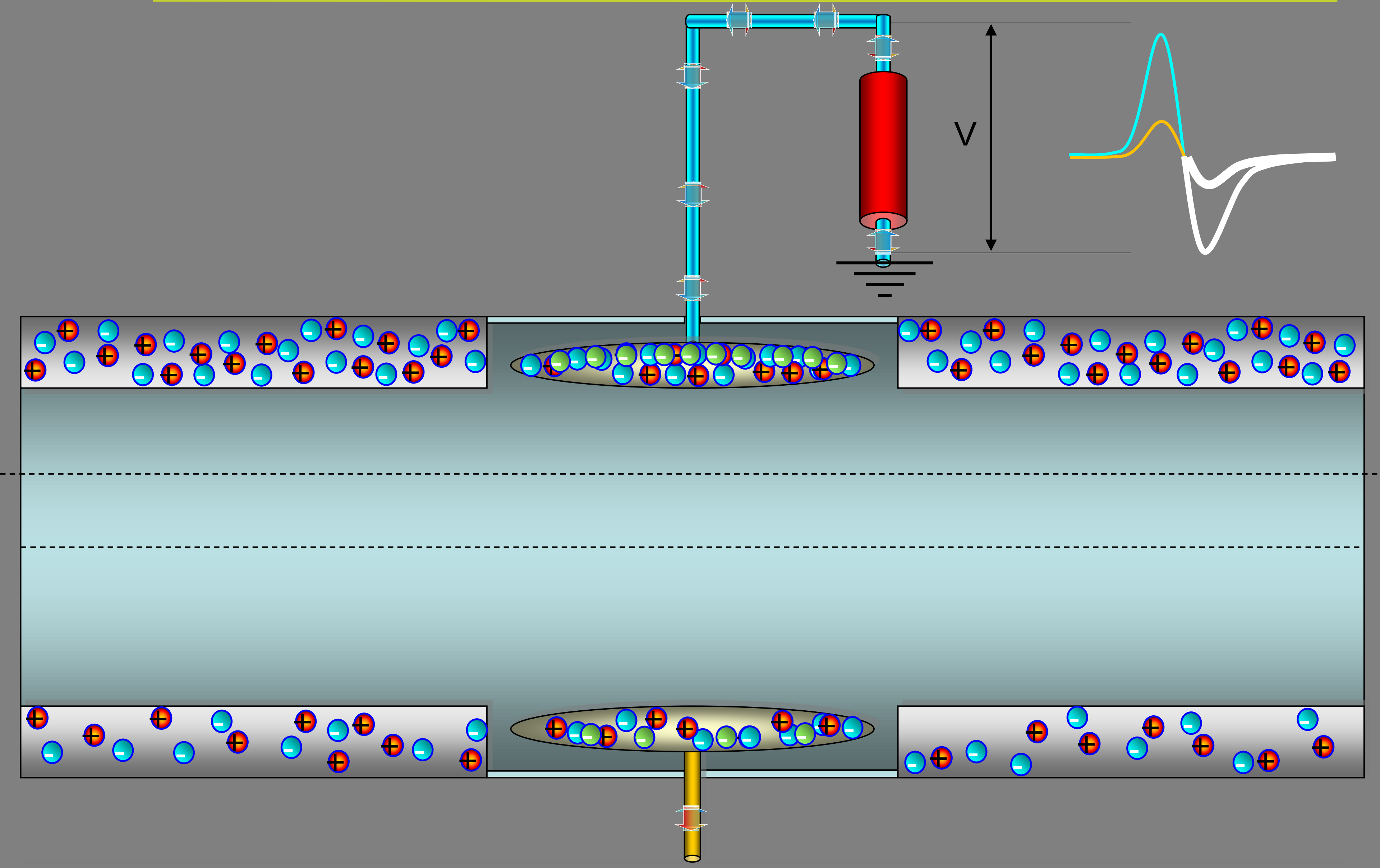
The Typical Instruments

- Beam Intensity
  - beam current transformers
- Beam Position
  - electrostatic or electromagnetic pick-ups and related electronics
- Beam Profile
  - secondary emission grids and screens
  - wire scanners
  - synchrotron light monitors
  - ionization and luminescence monitors
  - femtosecond diagnostics for ultra short bunches
- Beam Loss
  - ionization chambers or pin diodes
- Machine Tune and Chromaticity (derived quantities)

Electrostatic Monitor – The Principle



Electrostatic Beam Position Monitor

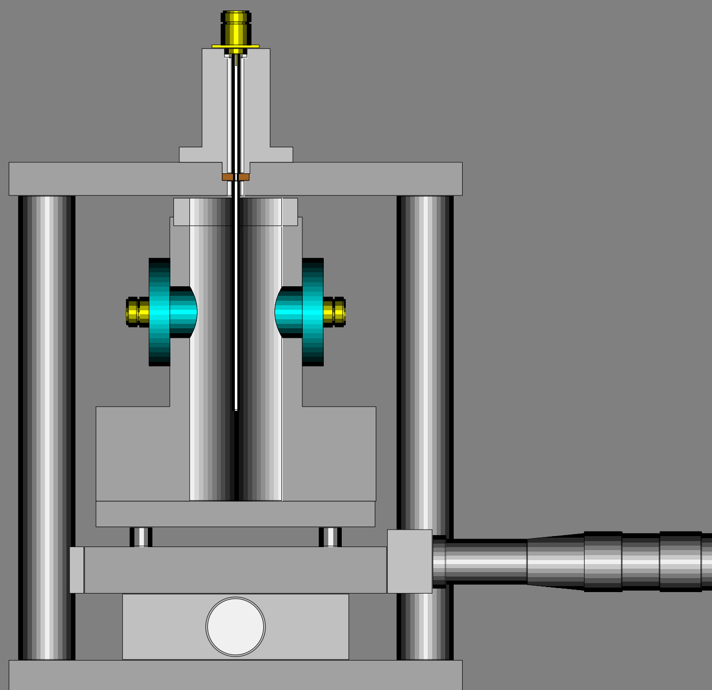


Principle of Beam Position Monitors

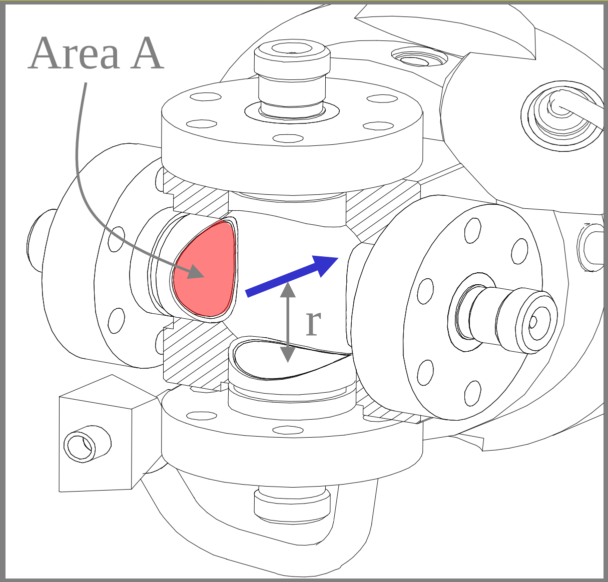
- Intercept “beam image current” in the vacuum chamber on two isolated (capacitive) pickups.
- Other pickups (more involved): shoebox (linear) pickups, stripline directional couplers….
- Use high precision Rf electronics to shape the signals (short bunches deliver signals with high frequency content)
  - amplifiers
  - filters
  - down converters
- Digitize the individual pickup signals
- Eliminate the intensity information from the pickup signals (= “normalization”)
- Compute the position from the pickup-signal difference
- Linearize the pickup response
- Calibrate the system in metric units

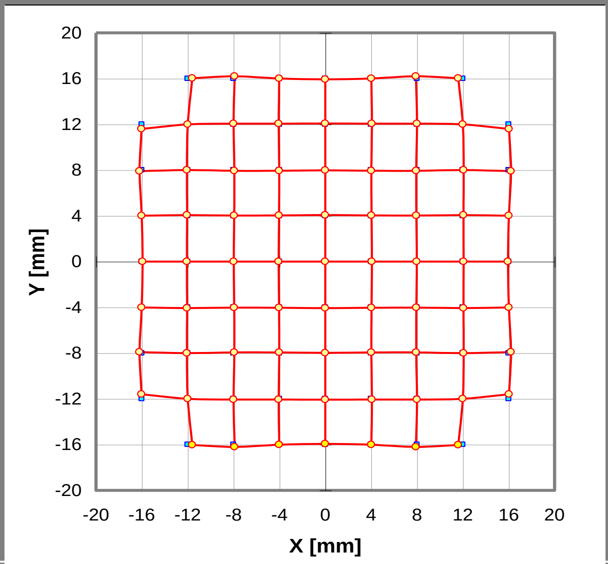
Electrostatic Pick-up – Button

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



Position mapping with movable antenna



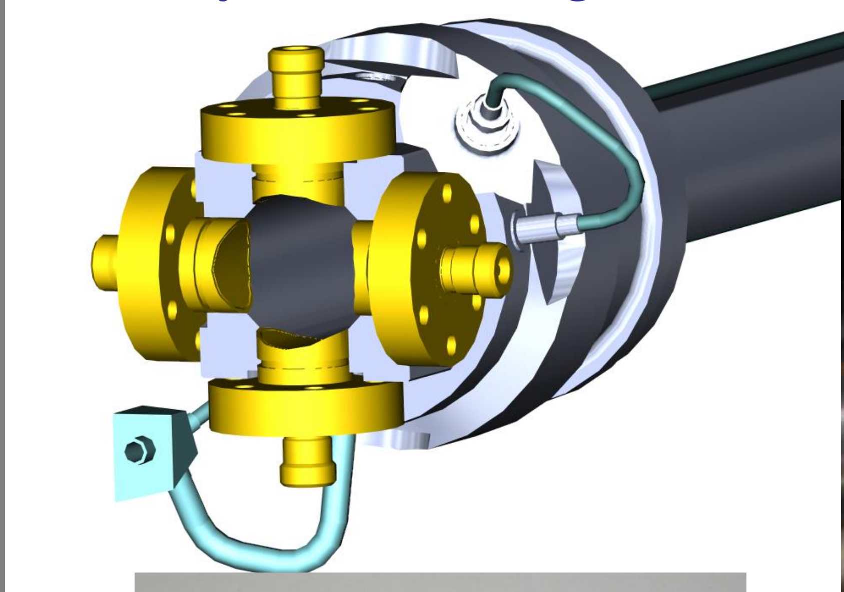


$$X = 2.30\cdot10^{-5}X_1^{5} + 3.70\cdot10^{-5}X_1^{3} + 1.035\,X_1 + 7.53\cdot10^{-6}X_1^{3}Y_1^{2} + 1.53\cdot10^{-5}X_1Y_1^{4}$$

Realization of Button BPM at LHC

Example LHC: ∅ 24 mm, half aperture a=25 mm, installed inside cryostat

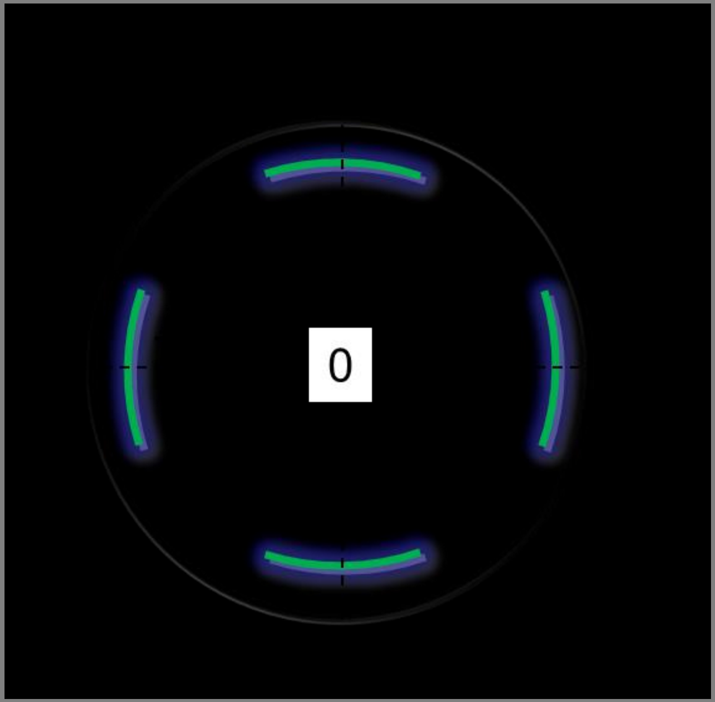
Critically: 50 Ω matching of button to standard feed-through.

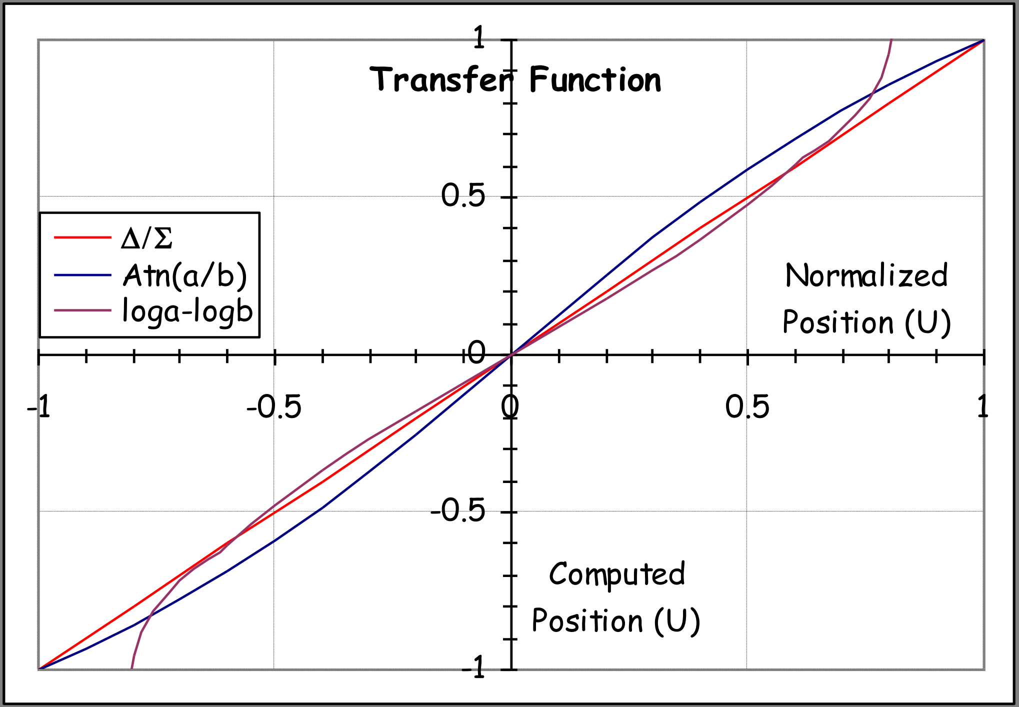


From C. Boccard, C. Palau-Montava et al.(CERN).

Normalising the Position Reading

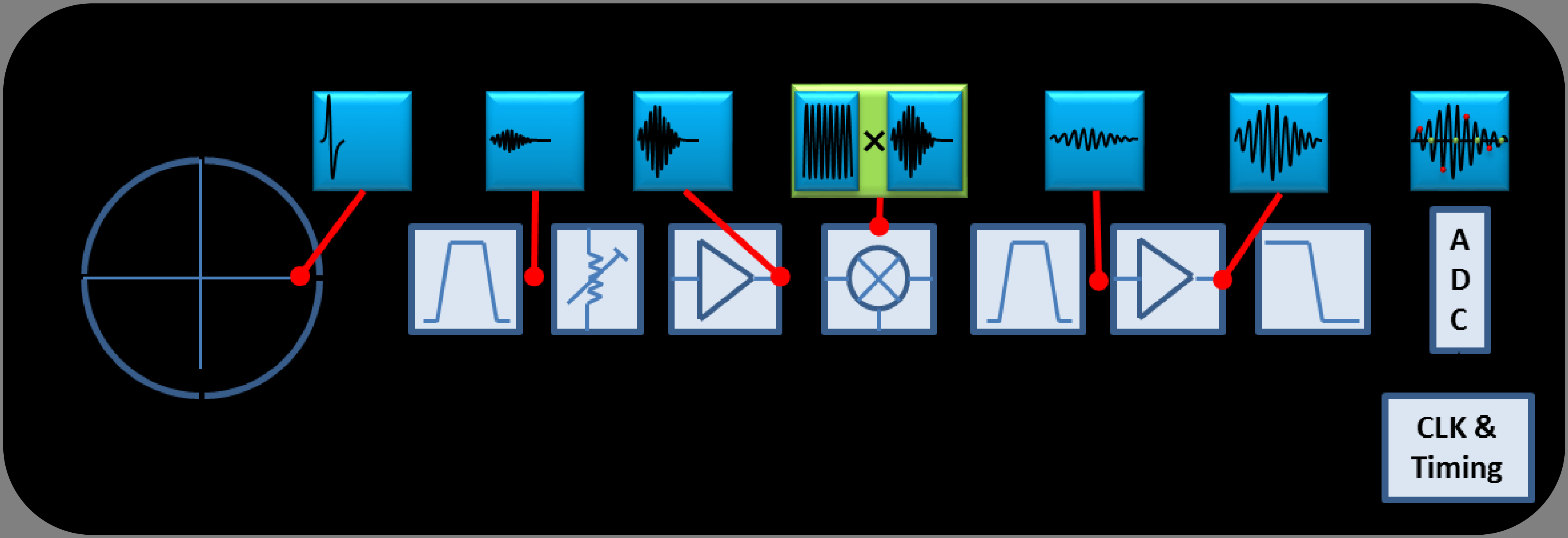
- To make it independent of intensity
- 3 main methods:
  - Difference/Sum : $(V_A - V_B) / (V_A + V_B) = \Delta / \Sigma$
  - Phase : $\mathrm{Arctan}(V_A / V_B)$
  - Logarithm : $\mathrm{Log}(V_A) - \mathrm{Log}(V_B)$



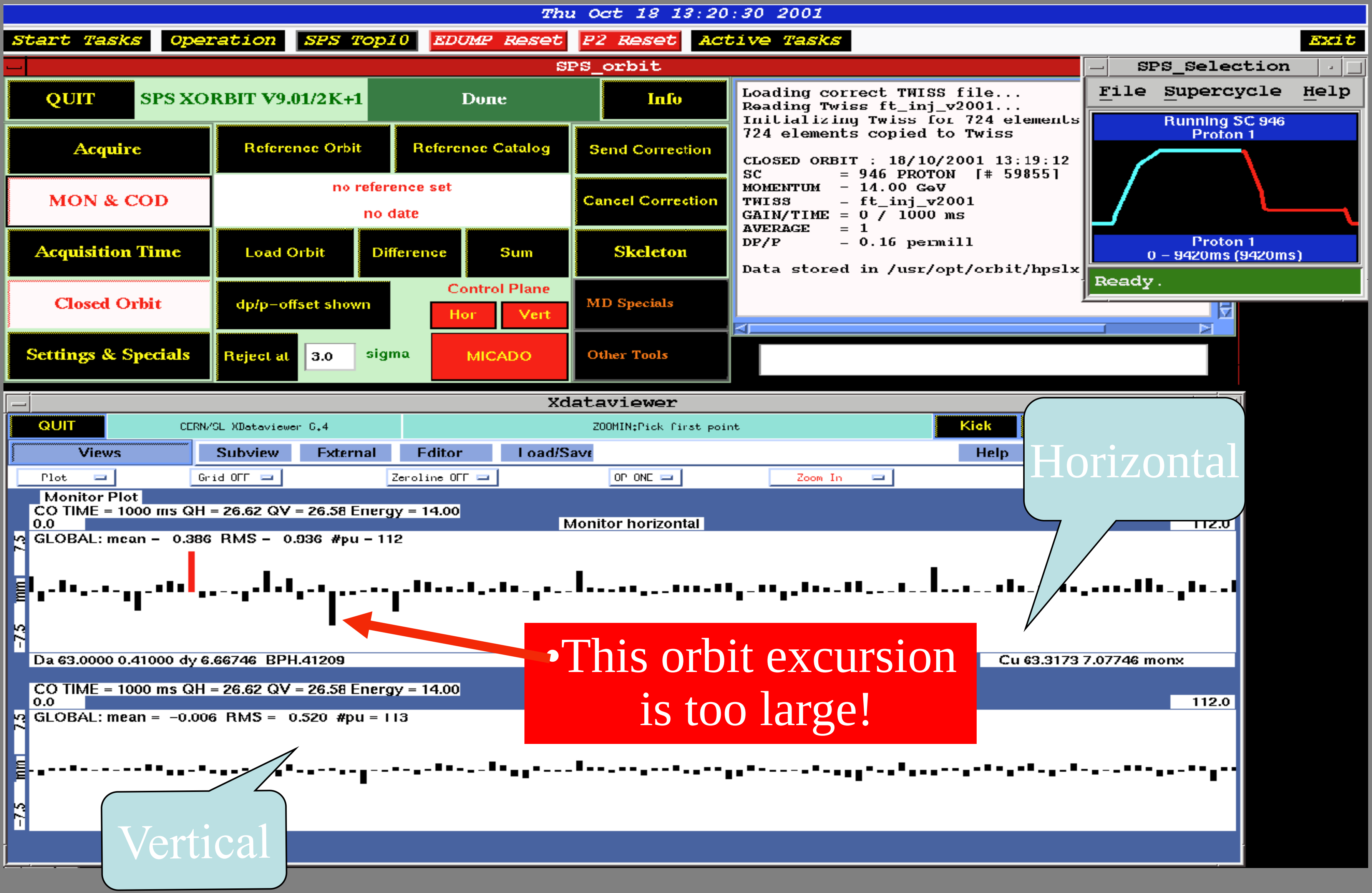


Modern BPM Read-out Electronics

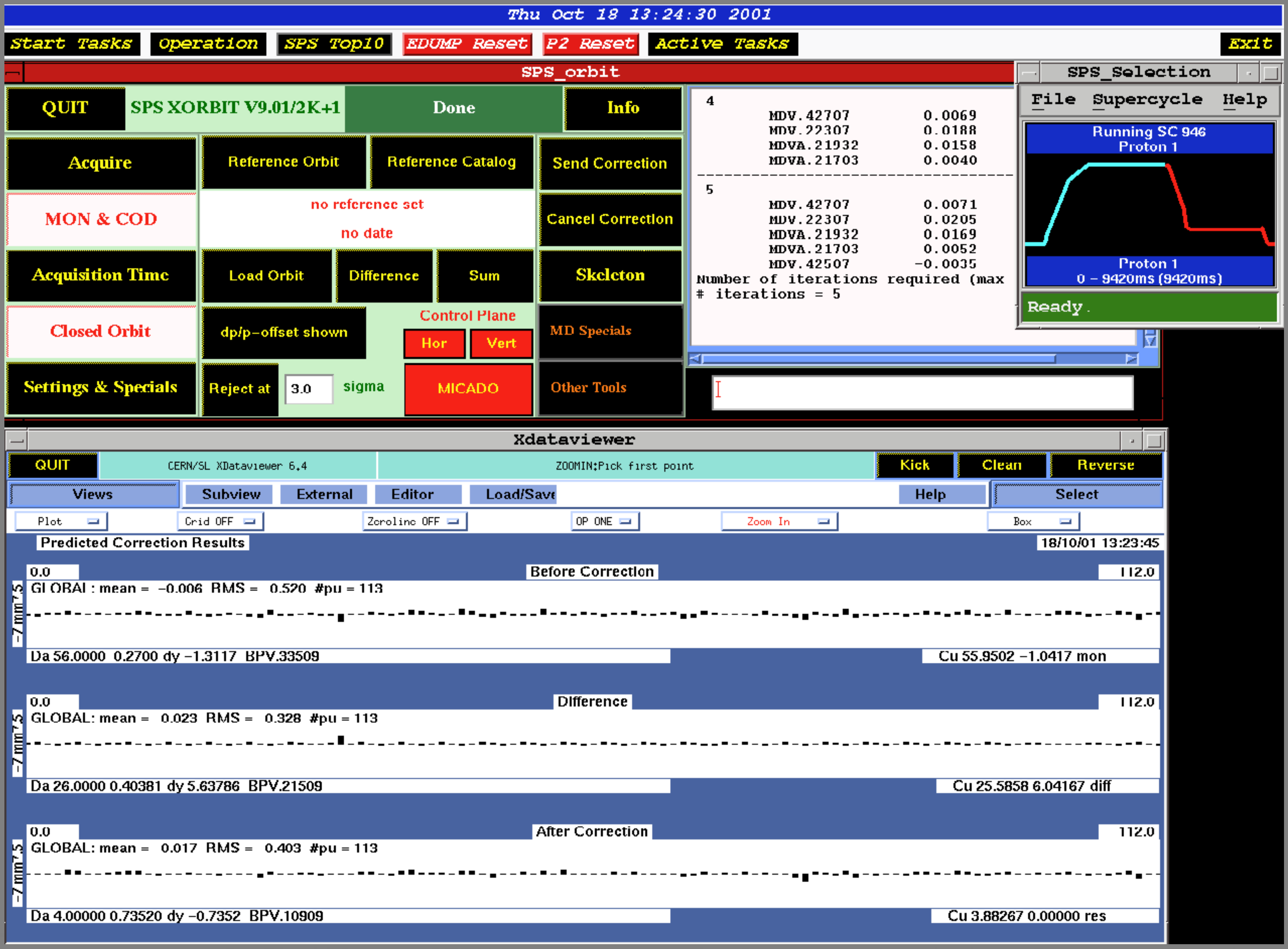
- Based on the individual treatment of the electrode signals
  - Use of frequency domain signal processing techniques
    - Developed for telecommunications market
  - Rely on high frequency & high resolution analogue to digital converters
    - Minimising analogue circuitry
    - Frequency down-conversion used if necessary to adapt to ADC sampling rate
    - All further processing carried out in the subsequent digital electronics



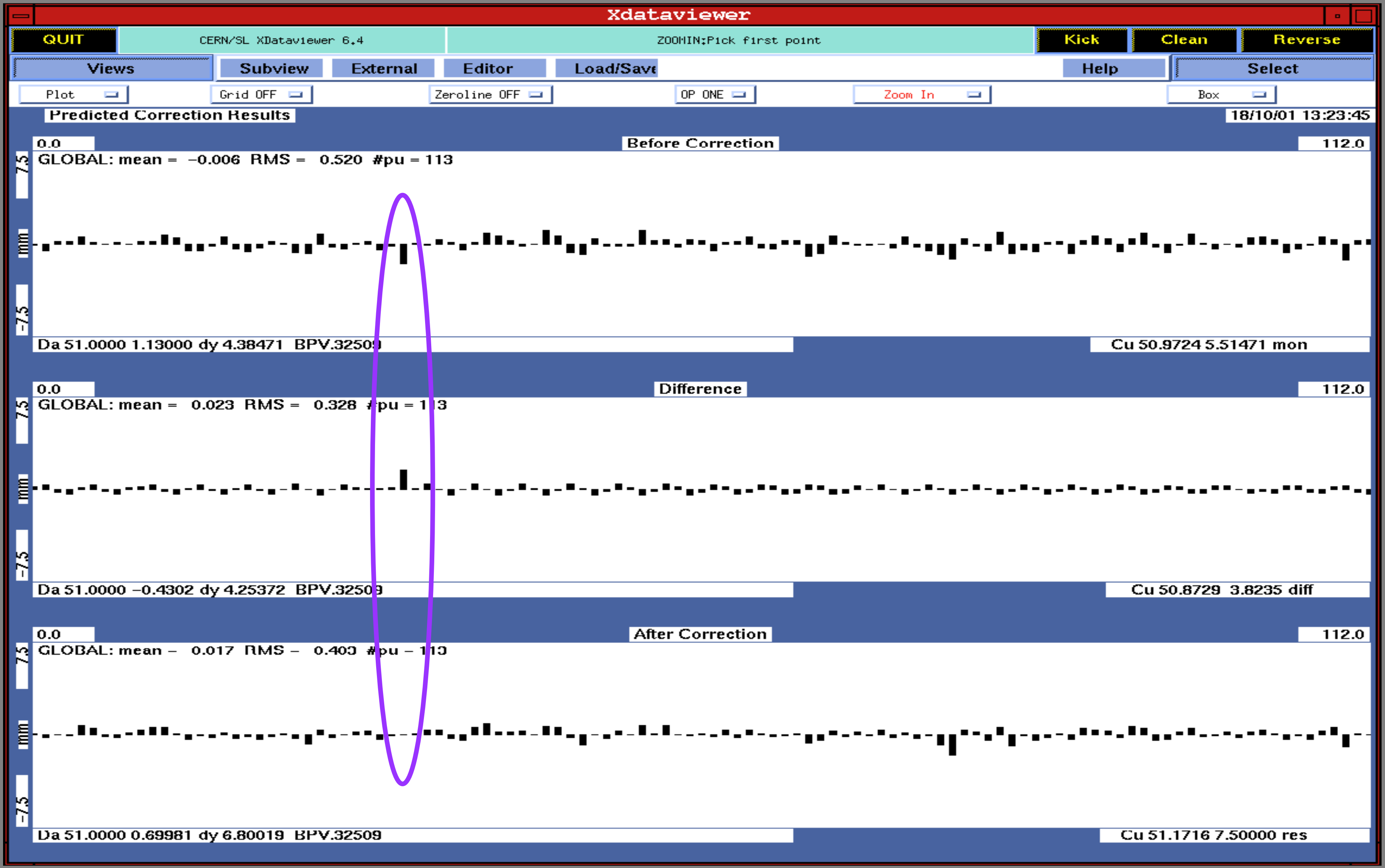
Orbit Acquisition



Orbit Correction (Operator Panel)



Orbit Correction (Detail)

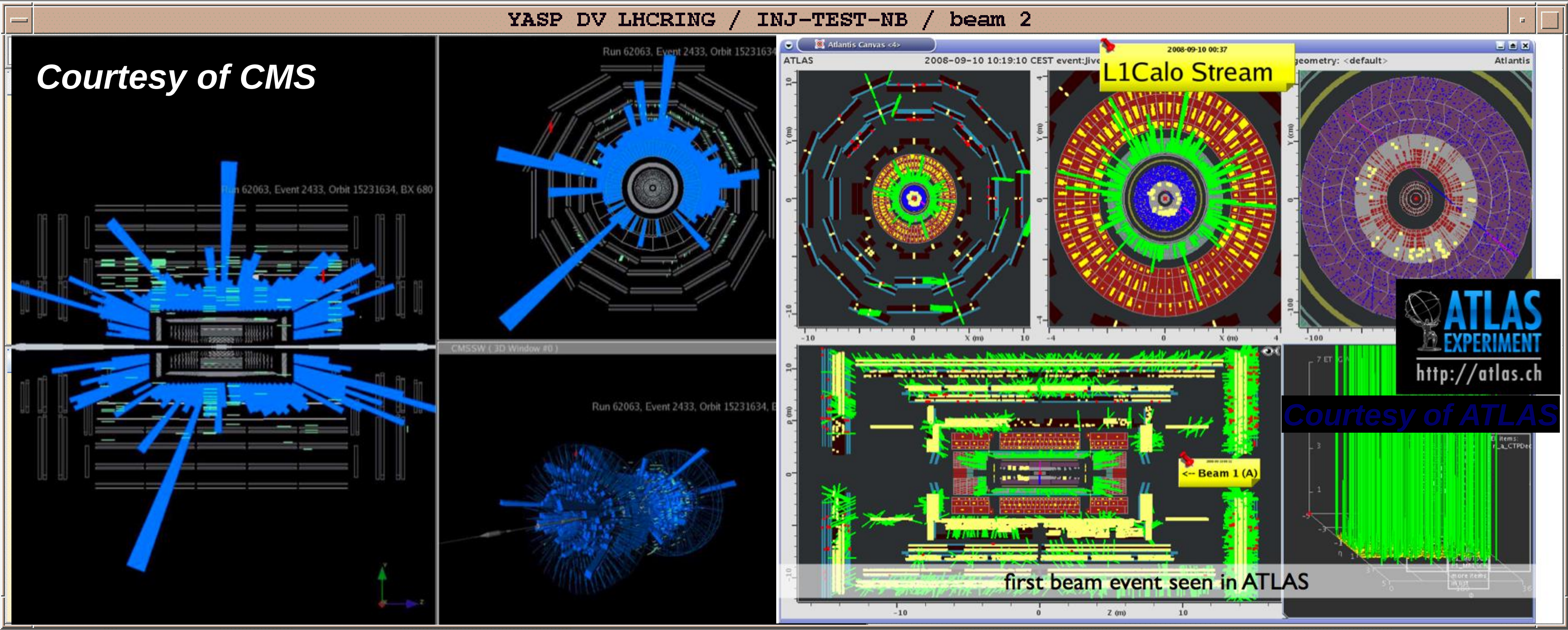


Beam Threading

- Threading the beam round the LHC ring (very first commissioning)
  - One beam at a time, one hour per beam.
  - Collimators were used to intercept the beam (1 bunch, 2×10^9 protons)
  - Beam through 1 sector (1/8 ring)
    - correct trajectory, open collimator and move on.

BPM availability ~ 99%

Beam 2 threading



Kind of boring: orbit corrections….but:

Beam physics data derived from BPM rawdata:

Examples:

orbit difference for different beam momenta→ dispersion

Orbit difference for different beam intensities → Transverse impedance of vacuum chamber

Turn by turn trajectory on each BPM; beam forced on constant oscillation → Beta function and phase advances

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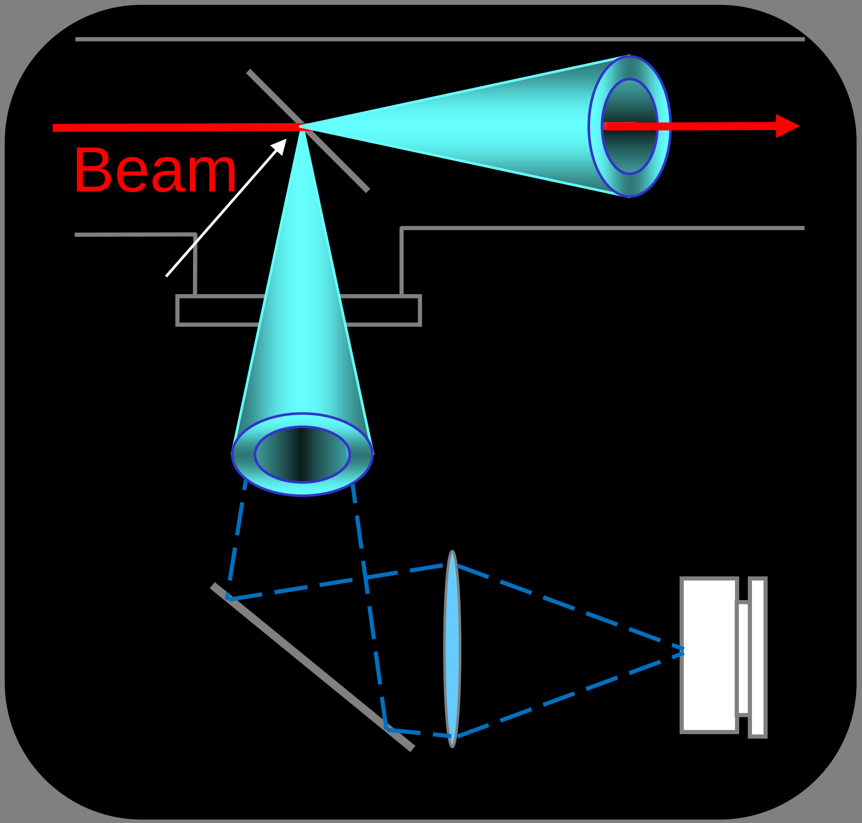
- Beam Loss
  - ionization chambers or pin diodes
- Machine Tune and Chromaticity (derived quantities)

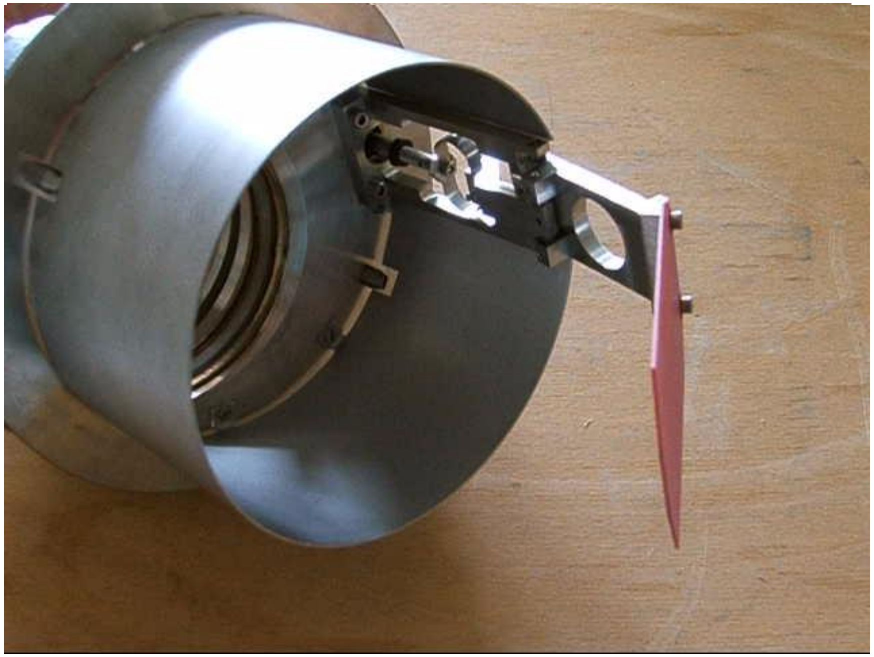
Beam Profile Monitoring using Screens

- Screen Types
  - Luminescence / Scintillating Screens
    - Destructive (thick) but work with low intensities
  - Optical Transition Radiation (OTR) screens
    - Much less destructive (thin) but require higher energy / intensity beam
- OTR
  - 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

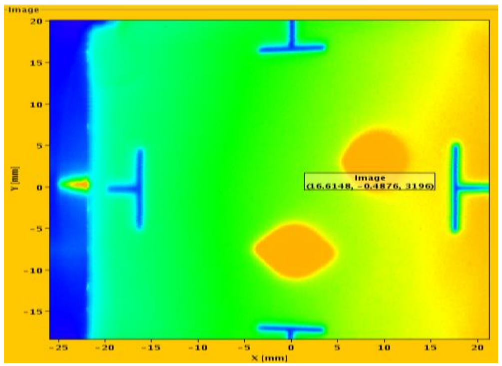


Screen mechanism

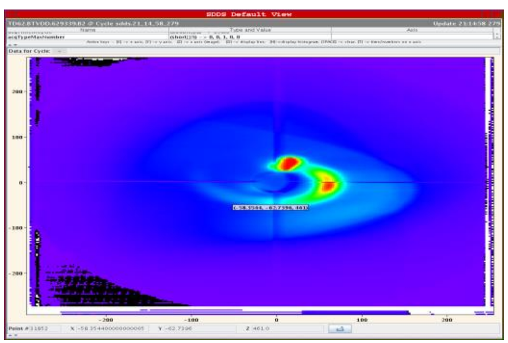
- Screen with graticule



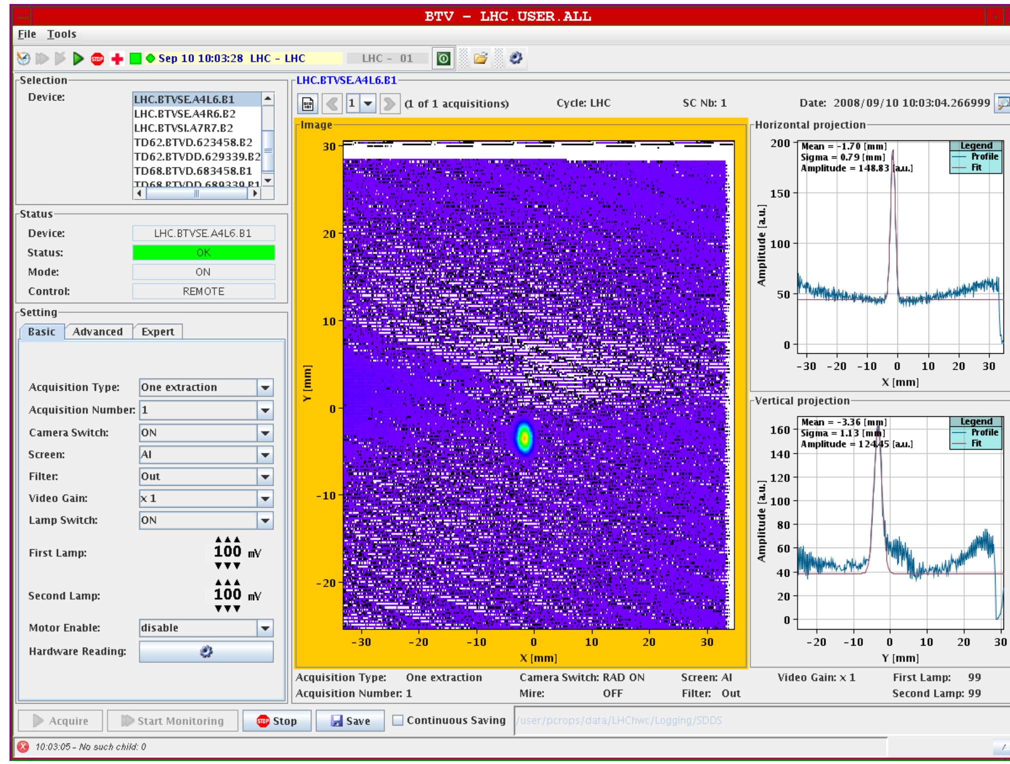
Results from TV Frame grabber



First full turn as seen by the BTV 10/9/2008



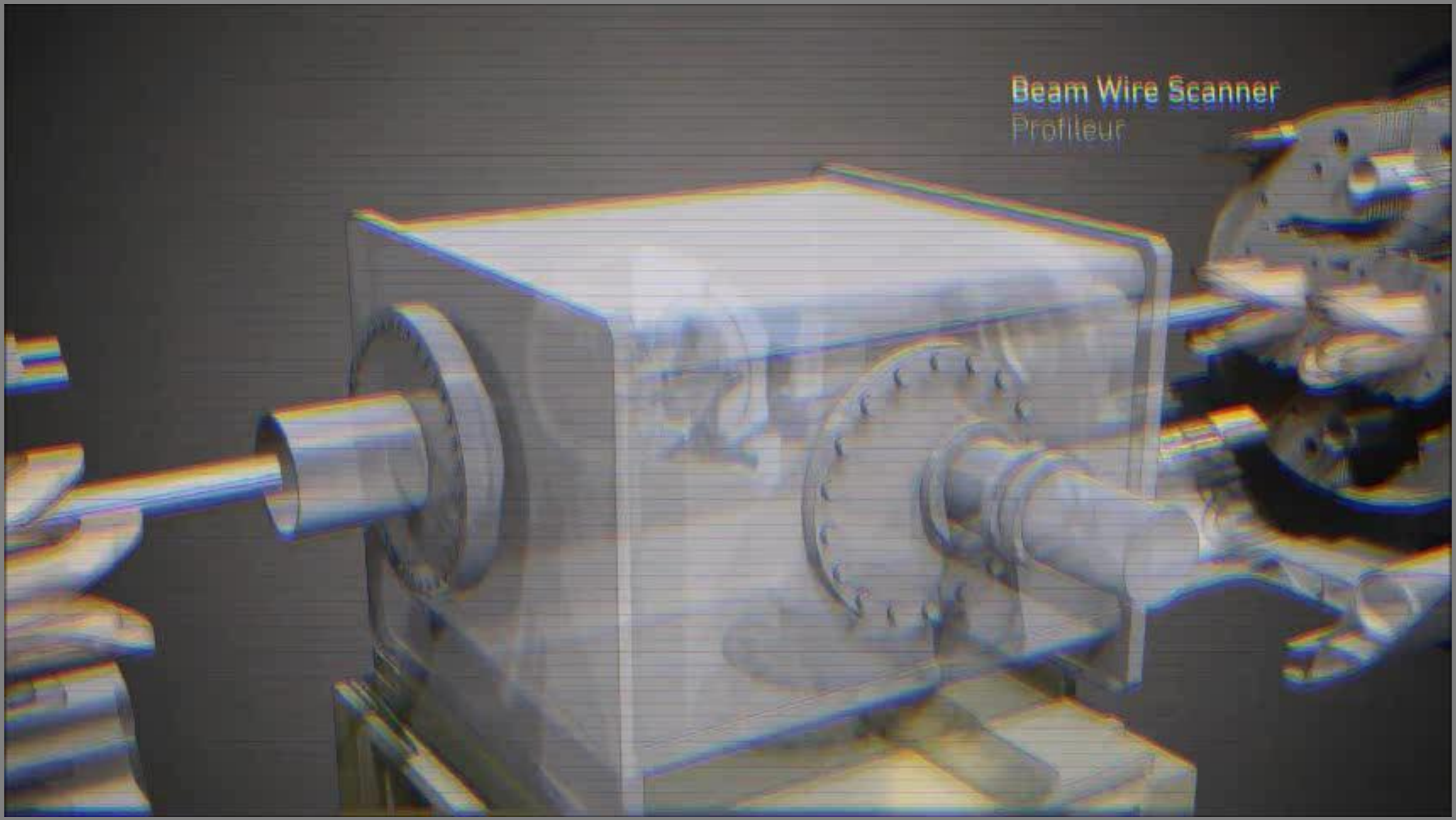
Un-captured beam sweeps through he dump line



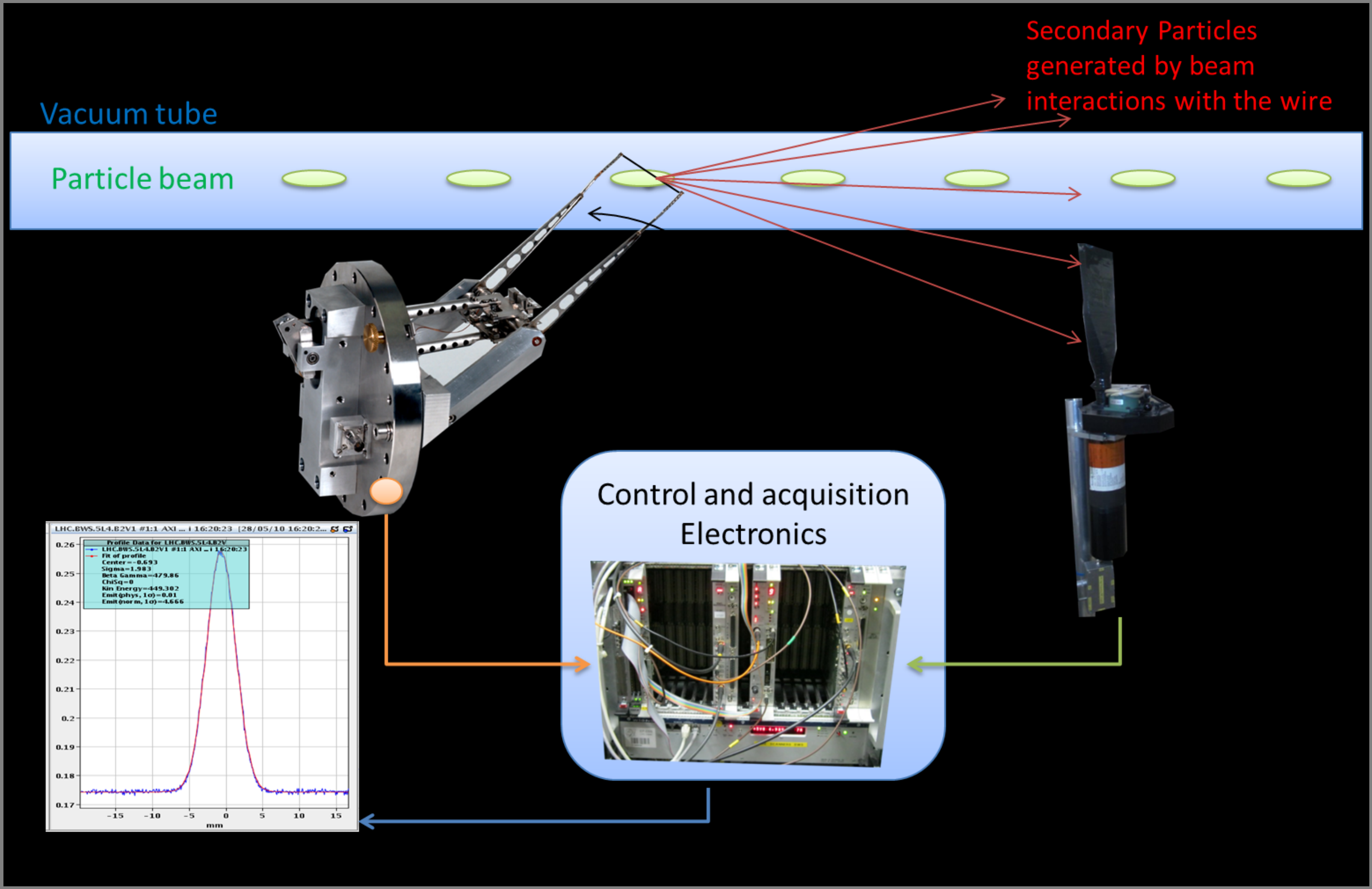
- For further evaluation the video signal is digitized, read-out and treated by program

Beam Profile Monitoring using Wire-Scanners

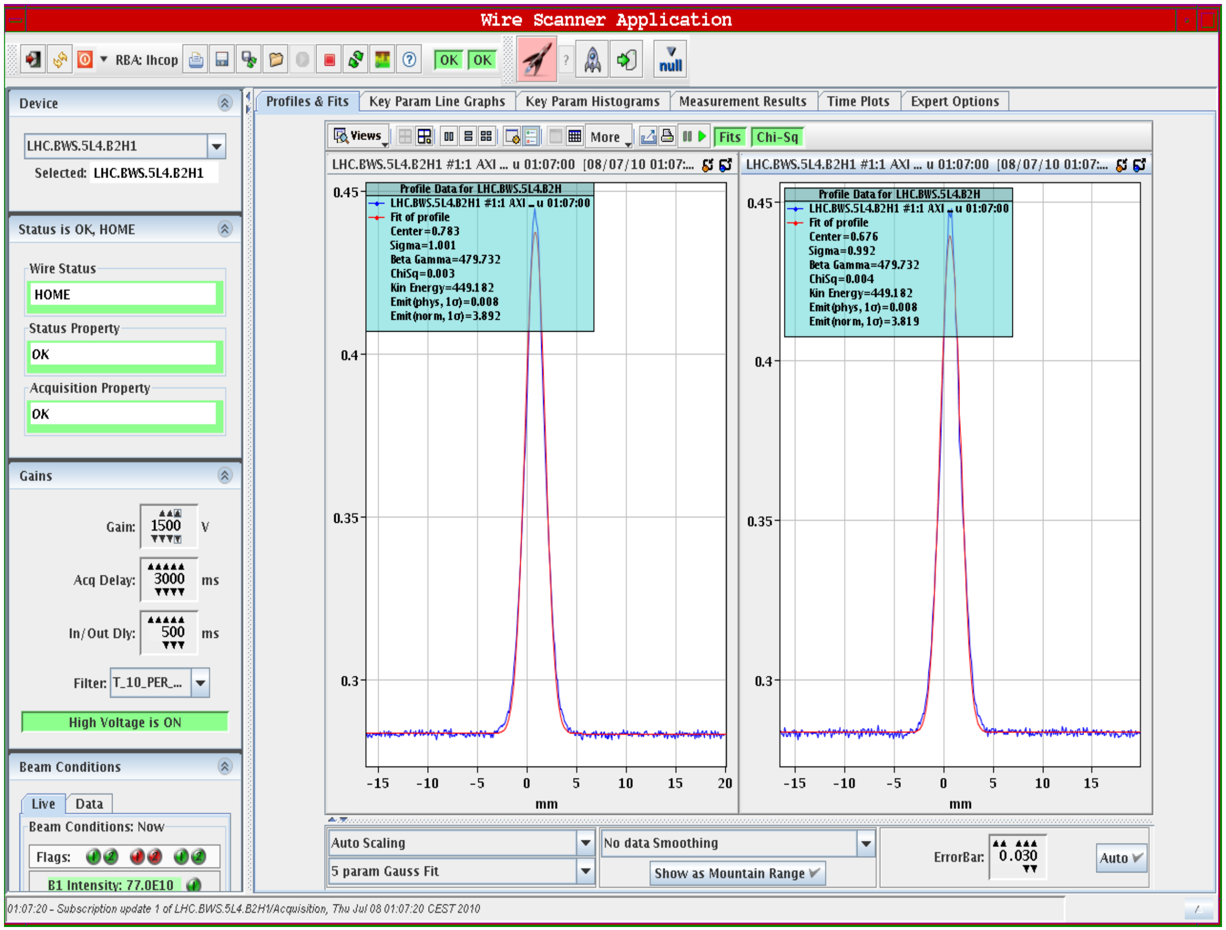
- A thin wire is moved across the beam
  - Has to move fast to avoid excessive heating of the wire
- Detection
  - Secondary particle shower detected outside vacuum chamber using scintillator/photo-multiplier
- Correlating wire position with detected signal gives the beam profile



Beam Profile Monitoring using Wire-Scanners



Wire scanner profile



High speed needed because of heating.

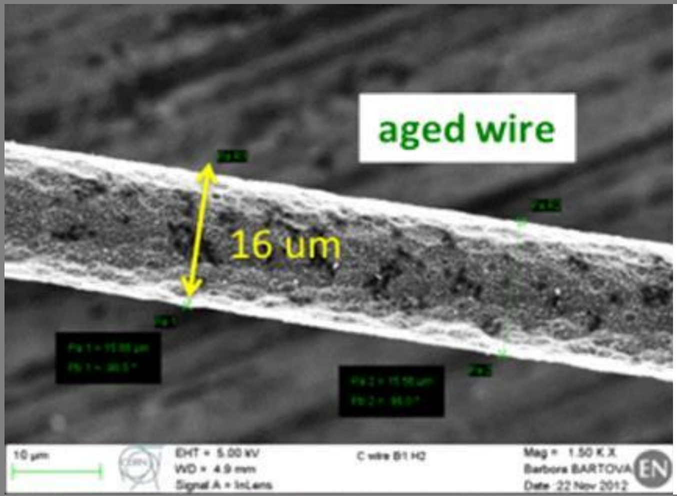
Adiabatic damping

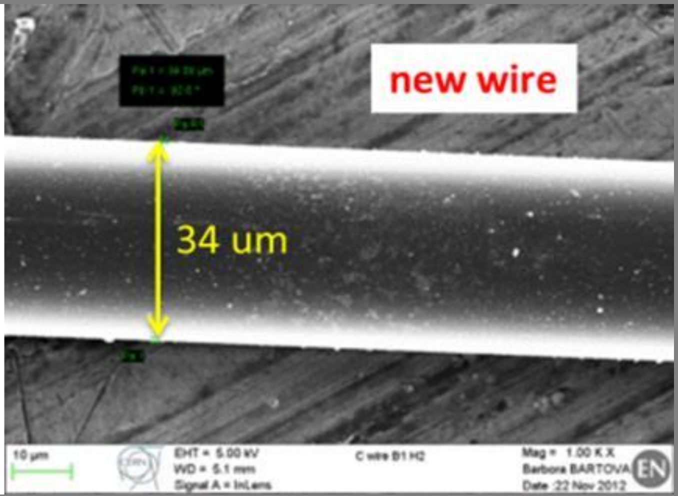
Current increase due to speed increase

Speeds of up to 20m/s => 200g acceleration

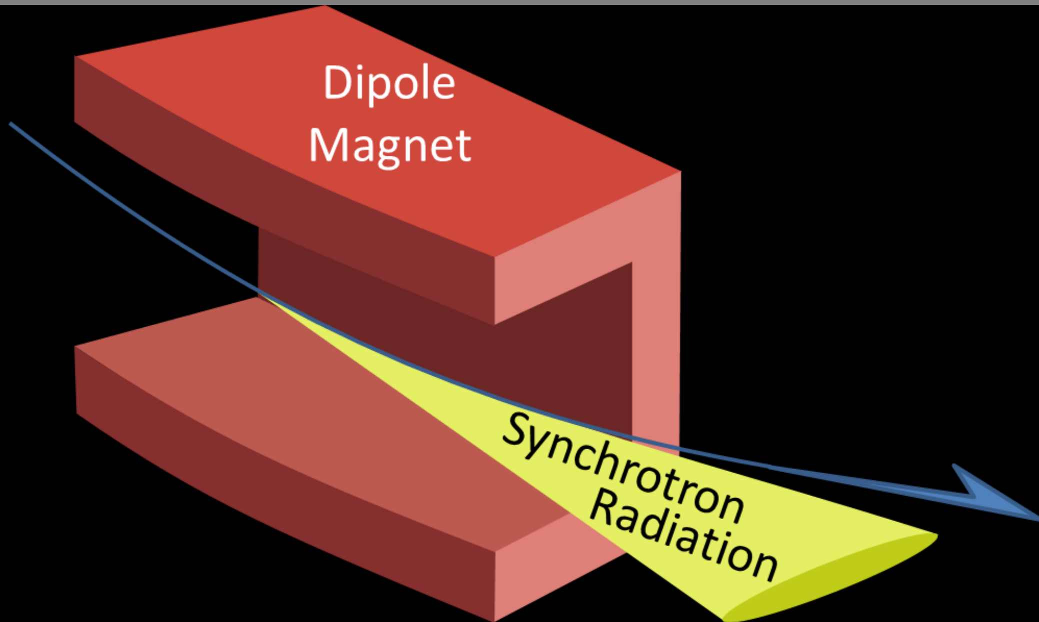
Limitation of WireScanners

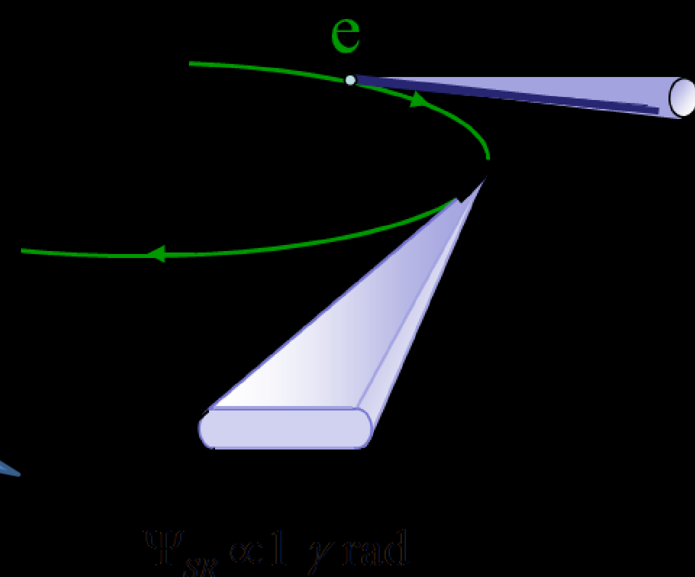
- Wire Breakage – why?
  - Brittle or Plastic failure (error in motor control)
  - Melting/Sublimation (main intensity limit)
    - Due to energy deposition in wire by proton beam
- Temperature evolution depends on
  - Heat capacity, which increases with temperature!
  - Cooling (radiative, conductive, 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

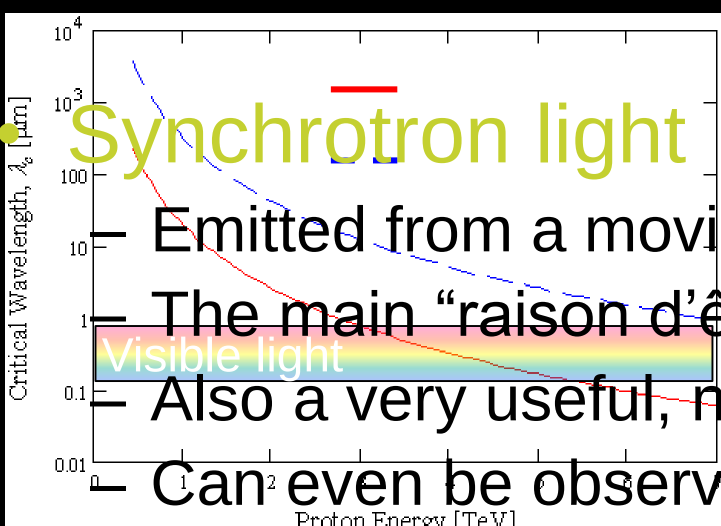


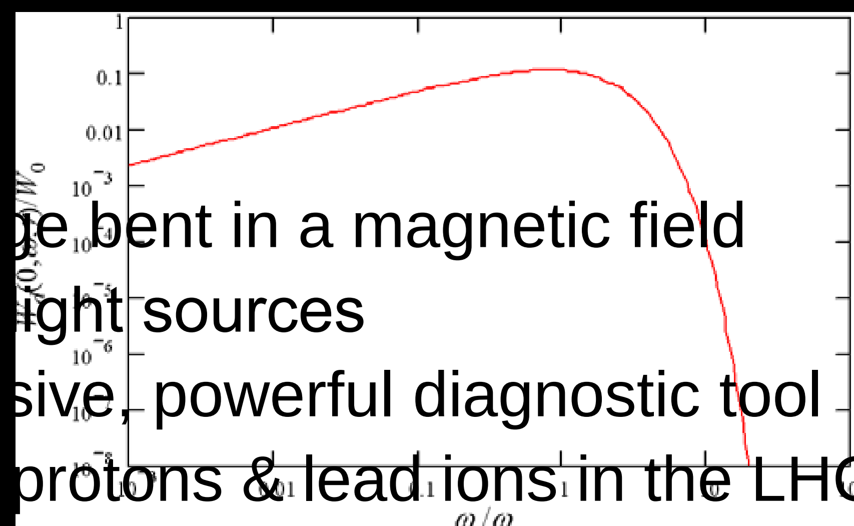


Synchrotron Light Monitors





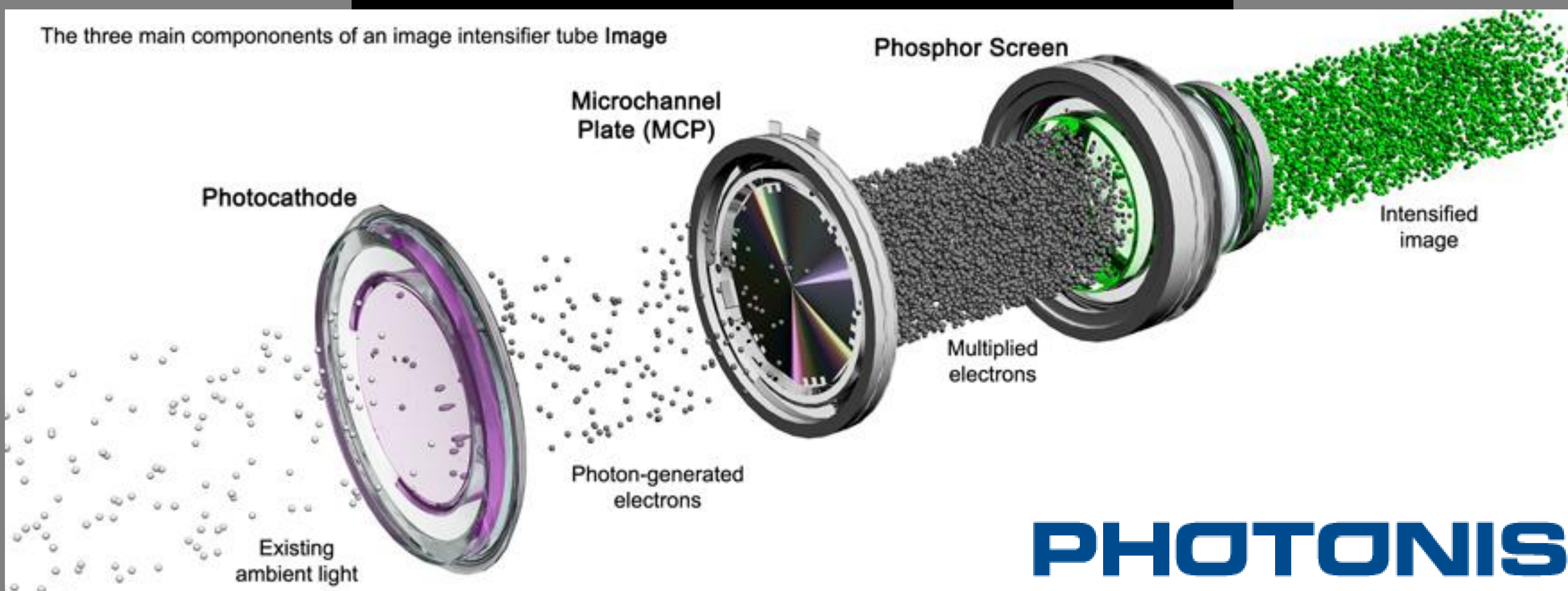




- Synchrotron light
  - Emitted from a movi ge bent in a magnetic field
  - The main “raison d’ê ight sources
  - Also a very useful, n sive, powerful diagnostic tool
  - Can even be observ protons & lead ions in the LHC

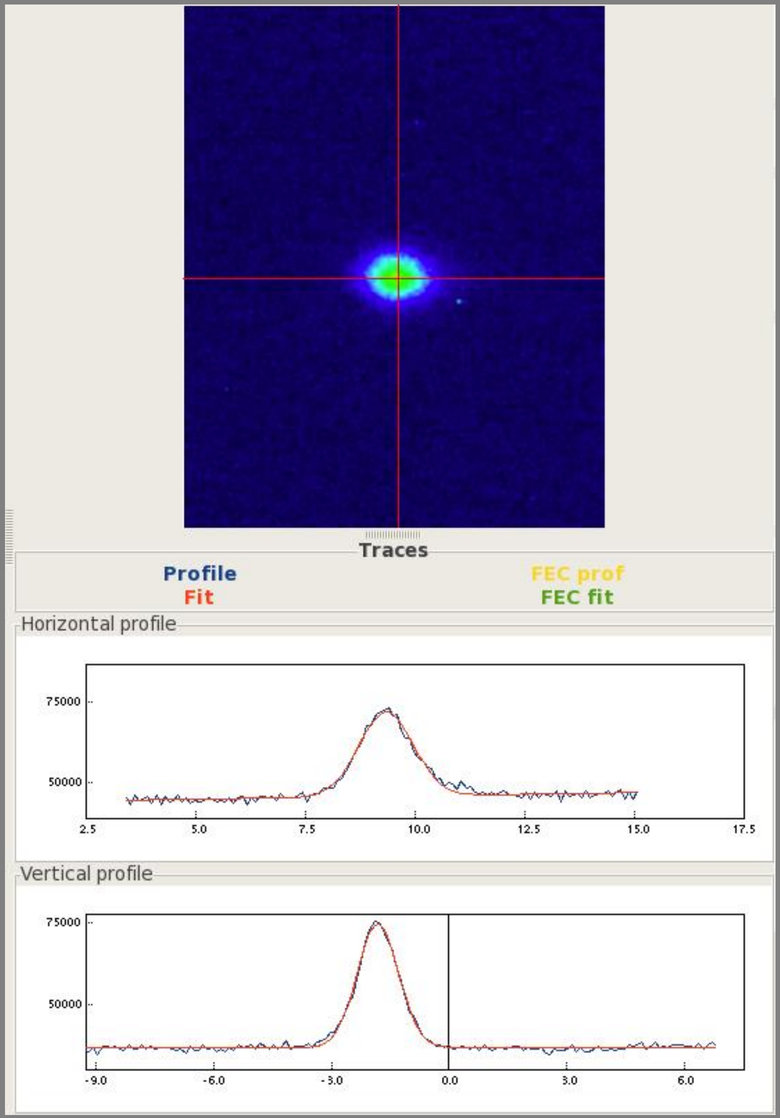
Synchrotron Light Image Acquisition

- Using various cameras
  - Standard CCD cameras for average beam size measurements
  - Gated intensified camera
    - For bunch by bunch diagnostics
  - Streak cameras
    - For short bunch diagnostics



Synchrotron Light Imaging

- Proton Beam Example
  - LHC single bunch ~1.1e11p @ 3.5 TeV
  - Acquistion accumulated over 4 turns at 200Hz



- Limitations
  - Aberrations
    - Mitigated by careful design
  - Diffraction
    - Need to go to lower wavelengths as the beam size becomes smaller

Measuring Ultra Short Bunches

- Next Generation FELs & Linear Colliders
  - Use ultra short bunches to increase brightness or improve luminosity
- How do we measure such short bunches?

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

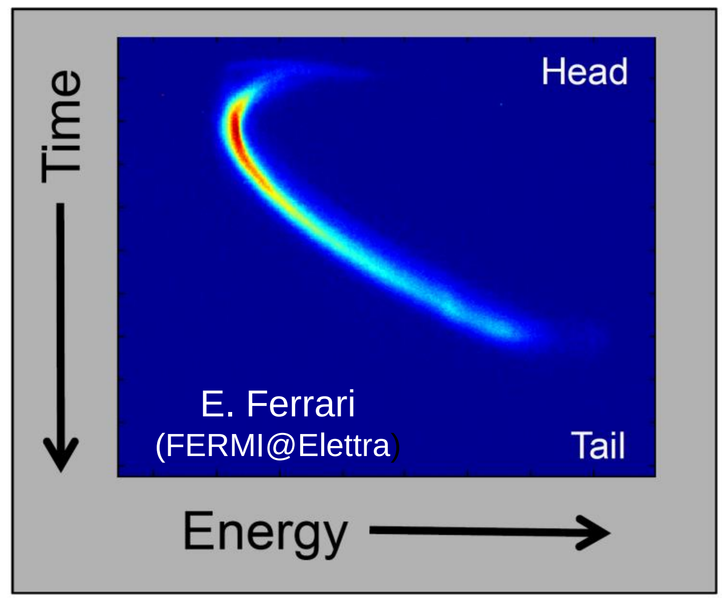
  - Direct Observation
    - Produce light & observe with dedicated instruments
    - Use of RF techniques
    - Use laser pulses and sampling techniques

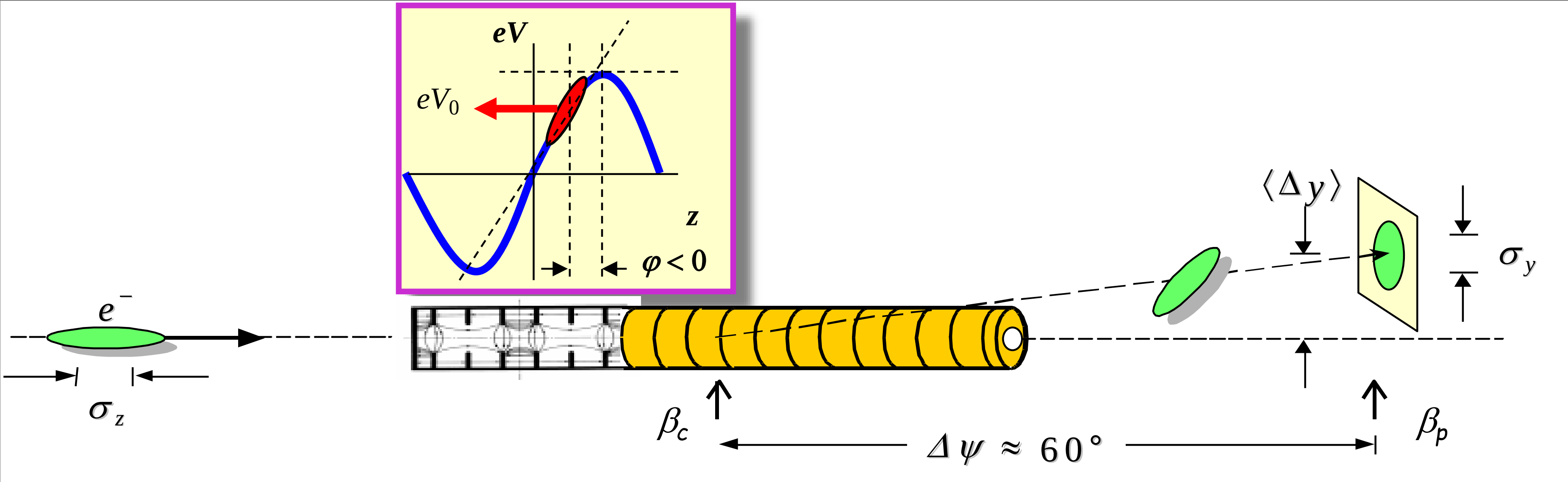
Destructive Measurement

  - Indirect Calculation
    - Reconstruct bunch length from frequency spectrum
      - Either directly from the bunch or through its radiation spectrum

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)





The Typical Instruments

- Beam Position
  - electrostatic or electromagnetic pick-ups and related electronics
- Beam Intensity
  - beam current transformers
- Beam Profile
  - secondary emission grids and screens
  - wire scanners
  - synchrotron light monitors
  - ionization and luminescence monitors
  - femtosecond diagnostics for ultra short bunches
- Beam Loss
  - ionization chambers or pin diodes
- Machine Tune and Chromaticity (derived quantities)

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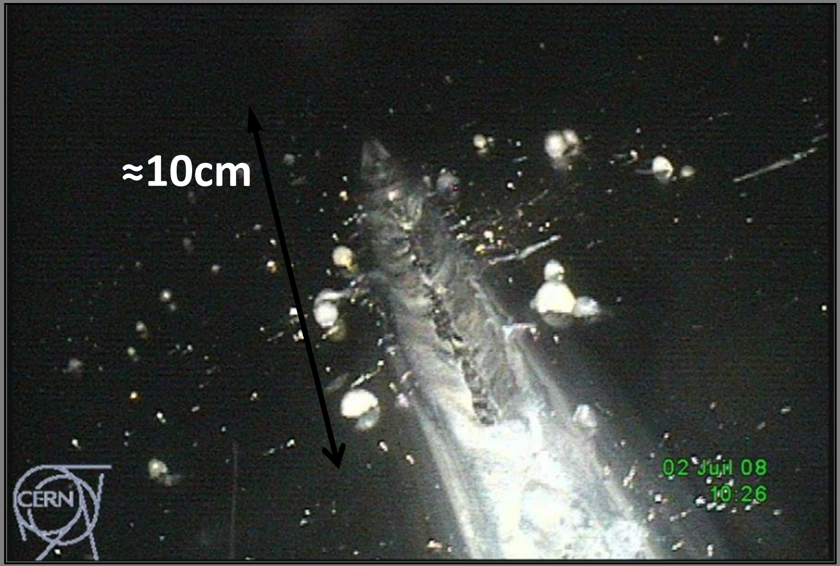
Beam Loss Detectors

- 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

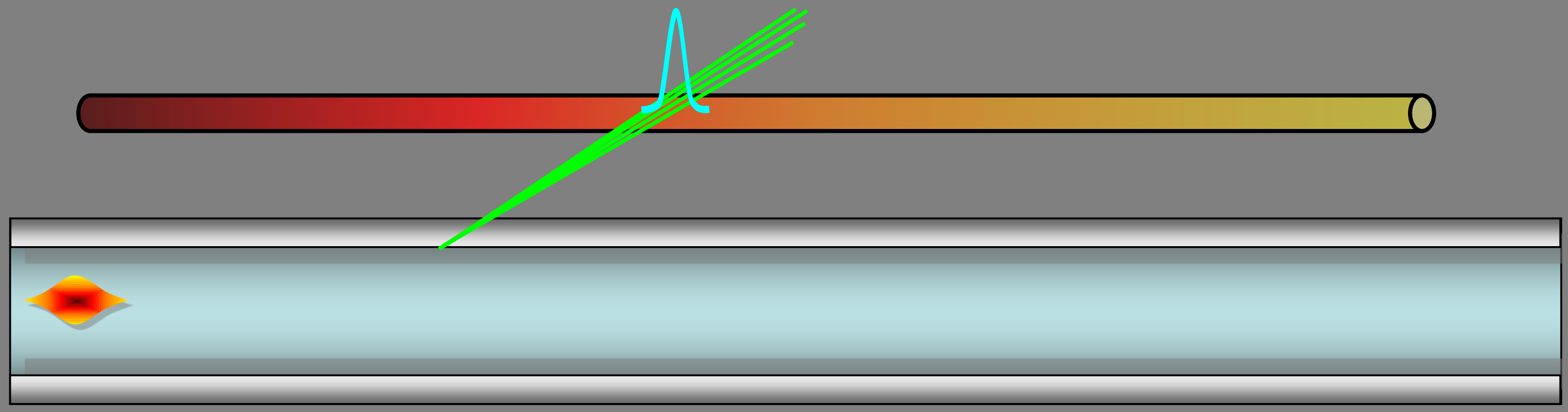
Quench and Damage at 7 TeV	
Quench level	≈ 1mJ/cm^3
Damage level	≈ 1 J/cm^3



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

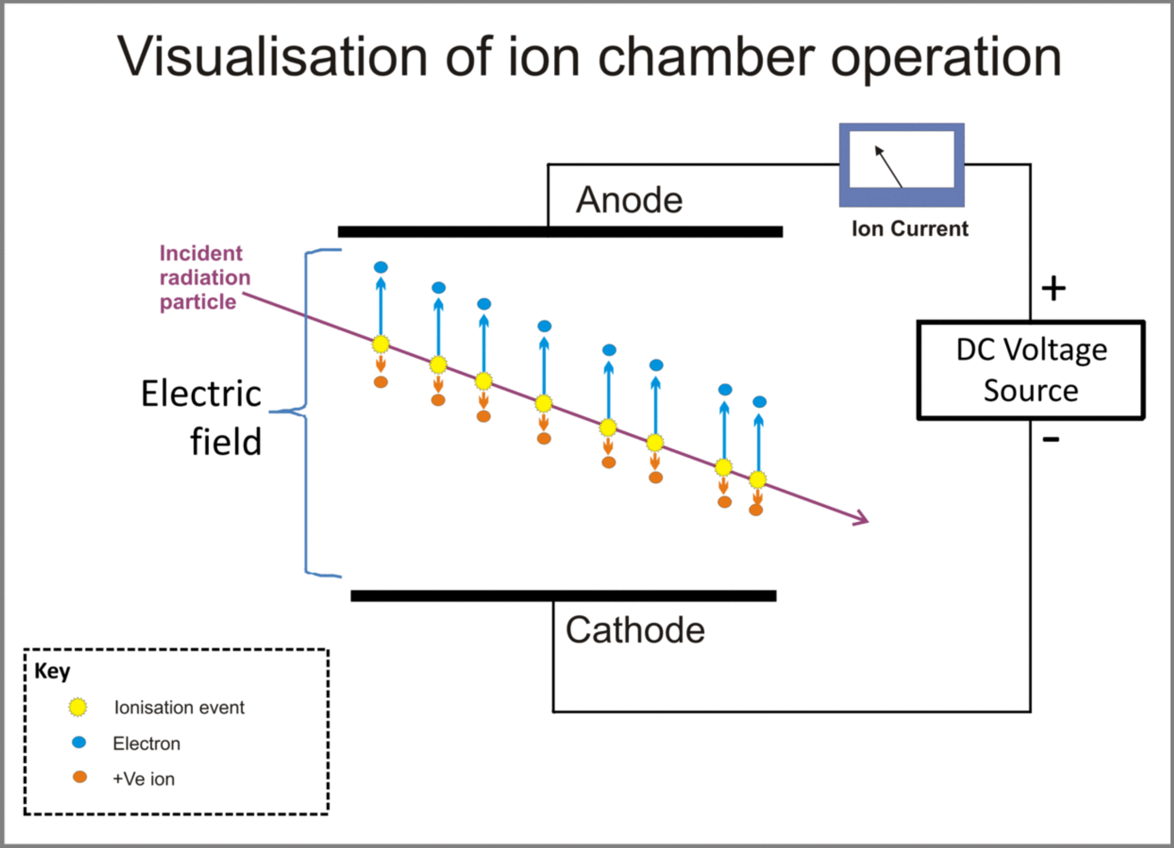
Beam Loss Detectors

- 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



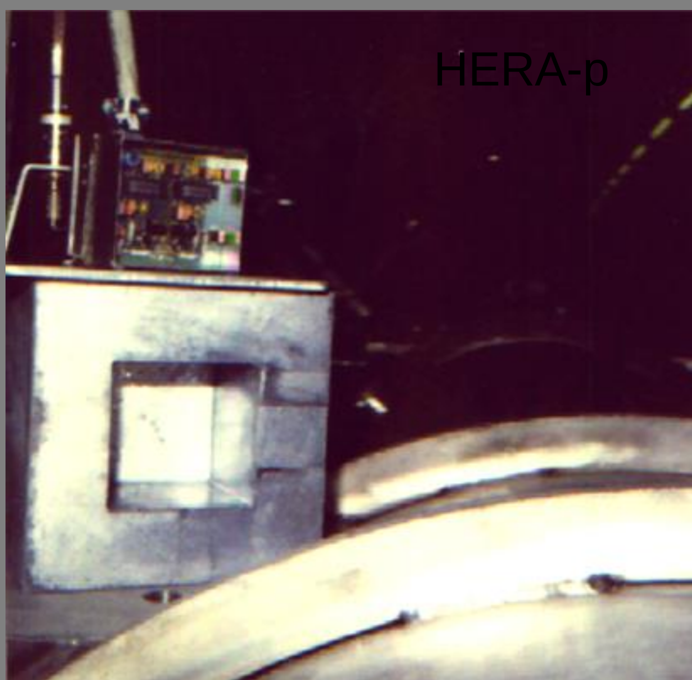
Beam Loss Detectors

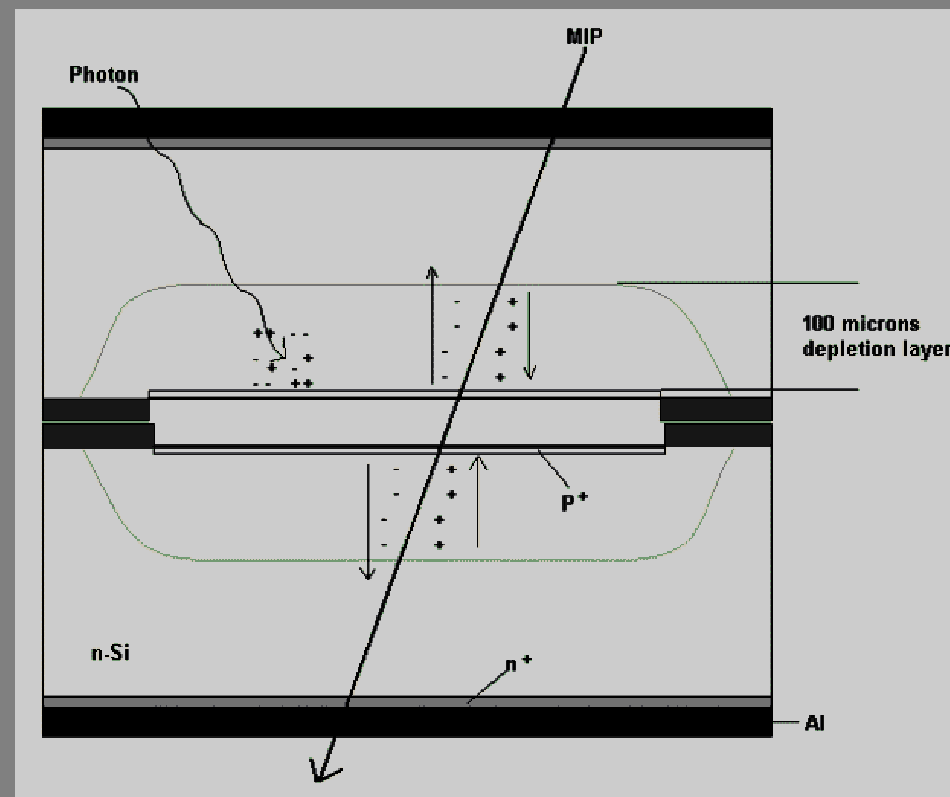
- Common types of monitor
  - Ionisation chambers
  - Dynamic range of < 10^8
  - Slow response (μs) due to ion drift time



Beam Loss Detectors

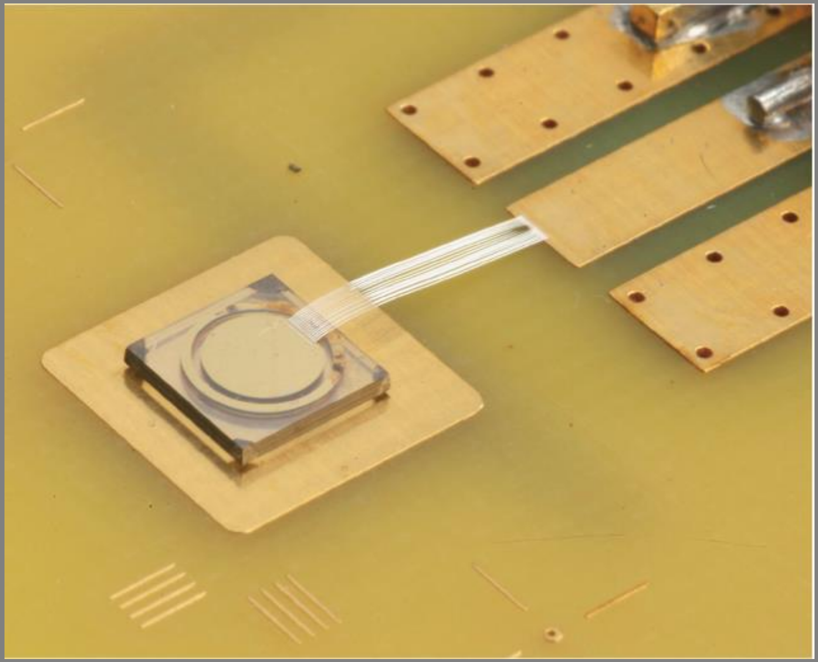
- Common types of monitor
  - PIN photodiode (solid state ionisation chamber)
    - Detect coincidence of ionising particle crossing photodiodes
    - Count rate proportional to beam loss with speed limited by integration time
    - Can distinguish between X-rays & ionising particles
    - Dynamic range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

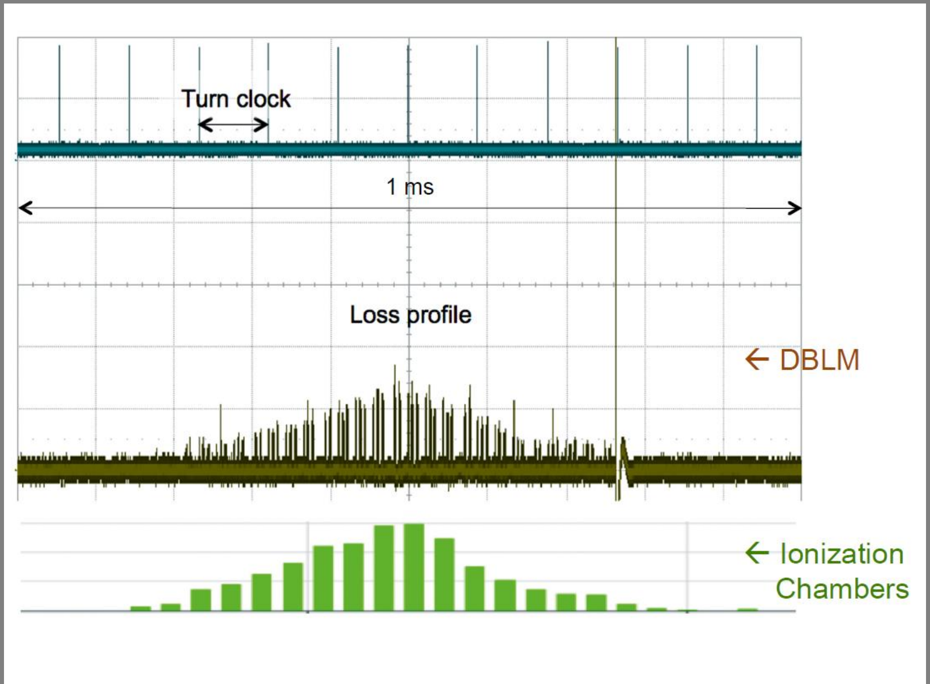


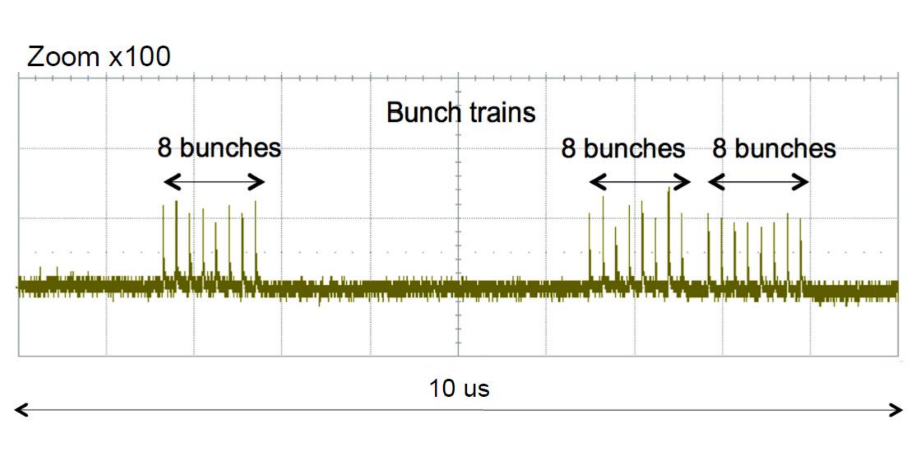


Beam Loss Detectors – New Materials

- 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







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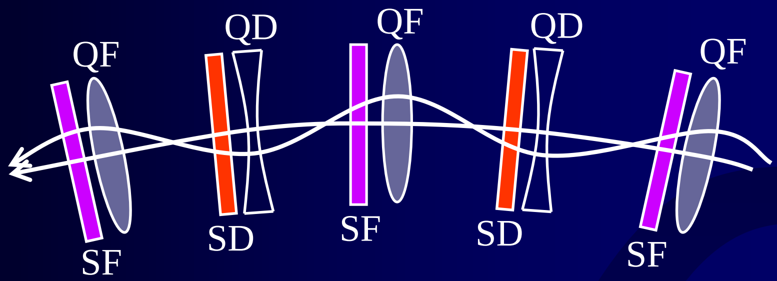
Measurement of Q (betatron tune)



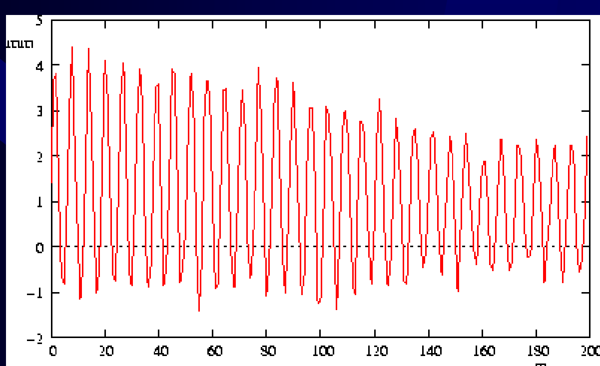
Characteristic Frequency of the Magnet Lattice

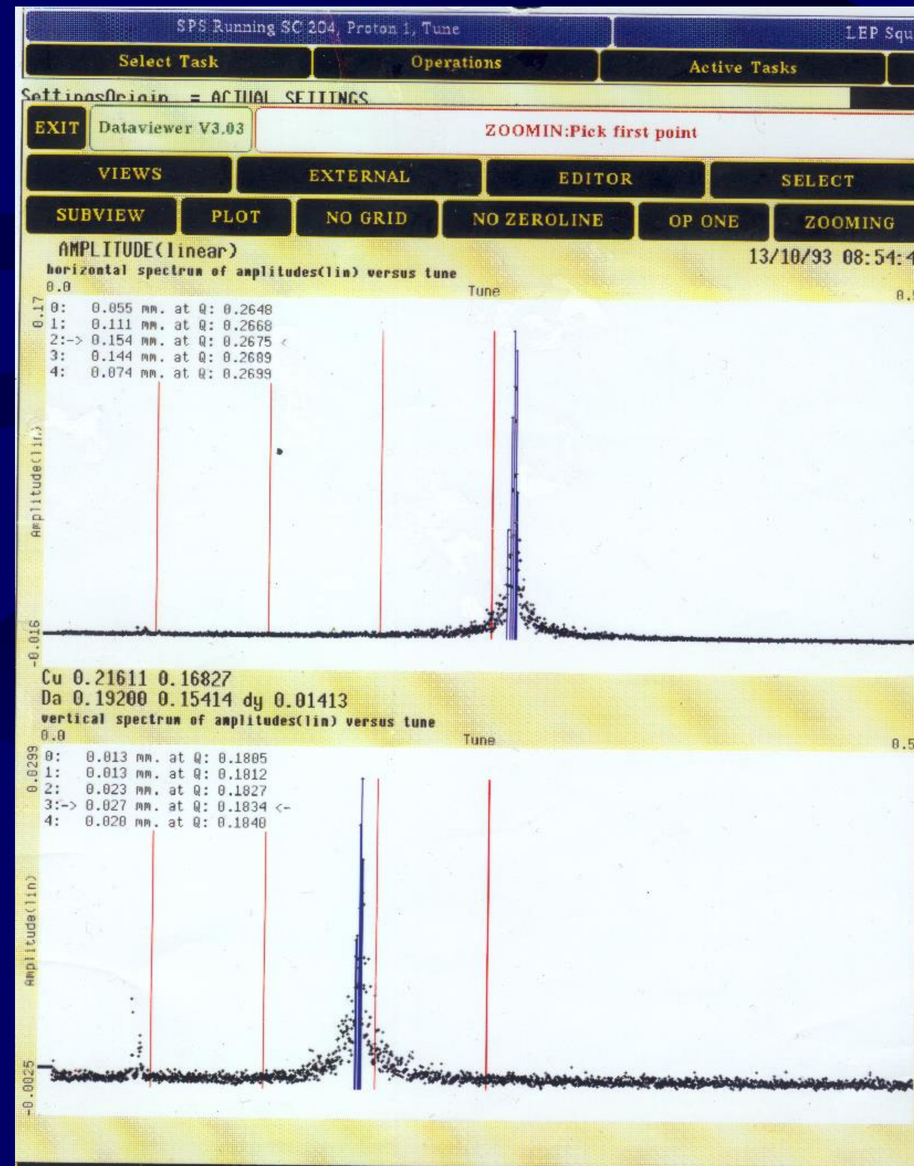
Produced by the strength of the Quadrupole magnets

- 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

Fourier analysis of turn by turn BPM measurements

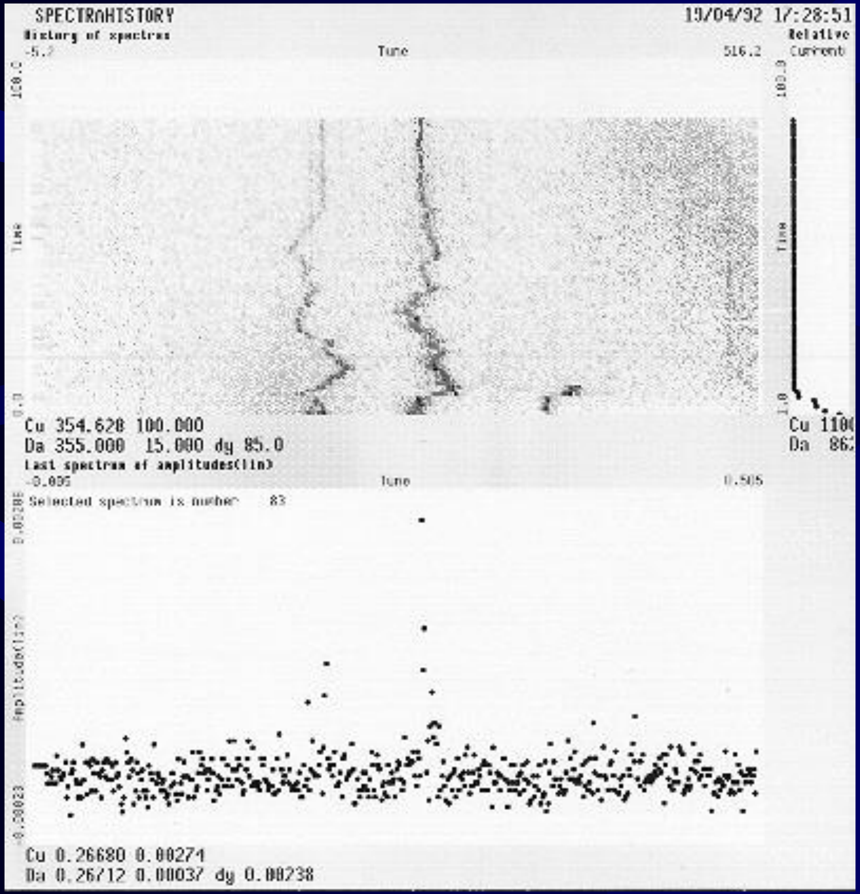
1) Stimulate transverse beam oscillation with a kicker magnet (short dipole kick during one revolution period)
2) Measure turn-by turn beam position
3) Fourier transform of data
4) Tune: = maximum of frequency spectrum
5) Resolution: dq/q = 2/Nsamp
6) Problems:
   - single shot measurement
   - oscillation has to last during measurement
   → strong damping in some accelerators
   → large initial excitation (emittance growth in case of hadron beams)

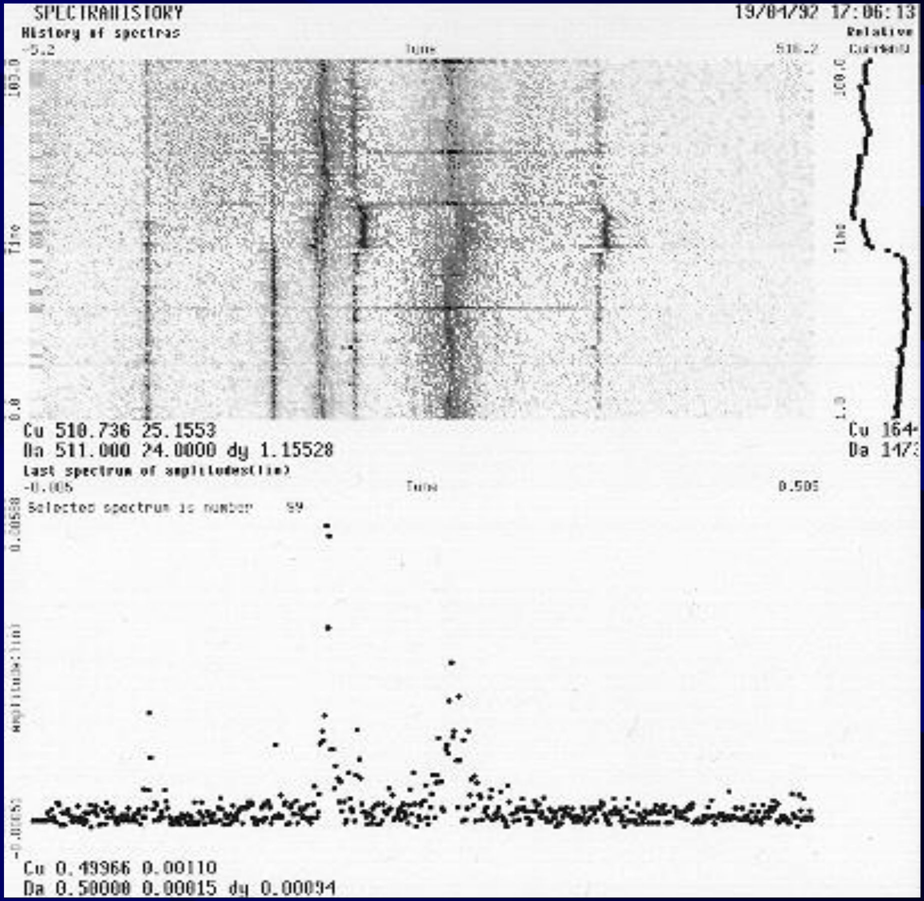




Time Resolved Measurements

- To follow betatron tunes during machine transitions we need time resolved measurements. Simplest example:
  - → repeated FFT spectra as before (spectrograms)



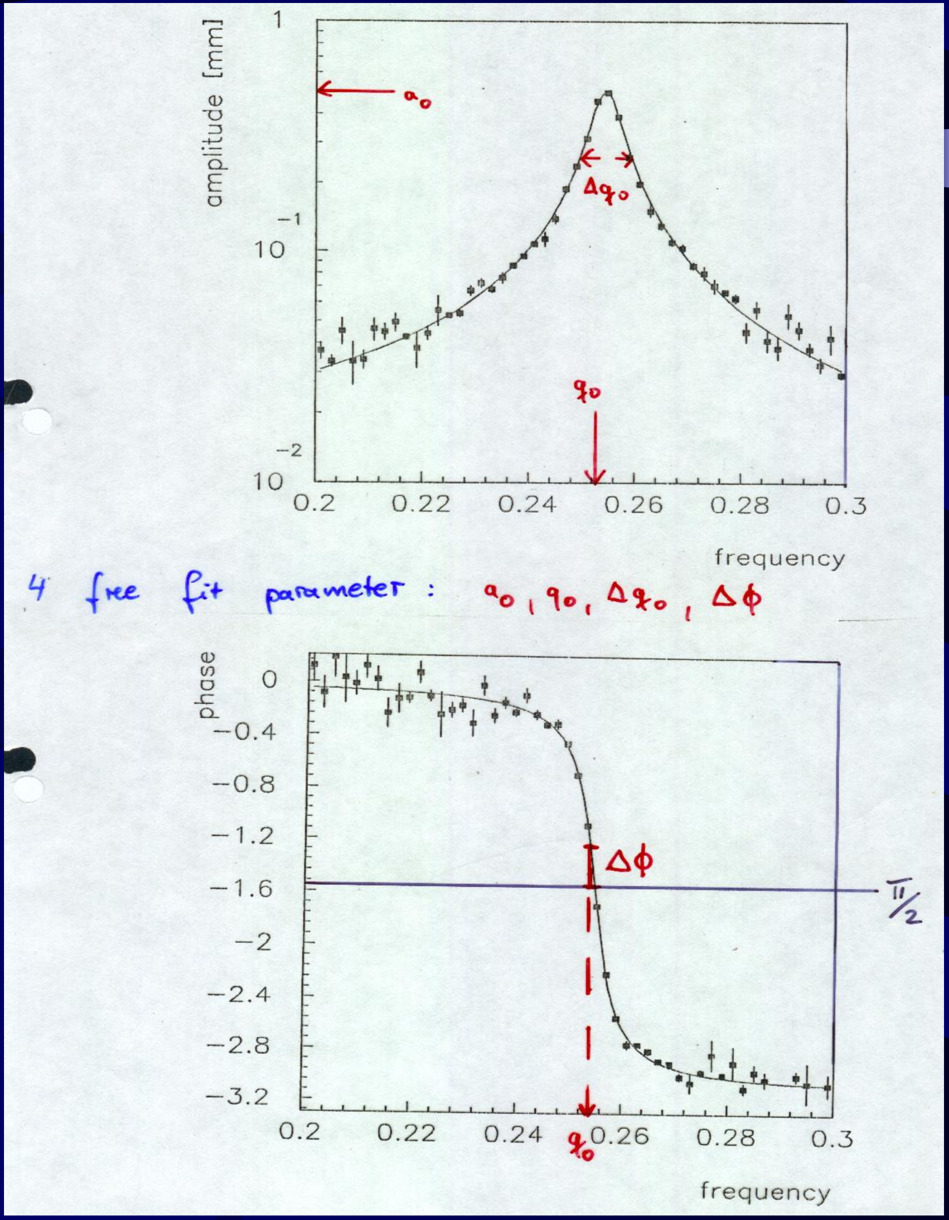


Network Analysis

1. Excite beams with a sinusoidal carrier

2. Measure beam response

3. Sweep excitation frequency slowly through beam response



Chromaticity (Q’ or ξ)

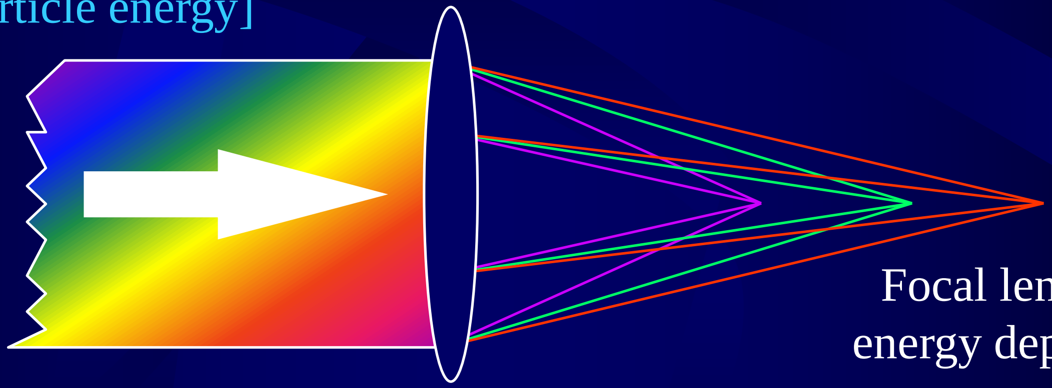
Spread in the Machine Tune due to Particle Energy Spread

Controlled by Sextupole magnets

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

Optics Analogy:

Achromatic incident light
[Spread in particle energy]

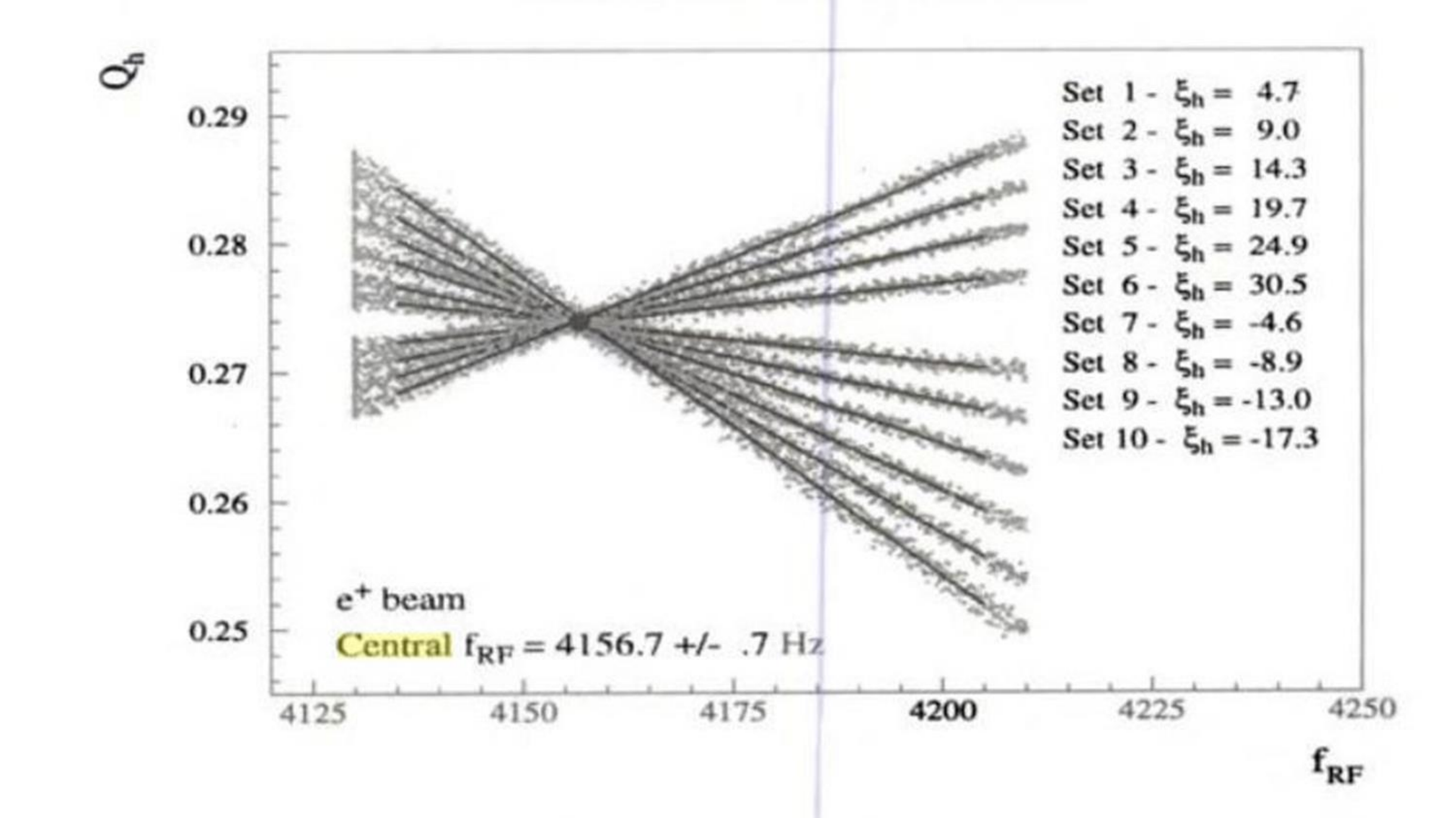


Focal length is energy dependent

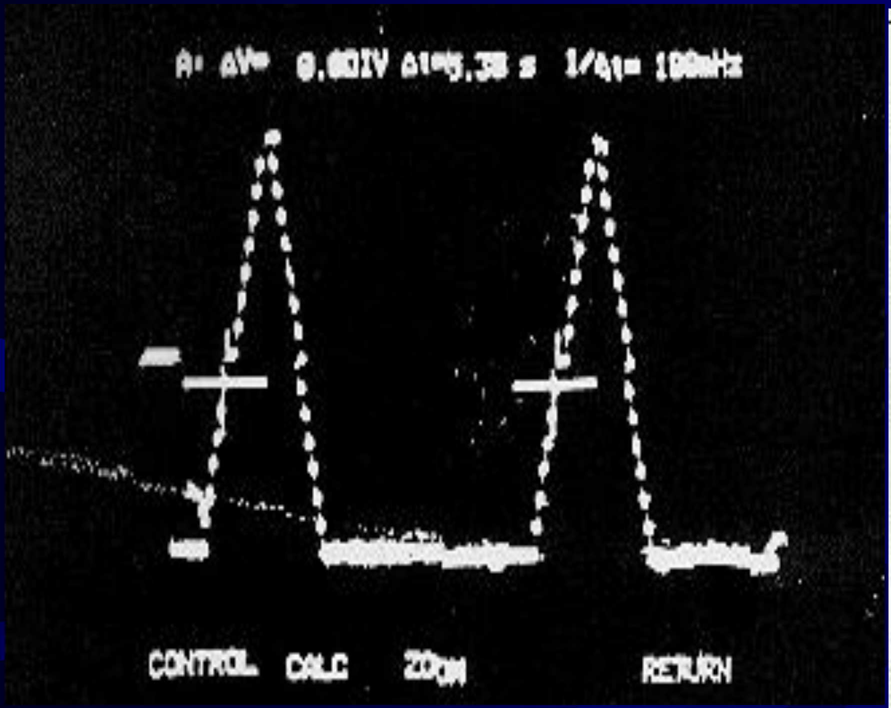
Lens
[Quadrupole]

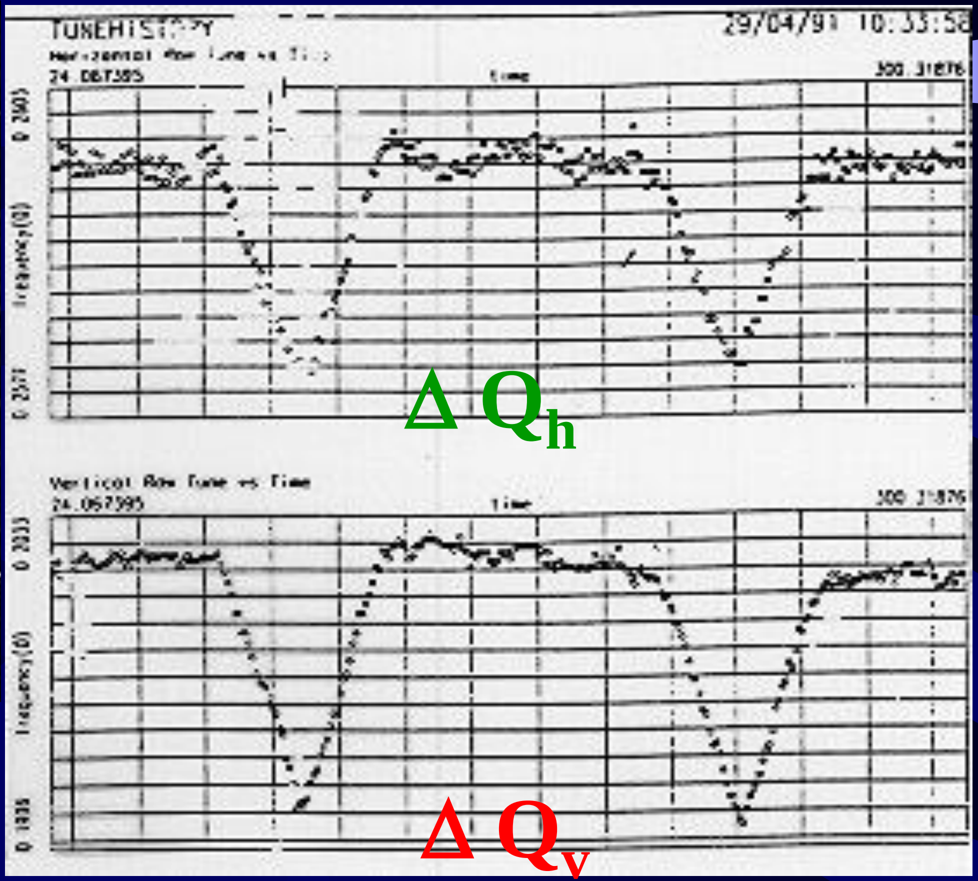
Chromaticity Measurements…

Simply by using the definition:
- Measure betatron tune for different beam momenta;
- vary beam momentum by changing the Rf-frequency



Time resolved Q' Measurement

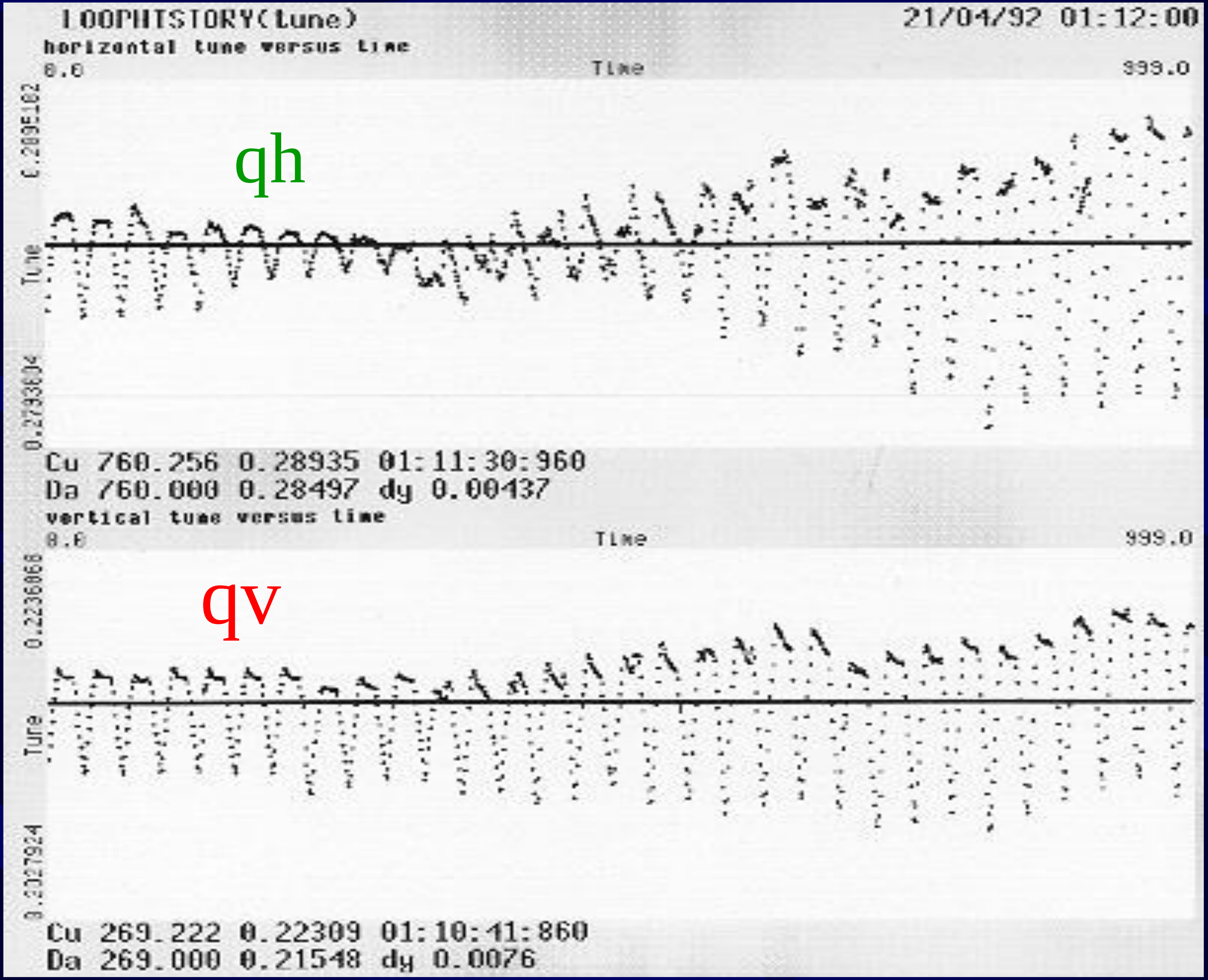




Applied Frequency Shift
Δ F (RF)

Amplitude & sign of chromaticity calculated from continuous tune plot

Measurement Example during LEP β-squeeze



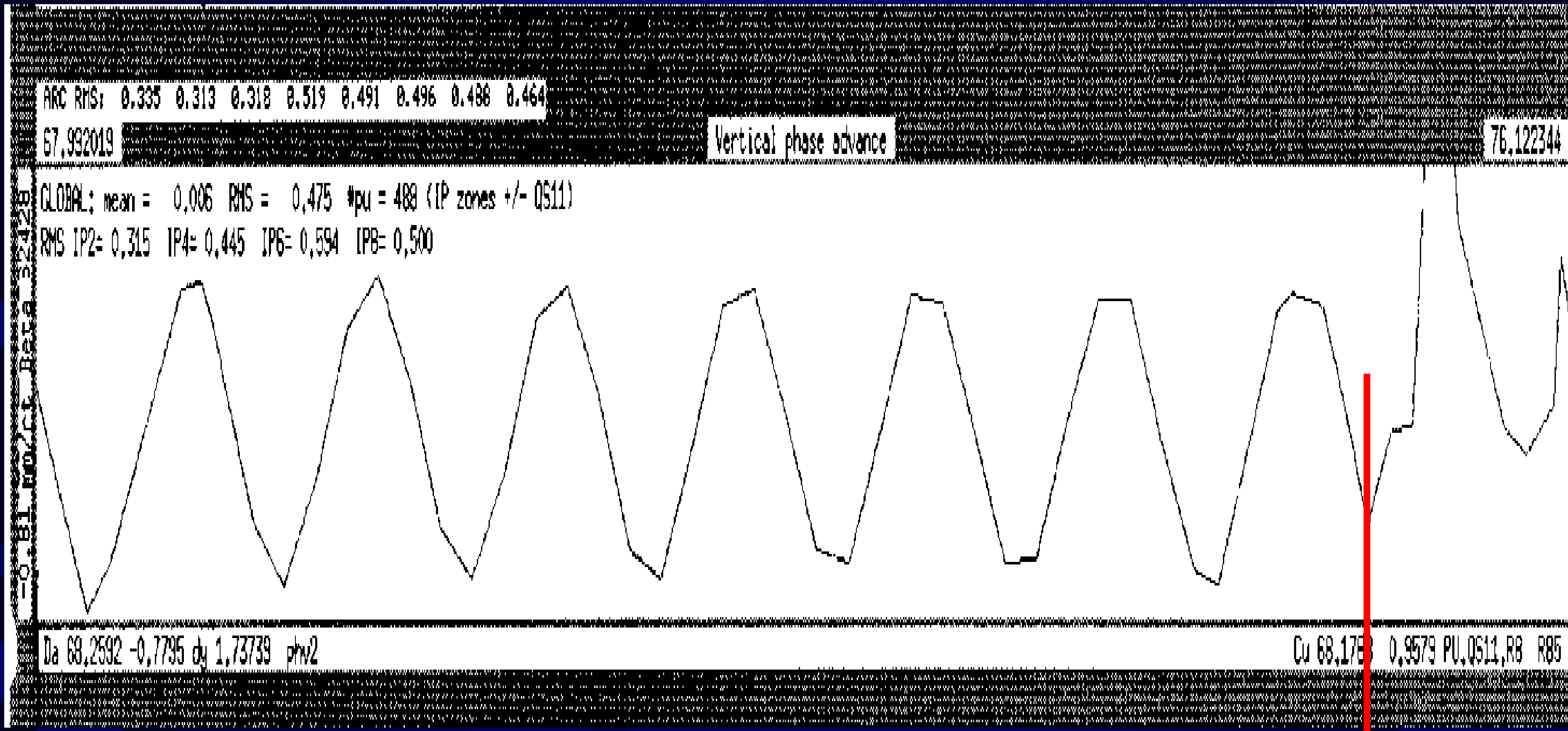
Last not least….

…a story from the good old days:

LEP after a technical stop
- no way to make the beam do one turn around the accelerator
- With BPM readings localize the problem to about 20 meters
- local check of equipment (quadrupole polarity…)
- radiography of beam pipe

- finally: cut beam pipe open

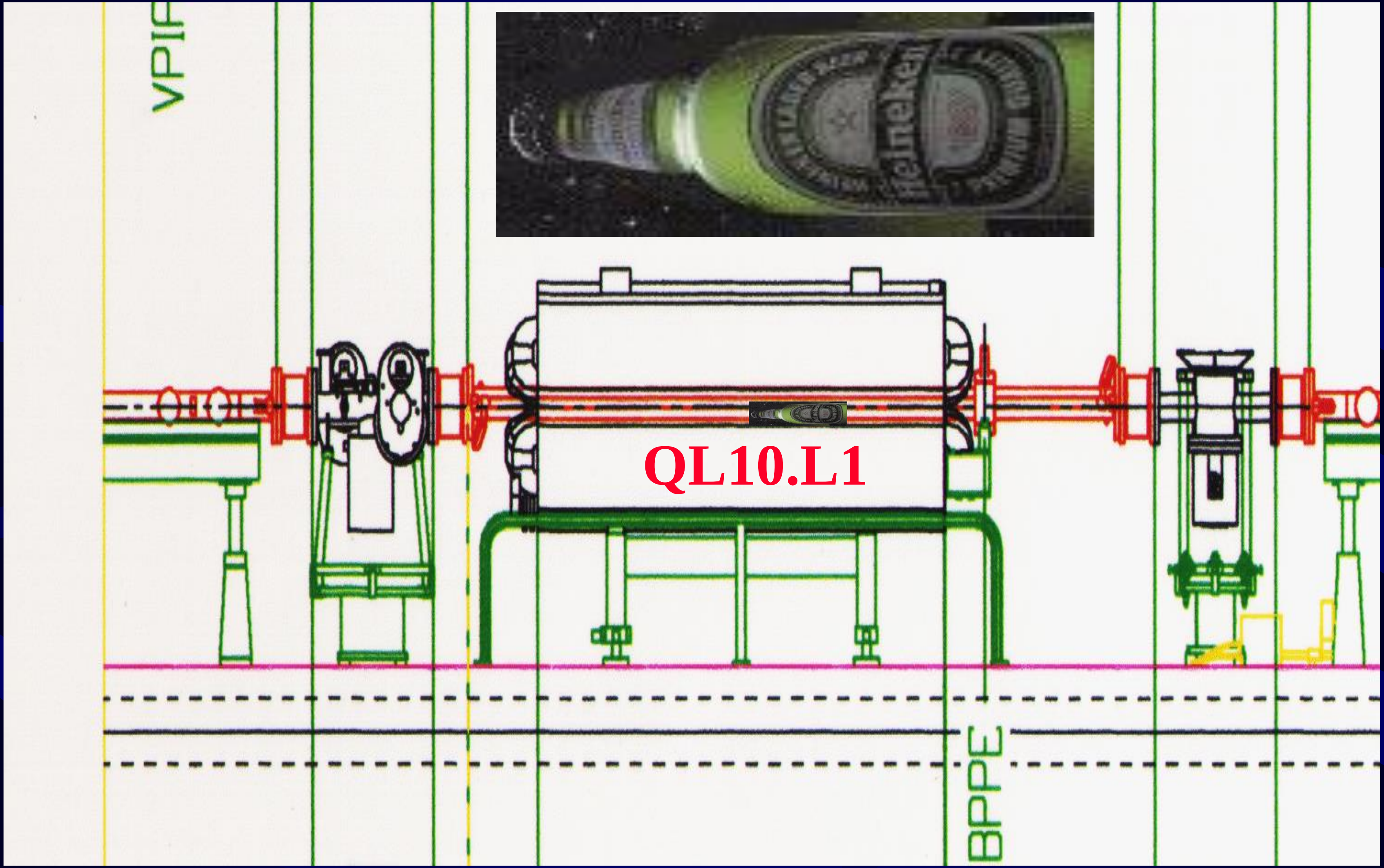
LEP – No Circulating Beam after at technical stop



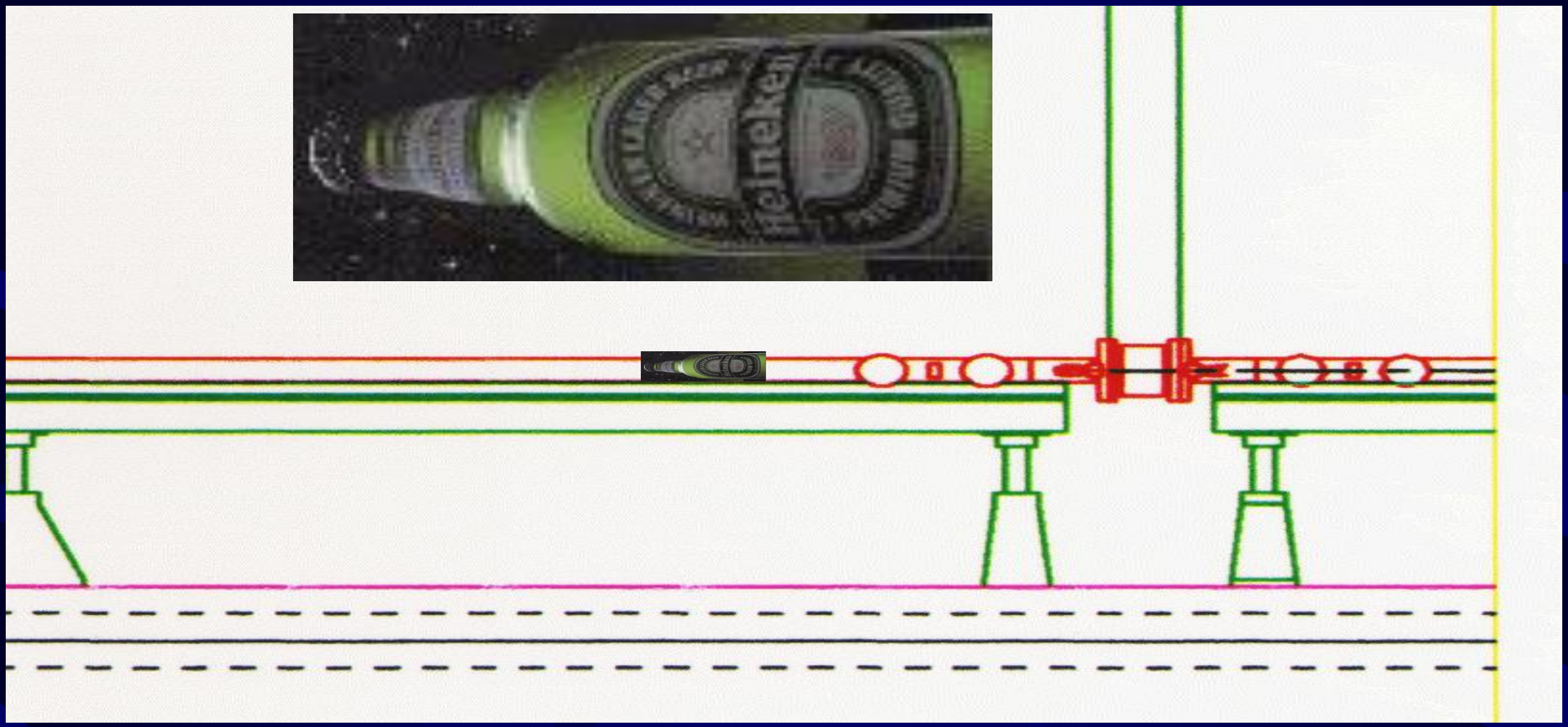
Positrons →

QL10.L1

Zoom on QL1



& 10 metres to the right …



Unsociable sabotage: both bottles were empty!!