# Beam Diagnostics

Ulrich Raich
CERN AB - BDI
(Beam Diagnostics and Instrumentation)

# Introduction

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

# Course Overview

- Generalities
- Intensity measurements
  - Faraday Cup
  - AC current transformer
  - DC current transformer
- Profile measurements
  - TV screens
  - SEMgrids
  - Wire scanners
- Emittance
  - Phase space scans
  - Pepperpot
- Position measurements

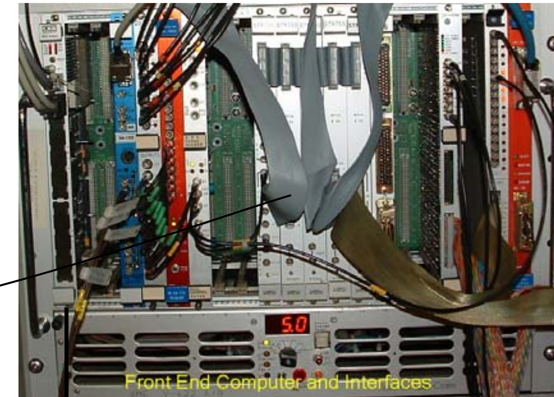
# Different uses of beam diagnostics

- **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*

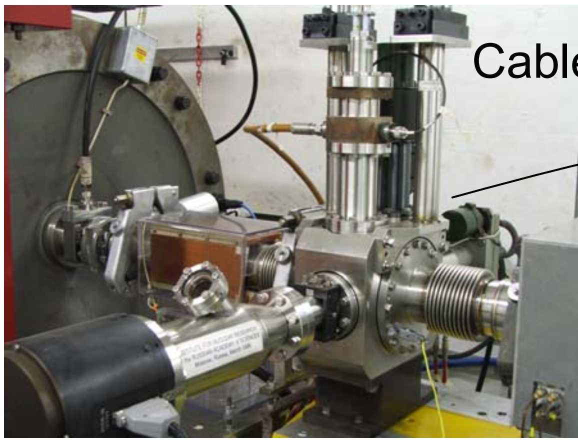
# Diagnostic devices and quantity measured

| 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<br>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

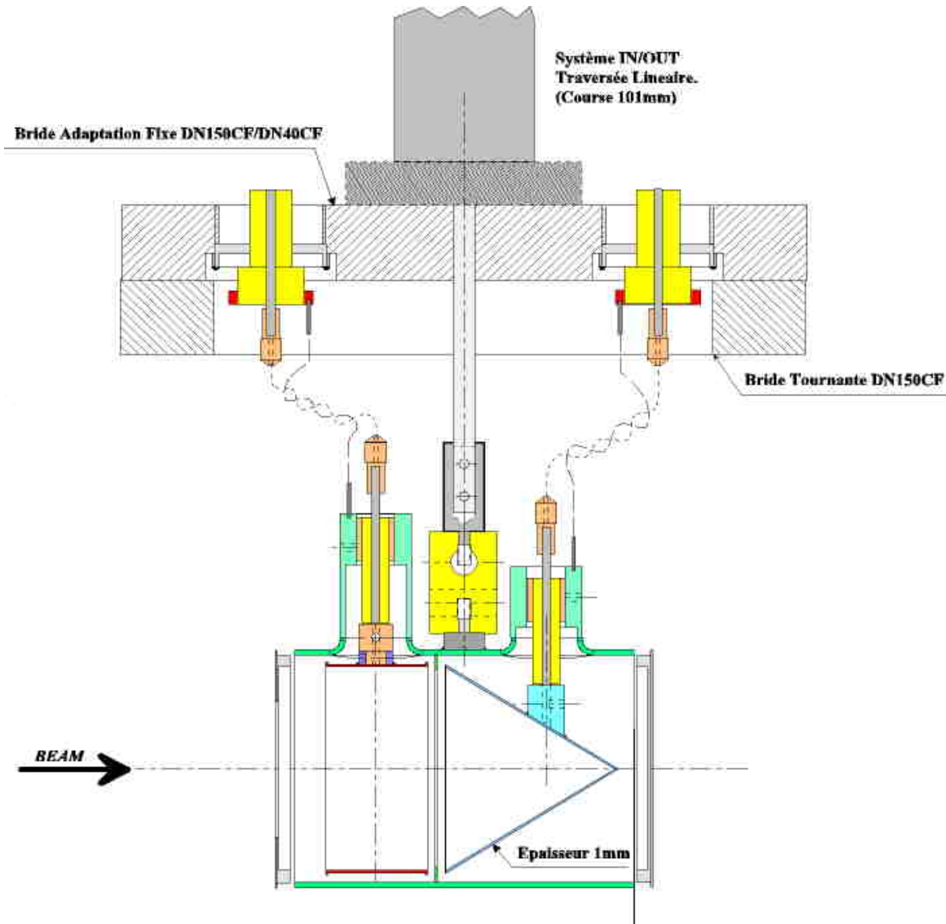
Computer network

# 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

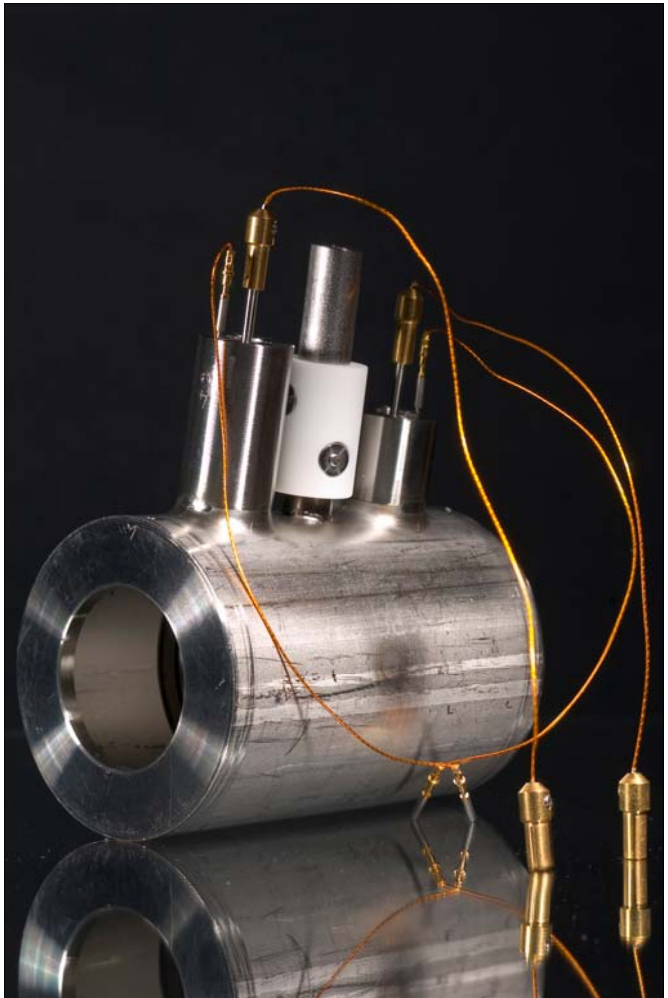


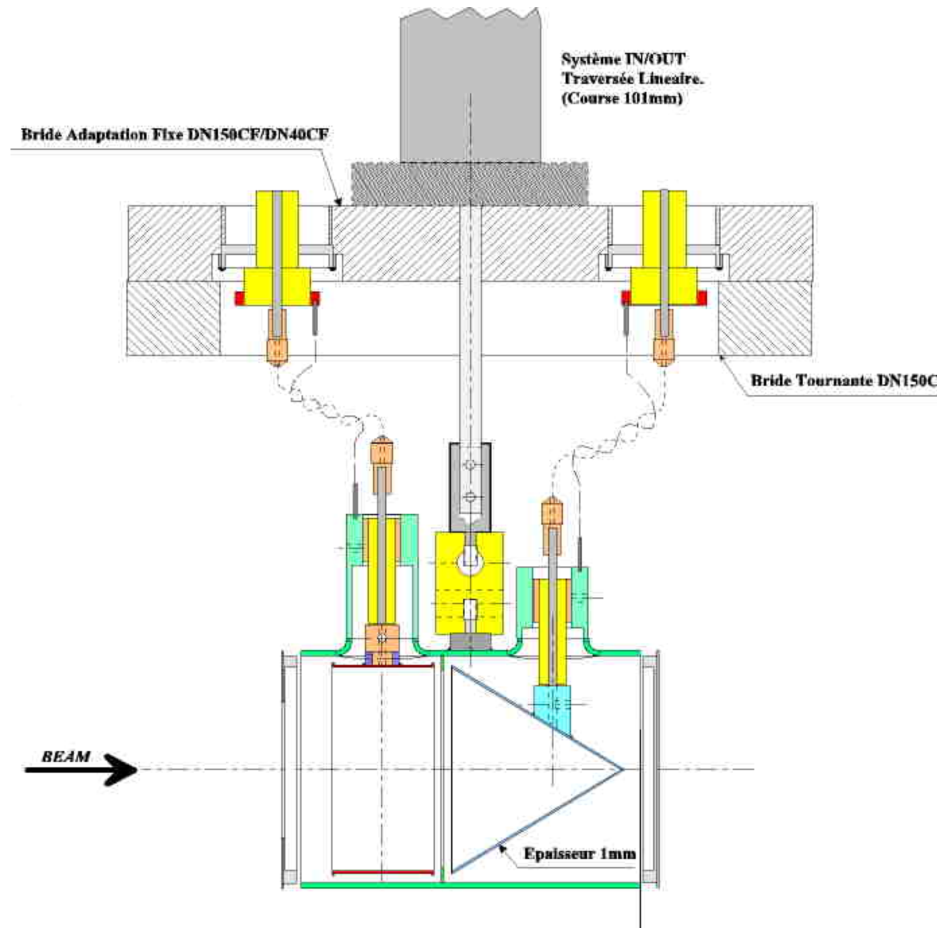



Schema: V. Prieto

THE CERN ACCELERATOR SCHOOL

# Faraday Cup

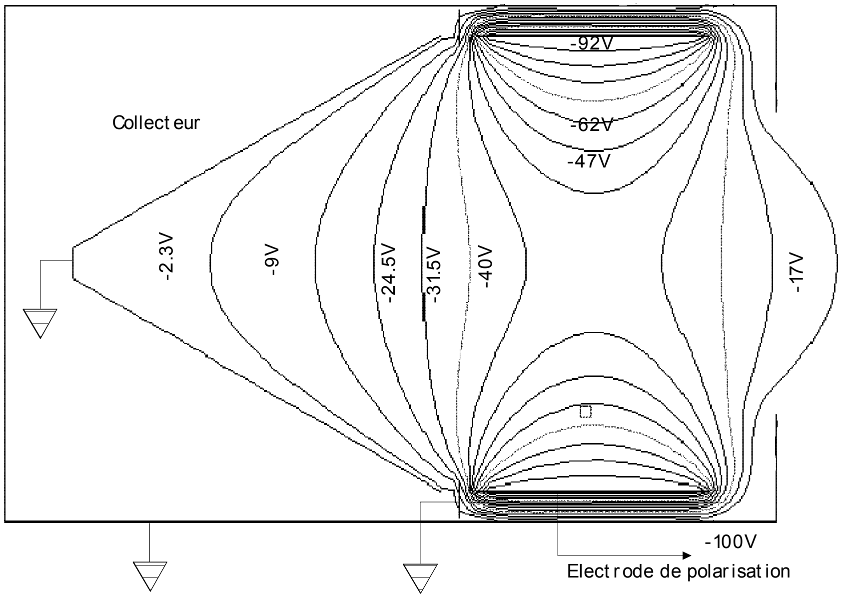



Système IN/OUT
Traversée Lineaire.
(Course 101mm)
Bride Adaptation Fixe DN150CF/DN40CF
Bride Tournante DN150CF
BEAM
Epaisseur 1mm

# Electro-static Field in Faraday Cup

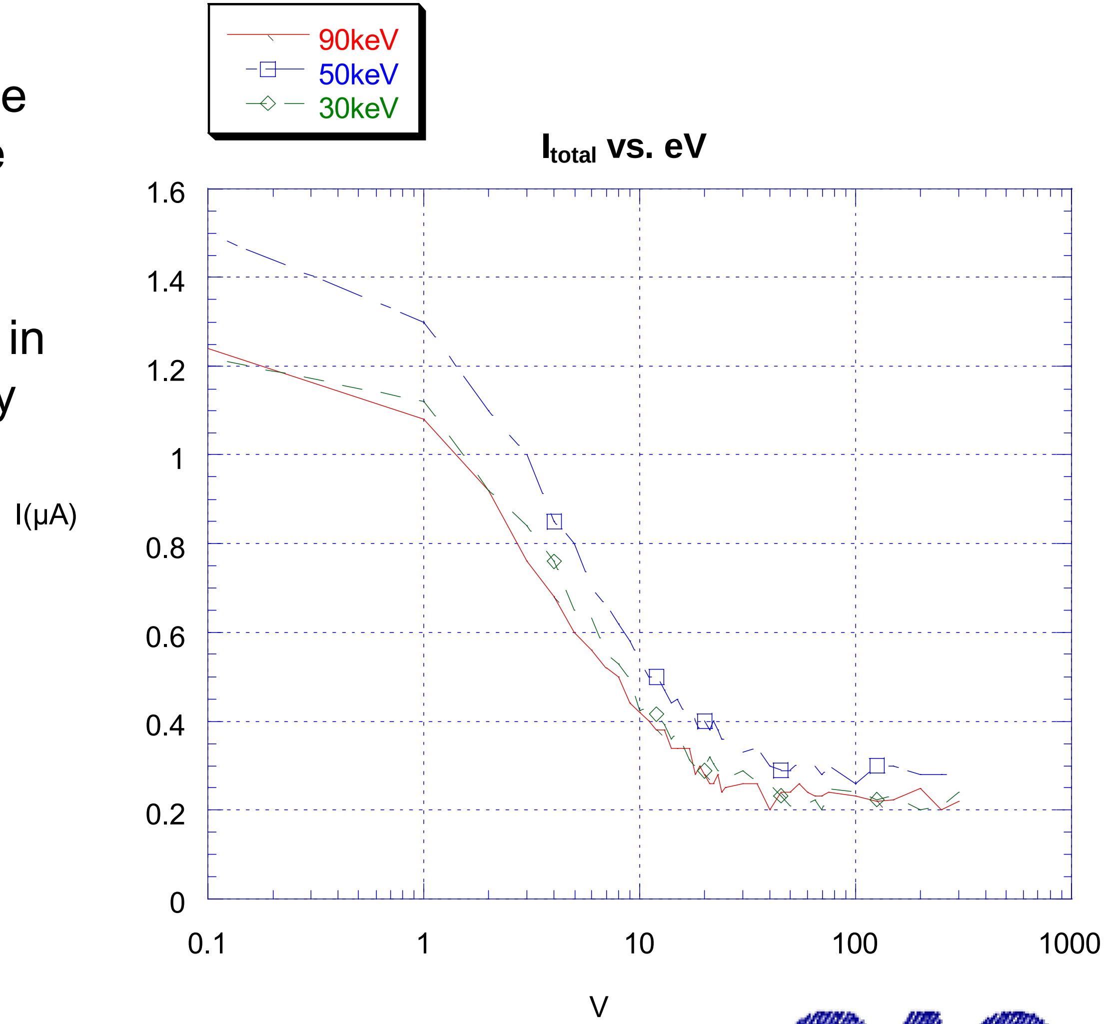
In order to keep secondary electrons with the cup a repelling voltage is applied to the polarization electrode

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






CAS
THE CERN ACCELERATOR SCHOOL

# Faraday Cup application
# Testing the decelerating RFQ

**Antiproton decelerator**

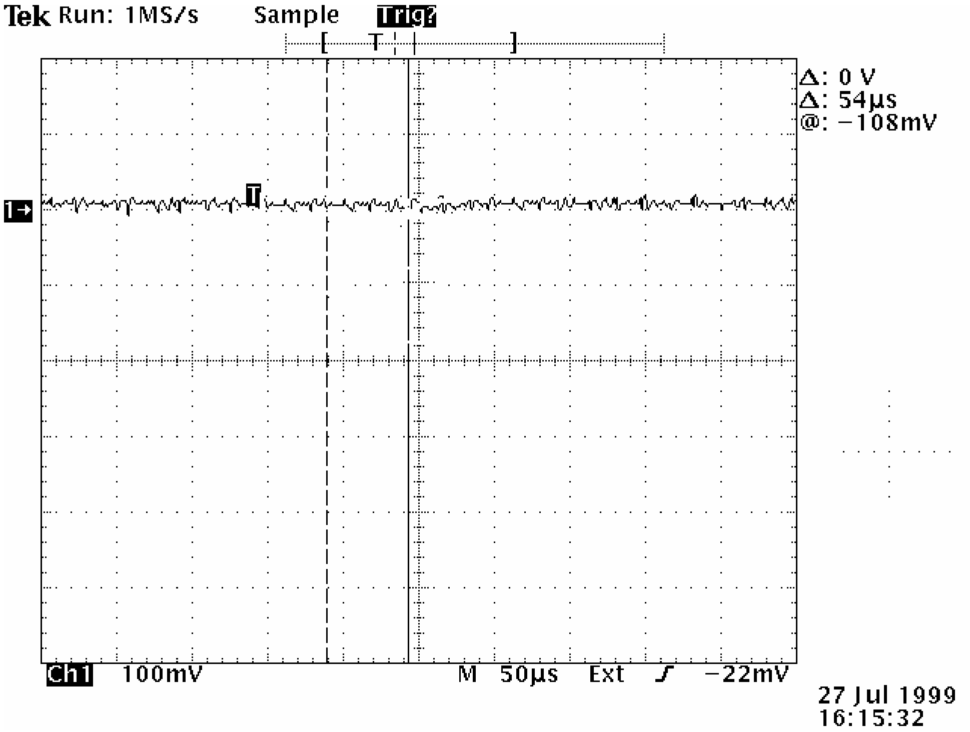
- Accelerate protons to 24 GeV and eject them onto a target
- Produce antiprotons at 2 GeV
- Collect the antiprotons and cool them
- Decelerate them and cool them
- Output energy: 100 MeV

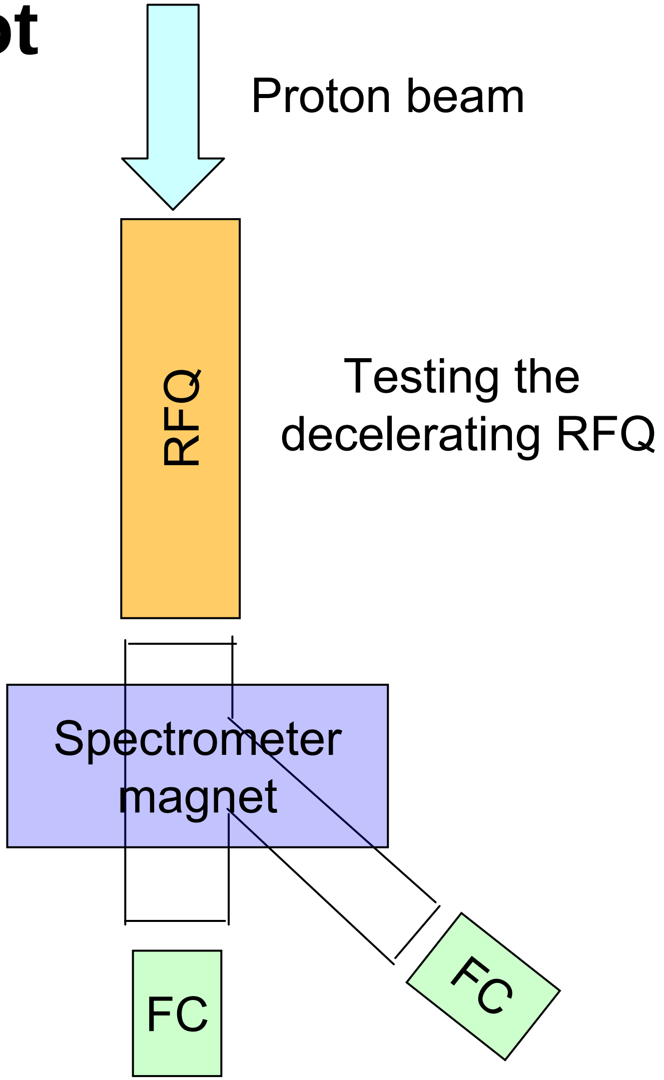
**In order to get even lower energies:**

- Pass them through a moderator
  - High losses
  - Large energy distribution

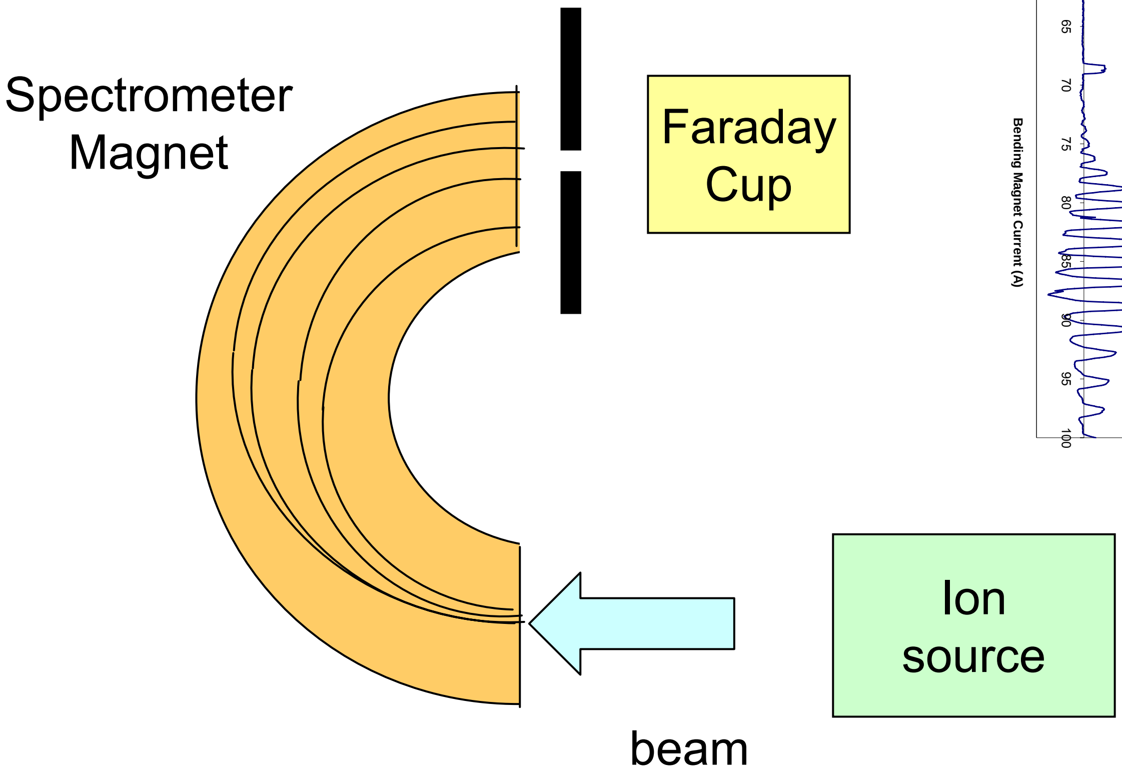
**=> Build a decelerating RFQ**

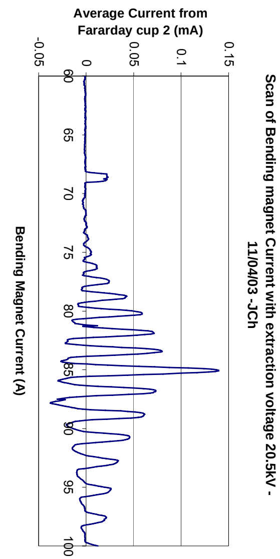
# Waiting for Godot



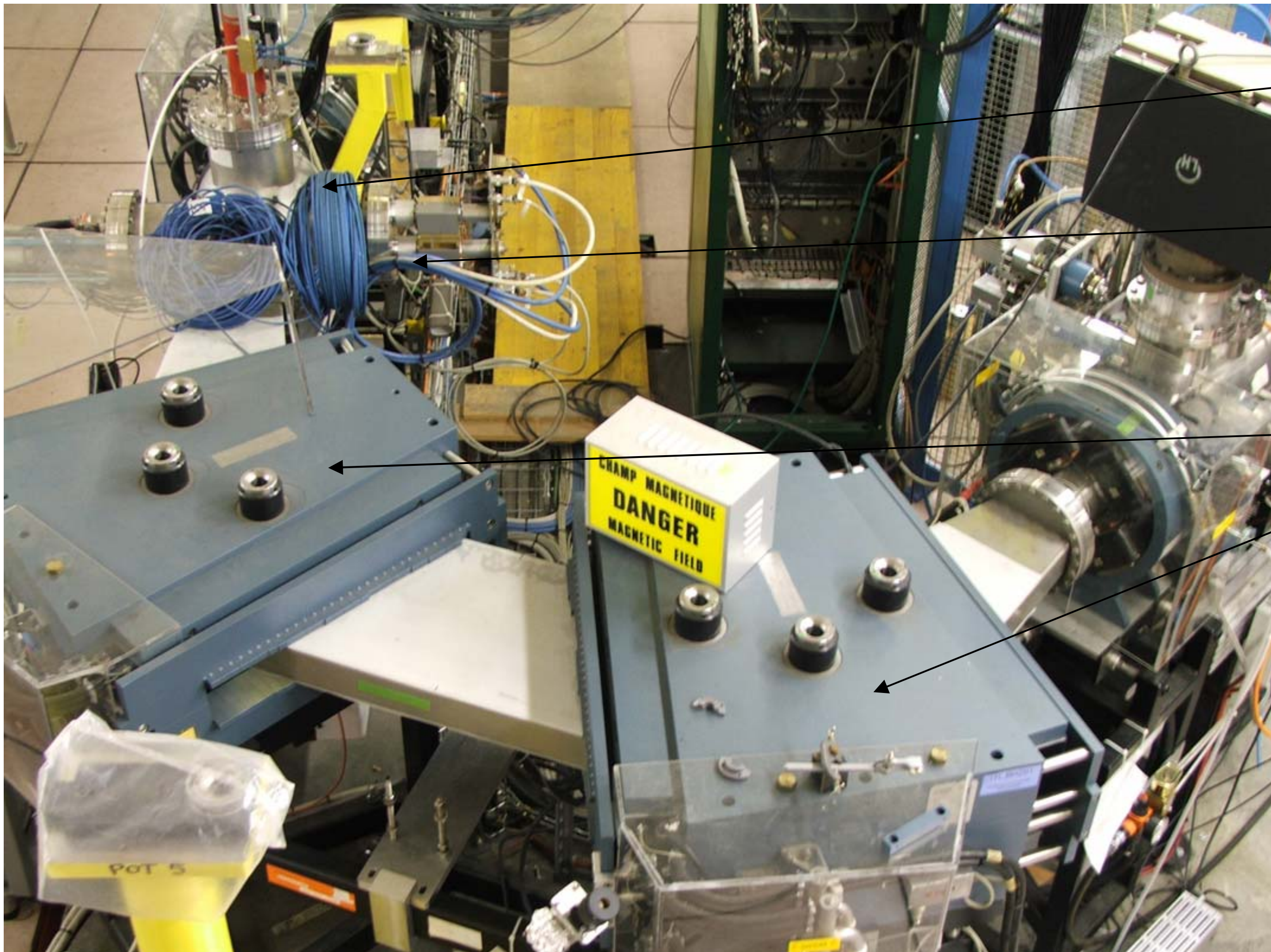
# Setup for charge state measurement




The spectrometer magnet is swept and the current passing the slit is measured

# Measuring charge state distribution




Faraday Cup

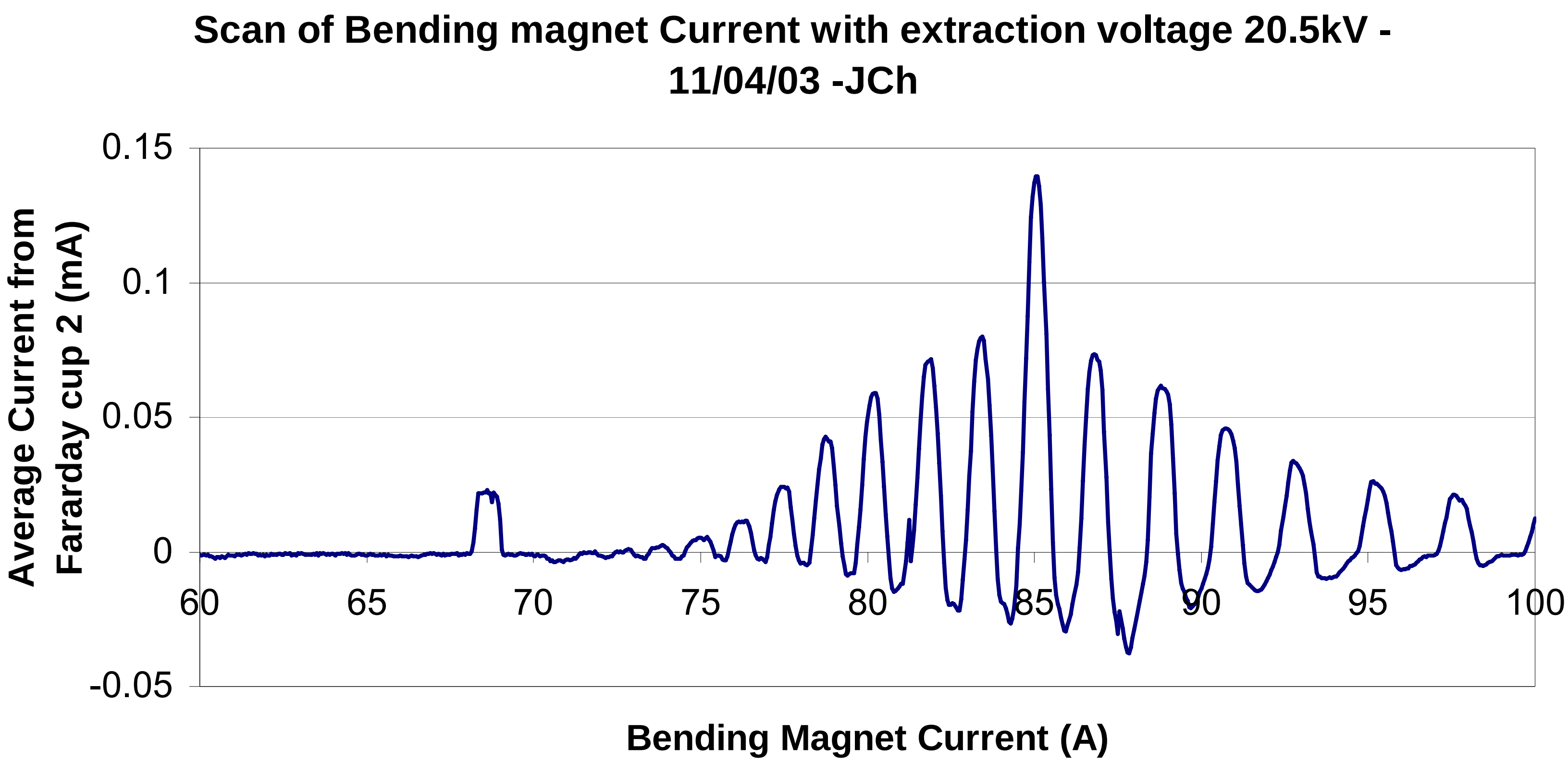
Slit

Spectrometer magnets



THE CERN ACCELERATOR SCHOOL

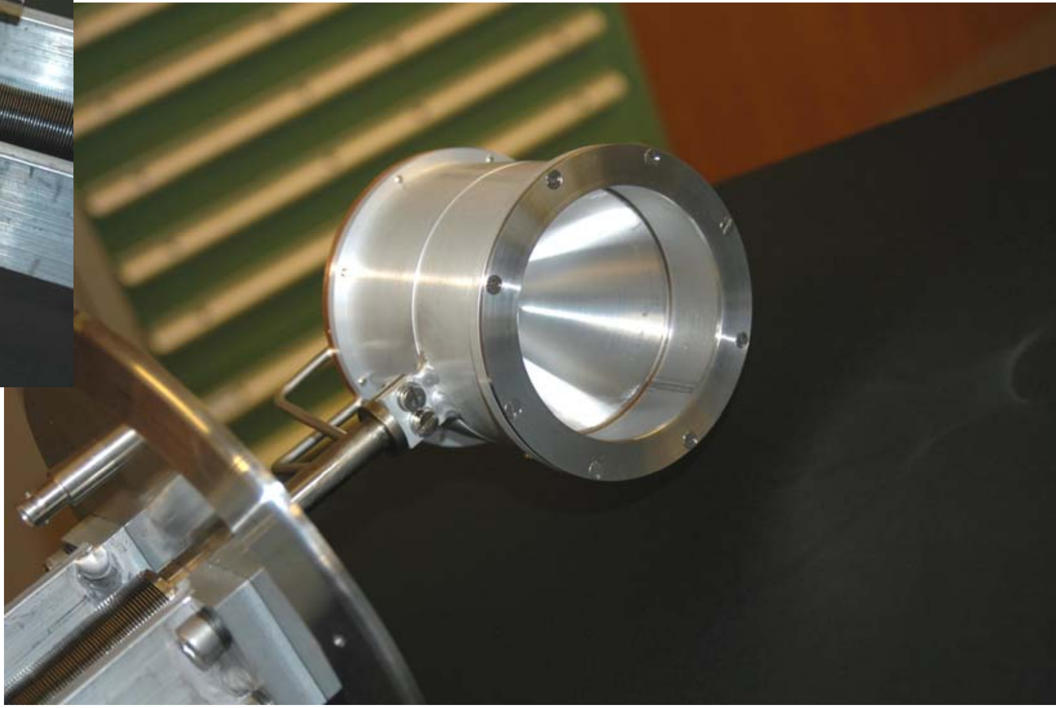
# Charge state distribution measured with a Faraday Cup on a heavy ion source





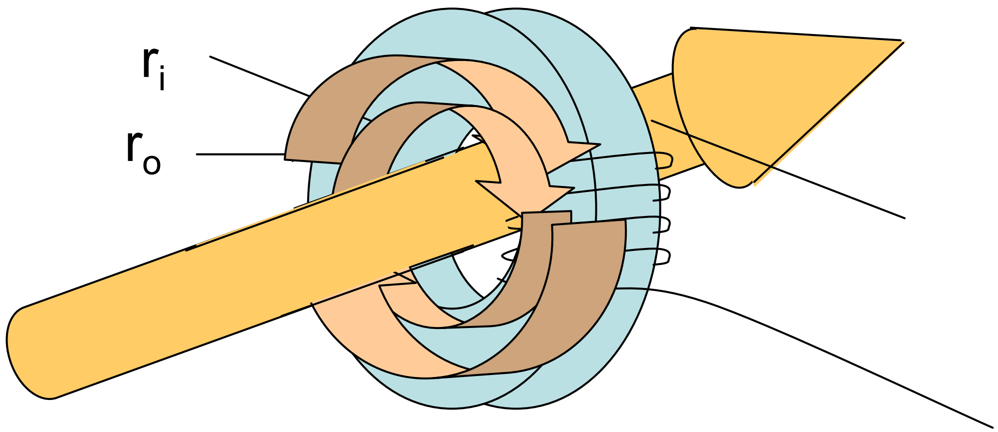

Histogram contributed by R. Scrivens

# 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

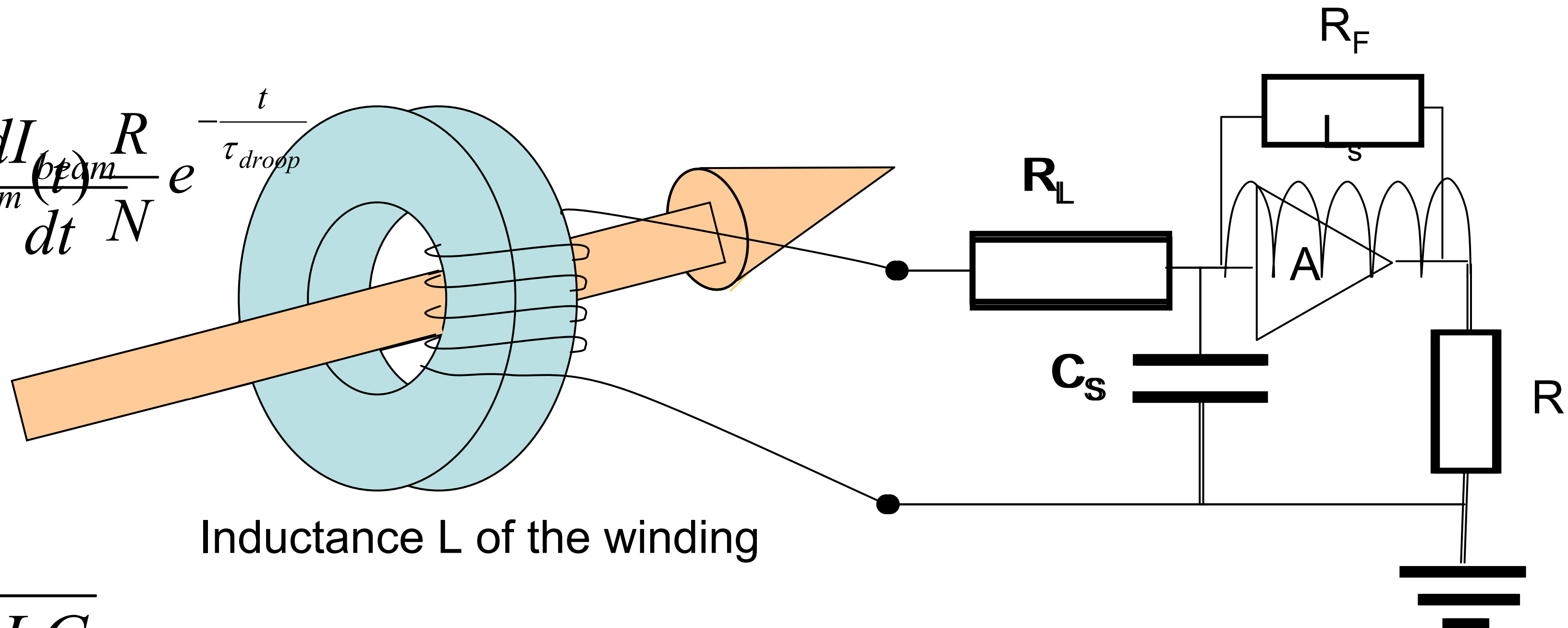
$$I_{beam} = \frac{qeN}{t} = \frac{qeN\beta c}{l}$$

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

# The ideal transformer
# The active AC transformer

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

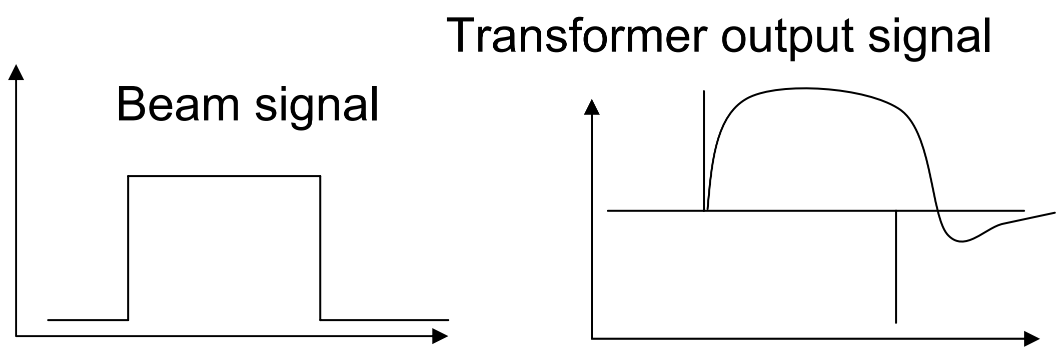
$$U = I_{beam}(t)\frac{R}{N}e^{-\frac{t}{\tau_{droop}}}$$




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

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

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



# Principle of a fast current transformer

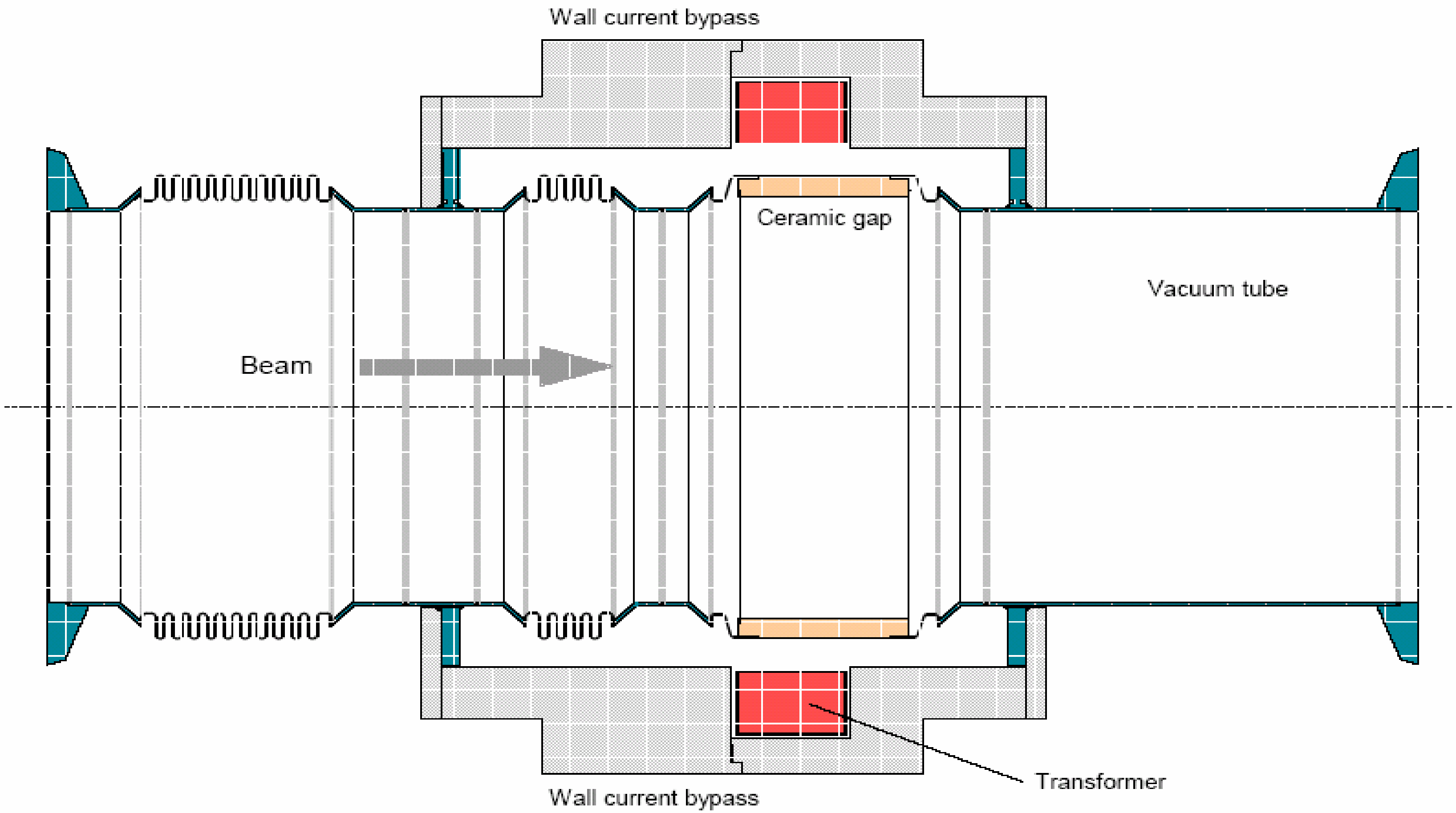
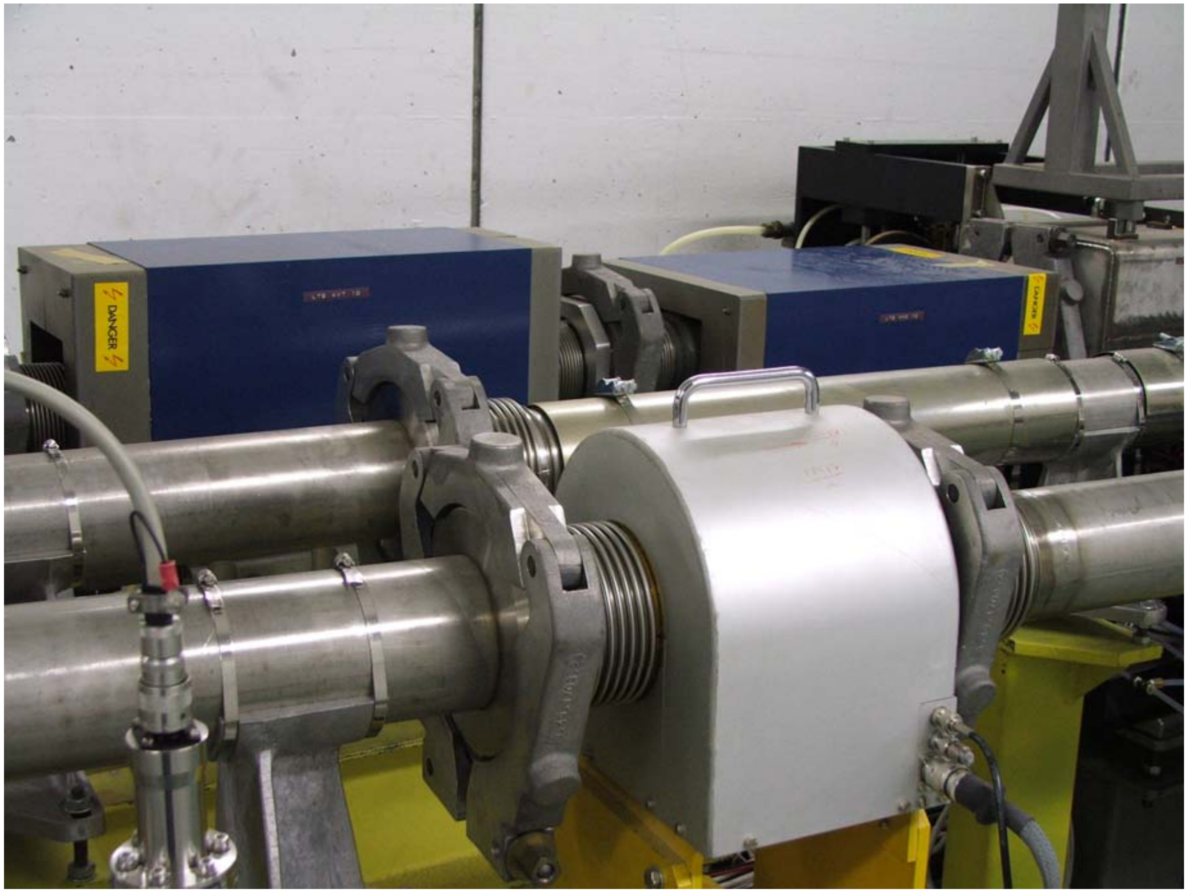





Diagram by H. Jakob

# The transformer installed in the machine

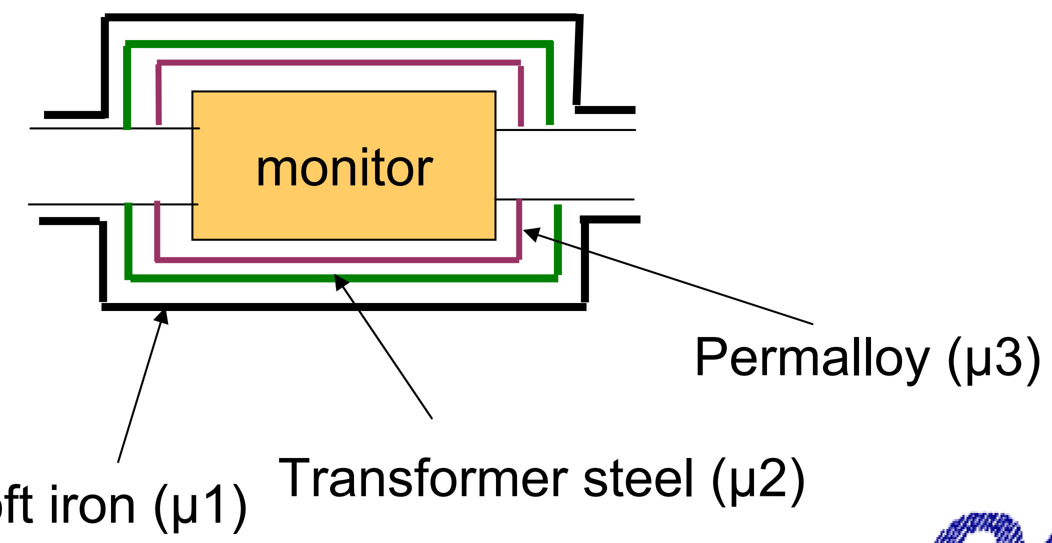


Needs

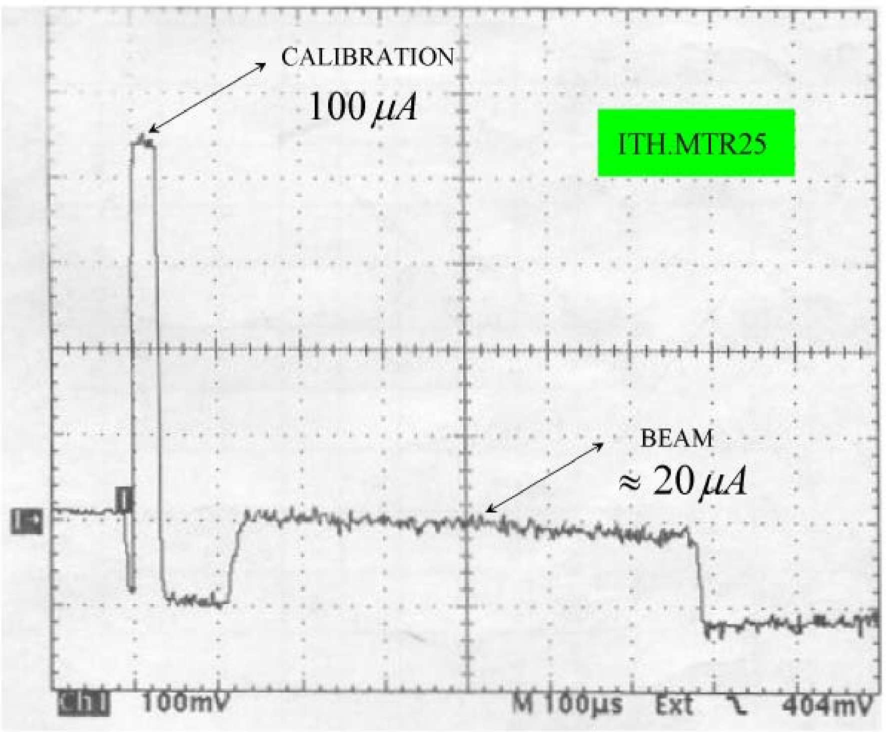
Magnetic Shielding

# 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

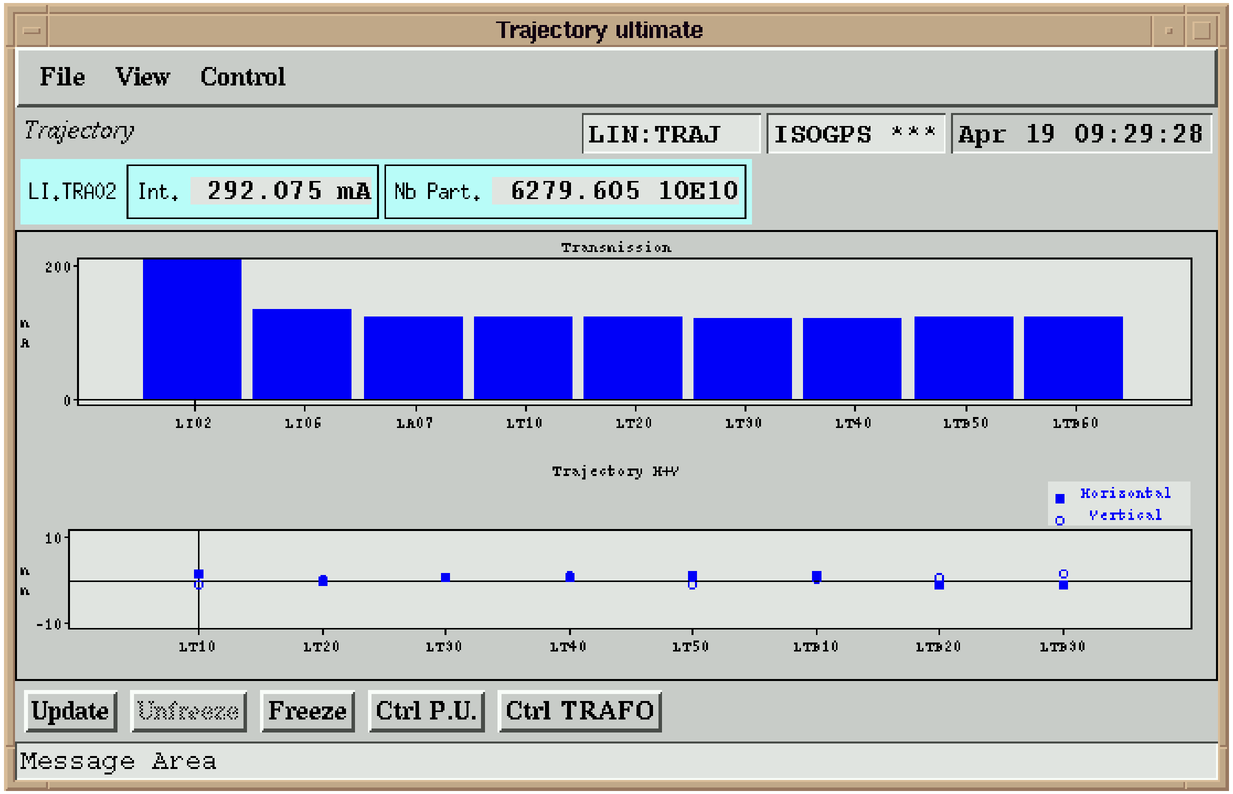
# Current transformer and its electronics




Photo: GSI Darmstatt

# Display of transformer readings

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

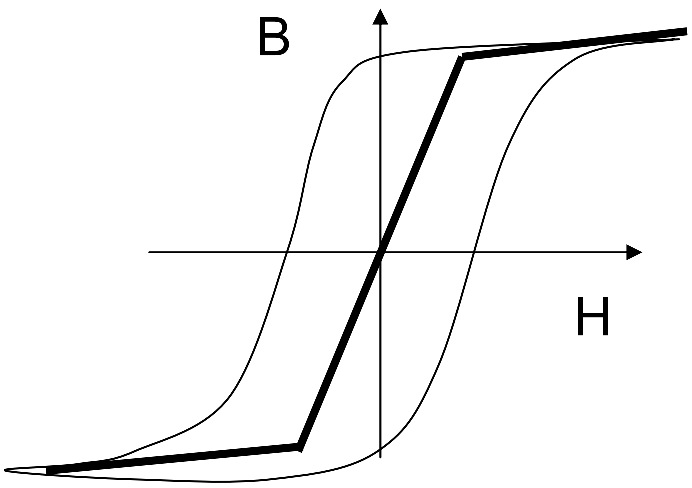




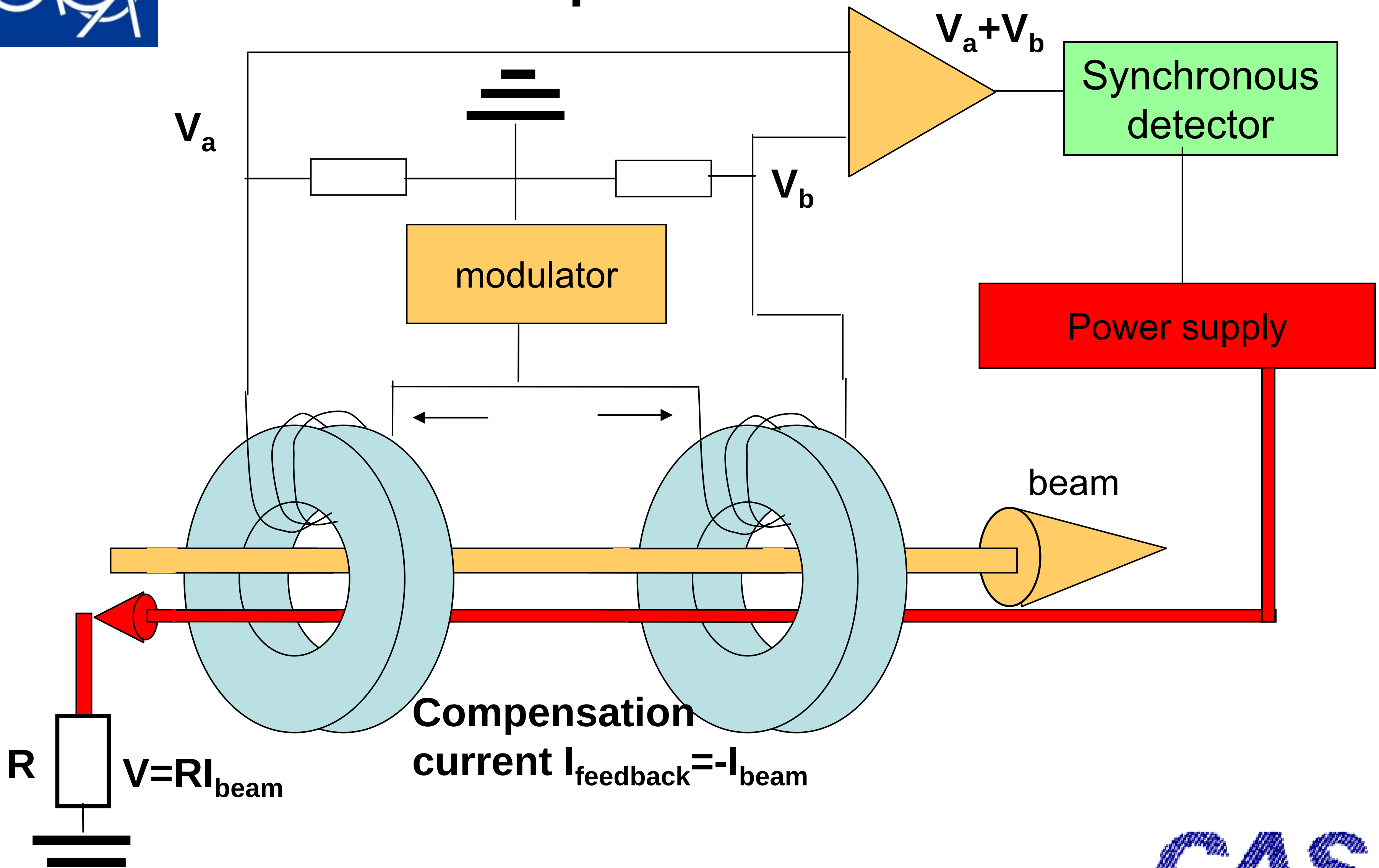

CAS
THE CERN ACCELERATOR SCHOOL

# The DC current transformer

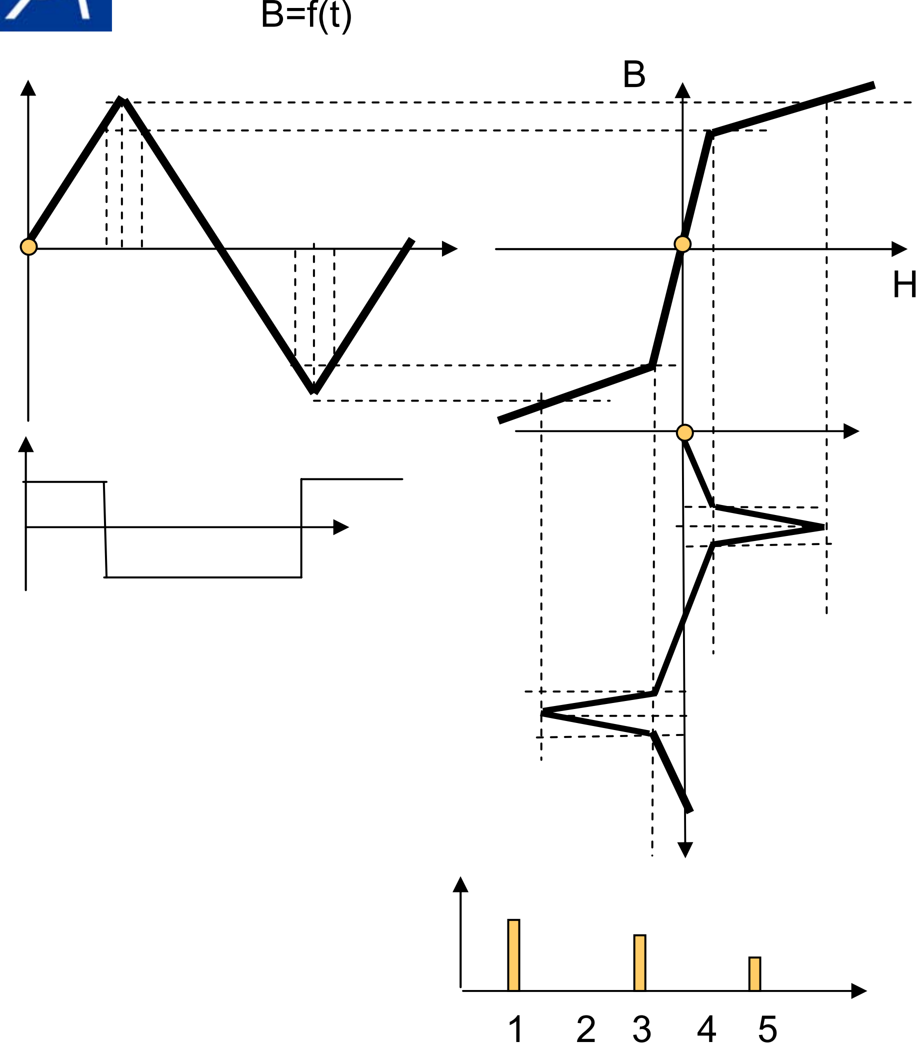
- AC current transformer can be extended to very long droop times but not to DC
- Measuring DC currents is needed in storage rings
- Must provide a modulation frequency
- Takes advantage of non/linear magnetisation curve



# Principle of DCCT



# Modulation of a DCCT  without beam

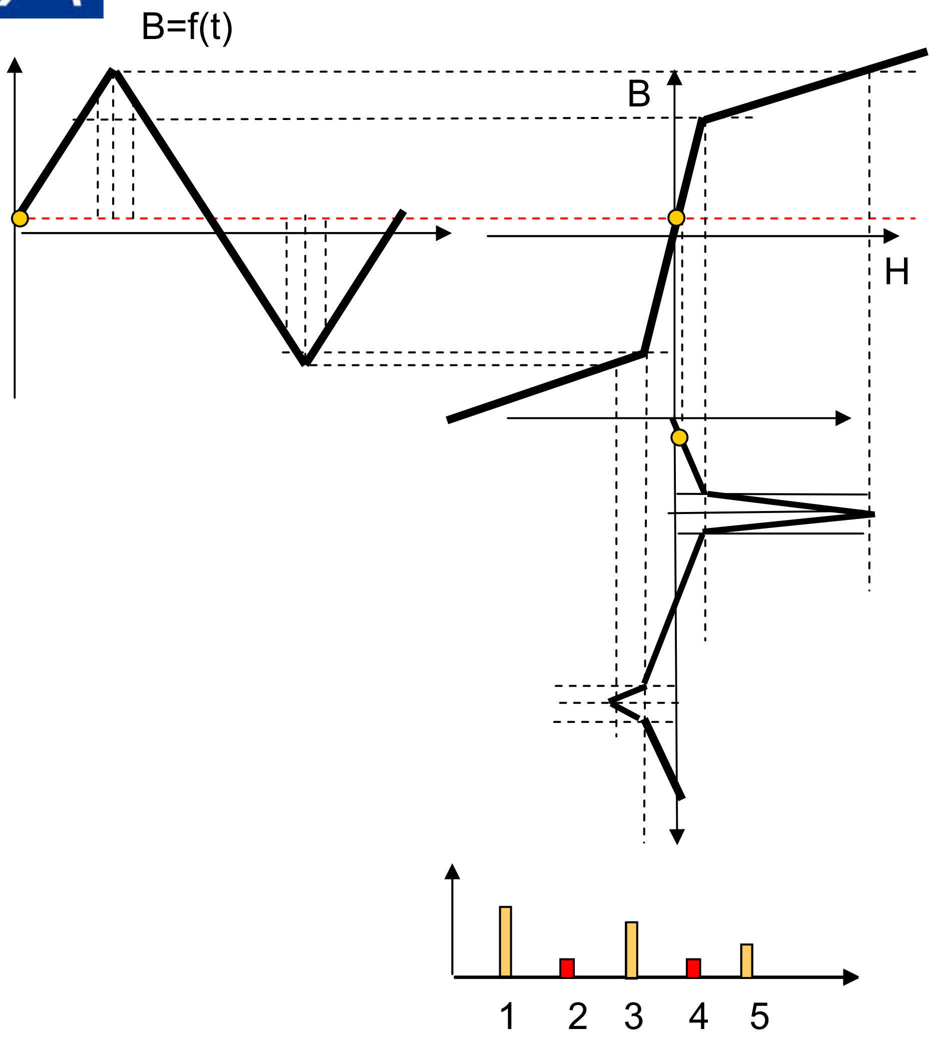



$$U = NA\frac{dB}{dt}$$

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

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

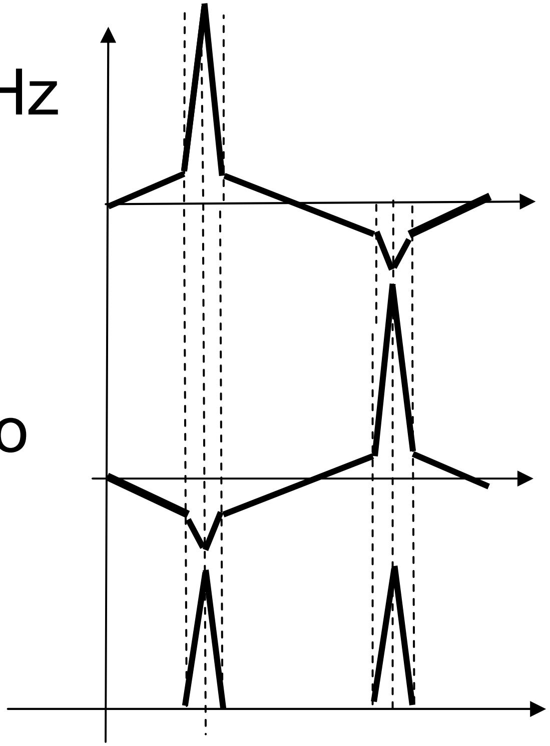
# Modulation of a DCCT with beam




Sum signal becomes non-zero
Even harmonics appear

# Modulation current difference signal with beam

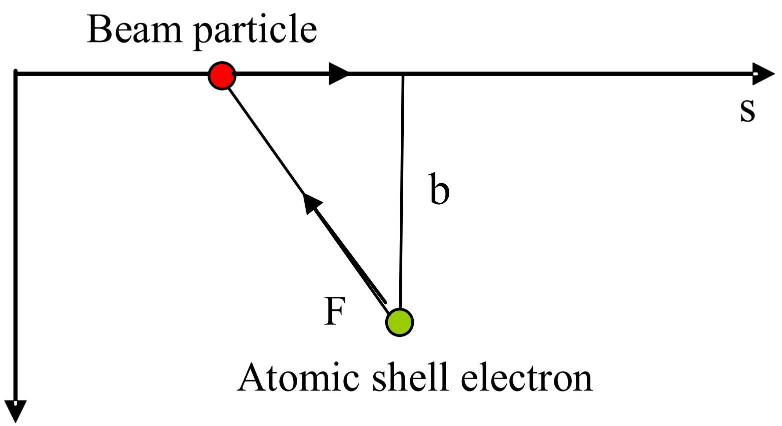
- Difference signal has $2\omega_m$
- $\omega_m$ typically 200 Hz – 10 kHz
- Use low pass filter with
  $\omega_c << \omega_m$
- Provide a 3rd core, normal AC transformer to extend to higher frequencies



# Photo of DCCT internals

# 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



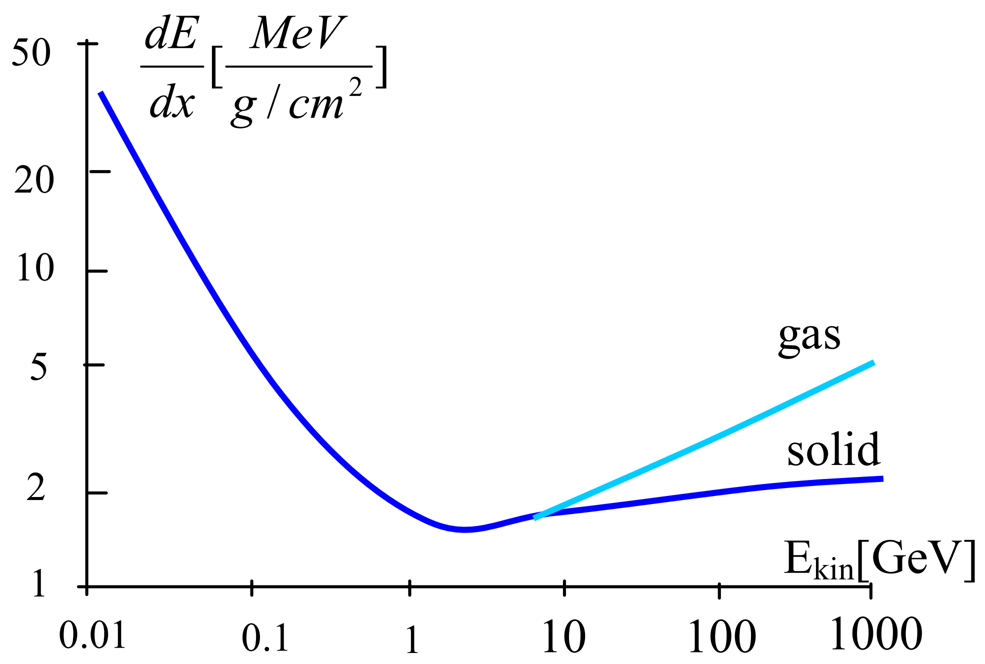
# Bethe Bloch formula

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

- 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 particle 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

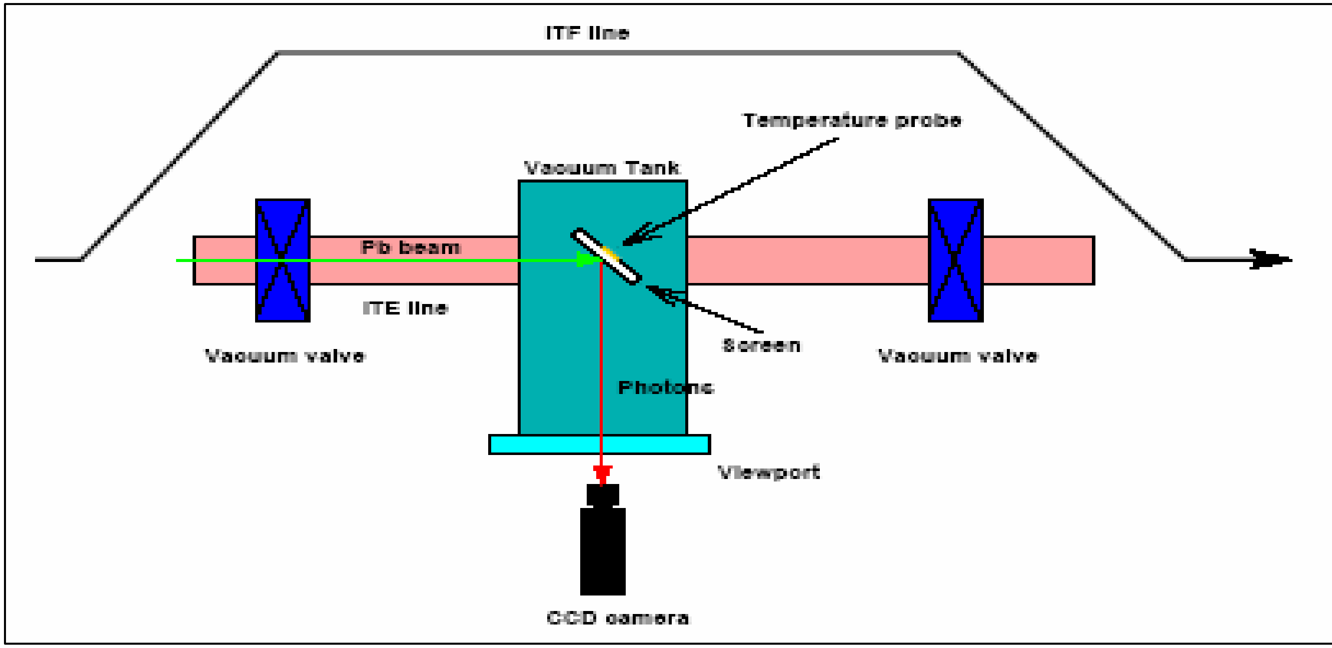
- Very simple
- Very convincing

Needed:

- Scintillating Material
- TV camera
- In/out mechanism

Problems:

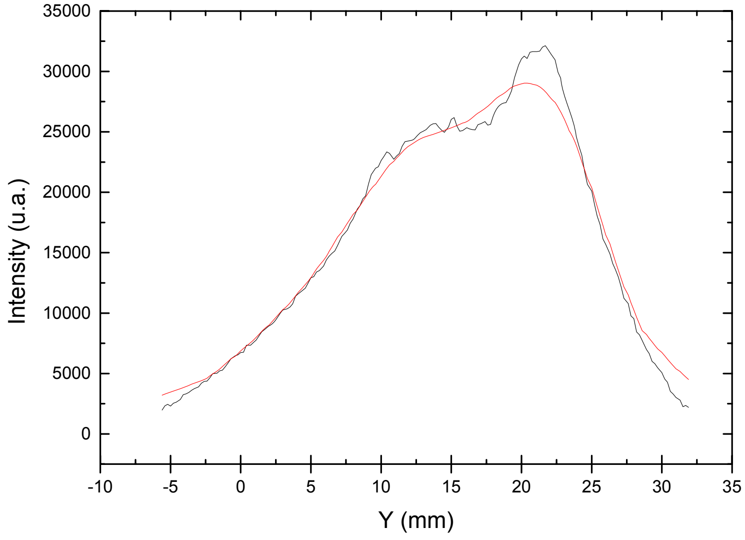
- Radiation resistance
- Heating of screen (absorption of beam energy)
- Evacuation of electric charges

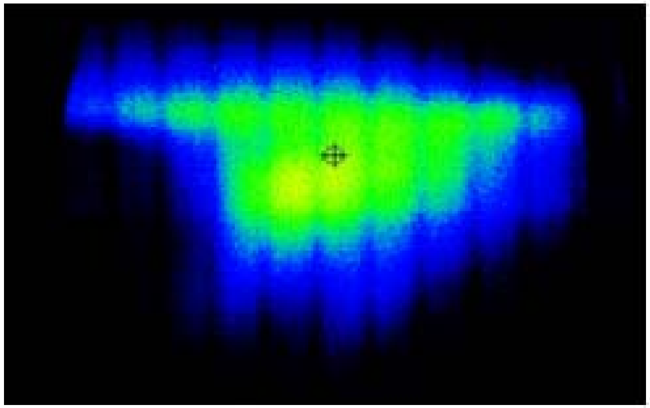


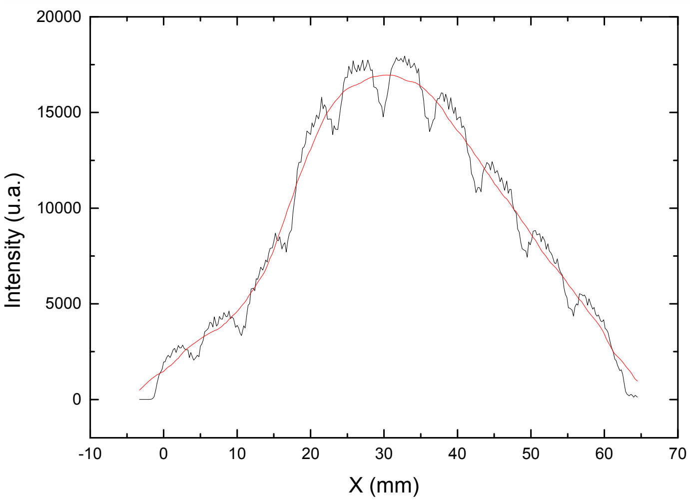



Transparencies on screens by T. Lefevre

# Frame grabber





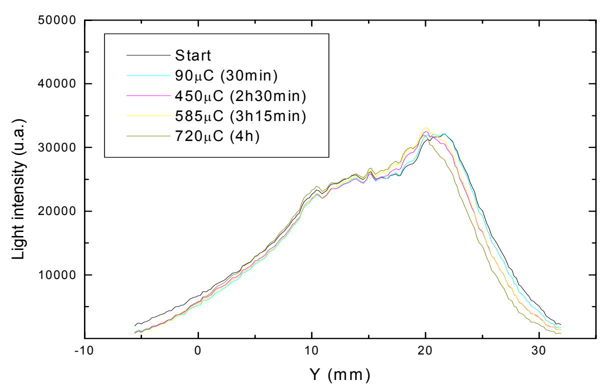

- For further evaluation the video signal is digitized, read-out and treated by program

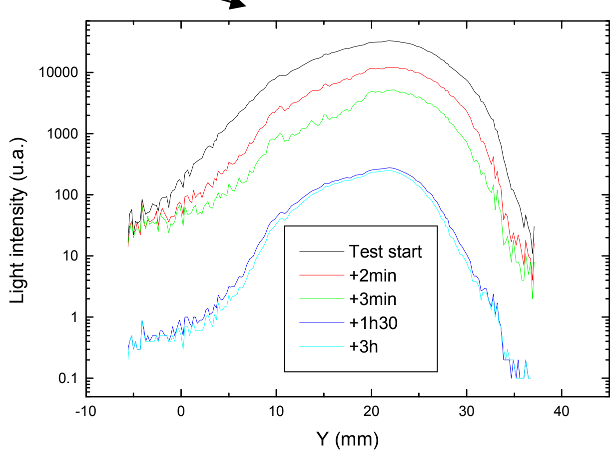
# Test for resistance against heat-shock

| Material | $\rho$ 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 | $10^{14}$ |

Better for electrical conductivity (>400ºC)

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



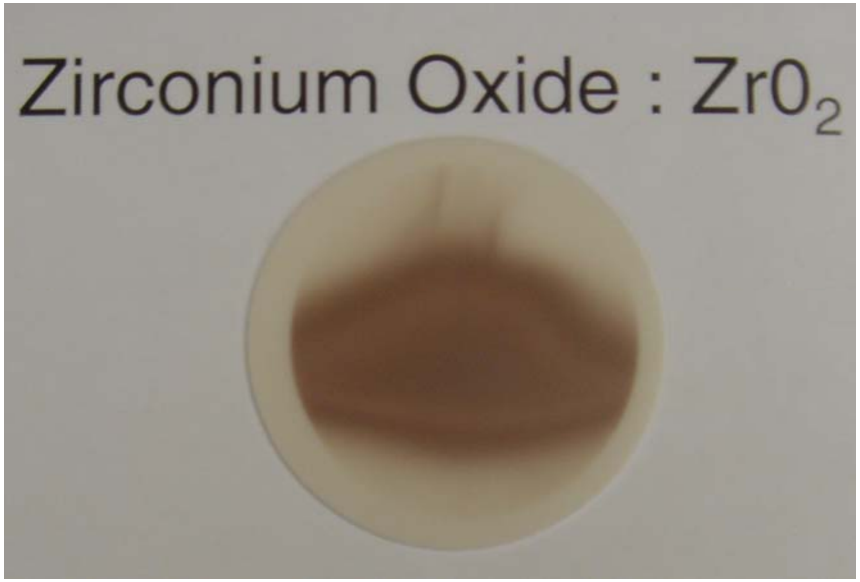






THE CERN ACCELERATOR SCHOOL

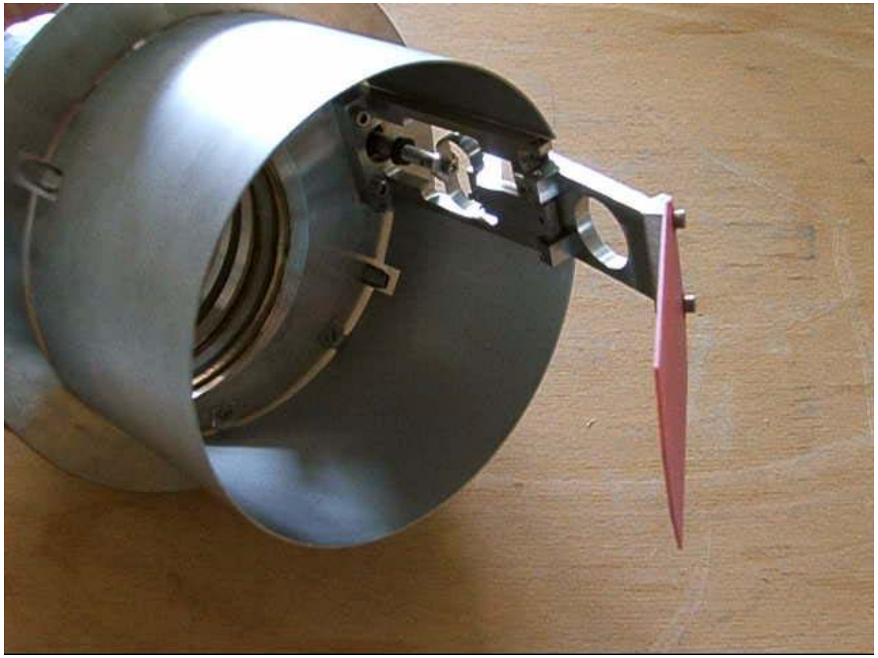
# Degradation of screen

Degradation clearly visible
However sensitivity stays essentially the same



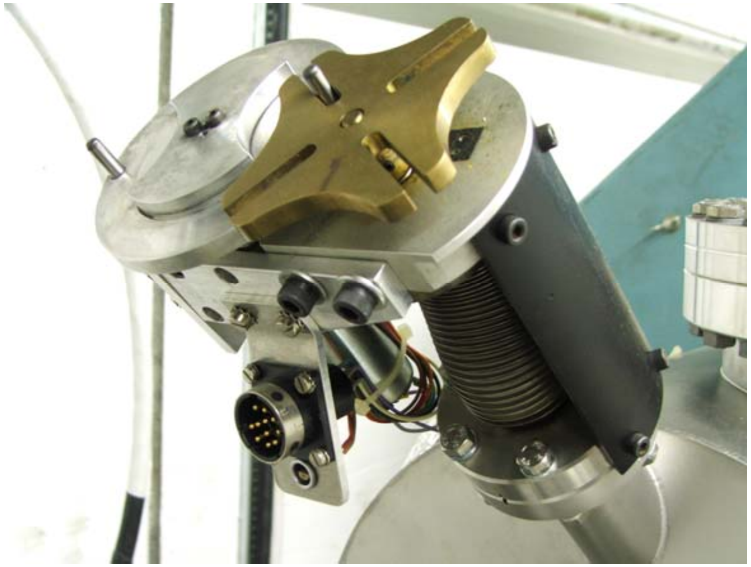
# Screen mechanism

- Screen with graticule

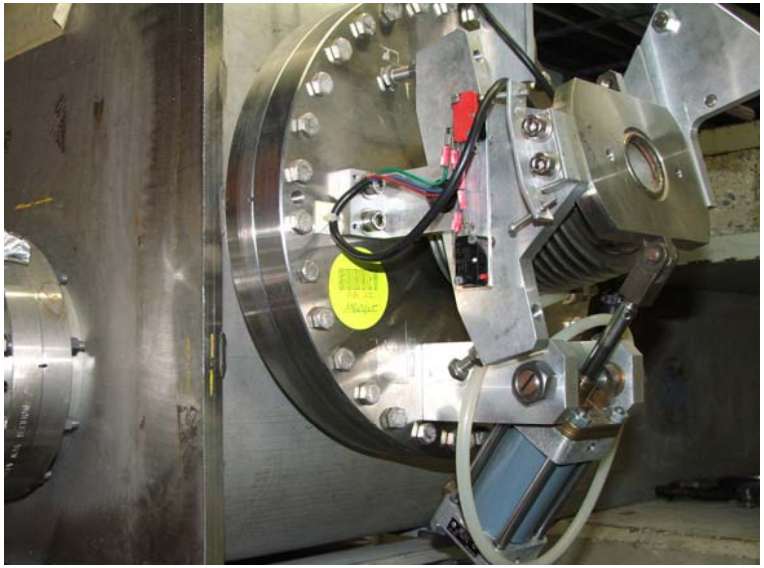


# In/out mechanisms

Rotary mechanism driven by electric motor



Mechanism driven pneumatically



# Profile measurements

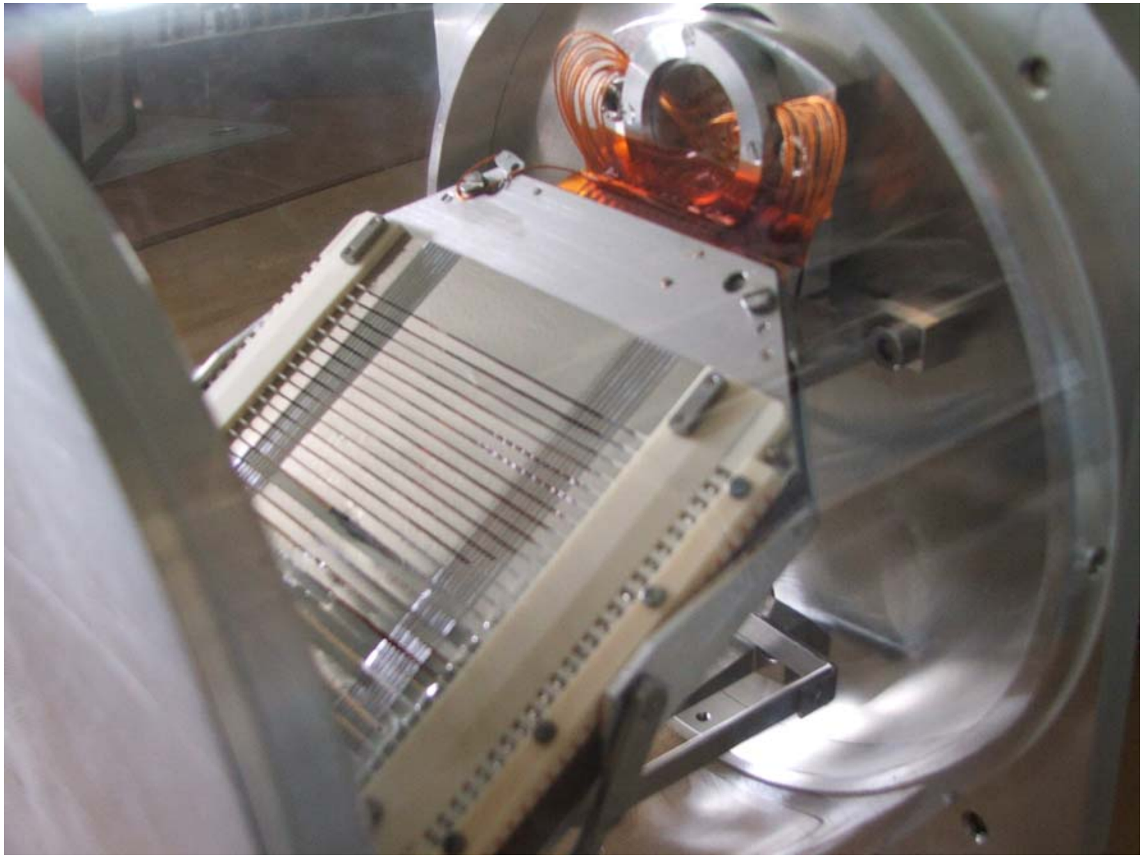
- Secondary emission grids (SEMgrids)

When the beam passes secondary electrons are ejected from the ribbons

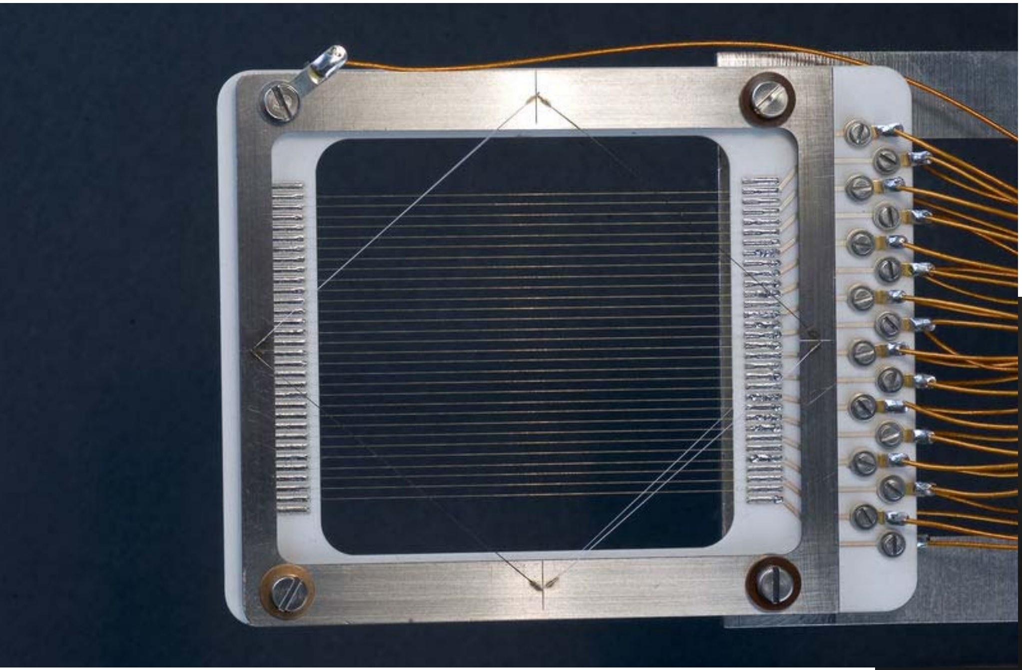
The current flowing back onto the ribbons is Measured

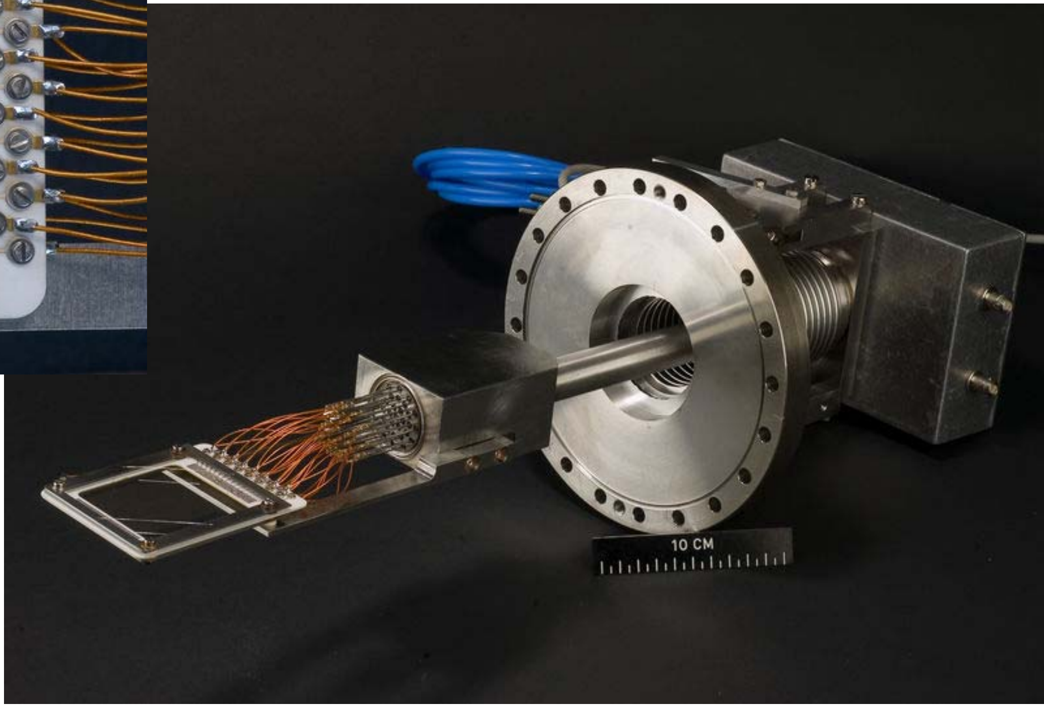
Electrons are taken away by polarisation voltage

One amplifier/ADC chain channel per ribbon



# SEMgrids with wires

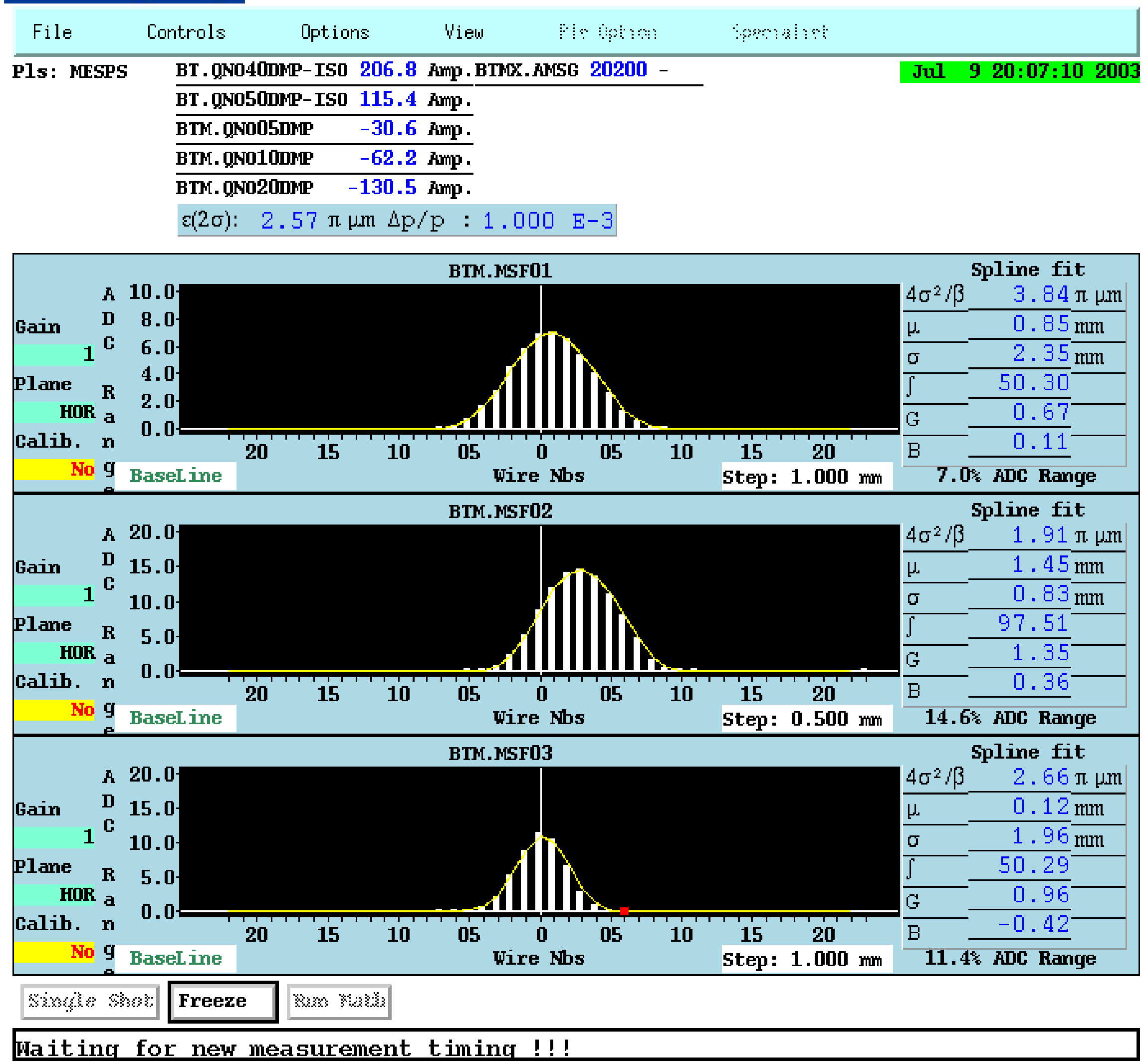







Photos received from C. Dutriat

# 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

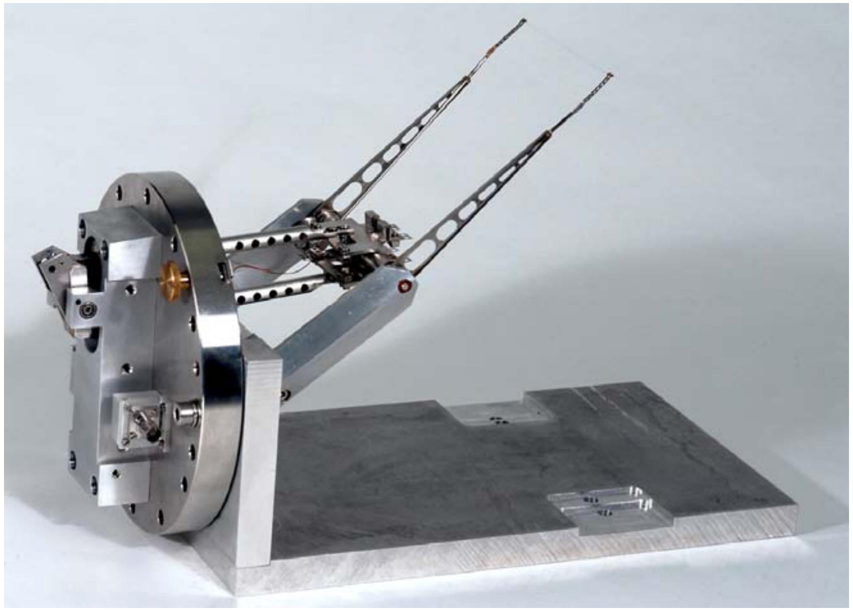
Used only in transfer lines



THE CERN ACCELERATOR SCHOOL

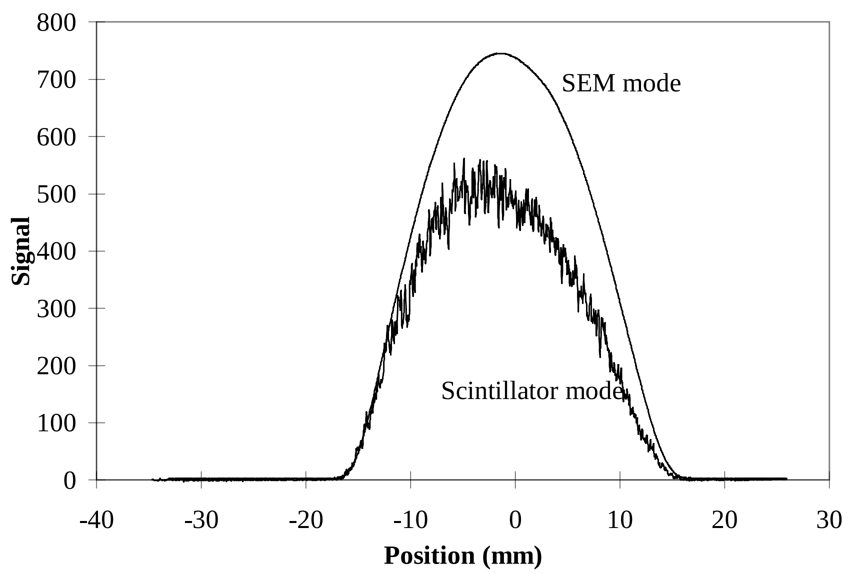
# Wire Scanners

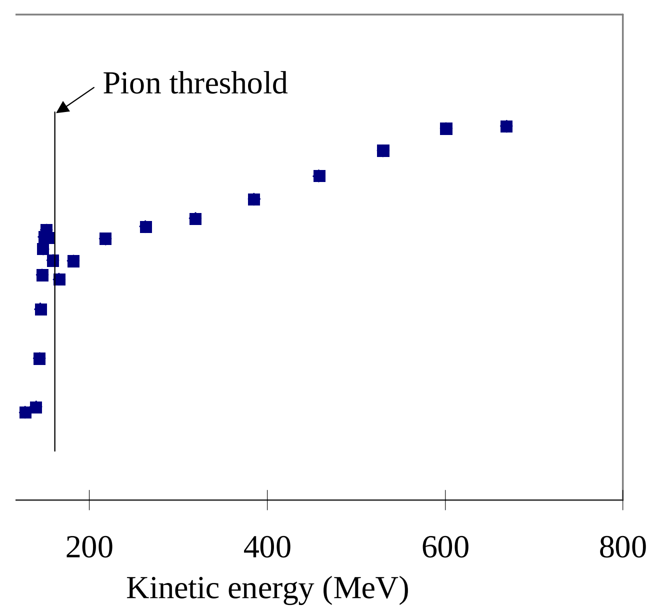
A thin wire is quickly moved across the beam
Secondary particle shower is detected outside the vacuum chamber on a scintillator/photo-multiplier assembly
Position and photo-multiplier signal are recorded simultaneously



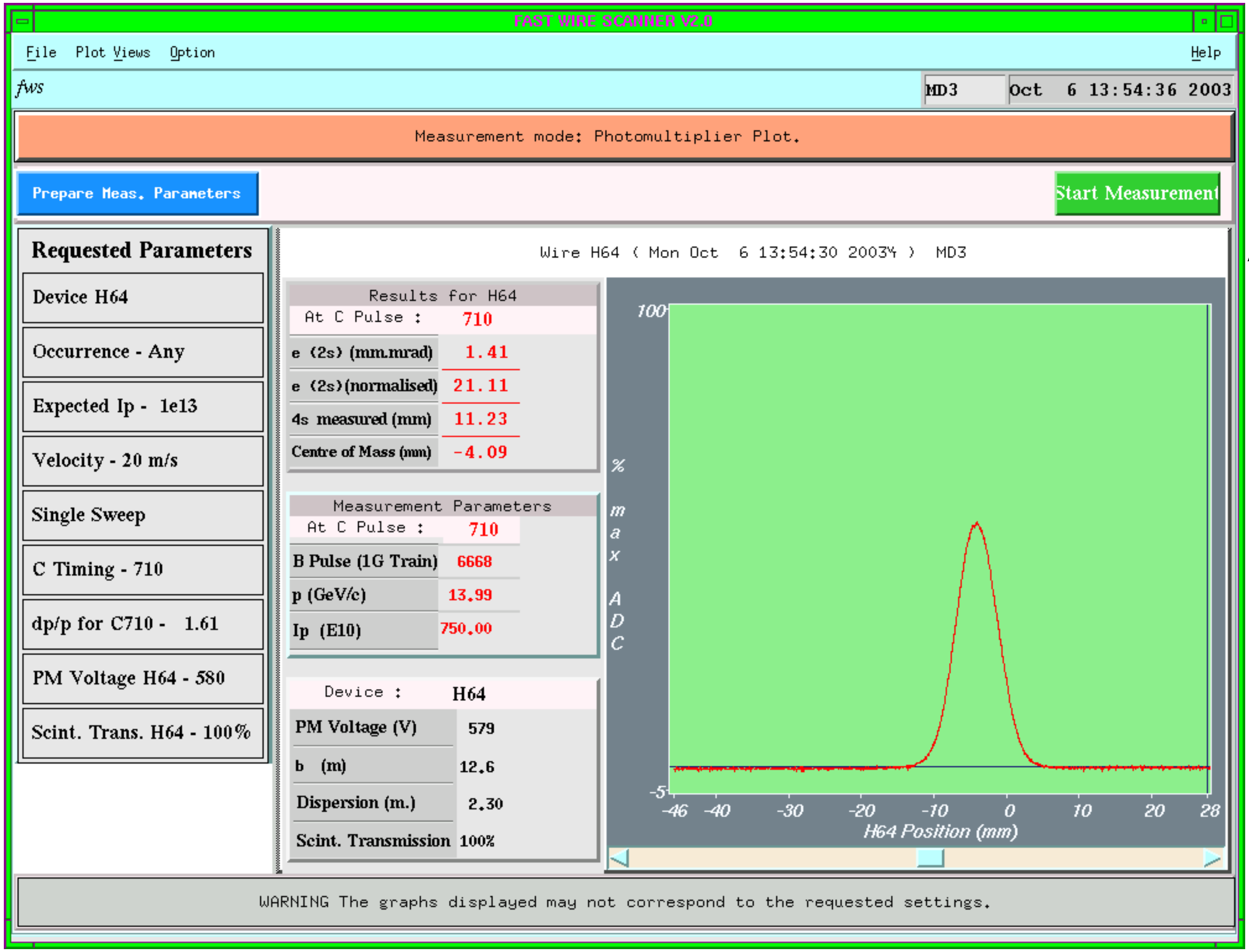
# Problems at low energy

- Secondary particle shower intensity in dependence of primary



# Wire scanner profile




High speed needed because of heating.

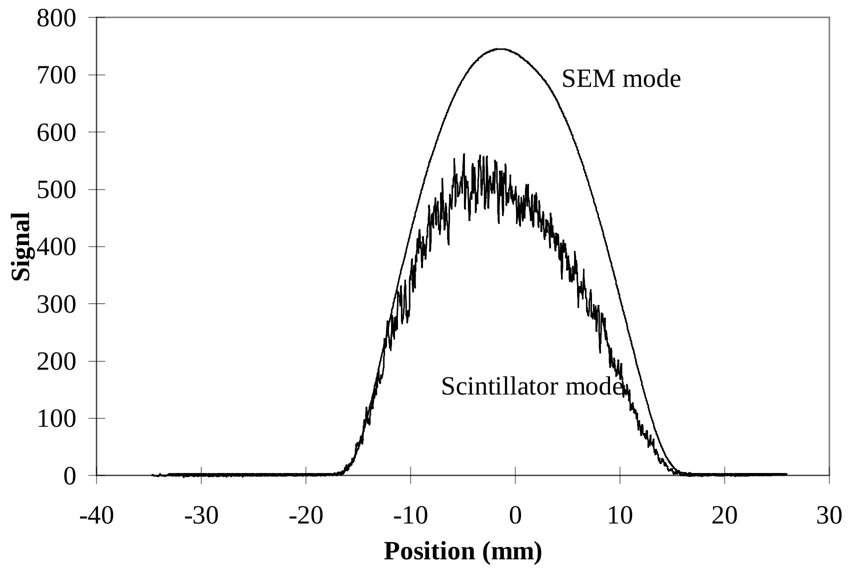
Adiabatic damping

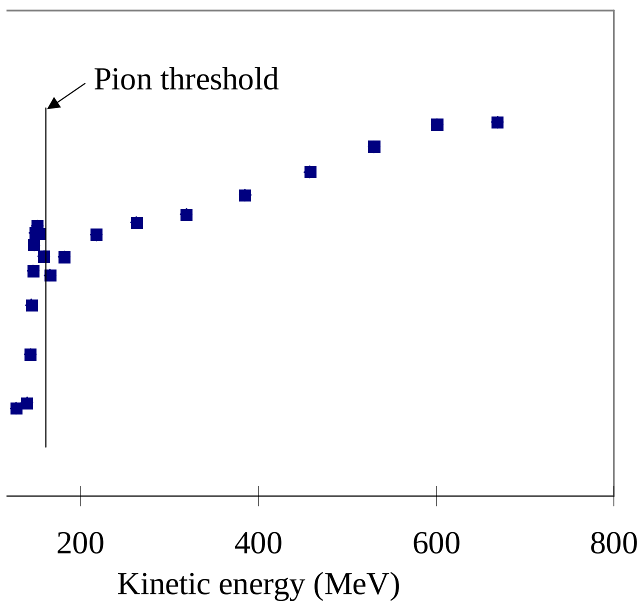
Current increase due to Speed increase

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

# Problems at low energy

- Secondary particle shower intensity in dependence of primary
  .



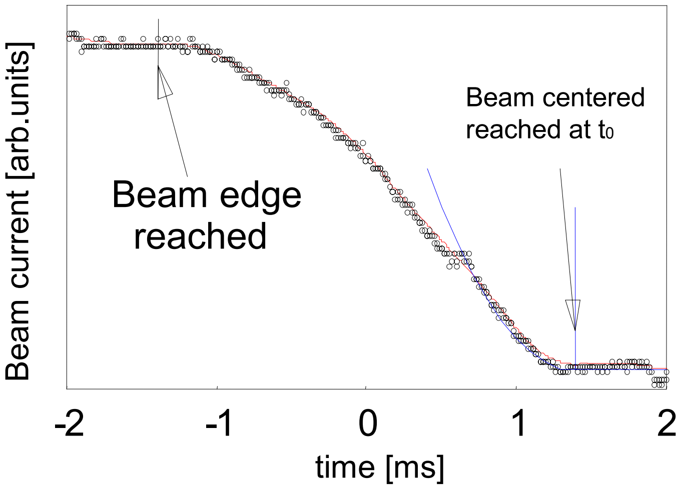



# Wire scanners and partially stripped ions

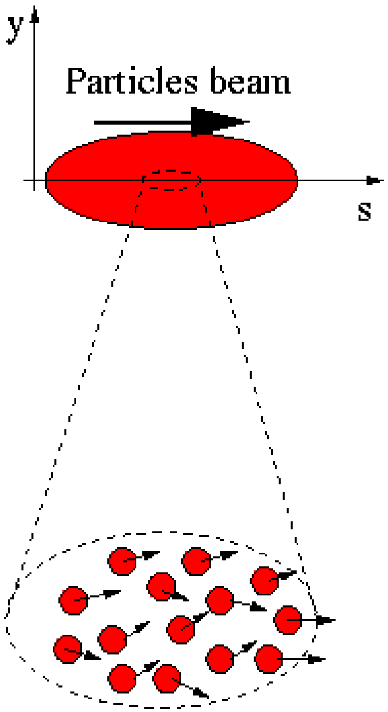
Partially stripped ions loose electrons when interacting with the wire

The beam is lost

Can measure amplitude distribution however



# Emittance measurements

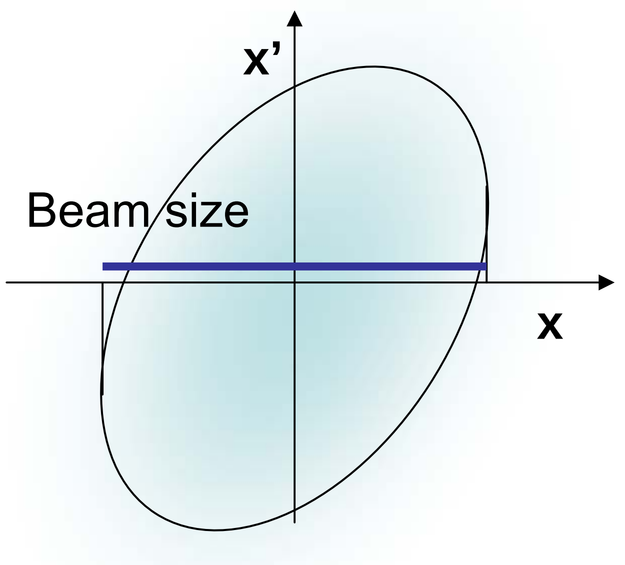



A beam is made of many many particles, each one of these particles is moving with a given velocity. Most of the velocity vector of a single particle is parallel to the direction of the beam as a whole (s). There is however a smaller component of the particles velocity which is perpendicular to it (x or y).

$$\vec{v}_{particle} = v_s \hat{u}_s + v_x \hat{u}_x + v_y \hat{u}_y$$

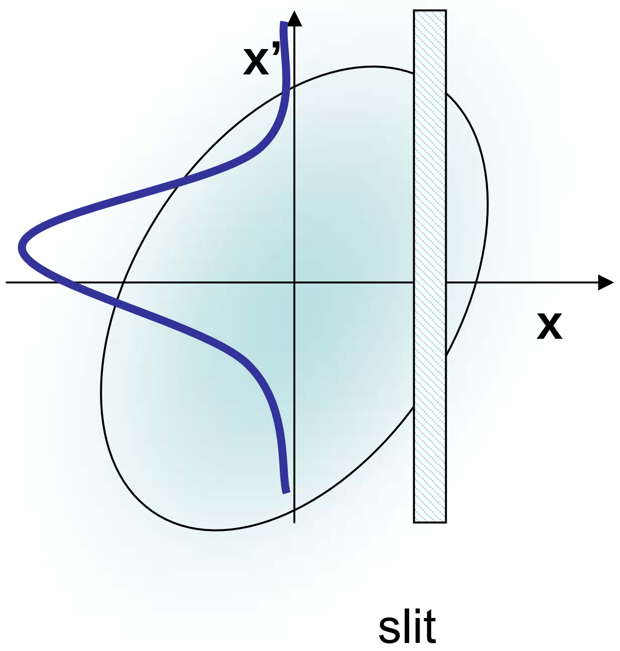
# Emittance measurements

- If for each beam particle we plot its position and its transverse angle we get a particle distribution who's boundary is an usually ellipse.
- The projection onto the x axis is the beam size

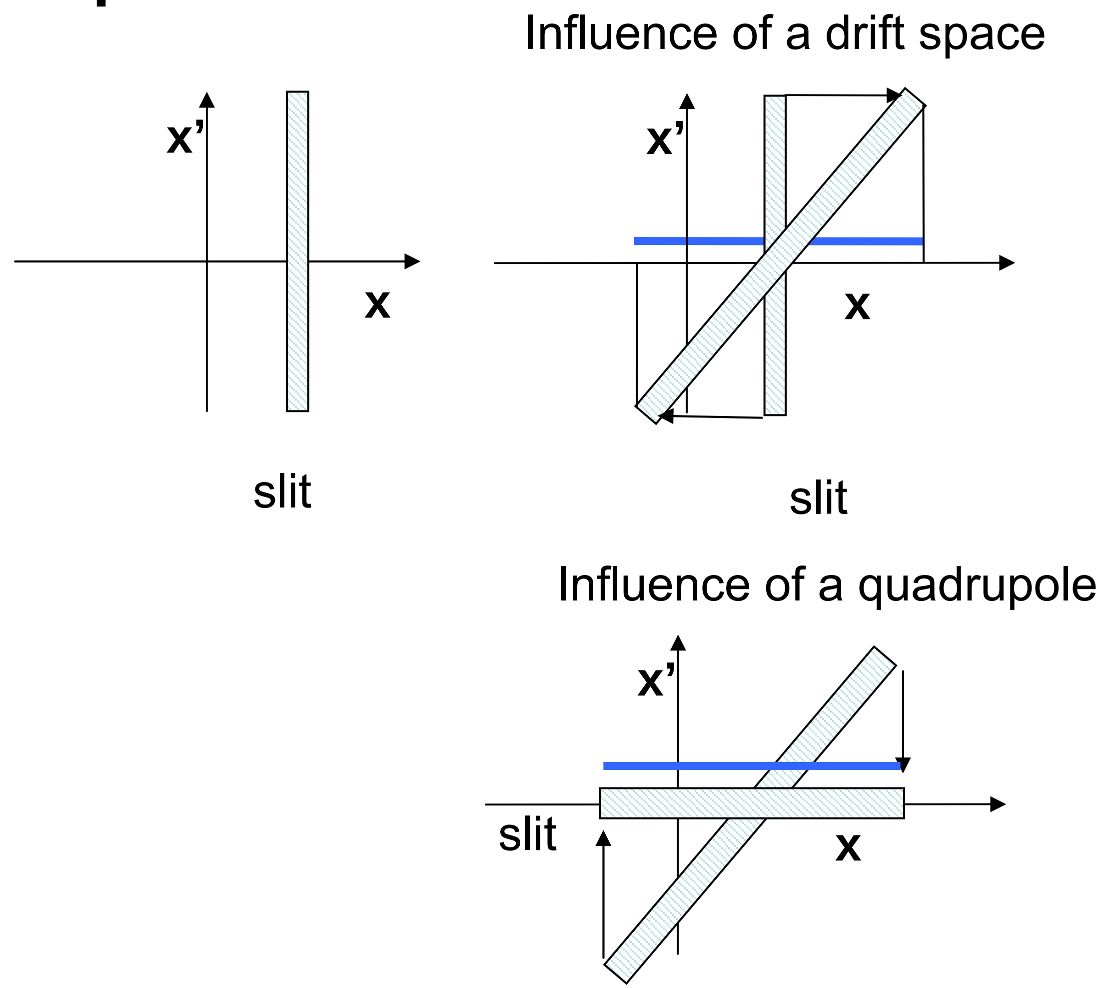


# The slit method

- If we place a slit into the beam we cut out a small vertical slice of phase space
- Converting the angles into position through a drift space allows to reconstruct the angular distribution at the position defined by the slit

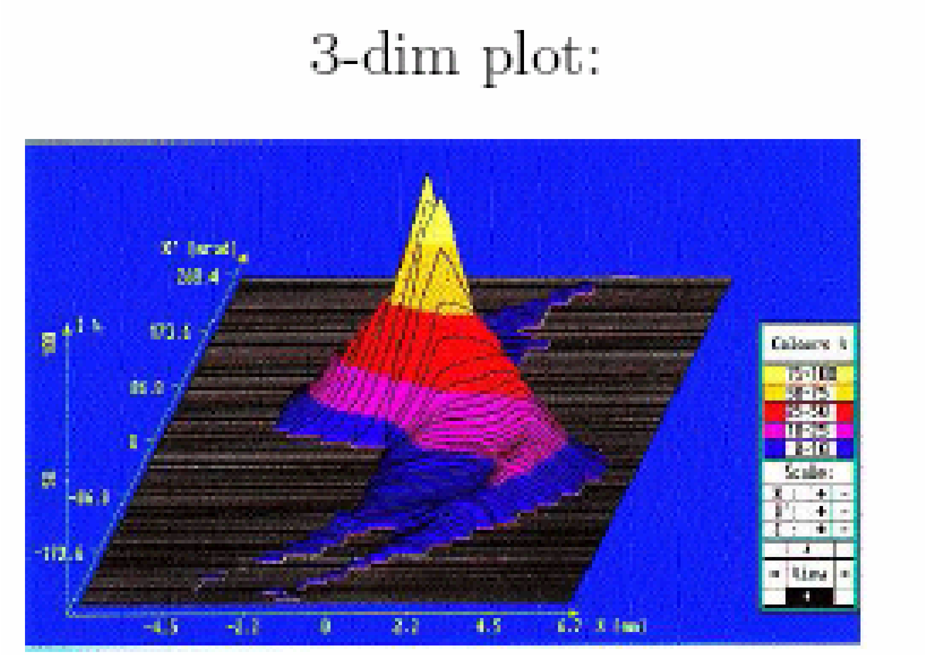


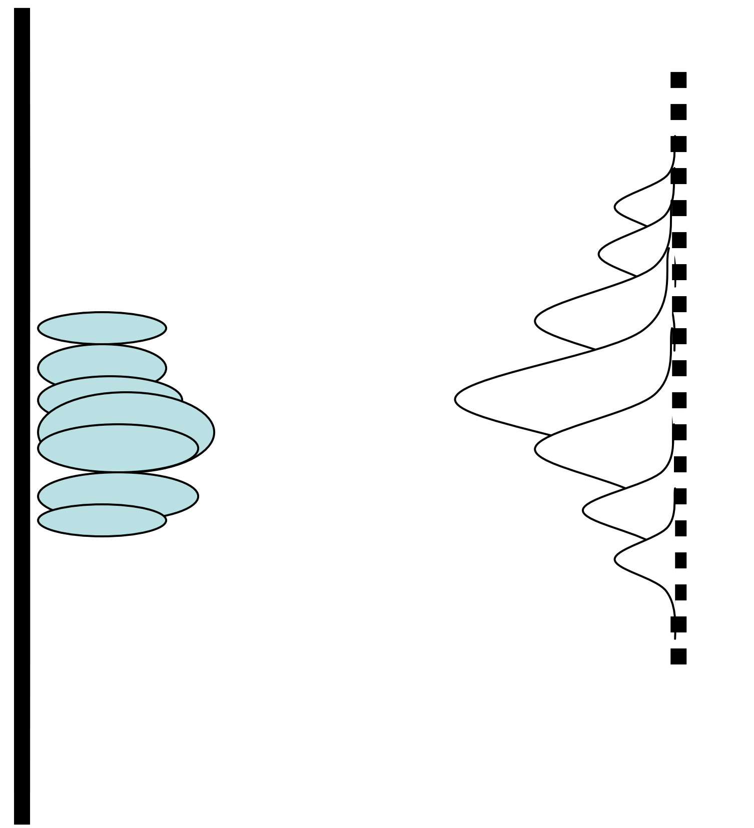
# Transforming angular distribution to profile




- When moving through a drift space the angles don't change (horizontal move in phase space)
- When moving through a quadrupole the position does not change but the angle does (vertical move in phase space)

# The Slit Method

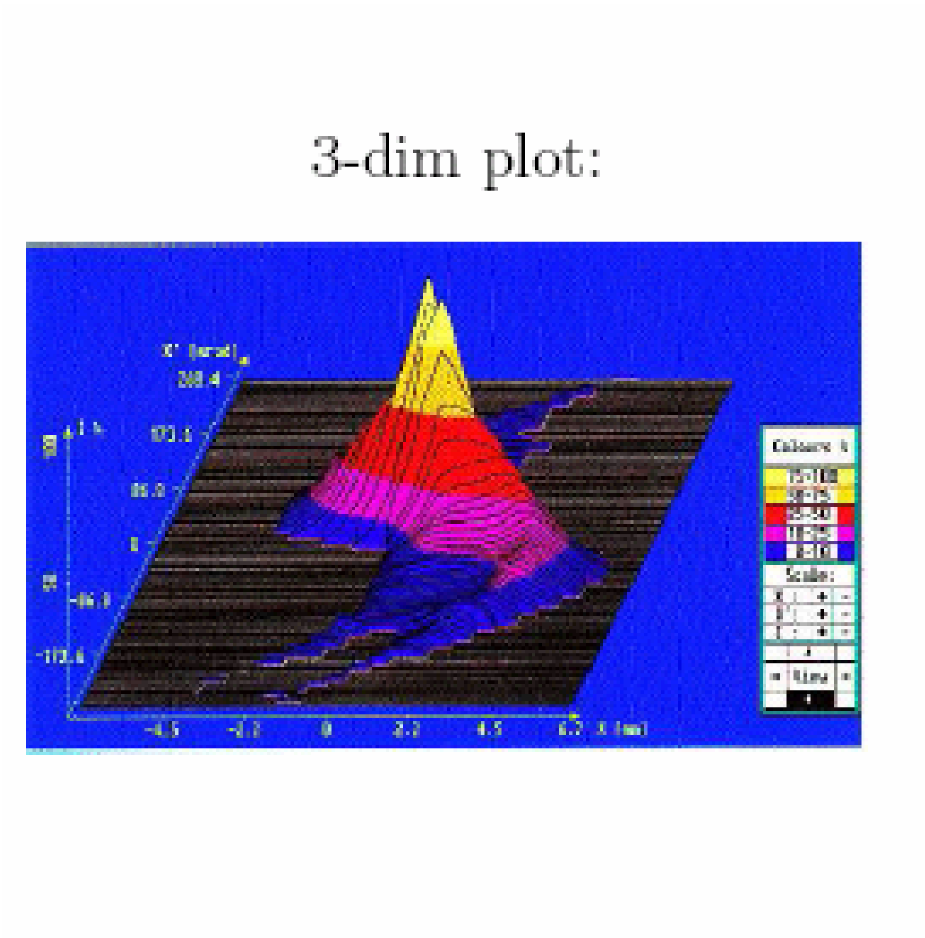


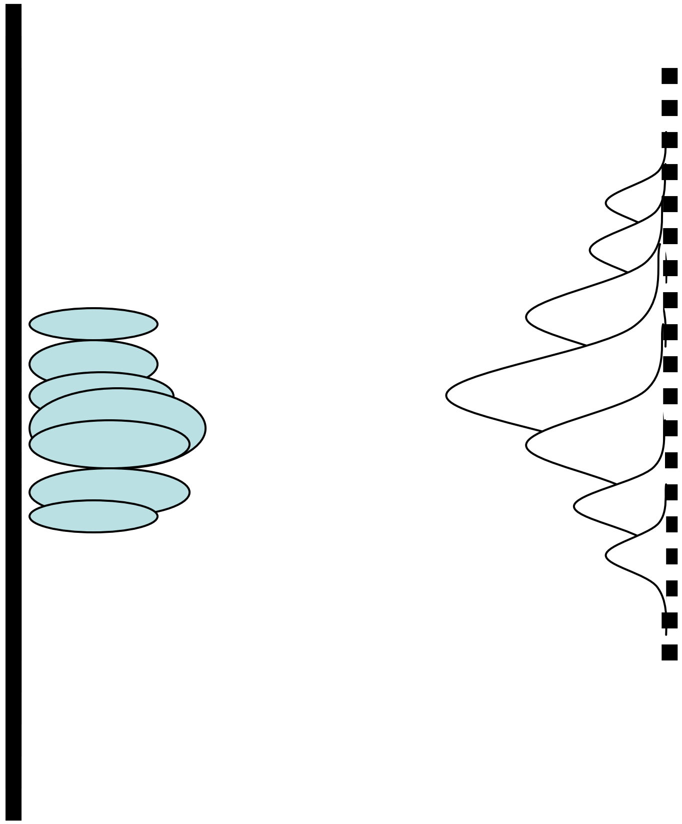





3d plot from P. Forck

# The Slit Method

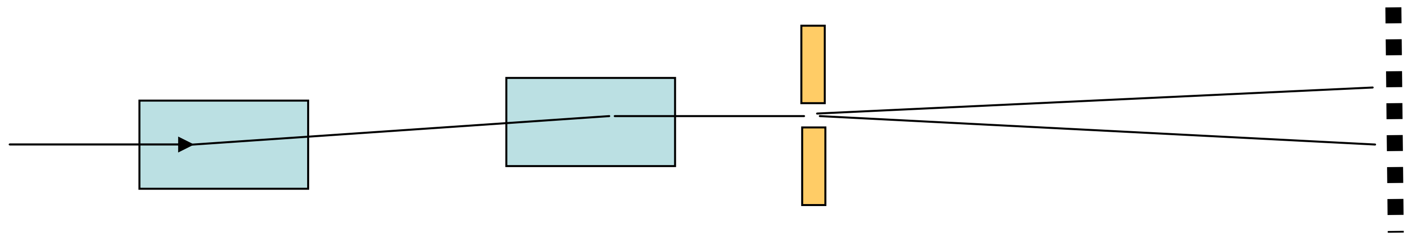


## Moving slit emittance measurement

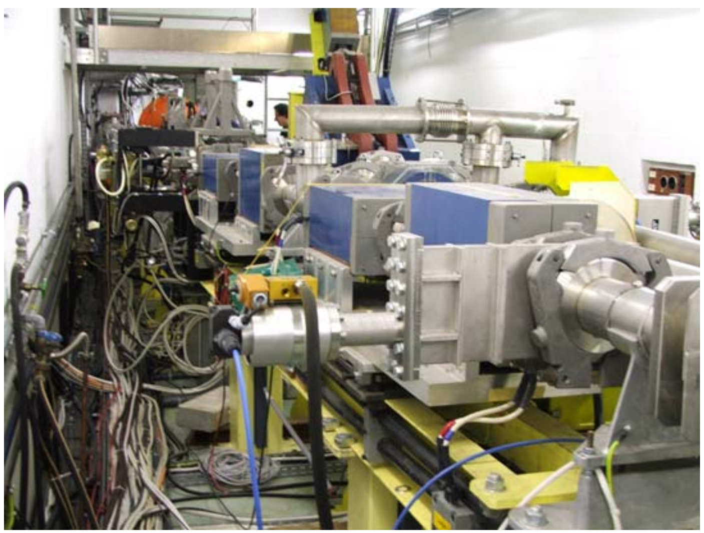
- Position resolution given by slit size and displacement
- Angle resolution depends on resolution of profile measurement device and drift distance
- High position resolution → many slit positions → slow
- Shot to shot differences result in measurement errors

# Single pulse emittance measurement

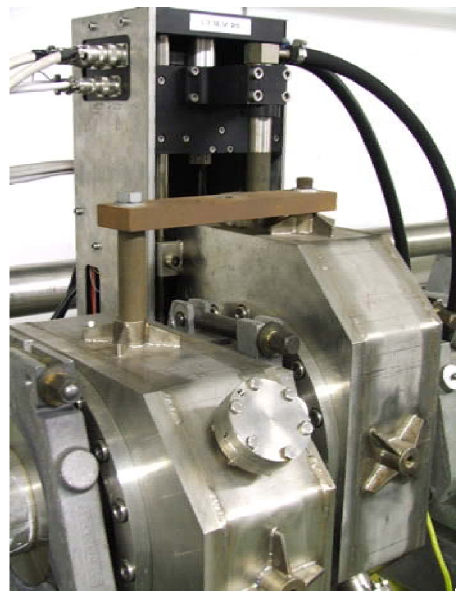


Every 100 ns
a new profile

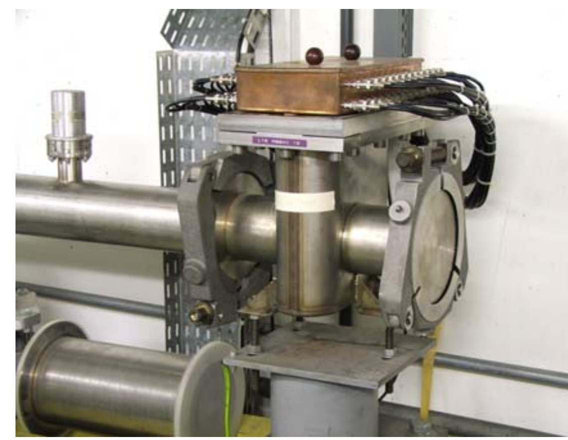
Kickers



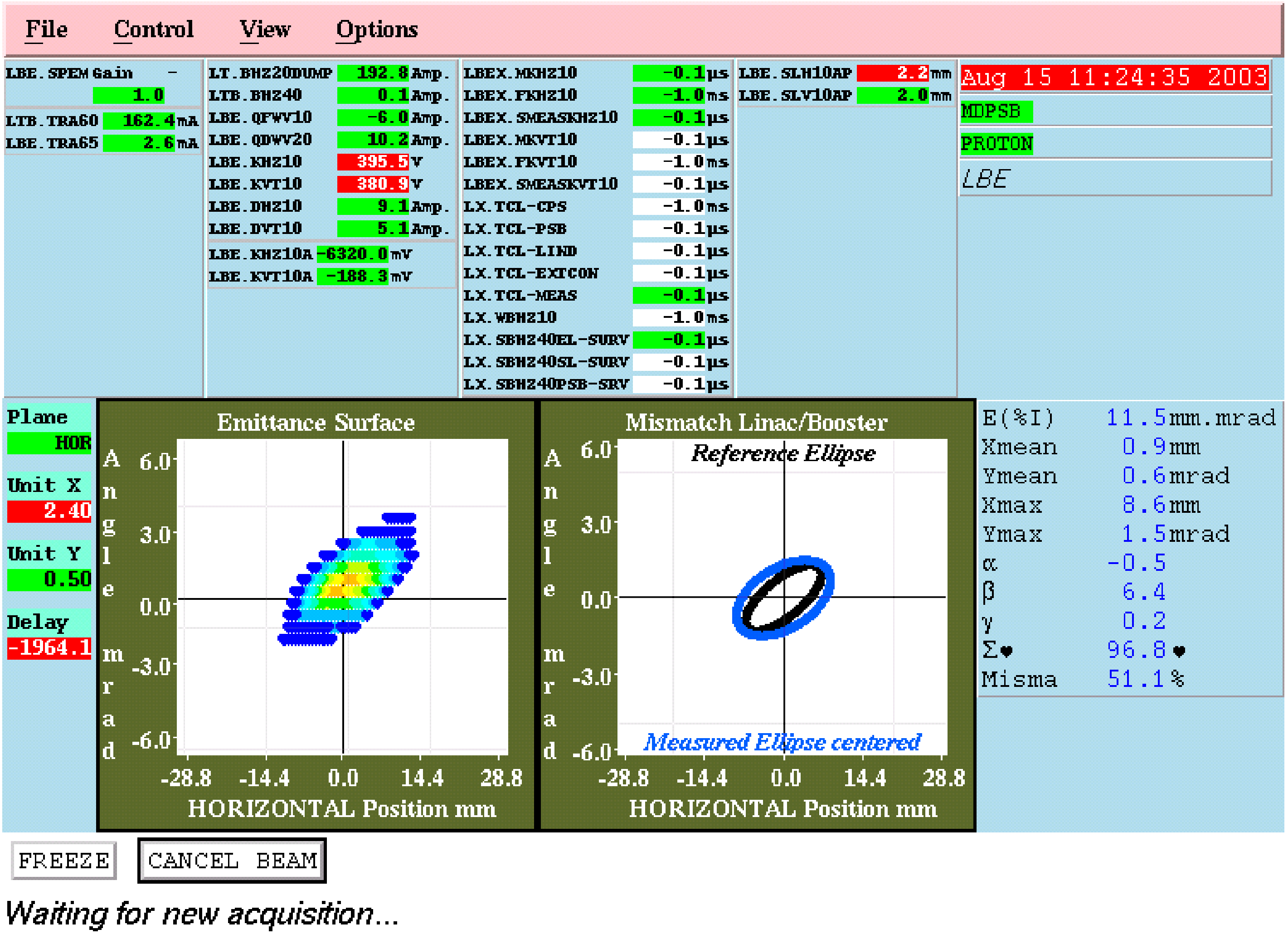
slit



SEMgrid



# Result of single pulse emittance measurement





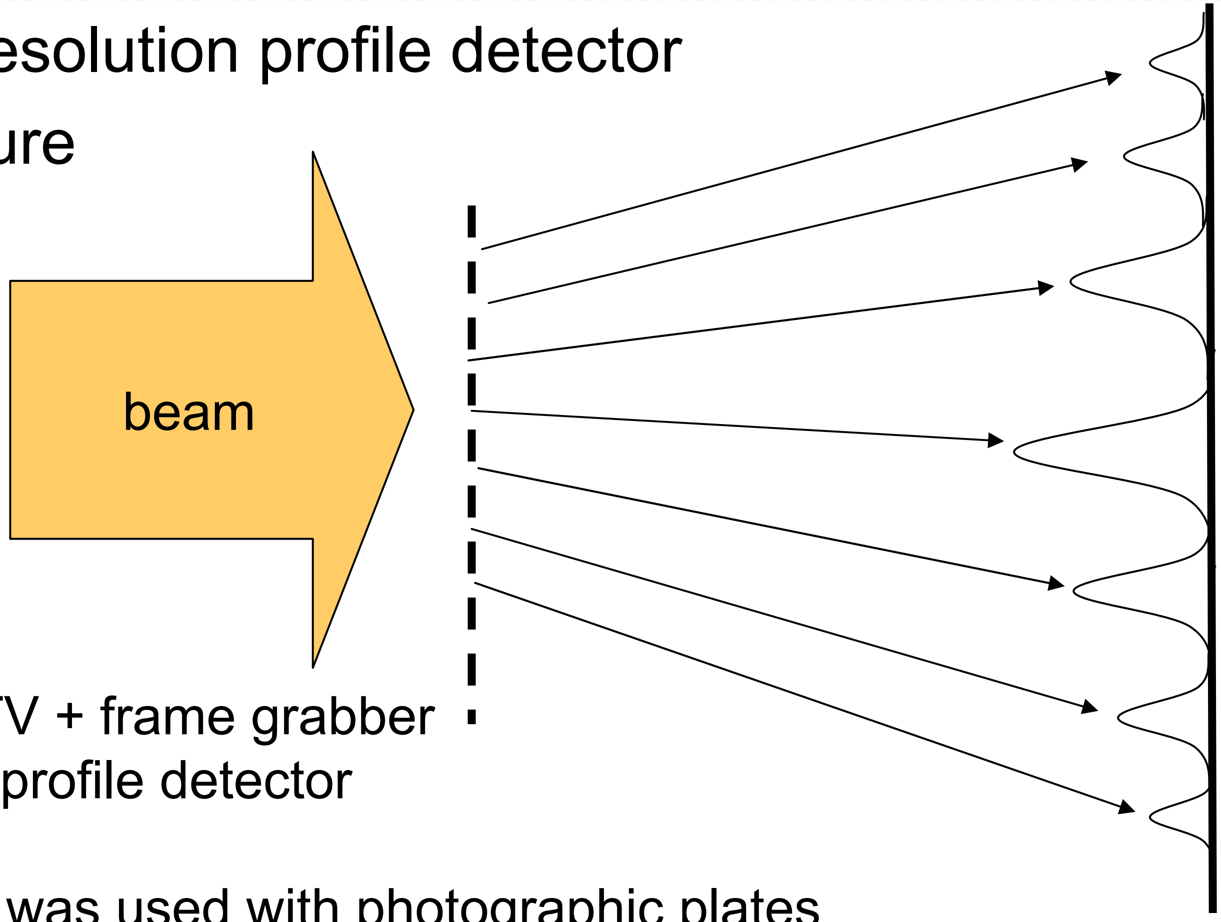

THE CERN ACCELERATOR SCHOOL

# Single Shot Emittance Measurement

- Advantage:
  - Full scan takes 20 μs
  - Shot by shot comparison possible
- Disadvantage:
  - Very costly
  - Needs dedicated measurement line
  - Needs a fast sampling ADC + memory for each wire
- Cheaper alternative:
  - Multi-slit measurement

# Multi-slit measurement

- Needs high resolution profile detector
- Must make sure that profiles dont overlap




Scintillator + TV + frame grabber often used as profile detector

Very old idea, was used with photographic plates

# Pepperpot

Uses small holes instead of slits

Measures horizontal and vertical emittance in a single shot

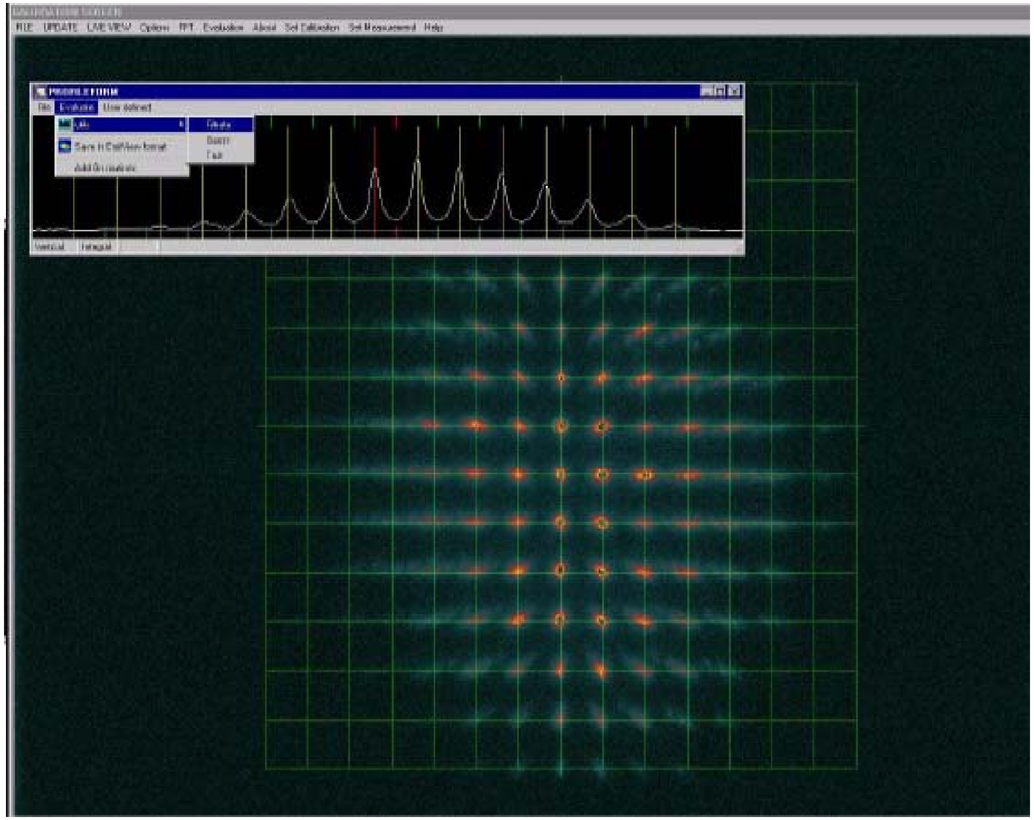
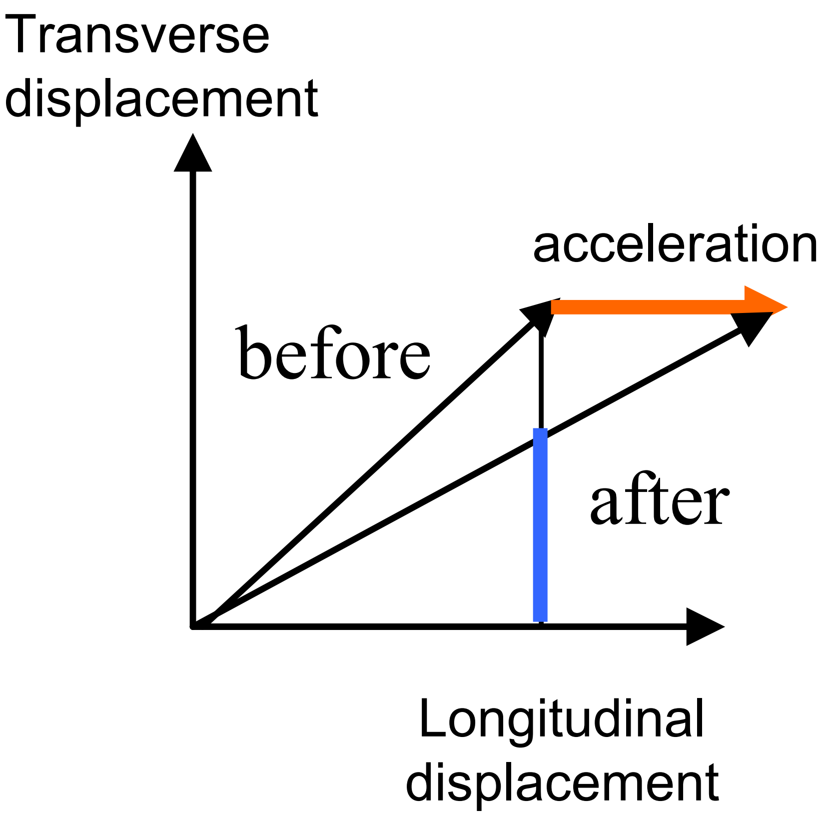




Photo P. Forck

# Adiabatic damping

- Change of emittance with acceleration

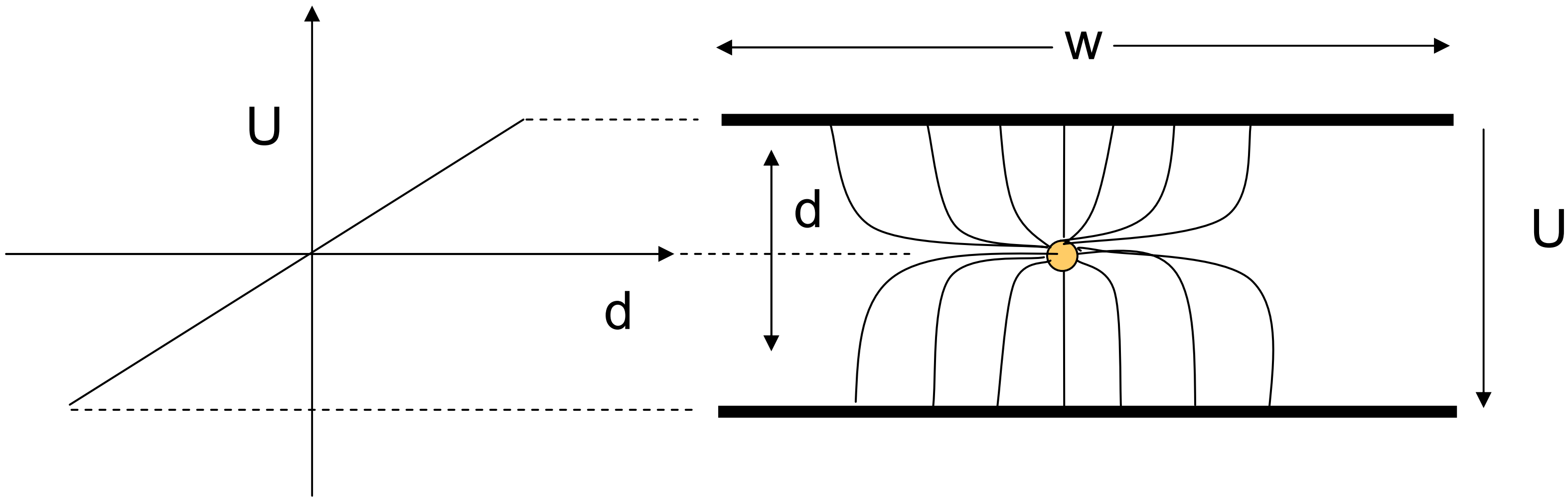



$$\varepsilon_{norm} = \varepsilon_{physical} \beta\gamma$$

β: speed
γ: Lorentz factor

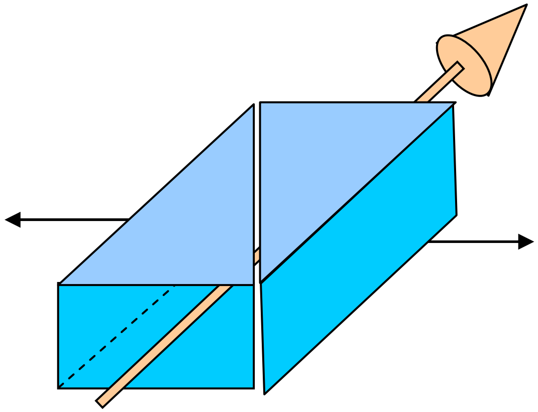
$$\gamma = \frac{1}{\sqrt{1-\beta^2}}$$

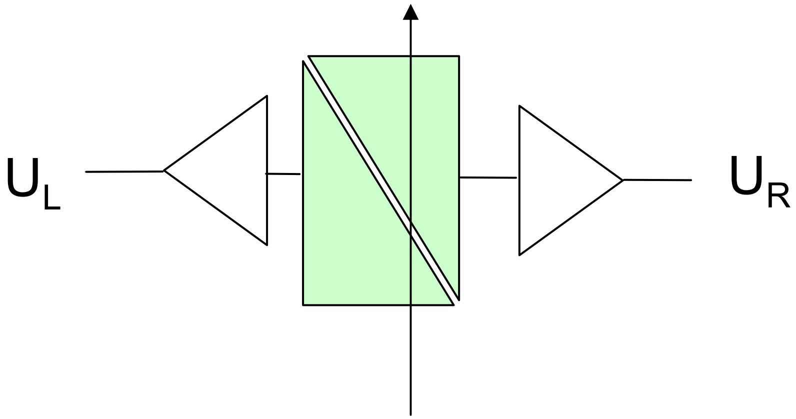
# Position measurements




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

# Shoebox pick-up



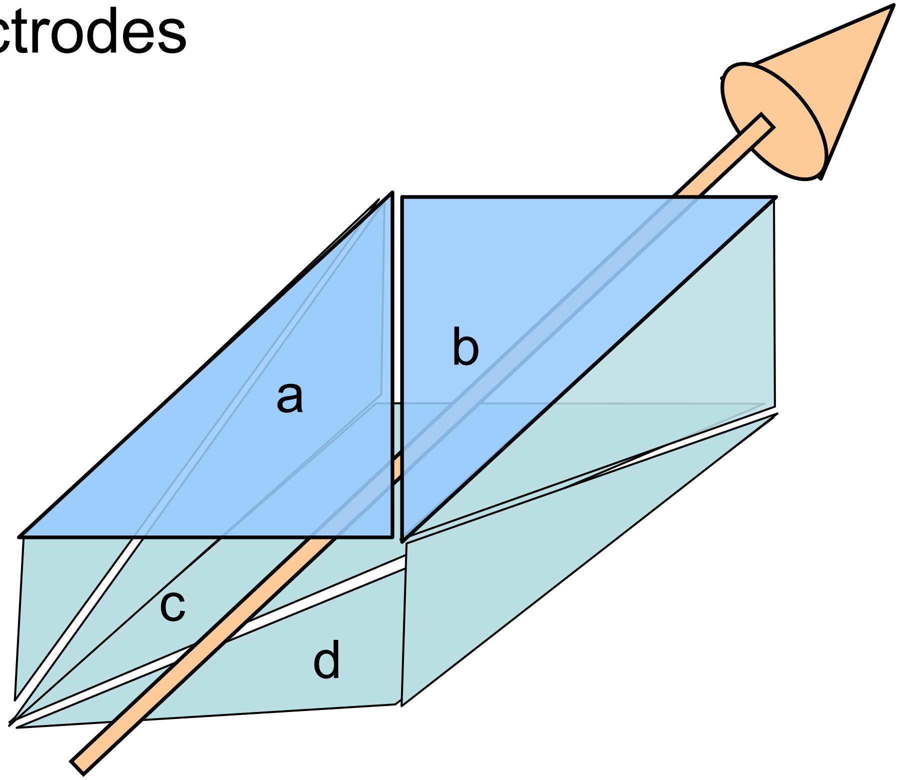



Linear cut through a shoebox

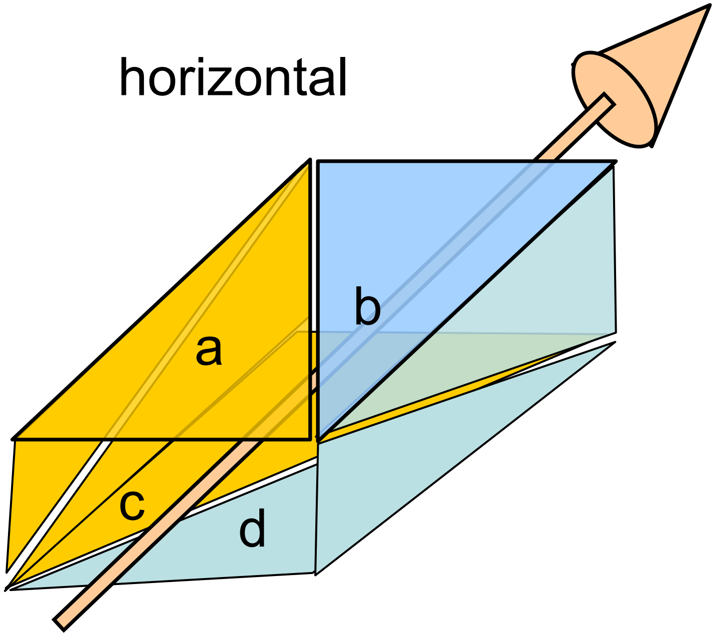
$$x \propto \frac{U_L - U_R}{U_L + U_R} = \frac{\Delta}{\Sigma}$$

# Doubly cut shoebox

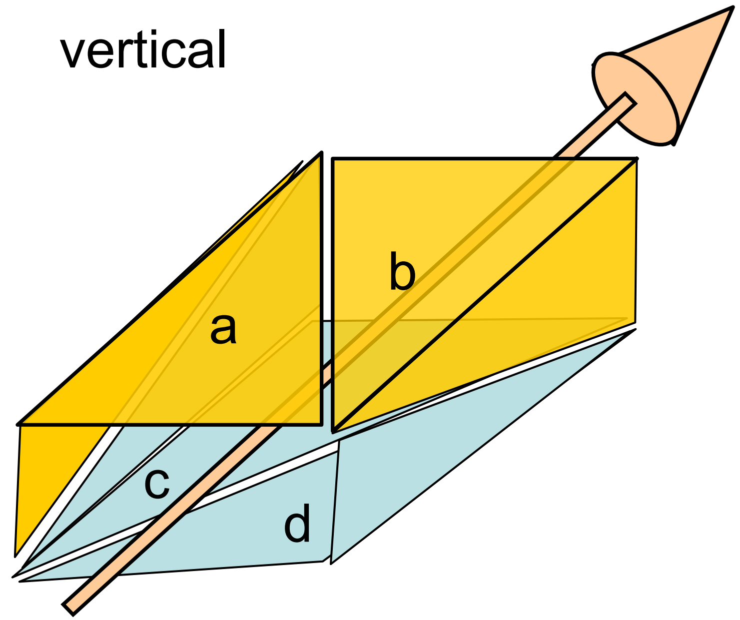
- Can measure horizontal and vertical position at once
- Has 4 electrodes



# Simulatenous horizontal and vertical measurement

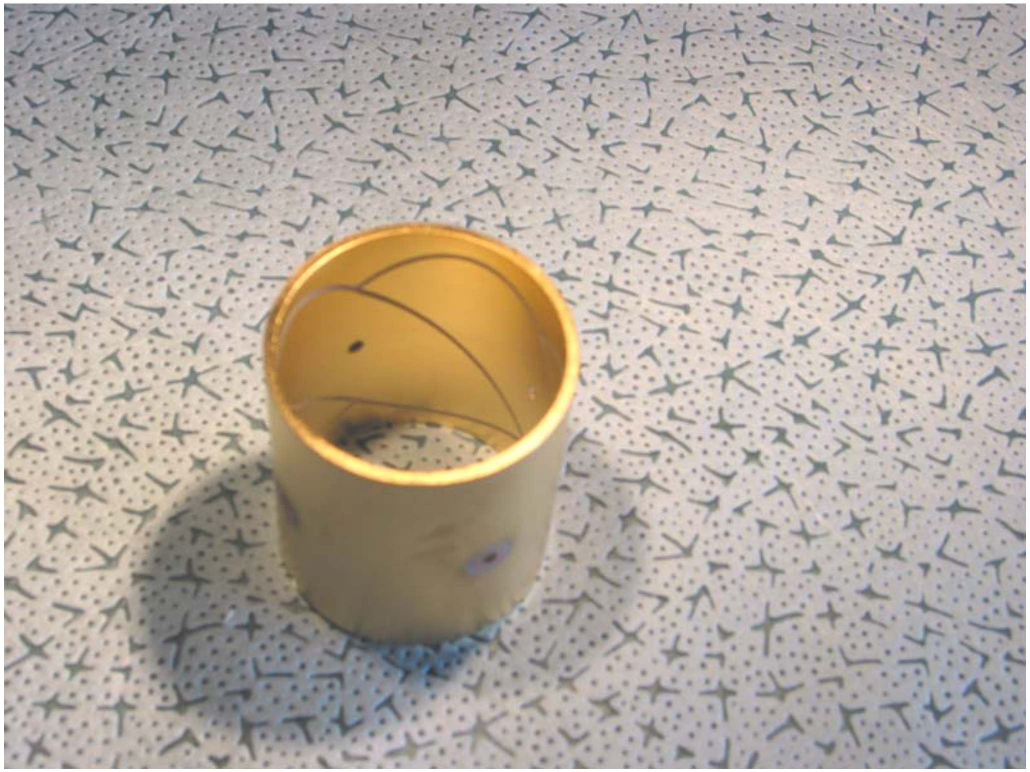



$$X = \frac{(U_a + U_c) - (U_b + U_d)}{\Sigma U}$$




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

# Photo of a cylindrical pick-up



A cylindrical pick-up with its connections

The cuts can be made by photo chemical means of mechanically

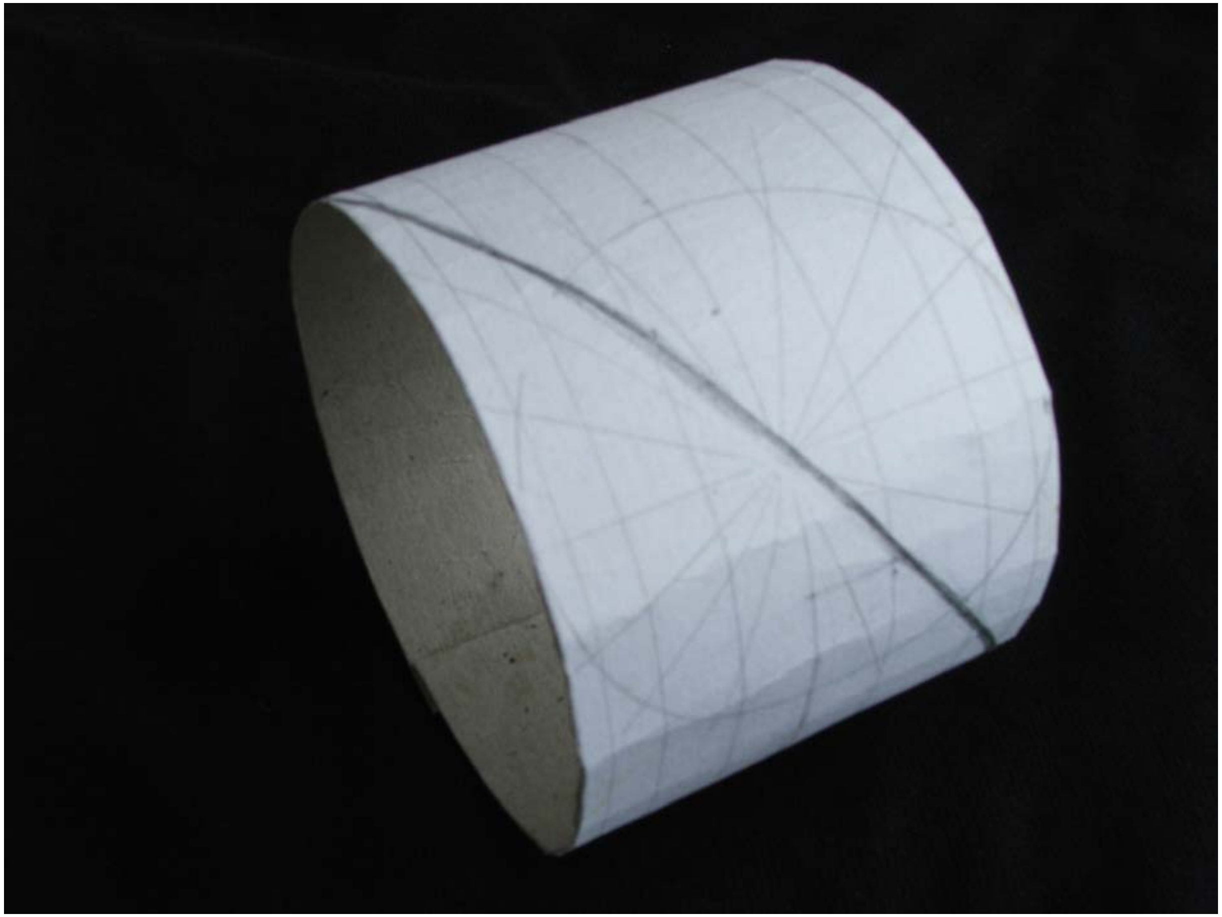
Here done with a sand-blasting device



Photo by L. Søby

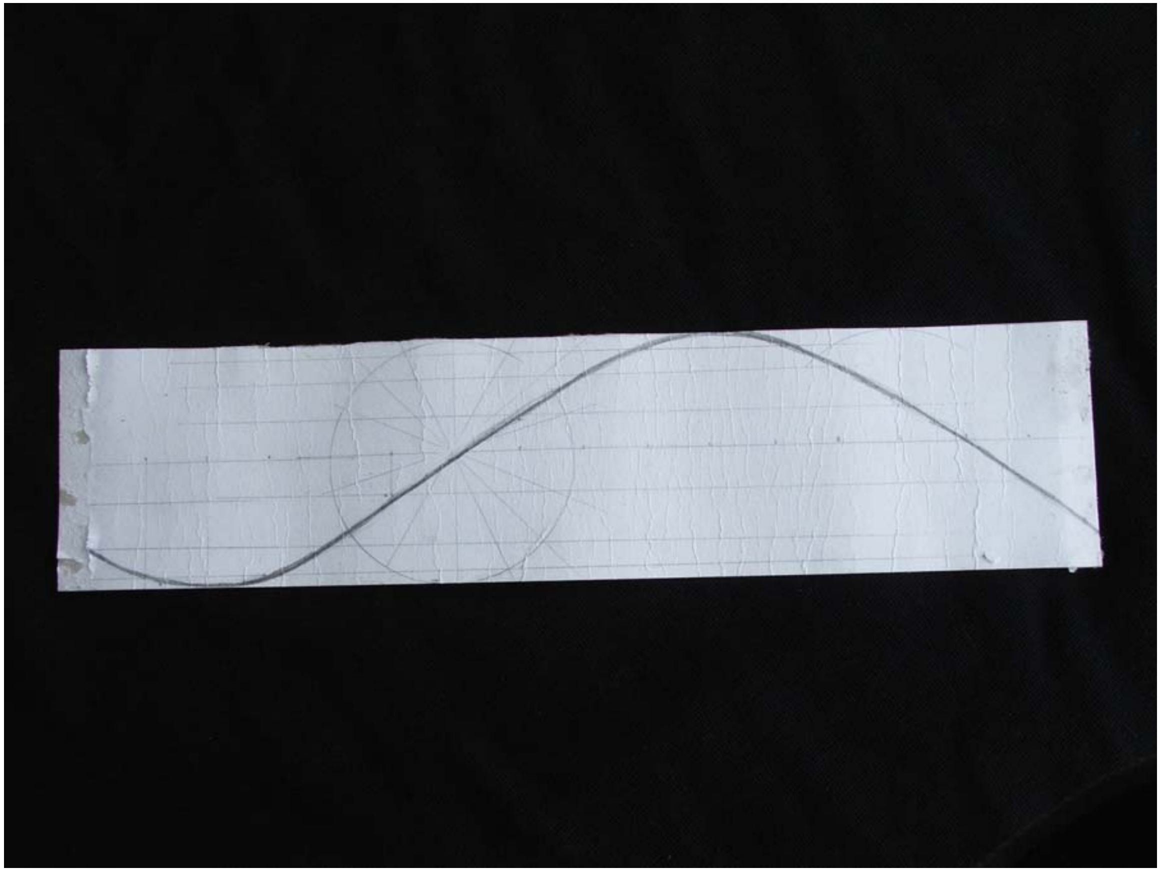
# Building a cylindrical paper pick-up

- A linear cut in a cylinder:



# Unfolding the cylinder

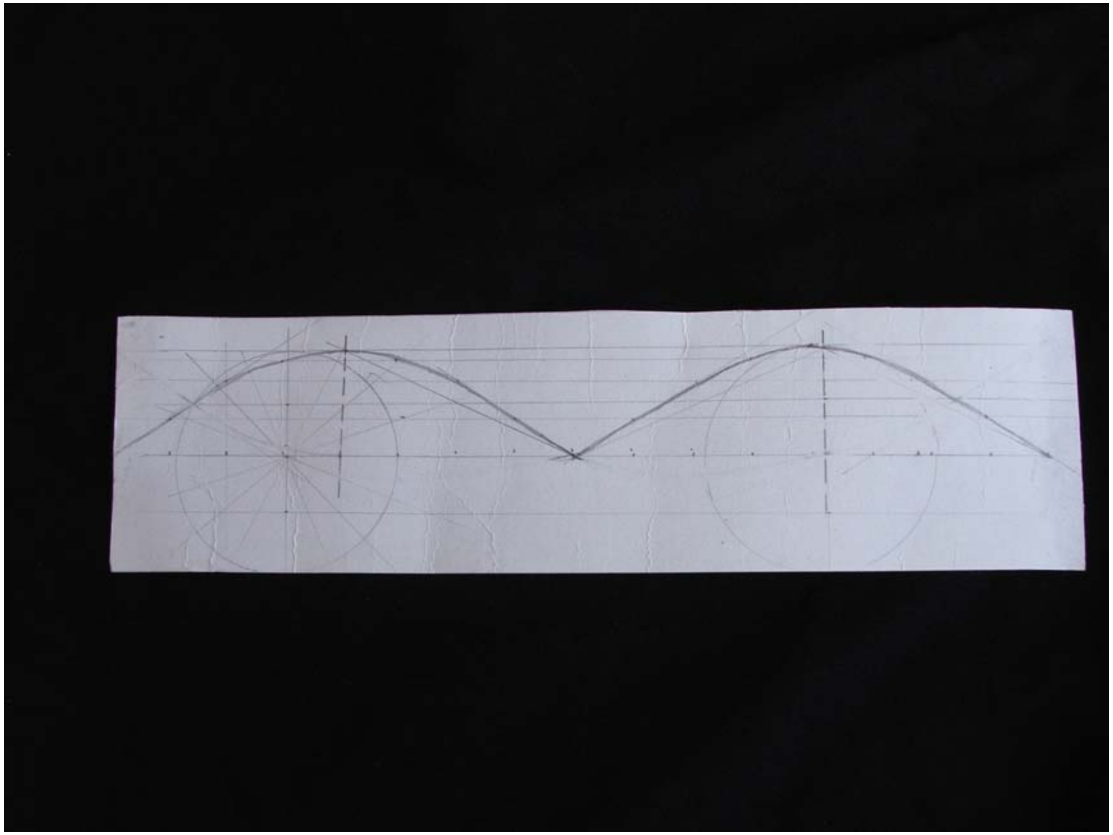
- When unfolded the cut becomes a sine curve



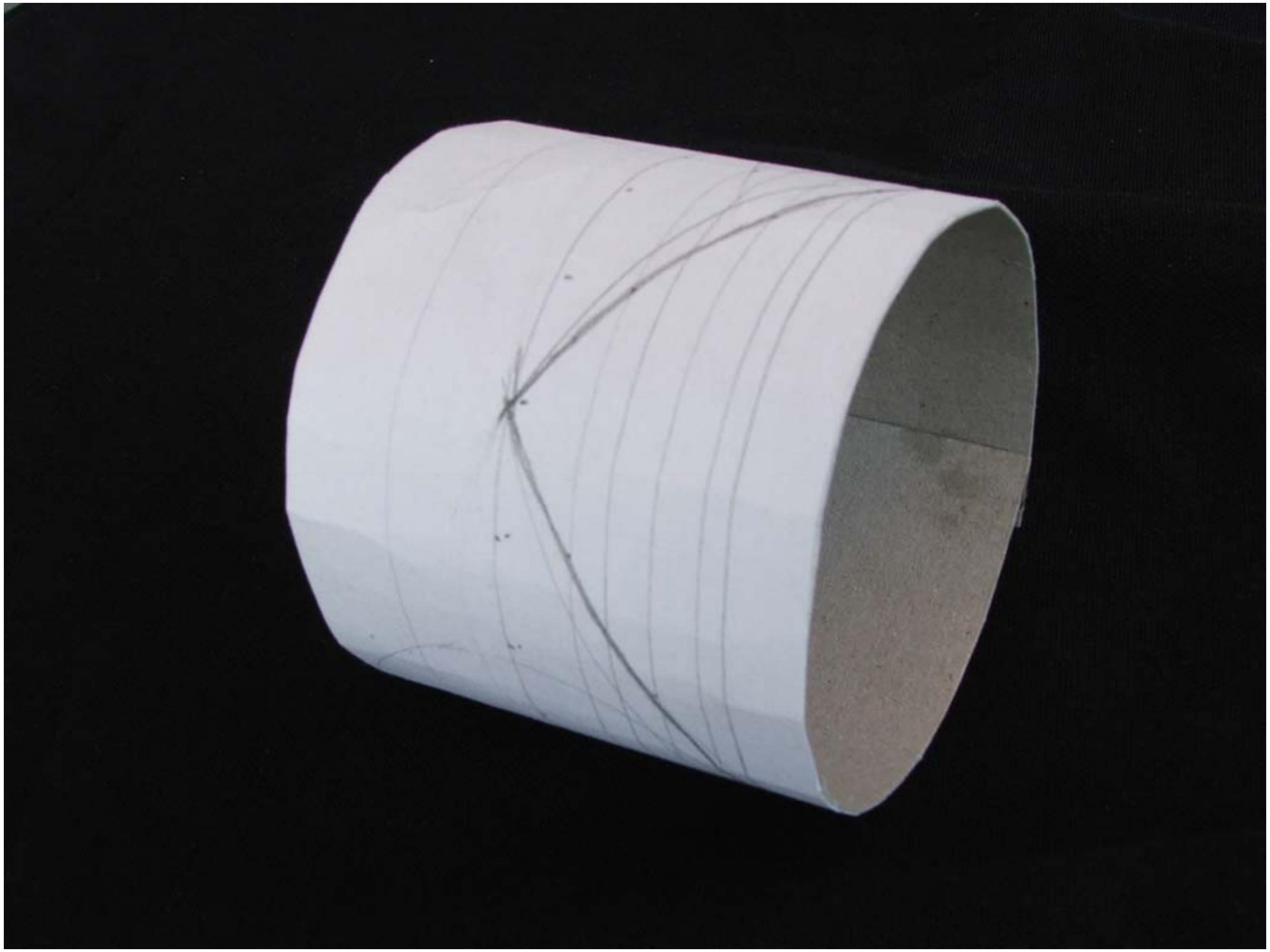
# Flipping the sine curve

What happens if we flip use abs (sin(x)) instead?

Mirror the negative sine part?

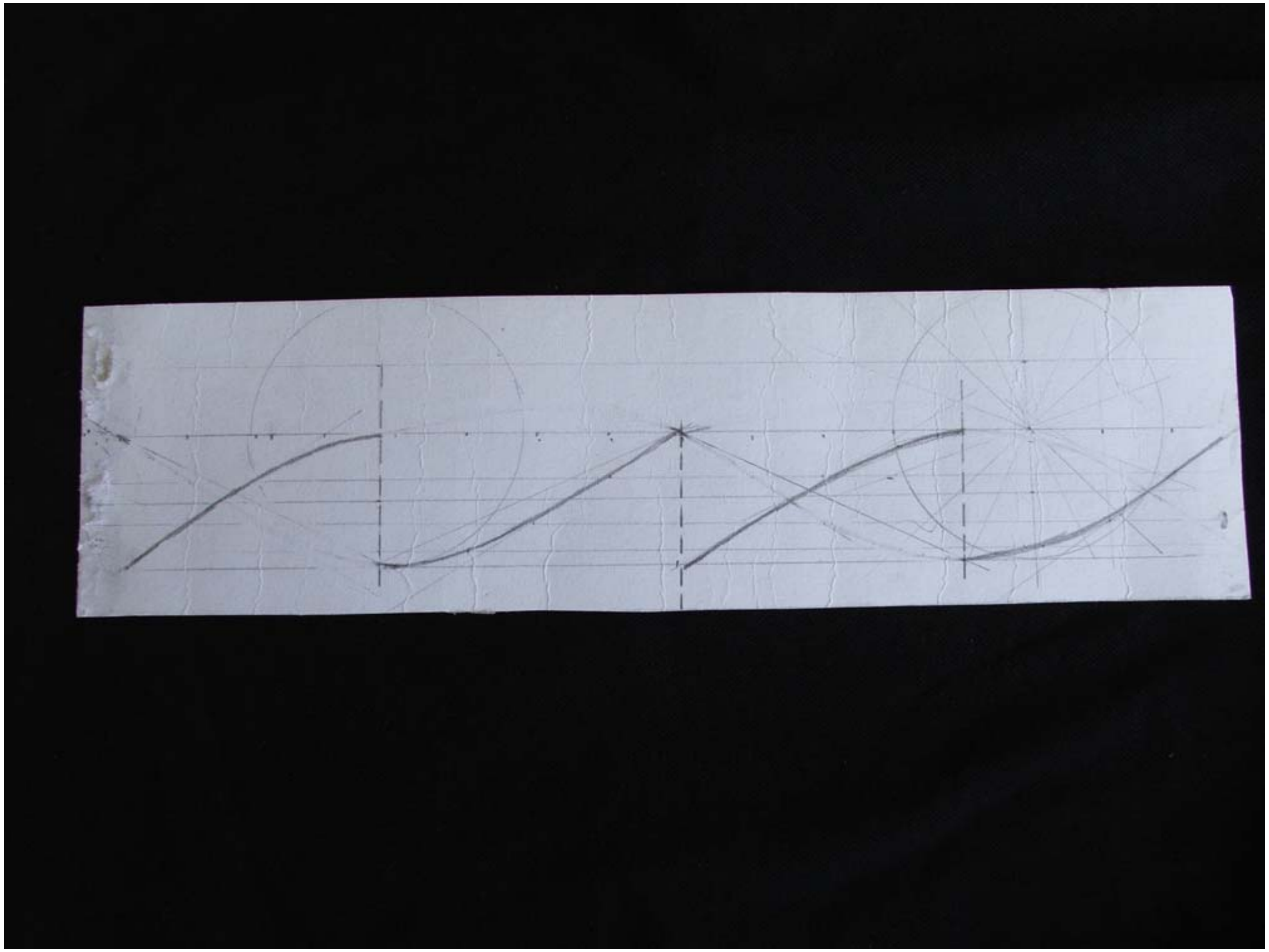


# The cylinder is cut twice!

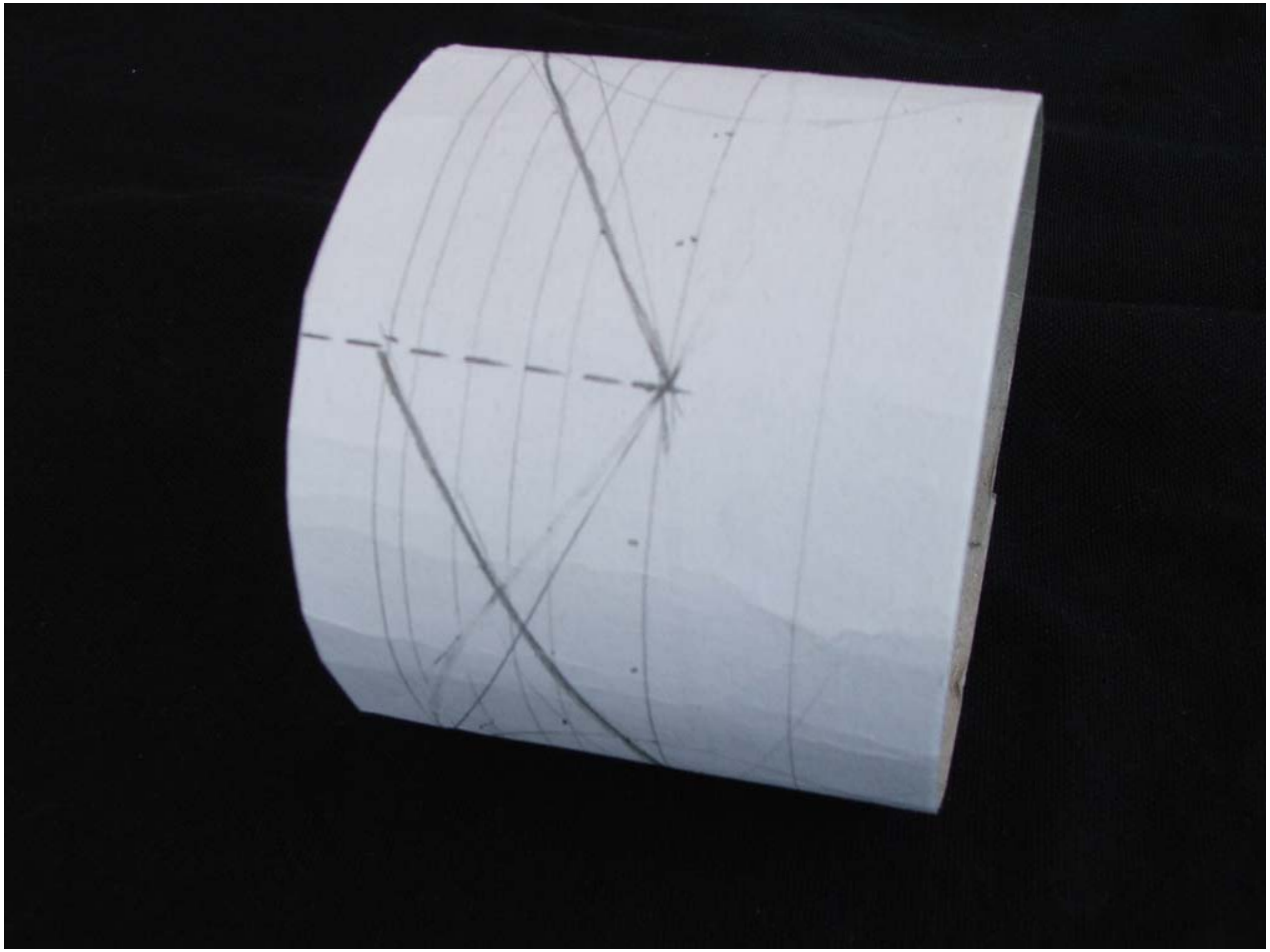


- Horizontal and vertical cut

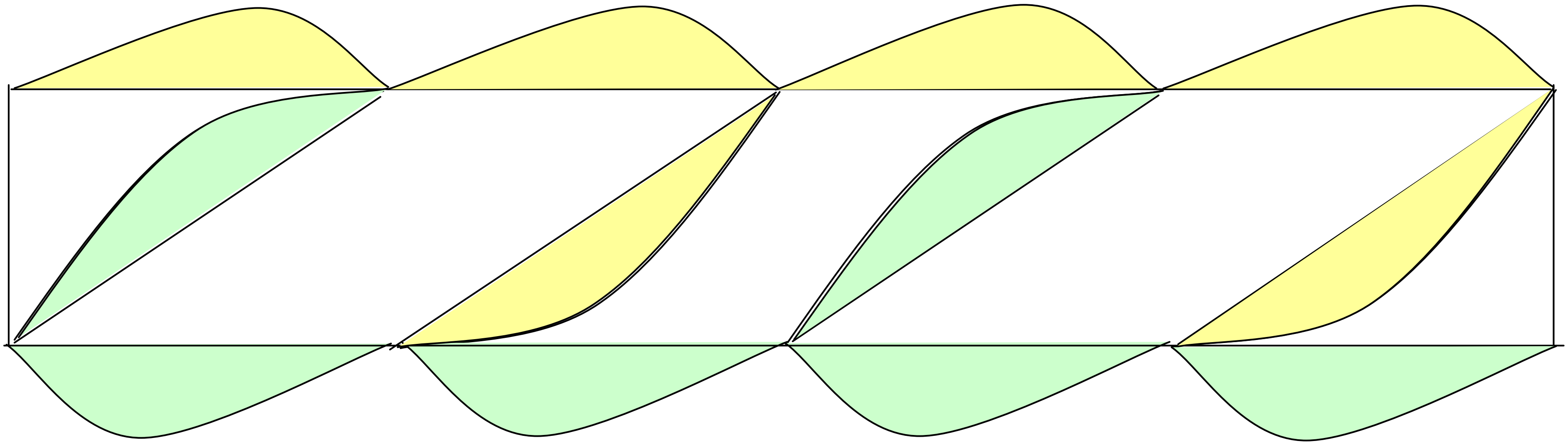
# Flipping half the sin curve upside down



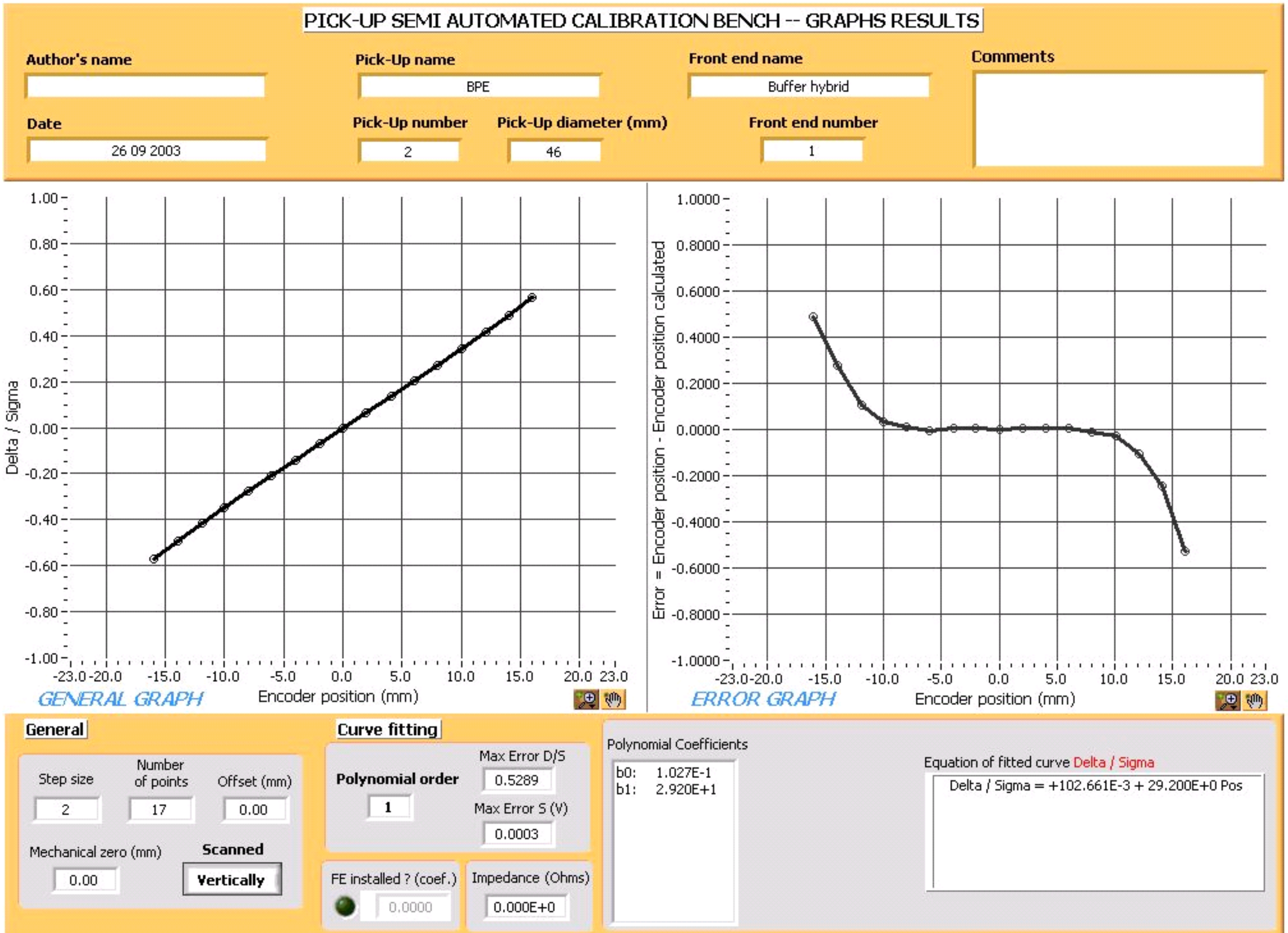
# Cut in the same direction



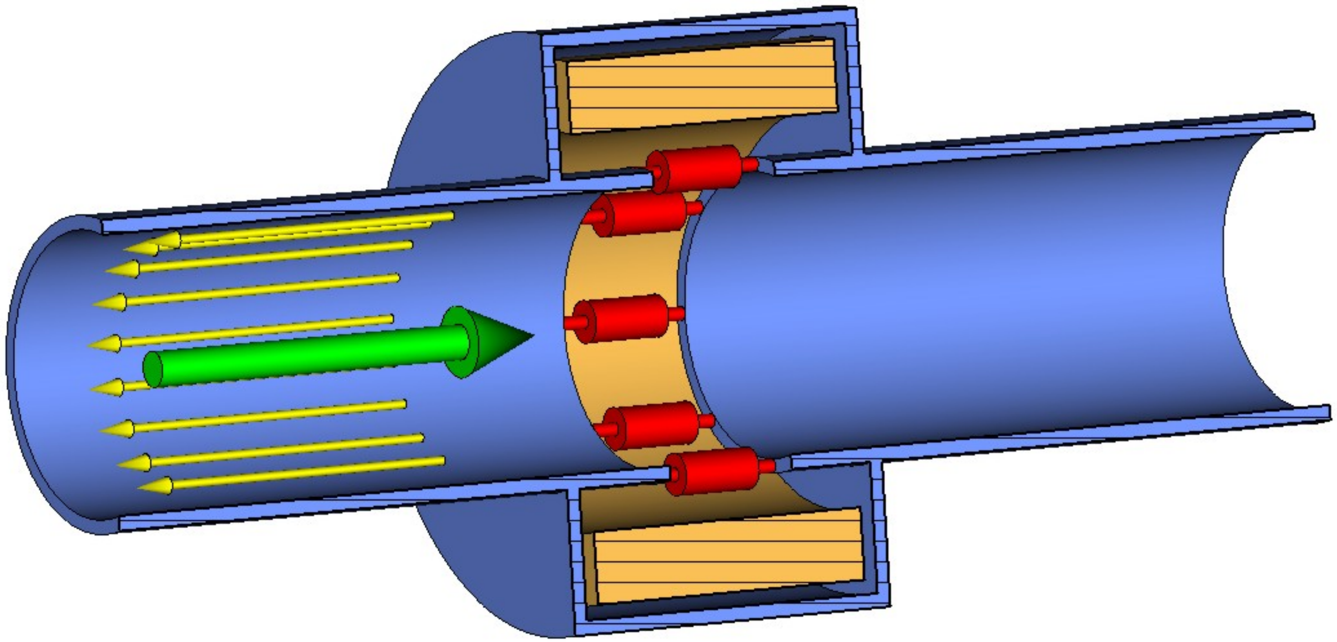
# Using all the electrode surface



# Calibration of the pick-up



# Wall Current Monitor (WCM) principle



- The **BEAM** current is accompanied by its **IMAGE**
- A voltage proportional to the beam current develops on the **RESISTORS** in the beam pipe gap
- The gap must be closed by a box to avoid floating sections of the beam pipe
- The box is filled with the **FERRITE** to force the image current to go over the resistors
- The ferrite works up to a given frequency and lower frequency components flow over the box wall

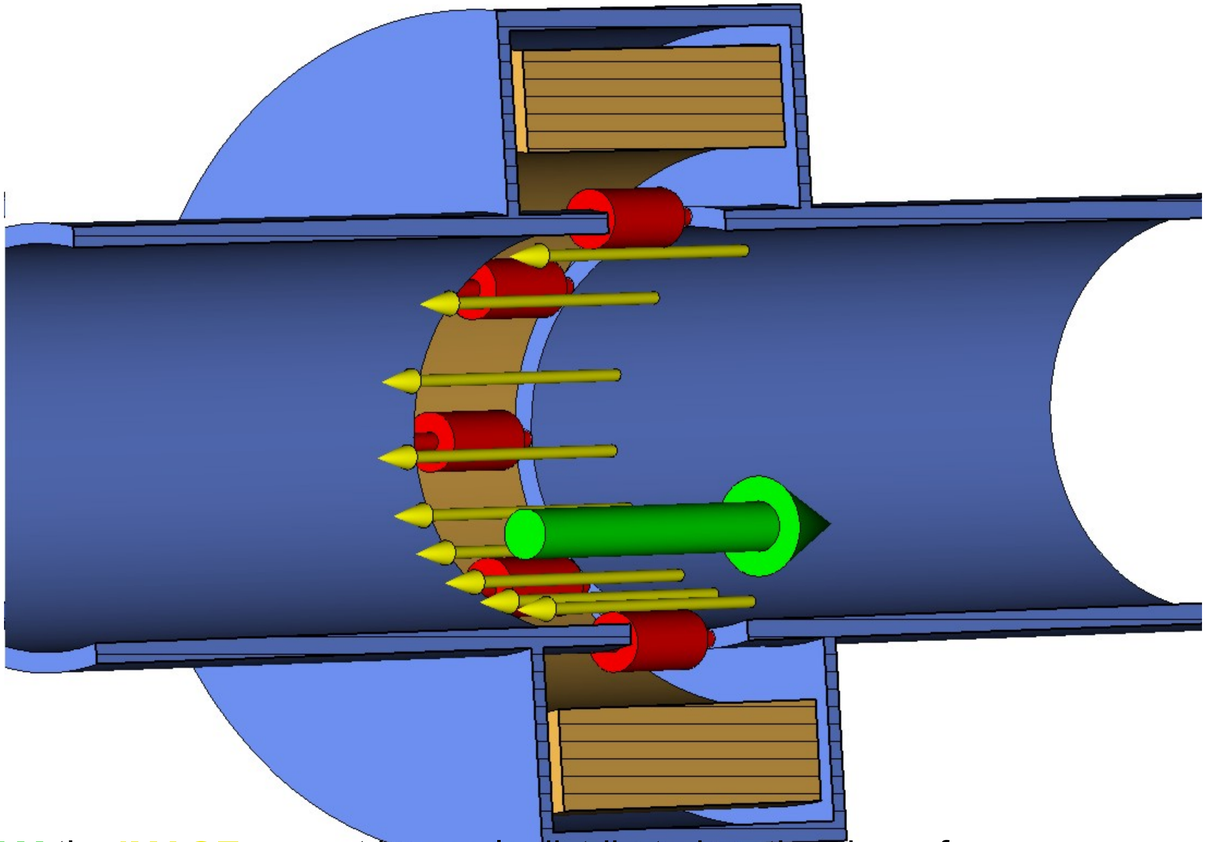


Slide by M. Gasior

# WCM as a Beam Position Monitor

$$f_{L\Sigma} = \frac{R}{2\pi L_{\Sigma}}$$

$$f_{L\Delta} = \frac{R}{2\pi L_{\Delta}}$$



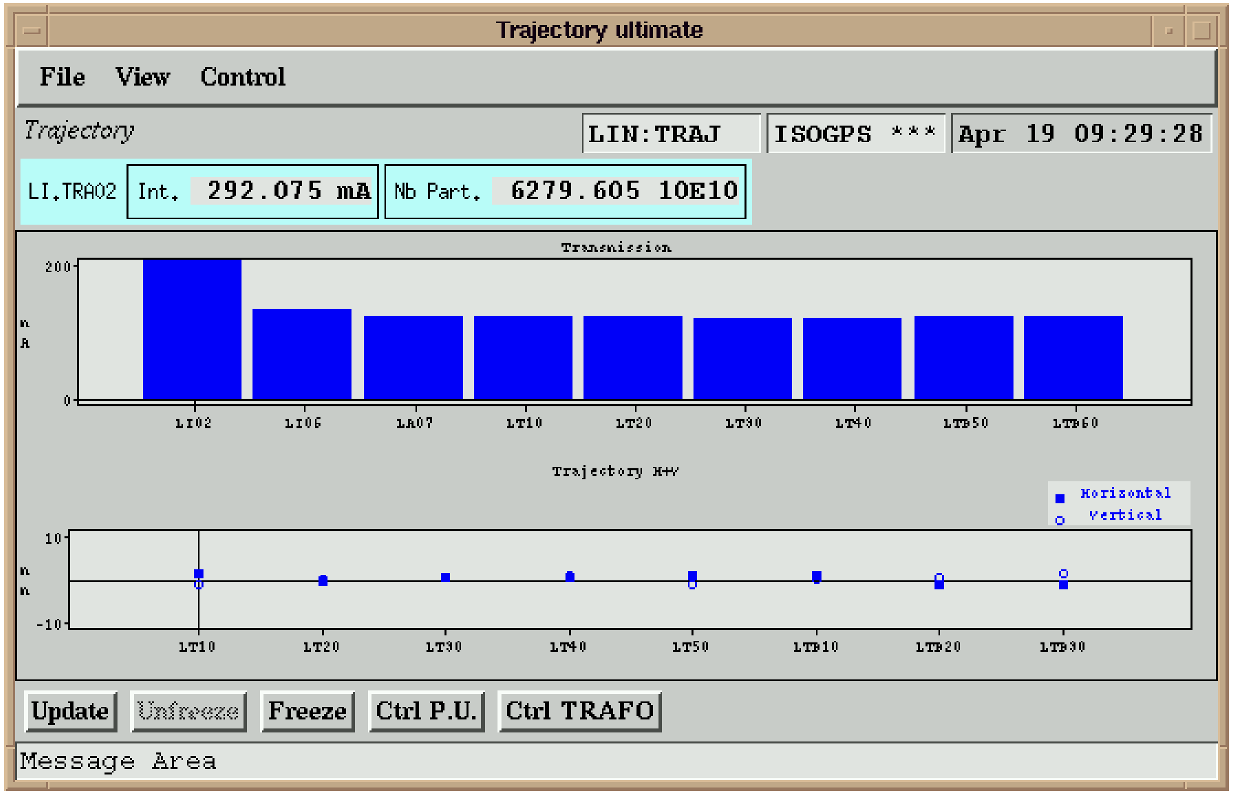
- For a centered **BEAM** the **IMAGE** current is evenly distributed on the circumference
- The image current distribution on the circumference changes with the beam position
- Intensity signal (Σ) = resistor voltages summed
- Position dependent signal (Δ) = voltages from opposite resistors subtracted
- The Δ signal is also proportional to the intensity, so the position is calculated according to Δ/Σ
- Low cut-offs depend on the gap resistance and box wall (for Σ) and the pipe wall (for Δ) inductances



**Slide by M. Gasior**

# Measurement with pick-ups

- Trajectory measurements in transfer lines
- Control beam steering

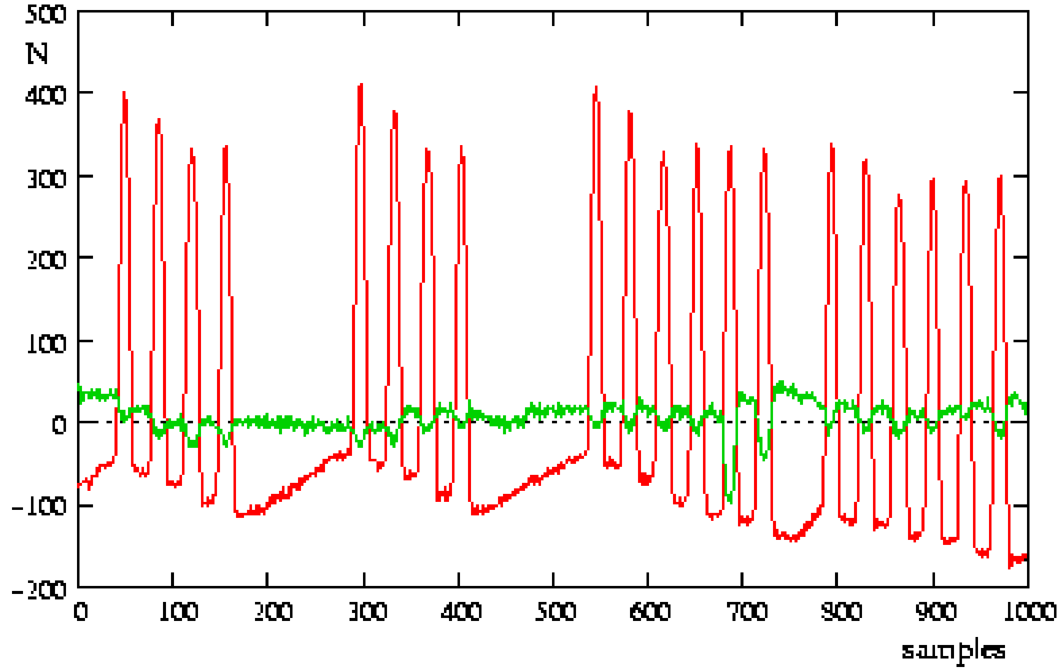





CAS
THE CERN ACCELERATOR SCHOOL

# Trajectory measurements in circular machines

Needs integration gate
Can be rather tricky
Distance between bunches
changes with acceleration
Number of bunches
may change



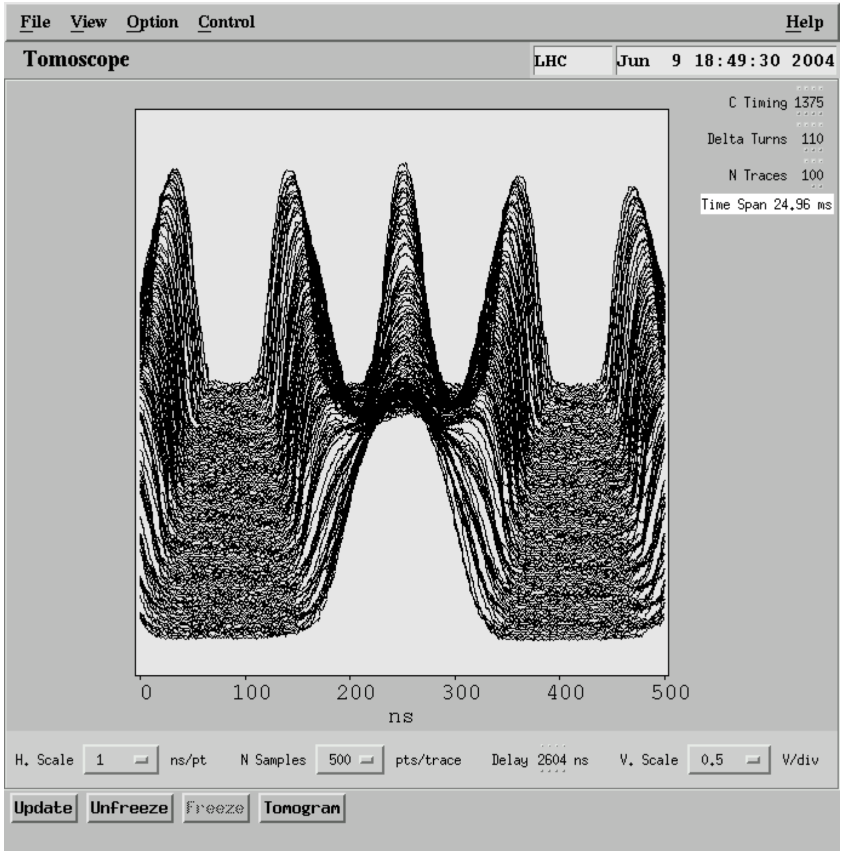

Raw data from pick-ups
double batch injection



Histograms by J. Belleman

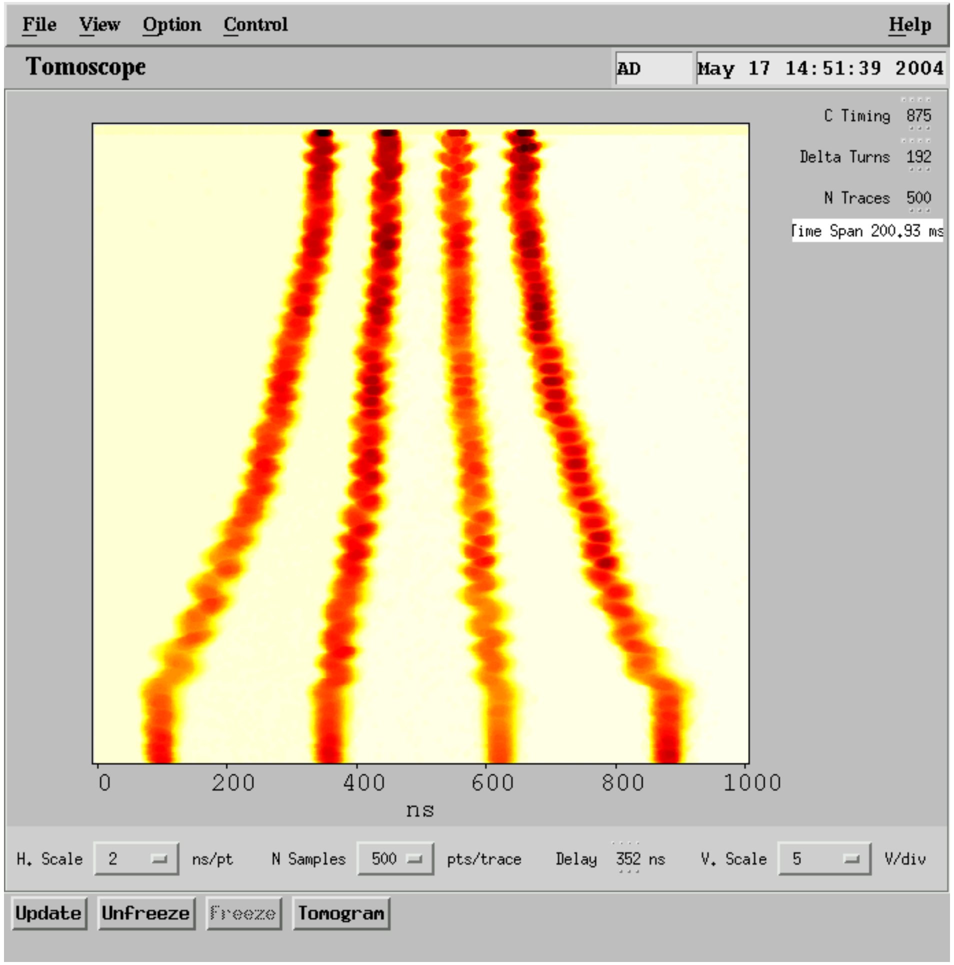
# Changing bunch frequency

- Bunch splitting or recombination
- One RF frequency is gradually decrease while the other one is increased
- Batch compression



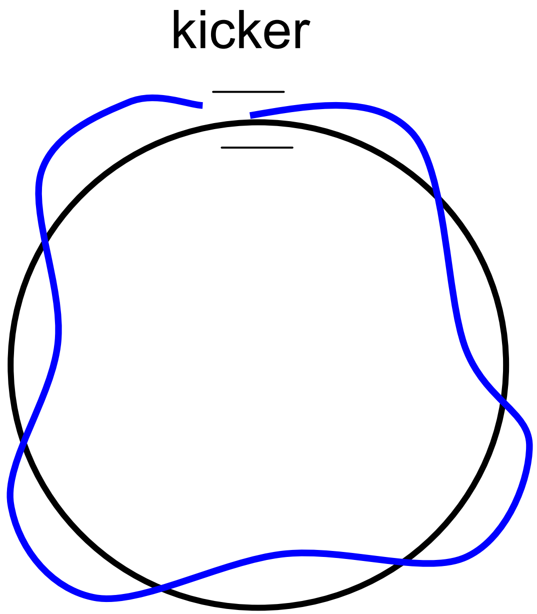

For all these cases the gate generator must be synchronized

# Batch compression



# Tune measurements

- When the beam is displaced (e.g. at injection or with a deliberate kick, it starts to oscillate around its nominal orbit (betatron oscillations)
- Measure the trajectory
- Fit a sine curve to it
- Follow it during one revolution

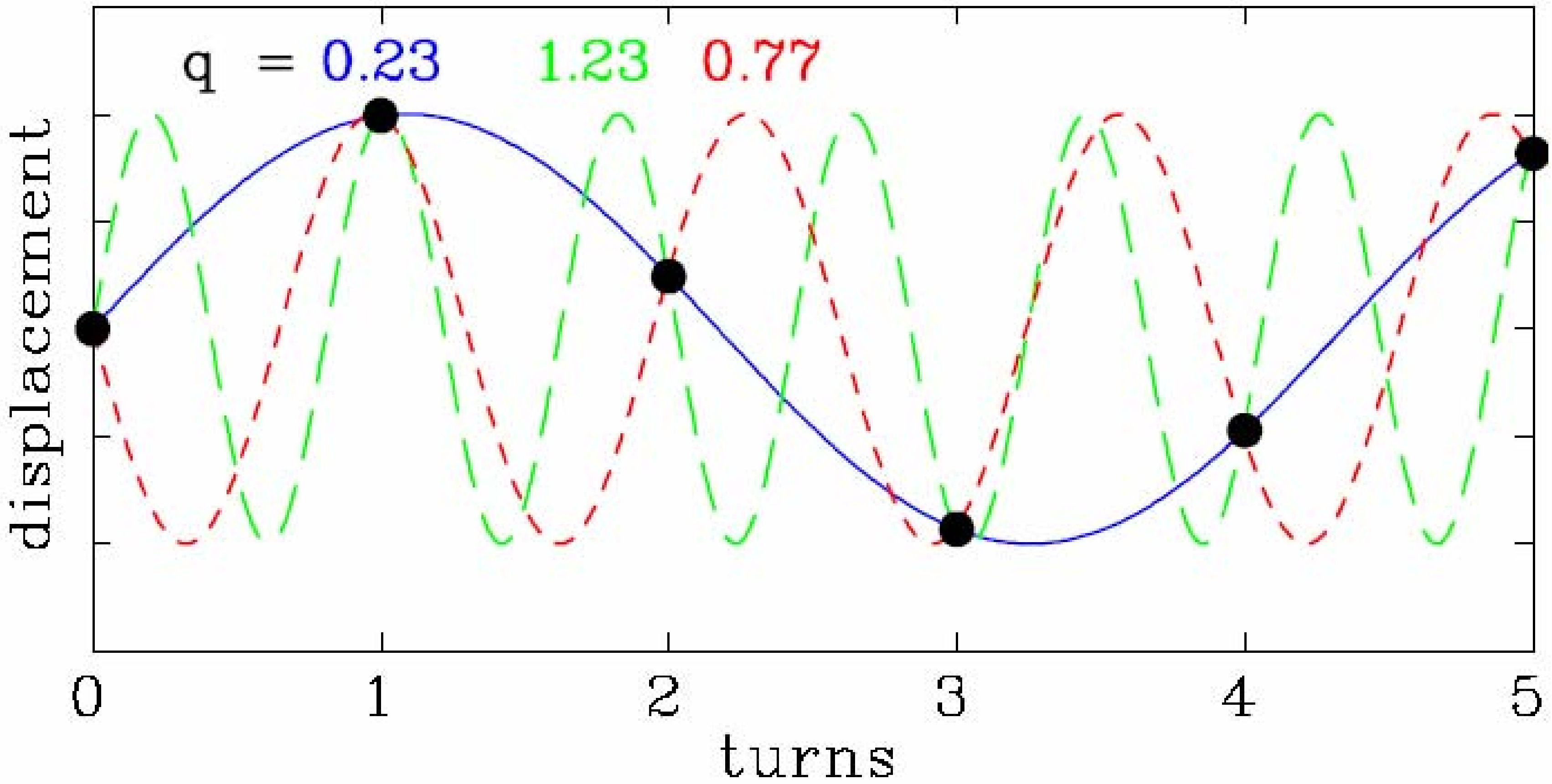





CAS

THE CERN ACCELERATOR SCHOOL

# Tune measurements with a single PU

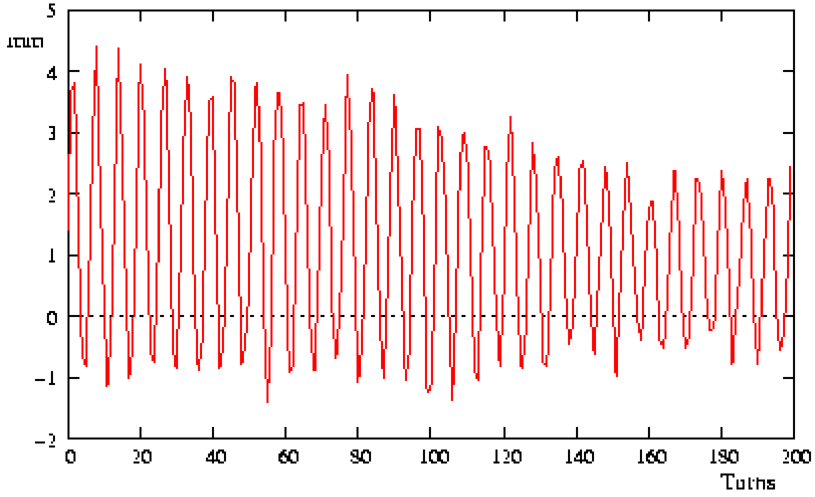


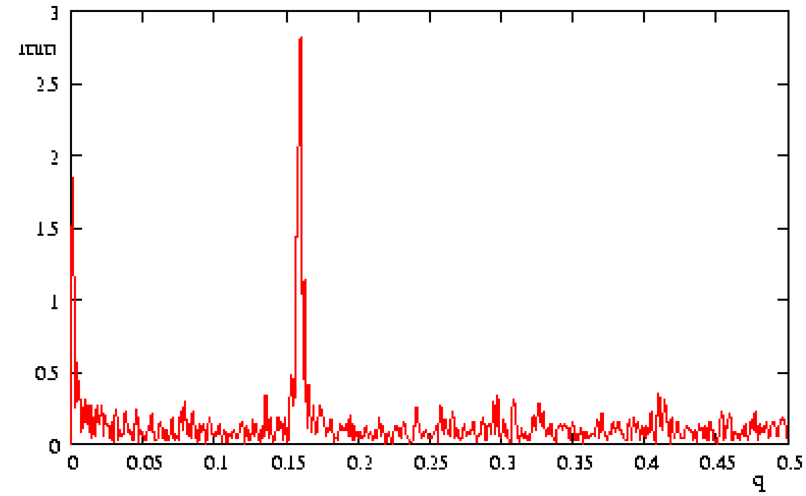



Design by P. Forck

# Kicker + 1 pick-up

- Measures only non-integral part of Q
- Measure a beam position at each revolution




Fourier transform of pick-up signal



Histograms by J. Belleman

# Further Reading

- P. Forck, Joint Universities Accelerator School (JUAS) Archamps, France
  Course notes: http://www-bd.gsi.de/conf/juas/juas.html
- Previous CERN Accelerator Courses
  (H. Koziol, Beam Diagnostics Jyväskylä )
- CAS on Beam Measurement 1998 Montreux (Switzerland)
- Proceedings of Diagnostics and Instrumentation for Particle Accelerators DIPAC (Europe) and Beam Instrumentation Workshop BIW (USA)