Introduction to Beam Instrumentation

Linear Collider school 2013, Antalya

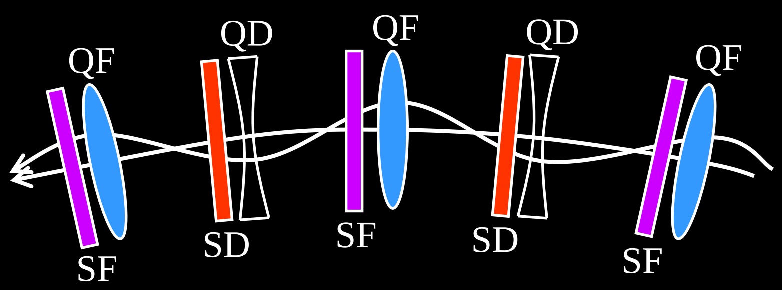
Hermann Schmickler – CERN Beam Instrumentation Group

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

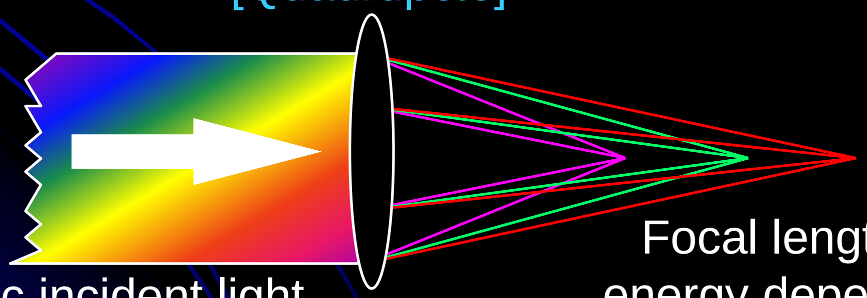


Characteristic Frequency of the Magnet Lattice

Given by the strength of the Quadrupole magnets

- Machine Chromaticity

Optics Analogy:



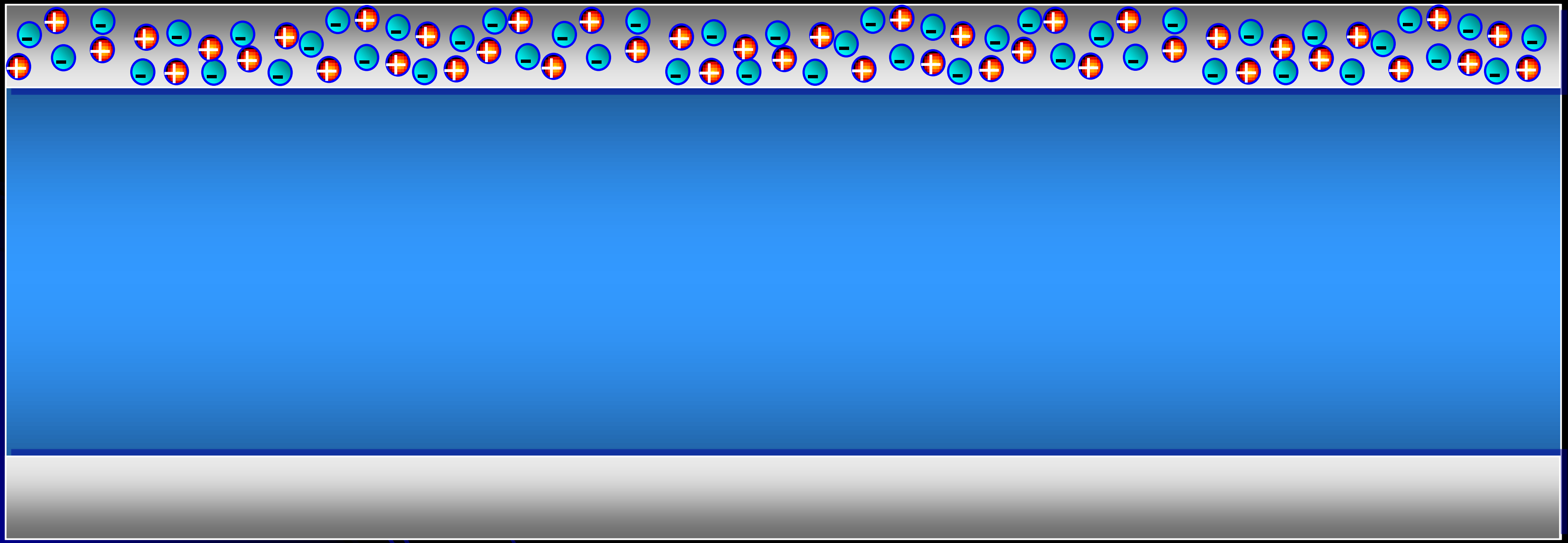
Spread in the Machine Tune due to Particle Energy Spread

Controlled by Sextupole magnets

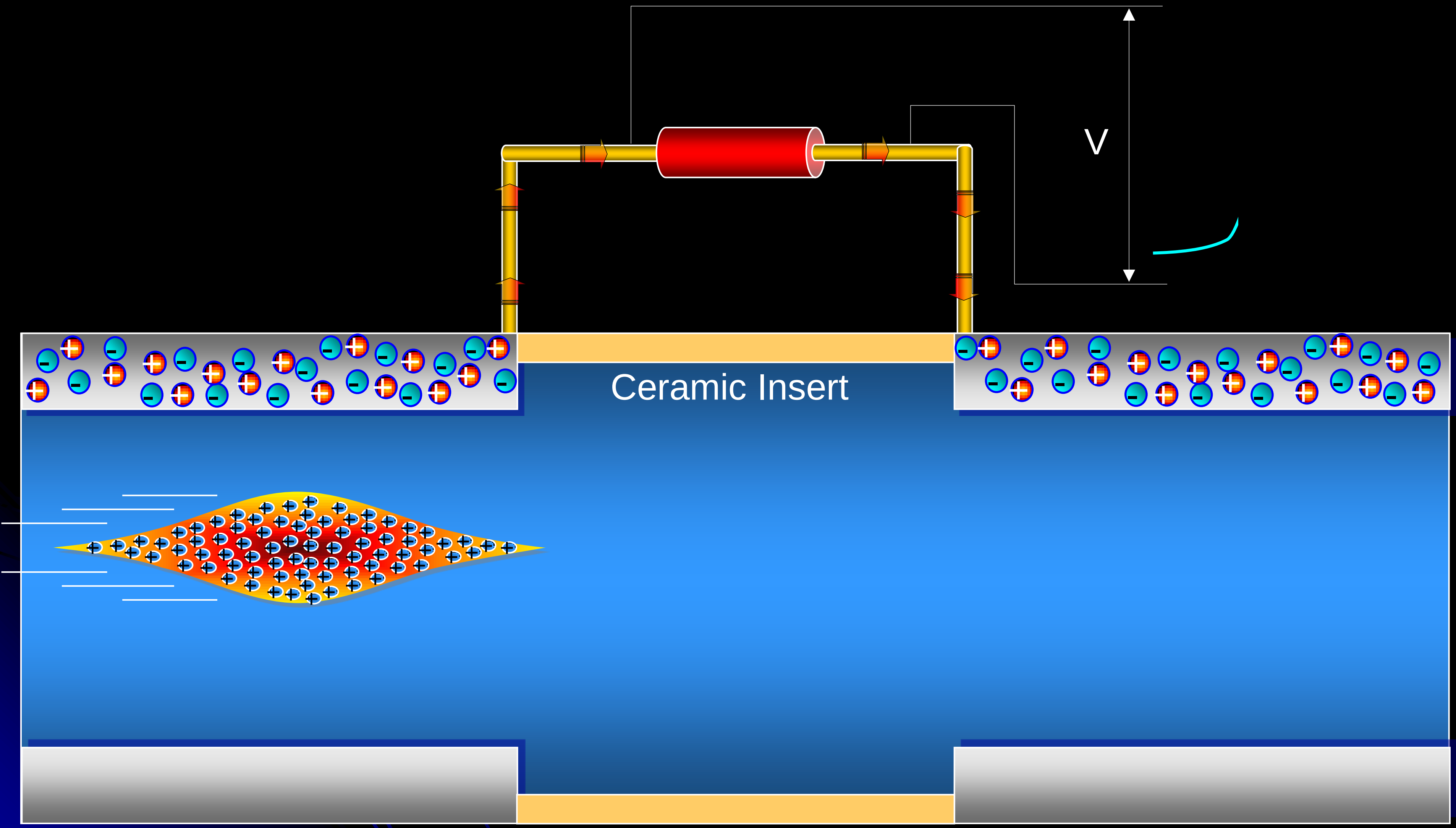
The Typical Instruments

- 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
- Beam Loss
  - ionisation chambers or pin diodes
- Machine Tune and Chromaticity
  - In second part
- Luminosity Monitoring
  - in second part

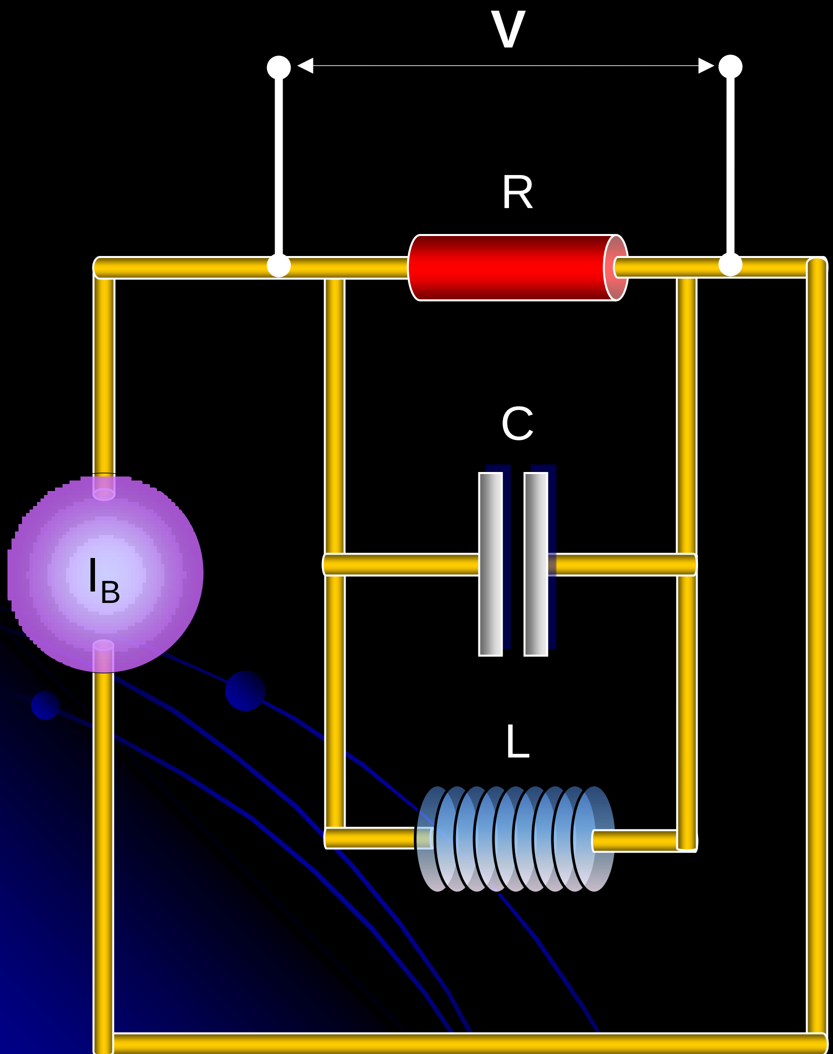
Measuring Beam Position – The Principle

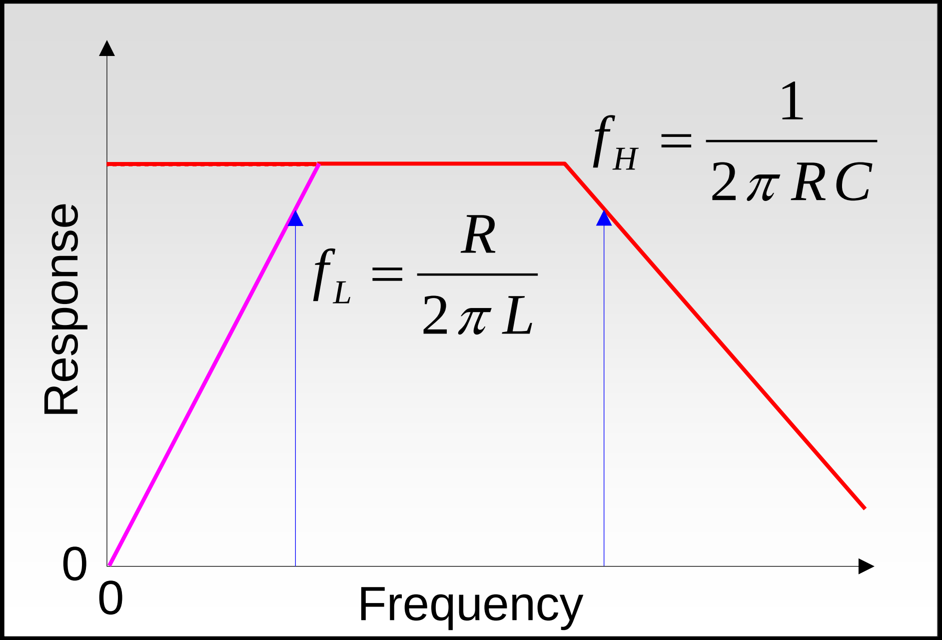


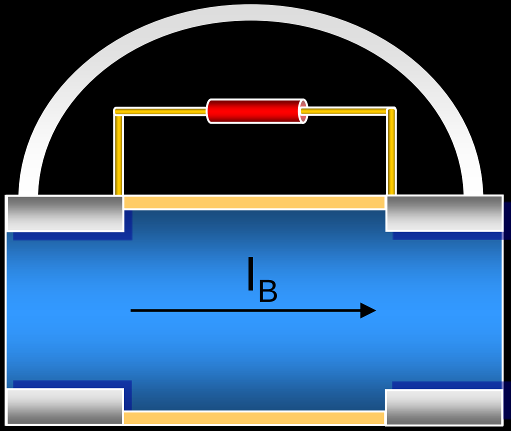
Wall Current Monitor – The Principle



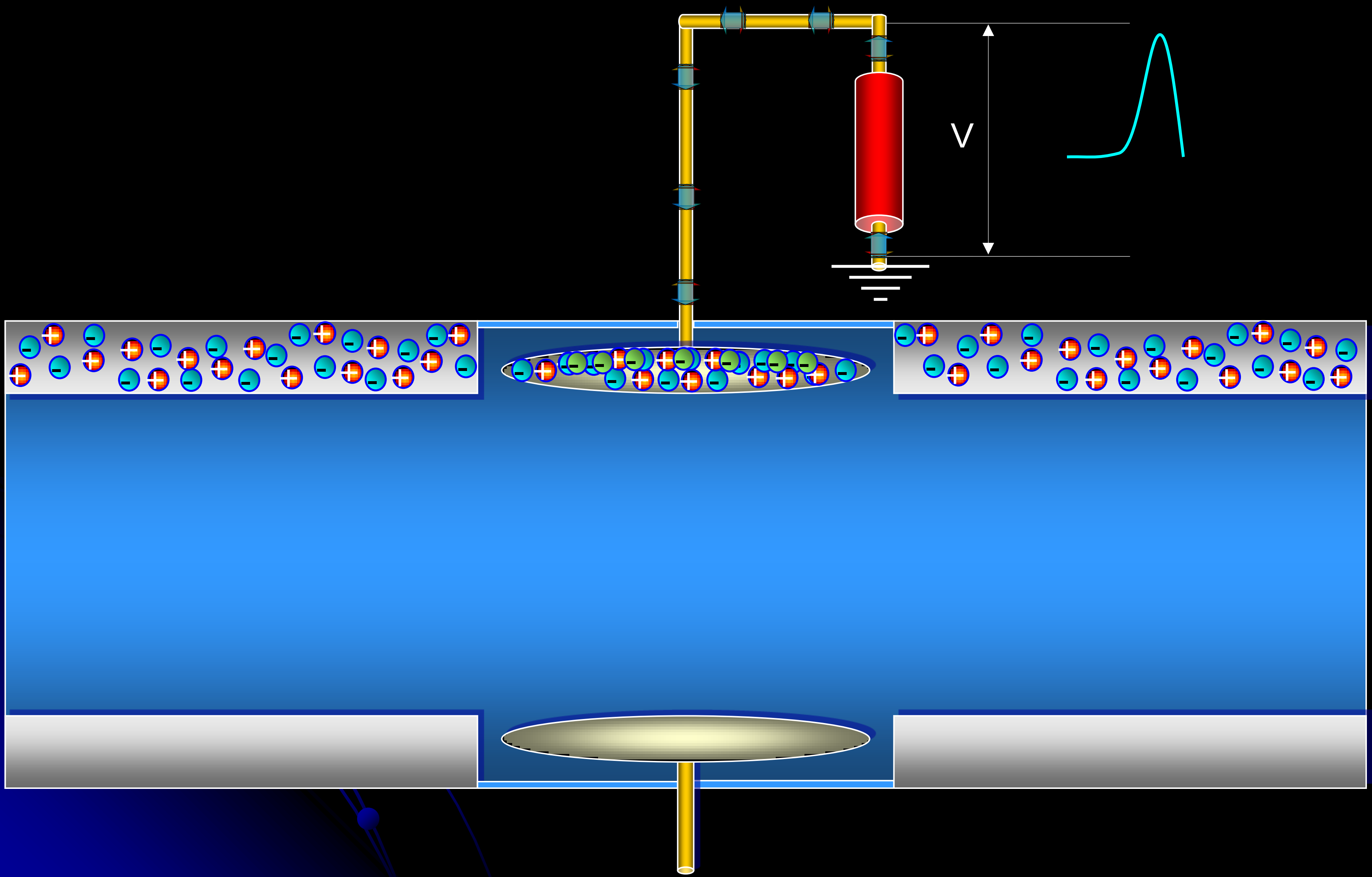
Wall Current Monitor – Beam Response



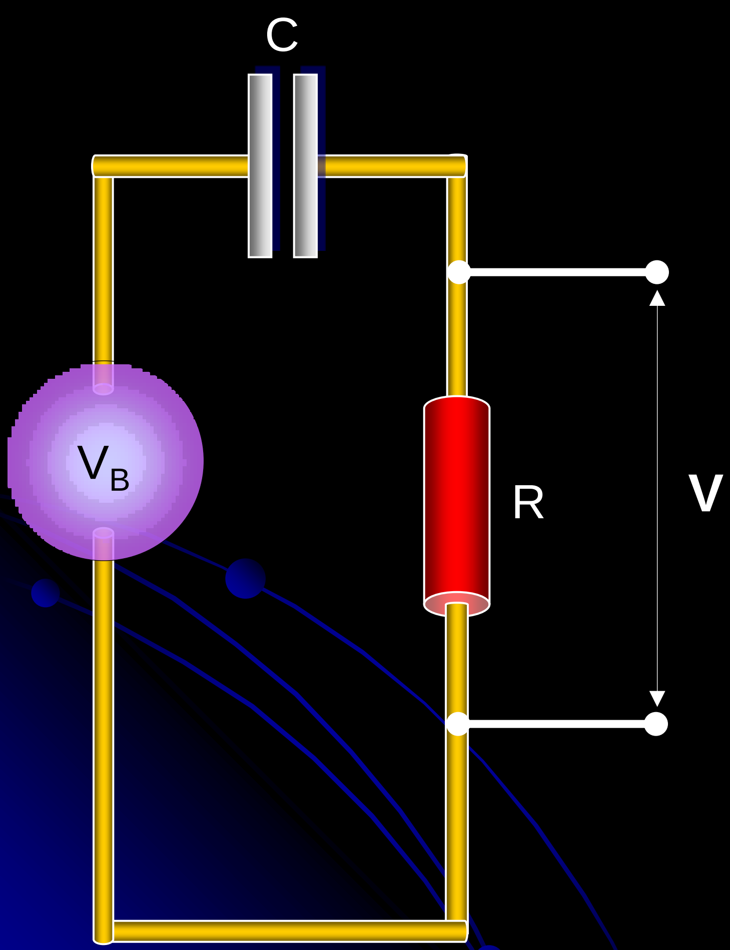


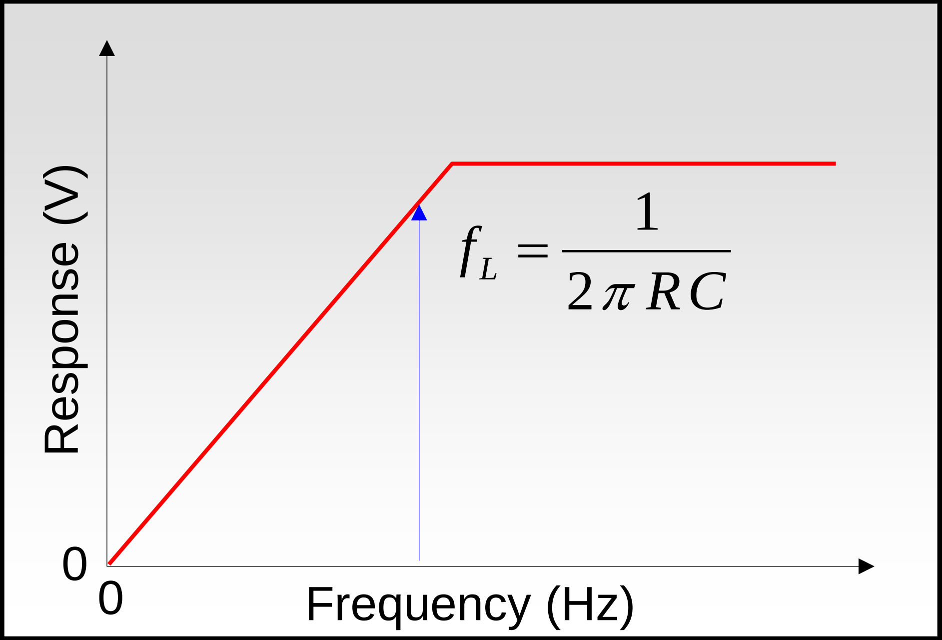


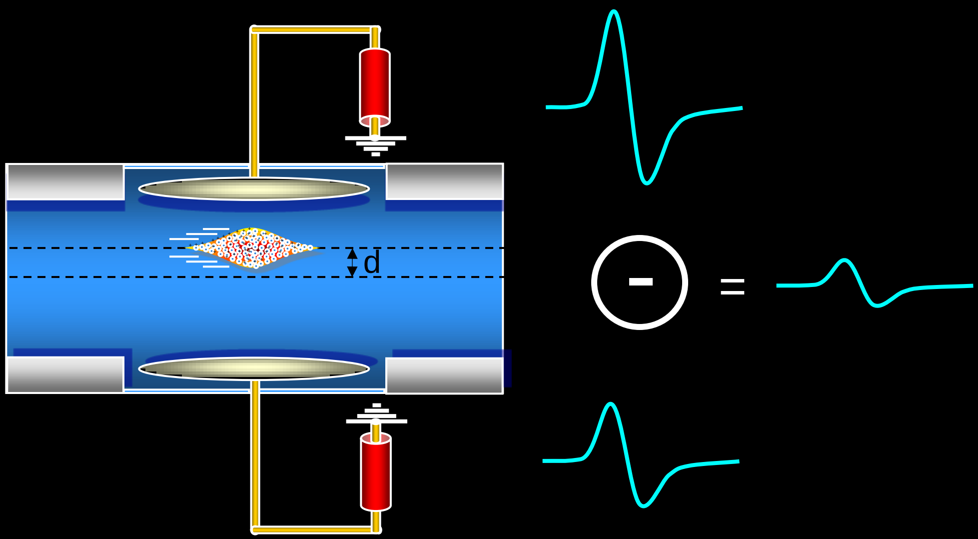
Electrostatic Monitor – The Principle



Electrostatic Monitor – Beam Response







Electrostatic Pick-up – Button

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

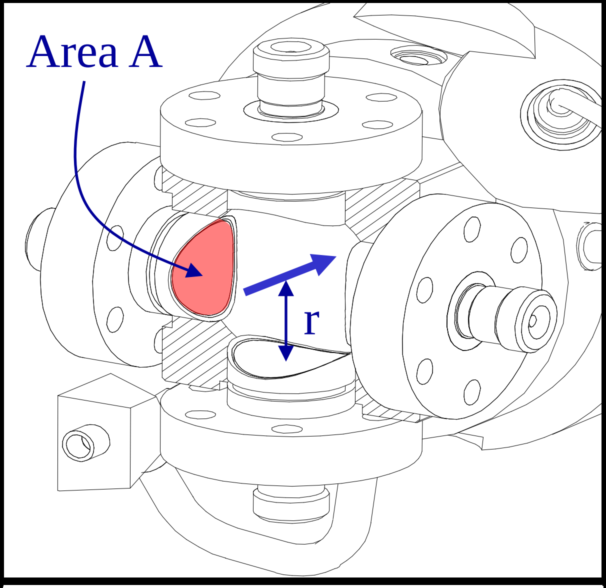
For Button with Capacitance C_e & Characteristic Impedance R_0

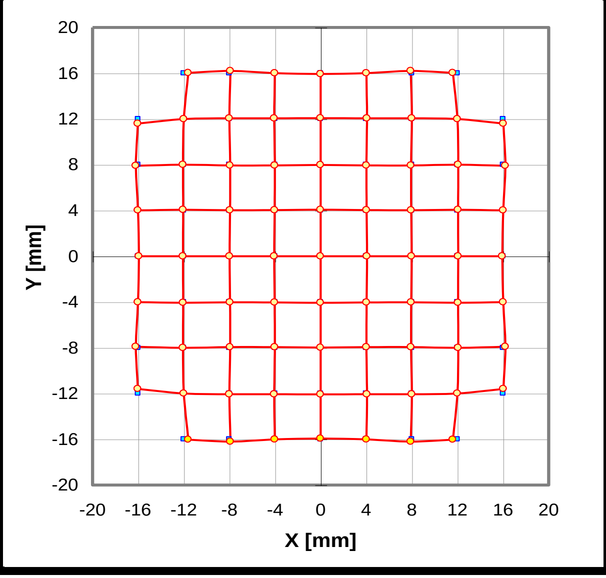
Transfer Impedance:

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

Lower Corner Frequency:

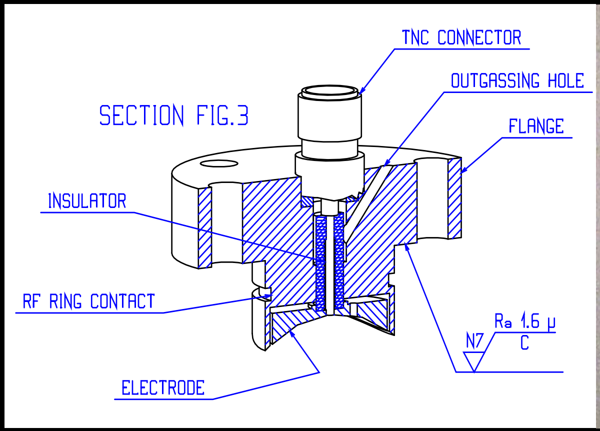
$$f_L = \frac{1}{2\pi R_0 C_e}$$

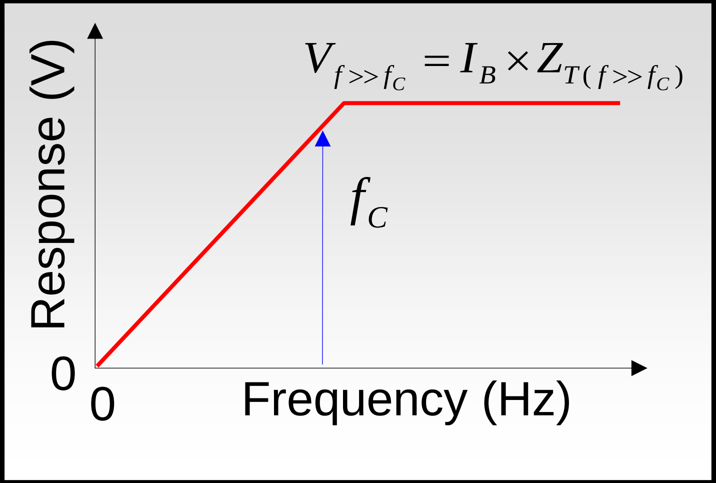




$$X = 2.30\cdot10^{-5}X_1^{\,5} + 3.70\cdot10^{-5}X_1^{\,3} + 1.035X_1 + 7.53\cdot10^{-6}X_1^{\,3}Y_1^{\,2} + 1.53\cdot10^{-5}X_1Y_1^{\,4}$$

A Real Example – The LHC Button





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

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

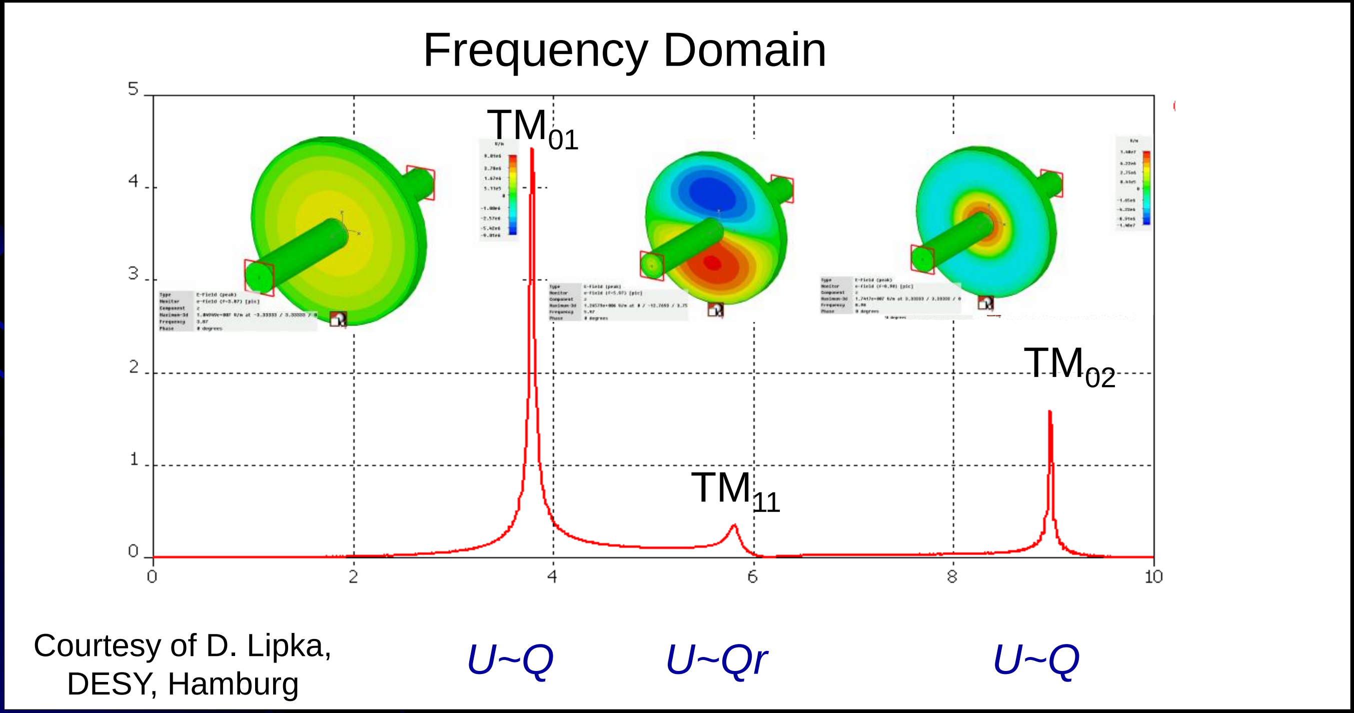
$$I_B = \frac{N_{pilot}e}{t} = \frac{5\times 10^9 \times 1.6\times 10^{-19}}{1\times 10^{-9}} = 0.8A_{peak} \Rightarrow V_{f=\infty} = 0.8\times 1.2 = 1V_{peak}$$

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

Improving the Precision for Next Generation Accelerators

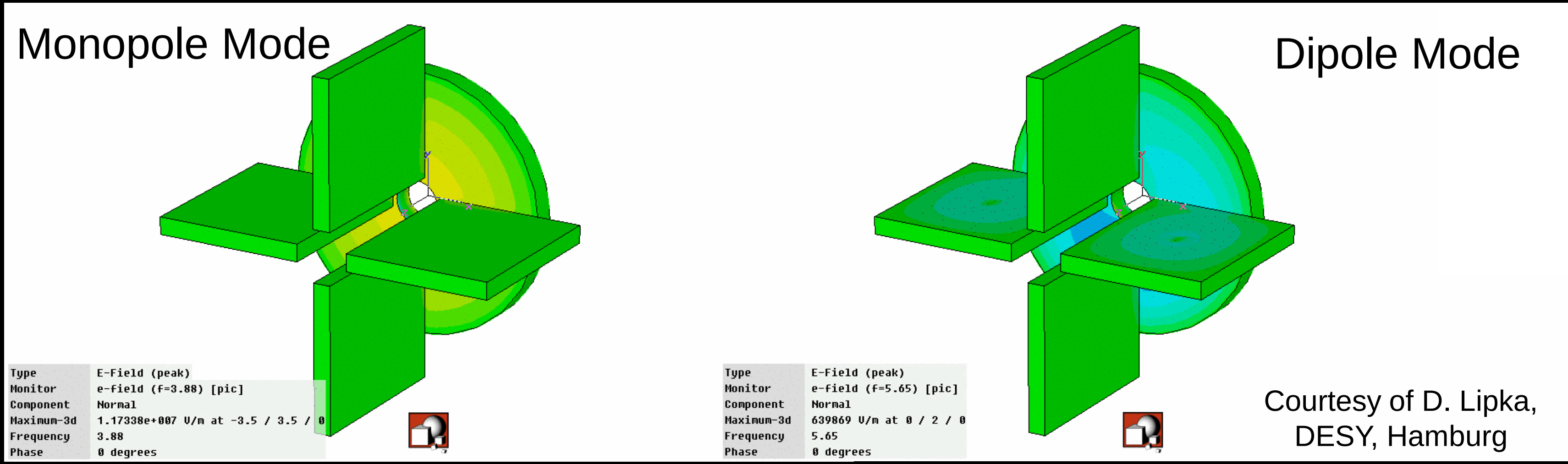
- Standard BPMs give intensity signals which need to be subtracted to obtain a difference which is then proportional to position
  - Difficult to do electronically without some of the intensity information leaking through
    - When looking for small differences this leakage can dominate the measurement
    - Typically 40-80dB (100 to 10000 in V) rejection ⇒ 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

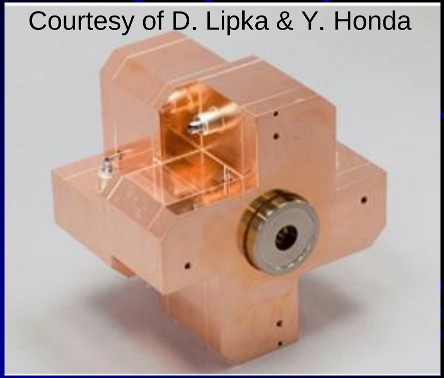


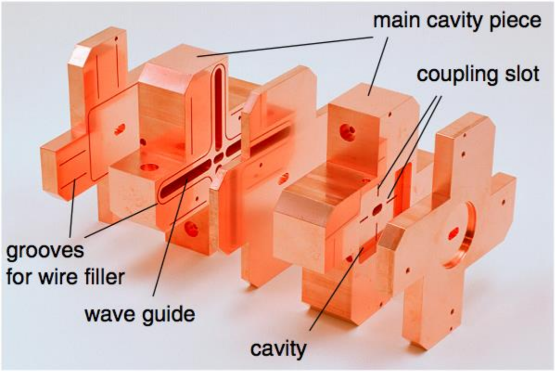
Today's State of the Art BPMs

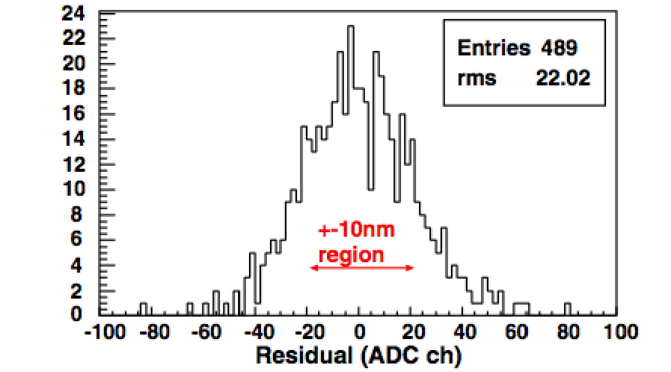
- Obtain signal using waveguides that only couple to dipole mode
  - Further suppression of monopole mode



- 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)



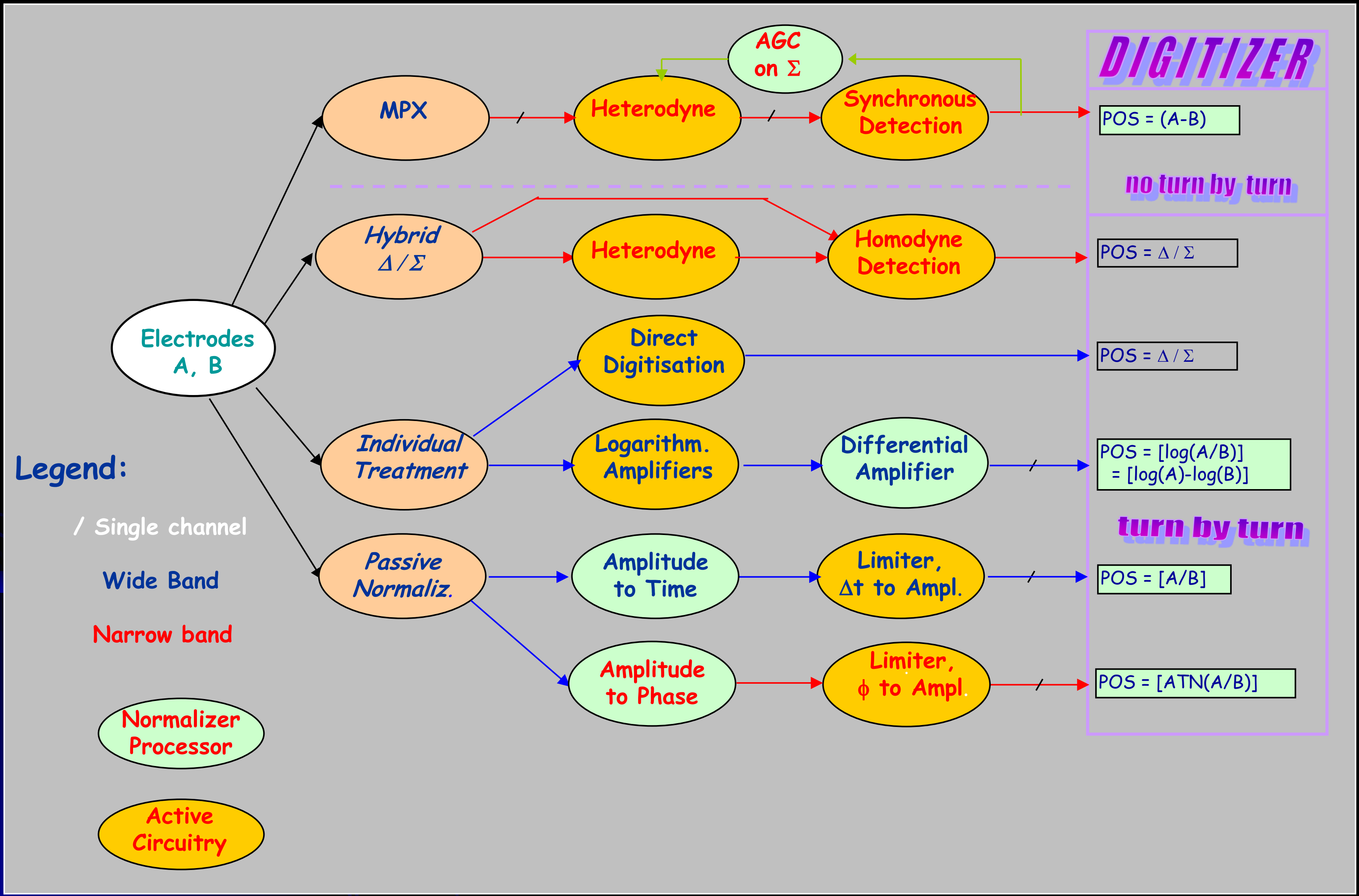




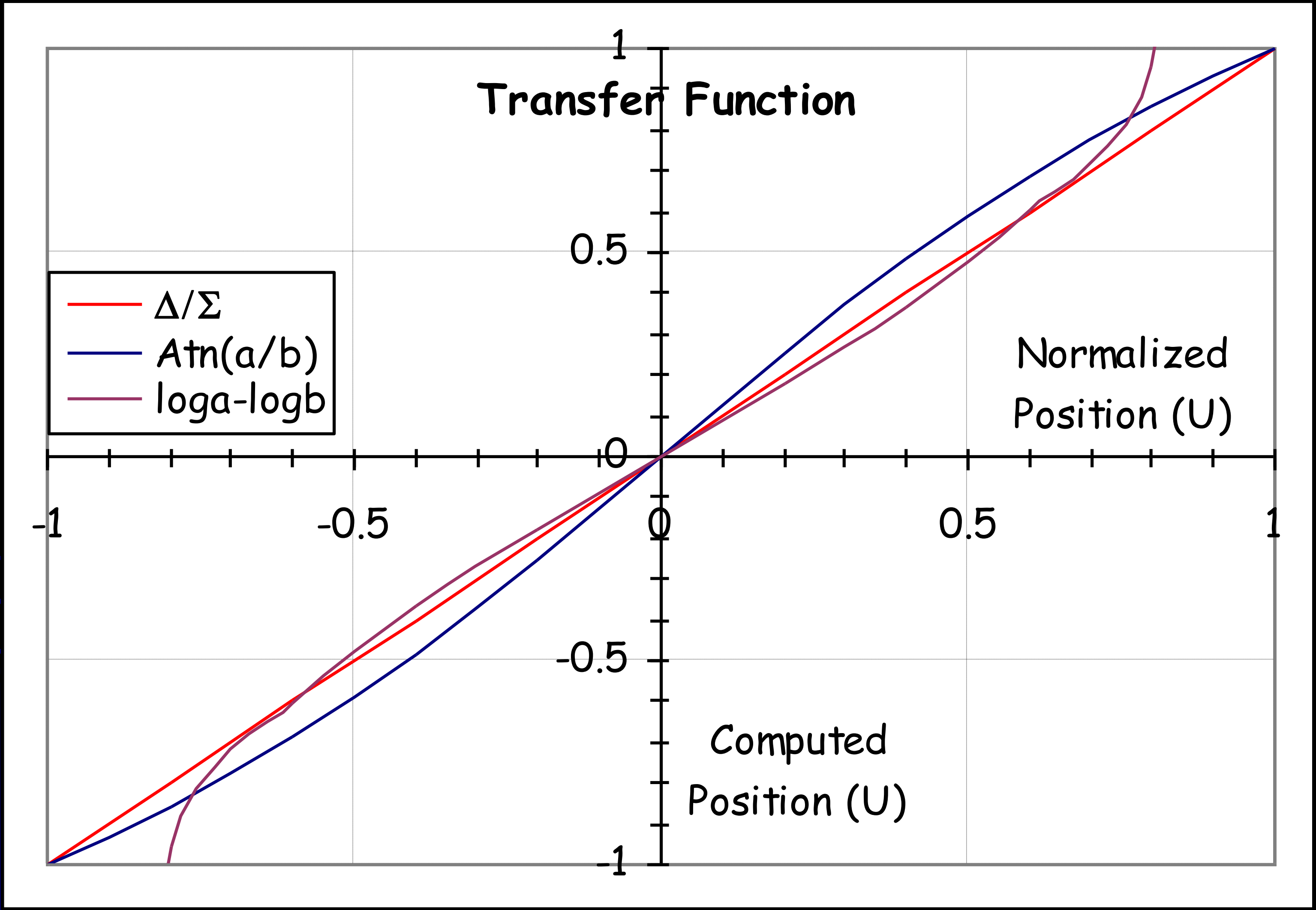
Criteria for Electronics Choice - so called "Processor Electronics"

- 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

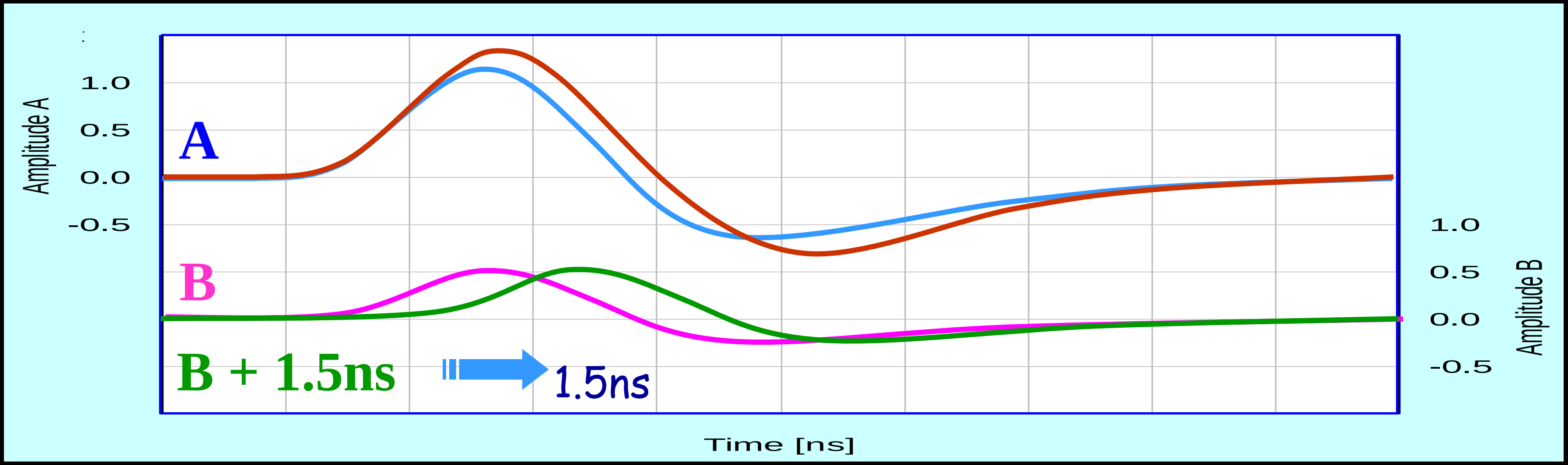
Processing System Families

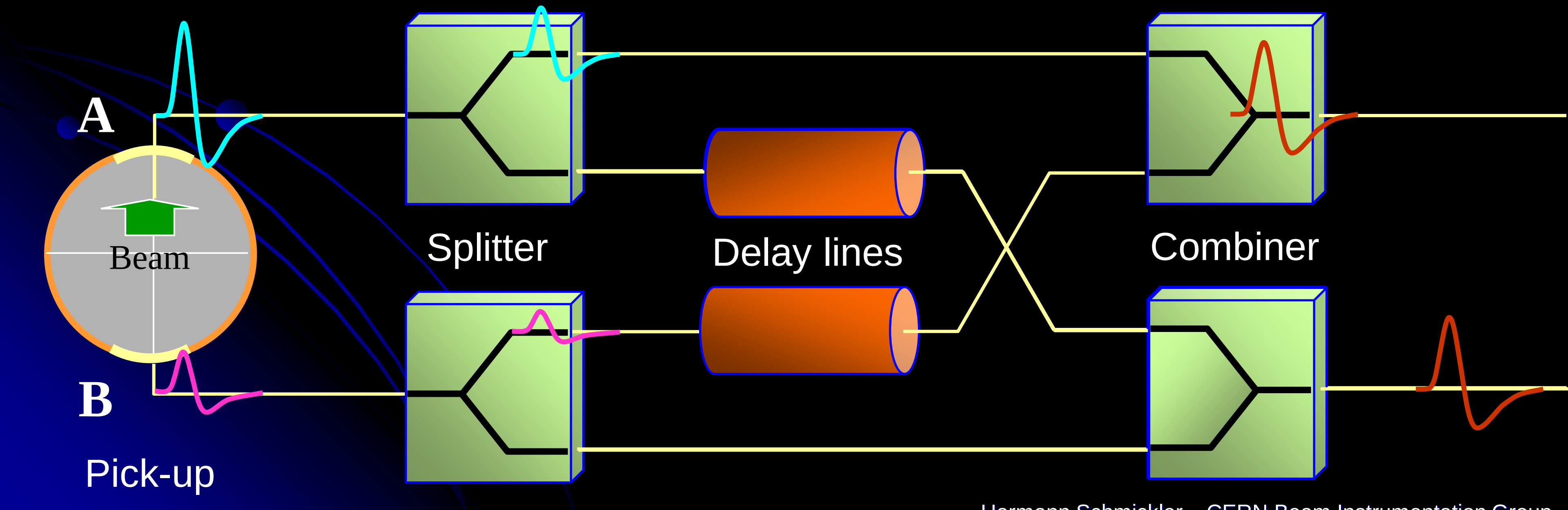


LINEARITY Comparison



Amplitude to Time Normalisation





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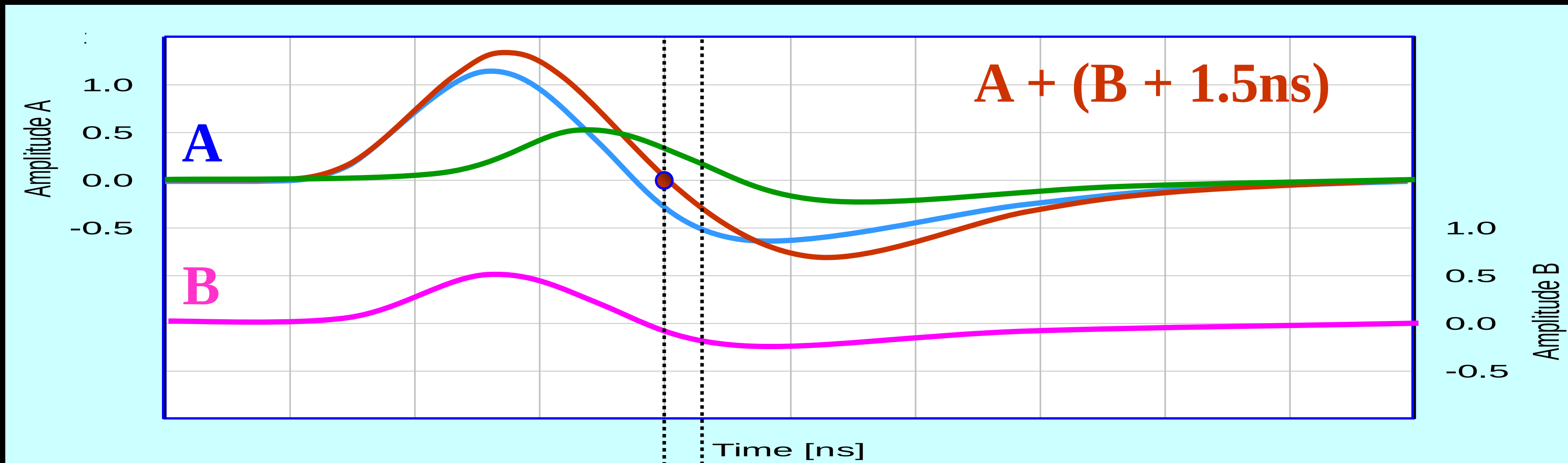
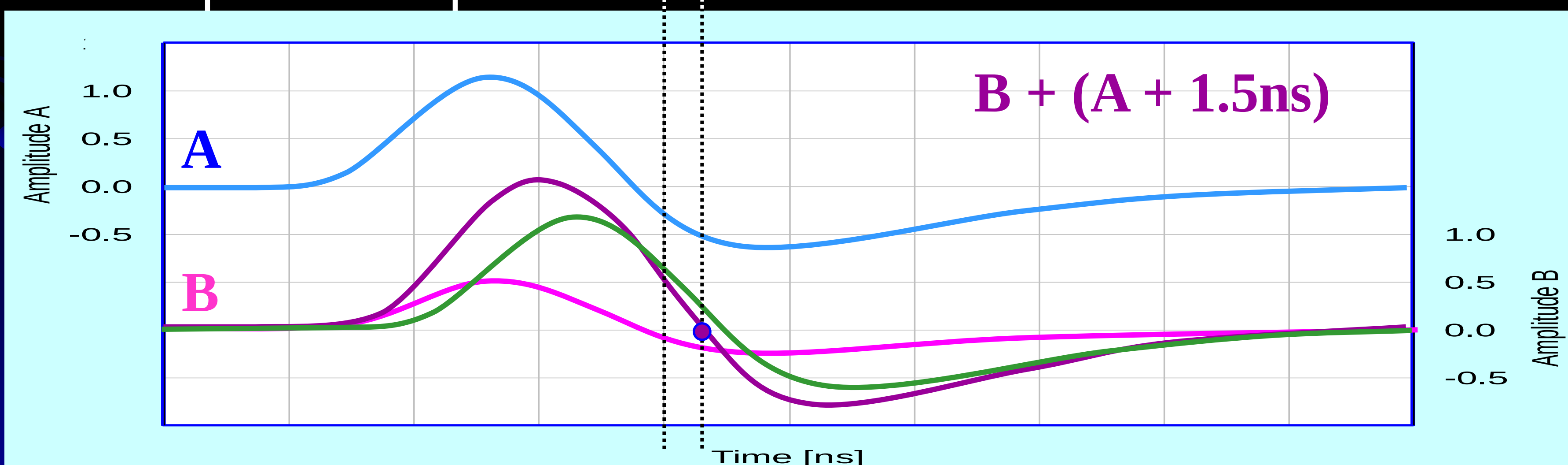


Δt depends on position



BPM Acquisition Electronics

Amplitude to Time Normaliser

Advantages

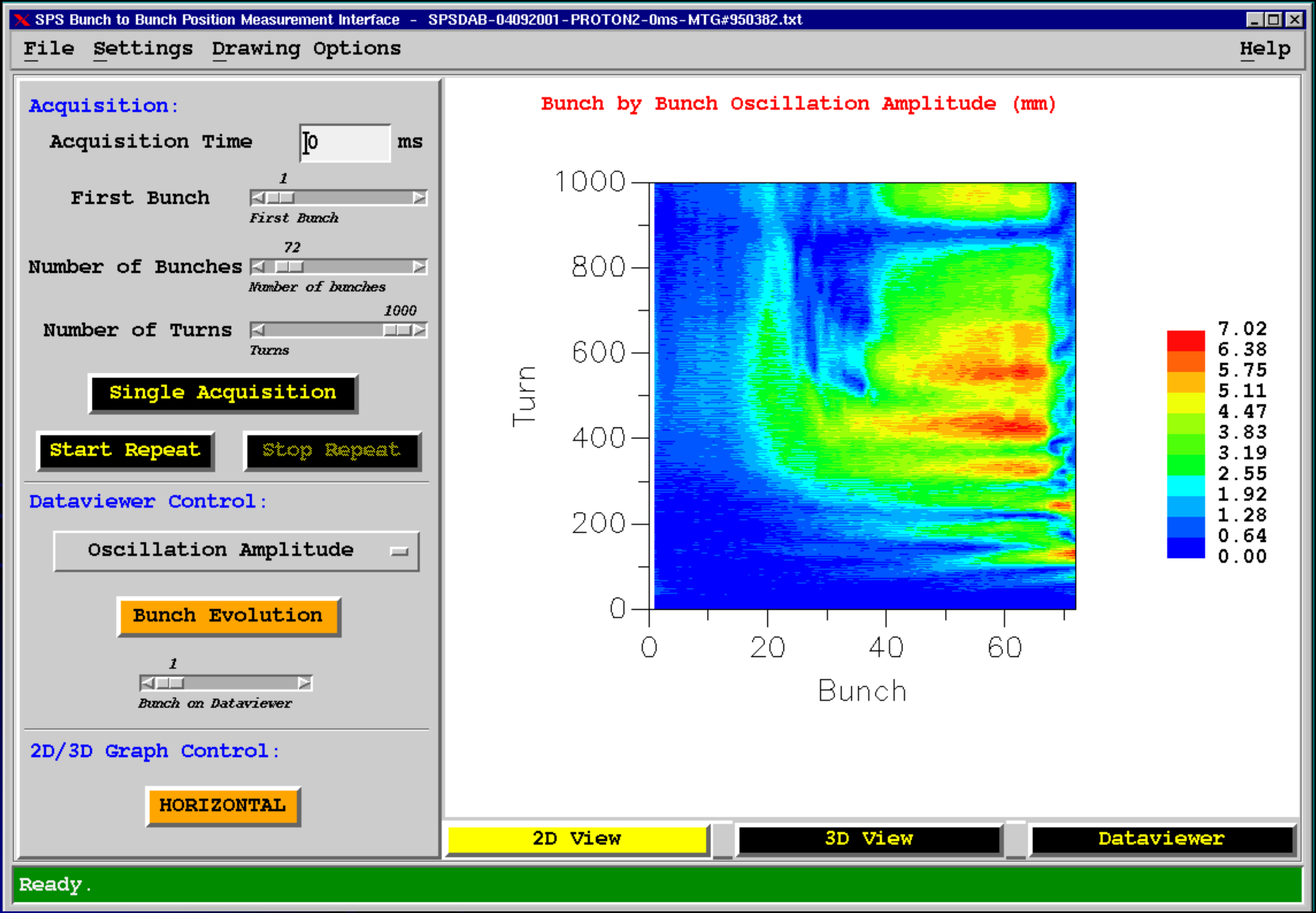
- Fast normalisation (< 25ns)
  - bunch to bunch measurement
- Signal dynamic independent of the number of bunches
  - Input dynamic range ~45 dB
  - No need for gain selection
- Reduced number of channels
  - normalisation at the front-end
- ~10 dB compression of the position dynamic due to the recombination 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.



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  - beam current transformers
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- Machine Tunes and Chromacitities
  - in diagnostics section of tomorrow
- Luminosity
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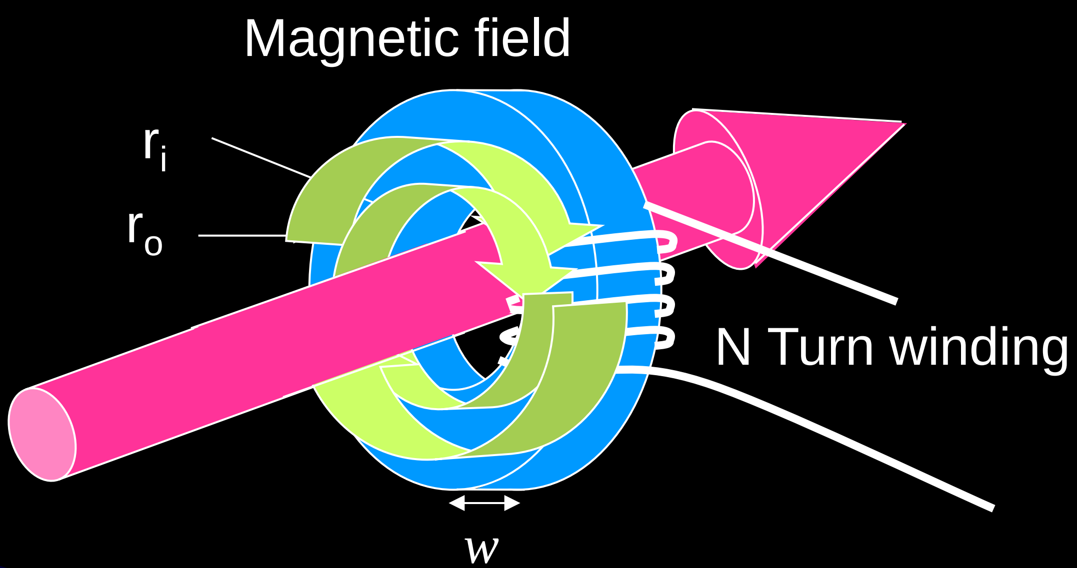
Current Transformers



Fields are very low

Capture magnetic field lines with cores of high relative permeability

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

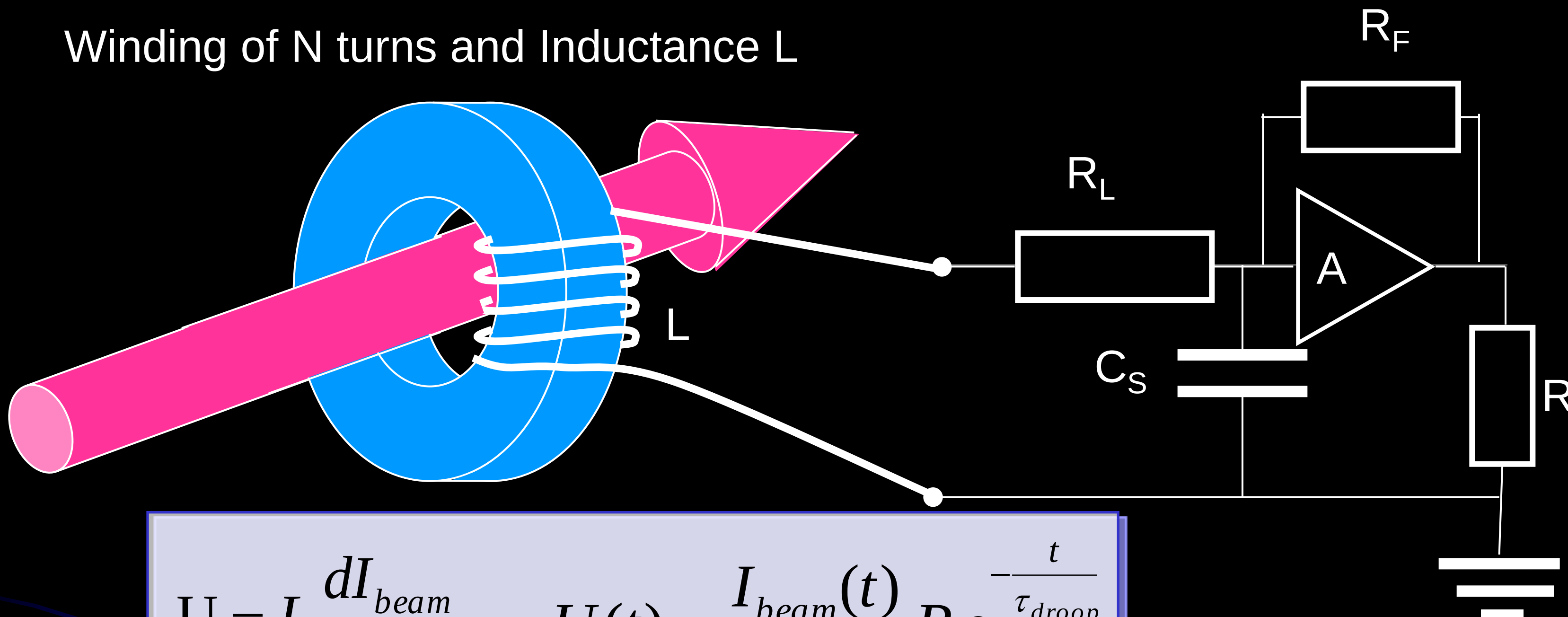
Beam current

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

Transformer Inductance

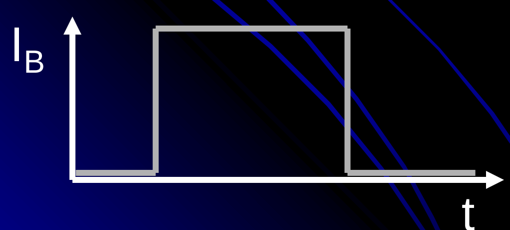
$$L = \frac{\mu_0 \mu_r}{2\pi} w N^2 \ln \frac{r_0}{r_i}$$

The Active AC transformer

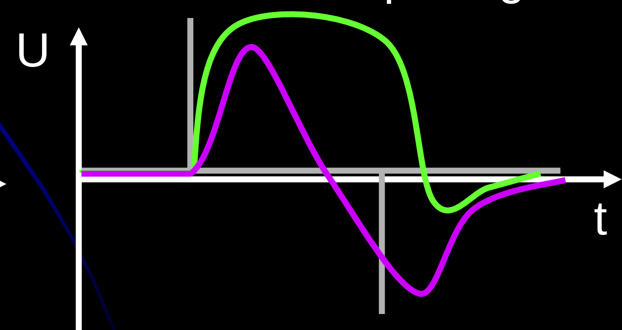


$$U = L\frac{dI_{beam}}{dt} \qquad U(t) = \frac{I_{beam}(t)}{N} R\, e^{-\frac{t}{\tau_{droop}}}$$

Beam signal



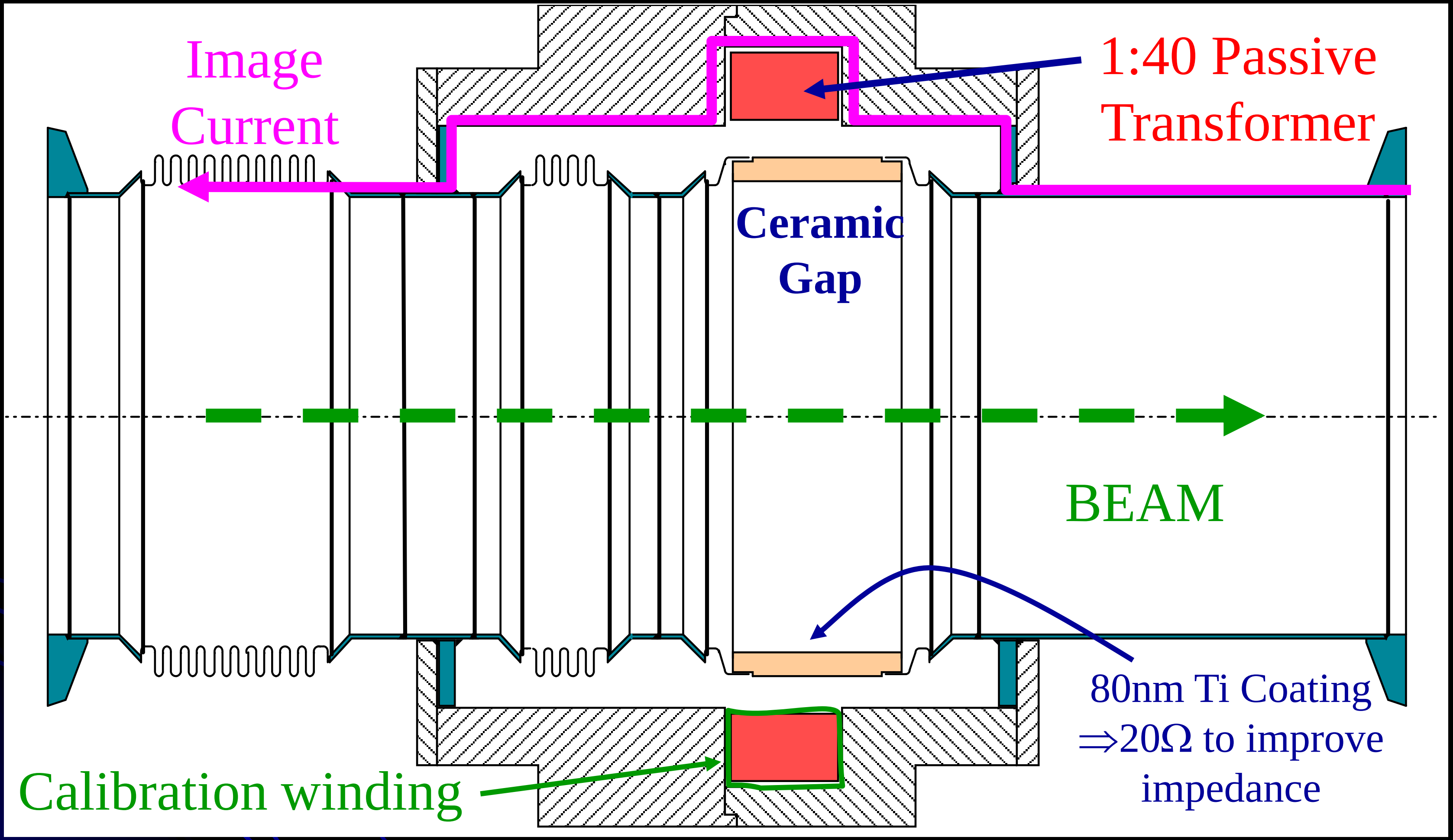
Transformer output signal



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

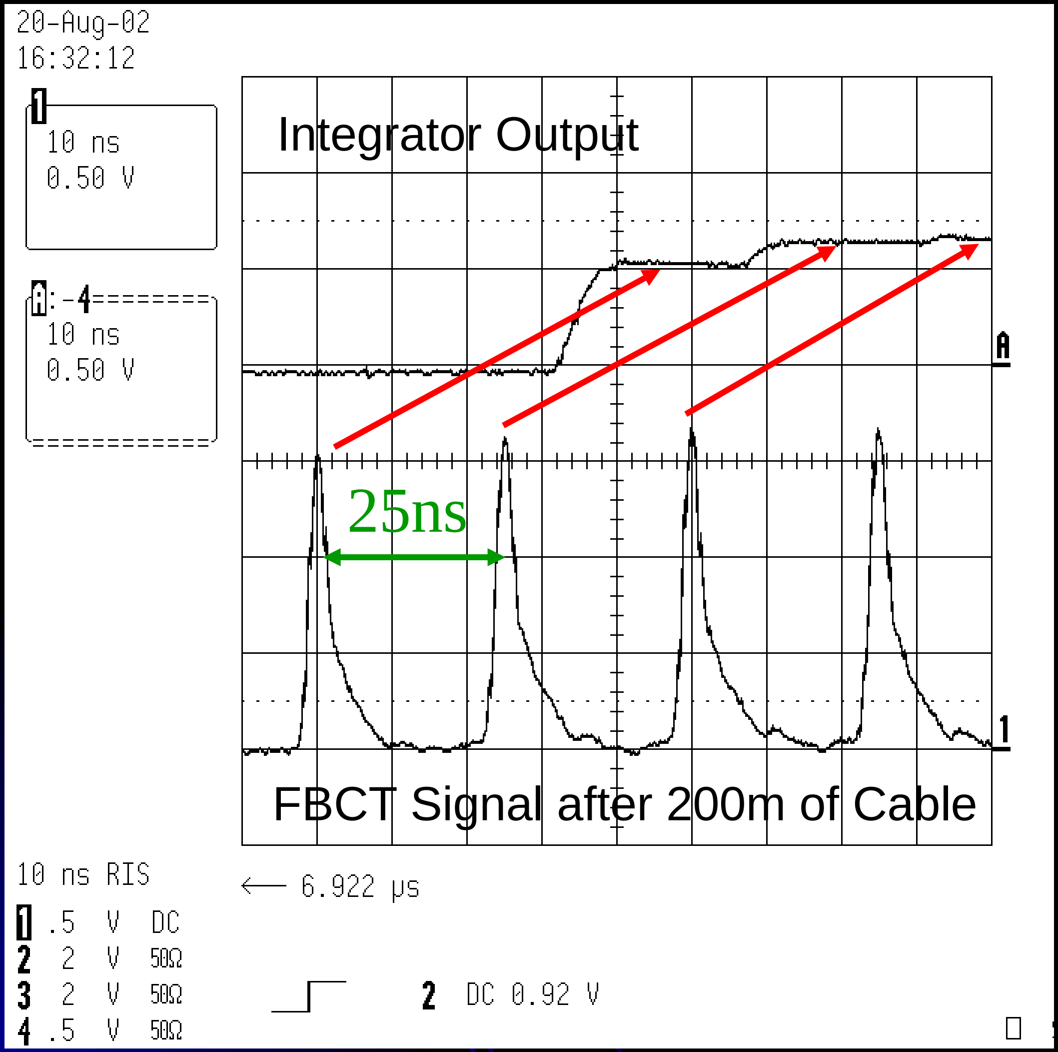
$$\tau_{droop} = \frac{L}{\frac{R_f}{A} + R_L} \approx \frac{L}{R_L}$$

Fast Beam Current Transformer



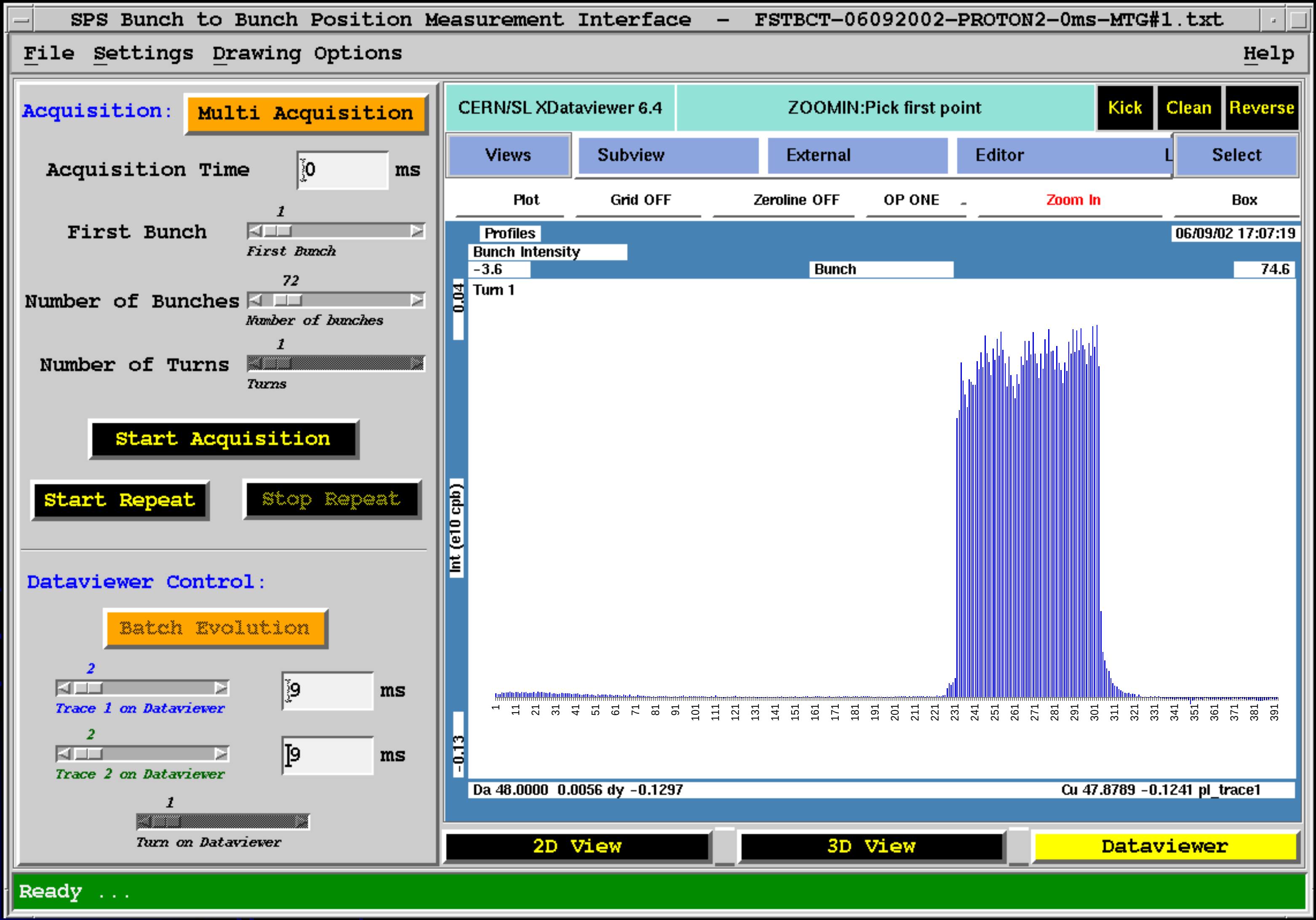
- 500MHz Bandwidth
- Low droop (< 0.2%/μs)

Acquisition Electronics



Data taken on LHC type beams at the CERN-SPS

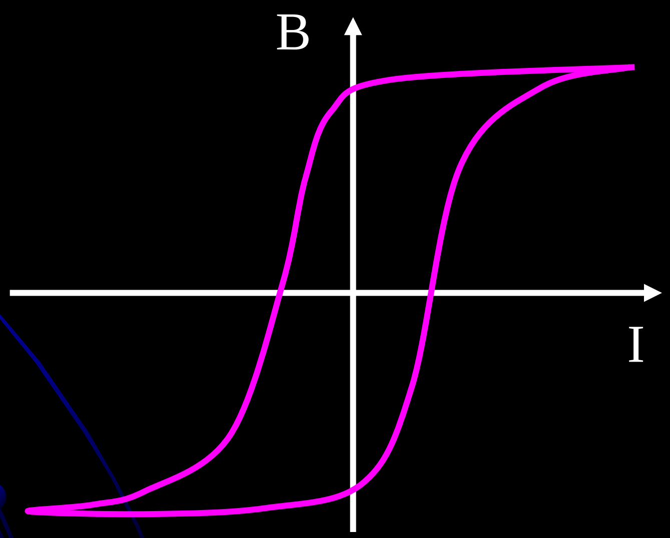
What one can do with such a System



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

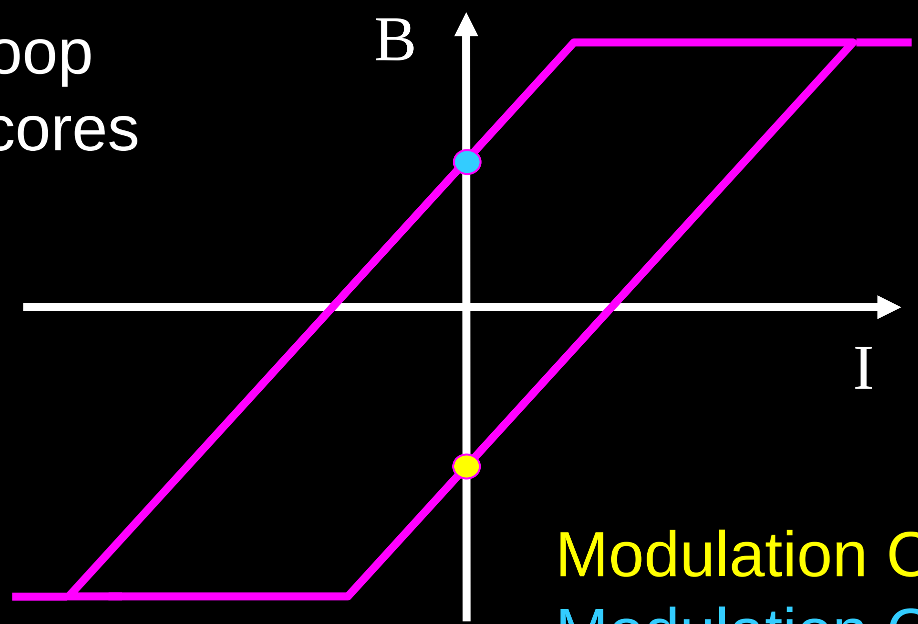
The DC current transformer

- AC current transformer can be extended to very low frequency but not to DC (no dI/dt !)
- 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

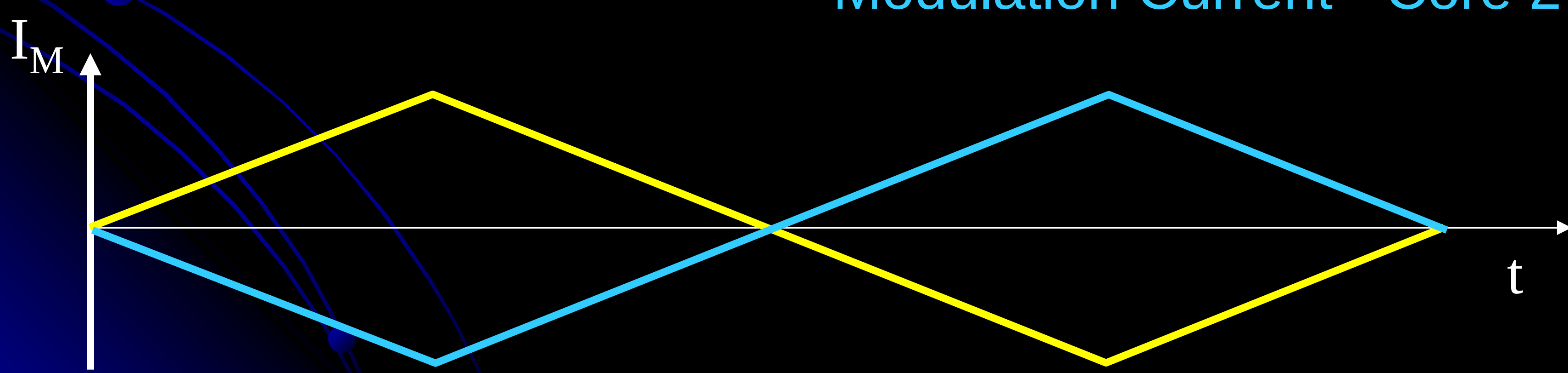


DCCT Principle – Case 1: no beam

Hysteresis loop
of modulator cores

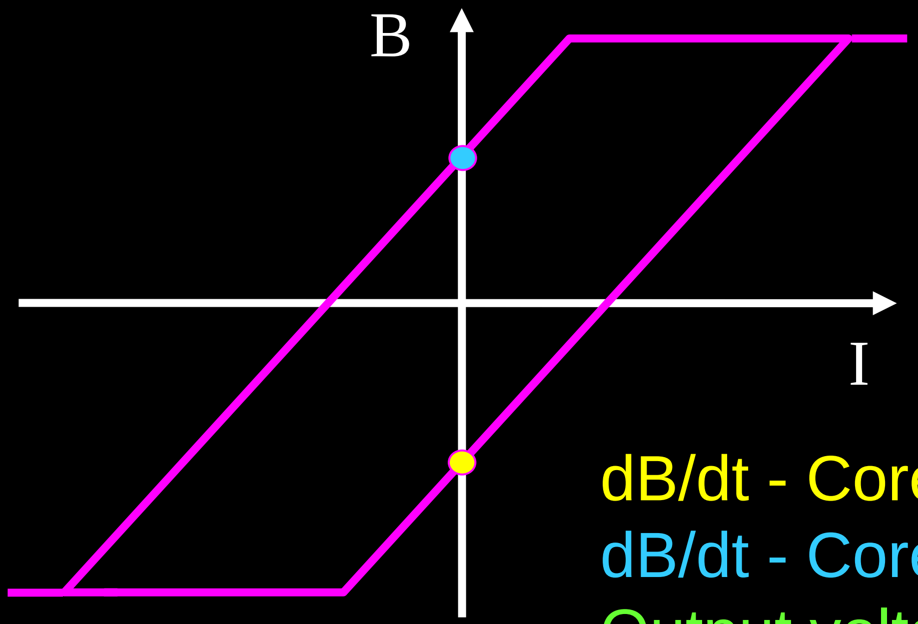


Modulation Current - Core 1
Modulation Current - Core 2



DCCT Principle – Case 1: no beam

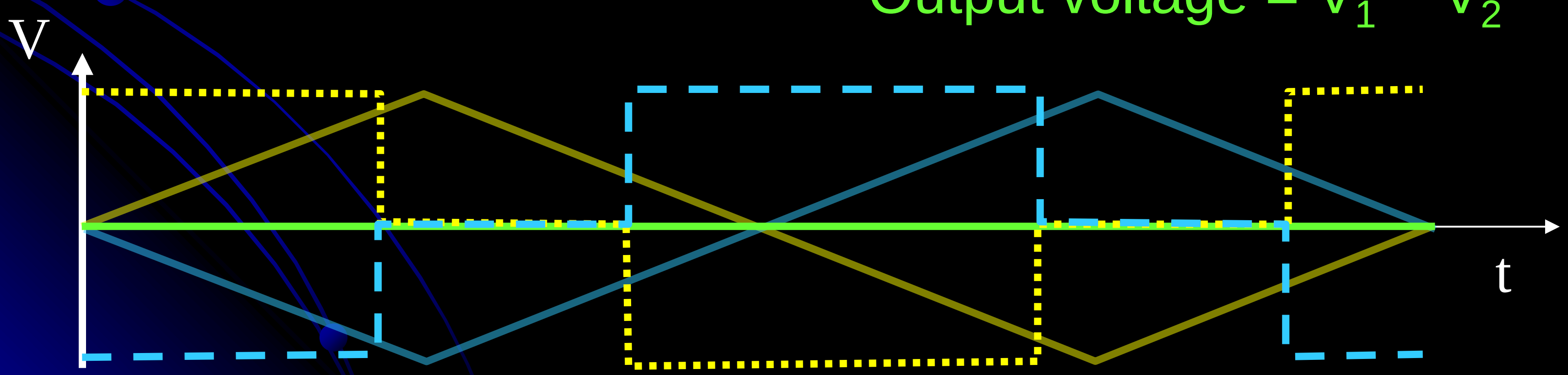
$$V \propto \frac{dB}{dt}$$



dB/dt - Core 1 (V1)

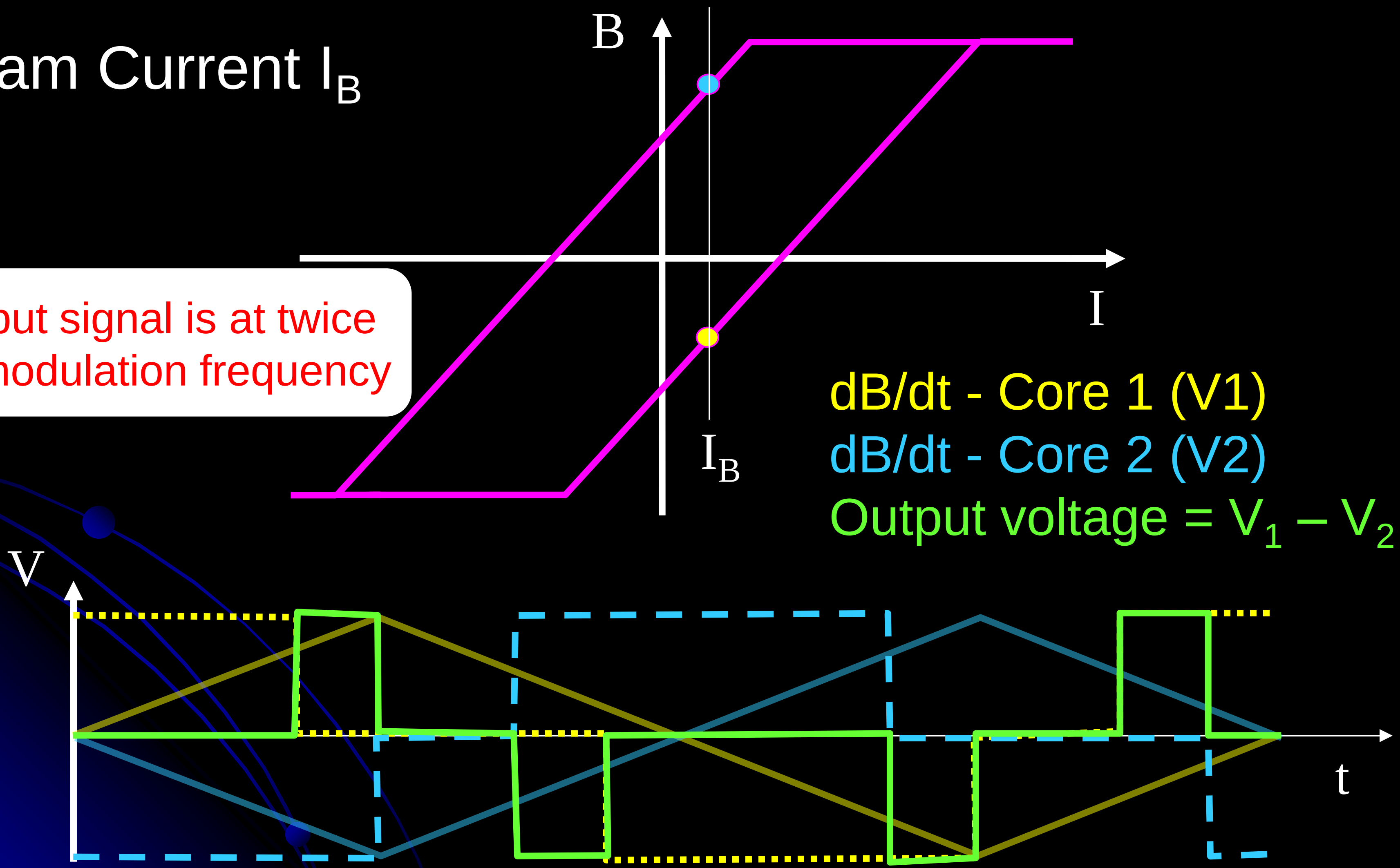
dB/dt - Core 2 (V2)

Output voltage = $V_1 - V_2$



DCCT Principle – Case 2: with beam

Beam Current I_B



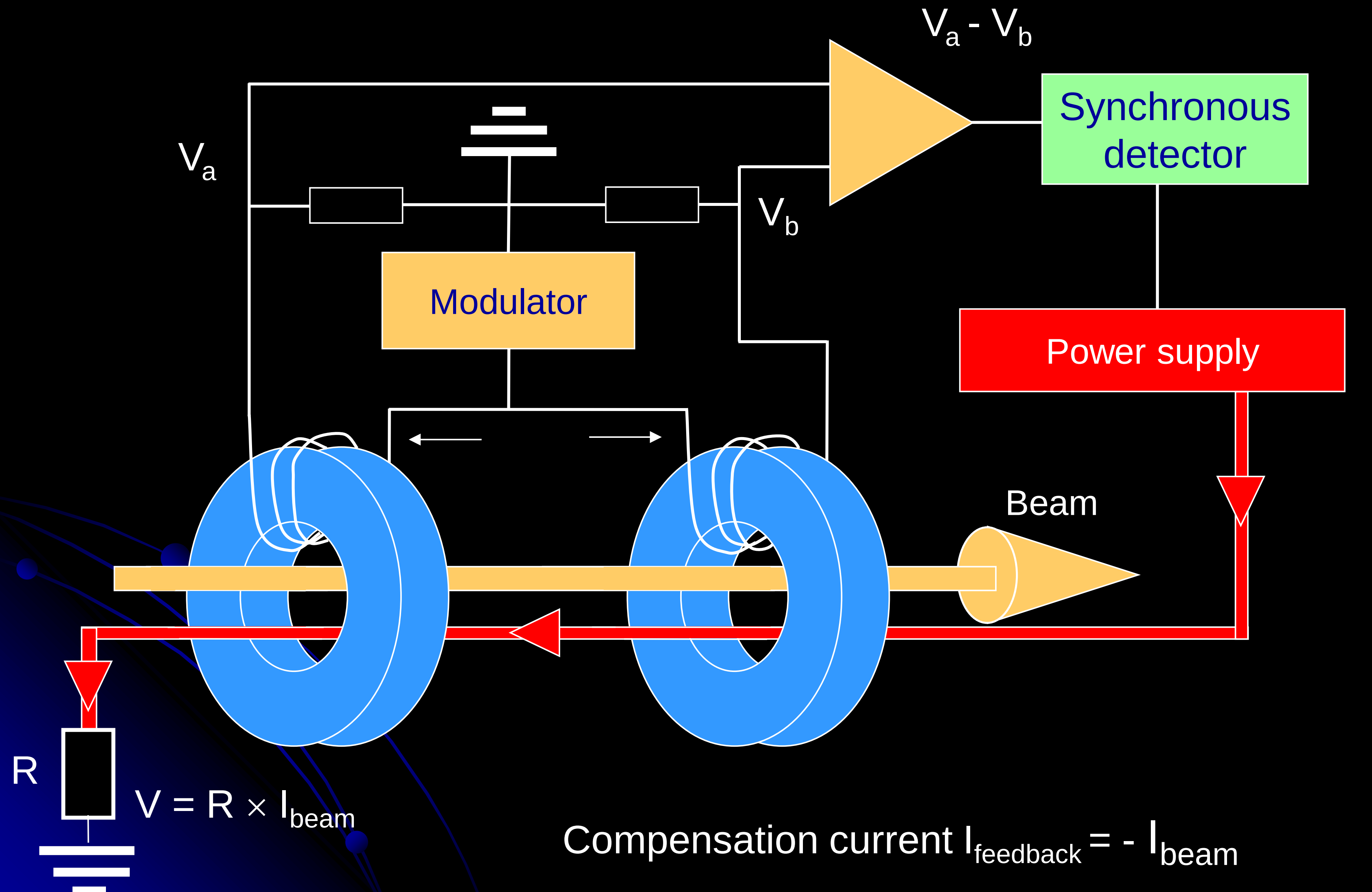
Output signal is at twice the modulation frequency

dB/dt - Core 1 (V1)

dB/dt - Core 2 (V2)

Output voltage = $V_1 - V_2$

Zero Flux DCCT Schematic



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

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- Machine Tunes and Chromacitities
  - in diagnostics section of tomorrow
- Luminosity
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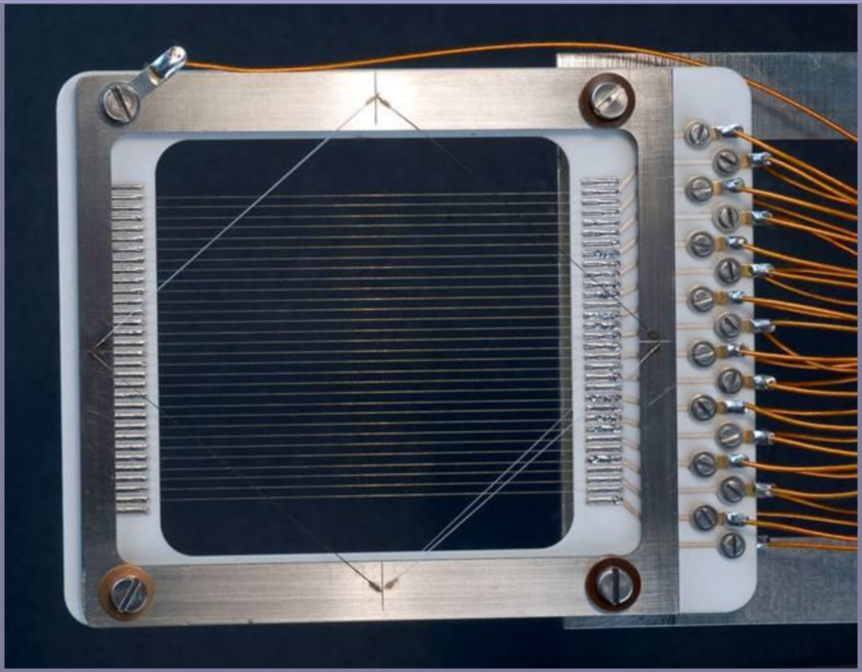
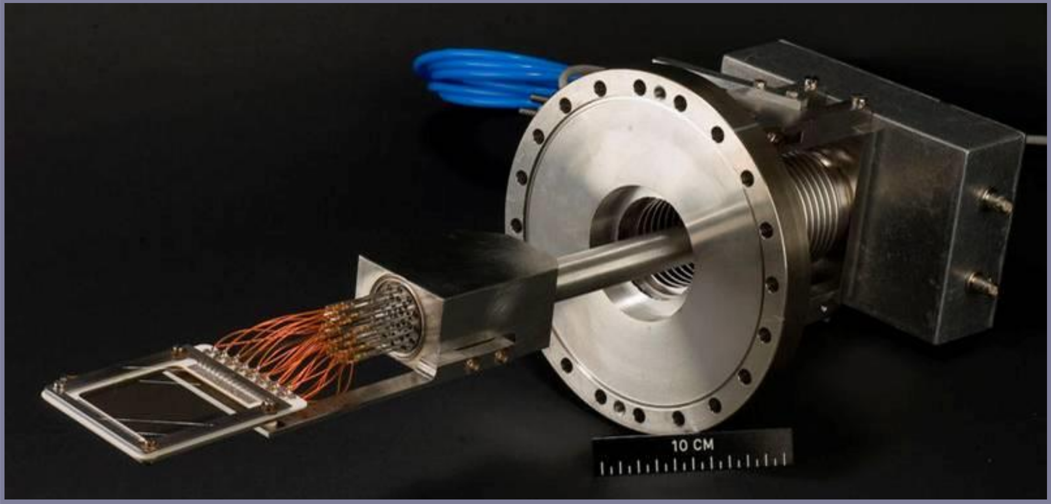
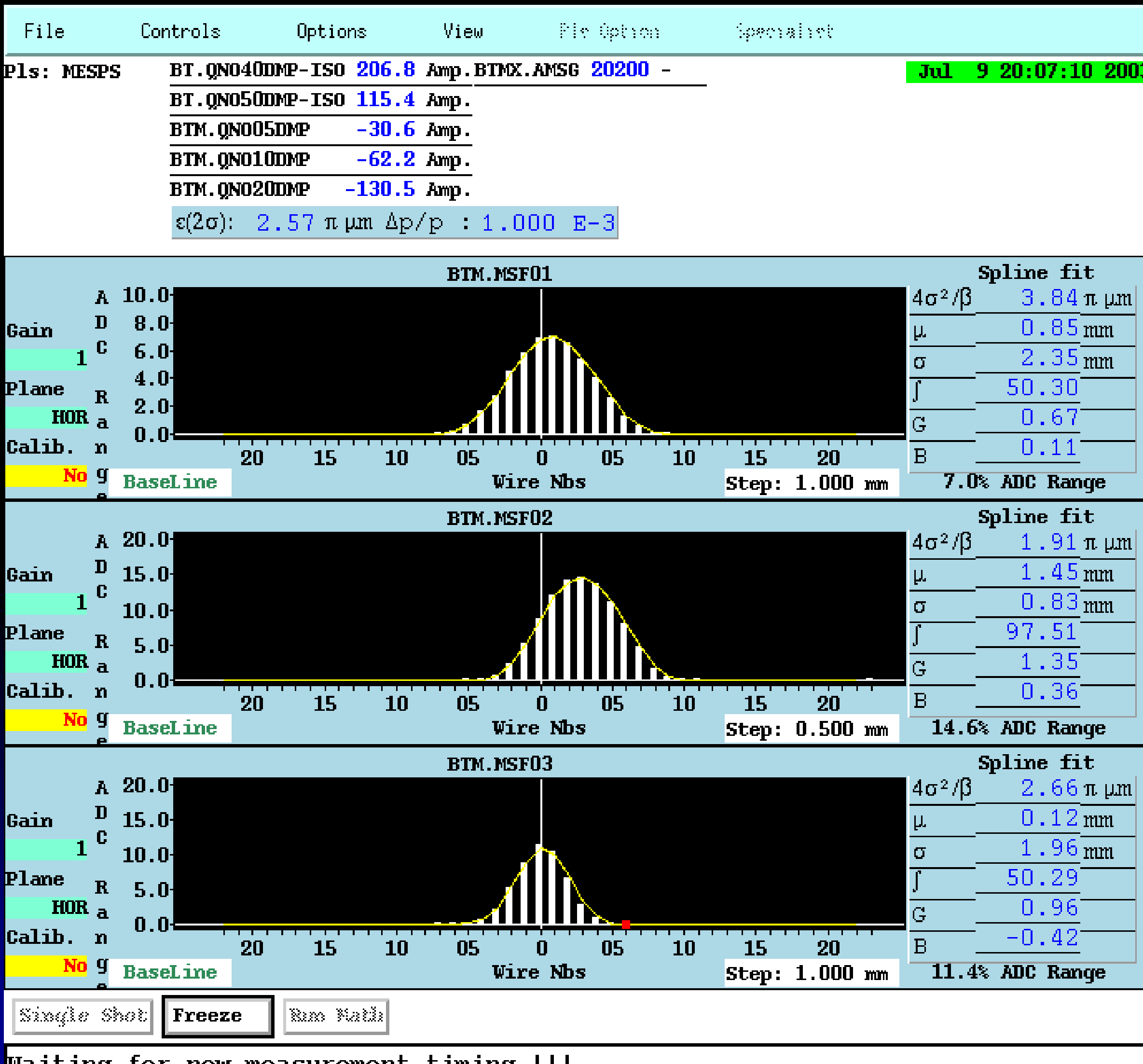
Secondary Emission (SEM) Grids

- 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





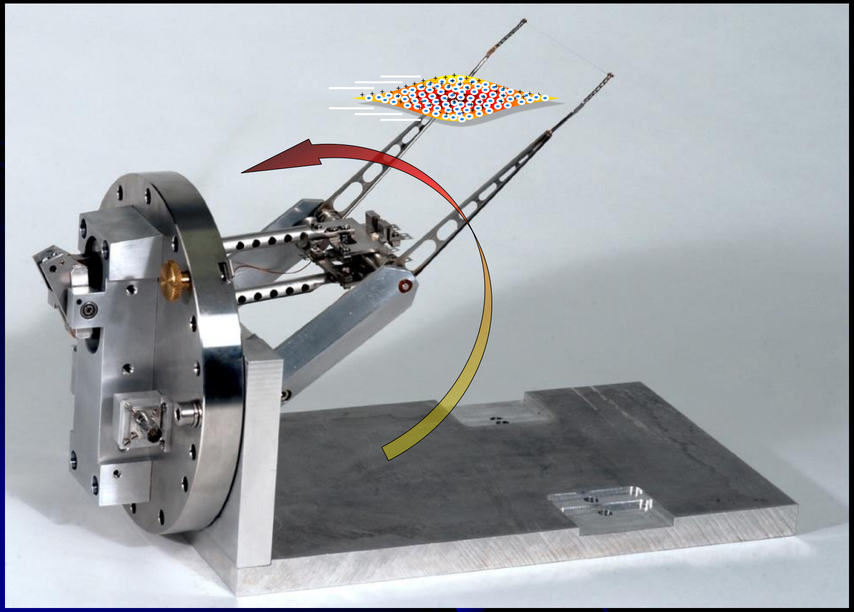
Profiles from SEM grids

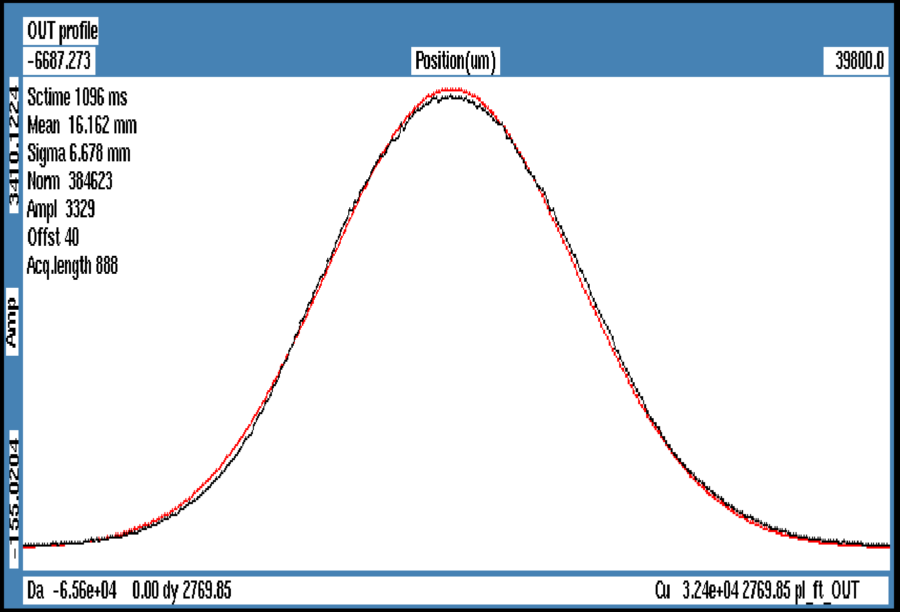


- Charge density measured from each wire gives a projection of the beam profile in either horizontal or vertical plane
- Resolution is given by distance between wires
- Used only in low energy linacs and transfer lines as heating is too great for circulating beams

Wire Scanners

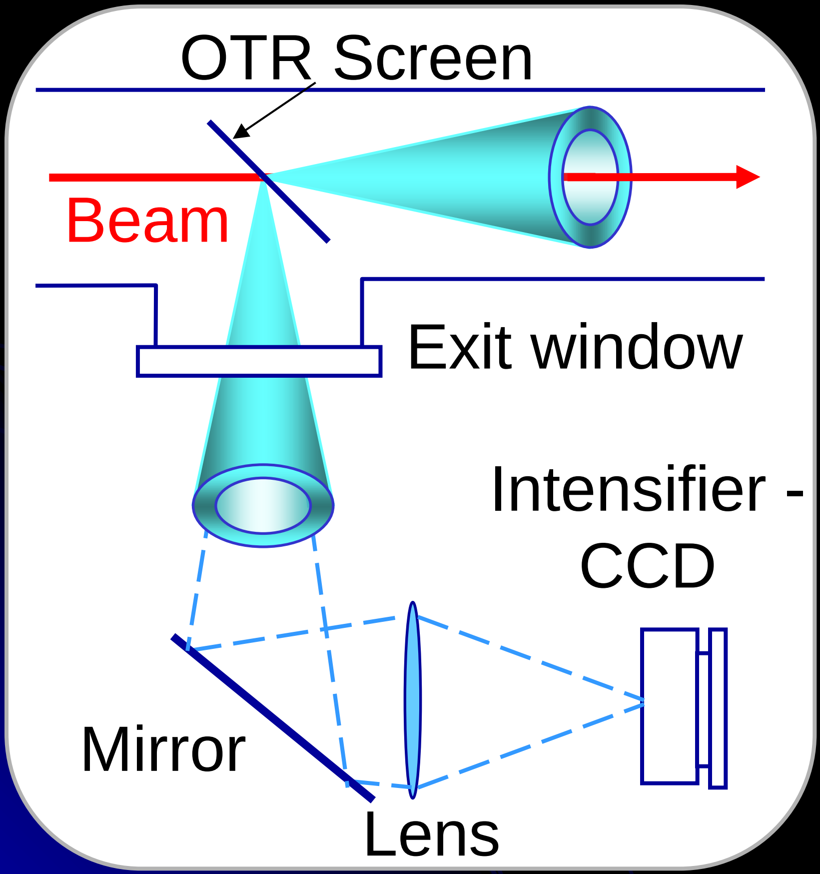
- A thin wire is moved across the beam
  - has to move fast to avoid excessive heating of the wire
- Detection
  - Secondary particle shower detected outside the vacuum chamber using a scintillator/photo-multiplier assembly
  - Secondary emission current detected as for SEM grids
- Correlating wire position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

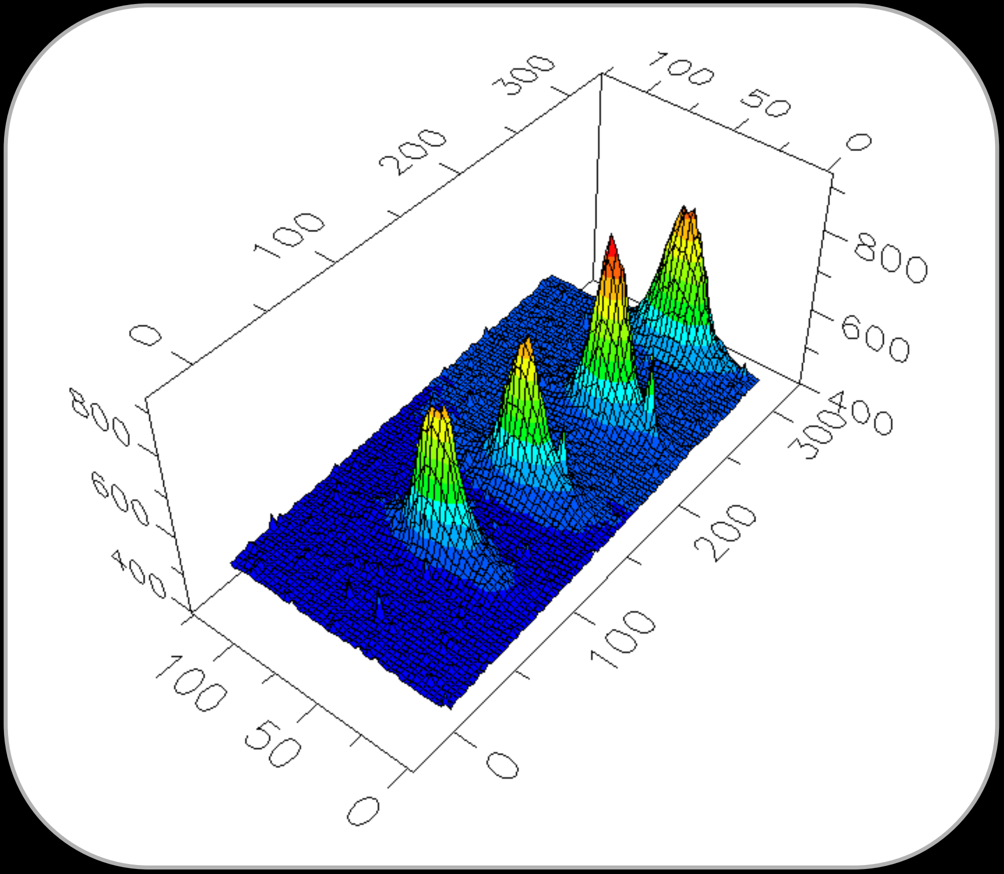




Beam Profile Monitoring using Screens

- 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

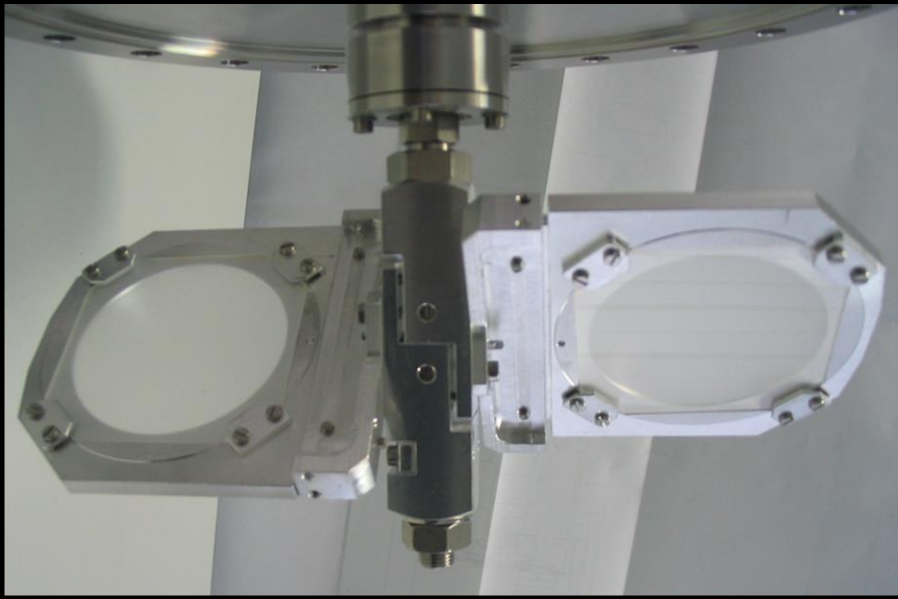
- Screen Types
  - Luminescence Screens
    - destructive (thick) but work during setting-up with low intensities
  - Optical Transition Radiation (OTR) screens
    - much less destructive (thin) but require higher intensity

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	*$2\ 10^7$*

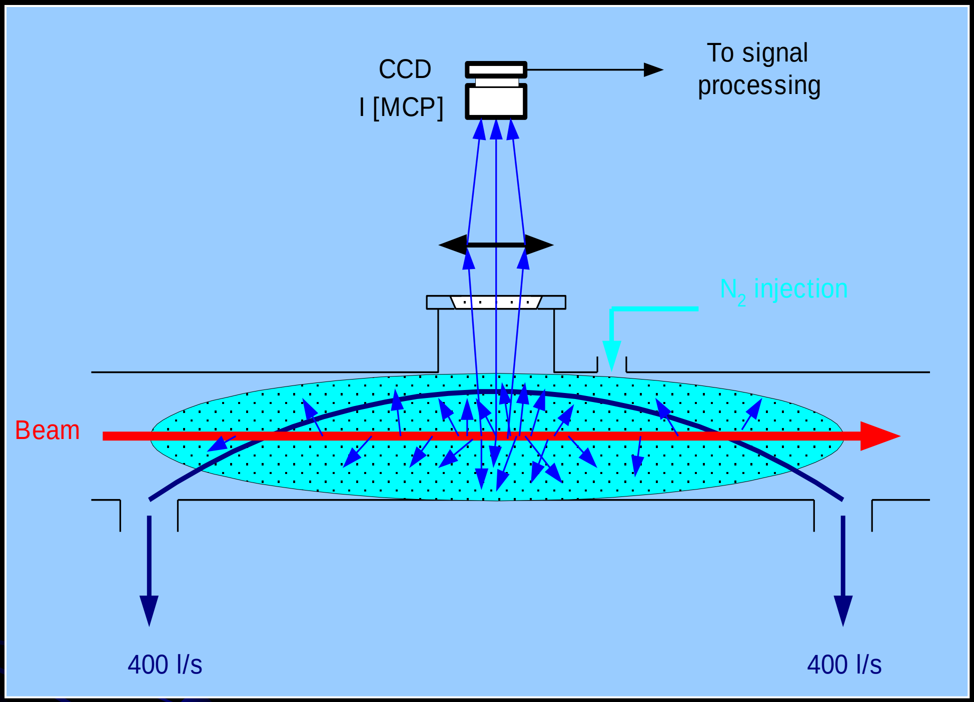
Beam Profile Monitoring using Screens

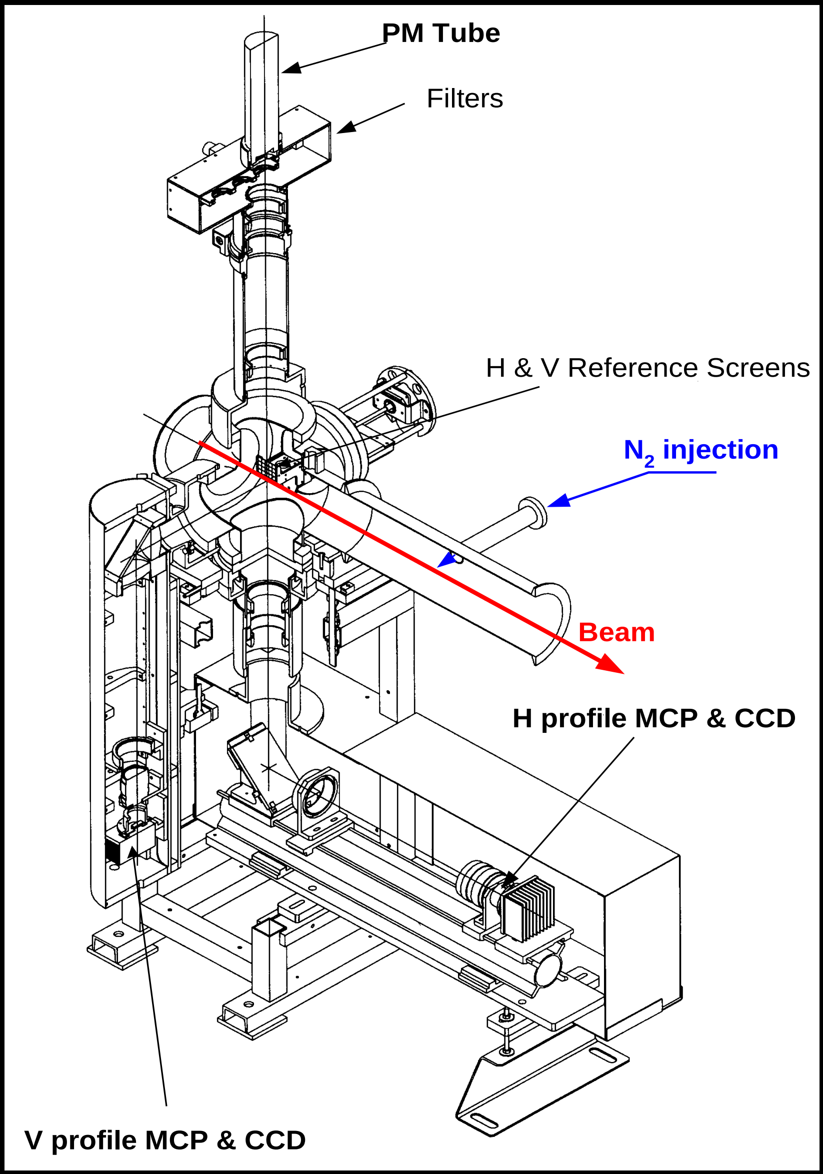
- Usual configuration
  - Combine several screens in one housing e.g.
    - Al_2O_3 luminescent screen for setting-up with low intensity
    - Thin (~10um) Ti OTR screen for high intensity measurements
    - Carbon OTR screen for very high intensity operation

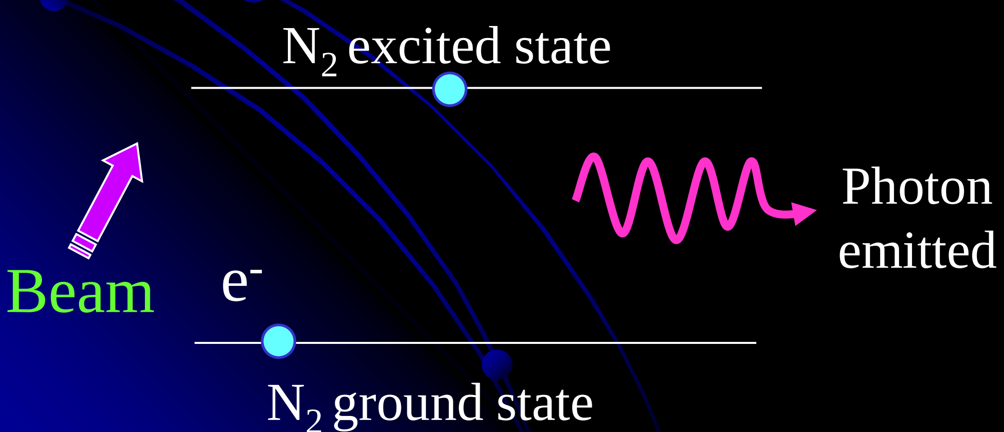


- Advantages compared to SEM grids
  - allows analogue camera or CCD acquisition
  - gives two dimensional information
  - high resolution: ~ 400 x 300 = 120’000 pixels for a standard CCD
  - more economical
    - Simpler mechanics & readout electronics
  - Time resolution depends on choice of image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

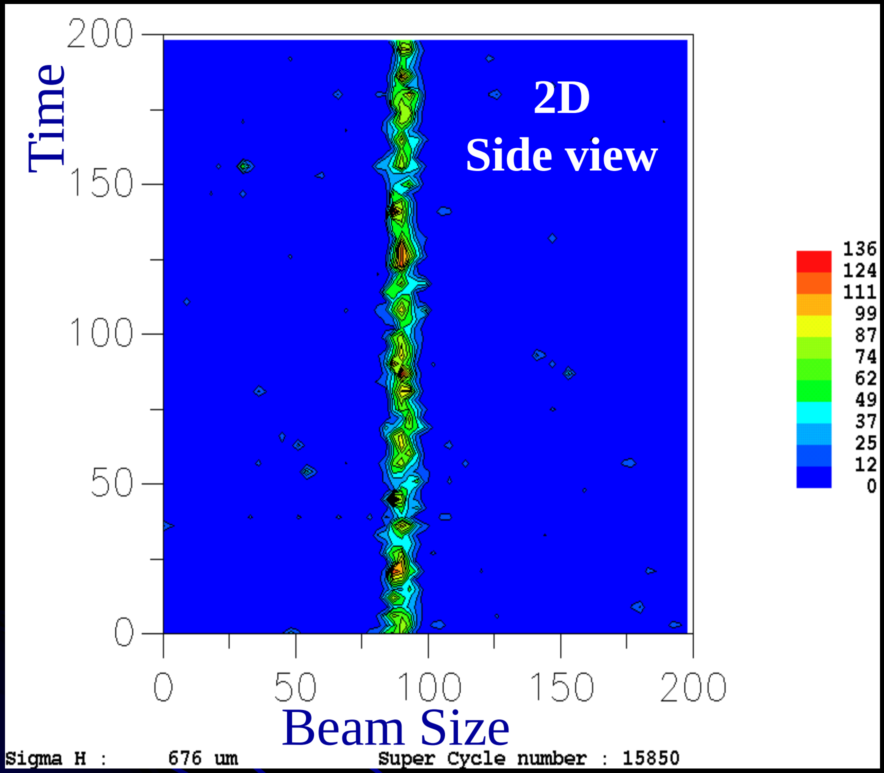
Luminescence Profile Monitor







Luminescence Profile Monitor

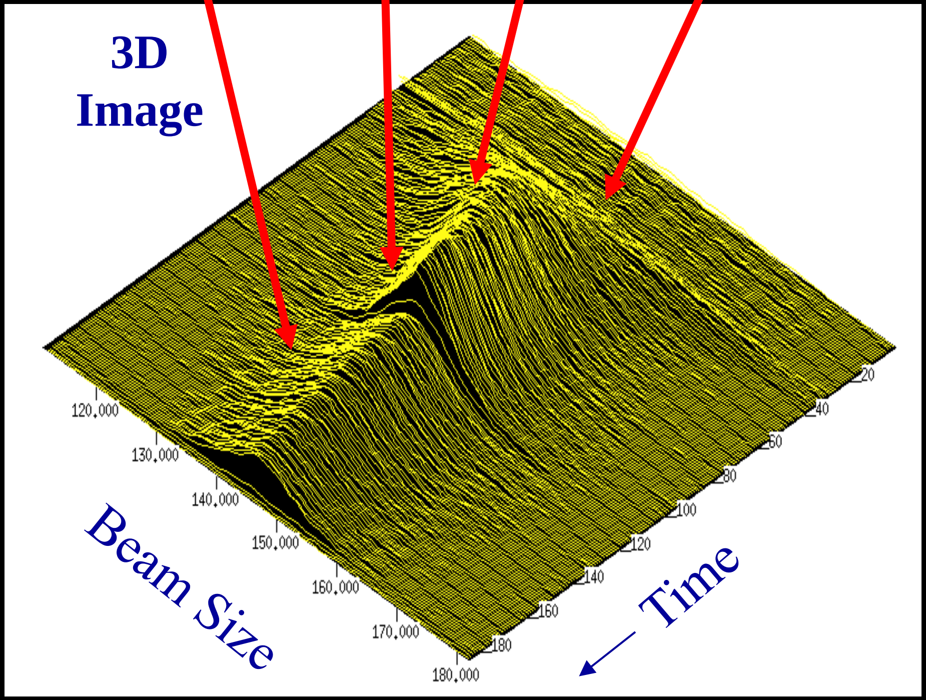


Beam size shrinks as beam is accelerated

Fast extraction

Injection

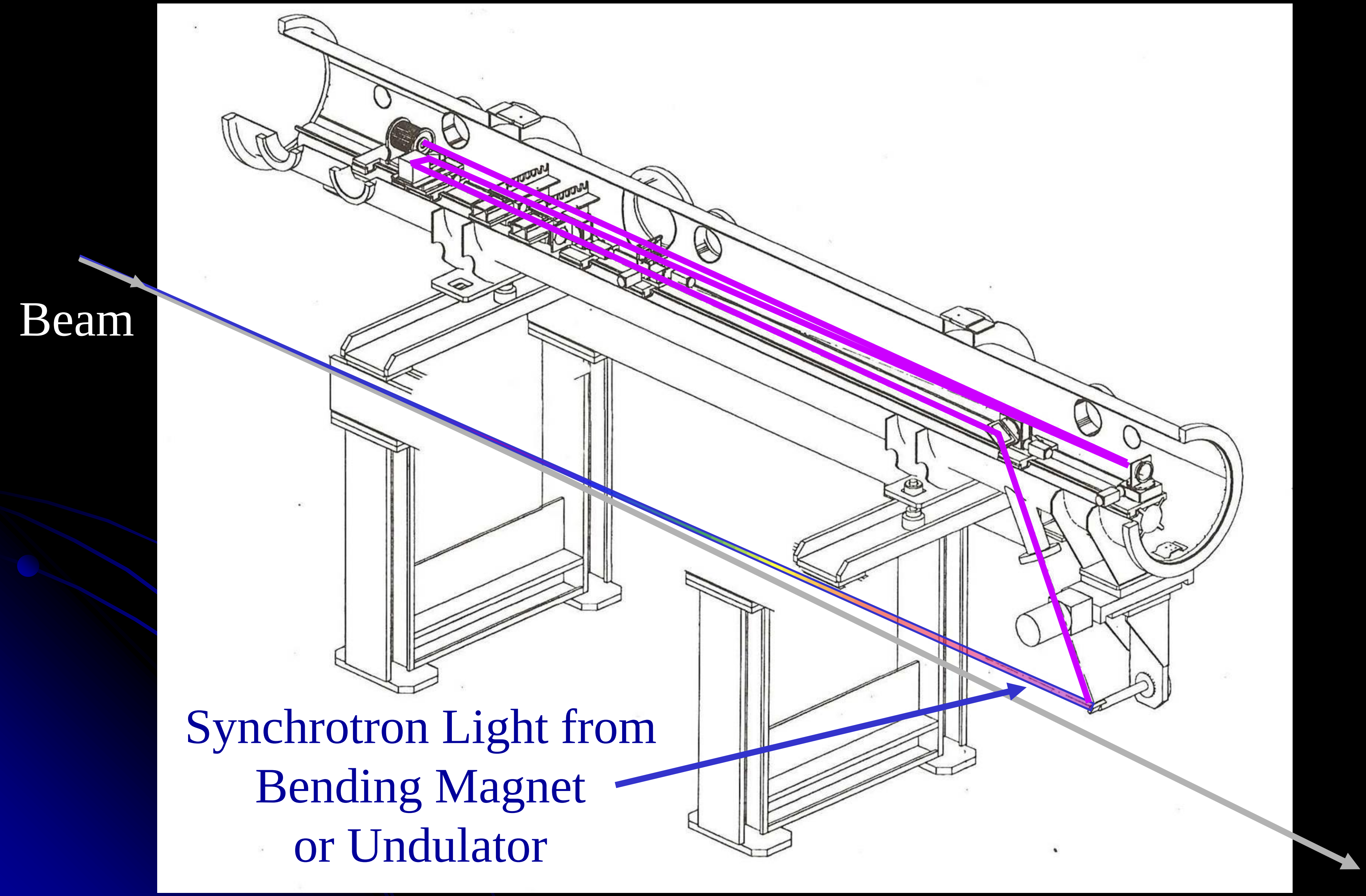
Slow extraction



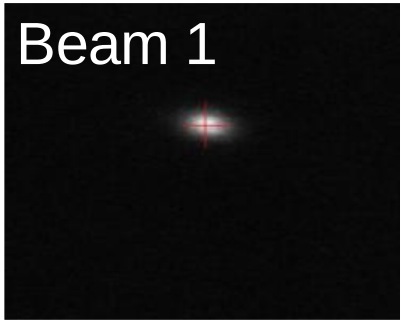
CERN-SPS Measurements

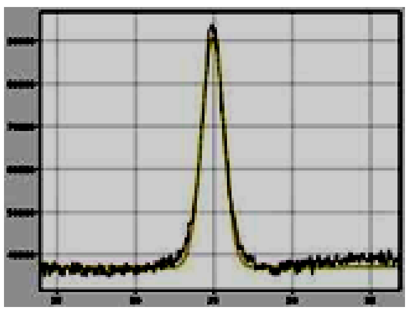
- Profile Collected every 20ms
- Local Pressure at ~5×10^{-7} Torr

The Synchrotron Light Monitor

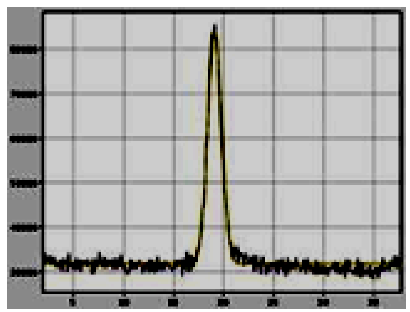


The Synchrotron Light Monitor

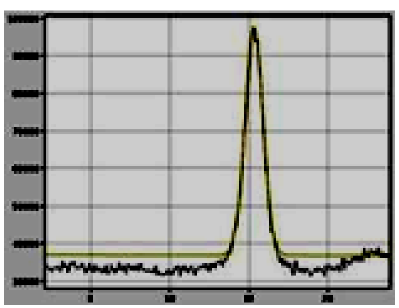




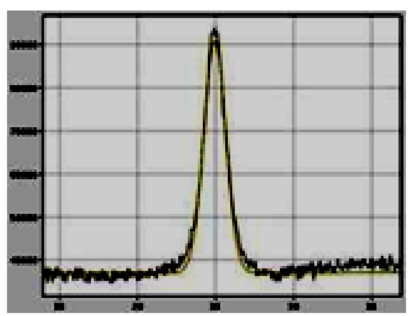
σ_h = 0.68mm



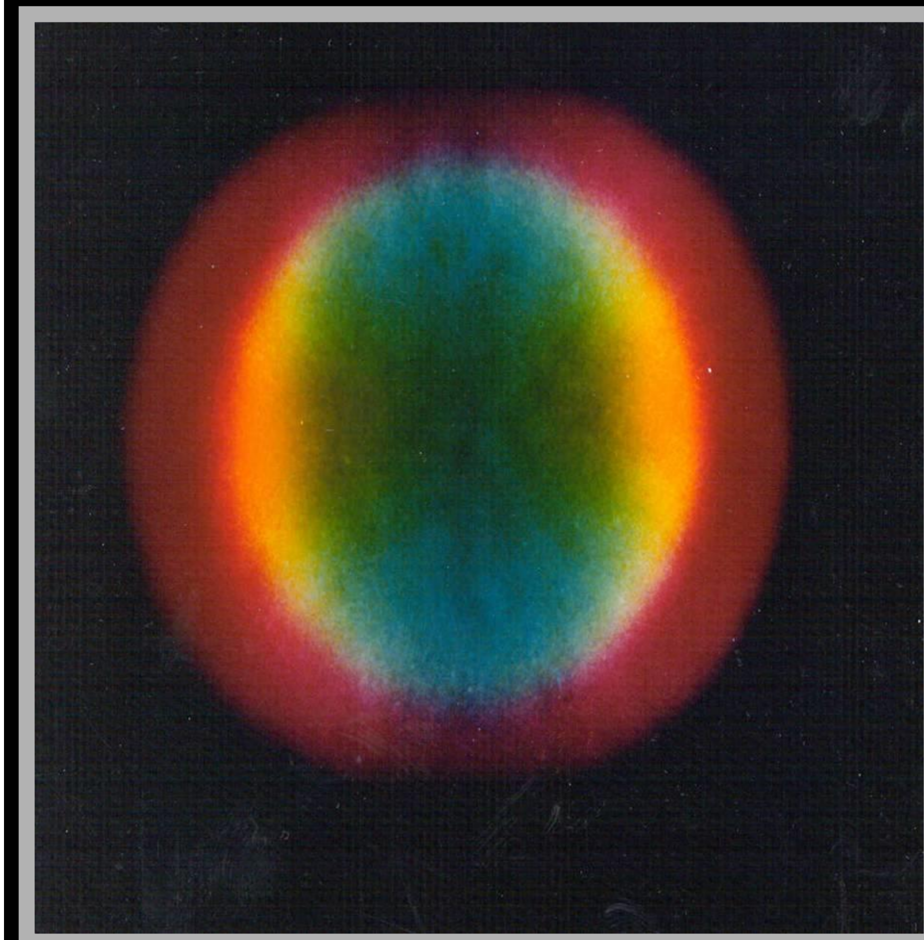
σ_h = 0.70mm



σ_v = 0.56mm



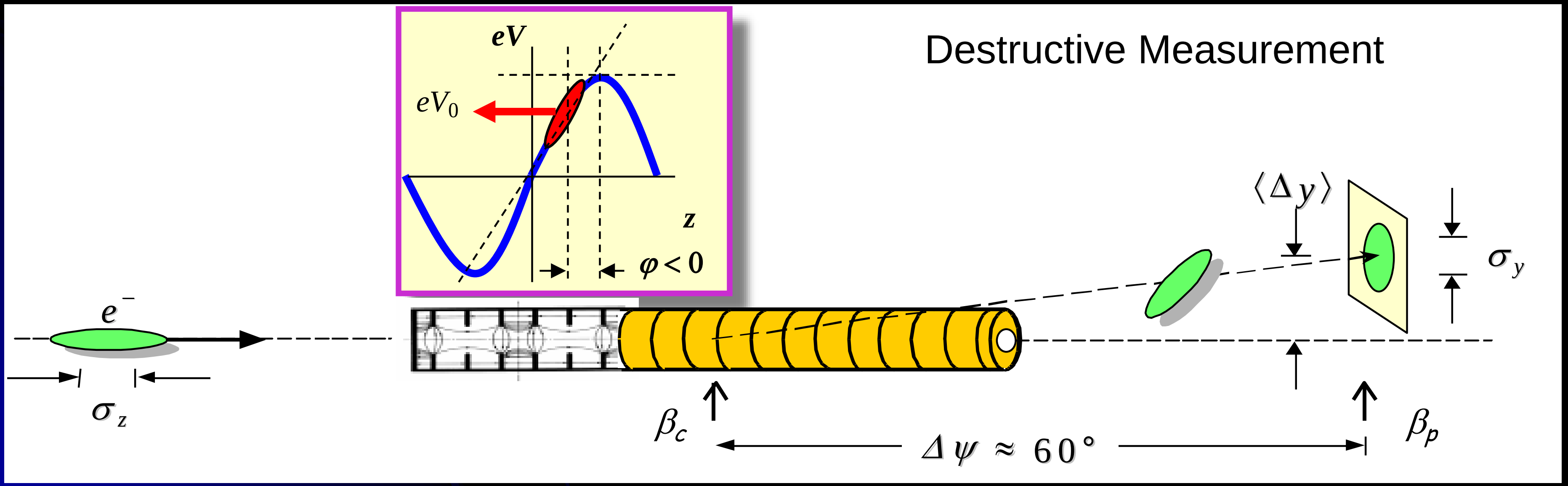
σ_v = 1.05mm



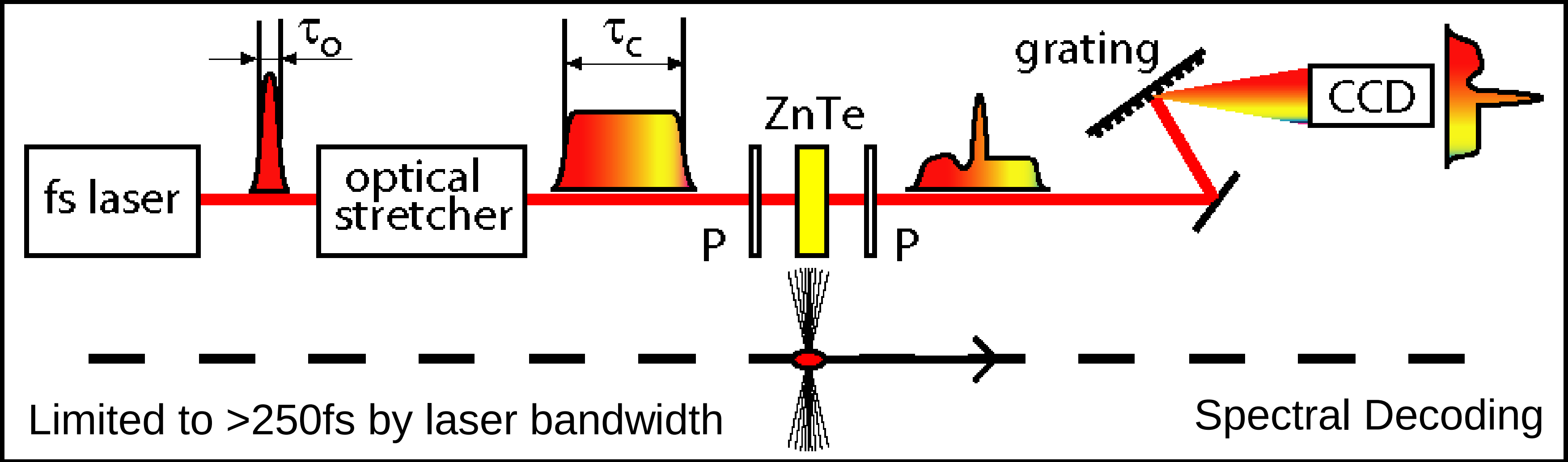
Measuring Ultra Short Bunches

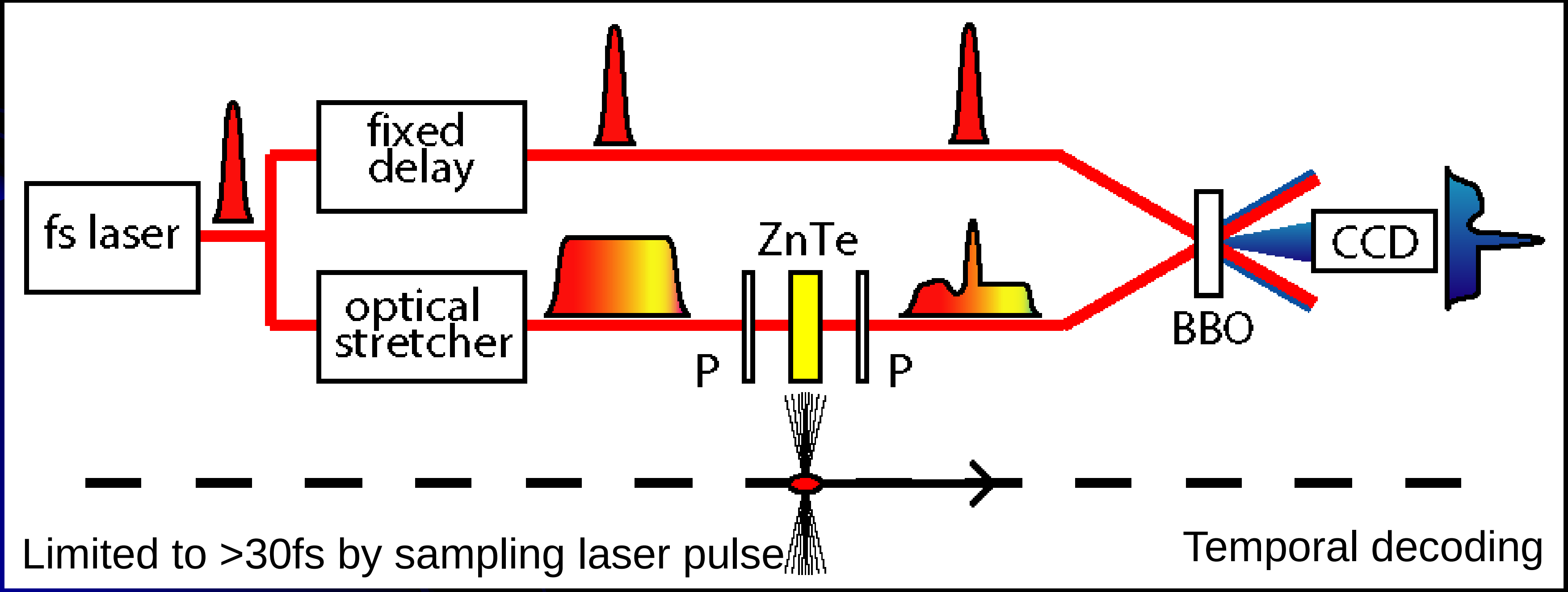
- Next Generation FELs & Linear Colliders
  - Use ultra short bunches to increase brightness or improve luminosity
- How do we measure such short bunches?
  - Transverse deflecting cavity

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



Electro-Optic Sampling – Non Destructive





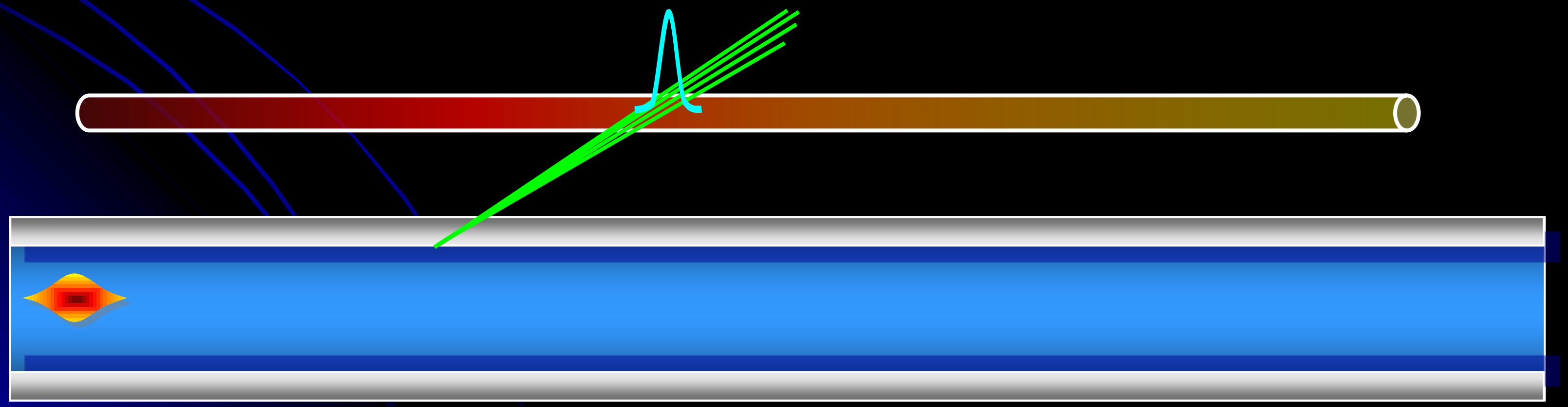
The Typical Instruments

- 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

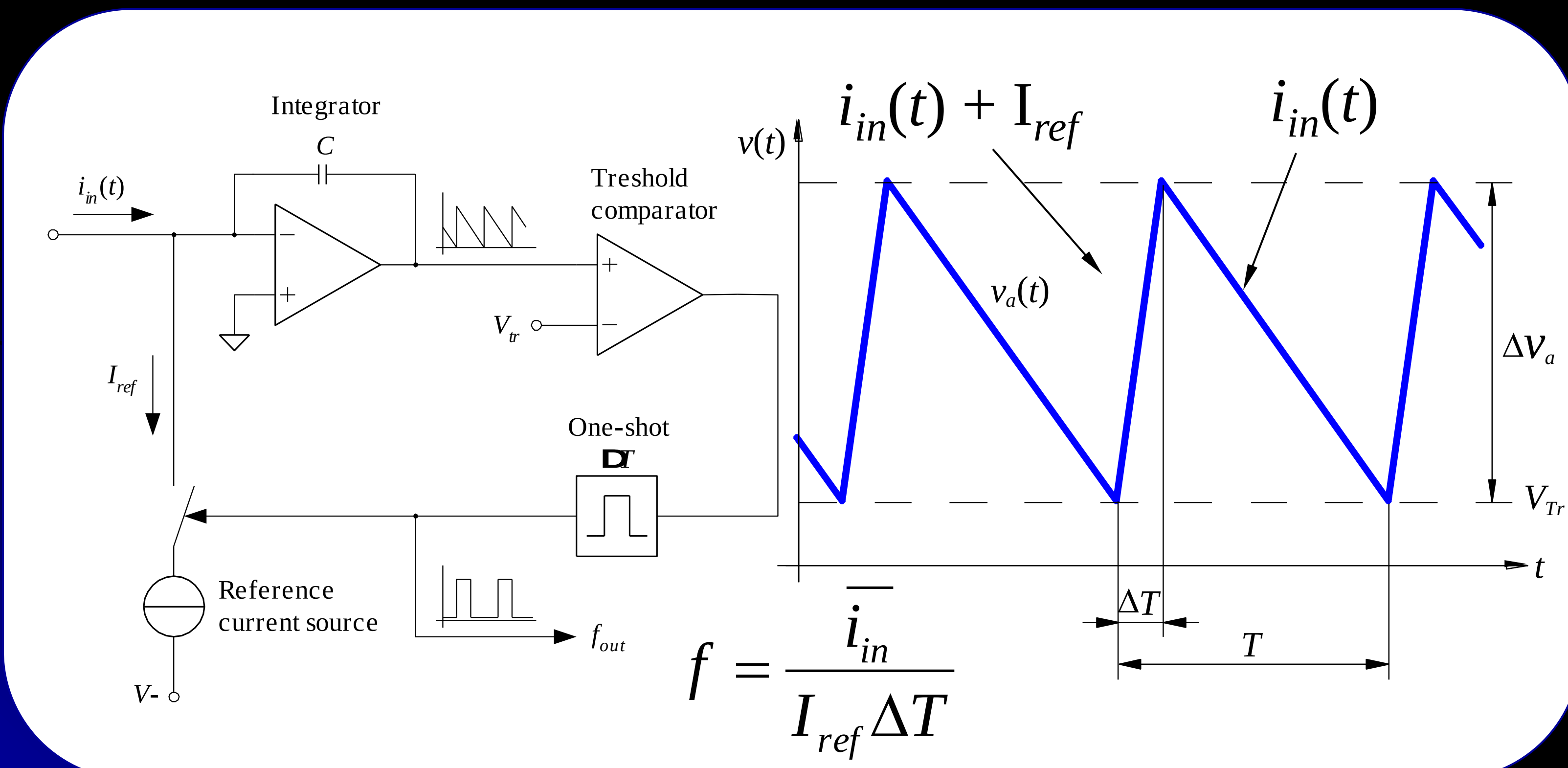
- Role of a BLM system:
  1. Protect the machine from damage
  2. Dump the beam to avoid magnet quenches (for SC magnets)
  3. Diagnostic tool to improve the performance of the accelerator

- 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



Beam Loss Detectors

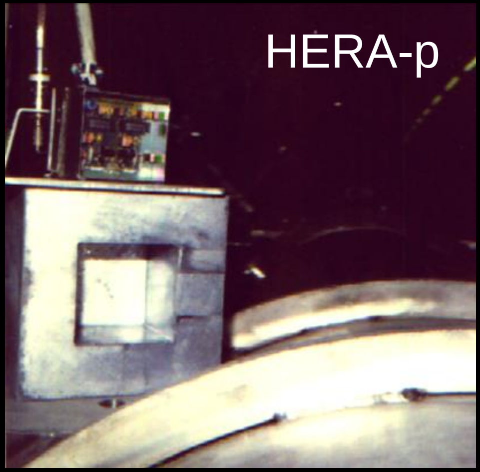
- Common types of monitor (cont)
  - Short ionisation chamber (charge detection)
    - Typically gas filled with many metallic electrodes and kV bias
    - Speed limited by ion collection time - tens of microseconds
    - Dynamic range of up to 10^8

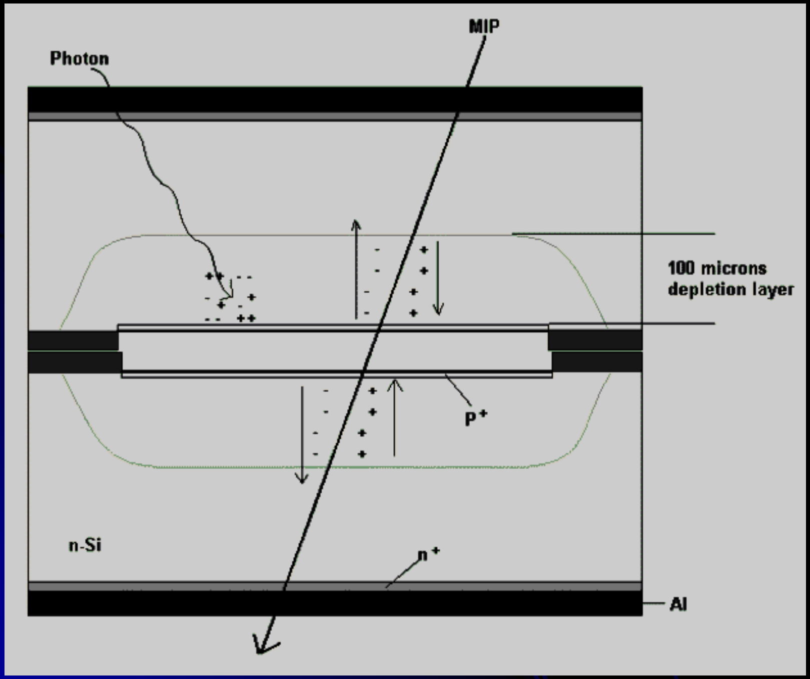


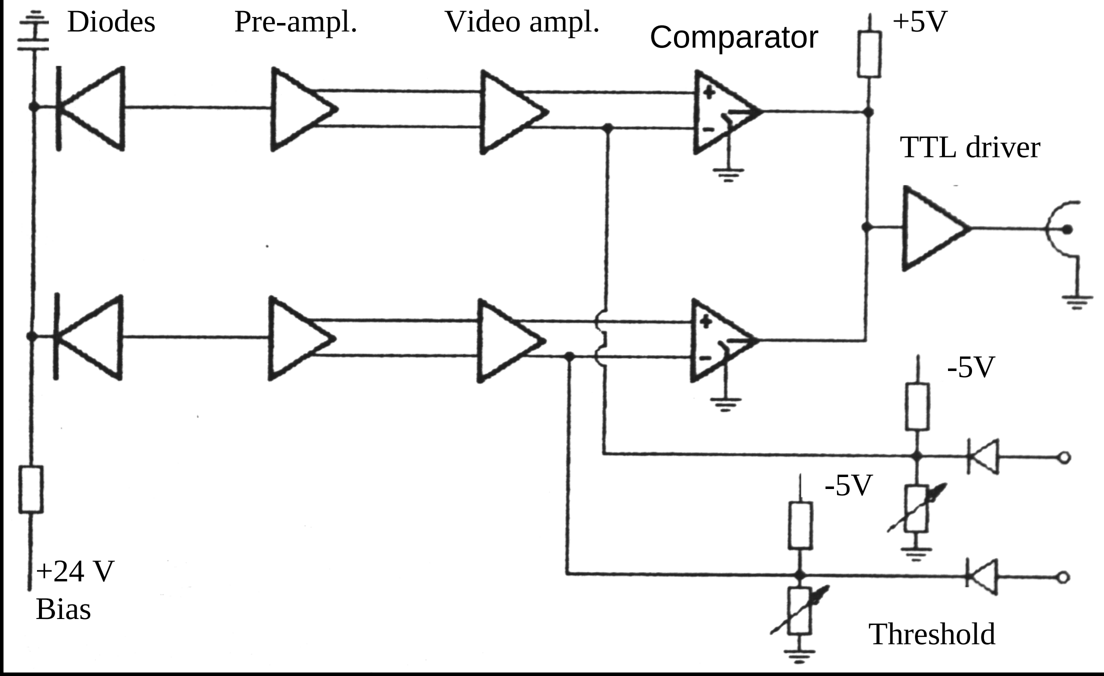
LHC

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