Beam Diagnostics
Lecture 1

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(Beam Instrumentation)

Overview

- First hour:
  - Introduction
  - Overview of measurement instruments
    - Faraday Cup
    - Beam Current Transformer
    - Beam Position Monitor
    - Profile Detectors
      - SEMGrids
      - Wire Scanners
    - Beam Loss Monitors
- Second hour
  - Some depicted examples of beam parameter measurements

Introduction

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

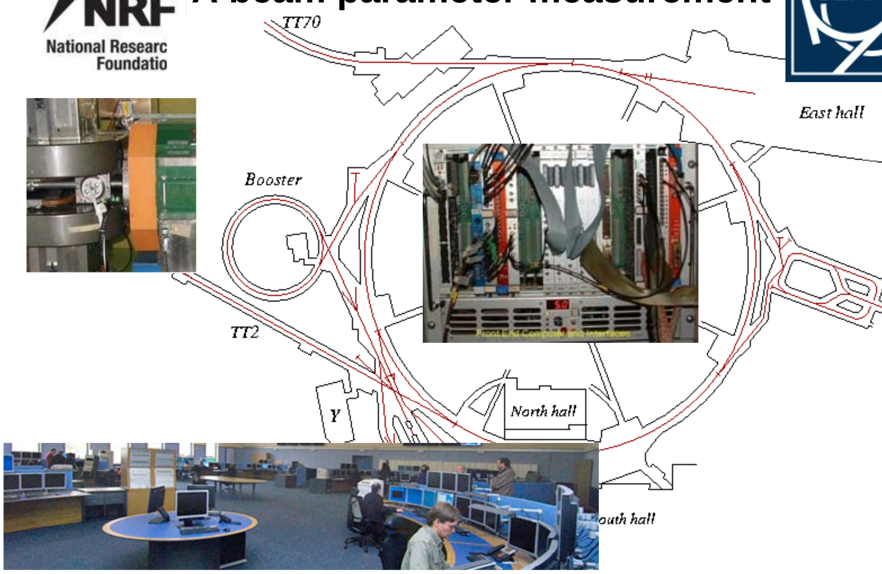
Different uses of beam diagnostics

- **Regular crude checks of accelerator performance**
  - Beam Intensity
  - Radiation levels
- **Standard regular measurements**
  - Emittance measurement
  - Trajectories
  - Tune
- **Sophisticated measurements e.g. during machine development sessions**
  - May require offline evaluation
  - May be less *comfortable*

Diagnostic devices and quantity measured

Instrument	Physical Effect	Measured Quantity	Effect on beam
Faraday Cup	Charge collection	Intensity	Destructive
Current Transformer	Magnetic field	Intensity	Non destructive
Wall current monitor	Image Current	Intensity Longitudinal beam shape	Non destructive
Pick-up	Electric/magnetic field	Position	Non destructive
Secondary emission monitor	Secondary electron emission	Transverse size/shape, emittance	Disturbing, can be destructive at low energies
Wire Scanner	Secondary particle creation	Transverse size/shape	Slightly disturbing
Scintillator screen	Atomic excitation with light emission	Transverse size/shape (position)	Destructive
Residual Gas monitor	Ionization	Transverse size/shape	Non destructive

A beam parameter measurement

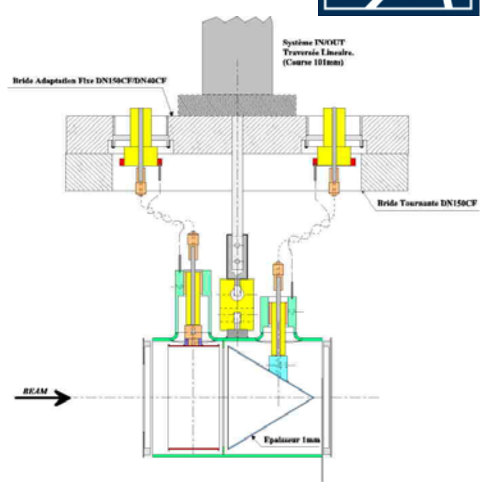


Required Competence in a beam diagnostics group

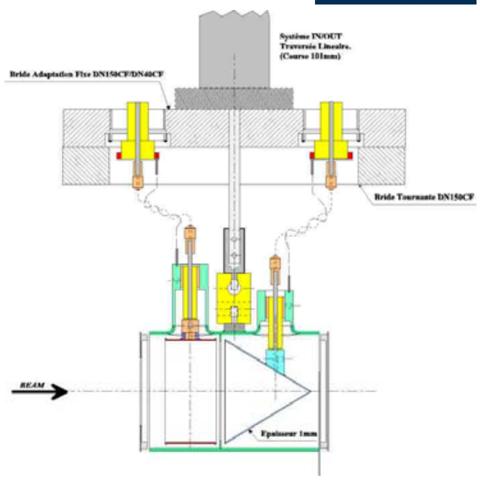
- Some beam physics in order to understand the beam parameters to be measured and to distinguish beam effects from sensor effects
- Detector physics to understand the interaction of the beam with the sensor
- Mechanics
- Analogue signal treatment
  - Low noise amplifiers
  - High frequency analogue electronics
- Digital signal processing
- Digital electronics for data readout
- Front-end and Application Software

Layout of a Faraday Cup

- Electrode: 1 mm stainless steel
- Only low energy particles can be measured
- Very low intensities (down to 1 pA) can be measured
- Creation of secondary electrons of low energy (below 20 eV)
- Repelling electrode with some 100 V polarisation voltage pushes secondary electrons back onto the electrode



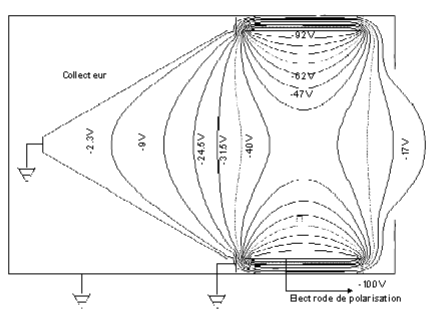
Faraday Cup



Electro-static Field in Faraday Cup

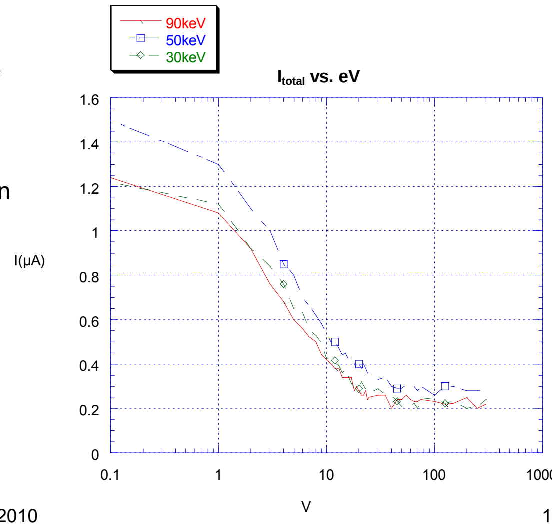
In order to keep secondary electrons with the cup a repelling voltage is applied to the polarization electrode

Since the electrons have energies of less than 20 eV some 100V repelling voltage is sufficient

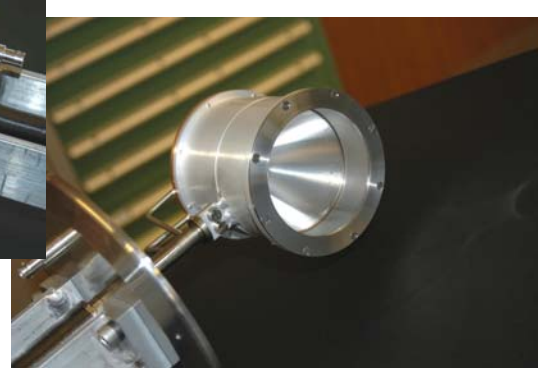


Energy of secondary emission electrons

- With increasing repelling voltage the electrons do not escape the Faraday Cup any more and the current measured stays stable.
- At 40V and above no decrease in the Cup current is observed any more



Faraday Cup with water cooling

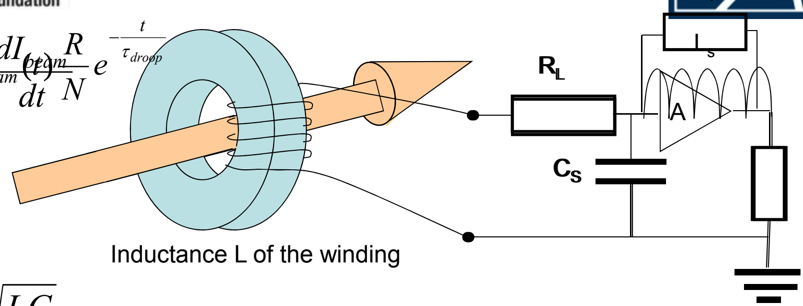


For higher intensities
water cooling may be needed

The Active AC Transformer

$$U(t) = L\frac{dI_{beam}(t)}{dt}$$

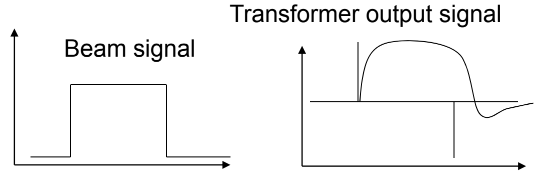
$$U = I_{beam}\frac{R}{N}e^{-\frac{t}{\tau_{droop}}}$$



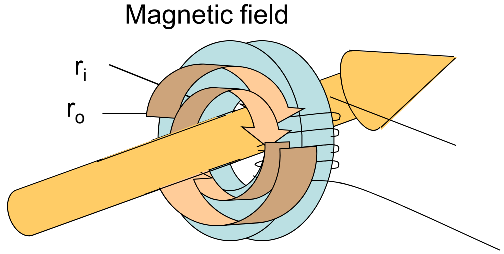
$$\tau_{rise} = \sqrt{L_s C_s}$$

$$\tau_{droop} = \frac{L}{R_L}$$

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



Current Transformers



Fields are very low

Capture magnetic field lines with cores of high relative permeability

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

Beam current

$$I_{beam} = \frac{qeN}{t} = \frac{qeN\beta c}{l} \qquad L = \frac{\mu_0 \mu_r}{2\pi} l N^2 \ln\frac{r_0}{r_i}$$

Principle of a fast current transformer

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

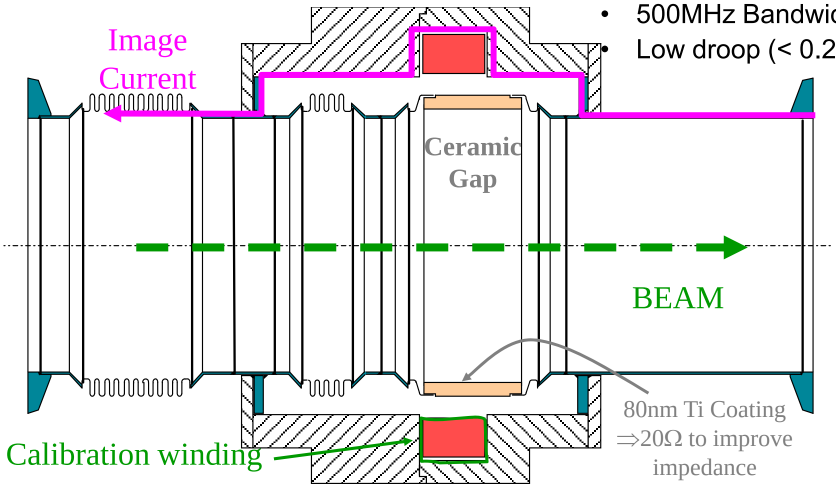


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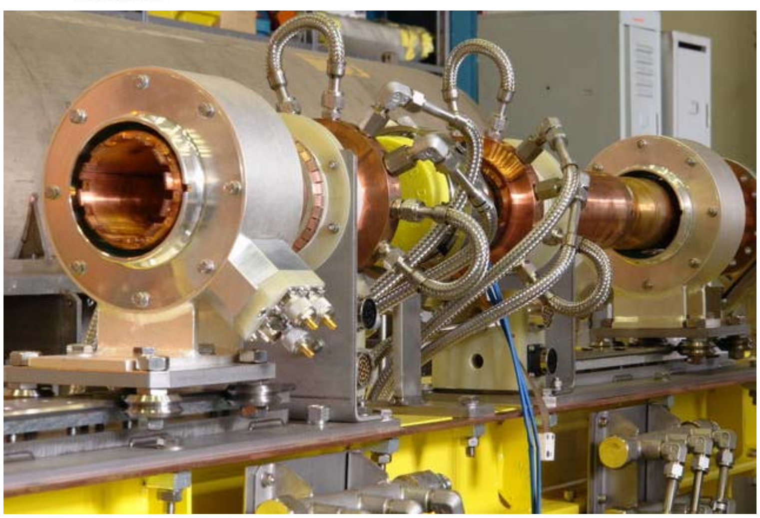
Diagram by H. Jakob

Fast current transformers for the LHC



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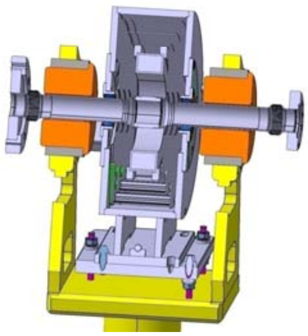
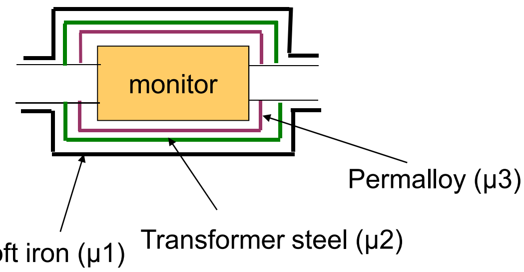
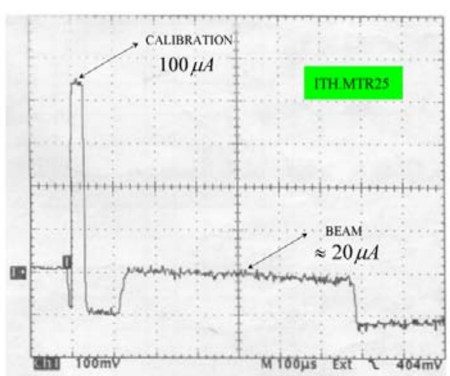
Magnetic shielding



- Shield should extend along the vacuum chamber length > diameter of opening
- Shield should be symmetrical to the beam axis
- Air gaps must be avoided especially along the beam axis
- Shield should have highest μ possible but should not saturate

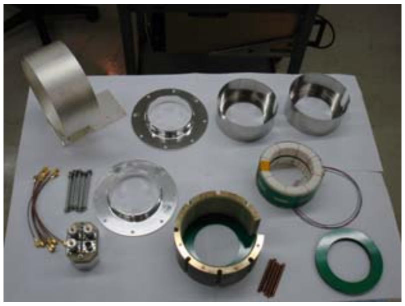


Calibration of AC current transformers



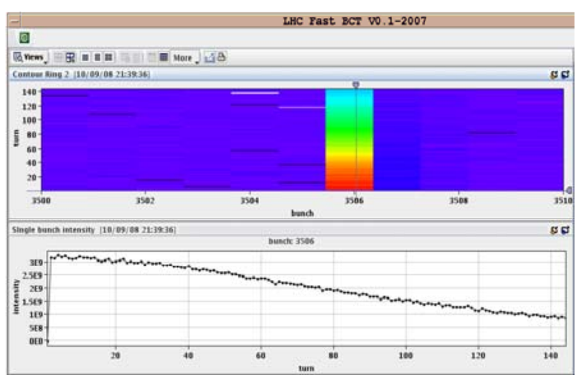
- The transformer is calibrated with a very precise current source
- The calibration signal is injected into a separate calibration winding
- A calibration procedure executed before the running period
- A calibration pulse before the beam pulse measured with the beam signal

Current transformer and electronics



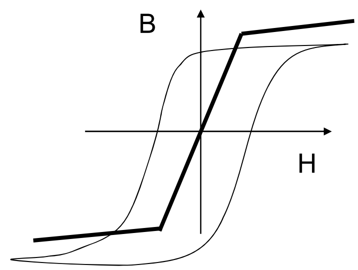
Display of transformer readings

- First result from LHC FBCT
- Measurement of bunch intensity
- Diminishing intensity due to debunching
- Beam losses will trigger machine protection system

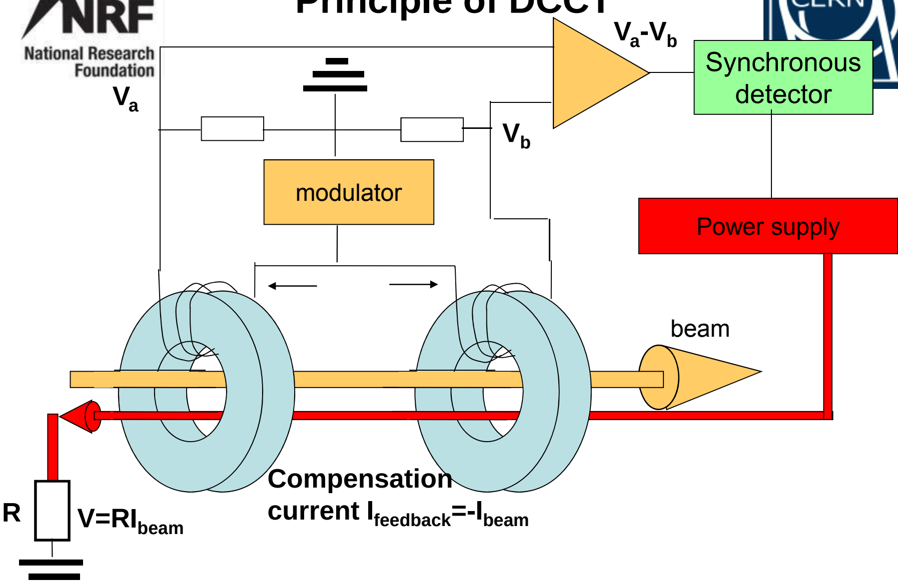


The DC current transformer

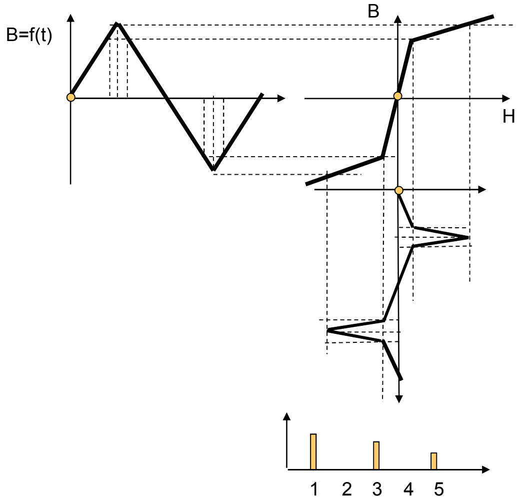
- AC current transformer can be extended to very long droop times but not to DC
- Measuring DC currents is needed in storage rings
- Must provide a modulation frequency
- Takes advantage of non/linear magnetisation curve



Principle of DCCT



Modulation of a DCCT without beam



$$U = NA\frac{dB}{dt}$$

$$B = \frac{\int U dt}{NA} + B_0$$

Modulation current has only odd harmonic frequencies since the signal is symmetric

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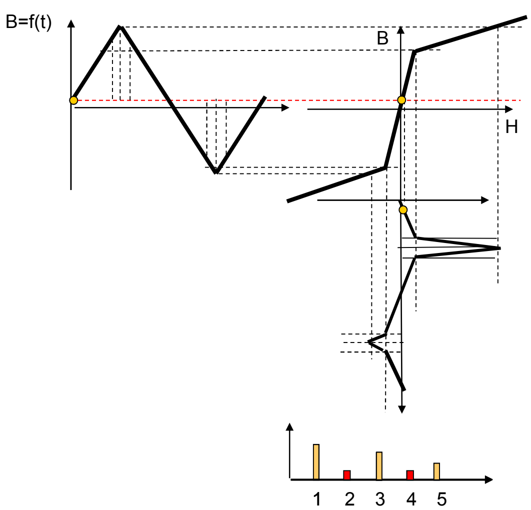
Modulation of a DCCT with beam



Sum signal becomes non-zero
Even harmonics appear

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Modulation current difference signal with beam

- Difference signal has $2\omega_m$
- ω_m typically 200 Hz – 10 kHz
- Use low pass filter with $\omega_c << \omega_m$
- Provide a 3rd core, normal AC transformer to extend to higher frequencies

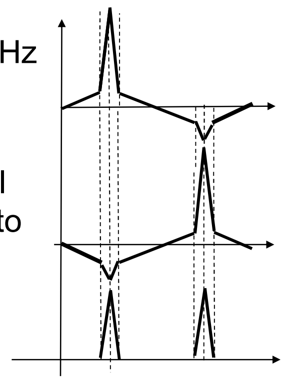
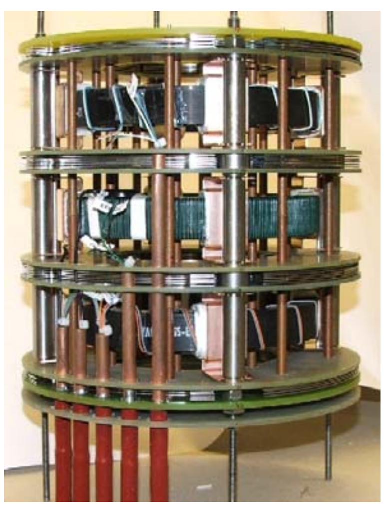


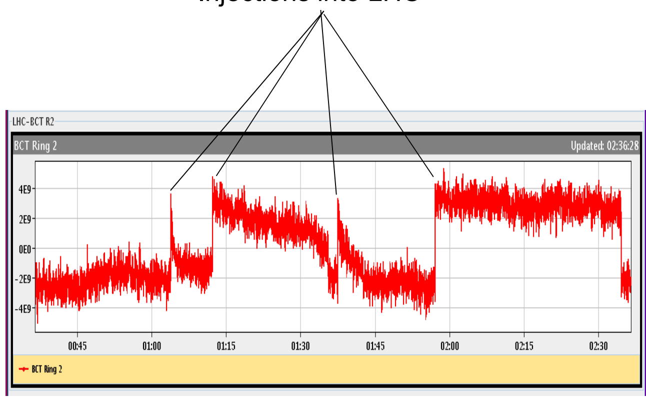
Photo of DCCT internals



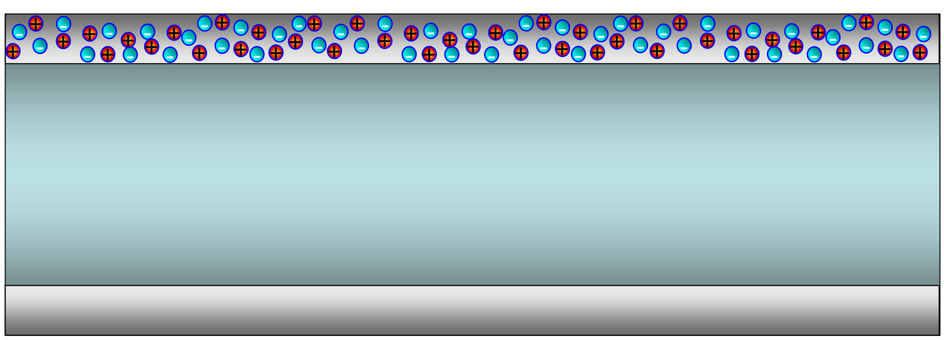
Results from DCCT

Injections into LHC

Beam 2
DCCT sees first circulating beam

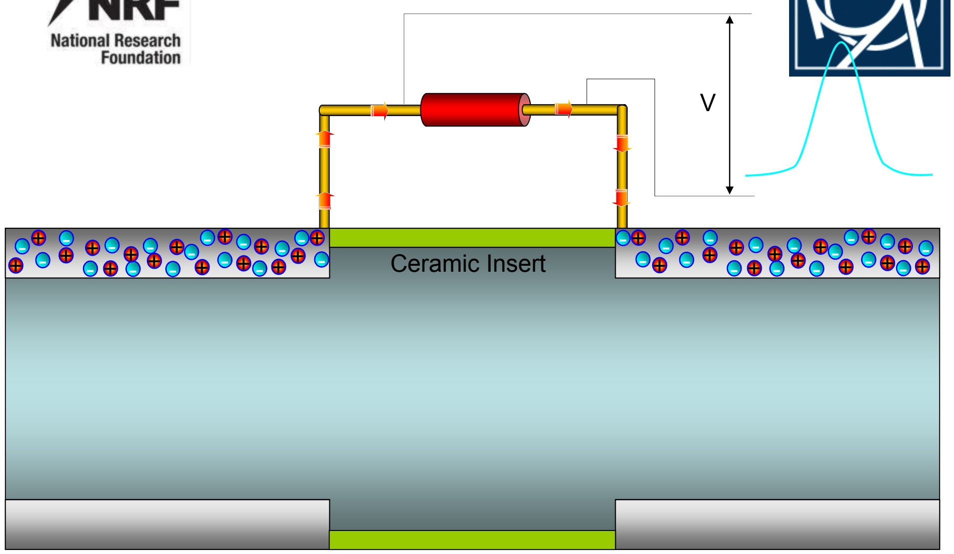


Measuring Beam Position – The Principle

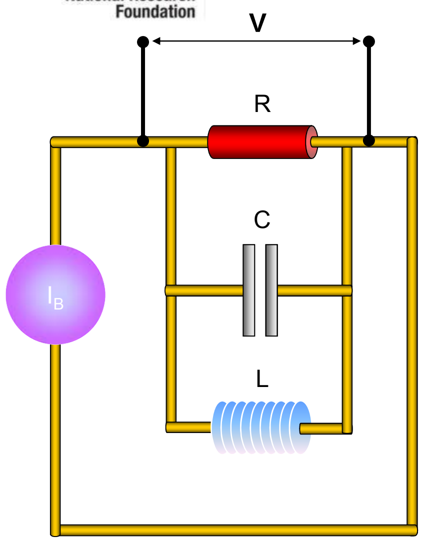


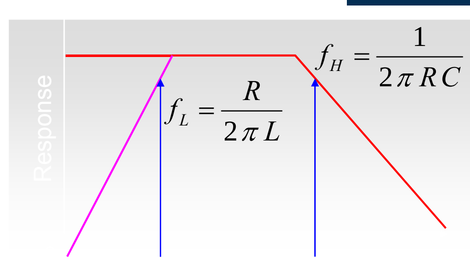
Slide by R. Jones

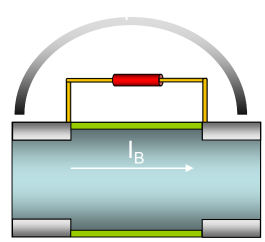
Wall Current Monitor – The Principle



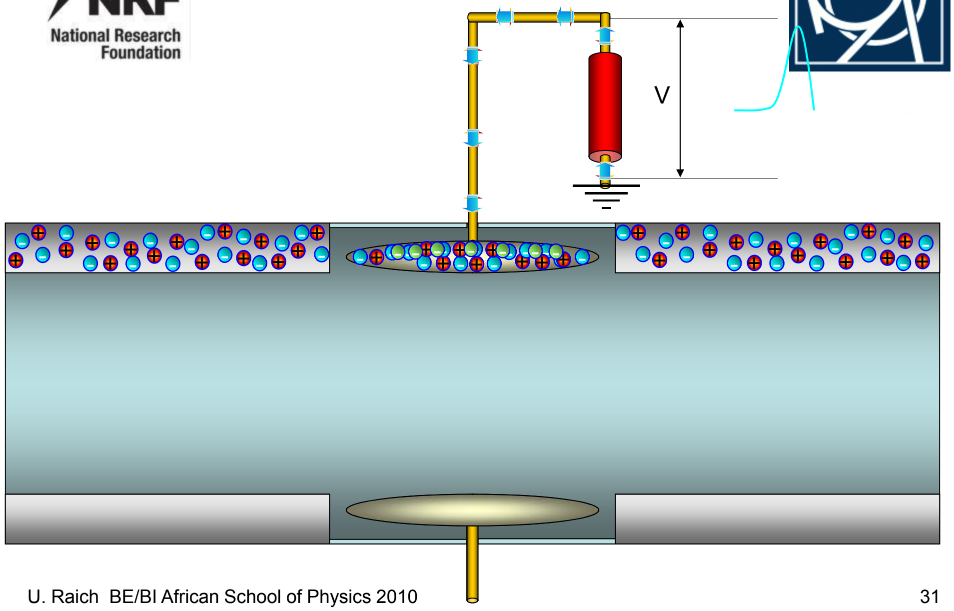
Wall Current Monitor – Beam Response



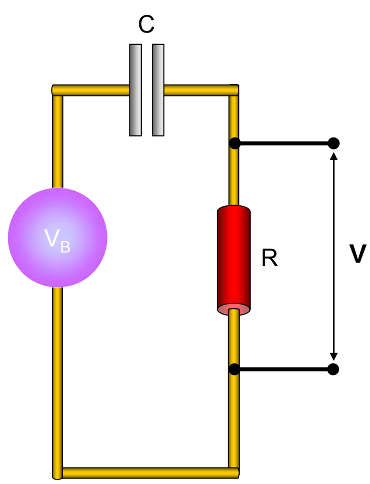


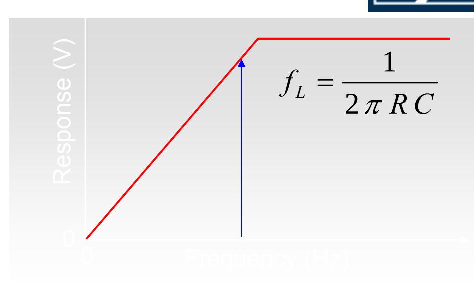


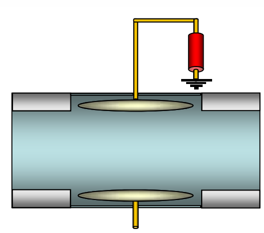
Electrostatic Monitor – The Principle



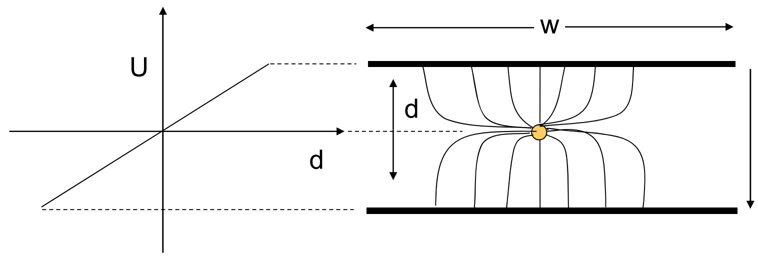
Electrostatic Monitor – Beam Response





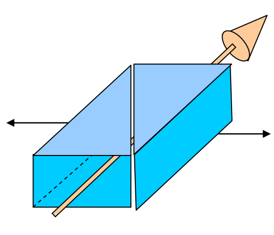


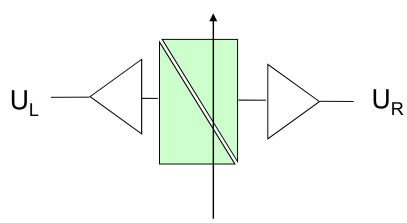
Position measurements



If the beam is much smaller than w, all field lines are captured and U is a linear function with replacement
else: Linear cut (projection to measurement plane must be linear)

Shoebox pick-up



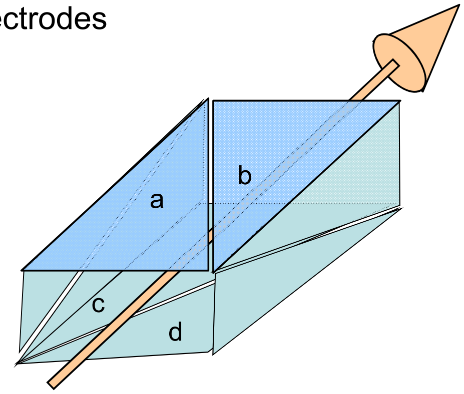


Linear cut through a shoebox

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

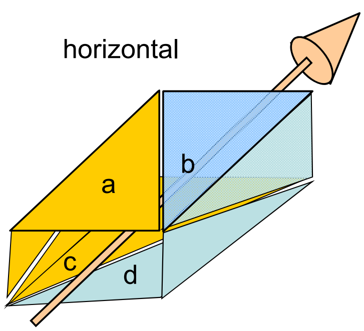
Doubly cut shoebox

- Can measure horizontal and vertical position at once
- Has 4 electrodes

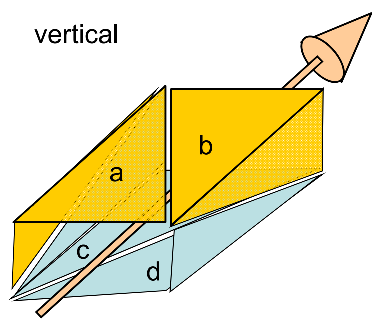


Simulatenous horizontal and vertical measurement

horizontal



vertical

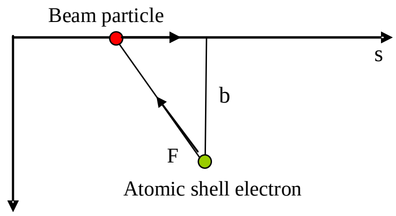


$$X = \frac{(U_a + U_c) - (U_b + U_d)}{\Sigma U}$$

$$Y = \frac{(U_a + U_b) - (U_c + U_d)}{\Sigma U}$$

Interaction of particles with matter

- Coulomb interaction
- Average force in s-direction=0
- Average force in transverse direction <> 0
- Mostly large impact parameter => low energy of ejected electron
- Electron mostly ejection transversely to the particle motion



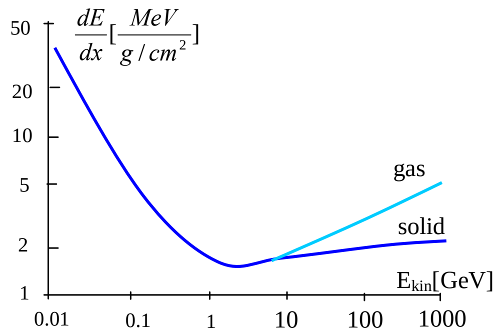
Bethe Bloch formula

$$-\frac{dE}{dx} = 4\pi N_A r_e^2 m_e c^2 \frac{Z_T}{A_T} \rho \frac{Z_p^2}{\beta^2}[\ln \frac{2m_e c^2 \gamma^2 \beta^2}{I} - \beta^2]$$

- with the following constants:
  - NA: Avogadro's number
  - m_e and r_e: electron rest mass and classical electron radius
  - c: speed of light
- the following target material properties:
  - ρ: material density
  - A_T and Z_T: the atomic mass and nuclear charge
- and the particle properties:
  - Z_p: particle charge
  - β: the particles velocity and $\gamma = \sqrt{1-\beta^2}$

Dependance on Z_p^2

High energy loss a low energies



Heavy ions at low energy are stopped within a few micro-meters
All energy is deposited in a very small volume

Scintillating Screens

Method already applied in cosmic ray experiments

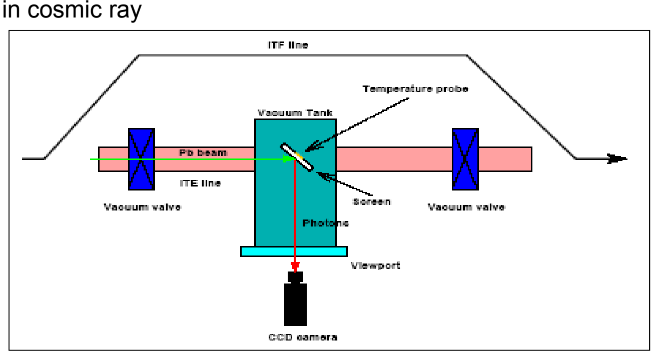
- Very simple
- Very convincing

Needed:

- Scintillating Material
- TV camera
- In/out mechanism

Problems:

- Radiation resistance of TV camera
- Heating of screen (absorption of beam energy)
- Evacuation of electric charges



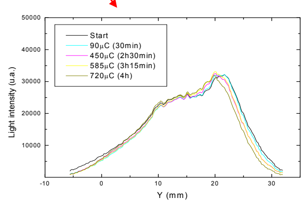
Test for resistance against heat-shock

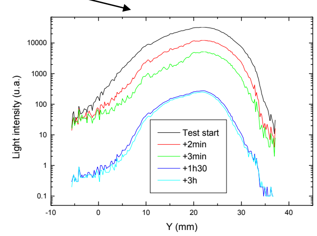
Material	ρ g/cm^3	c_p at 20°C J/gK	k at 100°C W/mK	T_{max} °C	R at 400 °C Ω.cm
Al_2O_3	3.9	0.9	30	1600	10^{12}
ZrO_2	6	0.4	2	1200	10^3
BN	2	1.6	35	2400	10^{14}

Often used in accelerators

Better for electrical conductivity (>400°C)

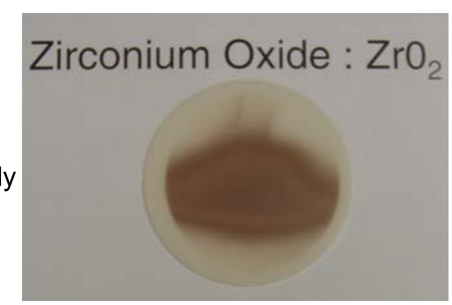
Better for thermal properties
(higher conductivity, higher heat capacity)





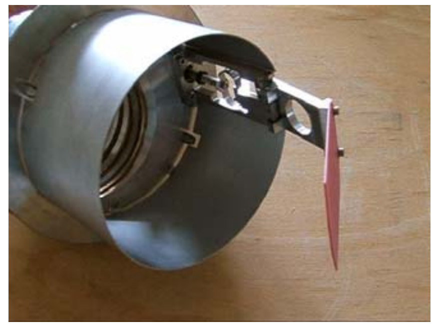
Degradation of screen

Degradation clearly visible
However sensitivity stays essentially the same

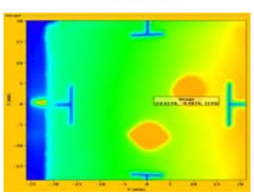


Screen mechanism

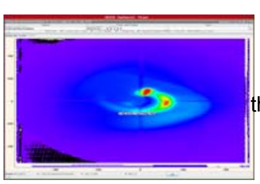
- Screen with graticule



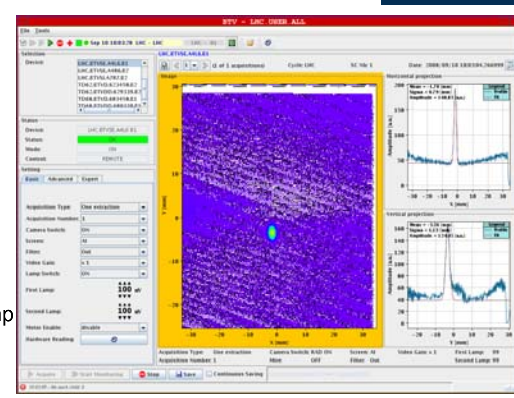
Results from TV Frame grabber



First full turn as seen by the BTV 10/9/2008



Uncaptured beam sweeps through he dump line



- For further evaluation the video signal is digitized, read-out and treated by program

Profile measurements

- Secondary emission grids (SEMgrids)

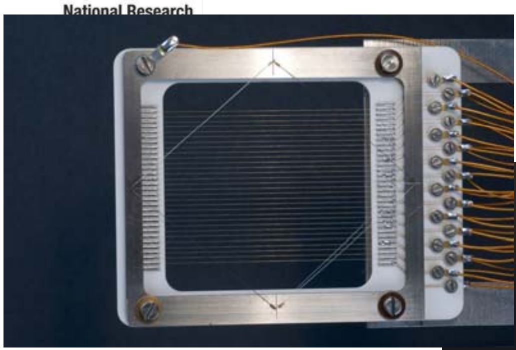
When the beam passes secondary electrons are ejected from the ribbons

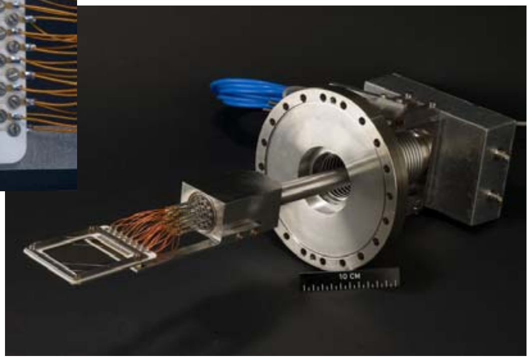
The current flowing back onto the ribbons is measured

Electrons are taken away by polarization voltage

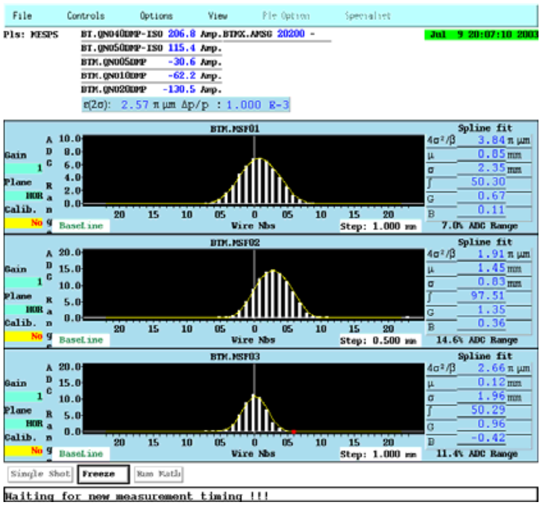
One amplifier/ADC chain channel per ribbon

SEMgrids with wires





Profiles from SEMgrids



Projection of charge density projected to x or y axis is Measured

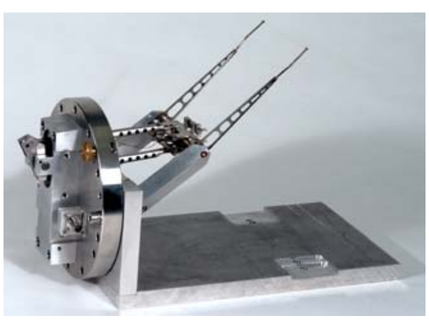
One amplifier/ADC per wire
Large dynamic range

Resolution is given by wire distance

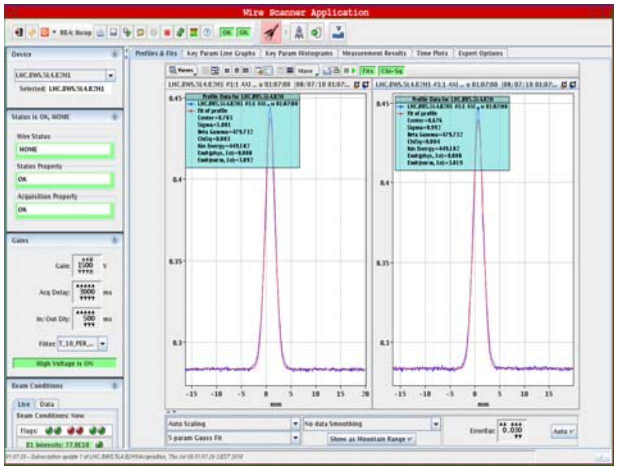
Used only in transfer lines

Wire Scanners

A thin wire is quickly moved across the beam
Secondary particle shower is detected outside the vacuum chamber on a scintillator/photo-multiplier assembly
Position and photo-multiplier signal are recorded simultaneously



Wire scanner profile



High speed needed because of heating.

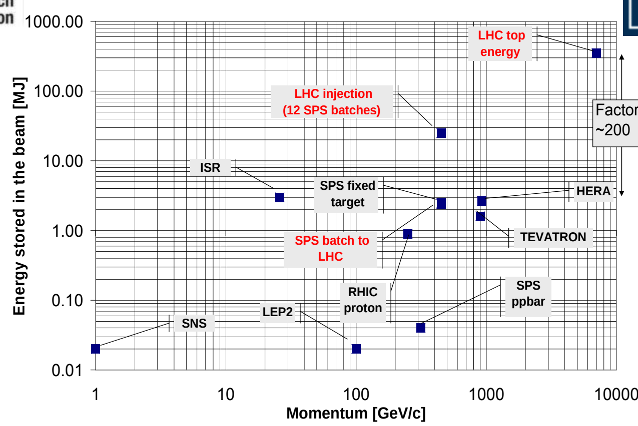
Adiabatic damping

Current increase due to Speed increase

Speeds of up to 20m/s
=> 200g acceleration

Stored Beam Energies

(Based on graph from R. Schmidt)



Quench Levels	Units	*Tevatron*	*RHIC*	*HERA*	*LHC*
***Instant loss* (0.01 - 10 ms)**	[J/cm^3]	4.5 10^{-03}	1.8 10^{-02}	2.1 10^{-03} - 6.6 10^{-03}	8.7 10^{-04}
***Steady loss* (> 100 s)**	[W/cm^3]	7.5 10^{-02}	7.5 10^{-02}		5.3 10^{-03}

Beam power in the LHC

The Linac beam (160 mA, 200μs, 50 MeV, 1Hz) is enough to burn a hole into the vacuum chamber
What about the LHC beam: 2808 bunches of $15*10^{11}$ particles at 7 TeV?
1 bunch corresponds to a 5 kg bullet at 800 km/h

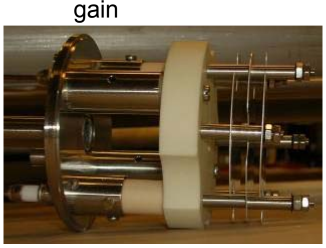
Beam Dammage

Fermi Lab'sTevatron has 200 times less beam power than LHC!

Beam Loss Monitor Types

- Design criteria: Signal speed and robustness
- Dynamic range (> 10^9) limited by leakage current through insulator ceramics (lower) and saturation due to space charge (upper limit).

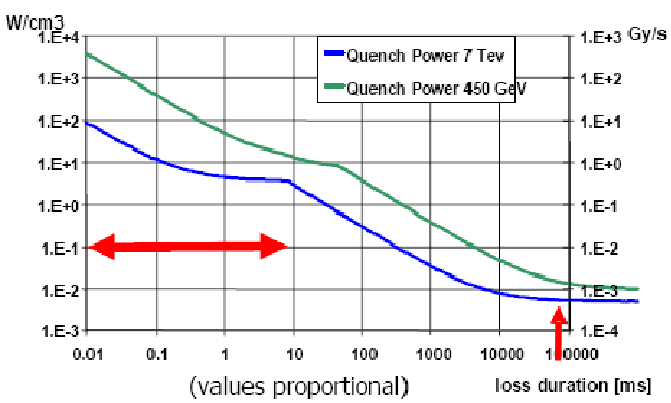
Secondary Emission Monitor (SEM):
- Length 10 cm
- P < 10^{-7} bar
- ~ 30000 times smaller gain



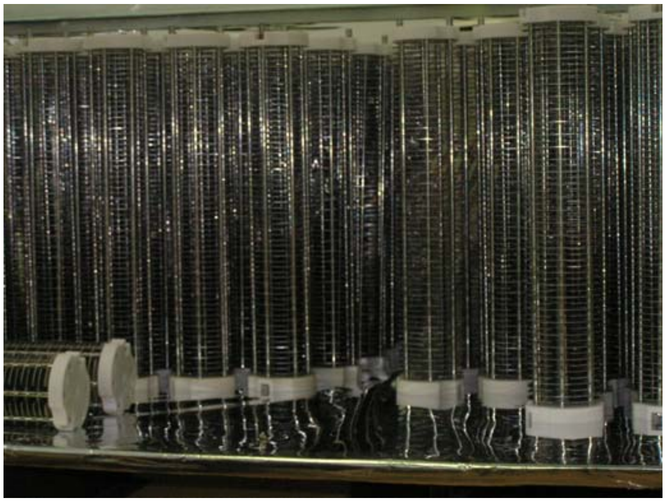
Ionization chamber:
- N_2 gas filling at 100 mbar over-pressure
- Length 50 cm
- Sensitive volume 1.5 l
- Ion collection time 85 μs

- Both monitors:
  - Parallel electrodes (Al, SEM: Ti) separated by 0.5 cm
  - Low pass filter at the HV input
  - Voltage 1.5 kV

Quench levels

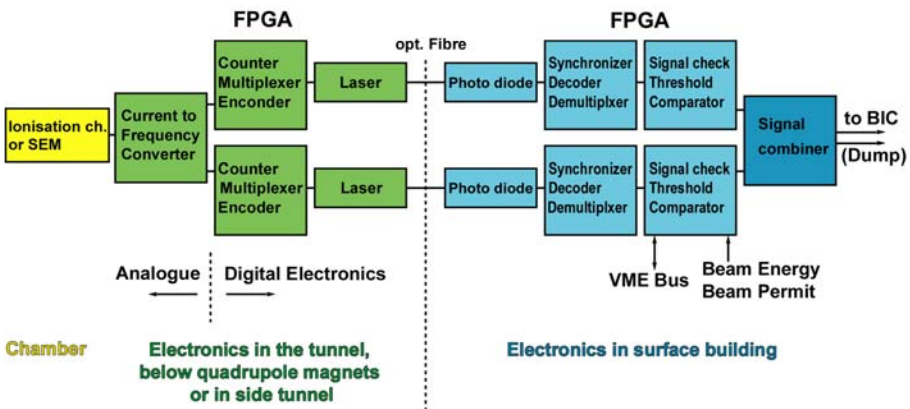


Industrial production of chambers



Beam loss must be measured all around the ring
=> 4000 sensors!

System layout



Successive running sums