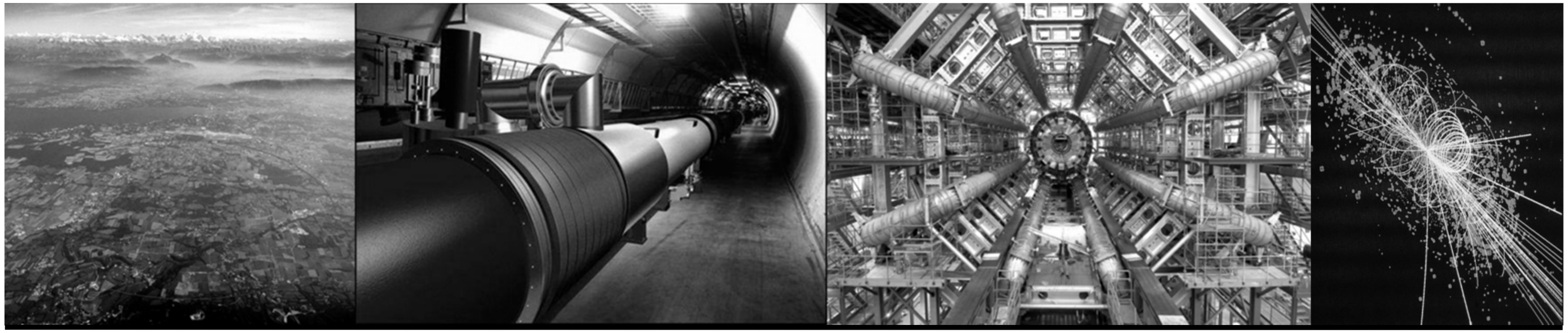


Introduction to Beam Instrumentation

CAS 2015

Warsaw, Poland

27th September – 9th October, 2015

Dr. Rhodri Jones

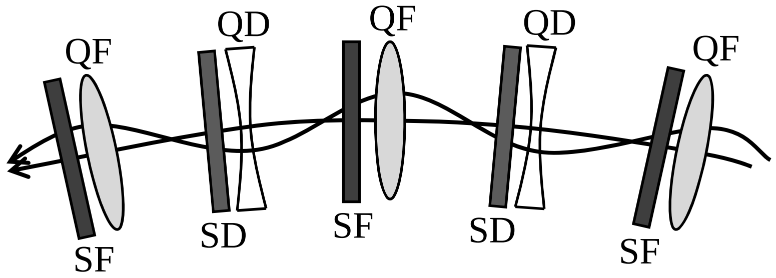
Head of the CERN Beam Instrumentation Group

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 superconducting machines
  - Beam profiles
    - Transverse and longitudinal distribution
  - Collision rate / Luminosity (for colliders)
    - Measure of how well the beams are overlapped at the collision point

More Measurements

- Machine Tune

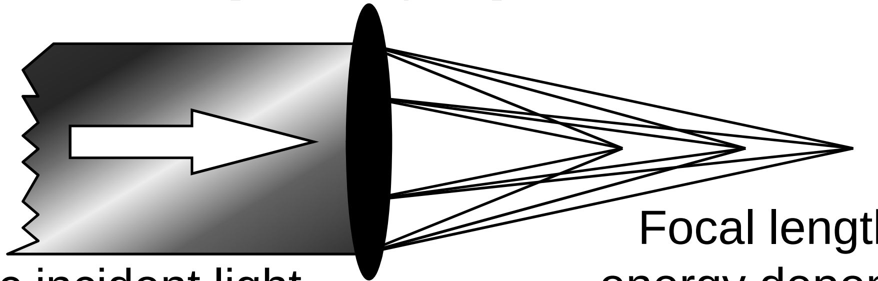


Characteristic Frequency of the Magnetic Lattice

Given by the strength of the Quadrupole magnets

- Machine Chromaticity

Optics Analogy:



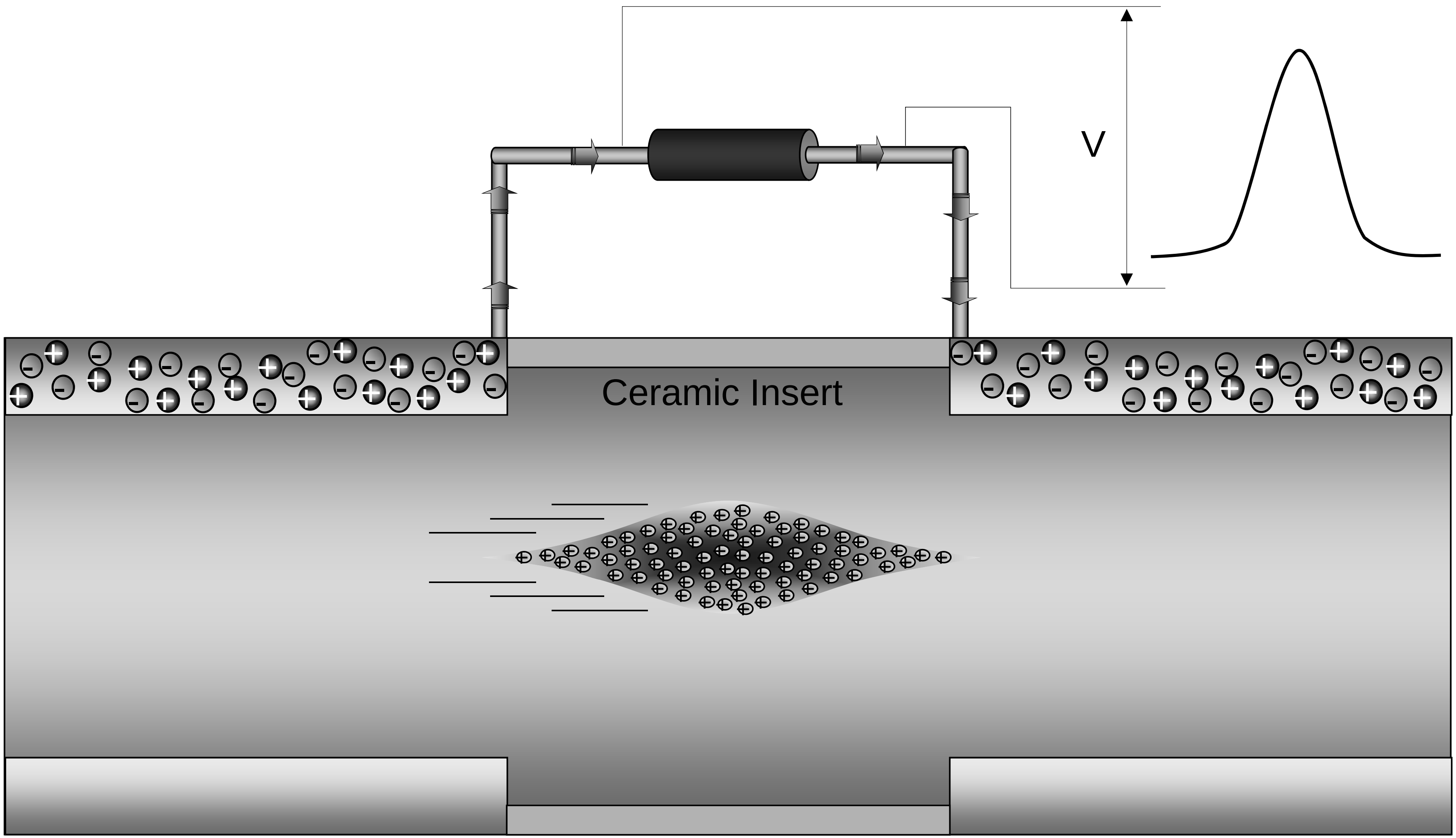
Spread in the Machine Tune due to Particle Energy Spread

Controlled by Sextupole magnets

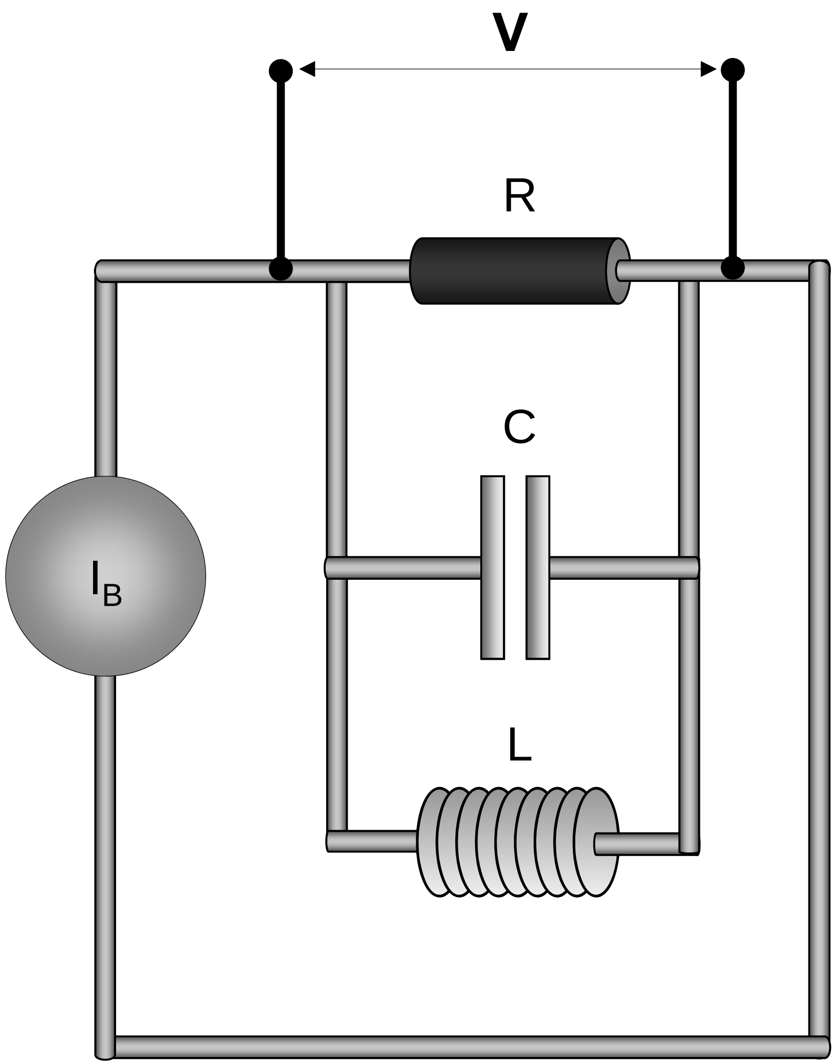
The Typical Instruments

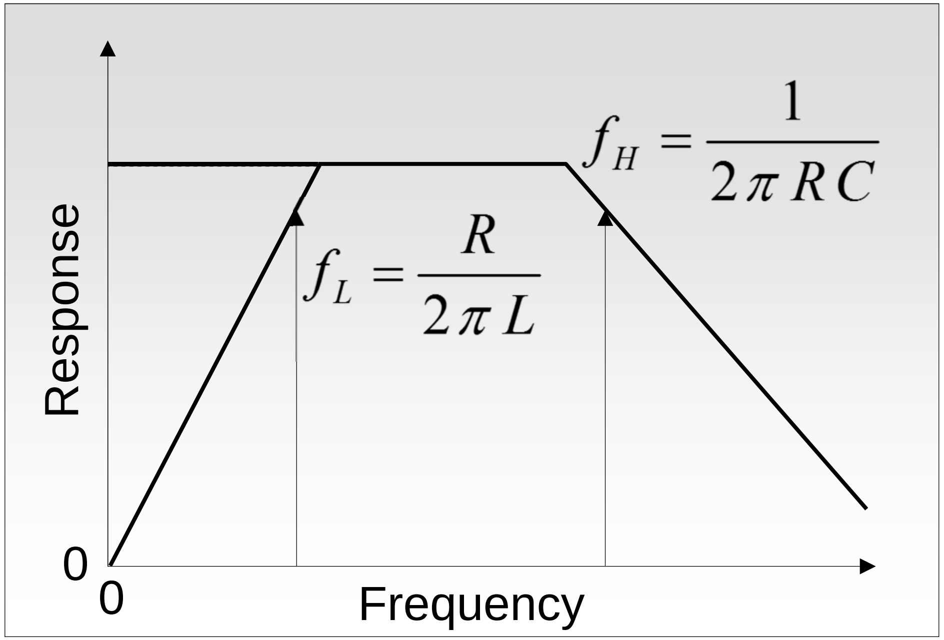
- **Beam Position**
  - **electrostatic or electromagnetic pick-ups and related electronics**
- Beam Intensity
  - beam current transformers
- Beam Profile
  - secondary emission grids and screens
  - wire scanners
  - synchrotron light monitors
  - ionisation and luminescence monitors
  - femtosecond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

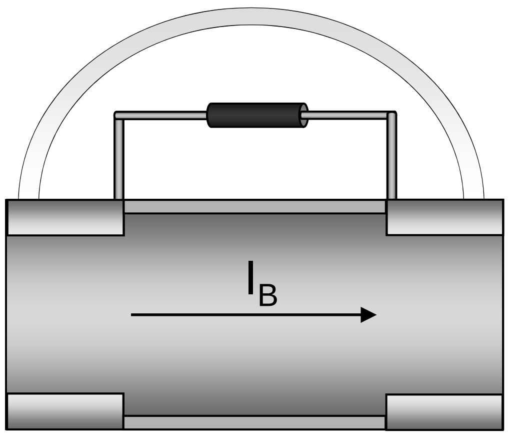
Wall Current Monitor – The Principle



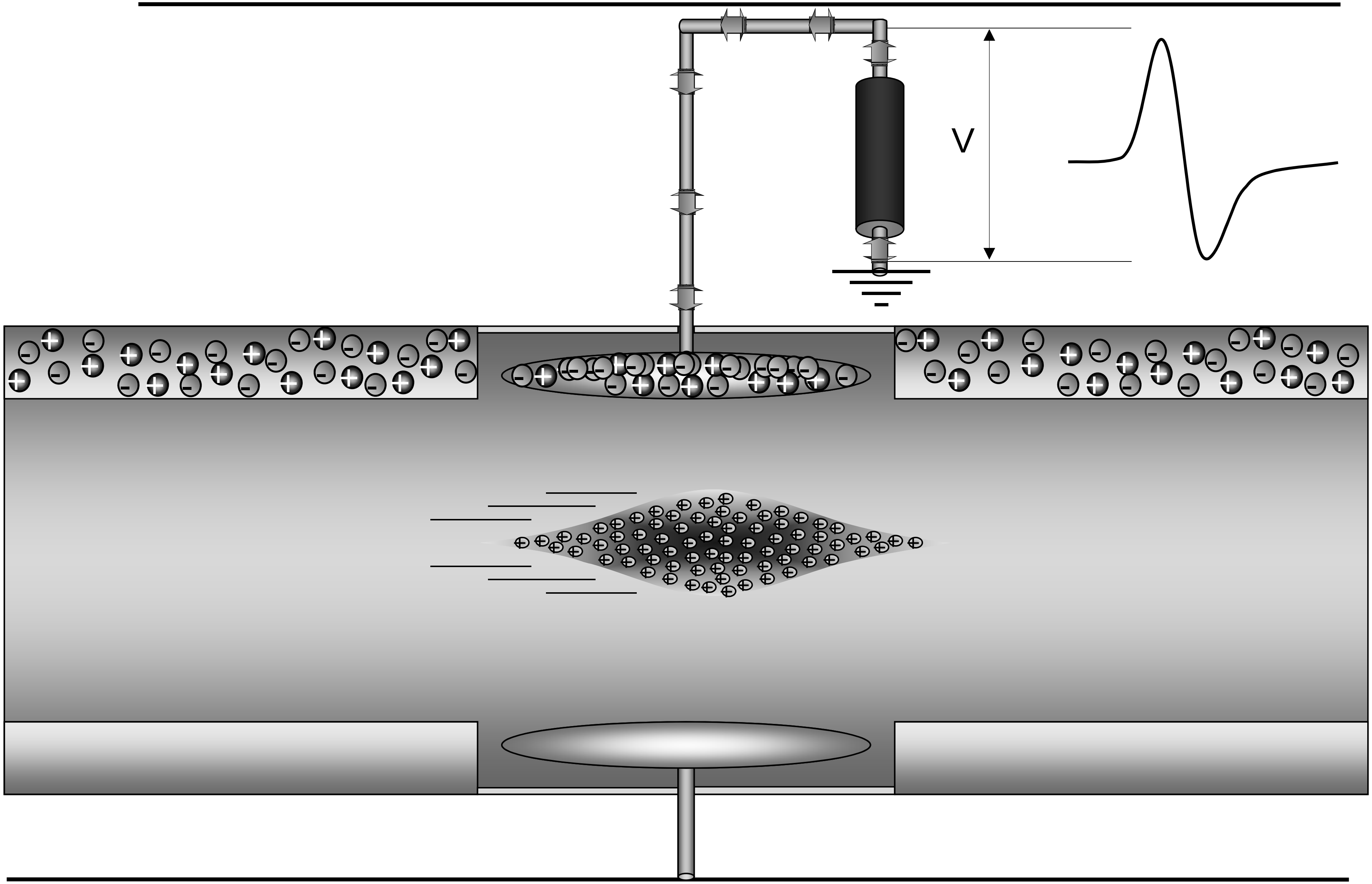
Wall Current Monitor – Beam Response



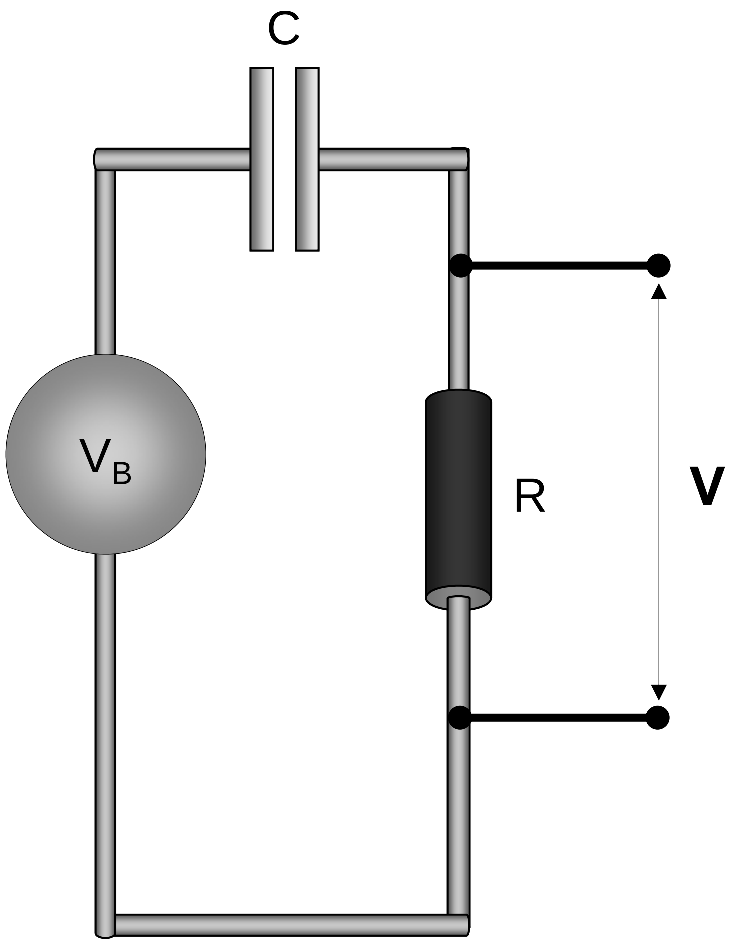


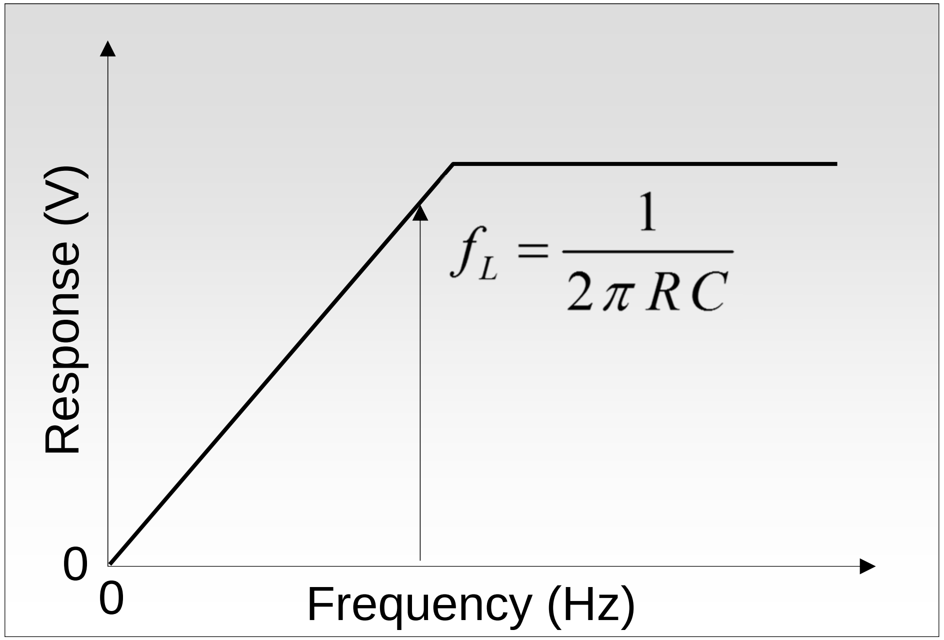


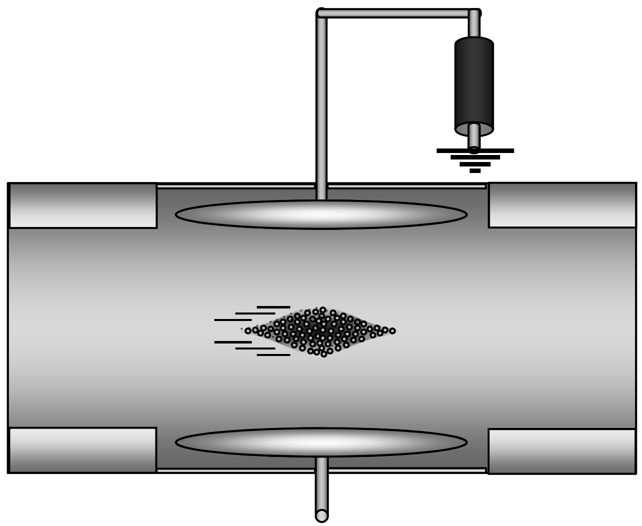
Electrostatic Monitor – The Principle



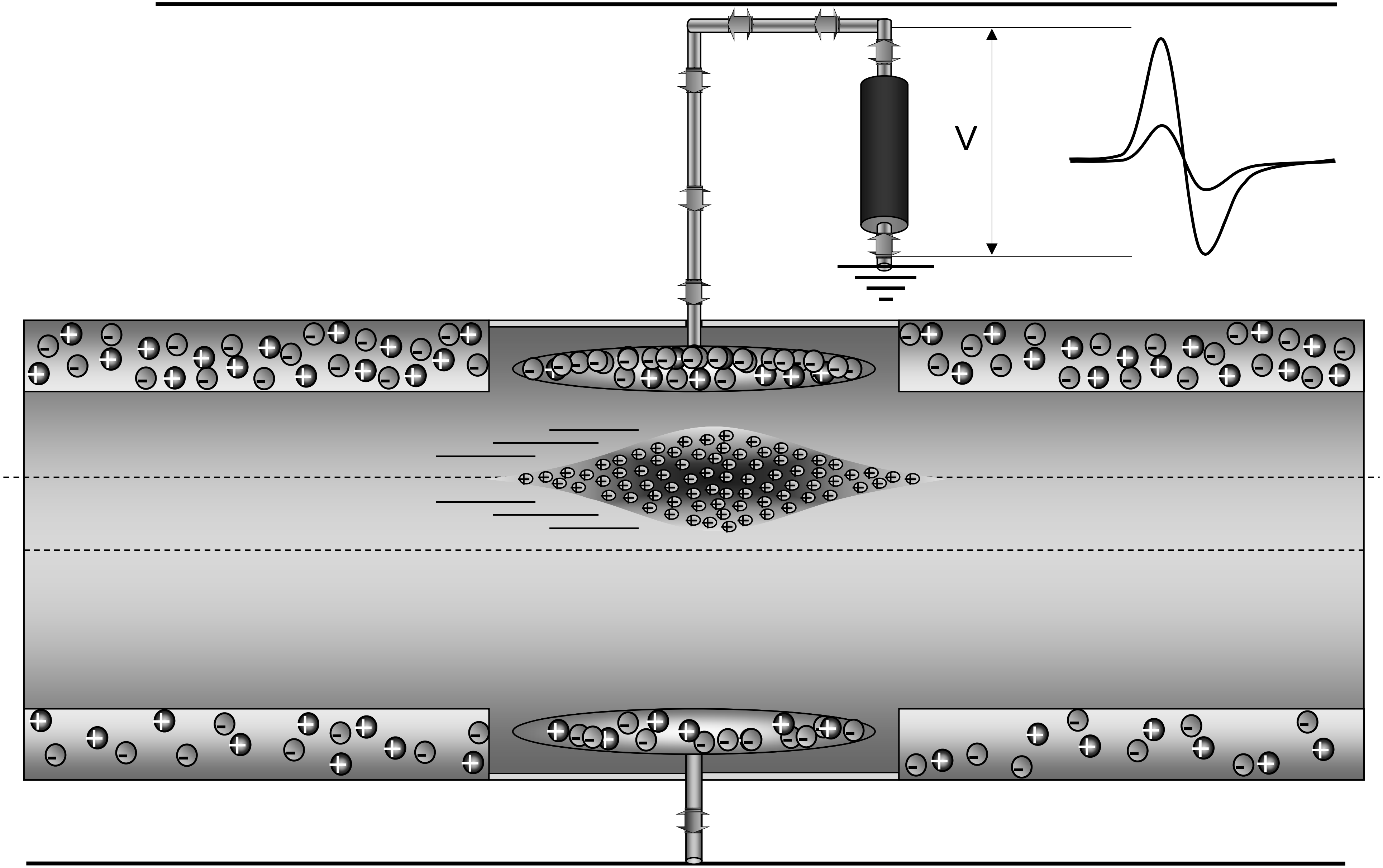
Electrostatic Monitor – Beam Response







Electrostatic Monitor – The Principle



Electrostatic Pick-up – Button

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

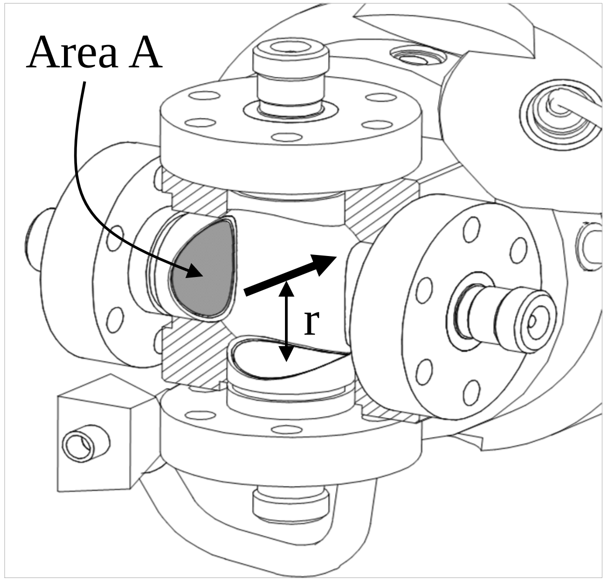
For Button with Capacitance C_e & Characteristic Impedance R_0

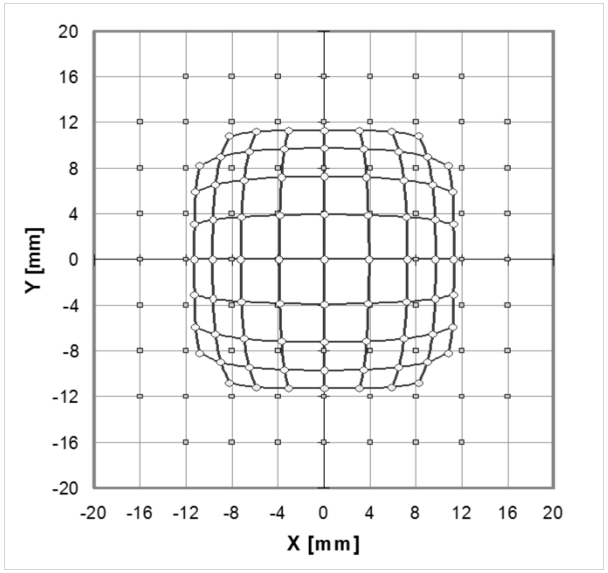
Transfer Impedance:

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

Lower Corner Frequency:

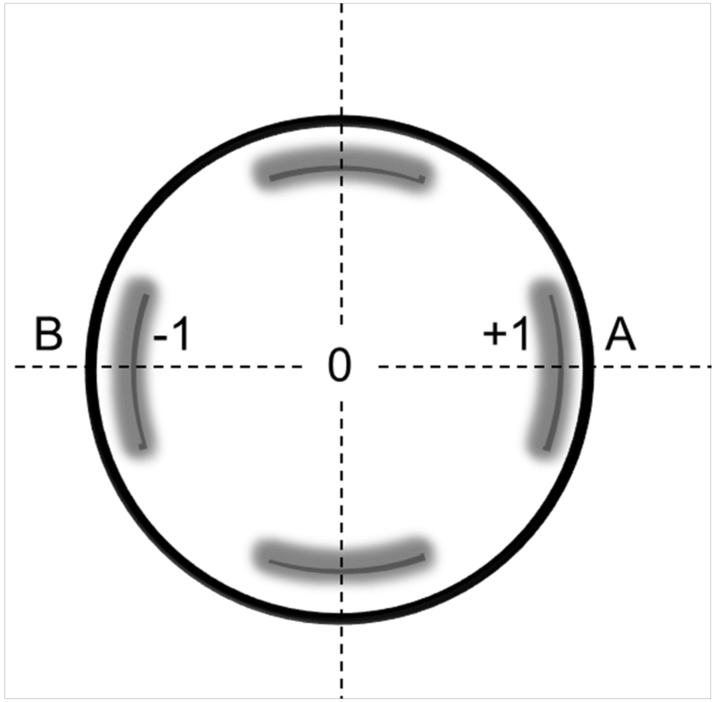
$$f_L = \frac{1}{2\pi R_0 C_e}$$

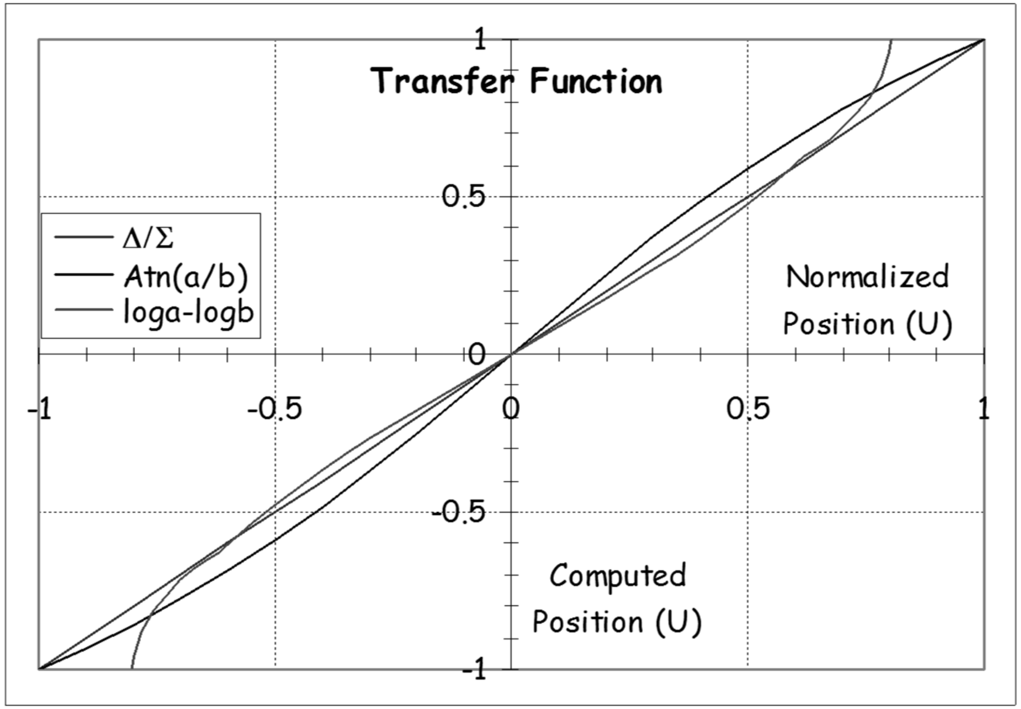




Normalising the Position Reading

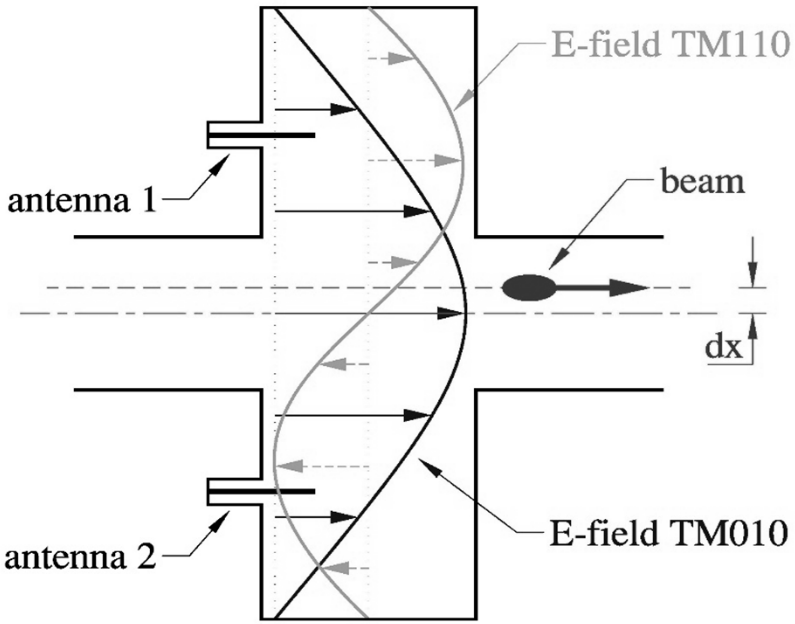
- To make it independent of intensity
- 3 main methods:
  - Difference/Sum : $(V_A - V_B) / (V_A + V_B) = \Delta / \Sigma$
  - Phase : $\mathrm{Arctan}(V_A / V_B)$
  - Logarithm : $\mathrm{Log}(V_A) - \mathrm{Log}(V_B)$

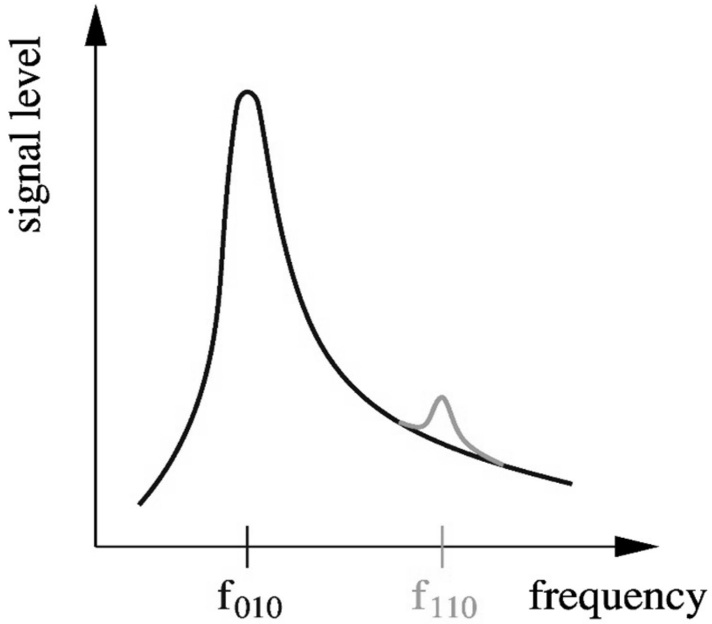




Improving the Precision for Next Generation Accelerators

- Standard BPMs give intensity signals which need to be subtracted to obtain a difference which is then proportional to position
  - Difficult to do electronically without some of the intensity information leaking through
    - When looking for small differences this leakage can dominate the measurement
    - Typically 40-80dB (100 to 10000 in V) rejection ⇒ tens micron resolution for typical apertures
- Solution – cavity BPMs allowing sub micron resolution
  - Design the detector to collect only the difference signal
    - Dipole Mode TM_{11} proportional to position & shifted in frequency with respect to monopole mode





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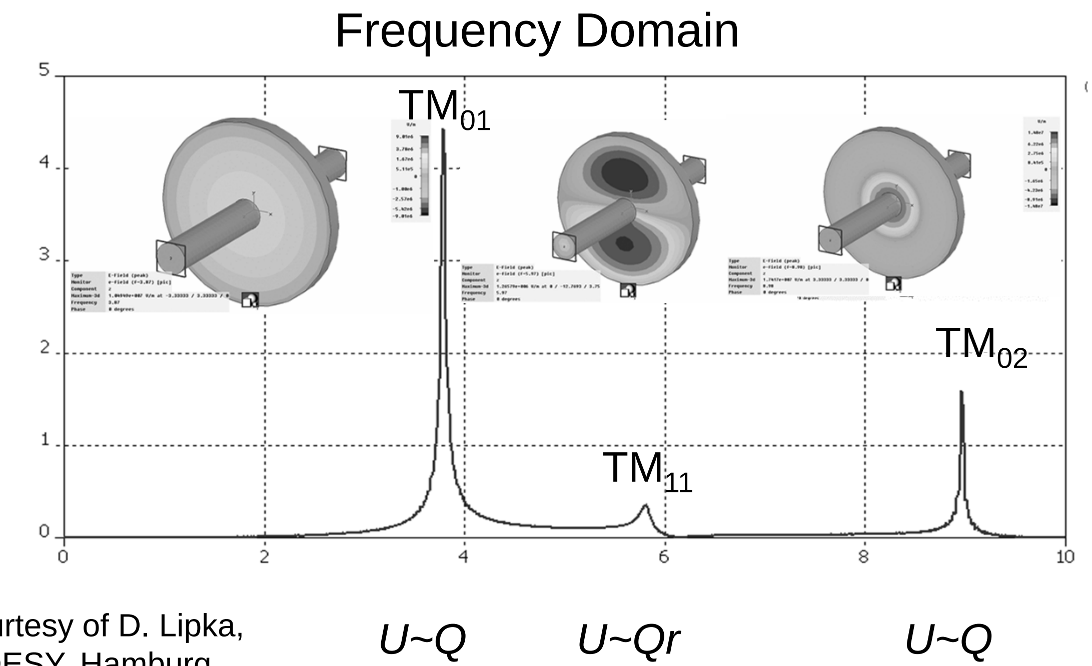
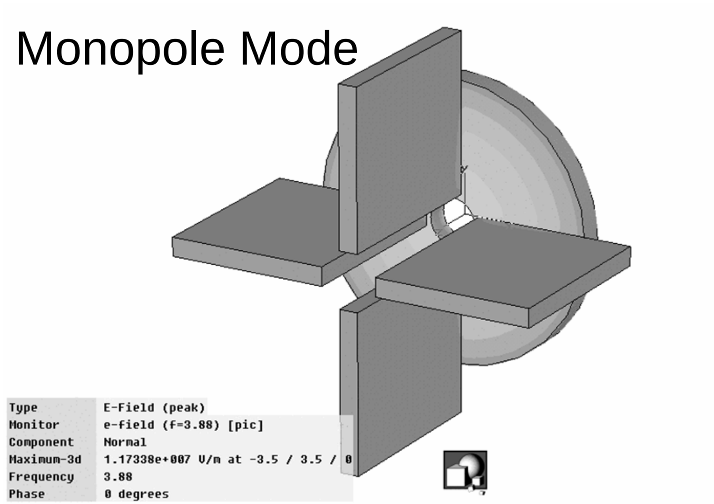
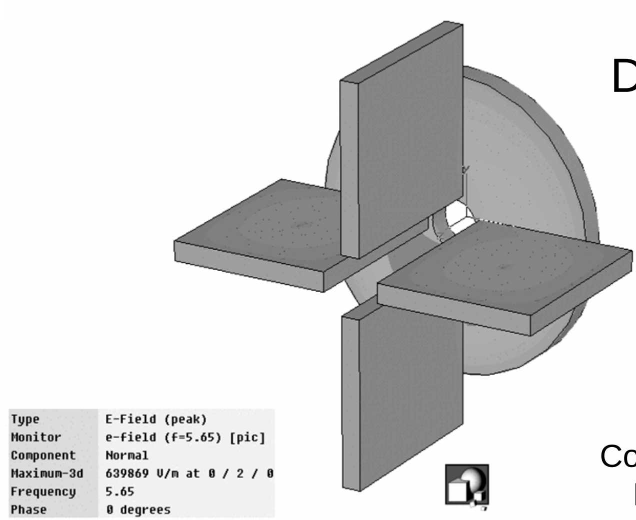


Courtesy of D. Lipka, DESY, Hamburg

Today's State of the Art BPMs

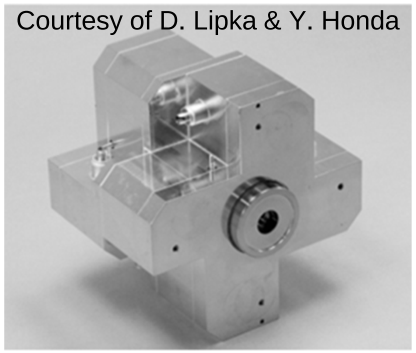
- Obtain signal using waveguides that only couple to dipole mode
  - Further suppression of monopole mode

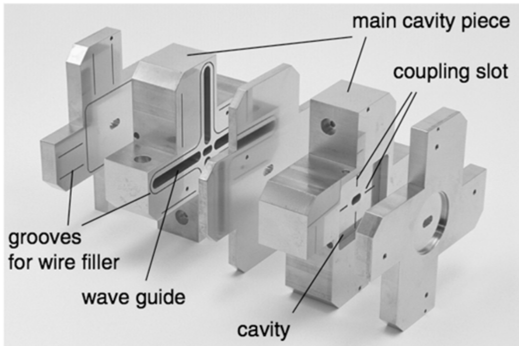


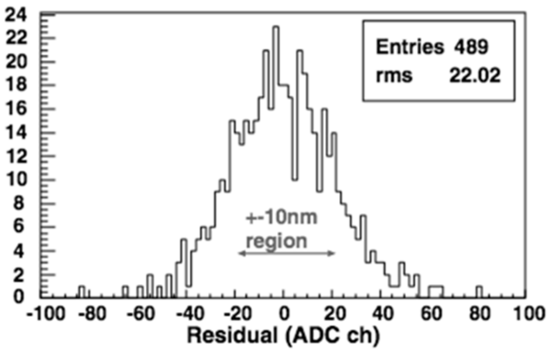


Courtesy of D. Lipka,
DESY, Hamburg

- 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)



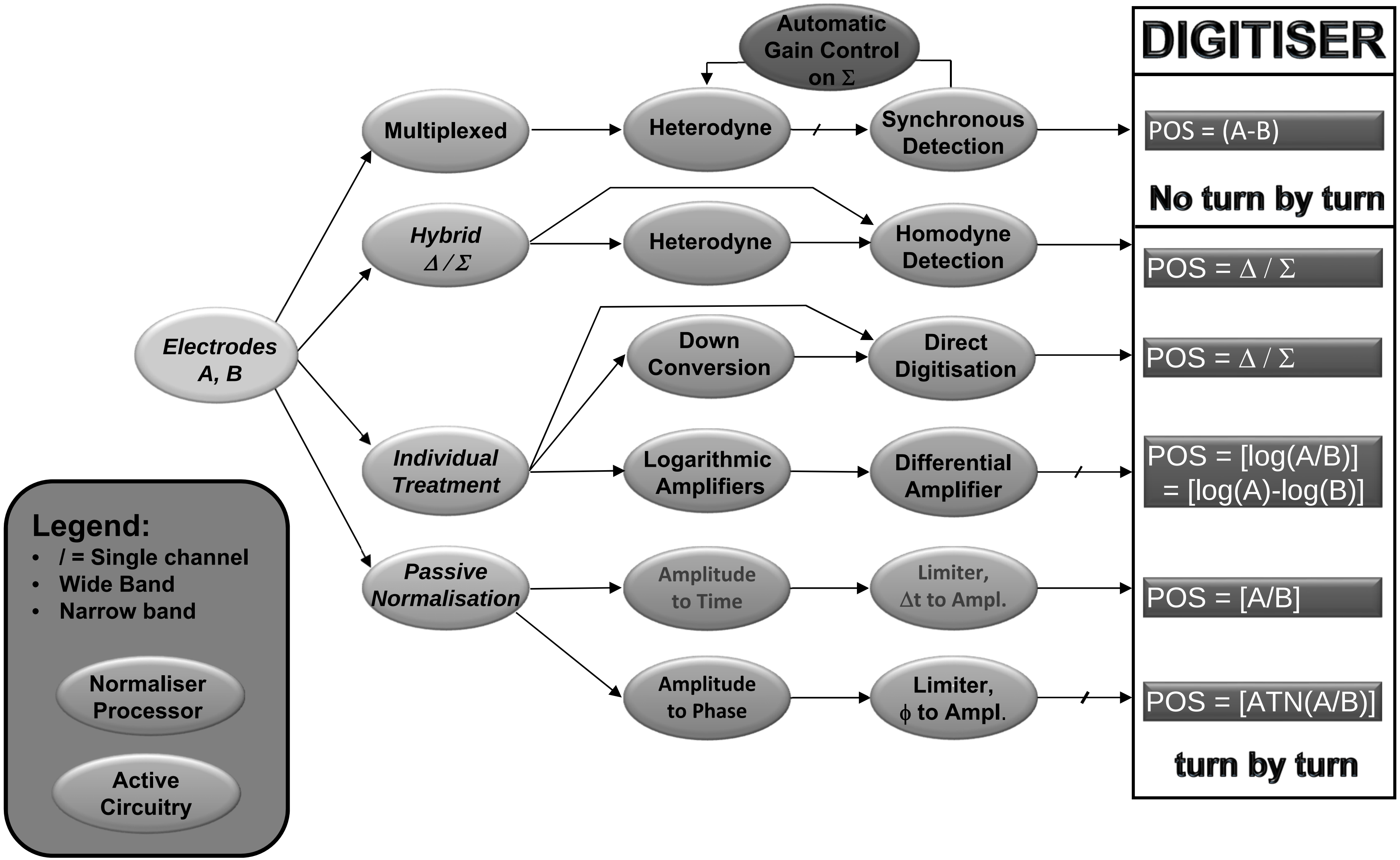




Criteria for Electronics Choice - so called "Processor Electronics"

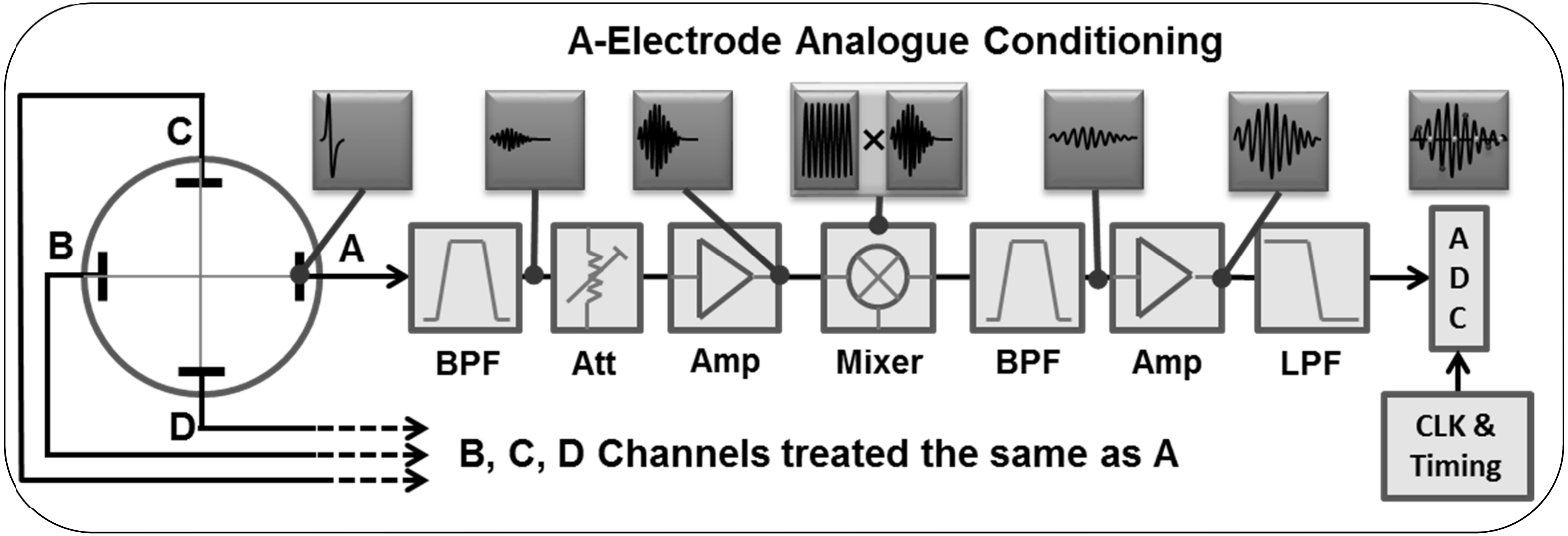
- Accuracy
  - mechanical and electromagnetic errors
  - electronic components
- Resolution
- Stability over time
- Sensitivity and Dynamic Range
- Acquisition Time
  - measurement time
  - repetition time
- Linearity
  - aperture & intensity
- Radiation tolerance

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 minimising analogue circuitry
  - Rely on high frequency & high resolution analogue to digital converters
    - Bandpass filters convert BPM signals into sinewave-like signal bursts
    - 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
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- Machine Tunes and Chromacitities
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- Luminosity
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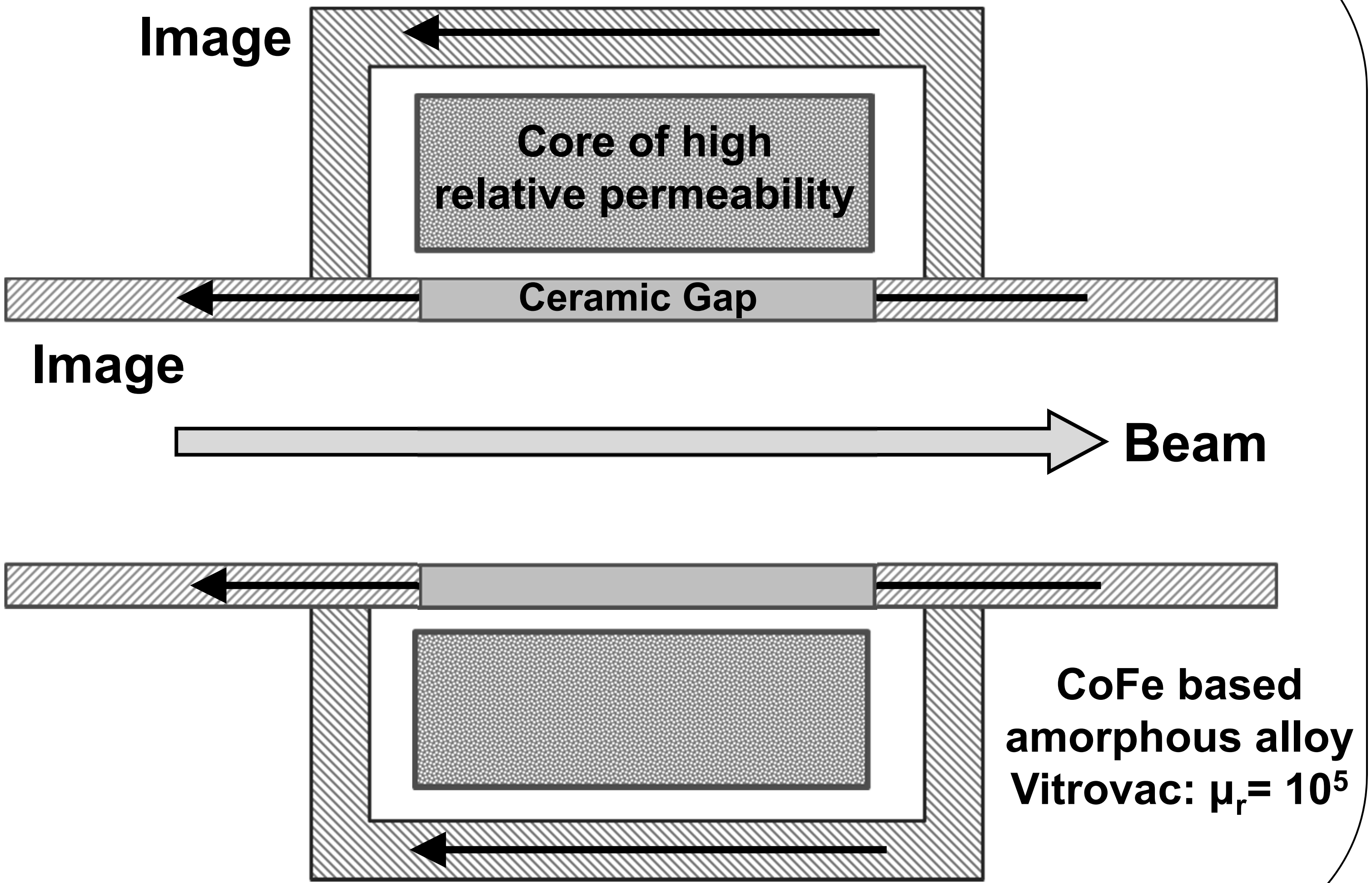
AC (Fast) Current Transformers



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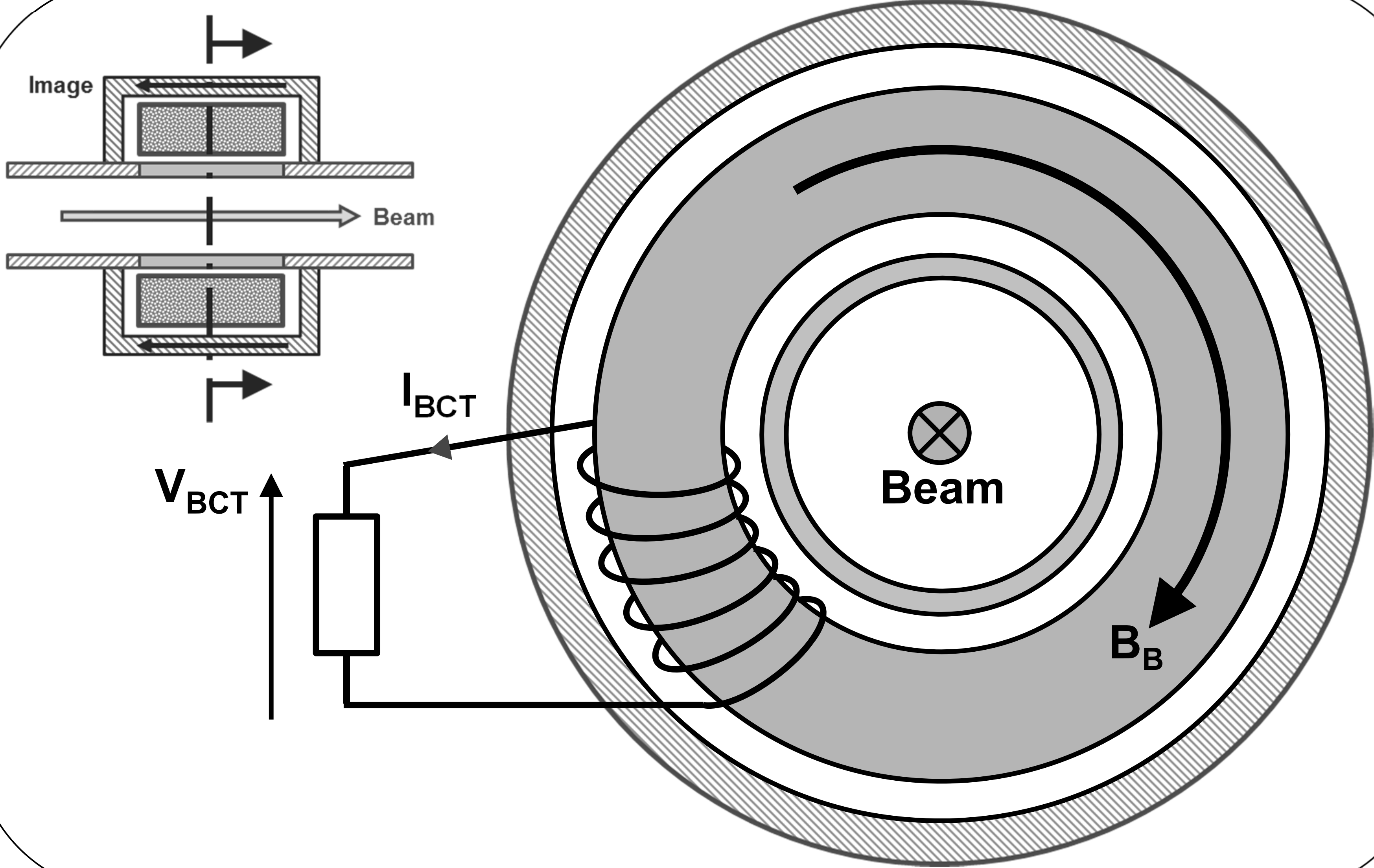
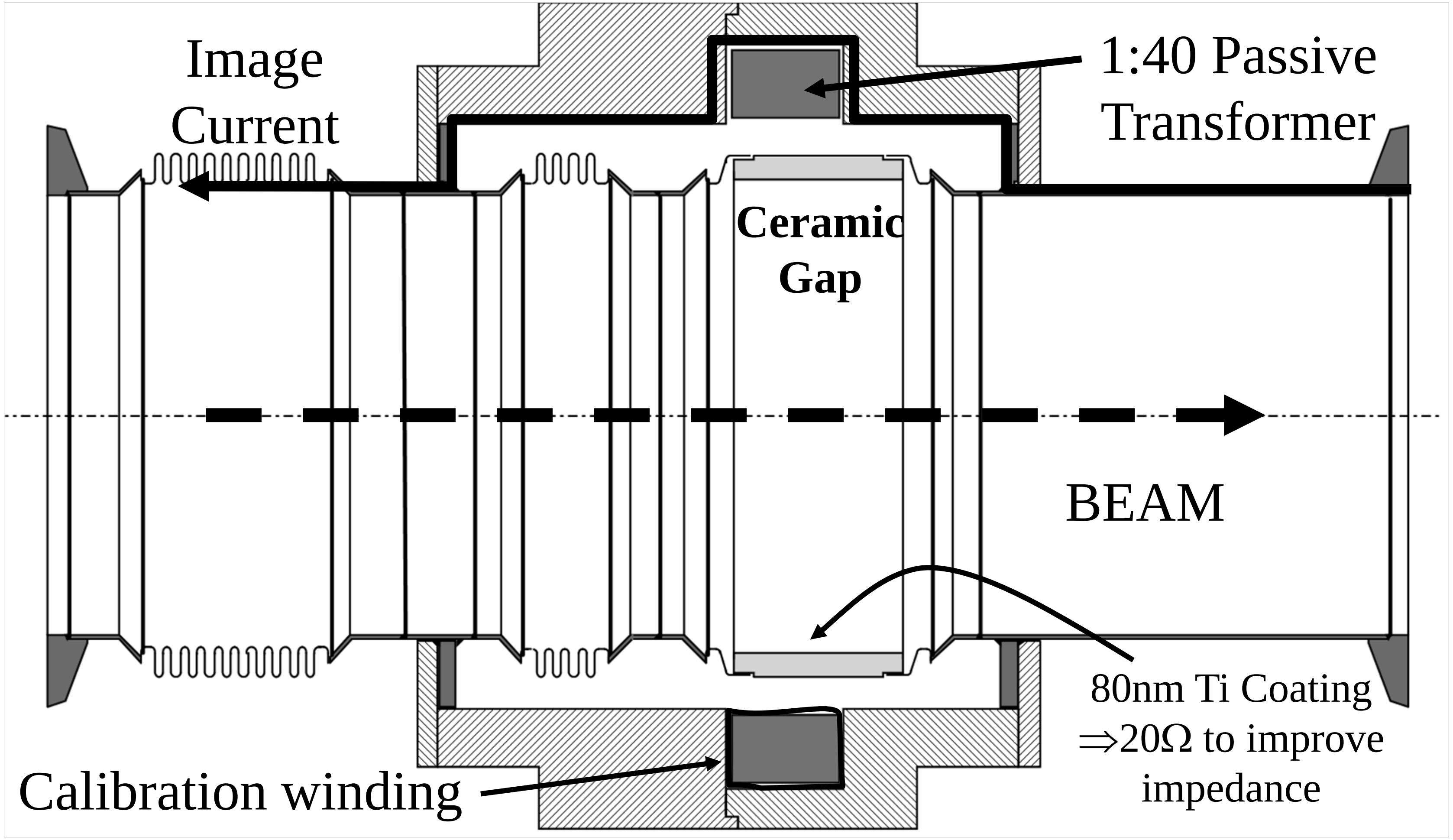
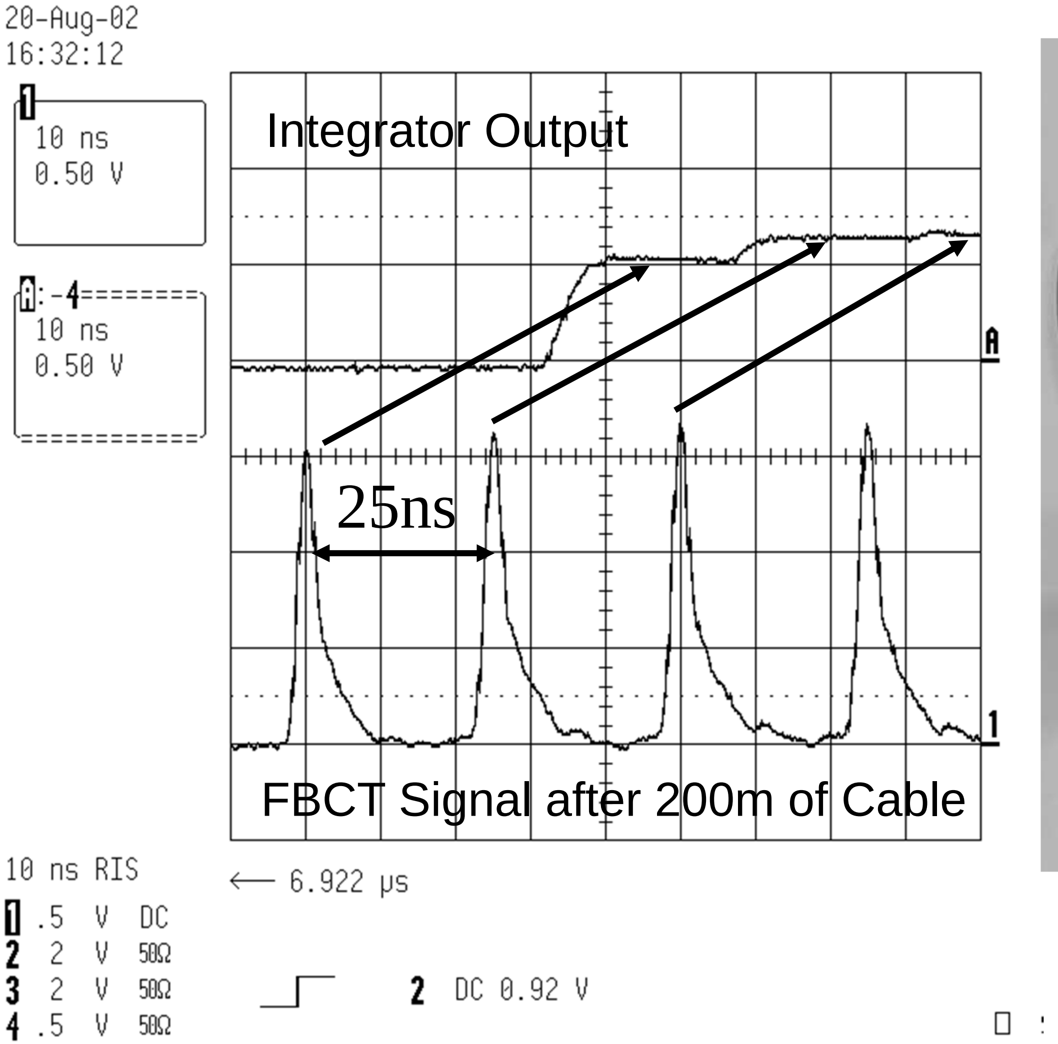


Fast Beam Current Transformer



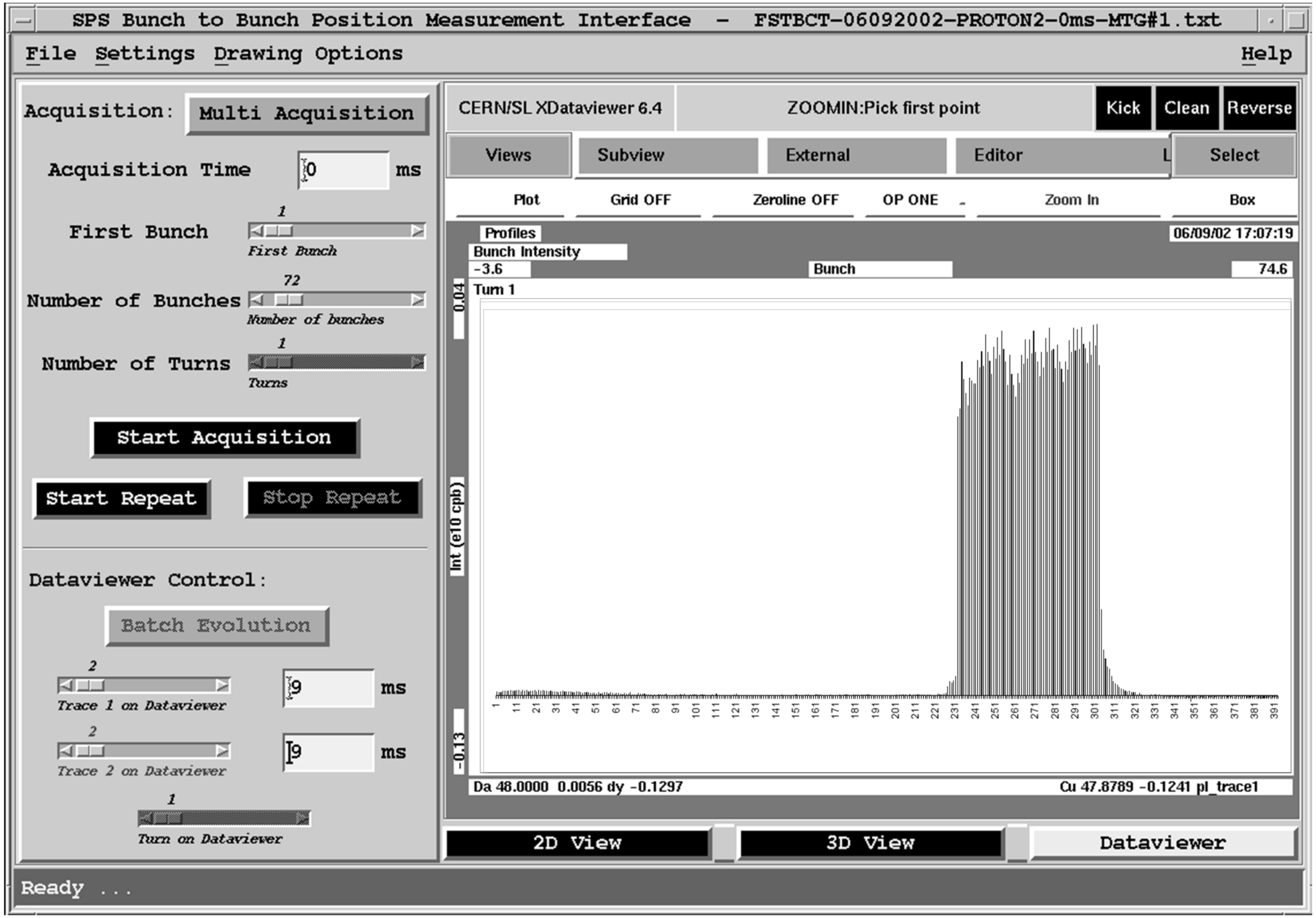
- 500MHz Bandwidth
- Low droop (< 0.2%/μs)

Acquisition Electronics



Data taken on LHC type beams at the CERN-SPS

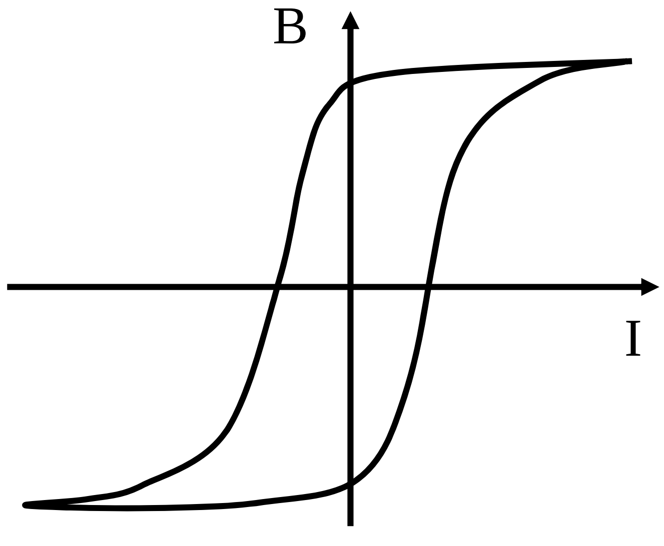
What one can do with such a System



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

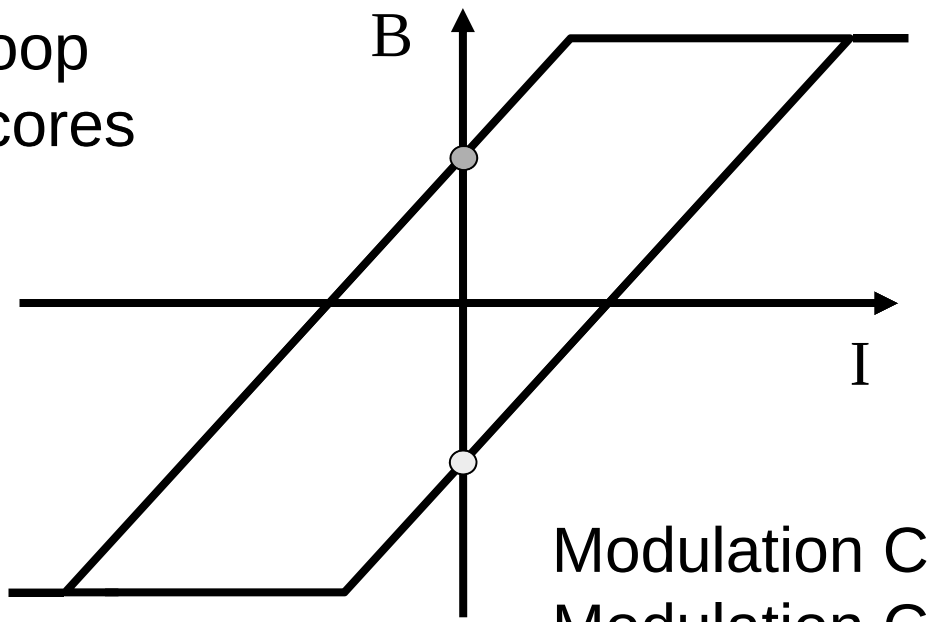
The DC transformer

- 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

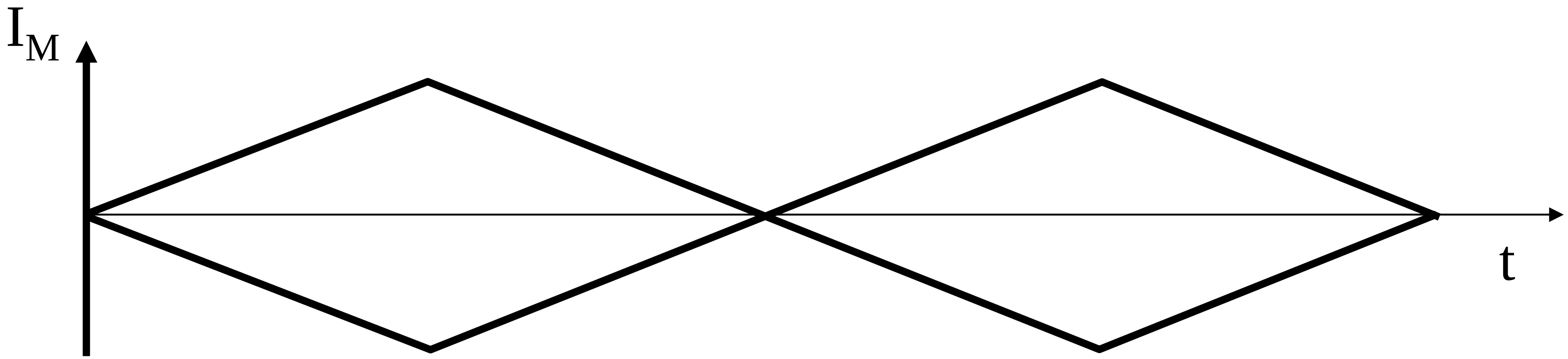


DCCT Principle – Case 1: no beam

Hysteresis loop
of modulator cores

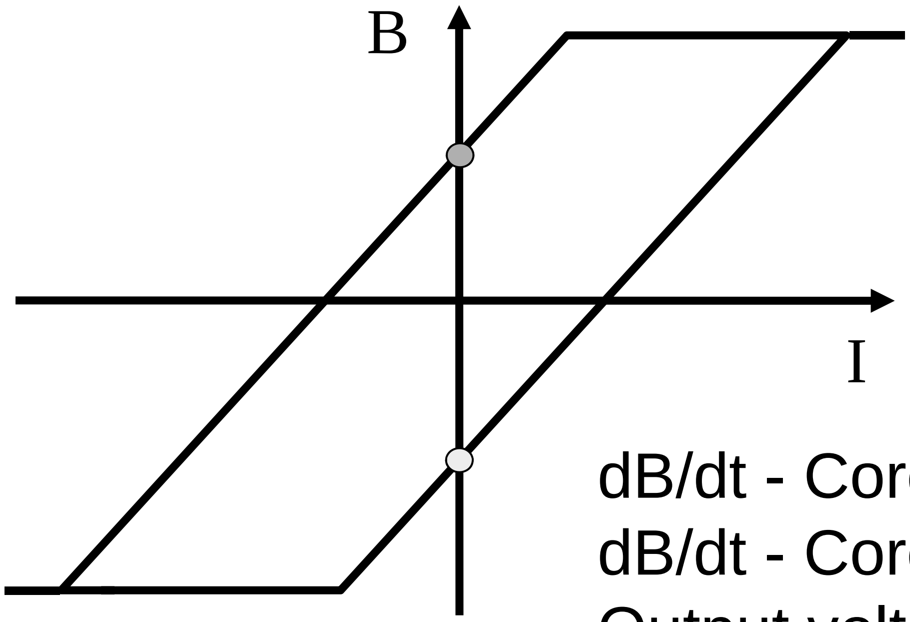


Modulation Current - Core 1
Modulation Current - Core 2

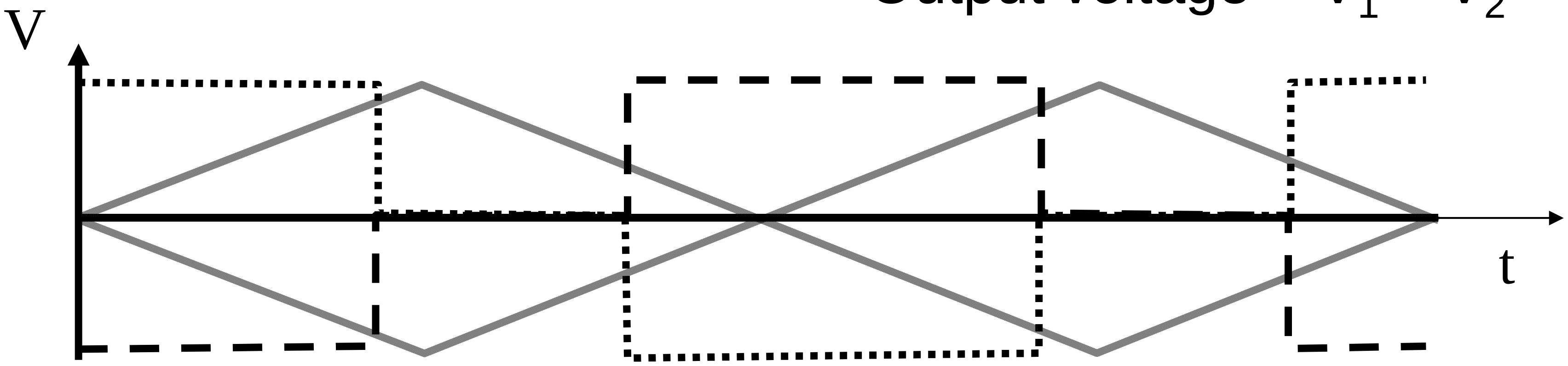


DCCT Principle – Case 1: no beam

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

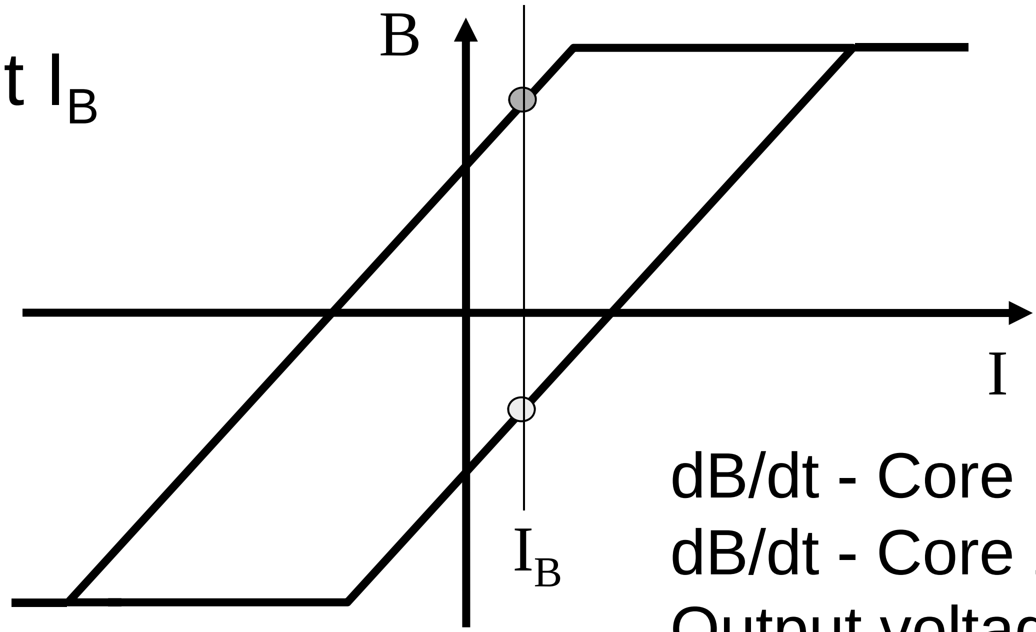


dB/dt - Core 1 (V1)
dB/dt - Core 2 (V2)
Output voltage = $V_1 - V_2$



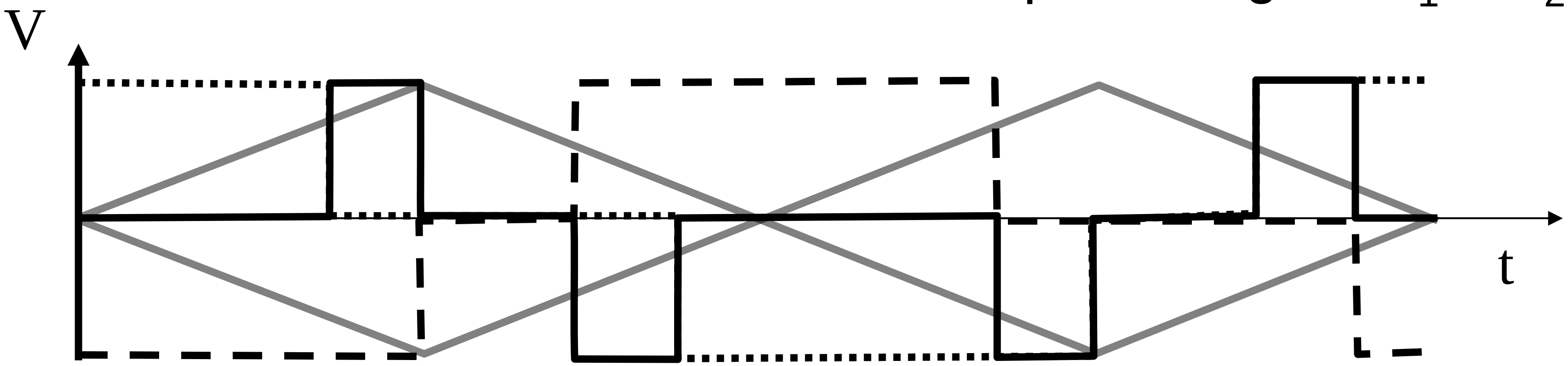
DCCT Principle – Case 2: with beam

Beam Current I_B

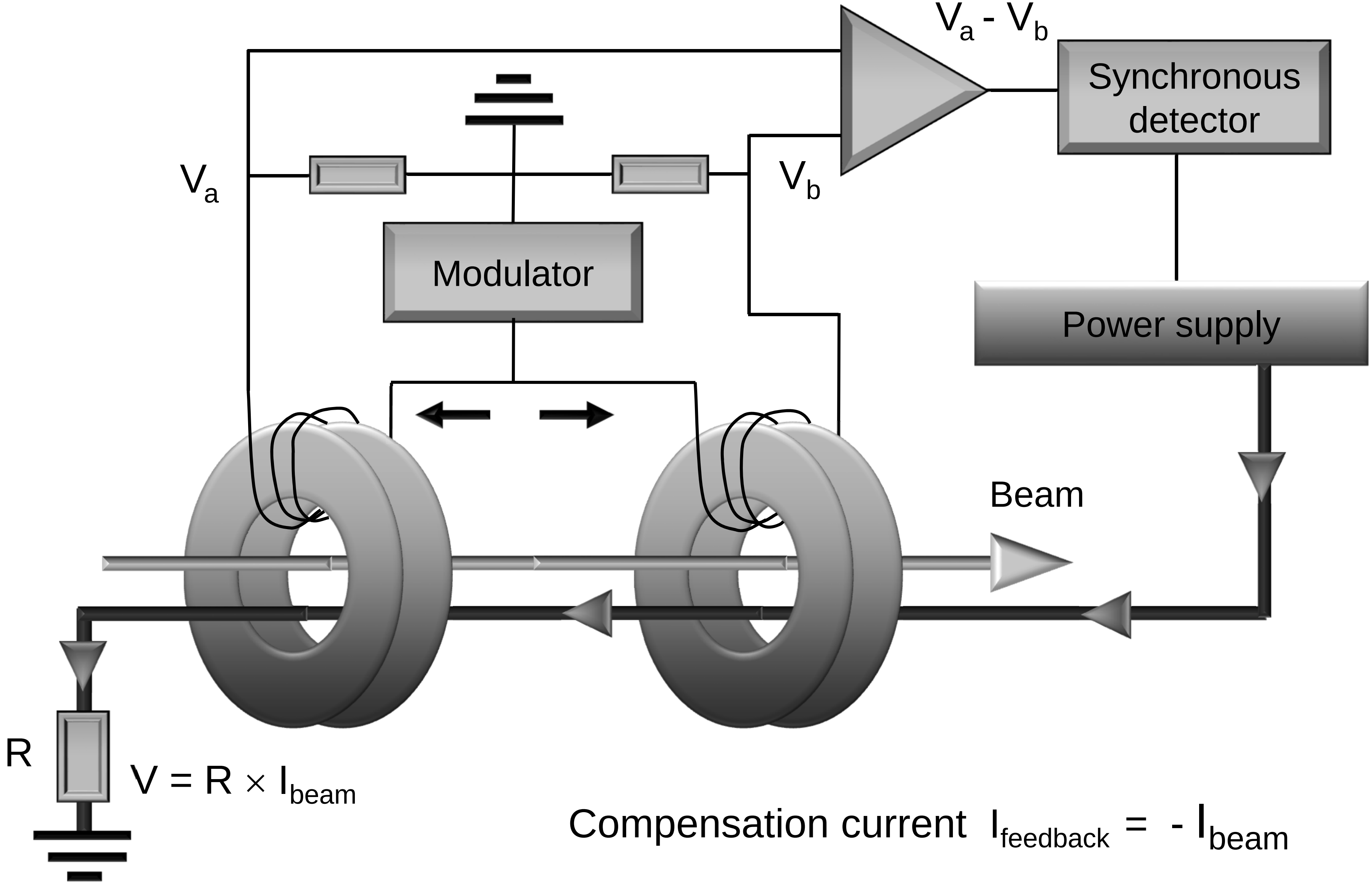


Output signal is at TWICE the modulation frequency

dB/dt - Core 1 (V1)
dB/dt - Core 2 (V2)
Output voltage = $V_1 – V_2$



Zero Flux DCCT Schematic



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

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**
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  - **femtosecond diagnostics for ultra short bunches**
- Beam Loss
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- Machine Tunes and Chromacitities
  - in diagnostics section of tomorrow
- Luminosity
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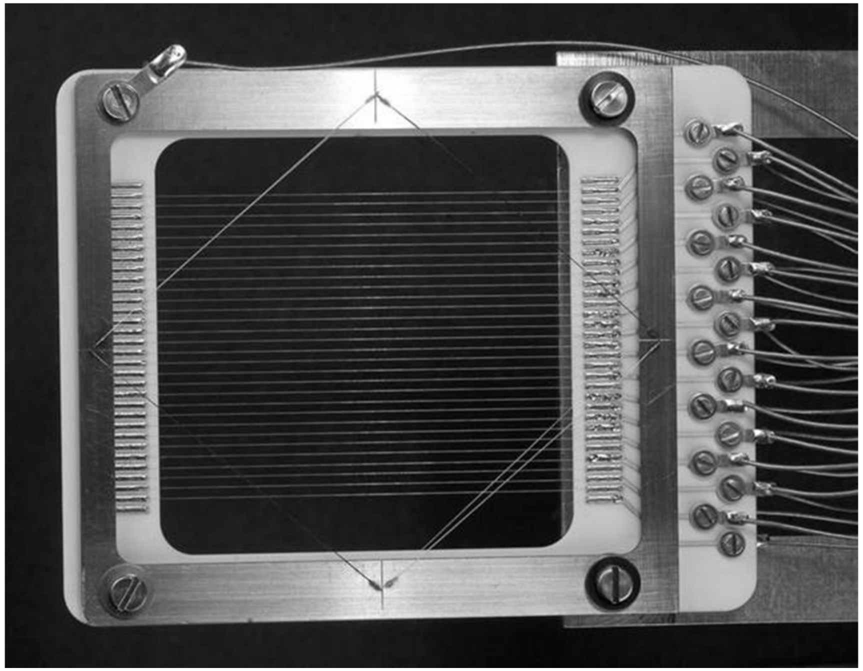
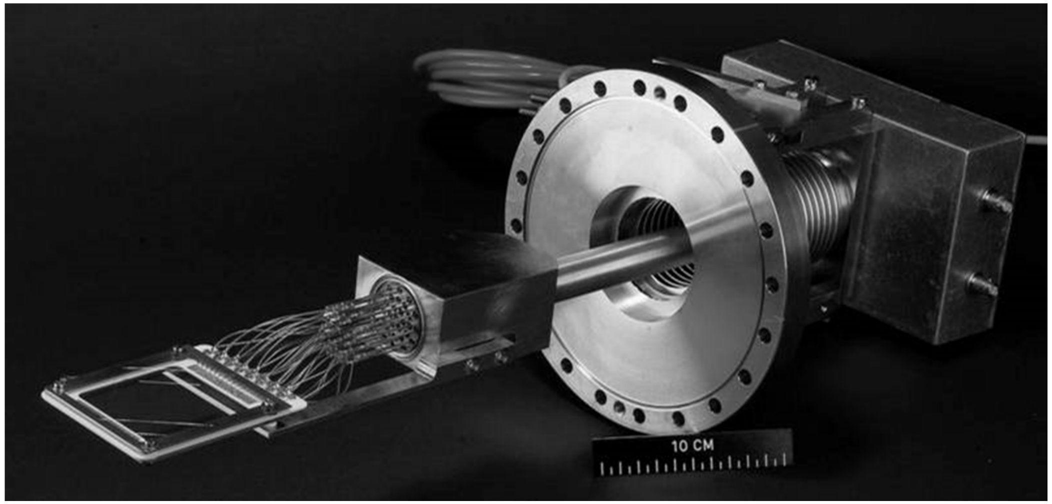
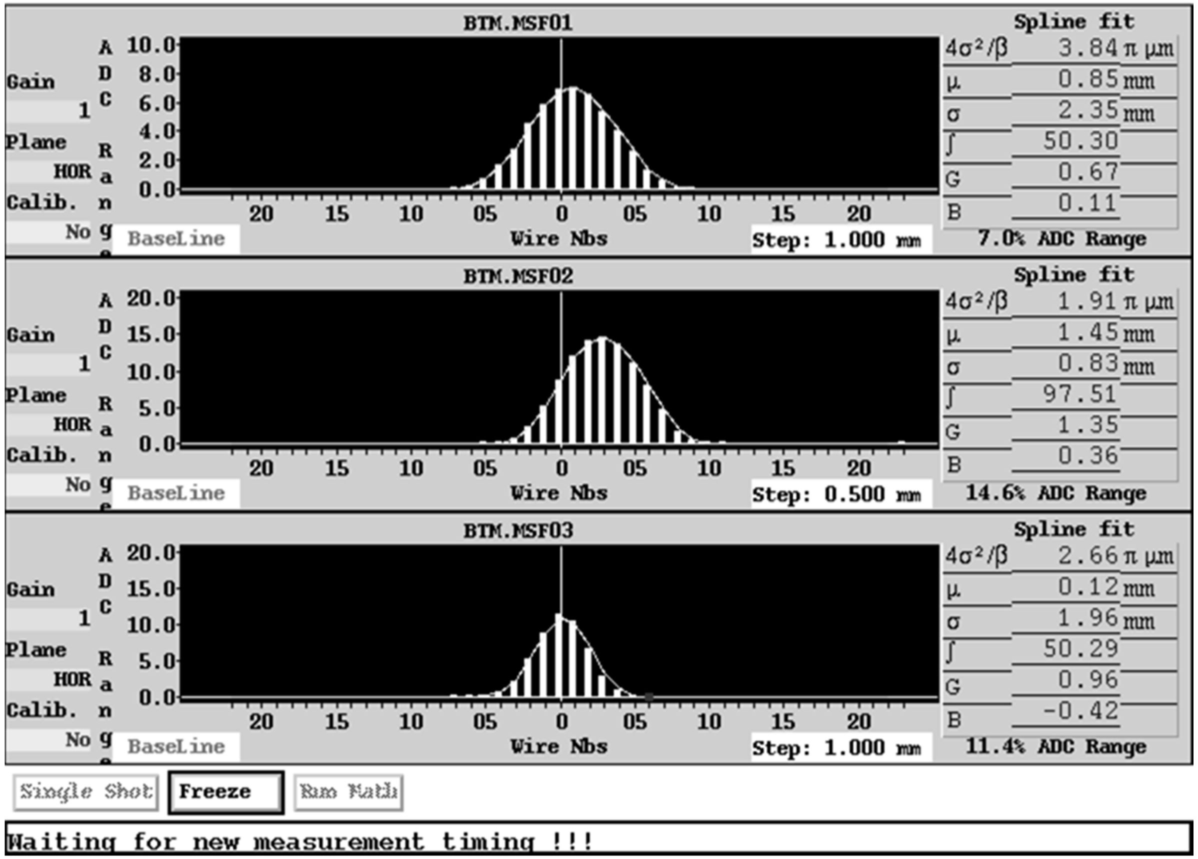
Secondary Emission (SEM) Grids

- When the beam passes through secondary electrons are ejected from the wires
- The liberated electrons are removed using a polarisation voltage
- The current flowing back onto the wires is measured
- One amplifier/ADC chain is used for each wire





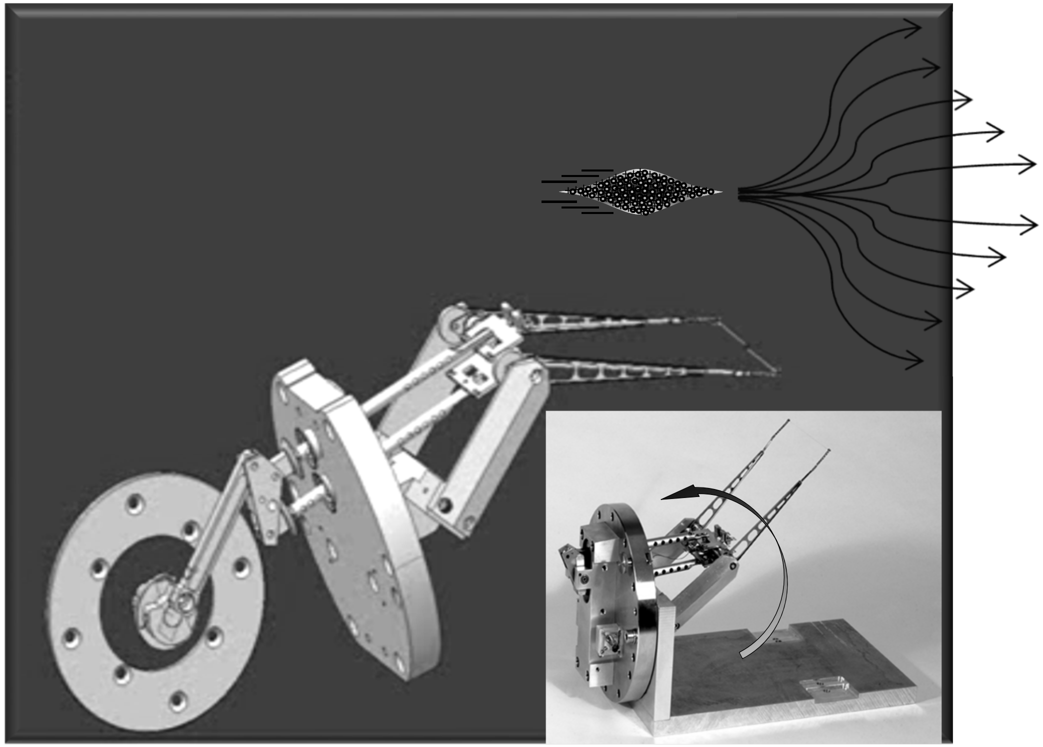
Profiles from SEM grids

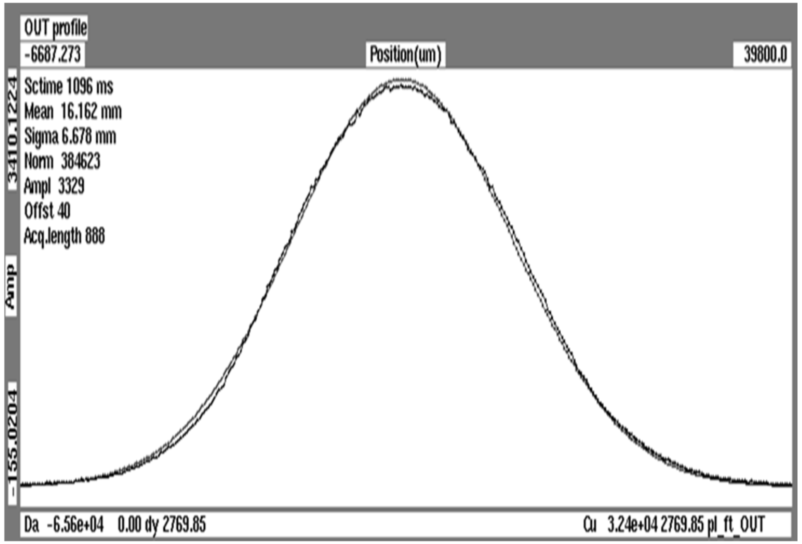


- Charge density measured from each wire gives a projection of the beam profile in either horizontal or vertical plane
- Resolution is given by distance between wires
- Used only in low energy linacs and transfer lines as heating is too great for circulating beams

Wire Scanners

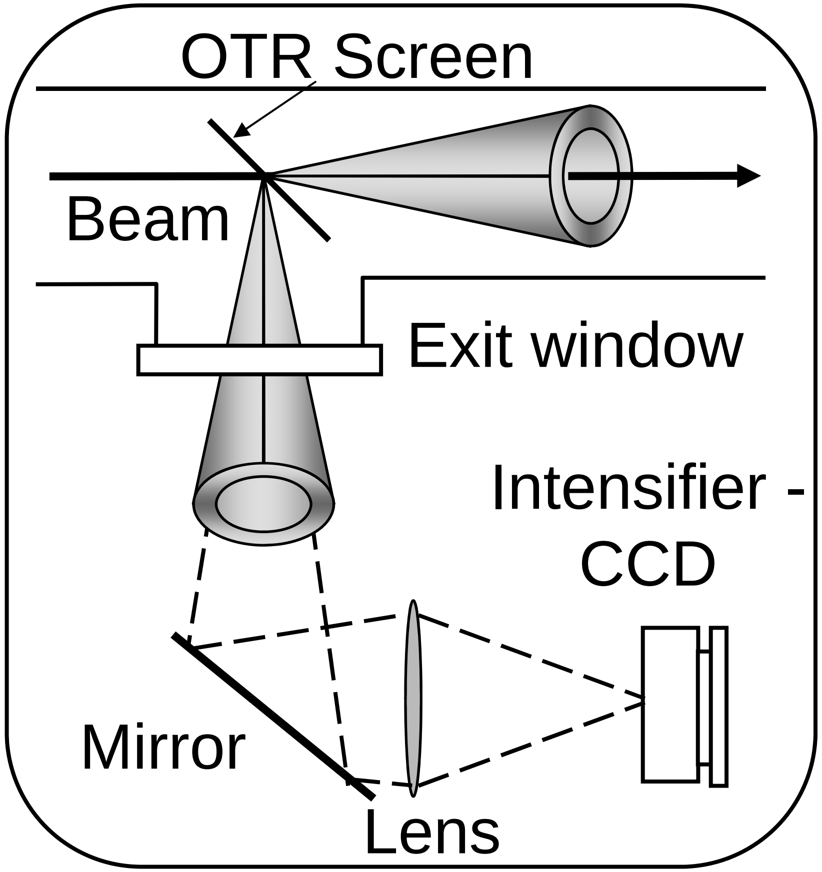
- A thin wire is moved across the beam
  - has to move fast to avoid excessive heating of the wire and/or beam loss
- Detection
  - Secondary particle shower detected outside the vacuum chamber using a scintillator/photo-multiplier assembly
  - Secondary emission current detected as for SEM grids
- Correlating wire position with detected signal gives the beam profile

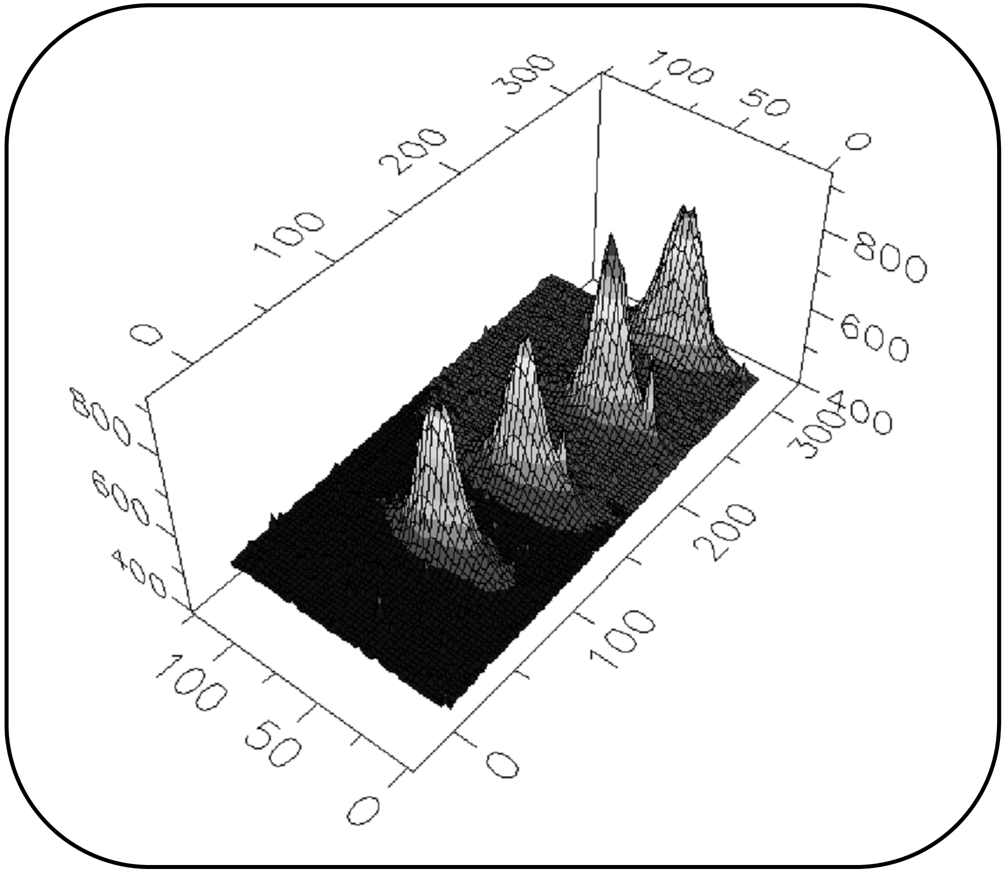




Beam Profile Monitoring using Screens

- Optical Transition Radiation
  - Radiation emitted when a charged particle beam goes through the interface of 2 media with different dielectric constants
  - surface phenomenon allows the use of very thin screens (~10μm)



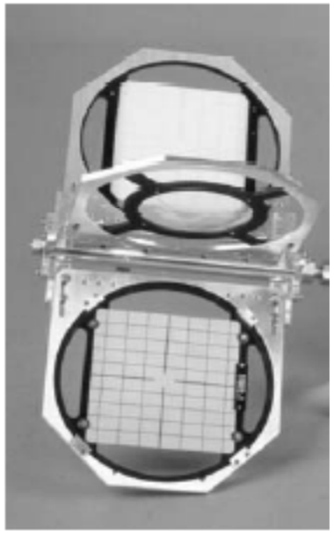


Beam Profile Monitoring using Screens

- Screen Types
  - Luminescence Screens
    - destructive (thick) but work during setting-up with low intensities
  - Optical Transition Radiation (OTR) screens
    - much less destructive (thin) but require higher intensity

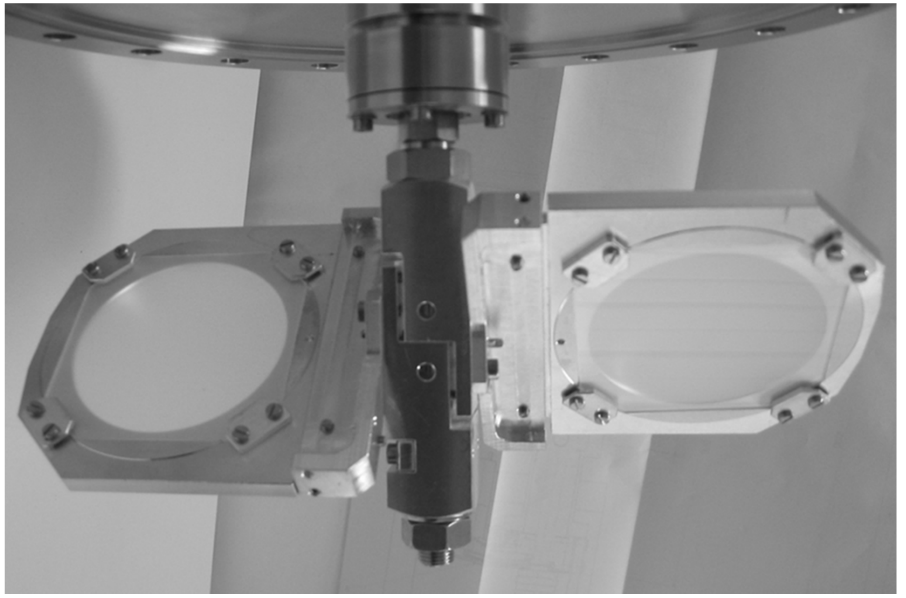
Sensitivities measured with protons with previous screen holder, normalised for 7 px/σ

Type	Material	Activator	Sensitivity
Luminesc.	CsI	Tl	$6\ 10^5$
"	Al_2O_3	0.5%Cr	$3\ 10^7$
"	Glass	Ce	$3\ 10^9$
"	Quartz	none	$6\ 10^9$
OTR [bwd]	Al		$2\ 10^{10}$
"	Ti		$2\ 10^{11}$
"	C		$2\ 10^{12}$
Luminesc. GSI	P43: Gd_2O_2 S	Tb	*$2\ 10^7$*



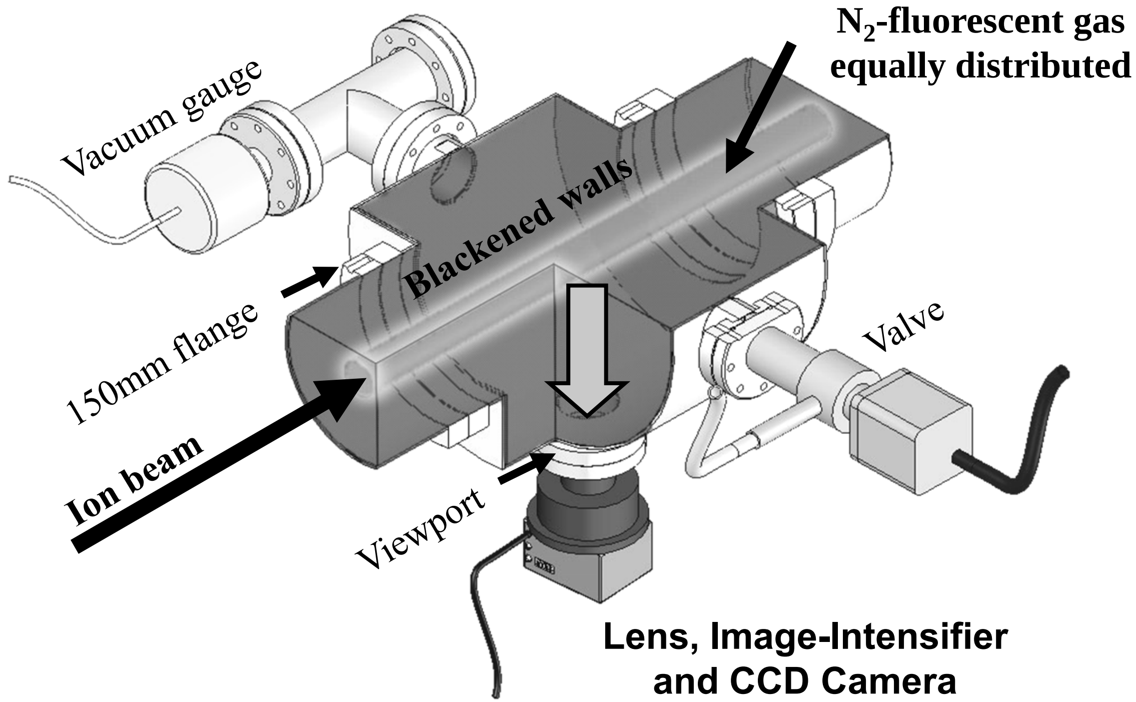
Beam Profile Monitoring using Screens

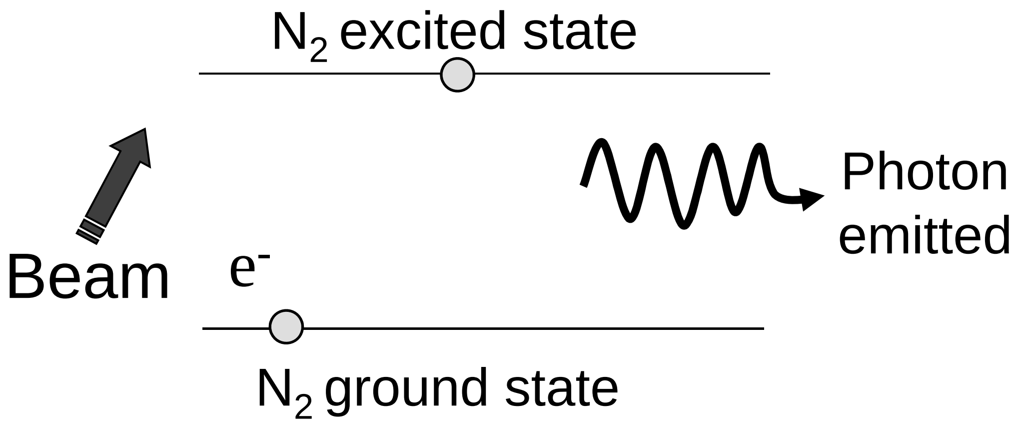
- Usual configuration
  - Combine several screens in one housing e.g.
    - Al_2O_3 luminescent screen for setting-up with low intensity
    - Thin (~10um) Ti OTR screen for high intensity measurements
    - Carbon OTR screen for very high intensity operation



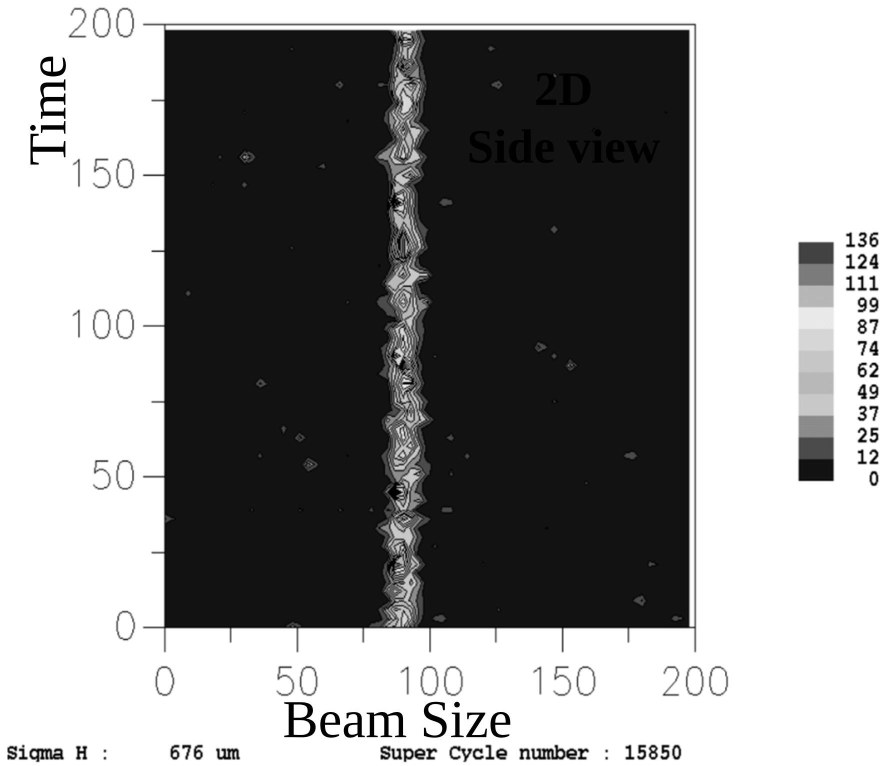
- Advantages compared to SEM grids
  - allows analogue camera or CCD acquisition
  - gives two dimensional information
  - high resolution: ~ 400 x 300 = 120'000 pixels for a standard CCD
  - more economical
    - Simpler mechanics & readout electronics
  - time resolution depends on choice of image capture device
    - From CCD in video mode at 50Hz to Streak camera in the GHz range

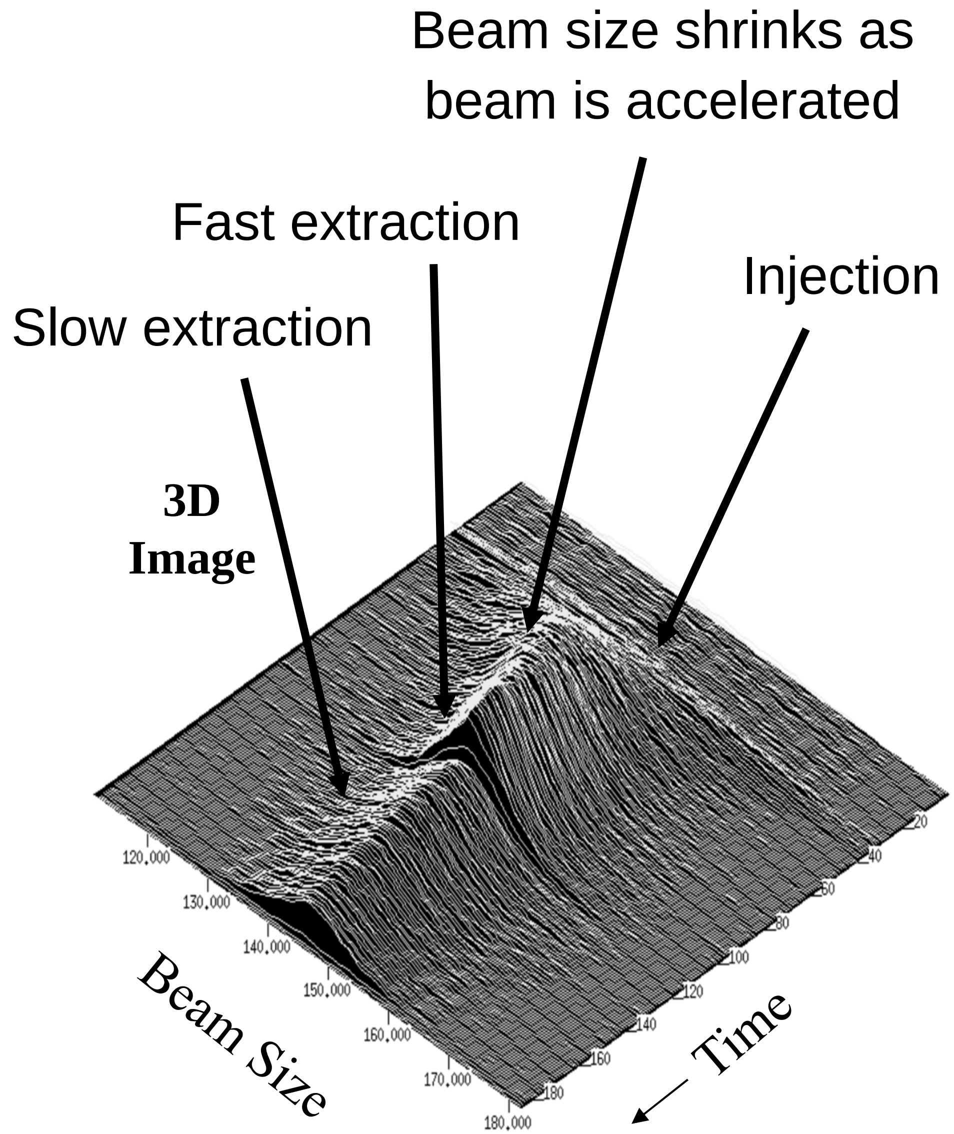
Luminescence Profile Monitor





Luminescence Profile Monitor

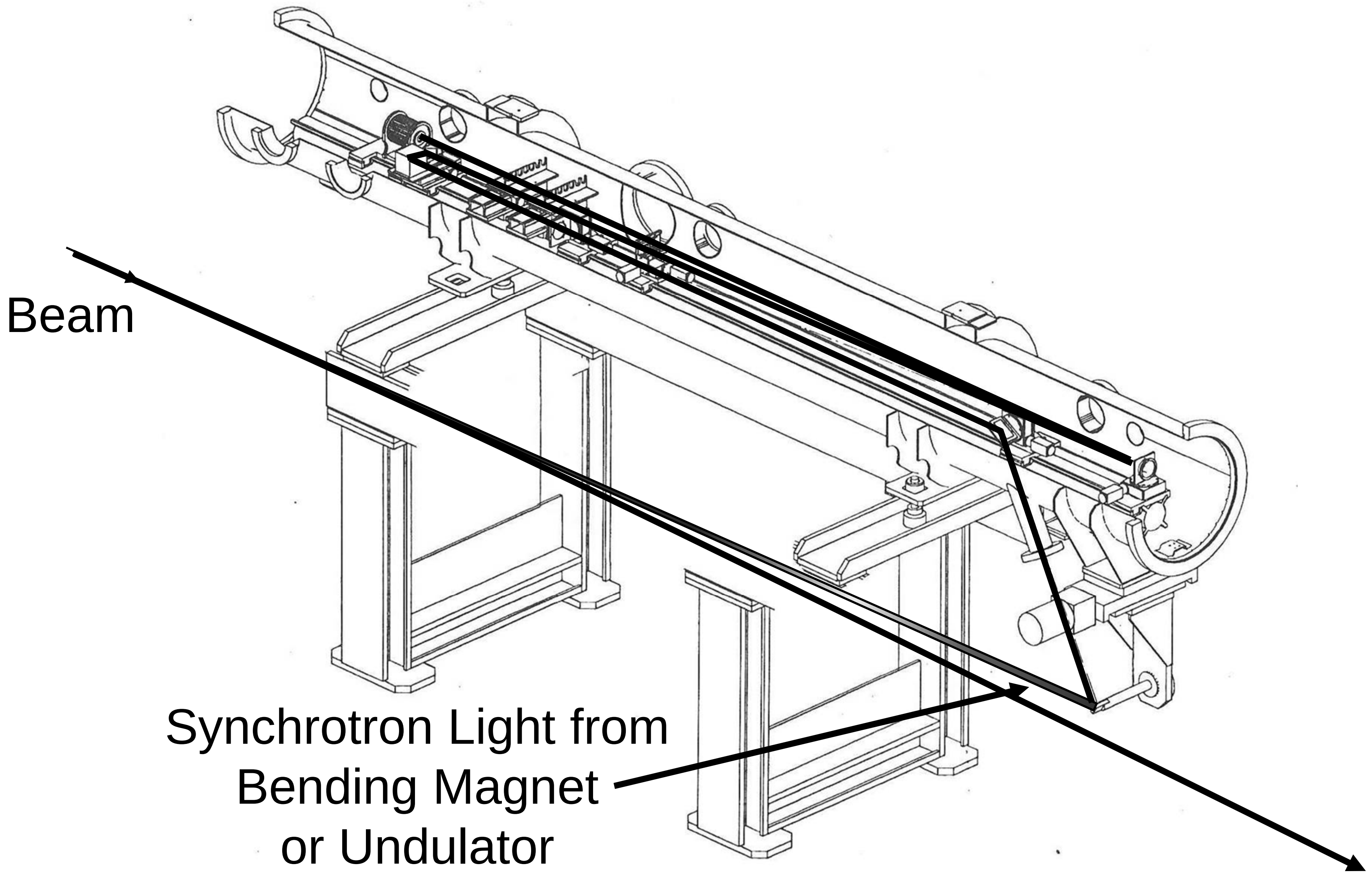




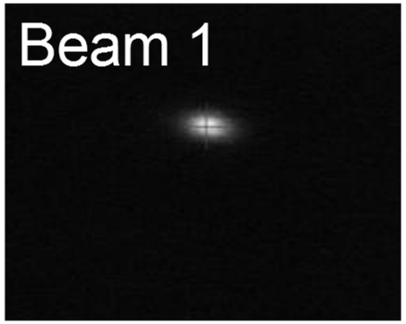
CERN-SPS Measurements

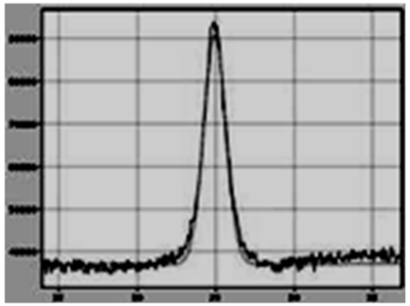
- Profile Collected every 20ms
- Local Pressure at ~5×10^{-7} Torr

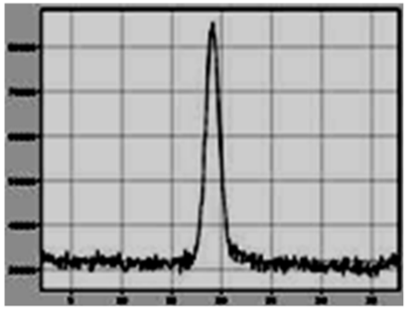
The Synchrotron Light Monitor



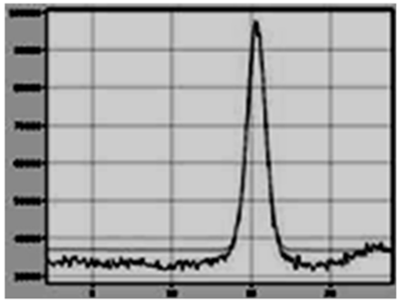
The Synchrotron Light Monitor

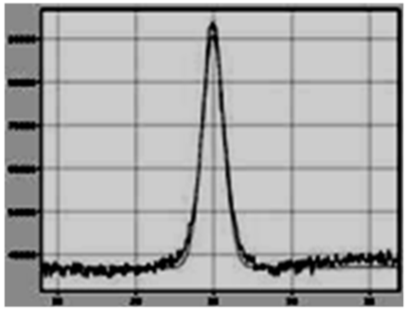




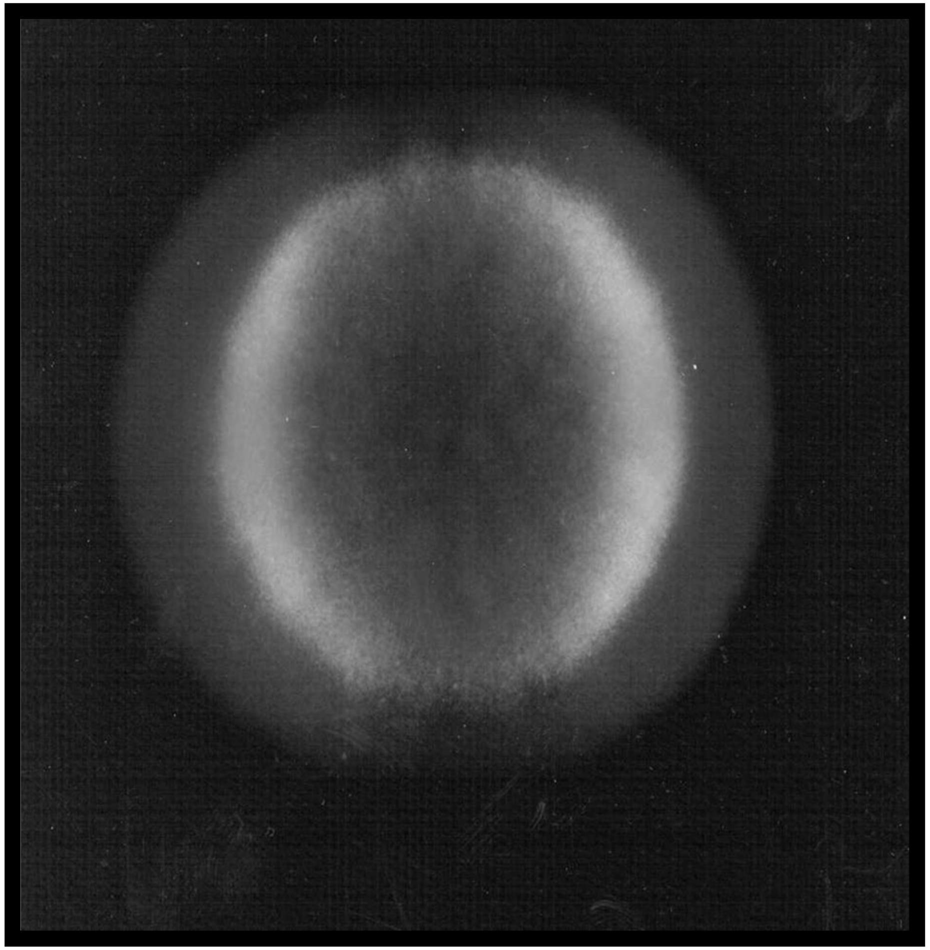


σ_h = 0.68mm σ_h = 0.70mm





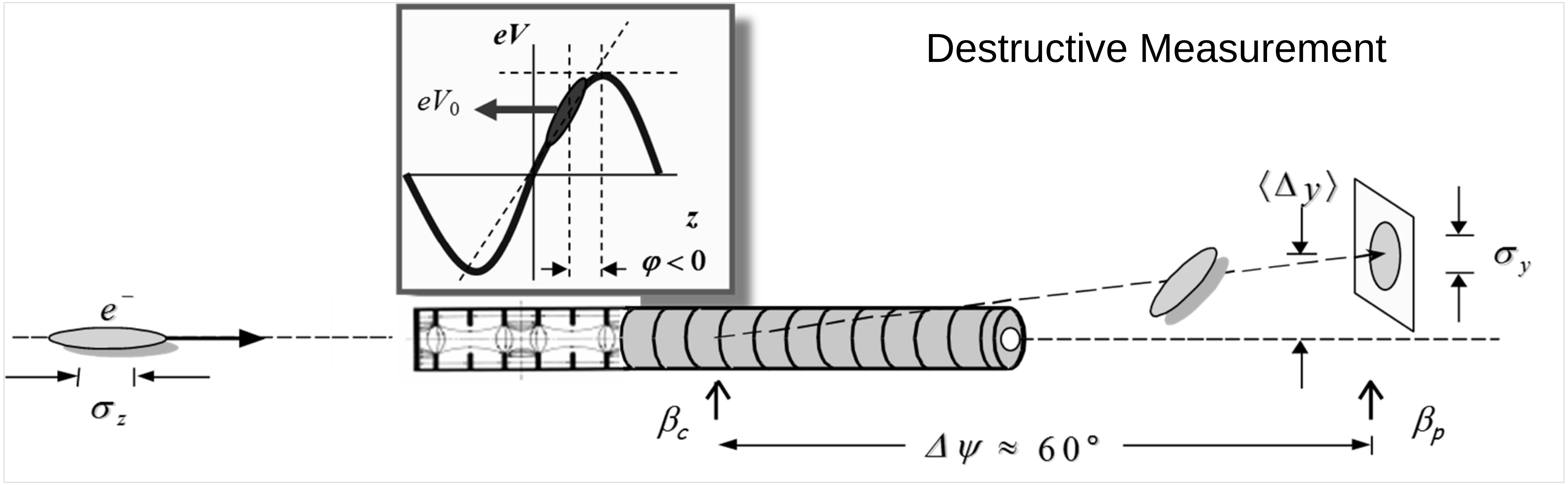
σ_v = 0.56mm σ_v = 1.05mm



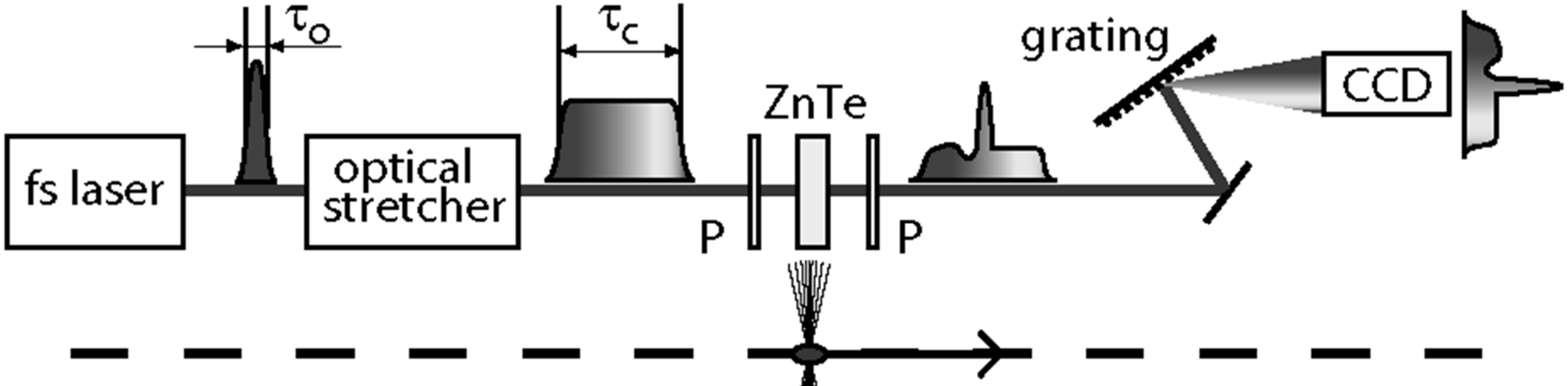
Measuring Ultra Short Bunches

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

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

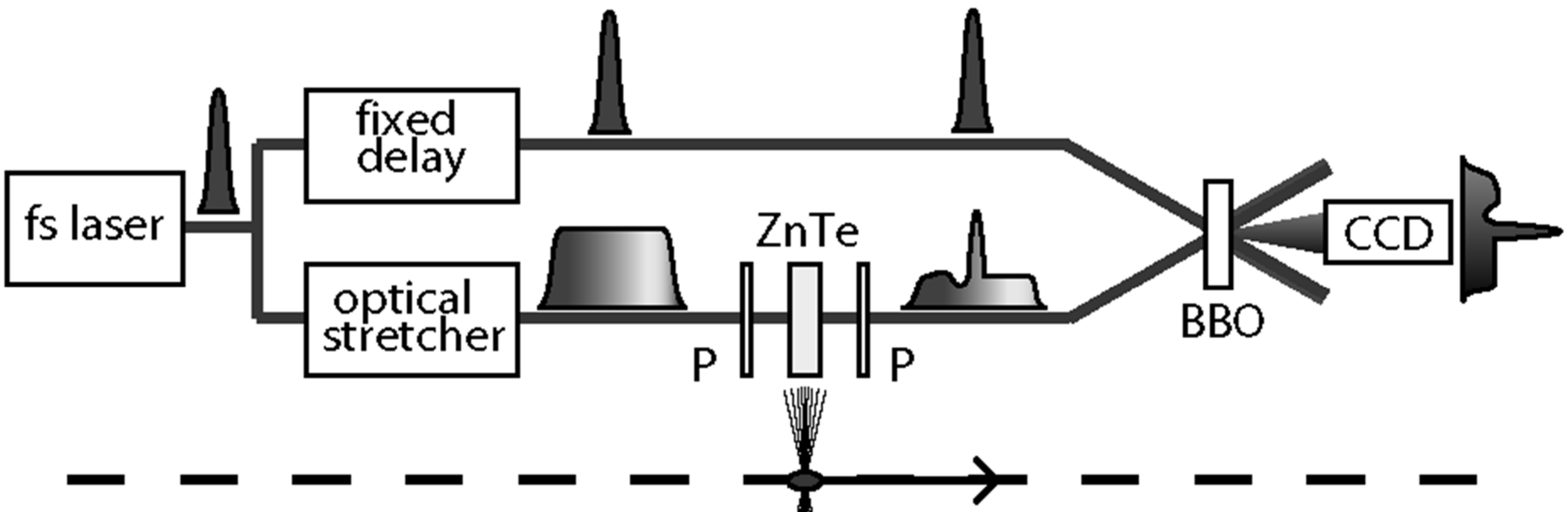


Electro-Optic Sampling – Non Destructive



Limited to >250fs by laser bandwidth

Spectral Decoding



Limited to >30fs by sampling laser pulse

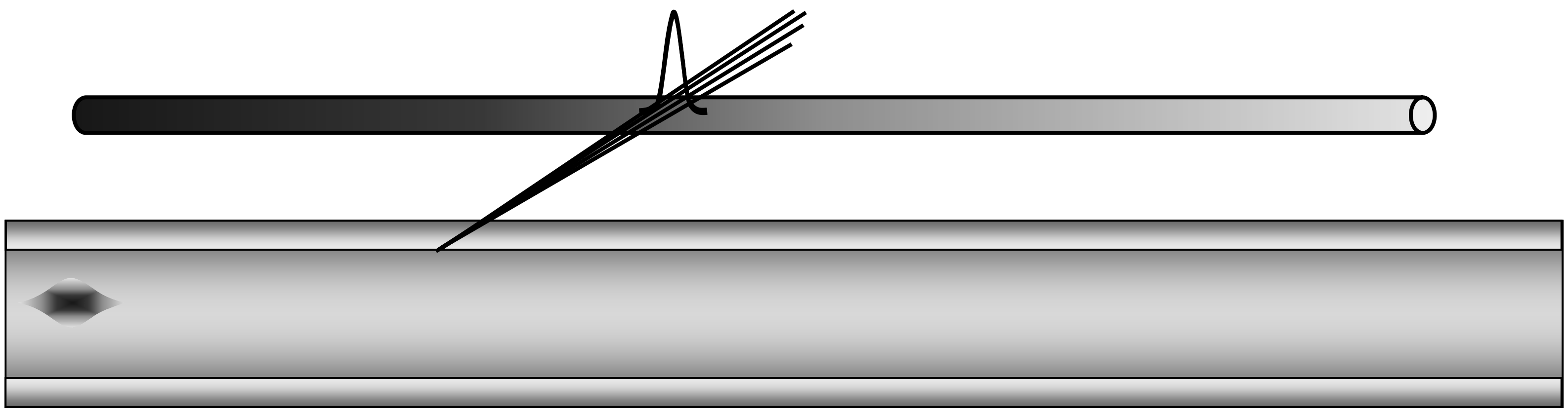
Temporal decoding

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 Tunes and Chromacitities
  - in diagnostics section of tomorrow
- Luminosity
  - in diagnostics section of tomorrow

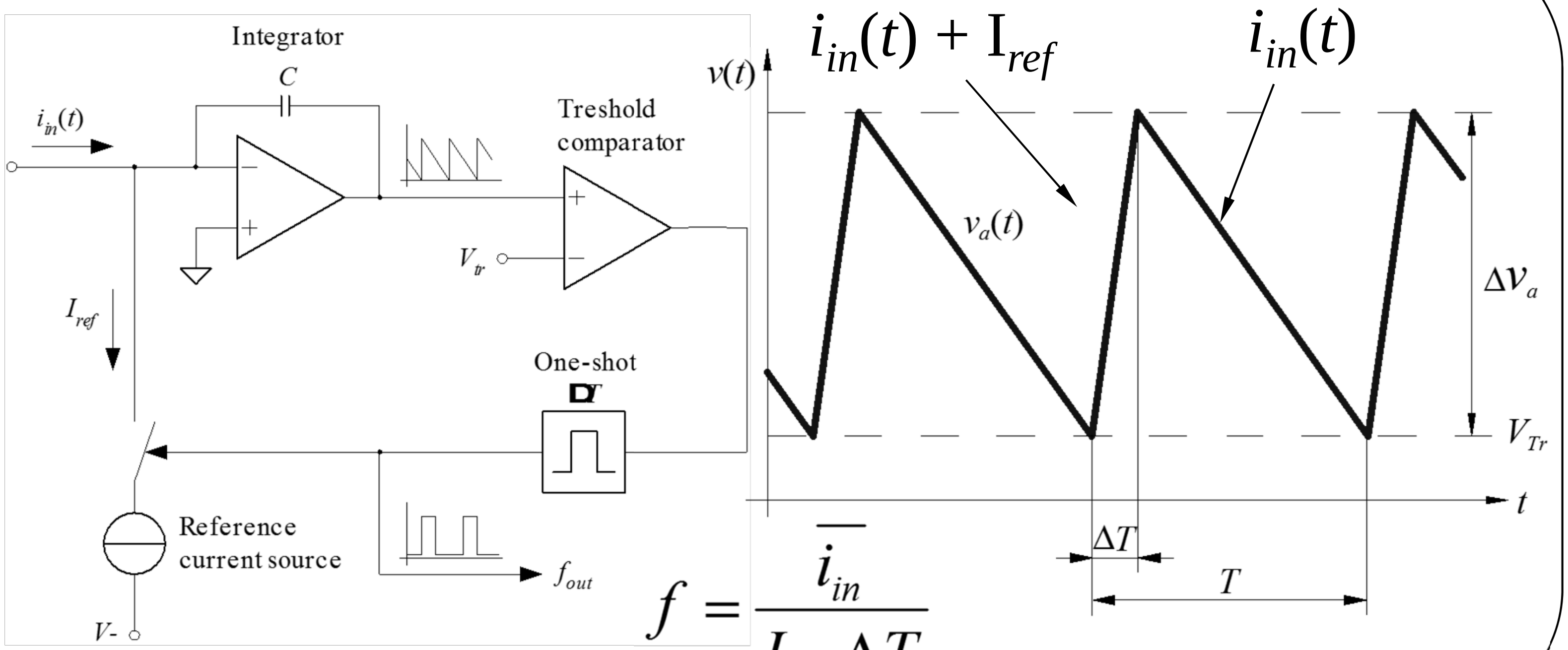
Beam Loss Detectors

- Role of a BLM system:
  1. Protect the machine from damage
  2. Dump the beam to avoid magnet quenches (for SC magnets)
  3. Diagnostic tool to improve the performance of the accelerator
- 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
    - Similar layout with electrical signals replaced by light produced through Cerenkov effect



Beam Loss Detectors

- Common types of monitor (cont)
  - Short ionisation chamber (charge detection)
    - Typically gas filled with many metallic electrodes and kV bias
    - Speed limited by ion collection time - tens of microseconds
    - Dynamic range of up to 10^8

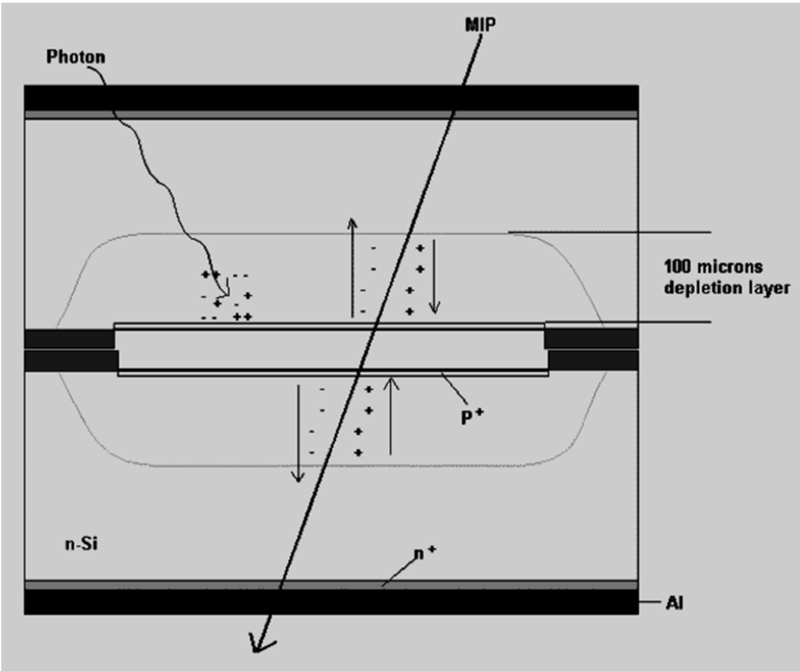


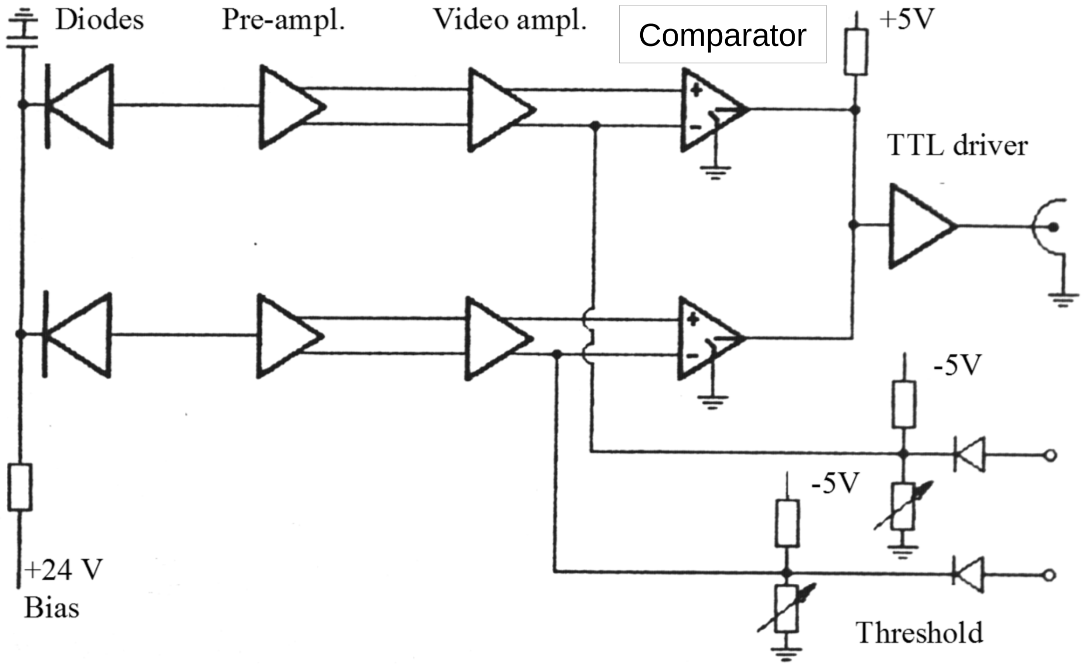
$$f = \frac{\overline{i_{in}}}{I_{ref}\Delta T}$$

LHC

Beam Loss Detectors

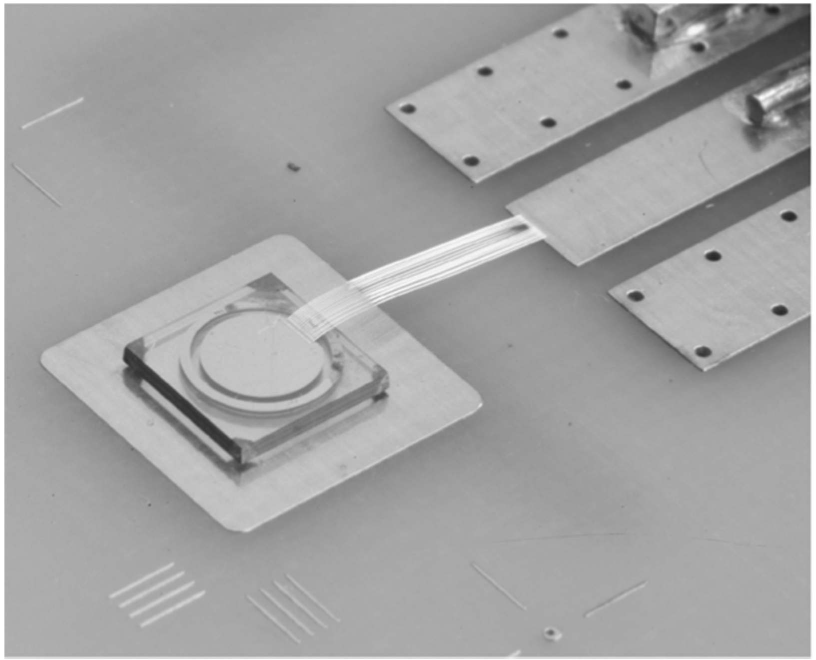
- Common types of monitor (cont)
  - PIN photodiode (count detection)
    - Detect MIP crossing photodiodes
    - Count rate proportional to beam loss
    - Speed limited by integration time
    - Dynamic range of up to 10^9

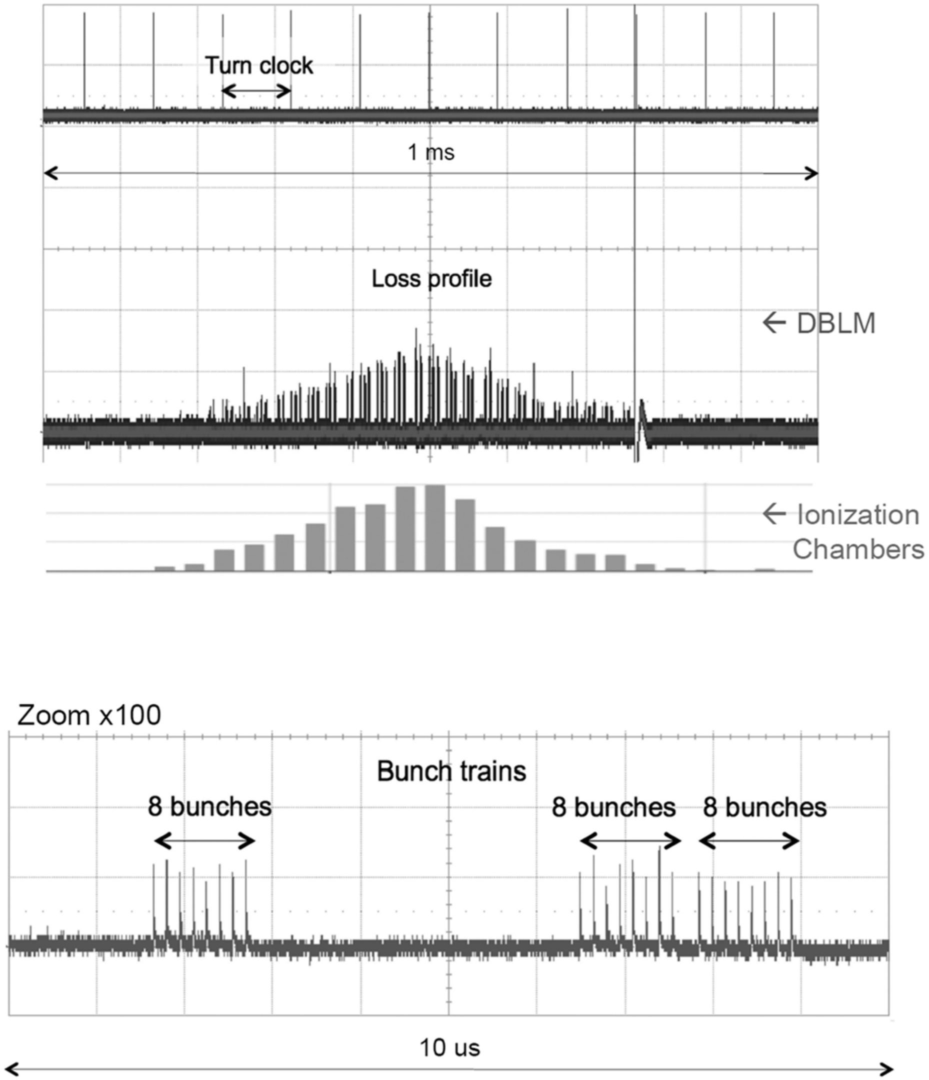




Beam Loss Detectors – New Materials

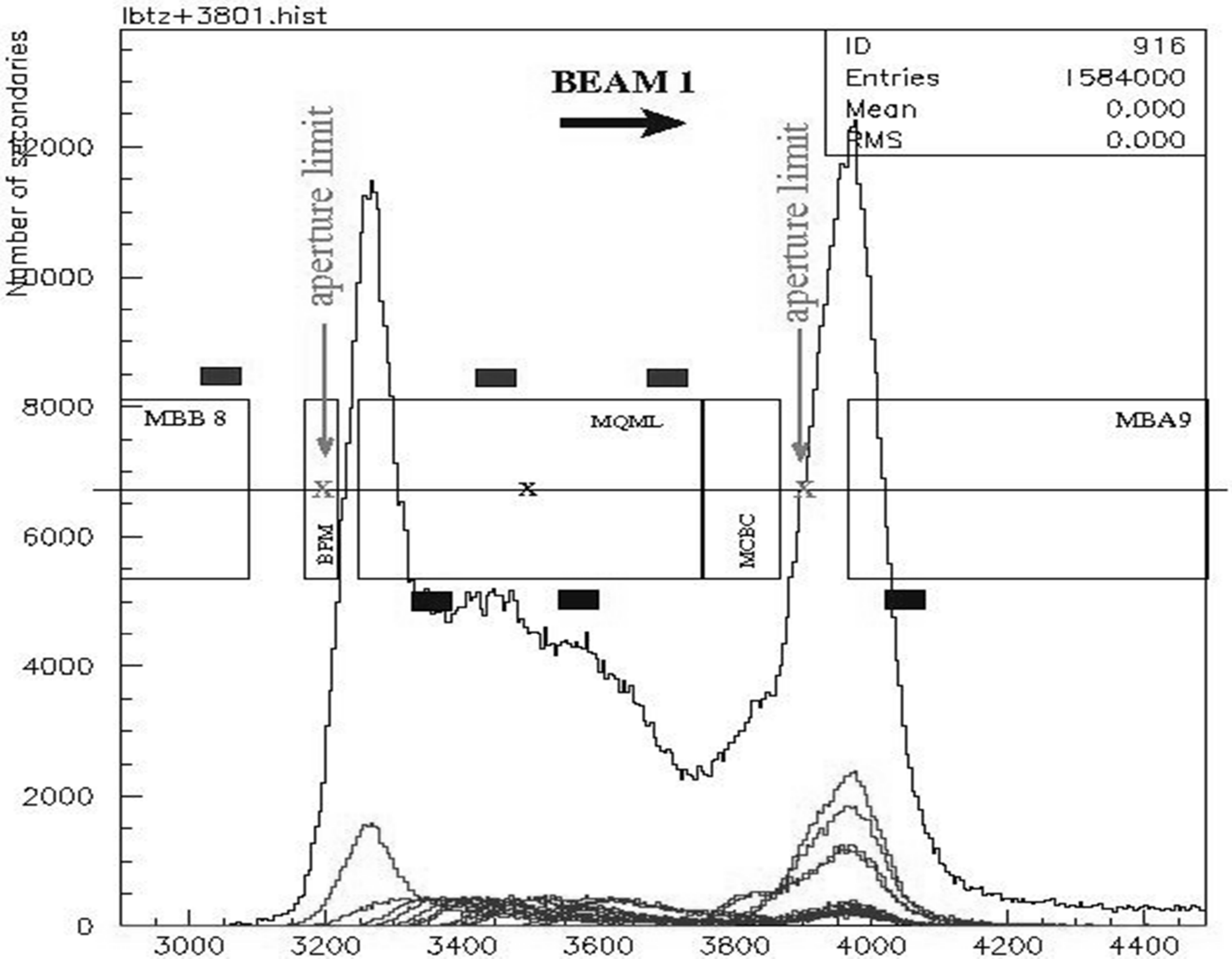
- Diamond Detectors
  - Fast & sensitive
  - Used in LHC to distinguish bunch by bunch losses
  - Investigations now ongoing to see if they can work in cryogenic conditions





Courtesy of E. Griesmayer

BLM Threshold Level Estimation



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 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
    - Group challenge to present this for a particular accelerator