Beam Diagnostics

Lecture 1

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(Beam Instrumentation)

Overview

- First 2 hours:
  - Introduction
  - Overview of measurement instruments
- Last hour
  - Some depicted examples of beam parameter measurements

Contents of lecture 1

- Introduction
- Generalities about beam diagnostic devices
- Current measurements
  - Faraday Cup
  - Fast current transformer
  - DC current transformer
- Beam Loss detectors


7th European Workshop on
Beam Diagnostics and Instrumentation
For Particle Accelerators
Powerful Instruments: yes, but...
7th
DIPAC
2005
...this time only for particle beams
The biannual DIPAC workshop aims at an active exchange of the latest experiences in the field of accelerator beam diagnostics and instrumentation with a program of oral presentations, poster sessions and discussion groups
Program Committee:
Local Committee and Secretariat
6-8 June,
2005
Hosted by CERN – AB-BDI

Introduction

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





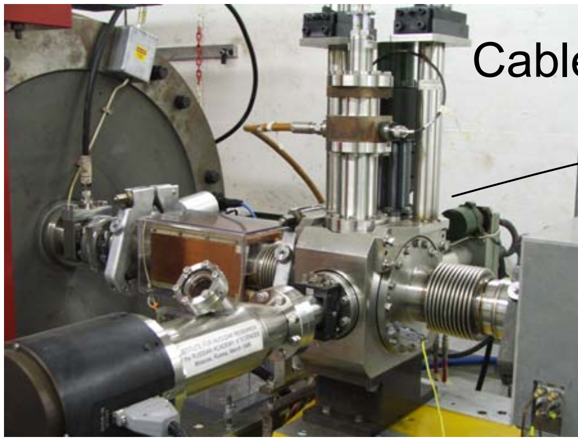

Different uses of beam diagnostics

- **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*

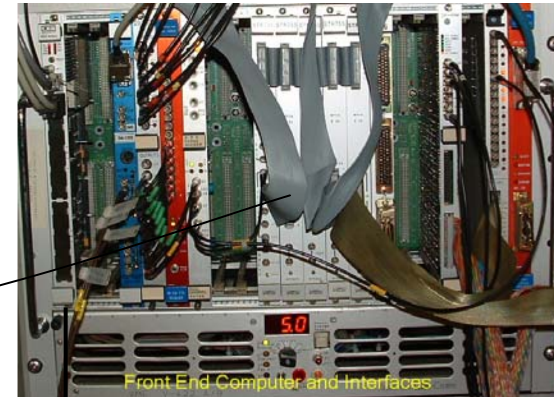
Diagnostic devices and quantity measured

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

Intensity measurements
Faraday Cups



Cable from ring to equipment room



Sensor + amplifier/shaper

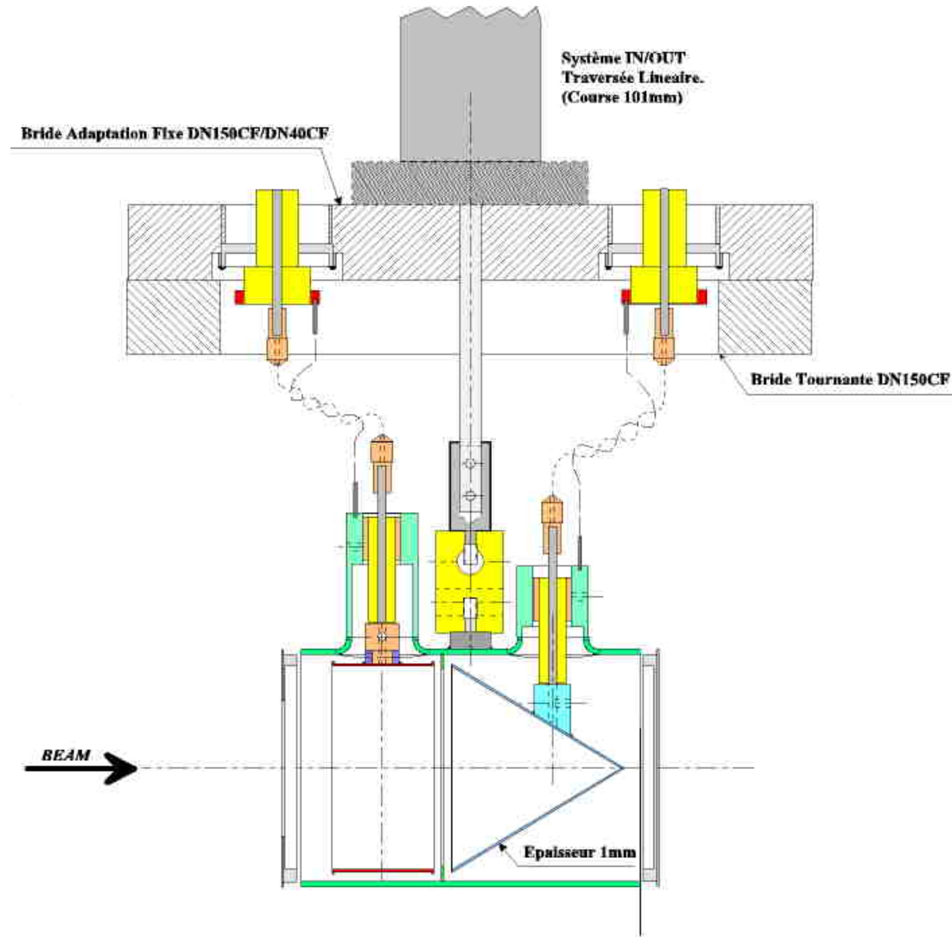
Computer network

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

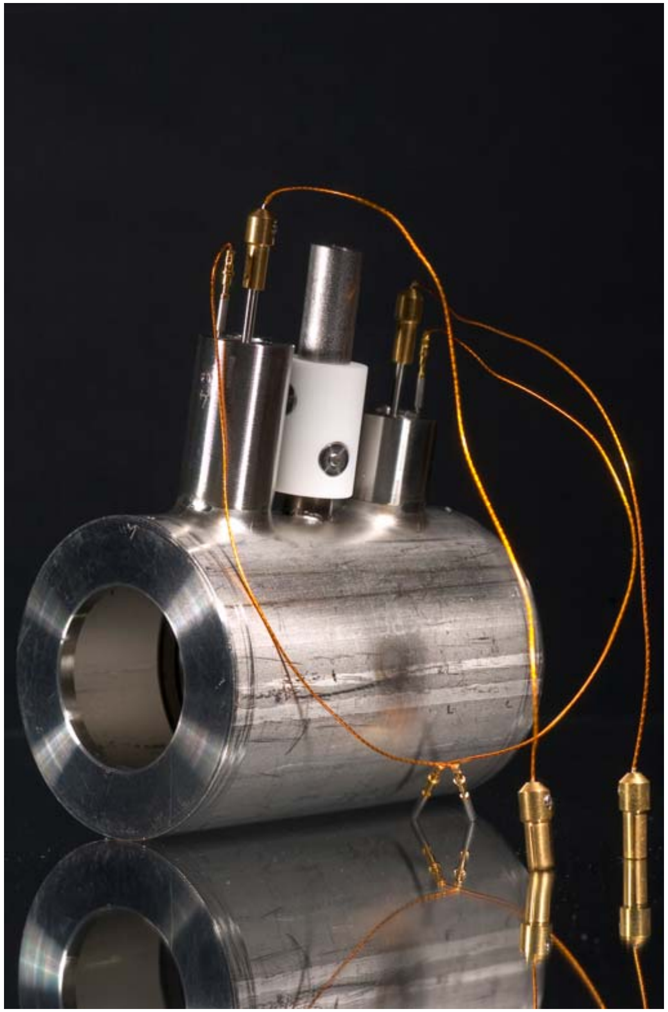
Layout of a Faraday Cup

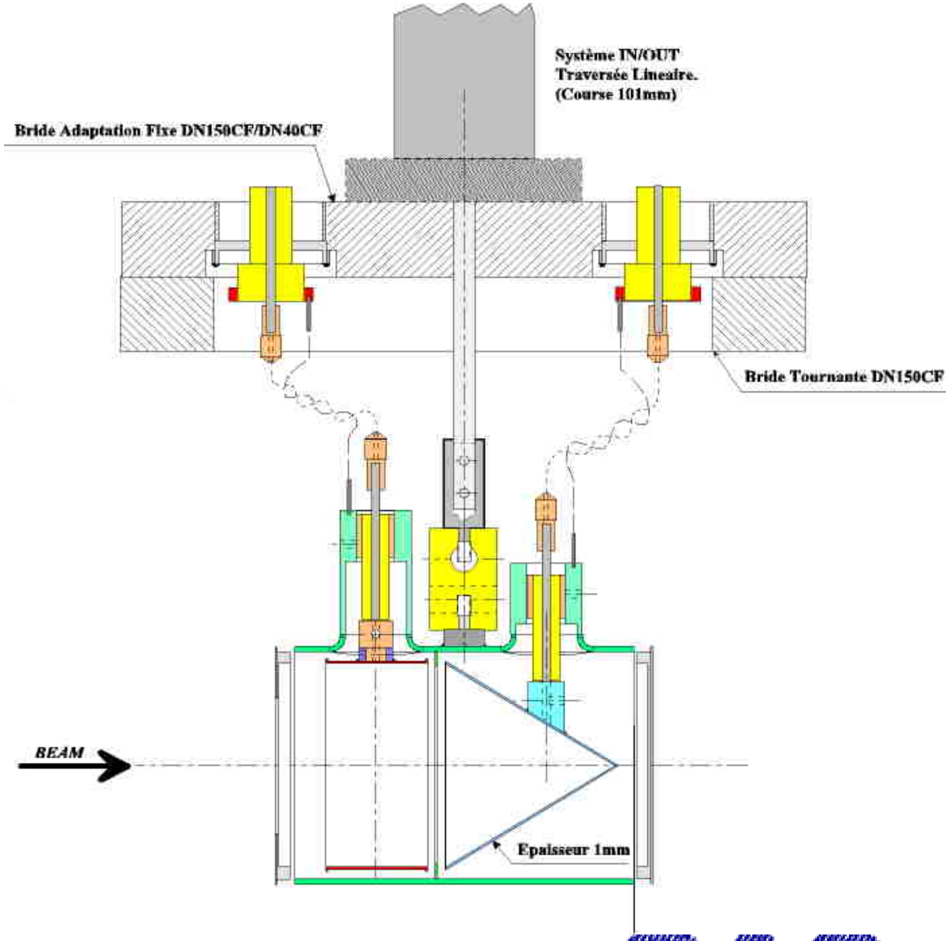
- Electrode: 1 mm stainless steel
- Only low energy particles can be measured
- Very low intensities (down to 1 pA) can be measured
- Creation of secondary electrons of low energy (below 20 eV)
- Repelling electrode with some 100 V polarisation voltage pushes secondary electrons back onto the electrode



Schema: V. Prieto

Faraday Cup

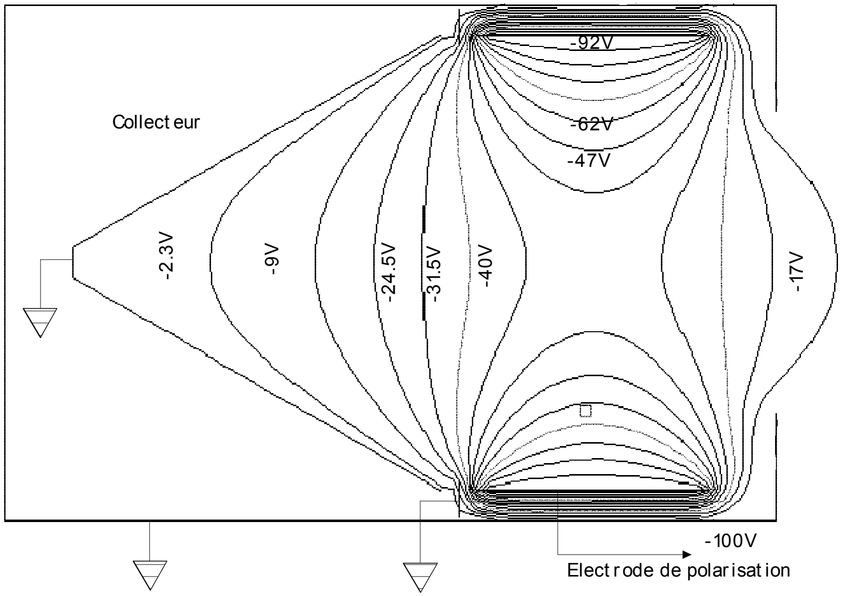



Système IN/OUT
Traversée Lineaire.
(Course 101mm)
Bride Adaptation Fixe DN150CF/DN40CF
Bride Tournante DN150CF
BEAM
Epaisseur 1mm

Electro-static Field in Faraday Cup

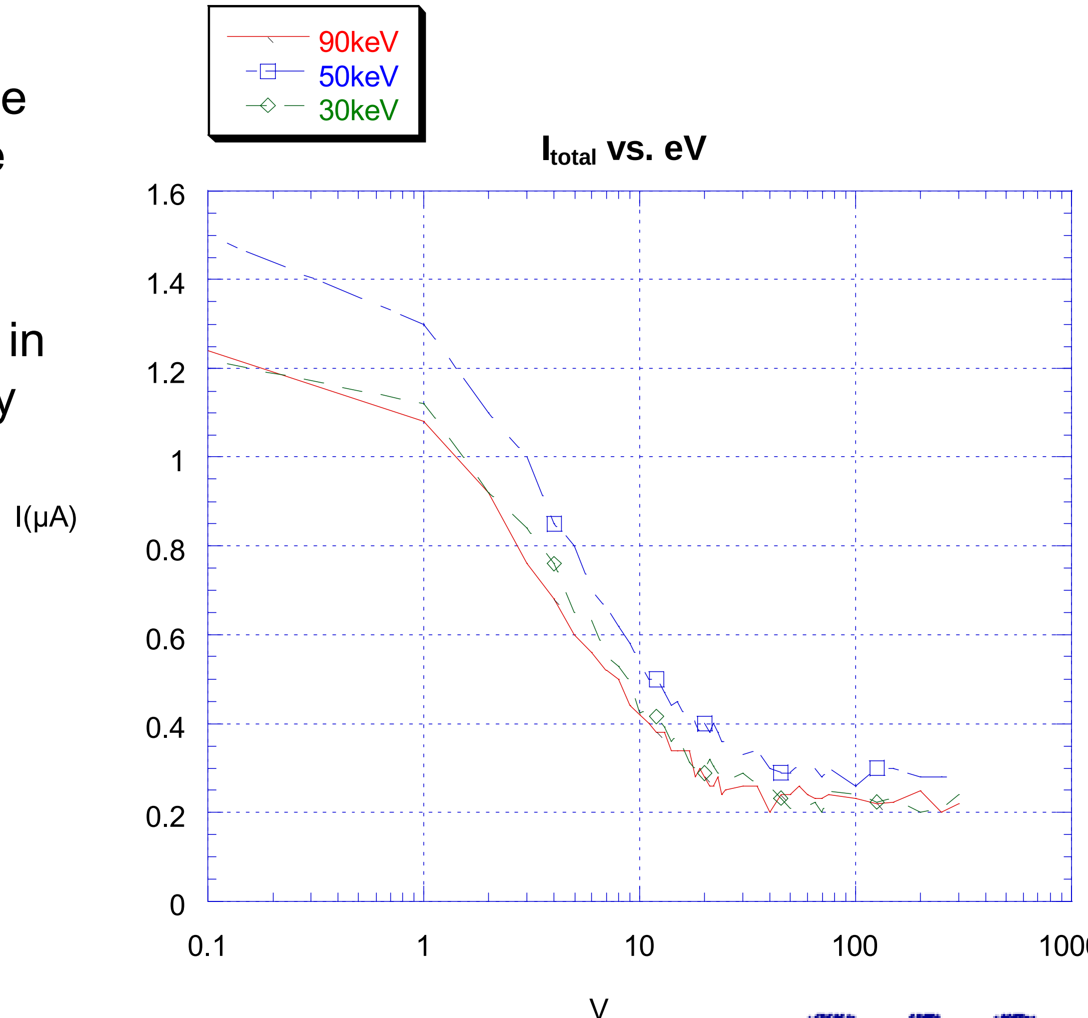
In order to keep secondary electrons within the cup a repelling voltage is applied to the polarization electrode

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

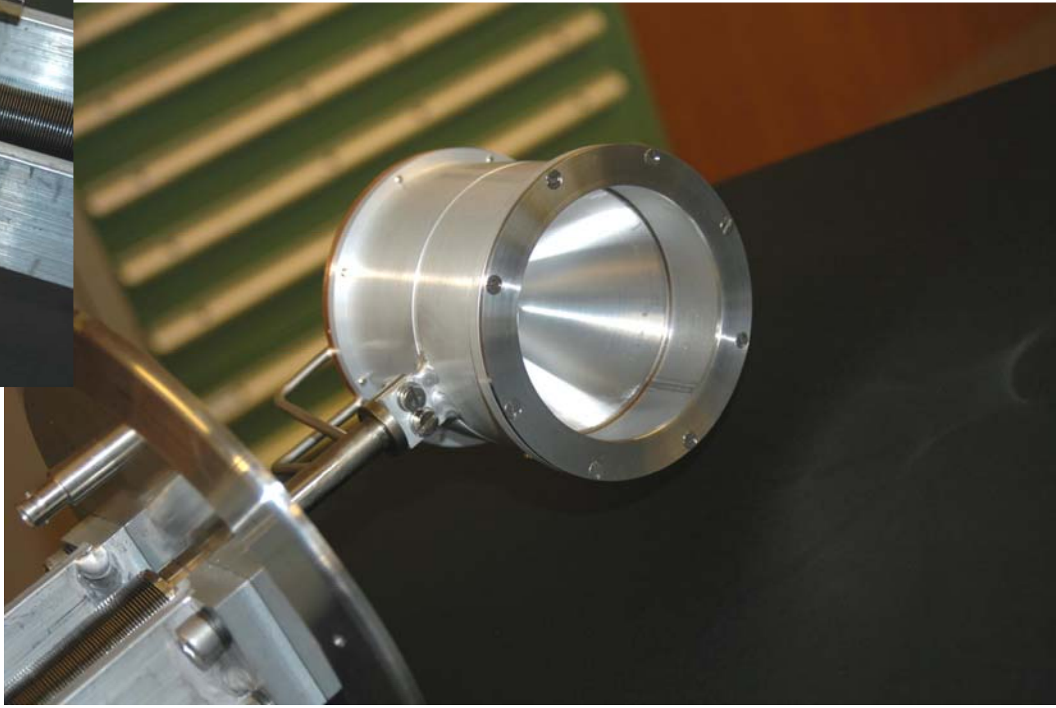


Energy of secondary emission electrons

- 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

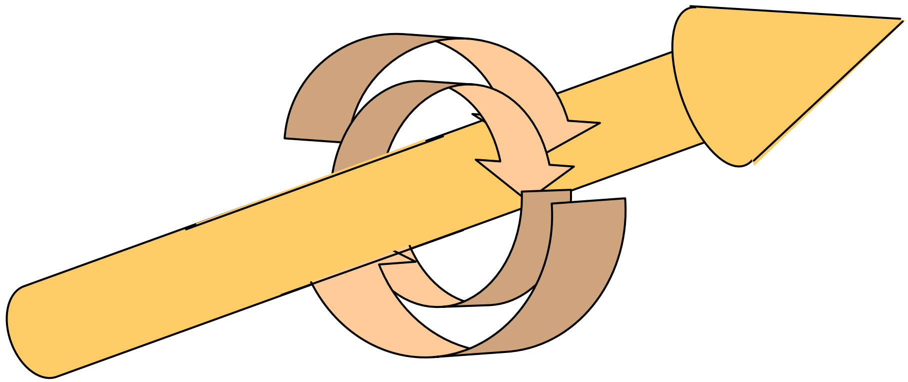


Faraday Cup with water cooling



For higher intensities
water cooling may be needed

Current Transformers



Fields are very low

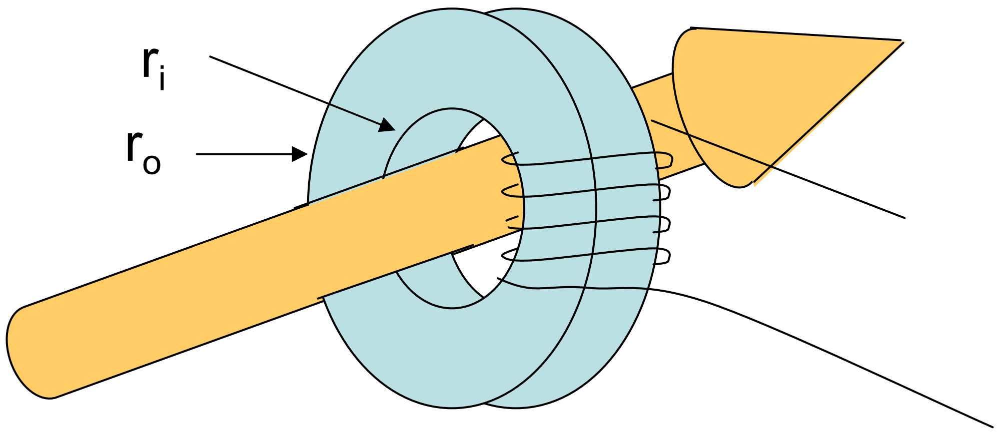
Capture magnetic field lines with cores of high relative permeability

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

Beam current

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

Current Transformers



Fields are very low

Capture magnetic field lines with cores of high relative permeability

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

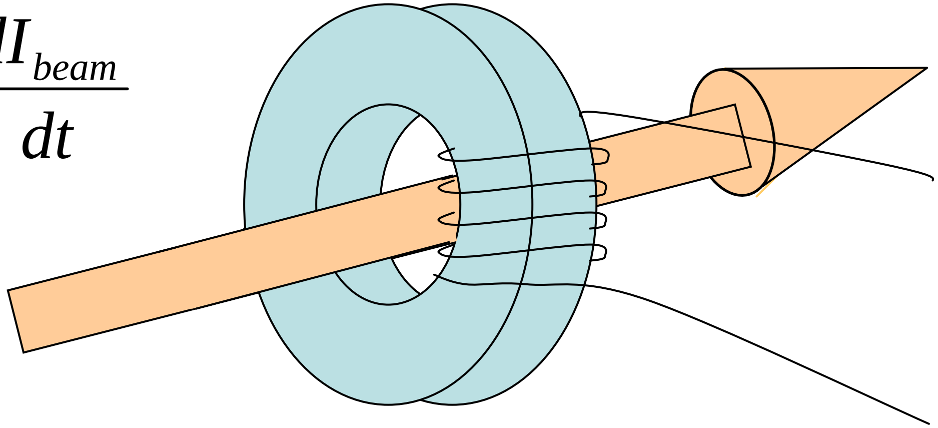
Beam current

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

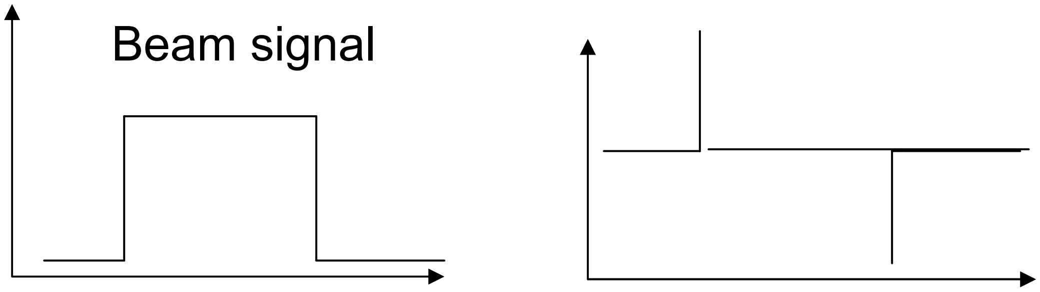
$$L = \frac{\mu_0 \mu_r}{2\pi} l N^2 \ln \frac{r_0}{r_i}$$

The ideal transformer

$$U = L\frac{dI_{beam}}{dt}$$

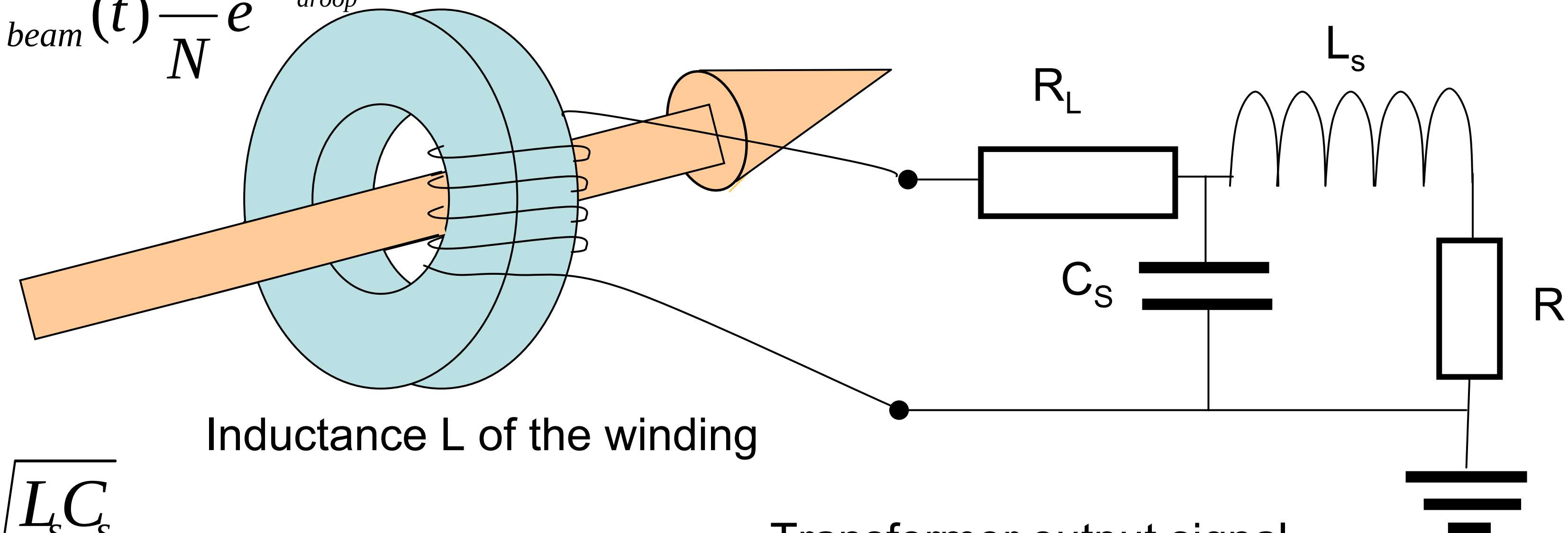


Inductance L of the winding



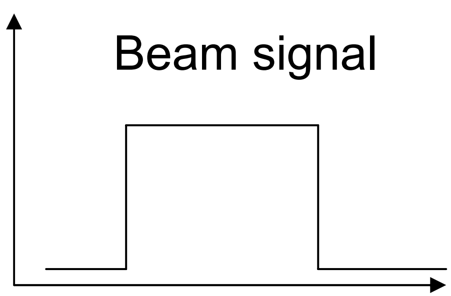
The AC transformer

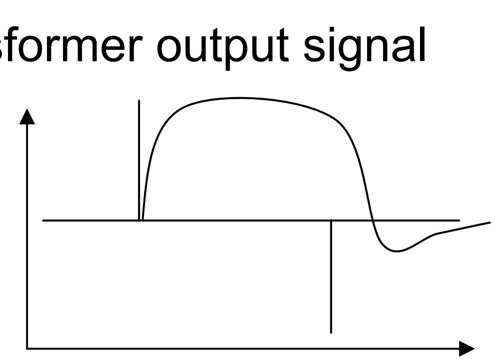
$$U(t) = I_{beam}(t)\frac{R}{N}e^{-\frac{t}{\tau_{droop}}}$$



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

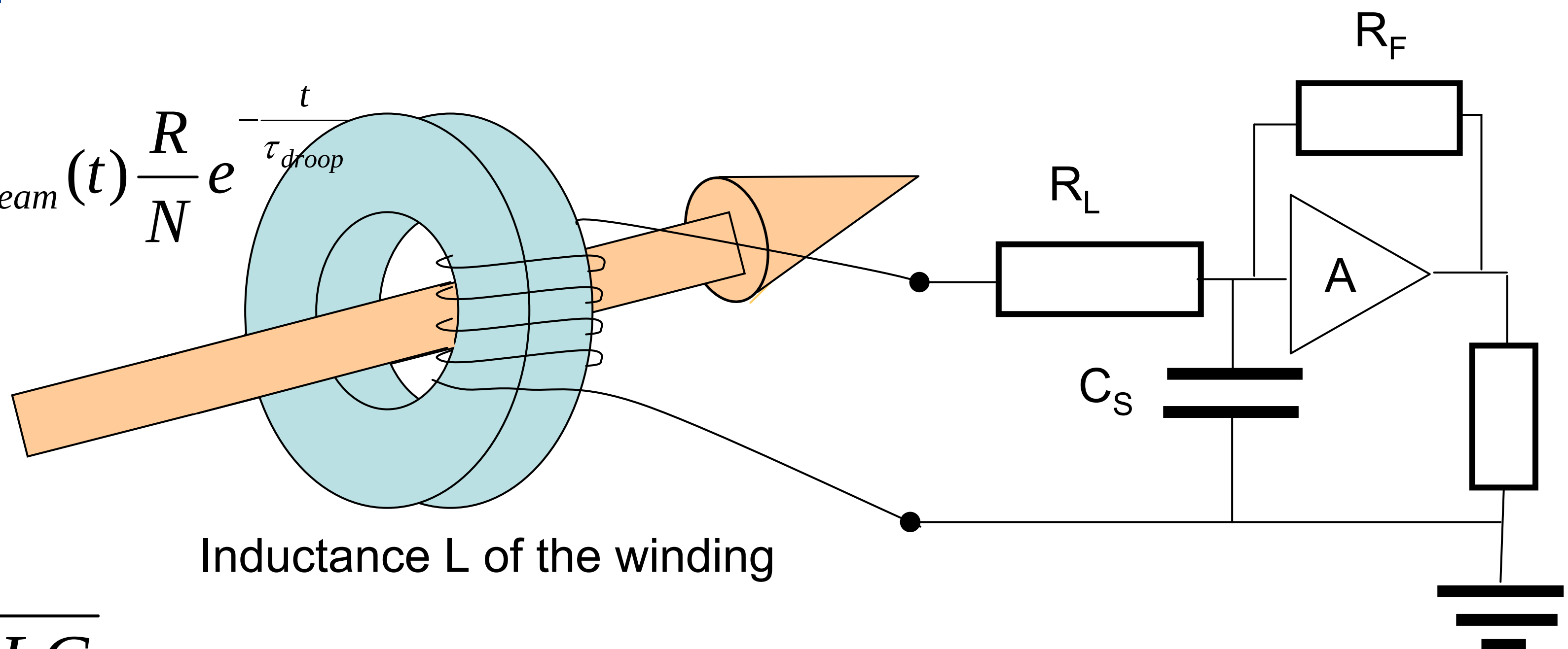
$$\tau_{droop} = \frac{L}{R + R_L}$$





The active transformer

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

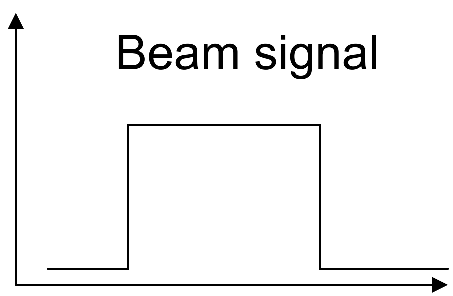


Inductance L of the winding

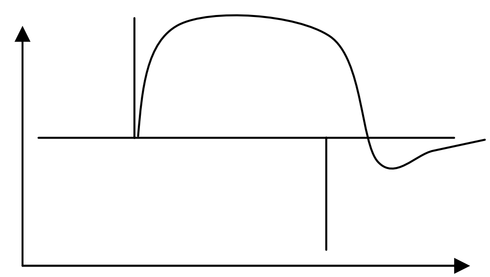
$$\tau_{rise} = \sqrt{L_s C_s}$$

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

Beam signal



Transformer output signal



Principle of a fast current transformer

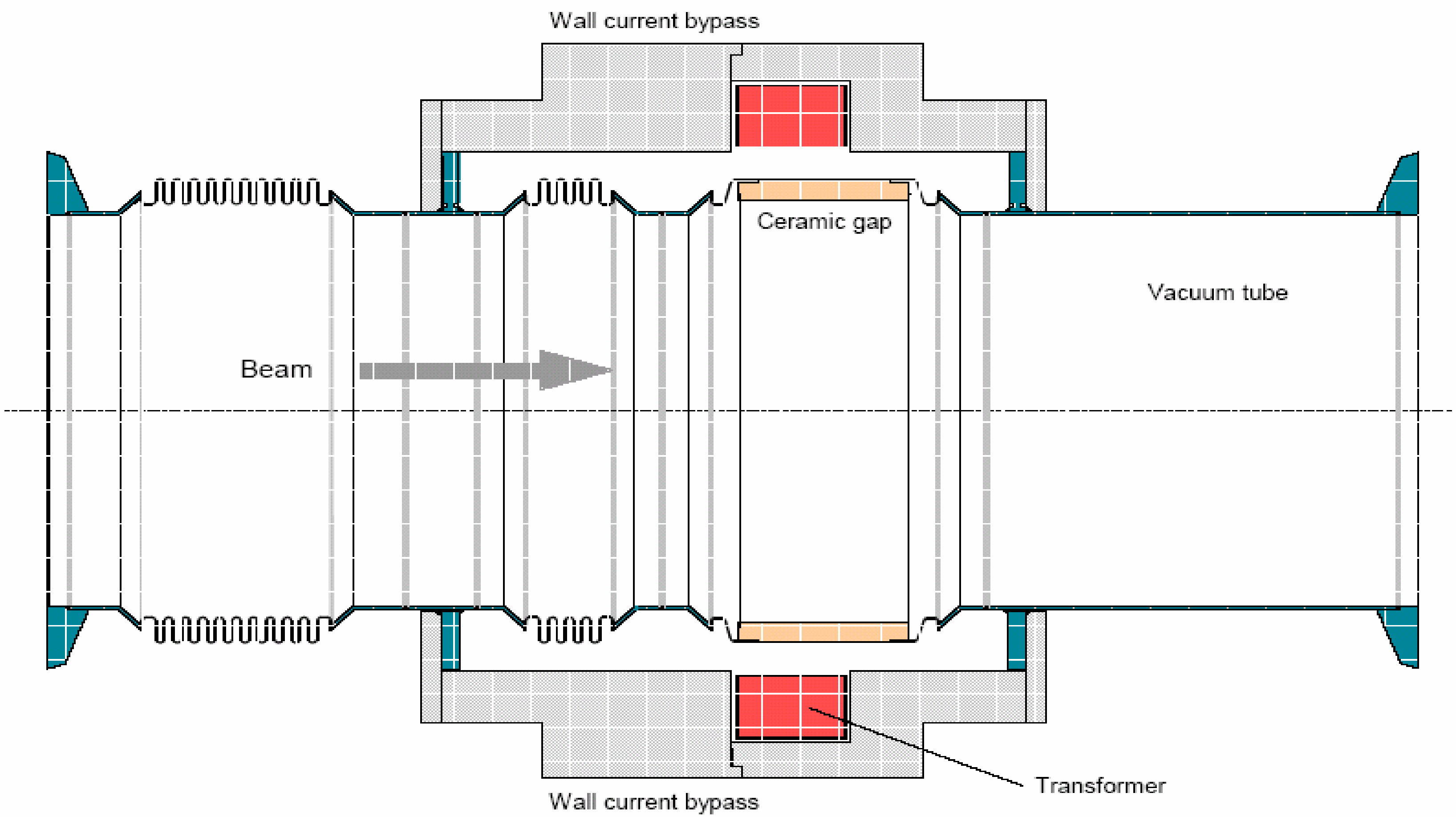
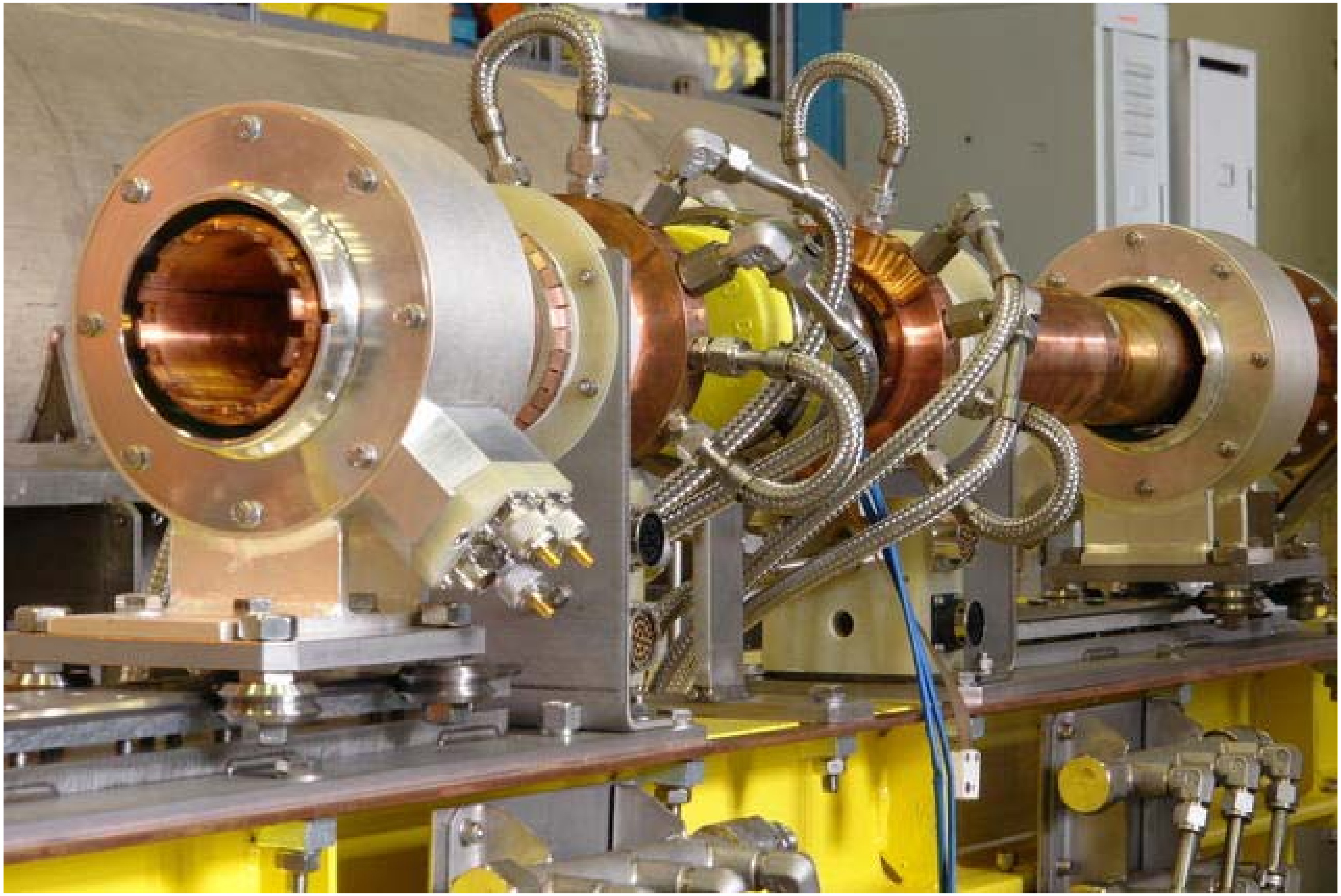
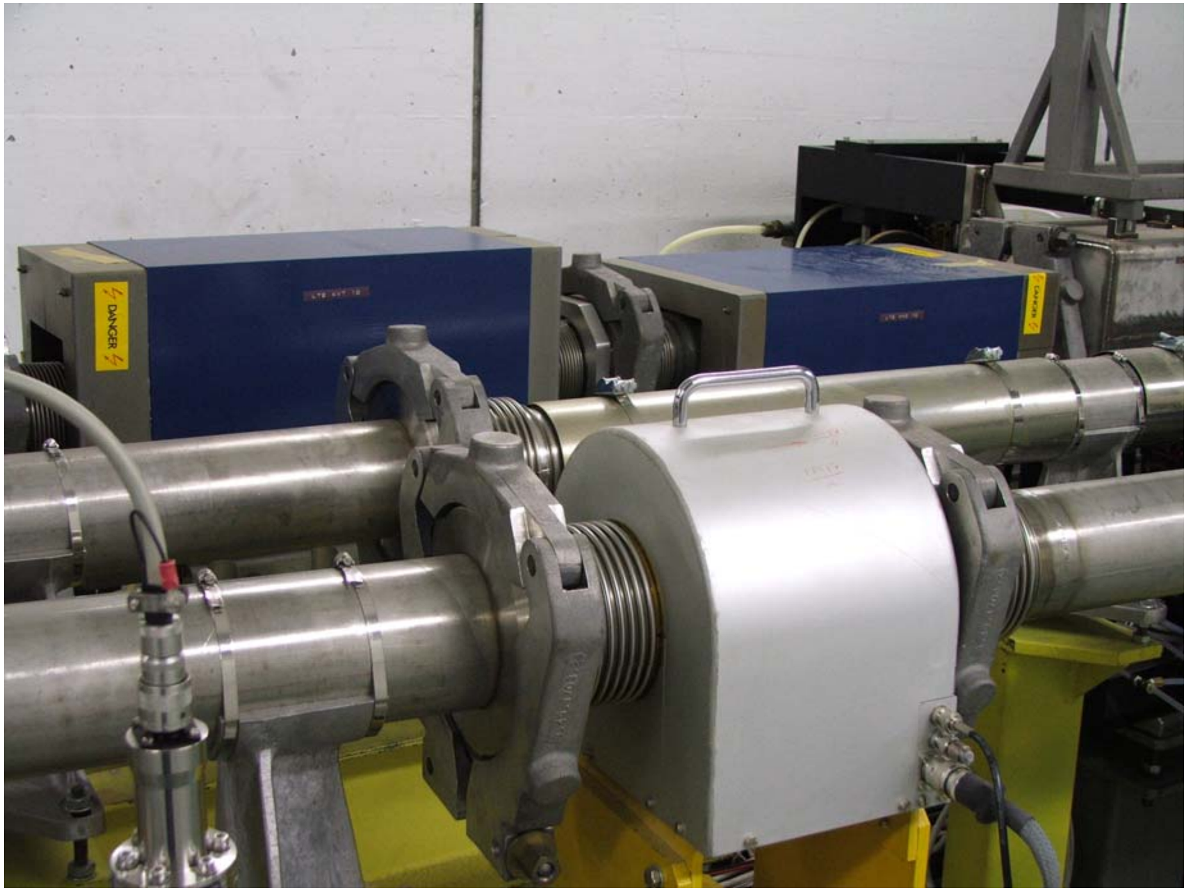


Diagram by H. Jakob

Fast current transformers for the LHC



The transformer installed in the machine

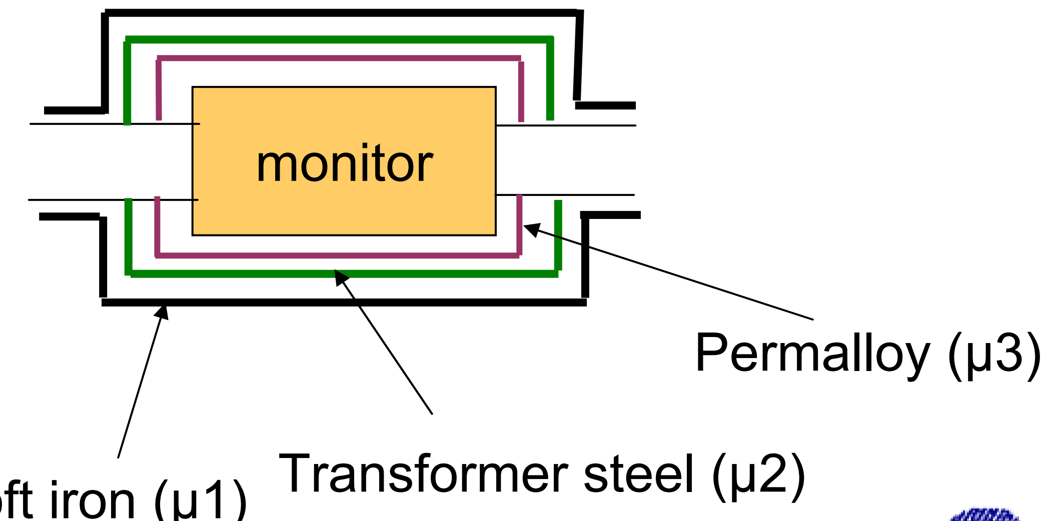


Needs

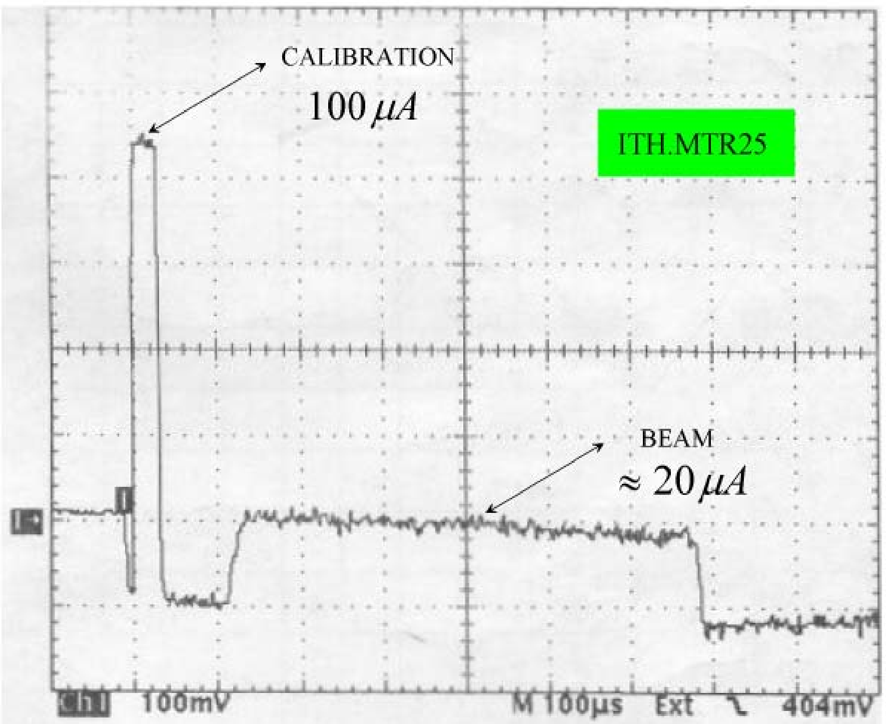
Magnetic Shielding

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

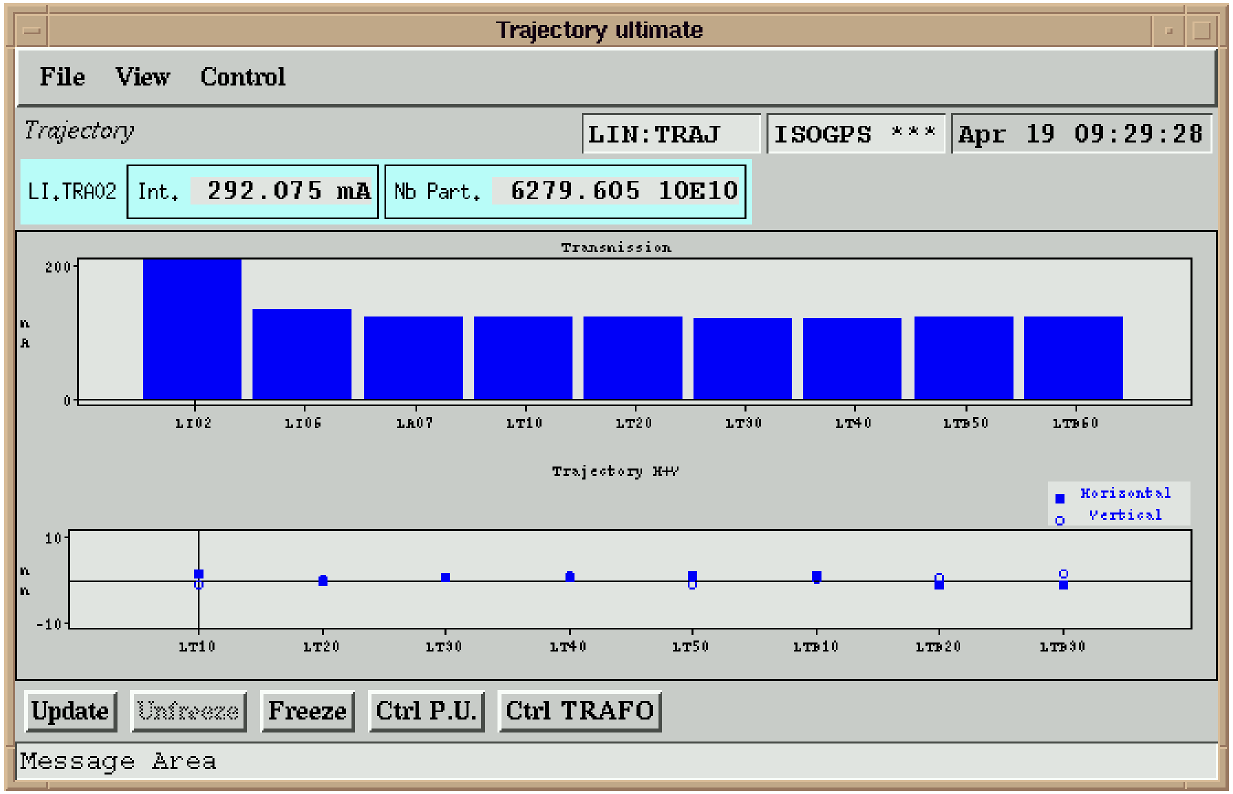


- The transformer is calibrated with a very precise current source
- The calibration signal is injected into a separate calibration winding
- A calibration procedure executed before the running period
- A calibration pulse before the beam pulse measured with the beam signal

Current transformer and its electronics

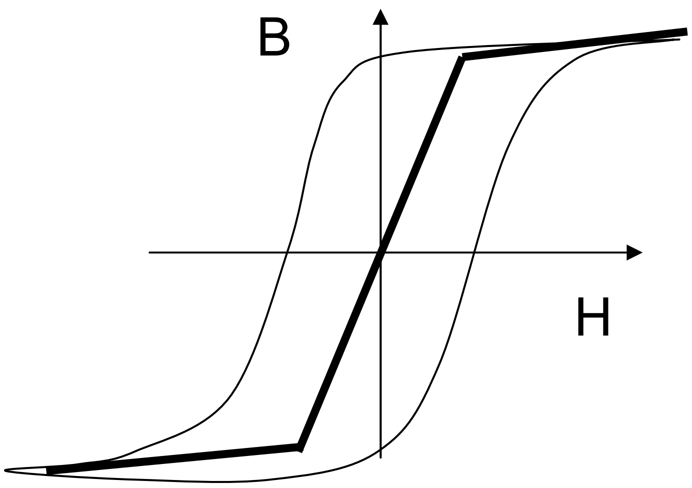
Display of transformer readings

- Transformers in a transfer line
- Calculated losses trigger a *watchdog*
- Display distributed via video signal

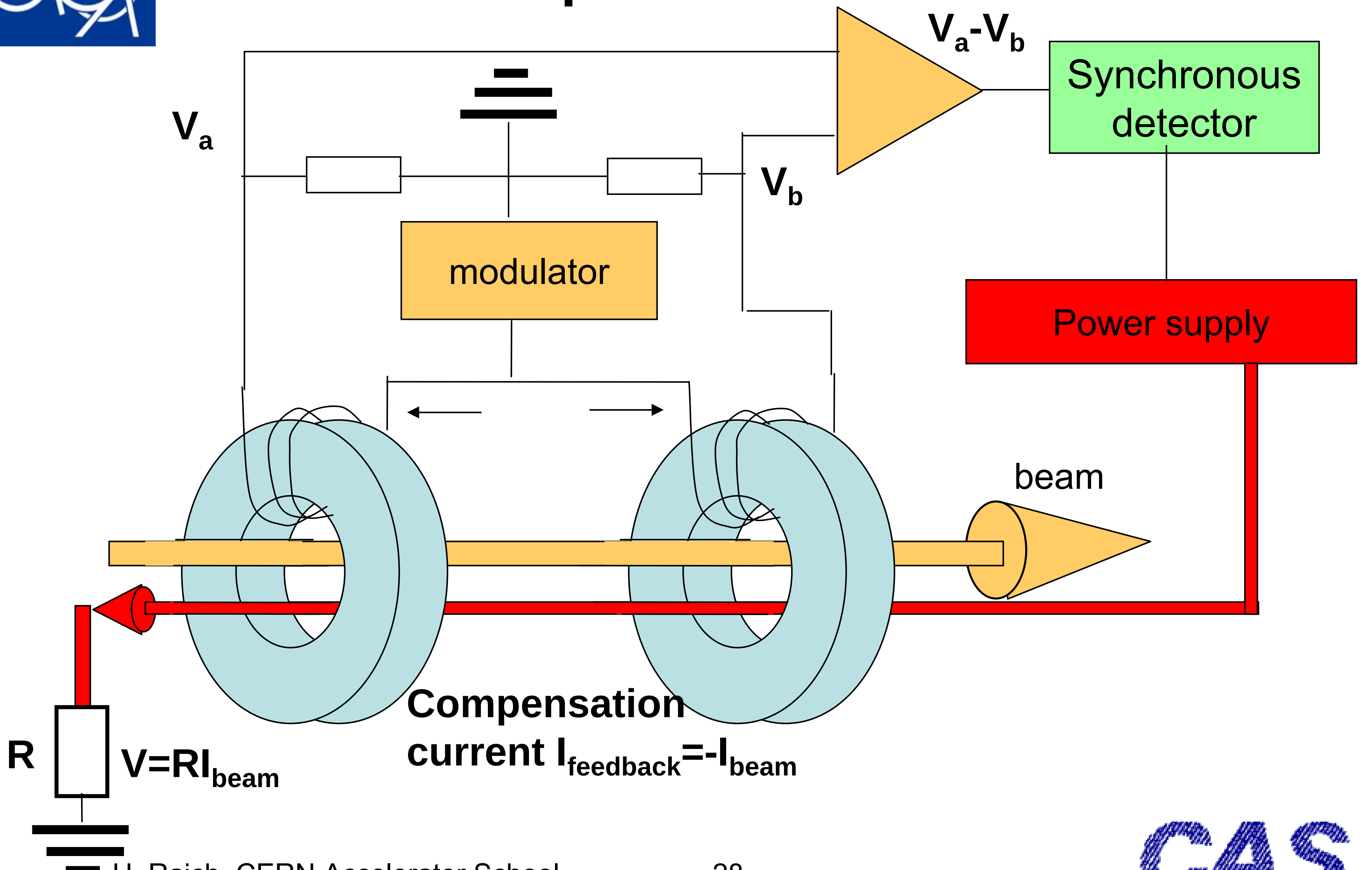


The DC current transformer

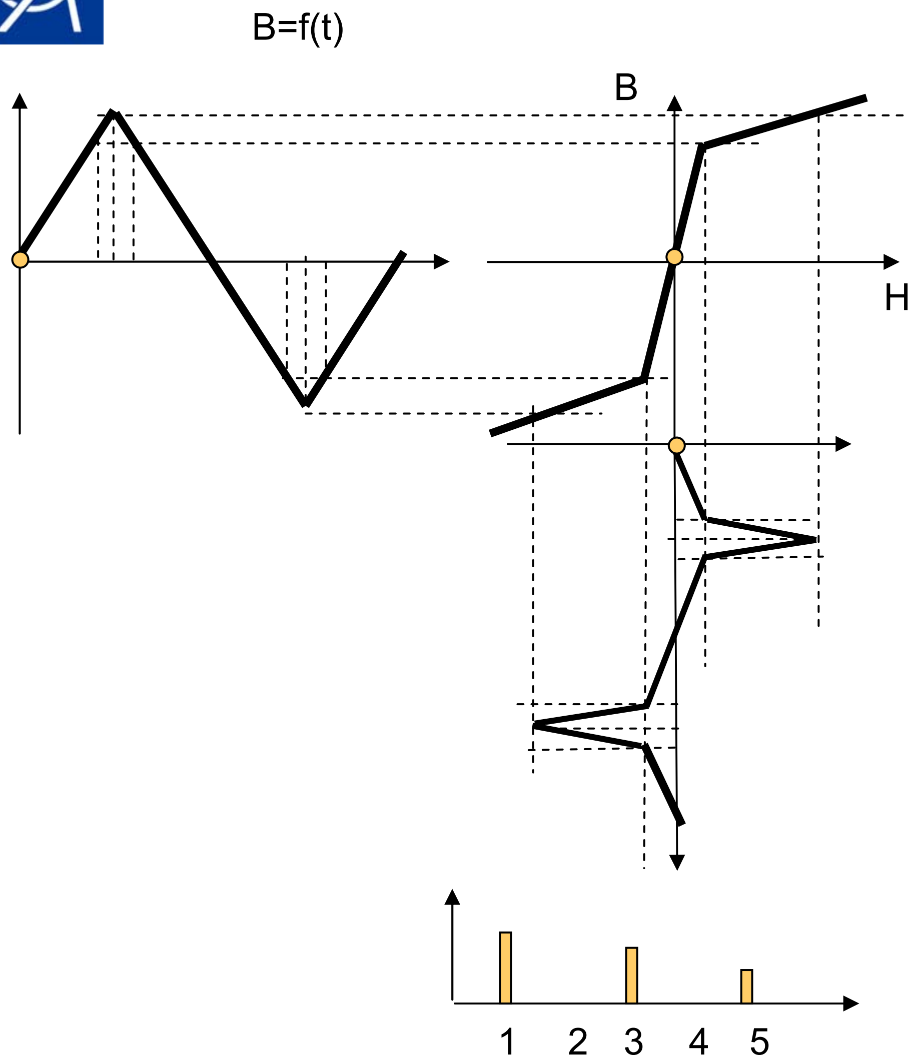
- AC current transformer can be extended to very long droop times but not to DC
- Measuring DC currents is needed in storage rings
- Must provide a modulation frequency
- Takes advantage of non/linear magnetisation curve



Principle of DCCT



Modulation of a DCCT without beam

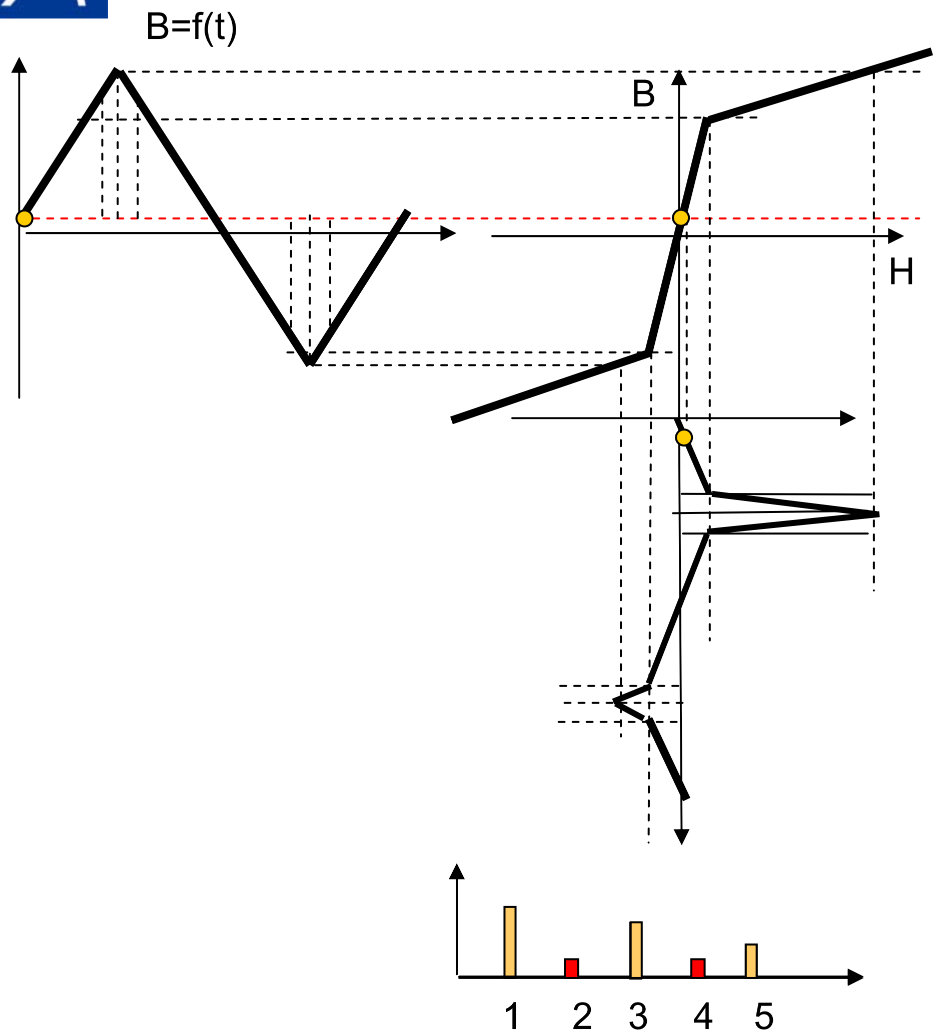


$$U = NA\frac{dB}{dt}$$

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

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

Modulation of a DCCT with beam



Sum signal becomes non-zero
Even harmonics appear

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

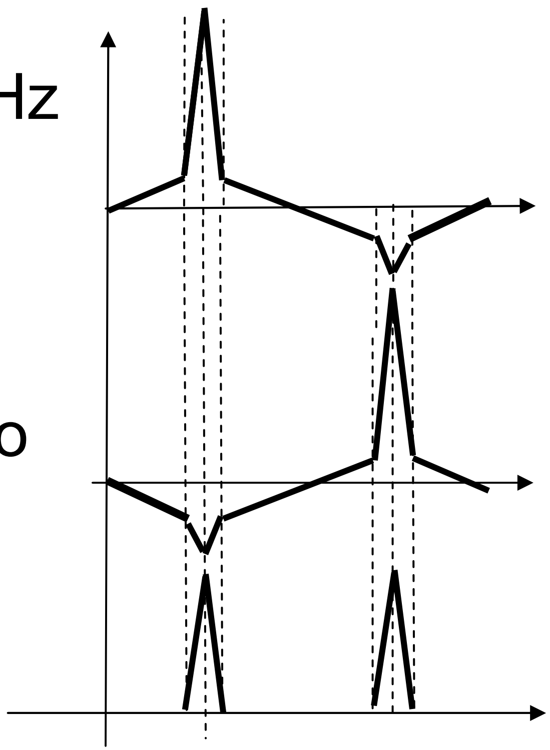
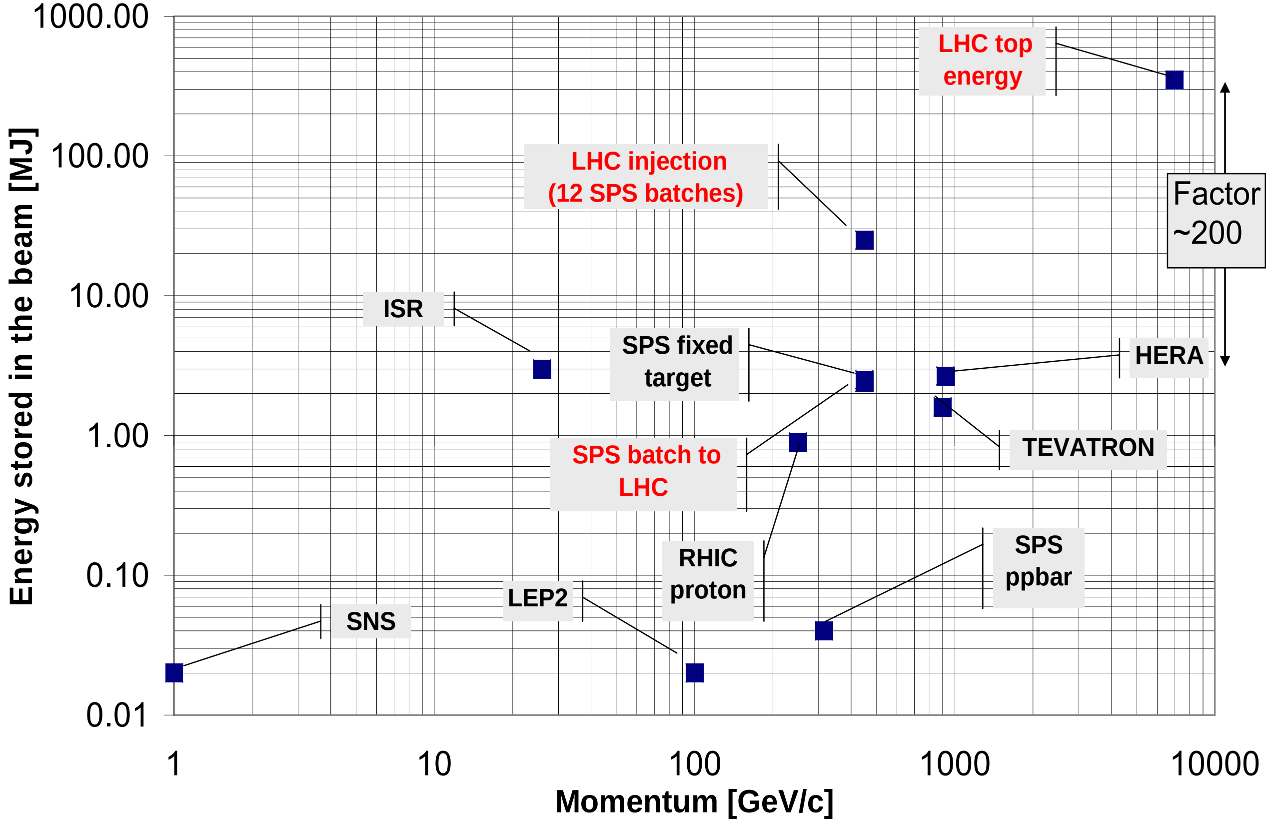


Photo of DCCT internals

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}

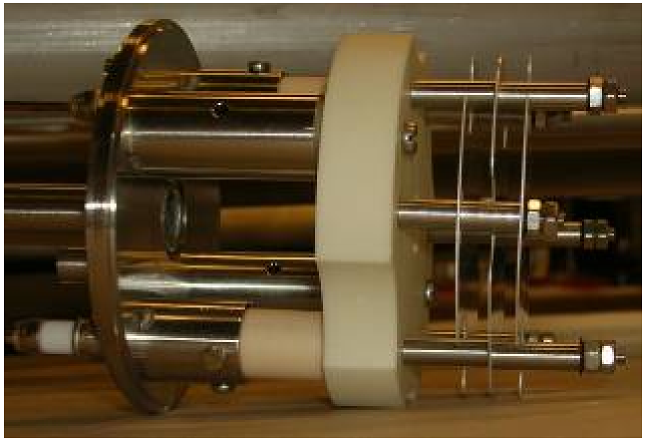
What does this mean?

- The power of the beam corresponds to this boat cruising at 30 nods passing a beam pipe of the size of spain on the 1 Euro coin

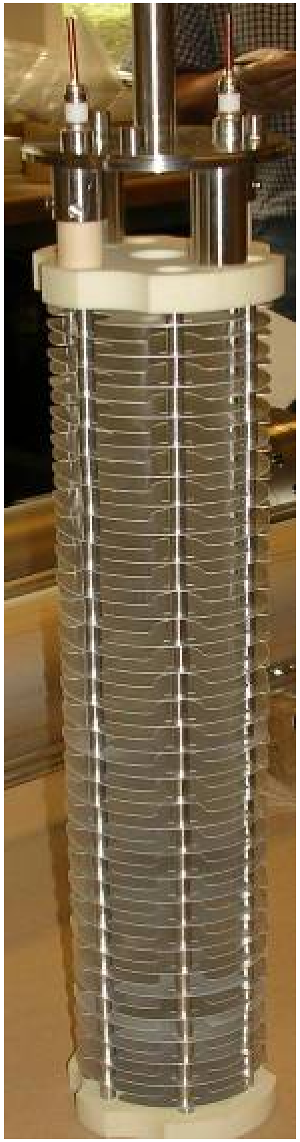
Beam Loss Monitor Types

- 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