



Introduction to Beam Instrumentation

CAS 2013

Trondheim, Norway

18th – 29th August, 2013

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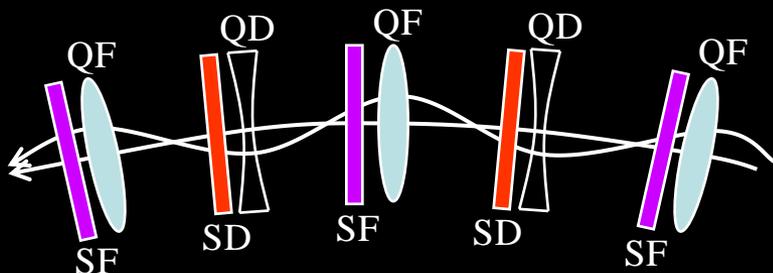


Introduction

- **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

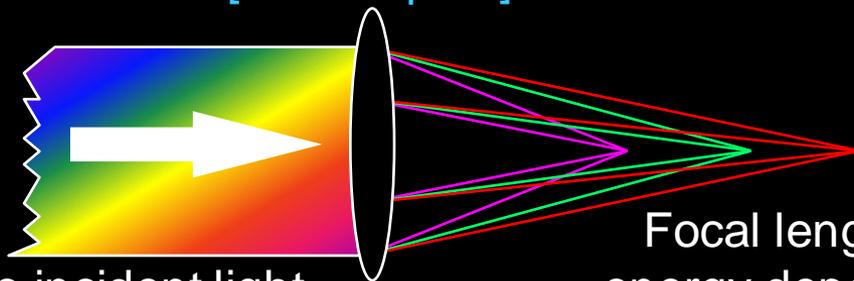


Characteristic Frequency of the Magnetic Lattice Given by the strength of the Quadrupole magnets

- Machine Chromaticity

Optics Analogy:

Lens
[Quadrupole]



Achromatic incident light
[Spread in particle energy]

Focal length is energy dependent

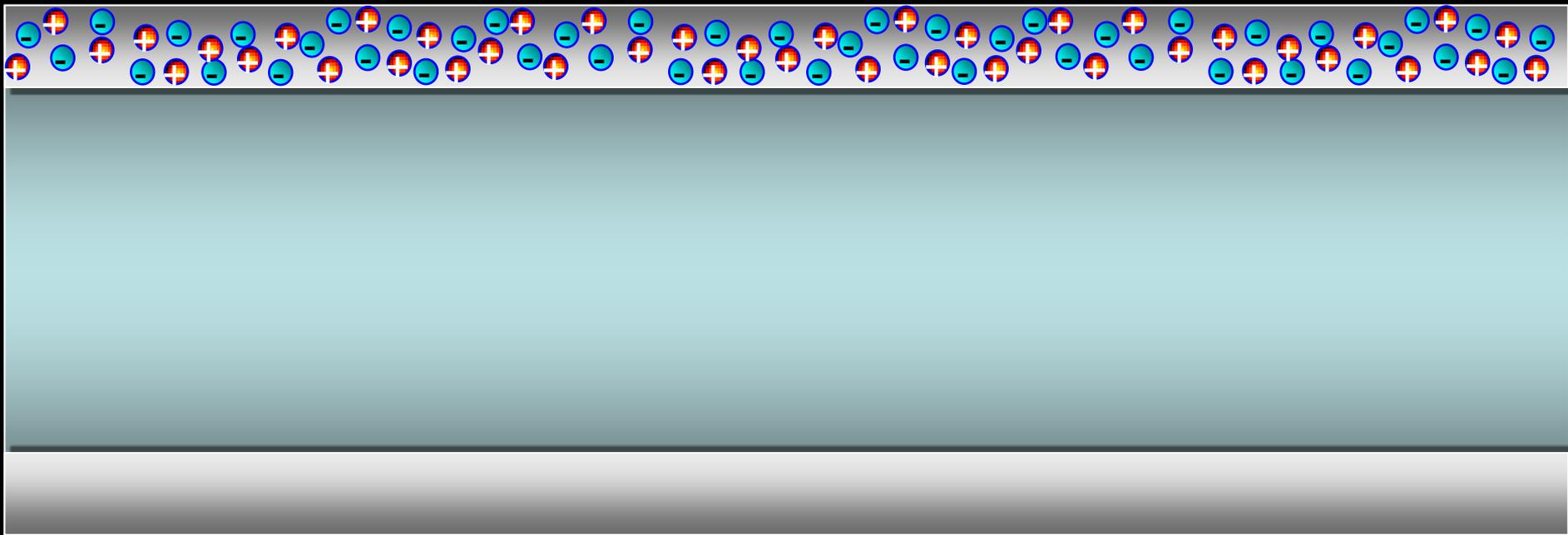
Spread in the Machine Tune due to Particle Energy Spread Controlled by Sextupole magnets



The Typical Instruments

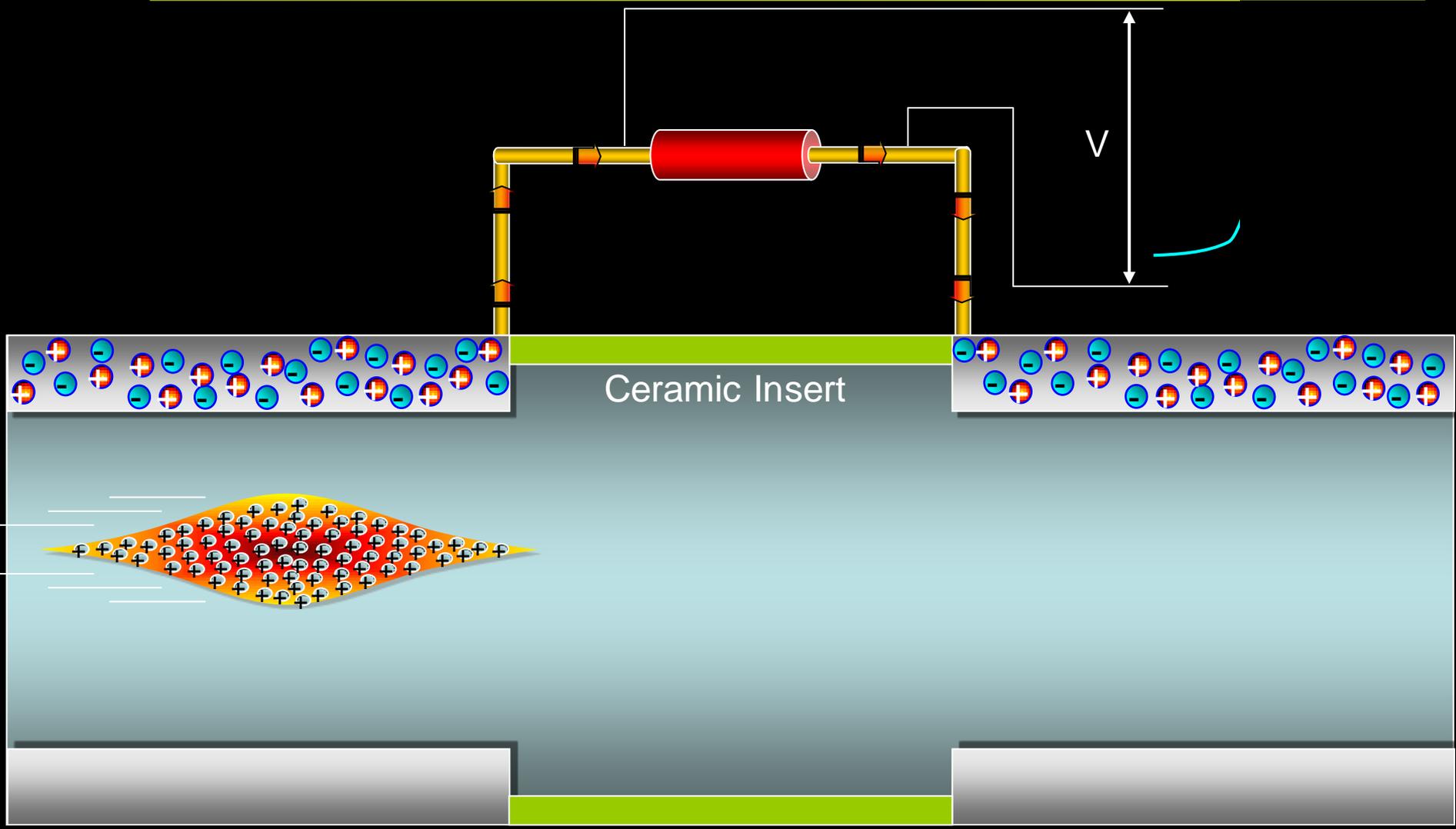
- **Beam Position**
 - electrostatic or electromagnetic pick-ups and related electronics
- **Beam Intensity**
 - beam current transformers
- **Beam Profile**
 - secondary emission grids and screens
 - wire scanners
 - synchrotron light monitors
 - ionisation and luminescence monitors
 - femtosecond diagnostics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

Measuring Beam Position – The Principle

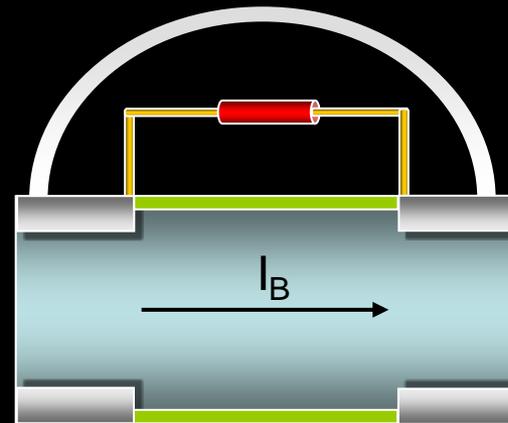
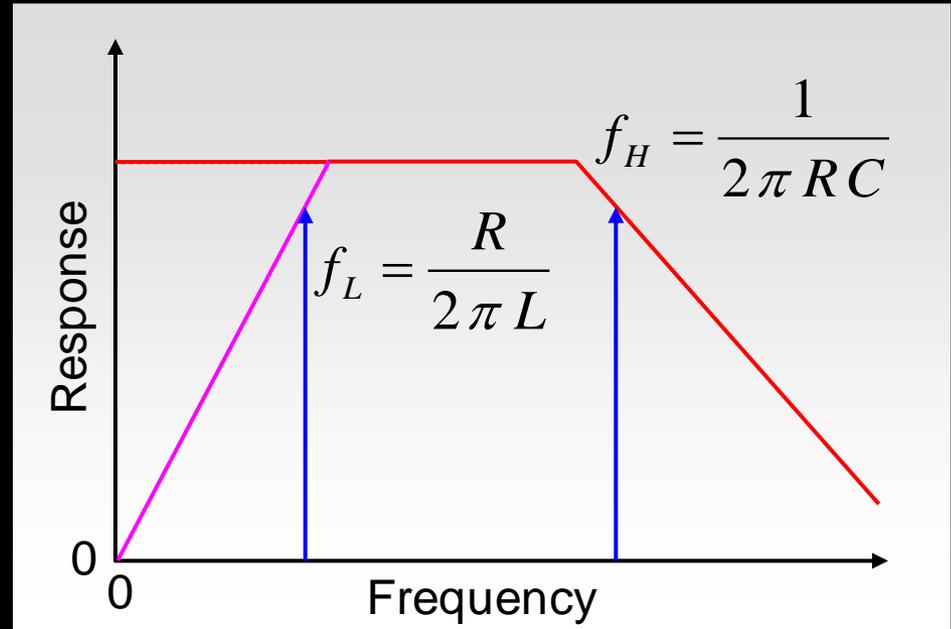
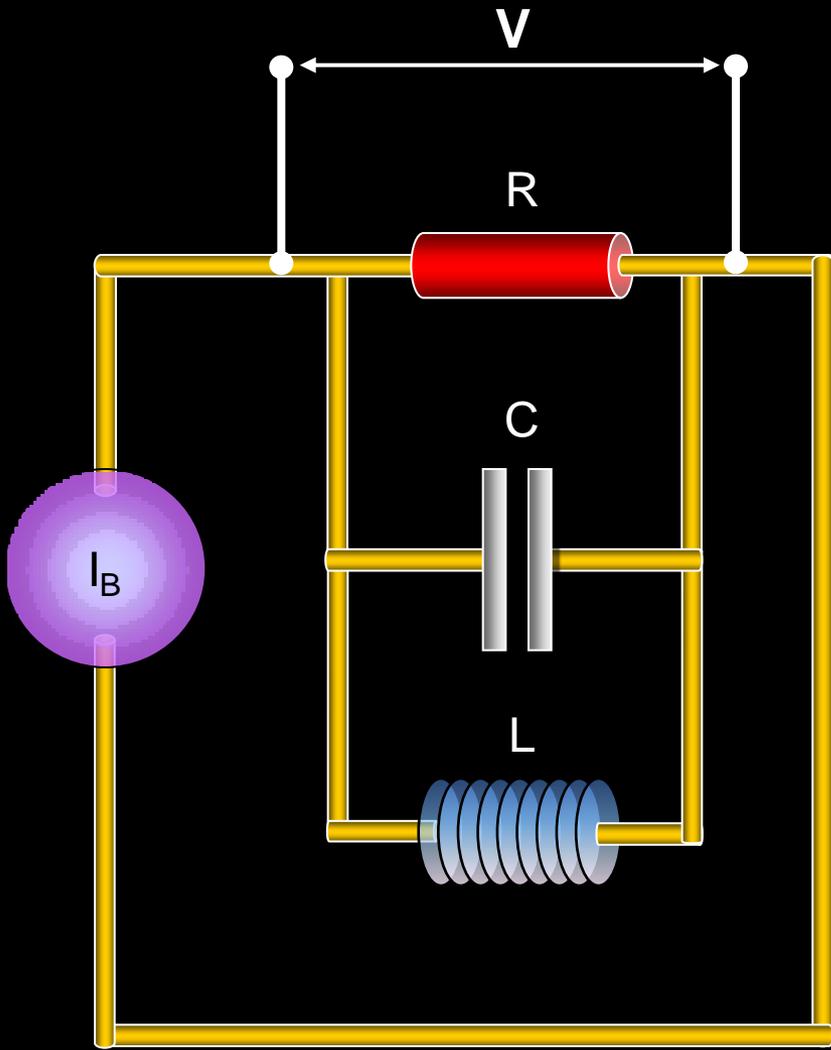




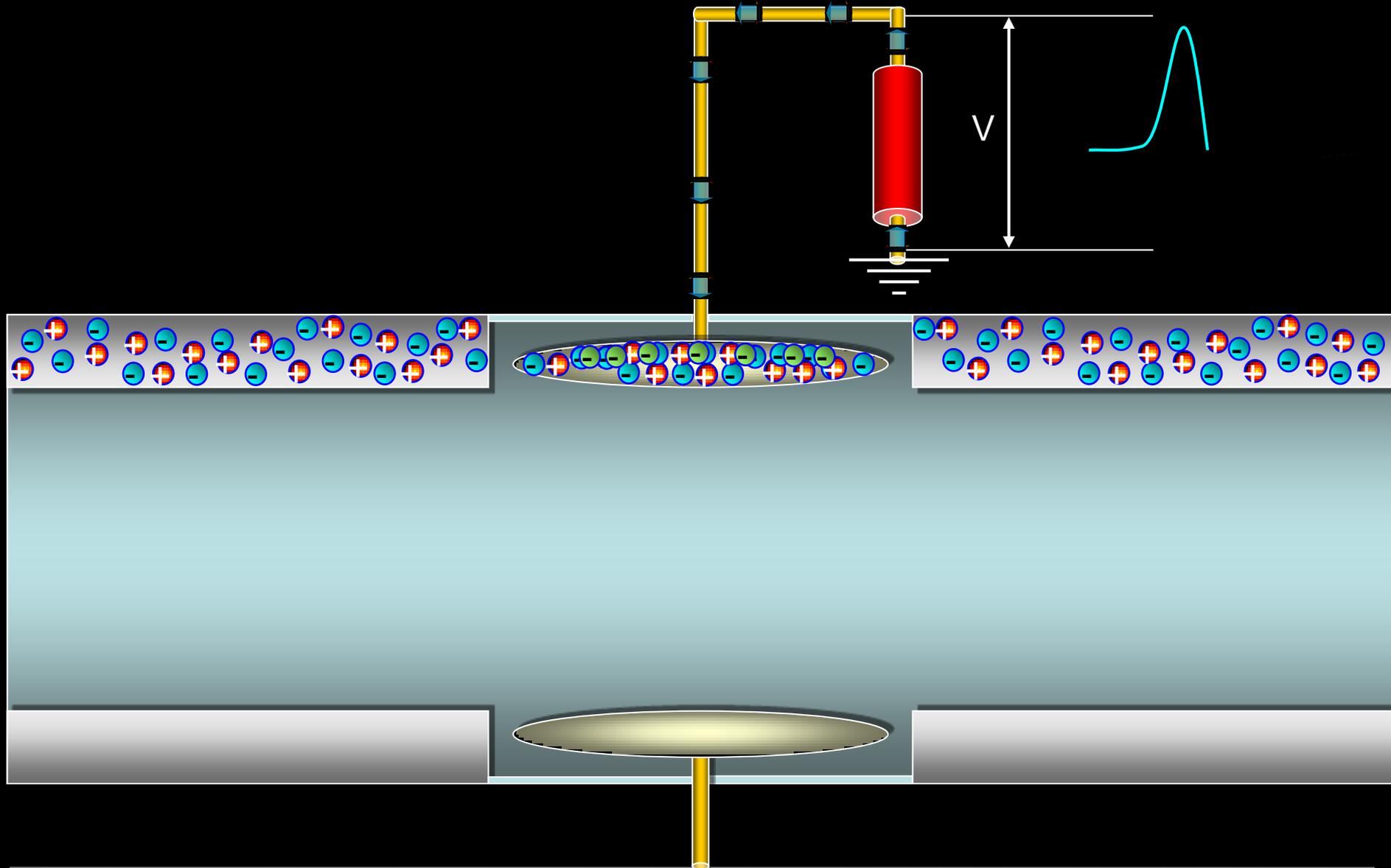
Wall Current Monitor – The Principle



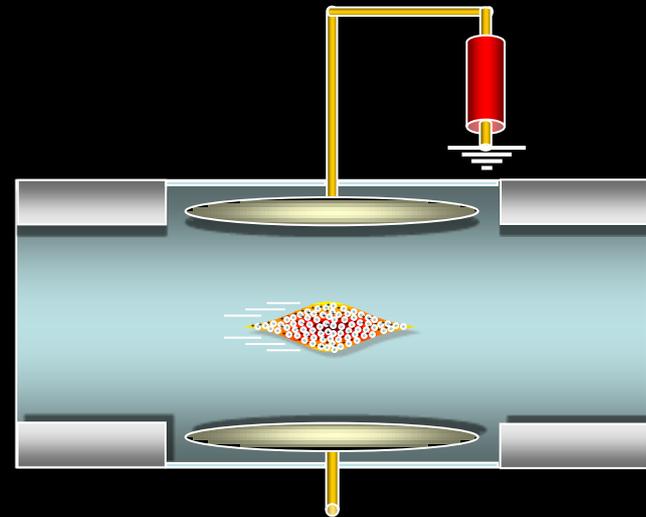
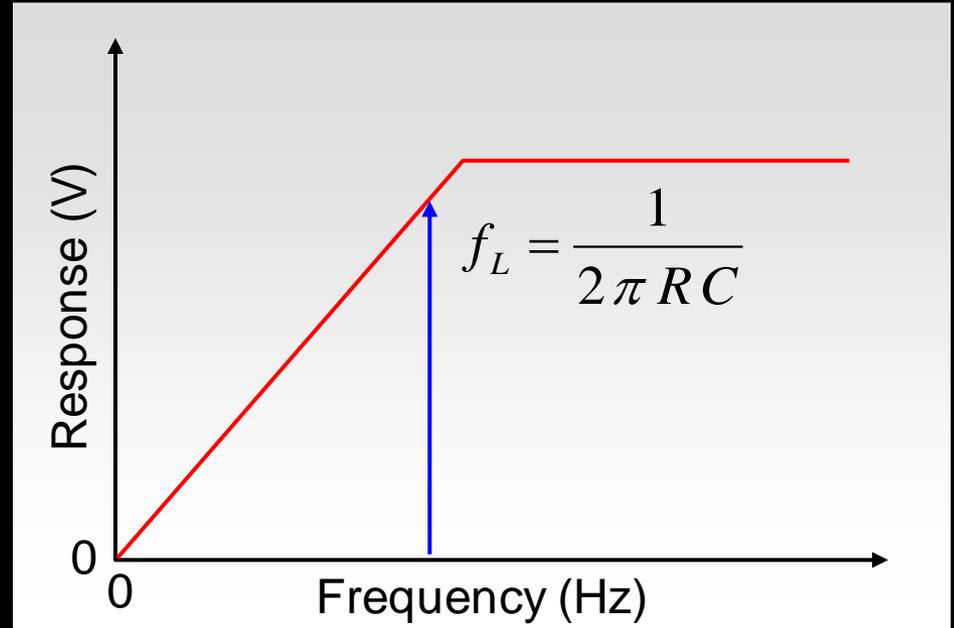
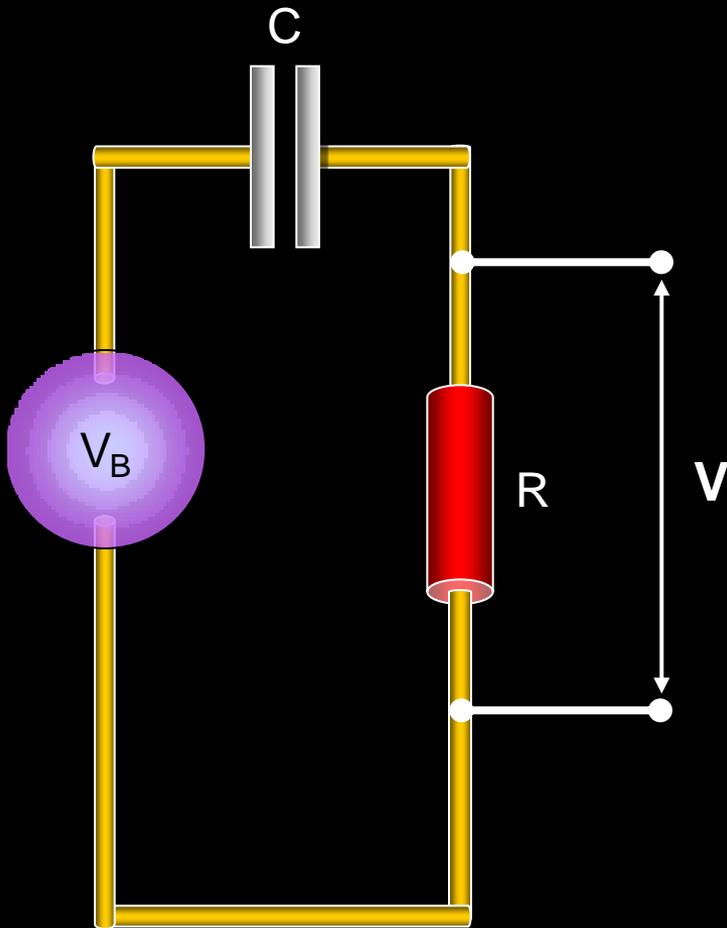
Wall Current Monitor – Beam Response



Electrostatic Monitor – The Principle

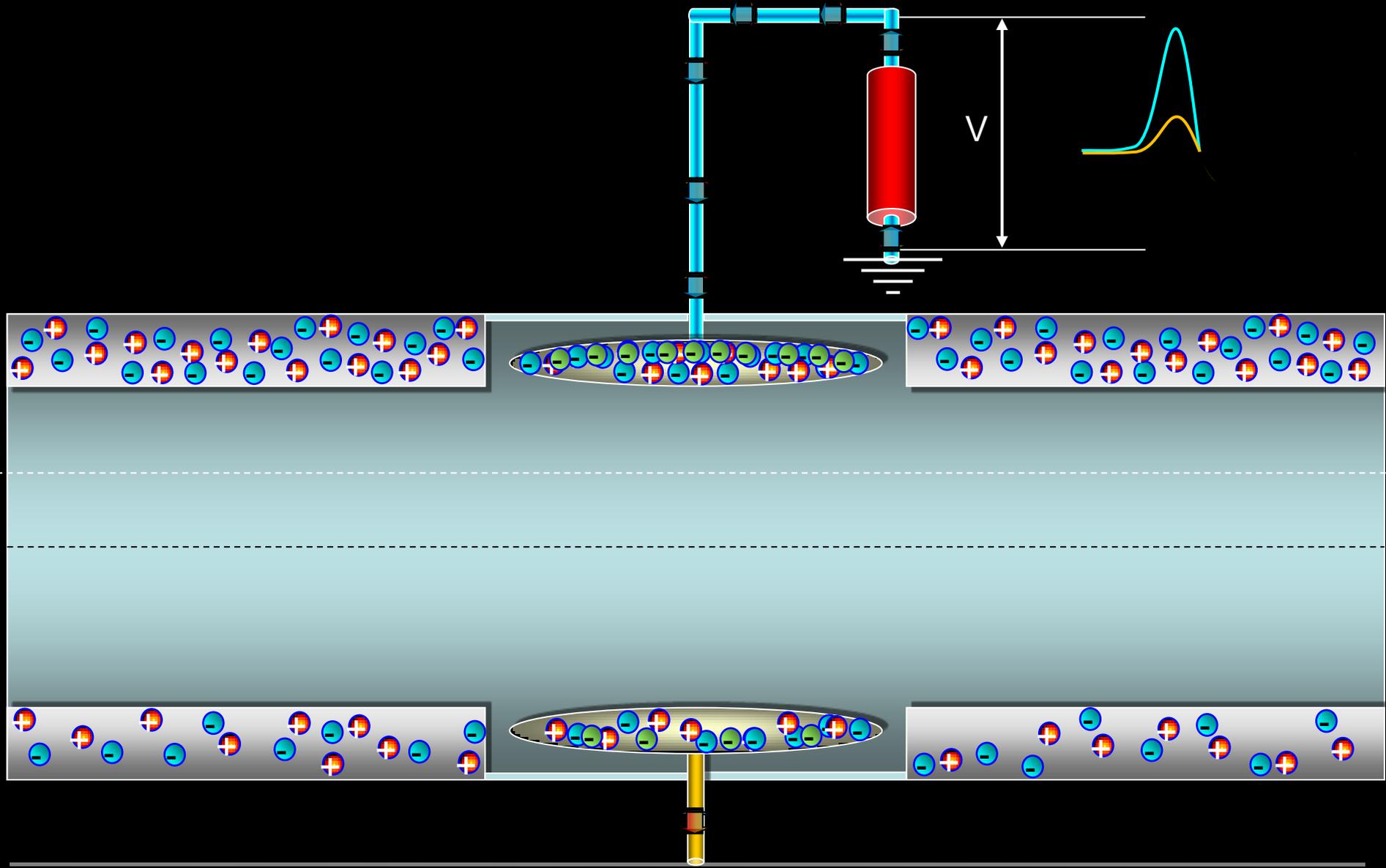


Electrostatic Monitor – Beam Response





Electrostatic Monitor – The Principle



Electrostatic Pick-up – Button

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

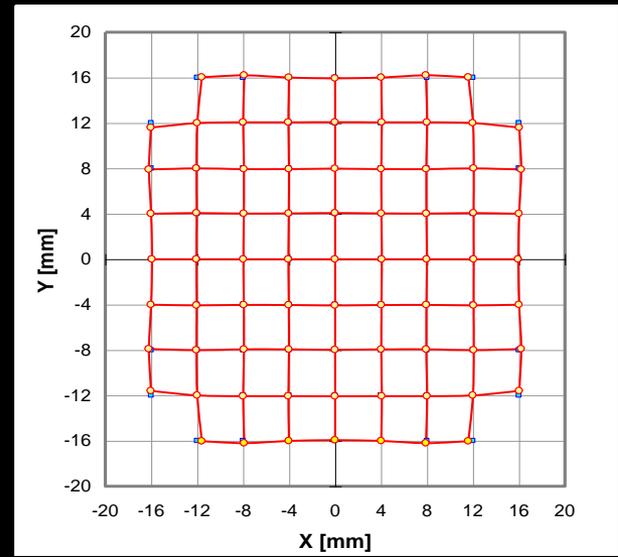
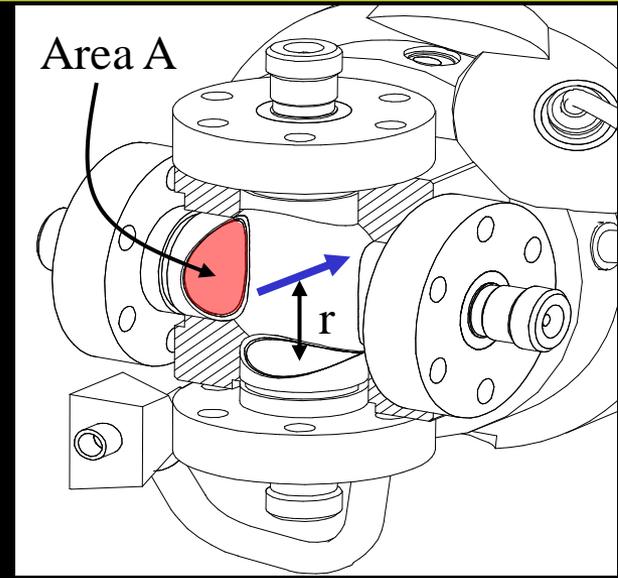
For Button with Capacitance C_e & Characteristic Impedance R_0

Transfer Impedance:

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

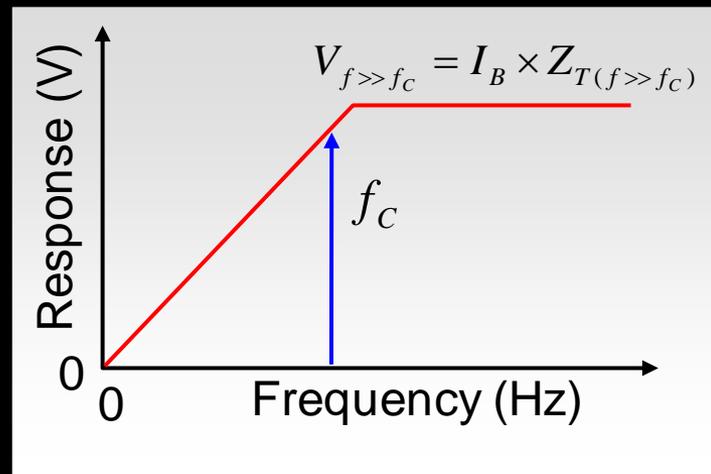
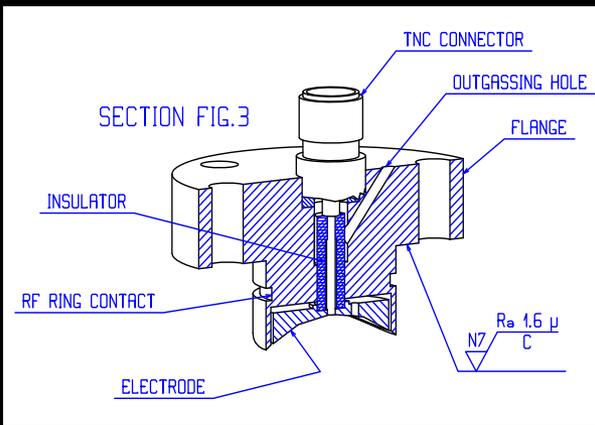
Lower Corner Frequency:

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



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

A Real Example – The LHC Button



$$f_L = \frac{1}{2\pi RC} = \frac{1}{2\pi \times 50\Omega \times 8pF} = 400 \text{ MHz}$$

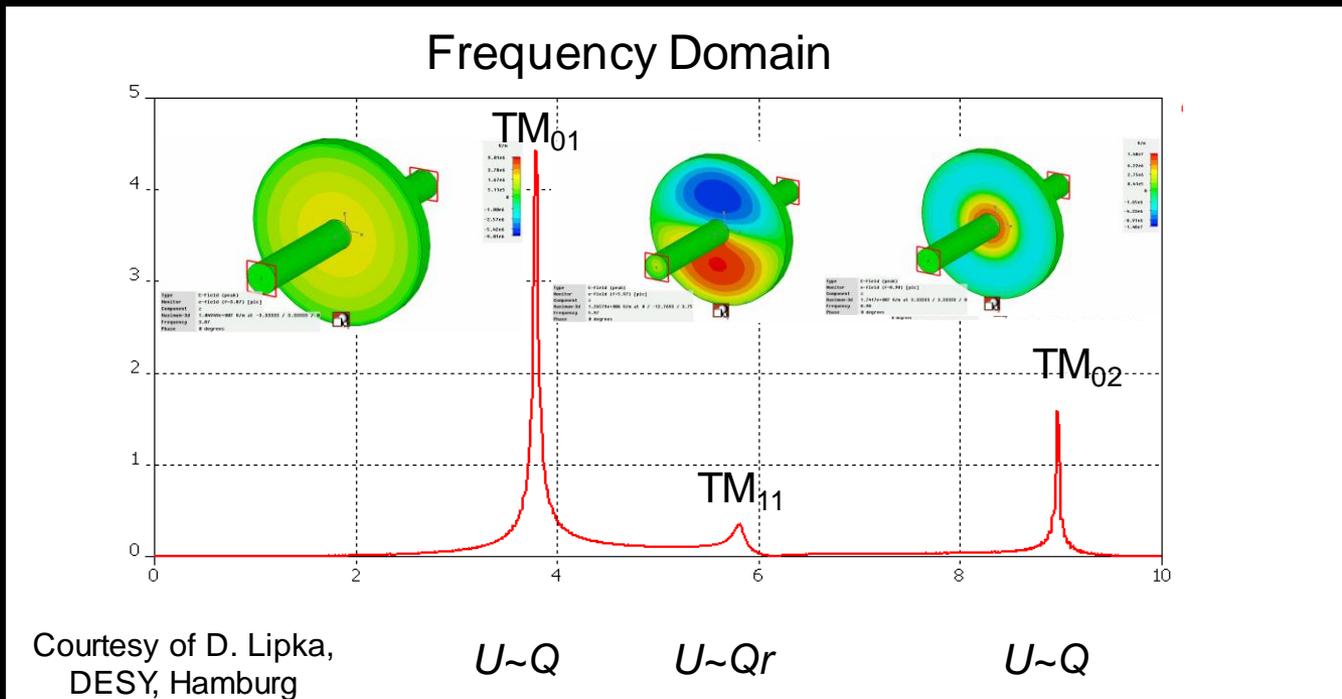
$$Z_{T\infty} = \frac{A}{(2\pi r) \times c \times C_e} = \frac{\pi \times (12\text{mm})^2}{(2\pi \times 24.5\text{mm}) \times c \times (8pF)} = 1.2\Omega$$

$$I_B = \frac{N_{pilot} e}{t} = \frac{5 \times 10^9 \times 1.6 \times 10^{-19}}{1 \times 10^{-9}} = 0.8 A_{peak} \Rightarrow V_{f=\infty} = 0.8 \times 1.2 = 1 V_{peak}$$

$$= \frac{N_{nom} e}{t} = \frac{1 \times 10^{11} \times 1.6 \times 10^{-19}}{1 \times 10^{-9}} = 16 A_{peak} \Rightarrow V_{f=\infty} = 16 \times 1.2 = 20 V_{peak}$$

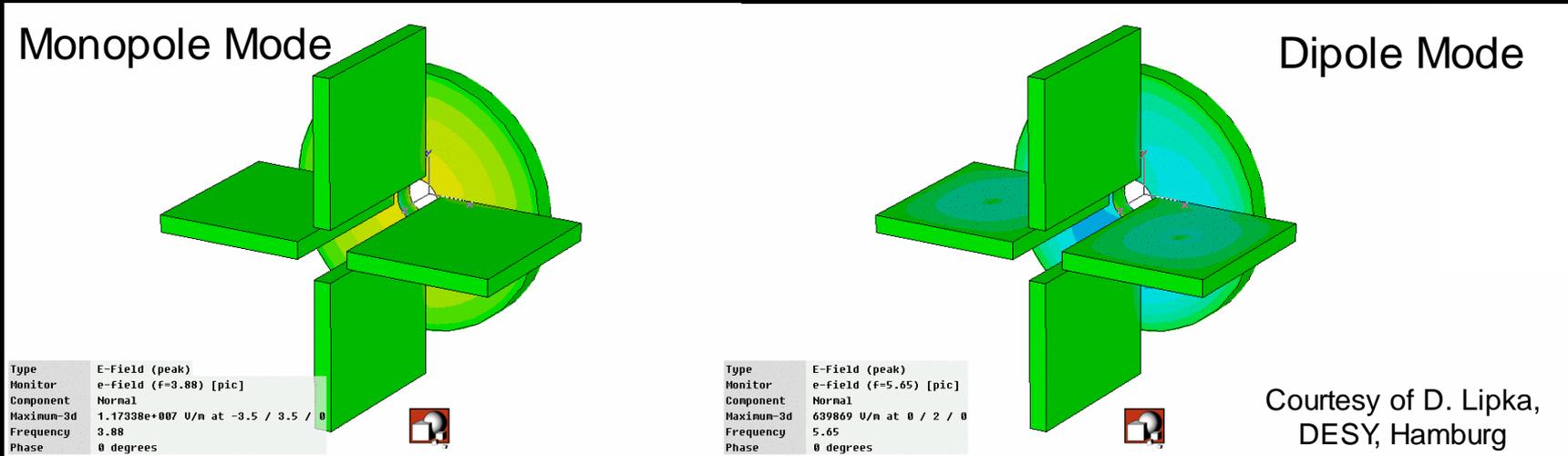
Improving the Precision for Next Generation Accelerators

- 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 \Rightarrow 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

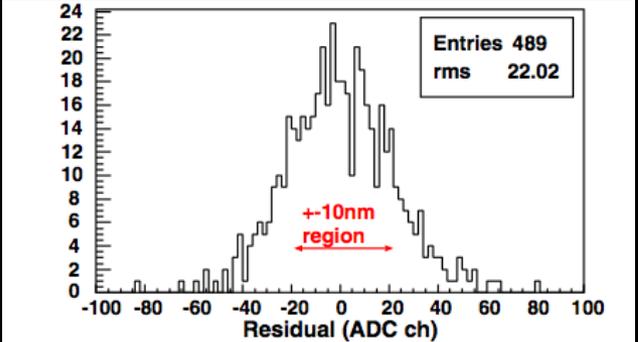
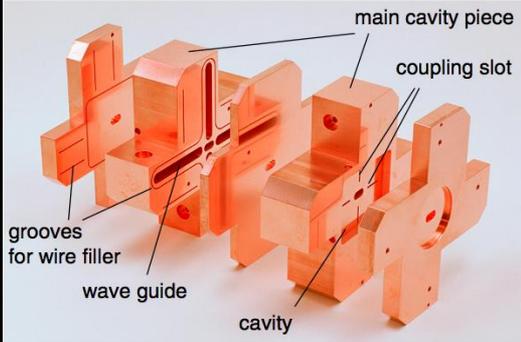
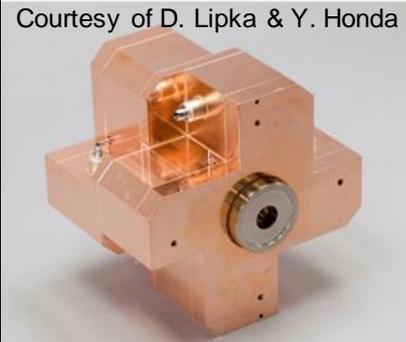


Today's State of the Art BPMs

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



- 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)



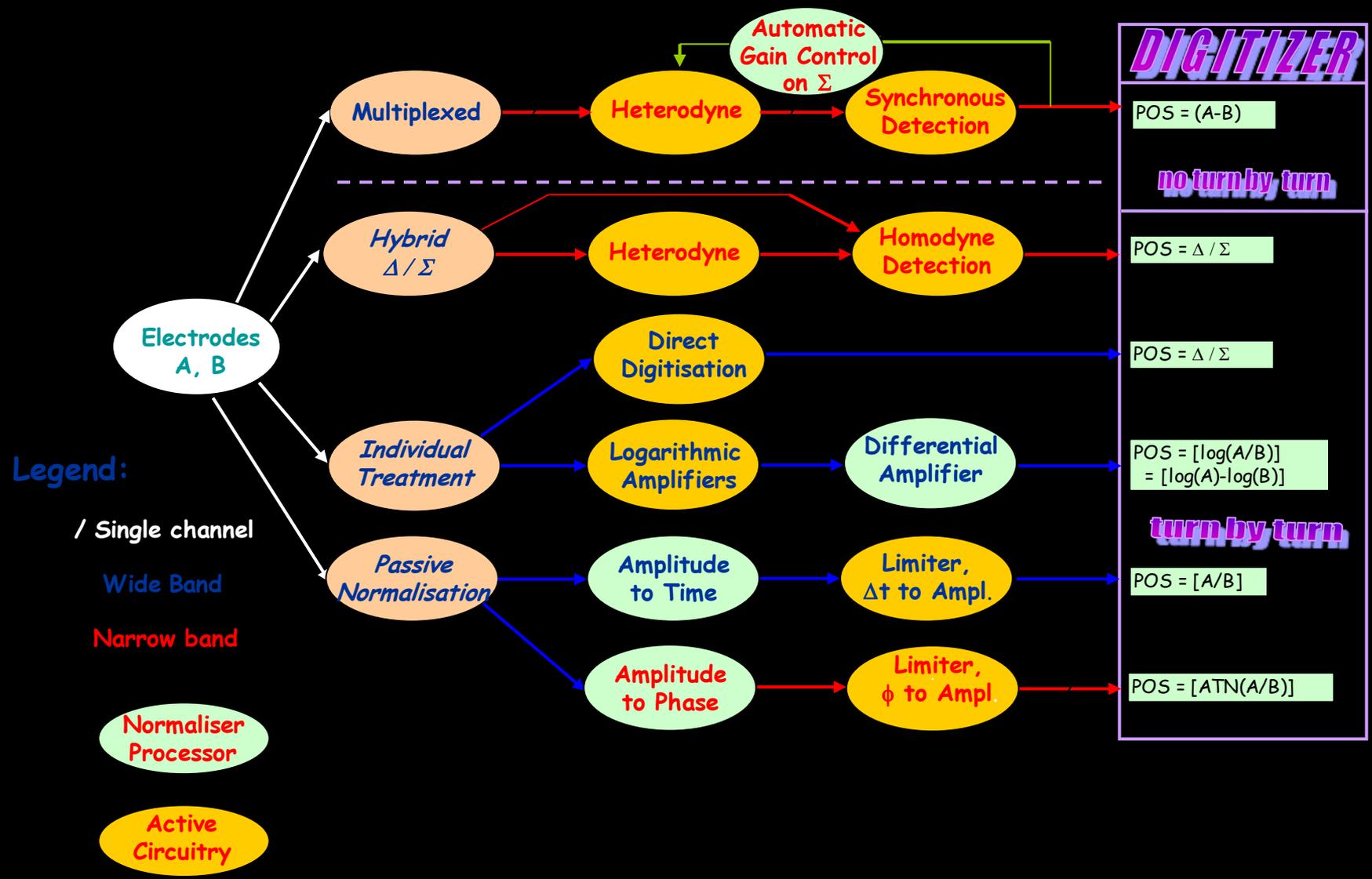


Criteria for Electronics Choice - so called “Processor Electronics”

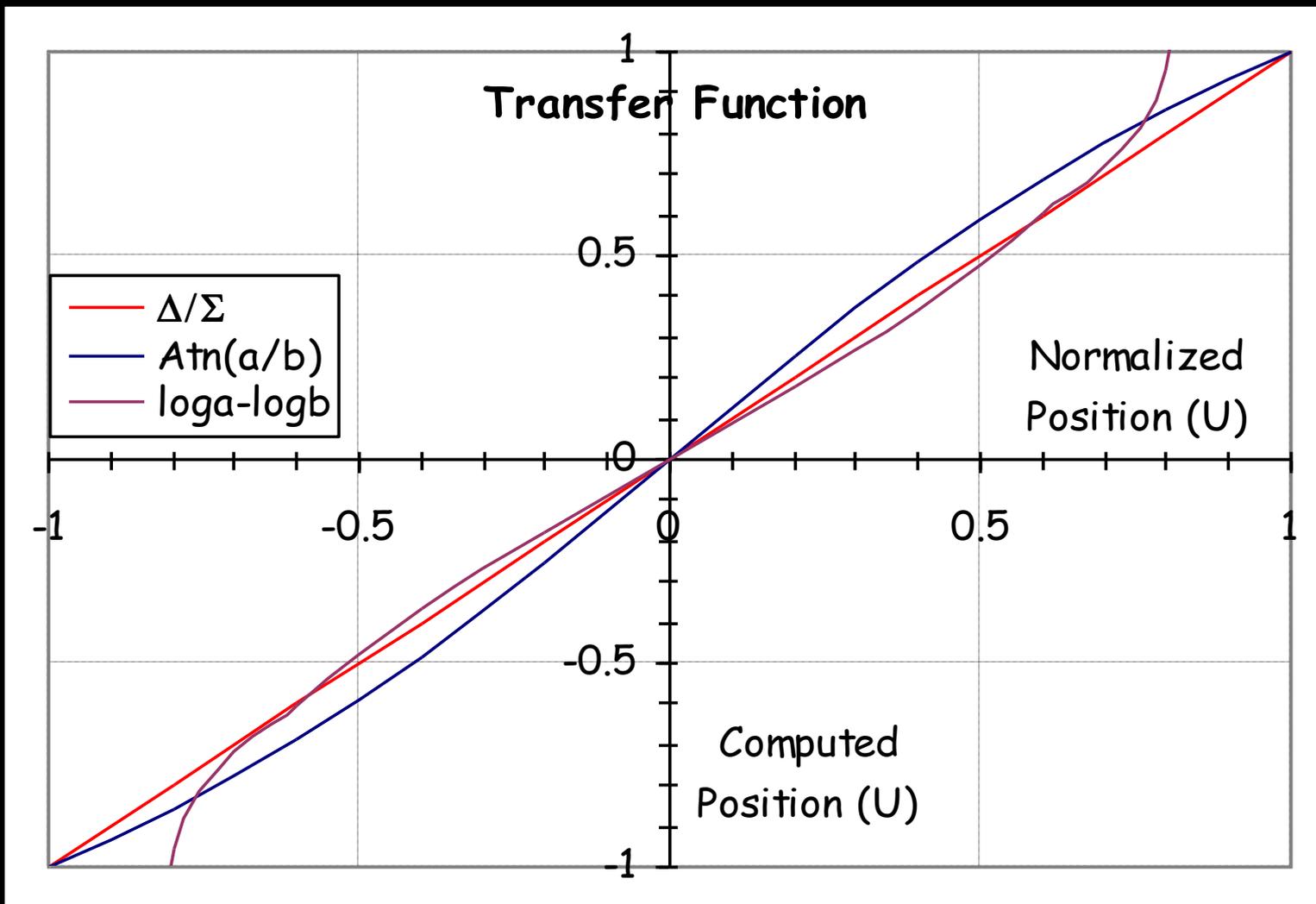
- **Accuracy**
 - mechanical and electromagnetic errors
 - electronic components
- **Resolution**
- **Stability over time**
- **Sensitivity and Dynamic Range**
- **Acquisition Time**
 - measurement time
 - repetition time
- **Linearity**
 - aperture & intensity
- **Radiation tolerance**



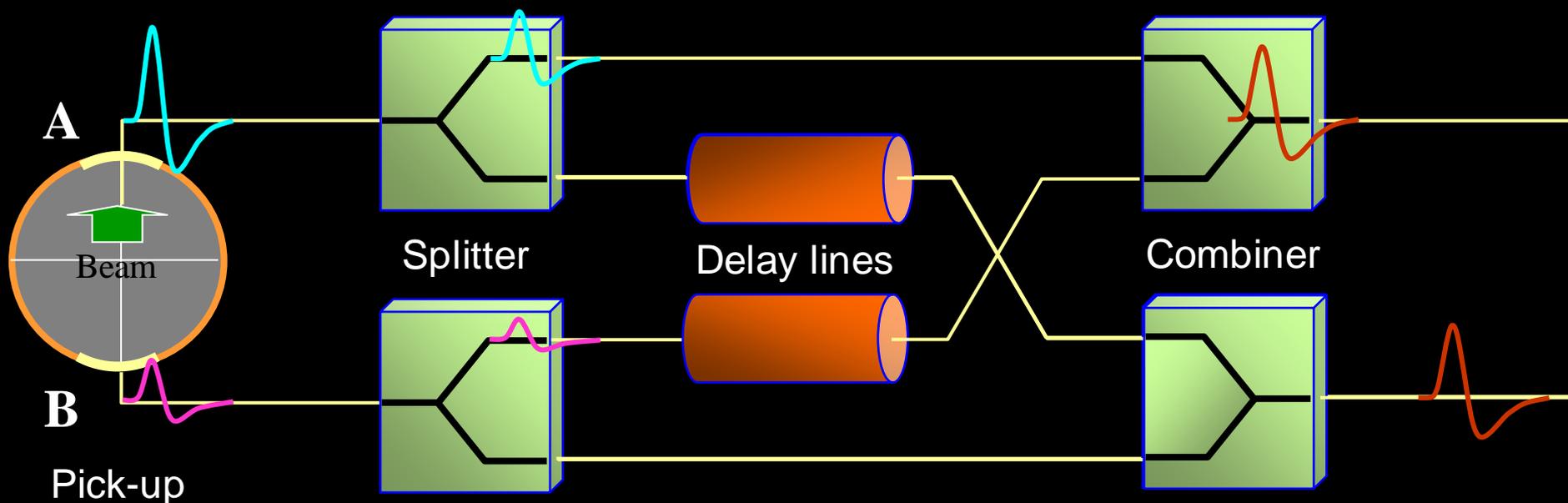
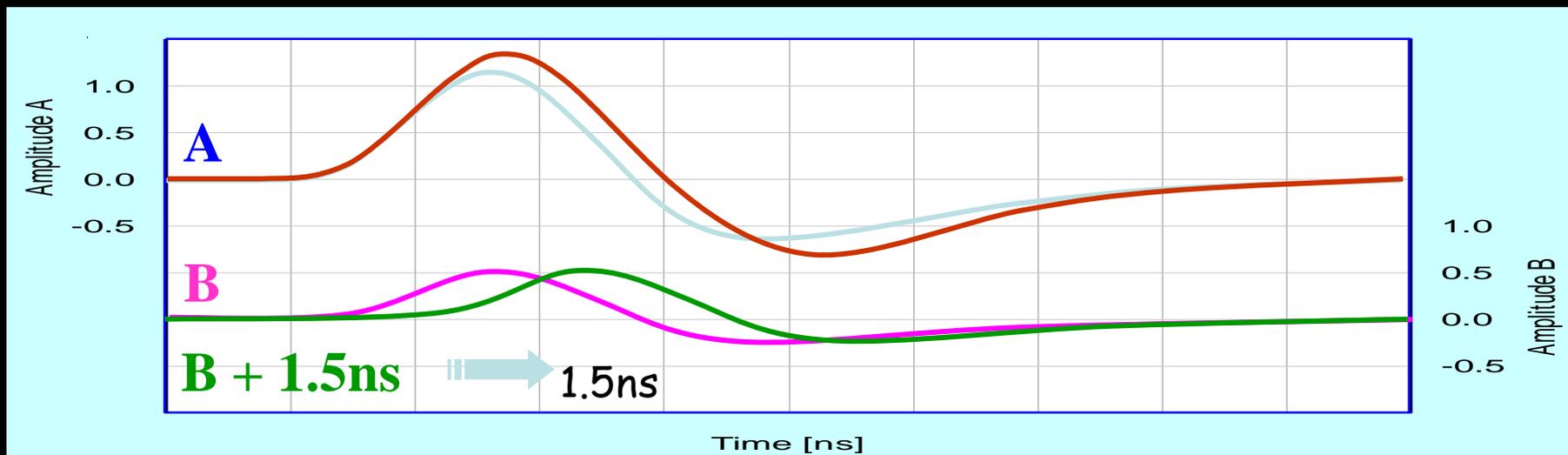
Processing System Families



Linearity Comparison

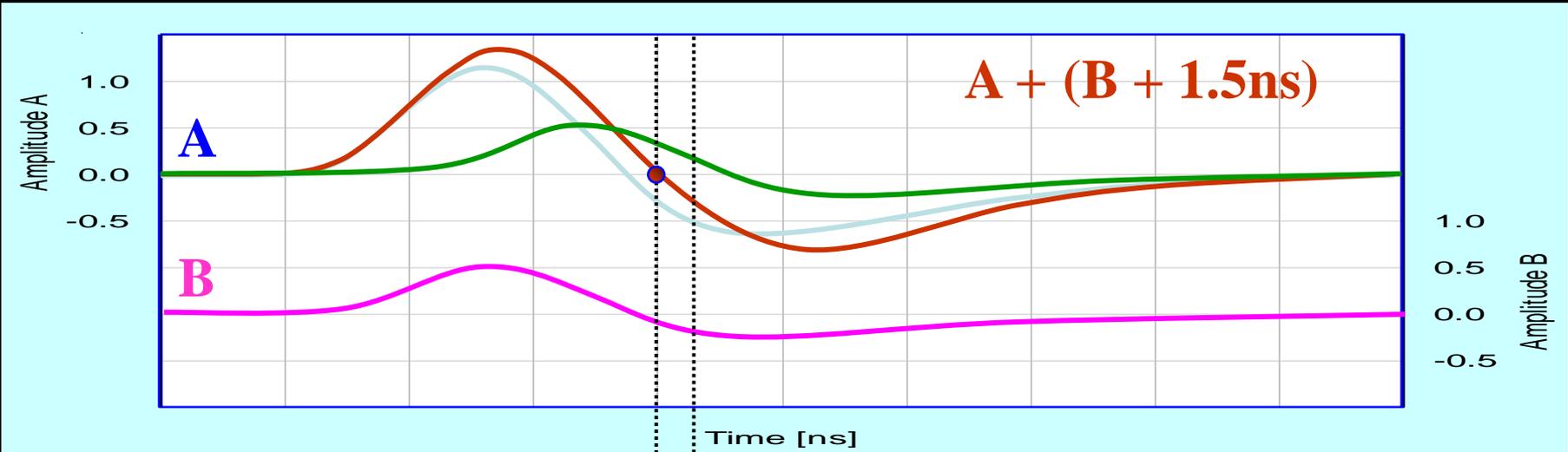


Amplitude to Time Normalisation

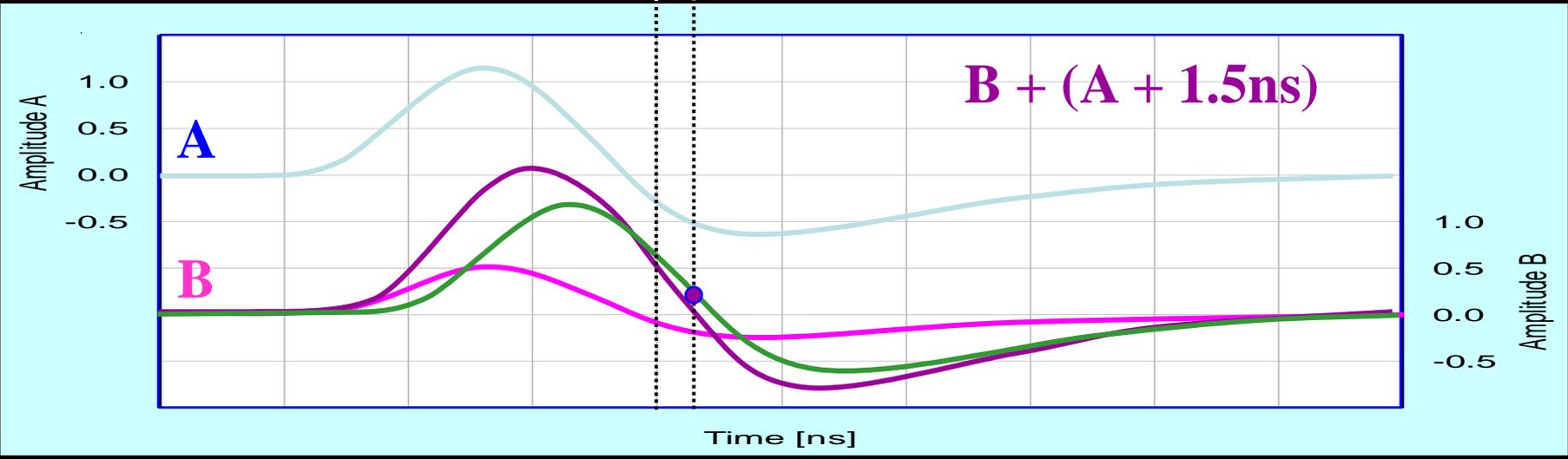




Amplitude to Time Normalisation



Δt depends on position \leftrightarrow





BPM Acquisition Electronics

Amplitude to Time Normaliser

Advantages

- Fast normalisation (< 25ns)
 - bunch to bunch measurement
- Signal dynamic independent of the number of bunches
 - Input dynamic range ~45 dB
 - No need for gain selection
- Reduced number of channels
 - normalisation at the front-end
- ~10 dB compression of the position dynamic due to the recombination of signals
- Independent of external timing
- Time encoding allows fibre optic transmission to be used

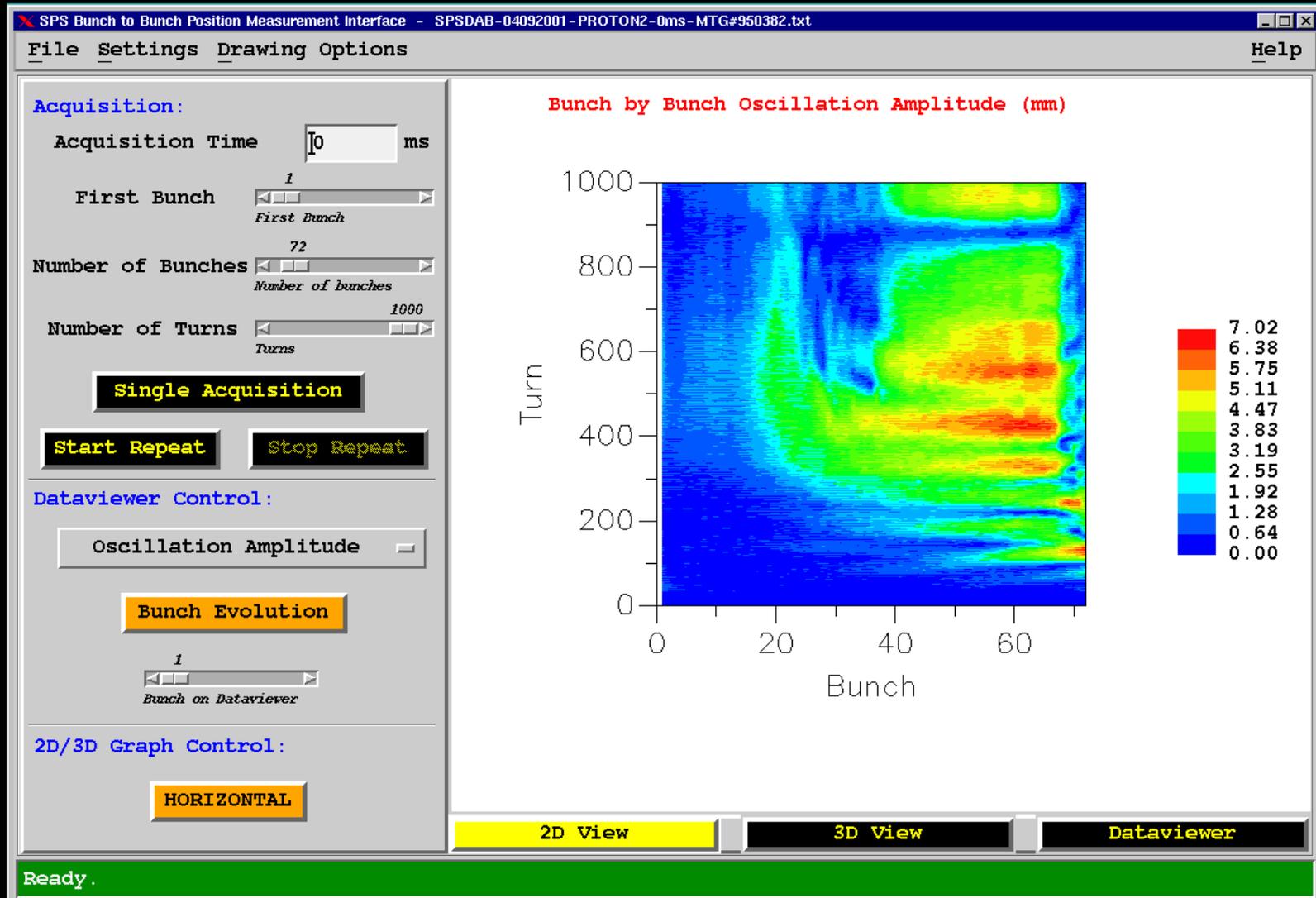
Limitations

- Currently reserved for beams with empty RF buckets between bunches e.g.
 - LHC 400MHz RF but 25ns spacing
 - 1 bunch every 10 buckets filled
- Tight time adjustment required
- No Intensity information
- Propagation delay stability and switching time uncertainty are the limiting performance factors



What one can do with such a System

Used in the CERN-SPS for electron cloud & instability studies

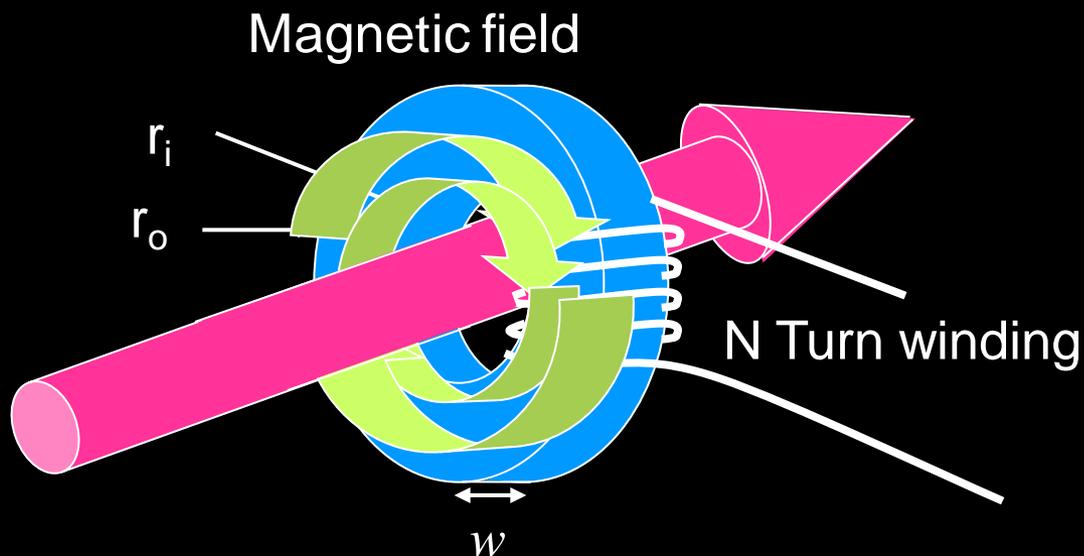




The Typical Instruments

- **Beam Position**
 - electrostatic or electromagnetic pick-ups and related electronics
- **Beam Intensity**
 - beam current transformers
- **Beam Profile**
 - secondary emission grids and screens
 - wire scanners
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 - in diagnostics section of tomorrow
- **Luminosity**
 - in diagnostics section of tomorrow

Current Transformers



Fields are very low

Capture magnetic field lines with cores of high relative permeability

(CoFe based amorphous alloy Vitrovac: $\mu_r = 10^5$)

Beam current

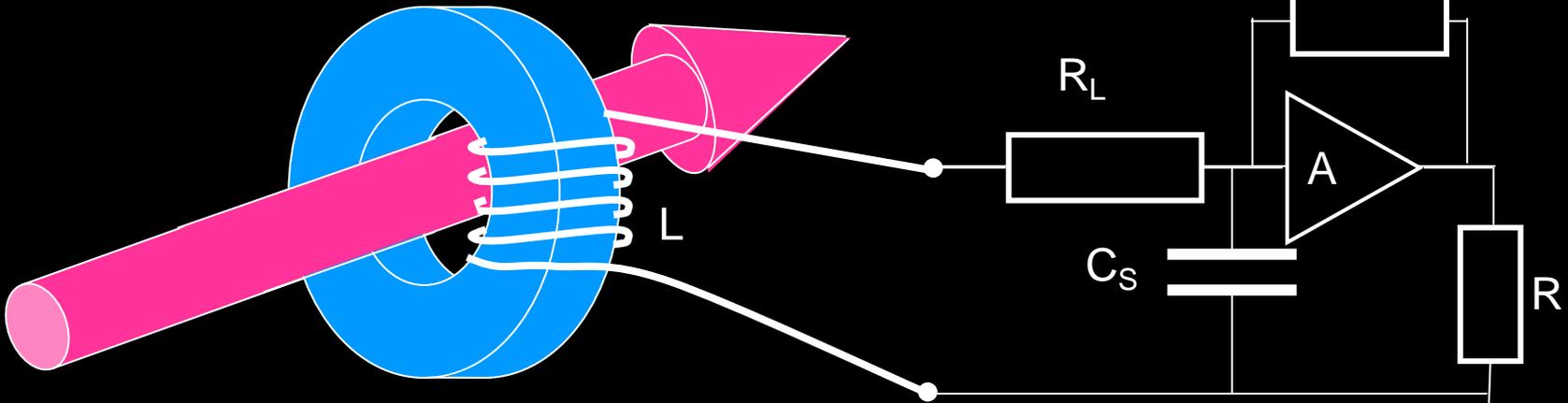
$$I_{Beam} = \frac{e N_q}{t} = \frac{e N_q \beta c}{w}$$

Transformer Inductance

$$L = \frac{\mu_0 \mu_r}{2\pi} w N^2 \ln \frac{r_o}{r_i}$$

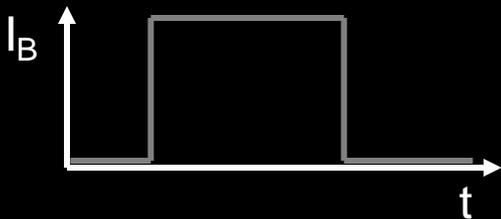
The Active AC transformer

Winding of N turns and Inductance L

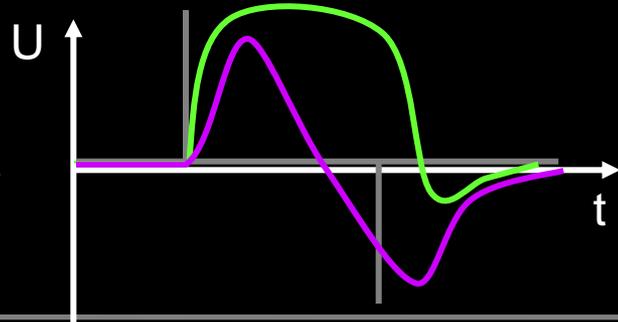


$$U = L \frac{dI_{beam}}{dt} \quad U(t) = \frac{I_{beam}(t)}{N} R e^{-\frac{t}{\tau_{droop}}}$$

Beam signal



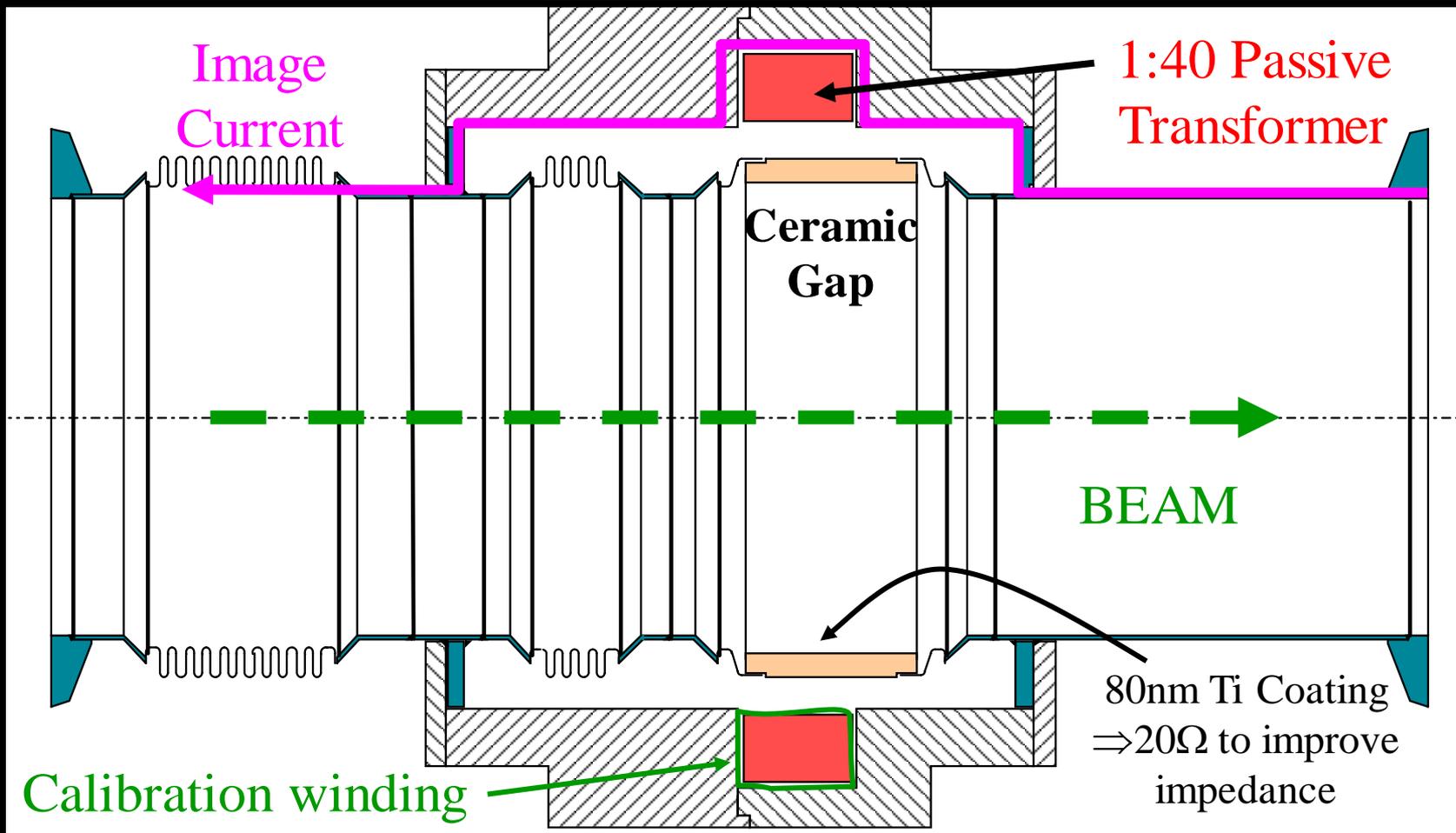
Transformer output signal



$$\tau_{rise} = \sqrt{L_s C_s}$$

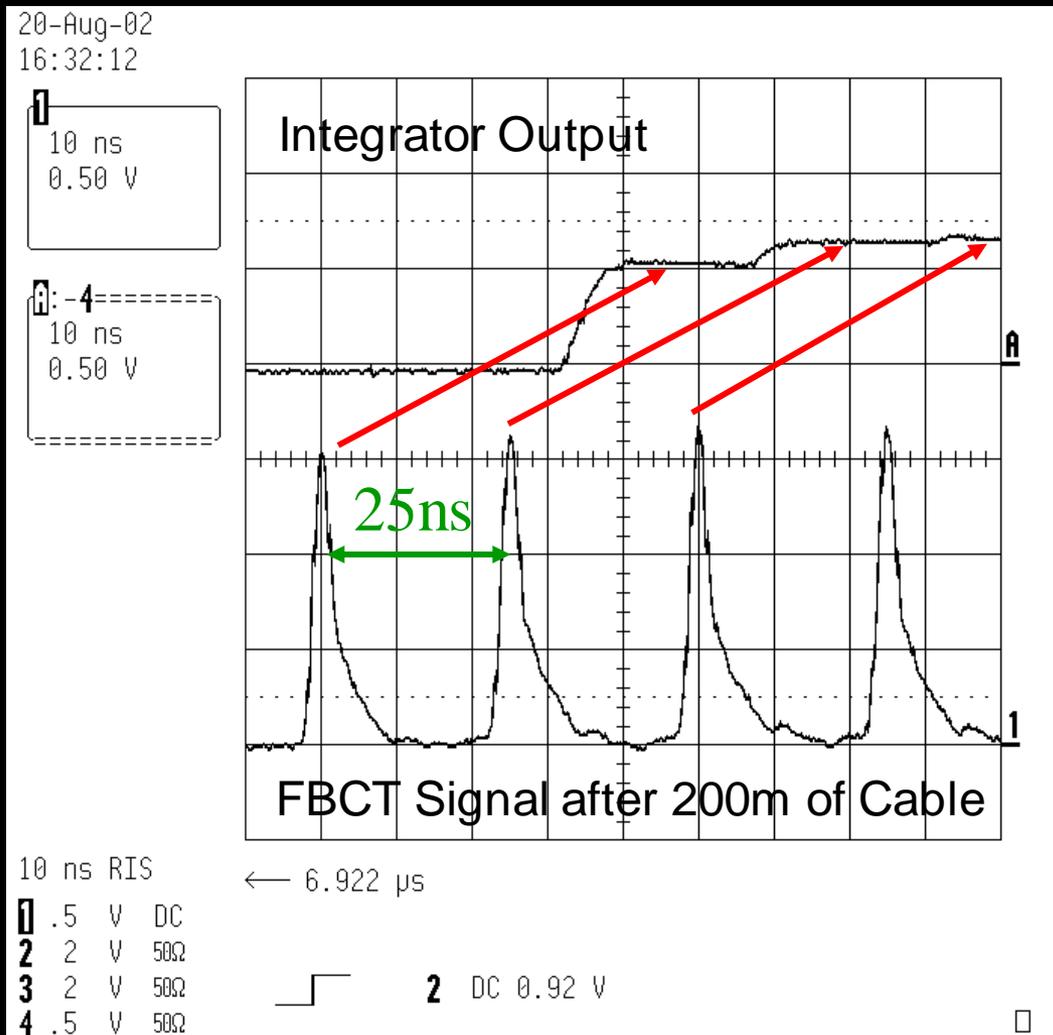
$$\tau_{droop} = \frac{L}{\frac{R_f}{A} + R_L} \approx \frac{L}{R_L}$$

Fast Beam Current Transformer



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

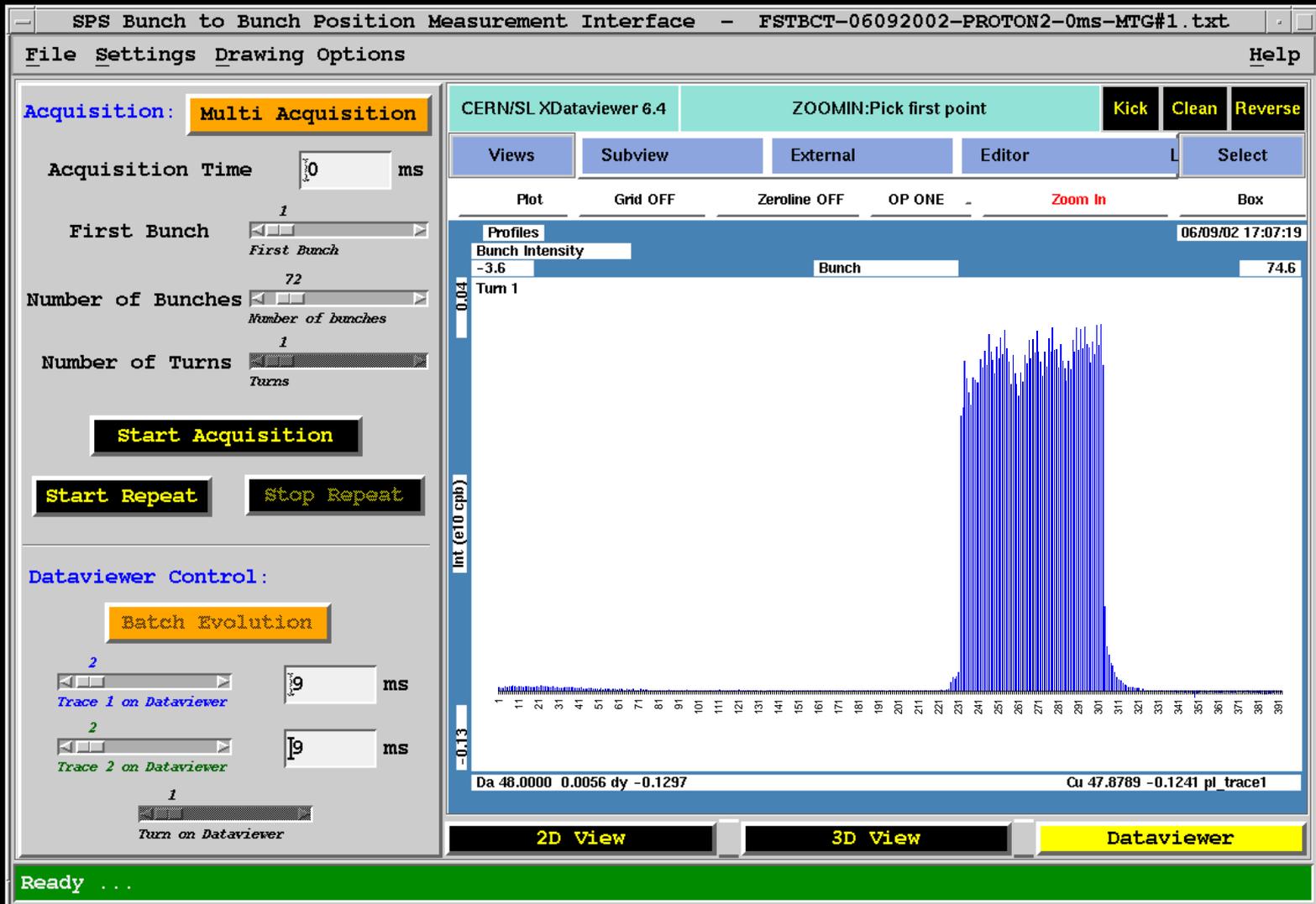
Acquisition Electronics



Data taken on LHC type beams at the CERN-SPS



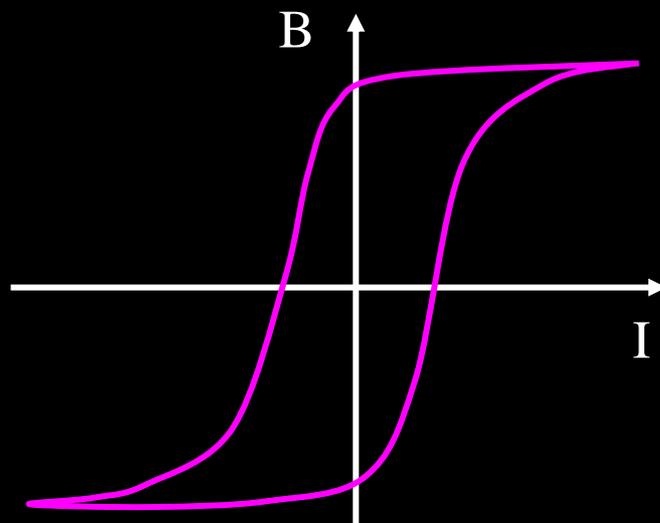
What one can do with such a System



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

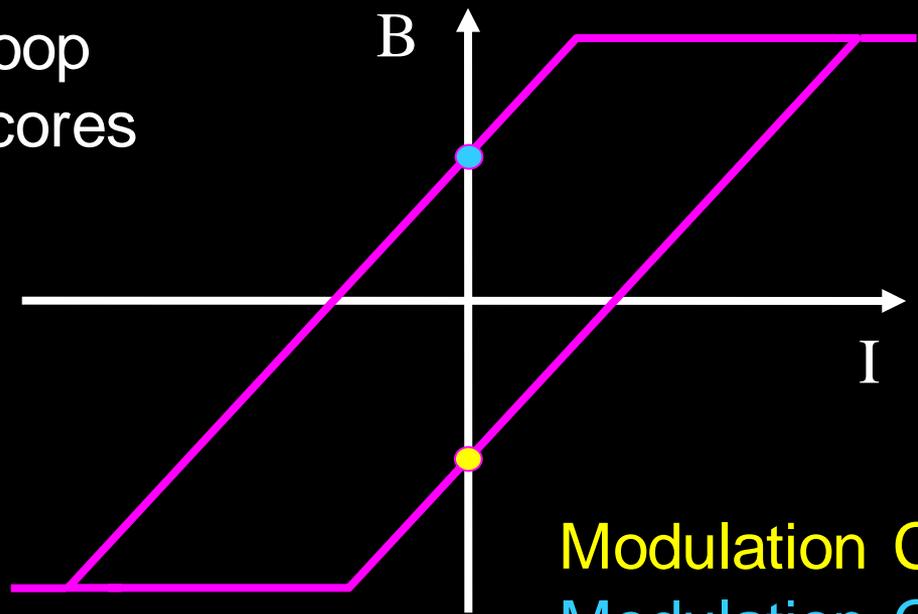
The DC transformer

- 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

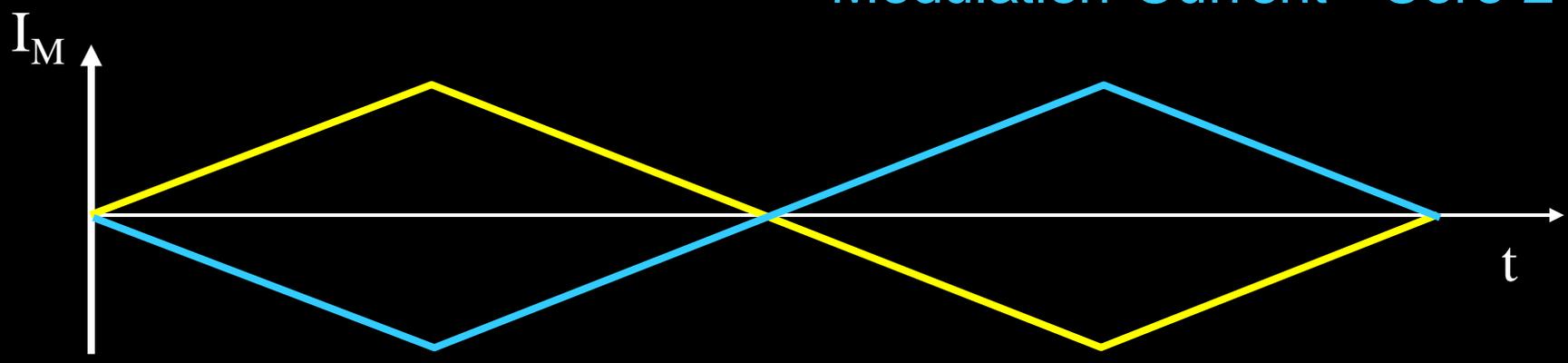


DCCT Principle – Case 1: no beam

Hysteresis loop of modulator cores

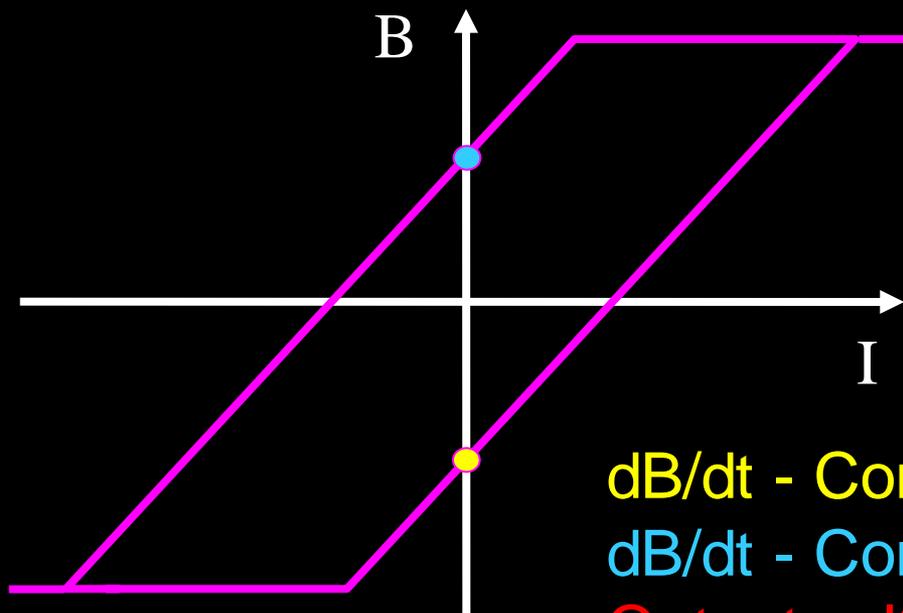


Modulation Current - Core 1
Modulation Current - Core 2



DCCT Principle – Case 1: no beam

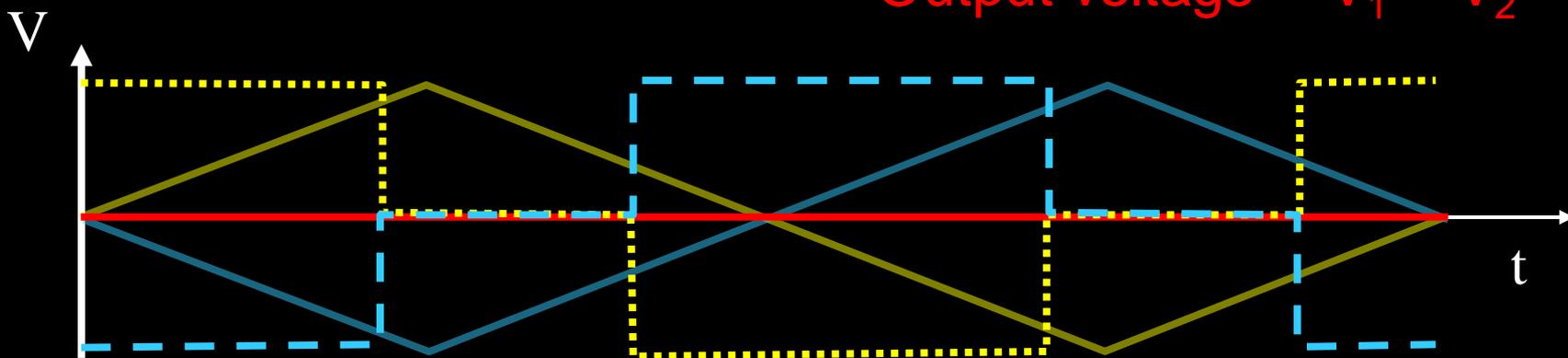
$$V \propto \frac{dB}{dt}$$



$\frac{dB}{dt}$ - Core 1 (V1)

$\frac{dB}{dt}$ - Core 2 (V2)

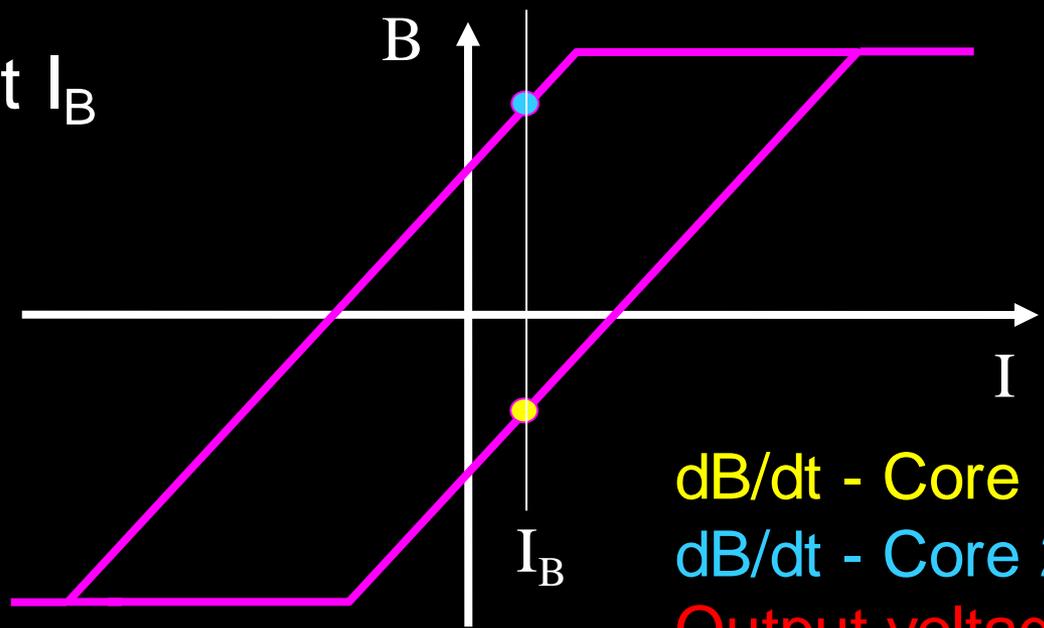
Output voltage = $V_1 - V_2$





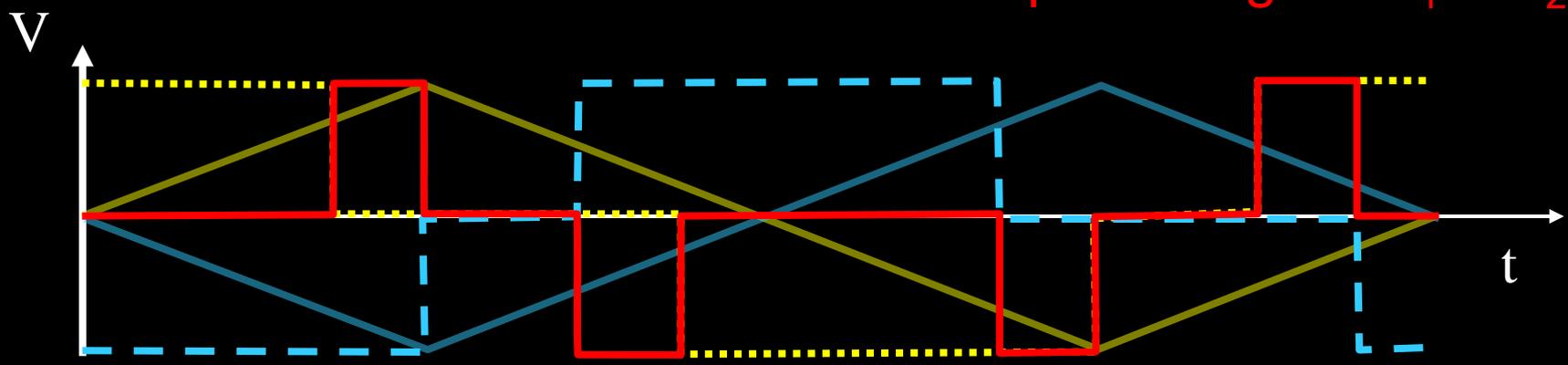
DCCT Principle – Case 2: with beam

Beam Current I_B

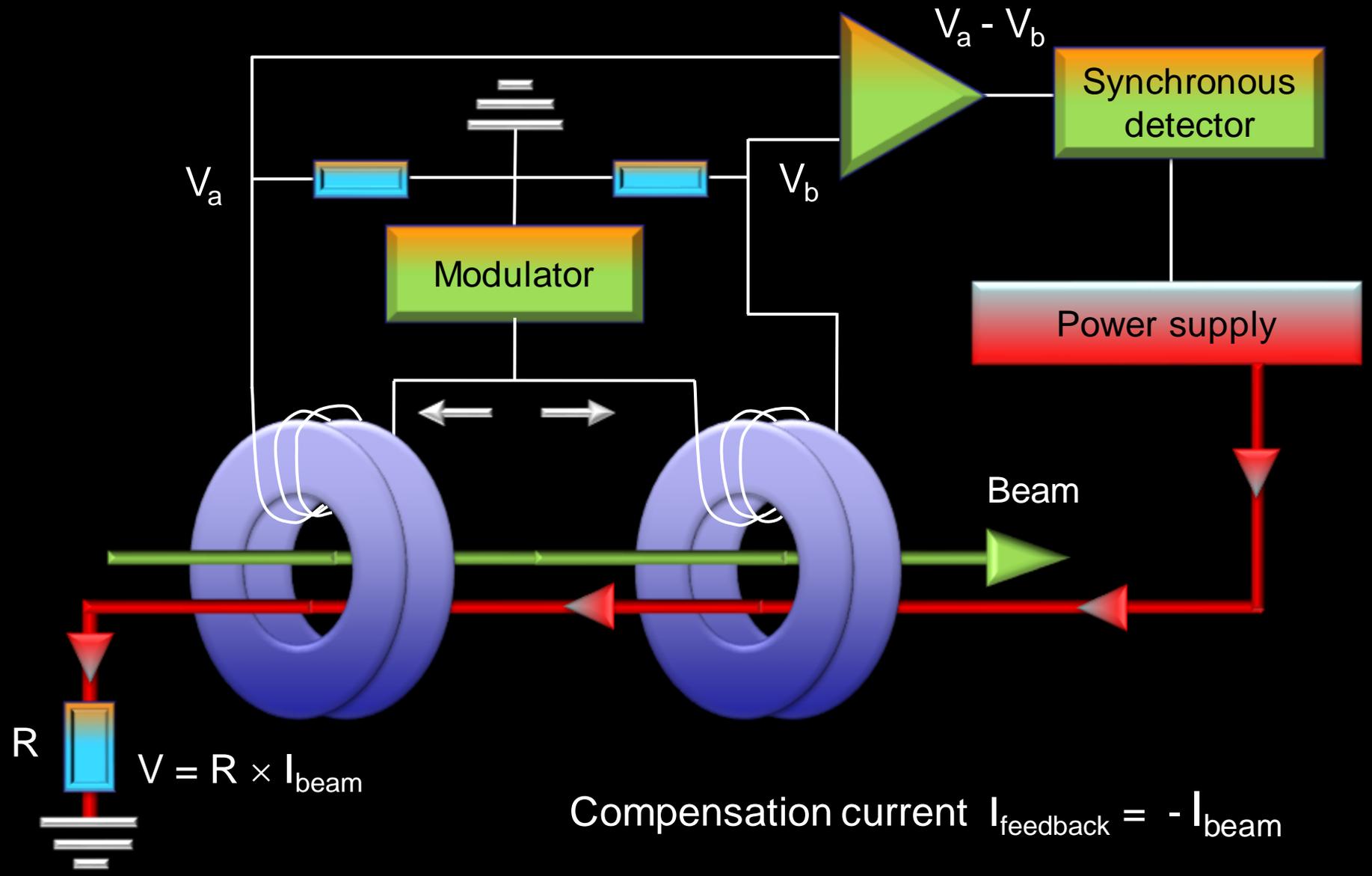


Output signal is at TWICE the modulation frequency

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



Zero Flux DCCT Schematic



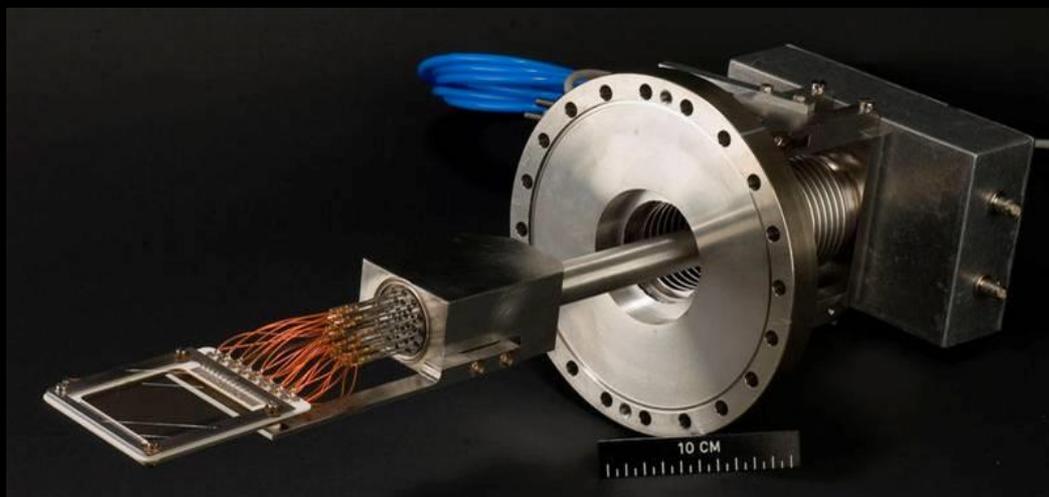
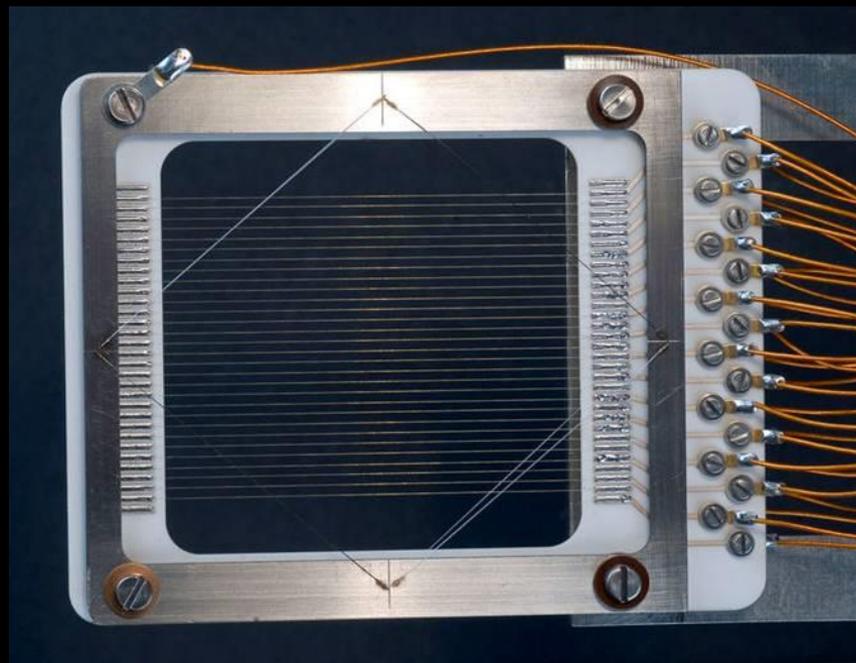


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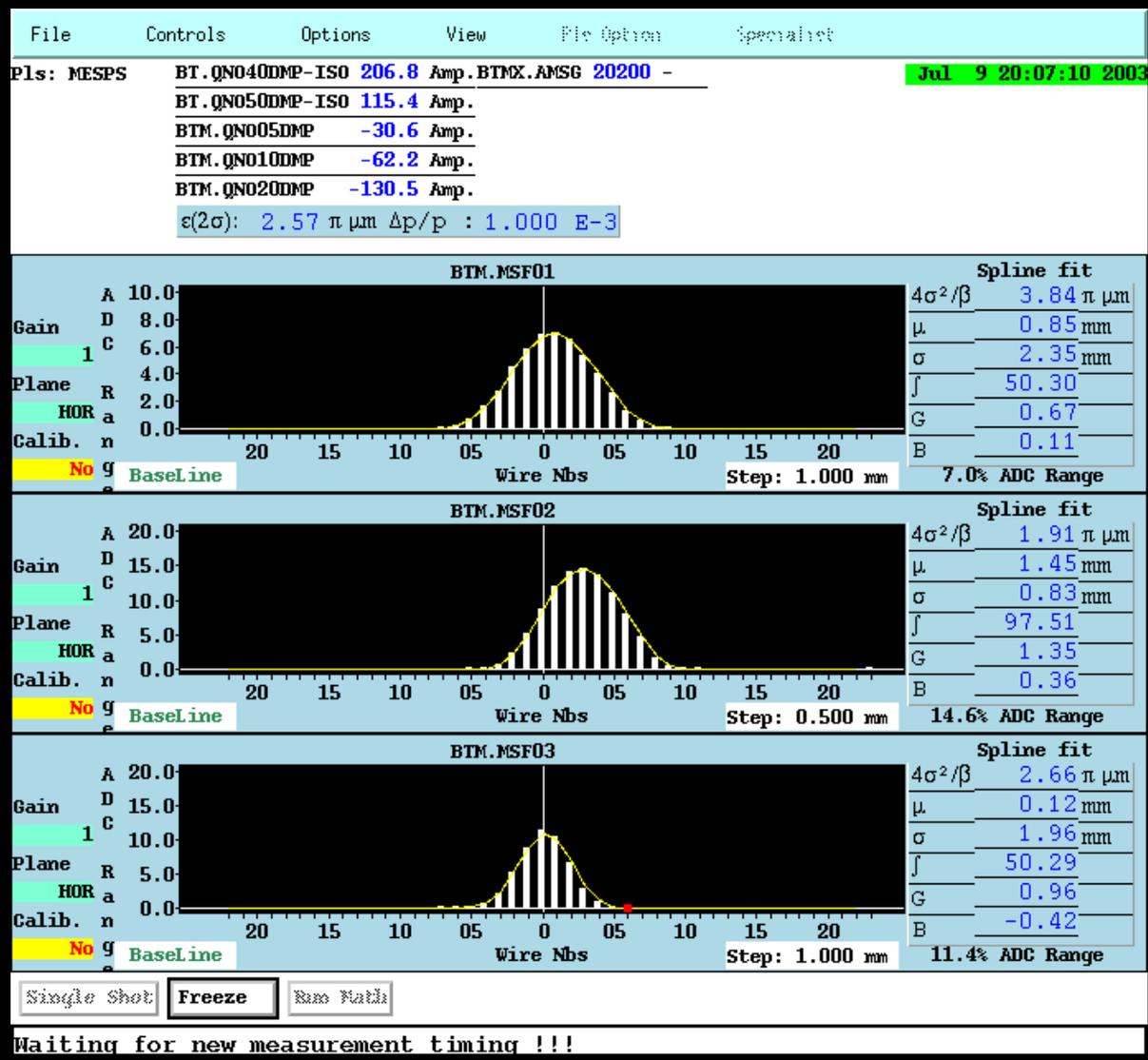
Secondary Emission (SEM) Grids

- 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





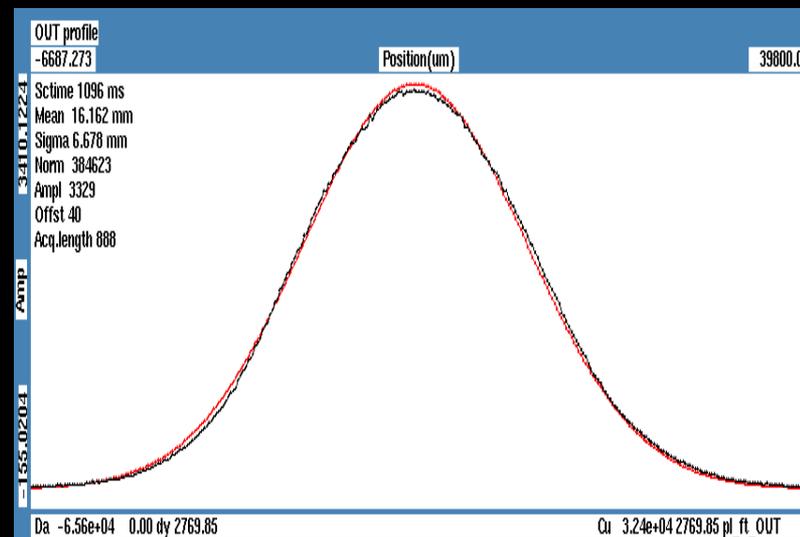
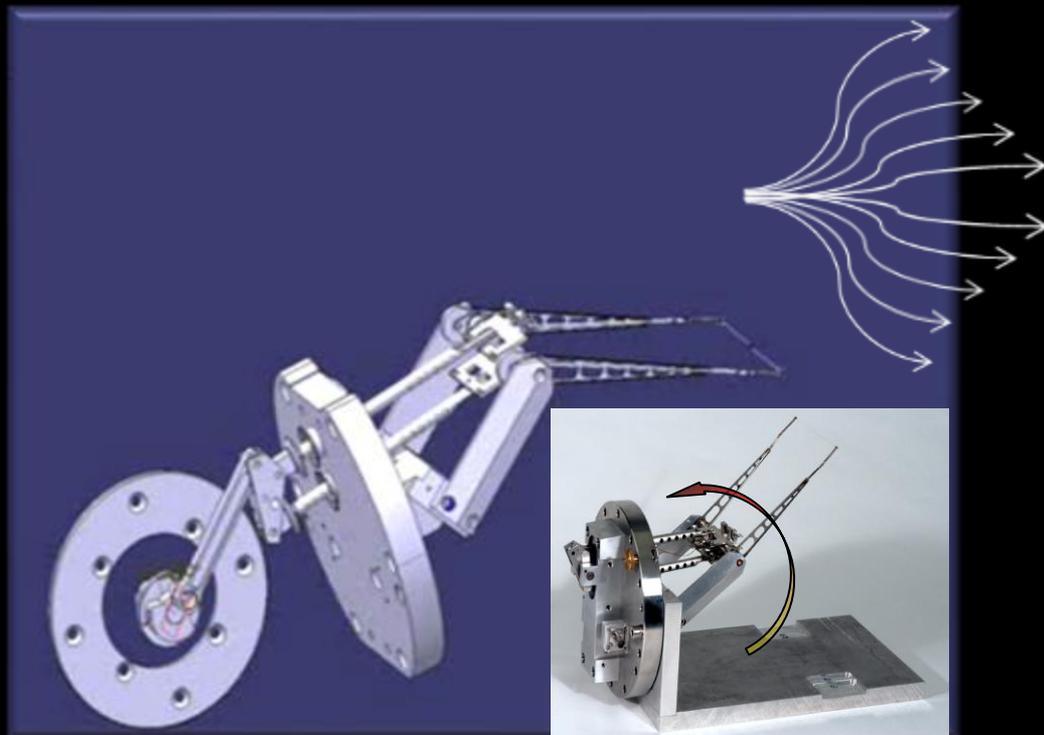
Profiles from SEM grids



- 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

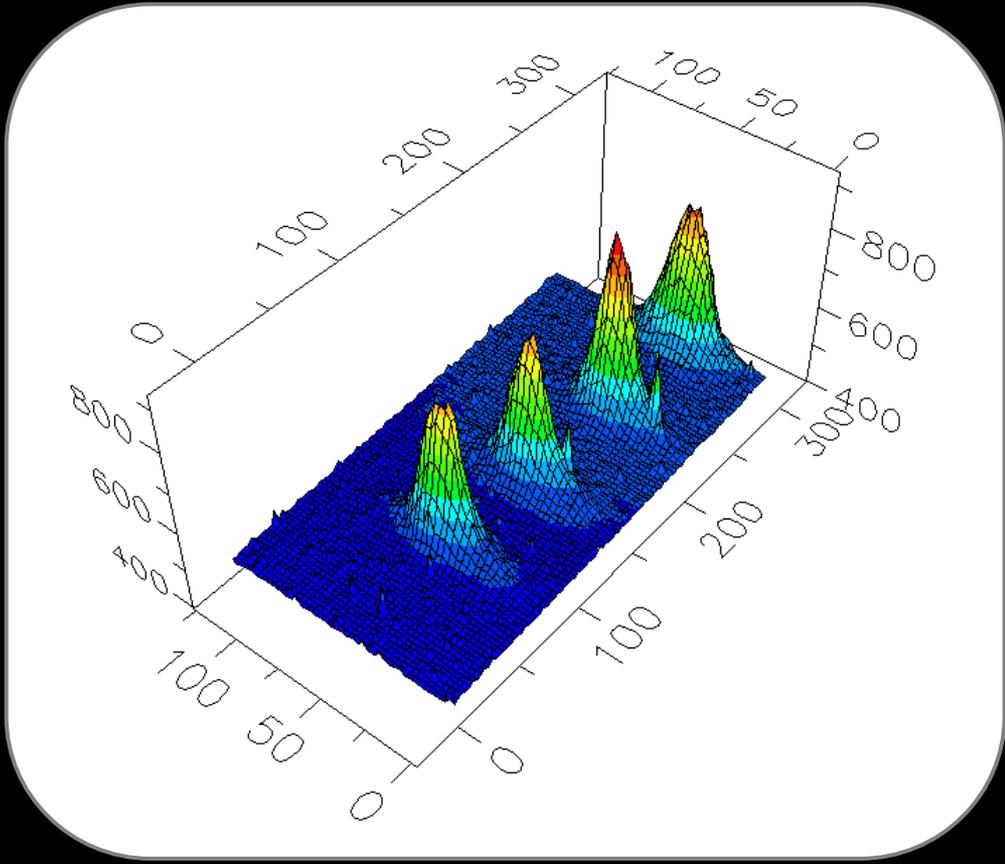
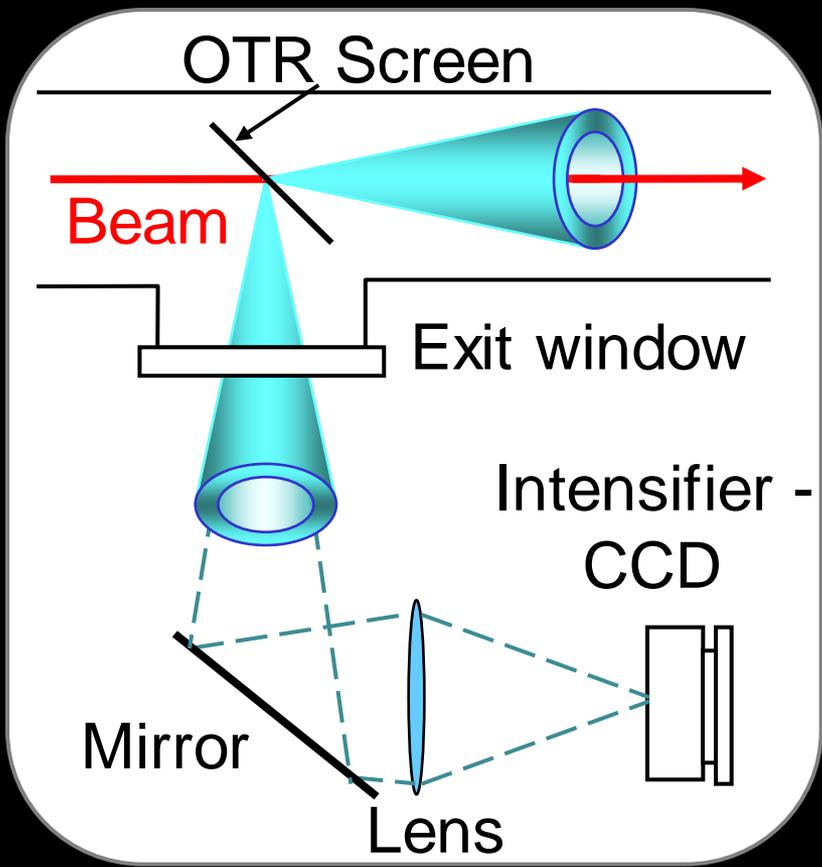
Wire Scanners

- **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 ($\sim 10\mu\text{m}$)



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 $7 \text{ px}/\sigma$

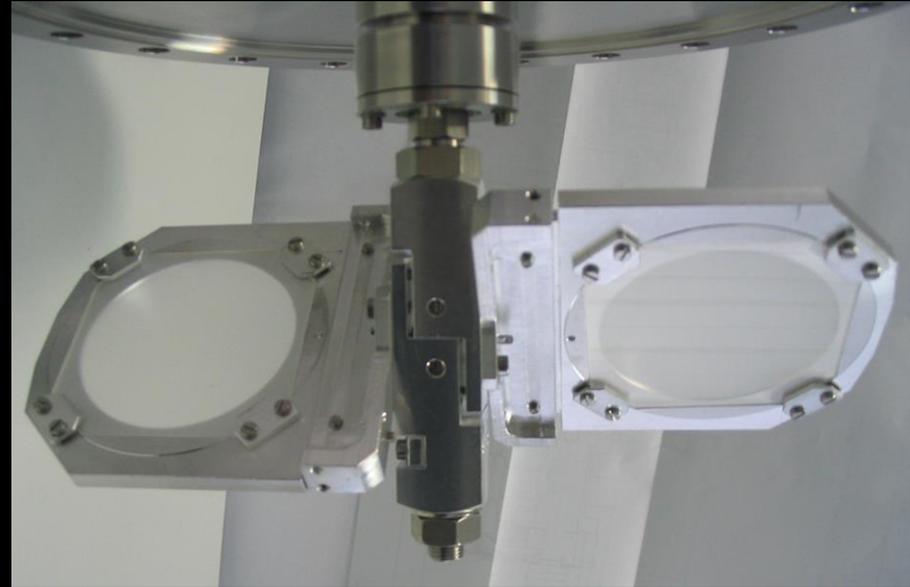
Type	Material	Activator	Sensitivity
Luminesc.	CsI	Tl	$6 \cdot 10^5$
“	Al_2O_3	0.5%Cr	$3 \cdot 10^7$
“	Glass	Ce	$3 \cdot 10^9$
“	Quartz	none	$6 \cdot 10^9$
OTR [bwd]	Al		$2 \cdot 10^{10}$
“	Ti		$2 \cdot 10^{11}$
“	C		$2 \cdot 10^{12}$
Luminesc. GSI	P43: $\text{Gd}_2\text{O}_2 \text{ S}$	Tb	$2 \cdot 10^7$



Beam Profile Monitoring using Screens

- Usual configuration

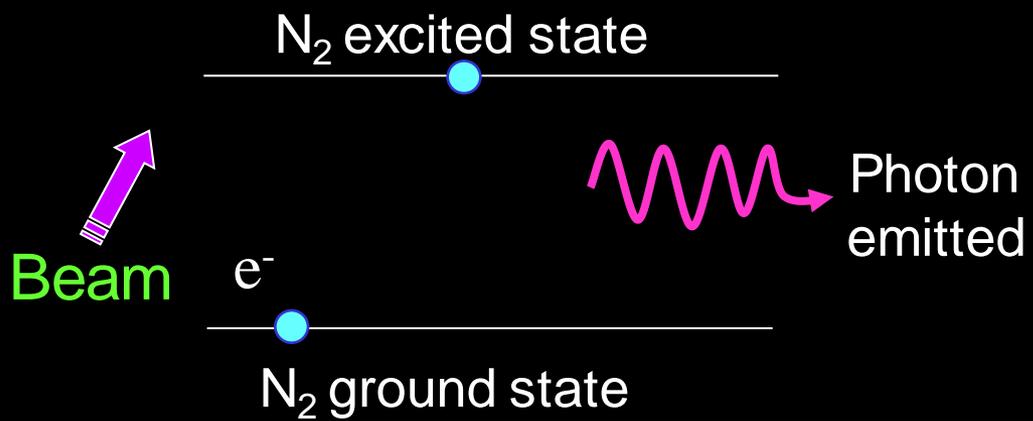
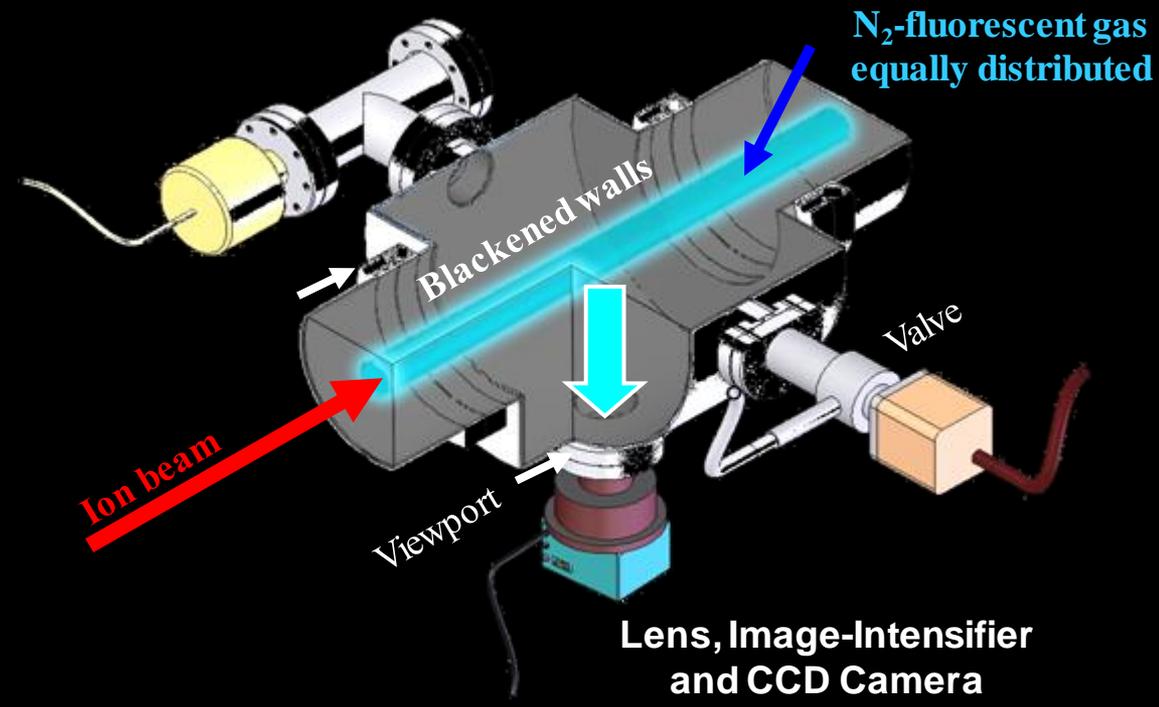
- Combine several screens in one housing e.g.
 - Al_2O_3 luminescent screen for setting-up with low intensity
 - Thin ($\sim 10\mu\text{m}$) Ti OTR screen for high intensity measurements
 - Carbon OTR screen for very high intensity operation



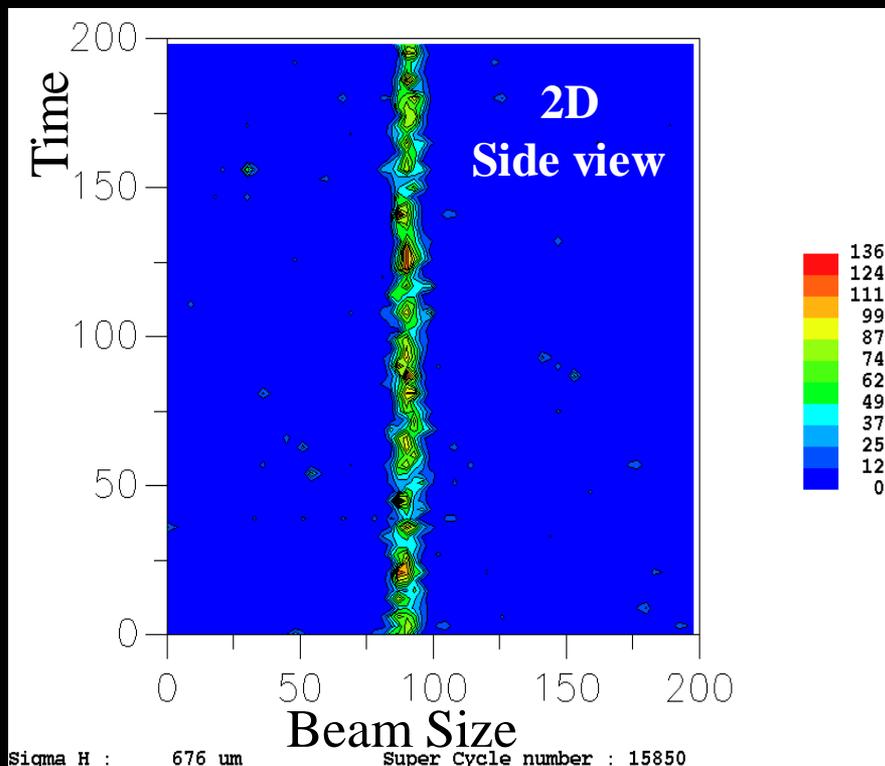
- Advantages compared to SEM grids

- allows analogue camera or CCD acquisition
- gives two dimensional information
- high resolution: $\sim 400 \times 300 = 120'000$ 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

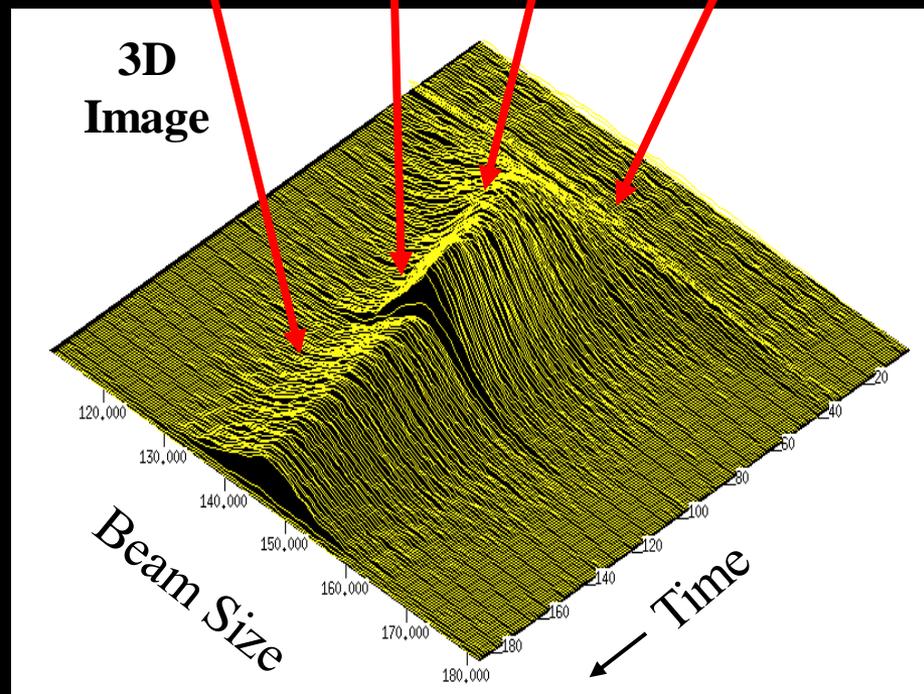


Beam size shrinks as beam is accelerated

Fast extraction

Slow extraction

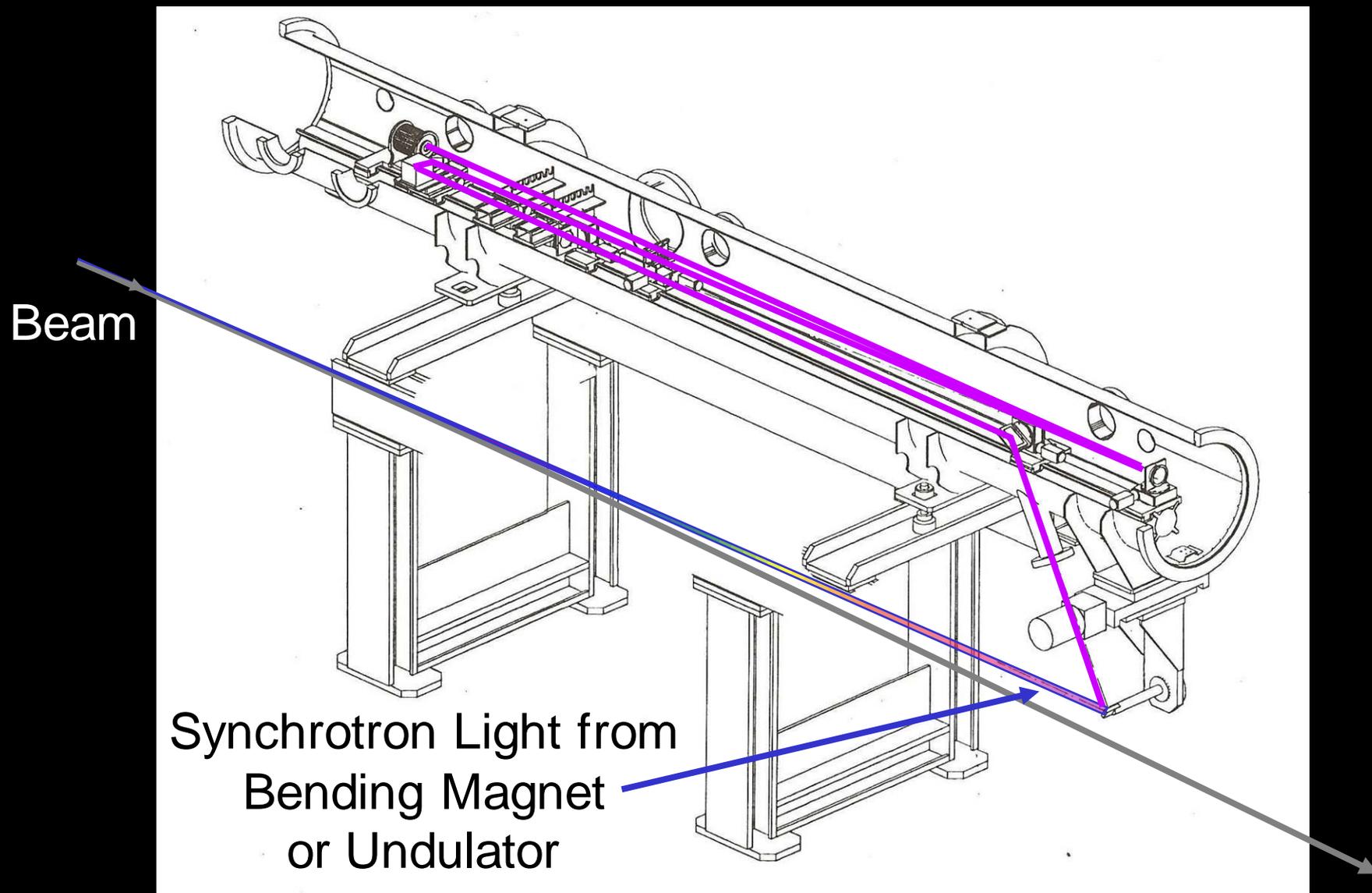
Injection



CERN-SPS Measurements

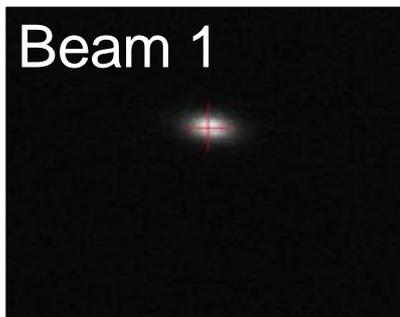
- Profile Collected every 20ms
- Local Pressure at $\sim 5 \times 10^{-7}$ Torr

The Synchrotron Light Monitor

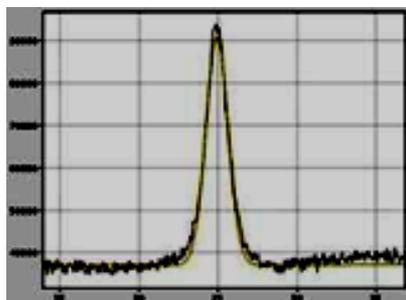


The Synchrotron Light Monitor

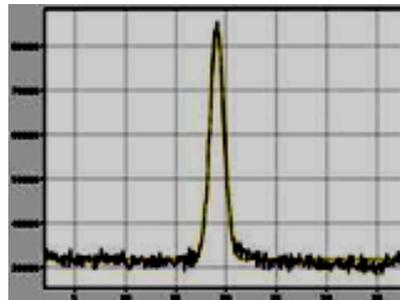
Beam 1



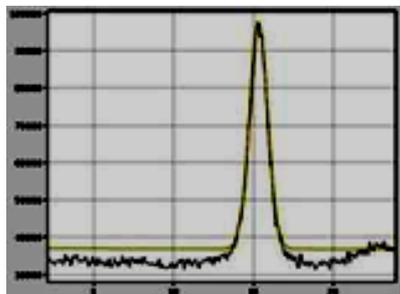
Beam 2



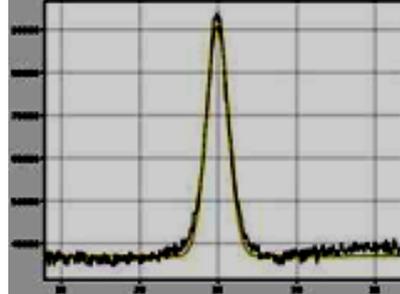
$$\sigma_h = 0.68\text{mm}$$



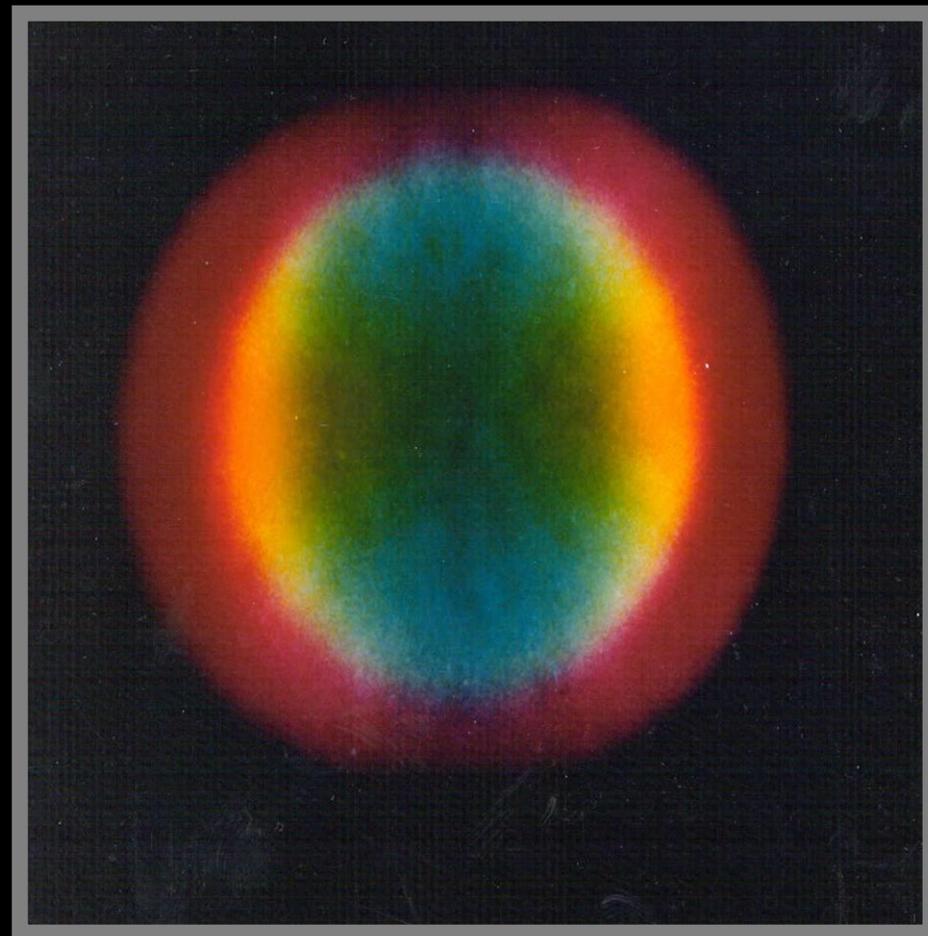
$$\sigma_h = 0.70\text{mm}$$



$$\sigma_v = 0.56\text{mm}$$



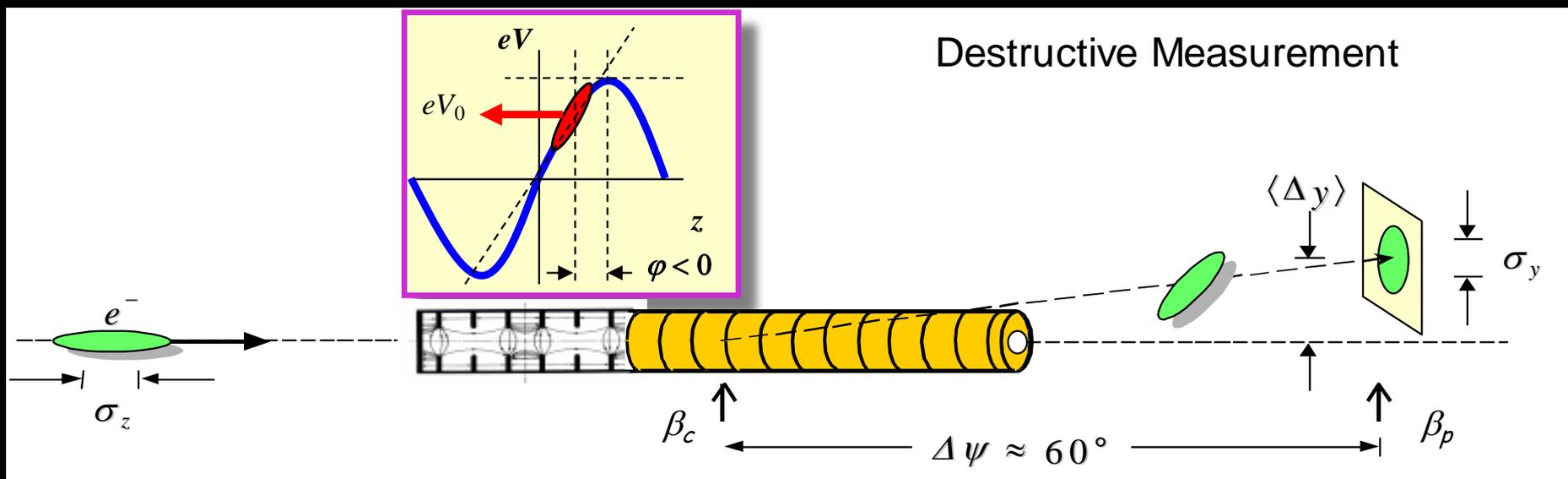
$$\sigma_v = 1.05\text{mm}$$



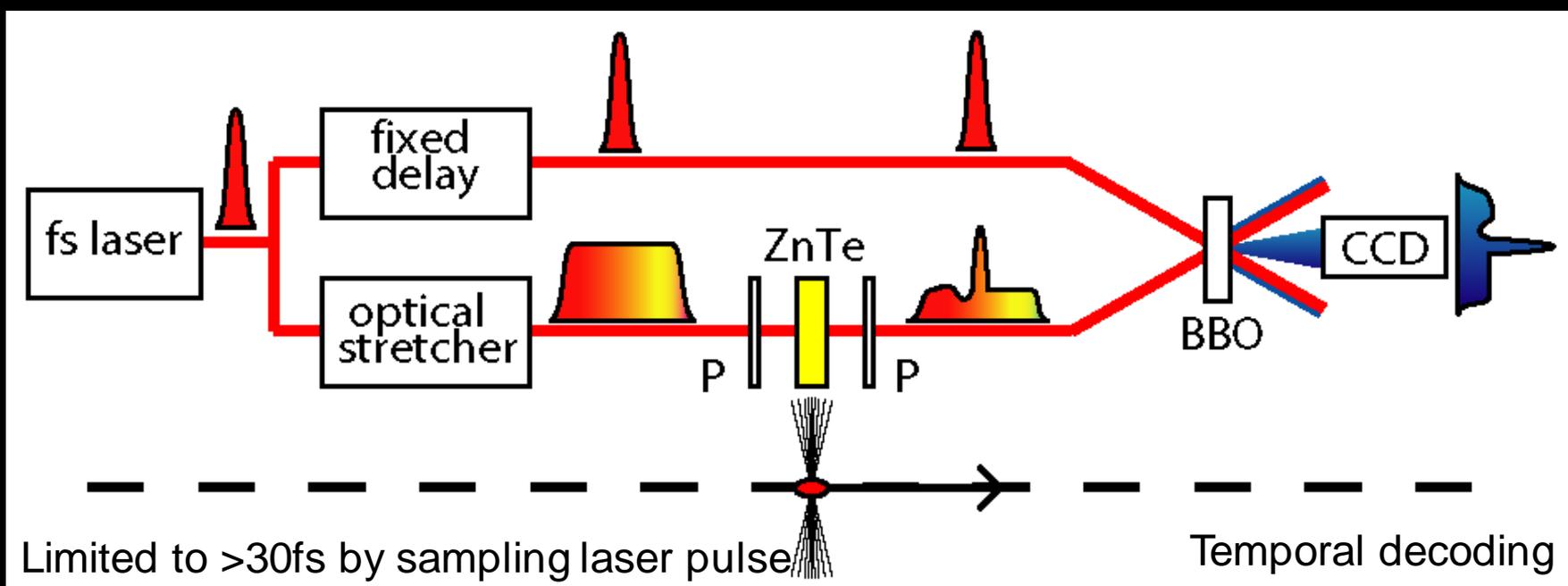
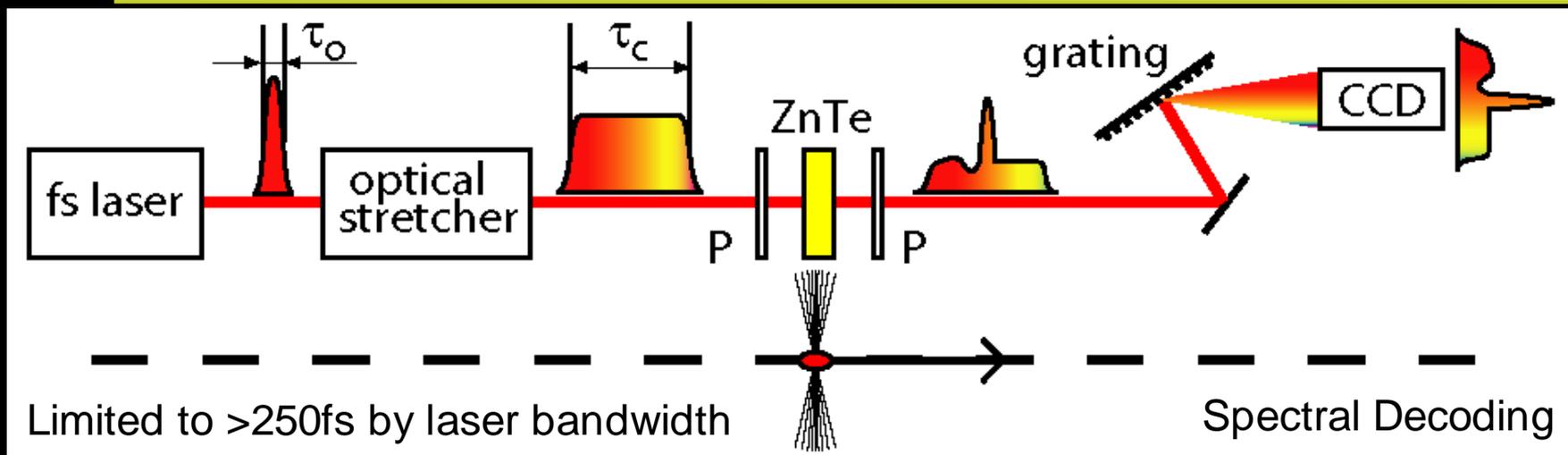
Measuring Ultra Short Bunches

- 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



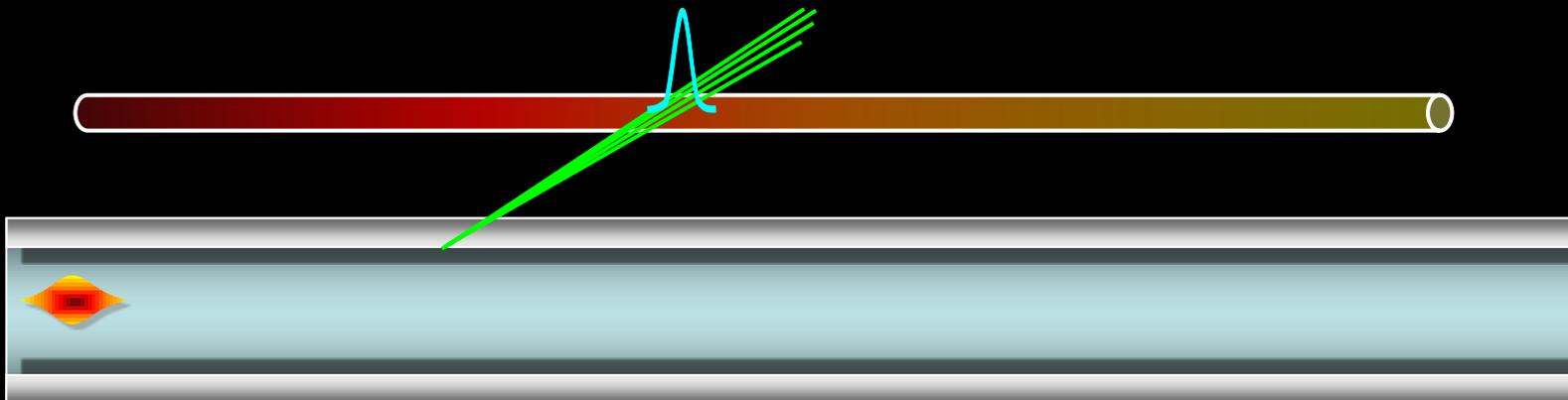


The Typical Instruments

- **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 Chromacities**
 - in diagnostics section of tomorrow
- **Luminosity**
 - in diagnostics section of tomorrow

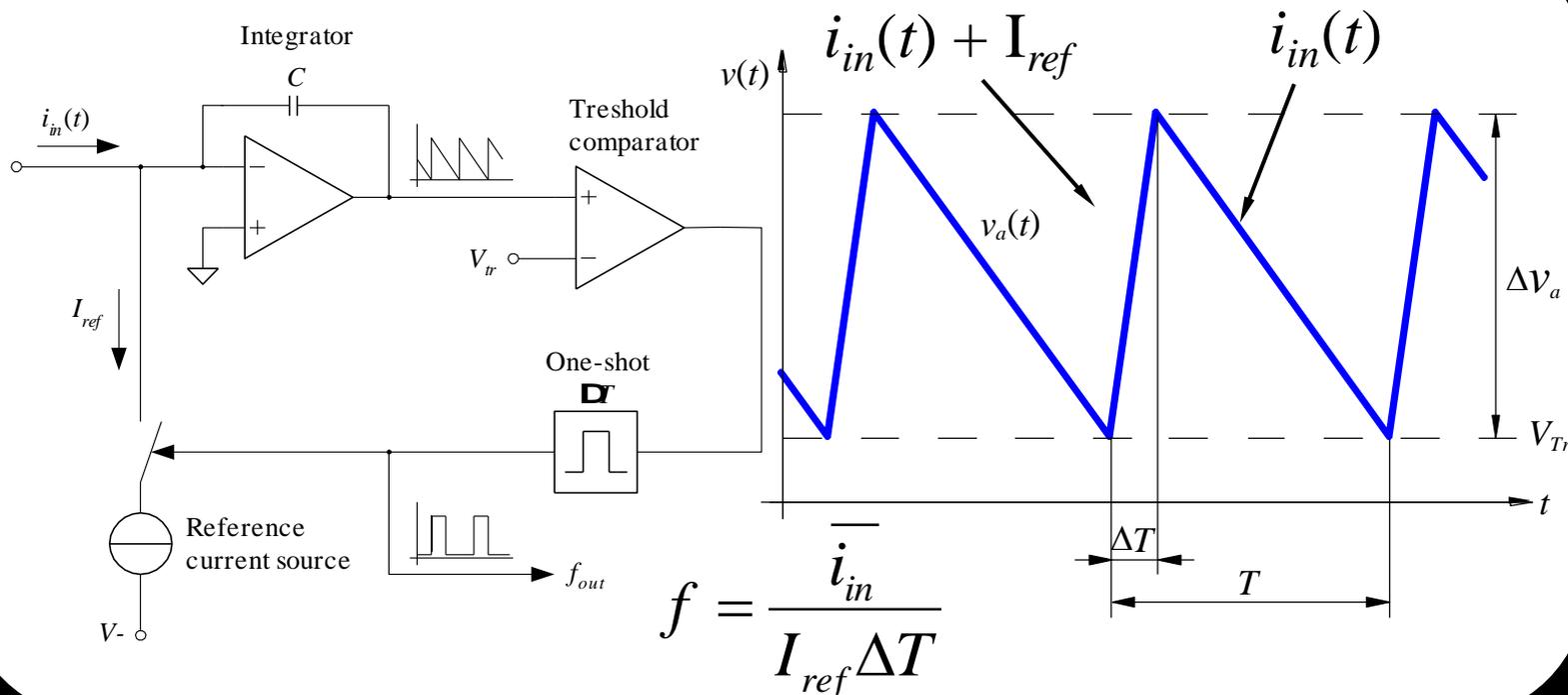
Beam Loss Detectors

- **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

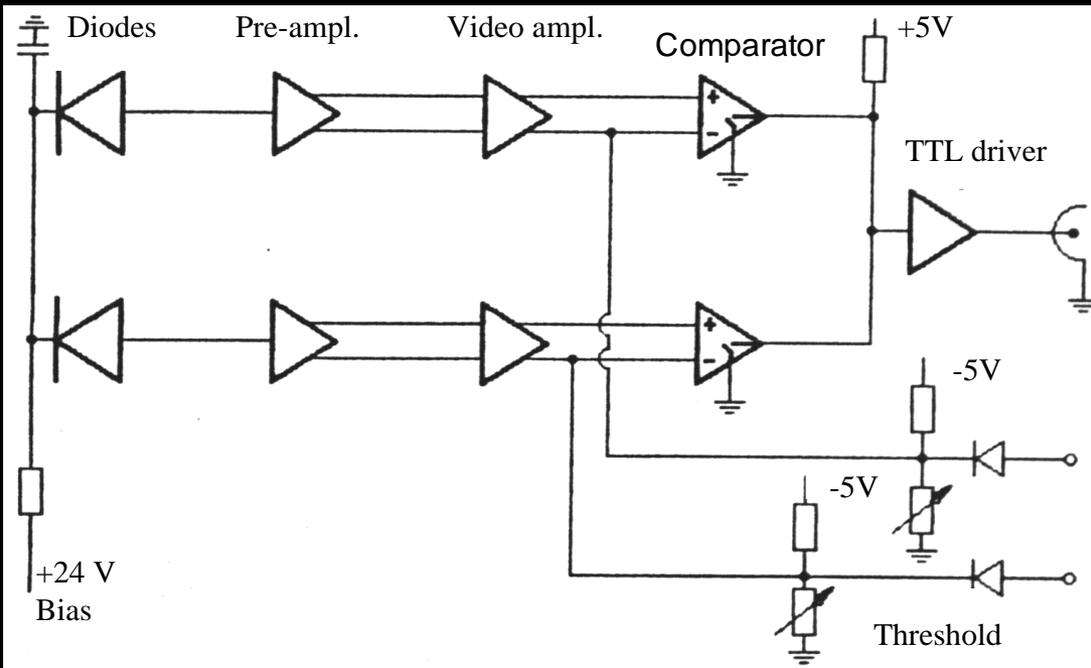
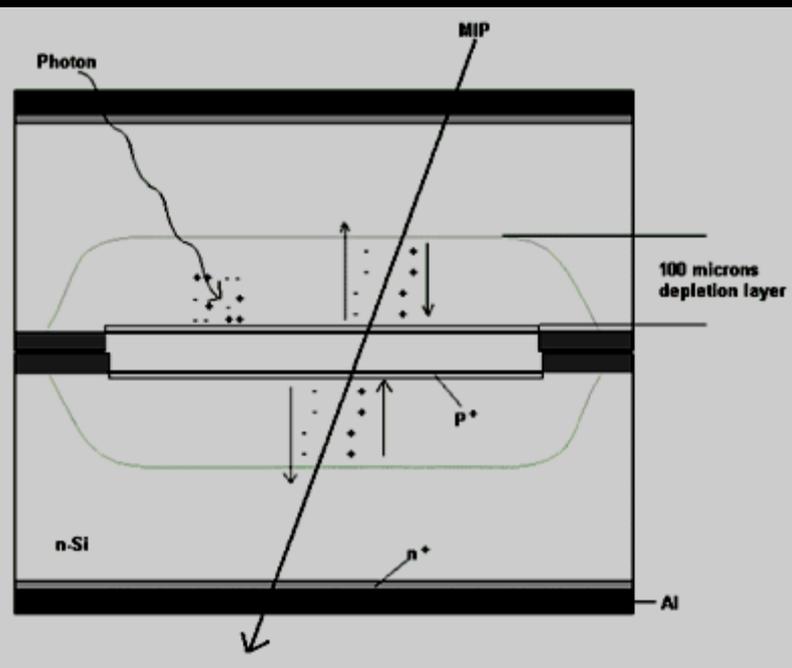
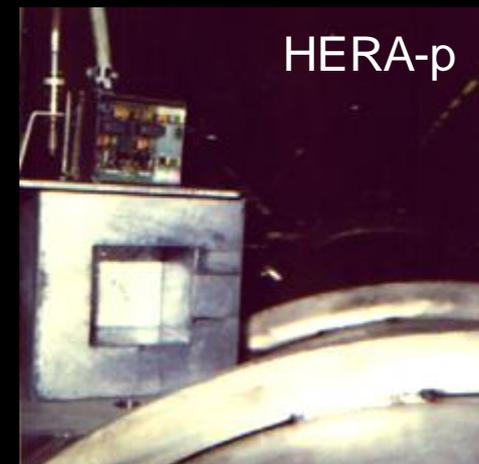
- Common types of monitor (cont)
 - Short ionisation chamber (charge detection)
 - Typically gas filled with many metallic electrodes and kV bias
 - Speed limited by ion collection time - tens of microseconds
 - Dynamic range of up to 10^8



Beam Loss Detectors

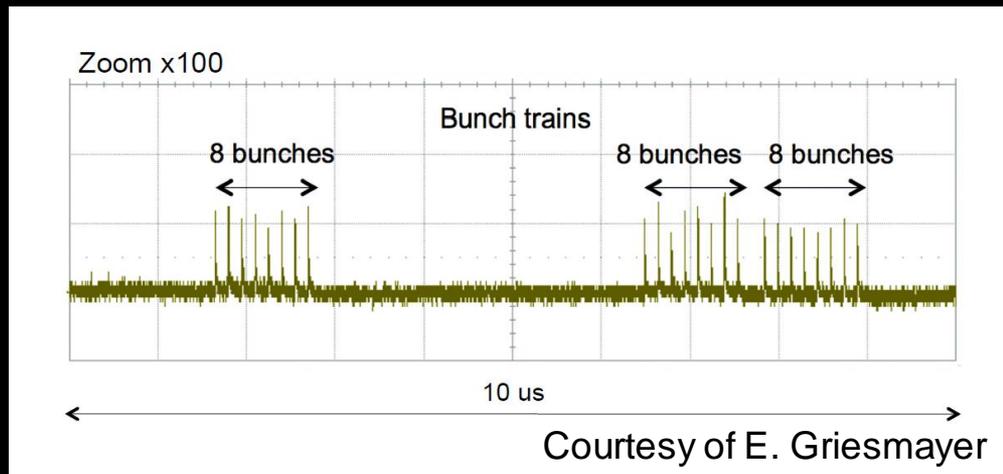
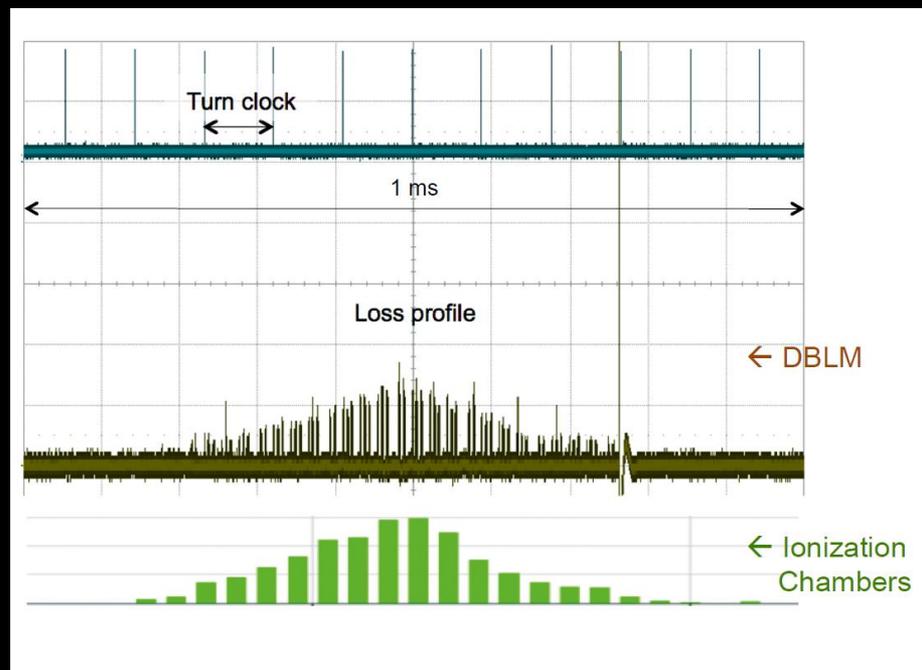
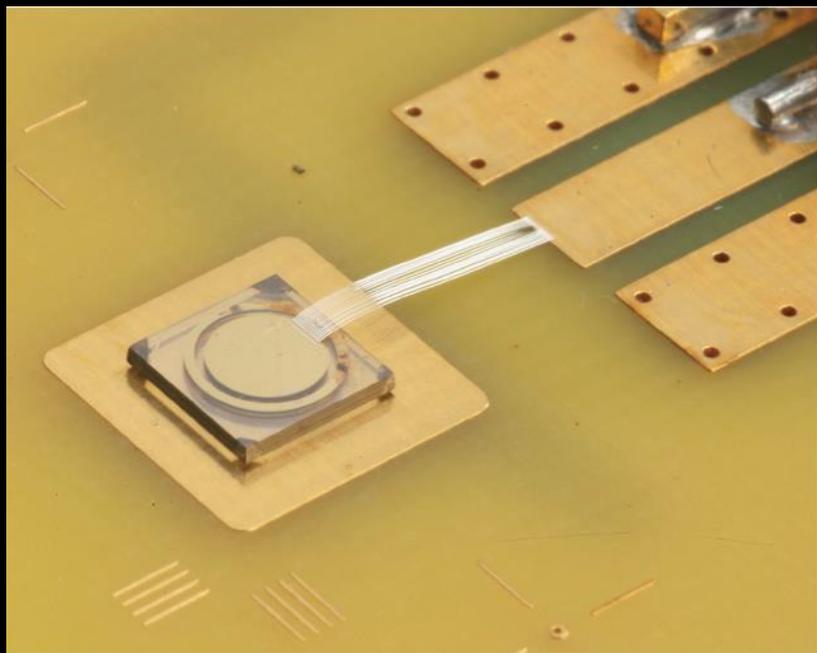
Common types of monitor (cont)

- 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

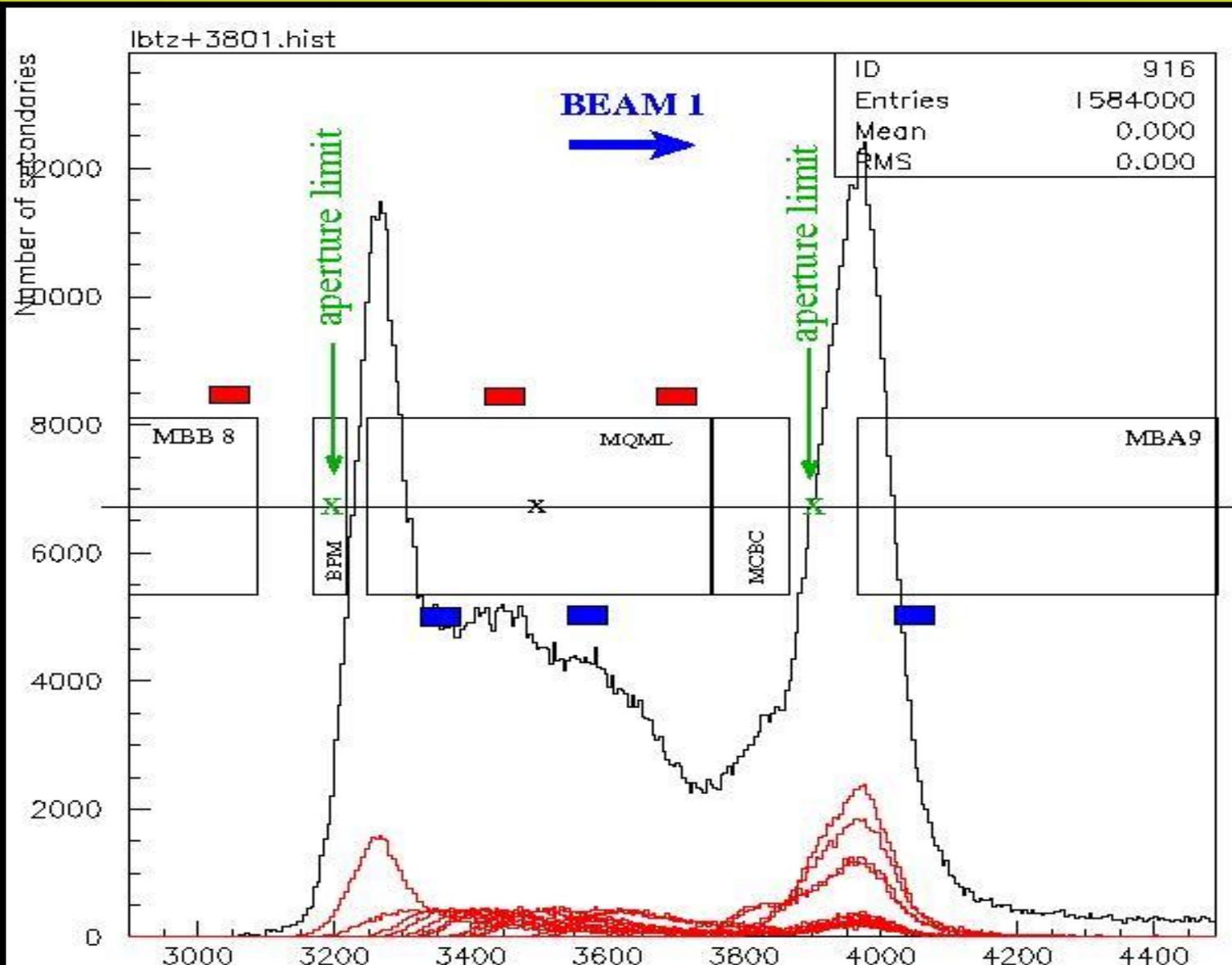


Beam Loss Detectors – New Materials

- **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



BLM Threshold Level Estimation





Summary

- This was an overview of the common types of instruments that can be found in most accelerators
 - Only a small subset of those currently in use or being developed with many exotic instruments tailored for specific accelerator needs existing
- Tomorrow you will see how to use these instruments to run and optimise accelerators
 - Introduction to Accelerator Beam Diagnostics (H. Schmickler)

Join the afternoon course:

- Beam Instrumentation & Diagnostics
 - For an in-depth analysis of all these instruments and on their application in various accelerators