

# Introduction to Beam Instrumentation

## CAS 2013

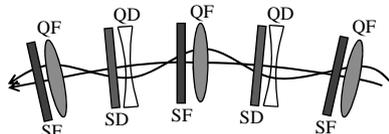
Trondheim, Norway  
18<sup>th</sup> – 29<sup>th</sup> August, 2013  
Rhodri Jones  
(CERN Beam Instrumentation Group)

## 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

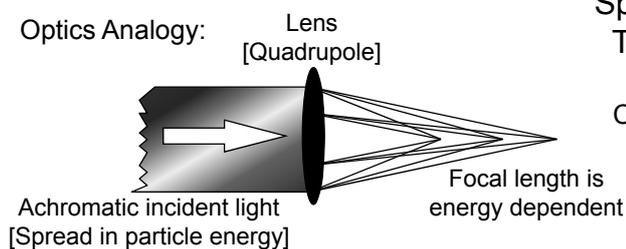
- Machine Tune



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

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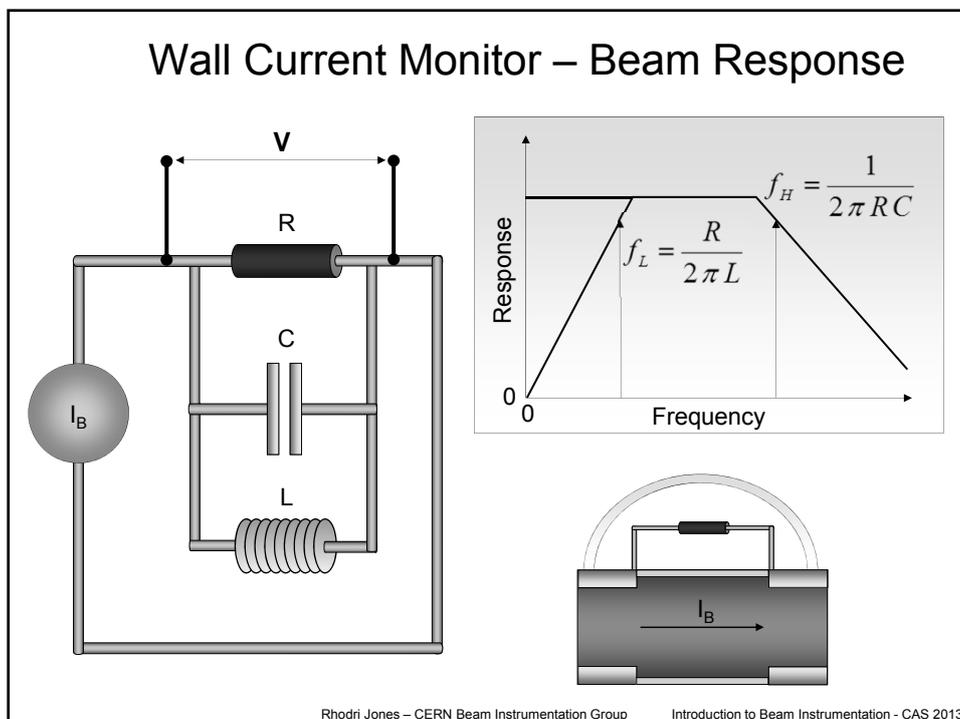
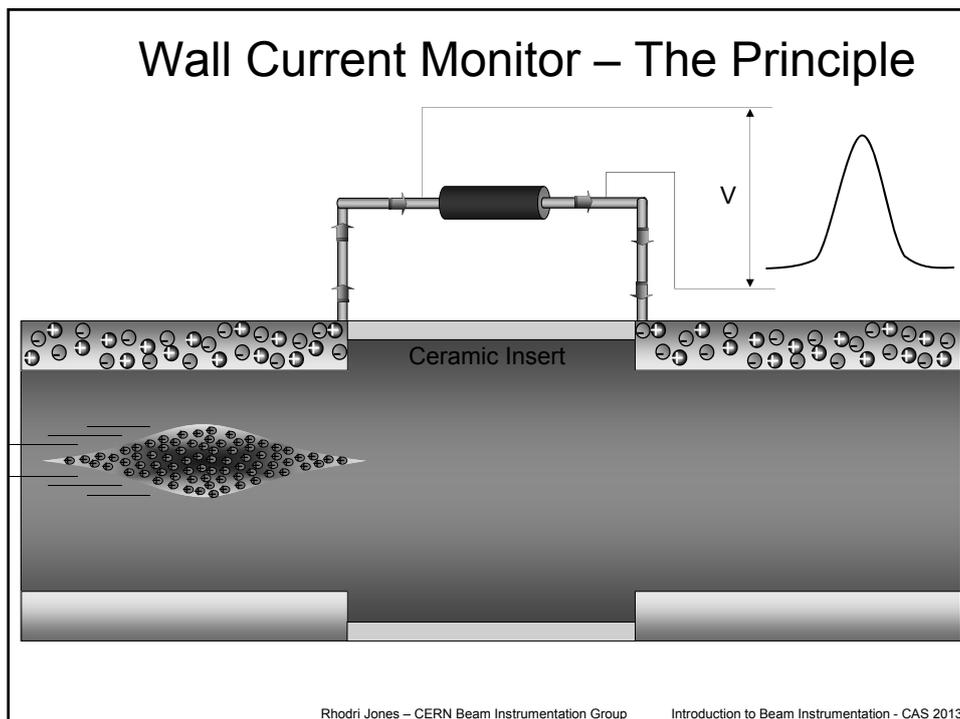
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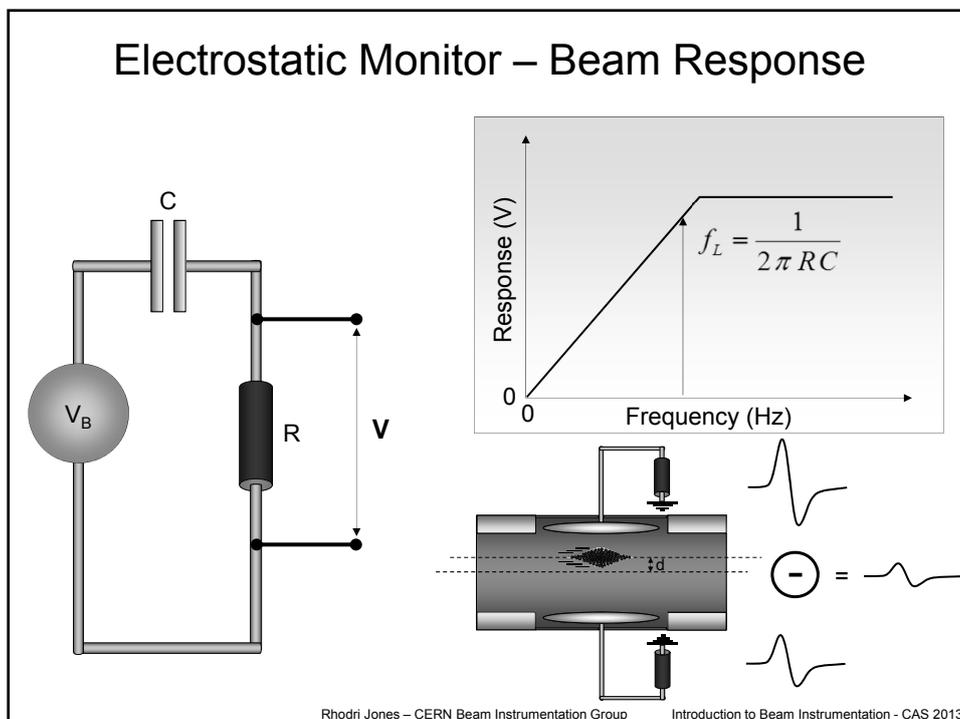
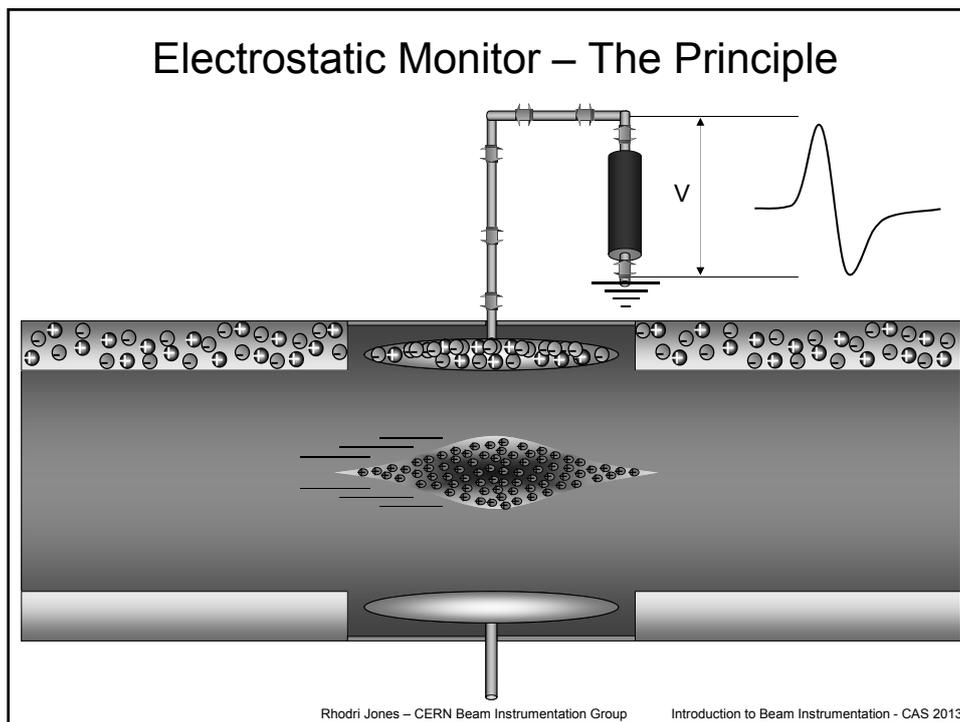
## The Typical Instruments

- 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

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## Electrostatic Pick-up – Button

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

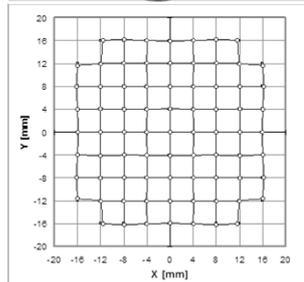
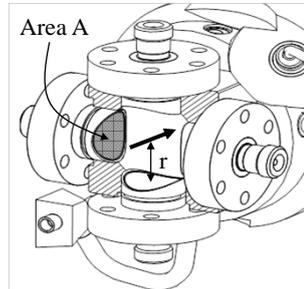
For Button with Capacitance  $C_e$  & Characteristic Impedance  $R_0$

Transfer Impedance:

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

Lower Corner Frequency:

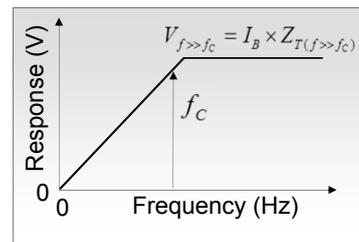
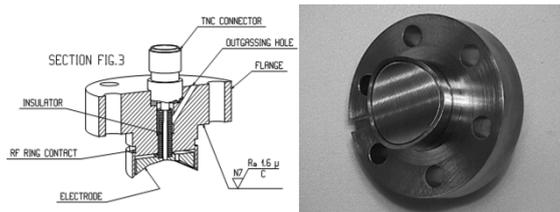
$$f_L = \frac{1}{2\pi R_0 C_e}$$



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

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## A Real Example – The LHC Button



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

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

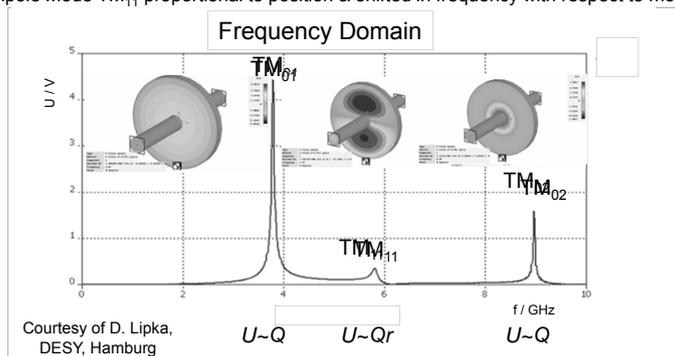
$$I_B = \frac{N_{pilot} e}{t} = \frac{5 \times 10^9 \times 1.6 \times 10^{-19}}{1 \times 10^{-9}} = 0.8 A_{peak} \Rightarrow V_{f=\infty} = 0.8 \times 1.2 = 1 V_{peak}$$

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

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## 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



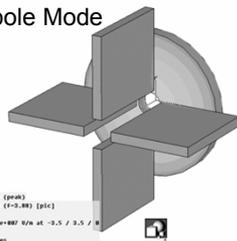
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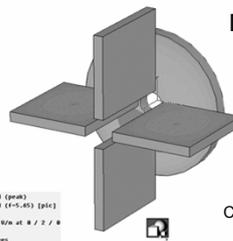
## Today's State of the Art BPMs

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

Monopole Mode



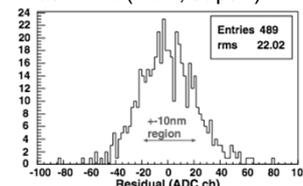
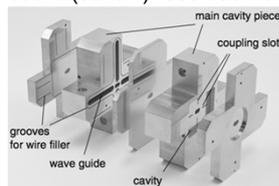
Dipole Mode



Courtesy of D. Lipka, DESY, Hamburg

- Prototype BPM for ILC Final Focus
  - Required resolution of 2nm (yes nano!) in a 6x12mm diameter beam pipe
  - Achieved World Record (so far!) resolution of 8.7nm at ATF2 (KEK, Japan)

Courtesy of D. Lipka & Y. Honda



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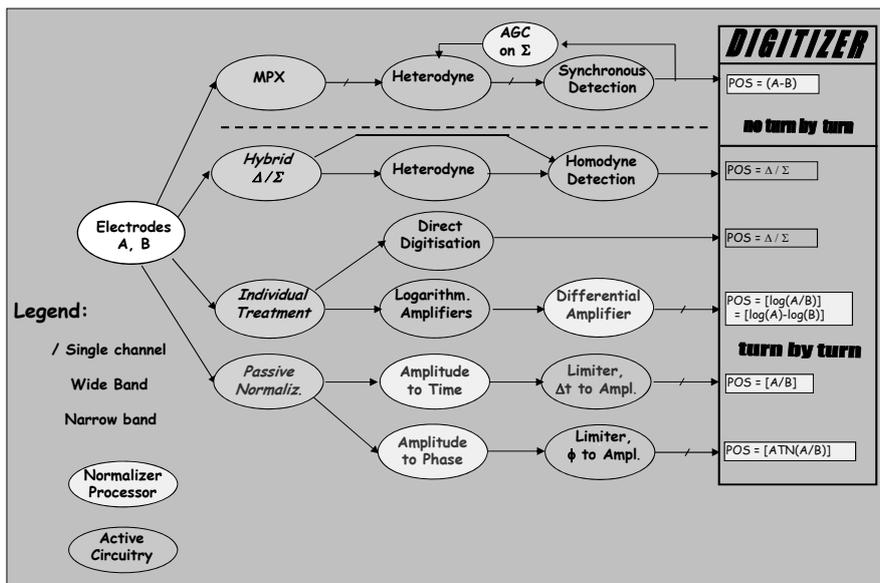
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## Criteria for Electronics Choice - so called "Processor Electronics"

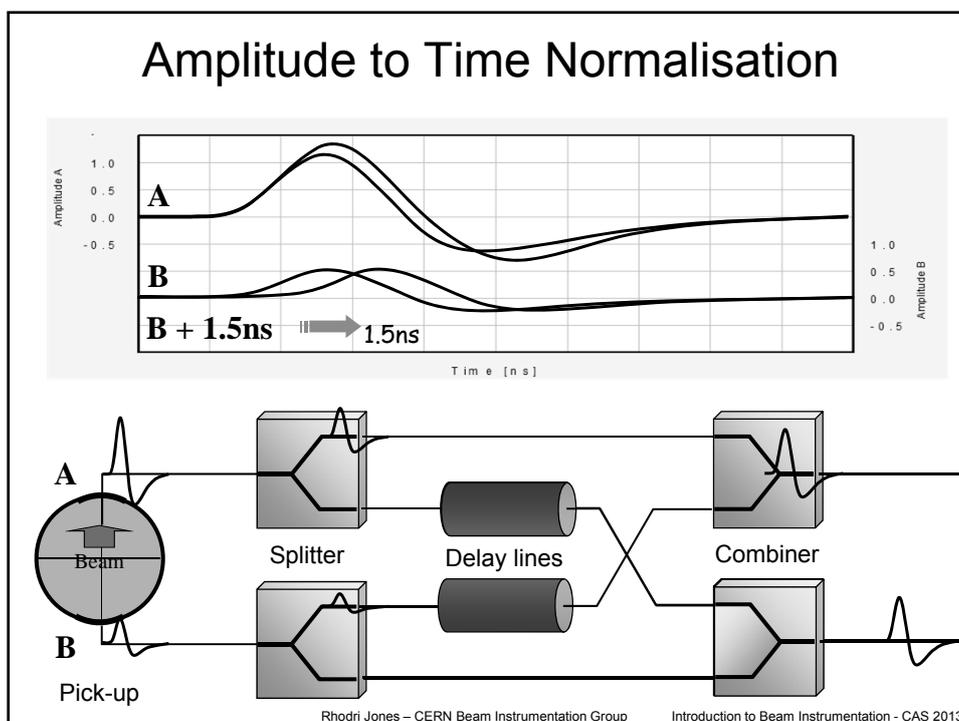
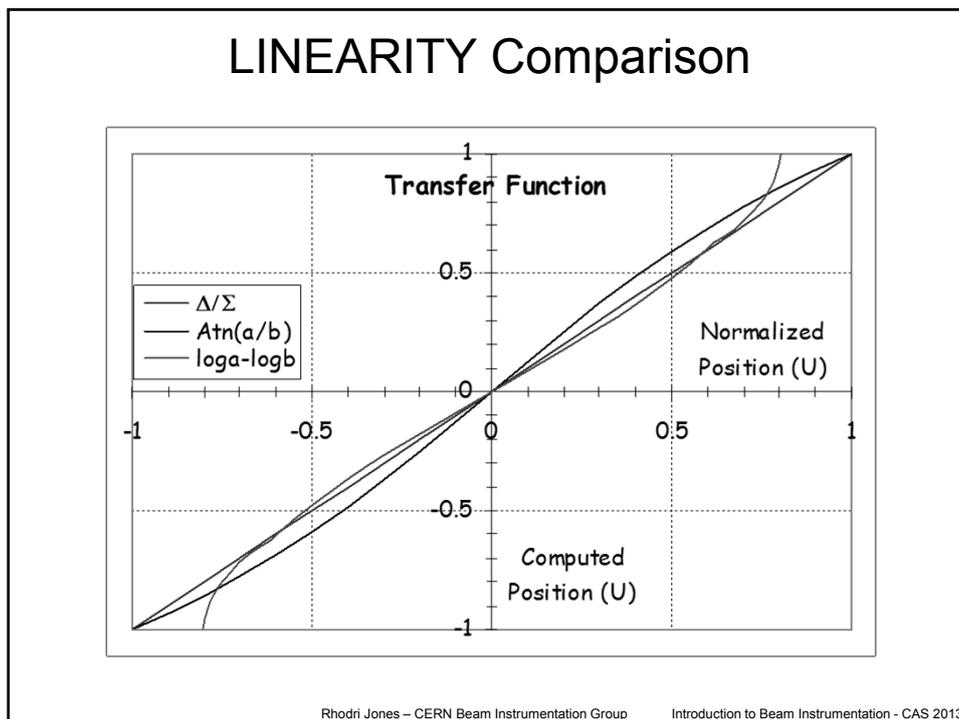
- Accuracy
  - mechanical and electromagnetic errors
  - electronic components
- Resolution
- Stability over time
- Sensitivity and Dynamic Range
- Acquisition Time
  - measurement time
  - repetition time
- Linearity
  - aperture & intensity
- Radiation tolerance

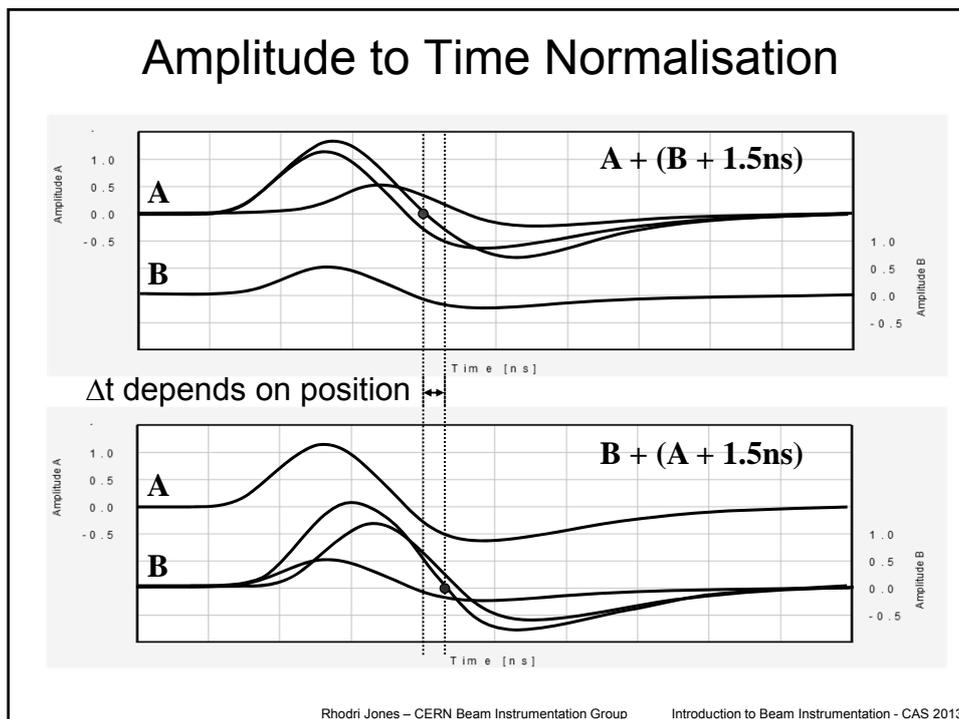
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## Processing System Families



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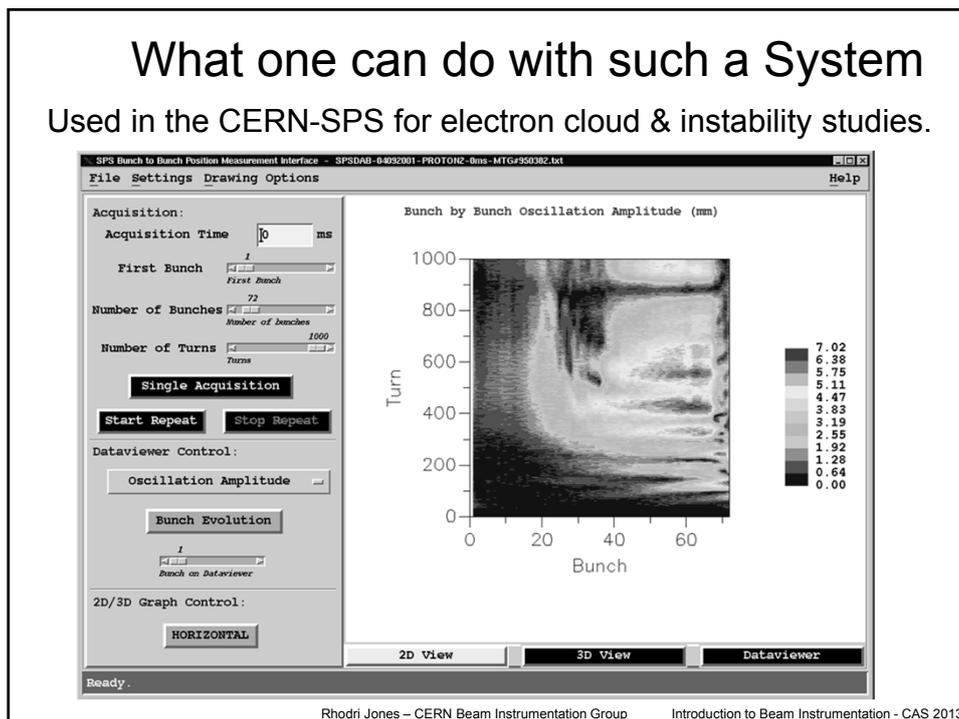
### BPM Acquisition Electronics Amplitude to Time Normaliser

Advantages	Limitations
<ul style="list-style-type: none"> <li>• Fast normalisation (&lt; 25ns)                             <ul style="list-style-type: none"> <li>• bunch to bunch measurement</li> </ul> </li> <li>• Signal dynamic independent of the number of bunches                             <ul style="list-style-type: none"> <li>• Input dynamic range ~45 dB</li> <li>• No need for gain selection</li> </ul> </li> <li>• Reduced number of channels                             <ul style="list-style-type: none"> <li>• normalisation at the front-end</li> </ul> </li> <li>• ~10 dB compression of the position dynamic due to the recombination of signals</li> <li>• Independent of external timing</li> <li>• Time encoding allows fibre optic transmission to be used</li> </ul>	<ul style="list-style-type: none"> <li>• Currently reserved for beams with empty RF buckets between bunches e.g.                             <ul style="list-style-type: none"> <li>• LHC 400MHz RF but 25ns spacing</li> <li>• 1 bunch every 10 buckets filled</li> </ul> </li> <li>• Tight time adjustment required</li> <li>• No Intensity information</li> <li>• Propagation delay stability and switching time uncertainty are the limiting performance factors</li> </ul>

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## What one can do with such a System

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

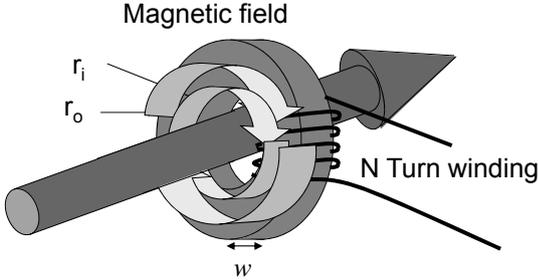


## The Typical Instruments

- 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
- Beam Loss
  - ionisation chambers or pin diodes
- Machine Tunes and Chromacities
  - in diagnostics section of tomorrow
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### Current Transformers



Beam current                      Transformer Inductance

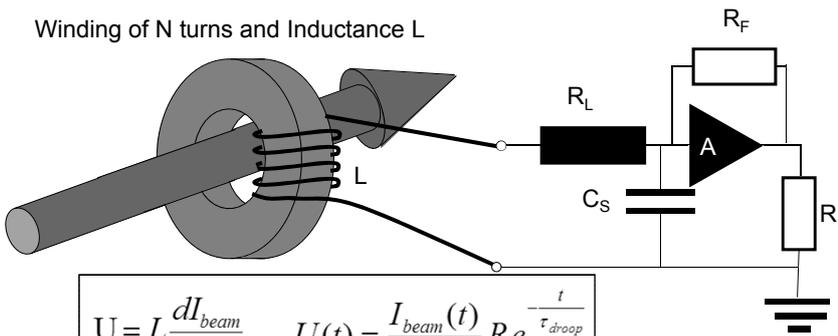
Fields are very low

Capture magnetic field lines with cores of high relative permeability

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

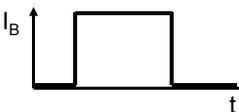
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### The Active AC transformer



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

Beam signal



Transformer output signal



$$\tau_{rise} = \sqrt{L C_S}$$

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

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### Fast Beam Current Transformer

Image Current  
 1:40 Passive Transformer  
 Ceramic Gap  
 BEAM  
 80nm Ti Coating  $\Rightarrow 20\Omega$  to improve impedance  
 Calibration winding

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

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### Acquisition Electronics

20-Aug-02  
16:32:12

10 ns  
0.50 V

Integrator Output

4  
10 ns  
0.50 V

25ns

10 ns RIS  
0.5 V DC  
2 2 V 500  
3 2 V 500  
4 0.5 V 500

FBCT Signal after 200m of Cable

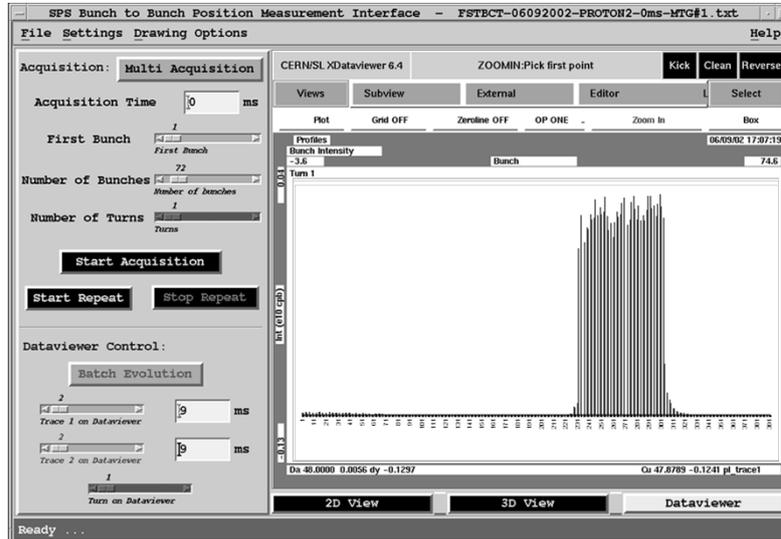
← 6.922 μs

2 DC 0.92 V

Data taken on LHC type beams at the CERN-SPS

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## What one can do with such a System



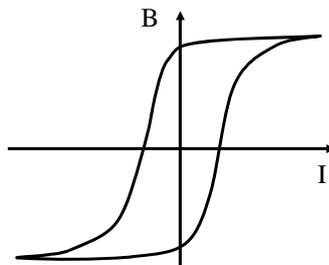
Bad RF Capture of a single LHC Batch in the SPS (72 bunches)

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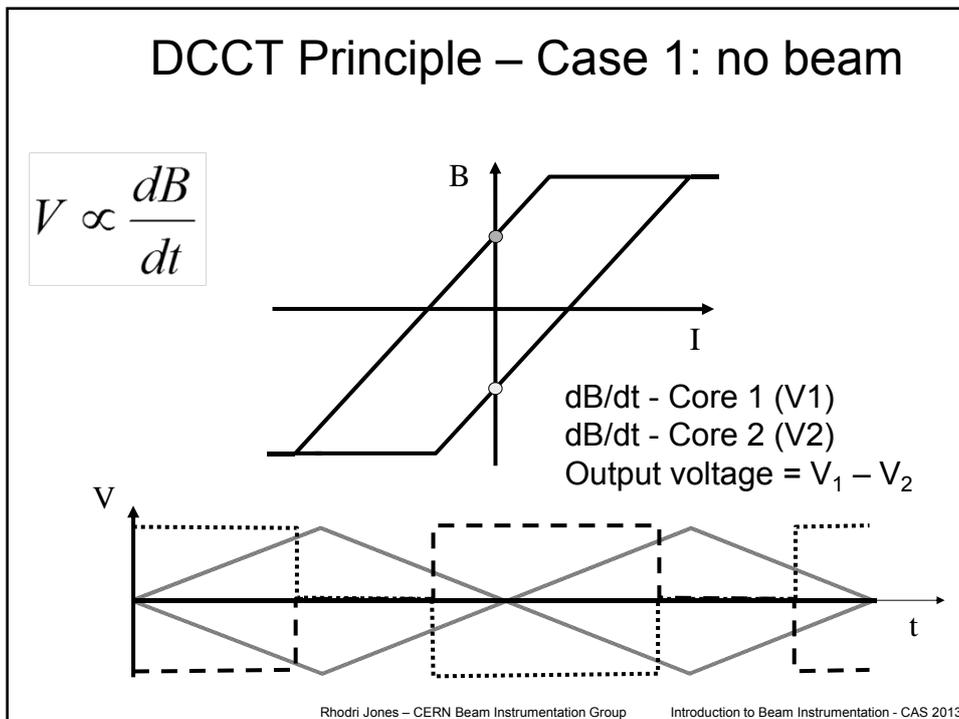
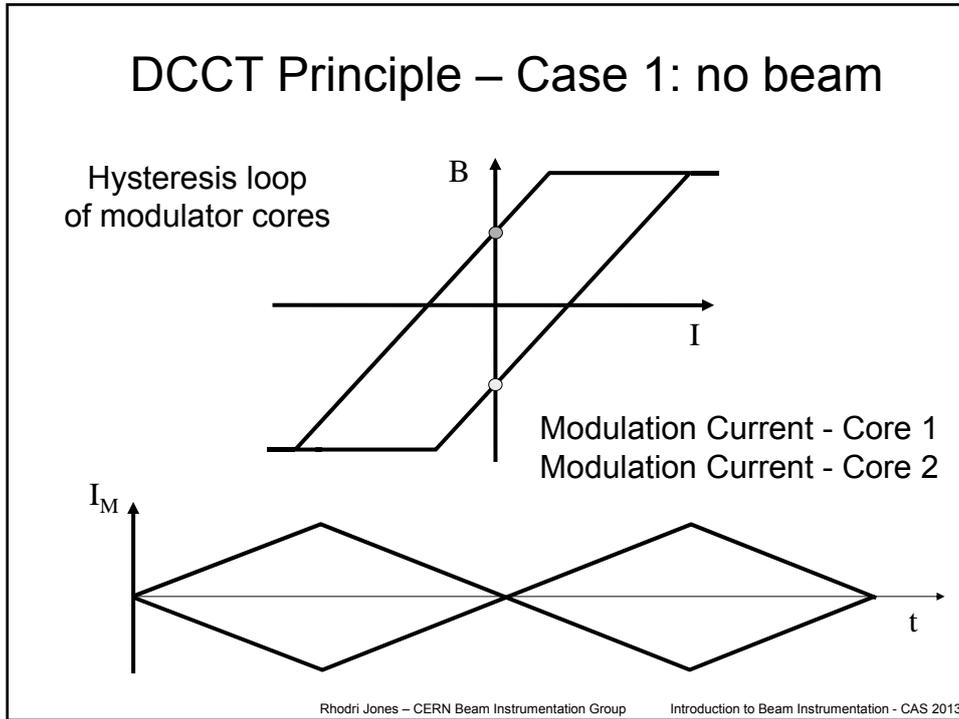
## The DC current transformer

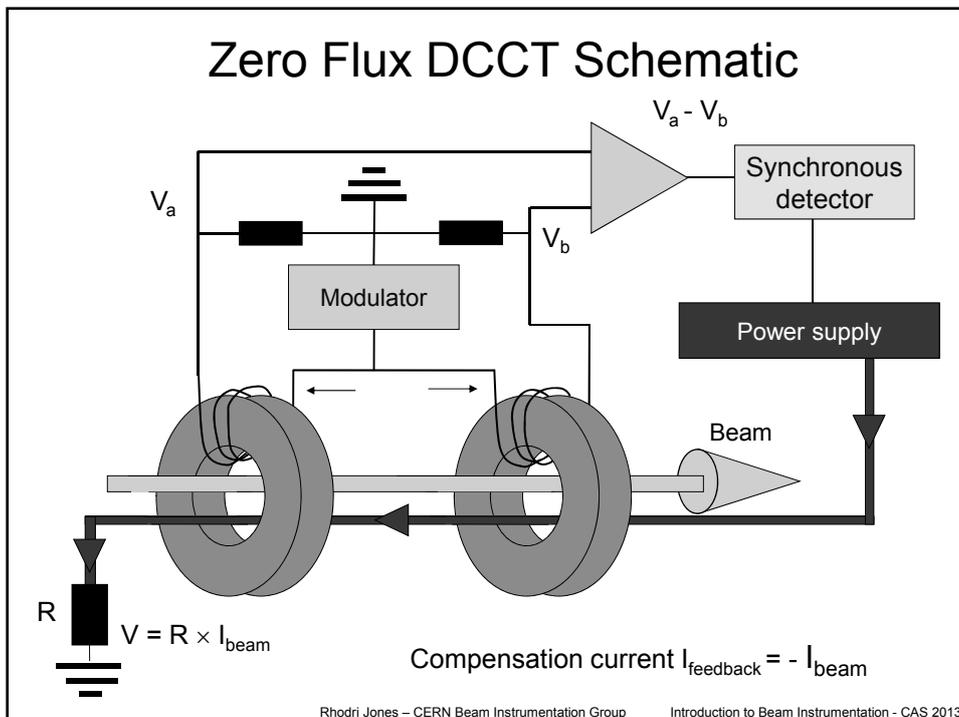
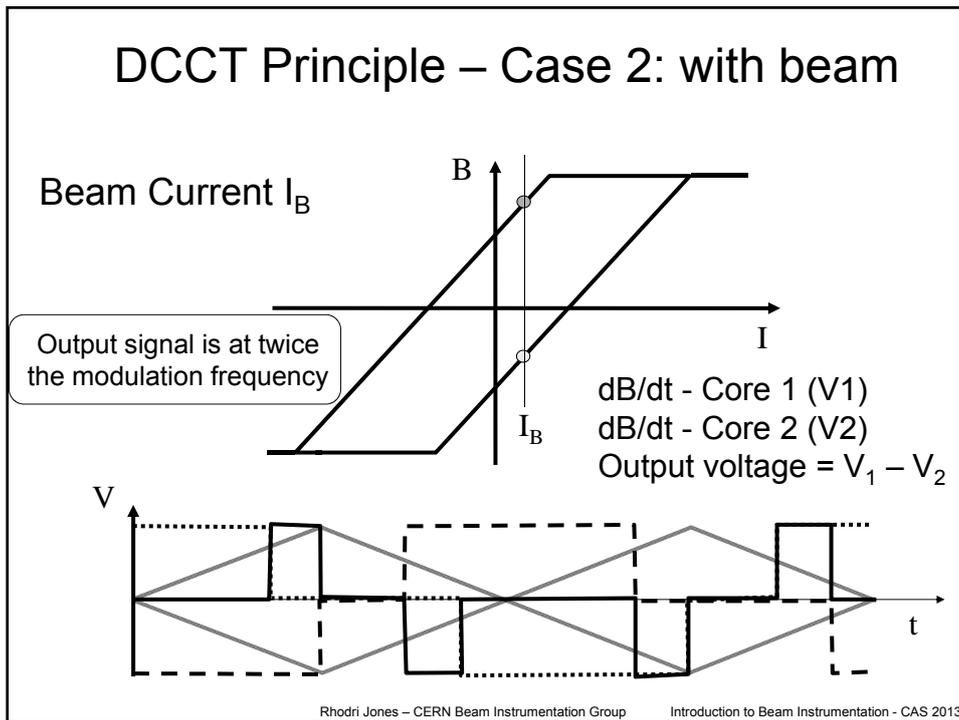
- AC current transformer can be extended to very low frequency but not to DC ( no  $dl/dt$  ! )
- DC current measurement is required in storage rings
- To do this:
  - Take advantage of non-linear magnetisation curve
  - Apply a modulation frequency to 2 identical cores



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## The Typical Instruments

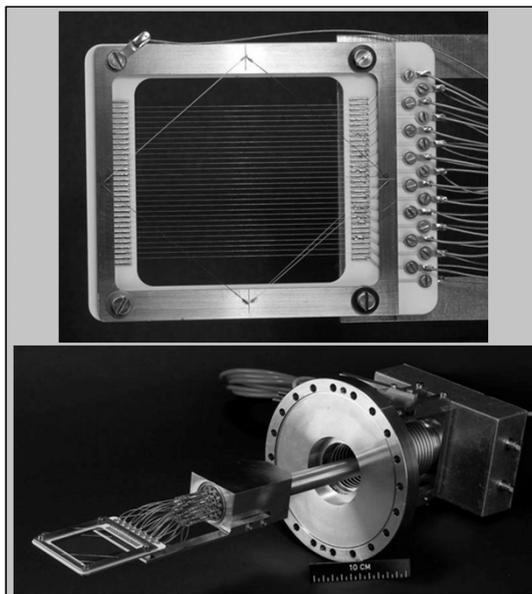
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## Secondary Emission (SEM) Grids

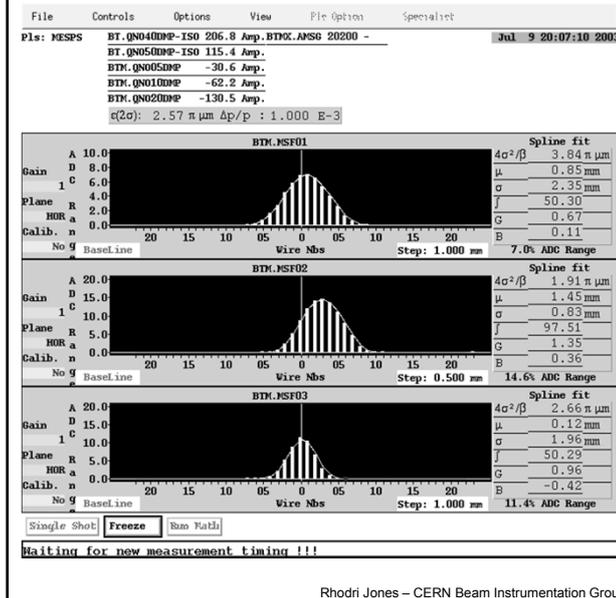
- When the beam passes through secondary electrons are ejected from the wires
- The liberated electrons are removed using a polarisation voltage
- The current flowing back onto the wires is measured
- One amplifier/ADC chain is used for each wire



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## Profiles from SEM grids



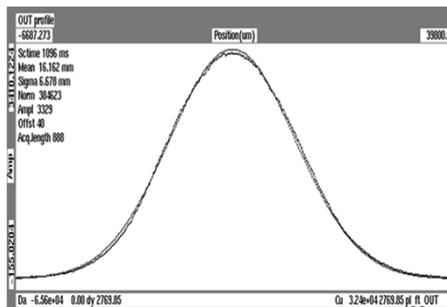
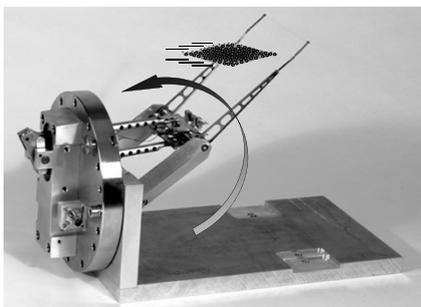
- Charge density measured from each wire gives a projection of the beam profile in either horizontal or vertical plane
- Resolution is given by distance between wires
- Used only in low energy linacs and transfer lines as heating is too great for circulating beams

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## 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

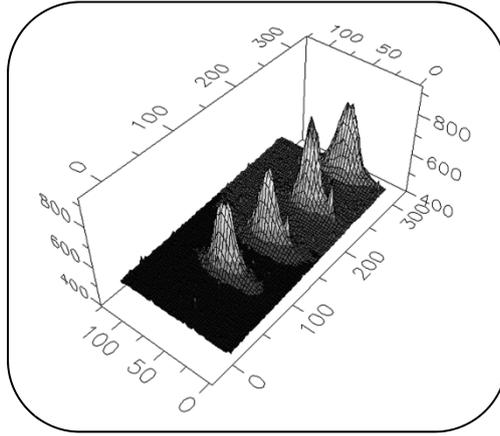
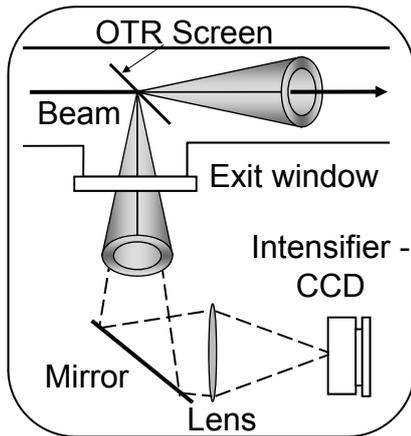


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## Beam Profile Monitoring using Screens

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



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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 higher intensity

Sensitivities measured with protons with previous screen holder,  
 normalised for  $7 \text{ px}/\sigma$



Type	Material	Activator	Sensitivity
Luminesc.	CsI	Tl	$6 \cdot 10^5$
"	$\text{Al}_2\text{O}_3$	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: $\text{Gd}_2\text{O}_3\text{S}$	Tb	$2 \cdot 10^7$



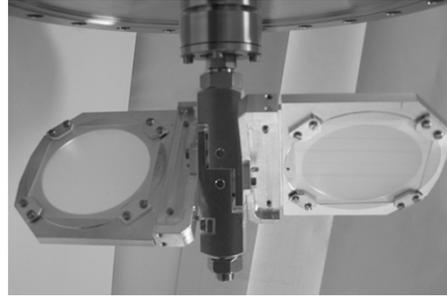
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## Beam Profile Monitoring using Screens

- Usual configuration

- Combine several screens in one housing e.g.
  - $\text{Al}_2\text{O}_3$  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



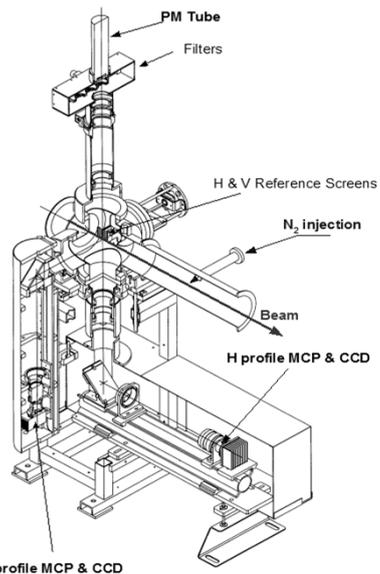
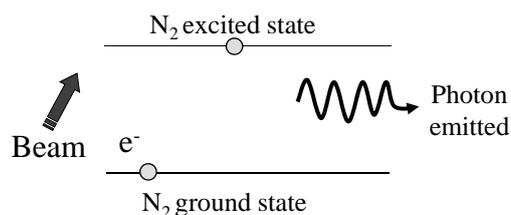
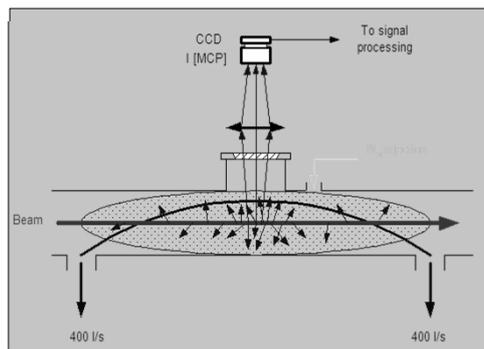
- Advantages compared to SEM grids

- 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

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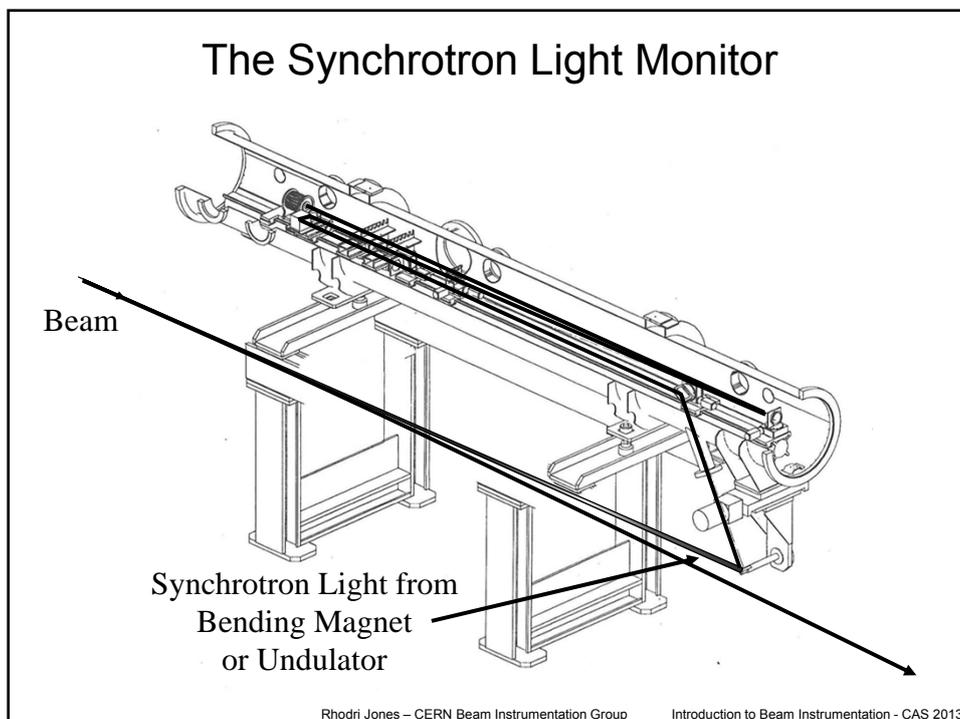
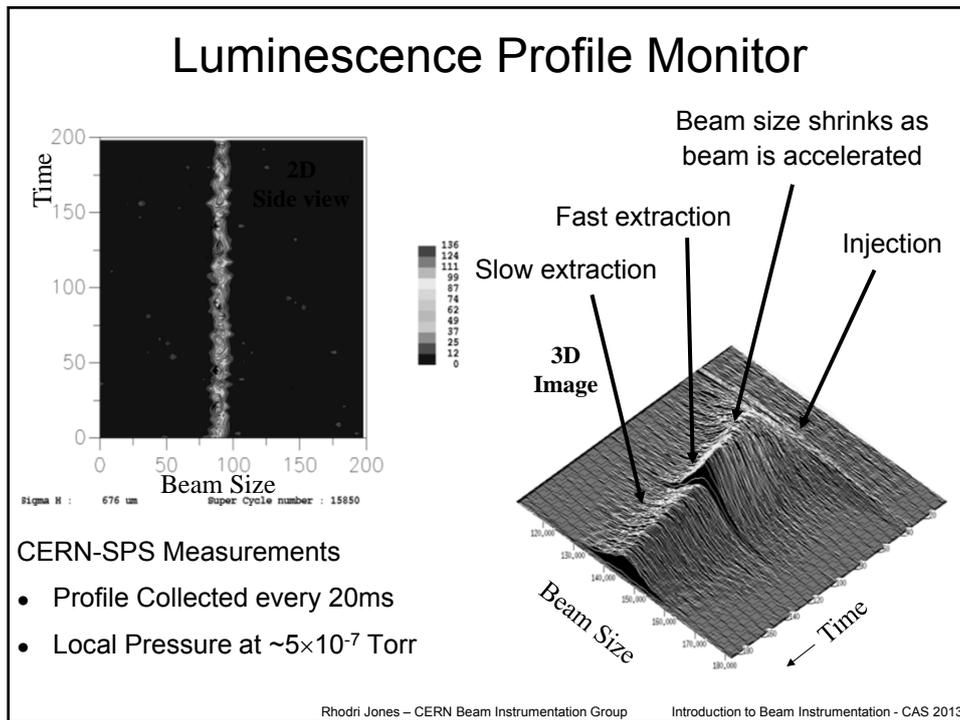
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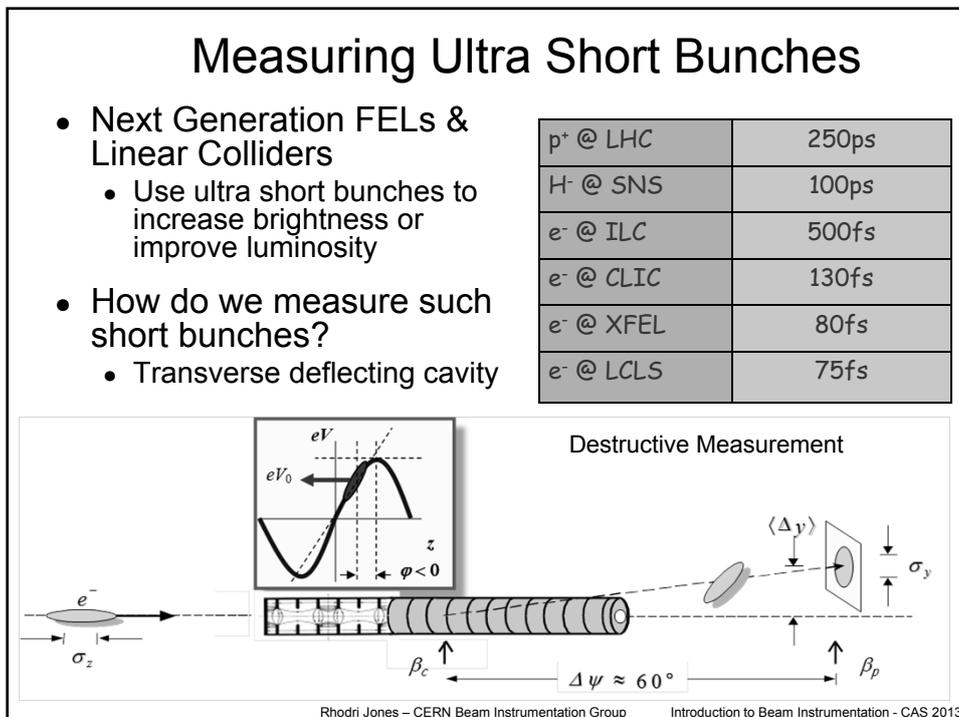
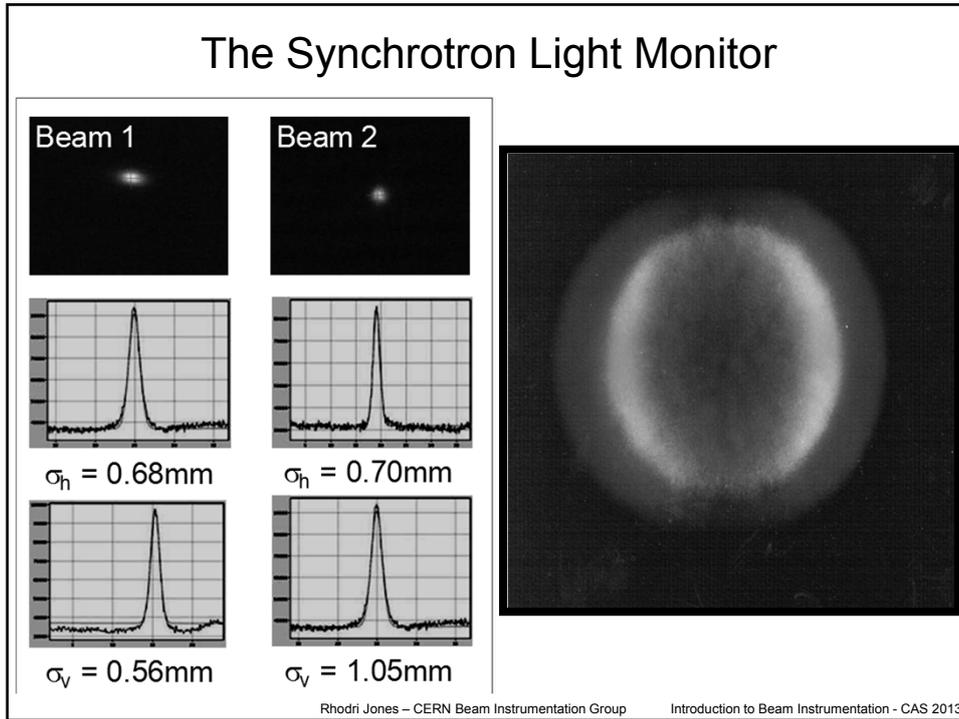
## Luminescence Profile Monitor

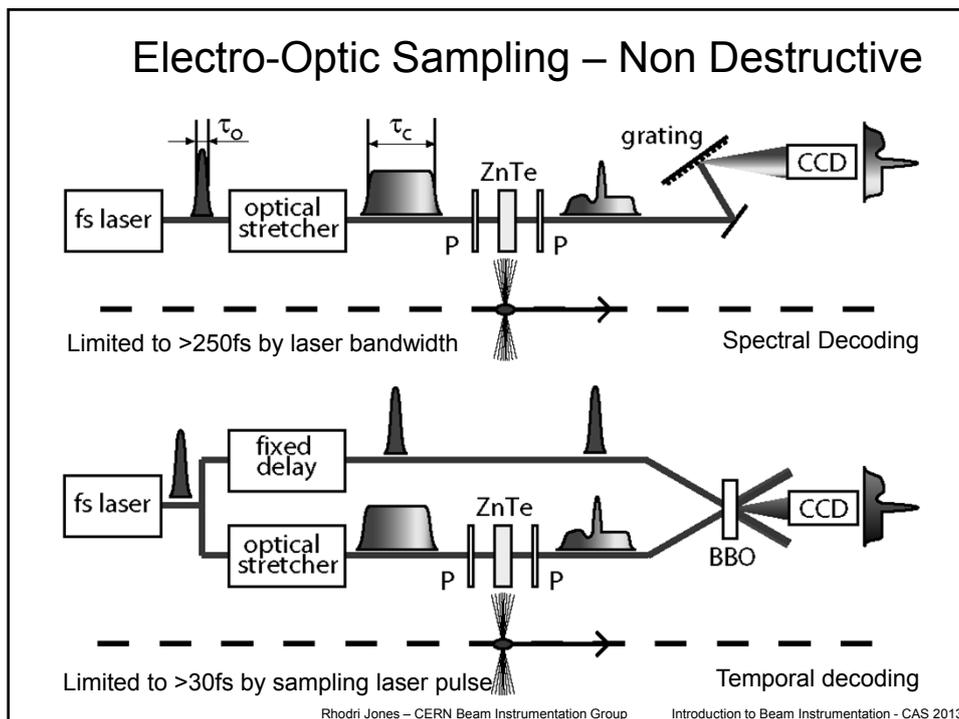


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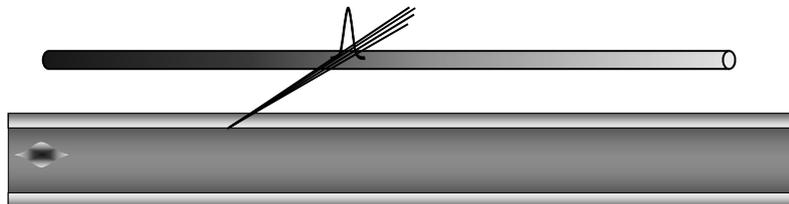
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  - synchrotron light monitors
  - ionisation and luminescence monitors
  - femtosecond diagnostics for ultra short bunches
- Beam Loss
  - ionisation chambers or pin diodes
- Machine Tunes and Chromacities
  - in diagnostics section of tomorrow
- Luminosity
  - in diagnostics section of tomorrow

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## Beam Loss Detectors

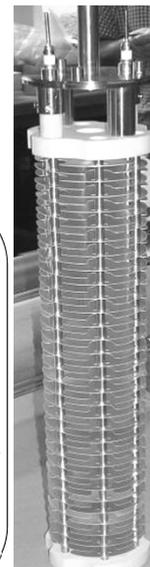
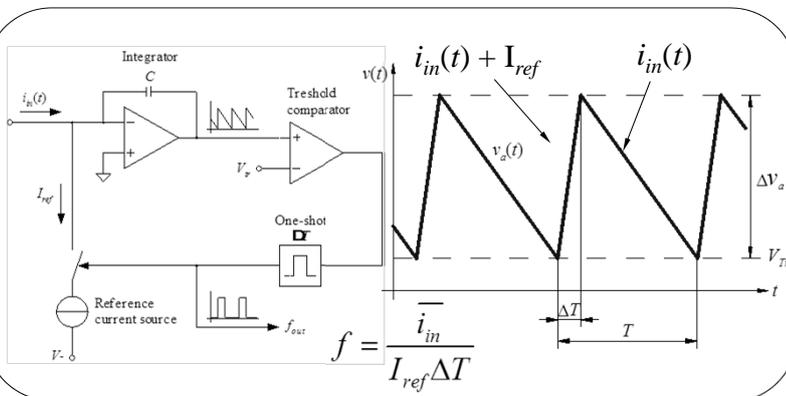
- Role of a BLM system:
  1. Protect the machine from damage
  2. Dump the beam to avoid magnet quenches (for SC magnets)
  3. Diagnostic tool to improve the performance of the accelerator
- Common types of monitor
  - Long ionisation chamber (charge detection)
    - Up to several km of gas filled hollow 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  $10^4$



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## 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  $10^8$

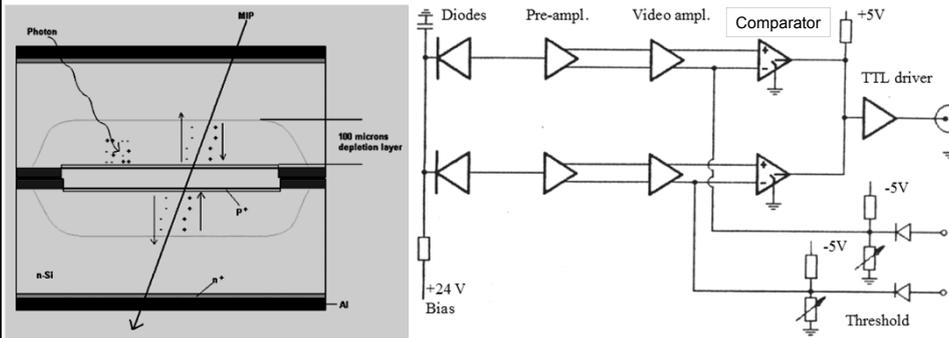
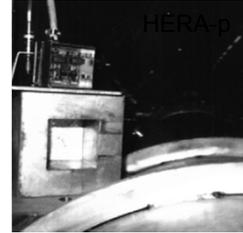


LHC

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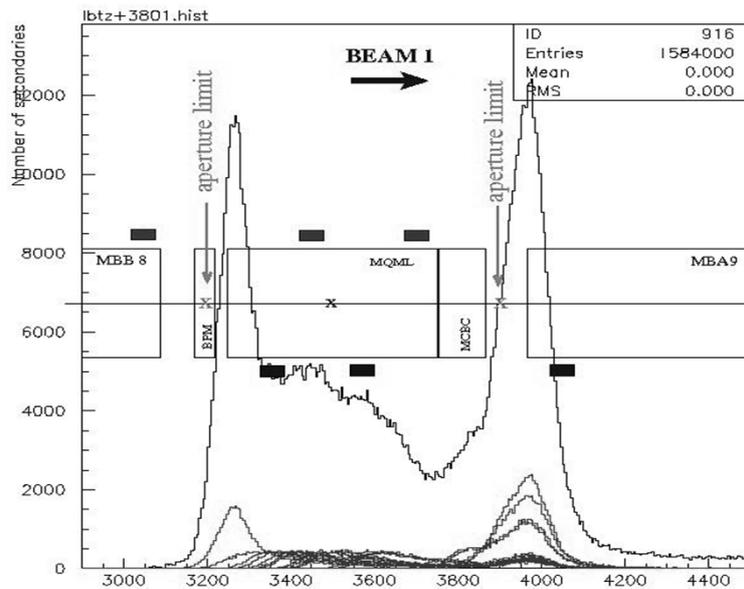
## Beam Loss Detectors

- 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  $10^9$



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## BLM Threshold Level Estimation



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## Summary

- I've tried to give you an overview of the common types of instruments that can be found in most accelerators
  - This is only a small subset of those currently in use or being developed with many exotic instruments tailored for specific accelerator needs
- Tomorrow you will see how to use these instruments to run and optimise accelerators
  - Introduction to Accelerator Beam Diagnostics (H. Schmickler)
- **Afternoon course : Beam Instrumentation & Diagnostics**
  - For an in-depth analysis of all these instruments and on their application in various accelerators

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