Introduction to Beam Instrumentation & Beam Diagnostics

CAS 2005

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(CERN)

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

A Beam Diagnostics and Instrumentation activity shall design, build, maintain and improve the diagnostic instruments that allow the observation of particle beams with the precision required to diagnose, tune, operate and improve the accelerators and associated transfer lines.

This means that Beam Instrumentation combines the disciplines of accelerator physics, mechanical engineering, electronic engineering and software engineering.

In Short: One of the most fascinating fields of work I can imagine

Introduction to Beam Instrumentation

Today we Focus on

"What and How we Measure"

& the technologies involved

- Introduction
  - → What do we mean by "Beam Instrumentation"
  - → What instruments are involved
- Beam Instrumentation Selection
  - → Beam Position Measurement
  - → Beam Intensity Measurement
  - → Beam Profile Measurement

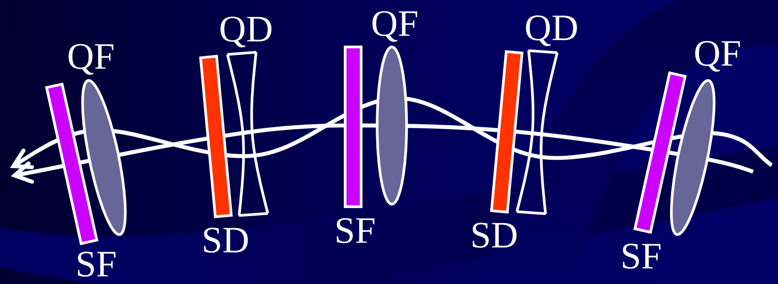
Introduction

- 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 all around the ring
    - Corrected using orbit corrector magnets (dipoles)
  - → Beam Intensity (& lifetime measurement for a collider)
    - Circulating current and bunch-by-bunch charge
  - → Beam Loss all around the ring
    - Especially important for superconducting machines
  - → Beam profiles
    - Transverse and longitudinal distribution
  - → Collision rate / Luminosity (for colliders)

More Measurements

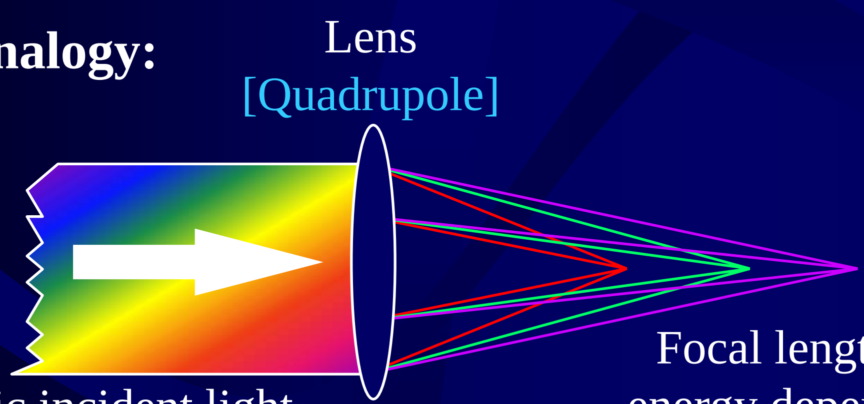
- Machine Tune



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
- Beam Loss
  - → ionisation chambers or pin diodes
- Luminosity
  - → ionisation chambers or semiconductors
  - → in diagnostics section of tomorrow
- Machine Tunes and Chromacitities
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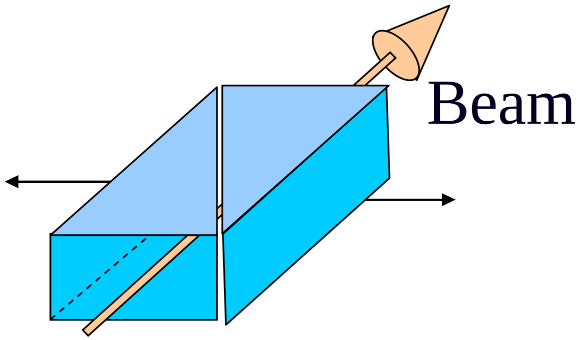
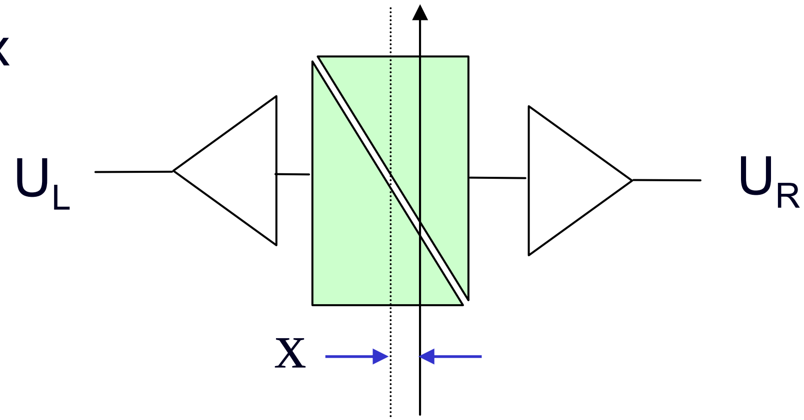
Shoebox pick-up

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

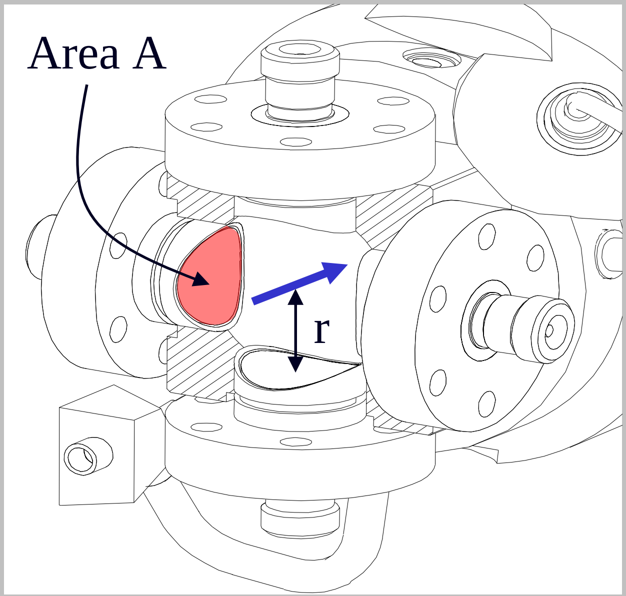
Electrostatic PU (Button)

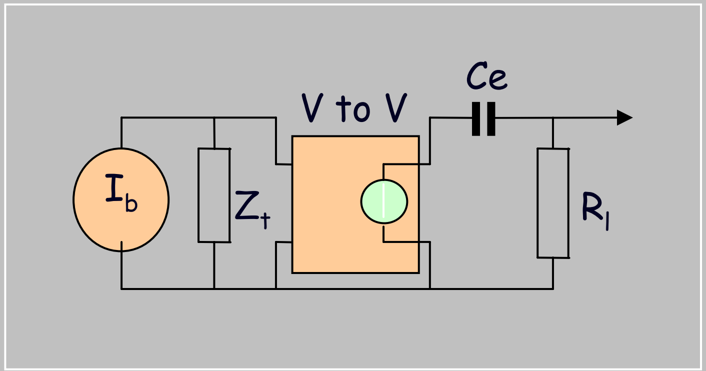
- ✓ Variant of electrostatic PU
- ✓ Low cost ⇒ most popular
- ✗ Non-linear
  - requires correction algorithm when beam is off-centre

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

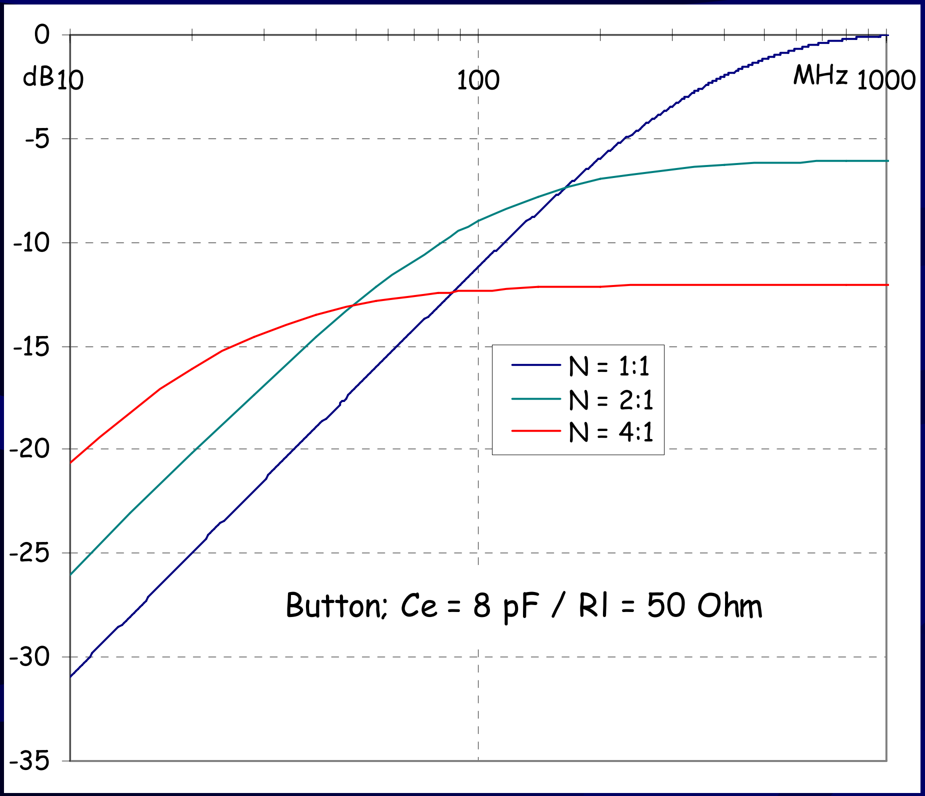
Low frequency cut-off

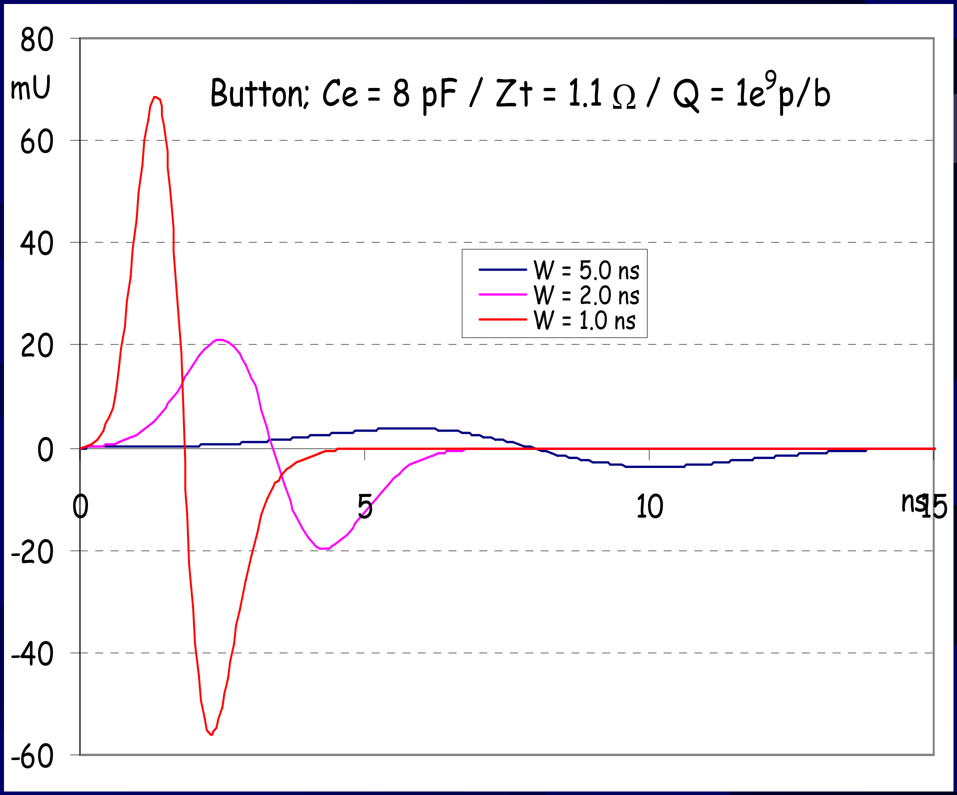
$T = R_l C_e$ (few hundreds MHz)





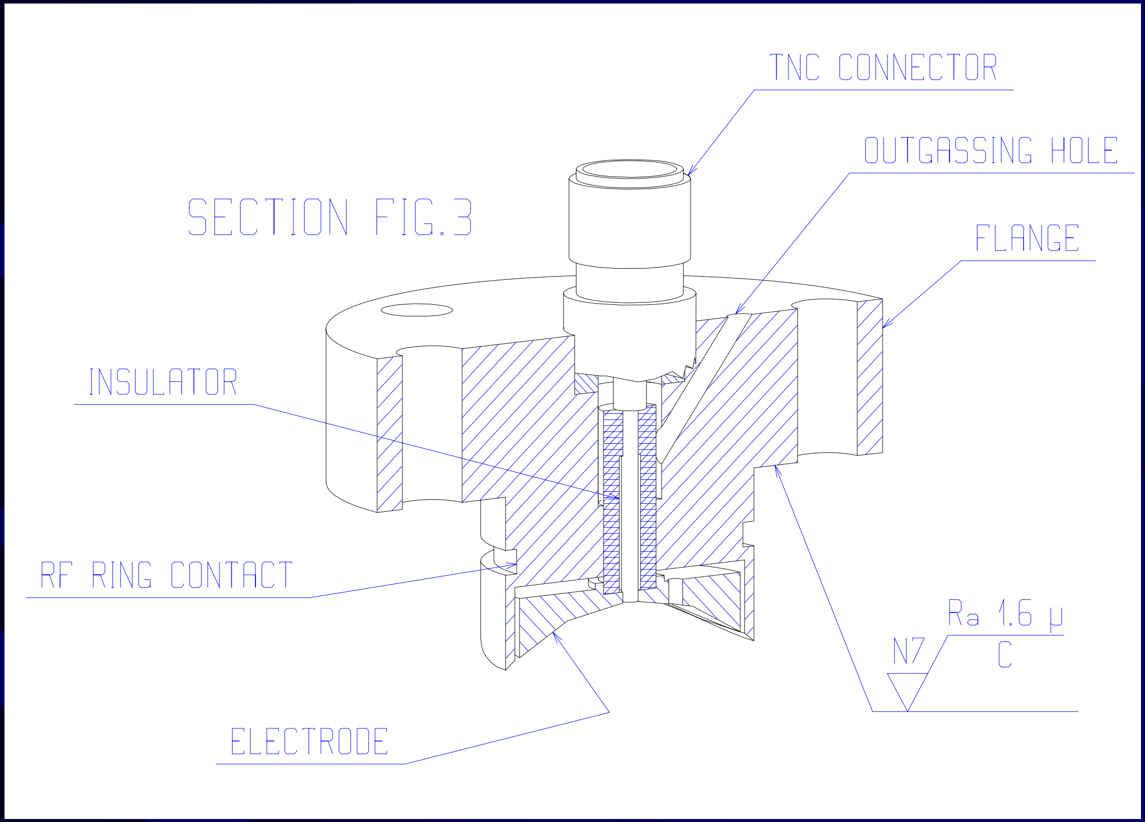
Button Frequency & Time Response





- 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

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

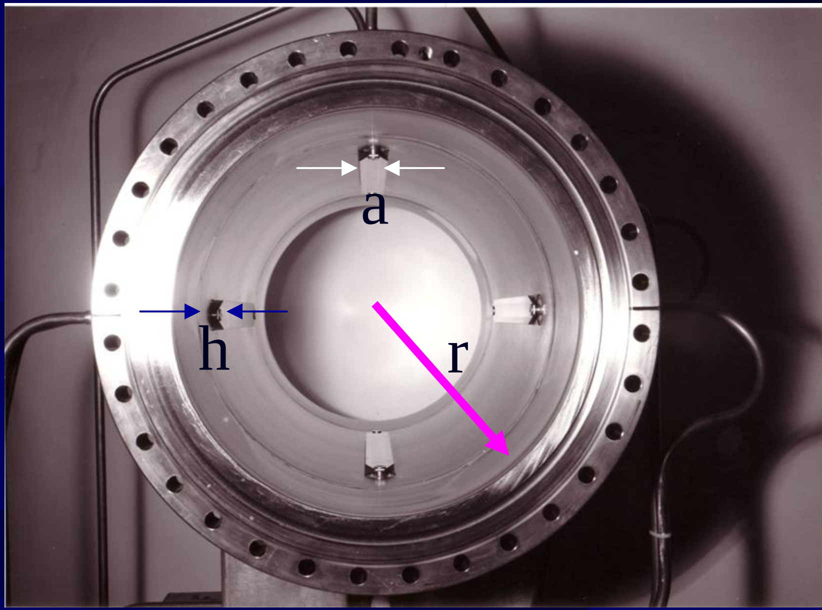


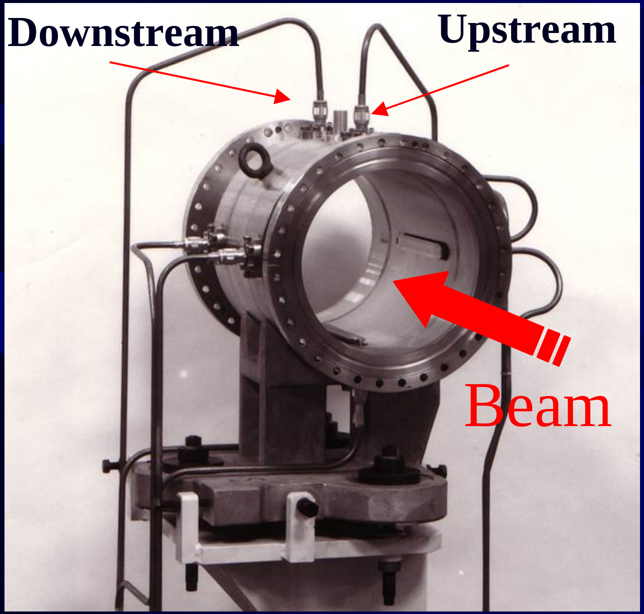
Electromagnetic (Directional) coupler

- Is a transmission line (strip line) which couples to the transverse electromagnetic (TEM) beam field

$$Z_{t\,\infty} = 60 \ln[(r+h)/r] \equiv Z_0 * [a/2\pi(r+h)]$$

  - Z_0 is the characteristic impedance
  - a, r, h, l are the mechanical dimensions
  - t = l/c is the propagation time in the coupler

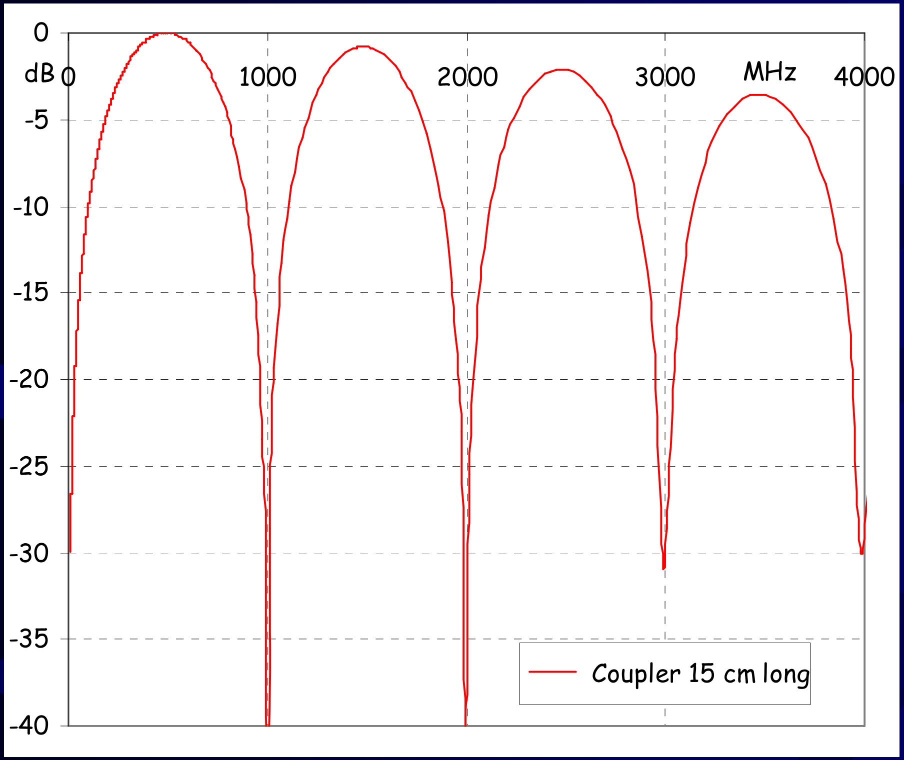


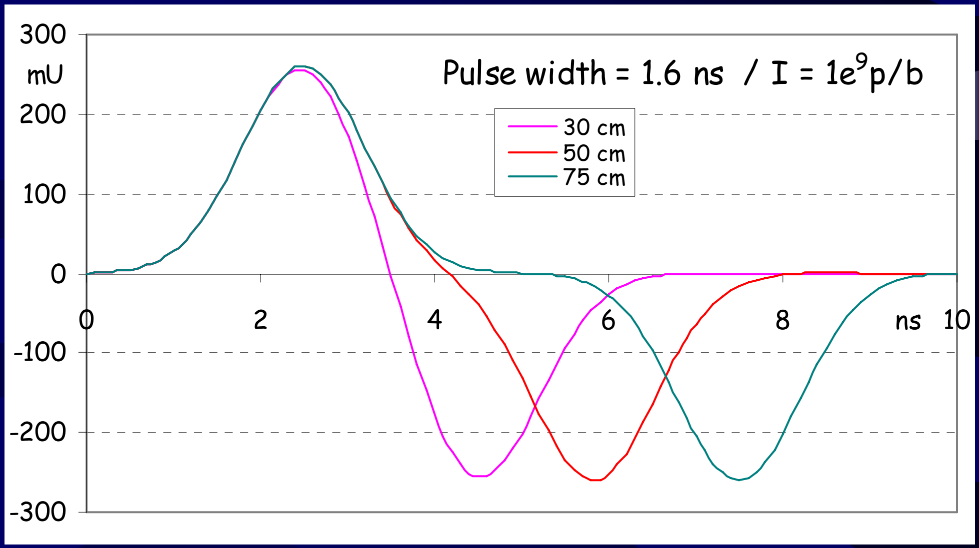


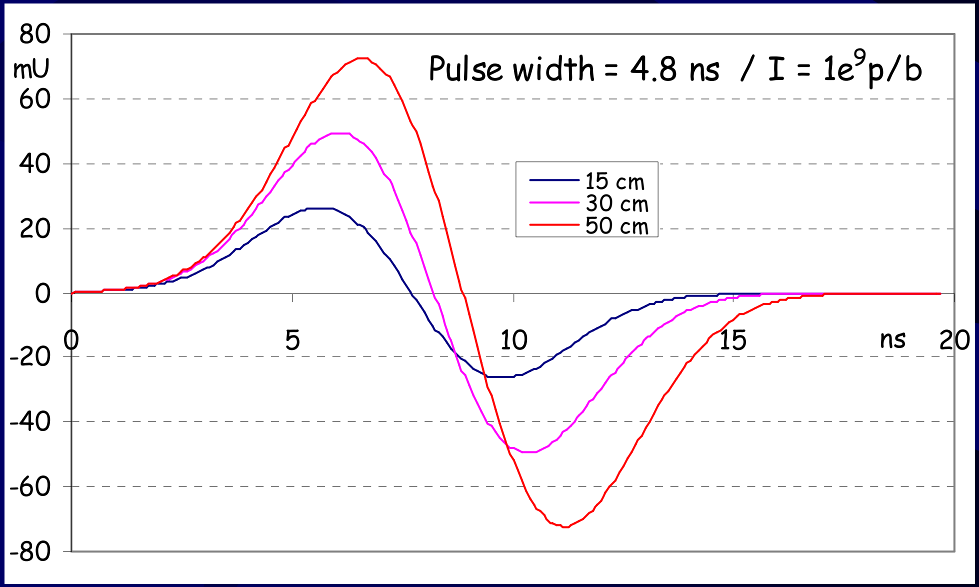
- Two termination ports
  - → Upstream: usually used to acquire signal.
    - Same signal seen whether Downstream port is open, shorted or terminated by Z_0
  - → Downstream: 2 cases
    - Upstream terminated by $Z_0 \Rightarrow$ no signal
    - Upstream short circuit $\Rightarrow$ delayed & inverted signal

Directivity!

Coupler frequency & time response

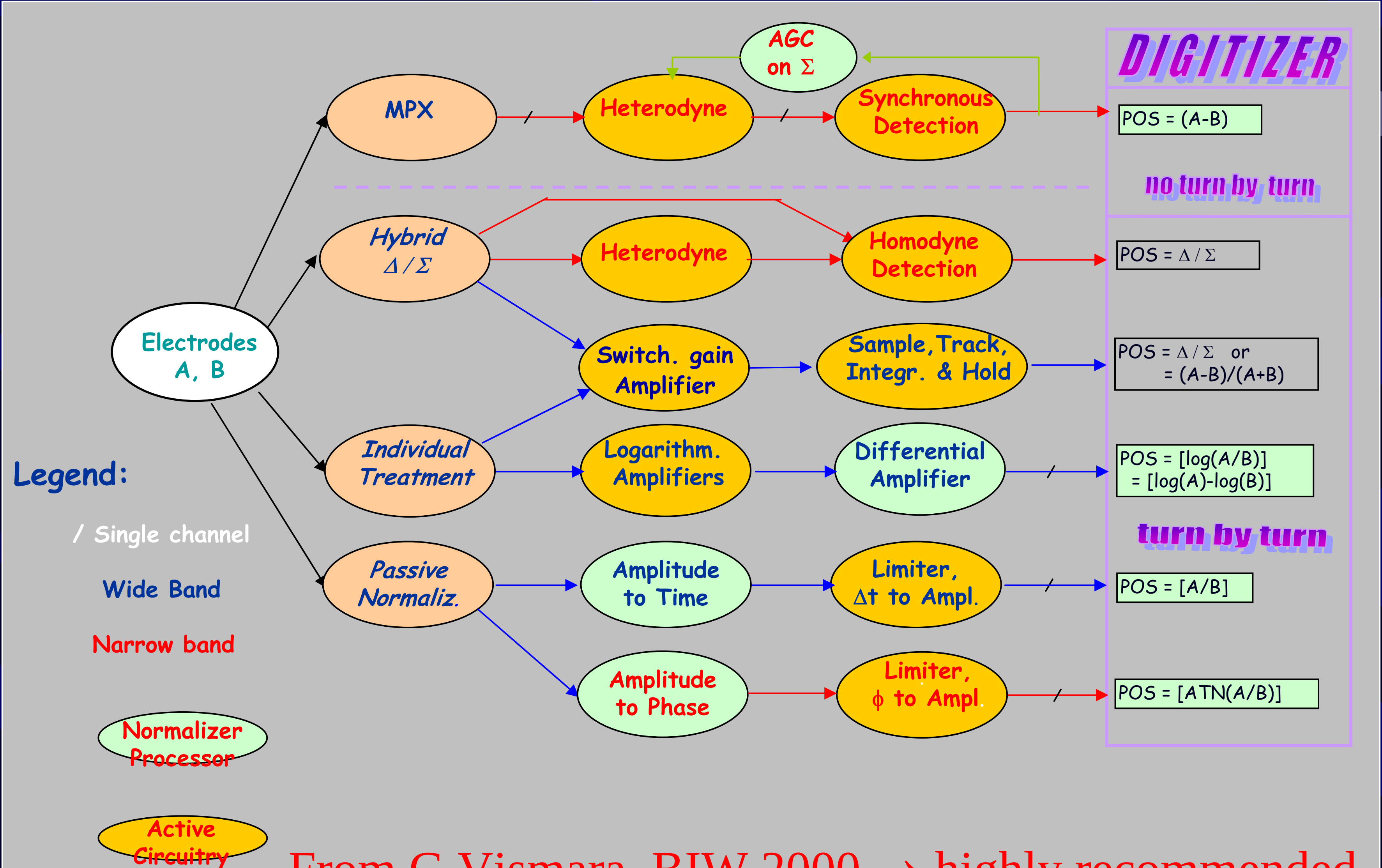






- Sinusoidal amplitude response
  - → Maximum signal for f = 1/4*t
  - → Zero signal for f = 1/2*t
- Time domain:
  - •Bipolar pulse

Processing system families

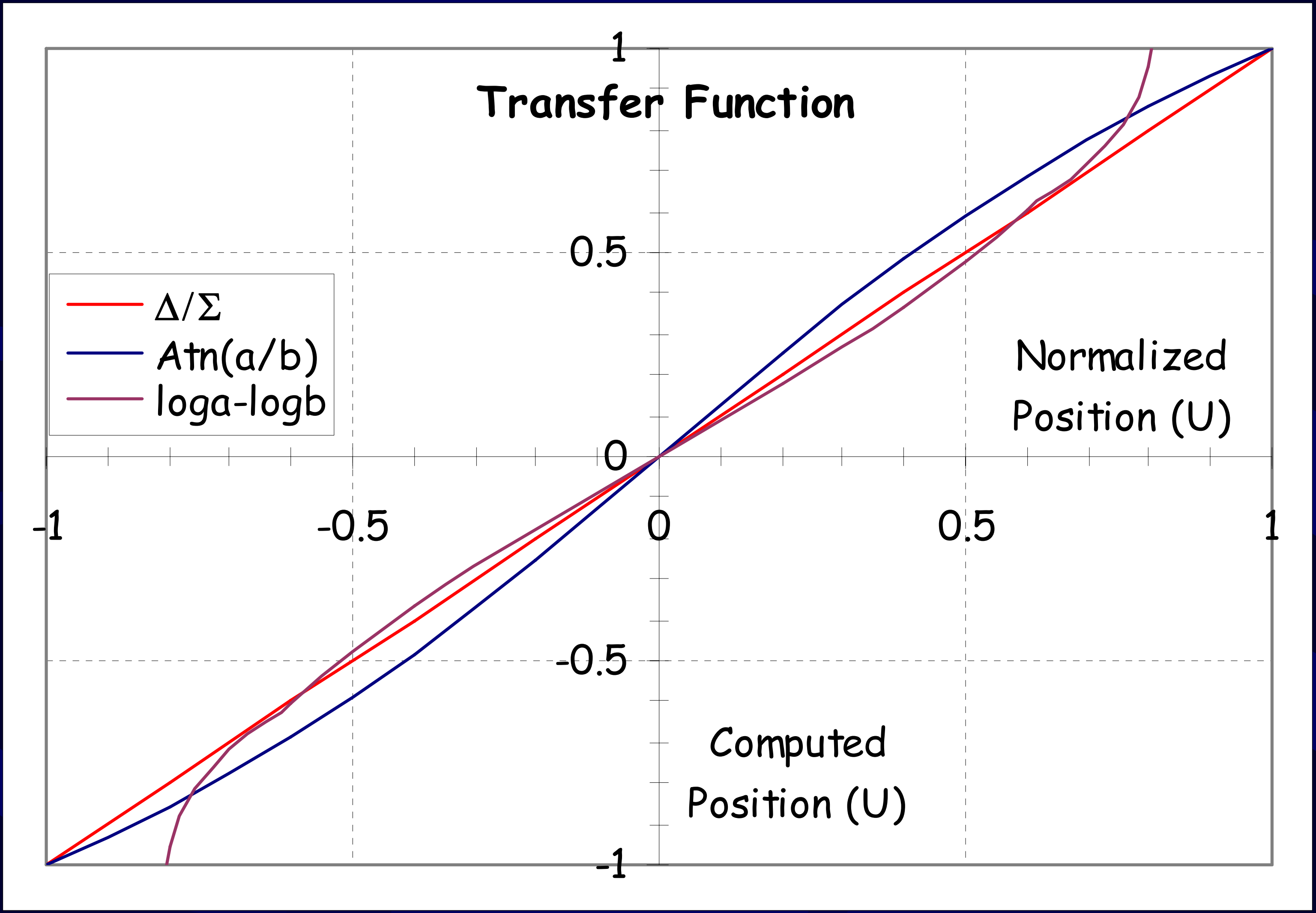


From G.Vismara, BIW 2000 → highly recommended

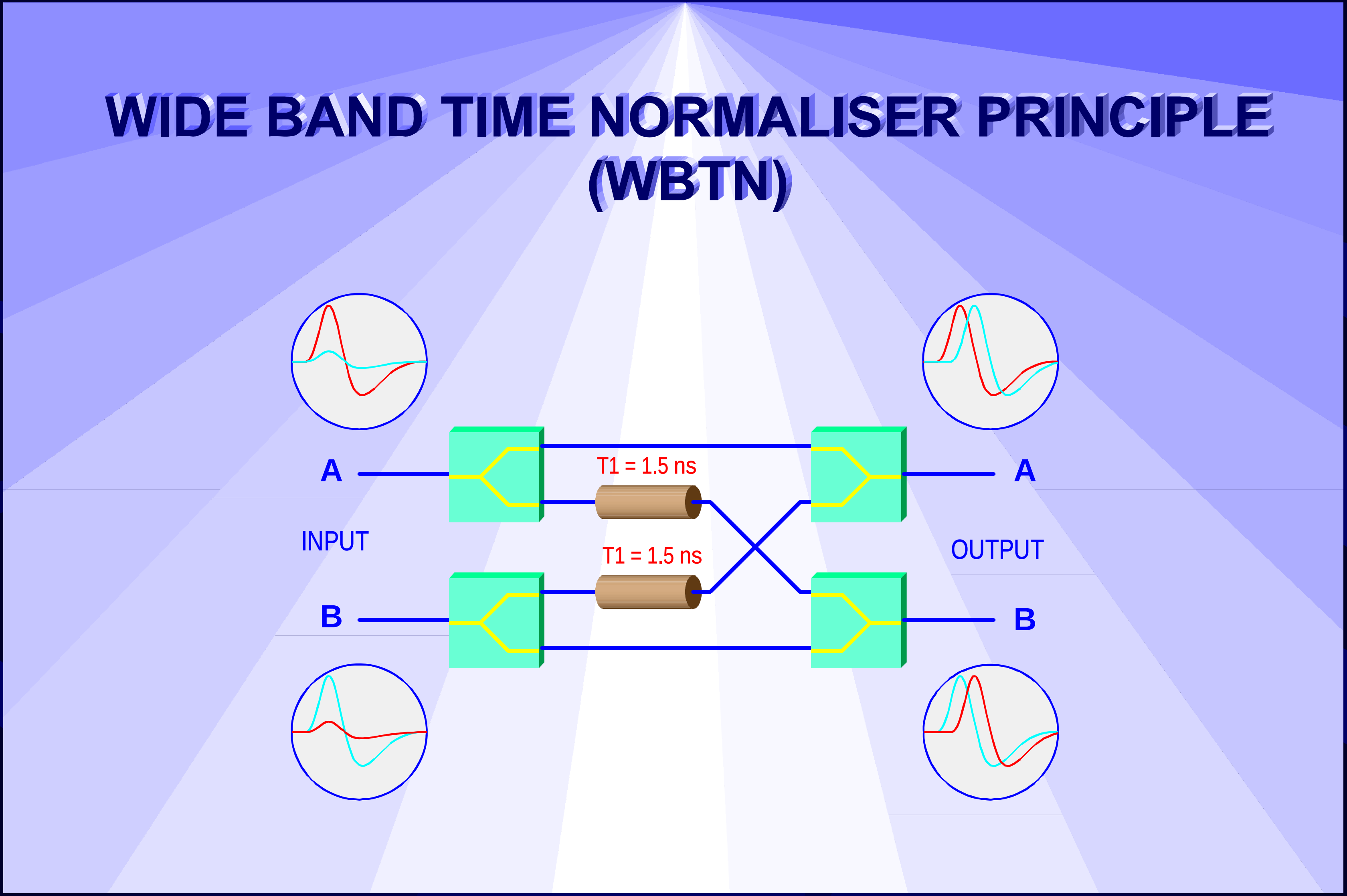
Criteria for Electronics Choice - so called "Processor Electronics"

- 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

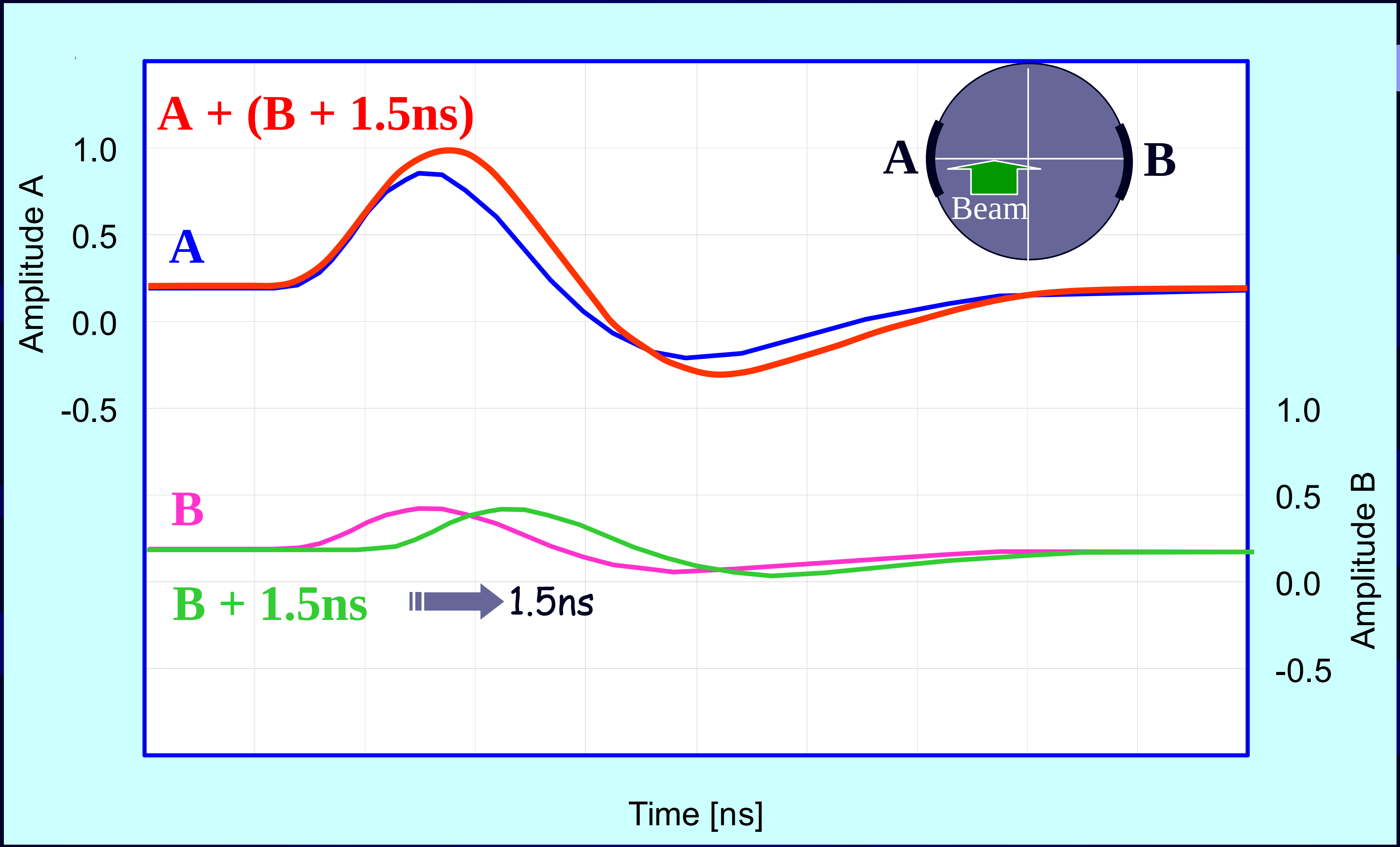
LINEARITY Comparison



A Real System:
LHC Amplitude to Time Normaliser Schematics



The Wide Band Time Normaliser



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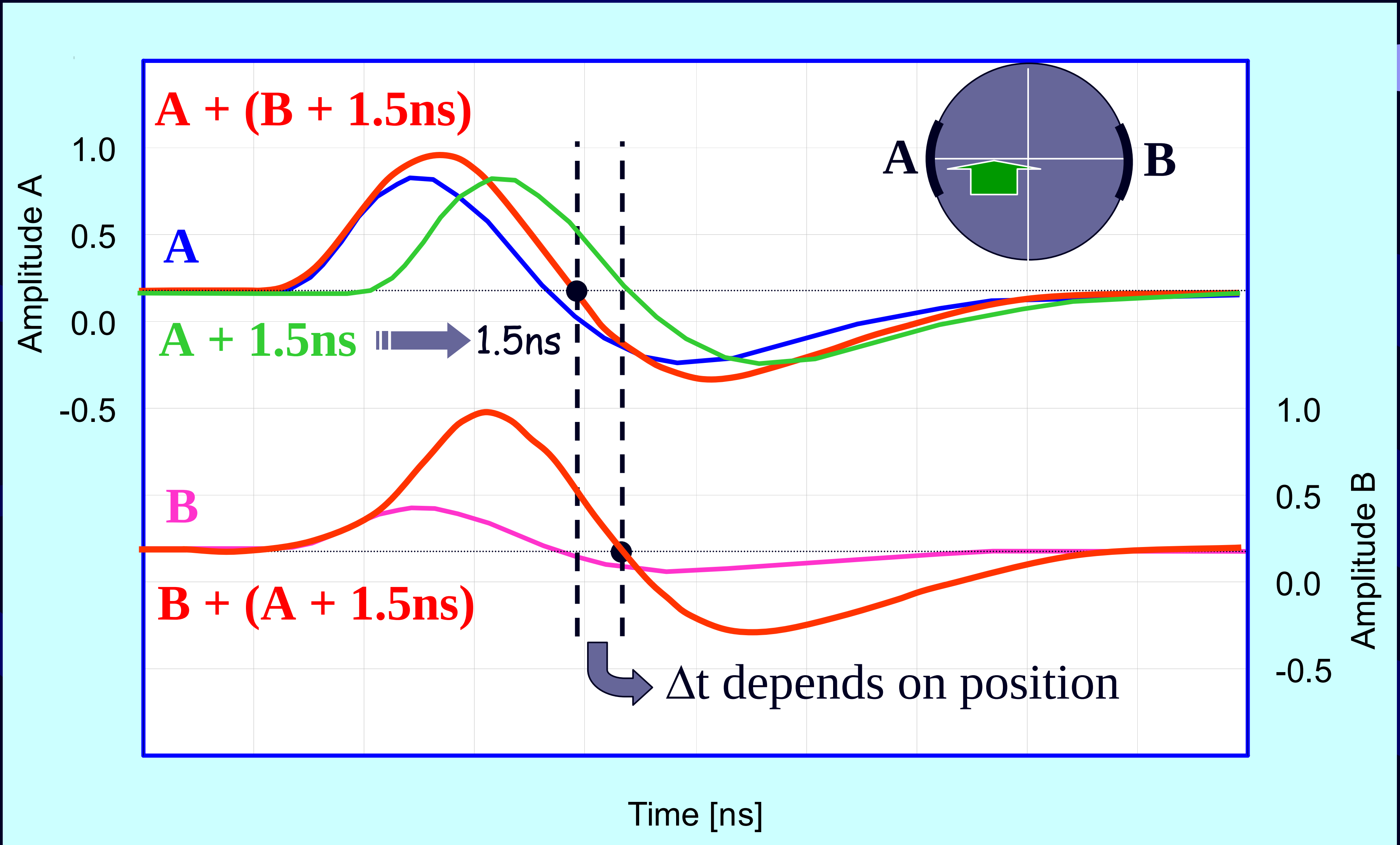

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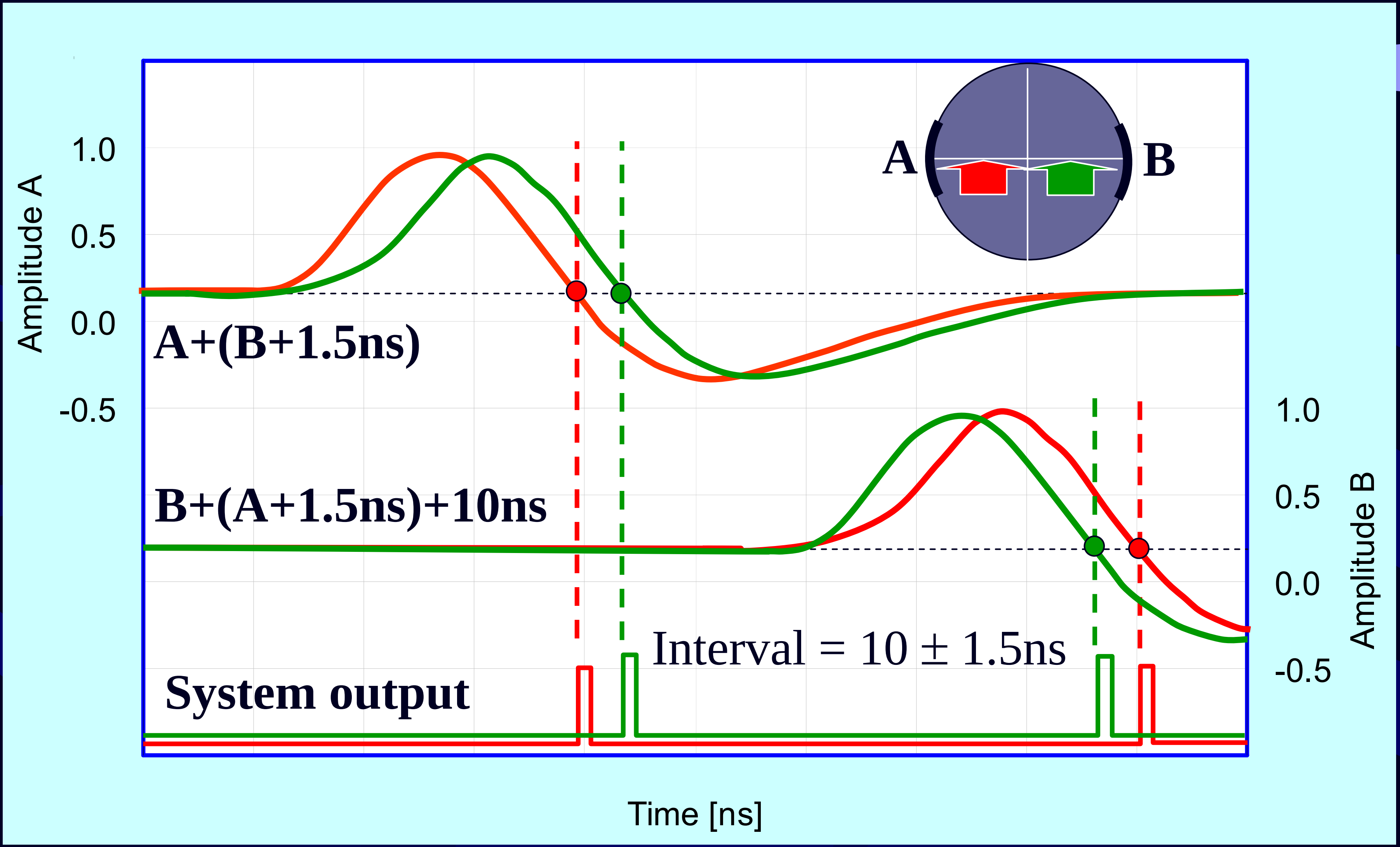


Amplitude to Time Normaliser Evaluation

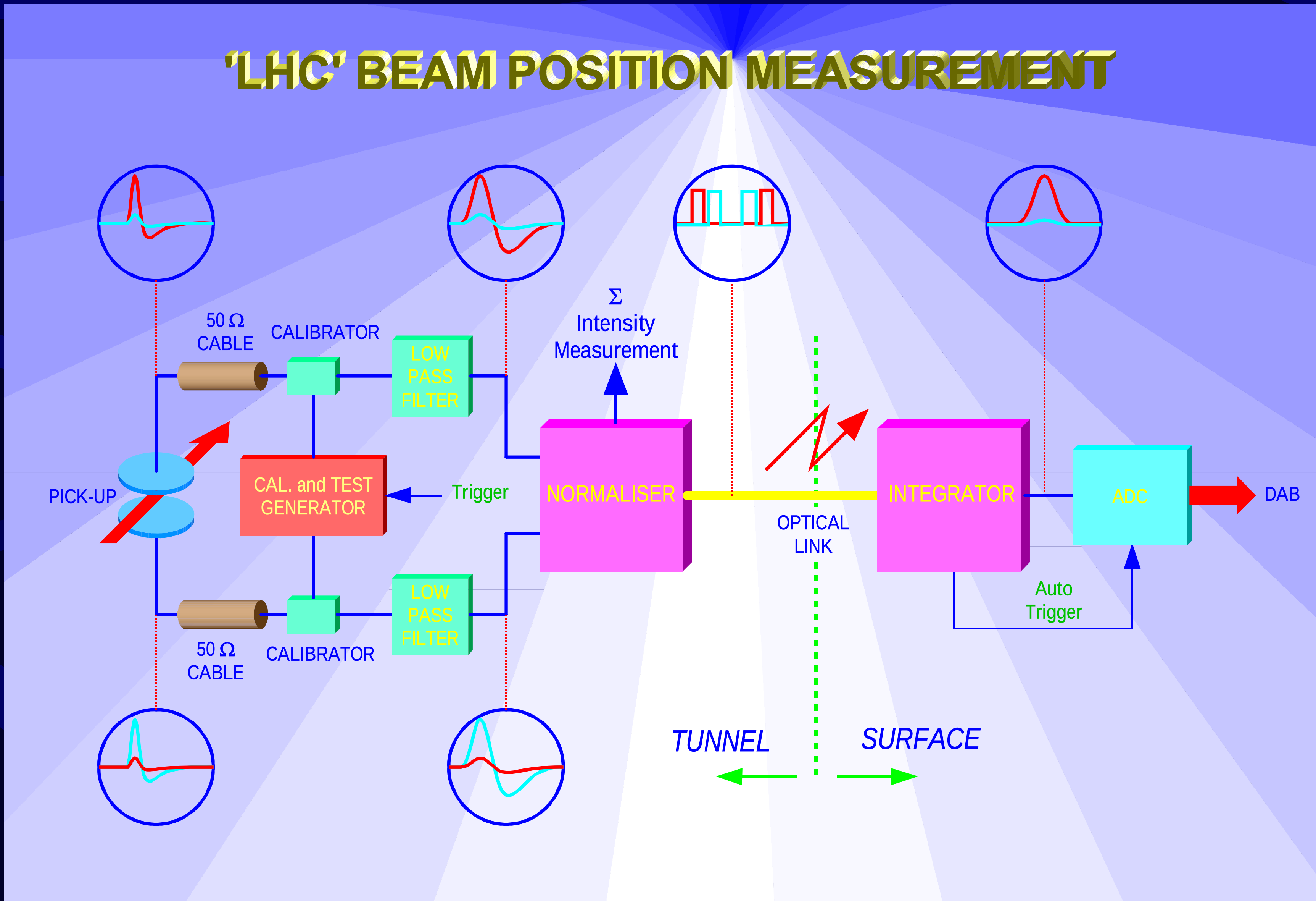
Advantages

- Fast normalisation (< 25ns)
  - → bunch to bunch measurement
- Reduced number of channels (x2)
  - → normalisation at the front-end
- Signal dynamic independent of the number of bunches
  - → Input dynamic ~ 40 dB
  - → No need for gain selection
- ~10 dB compression of the position dynamic due to the recombination of signals
- Independent of external timing

Limitations

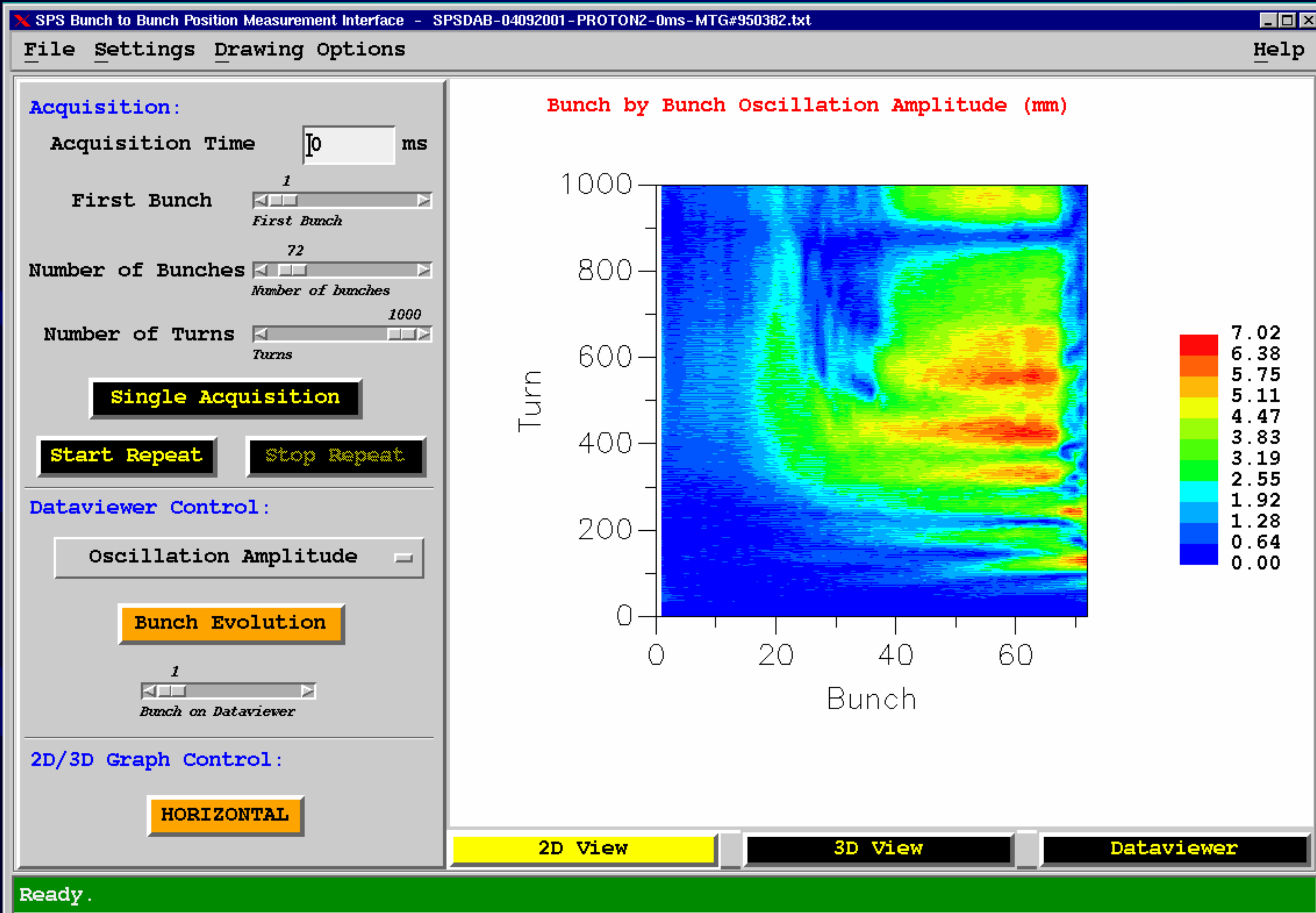
- Reserved for beams with empty RF buckets between bunches
- Tight time adjustment
- No Intensity information
- Propagation delay stability and switching time uncertainty are the limiting performance factors

LHC Beam Position System Layout



What one can do with such a System

Used extensively in 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
- Beam Loss
  - → ionisation chambers or pin diodes
- Luminosity
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- Machine Tunes and Chromacitities
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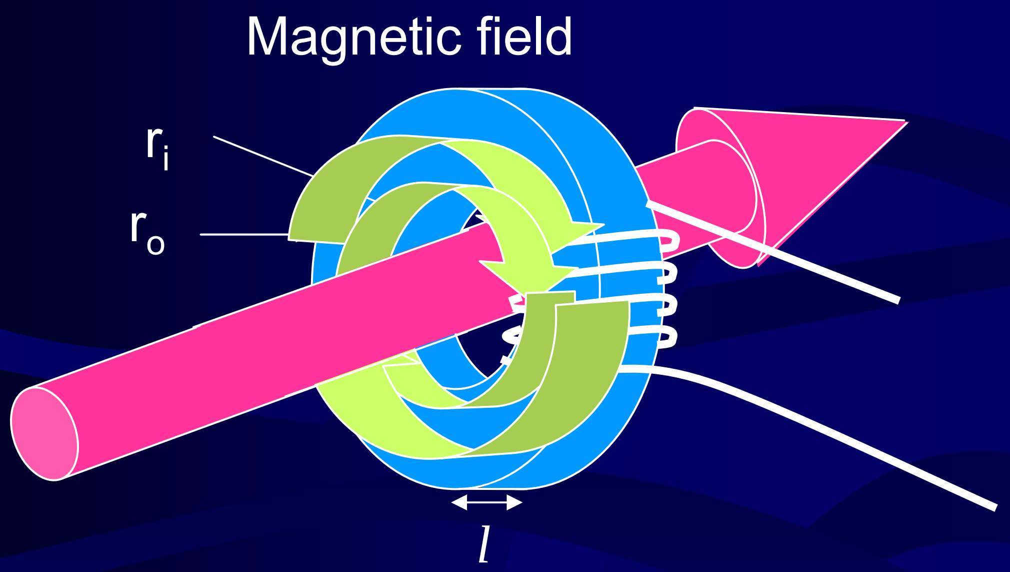
Current Transformers



Fields are very low

Capture magnetic field lines with cores of high relative permeability

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

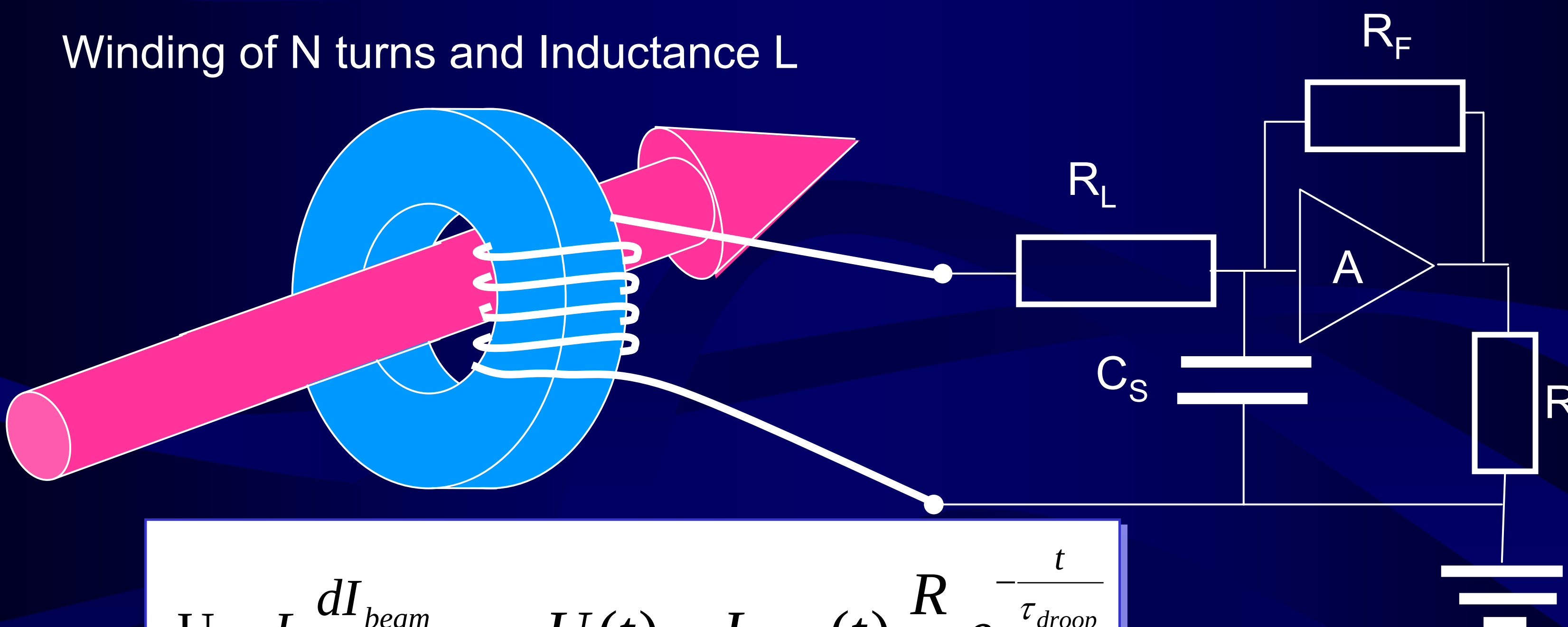
Beam current

$$I_{beam} = \frac{qeN}{t} = \frac{qeN\beta c}{l}$$

Transformer Inductance

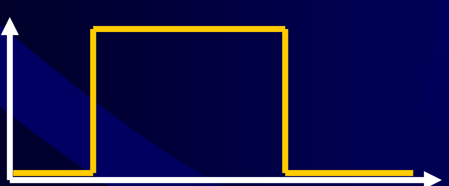
$$L = \frac{\mu_0 \mu_r}{2\pi} l N^2 \ln \frac{r_0}{r_i}$$

The Active AC transformer

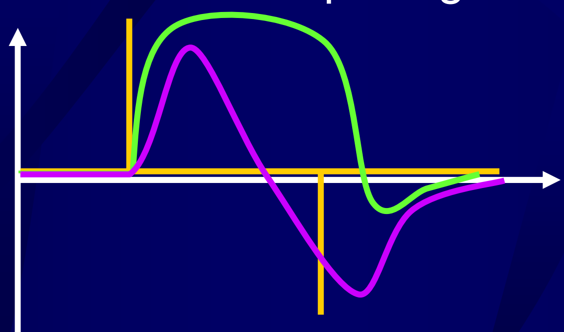


$$U = L\frac{dI_{beam}}{dt} \qquad U(t) = I_{beam}(t)\frac{R}{N}e^{-\frac{t}{\tau_{droop}}}$$

Beam signal



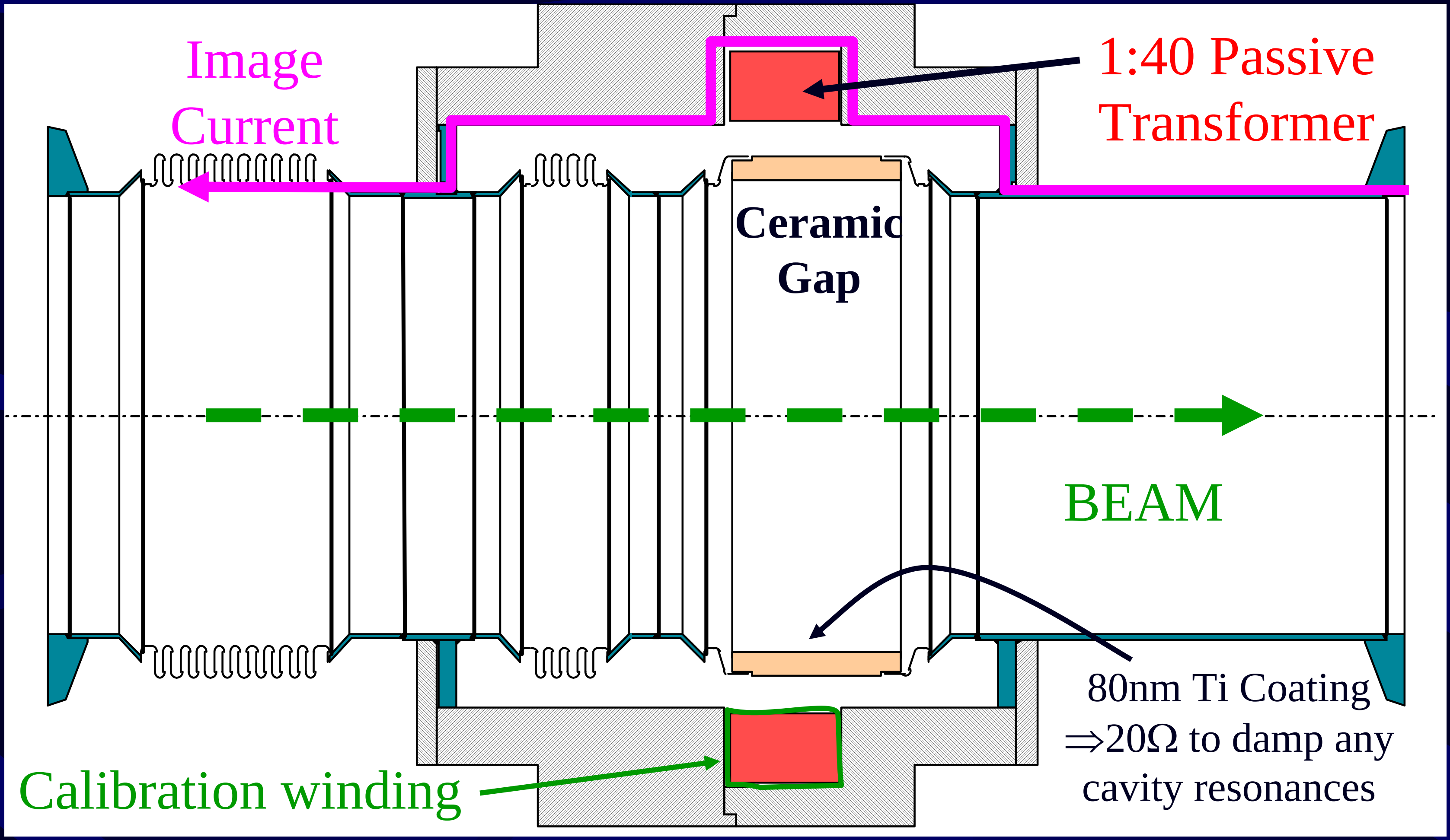
Transformer output signal



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

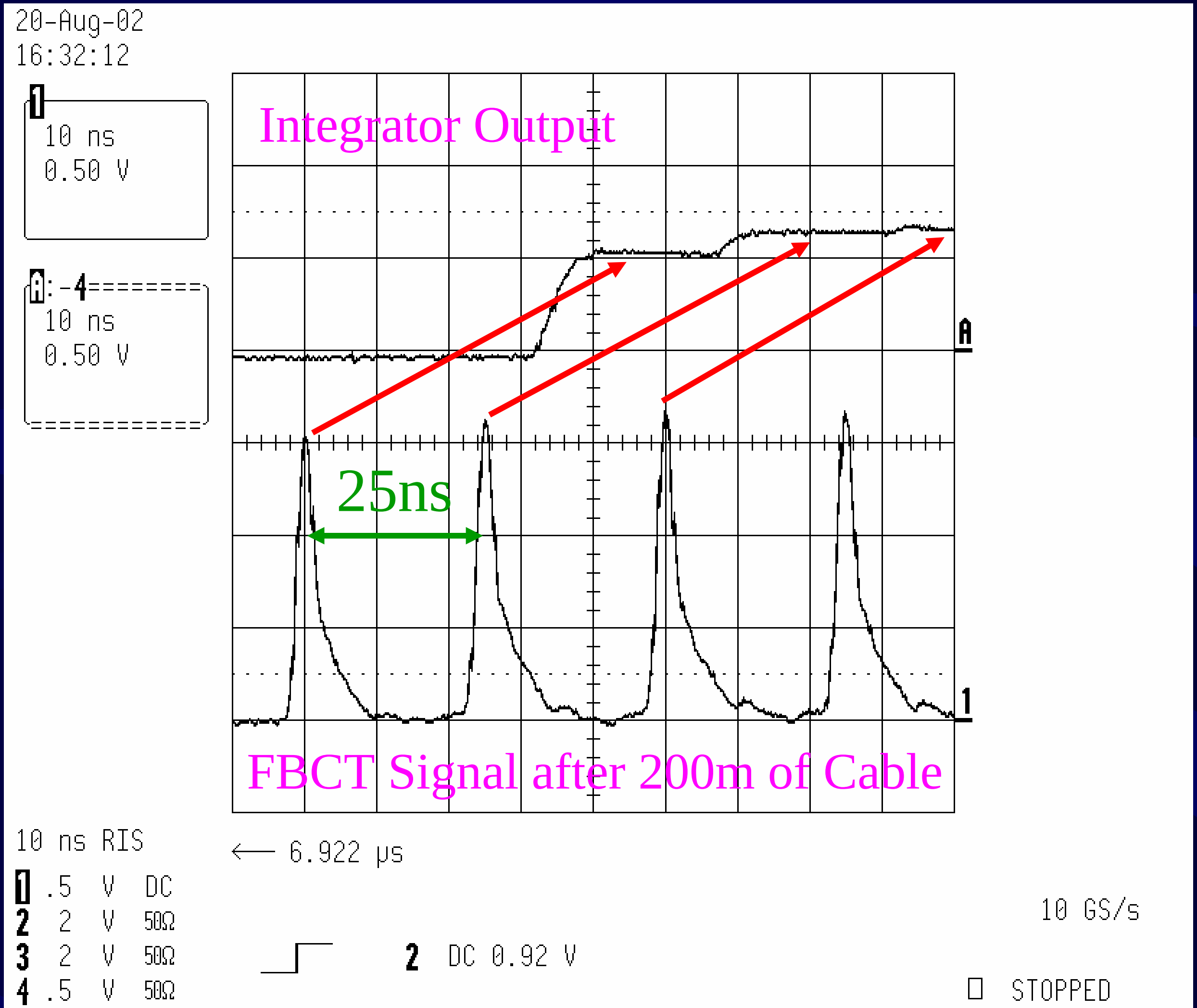
$$\tau_{droop} = \frac{L}{\frac{R_f}{A} + R_L} \approx \frac{L}{R_L}$$

Fast Beam Current Transformer



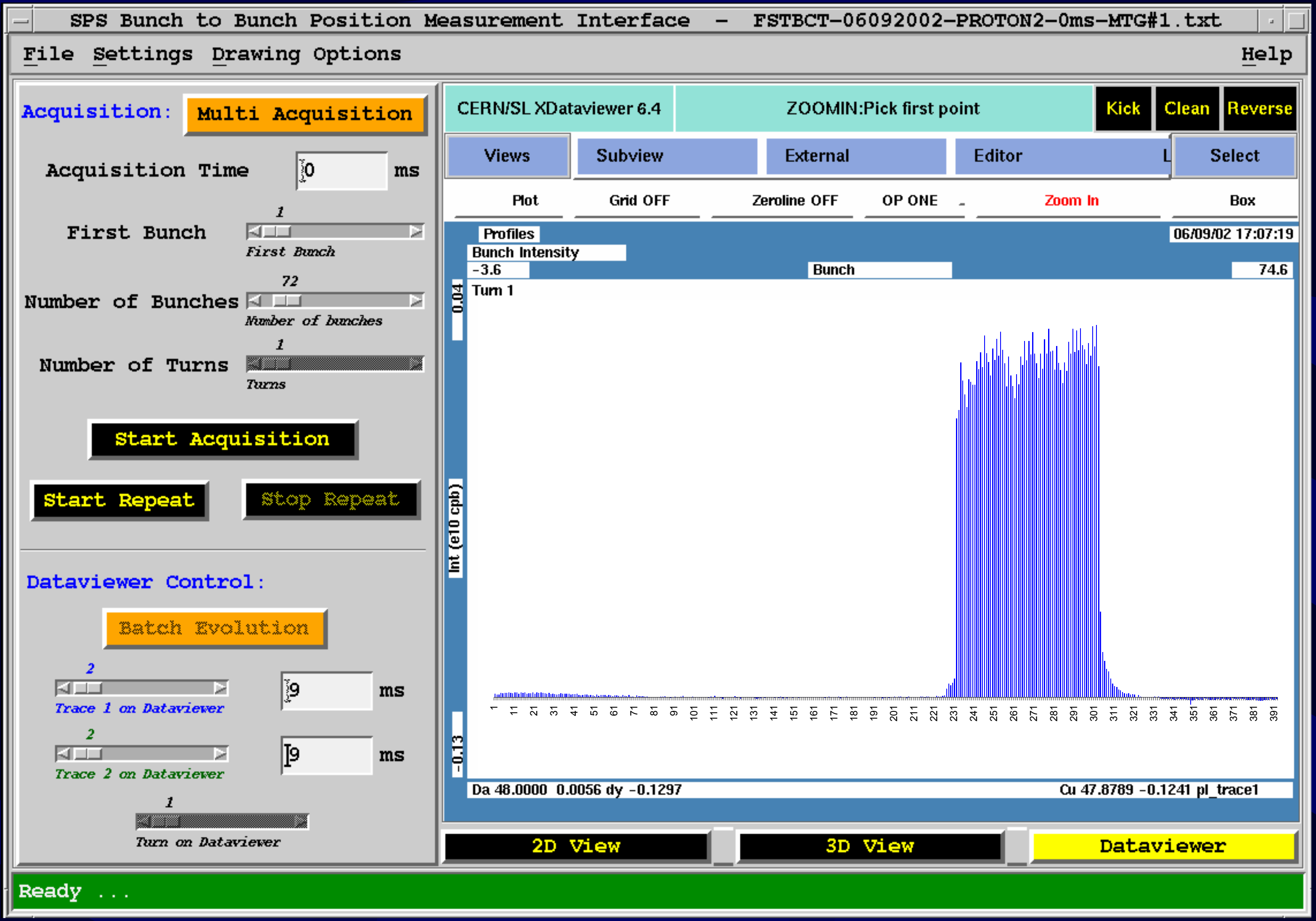
- 500MHz Bandwidth
- Low droop (< 0.2%/μs)

Acquisition Electronics



Data taken on LHC type beams at the CERN-SPS

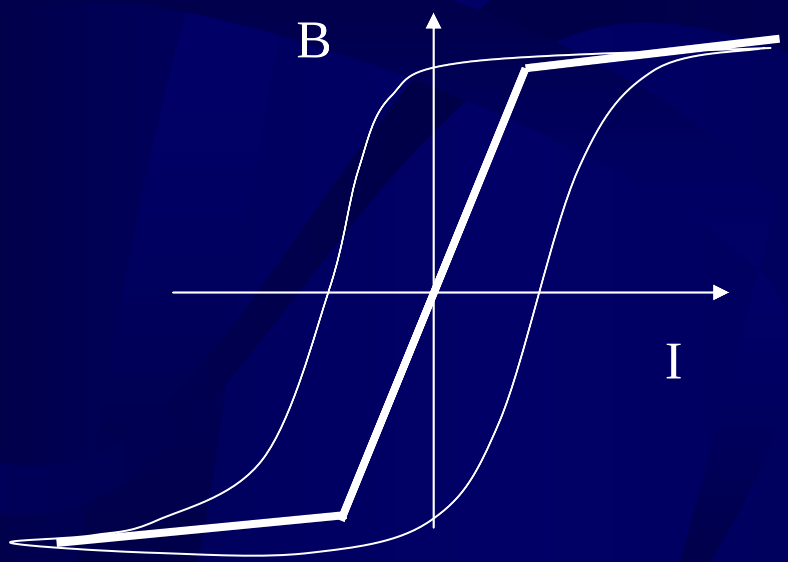
Results from the CERN-SPS



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

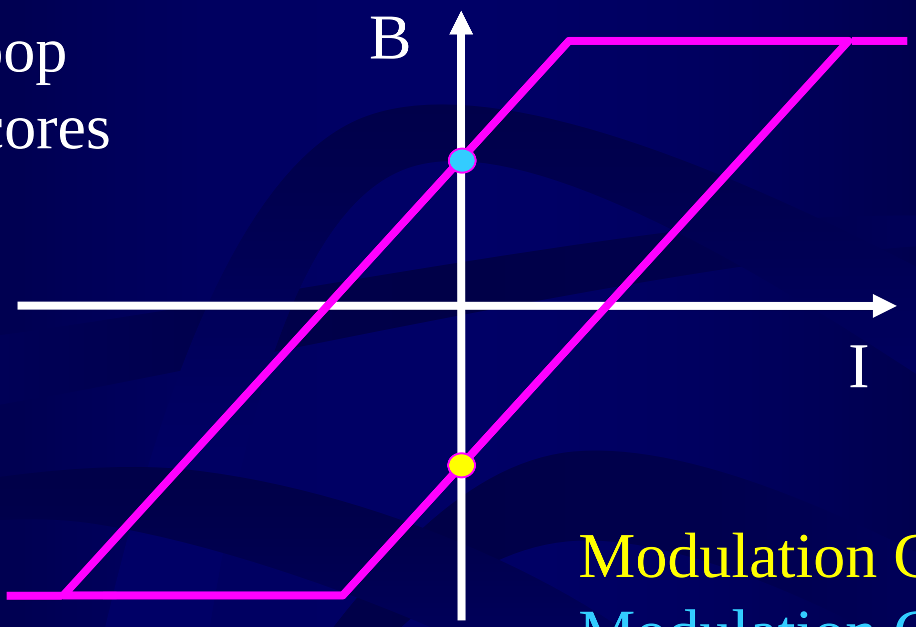
The DC current transformer

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

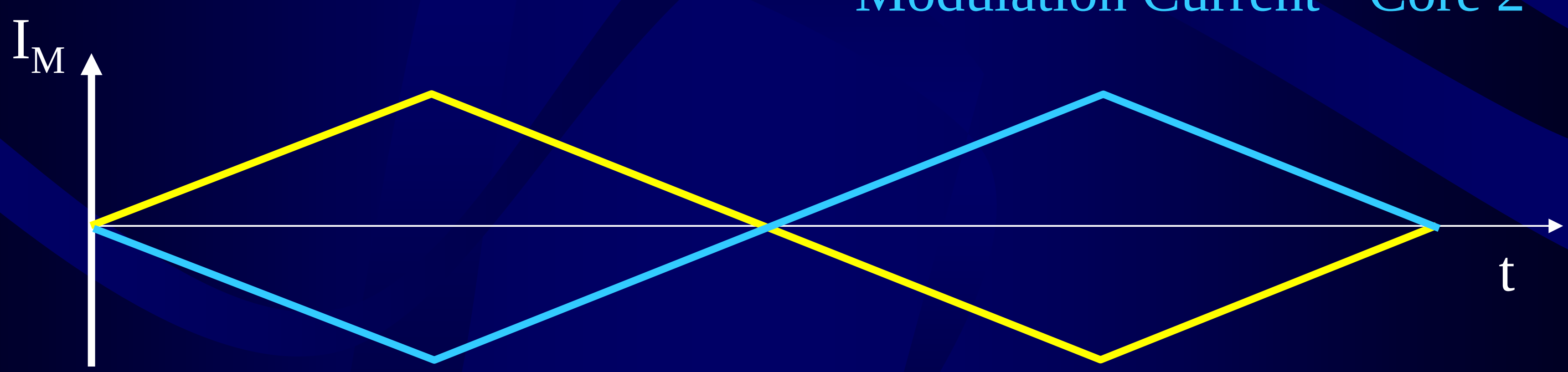


DCCT Principle – Case 1: no beam

Hysteresis loop
of modulator cores

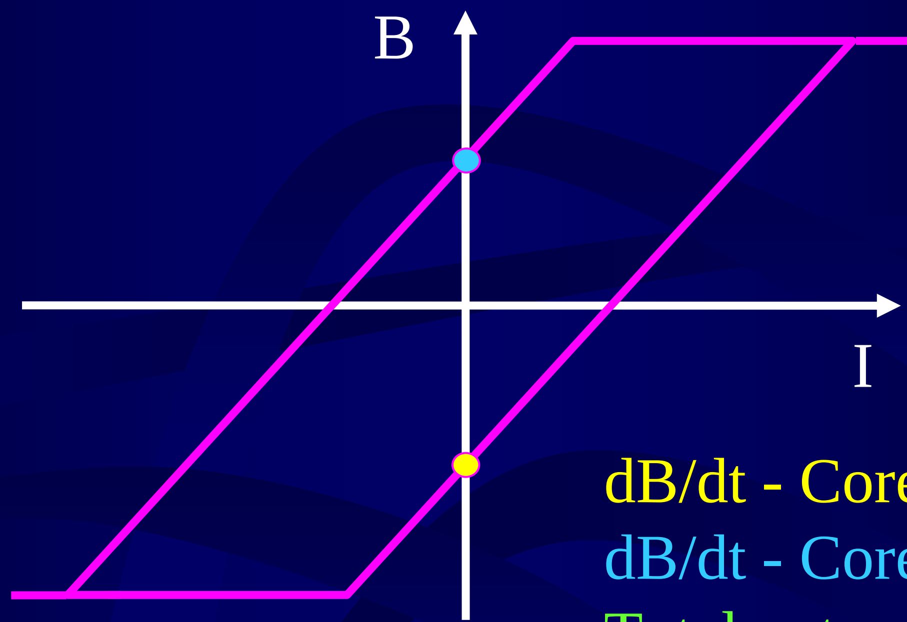


Modulation Current - Core 1
Modulation Current - Core 2



DCCT Principle – Case 1: no beam

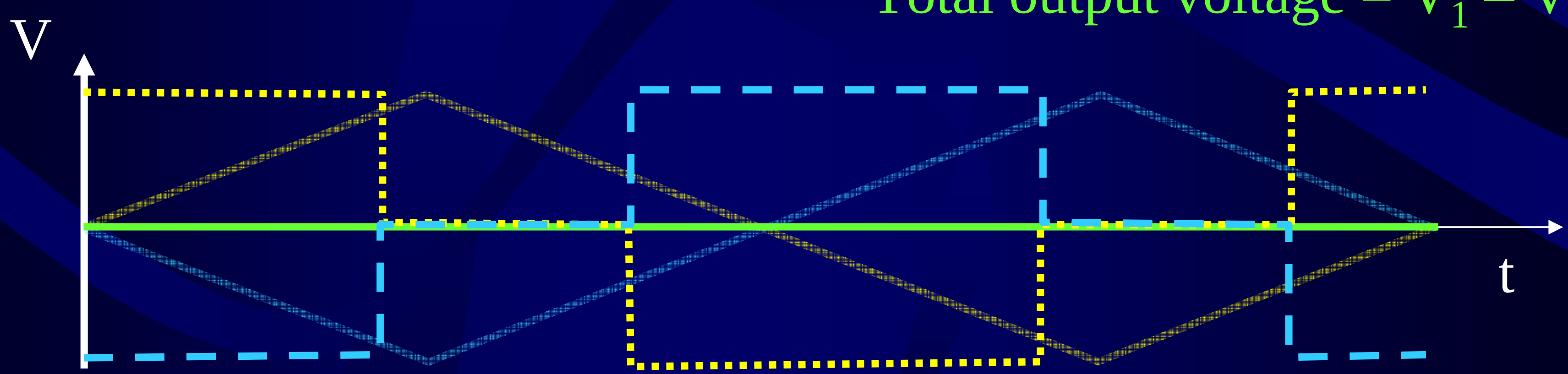
$$V \propto \frac{dB}{dt}$$



dB/dt - Core 1 (V1)

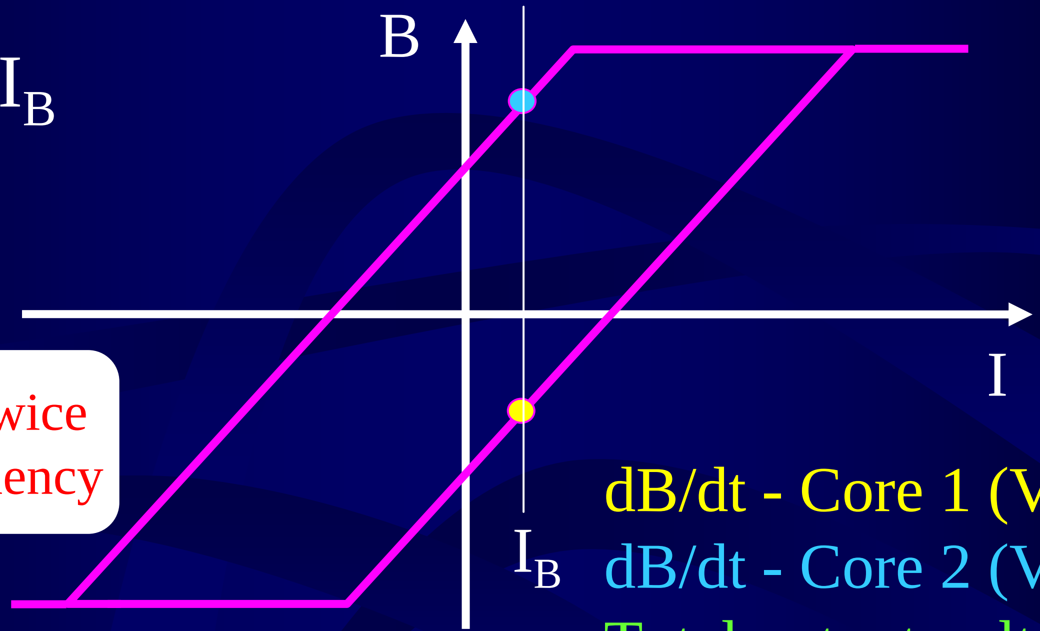
dB/dt - Core 2 (V2)

Total output voltage = $V_1 - V_2$



DCCT Principle – Case 2: with beam

Beam Current I_B

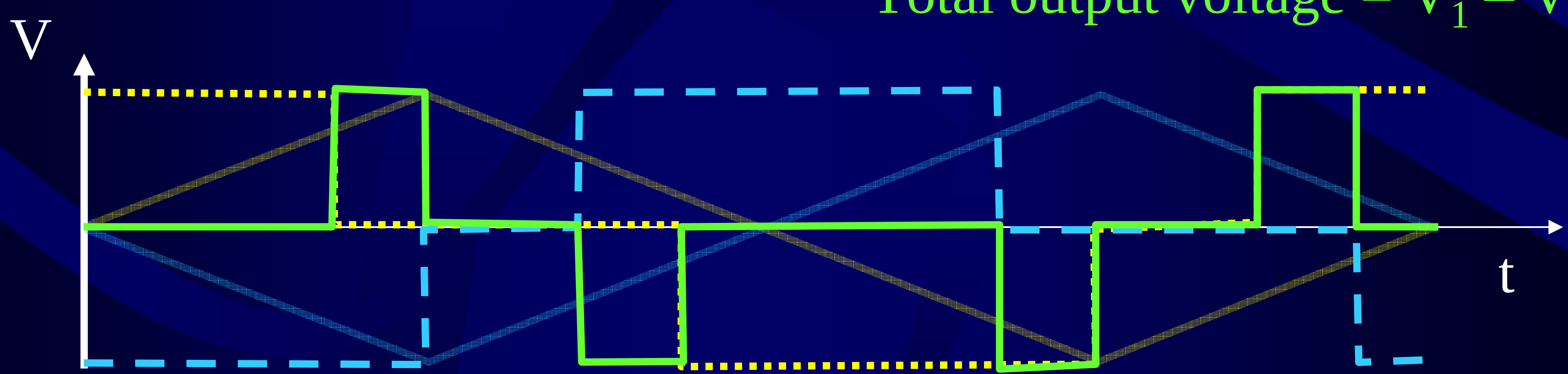


Output signal is at twice the modulation frequency

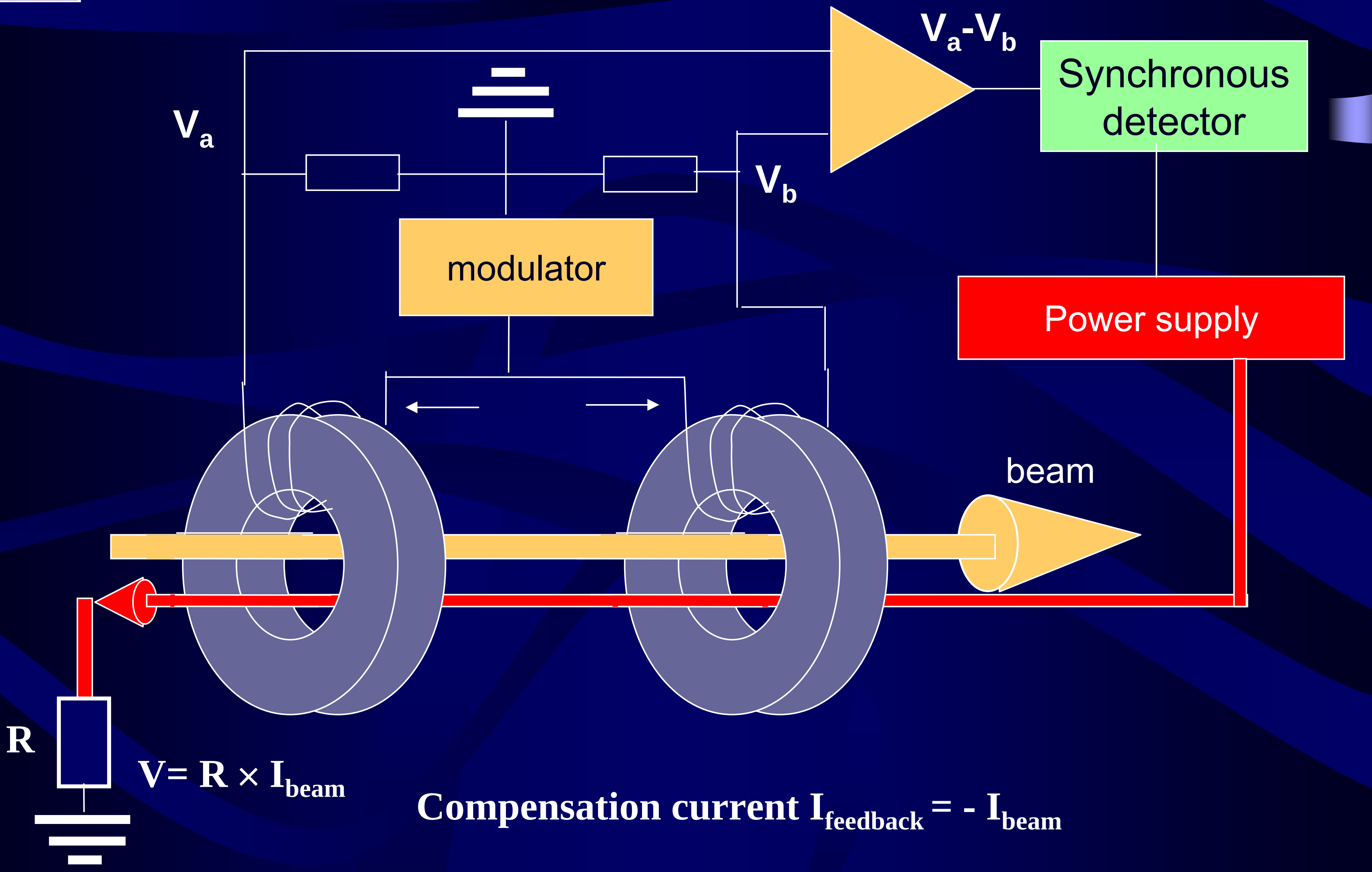
dB/dt - Core 1 (V1)

dB/dt - Core 2 (V2)

Total output voltage = $V_1 - V_2$



Zero Flux DCCT Schematic



$V = R \times I_{beam}$

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

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Measuring Beam Size

- Beam Profile Measurement Methods

→ Secondary emission (SEM) grids

→ Wire Scanners

→ Beam interaction with a screen

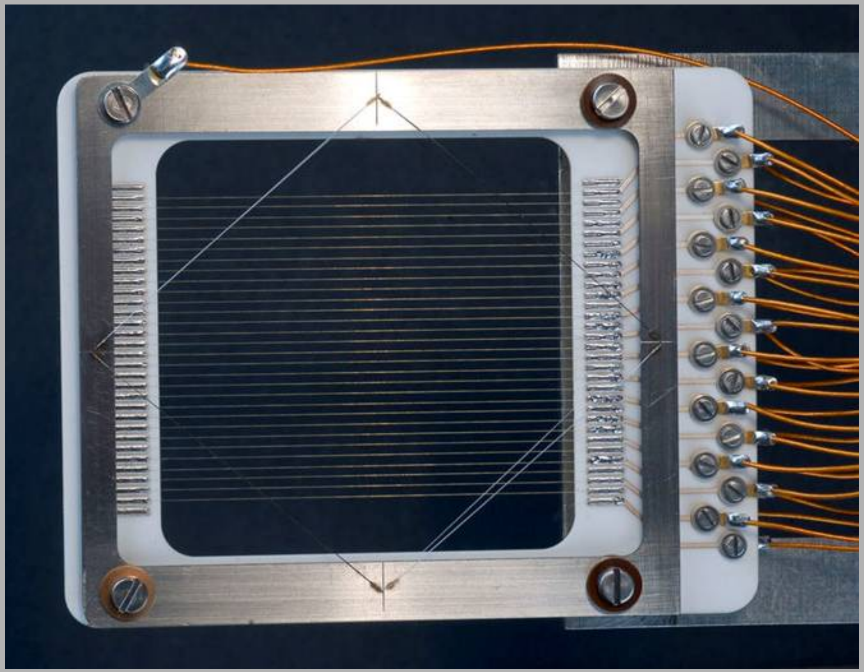
- semi or fully destructive

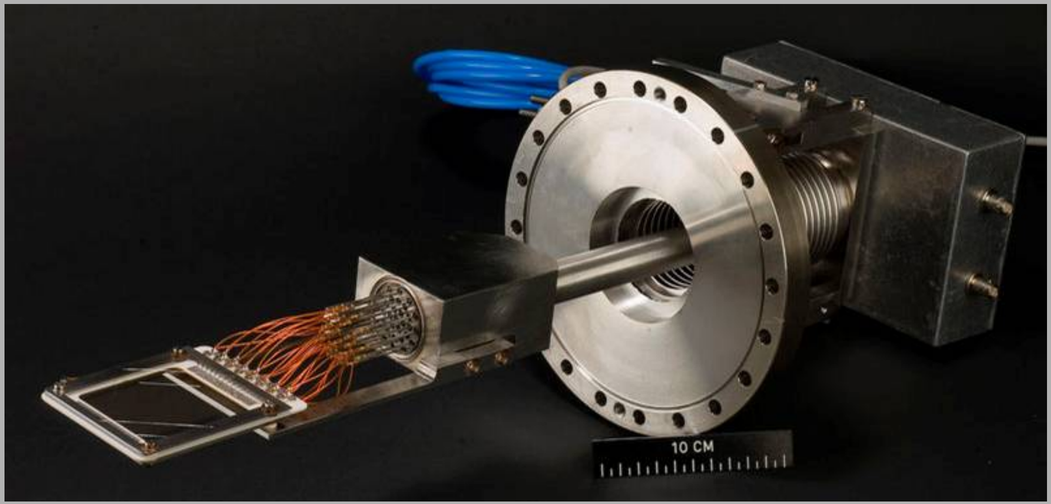
→ Monitors based on interaction of beam with gas (residual or injected) in vacuum chamber

→ Synchrotron light monitors

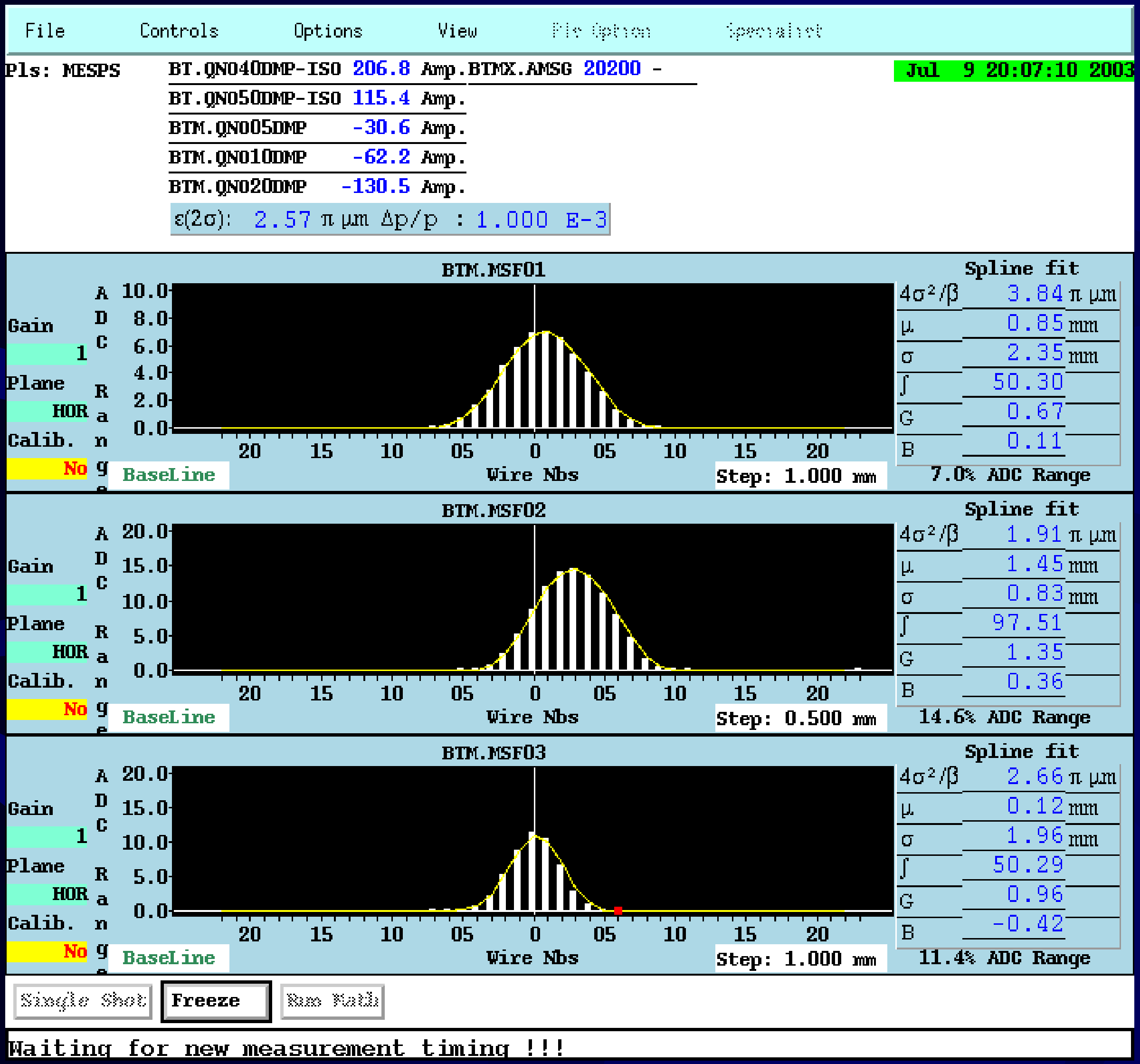
Secondary Emission (SEM) Grids

- 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

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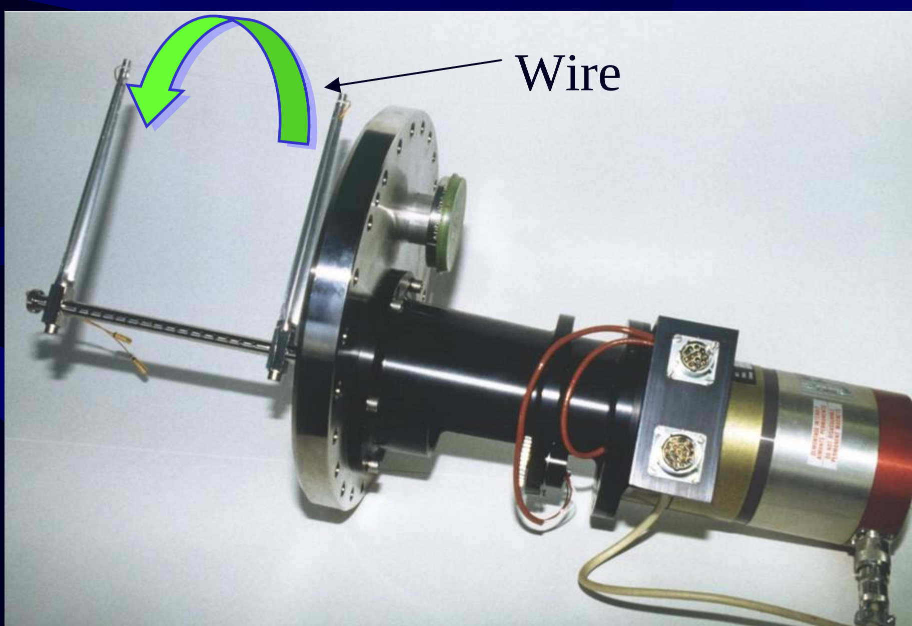
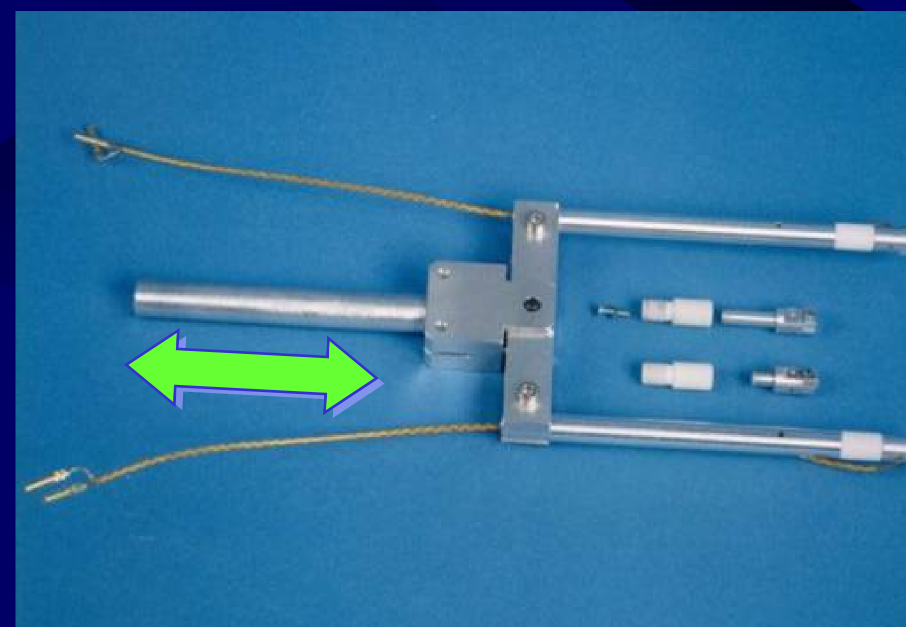
Wire Scanners

- 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

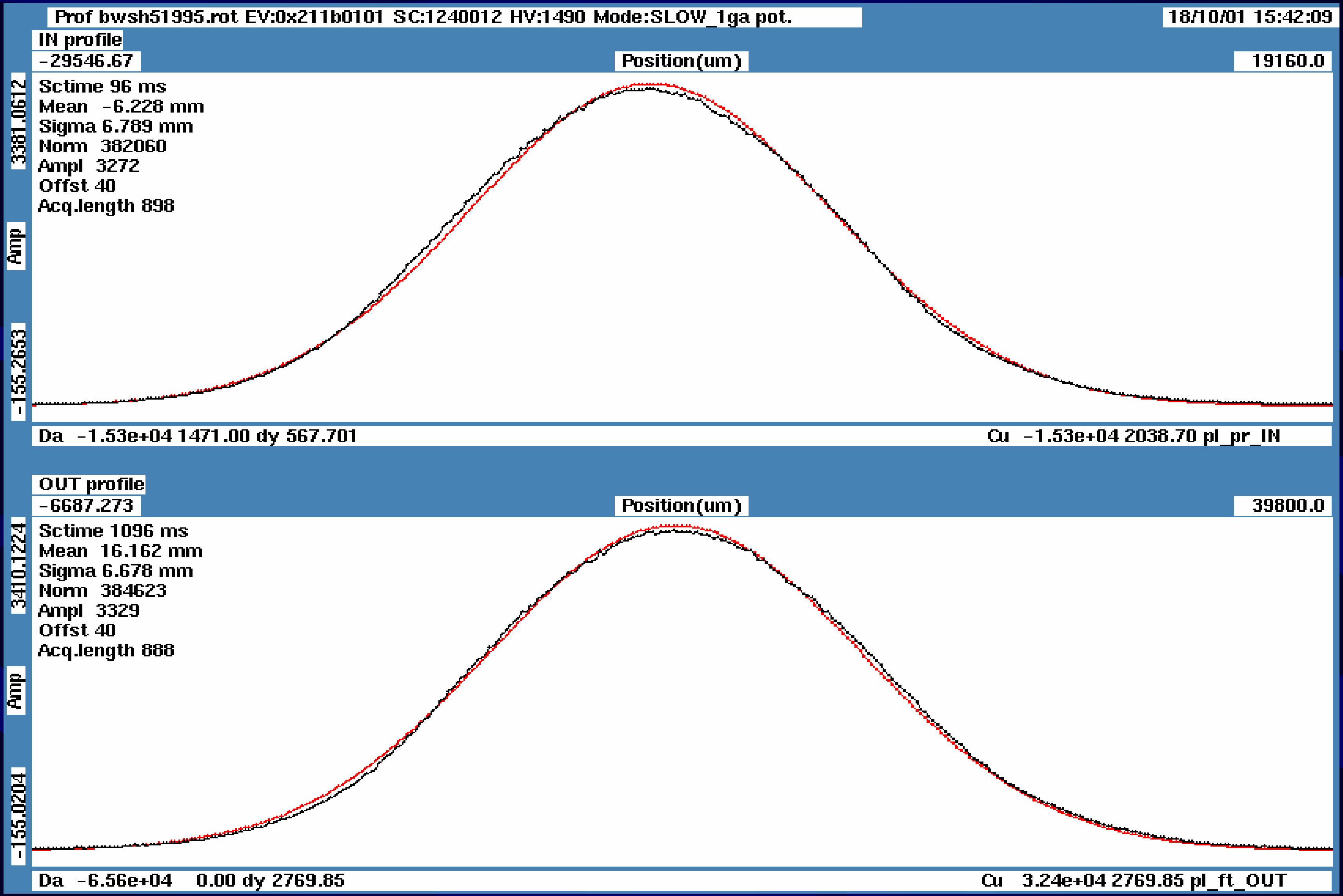


Rotative wire scanner



Linear wire scanner

Measurement Results



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Beam Profile Monitoring using Screens

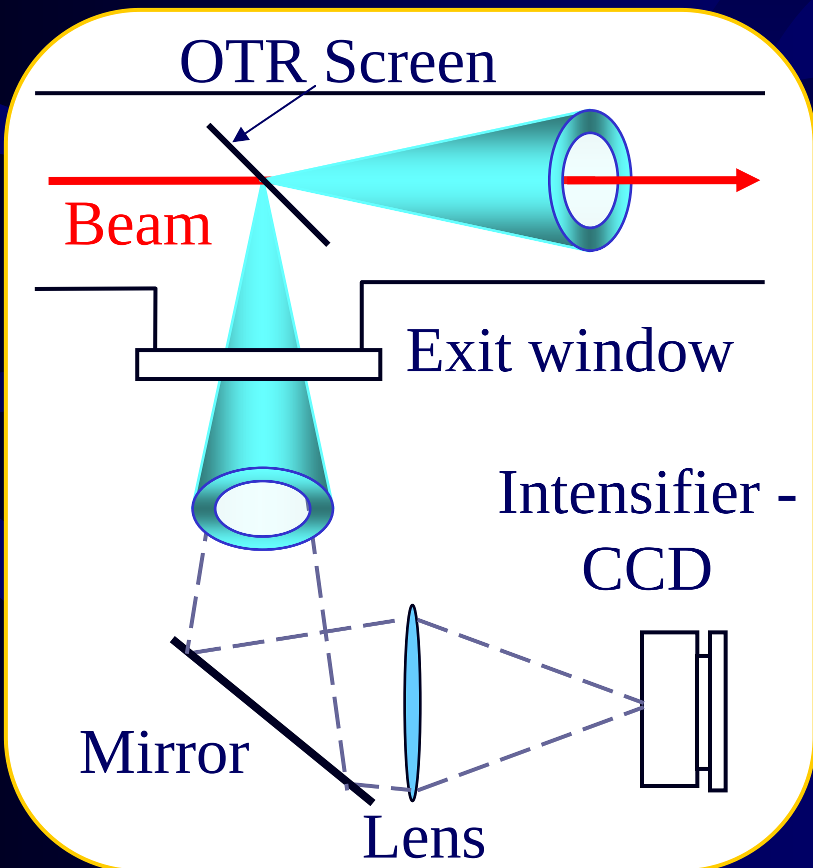
- Screen Types
  - → Luminescence Screens
    - destructive (thick) but work during setting-up with low intensities
  - → Optical Transition Radiation (OTR) screens
    - much less destructive (thin) but require high intensity

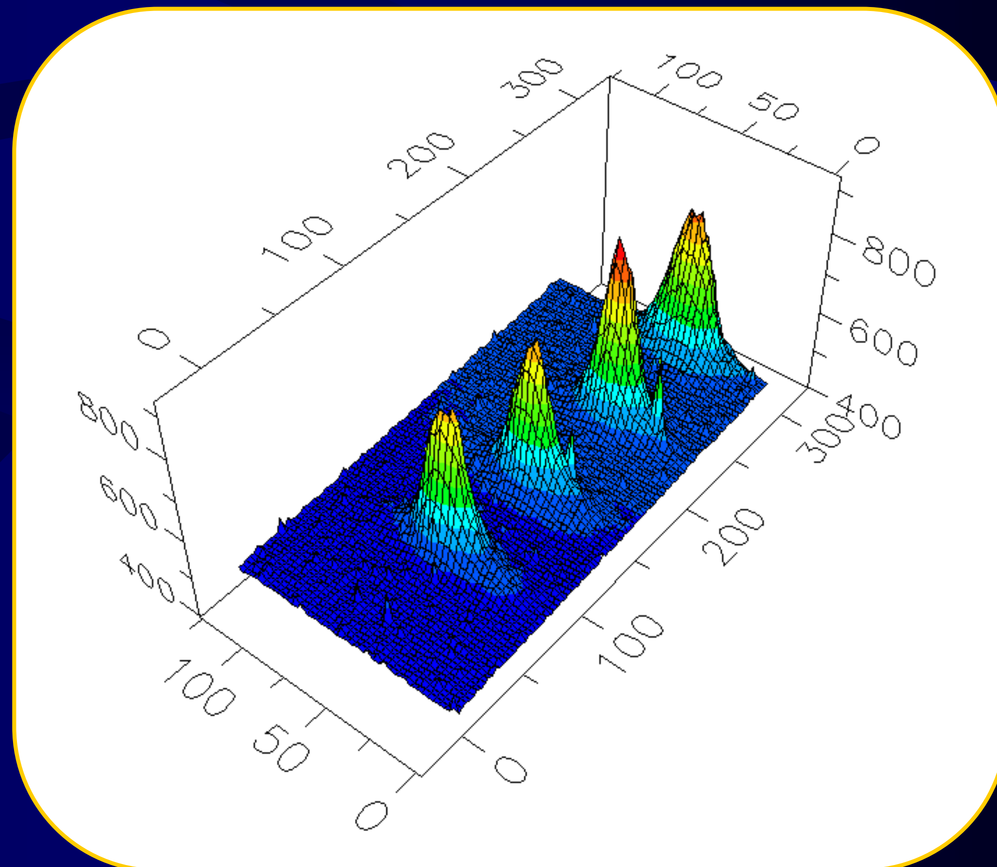
Sensitivities measured with protons with previous screen holder, normalised for 7 px/σ

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

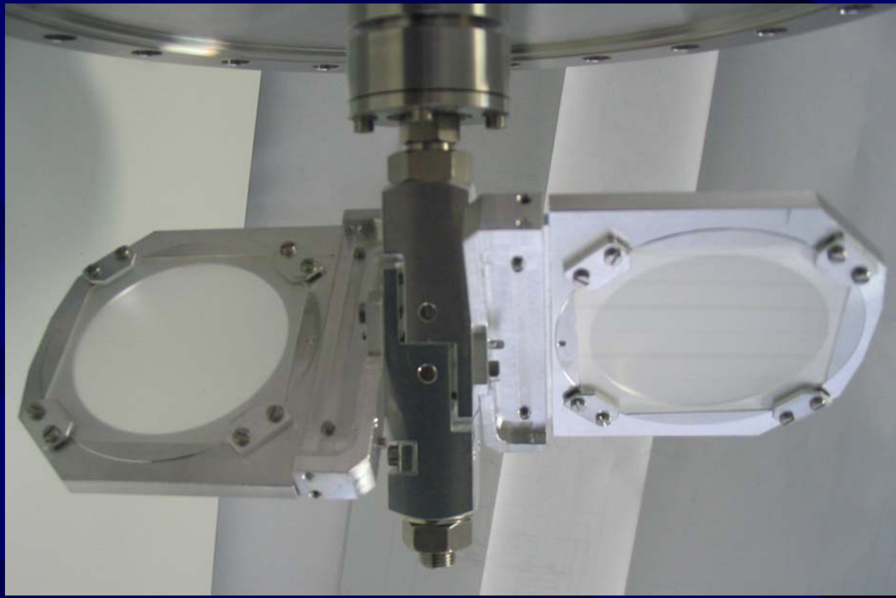
- Radiation emitted when a charged particle beam goes through the interface of 2 media with different dielectric constants
  - → surface phenomenon allows the use of very thin screens (~10µm)





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 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

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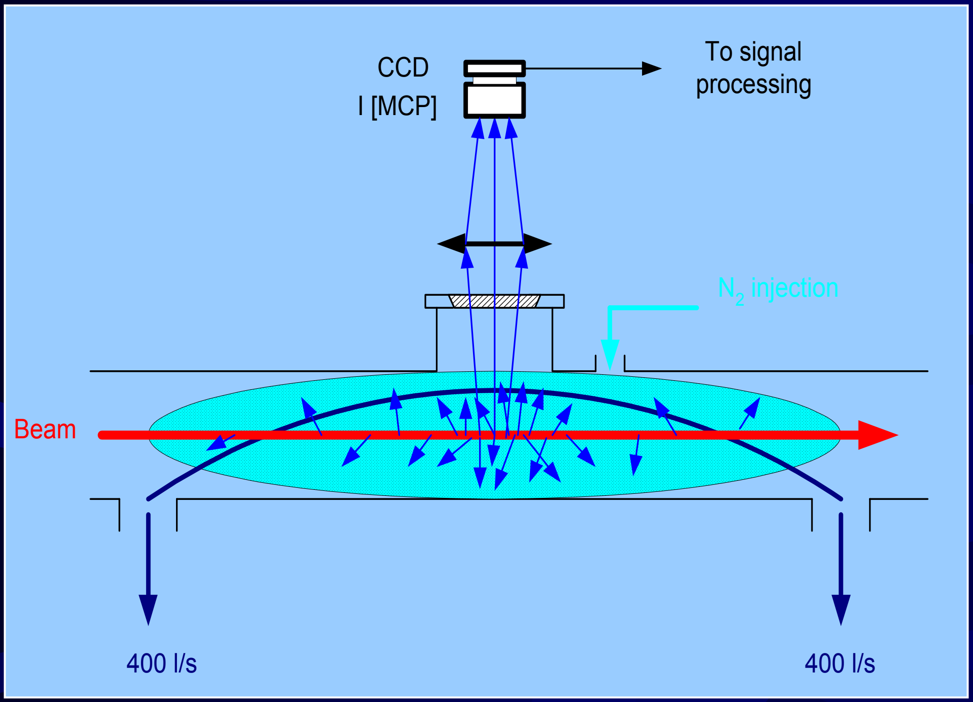
→ Beam interaction with a screen

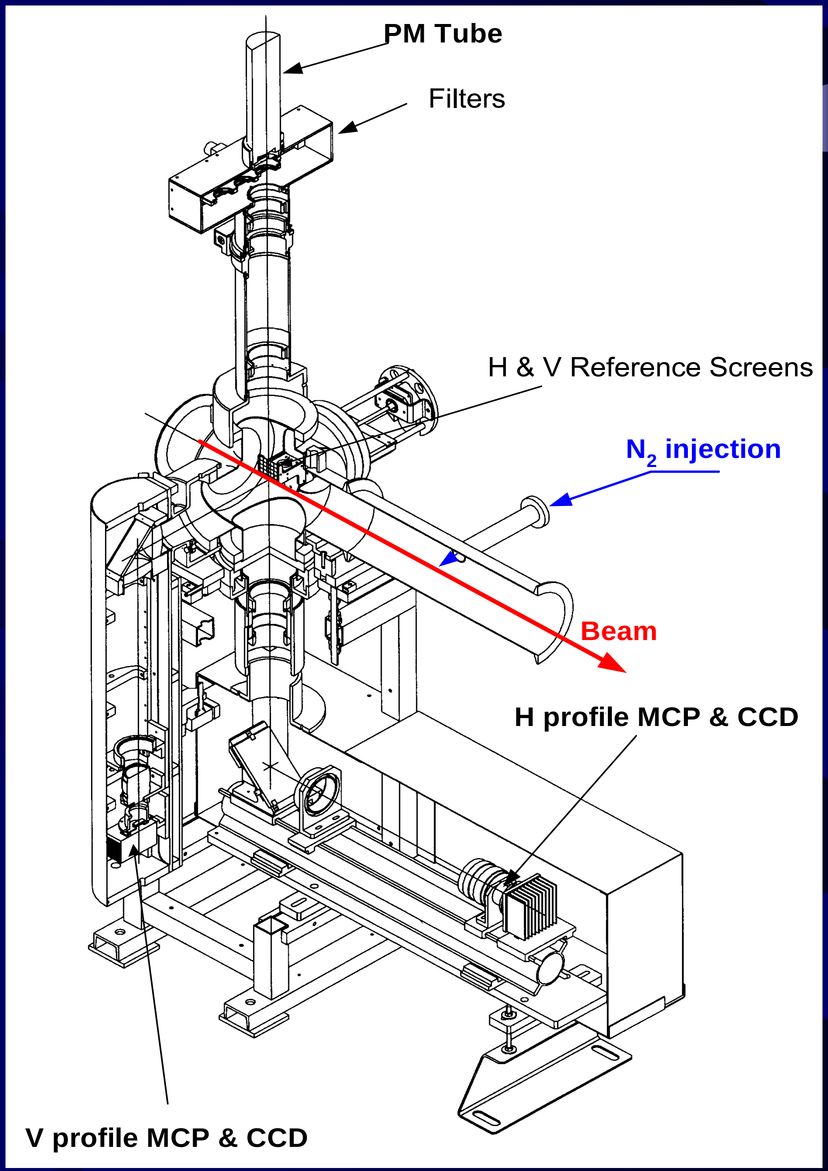
- semi or fully destructive

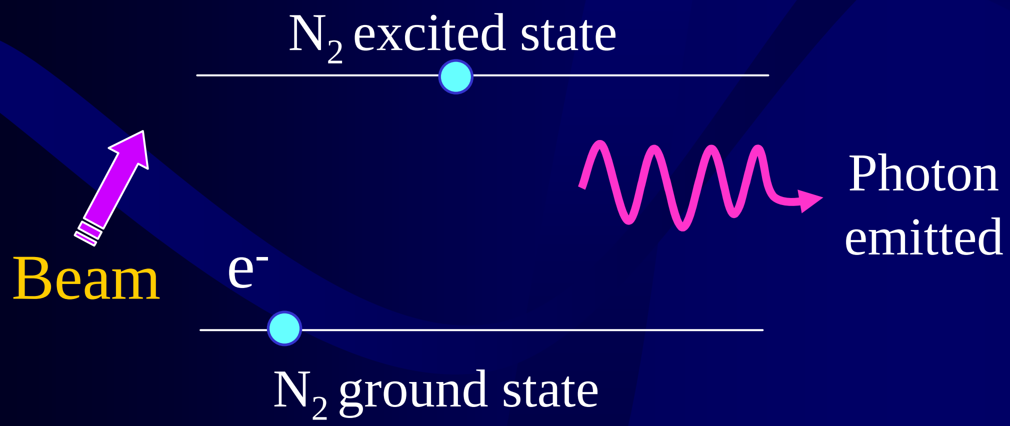
→ Monitors based on interaction of beam with gas (residual or injected) in vacuum chamber

→ Synchrotron light monitors

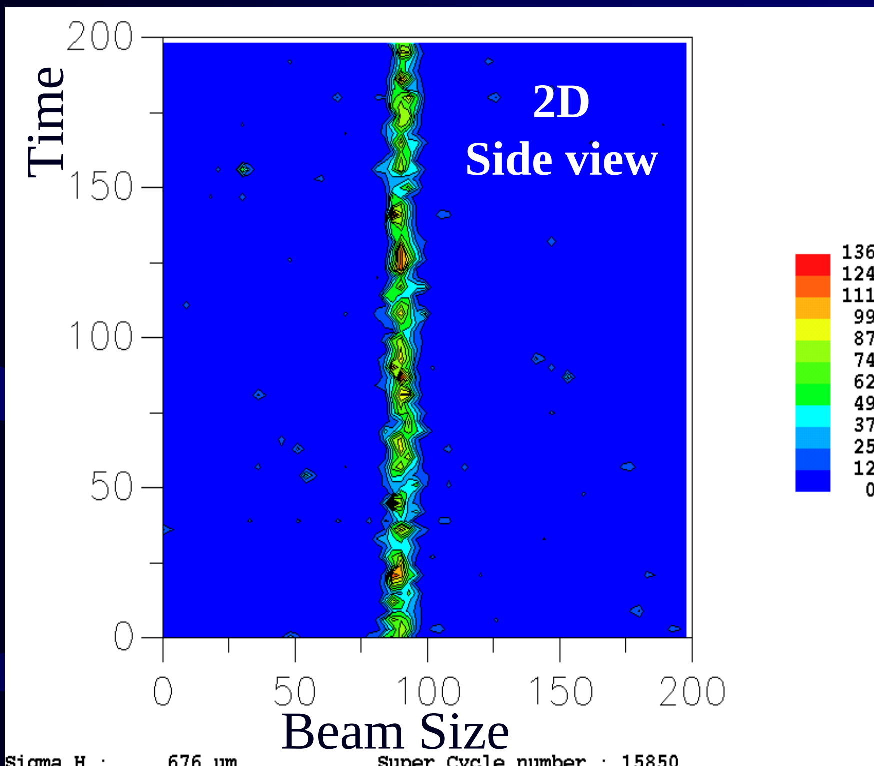
Luminescence Profile Monitor







Luminescence Profile Monitor

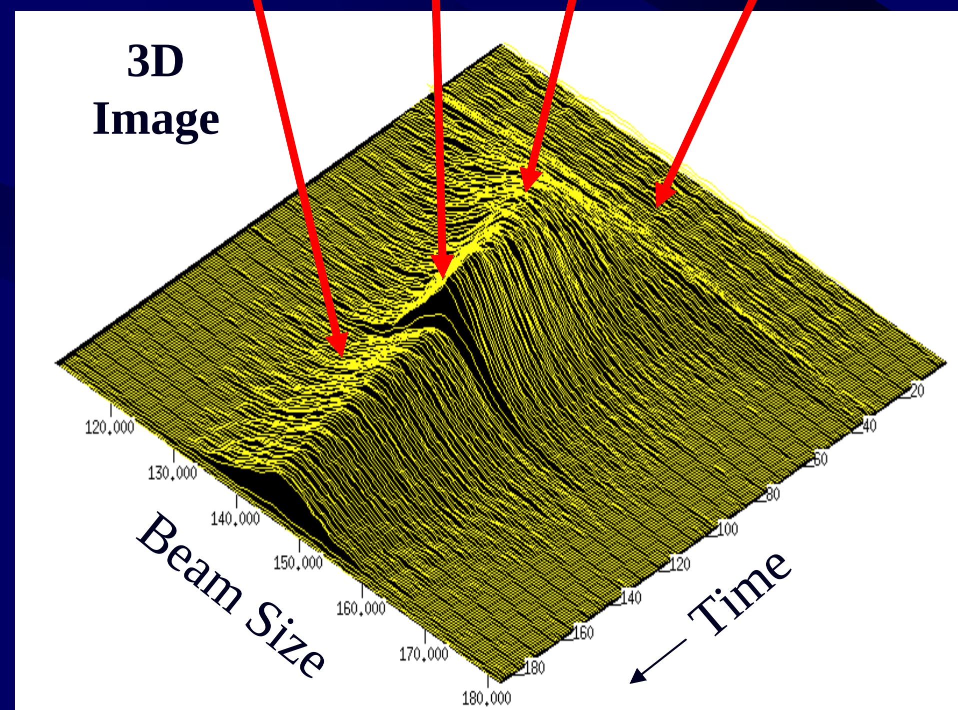


Beam size shrinks as beam is accelerated

Fast extraction

Injection

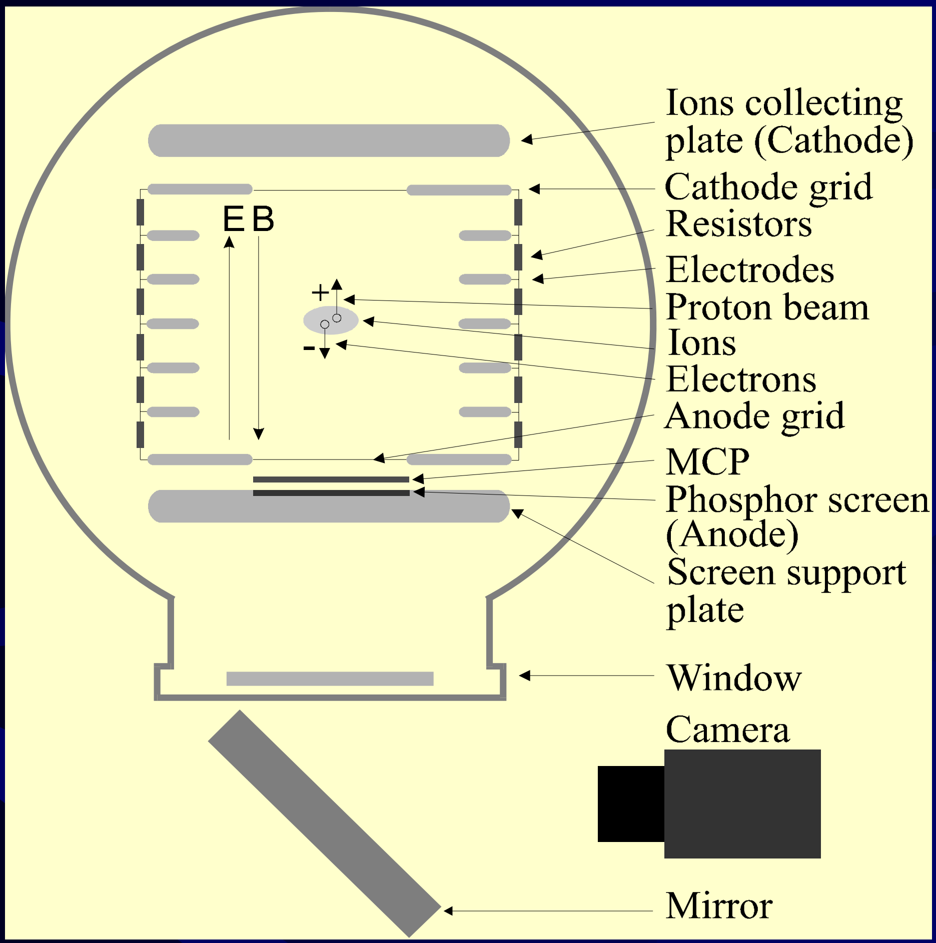
Slow extraction



CERN-SPS Measurements

- Profile Collected every 20ms
- Local Pressure at $\sim 5\times10^{-7}$ Torr

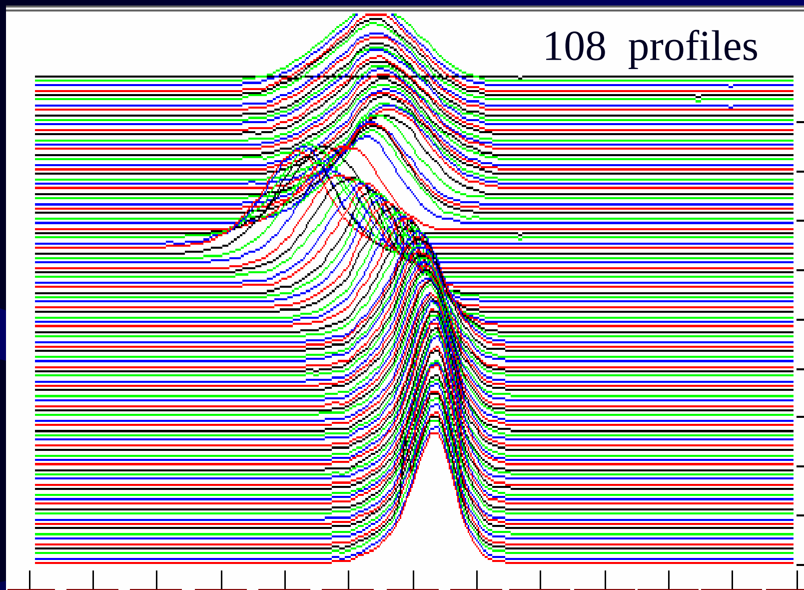
(Rest Gas) Ionisation Profile Monitor - IPM

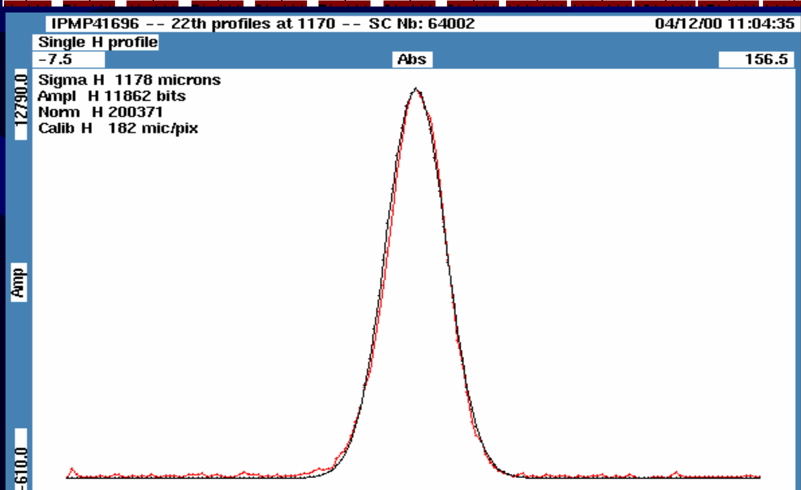


IPM Single Bunch Measurements

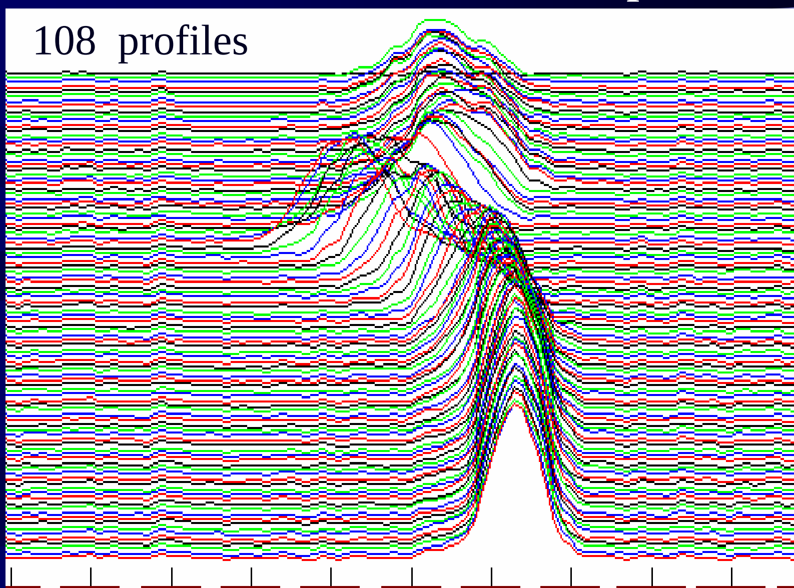
(CCD - 870 SPS turns (20 ms) per profile)

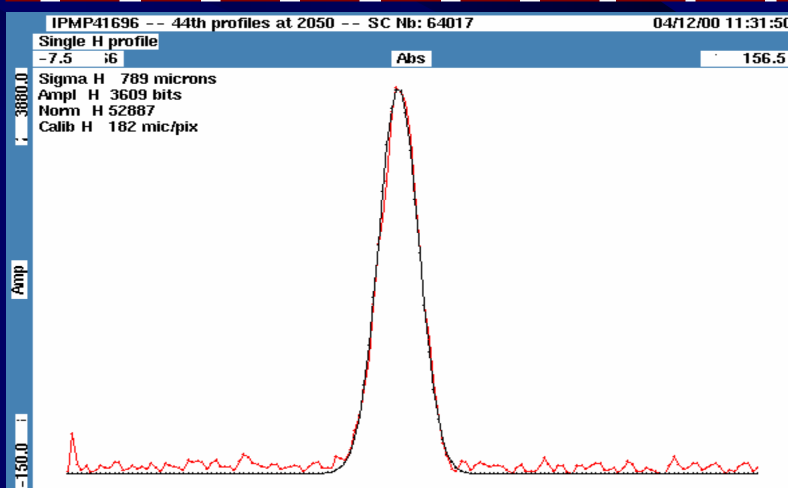
6×10^{10} p/bunch





2×10^{10} p/bunch





Measuring Beam Size

- Beam Profile Measurement Methods

  → Secondary emission (SEM) grids

  → Wire Scanners

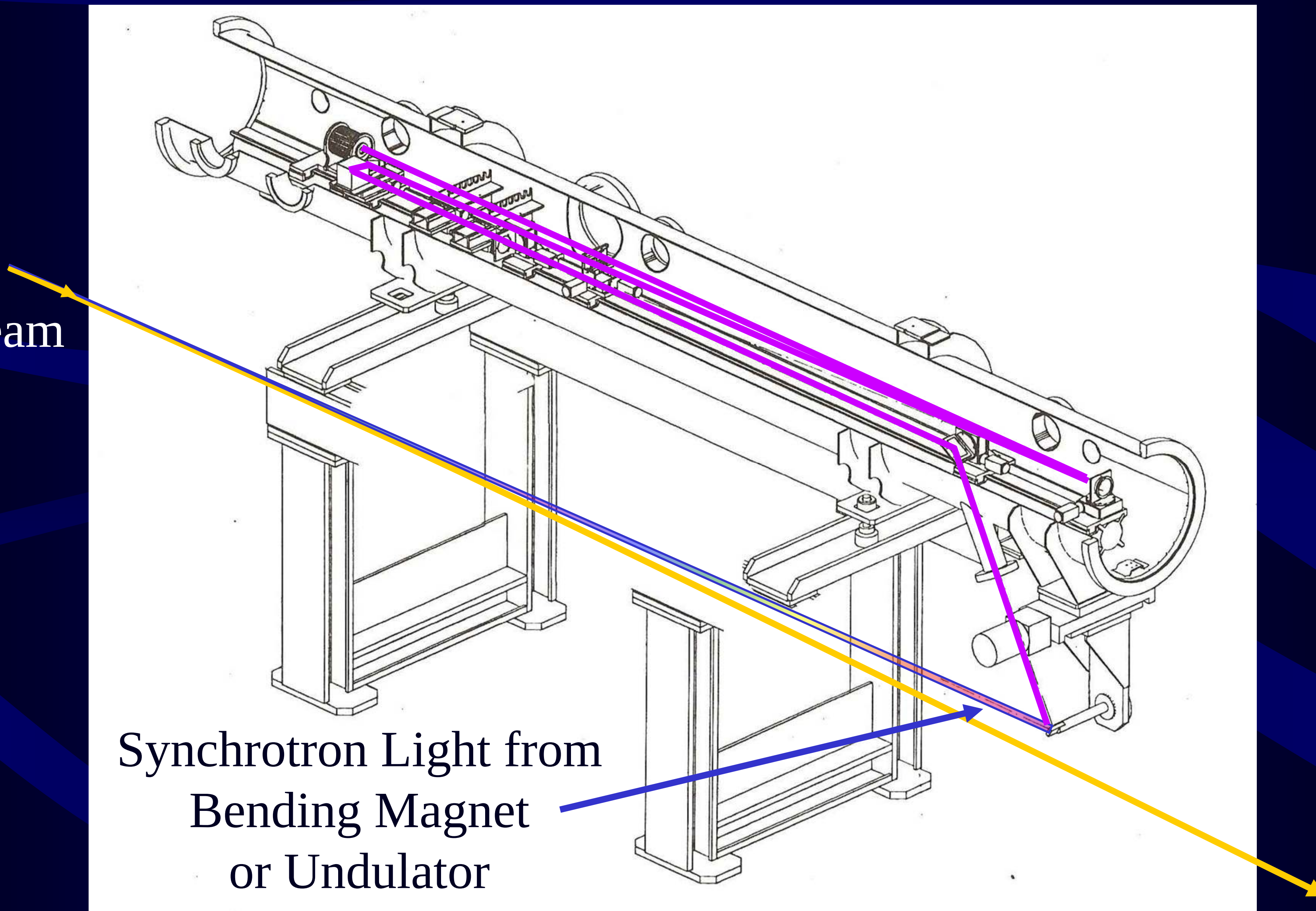
  → Beam interaction with a screen

    - semi or fully destructive

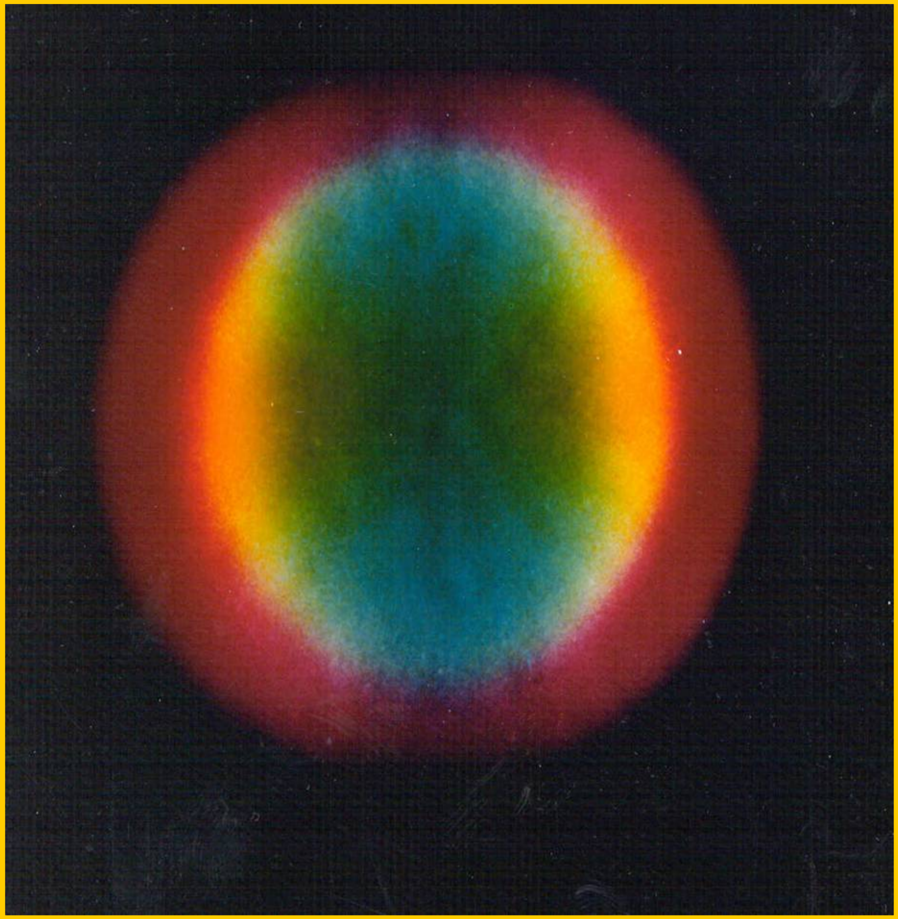
  → Monitors based on interaction of beam with gas (residual or injected) in vacuum chamber

  → Synchrotron light monitors

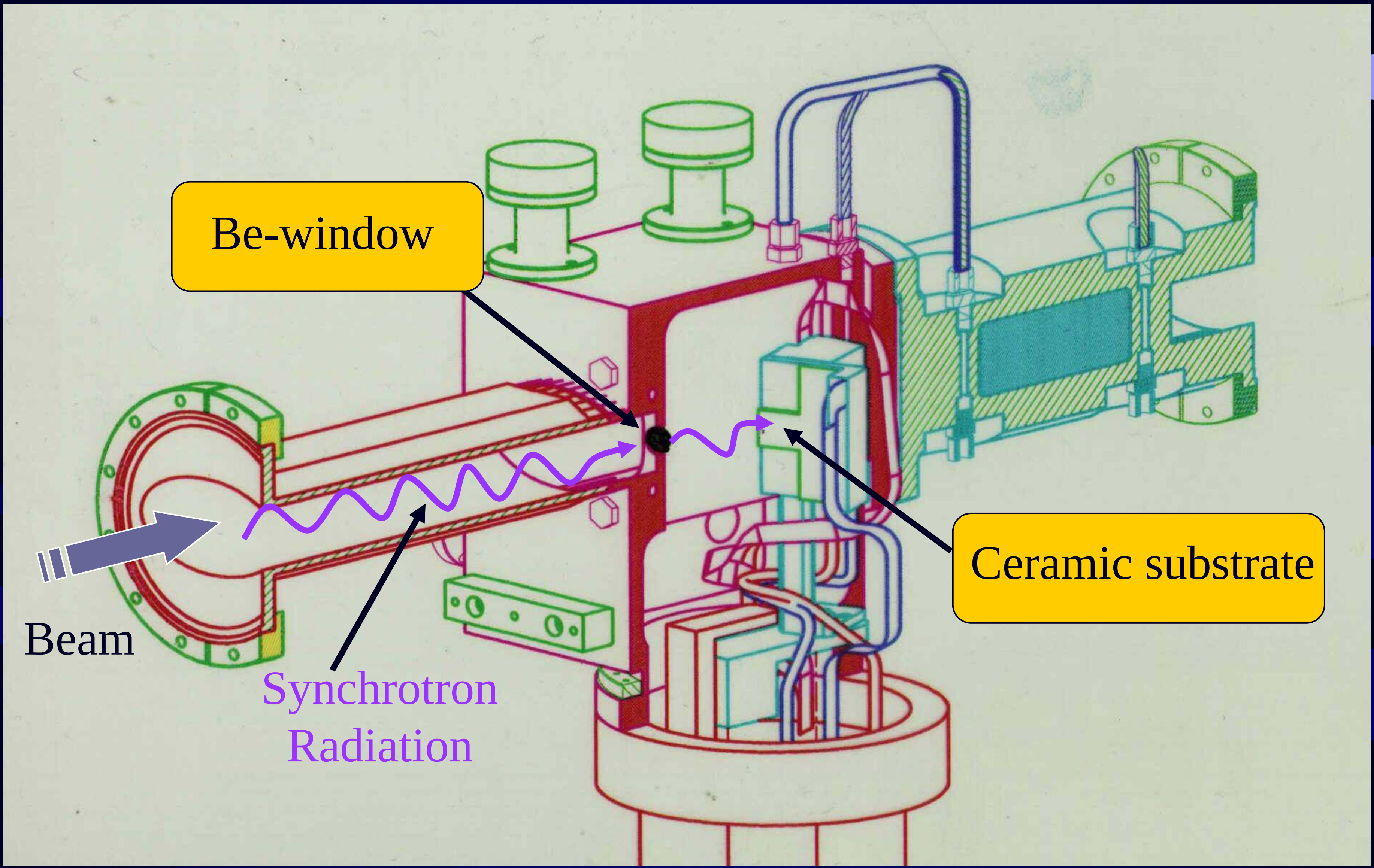
The Synchrotron Light Monitor



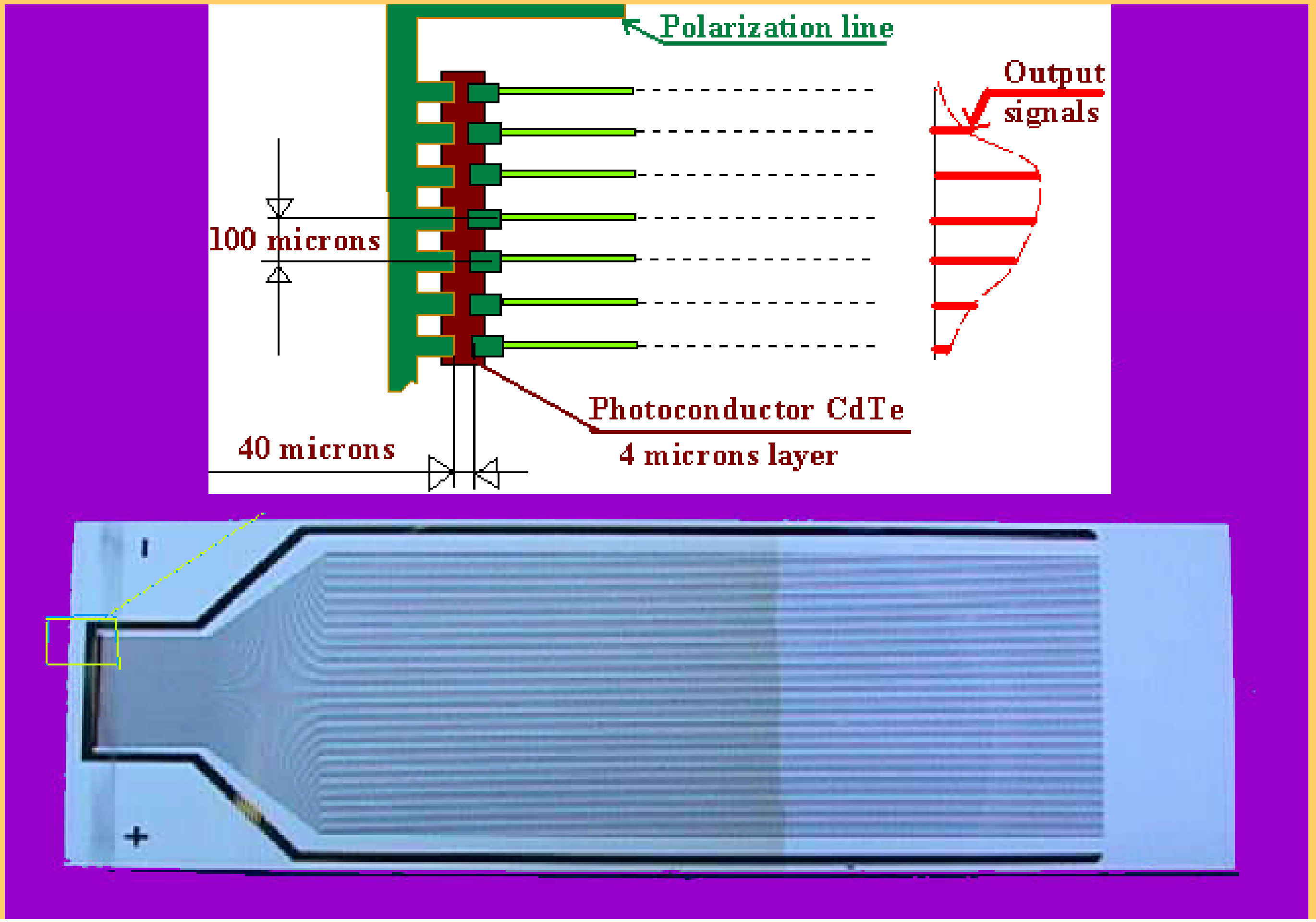
The Synchrotron Light Monitor



LEP X-Ray Monitor (BEXE system)



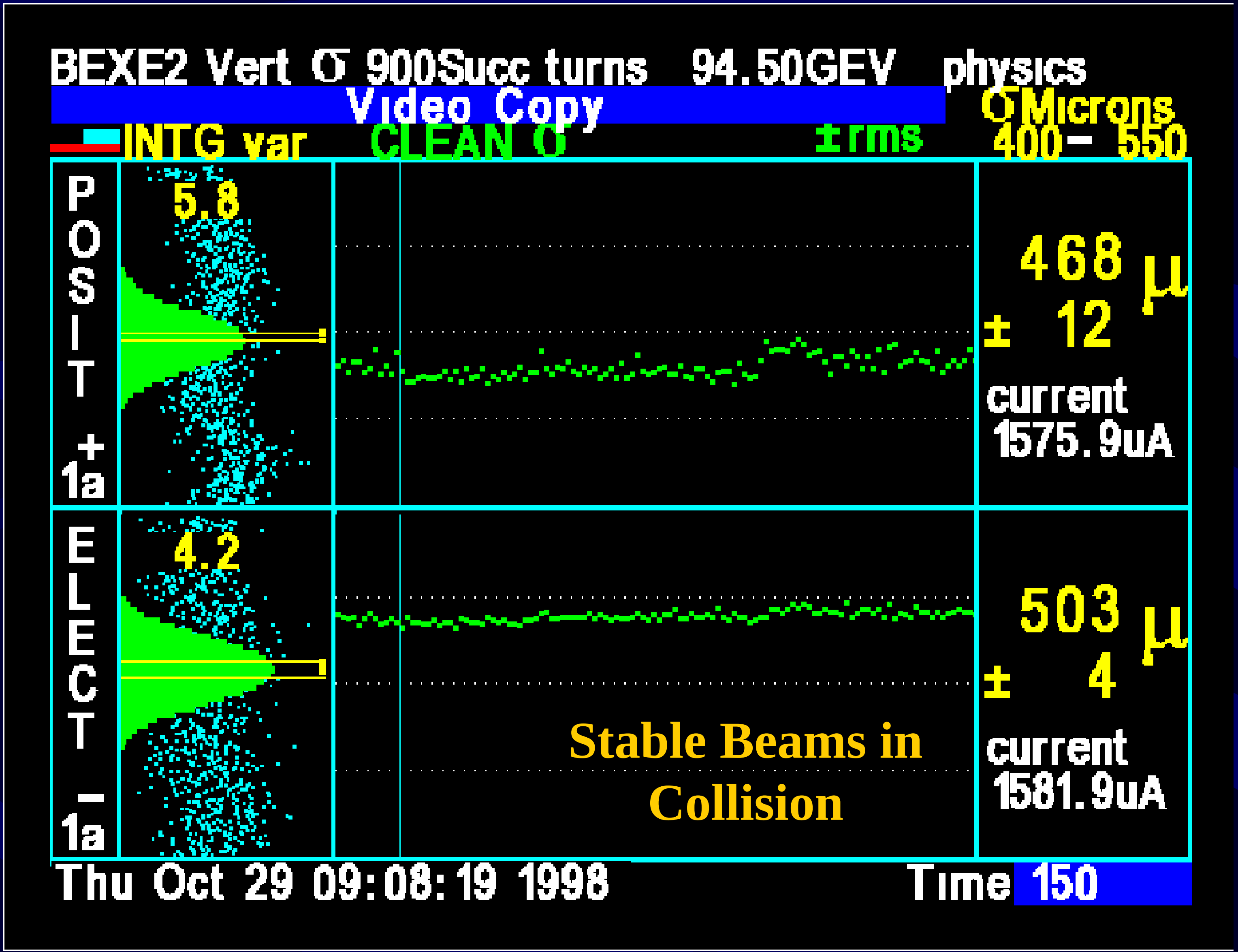
X-ray Beam Intercepting Strip Line Detector
(Cd-Te photo-conductors)



The detector is made from a 4 micrometer layer of photoconductive CdTe deposited on a 20 X 50 mm ceramic substrate

Online Display in LEP Control Room
(e^+ & e^- vertical beam size versus time)

Histograms of Individual Cd-Te Channels



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 Diagnostics

Correction to Beam Instrumentation & Diagnostics Course Abstract

- Electromagnetic Monitors
  - → position pick-ups & acquisition systems
- Profile Monitoring and Emittance Measurements
- Transverse Diagnostics
  - → tune, chromaticity and coupling
- Beam Loss Monitoring
- Advanced Instrumentation
  - → head-tail chromaticity measurement
  - → injection matching