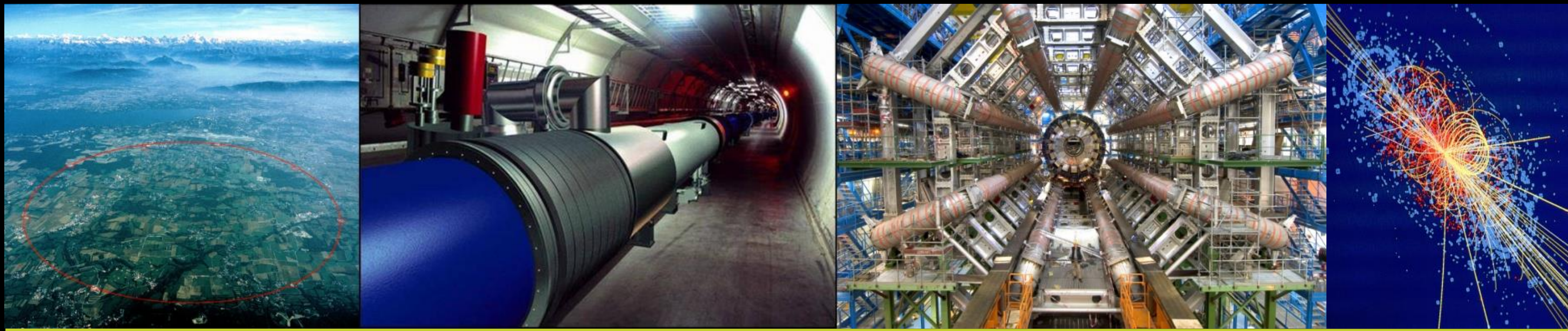


Introduction to Beam Instrumentation

CAS 2015

Warsaw, Poland

27th September – 9th October, 2015

Dr. Rhodri Jones

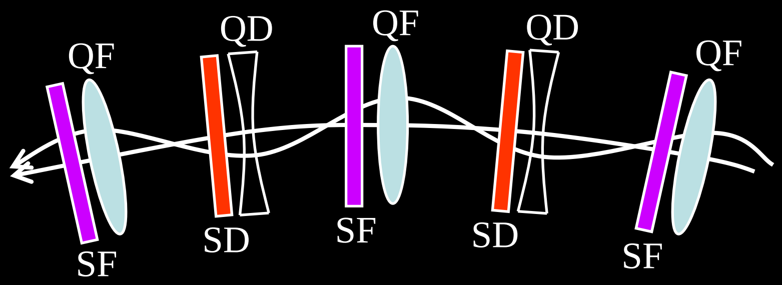
Head of the CERN Beam Instrumentation Group

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
  - A fascinating field of work!
- 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

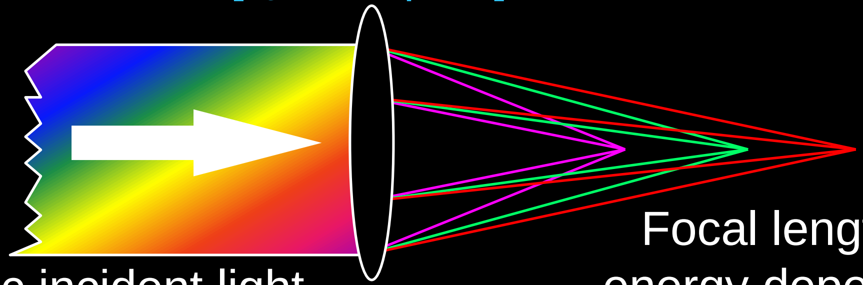


Characteristic Frequency of the Magnetic Lattice
Given by the strength of the Quadrupole magnets

- Machine Chromaticity

Optics Analogy:

Lens
[Quadrupole]



Achromatic incident light
[Spread in particle energy]

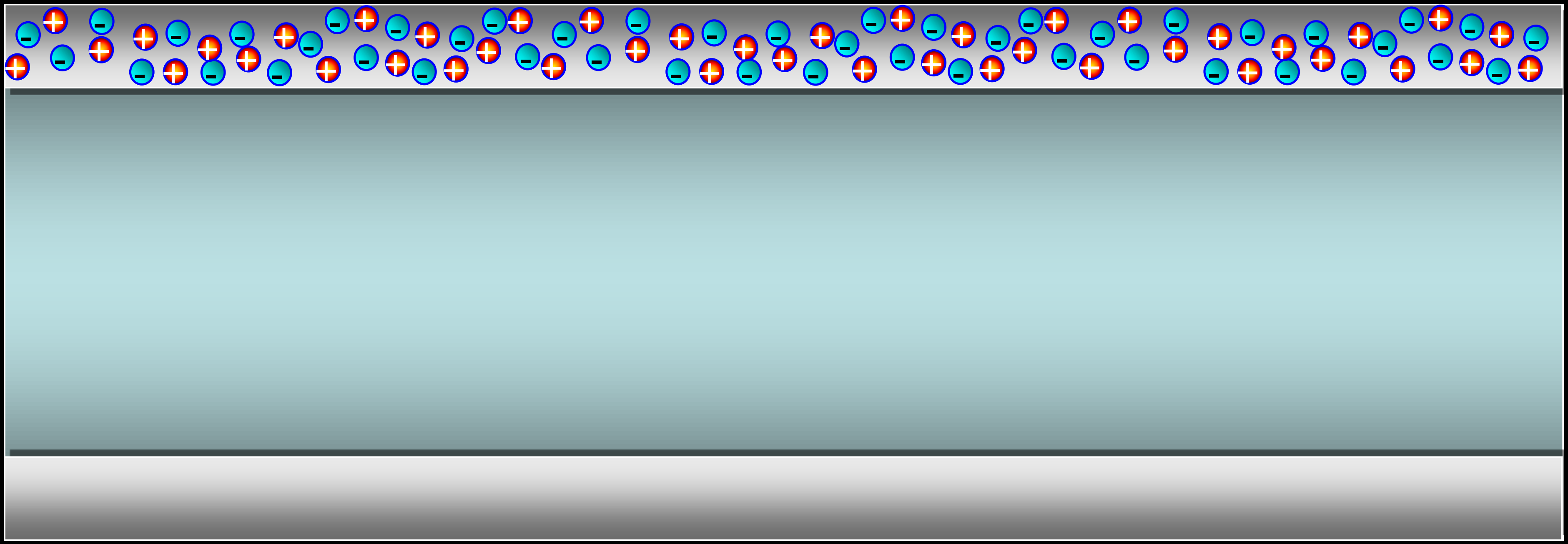
Focal length is energy dependent

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

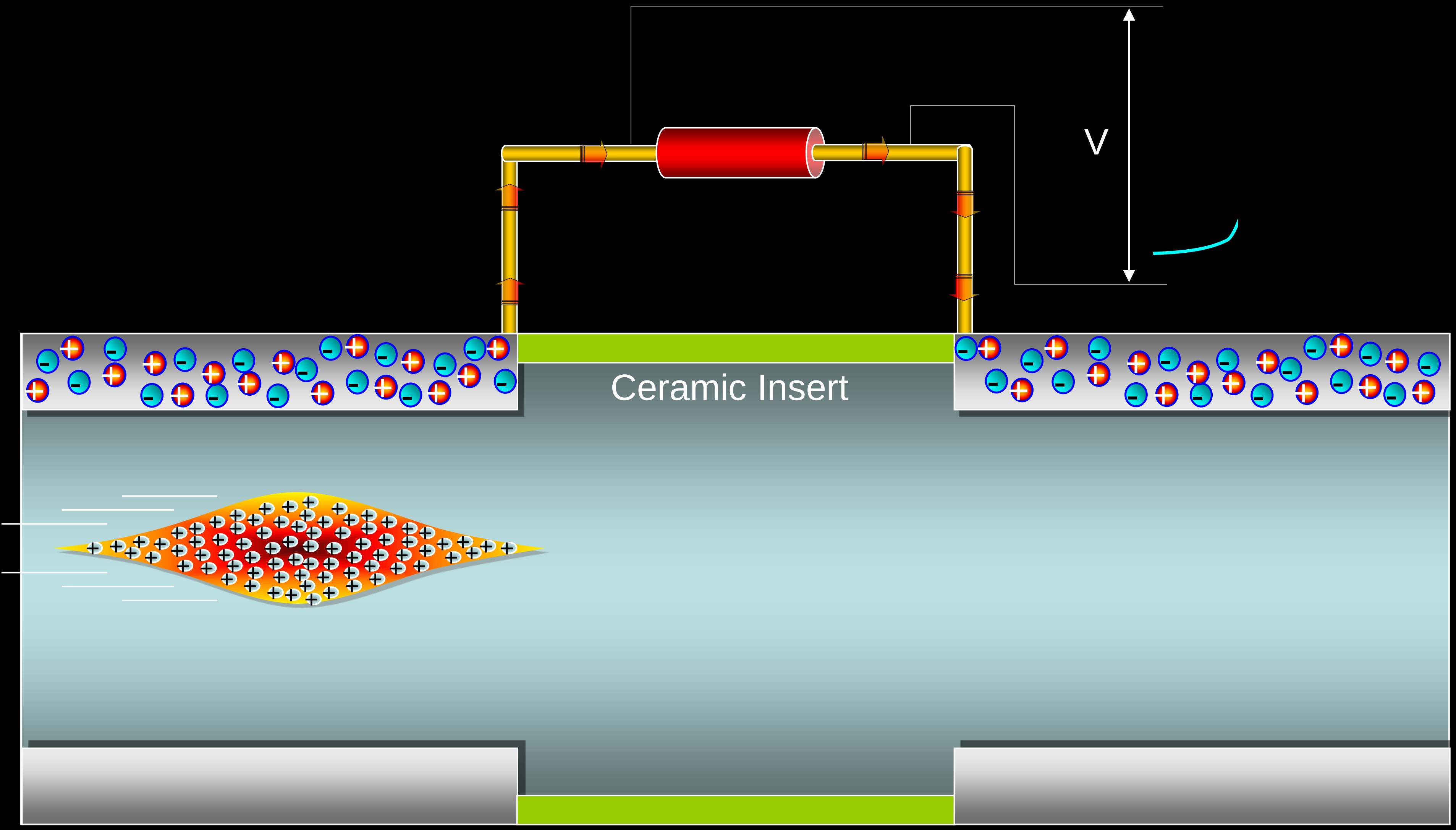
The Typical Instruments

- 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
  - ionisation and luminescence monitors
  - femtosecond diagnostics for ultra short bunches
- Beam Loss
  - ionisation chambers or pin diodes
- Machine Tune and Chromaticity
  - in Beam Diagnostics lecture of tomorrow

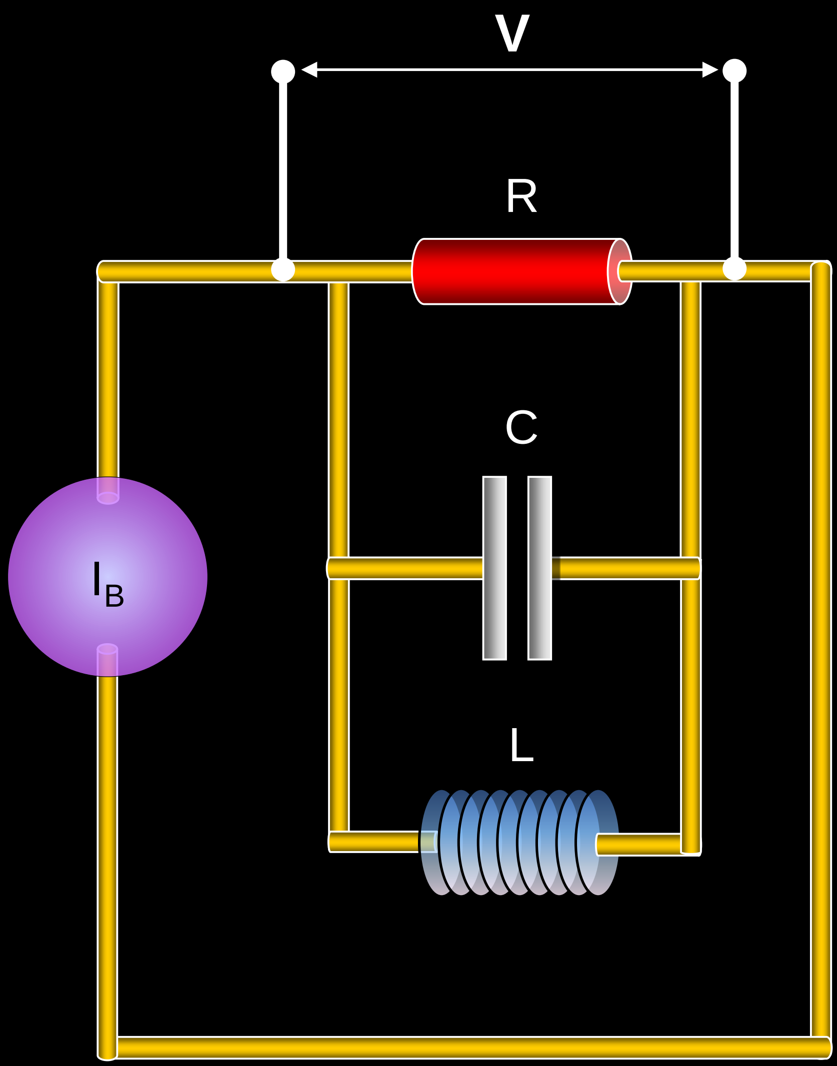
Measuring Beam Position – The Principle

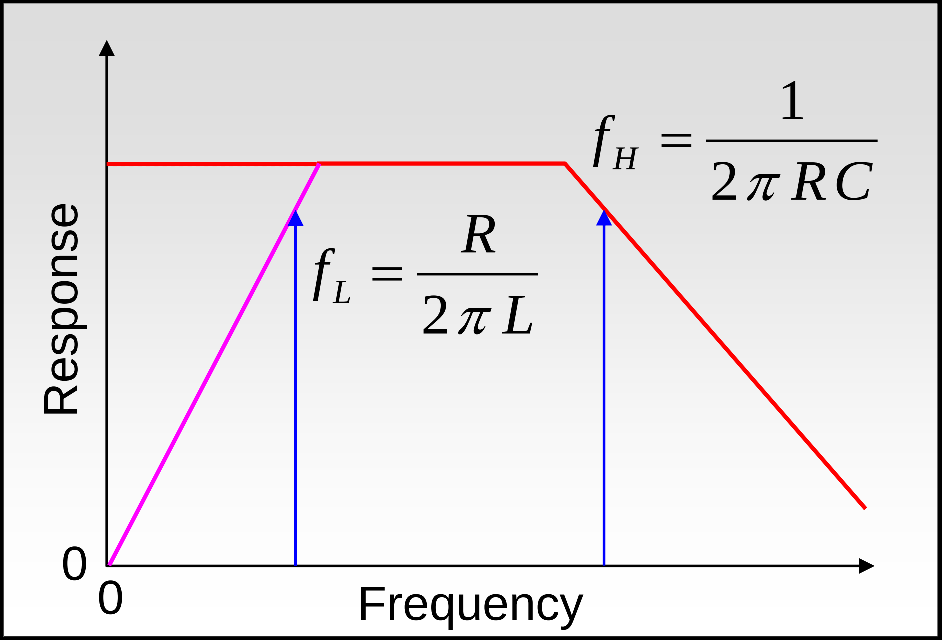


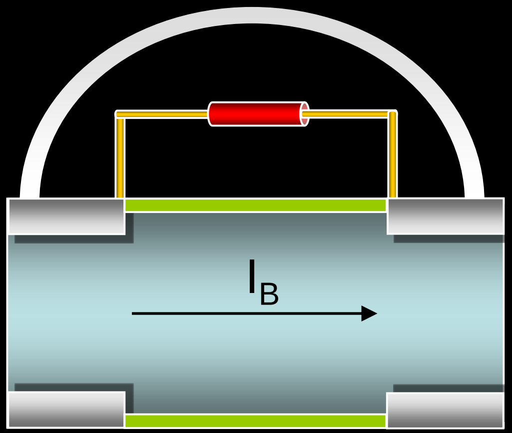
Wall Current Monitor – The Principle



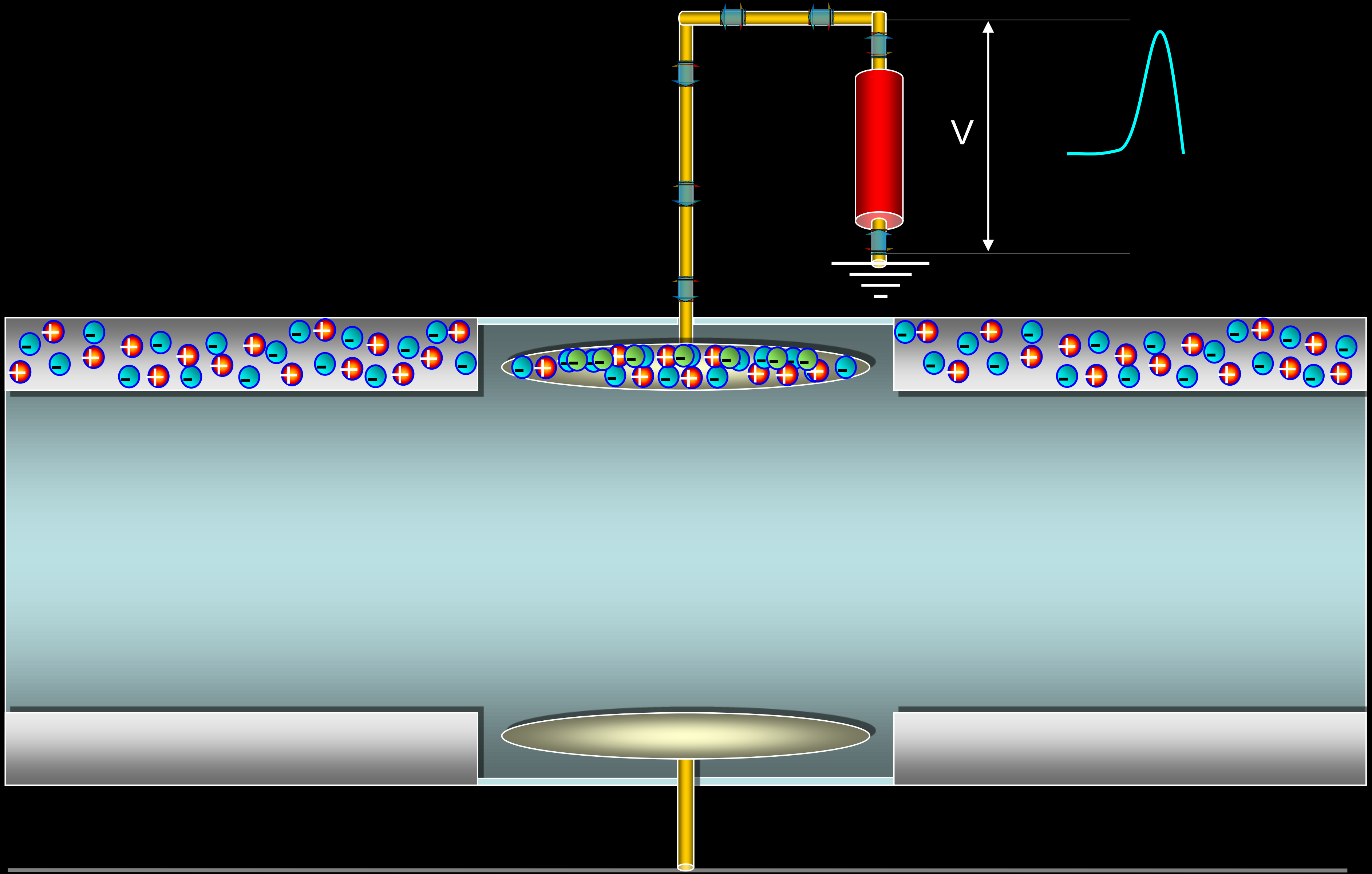
Wall Current Monitor – Beam Response



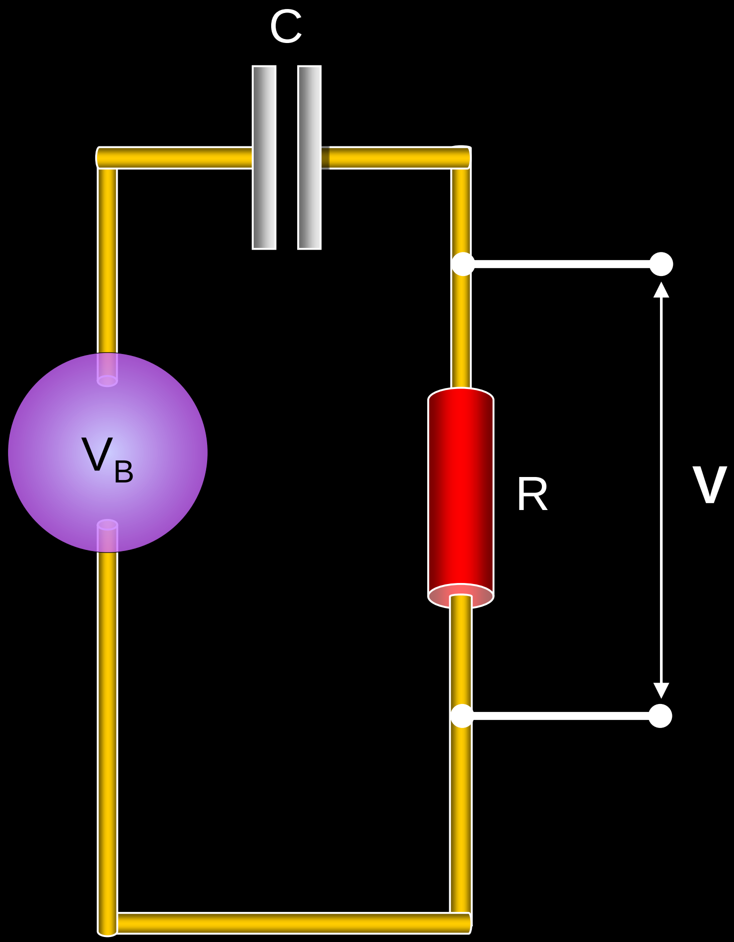


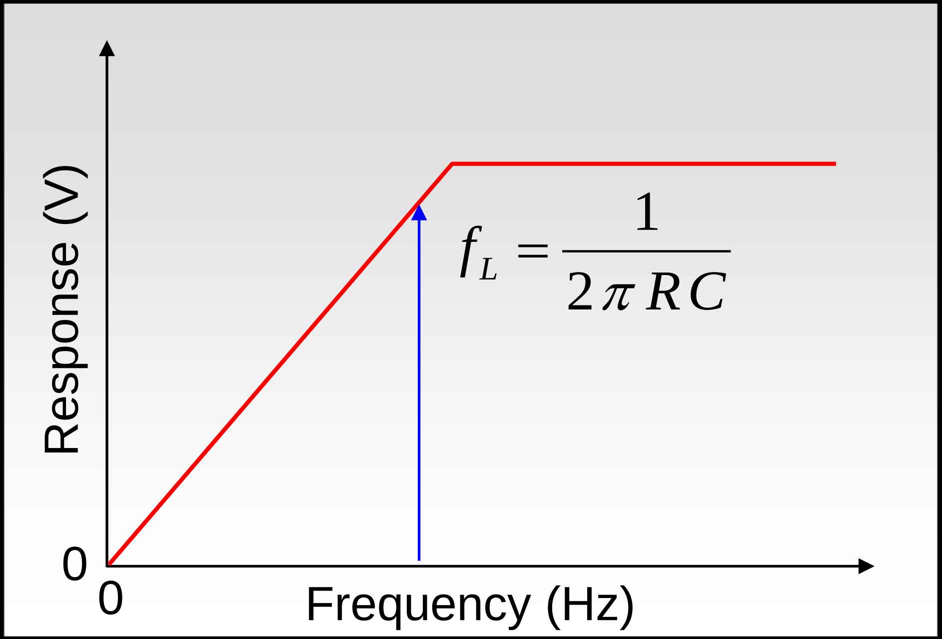


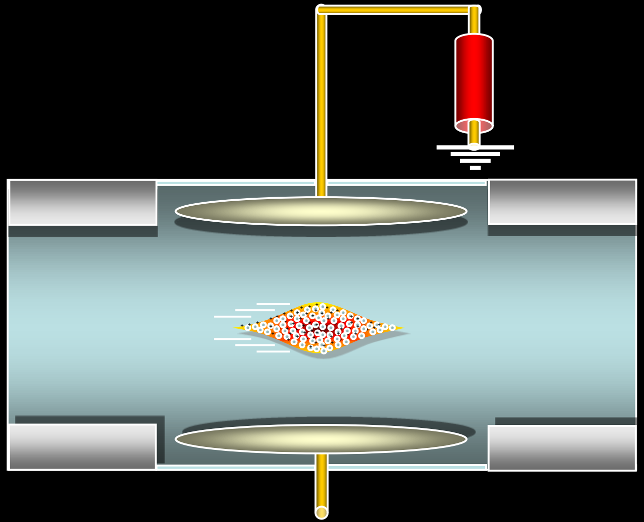
Electrostatic Monitor – The Principle



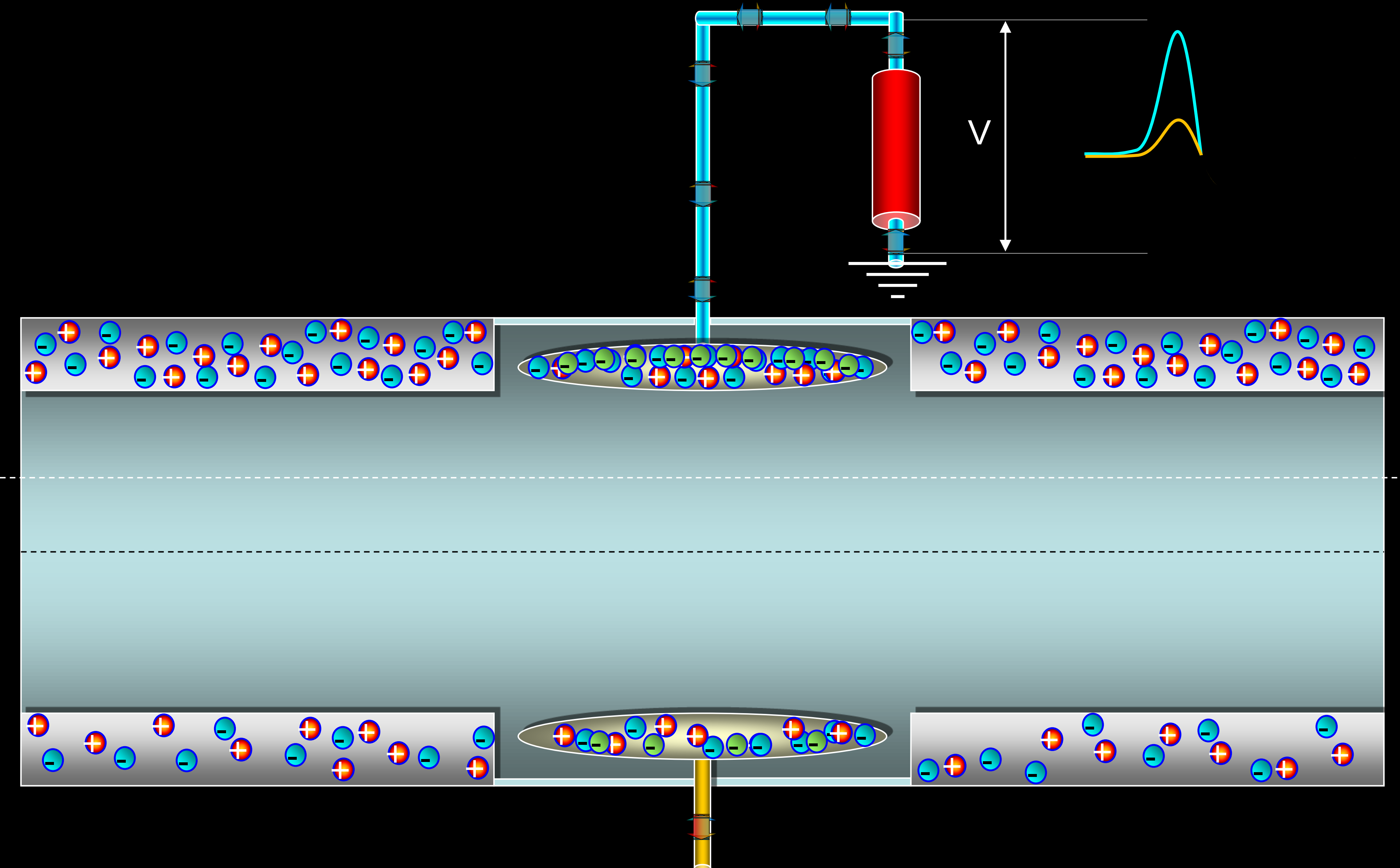
Electrostatic Monitor – Beam Response







Electrostatic Beam Position Monitor



Electrostatic Pick-up – Button

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

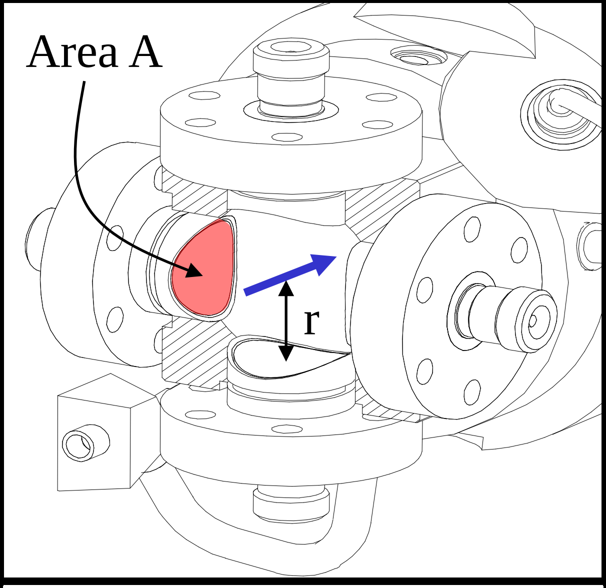
For Button with Capacitance C_e & Characteristic Impedance R_0

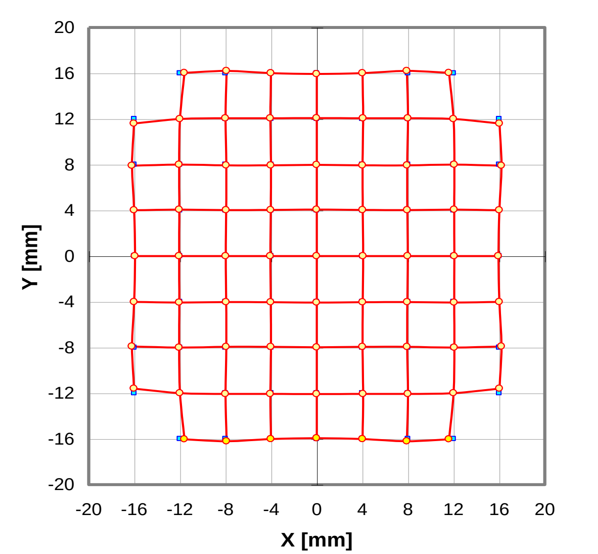
Transfer Impedance:

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

Lower Corner Frequency:

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

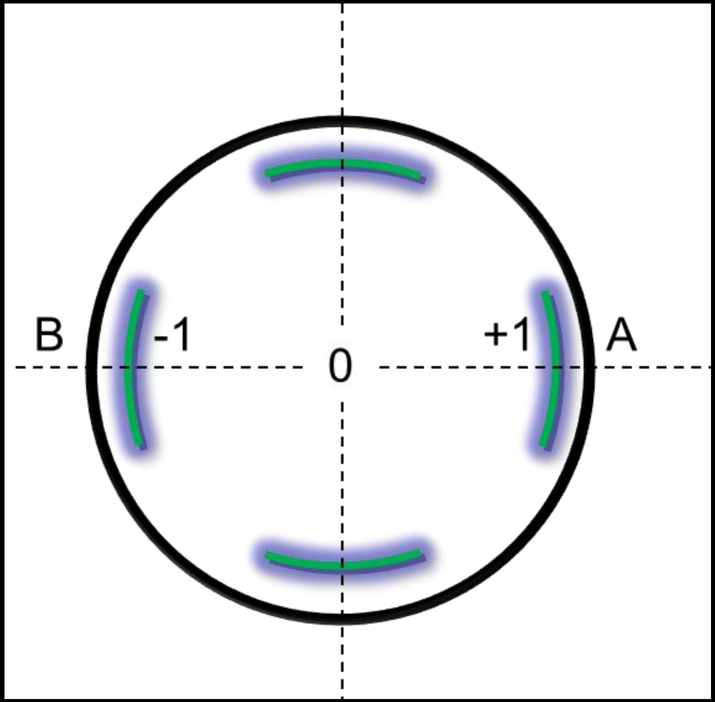


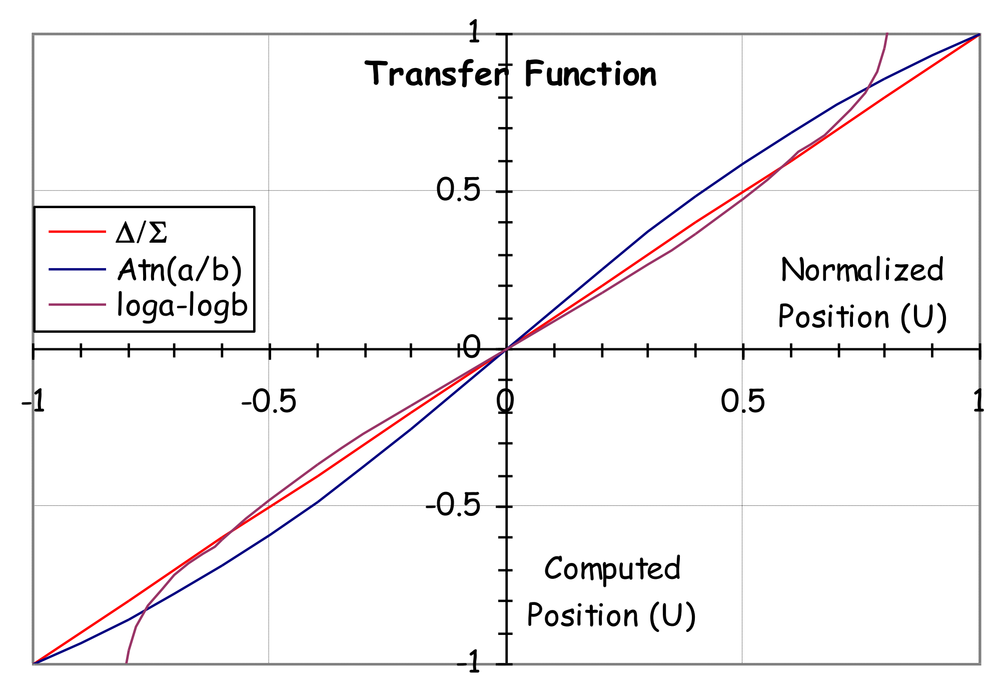


$$X = 2.30\cdot10^{-5} X_1^{\ 5} + 3.70\cdot10^{-5} X_1^{\ 3} + 1.035 X_1 + 7.53\cdot10^{-6} X_1^{\ 3} Y_1^{\ 2} + 1.53\cdot10^{-5} X_1 Y_1^{\ 4}$$

Normalising the Position Reading

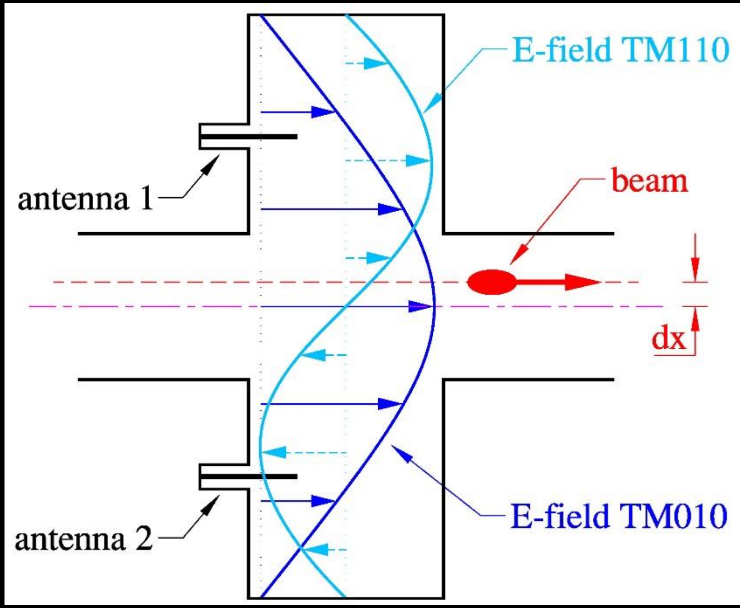
- To make it independent of intensity
- 3 main methods:
  - Difference/Sum : $(V_A - V_B) / (V_A + V_B) = \Delta / \Sigma$
  - Phase : $\mathrm{Arctan}(V_A / V_B)$
  - Logarithm : $\mathrm{Log}(V_A) - \mathrm{Log}(V_B)$

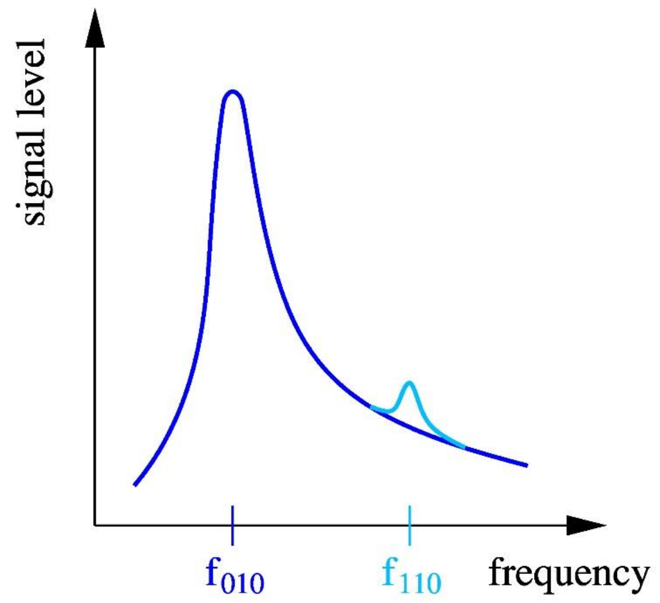




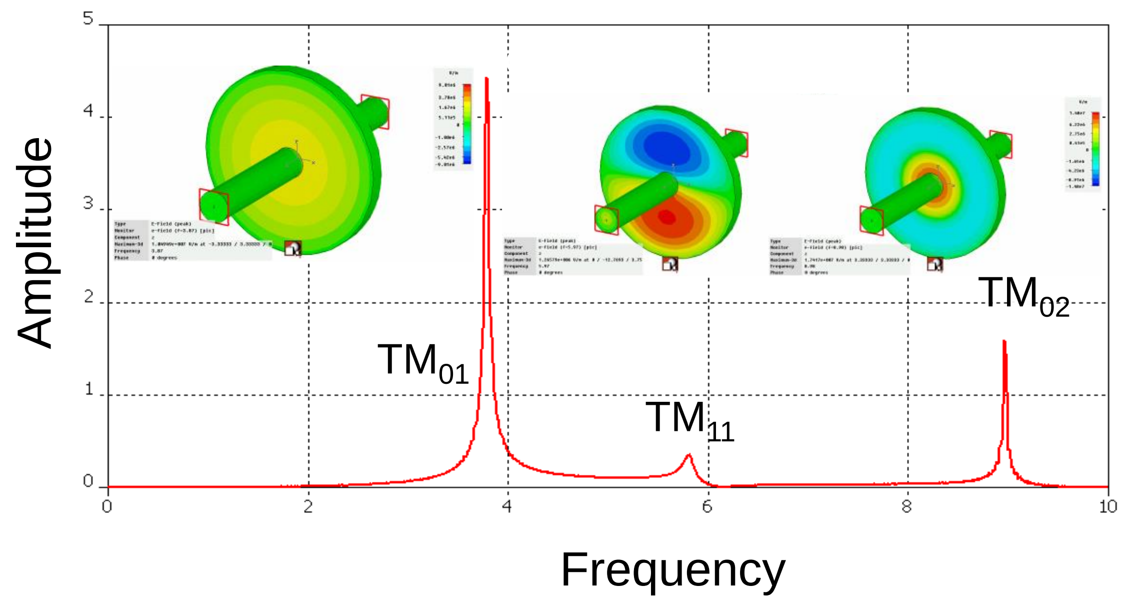
Improving Precision for Next Generation Accelerators

- 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}



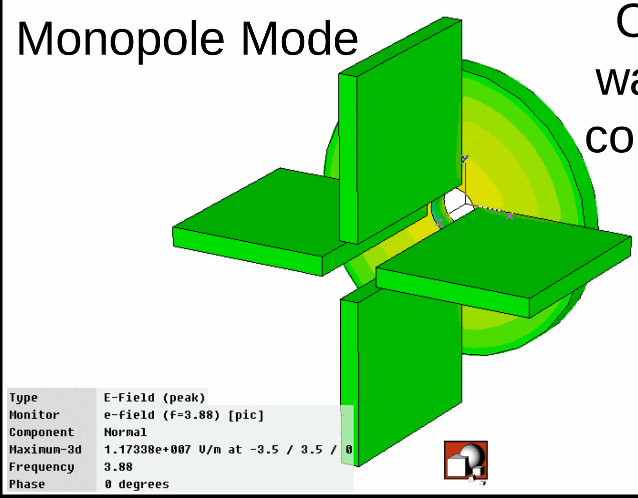


Cavity Beam Position Monitors



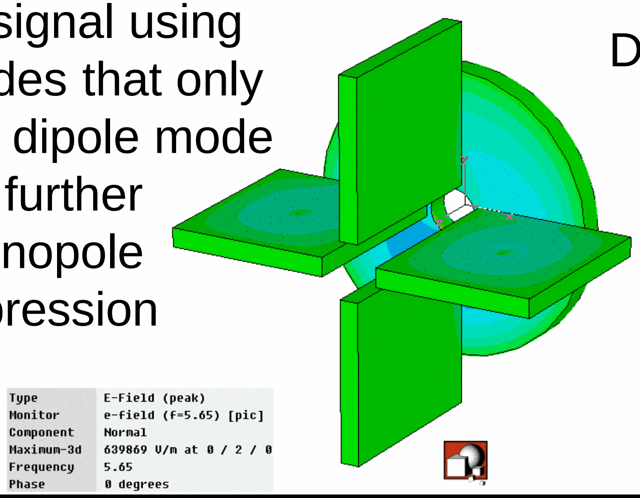
Courtesy of D. Lipka, DESY, Hamburg

Monopole Mode



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

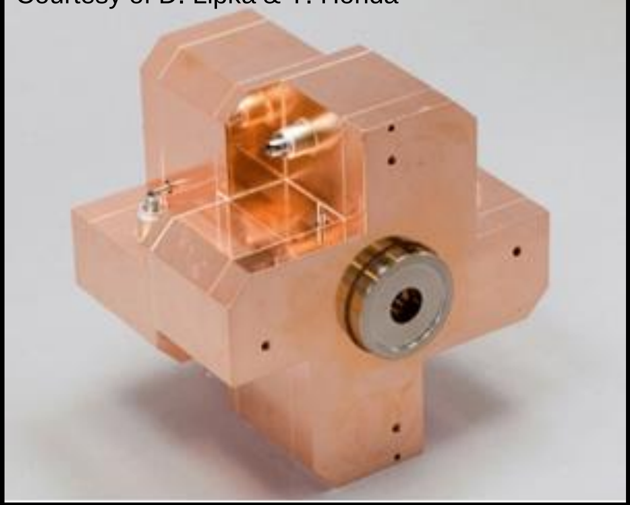
Dipole Mode

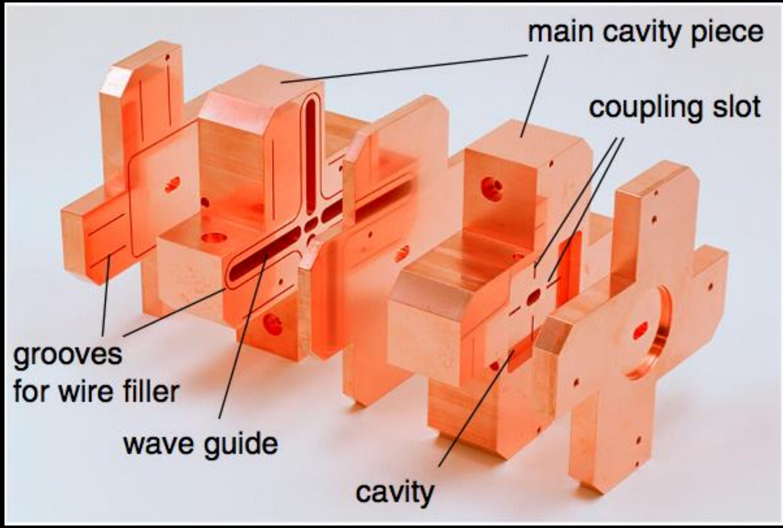


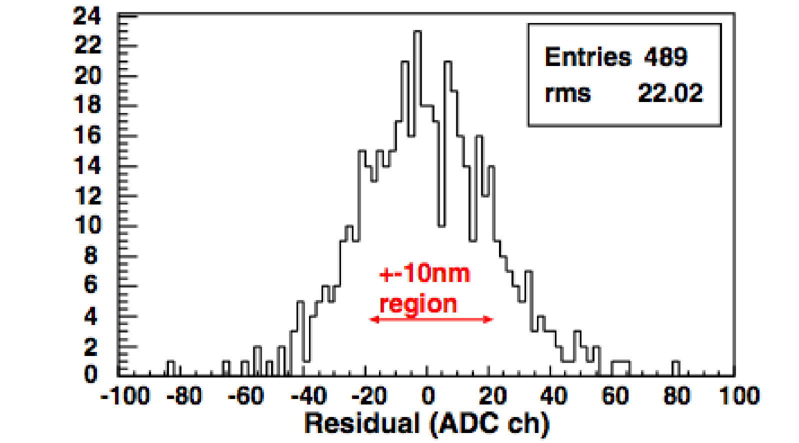
Today's State of the Art BPMs

- 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)

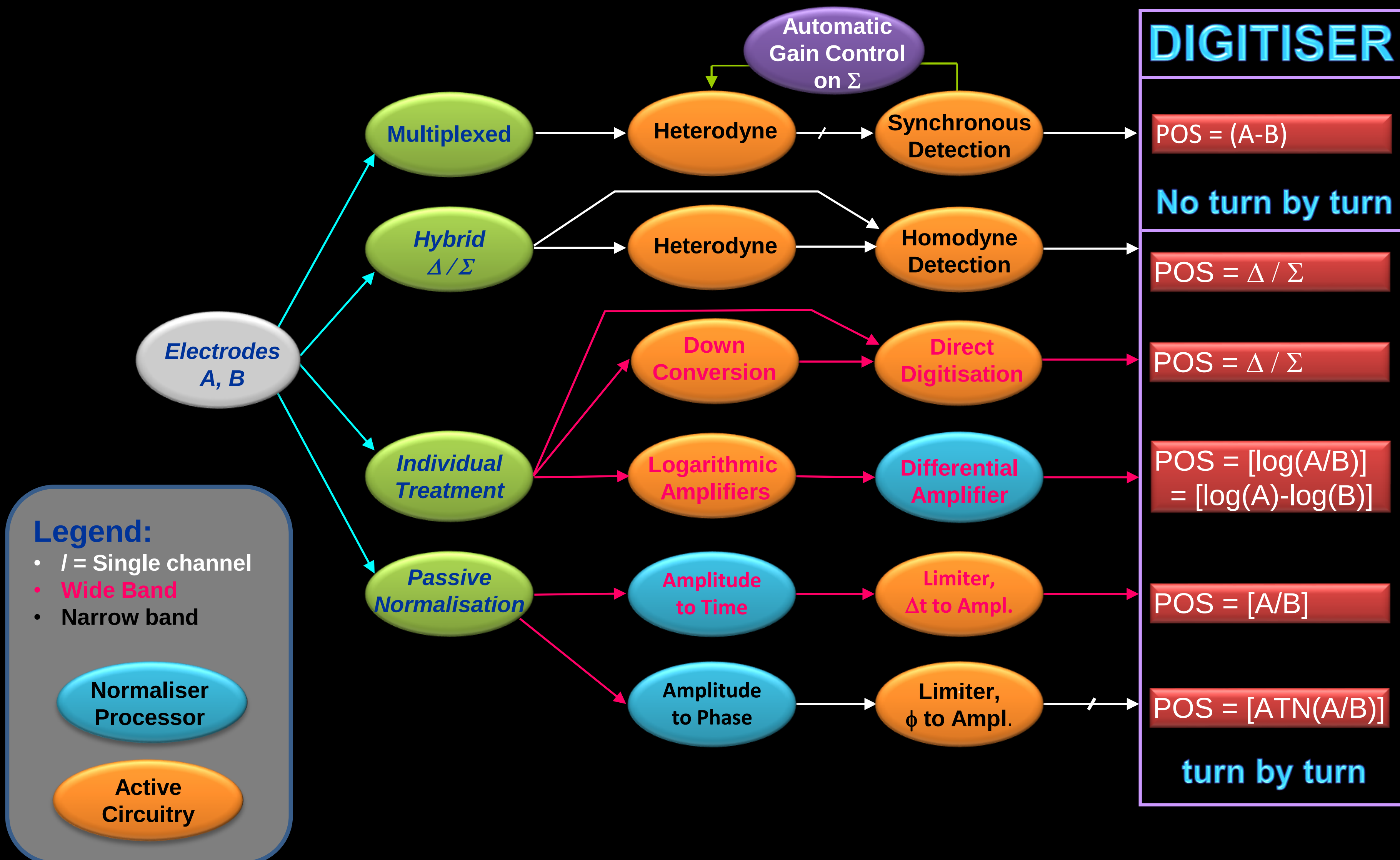
Courtesy of D. Lipka & Y. Honda





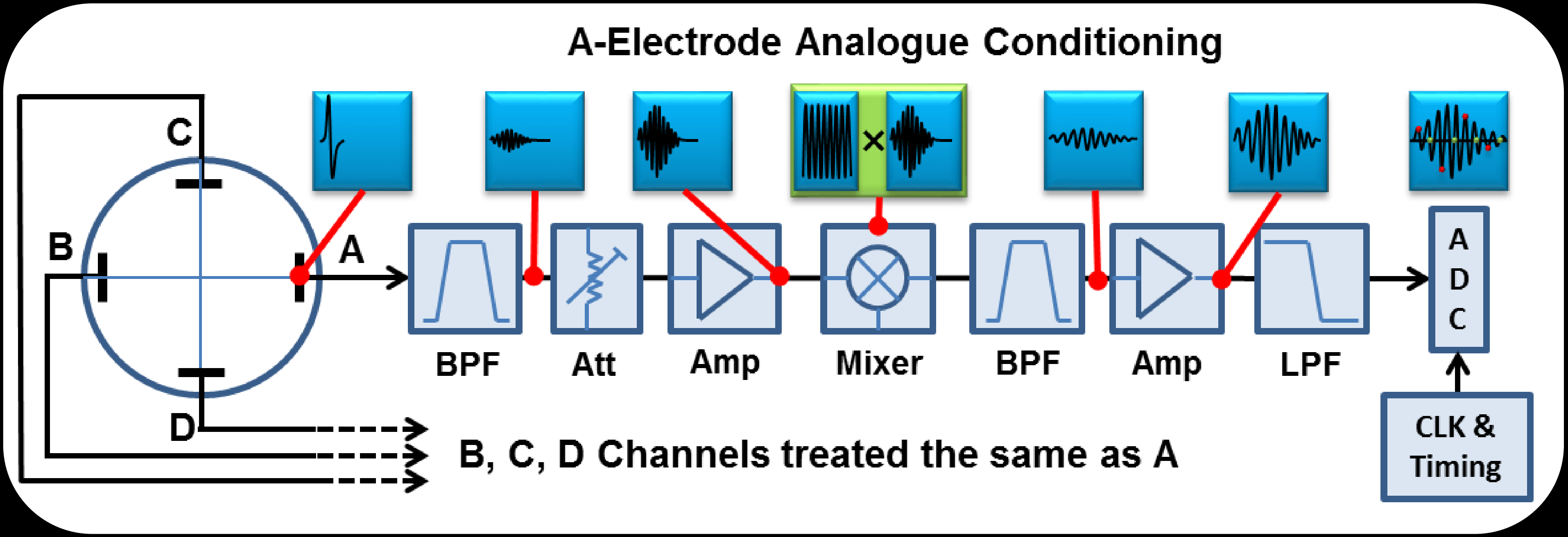


Processing System Families



Modern BPM Read-out Electronics

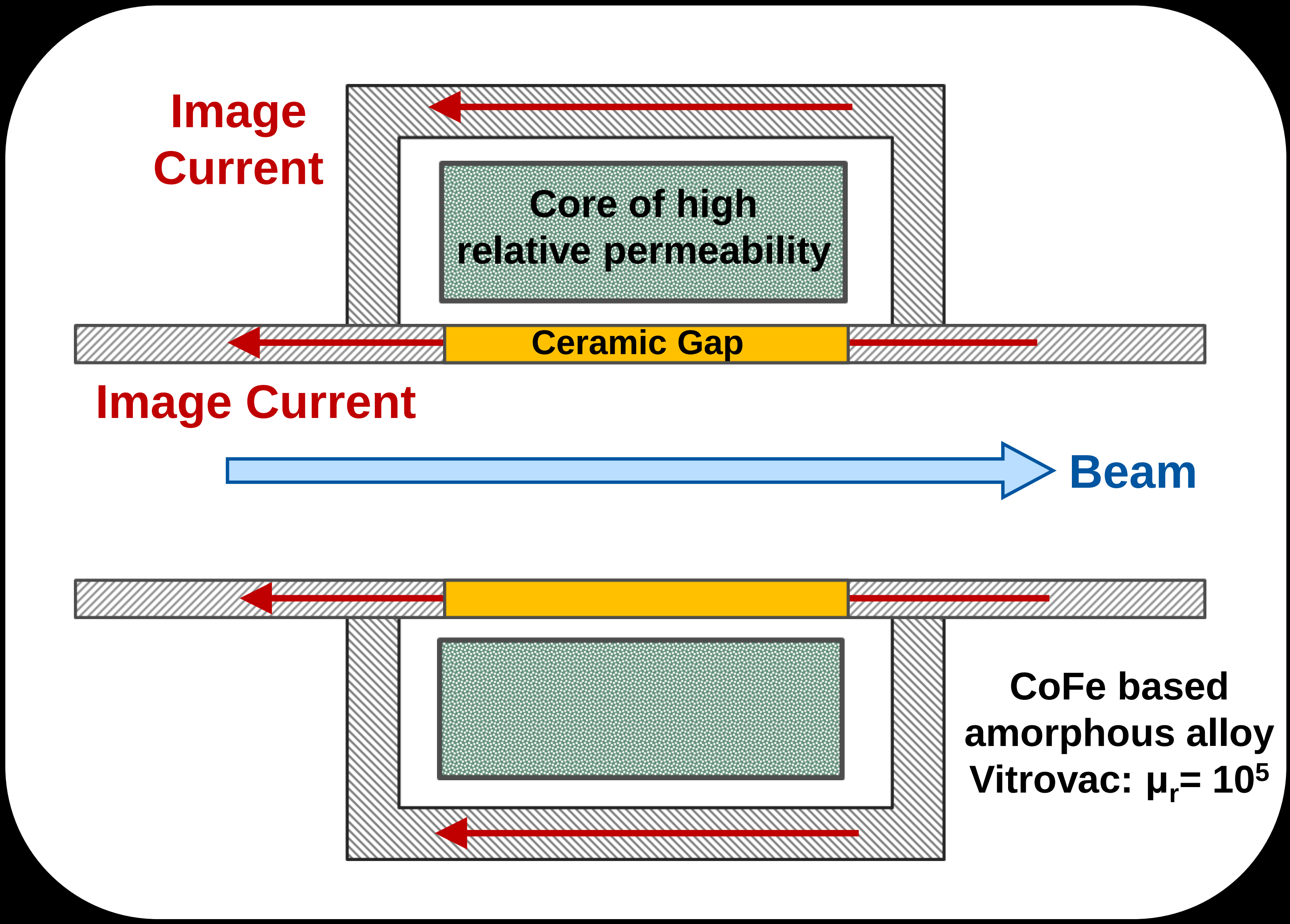
- Based on the individual treatment of the electrode signals
  – Use of frequency domain signal processing techniques
    - Developed for telecommunications market
  – Rely on high frequency & high resolution analogue to digital converters
    - Minimising analogue circuitry
    - Frequency down-conversion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



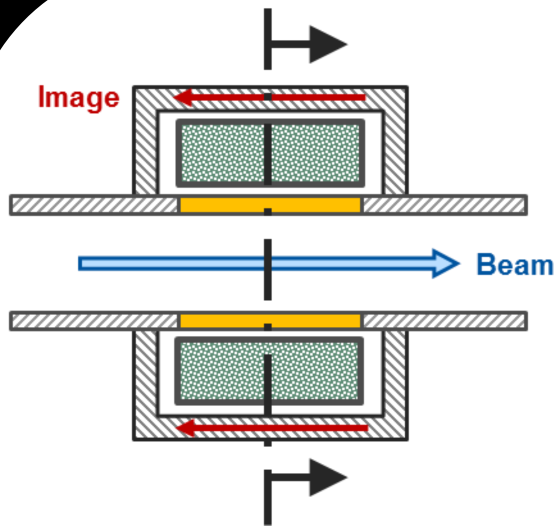
The Typical Instruments

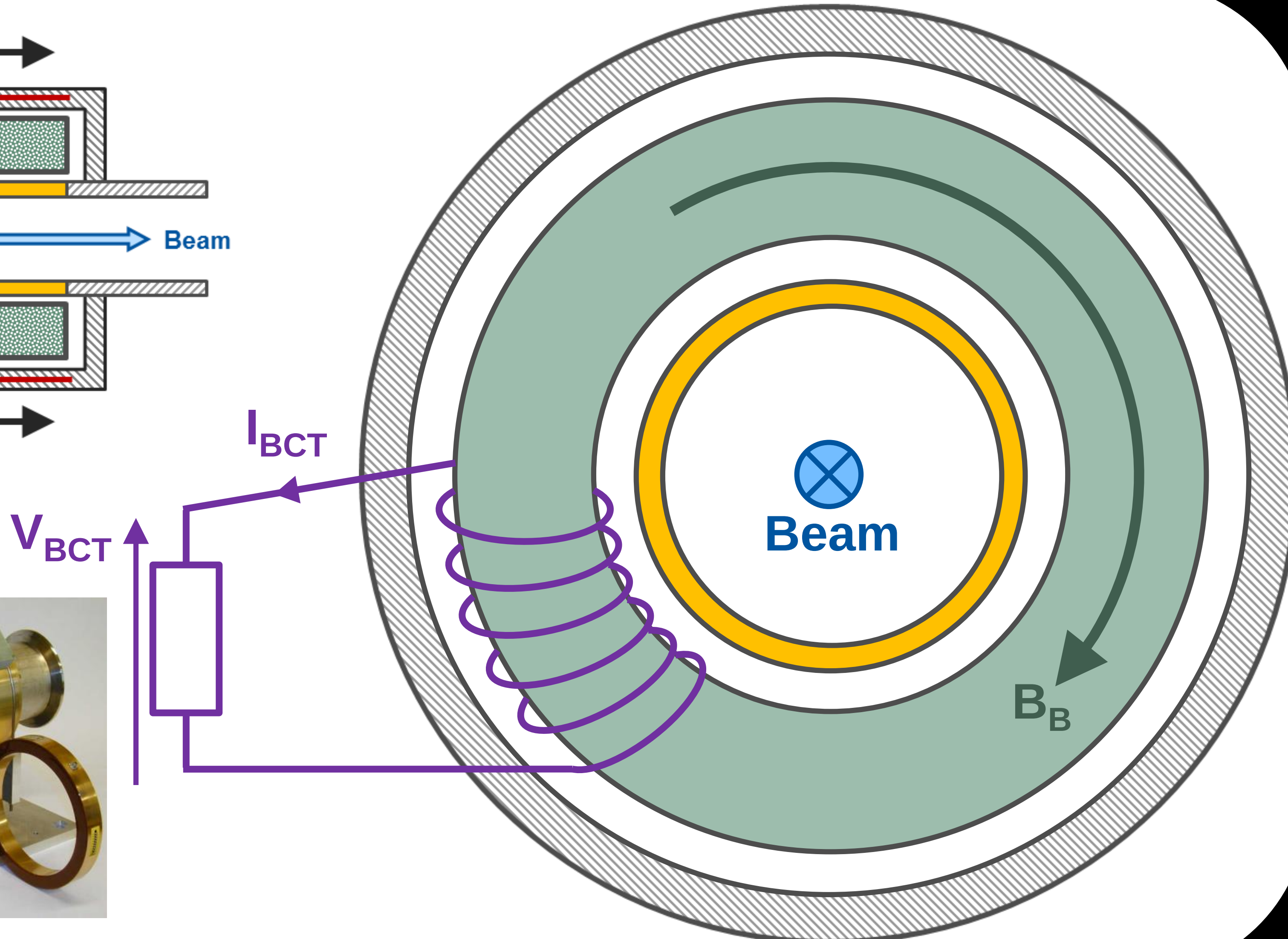
- Beam Position
  - electrostatic or electromagnetic pick-ups and related electronics
- Beam Intensity
  - beam current transformers
- Beam Profile
  - secondary emission grids and screens
  - wire scanners
  - synchrotron light monitors
  - ionisation and luminescence monitors
  - femtosecond diagnostics for ultra short bunches
- Beam Loss
  - ionisation chambers or pin diodes
- Machine Tune and Chromaticity
  - in Beam Diagnostics lecture tomorrow

AC (Fast) Current Transformers



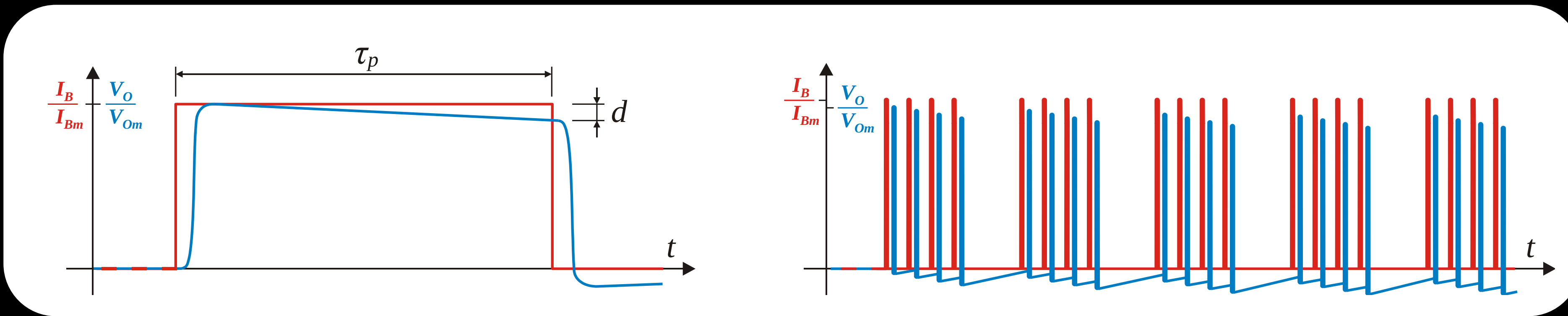
AC (Fast) Current Transformers

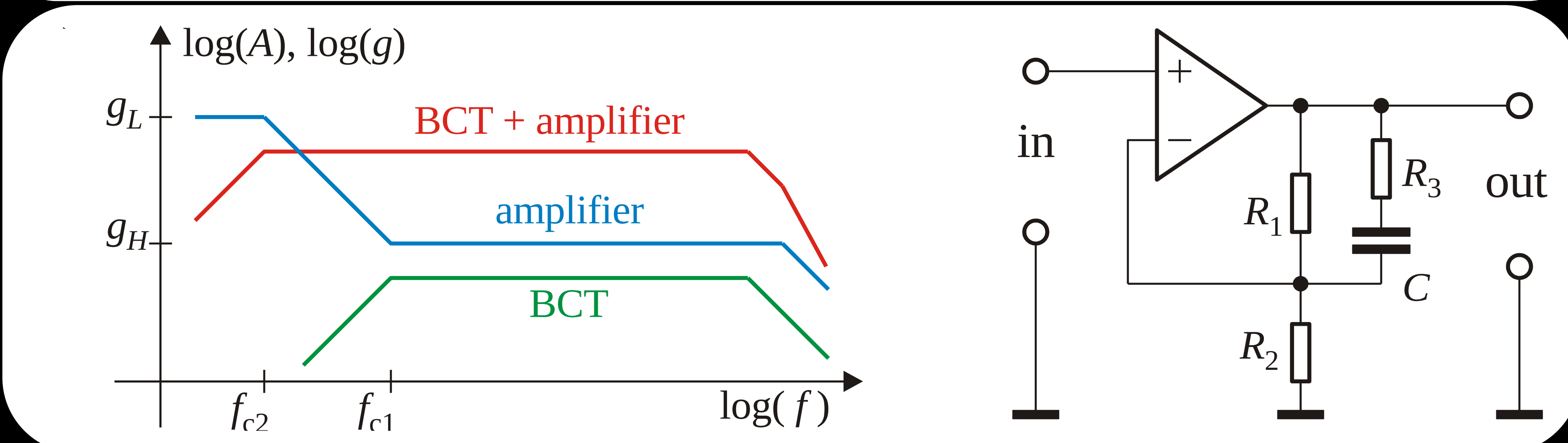




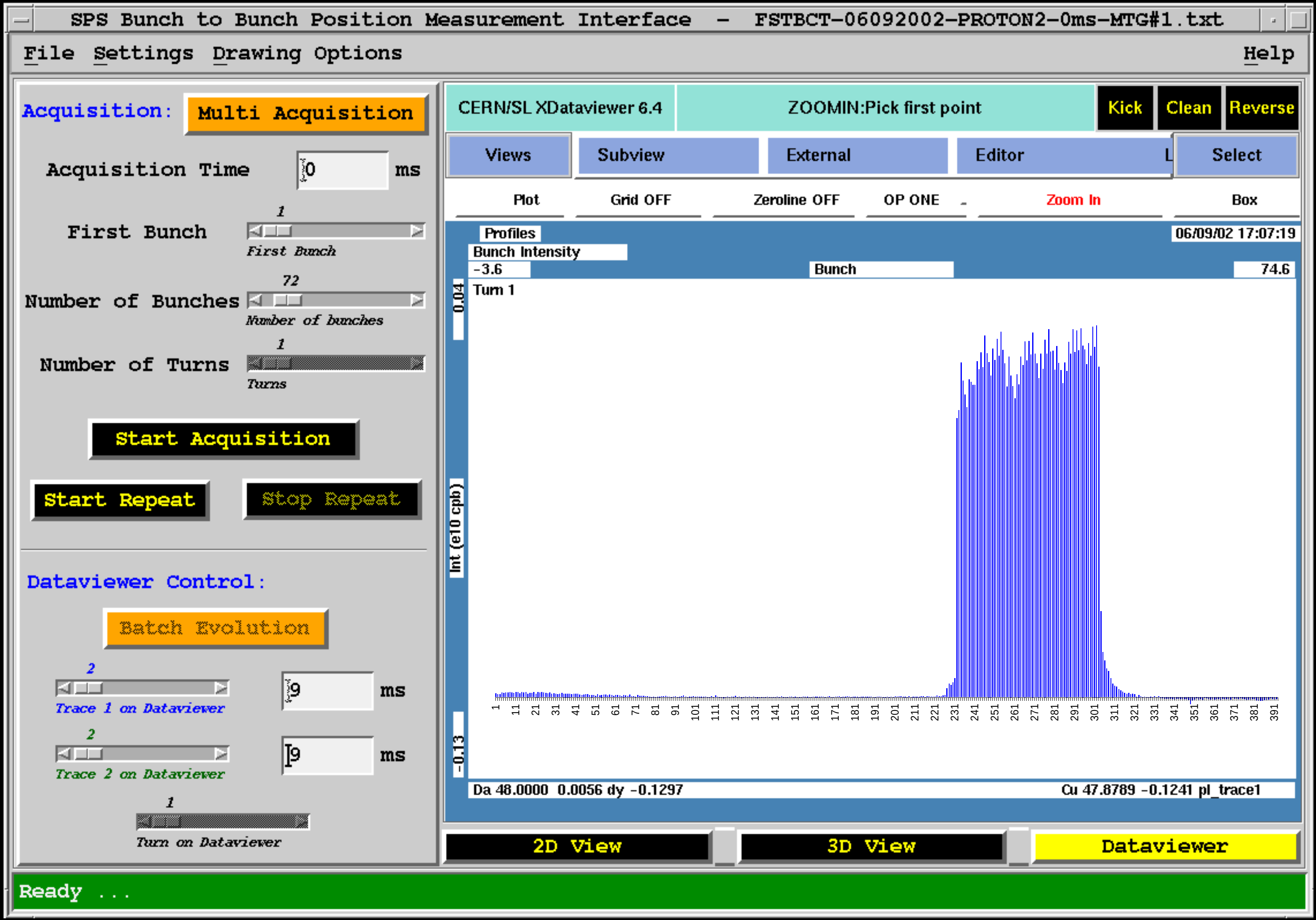
AC (Fast) Transformer Response

- 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)





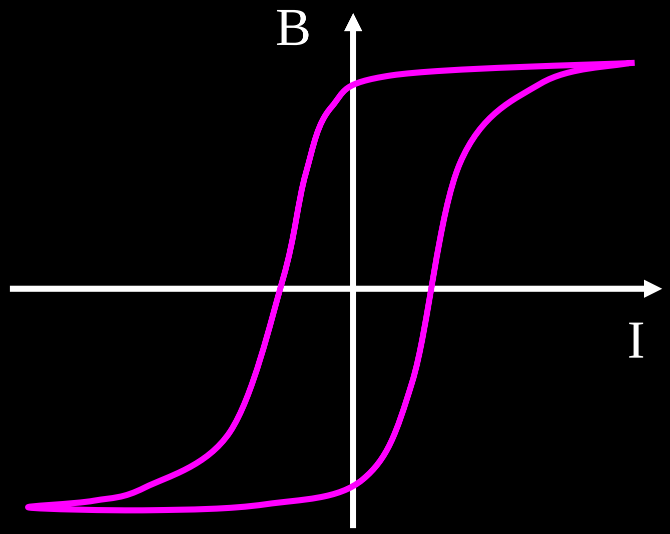
What one can do with such a System



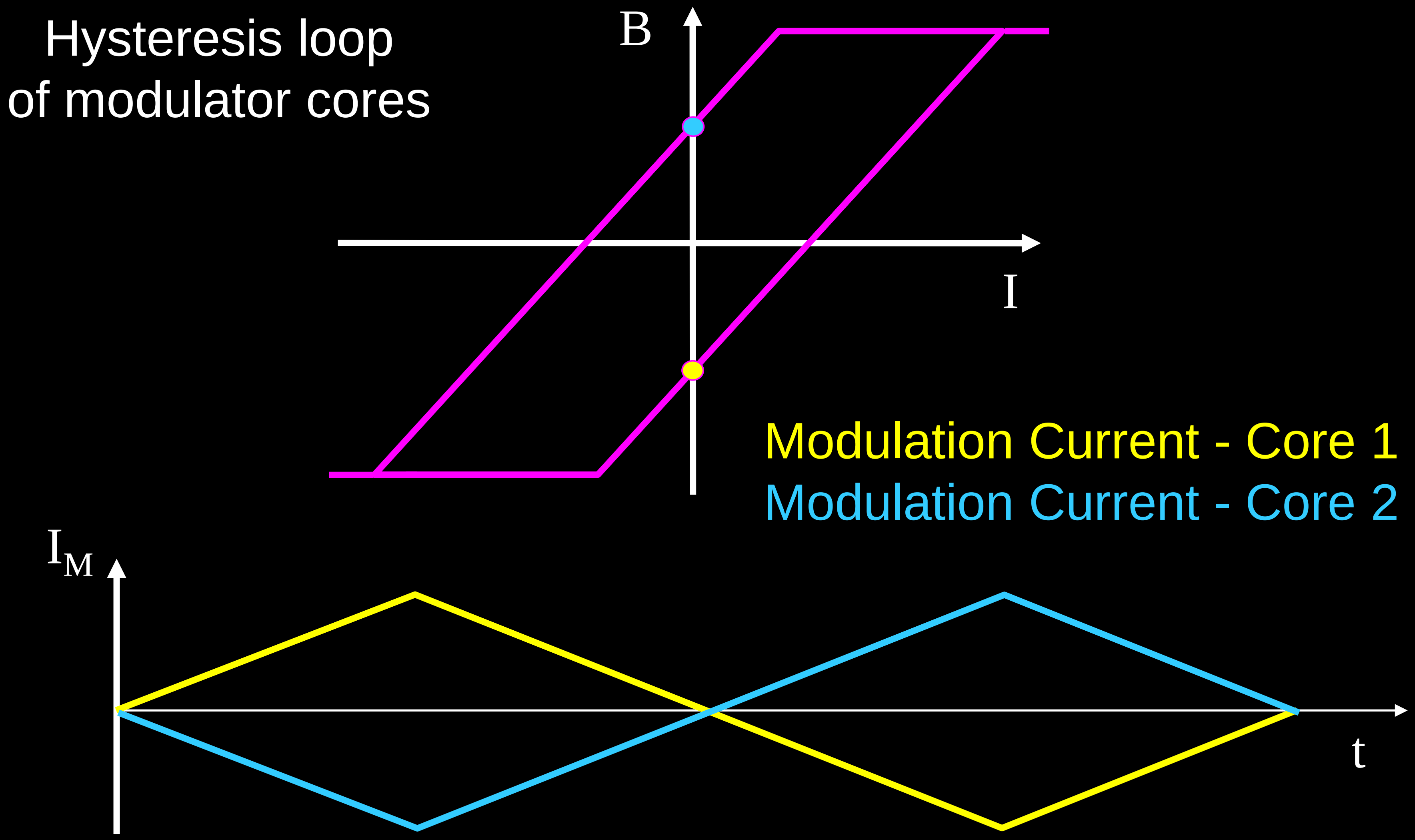
Bad RF Capture of a single LHC Batch in the SPS (72 bunches)

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

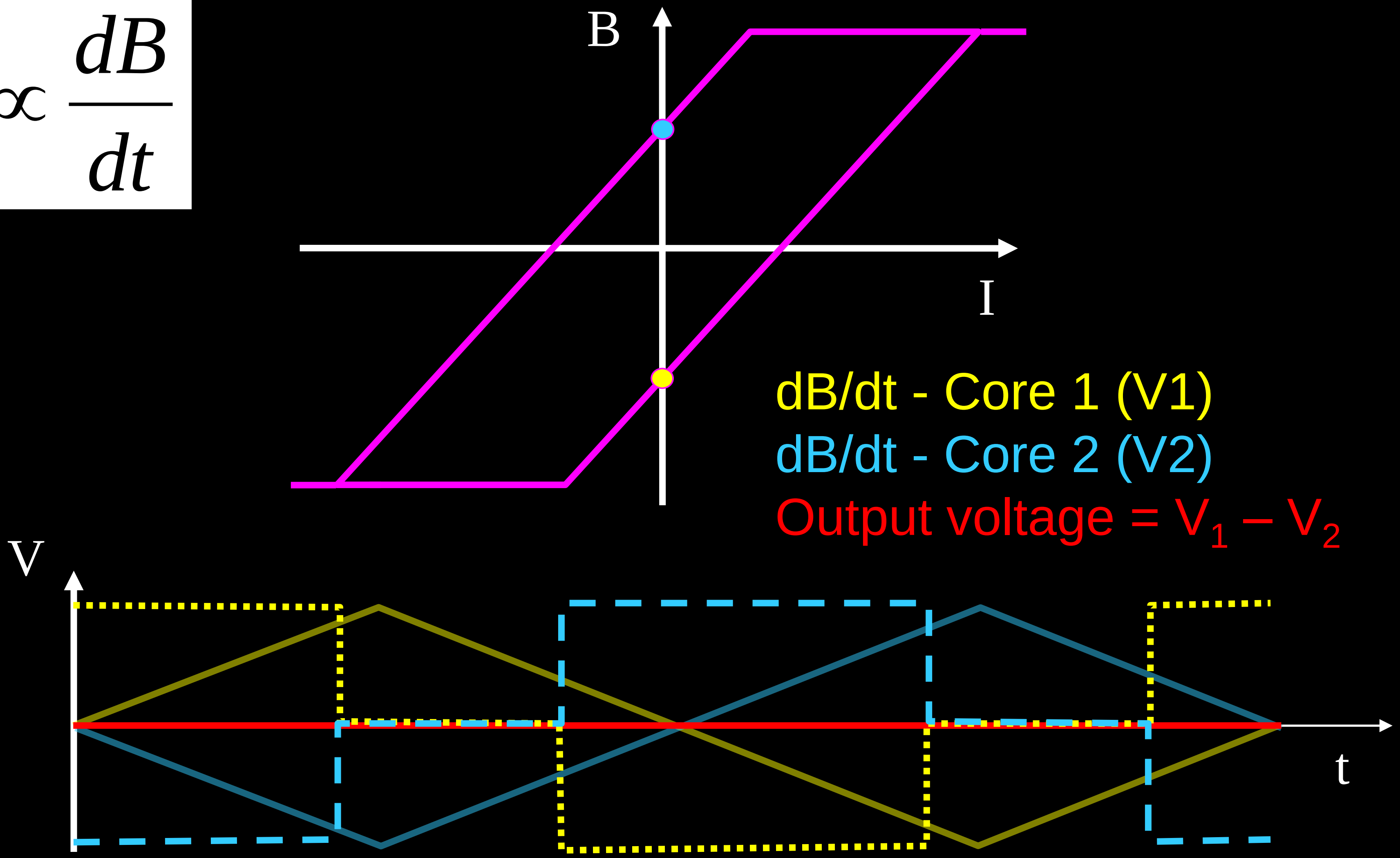


DCCT Principle – Case 1: no beam



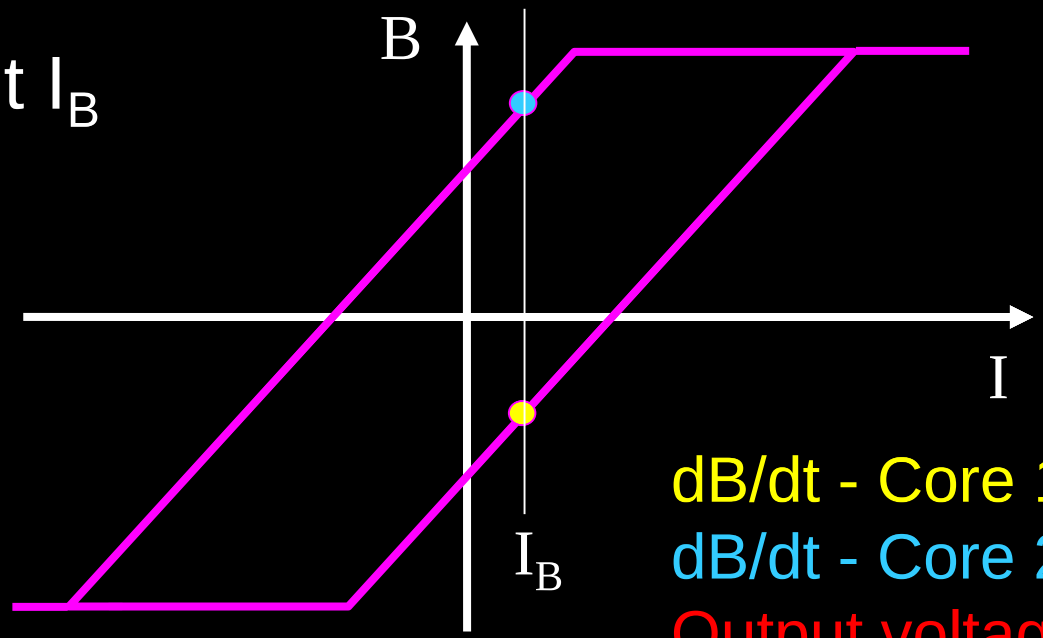
DCCT Principle – Case 1: no beam

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



DCCT Principle – Case 2: with beam

Beam Current I_B

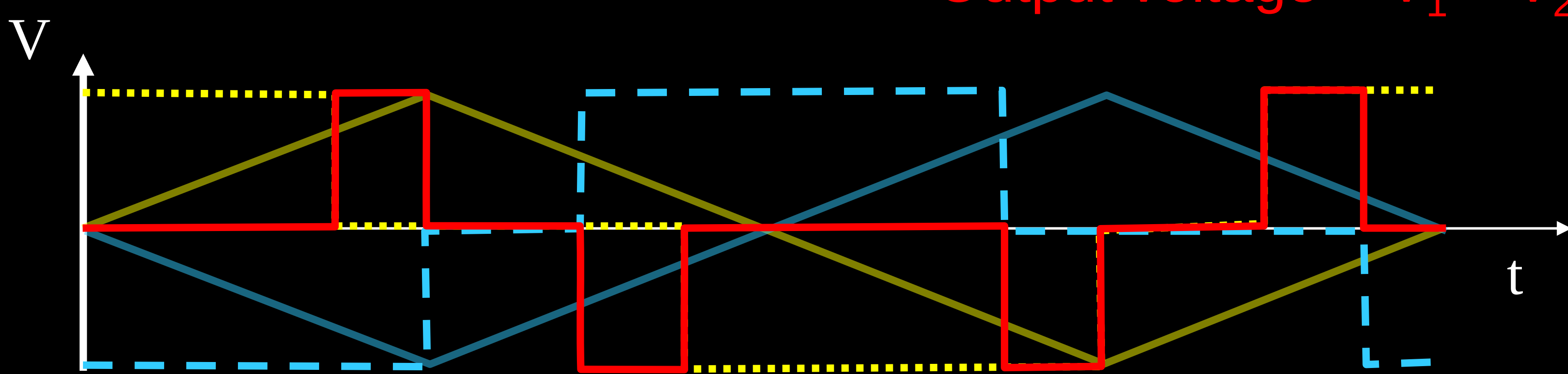


Output signal is at TWICE the modulation frequency

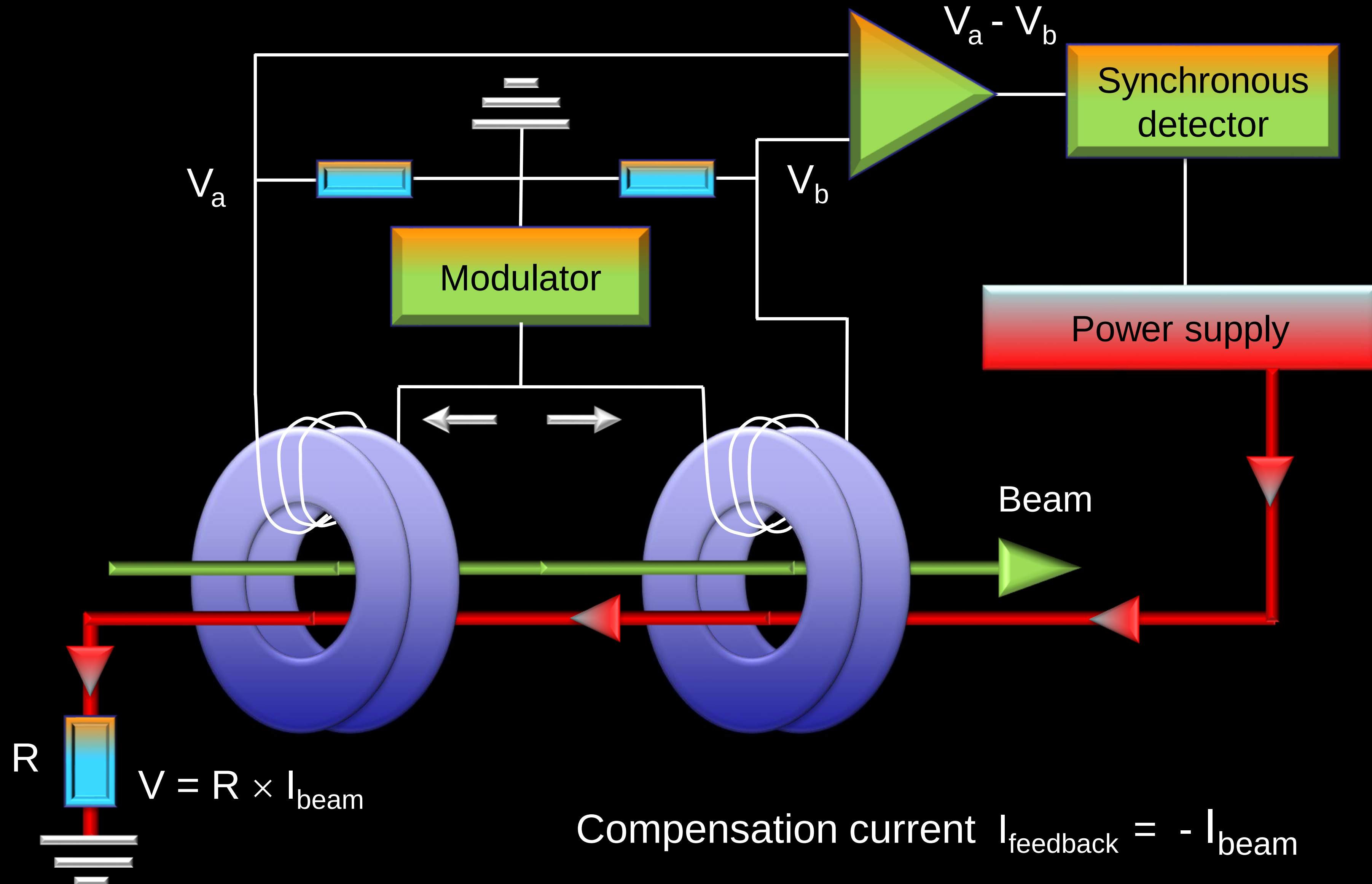
dB/dt - Core 1 (V1)

dB/dt - Core 2 (V2)

Output voltage = $V_1 - V_2$



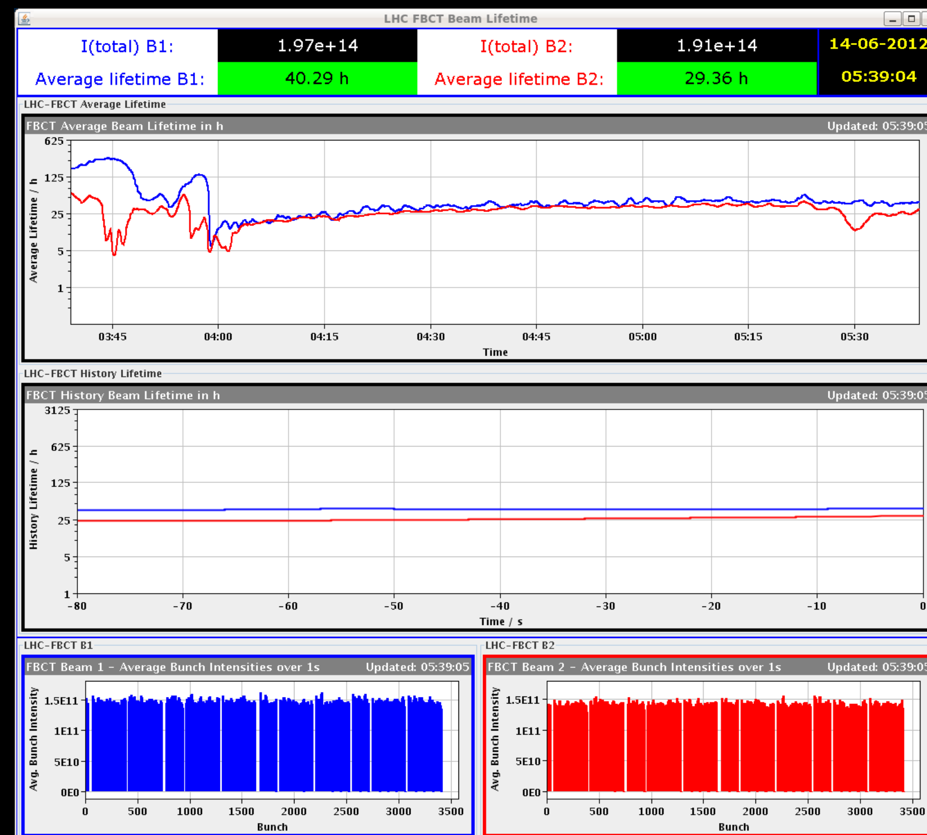
Zero Flux DCCT Schematic



Compensation current $I_{feedback} = - I_{beam}$

BCTs in Operation

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



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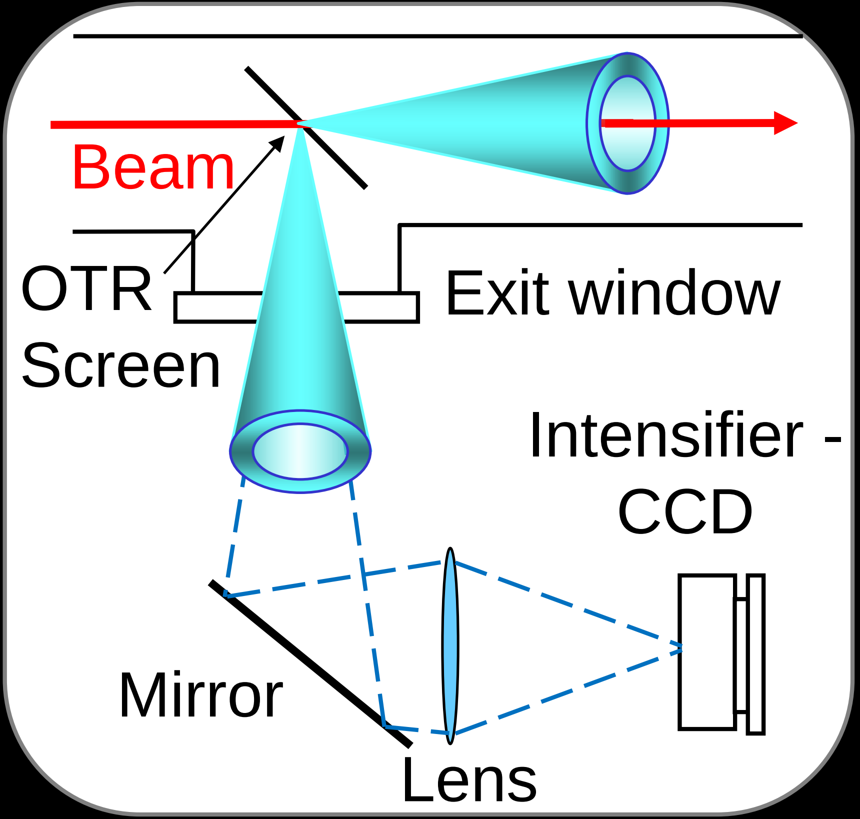
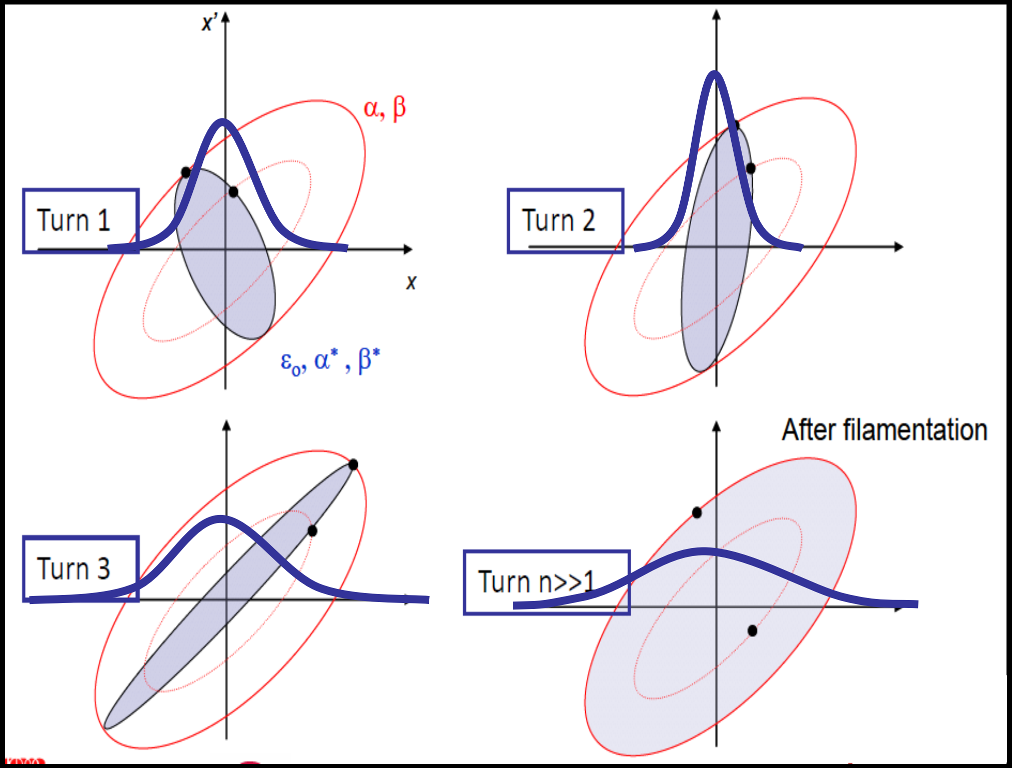
Beam Profile Monitoring using Screens

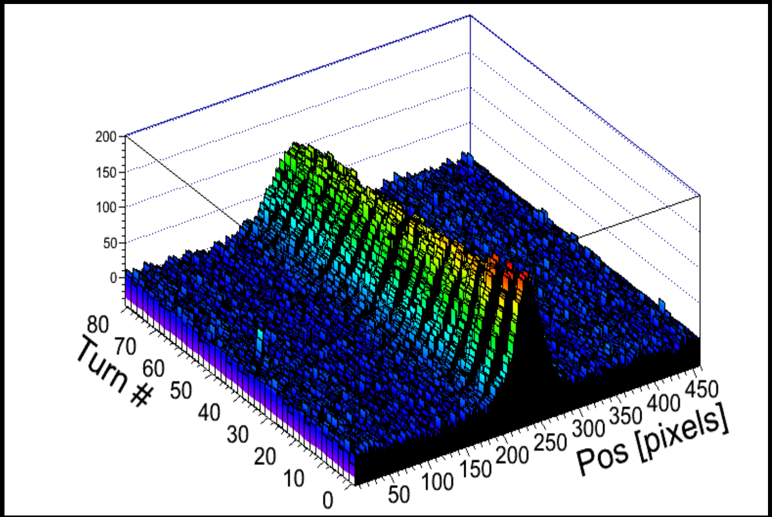
- Screen Types
  - Luminescence / Scintillating Screens
    - Destructive (thick) but work with low intensities
  - Optical Transition Radiation (OTR) screens
    - Much less destructive (thin) but require higher energy / intensity beam
- OTR
  - Radiation emitted when a charged particle goes through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

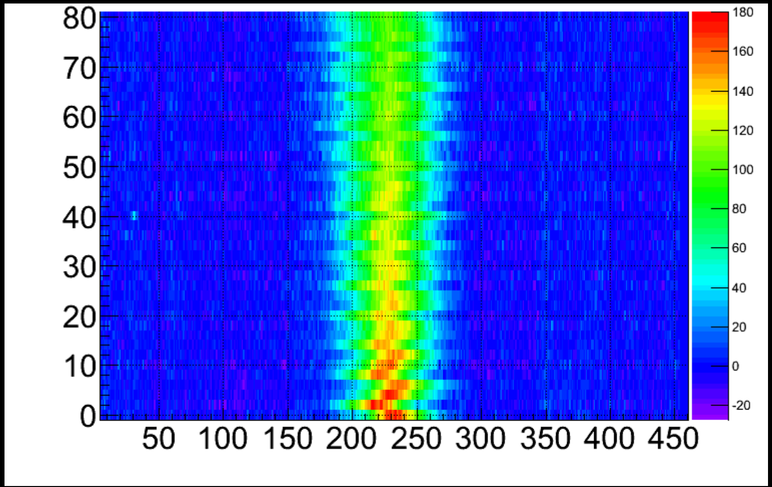


Measurements with Screens

- Injection matching measurements with OTR
  - Filamentation
  - Machine Settings Mismatch

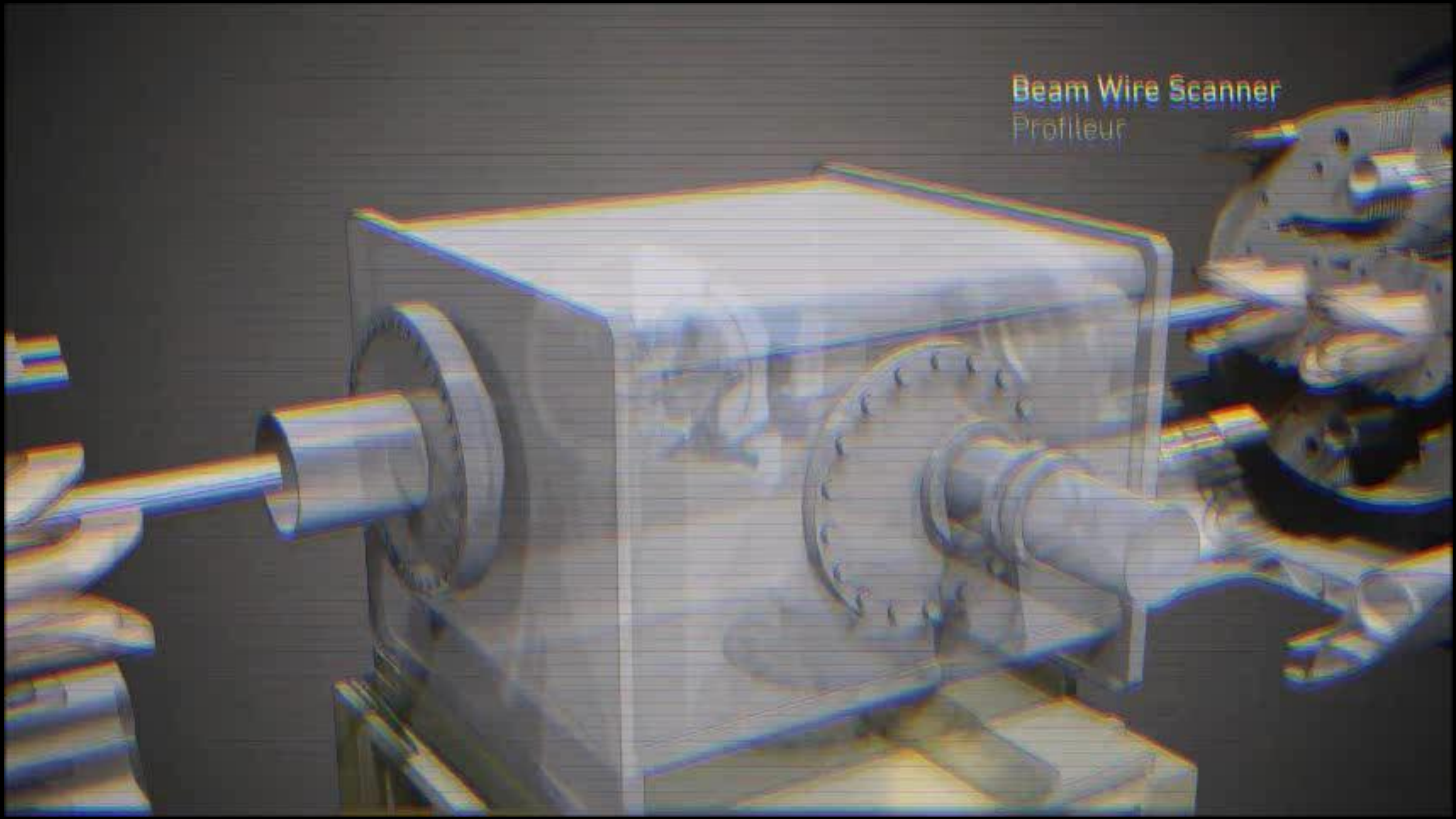




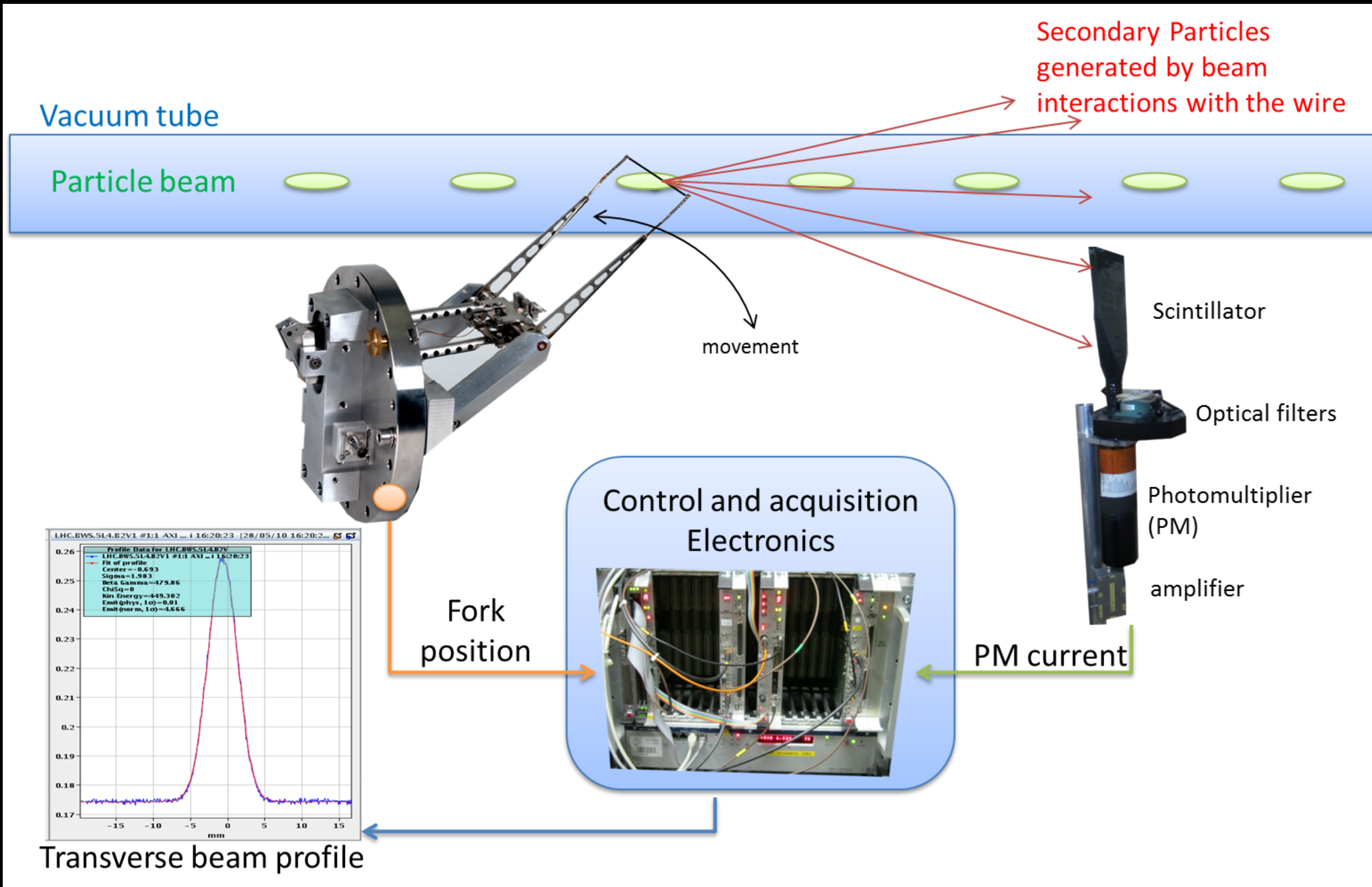


Beam Profile Monitoring using Wire-Scanners

- 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

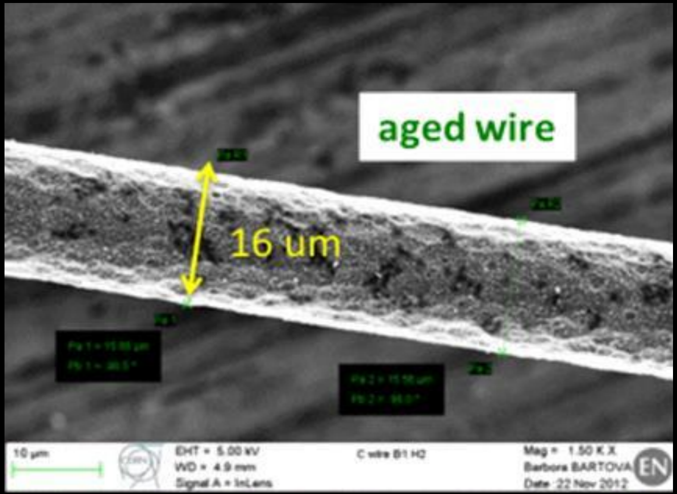


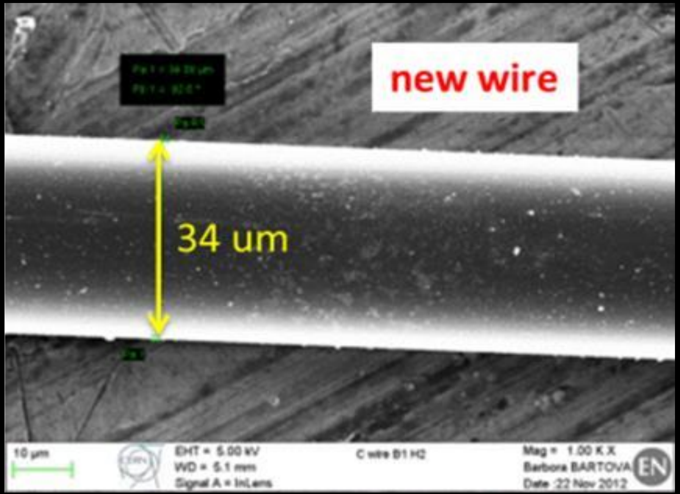
Beam Profile Monitoring using Wire-Scanners



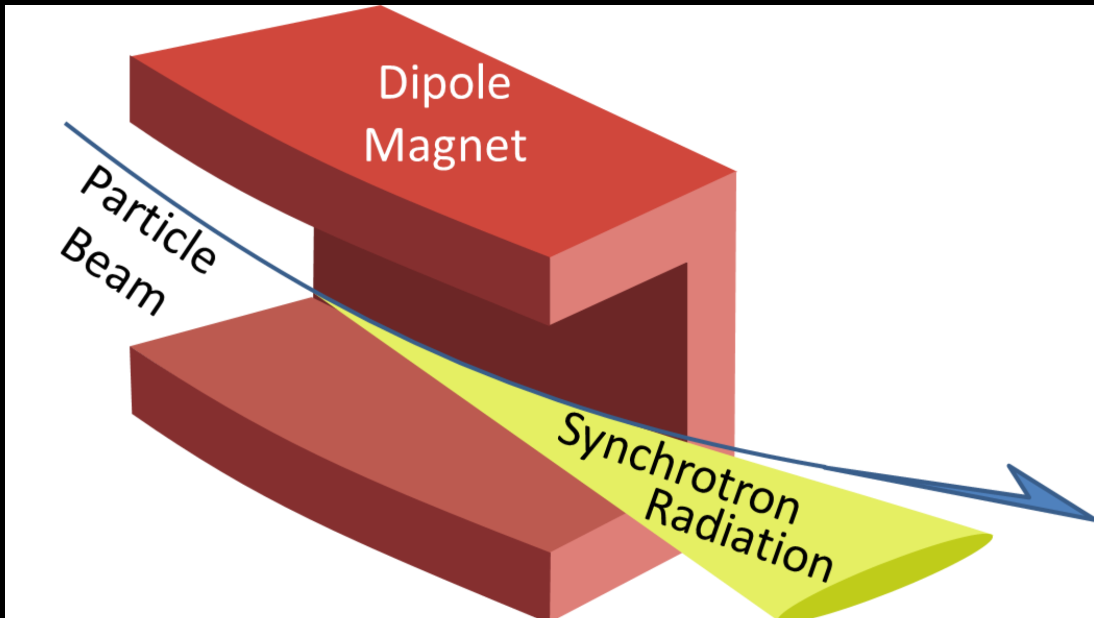
Limitation of WireScanners

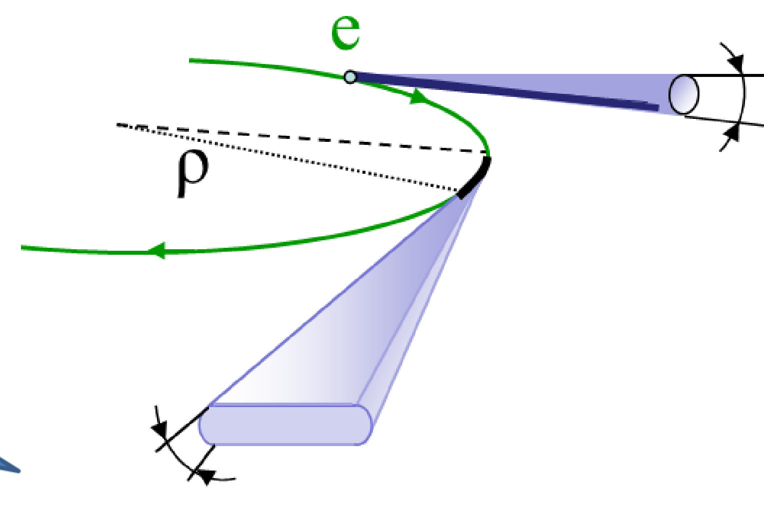
- Wire Breakage – why?
  - Brittle or Plastic failure (error in motor control)
  - Melting/Sublimation (main intensity limit)
    - Due to energy deposition in wire by proton beam
- Temperature evolution depends on
  - Heat capacity, which increases with temperature!
  - Cooling (radiative, conductive,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





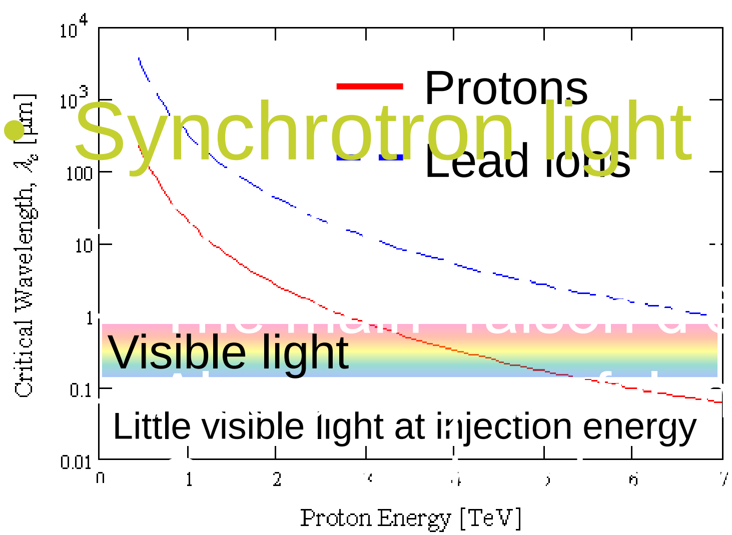
Synchrotron Light Monitors

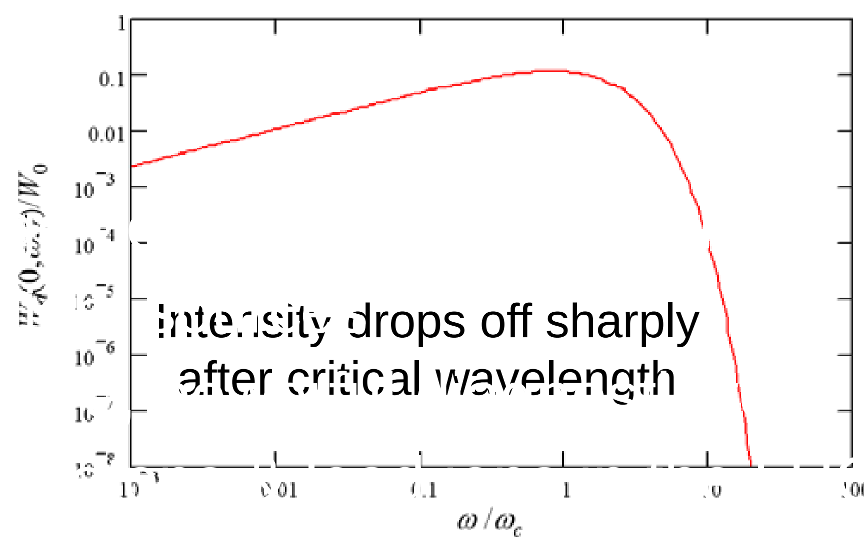




$\Psi_{SR} \propto 1/\gamma$ rad

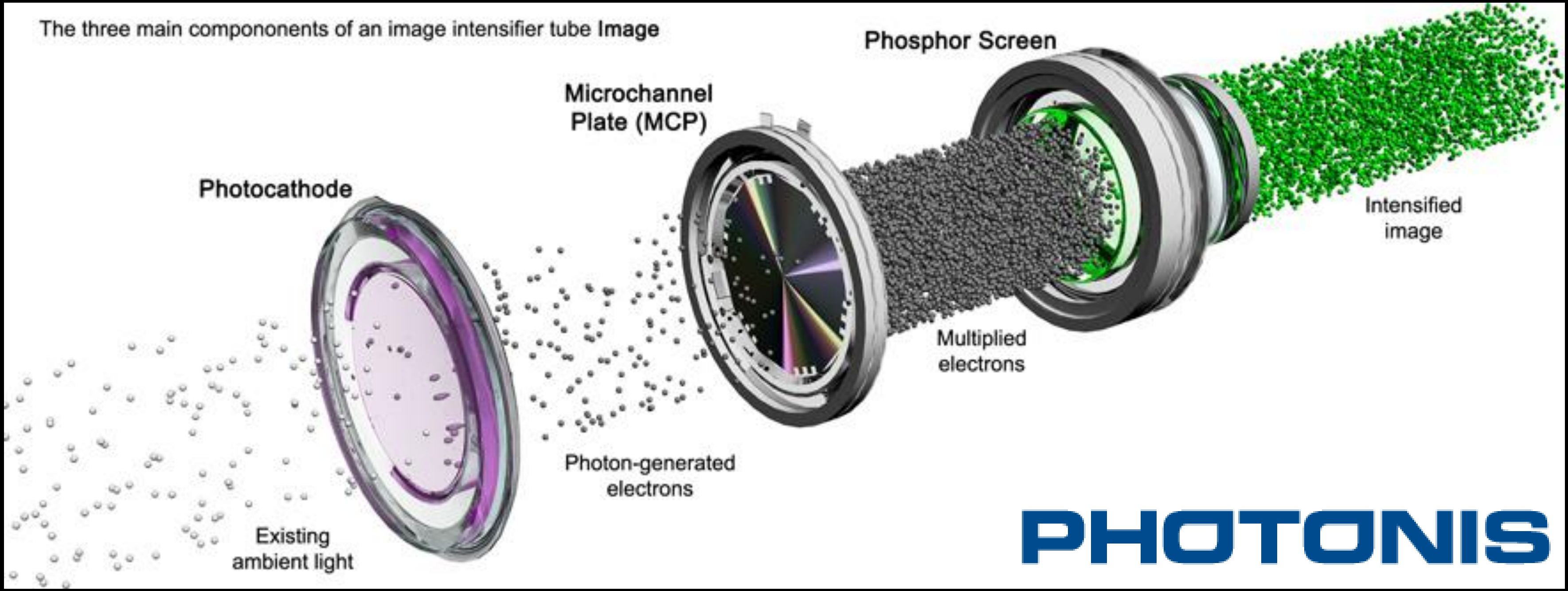
- Synchrotron light





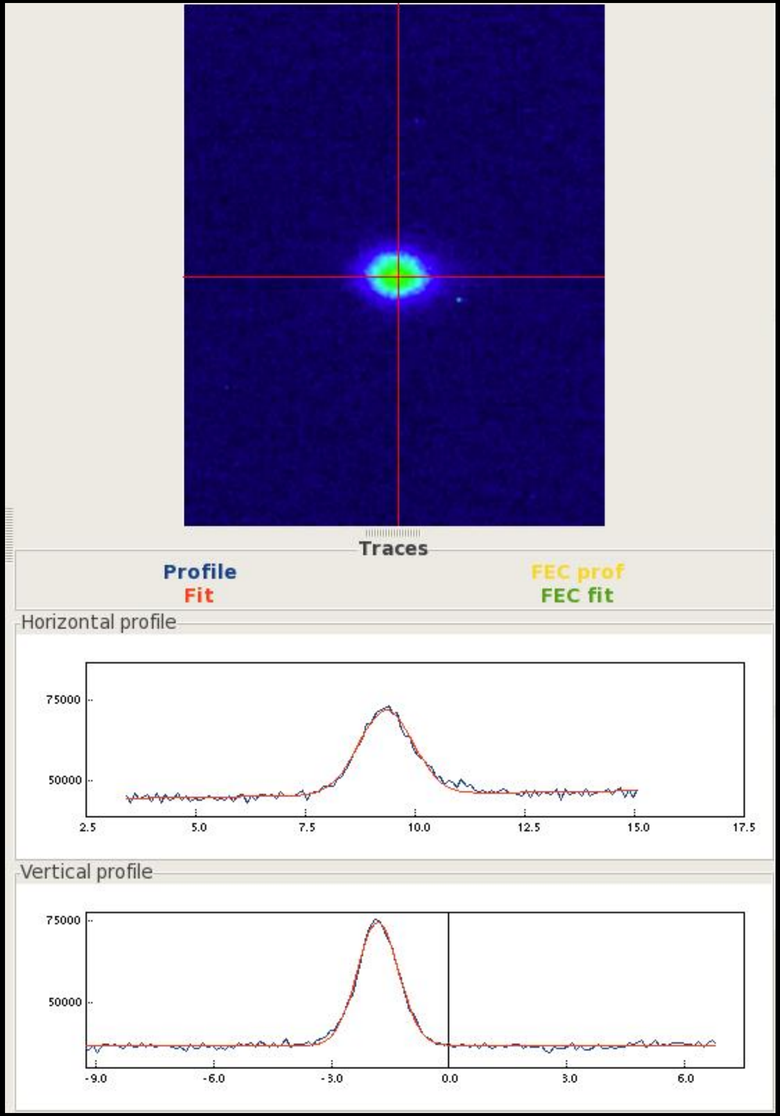
Synchrotron Light Image Acquisition

- 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

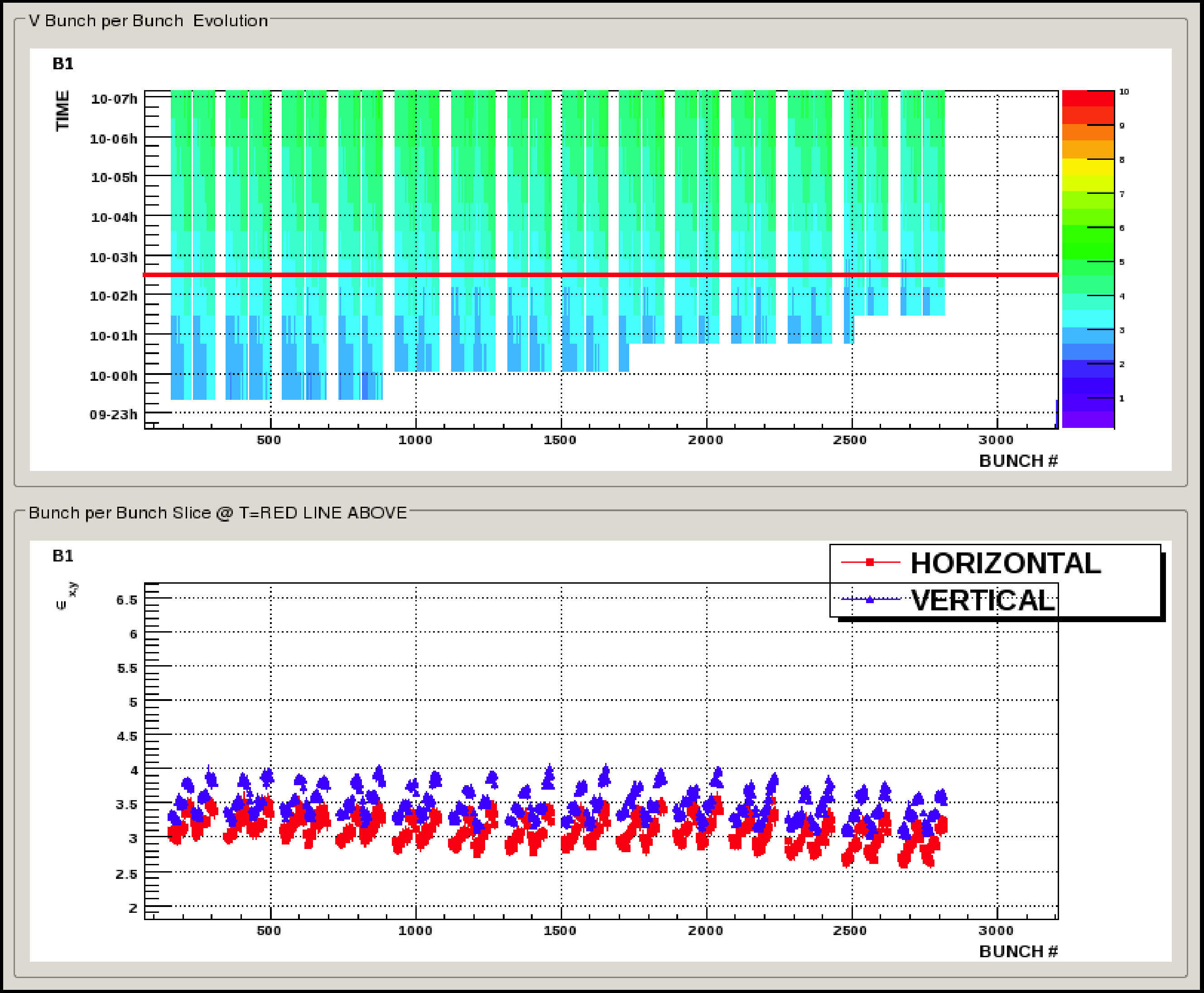
- Proton Beam Example
  - LHC single bunch ~1.1e11p @ 3.5 TeV
  - Acquistion accumulated over 4 turns at 200Hz
- Limitations
  - Aberrations
    - Mitigated by careful design
  - Diffraction
    - Need to go to lower wavelengths as the beam size becomes smaller



Bunch by Bunch Profile Measurement

Diagnostics

- Allows diagnosis of systematic emittance patterns from the LHC injectors
  - In this case variations in the emittance from the 4 different PS Booster rings



Measuring Ultra Short Bunches

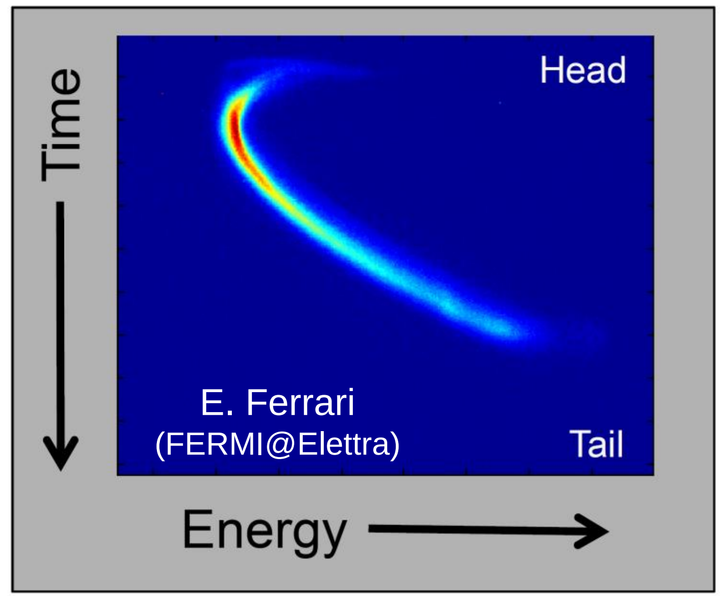
- Next Generation FELs & Linear Colliders
  - Use ultra short bunches to increase brightness or improve luminosity
- How do we measure such short bunches?

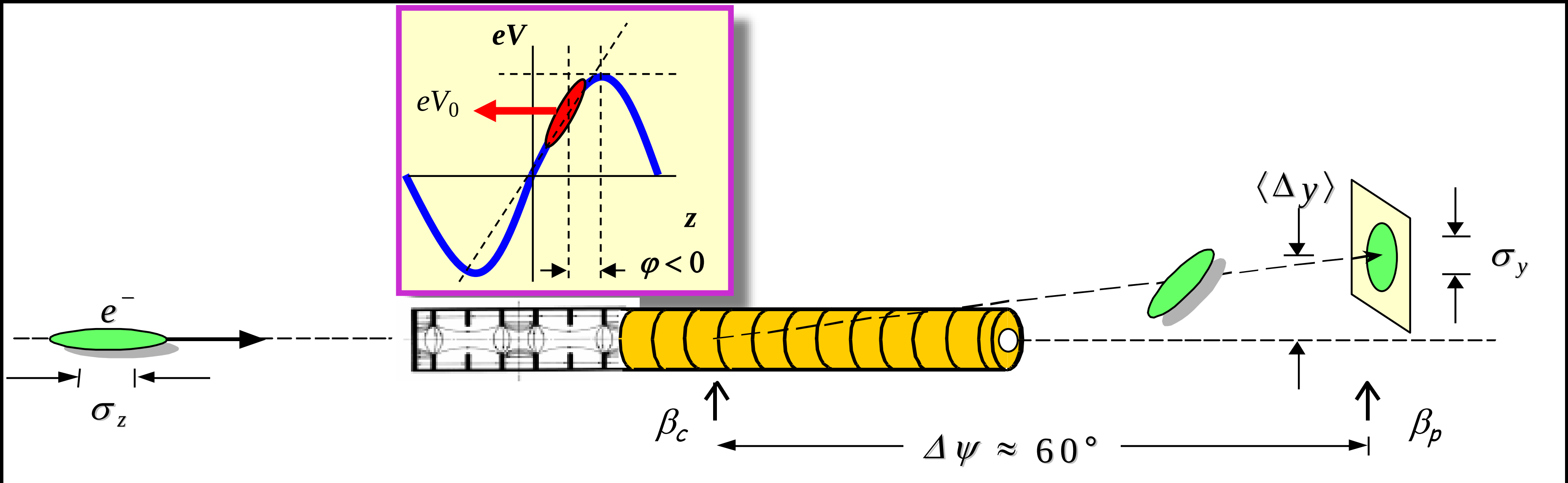
p^+ @ LHC	250ps
H^- @ SNS	100ps
e^- @ ILC	500fs
e^- @ CLIC	130fs
e^- @ XFEL	80fs
e^- @ LCLS	<75fs

  - 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

Measuring Ultra Short Bunches

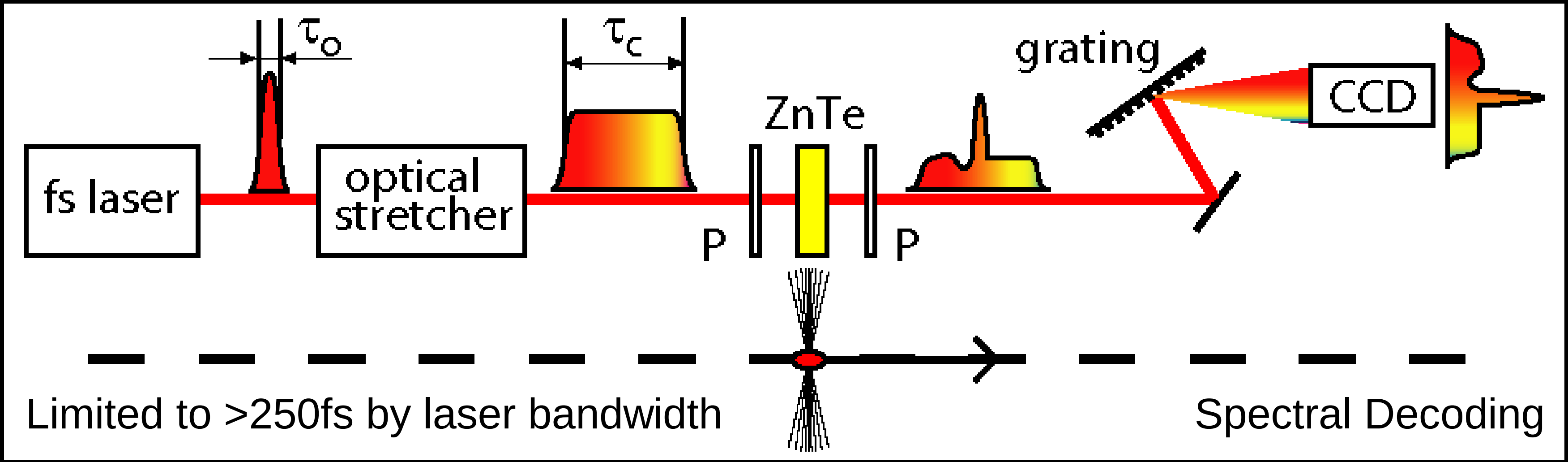
- RF Deflection
  - Converts time information to spatial information
  - Coupled to spectrometer also provides energy information
  - Destructive technique
  - Resolution down to 1.3 fs
    - X-band RF cavity
    - Linac Coherent Light Source (SLAC)





Measuring Ultra Short Bunches

- Electro-Optic Sampling
  - Use a birefringent crystal to map the electric field of the bunch onto a chirped (time varying wavelength) laser pulse
    - Electric field modified the polarisation of the light in the crystal
  - Sample this light pulse to obtain the longitudinal bunch distribution
    - Can be done in a variety of ways
  - Non destructive technique
  - Resolution down to 30 fs possible



The Typical Instruments

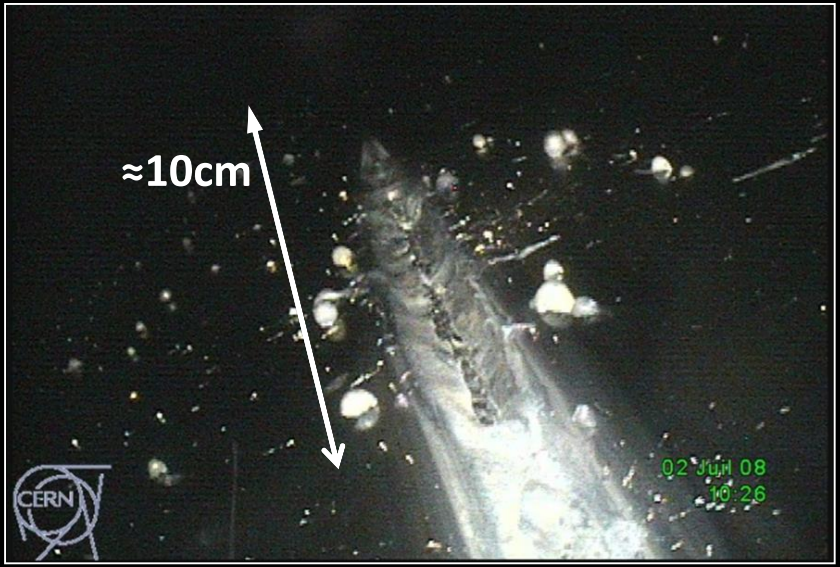
- Beam Position
  - electrostatic or electromagnetic pick-ups and related electronics
- Beam Intensity
  - beam current transformers
- Beam Profile
  - secondary emission grids and screens
  - wire scanners
  - synchrotron light monitors
  - ionisation and luminescence monitors
  - femtosecond diagnostics for ultra short bunches
- Beam Loss
  - ionisation chambers or pin diodes
- Machine Tune and Chromaticity
  - in Beam Diagnostics lecture tomorrow

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

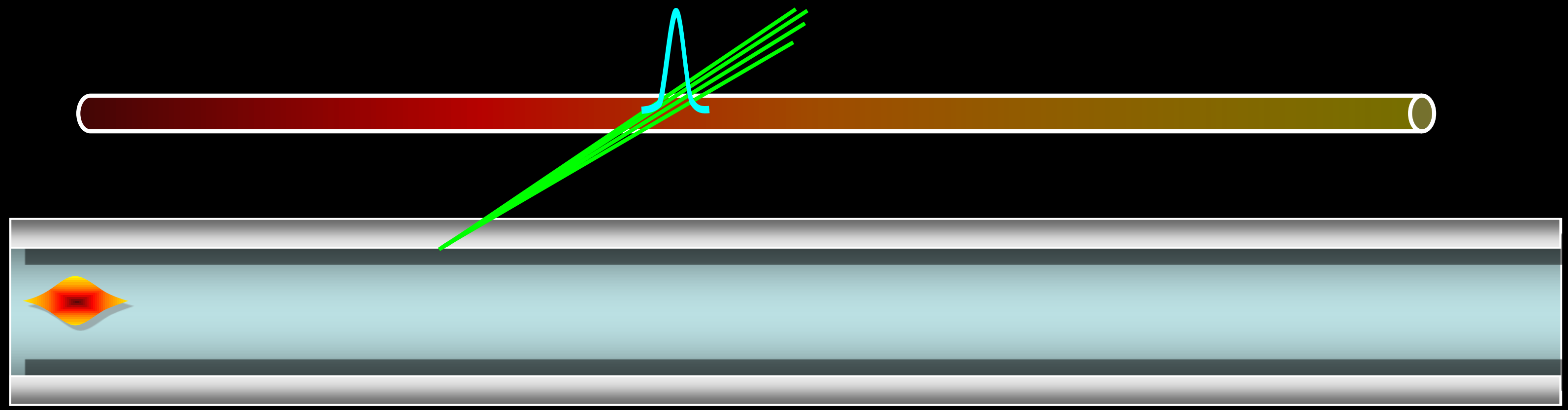
Quench and Damage at 7 TeV	
Quench level	≈ 1mJ/cm^3
Damage level	≈ 1 J/cm^3



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

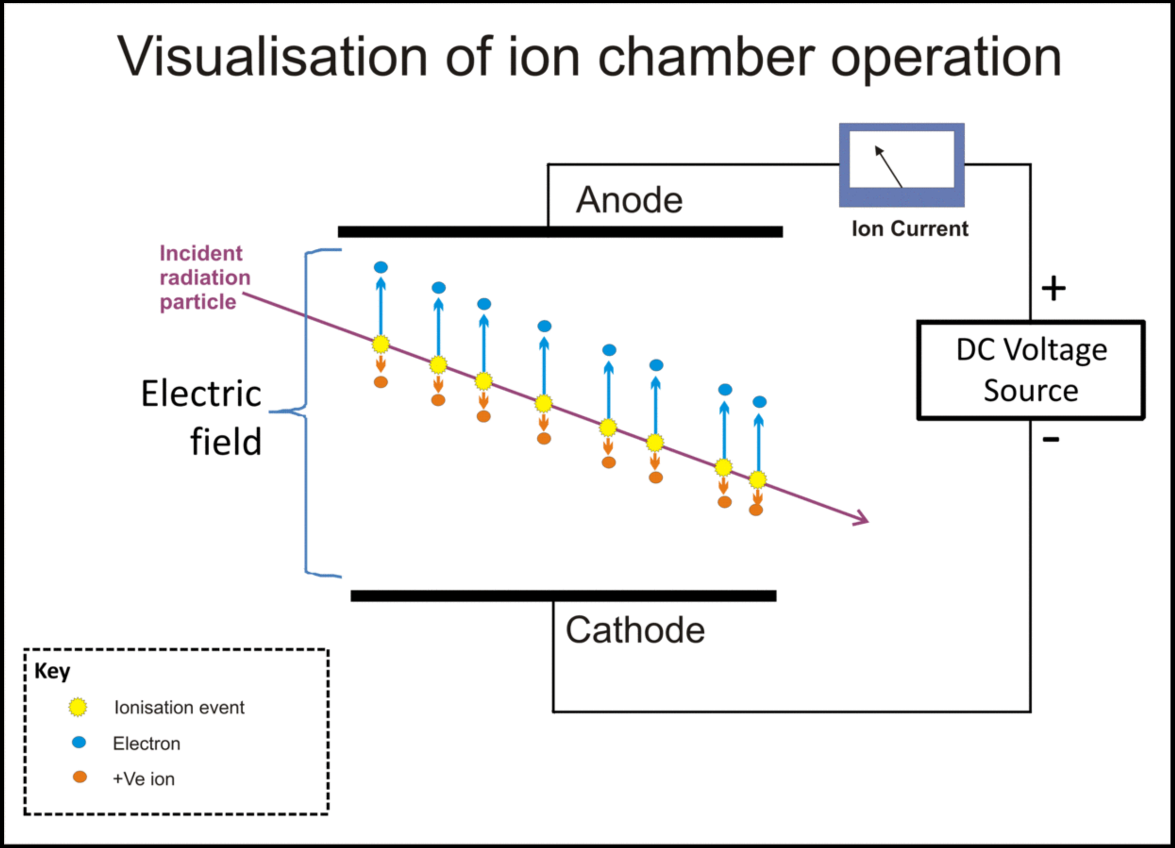
Beam Loss Detectors

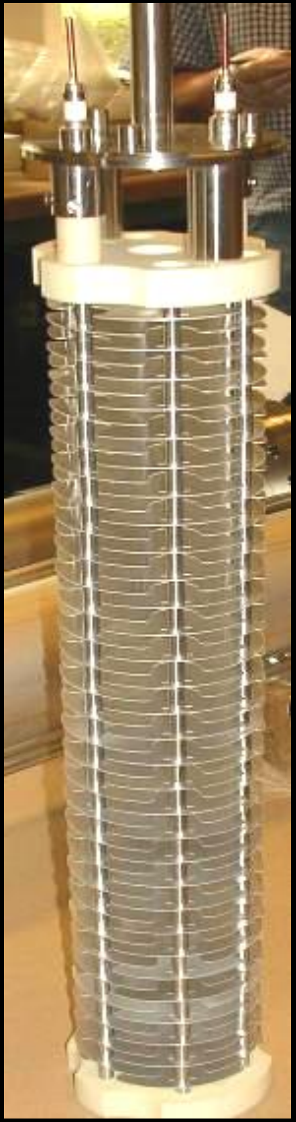
- Common types of monitor
  - Long ionisation chamber (charge detection)
    - Up to several km of gas filled hollow coaxial cables
    - Position sensitivity achieved by comparing direct & reflected pulse
      - e.g. SLAC – 8m position resolution (30ns) over 3.5km cable length
    - Dynamic range of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



Beam Loss Detectors

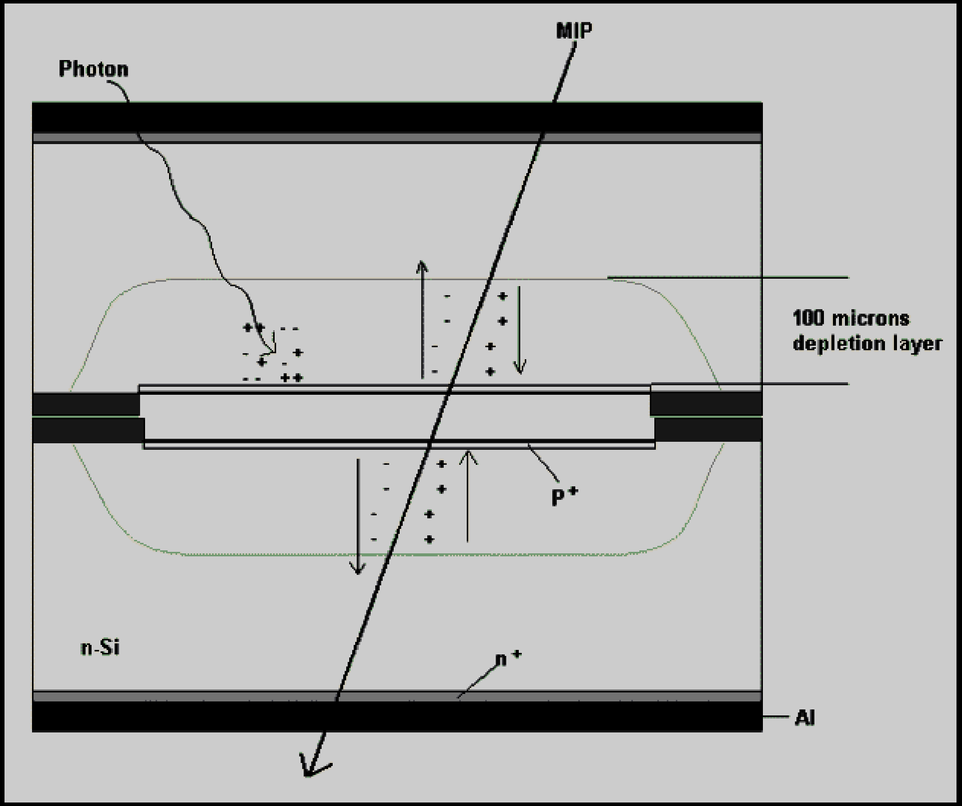
- Common types of monitor
  - Ionisation chambers
  - Dynamic range of < 10^8
  - Slow response (μs) due to ion drift time





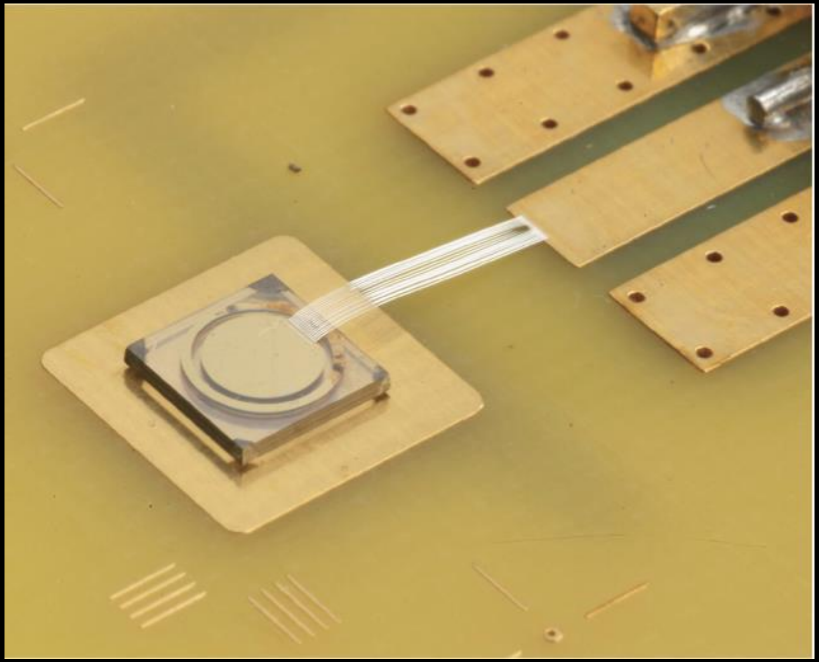
Beam Loss Detectors

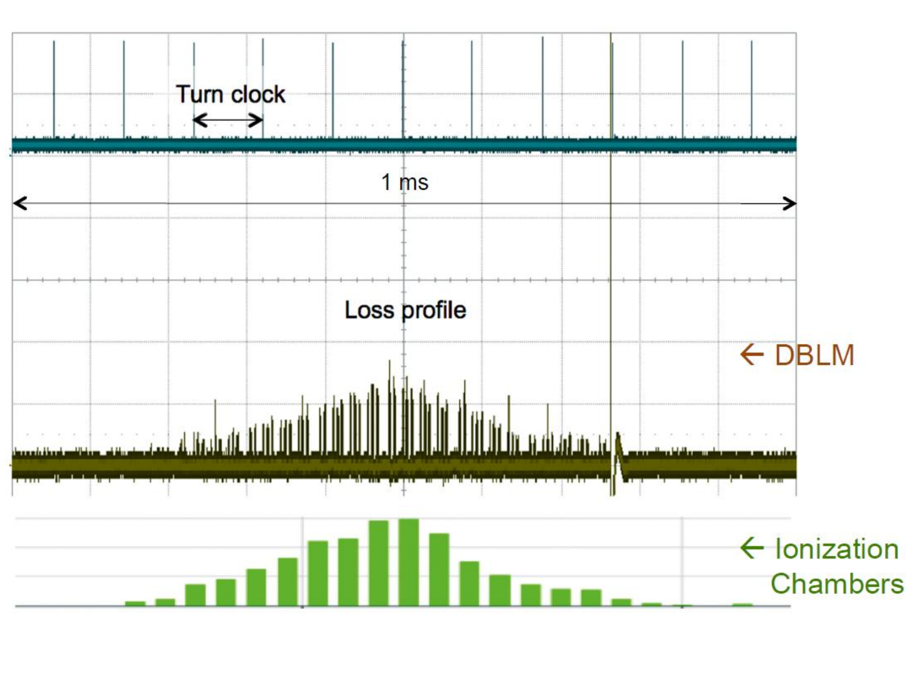
- Common types of monitor
  - PIN photodiode (solid state ionisation chamber)
    - Detect coincidence of ionising particle crossing photodiodes
    - Count rate proportional to beam loss with speed limited by integration time
    - Can distinguish between X-rays & ionising particles
    - Dynamic range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

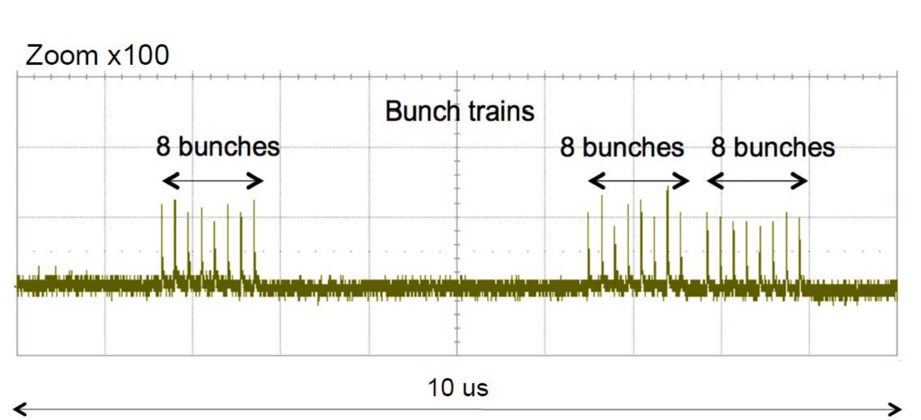


Beam Loss Detectors – New Materials

- 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



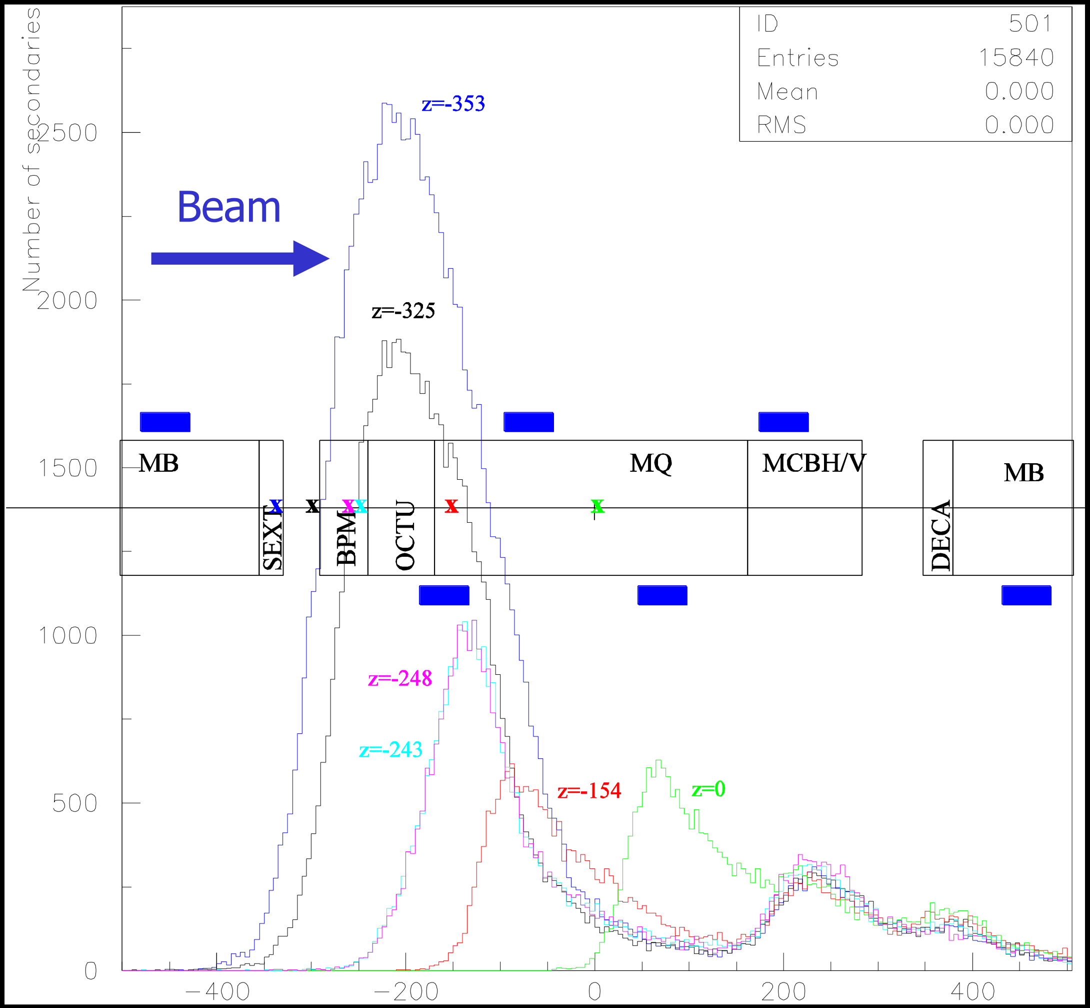




Courtesy of E. Griesmayer

Where should we place our BLMs?

- Secondary shower simulation
  - to determine what energy is deposited where
- Impact position varied along quadrupole
- Position of detectors optimized
  - to catch losses & minimize uncertainty of ratio of energy deposition in coil and detector
  - To discriminate between Beams
  - To have good probability that losses are seen by two BLM detectors



Summary

- This was an overview of the common types of instruments that can be found in most accelerators
  - Only small subset of those currently in use or being developed
  - Many exotic instruments are tailored for specific accelerator needs

- Tomorrow you will see how to use these instruments to run and optimise accelerators
  - Introduction to Accelerator Beam Diagnostics (H. Schmickler)

Want to know more? Then Join the afternoon course:

- Beam Instrumentation & Diagnostics
  - For an in-depth analysis of these instruments & their applications
  - 3 Sessions : BPM design & Tune Measurement
    - Using specially developed software & laboratory measurements
  - 2 Sessions : Emittance measurements & ultra-fast diagnostics
  - 1 Session : Design your own beam instrumentation suite
    - Present your Group's ideas on how to equip an accelerator