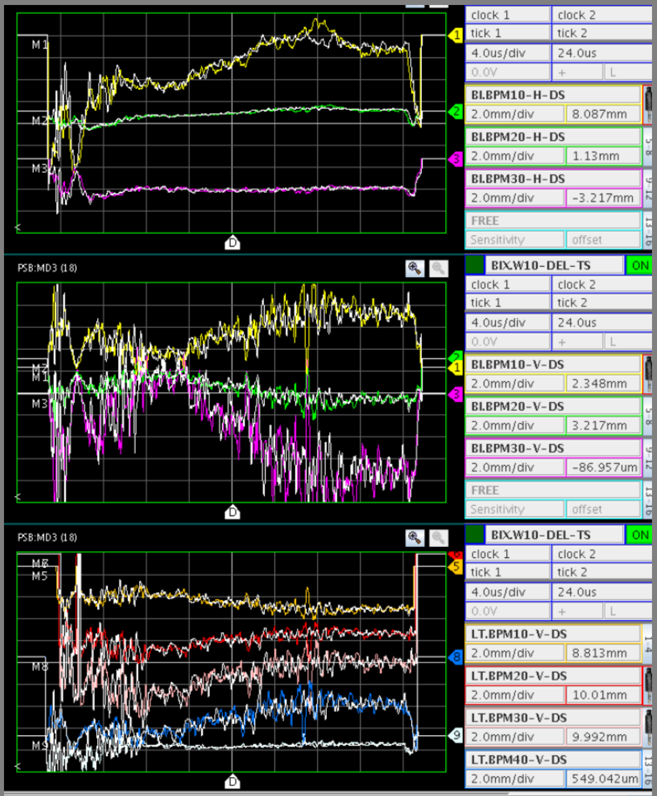
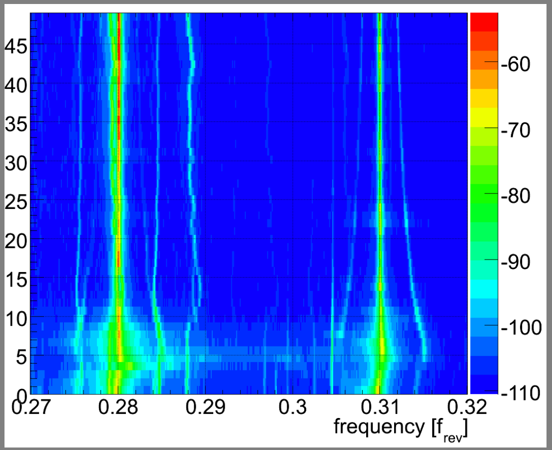




Beam Instrumentation

Basic CAS 2021 – Video course

H.Schmickler, CERN

Introduction

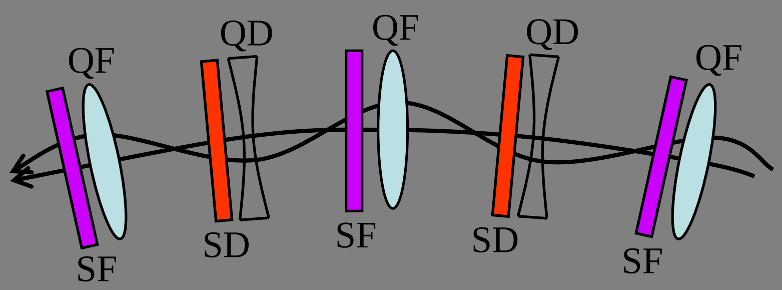
- What do we mean by beam instrumentation?
  - The “eyes” of the machine operators
    - i.e. the instruments that observe beam behaviour
    - “An accelerator can never be better than the instruments measuring its performance!”

- 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

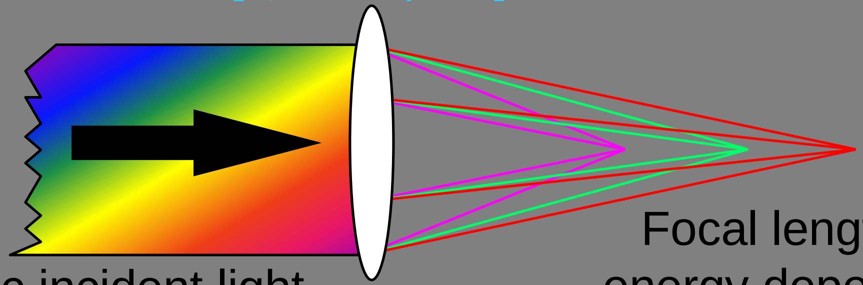


Characteristic Frequency of the Magnetic Lattice
Given by the strength of the Quadrupole magnets

- 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:

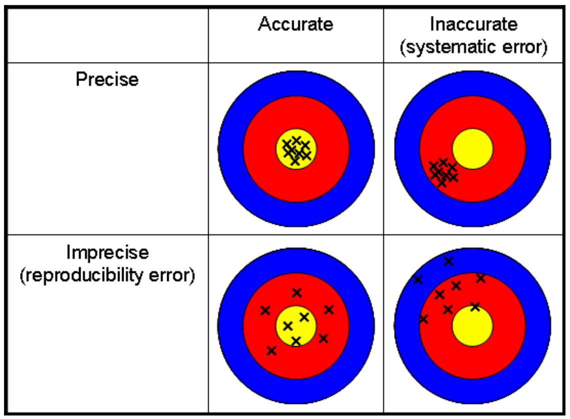
- Luminosity Measurements
  (dedicated arrangements close to the IP)
- Direct Emittance Measurements
  (simultaneous measurement of size and divergence)
- Particle identification, Time of flight…
  (relevant for secondary beam lines)
- Synchronization,
  beam arrival time monitors
  …this needs a full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

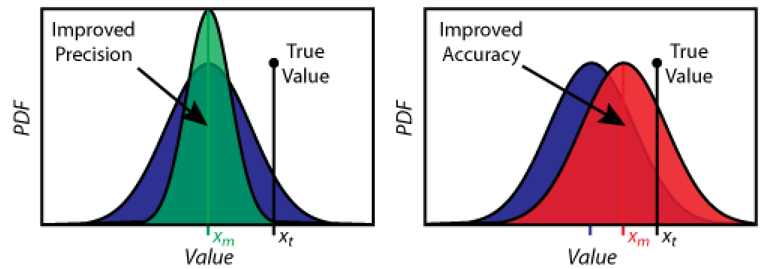
....in general...

- 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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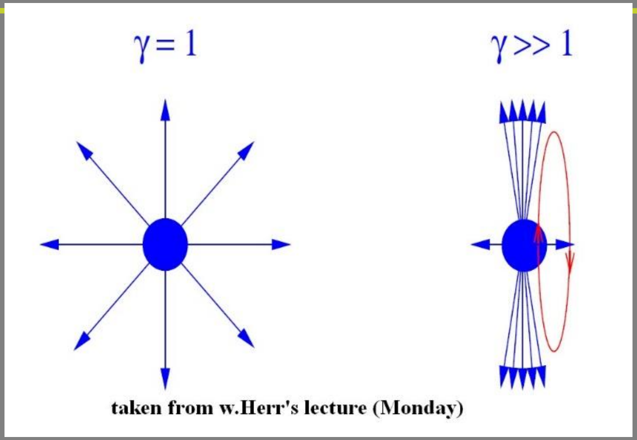
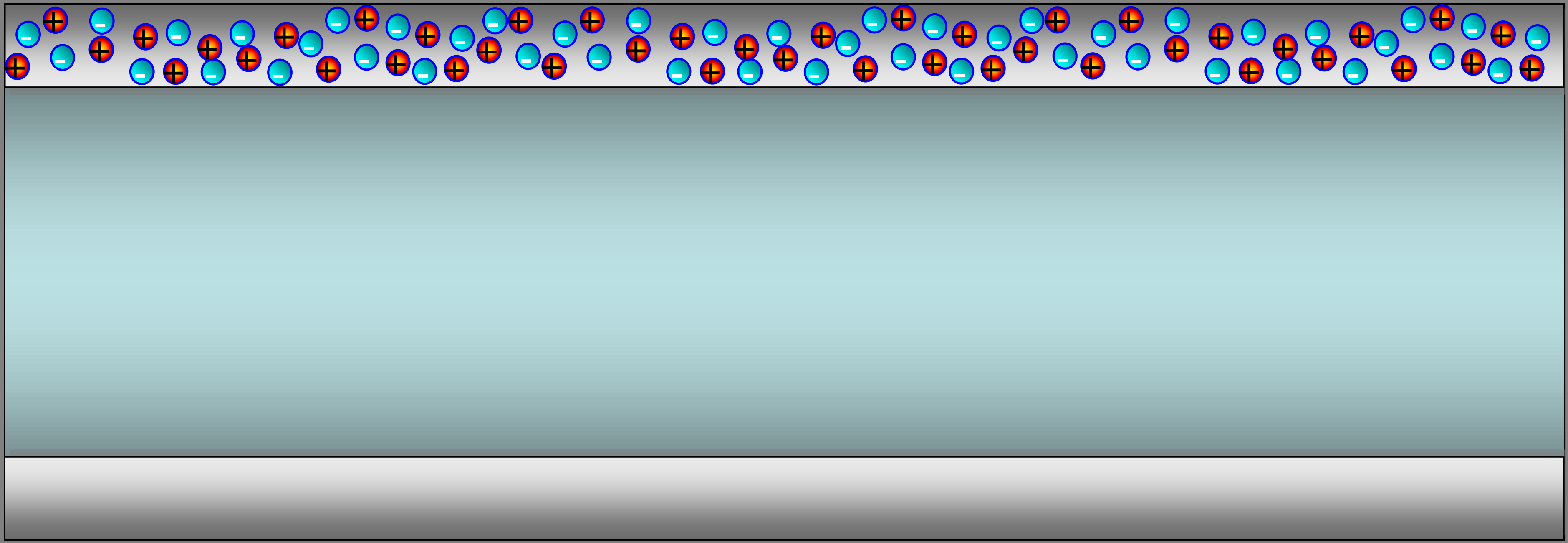
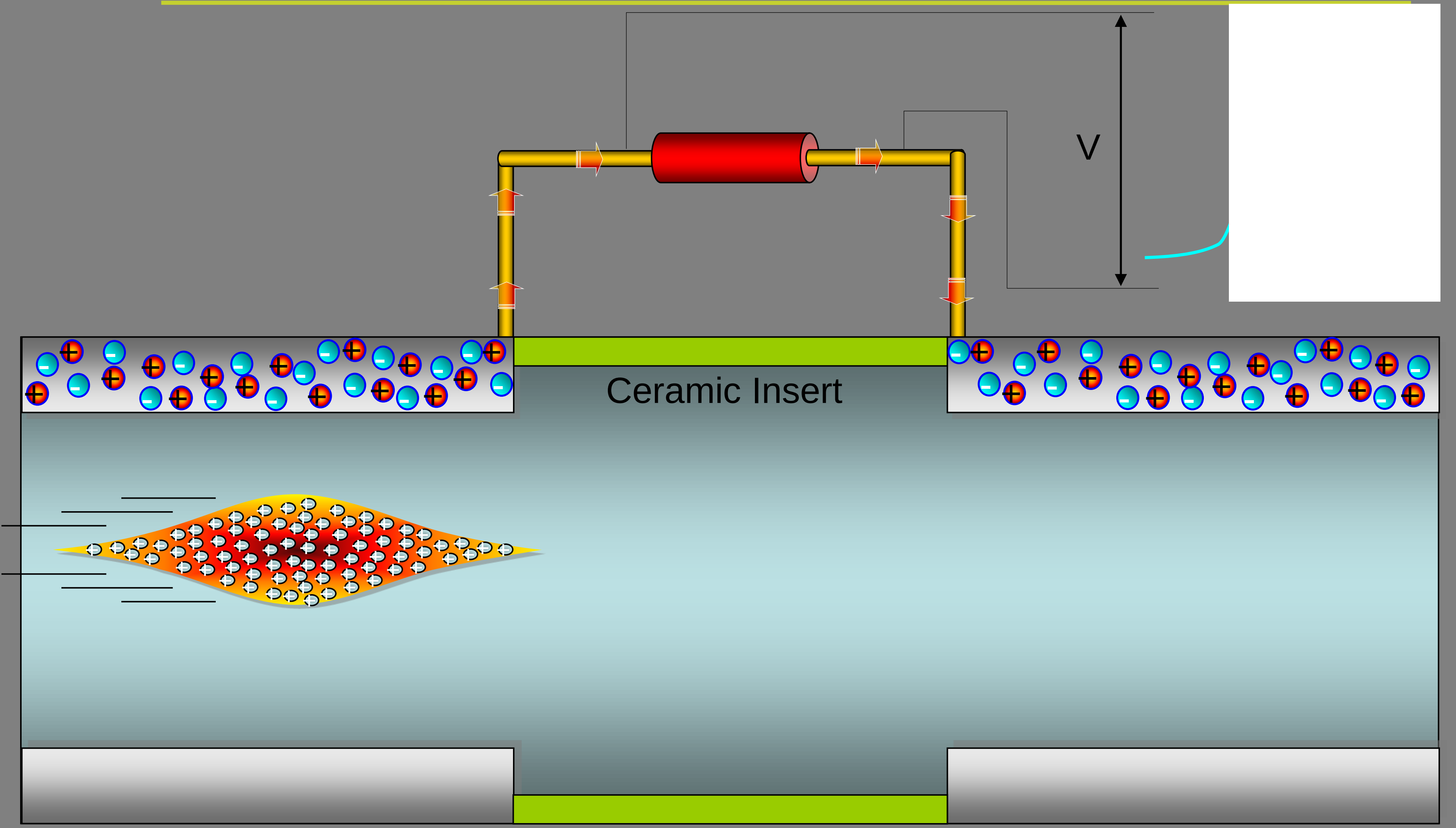
Beam Image (wall) current– The Principle

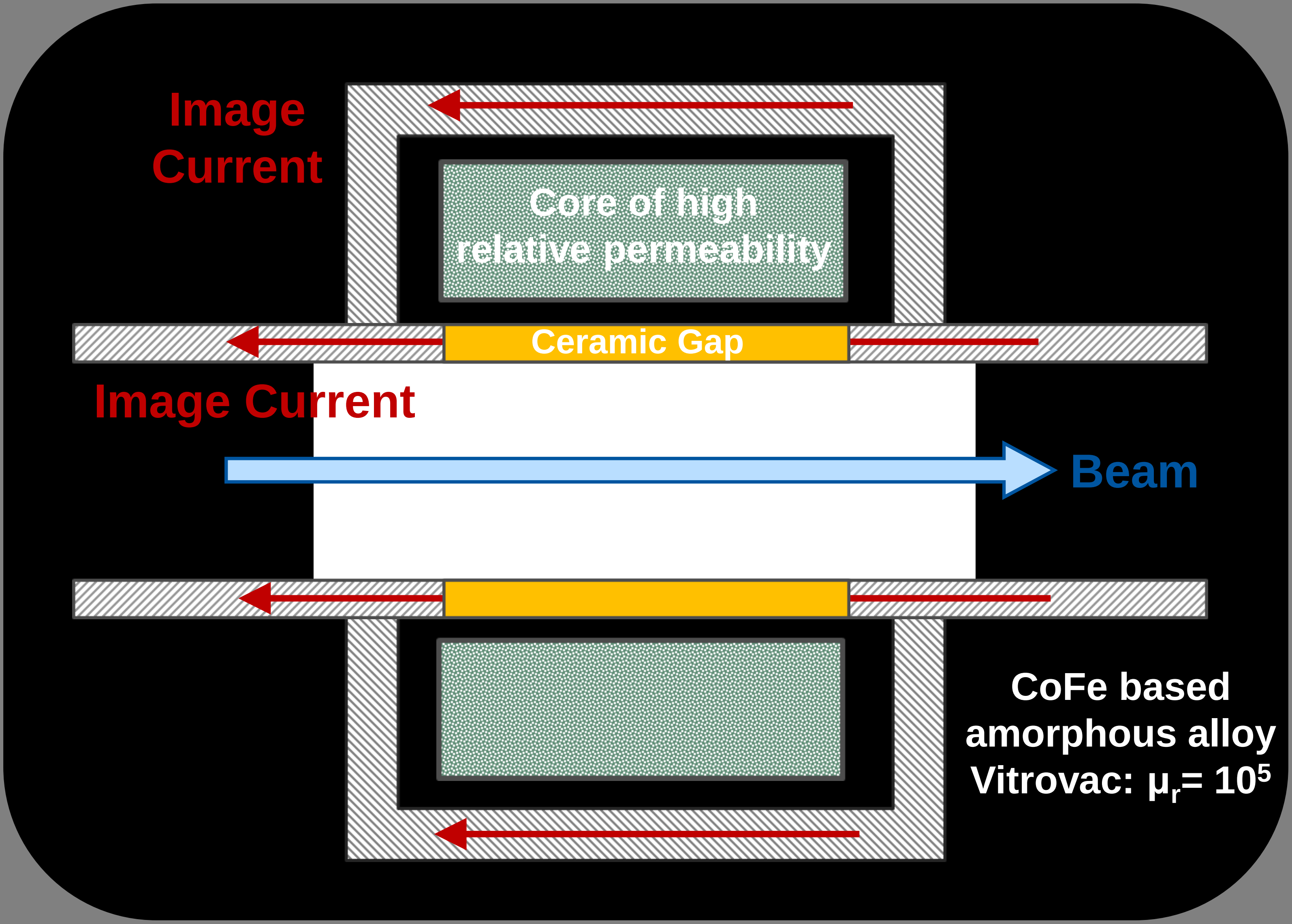




Wall Current Monitor – The Principle



AC (Fast) Current Transformers



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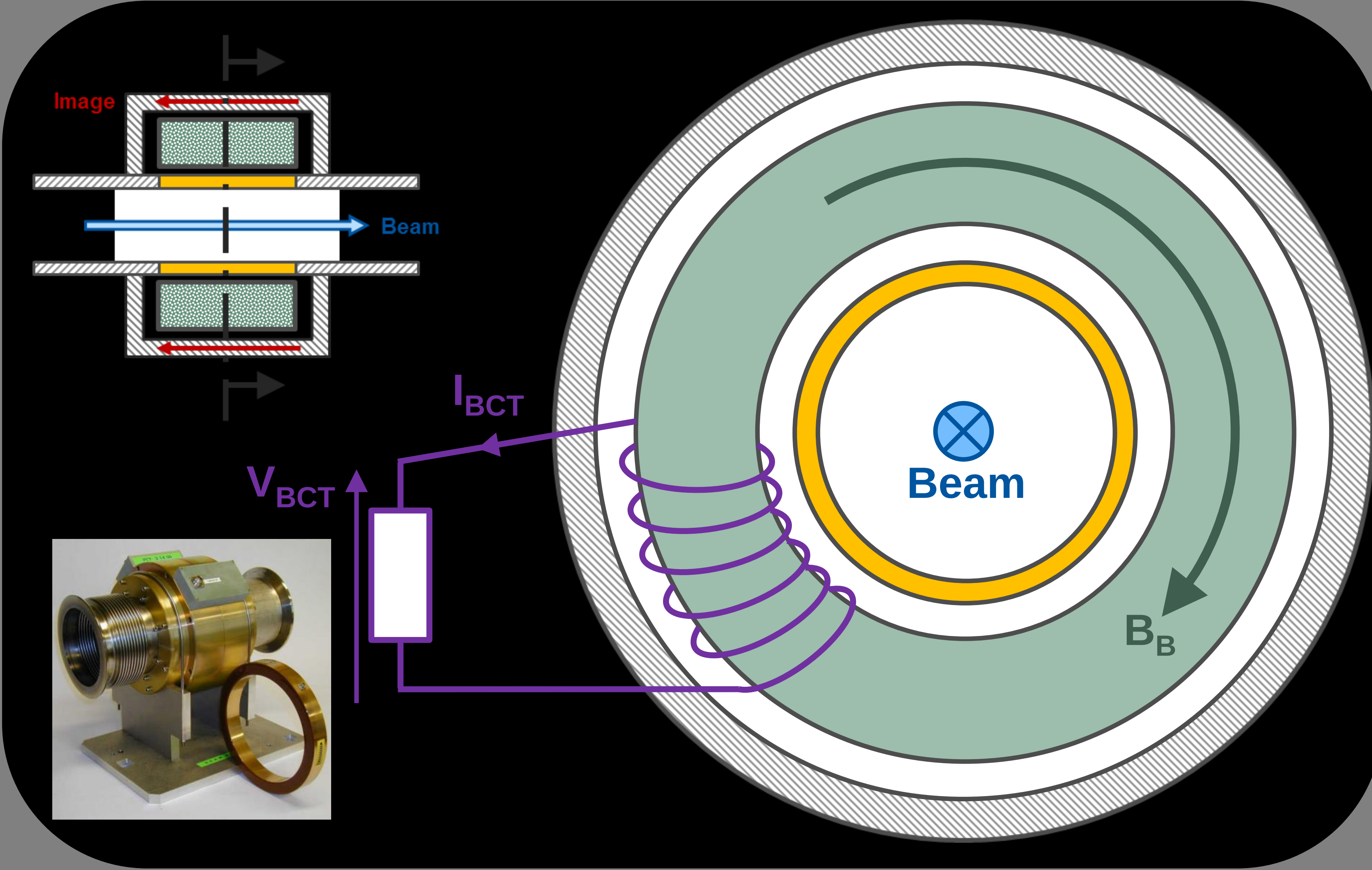
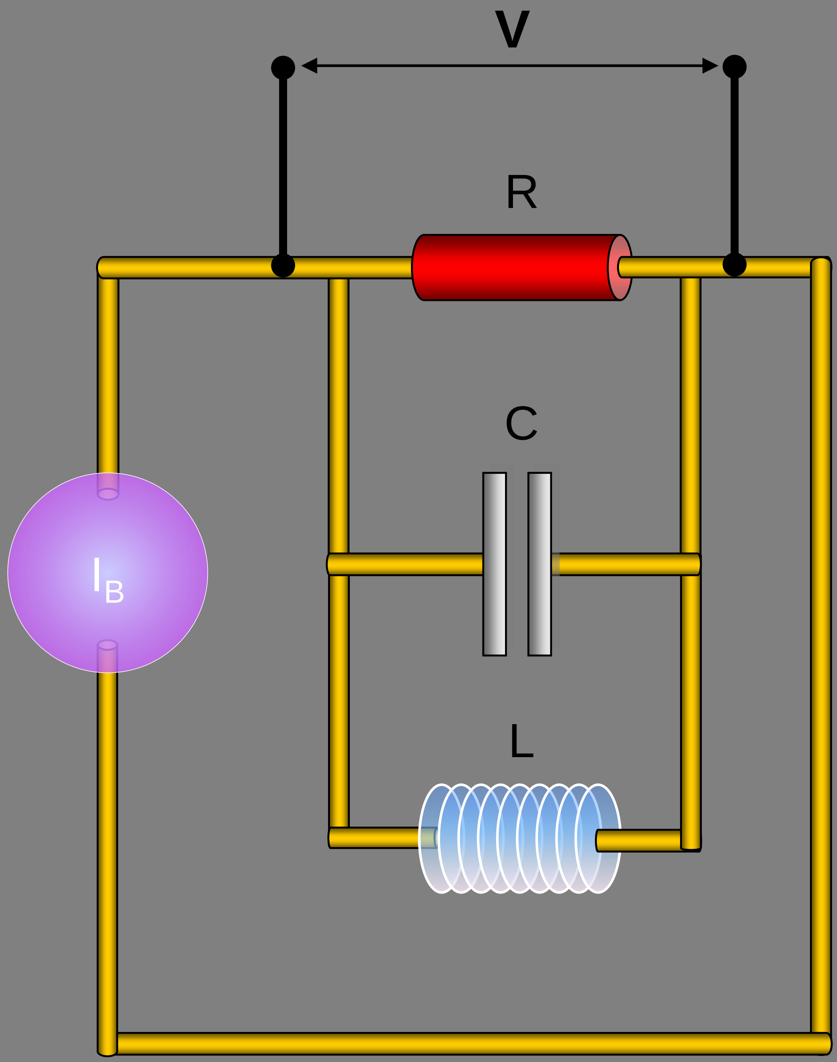
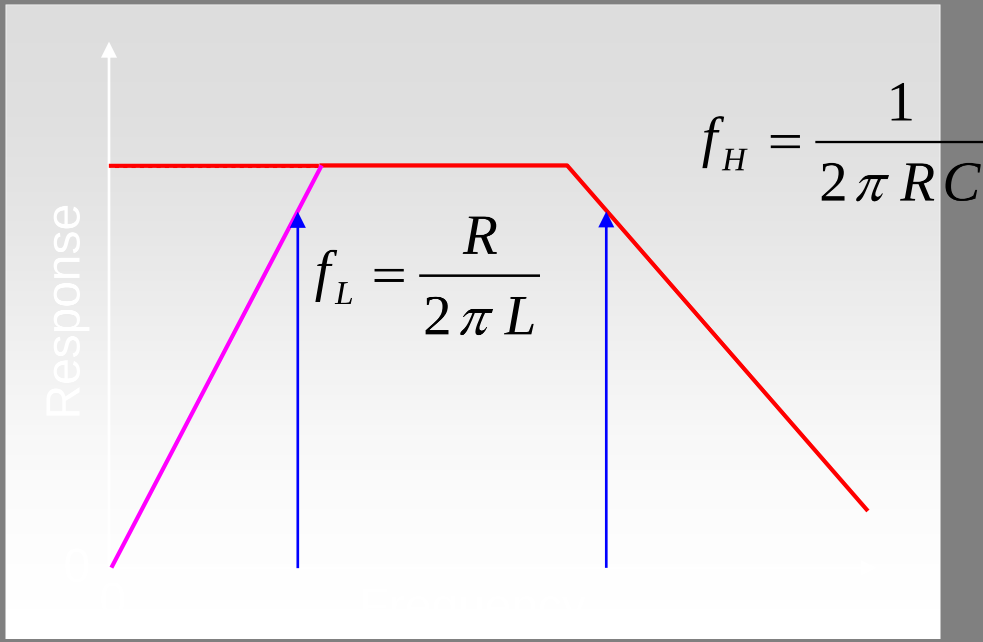
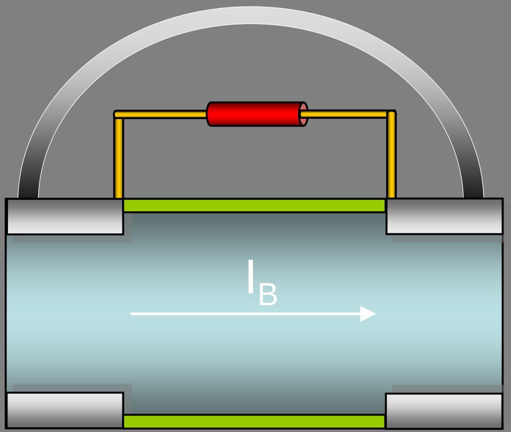


Wall Current Monitor – Beam Response

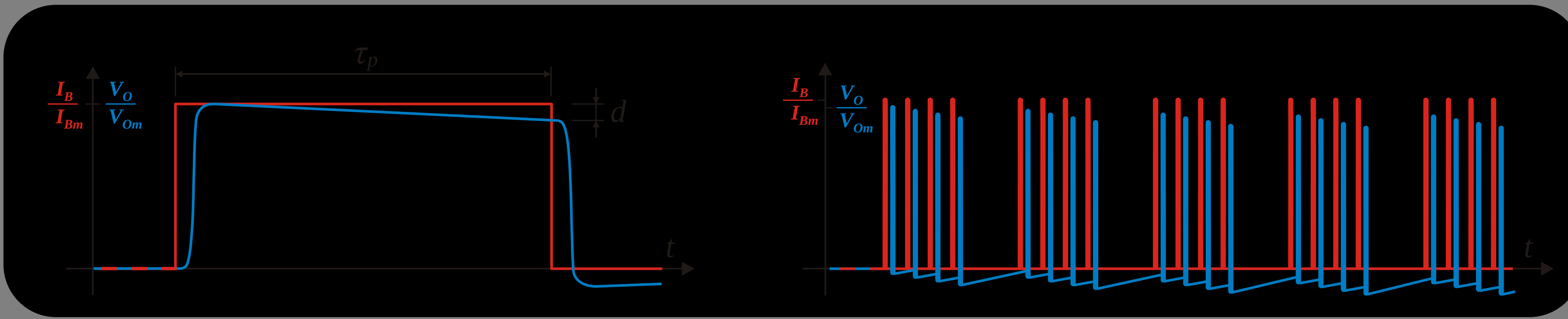


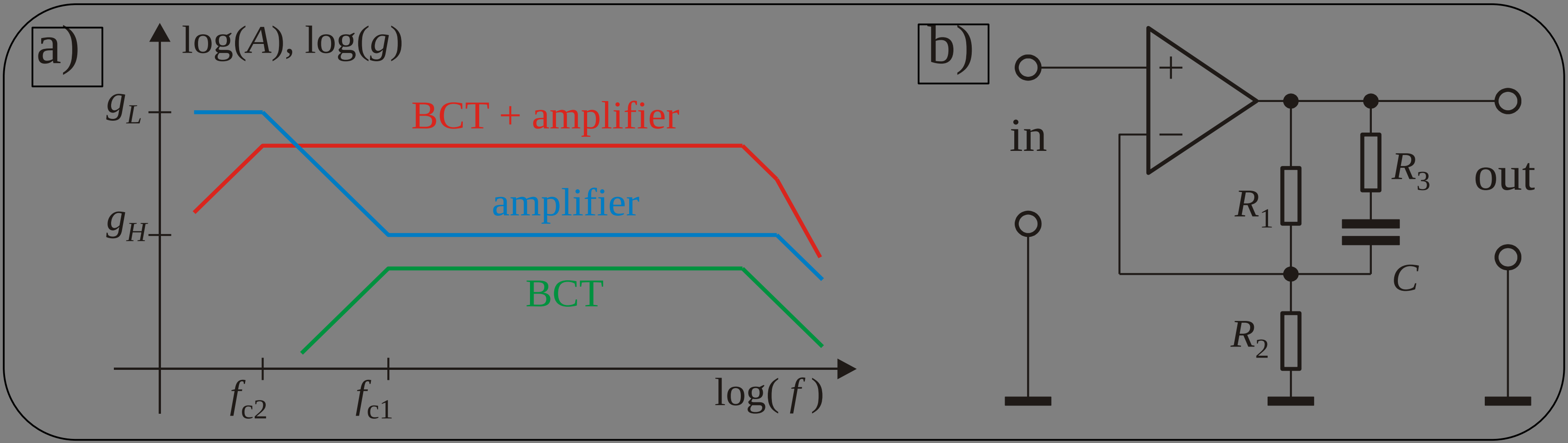




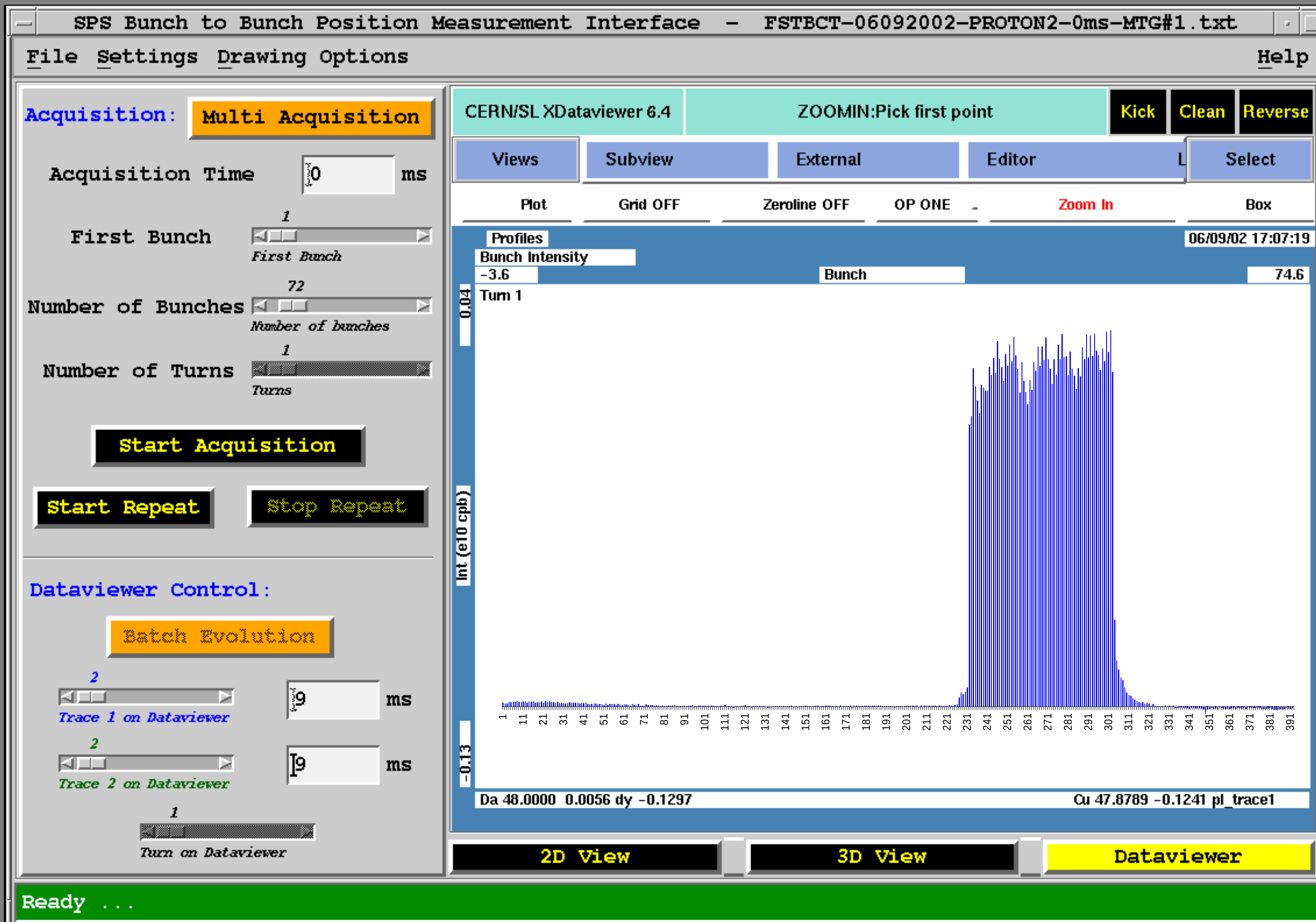
AC (Fast) Transformer Response

- 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

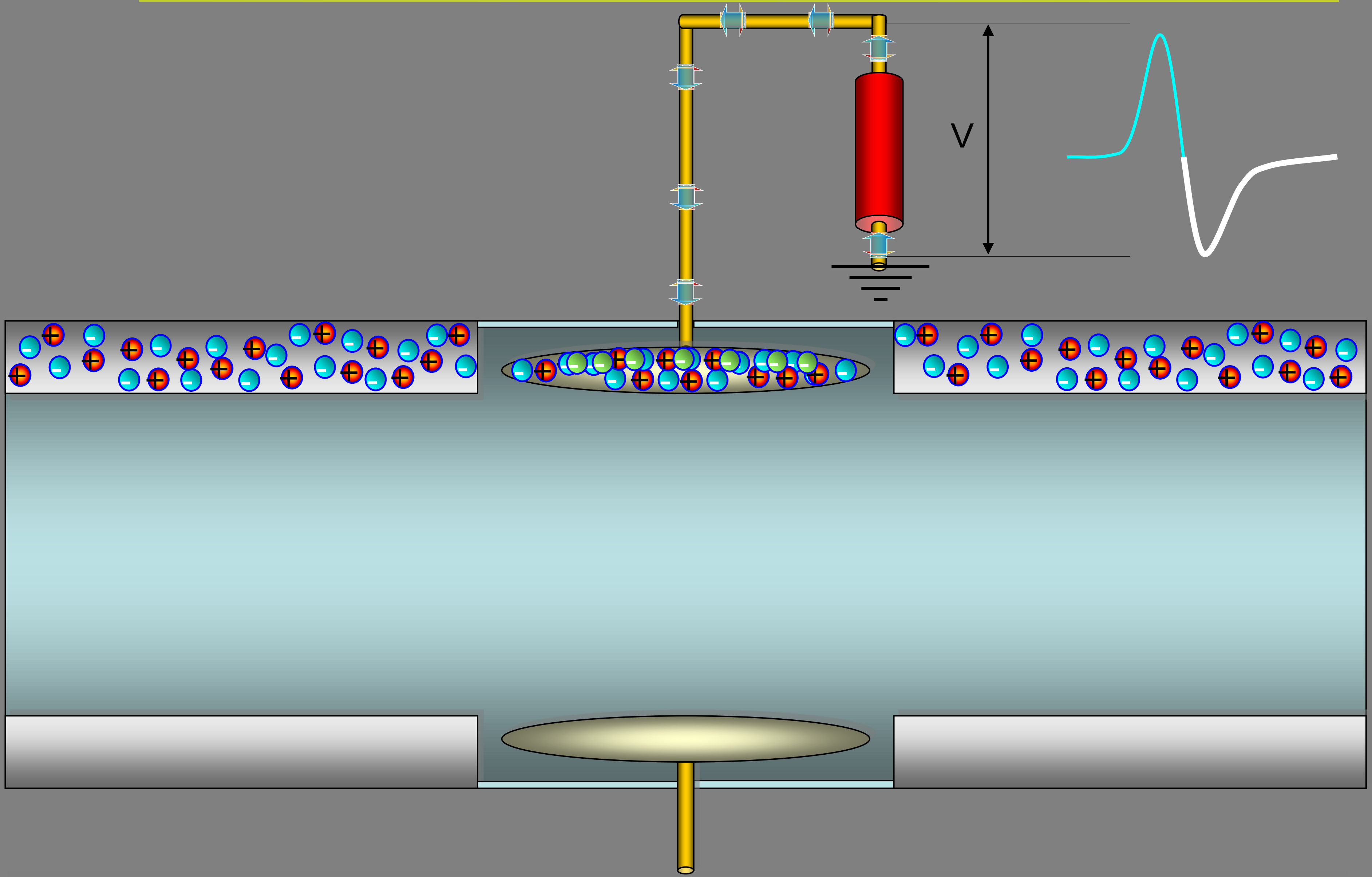


Bad RF Capture of a single LHC Batch in the SPS (72 bunches)

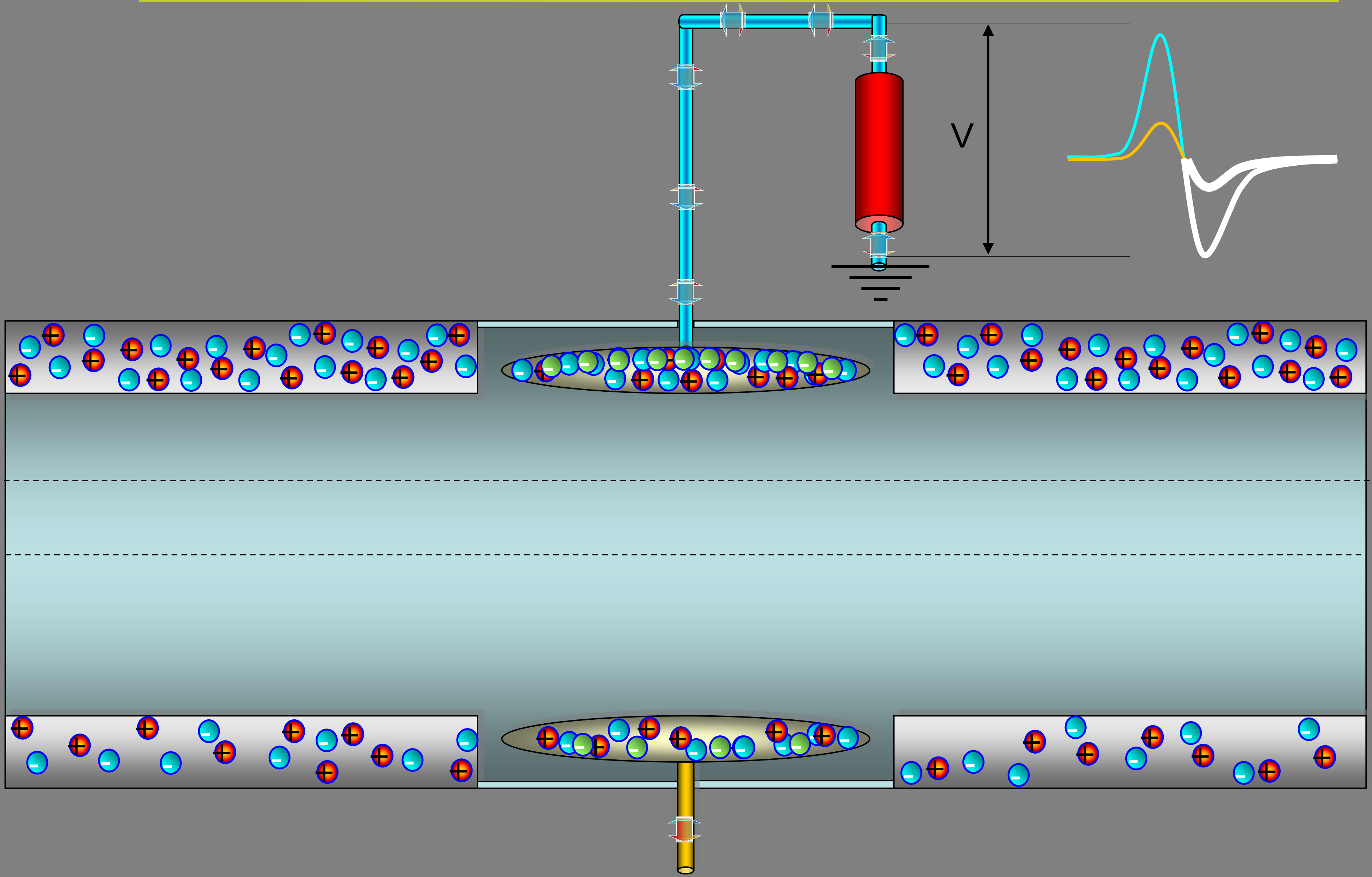
The Typical Instruments

- 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

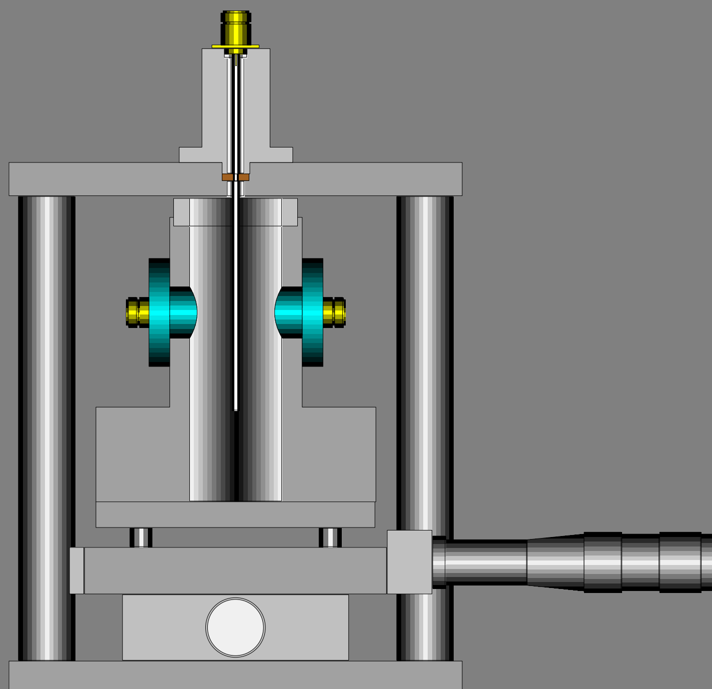


Principle of Beam Position Monitors

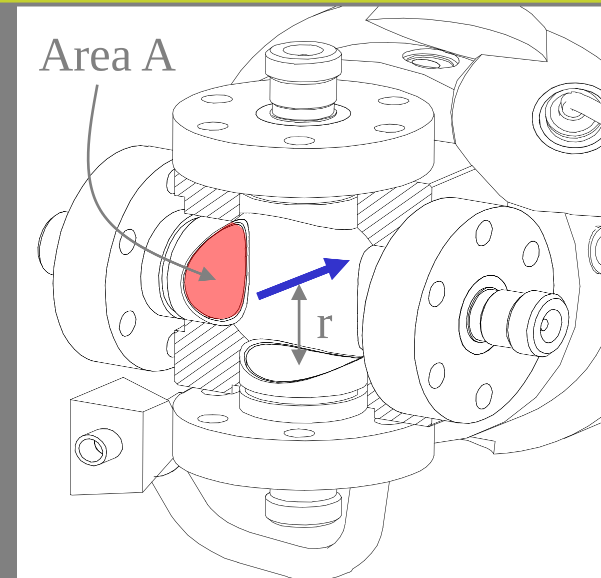
- Intercept “beam image current” in the vacuum chamber on two isolated (capacitive) pickups.
- Other pickups (more involved): shoebox (linear) pickups, stripline directional couplers….
- Use high precision Rf electronics to shape the signals (short bunches deliver signals with high frequency content)
  - 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

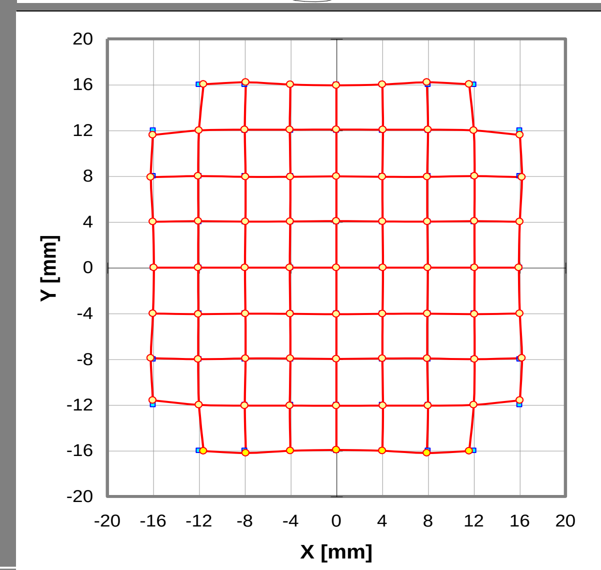
Electrostatic Pick-up – Button

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



Position mapping with movable antenna



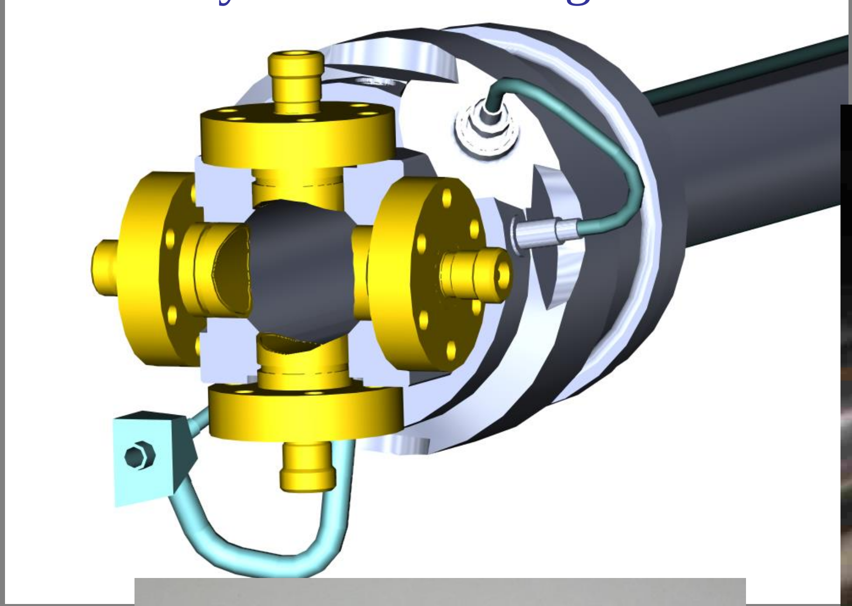


$$X = 2.30 \cdot 10^{-5} X_1^{\,5} + 3.70 \cdot 10^{-5} X_1^{\,3} + 1.035 X_1 + 7.53 \cdot 10^{-6} X_1^{\,3} Y_1^{\,2} + 1.53 \cdot 10^{-5} X_1 Y_1^{\,4}$$

Realization of Button BPM at LHC

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

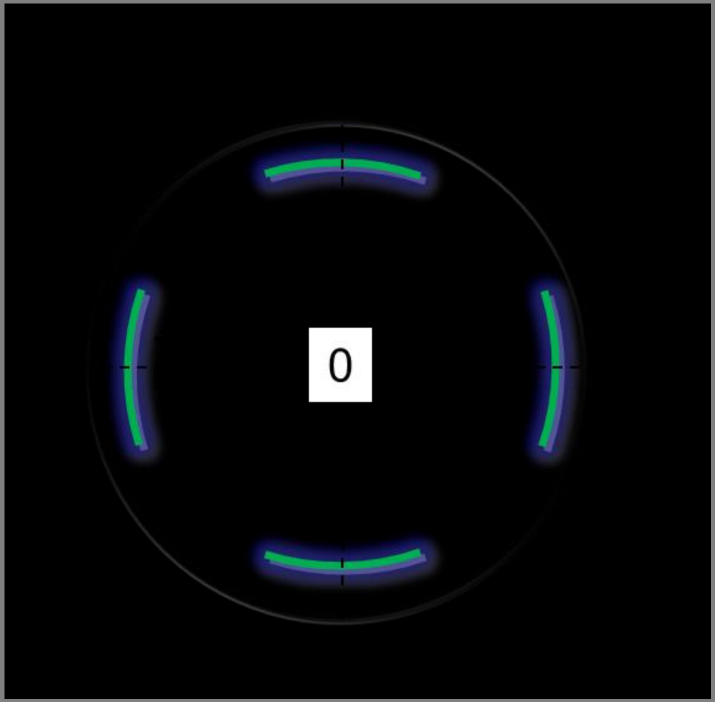
Critically: 50 Ω matching of button to standard feed-through.

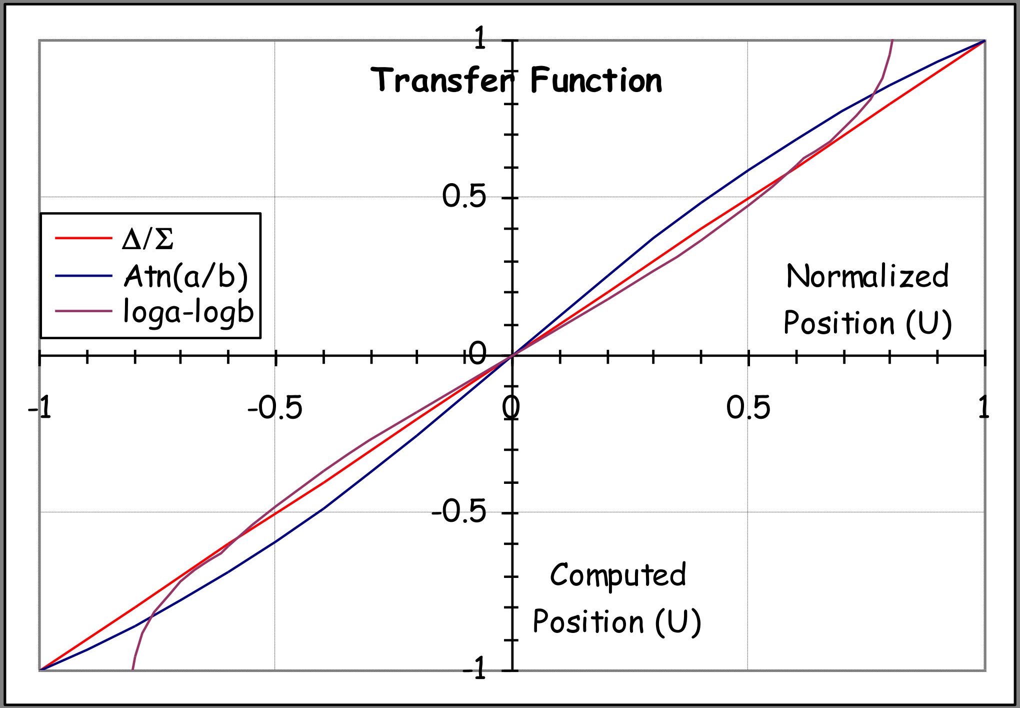


From C. Boccard, C. Palau-Montava et al.(CERN).

Normalising the Position Reading

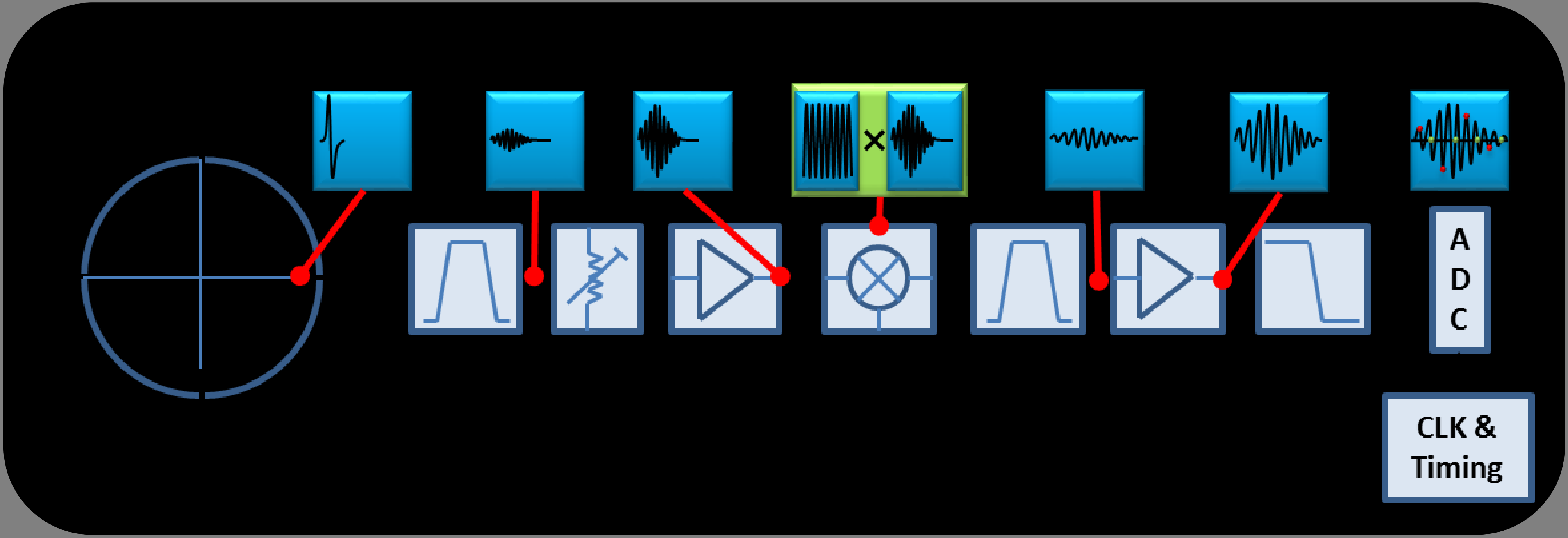
- To make it independent of intensity
- 3 main methods:
  - Difference/Sum : $(V_A - V_B) / (V_A + V_B) = \Delta / \Sigma$
  - Phase : $\text{Arctan}(V_A / V_B)$
  - Logarithm : $\text{Log}(V_A) - \text{Log}(V_B)$



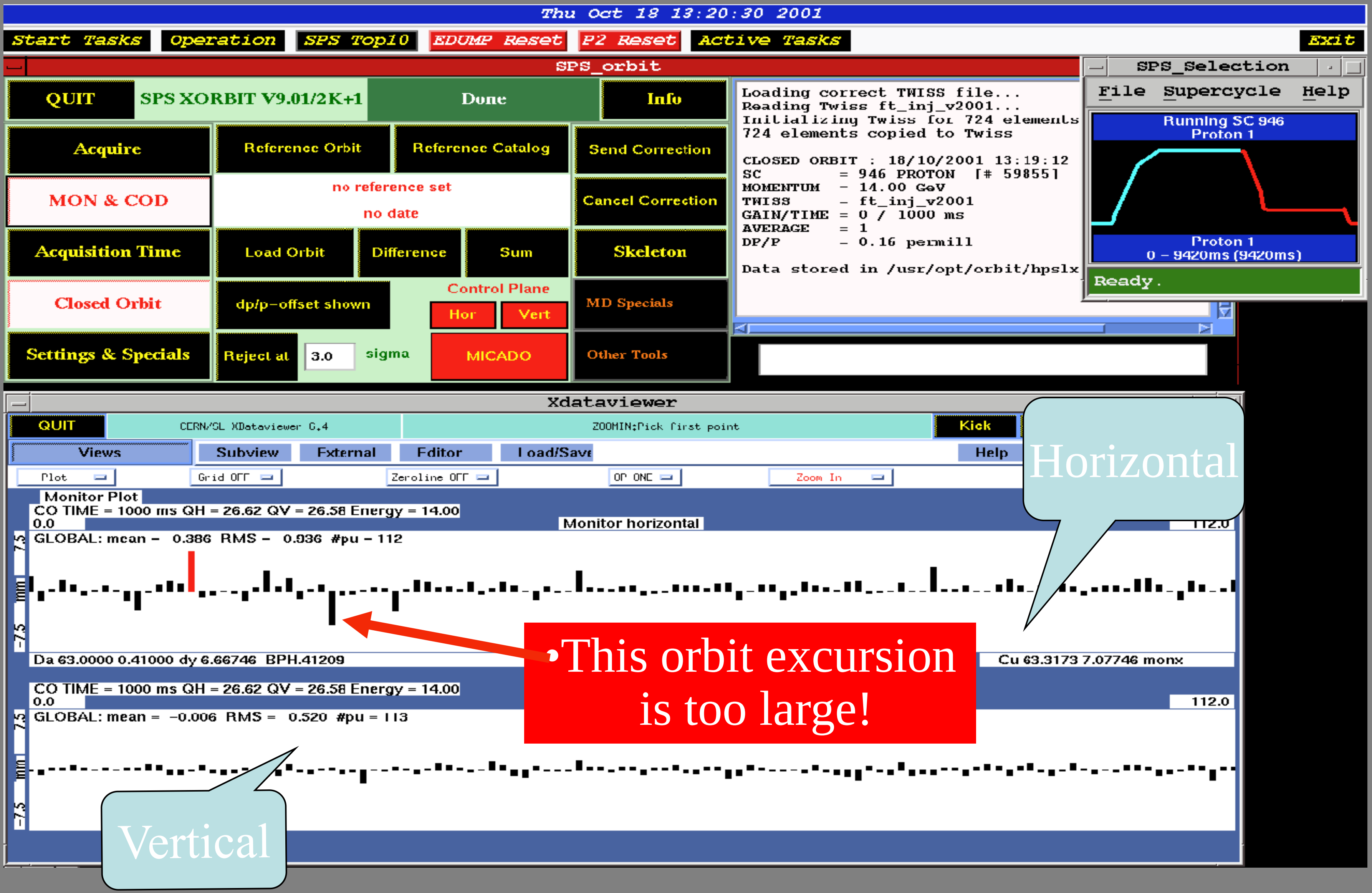


Modern BPM Read-out Electronics

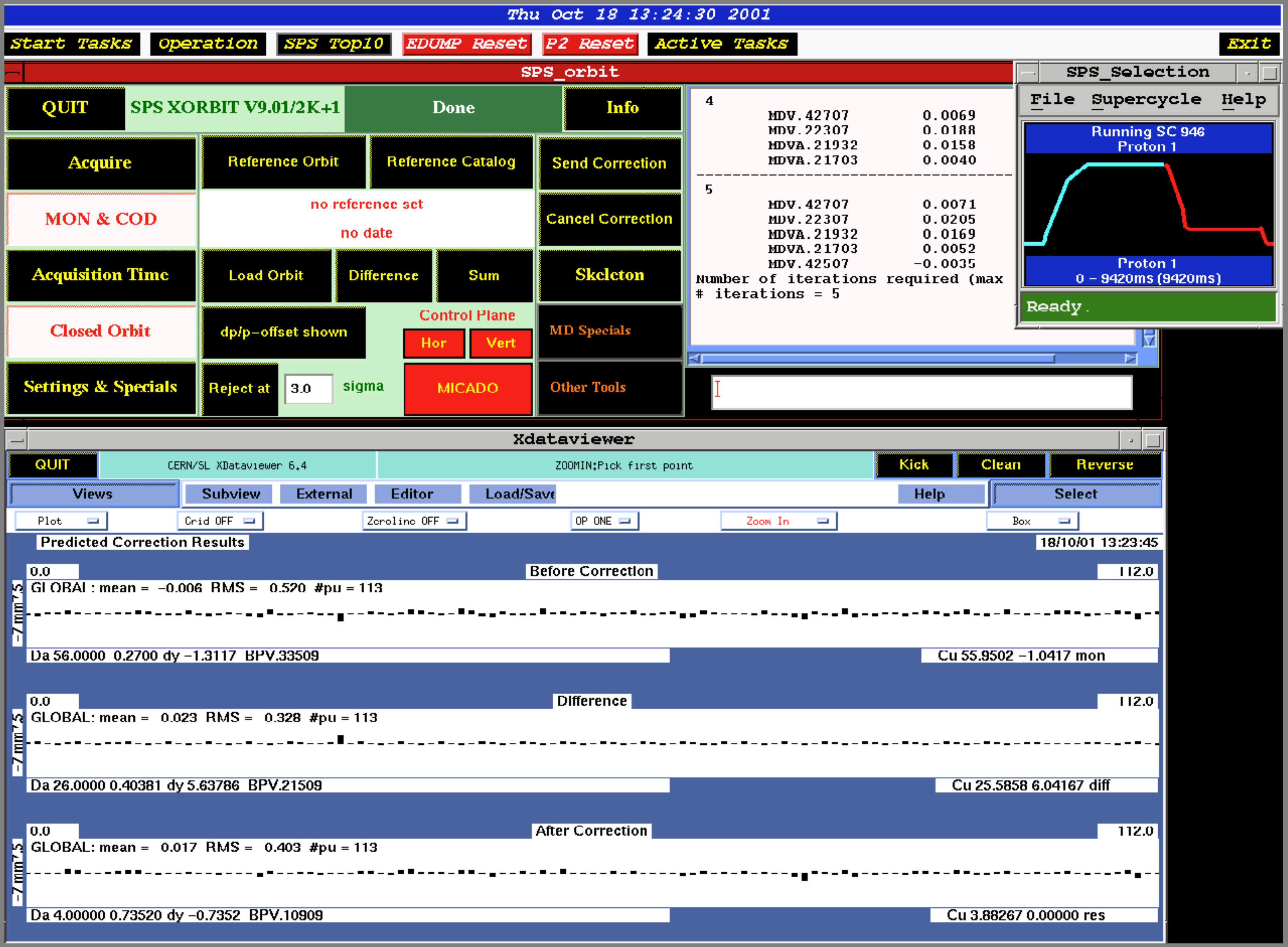
- Based on the individual treatment of the electrode signals
  - Use of frequency domain signal processing techniques
    - Developed for telecommunications market
  - Rely on high frequency & high resolution analogue to digital converters
    - Minimising analogue circuitry
    - Frequency down-conversion 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)



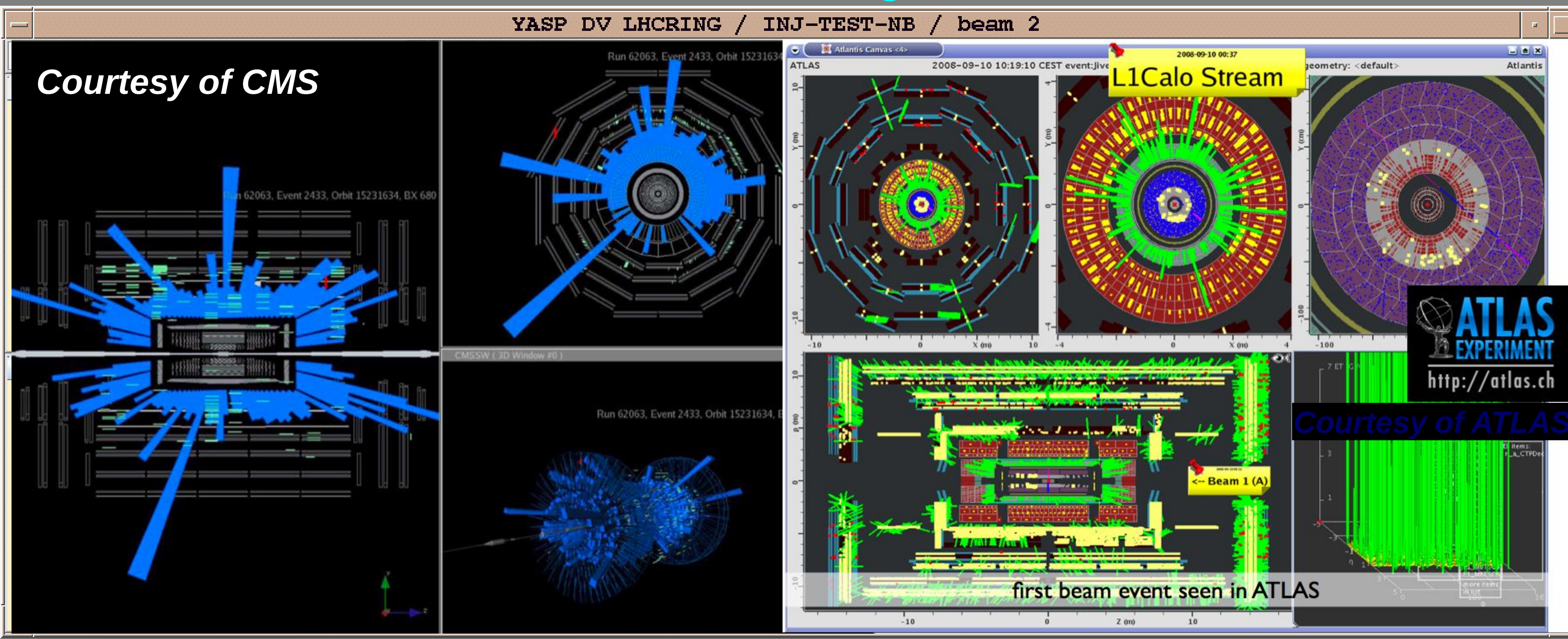
Orbit Correction (Detail)

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

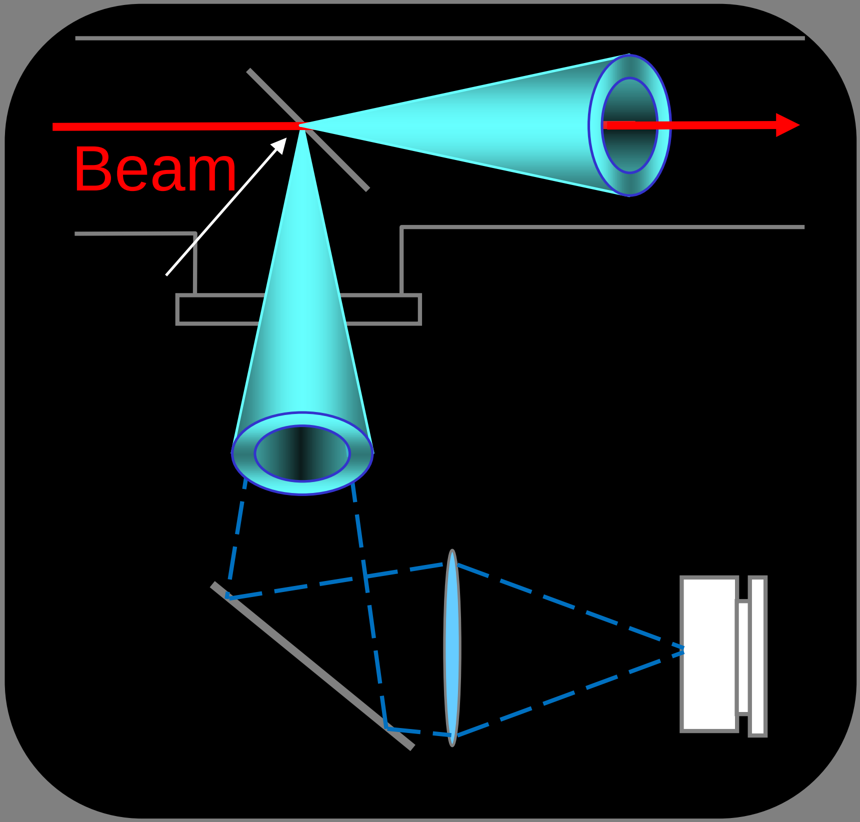
Turn by turn trajectory on each BPM; beam forced on constant oscillation → Beta function and phase advances

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)

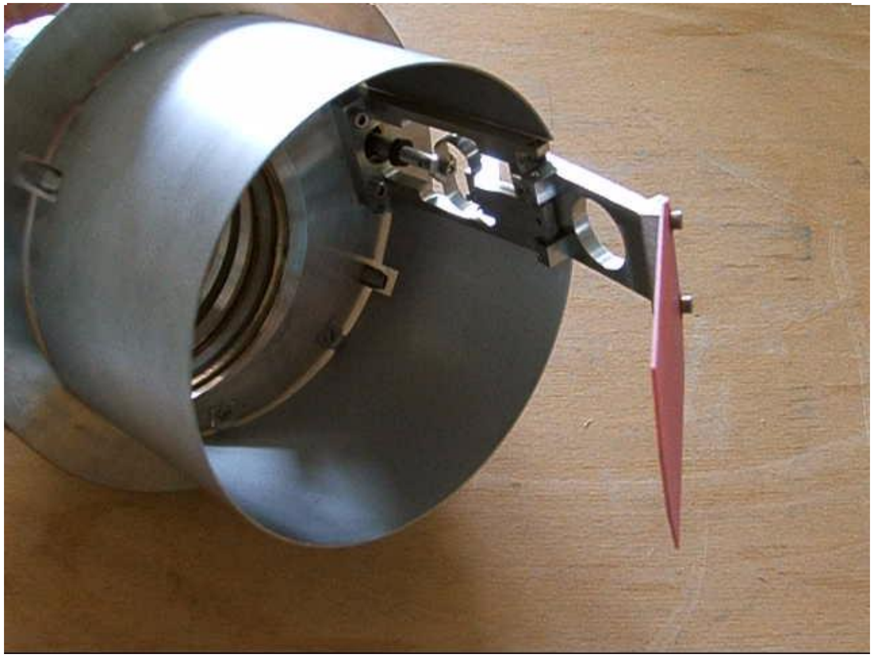
Beam Profile Monitoring using Screens

- 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

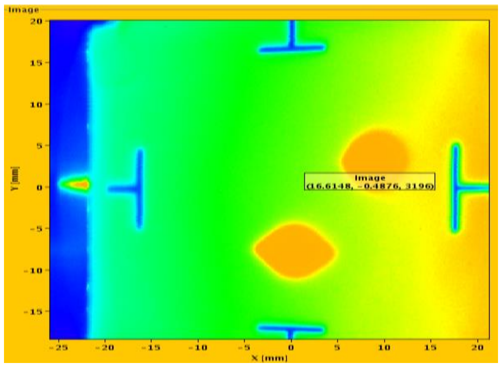


Screen mechanism

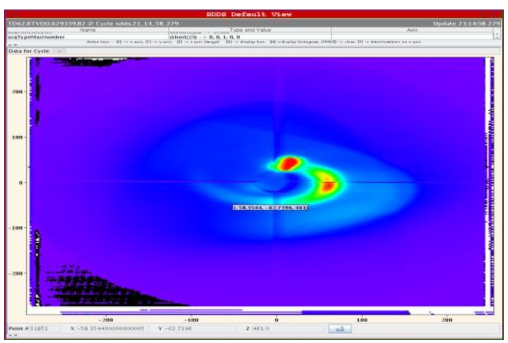
- Screen with graticule



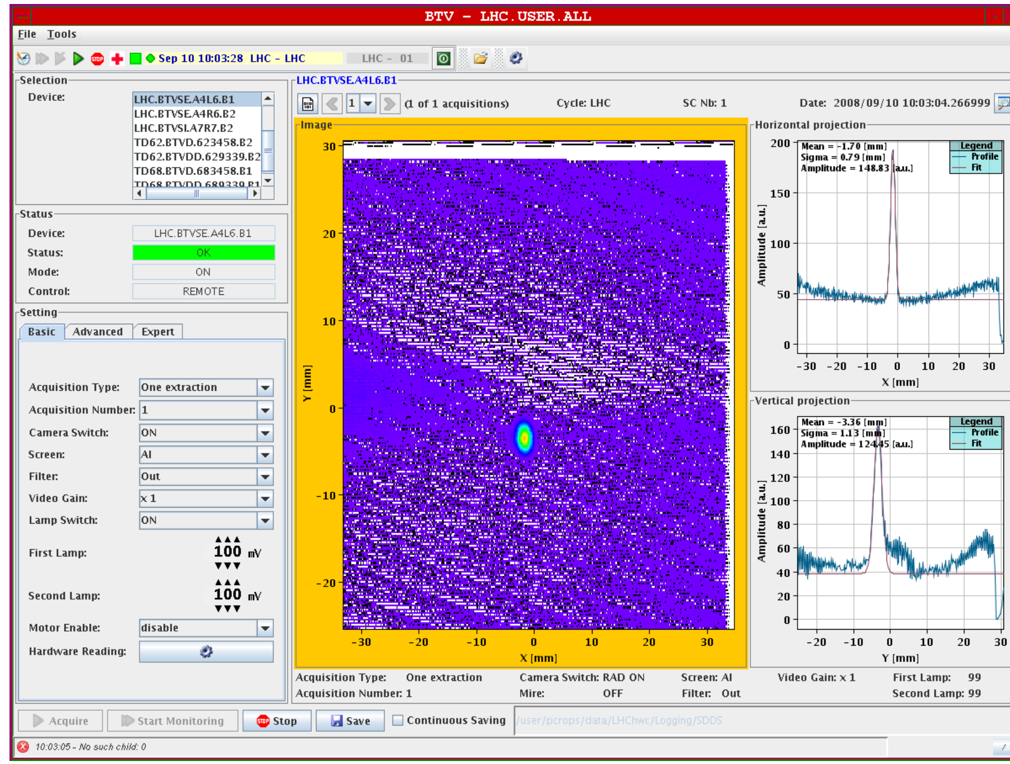
Results from TV Frame grabber



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

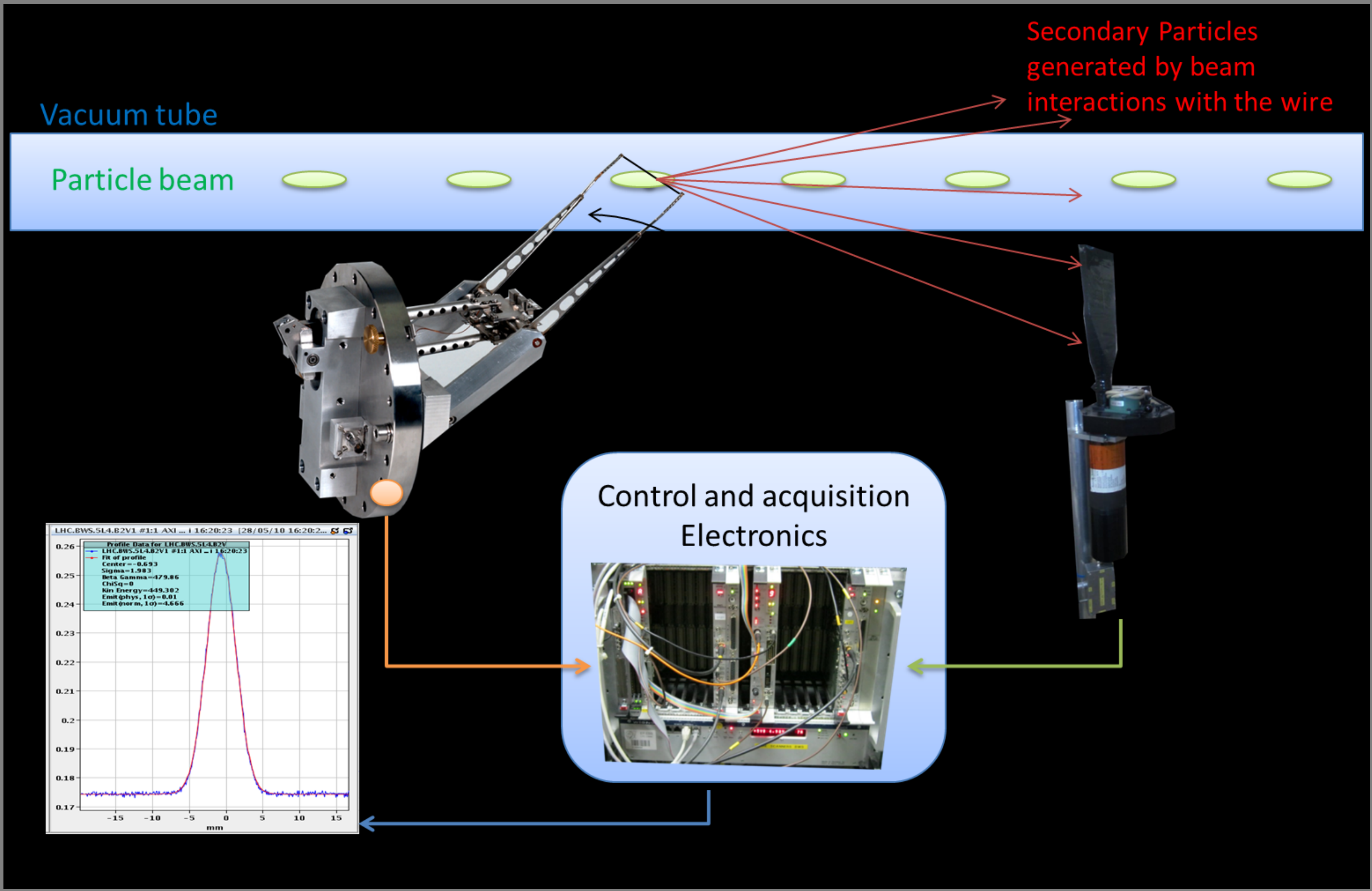


Un-captured beam sweeps through he dump line

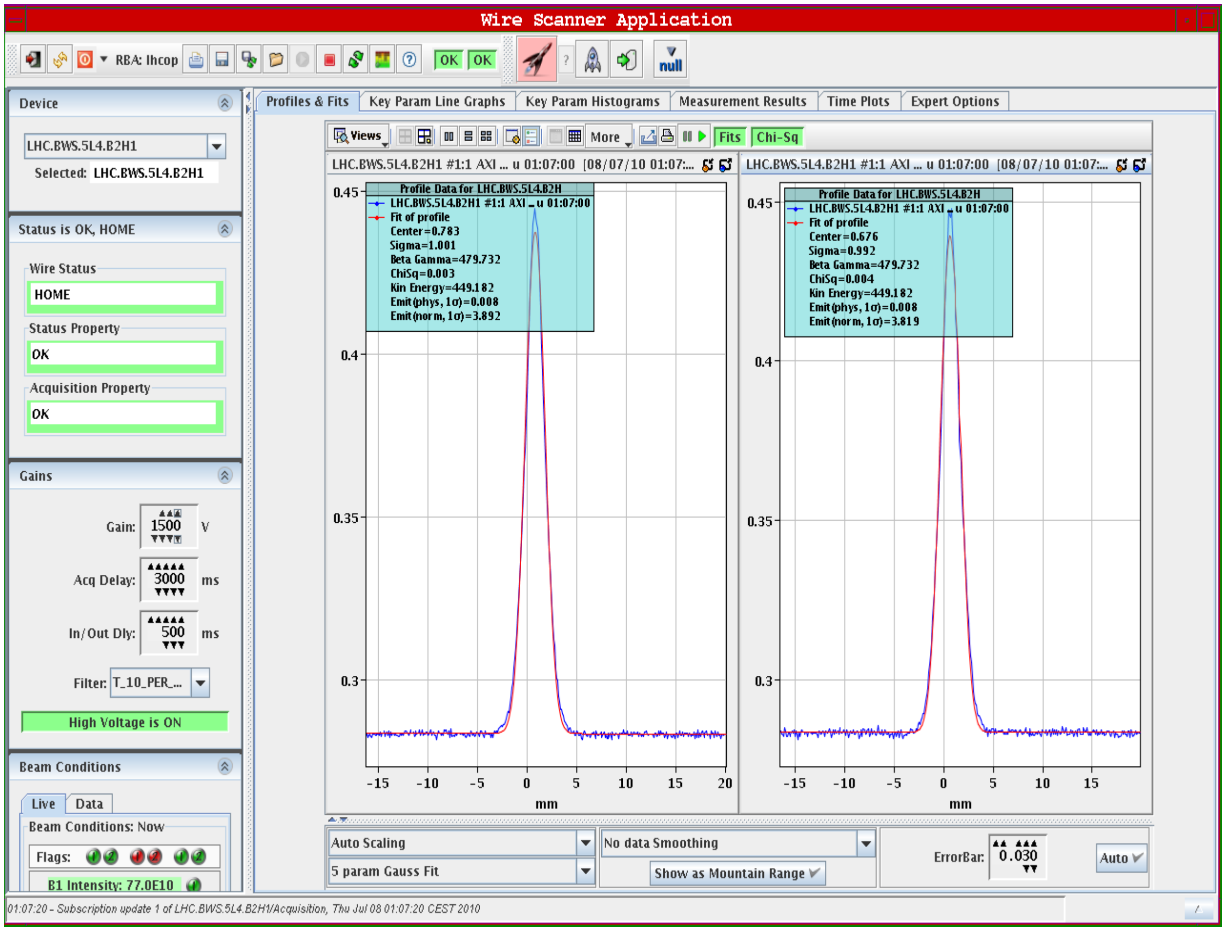


- For further evaluation the video signal is digitized, read-out and treated by program

Beam Profile Monitoring using Wire-Scanners



Wire scanner profile



High speed needed because of heating.

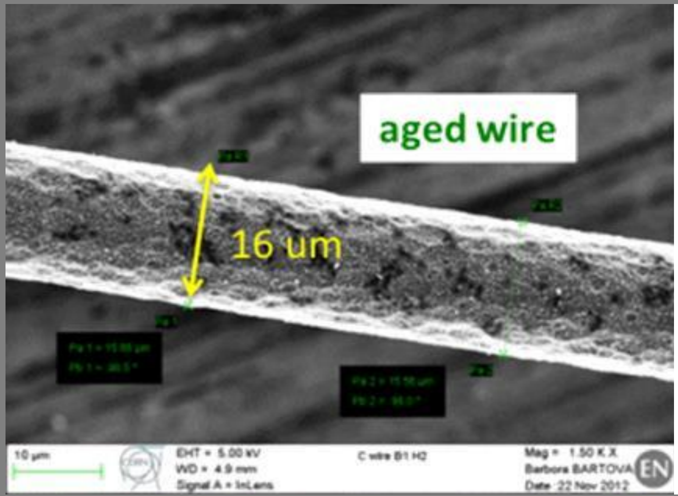
Adiabatic damping

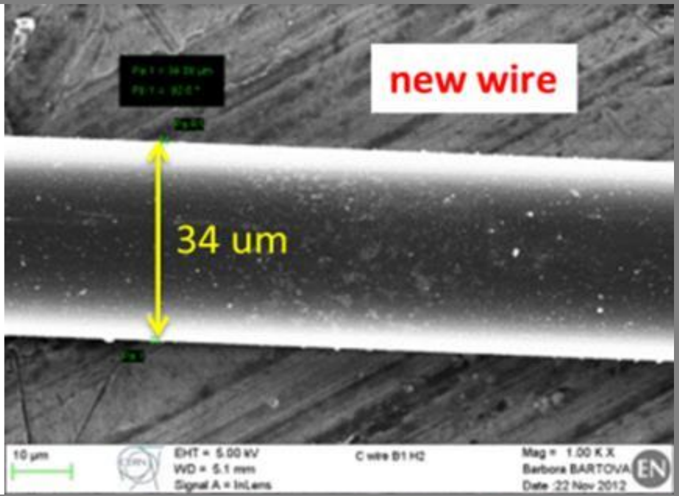
Current increase due to speed increase

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

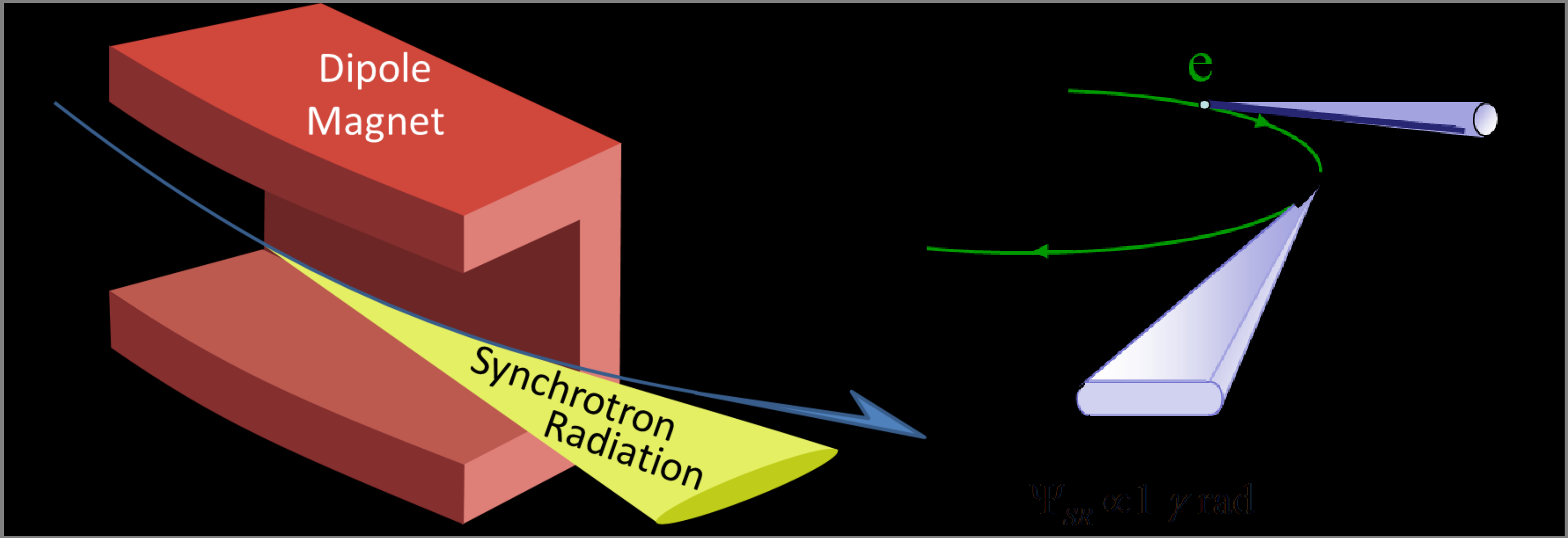
Limitation of WireScanners

- 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

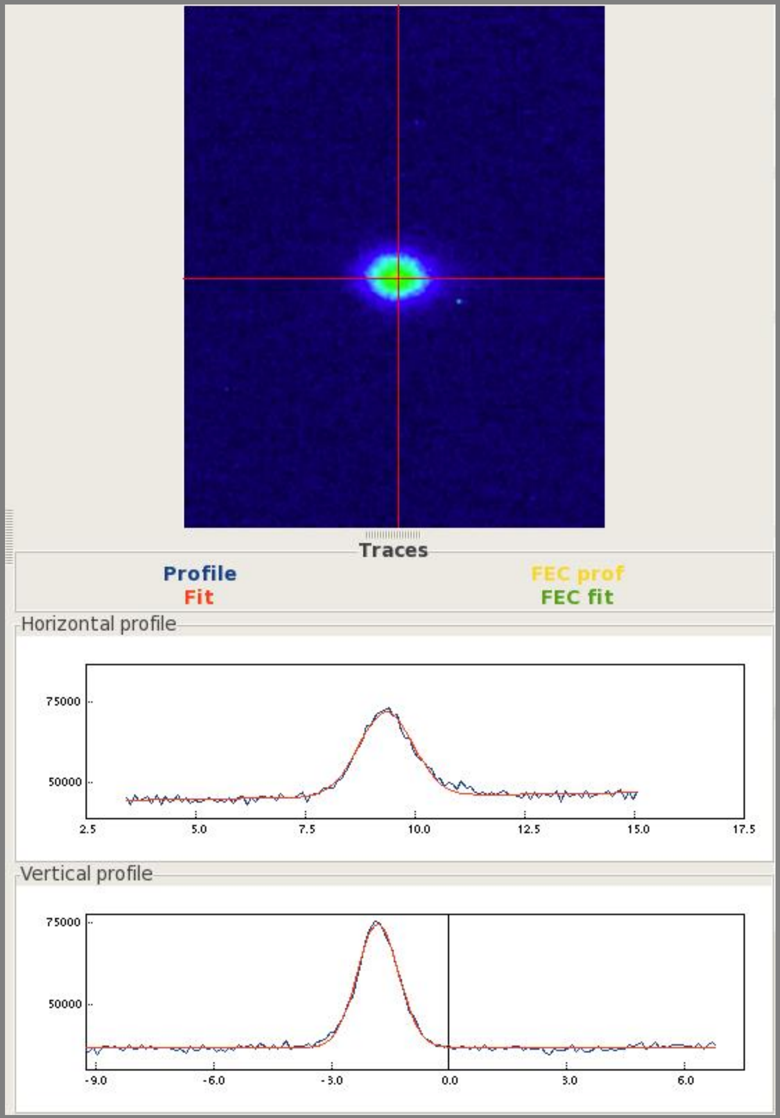


- Synchrotron light
  - Emitted from a moving charge bent in a magnetic field
  - The main “raison d’être” for light sources
  - Also a very useful, non-invasive, powerful diagnostic tool
  - Can even be observed with protons & lead ions in the LHC

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 shorter 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?

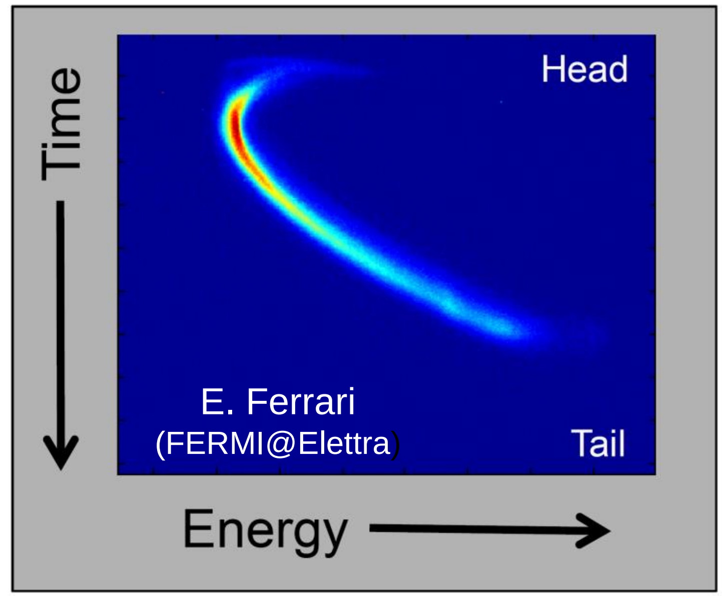
p^+ @ LHC	250ps
H^- @ SNS	100ps
e^- @ ILC	500fs
e^- @ CLIC	130fs
e^- @ XFEL	80fs
e^- @ LCLS	<75fs

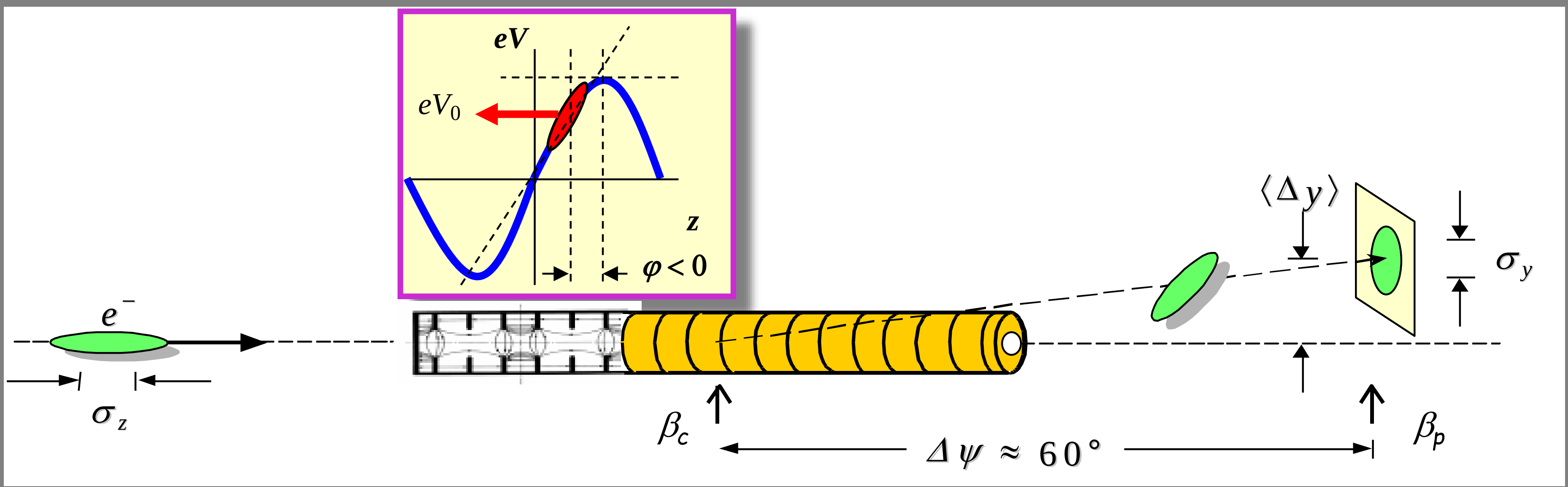
  - Direct Observation
    - Produce light & observe with dedicated instruments
    - Use of RF techniques
    - Use laser pulses and sampling techniques
  - Indirect Calculation
    - Reconstruct bunch length from frequency spectrum
      - Either directly from the bunch or through its radiation spectrum

Destructive Measurement

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)





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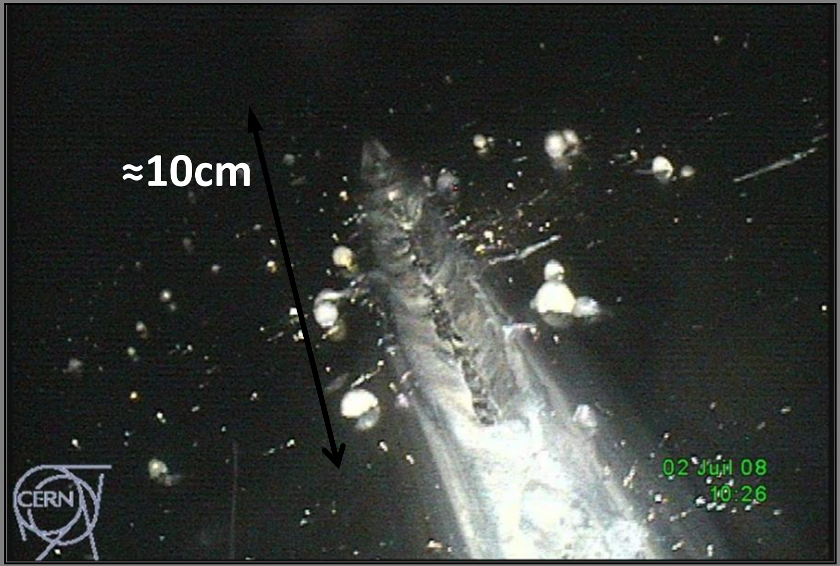
Beam Loss Detectors

- 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

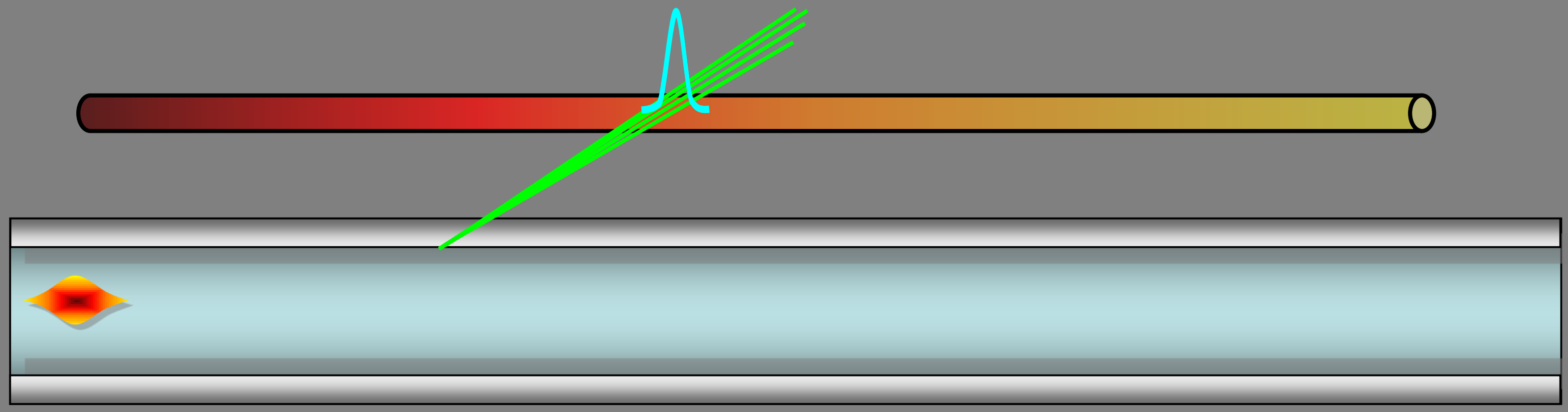
Quench and Damage at 7 TeV	
Quench level	≈ 1mJ/cm^3
Damage level	≈ 1 J/cm^3



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

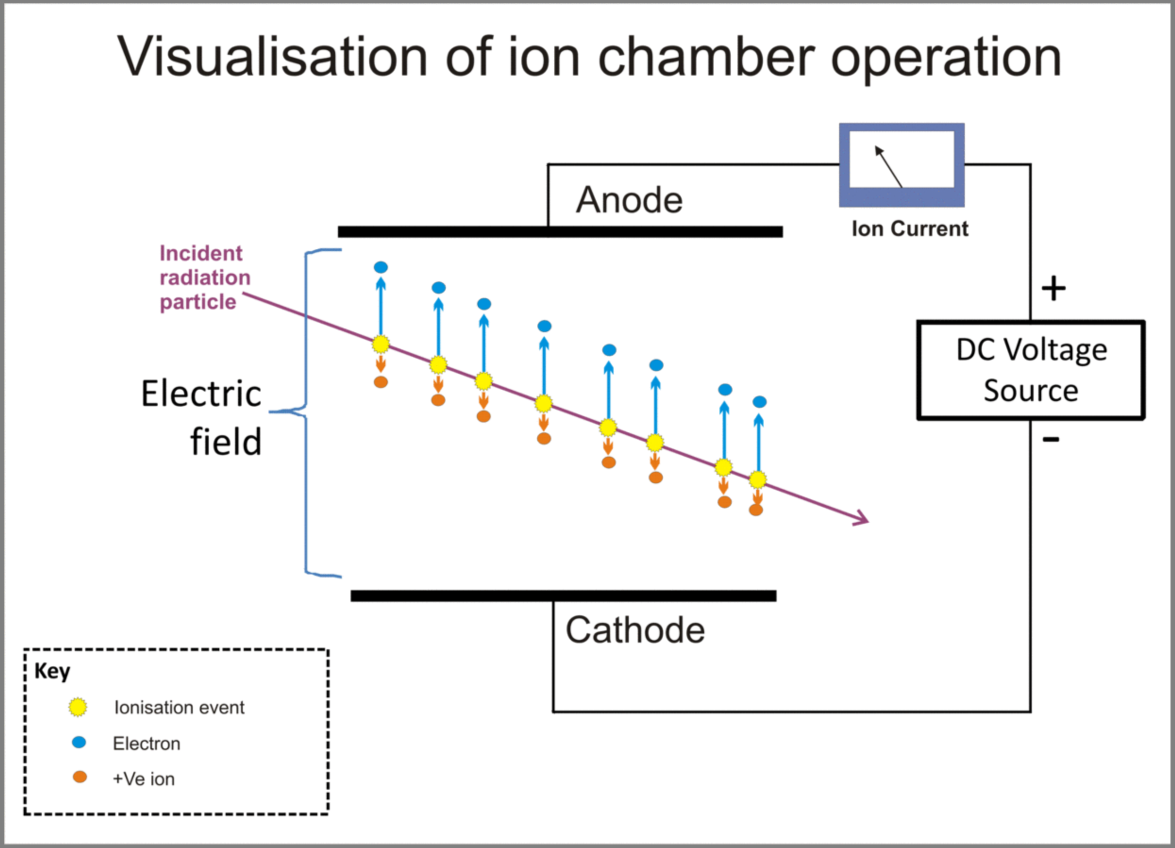
Beam Loss Detectors

- 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



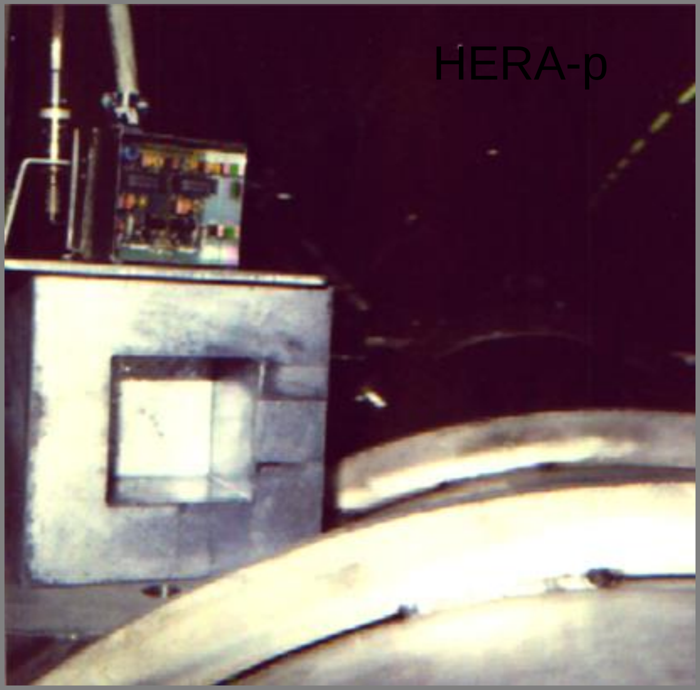
Beam Loss Detectors

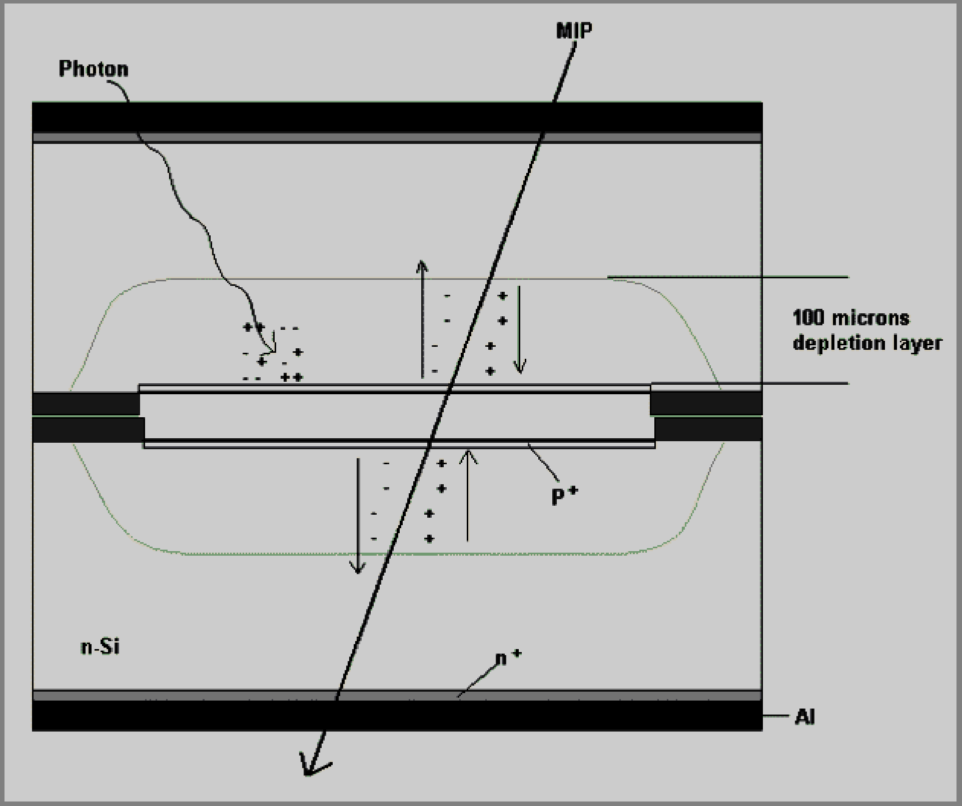
- Common types of monitor
  - Ionisation chambers
  - Dynamic range of < 10^8
  - Slow response (μs) due to ion drift time



Beam Loss Detectors

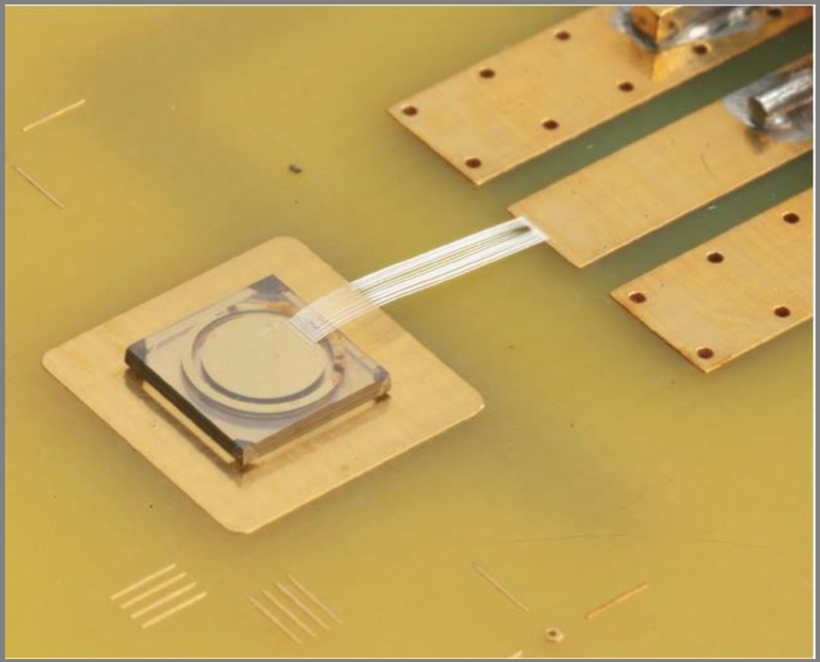
- Common types of monitor
  - PIN photodiode (solid state ionisation chamber)
    - Detect coincidence of ionising particle crossing photodiodes
    - Count rate proportional to beam loss with speed limited by integration time
    - Can distinguish between X-rays & ionising particles
    - Dynamic range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

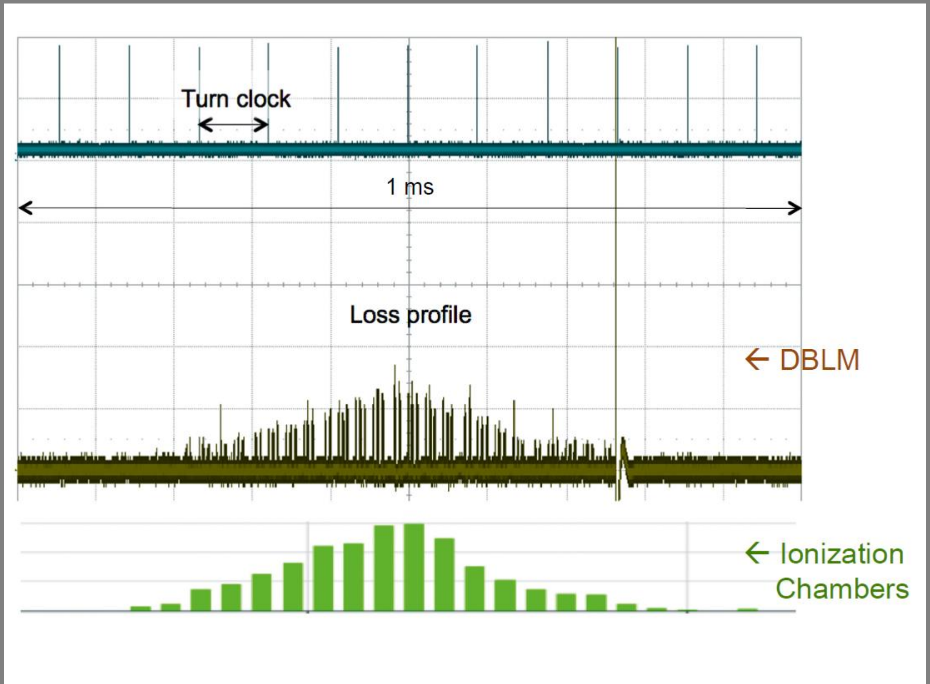


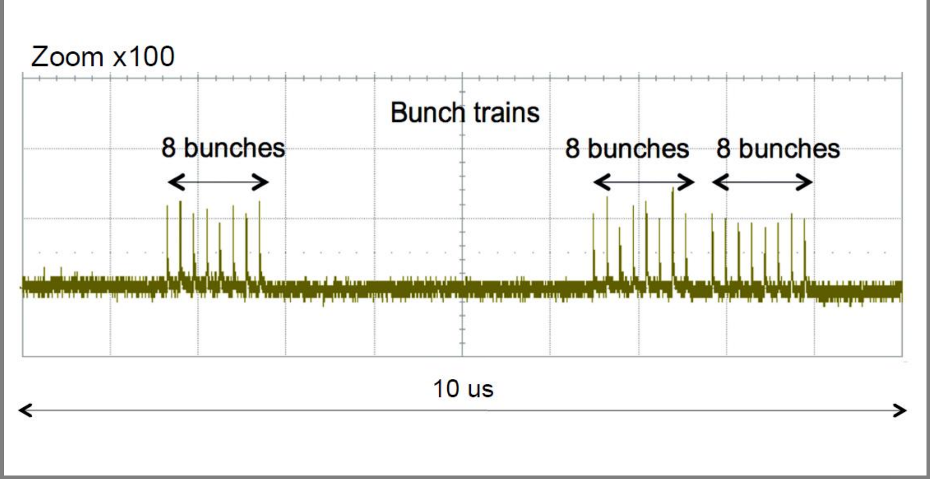


Beam Loss Detectors – New Materials

- 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



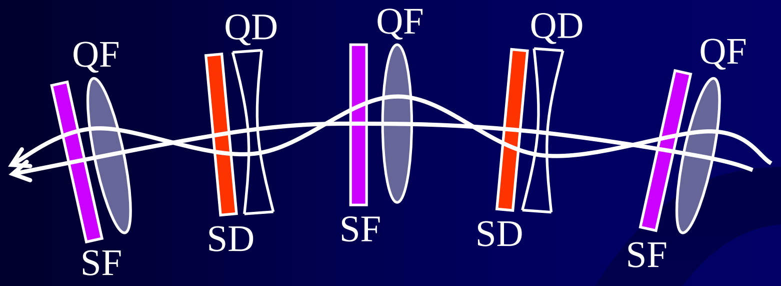




The Typical Instruments

- 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)

Measurement of Q (betatron tune)

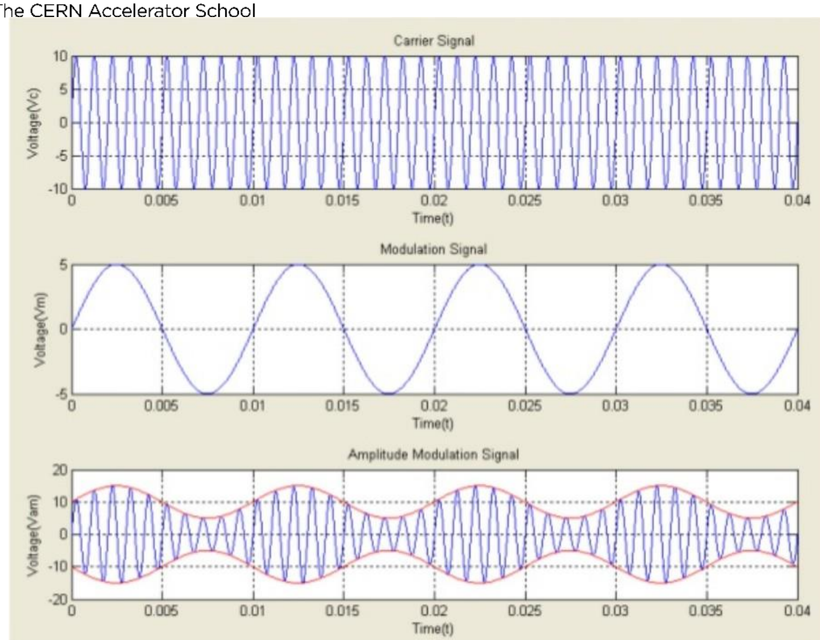


Characteristic Frequency of the Magnet Lattice

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

Amplitude modulation



$$v = V_{env} \sin 2\pi f_c t$$
$$= V_c (1 + m \sin 2\pi f_m t) \bullet \sin 2\pi f_c t$$

m= modulation index 0…1 ($V_{env} = V_c$)

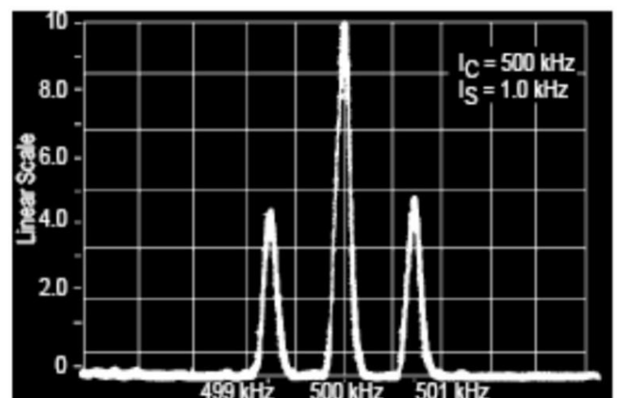
Using trigonometric identity:

$$(\sin a)(\sin b) = 1/2[\cos(a-b) - \cos(a+b)]$$

$$v = V_c \sin 2\pi f_c t + \frac{m}{2} V_c \cos 2\pi (f_c - f_m)t - \frac{m}{2} V_c \cos 2\pi (f_c + f_m)t$$

$$v_{AM} = V_c \sin 2\pi f_c t + \frac{V_m}{2} \cos 2\pi (f_c - f_m)t - \frac{V_m}{2} \cos 2\pi (f_c + f_m)t$$

Carrier LSB USB



Relevant example of amplitude modulation: stimulated betatron oscillation(or: tune measurement)

taken from R.Jones,
proc. of BI-CAS 2018

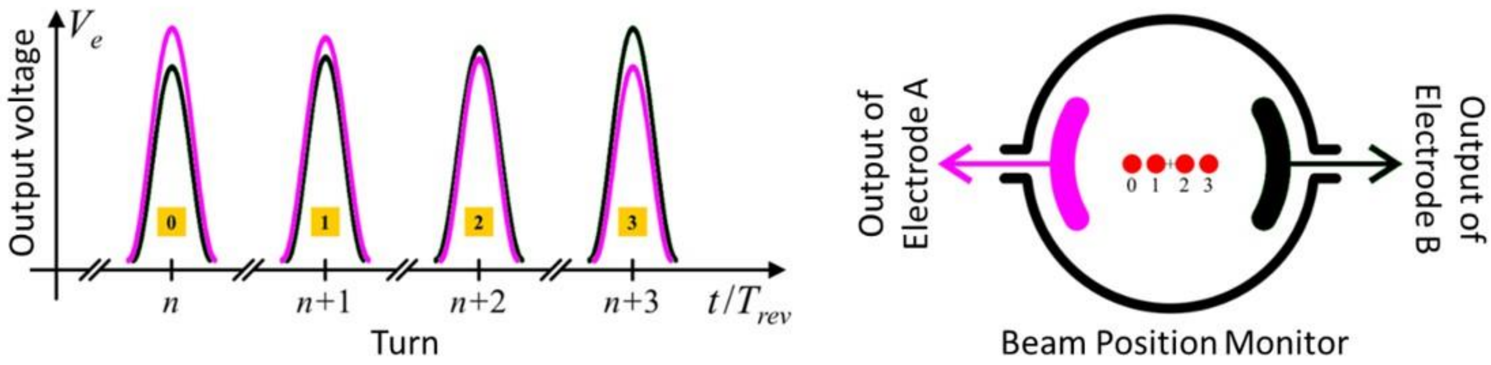


Fig. 4: Detecting oscillations using a beam position monitor. The oscillation information is superimposed as a small modulation on a large intensity signal.

Beam centre of charge makes small betatron oscillation around the closed orbit
(- stimulated by an exciter or by a beam instability)

Depending on the proximity to an EM sensor the measured signal amplitude varies.

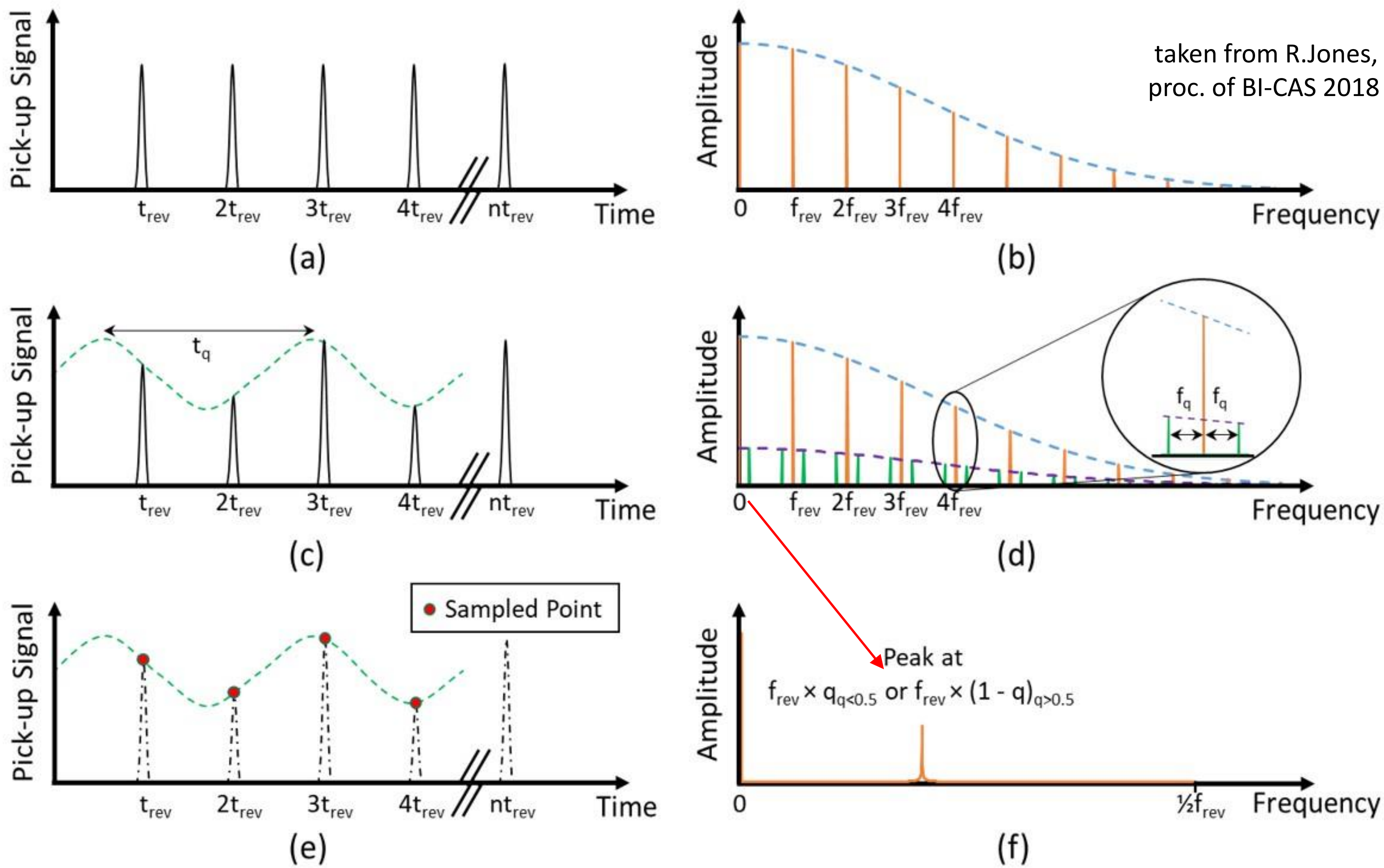
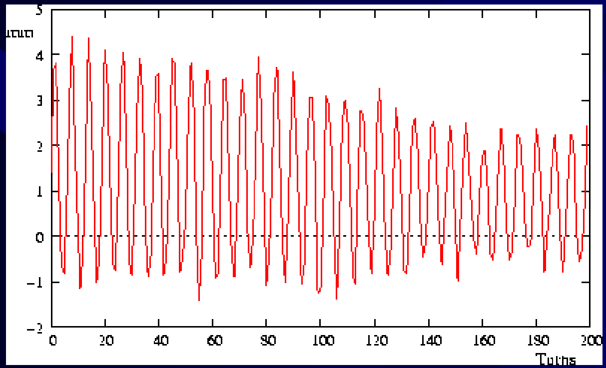
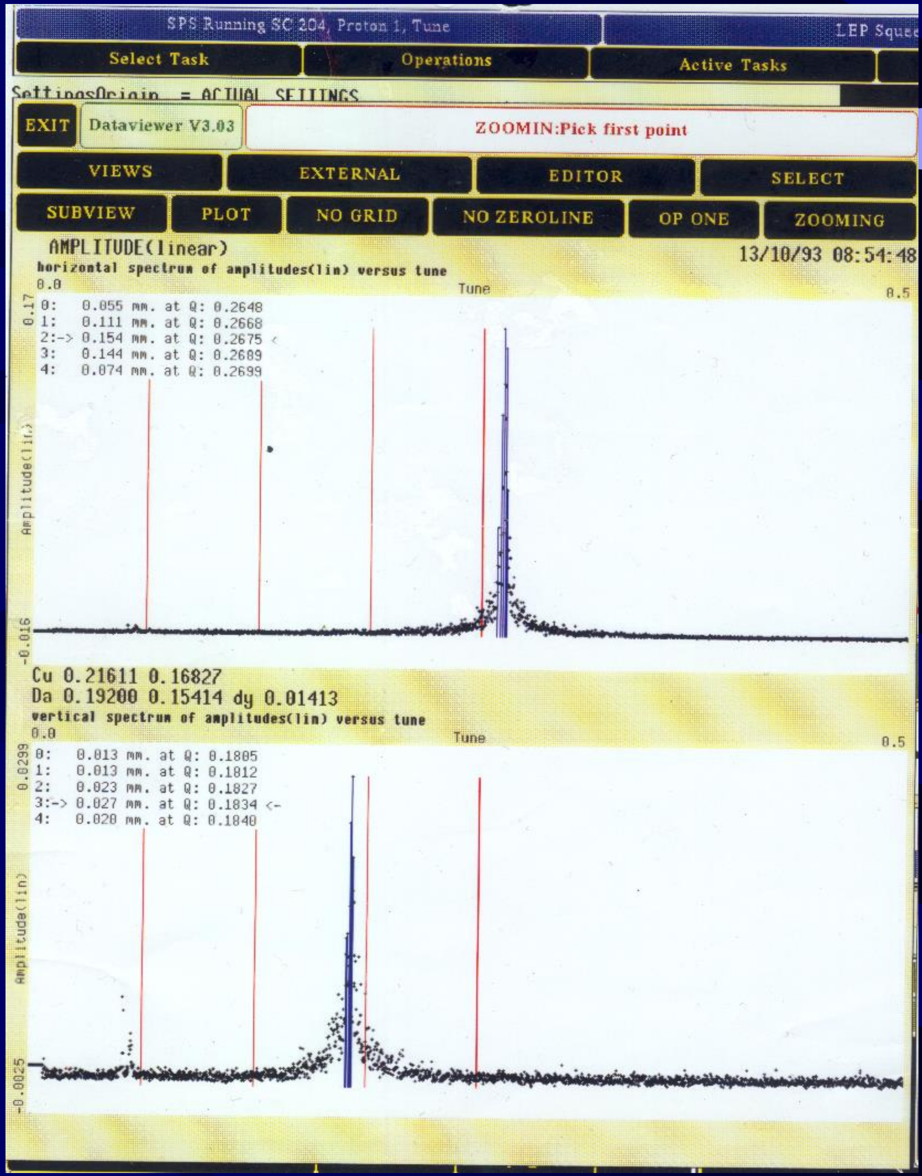


Fig. 2: Time and frequency domain representation for a bunch of particles observed at one single location on the circumference of the accelerator. (a & b) continuous measurement without betatron oscillation; (c & d) continuous measurement undergoing betatron oscillation (50% modulation); (e & f) sampled once per revolution.

Fourier analysis of turn by turn BPM measurements

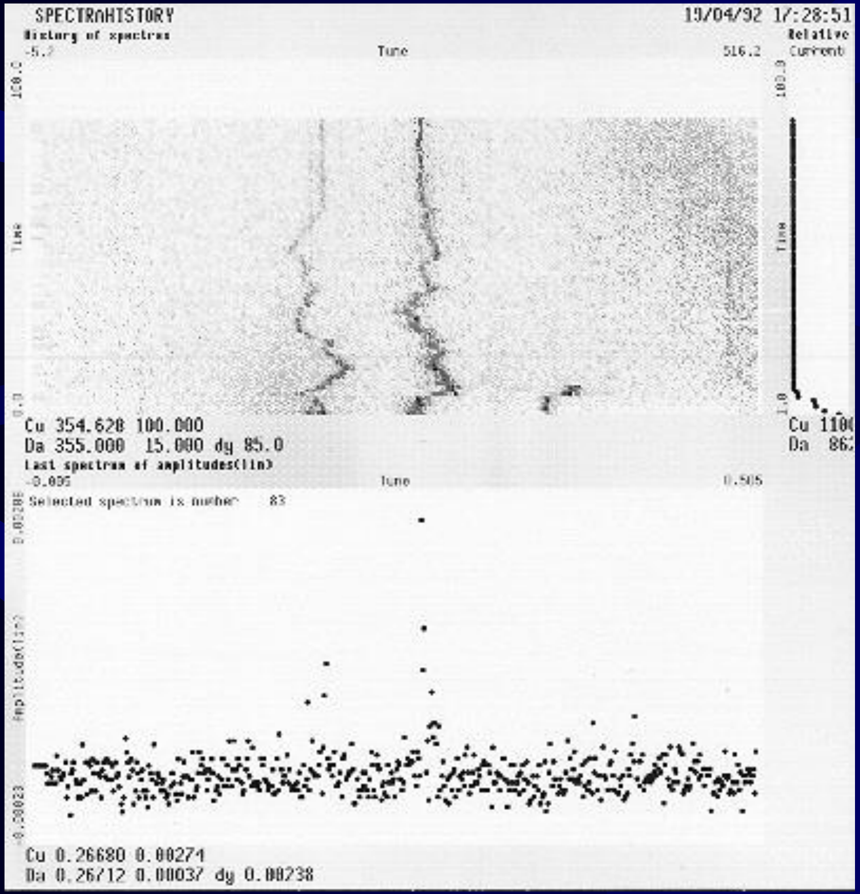
1) Stimulate transverse beam oscillation with a kicker magnet (short dipole kick during one revolution period)
2) Measure turn-by turn beam position
3) Fourier transform of data
4) Tune: = maximum of frequency spectrum
5) Resolution: dq/q = 2/Nsamp
6) Problems:
   - single shot measurement
   - oscillation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

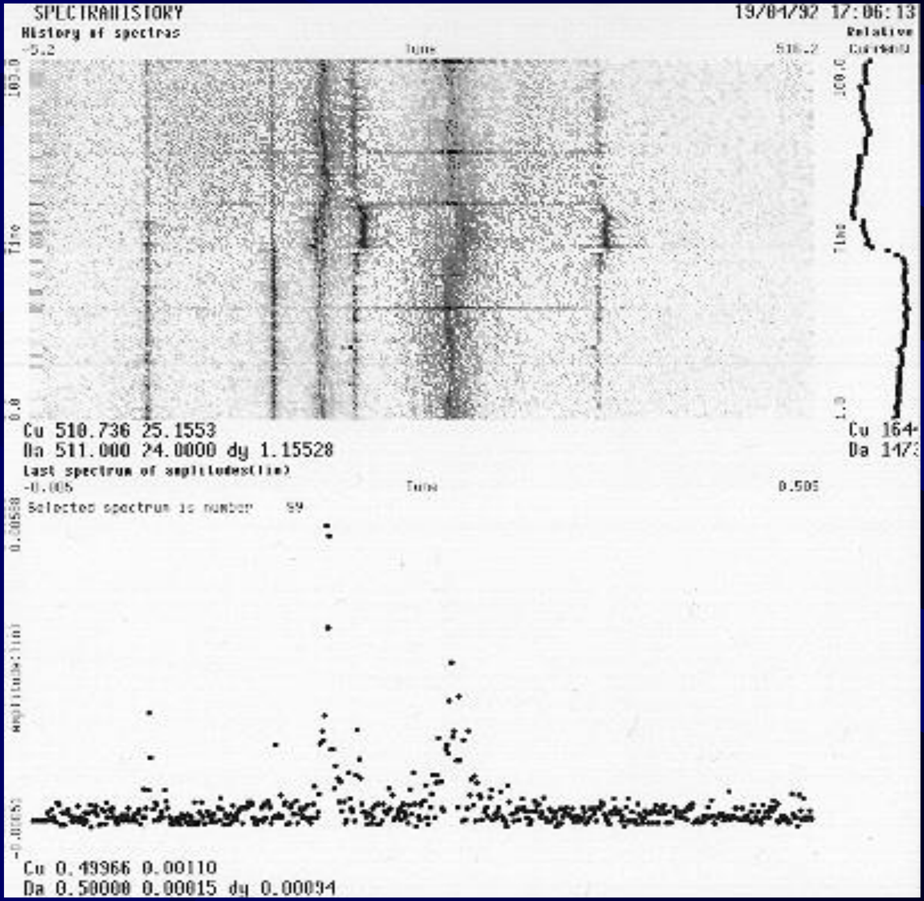




Time Resolved Measurements

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



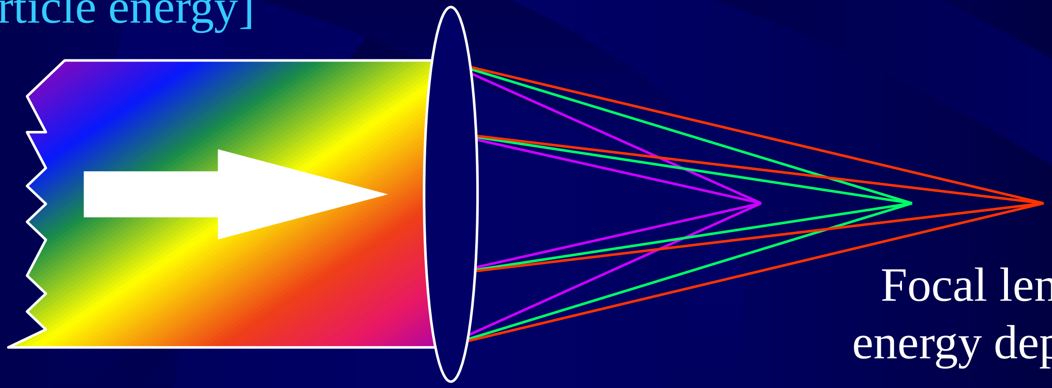


Chromaticity (Q' or ξ)

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

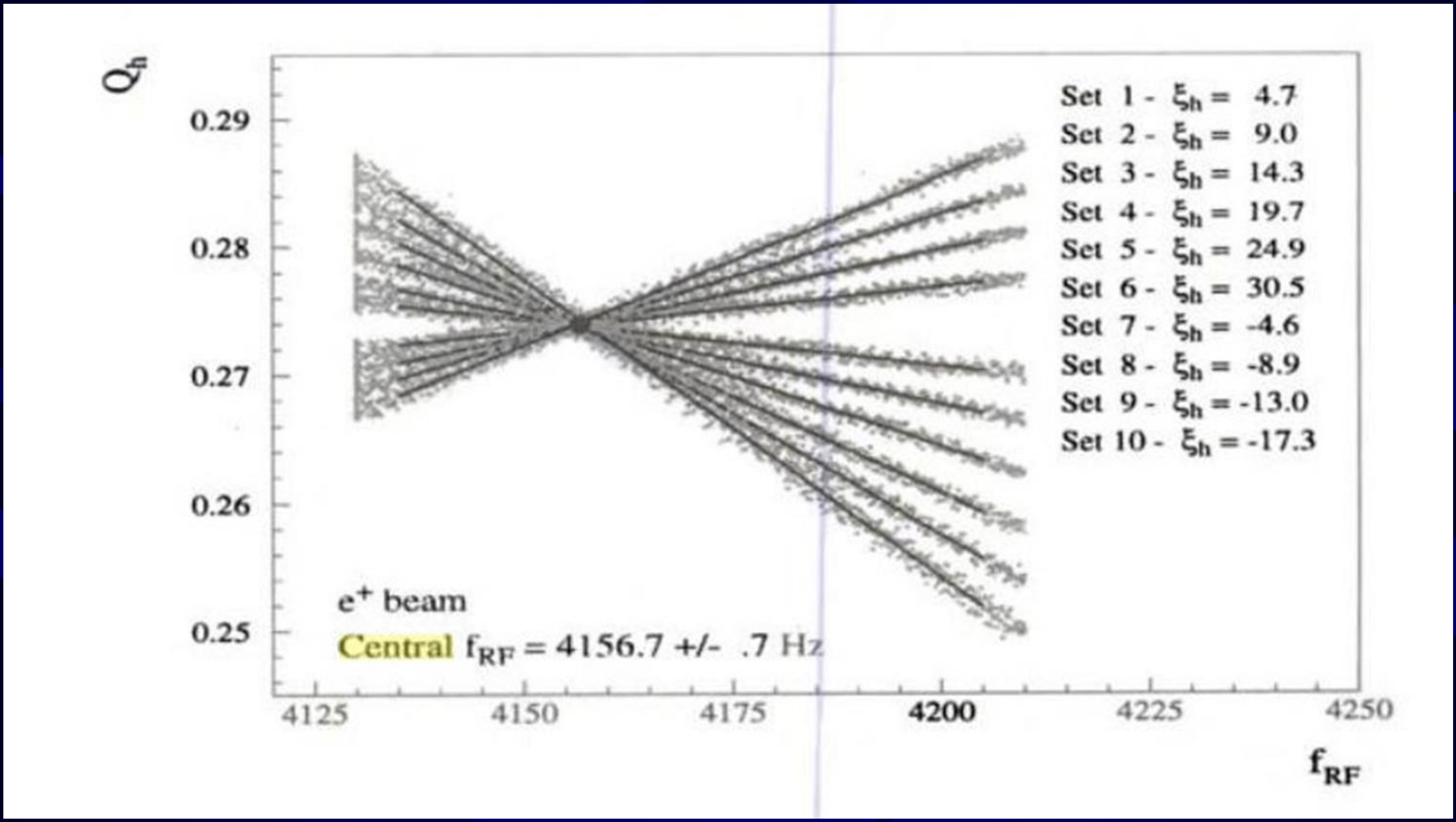
$$\Delta Q = Q' \frac{\Delta p}{p} = \left(\frac{1}{\gamma^2} - \alpha \right)^{-1} Q' \frac{\Delta f}{f}$$

Optics Analogy:

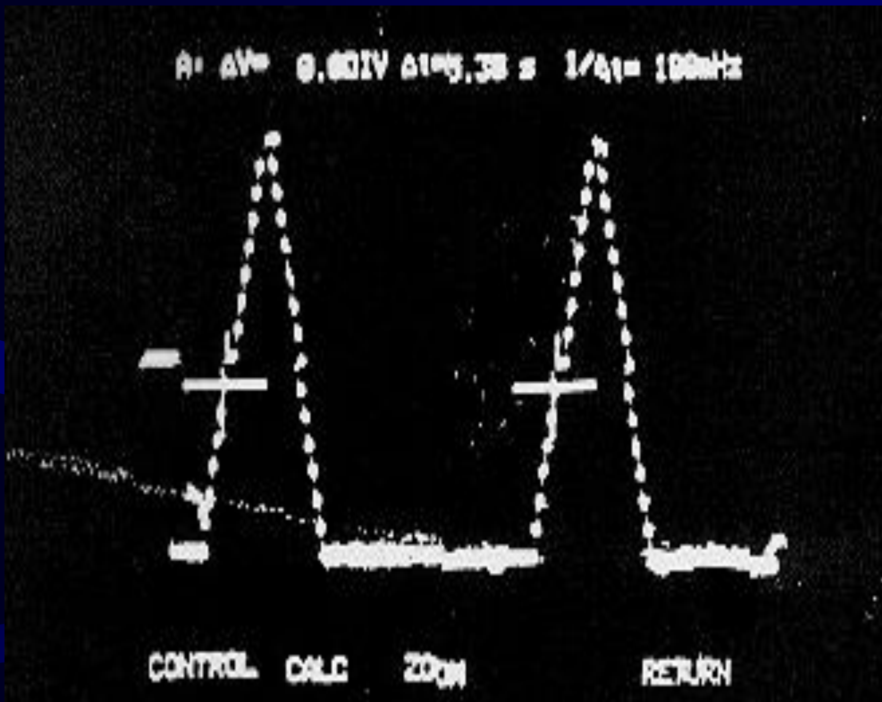


Chromaticity Measurements…

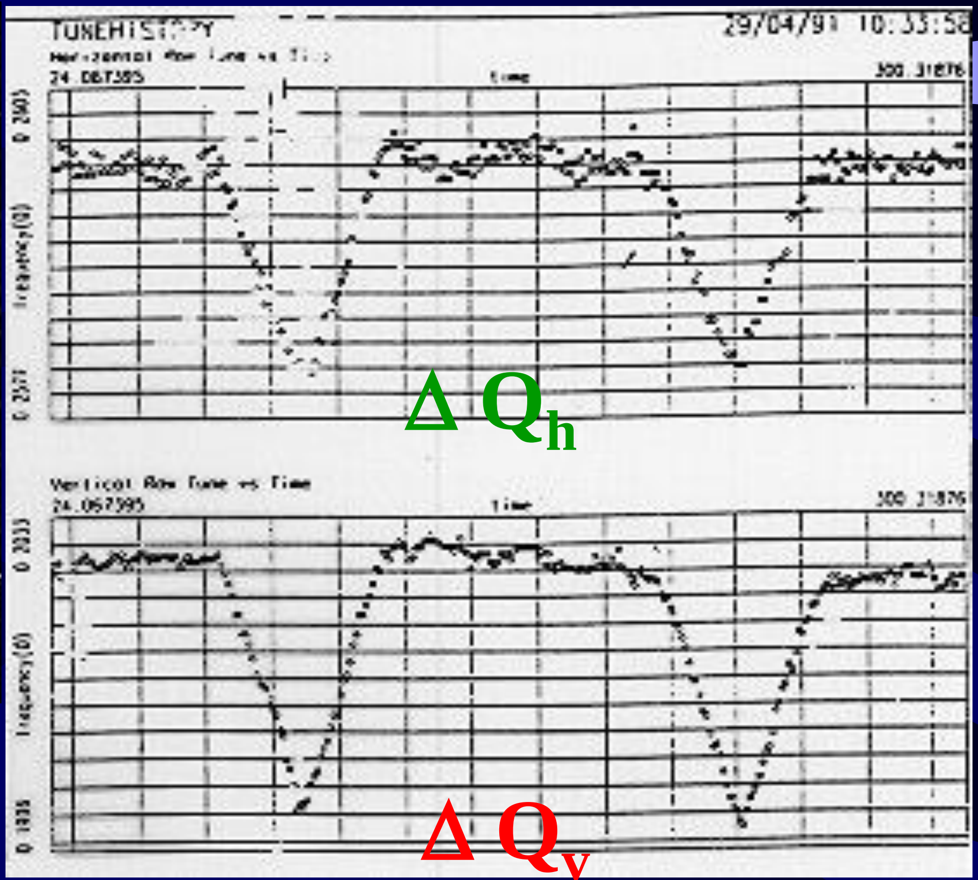
Simply by using the definition:
- Measure betatron tune for different beam momenta;
- vary beam momentum by changing the Rf-frequency



Time resolved Q' Measurement

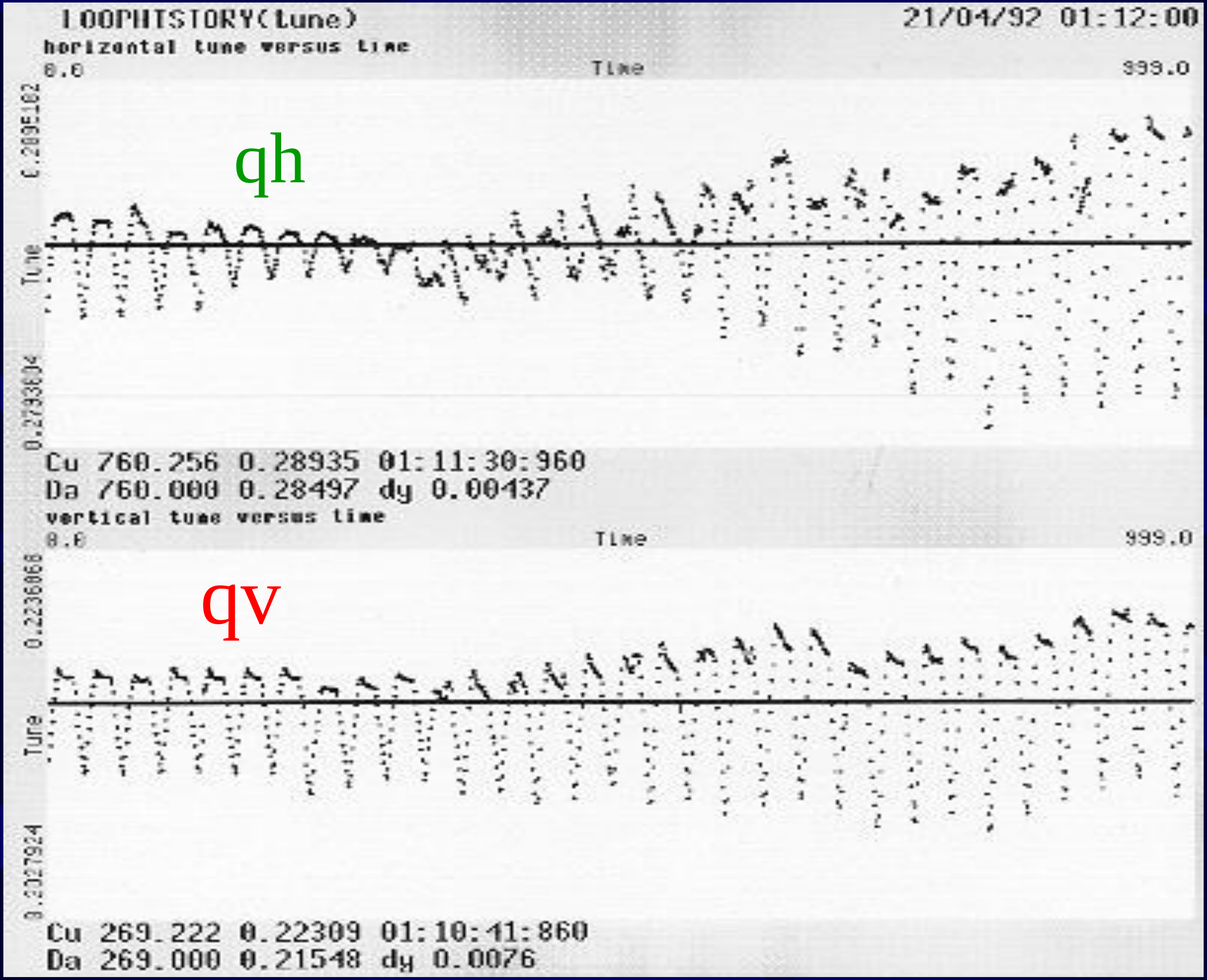


Applied Frequency Shift
Δ F (RF)



Amplitude & sign of chromaticity calculated from continuous tune plot

Measurement Example during LEP β-squeeze



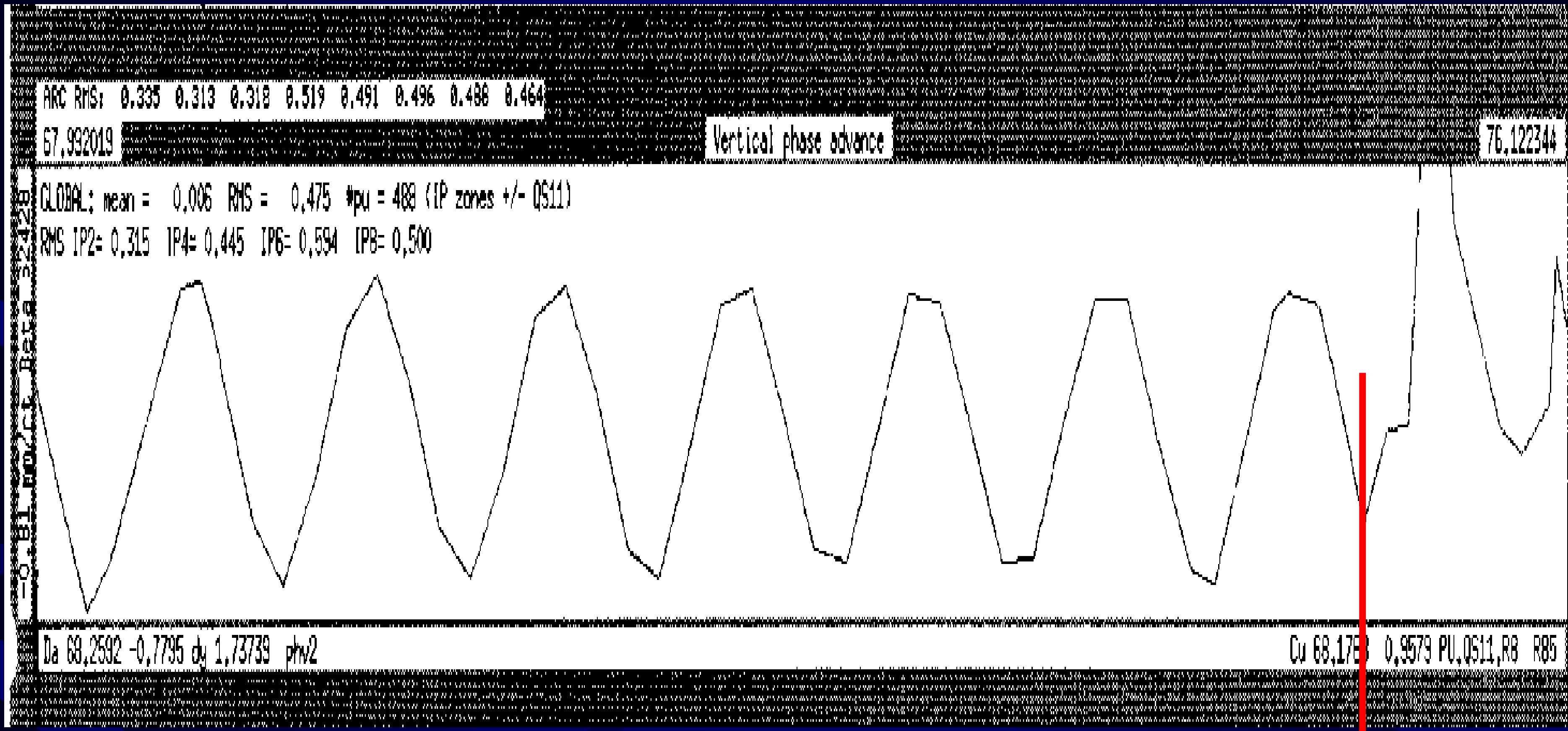
Last not least….

…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

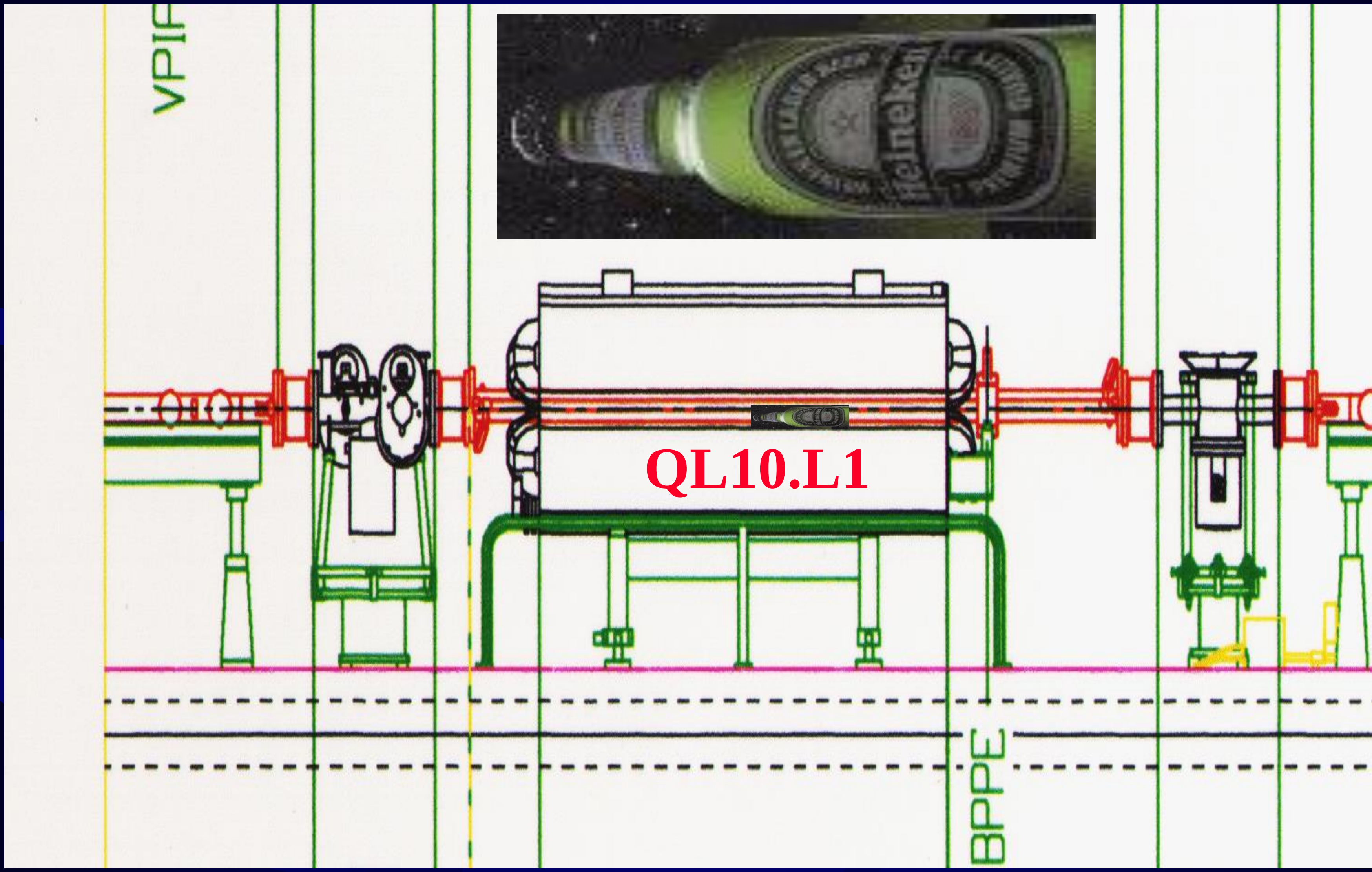
LEP – No Circulating Beam after a technical stop



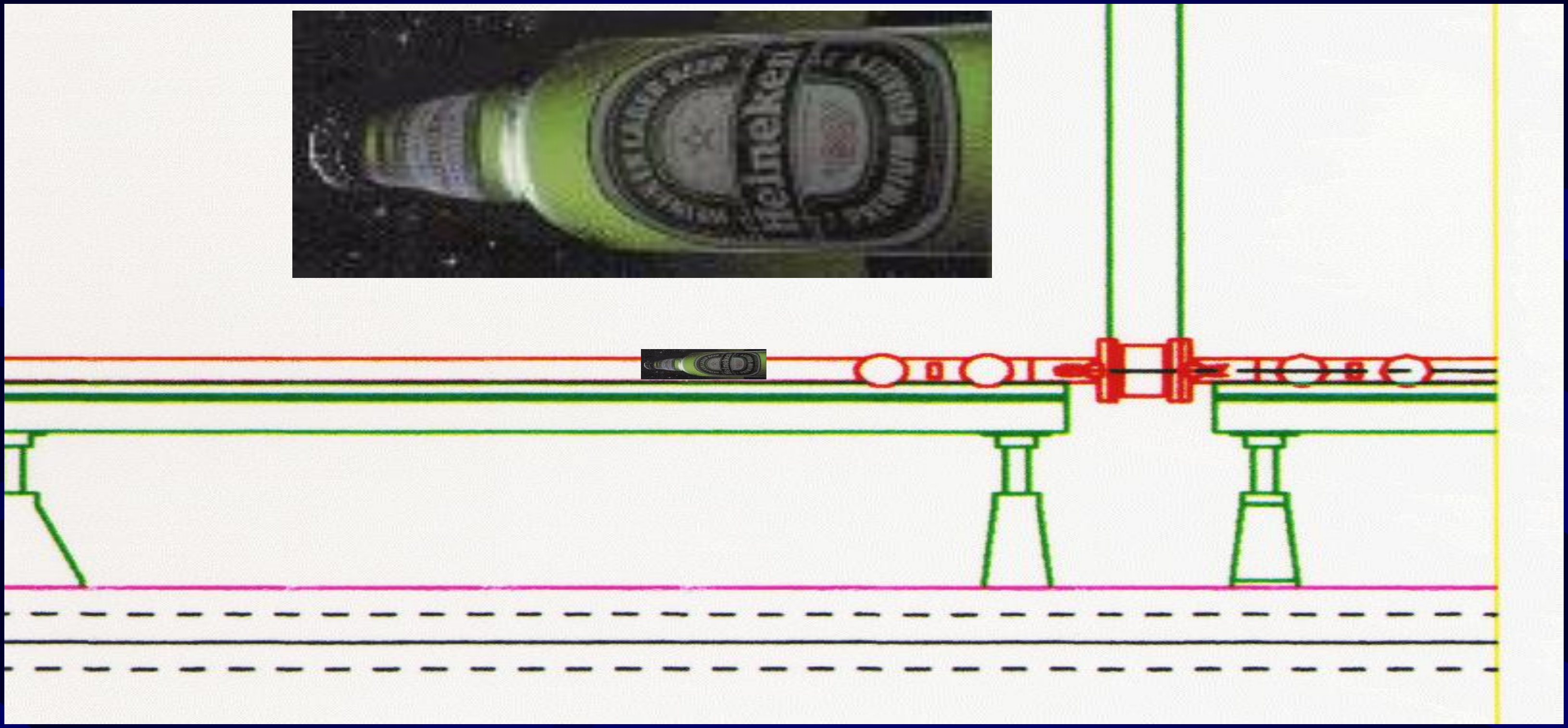
Positrons →

QL10.L1

Zoom on QL1



& 10 metres to the right …



Unsociable sabotage: both bottles were empty!!