Introduction to Beam Instrumentation

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An accelerator can never be better than the instruments measuring its performance!

- A Beam Diagnostics and Instrumentation activity
  - Designs & builds
  - Maintains & improves

  the diagnostic instruments that allow the observation of particle beams with the precision required to diagnose, tune, operate and improve an accelerator and its associated transfer lines.

- Beam Instrumentation combines the disciplines of:
  - accelerator physics
  - mechanical engineering
  - electronic engineering
  - software engineering.

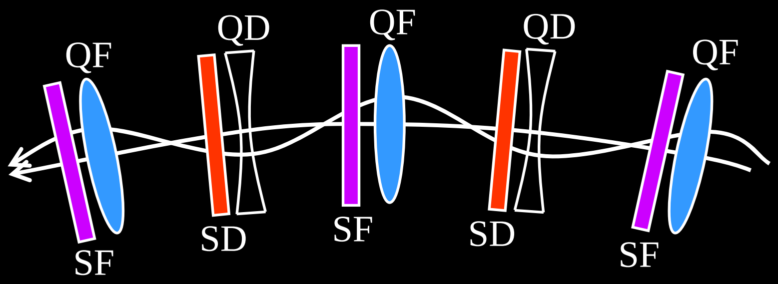
In Short: A fascinating field of work

Introduction

- What do we mean by beam instrumentation?
  - The "eyes" of the machine operators
    - i.e. the instruments that observe beam behaviour
- What beam parameters do we measure?
  - Beam Position
    - Horizontal and vertical throughout the accelerator
    - Corrected using orbit corrector magnets (dipoles)
  - Beam Intensity (& lifetime measurement for a storage ring/collider)
    - bunch-by-bunch charge and 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

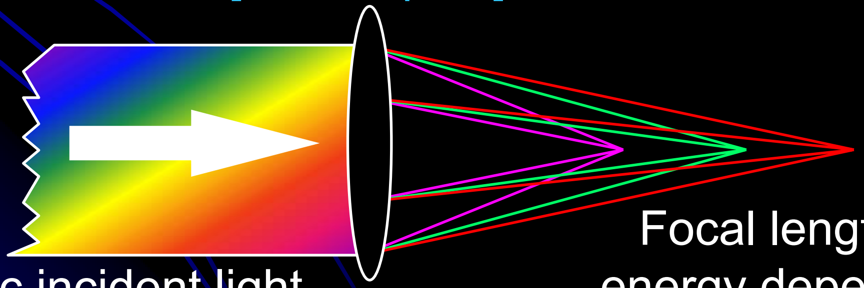


Characteristic Frequency of the Magnet Lattice

Given by the strength of the Quadrupole magnets

- Machine Chromaticity

Optics Analogy:



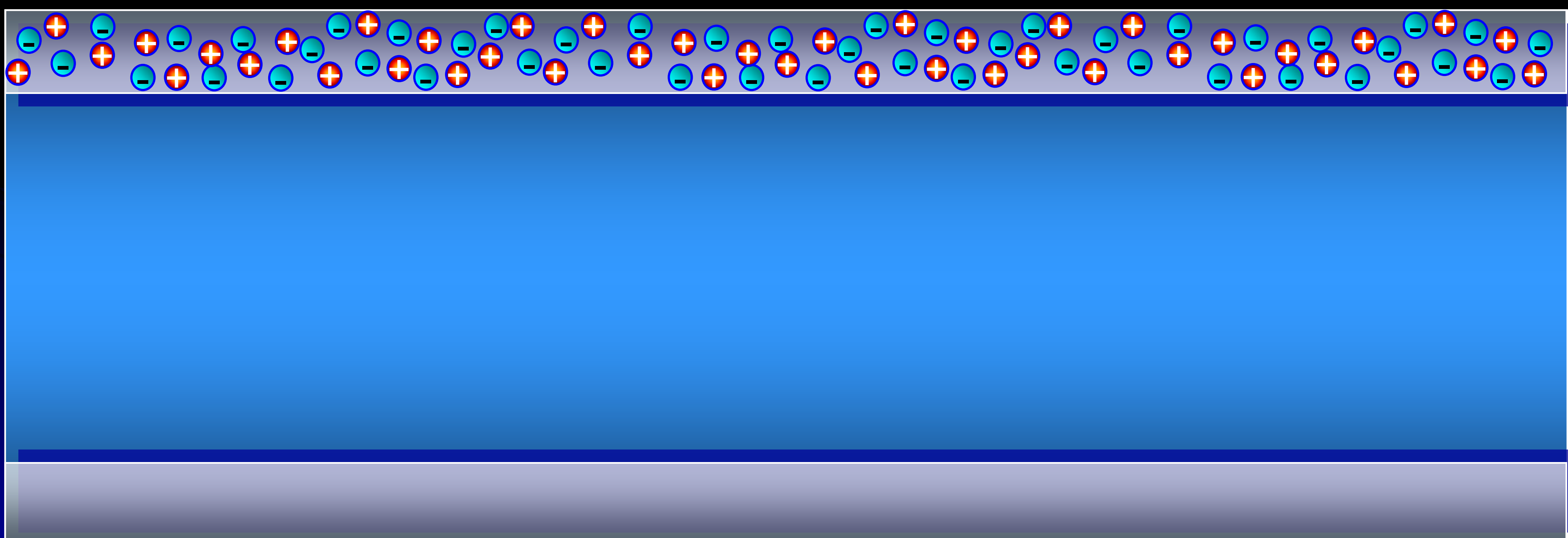
Spread in the Machine Tune due to Particle Energy Spread

Controlled by Sextupole magnets

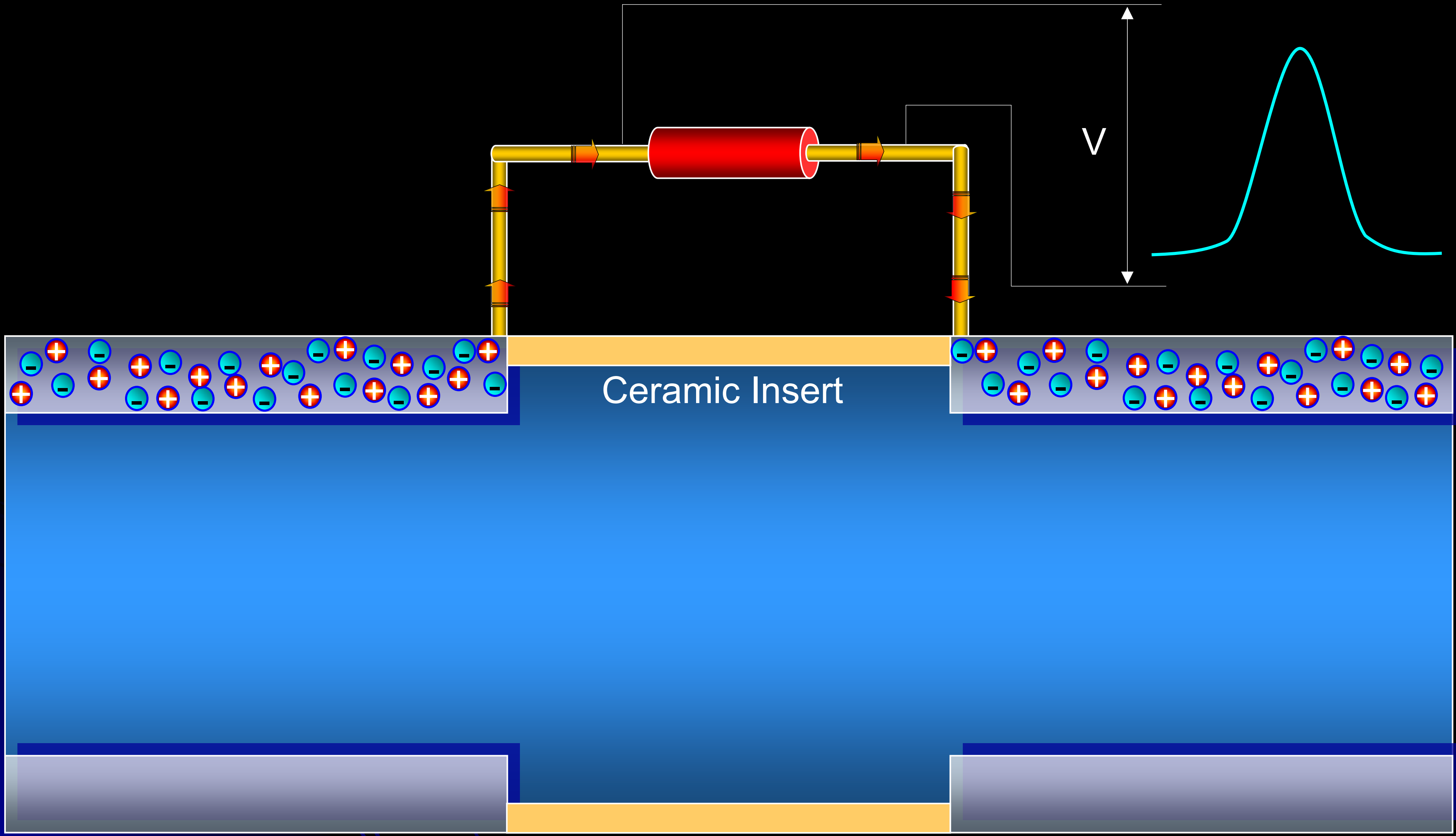
The Typical Instruments

- 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 (afternoon course)
- Beam Loss
  - ionisation chambers or pin diodes
- Machine Tune and Chromaticity
  - in diagnostics section of tomorrow
- Luminosity
  - in diagnostics section of tomorrow

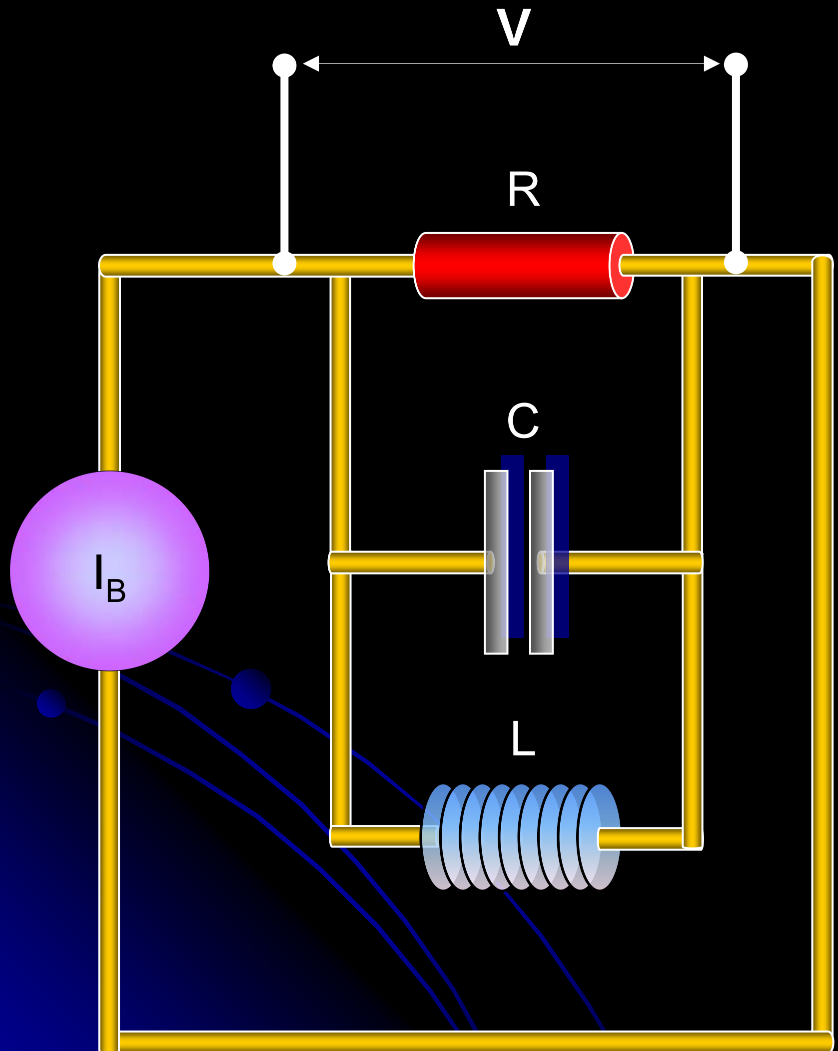
Measuring Beam Position – The Principle

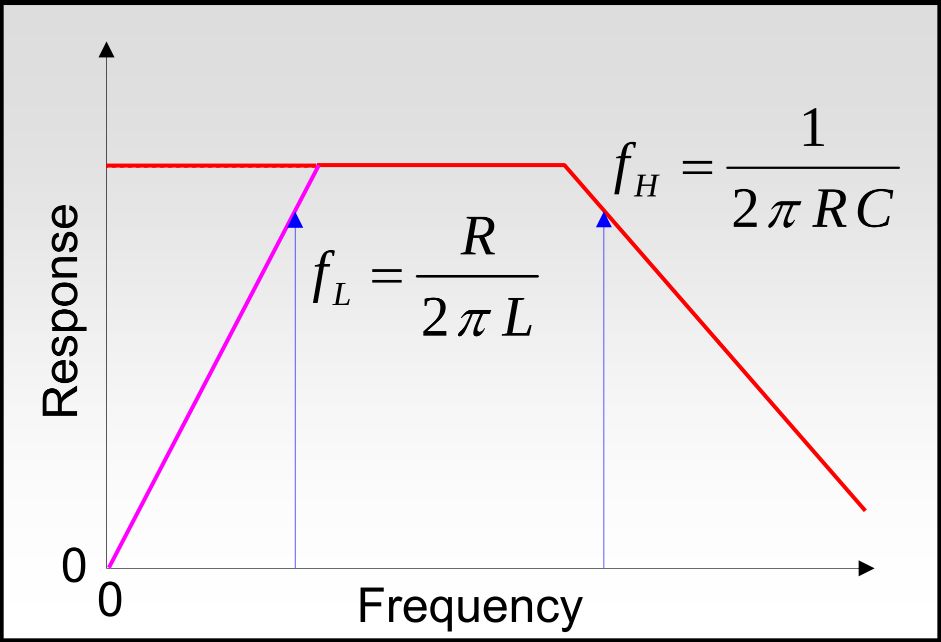


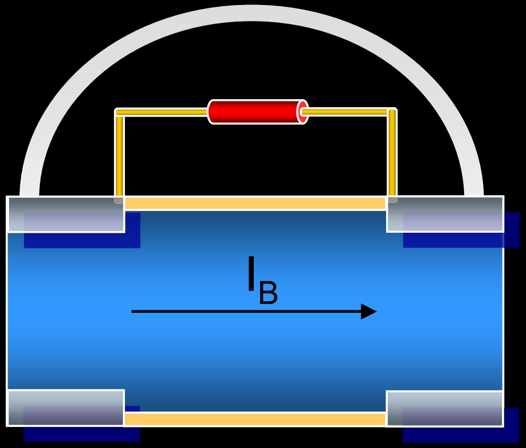
Wall Current Monitor – The Principle



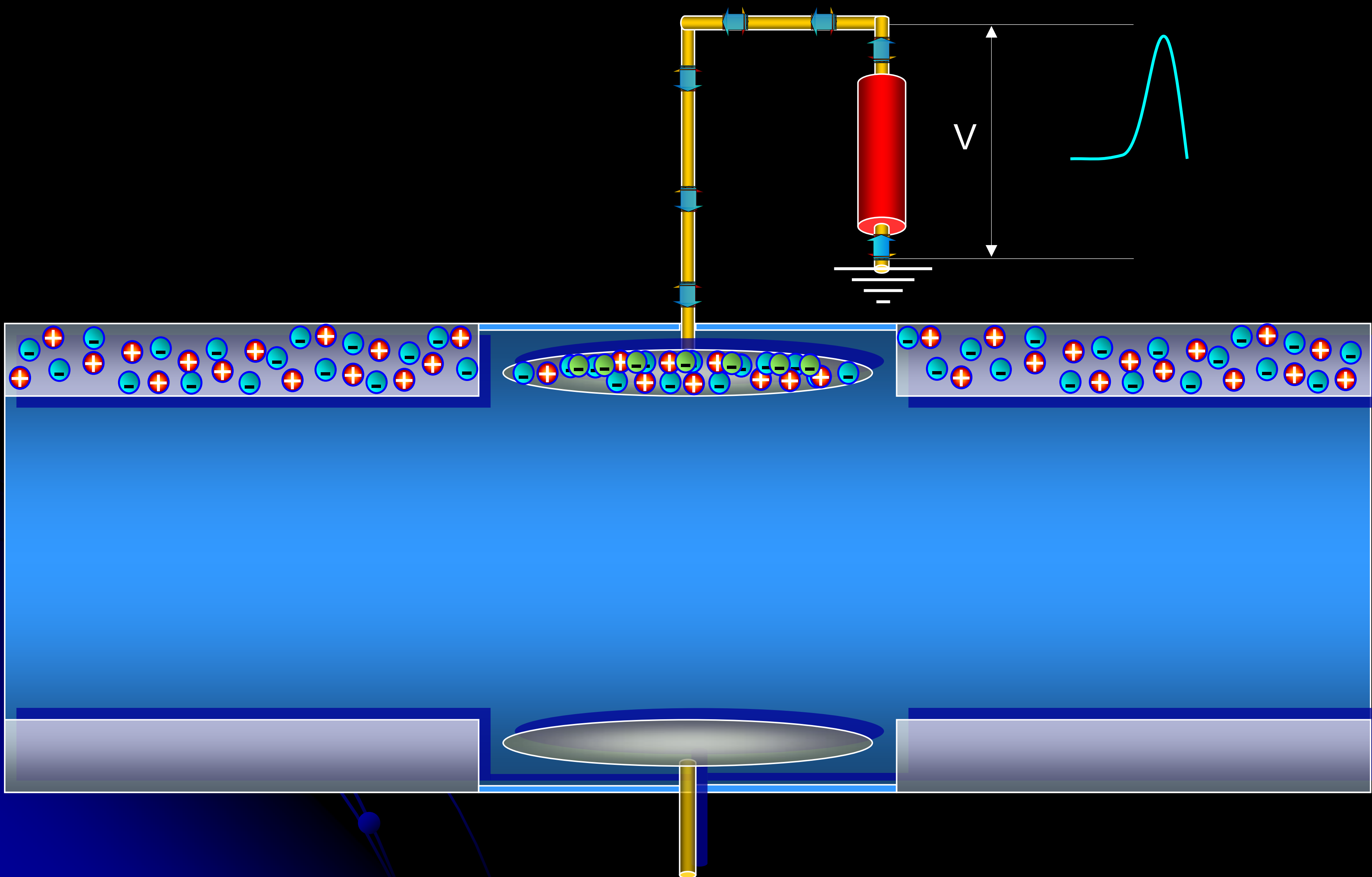
Wall Current Monitor – Beam Response



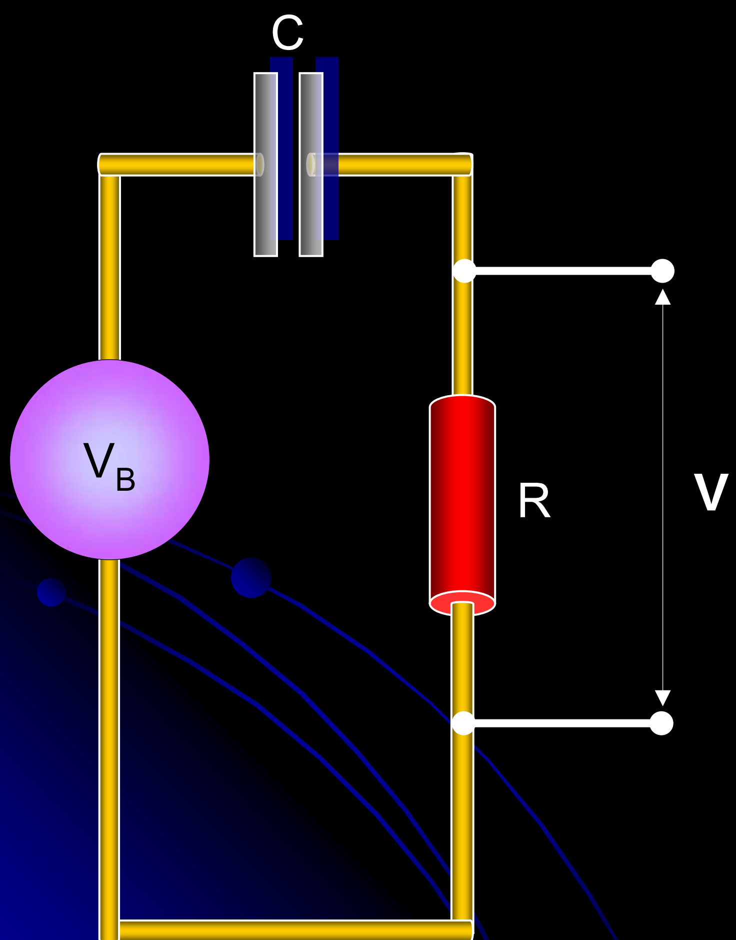


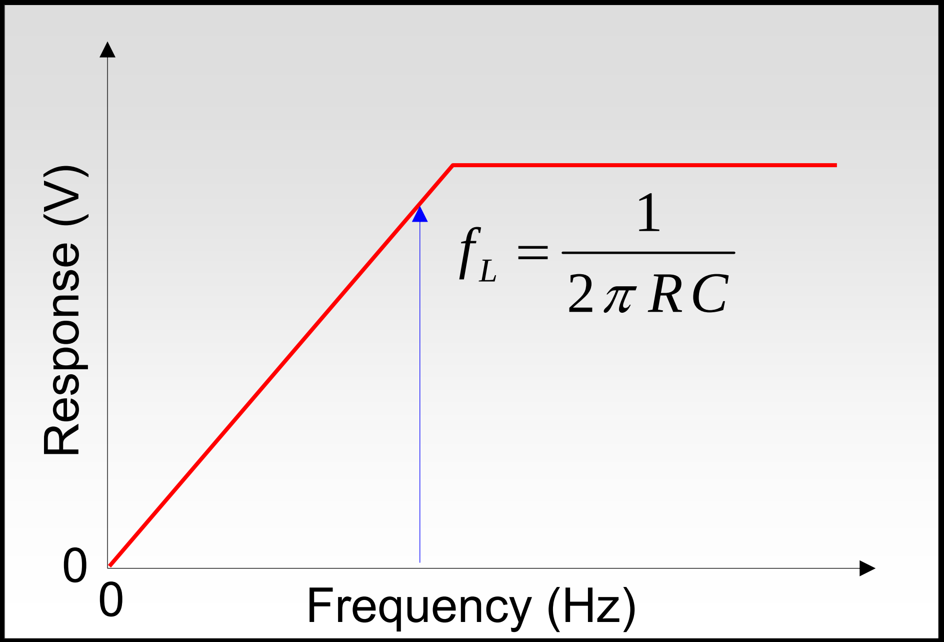


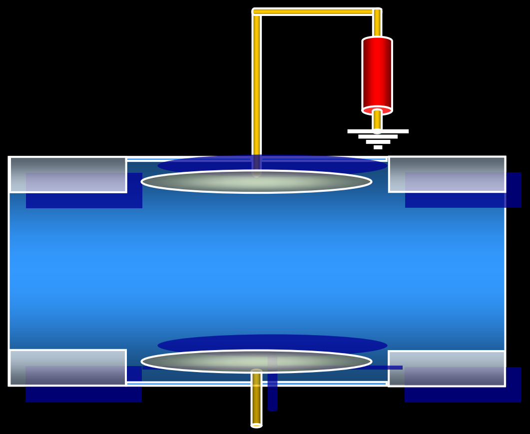
Electrostatic Monitor – The Principle



Electrostatic Monitor – Beam Response

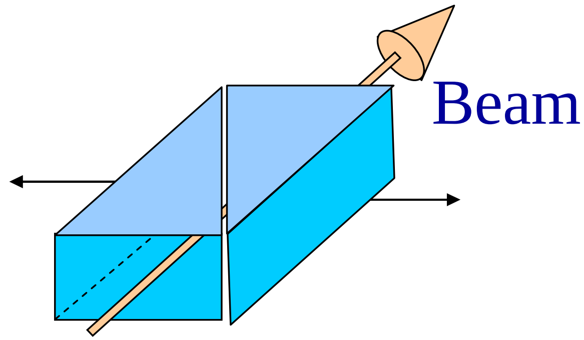


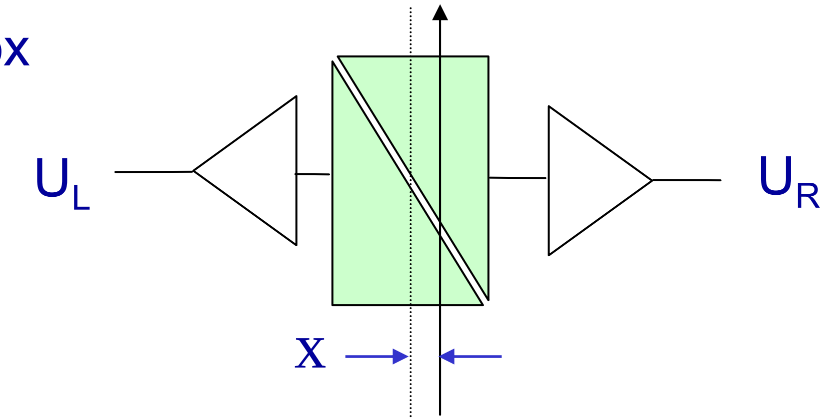




Electrostatic Pick-up – Shoebox

Linear cut through a shoebox





Linear Response across the aperture

$$x \propto \frac{U_L - U_R}{U_L + U_R} = \frac{\Delta}{\Sigma}$$

Same principle applied to a cylindrical pick-up

- The cuts can be made by photo-chemical or mechanical means
  - Here done with a sand-blasting device

Electrostatic Pick-up – Button

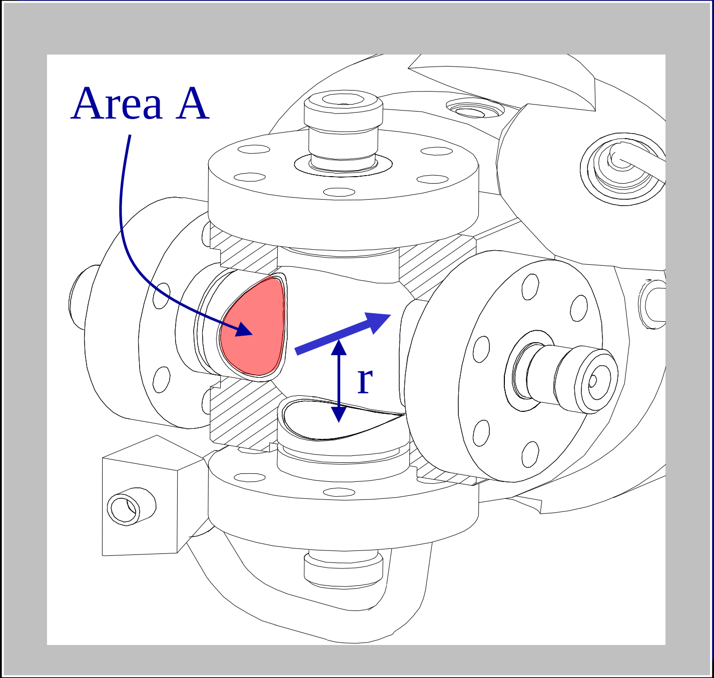
- ✓ Variant of electrostatic PU
- ✓ Low cost ⇒ most popular
- ✗ Non-linear
  - requires correction algorithm when beam is off-centre

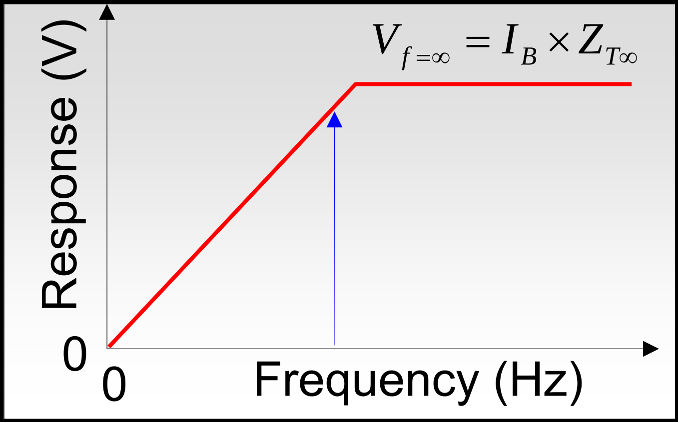
Transfer Impedance:

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

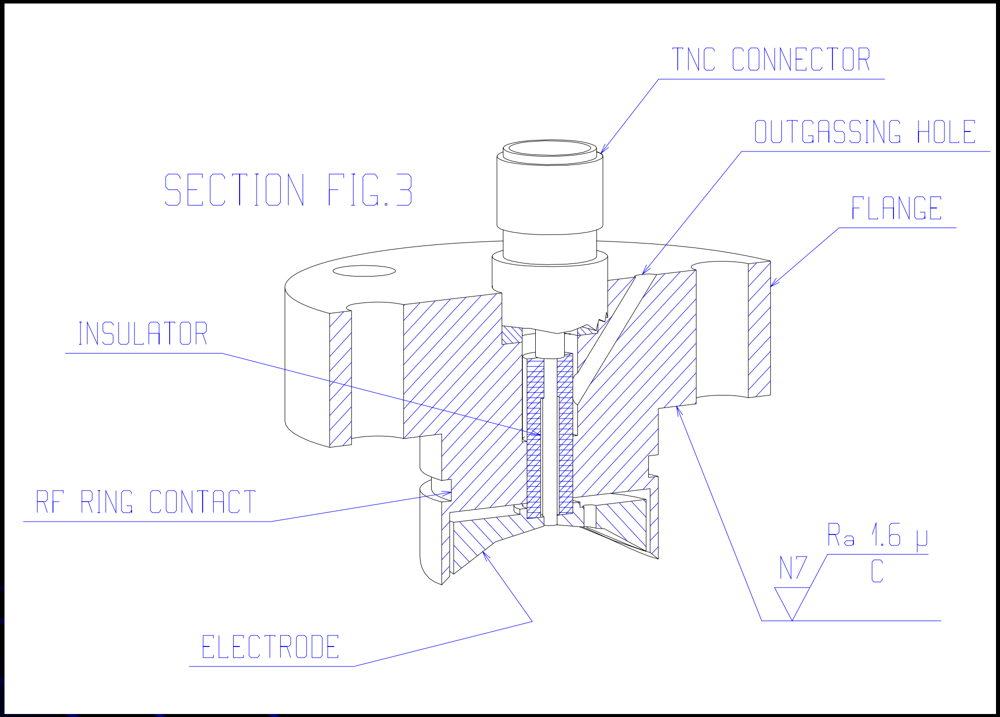
Low frequency cut-off:

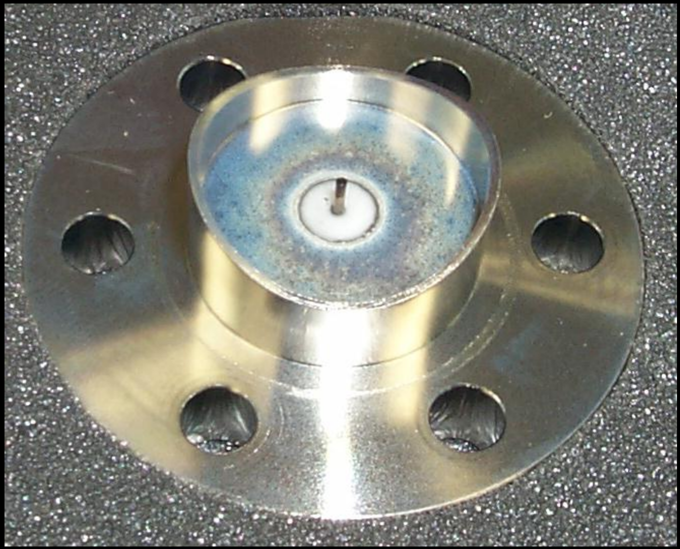
$$f_L = \frac{1}{2\pi RC}$$





What does a real (LHC) electrostatic button monitor look like?

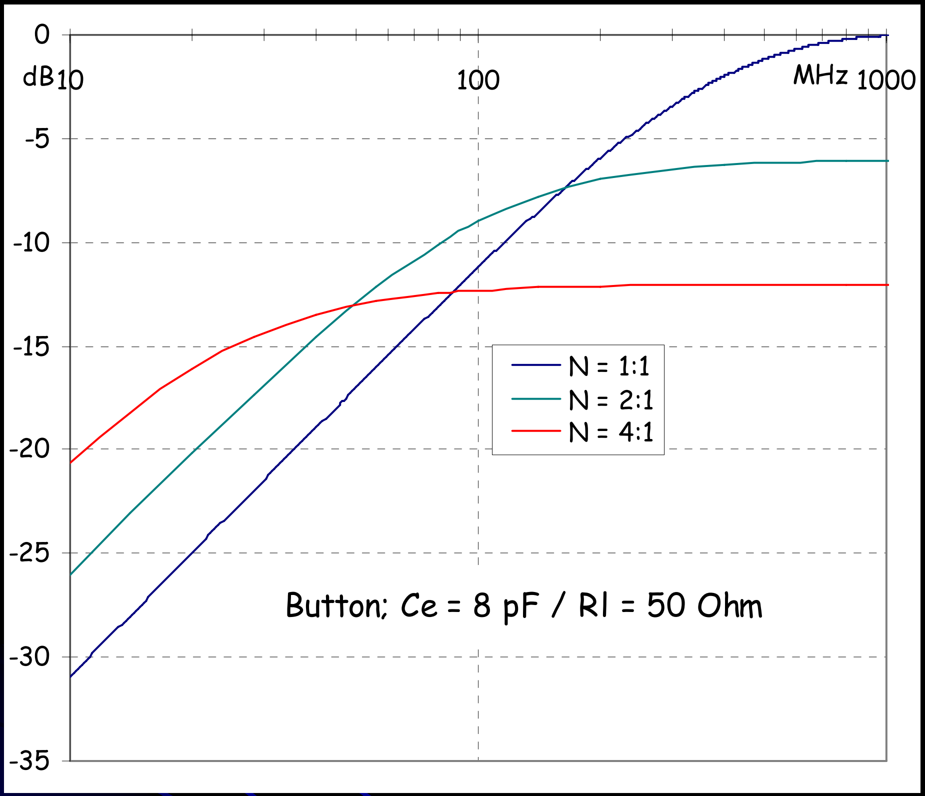


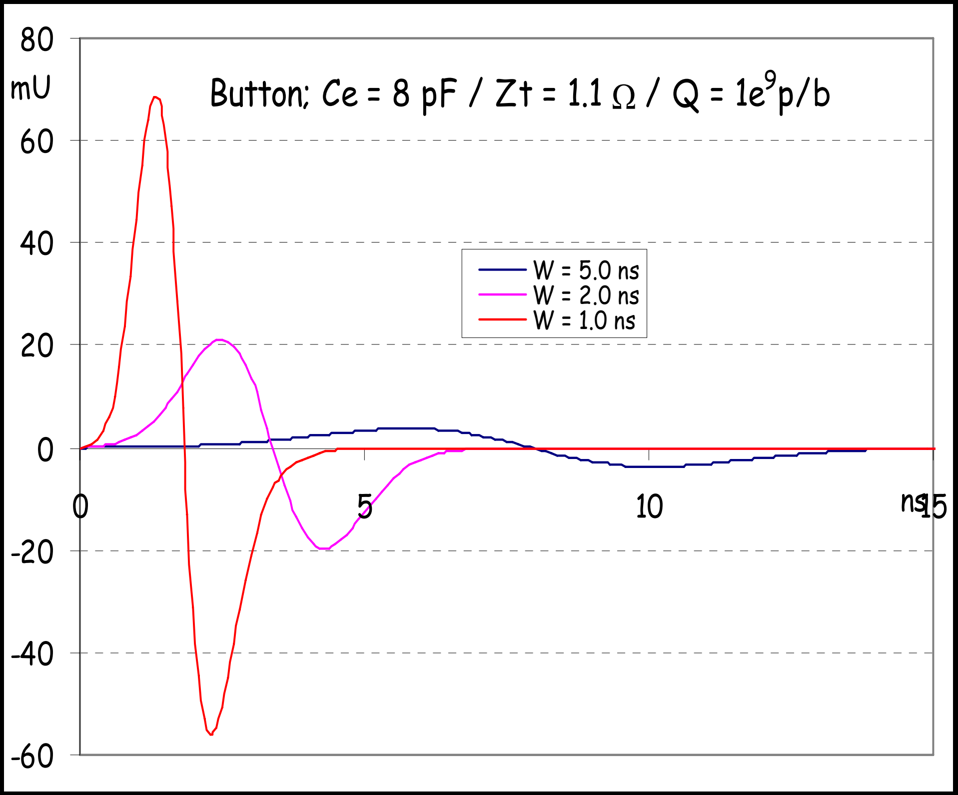


$$Z_{T\infty} = \frac{A}{(2\pi r)\times c\times C_e} = \frac{\pi\times(12mm)^2}{(2\pi\times 24.5mm)\times c\times(8pF)} = 1.2\Omega$$

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

Button Frequency & Time Response



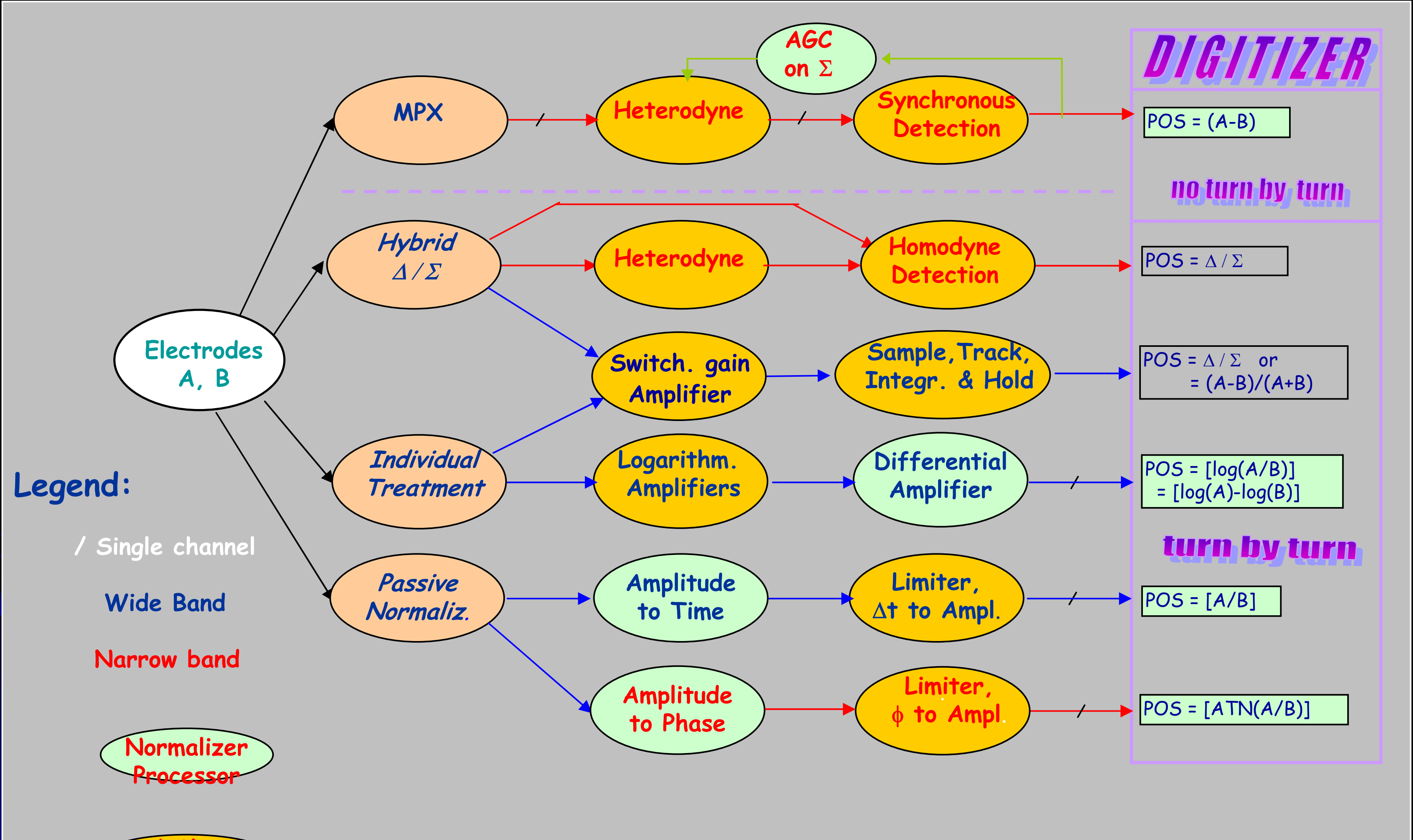


- Frequency domain:
  - Impedance transformers improve the low frequency levels at the expense of the high frequency
- Time domain:
  - Differentiated pulse
  - Exponential dependence of amplitude on bunch length

Criteria for Electronics Choice - so called "Processor Electronics"

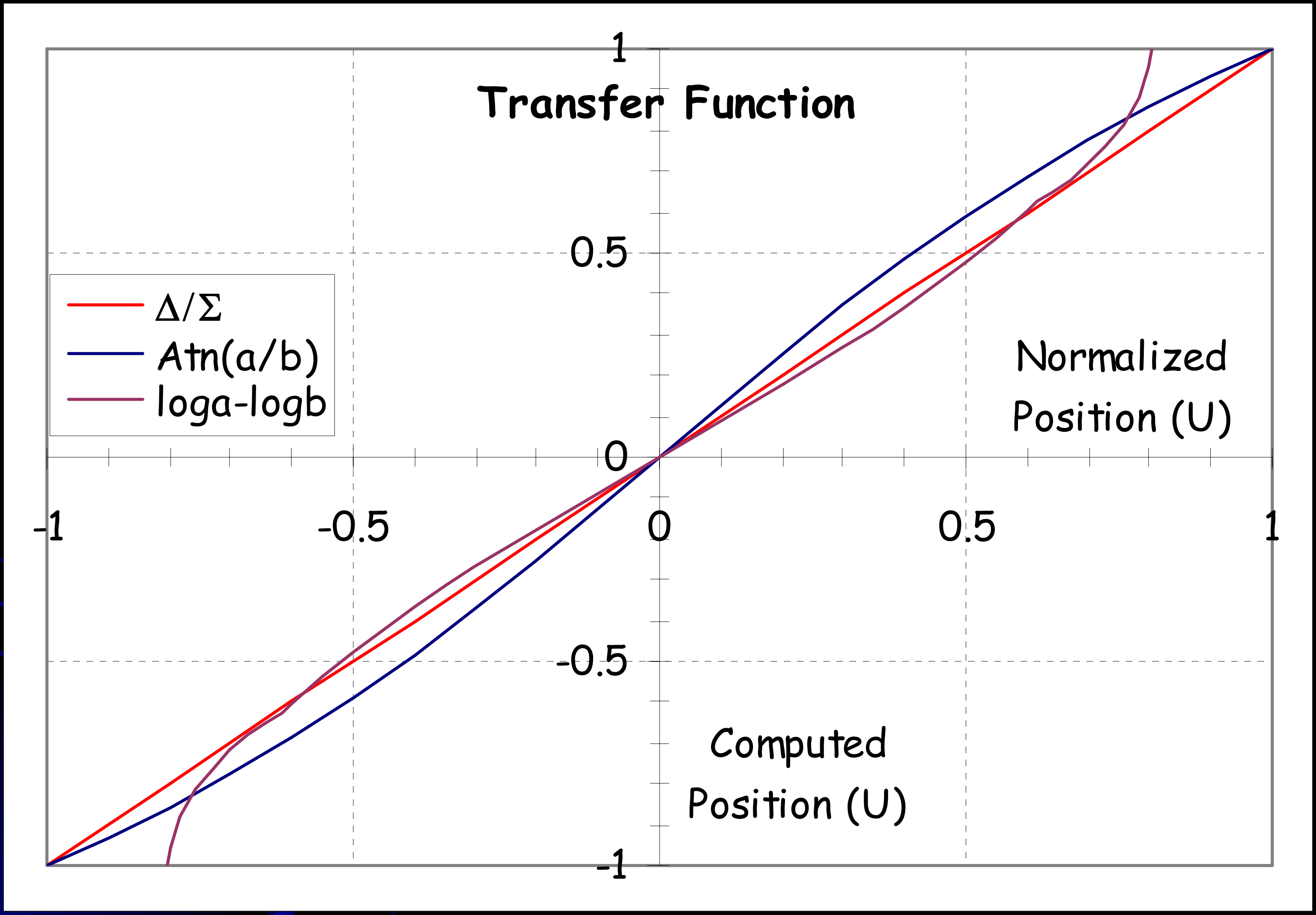
- Accuracy
  - mechanical and electromagnetic errors
  - electronic components
- Resolution
- Stability over time
- Sensitivity and Dynamic Range
- Acquisition Time
  - measurement time
  - repetition time
- Linearity
  - aperture & intensity
- Radiation tolerance

Processing System Families

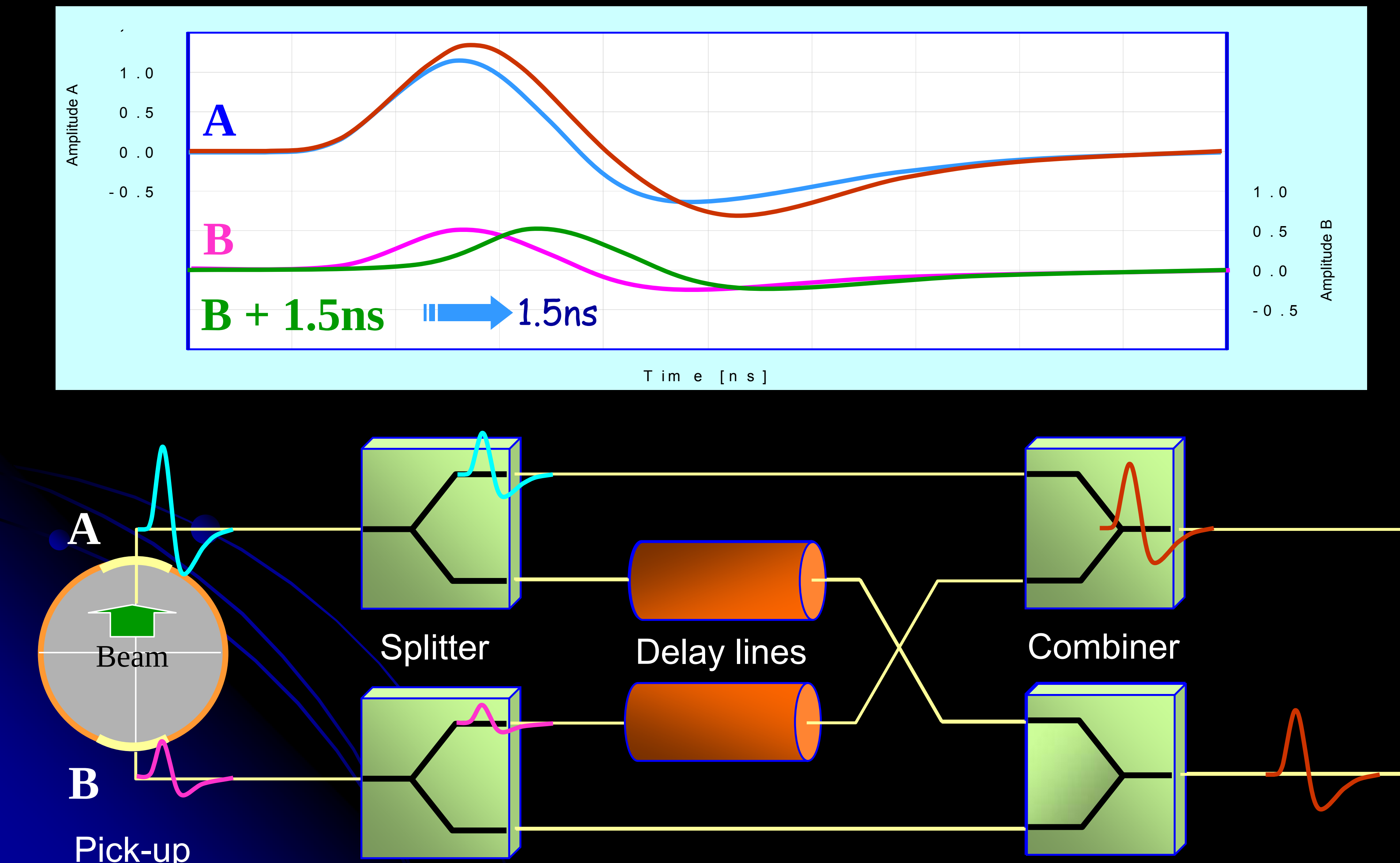


From G.Vismara, BIW 2000 → highly recommended

LINEARITY Comparison



Amplitude to Time Normalisation



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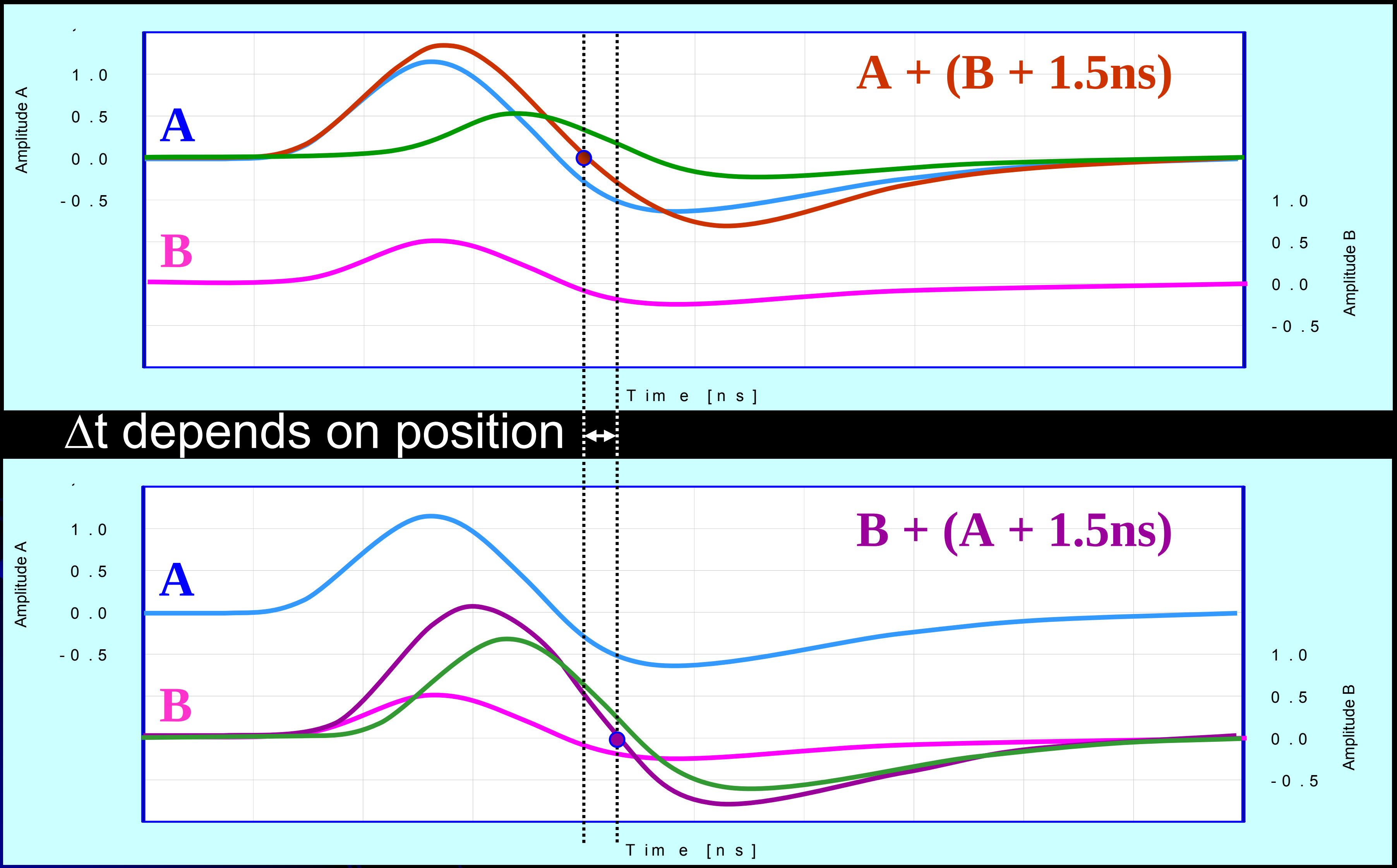


BPM Acquisition Electronics

Amplitude to Time Normaliser

Advantages

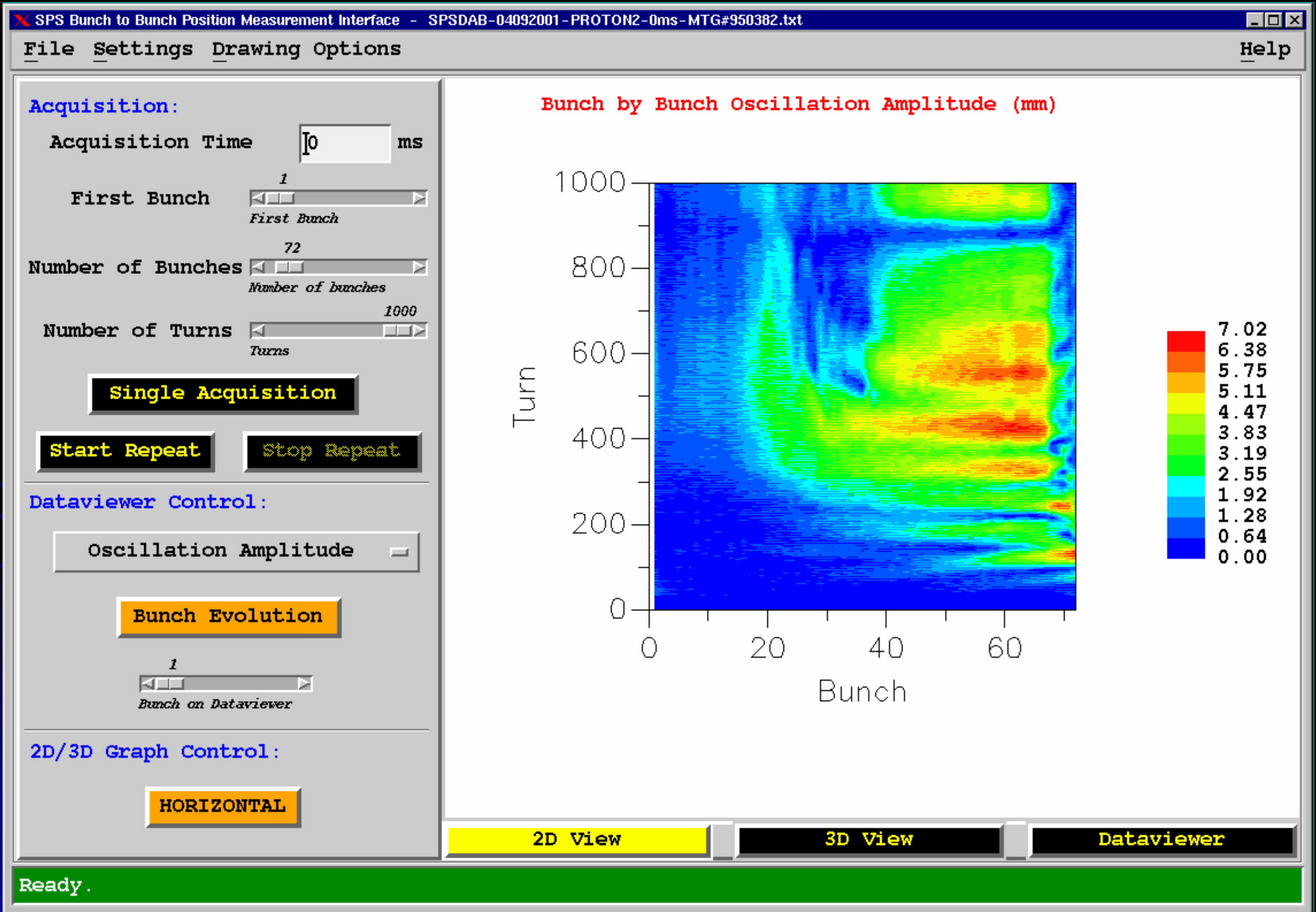
- Fast normalisation (< 25ns)
  - bunch to bunch measurement
- Signal dynamic independent of the number of bunches
  - Input dynamic range ~45 dB
  - No need for gain selection
- Reduced number of channels
  - normalisation at the front-end
- ~10 dB compression of the position dynamic due to the recombination 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
  - synchrotron light monitors
  - ionisation and luminescence monitors
  - Femtosecond diagnostics for ultra short bunches (afternoon course)
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  - ionisation chambers or pin diodes
- Machine Tunes and Chromacitities
  - in diagnostics section of tomorrow
- Luminosity
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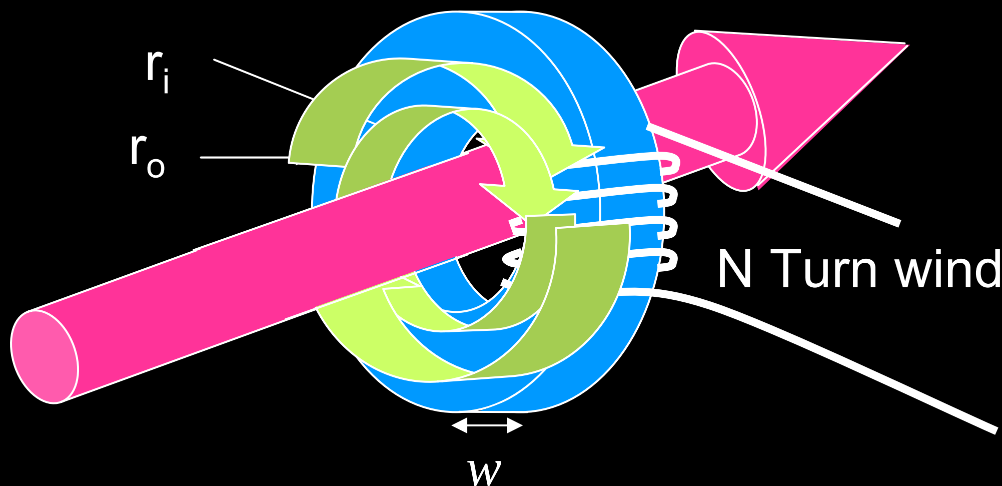
Current Transformers



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

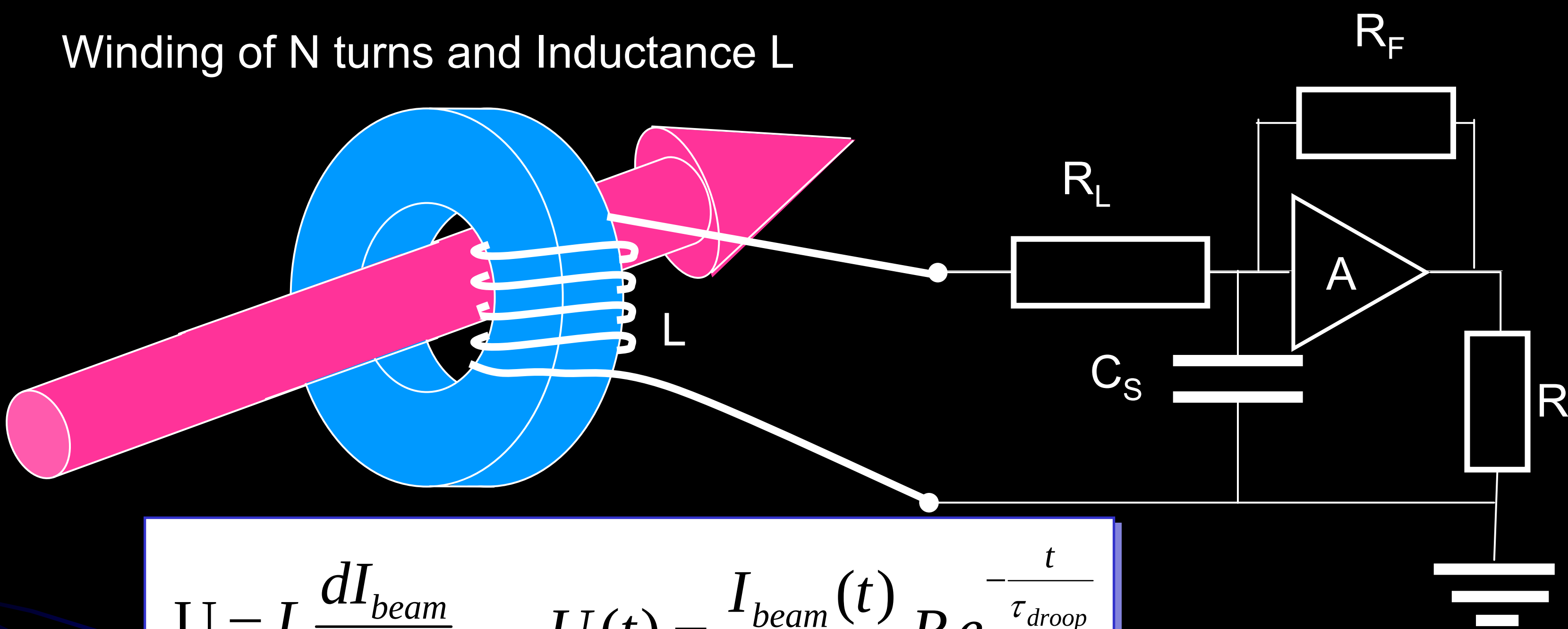
$$I_{Beam} = \frac{e N_q}{t} = \frac{e N_q \beta c}{w}$$

Transformer Inductance

$$L = \frac{\mu_0 \mu_r}{2\pi} w N^2 \ln \frac{r_0}{r_1}$$

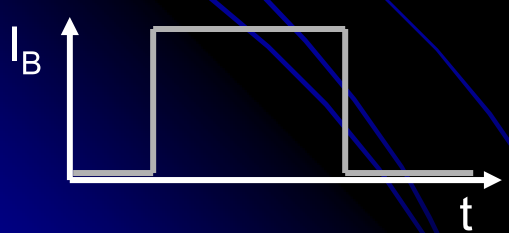
The Active AC transformer

Winding of N turns and Inductance L

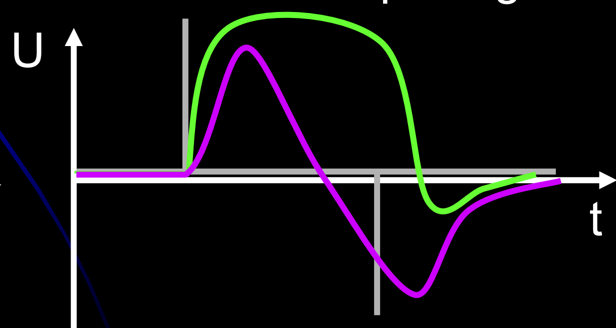


$$U = L\frac{dI_{beam}}{dt} \qquad U(t) = \frac{I_{beam}(t)}{N} R\, e^{-\frac{t}{\tau_{droop}}}$$

Beam signal



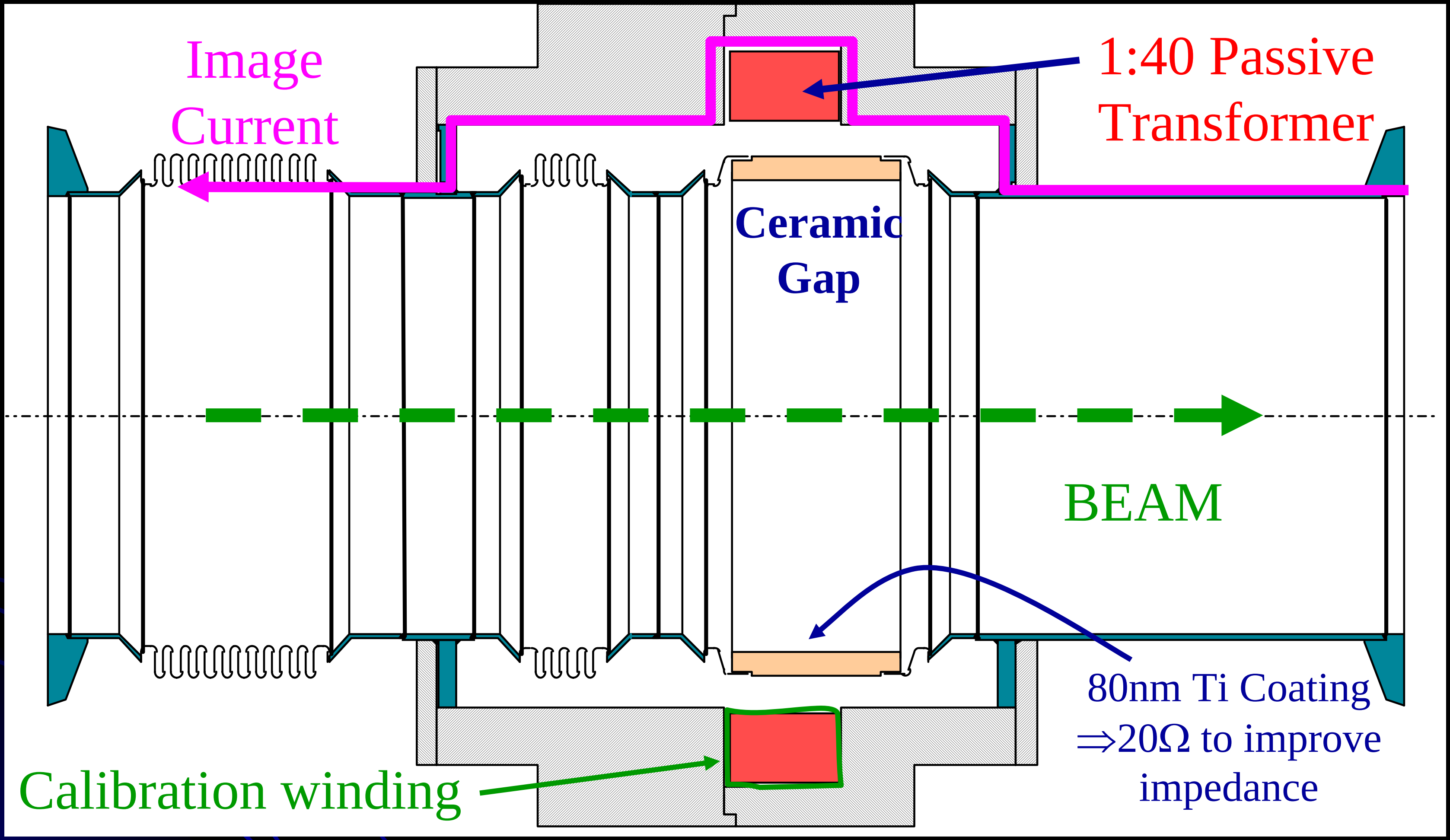
Transformer output signal



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

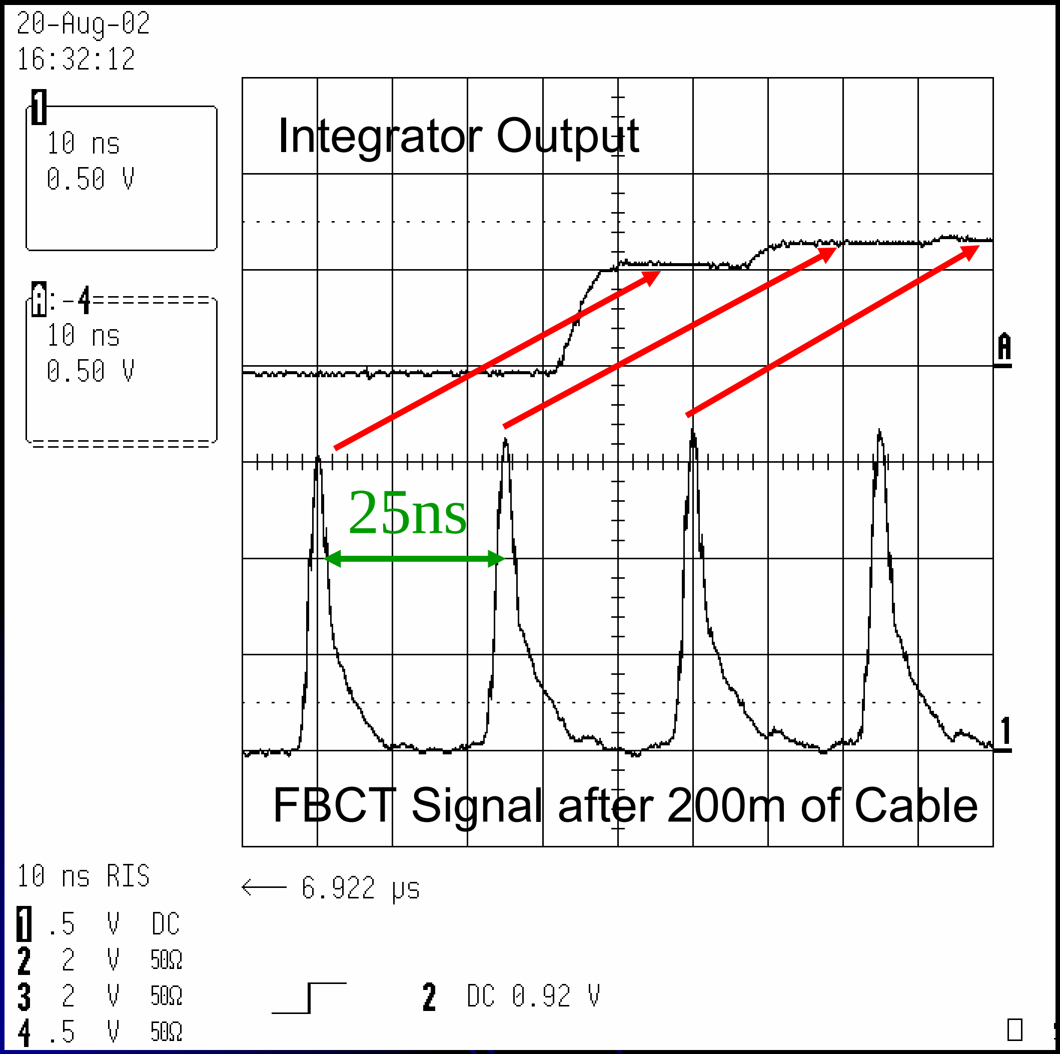
$$\tau_{droop} = \frac{L}{\frac{R_f}{A} + R_L} \approx \frac{L}{R_L}$$

Fast Beam Current Transformer



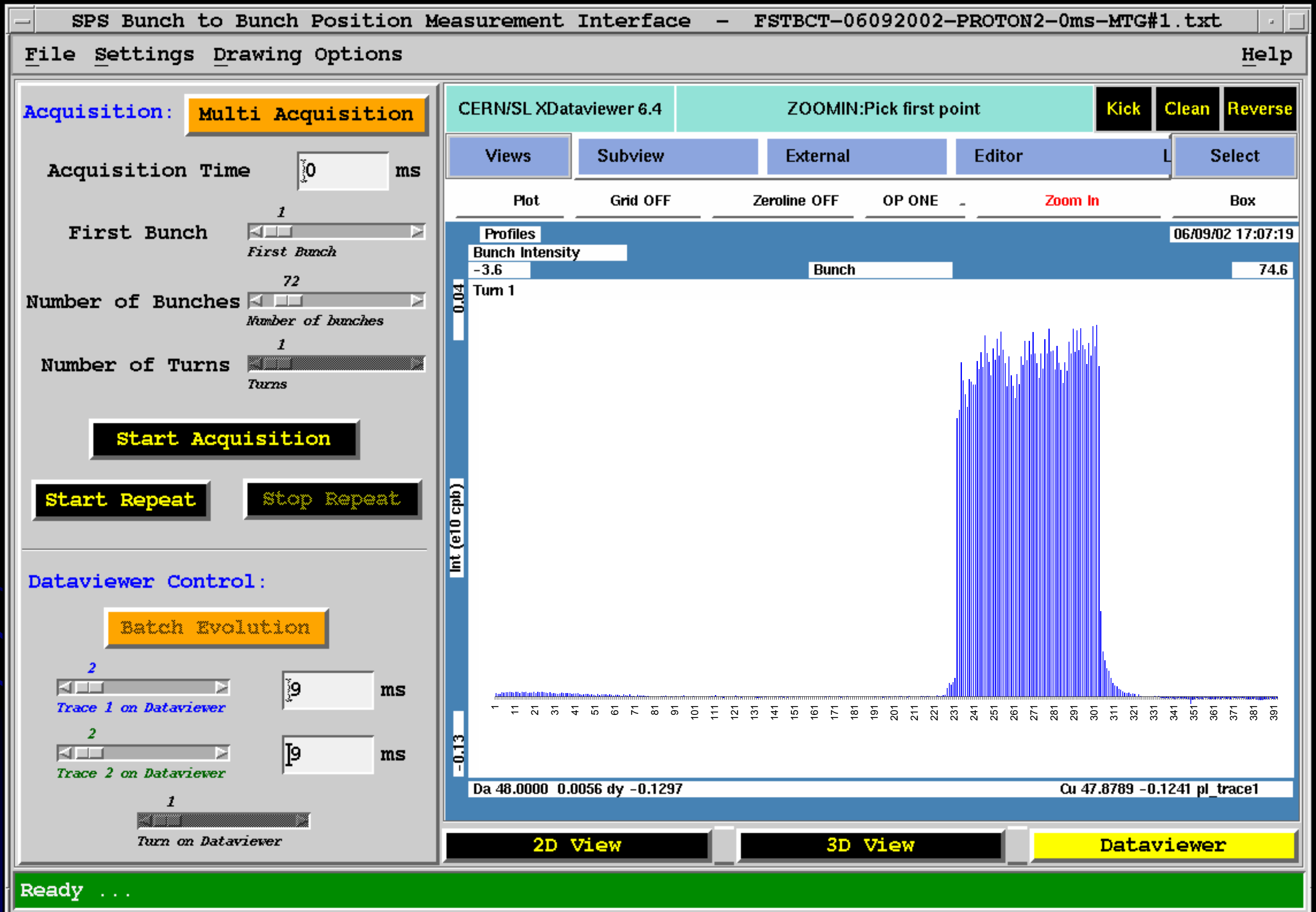
- 500MHz Bandwidth
- Low droop (< 0.2%/μs)

Acquisition Electronics



Data taken on LHC type beams at the CERN-SPS

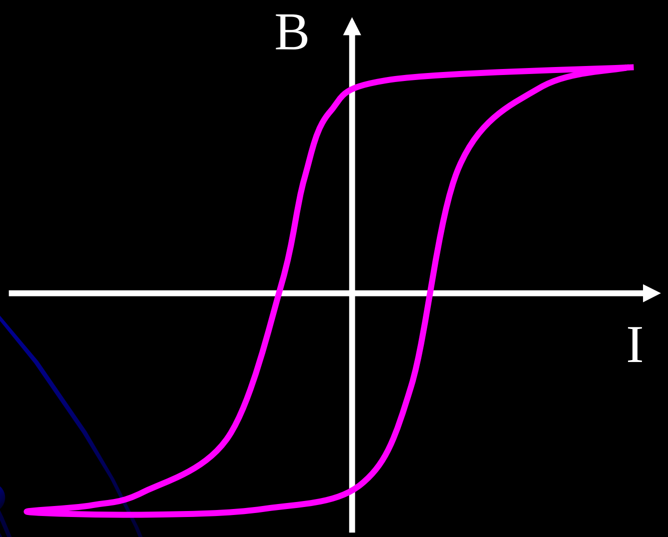
What one can do with such a System



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

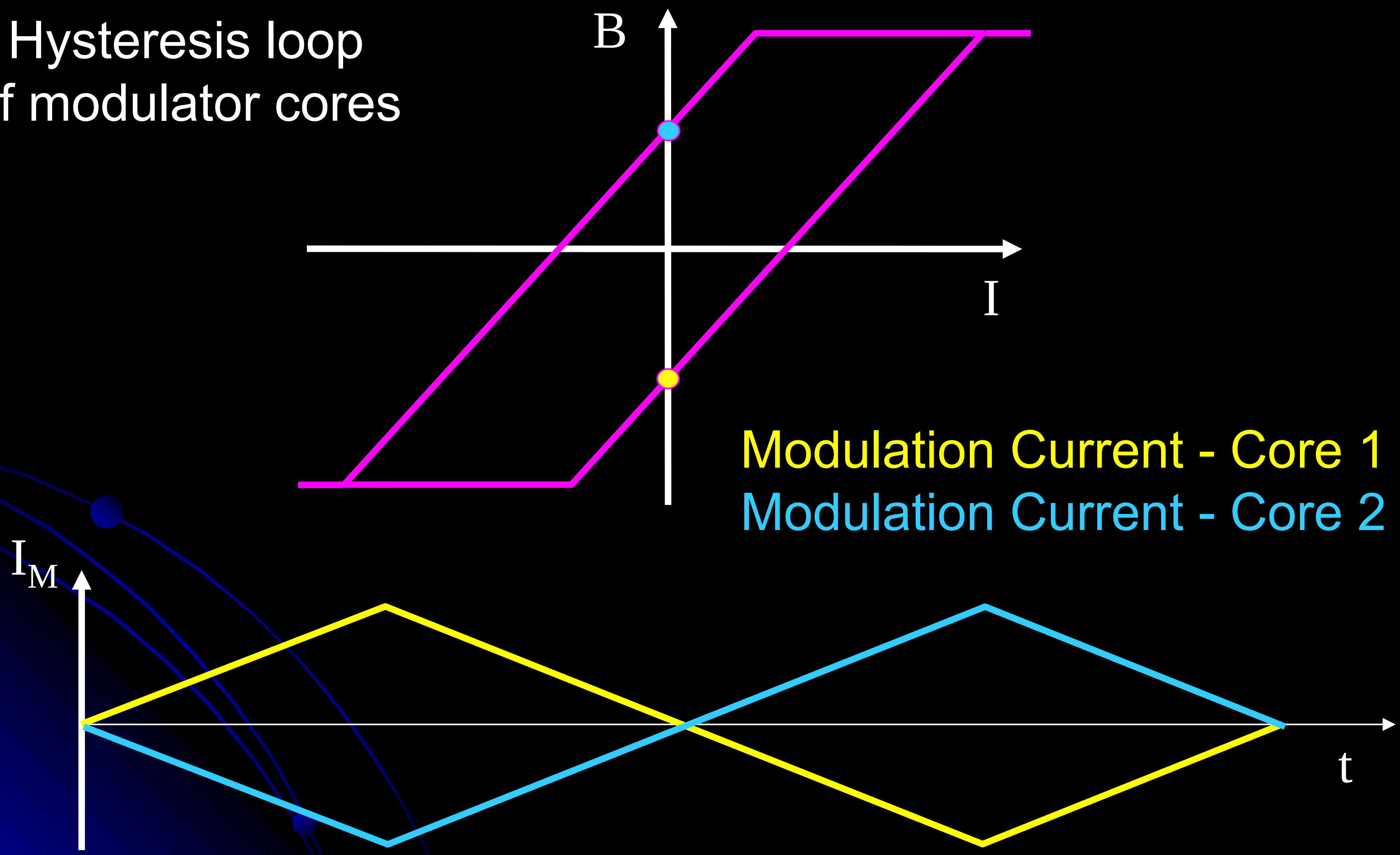
The DC current transformer

- AC current transformer can be extended to very long droop times but not to DC
- DC current measurement is required in storage rings
- To do this:
  - Take advantage of non-linear magnetisation curve
  - Apply a modulation frequency to 2 identical cores



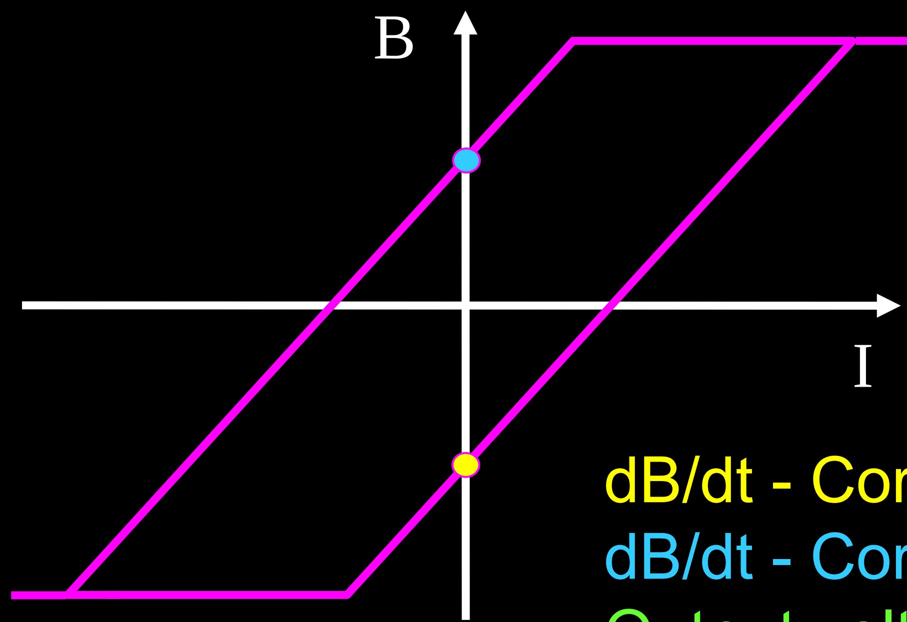
DCCT Principle – Case 1: no beam

Hysteresis loop
of modulator cores

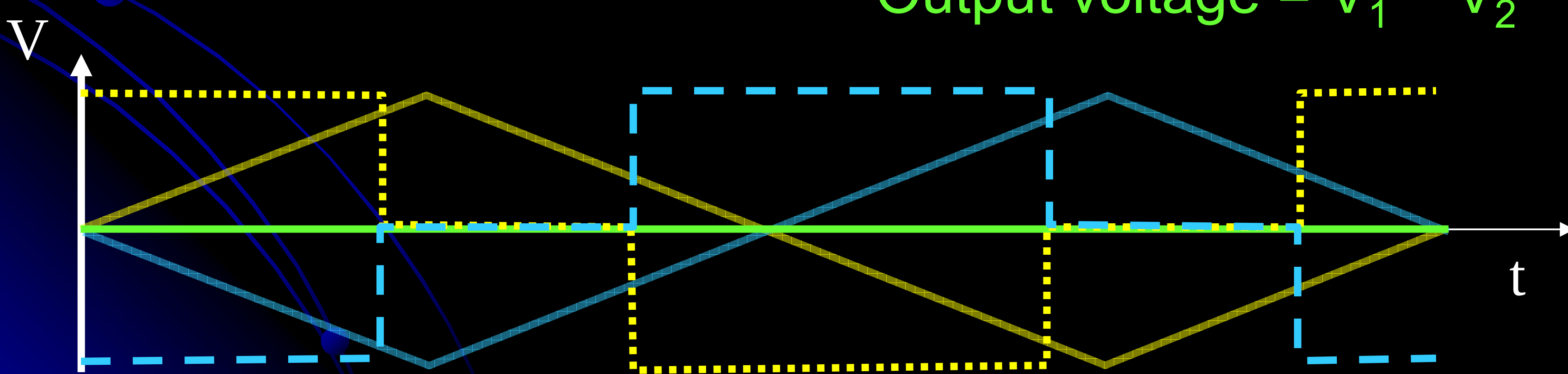


DCCT Principle – Case 1: no beam

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

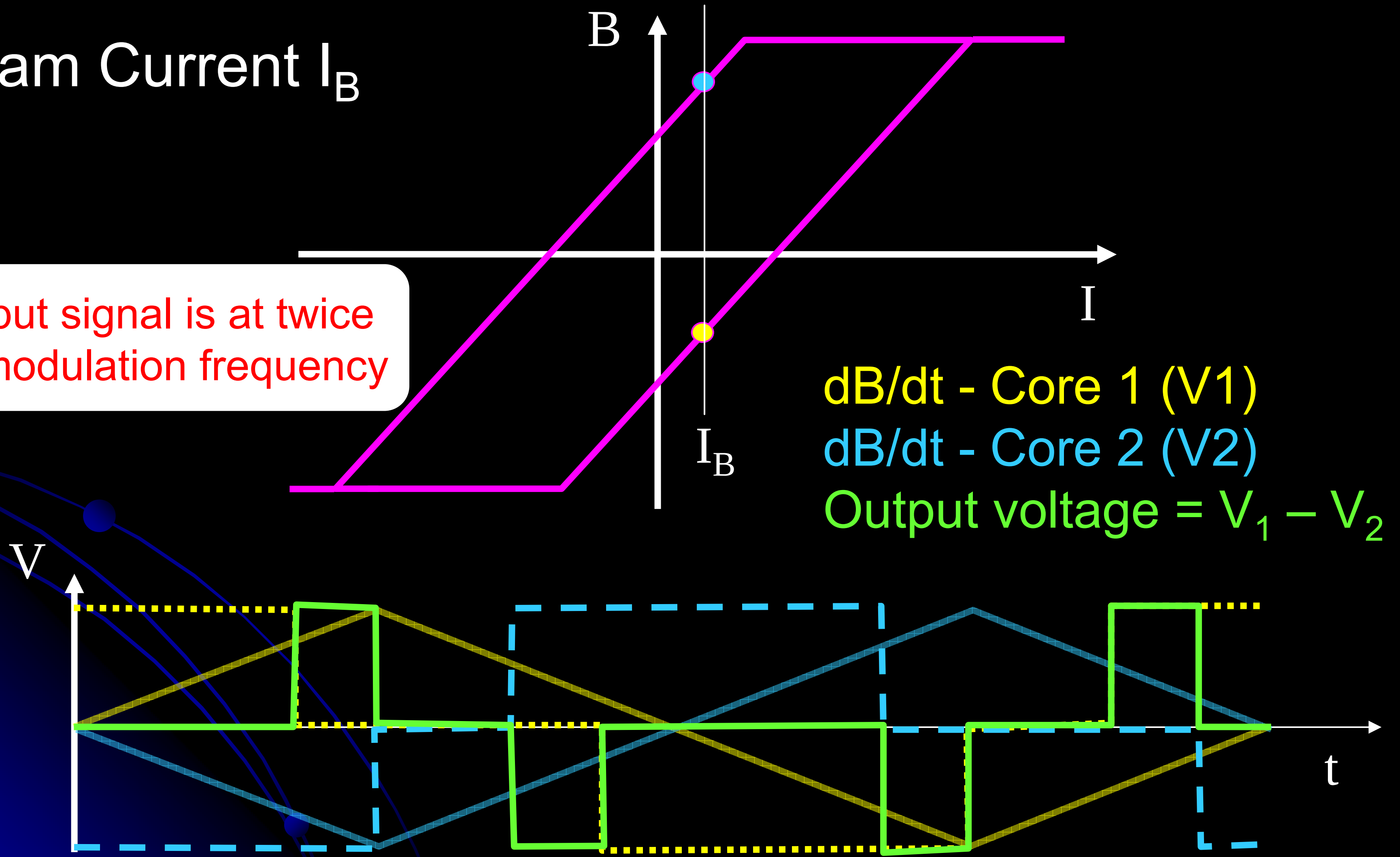


dB/dt - Core 1 (V1)
dB/dt - Core 2 (V2)
Output voltage = $V_1 - V_2$



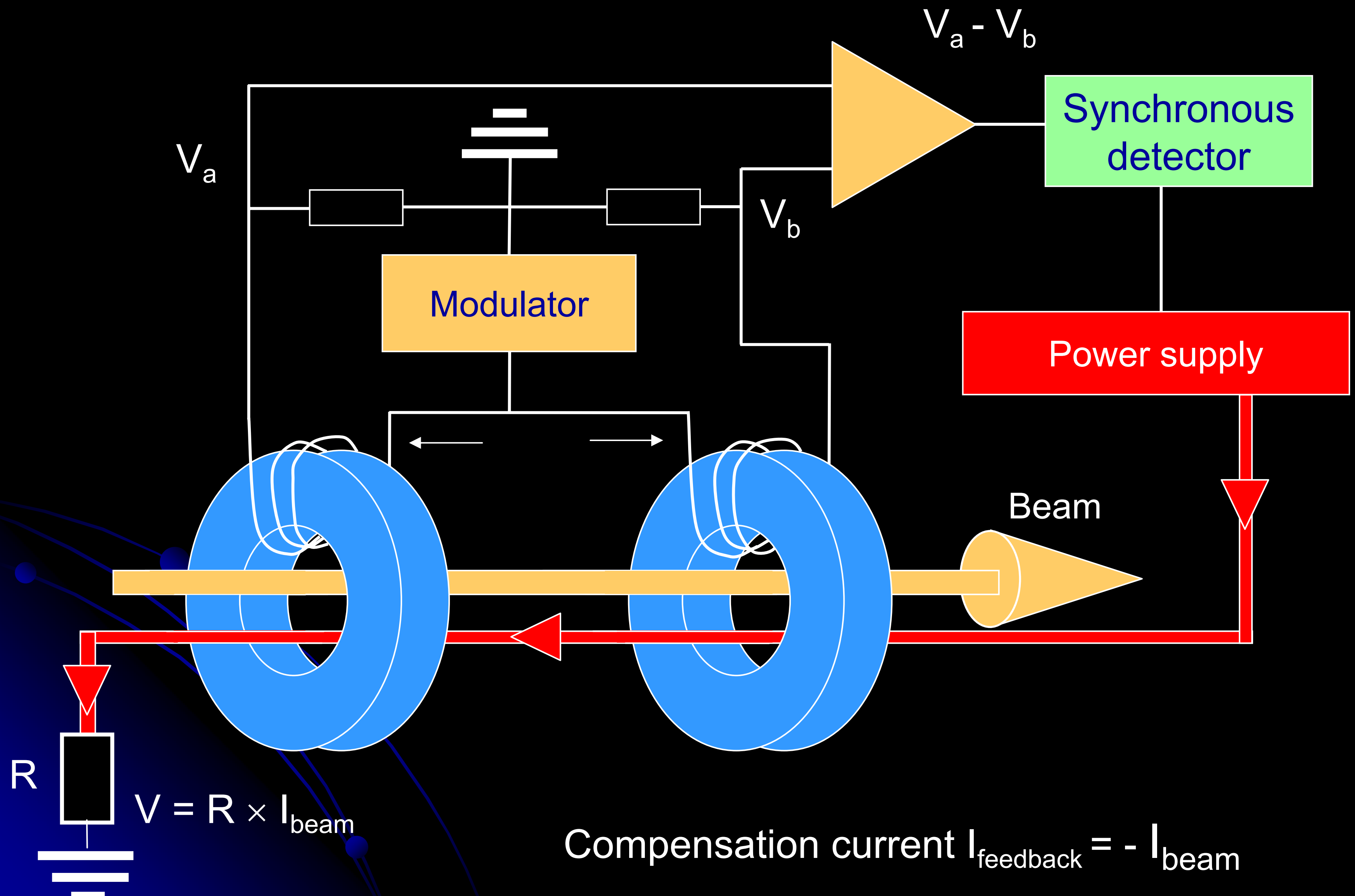
DCCT Principle – Case 2: with beam

Beam Current I_B



Output signal is at twice the modulation frequency

Zero Flux DCCT Schematic



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

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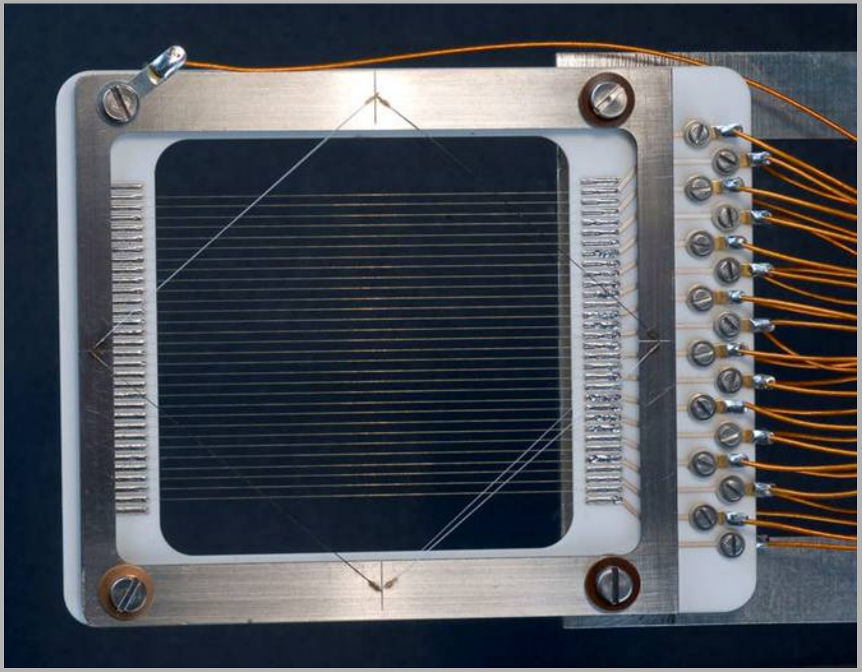
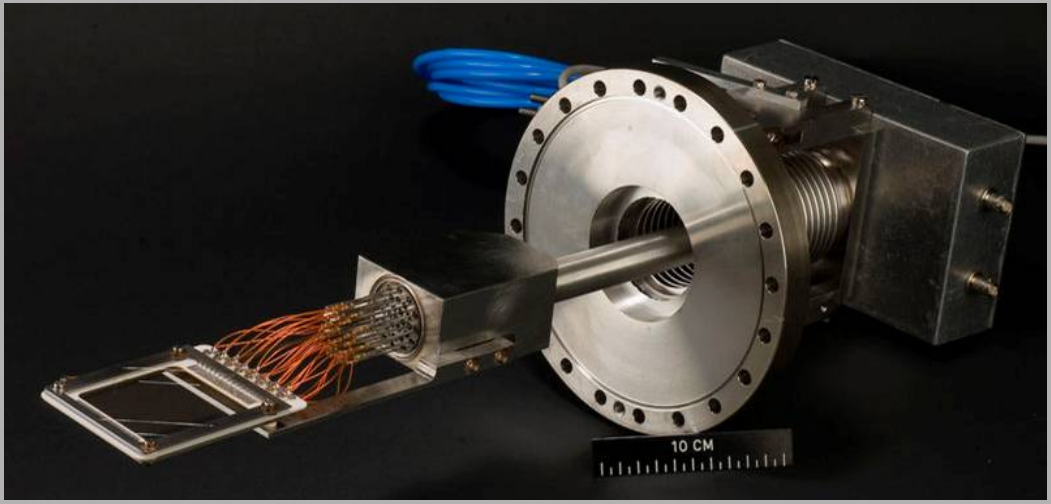
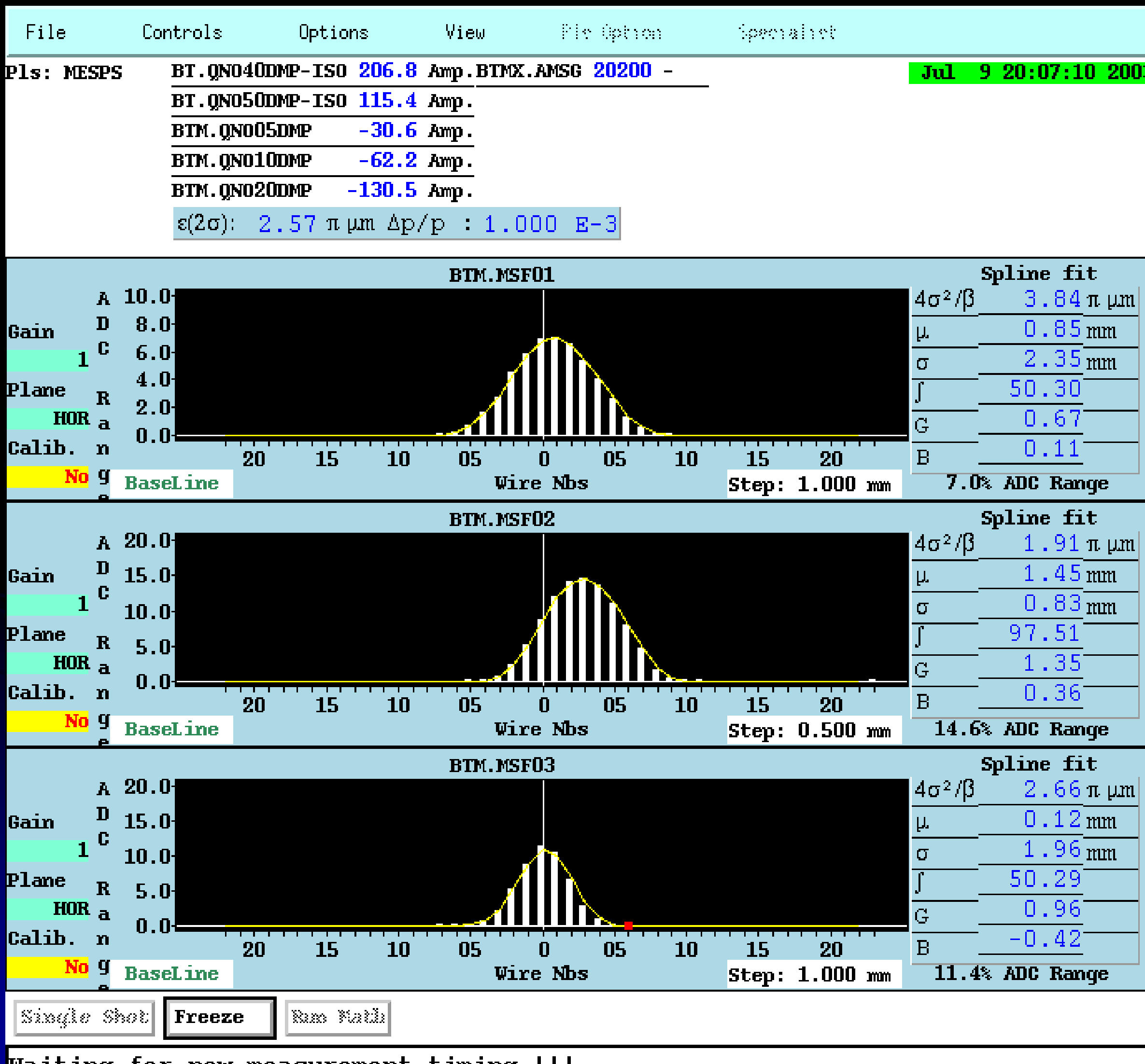
Secondary Emission (SEM) Grids

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





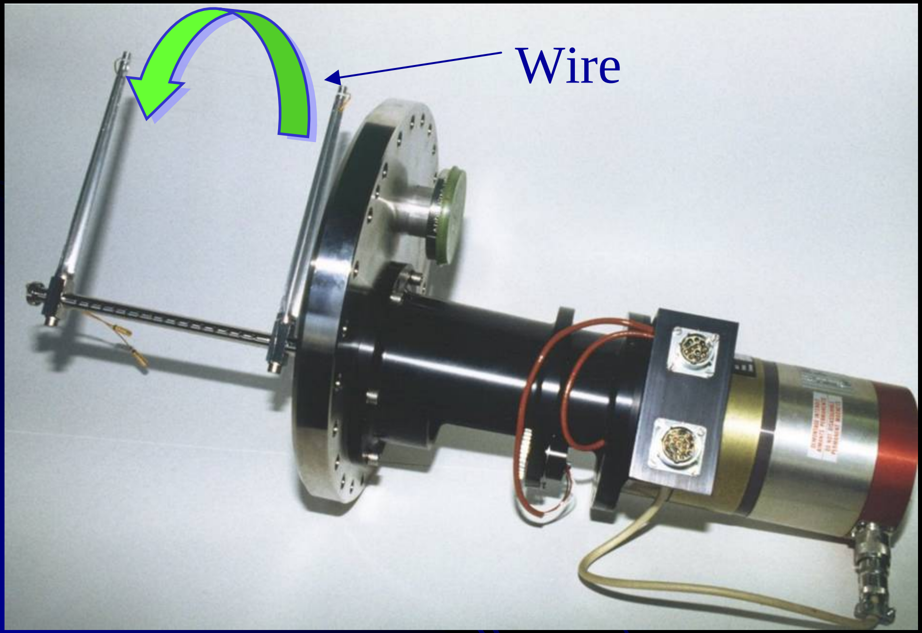
Profiles from SEM grids



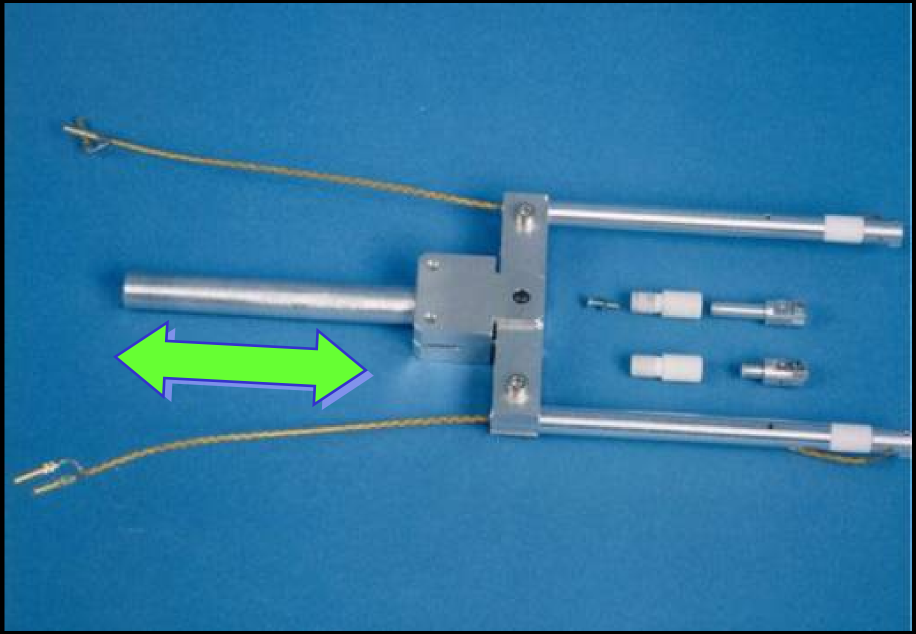
- Charge density measured from each wire gives a projection of the beam profile in either horizontal or vertical plane
- Resolution is given by distance between wires
- Used only in transfer lines as heating is too great for circulating beams

Wire Scanners

- For circulating beams 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 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

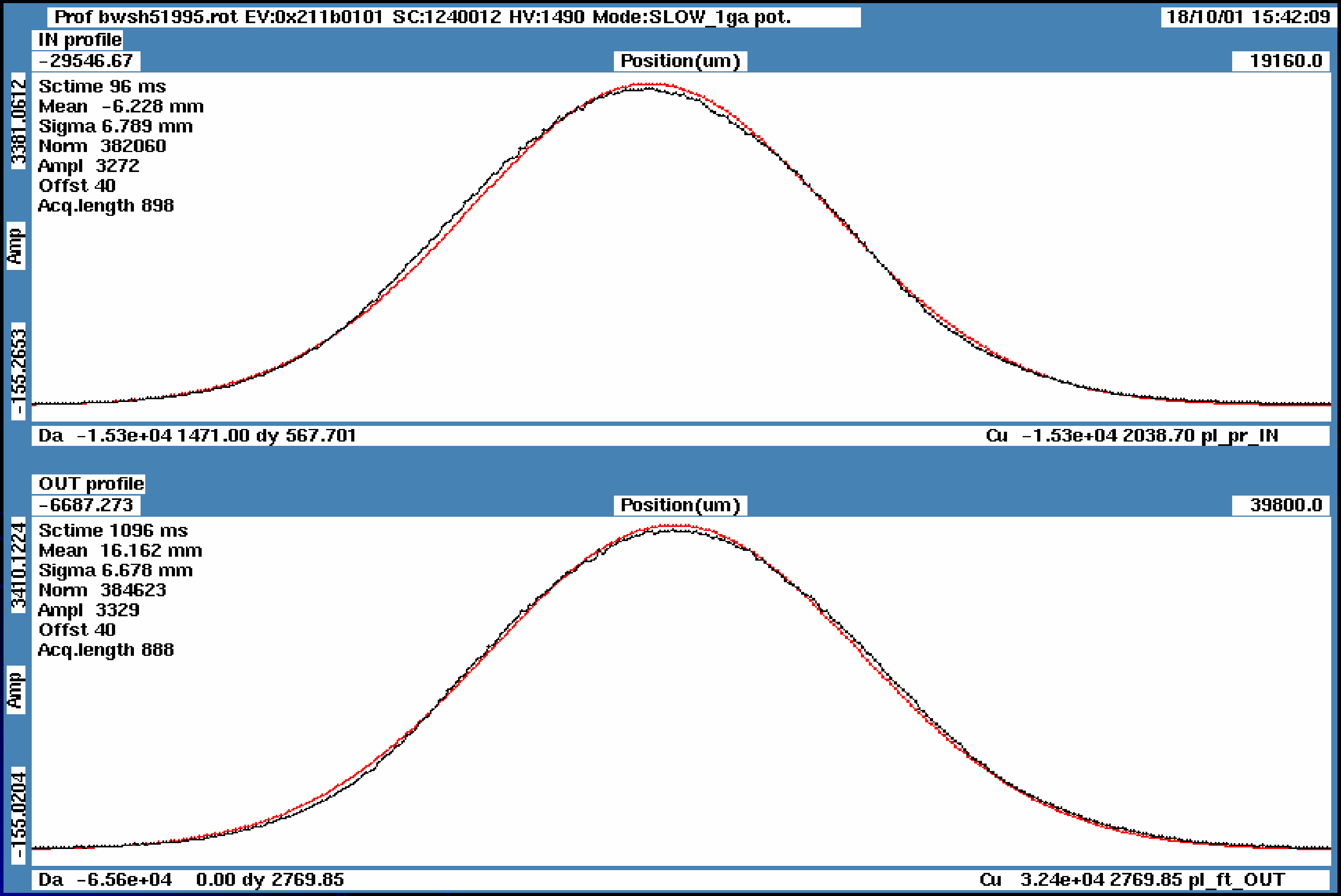


Rotative wire scanner



Linear wire scanner

Measurement Results



Beam Profile Monitoring using Screens

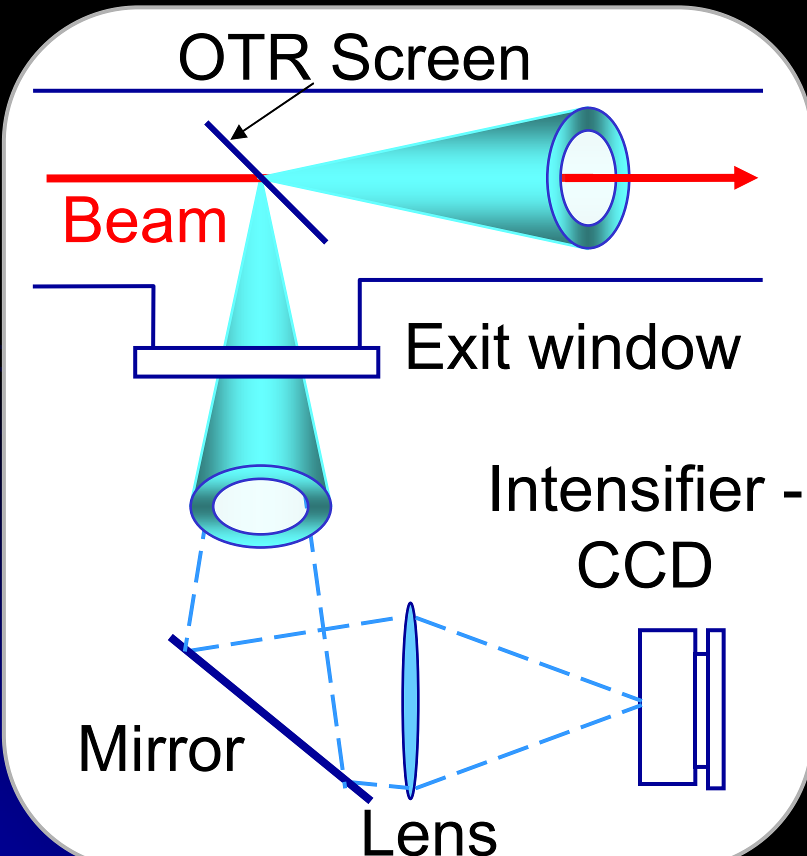
- Screen Types
  - Luminescence Screens
    - destructive (thick) but work during setting-up with low intensities
  - Optical Transition Radiation (OTR) screens
    - much less destructive (thin) but require higher intensity

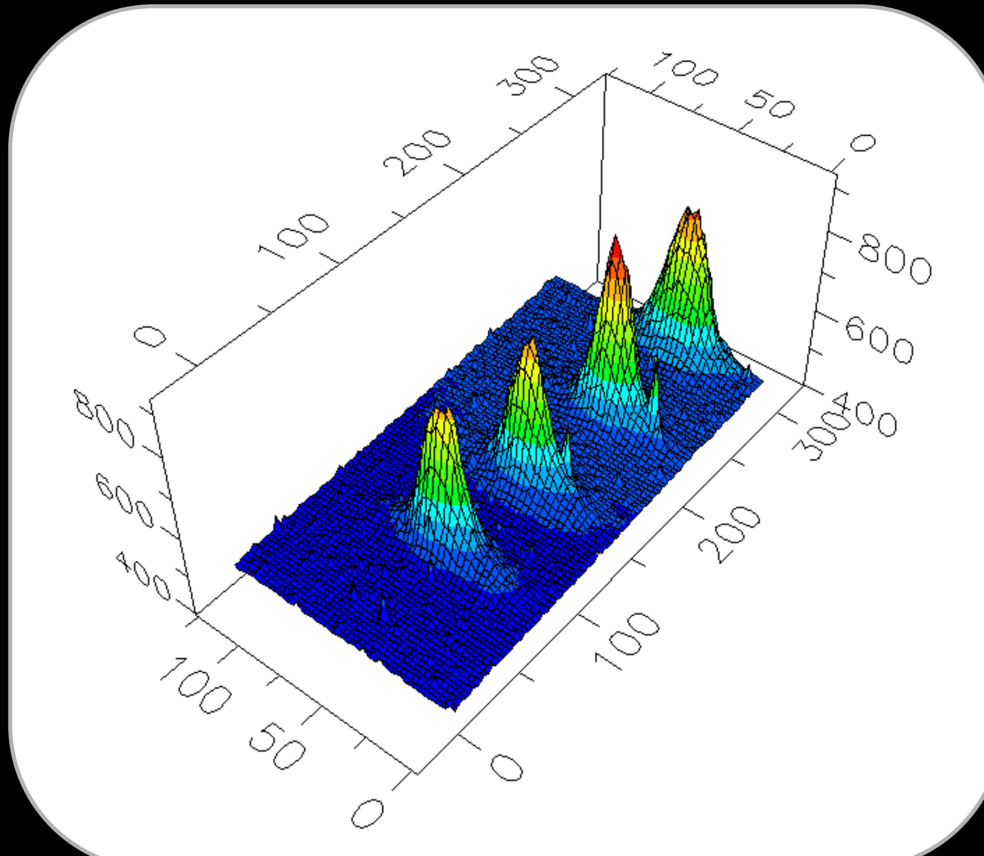
Sensitivities measured with protons with previous screen holder, normalised for 7 px/σ

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	*$2\ 10^7$*

OTR – The Principle

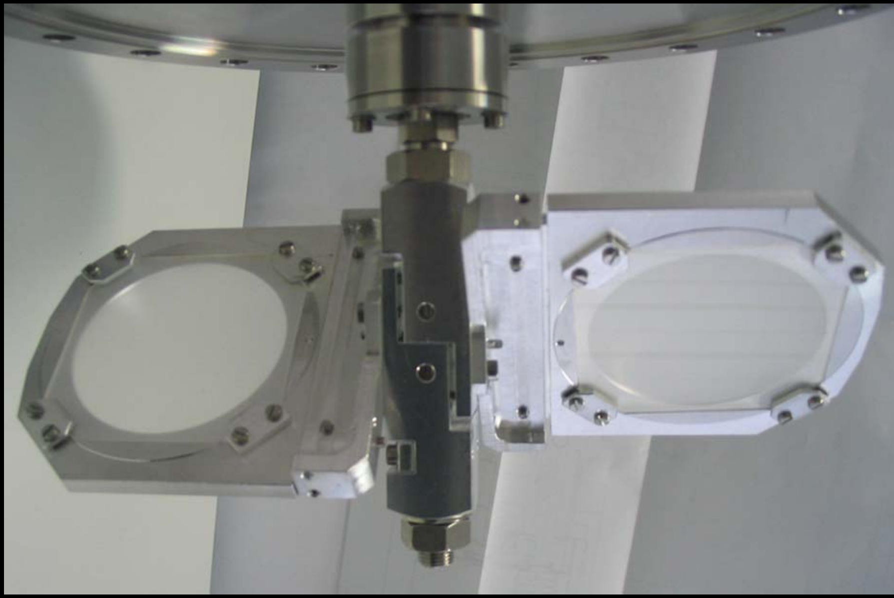
- Radiation emitted when a charged particle beam goes through the interface of 2 media with different dielectric constants
  - surface phenomenon allows the use of very thin screens (~10mm)





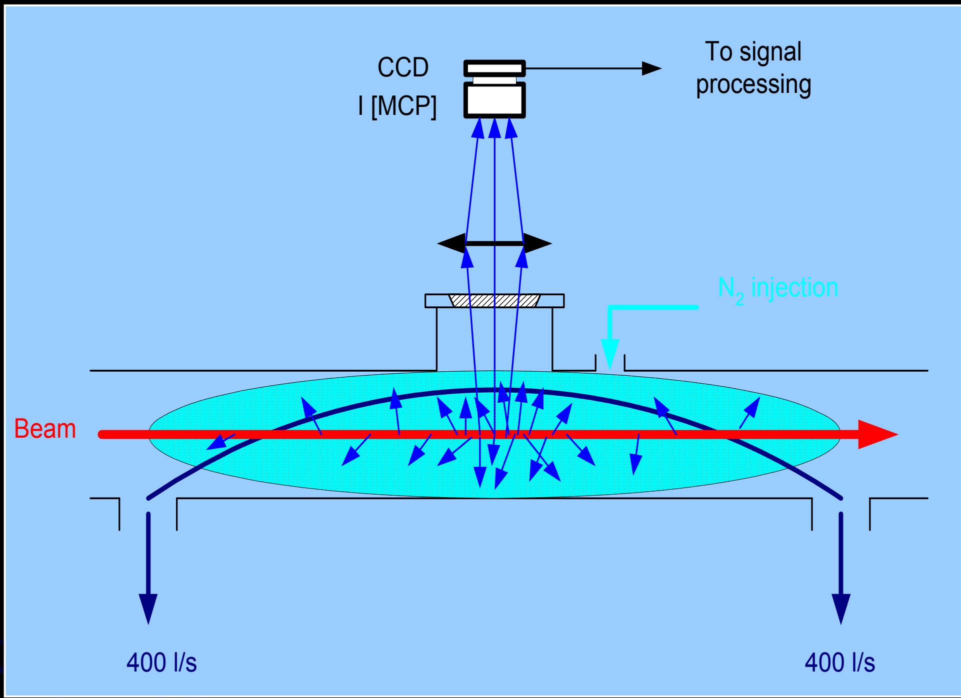
Beam Profile Monitoring using Screens

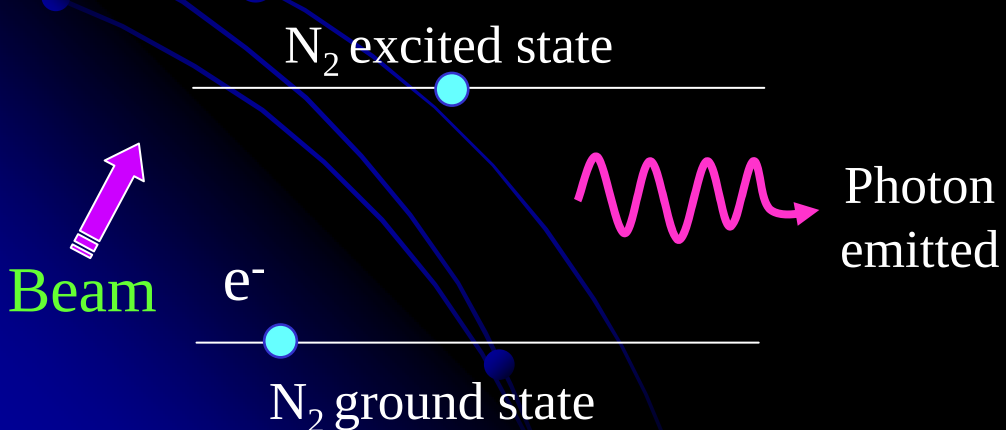
- Usual configuration
  - Combine several screens in one housing e.g.
    - Al_2O_3 luminescent screen for setting-up with low intensity
    - Thin (~10um) Ti OTR screen for high intensity measurements
    - Carbon OTR screen for very high intensity operation

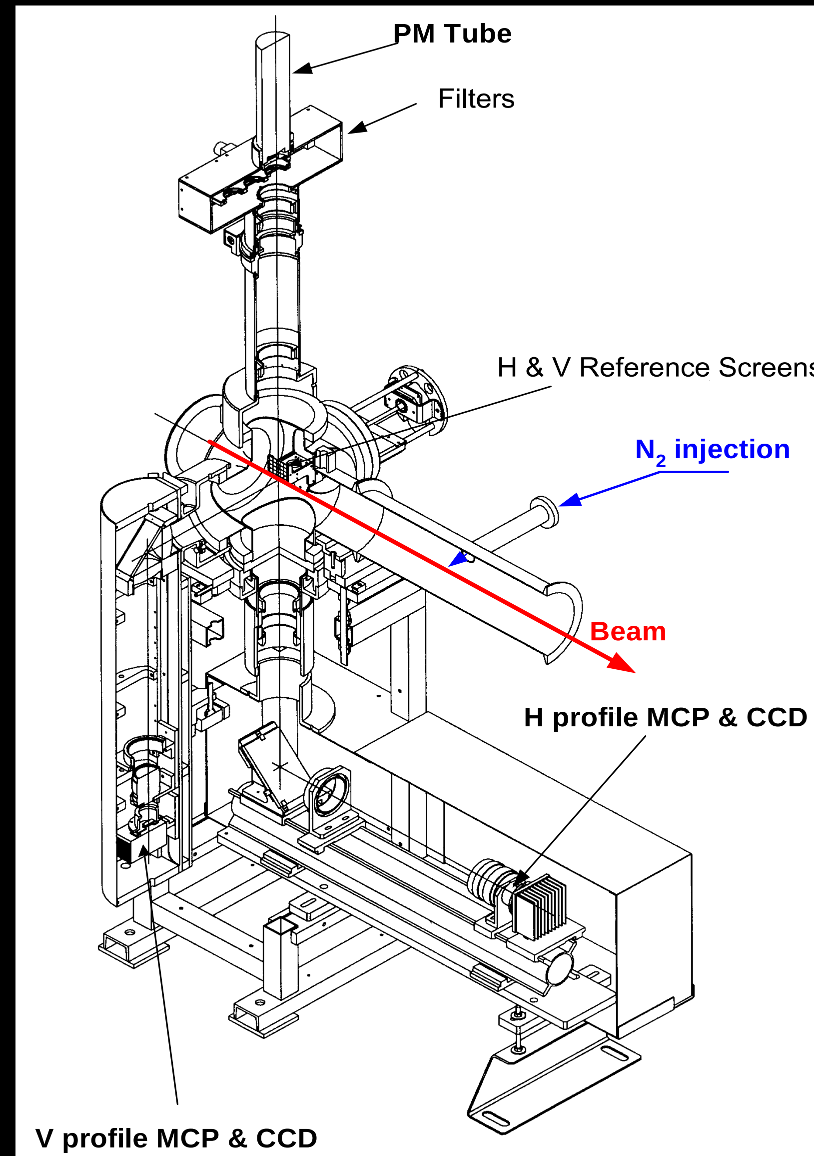


- Advantages compared to SEM grids
  - allows analogue camera or CCD acquisition
  - gives two dimensional information
  - high resolution: ~ 400 x 300 = 120’000 pixels for a standard CCD
  - more economical
    - Simpler mechanics & readout electronics
  - Time resolution depends on choice of image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

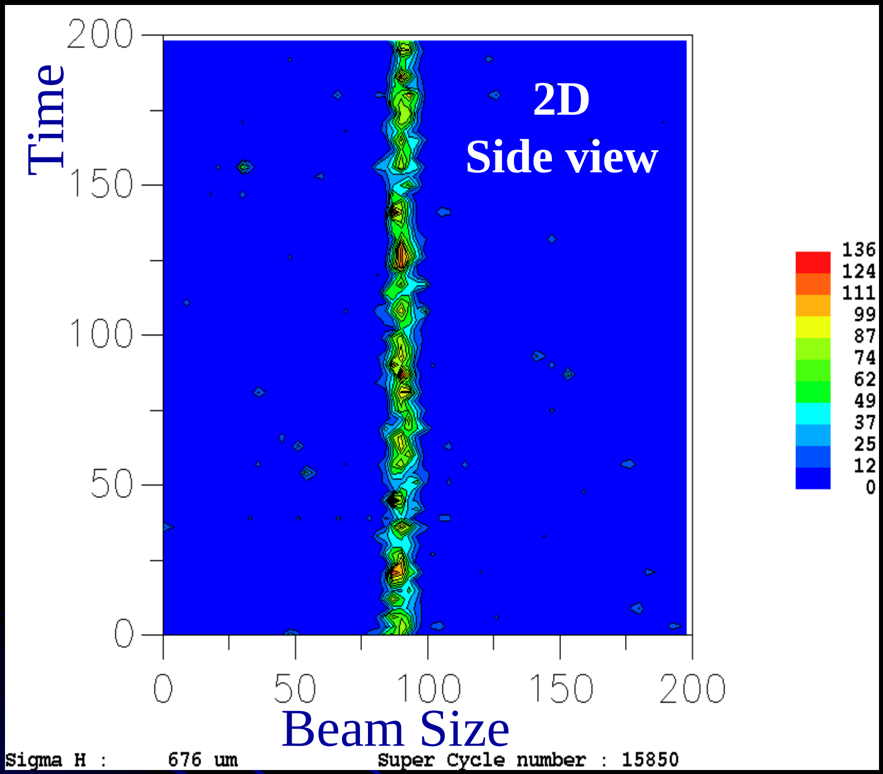
Luminescence Profile Monitor

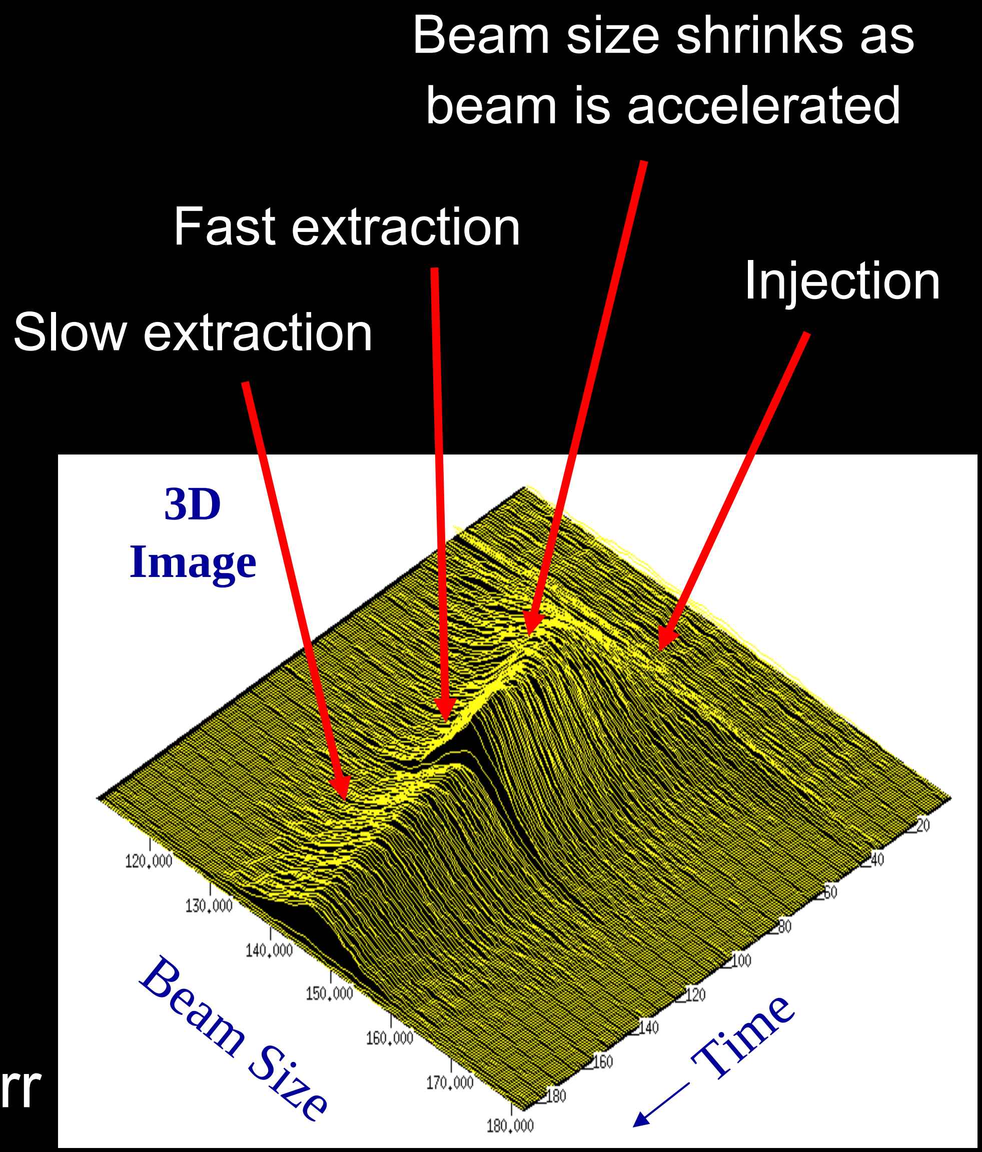






Luminescence Profile Monitor

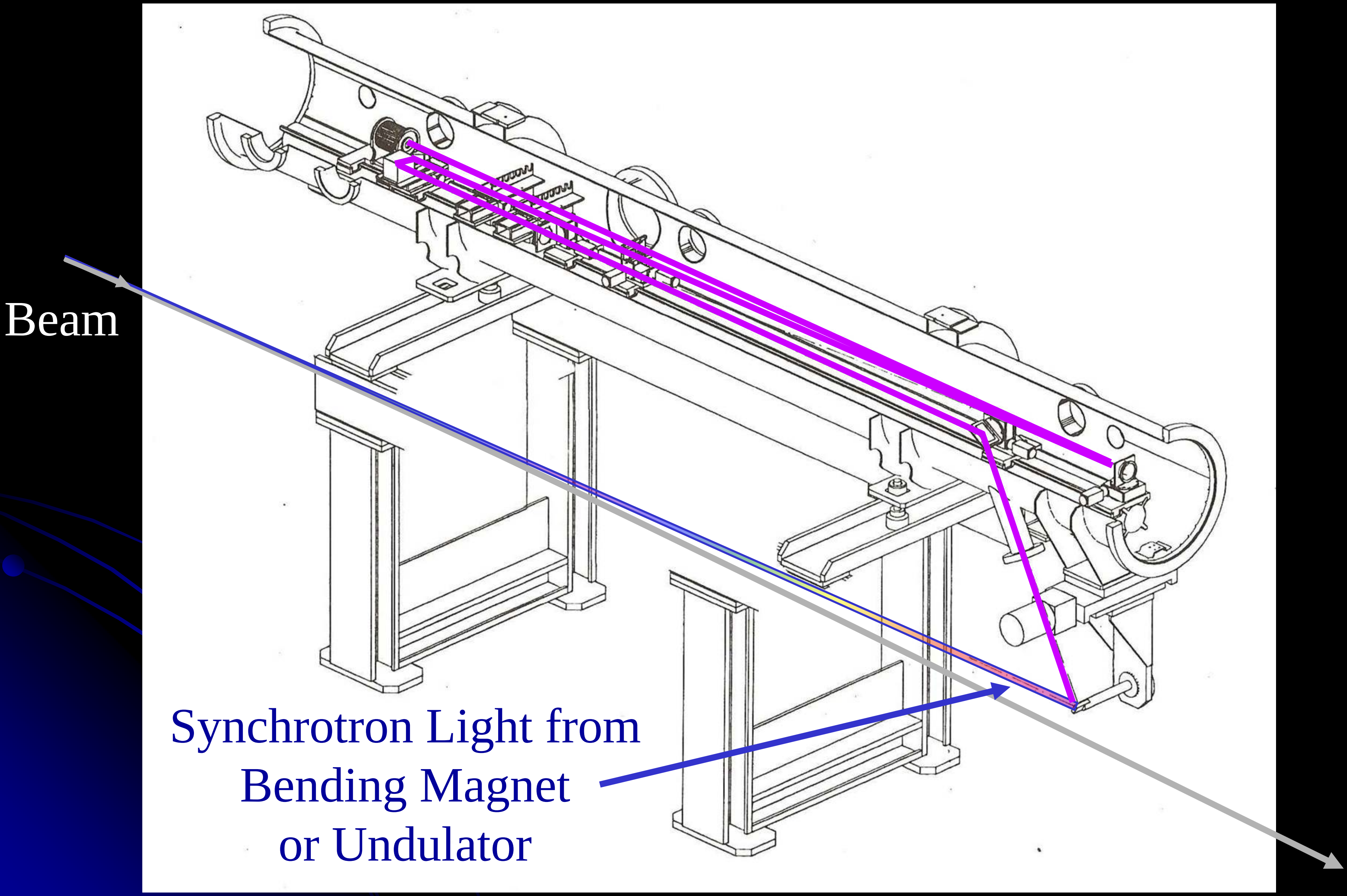




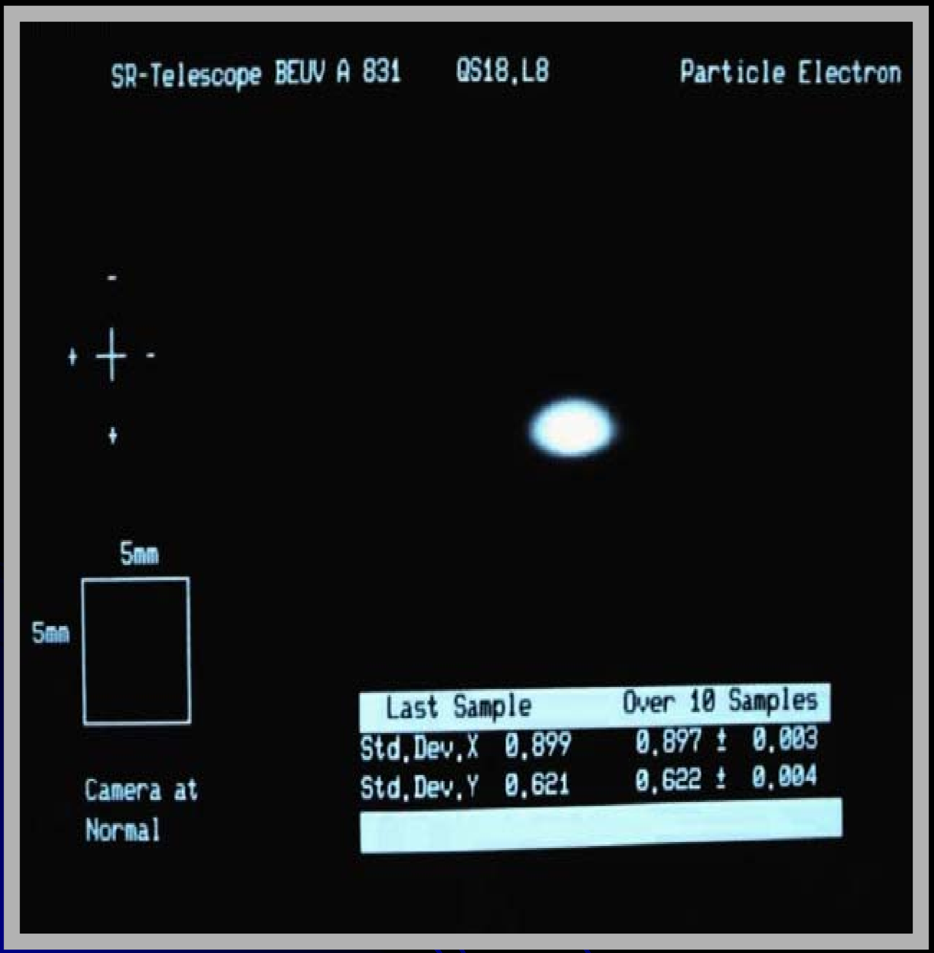
CERN-SPS Measurements

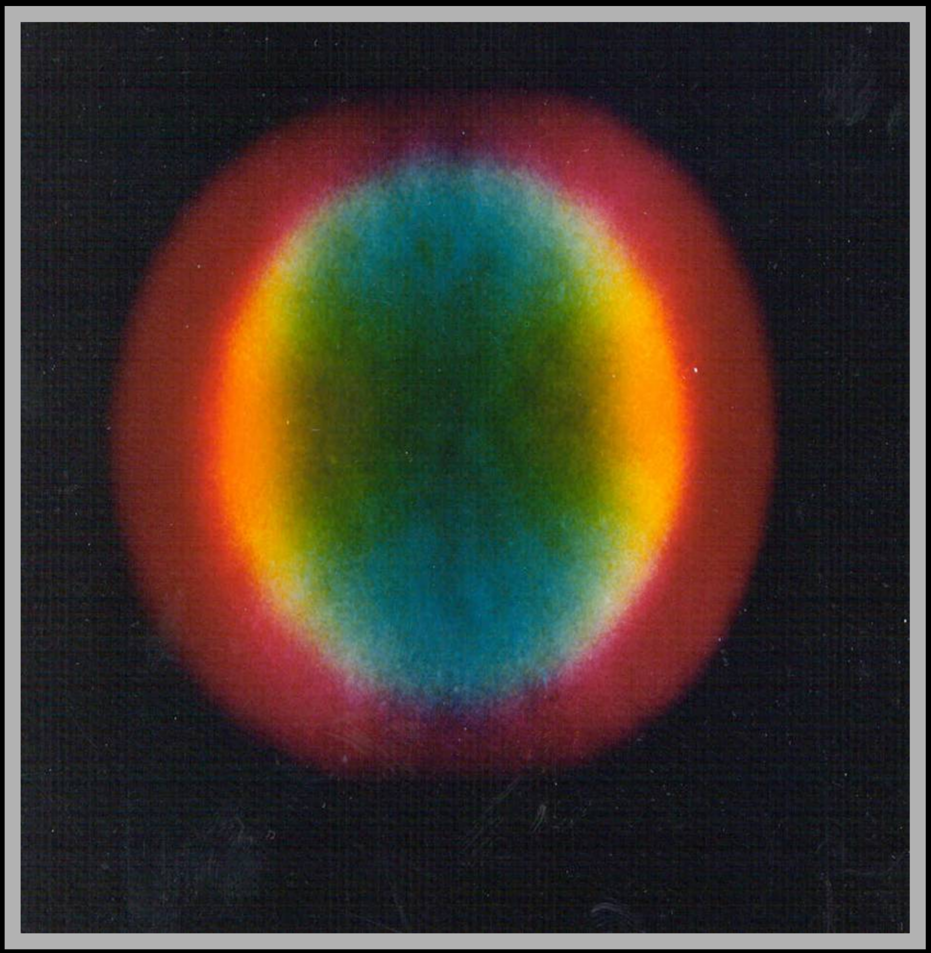
- Profile Collected every 20ms
- Local Pressure at ~5×10^{-7} Torr

The Synchrotron Light Monitor



The Synchrotron Light Monitor





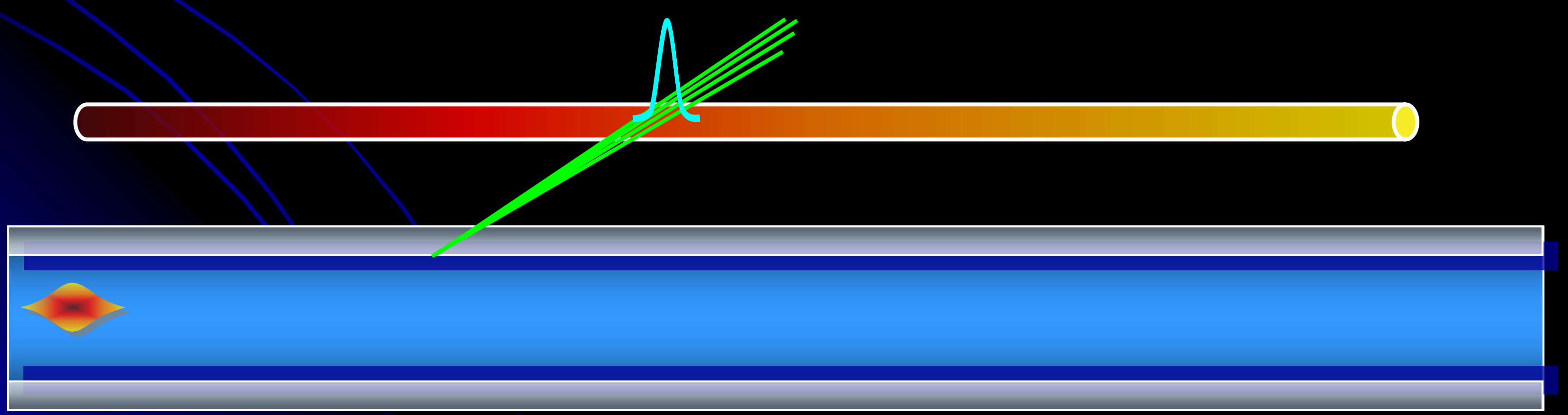
The Typical Instruments

- 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 (afternoon course)
- 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

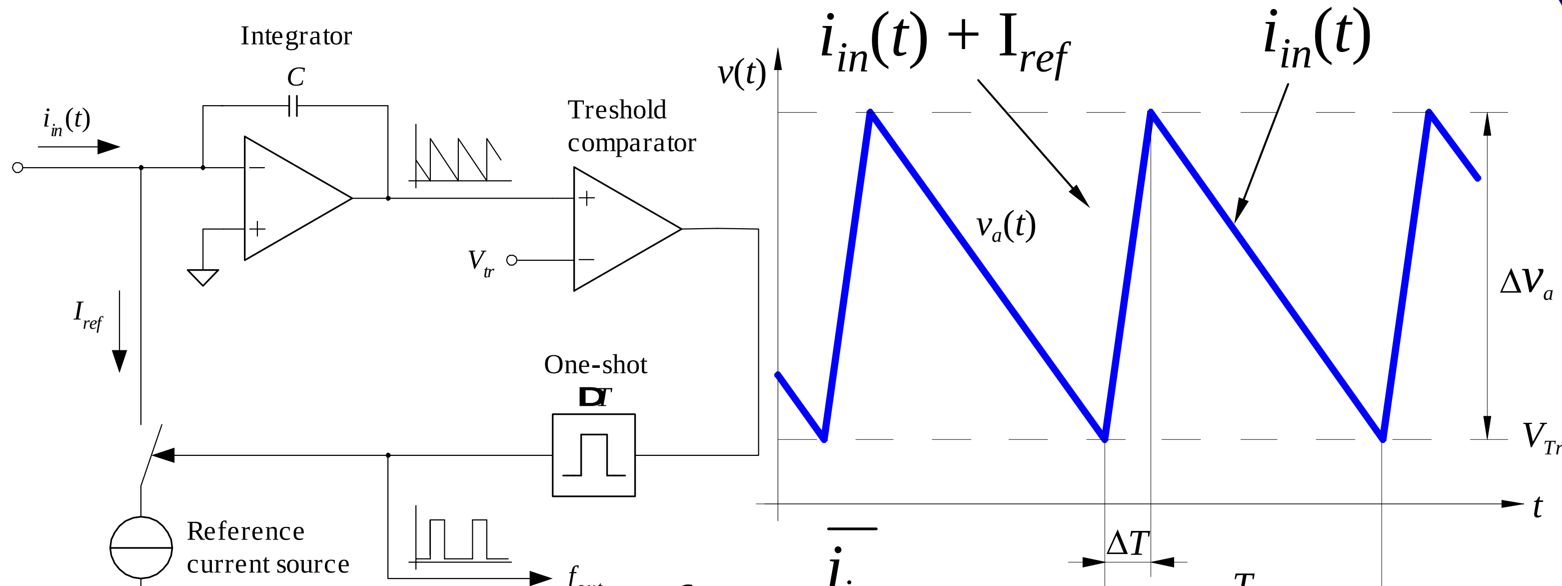
- Role of a BLM system:
  1. Protect the machine from damage
  2. Dump the beam to avoid magnet quenches (for SC magnets)
  3. Diagnostic tool to improve the performance of the accelerator

- 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 to10^4



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 to10^8

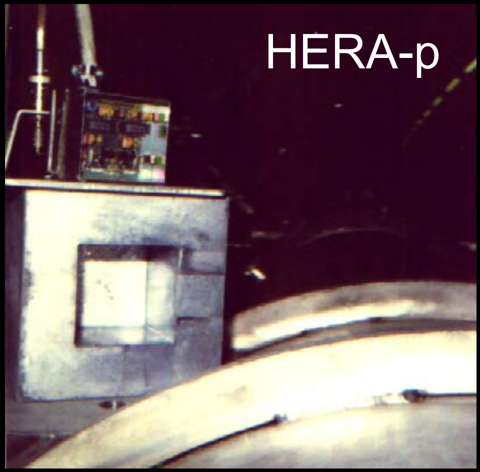


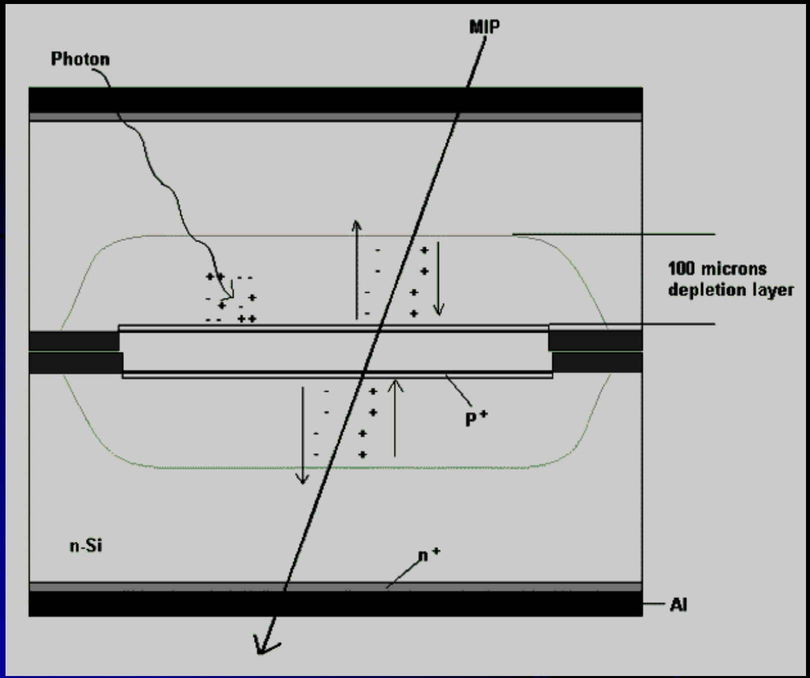
$$f = \frac{\overline{i_{in}}}{I_{ref}\Delta T}$$

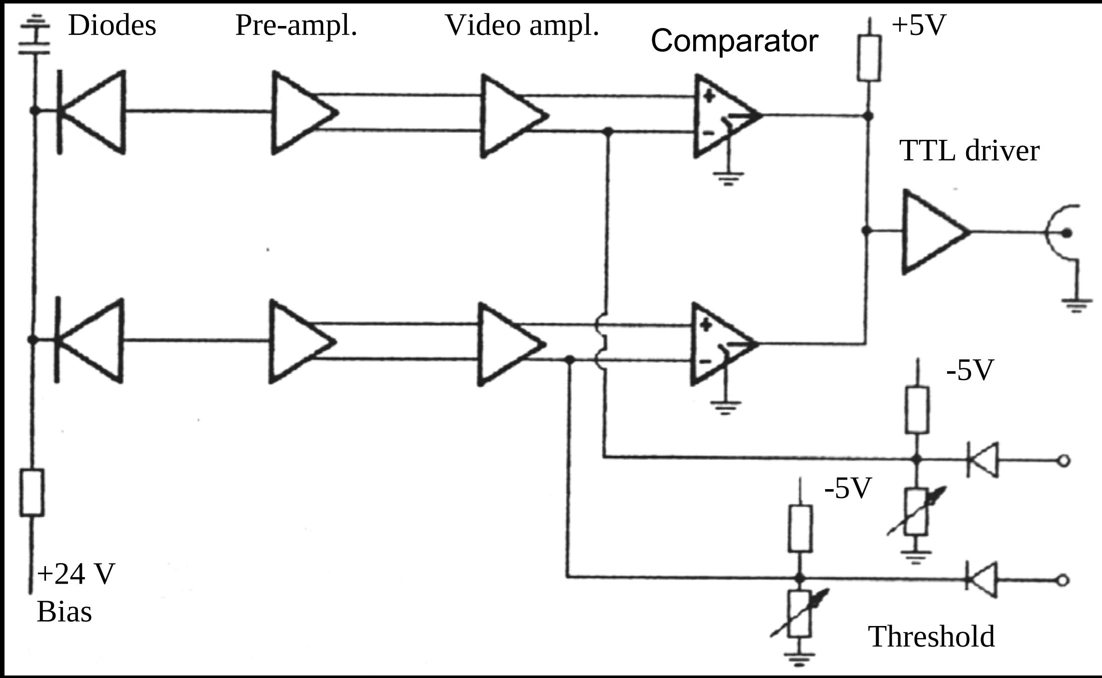
LHC

Beam Loss Detectors

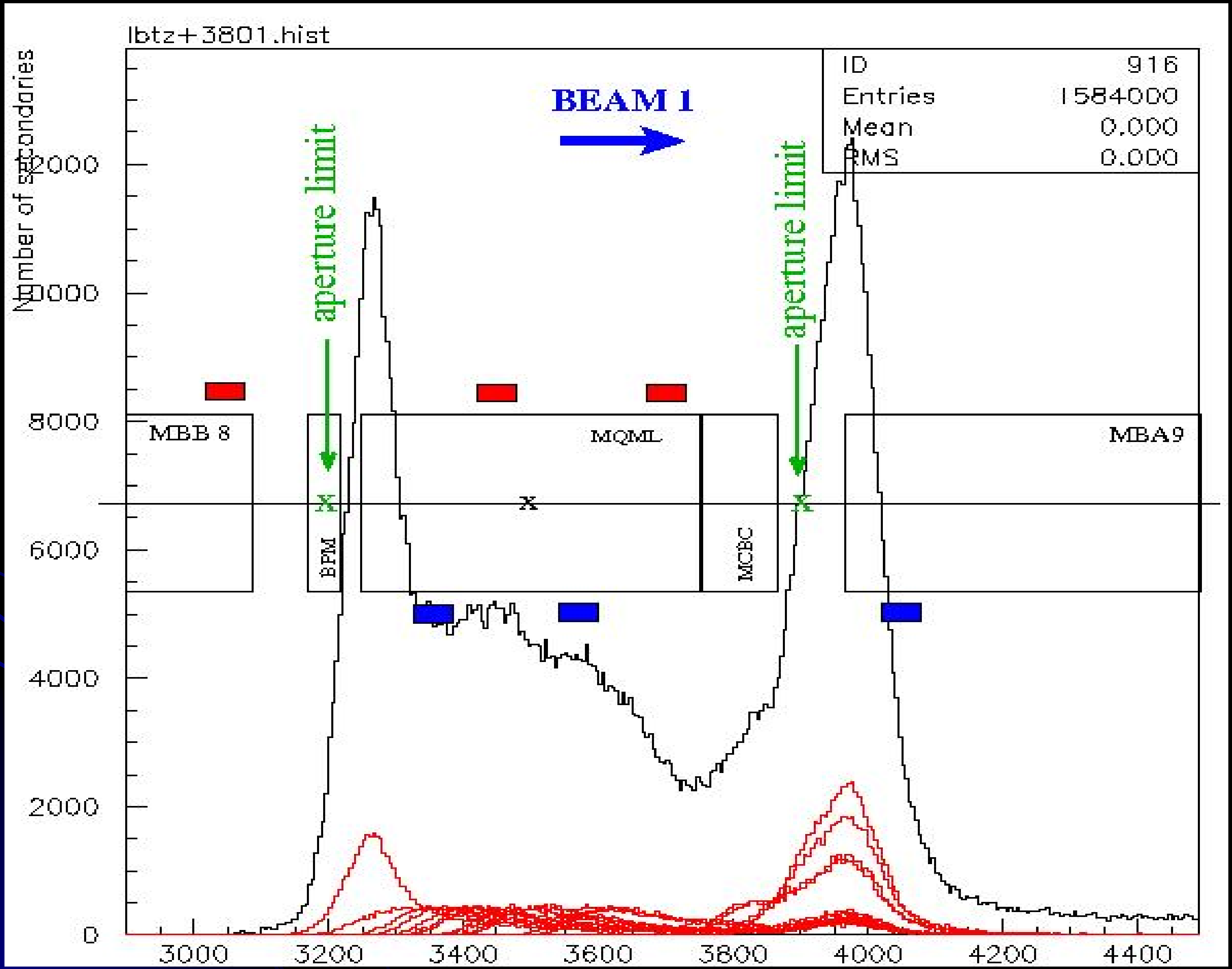
- Common types of monitor (cont)
  - PIN photodiode (count detection)
    - Detect MIP crossing photodiodes
    - Count rate proportional to beam loss
    - Speed limited by integration time
    - Dynamic range of up to 10^9







BLM Threshold Level Estimation



Summary

We have seen a wide variety of instruments using many different technologies

Tomorrow you will see how to use these instruments to run and optimise accelerators

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Accelerator Beam Diagnostics