Beam Diagnostics for Ion Sources

CERN Accelerator School 2012

Uli Raich CERN BE/BI

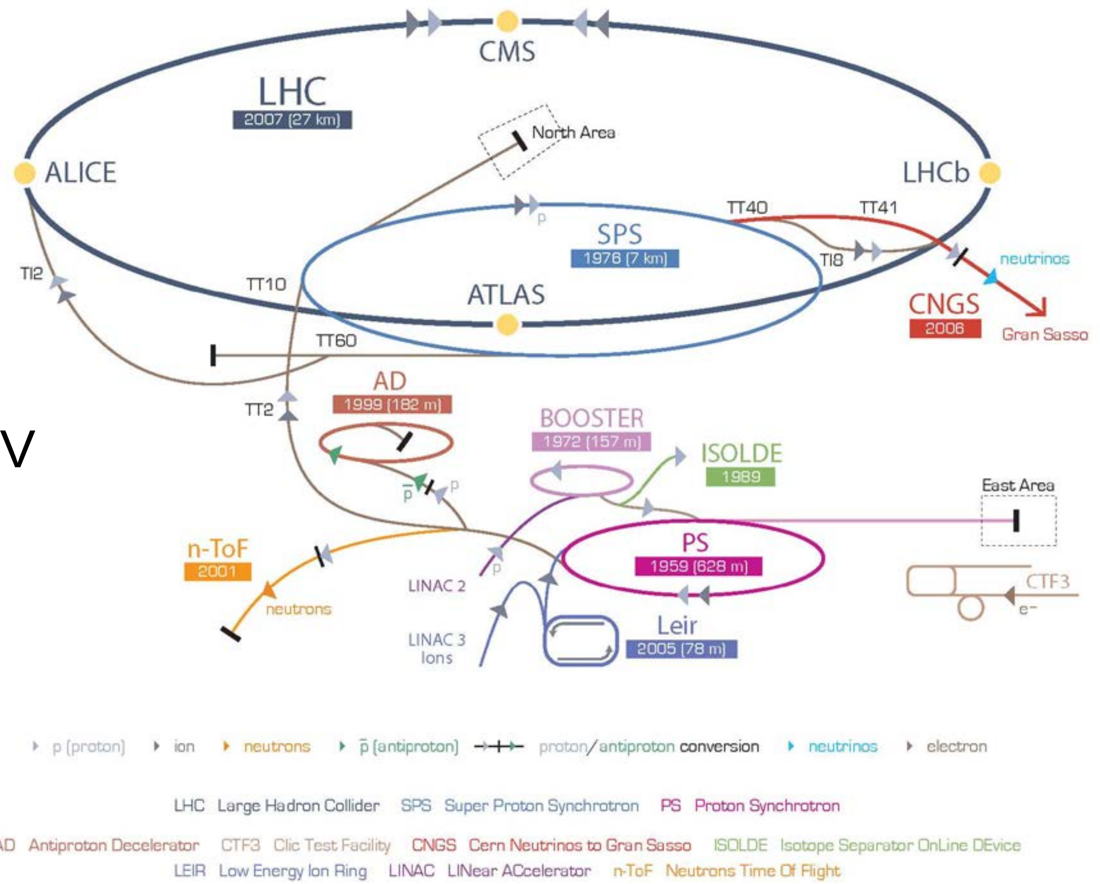
The LHC and its injectors

$$\mathscr{L} = f \frac{n_1 n_2}{4\sqrt{\epsilon_x \, \beta_x^* \, \epsilon_y \, \beta_y^*}}$$

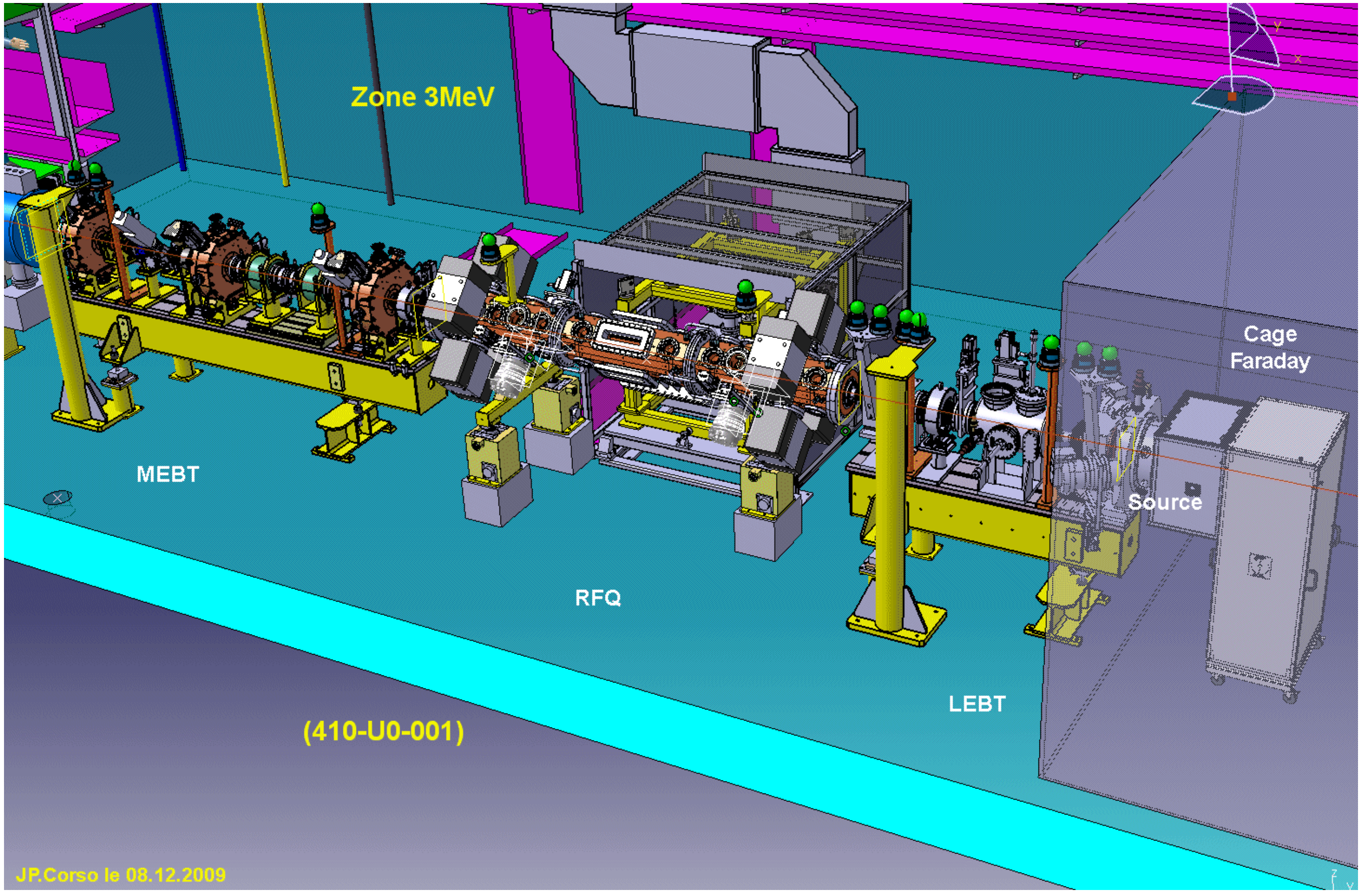
High particle density,
small emittance
-> high luminosity

CERN accelerator chain for Hadrons

- Source: up to 100 KeV
- RFQ: up to some MeV
- Linac: 50 Mev – few GeV
- Synchrotons: up to some TeV



Source and RFQ

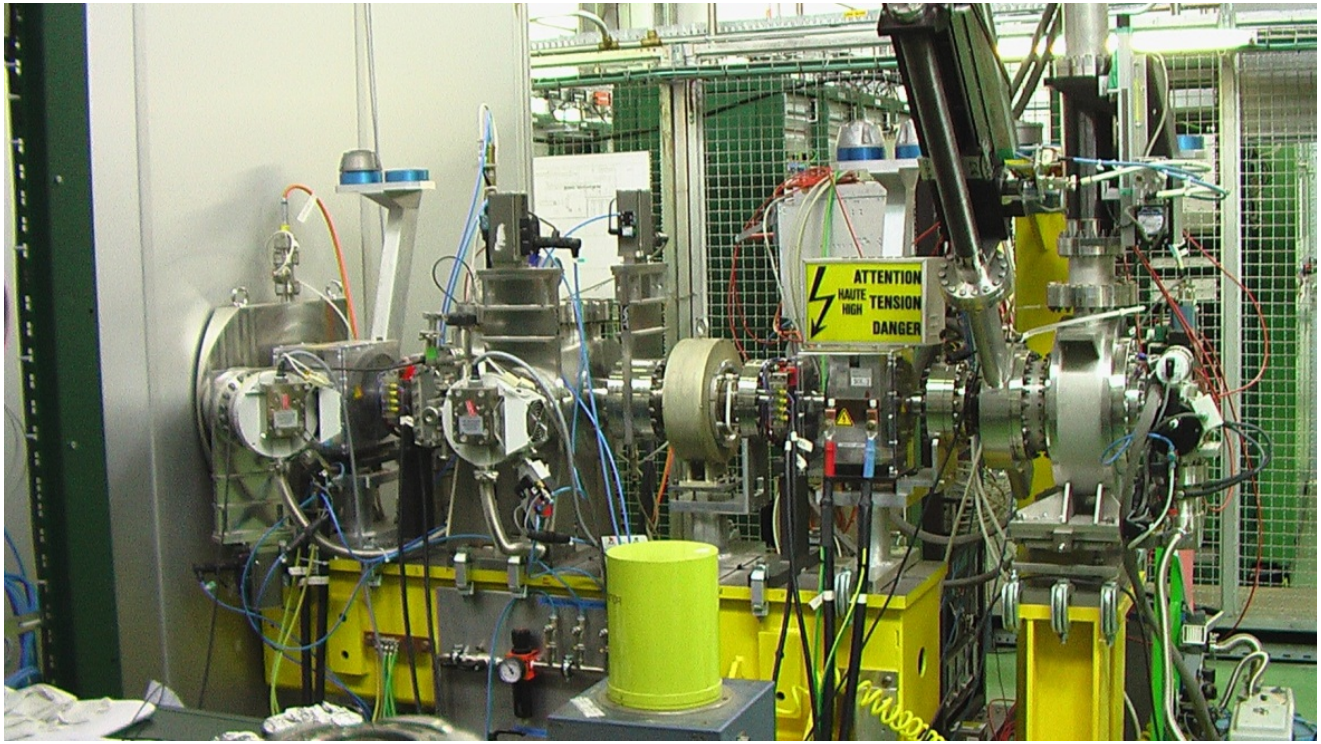


Source and LEBT determine beam properties later in the accelerator chain

Need to measure beam parameters before entering the RFQ

LEBT

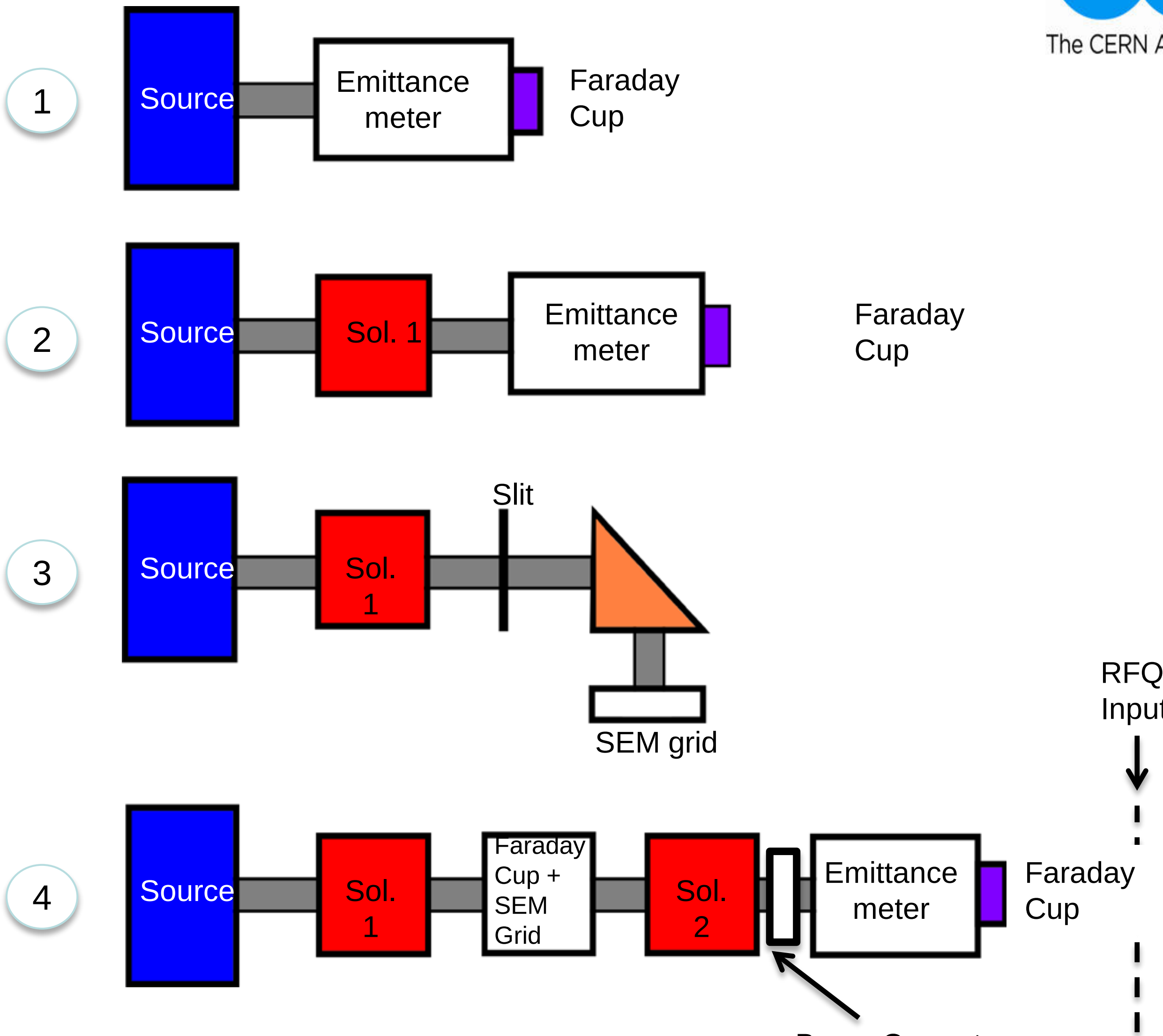
- Transport beam from the source to the RFQ



Parameters to be measured

- Beam Intensity
  - Faraday Cup (destructive)
  - Transformer (non destructive)
- Transverse Profile
  - Wire Harps and Wire Scanners
  - Residual Gas Monitors
- Transverse Phase space
  - Slit/Grid device
  - Allison Scanner
  - Pepperpot
- Energy and Energy Spread
  - Spectrometer

LEBT Commissioning Stages



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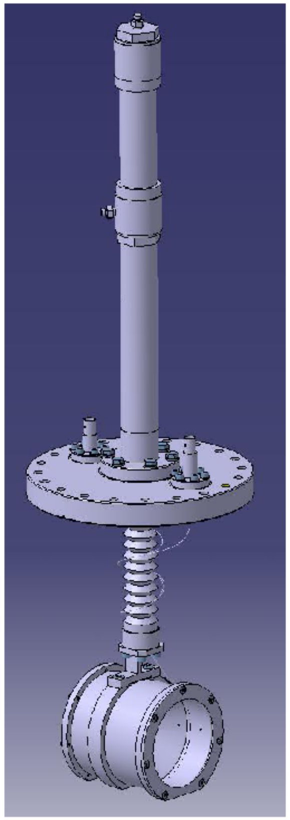
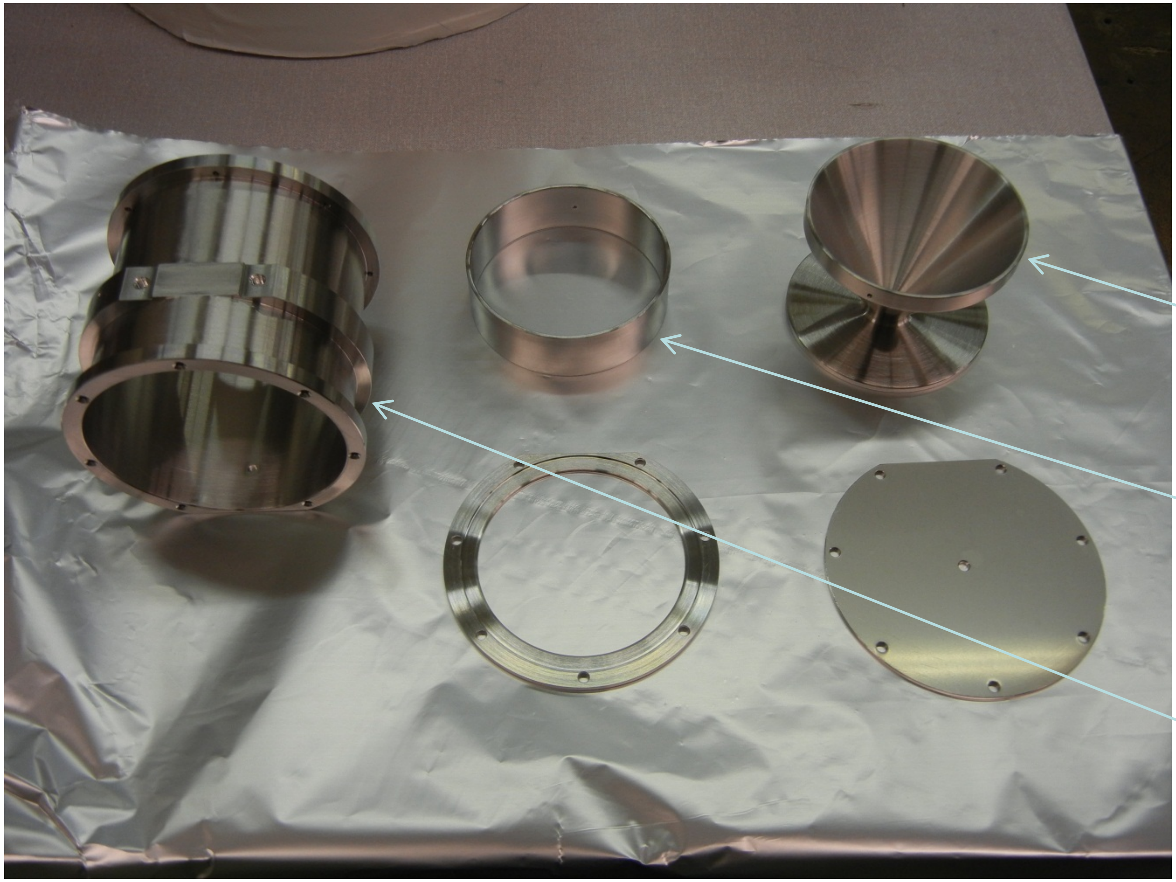
Faraday Cup



- Source intensity measured by a retractable Faraday Cup
- Secondary electron emission is suppressed by polarization voltage which also eliminates parasitic electrons created in the source
- Pneumatic in/out mechanism on PLC is used to enter and retract the cup into/from the beam
- Oscilloscope is used for signal observation
- A ~ 1 MHz sampling ADC may be used to acquire the Faraday Cup signal

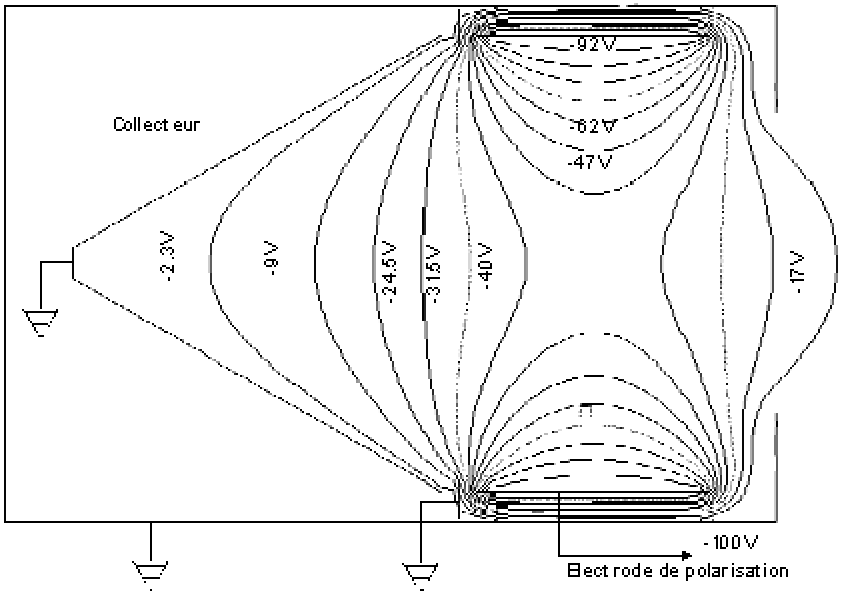
Faraday Cup pieces



Electro-static Field in Faraday Cup

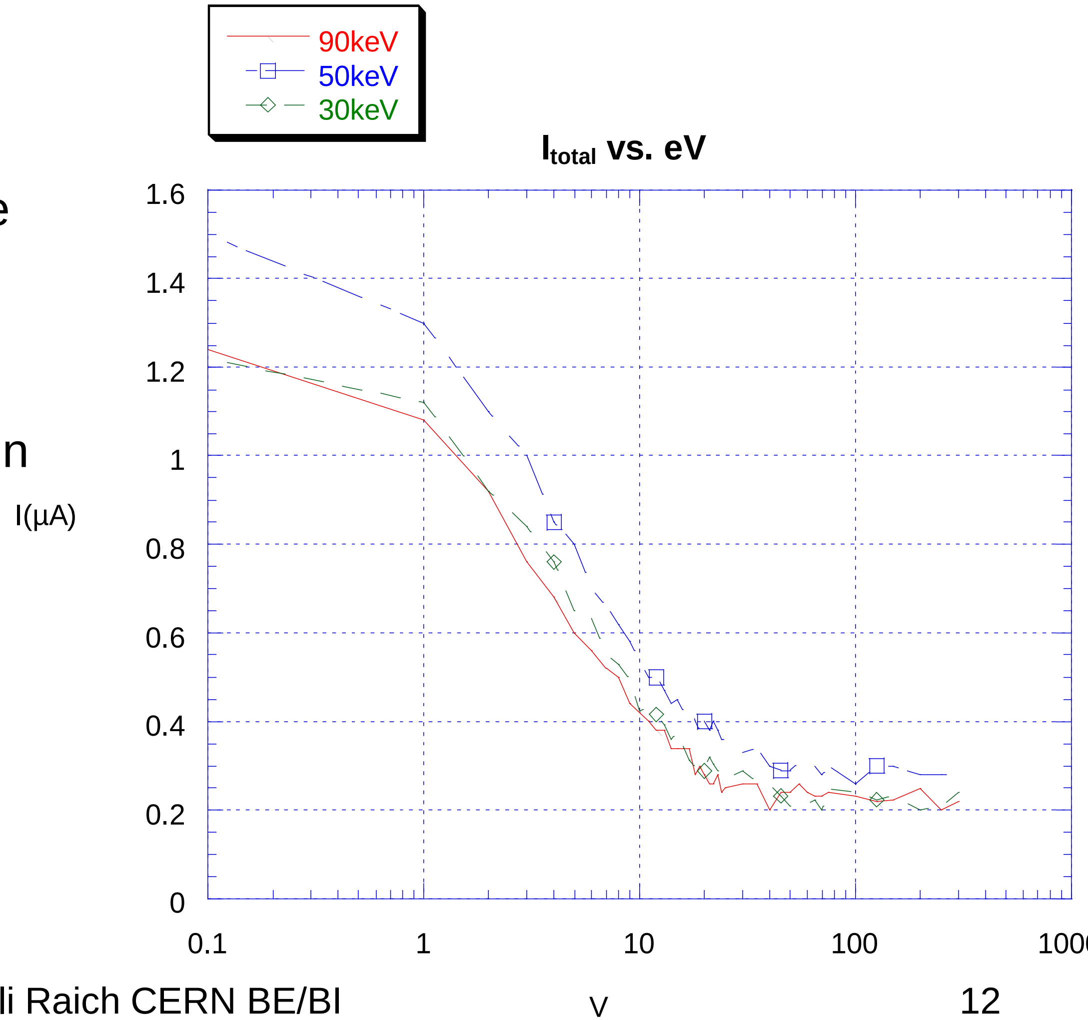
In order to keep secondary electrons within the cup a repelling voltage is applied to the polarization electrode

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

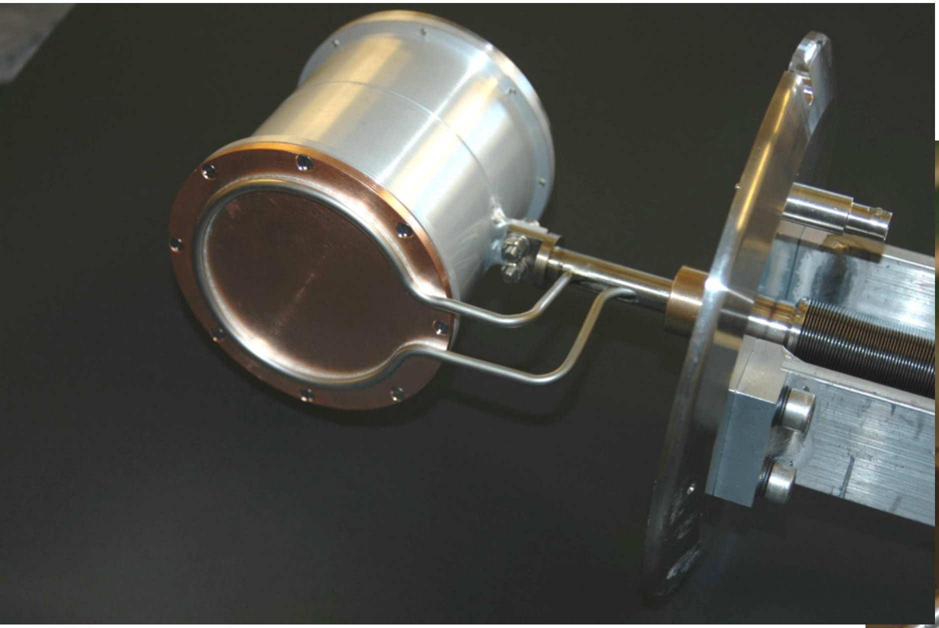


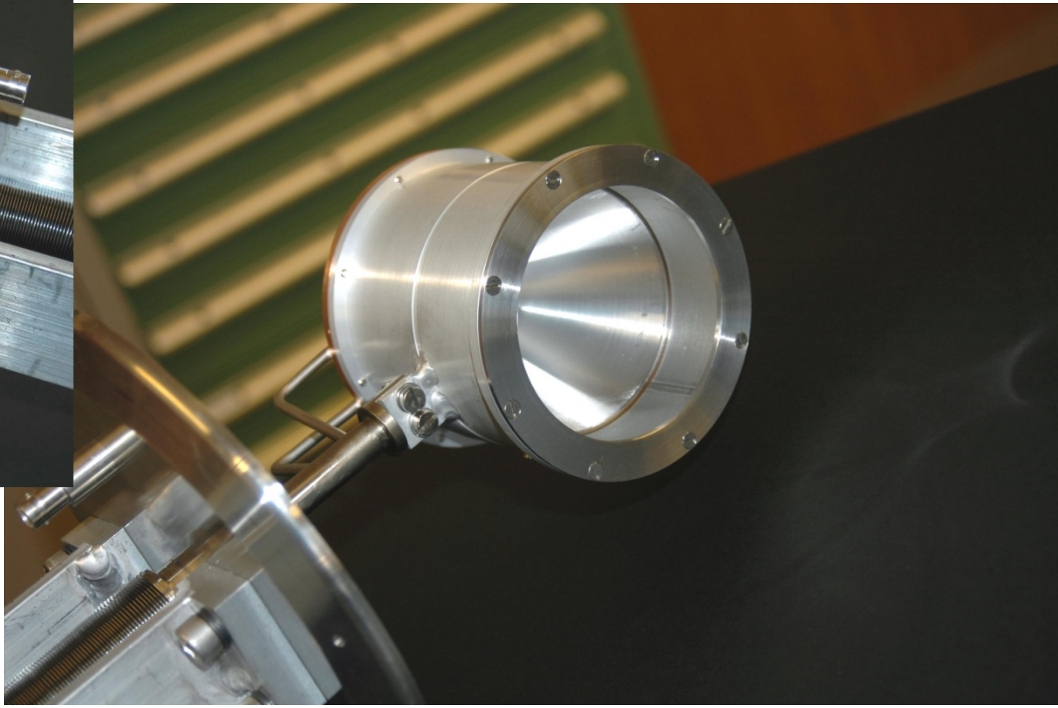
Energy of secondary emission electrons

- 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

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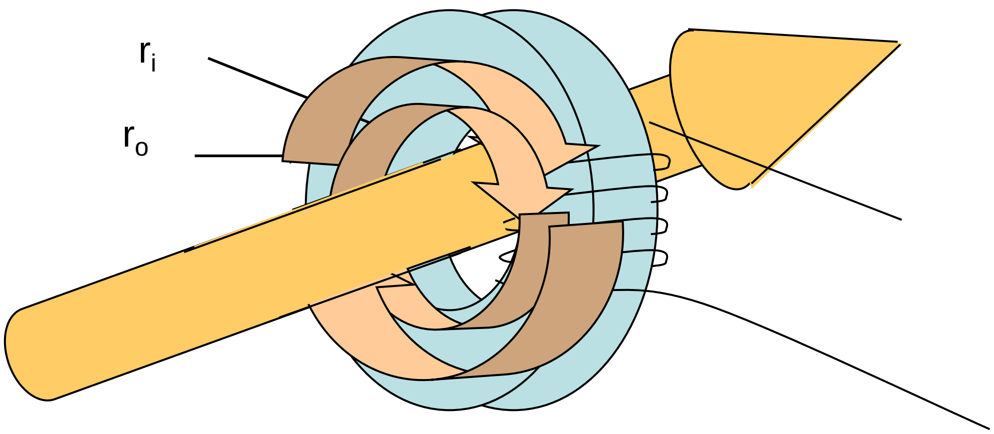
Current Transformers



Fields are very low

Capture magnetic field lines with cores of high relative permeability

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

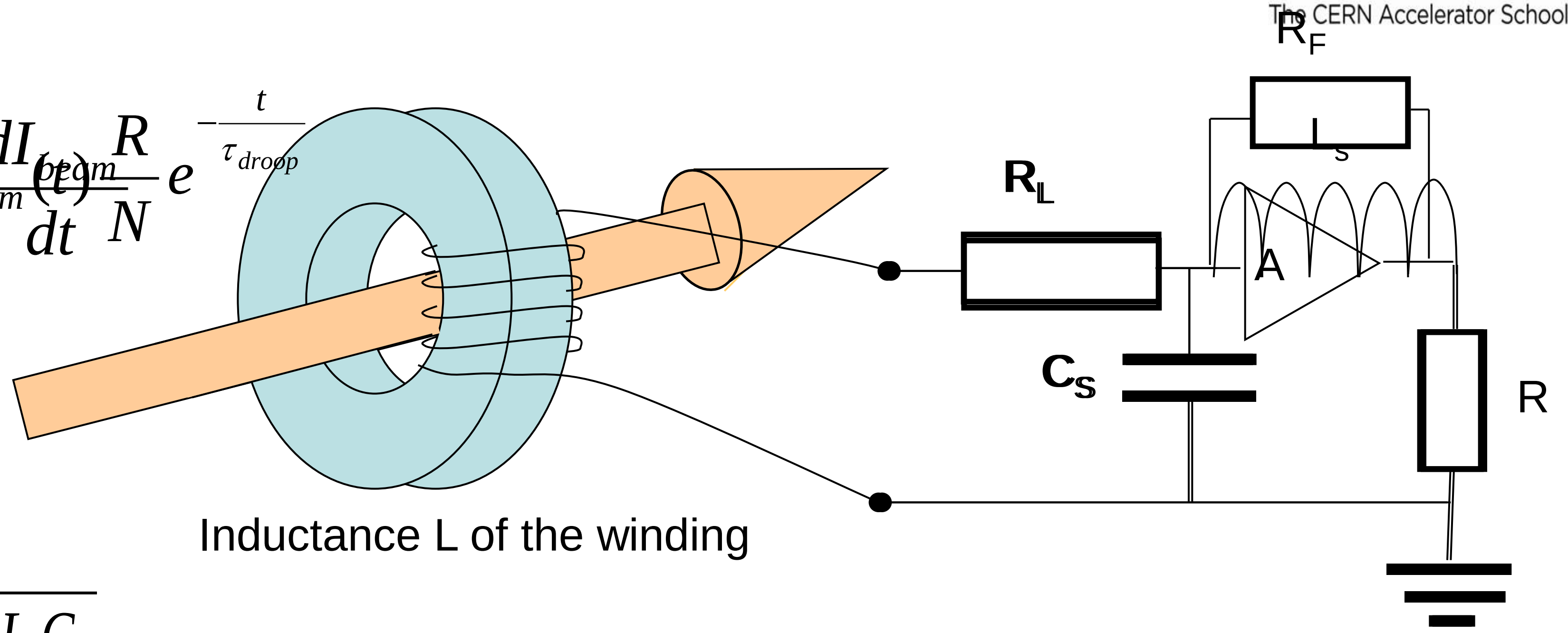
$$I_{beam} = \frac{qeN}{t} = \frac{qeN\beta c}{l}$$

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

The passive AC transformer / The ideal transformer

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

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

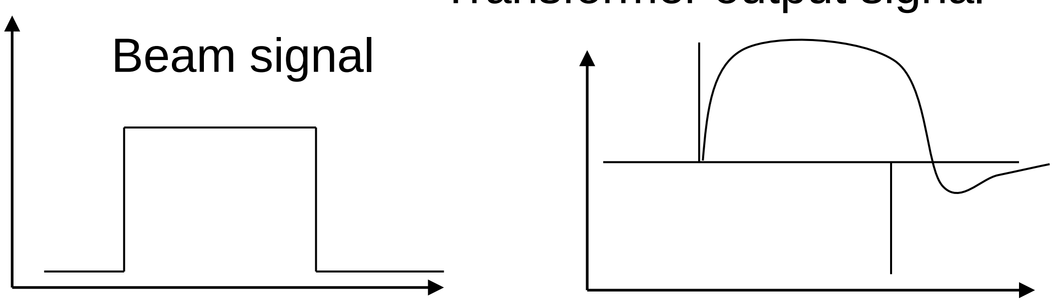


Inductance L of the winding

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

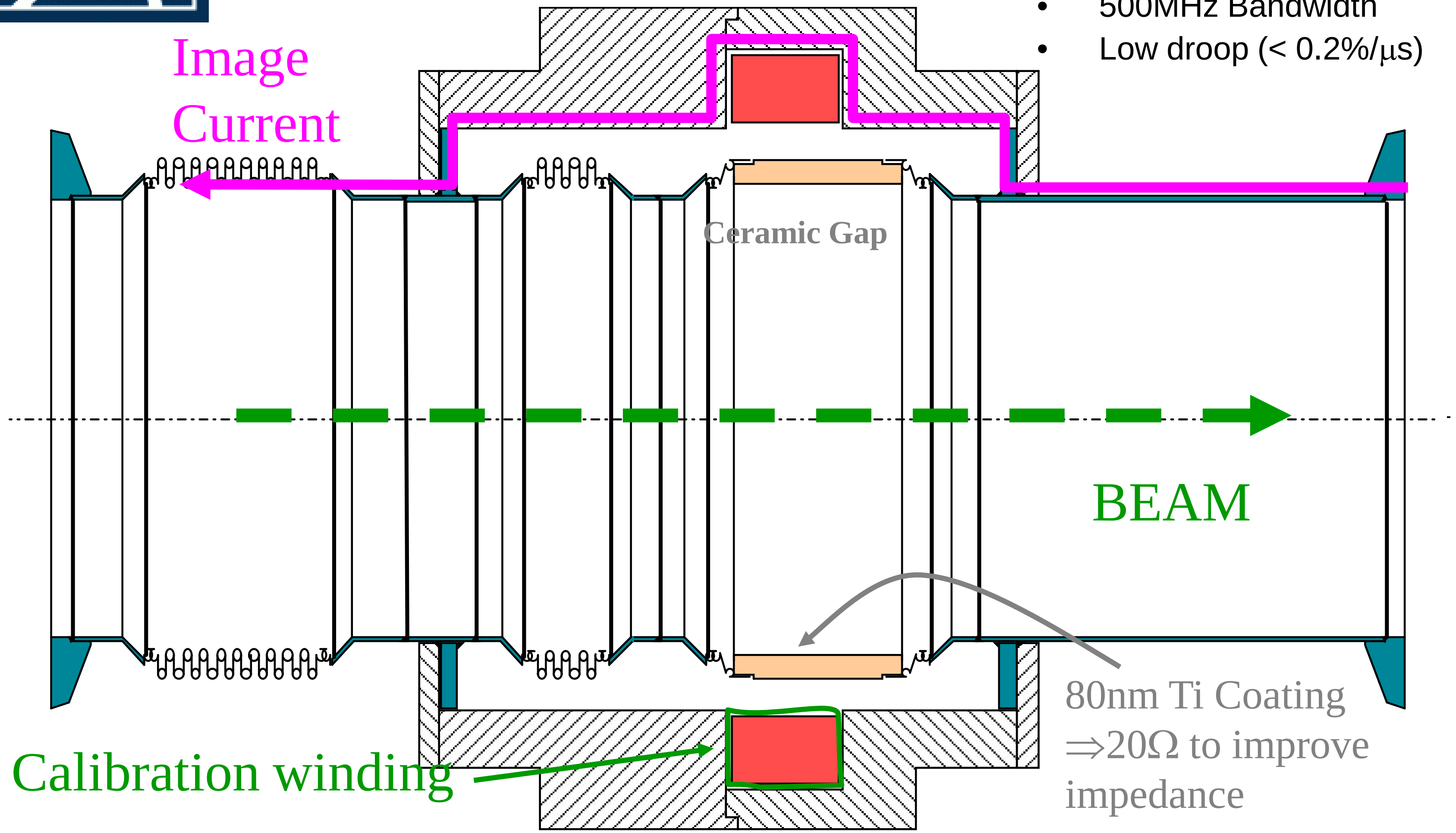
$$\tau_{droop} = \frac{L}{R + R_L} \approx \frac{L}{R_L}$$

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



Principle of a fast current transformer

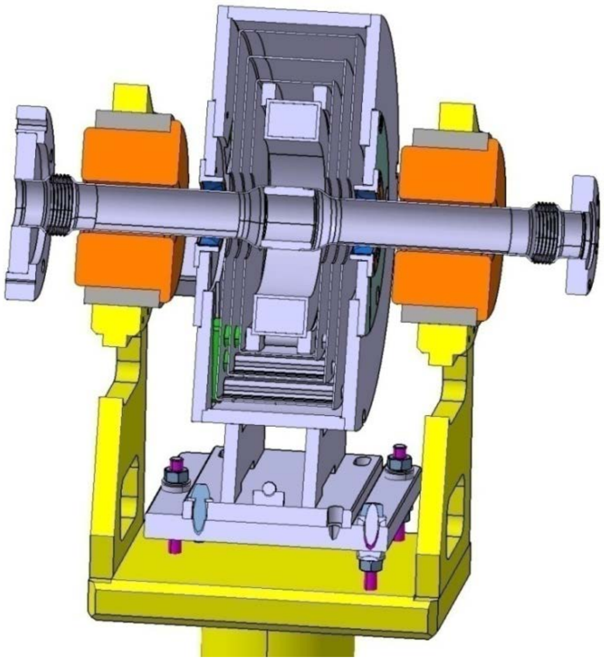
- 500MHz Bandwidth
- Low droop (< 0.2%/μs)

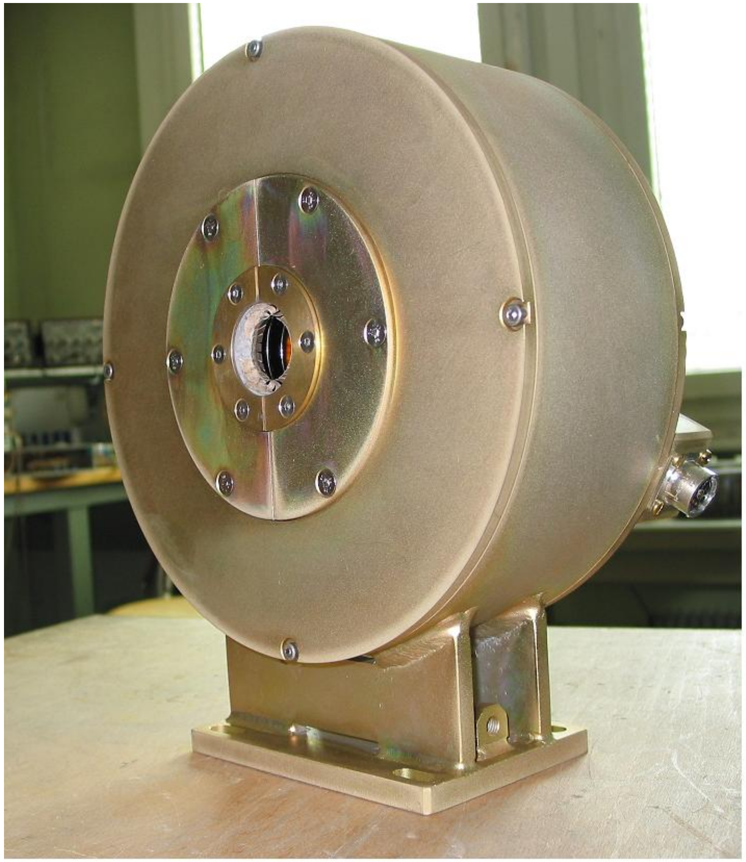


Current Transformers

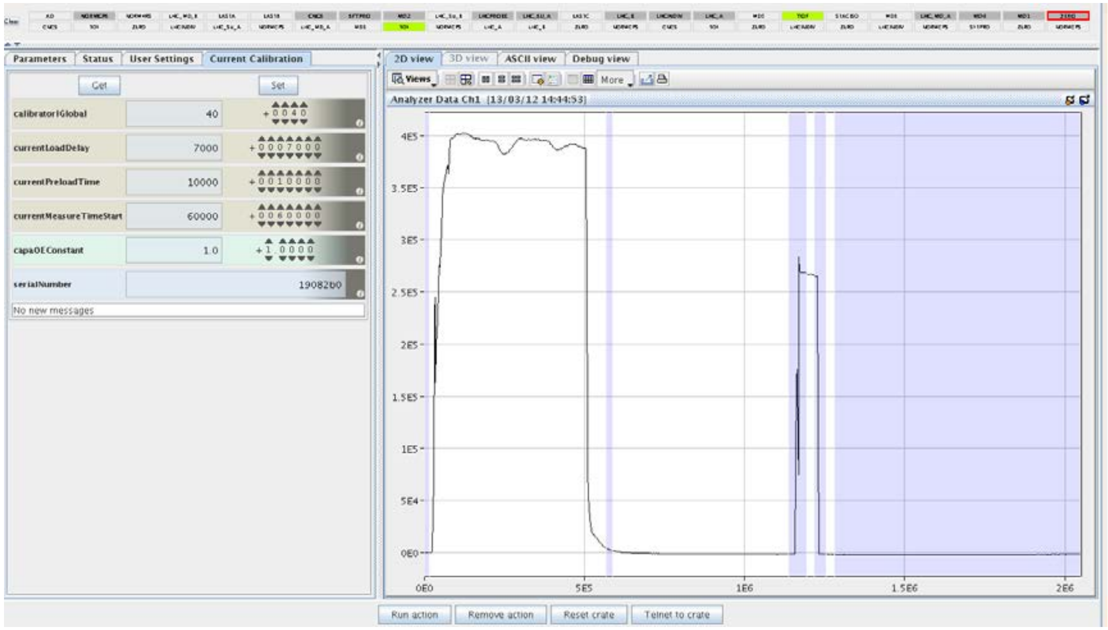
Good magnetic shielding avoids interference from nearby pulsing magnets

Shielding simulation and test measurements have been done





Typical Transformer Signal



Calibration signal before after beam pulse

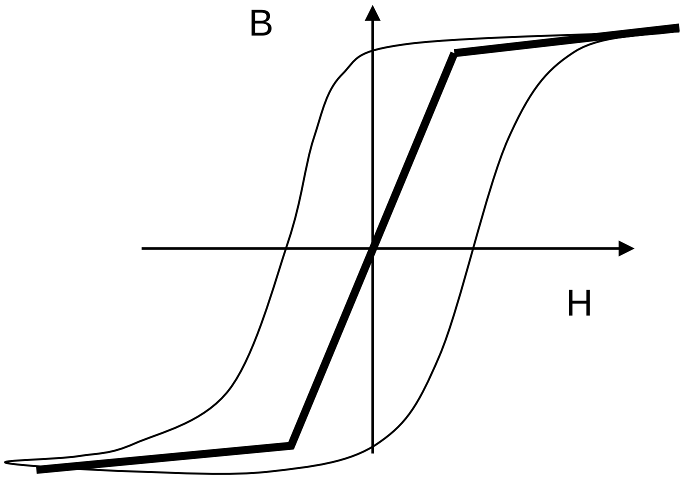
Digitization of 400 µs pulse at 10 MHz

Measures
- total intensity
- intensity per Booster ring

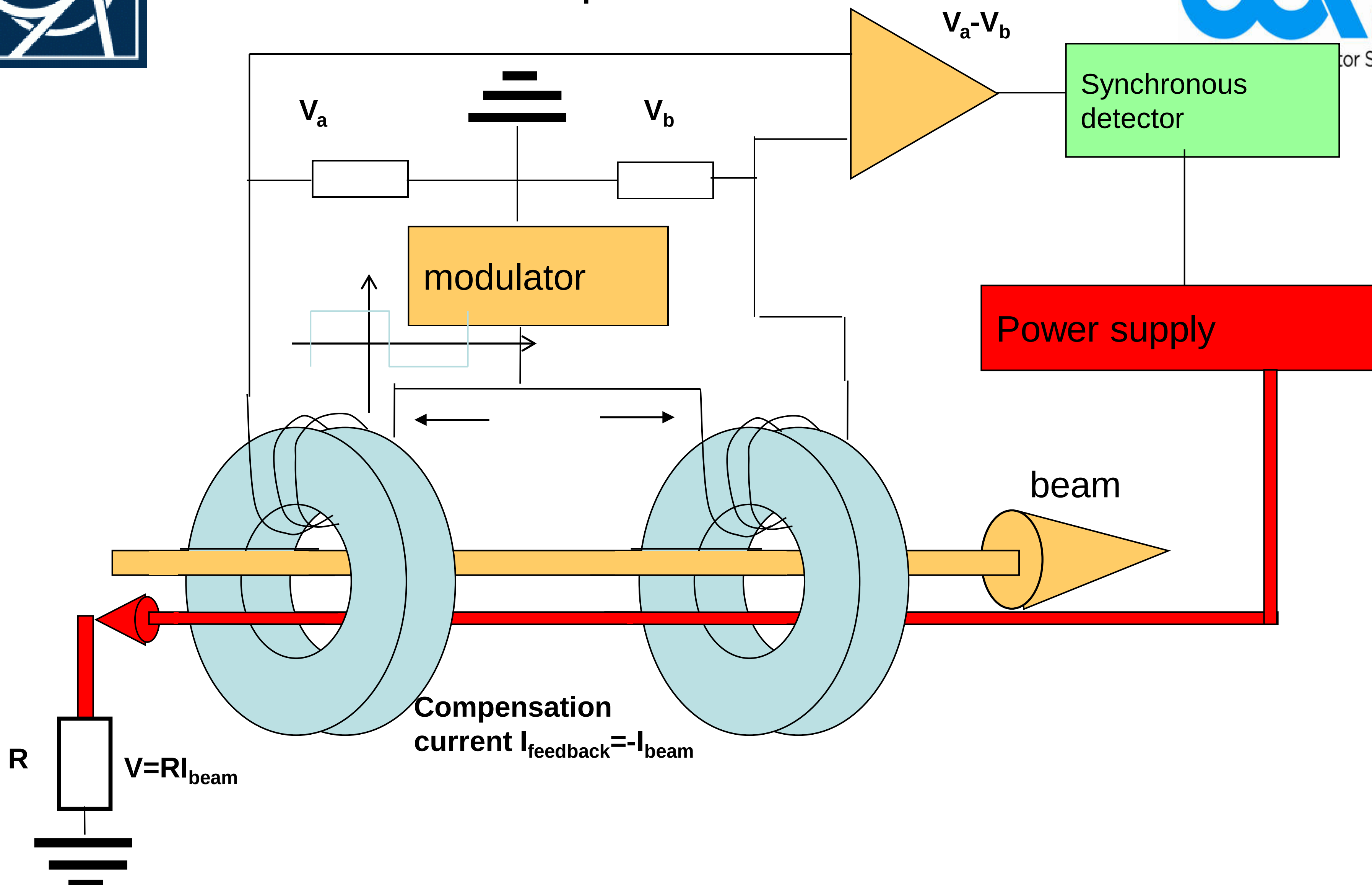
Background suppression by software

The DC current transformer

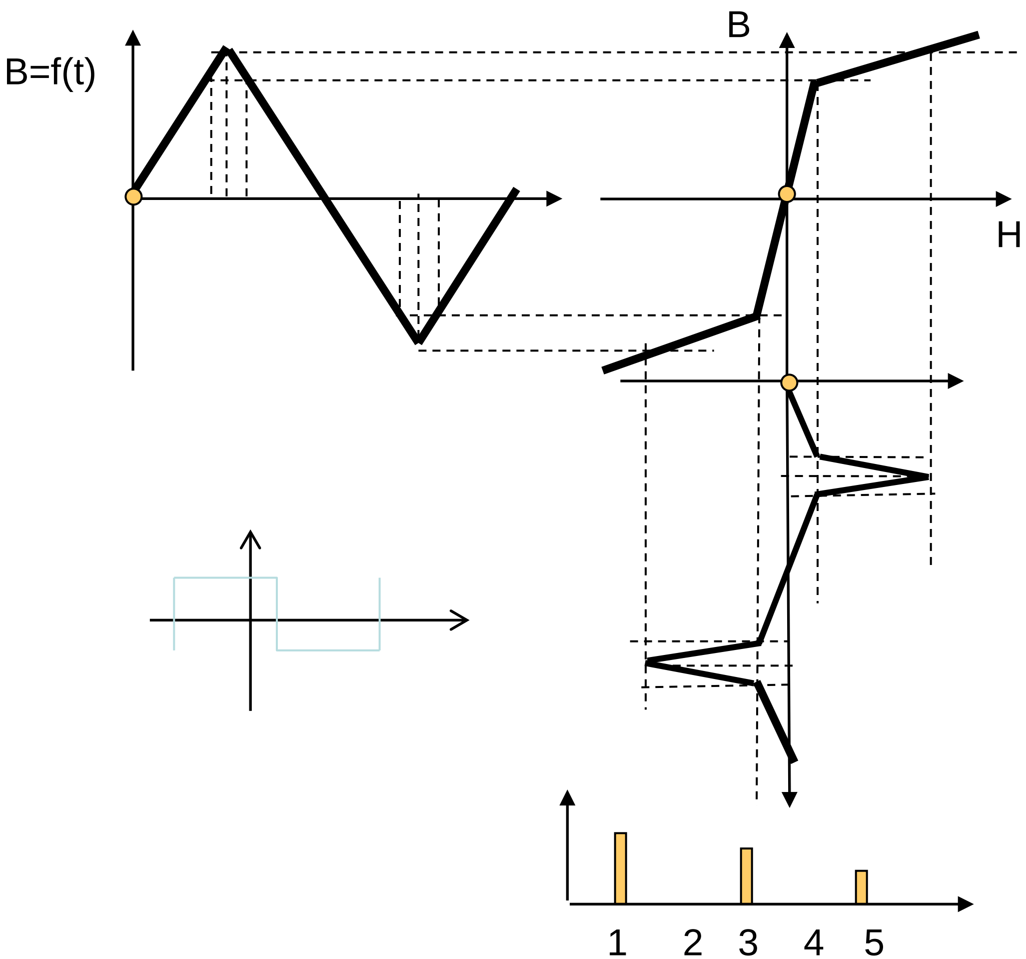
- AC current transformer can be extended to very long droop times but not to DC
- Measuring DC currents is needed on DC ion sources
- Must provide a modulation frequency
- Takes advantage of non/linear magnetisation curve



Principle of DCCT



Modulation of a DCCT without beam

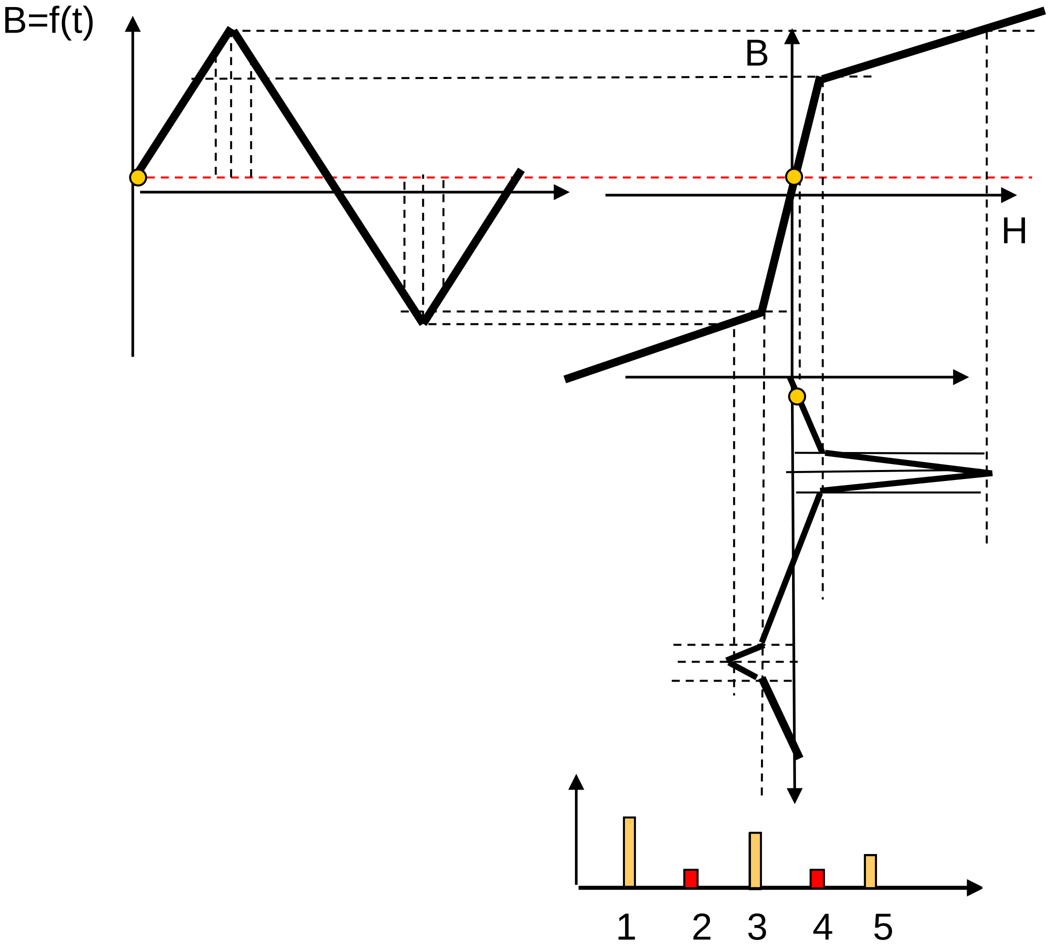


$$U = NA\frac{dB}{dt}$$

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

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

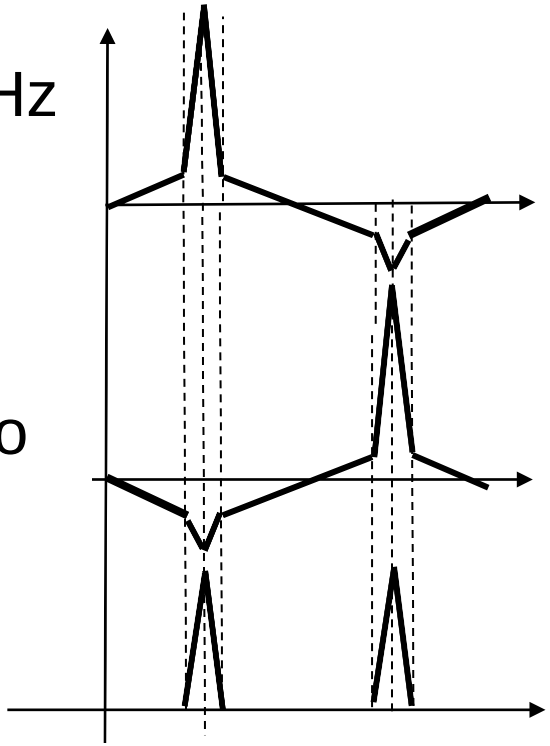


Photo of DCCT internals

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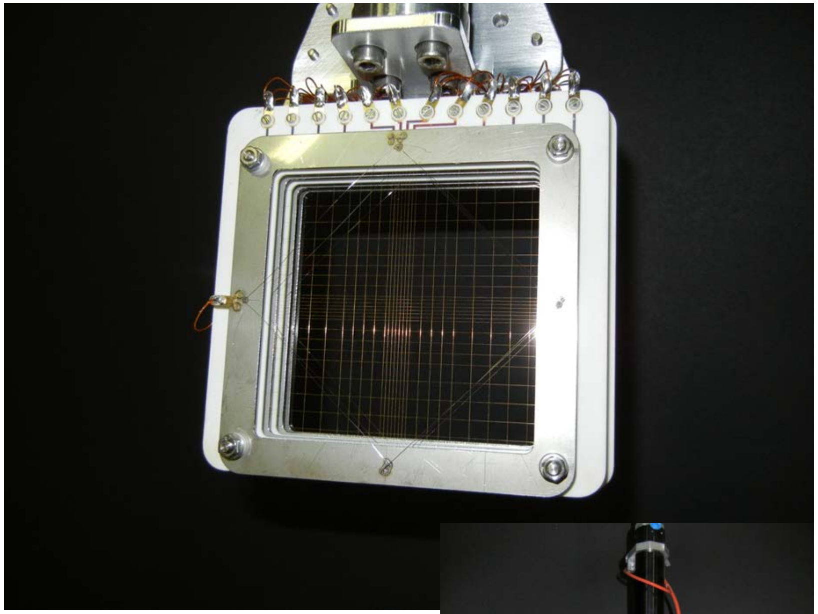
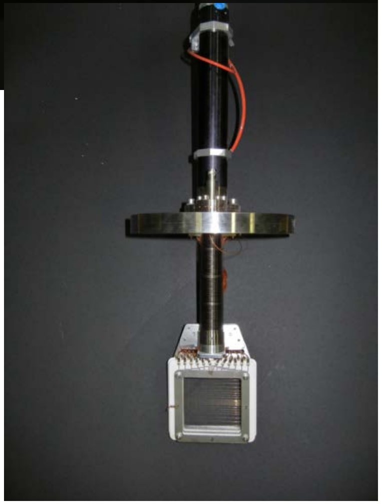
SEMGrids for Profile Meas.

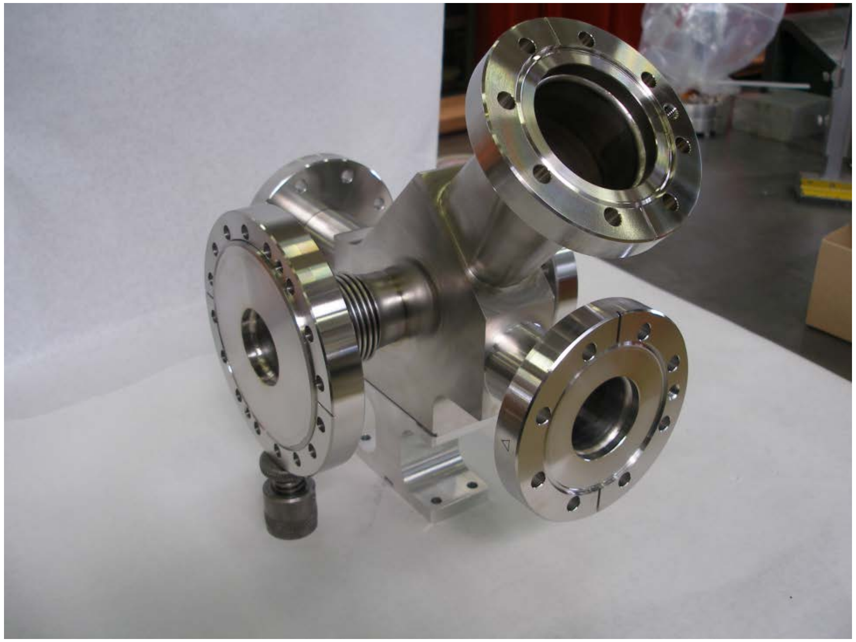


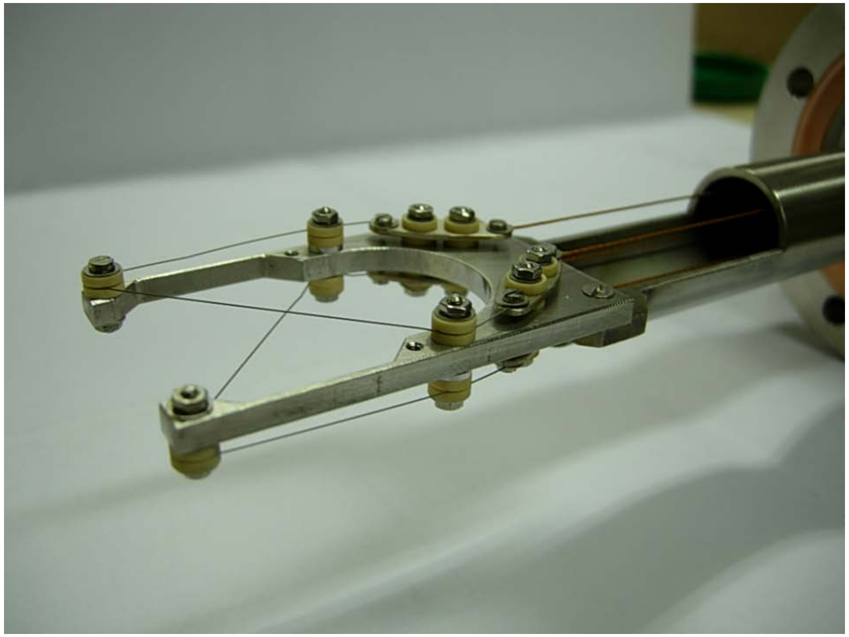


- SEMGrid resolution: up to 0.5mm, up to 36 wires
- New analogue electronics for 36 under design
- Needs time resolved measurements (200 kHz)
- New VME readout card has been developed (36 channels), series of 50 cards have been produced
- In/out mechanism by motor with PLC control

Wire Scanners

Slowly drives the wire through the beam
Measures wire position and collected current on the wire
Reconstructs the beam profile





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Ionisation Profile Monitor

- An **Ionization Profile Monitor** (IPM) measures beam profile by collecting rest gas molecules/electrons ionized by the beam.
- The ions/electrons are guided by electric field to MCP
- Gas injection may be needed to increase yield
- Micro-channel plates age, and need to be replaced.

P. Forck GSI

Luminescence Monitor

- **Gas fluorescence monitor** measures light emitted by atoms/molecules excited by the beam.
- Cross sections much lower than for ionization
- Light emittance isotropically.
- What is the rest gas pressure?

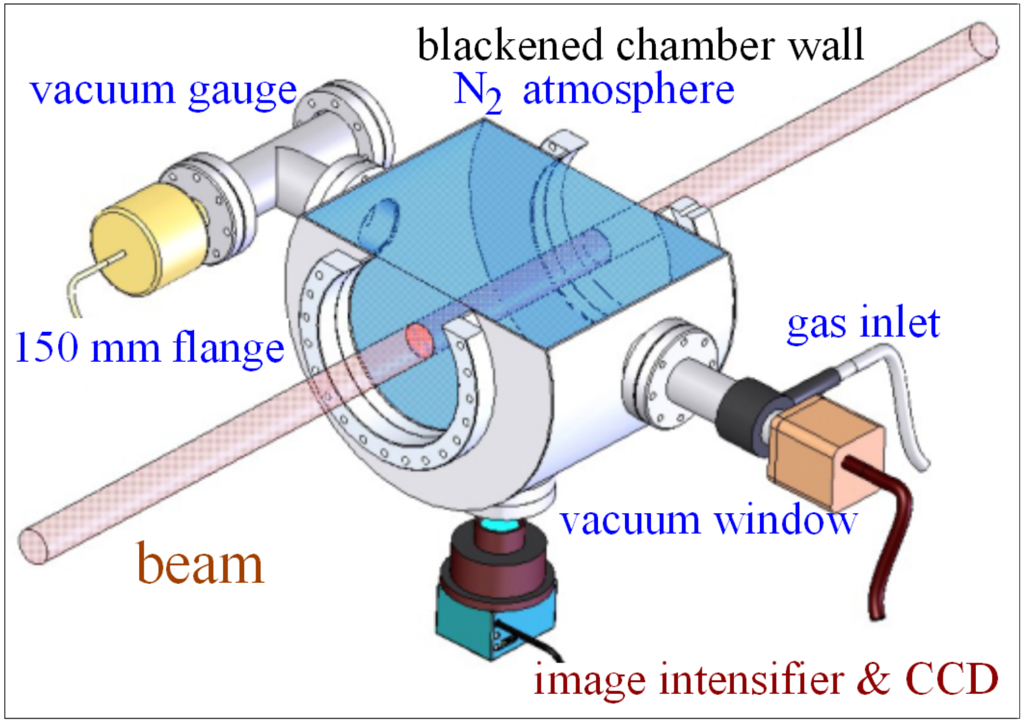

Figure 1: Scheme of a BIF-Monitor.

F. Becker et al, GSI

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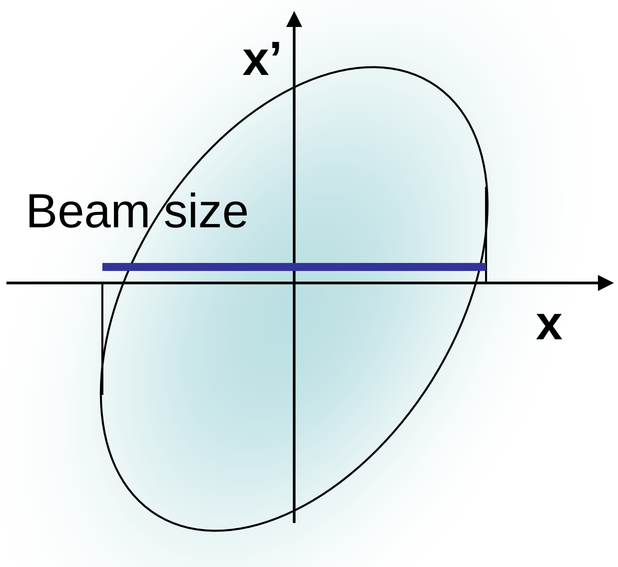
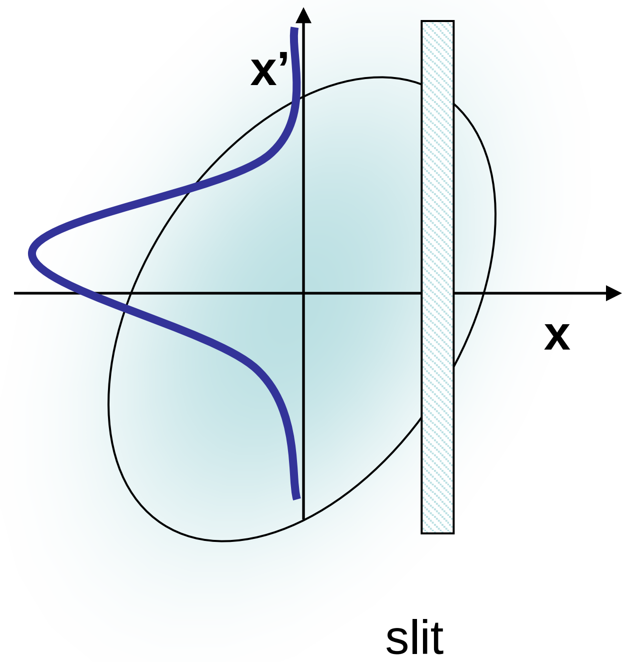
Emittance measurements

- 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



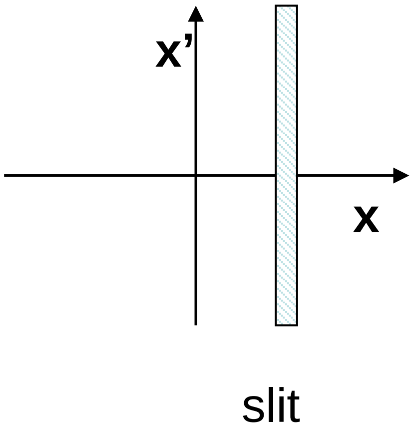
The slit and grid method

- 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

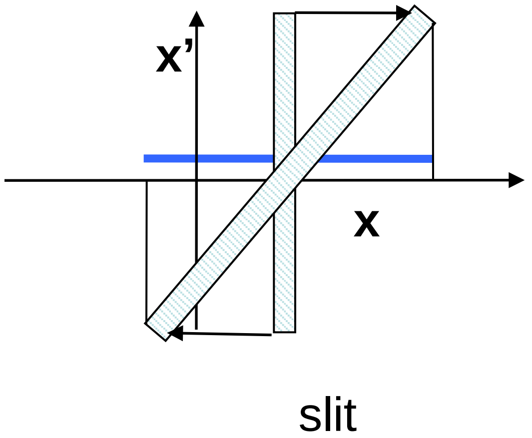


Transforming angular distribution to profile

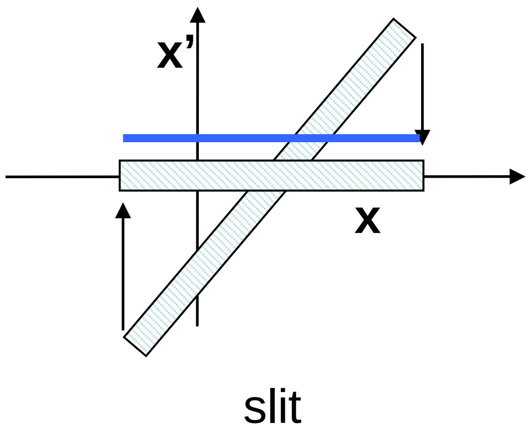
- When moving through a drift space the angles don't change (horizontal move in phase space)
- When moving through a quadrupole the position does not change but the angle does (vertical move in phase space)



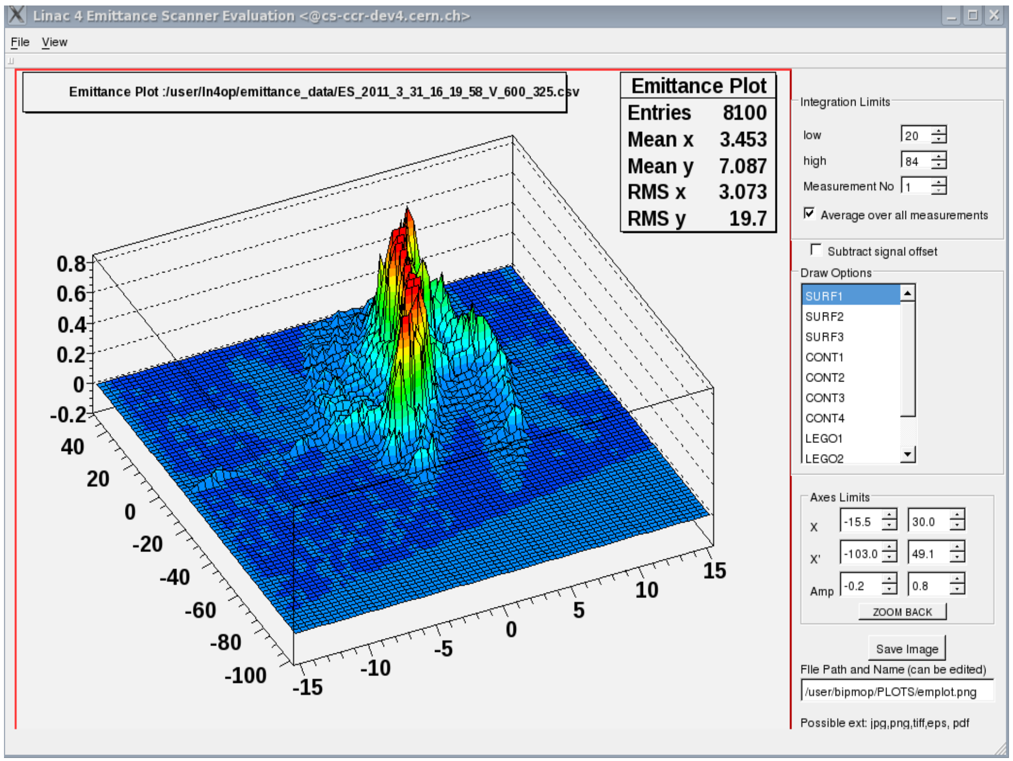
Influence of a drift space

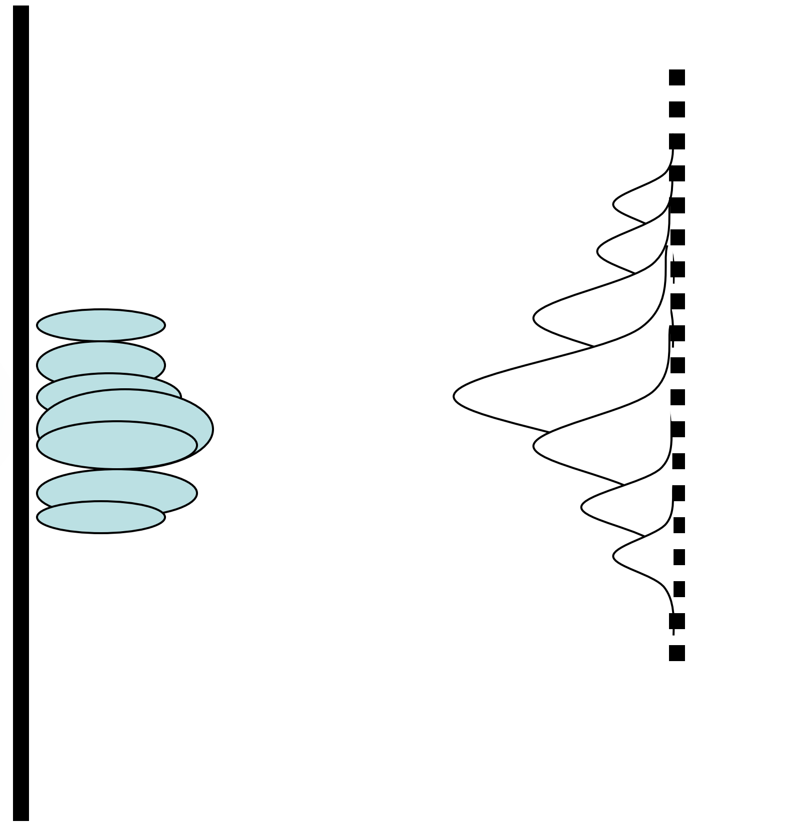


Influence of a quadrupole



The Slit Method

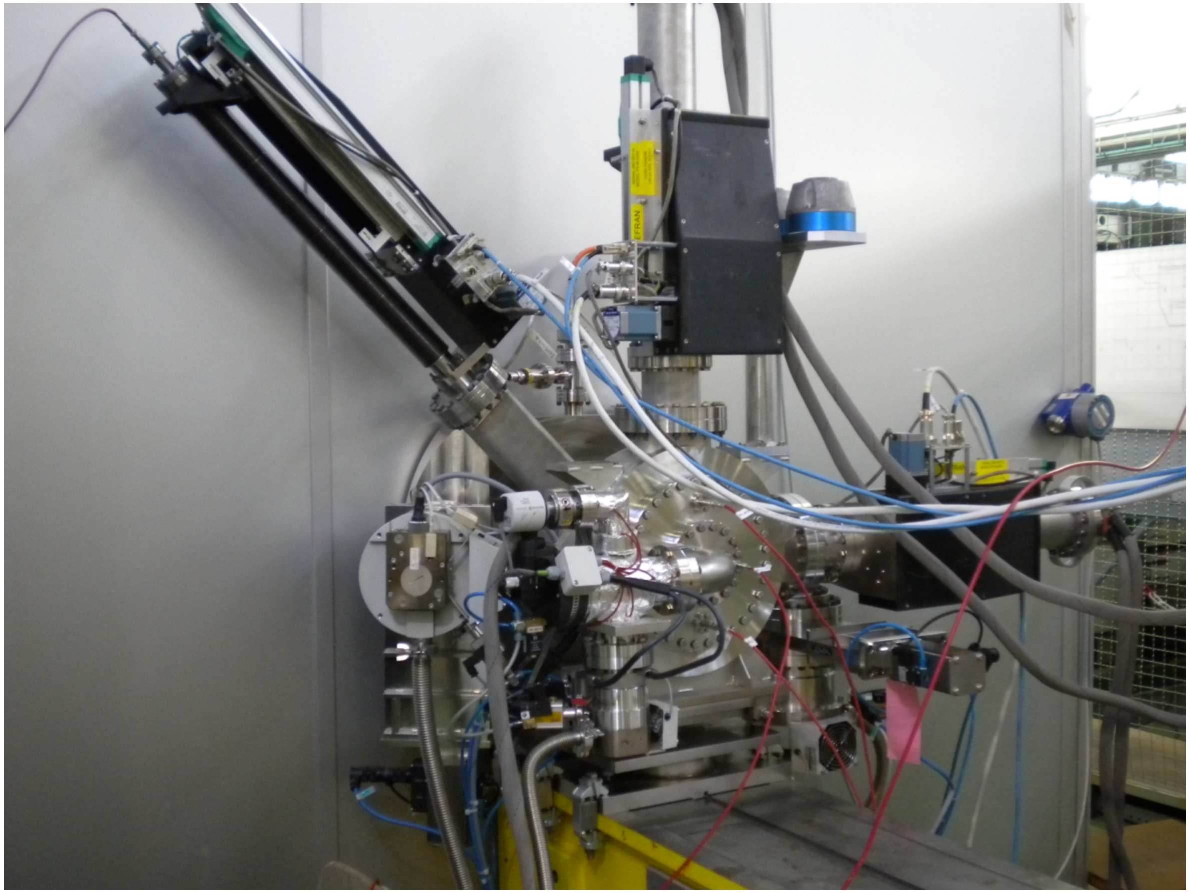




Emittance Meter

- SEM grid read-out 250kHz
- Stepping motors to allow coarse + fine position tuning

Transverse Emittance Measurement



Slit and grid phase space scanner

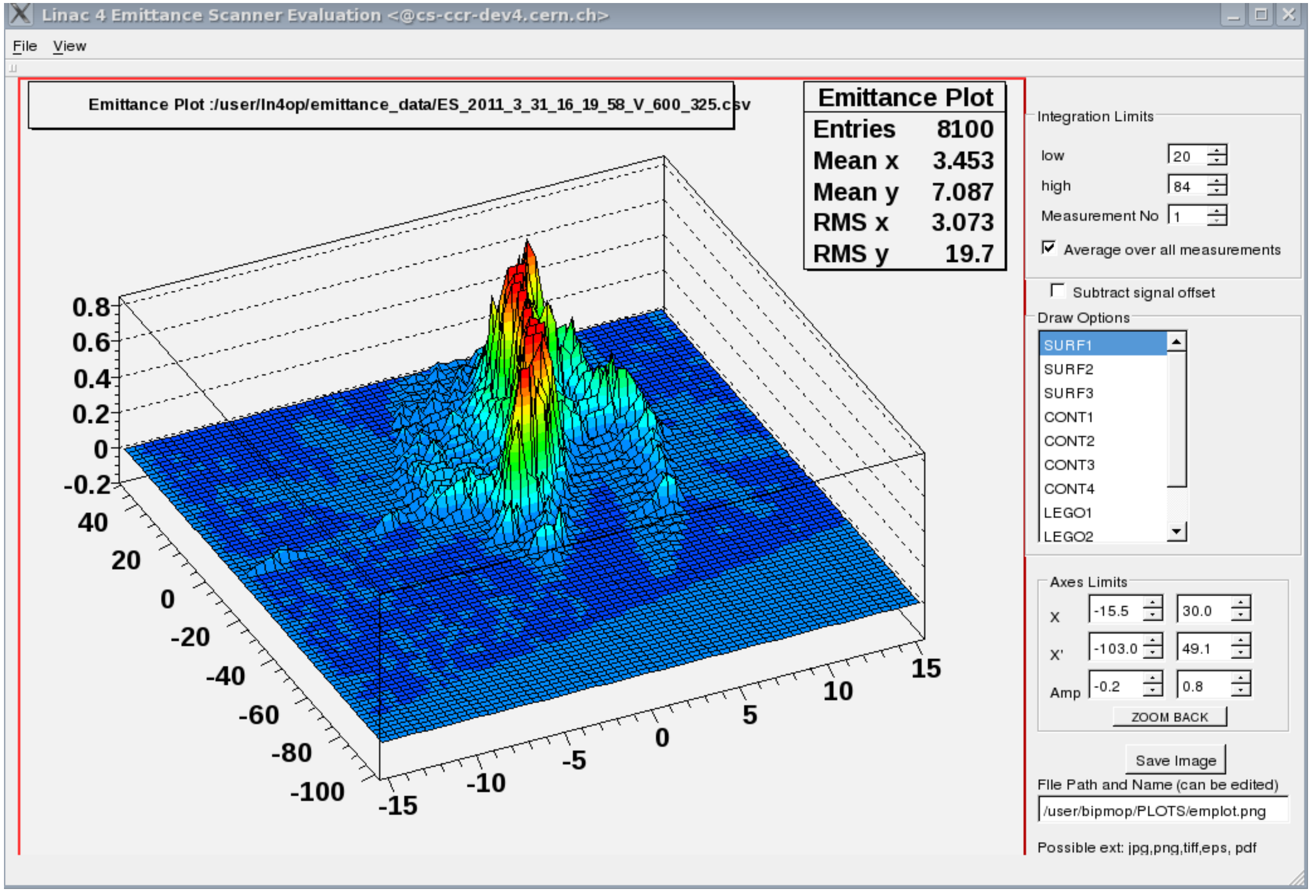
L-shaped 0.1mm slit moves under 45 degrees

Slit and grids move independently
Positioning precision: 50 µm
Movement PLC controlled

Slit and grids mounted in 2 independent vacuum boxes which can be separated

Horizontal and vertical SEMGrid
- wire distance .75 mm
- 30 signal wires
- readout with home built 36 channel 250 kHz ADC
- time resolved profiles

Emittance Evaluation



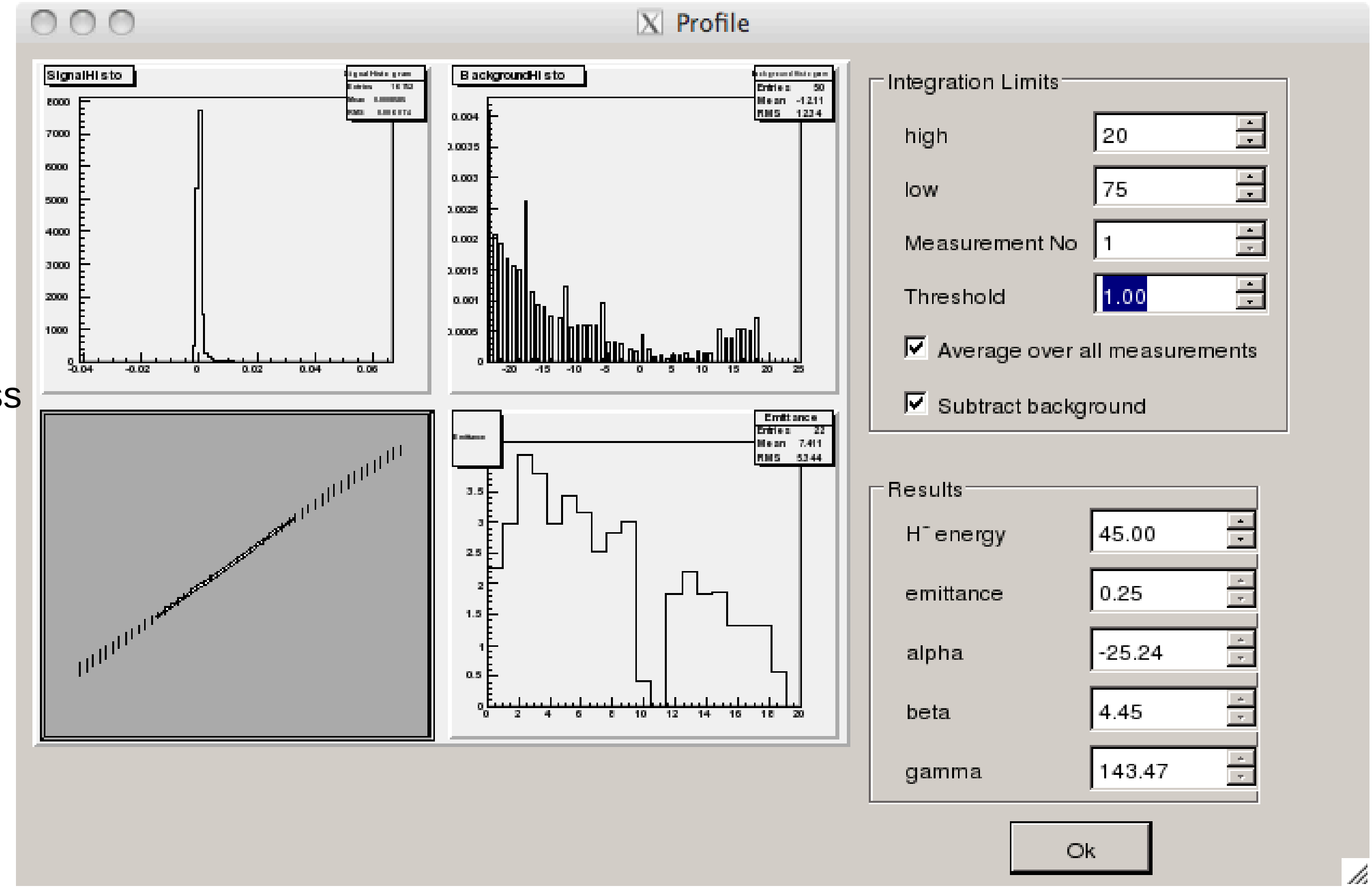
Pseudo Scubexx evaluation

Histogram of signal levels

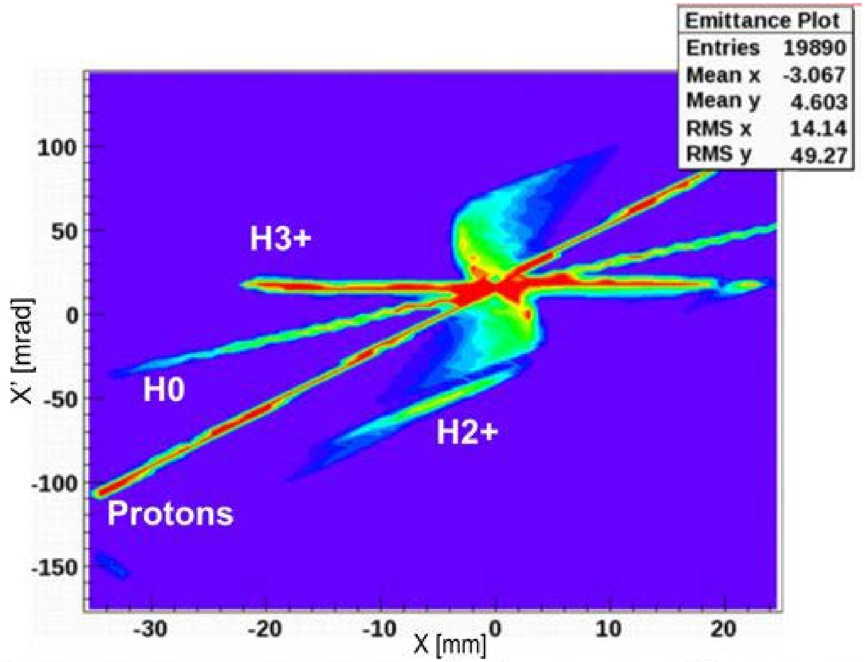
Background for each slit Position

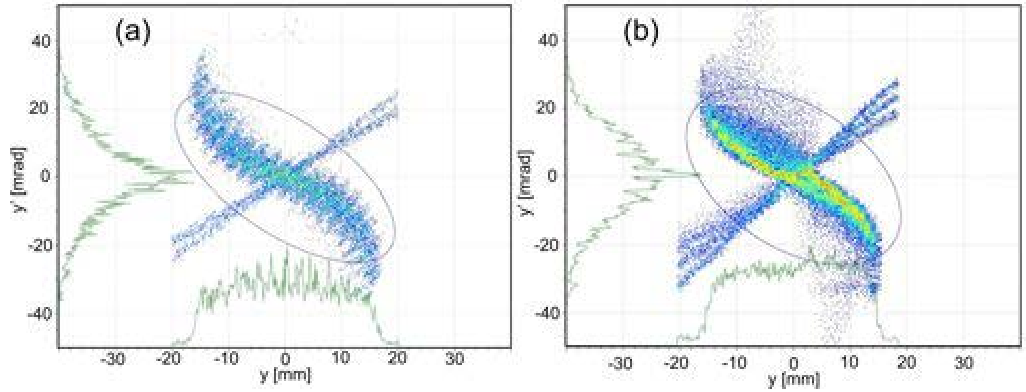
Emittance Plot

Emittance when taking less and less channels around peak



Emittance plot Solenoid





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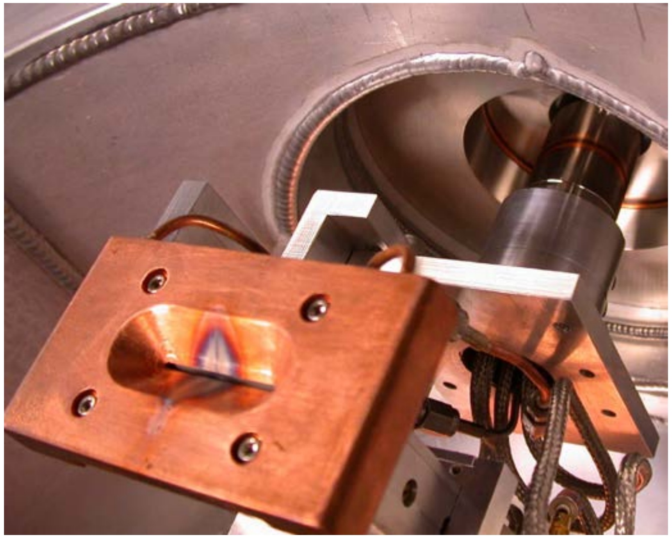
Allison Scanner

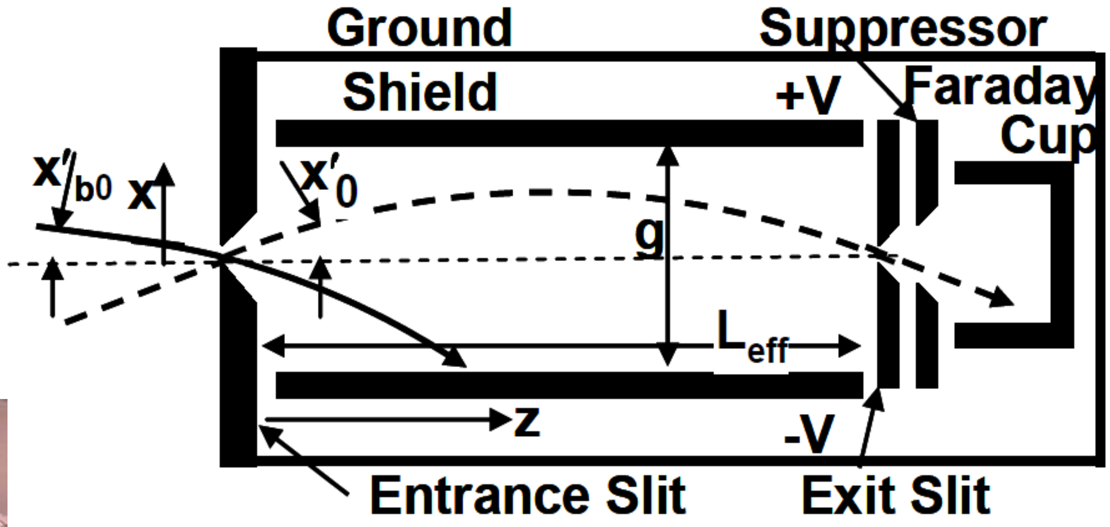
The whole detector is passed through the beam

Slit defines position

Deflection plates with ramped electric field determine particle angles

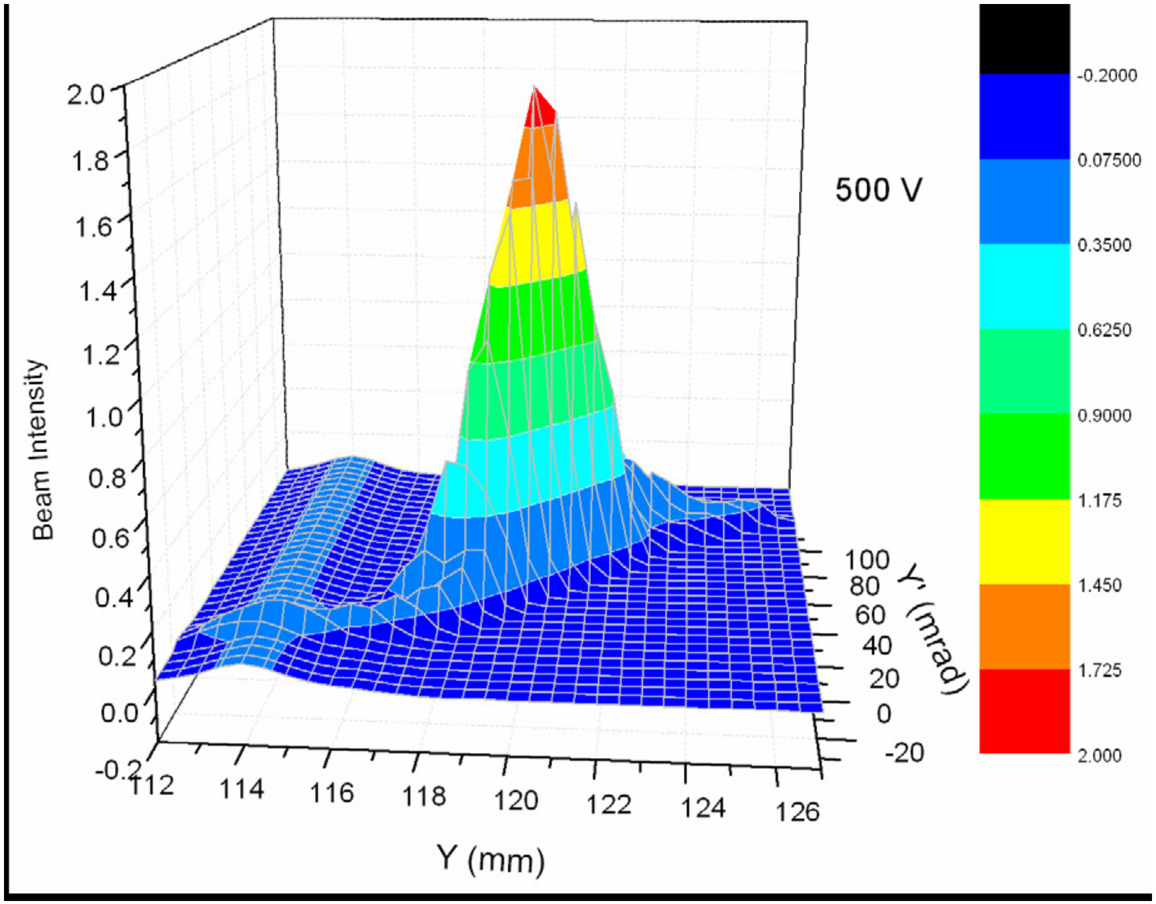
Angle distribution is measured with a Faraday Cup





M. Stöckli, ORNL

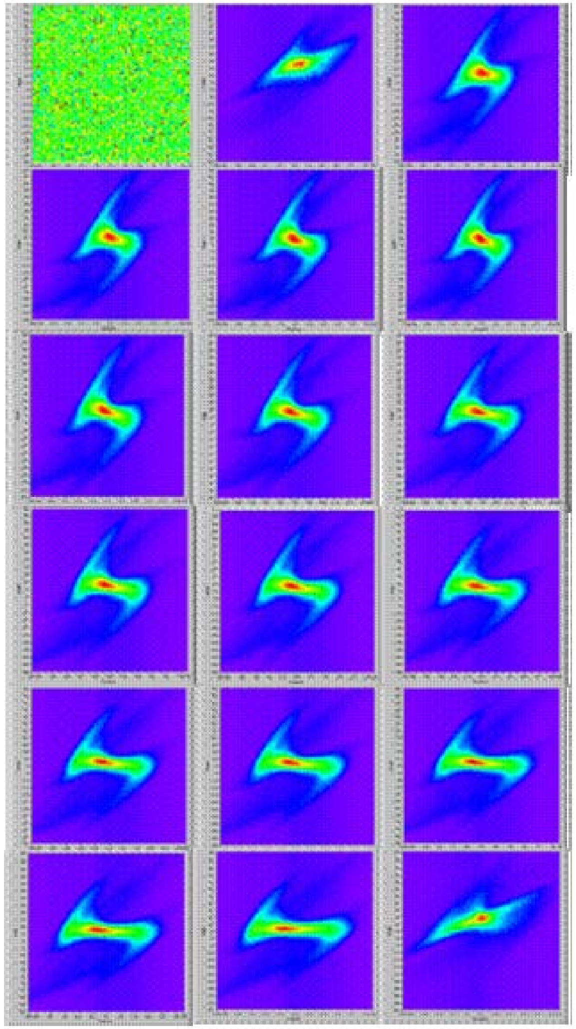
Allison Scanner results SNS



Apply 10% threshold to get rid of background

Emittance results along time axis

- First plot: no beam yet
- Big changes during the first 2 time slices (source plasma not stabilized yet)
- Then only small changes
- Last time slice: Big change due to decaying plasma when RF is switched off.



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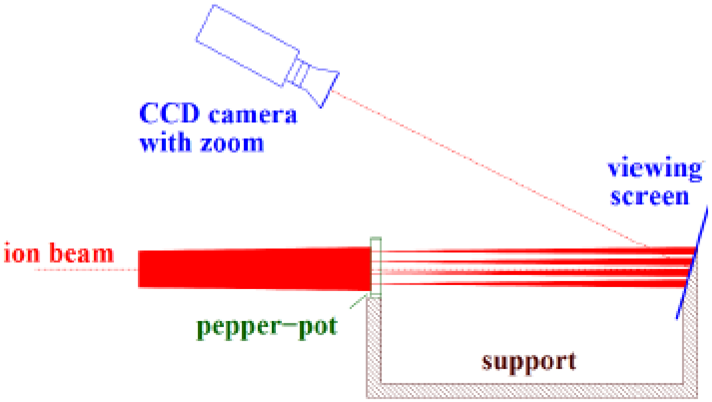
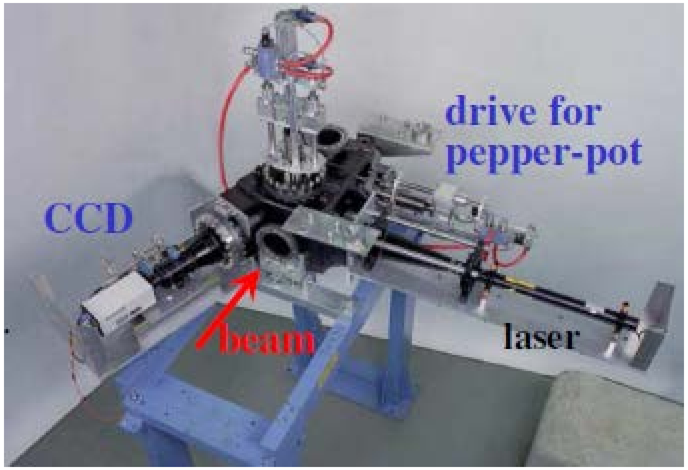
Pepperpot Emittance Measurement

Advantage: Single shot measurement

Pepperpot: 15x15 holes on copper plate
Luminescent screen
Data acquisition: high resolution CCD
Example from GSI Darmstadt





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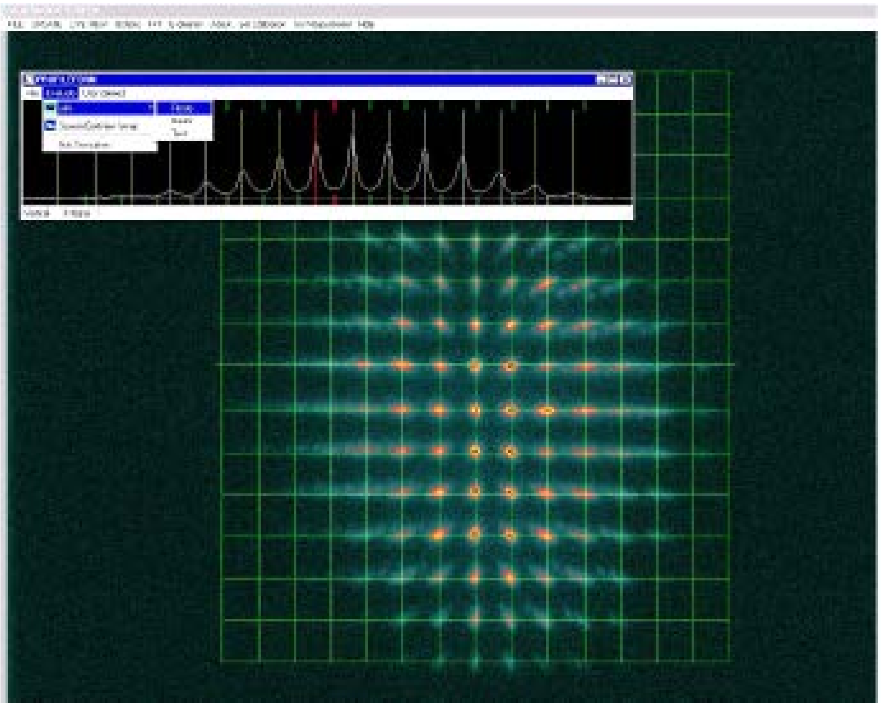
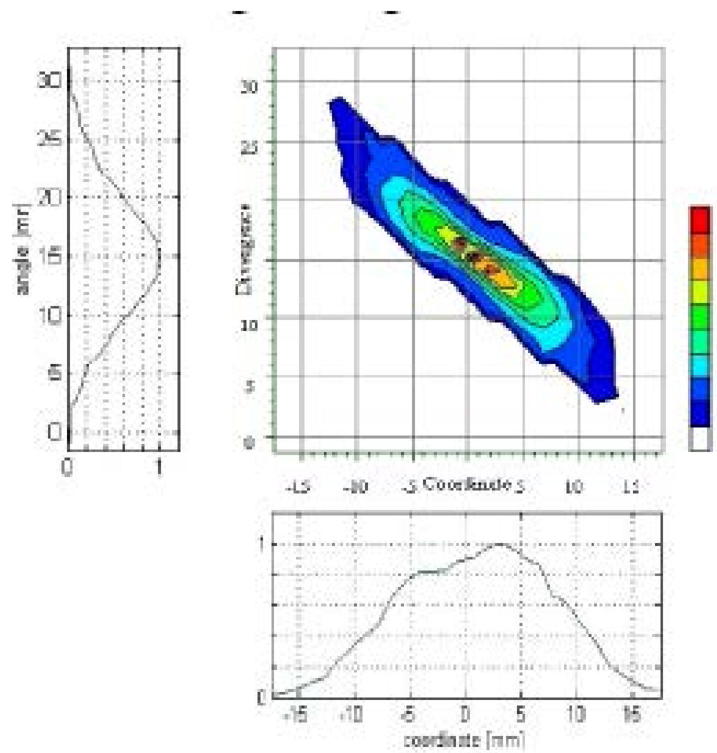
Pepperpot Results





Needs calibration of the screen to determine
Orientation of the emittance ellipse

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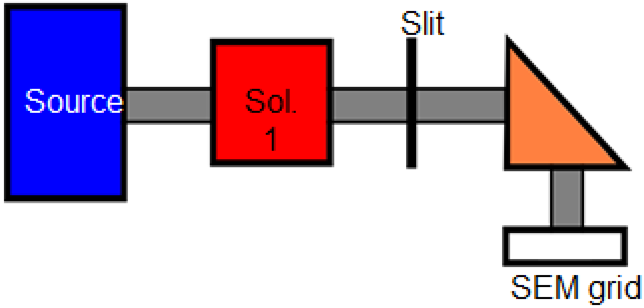
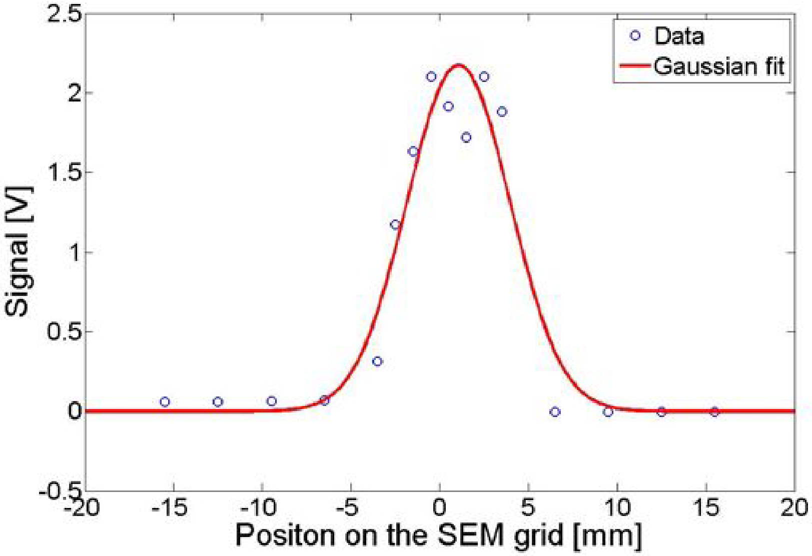
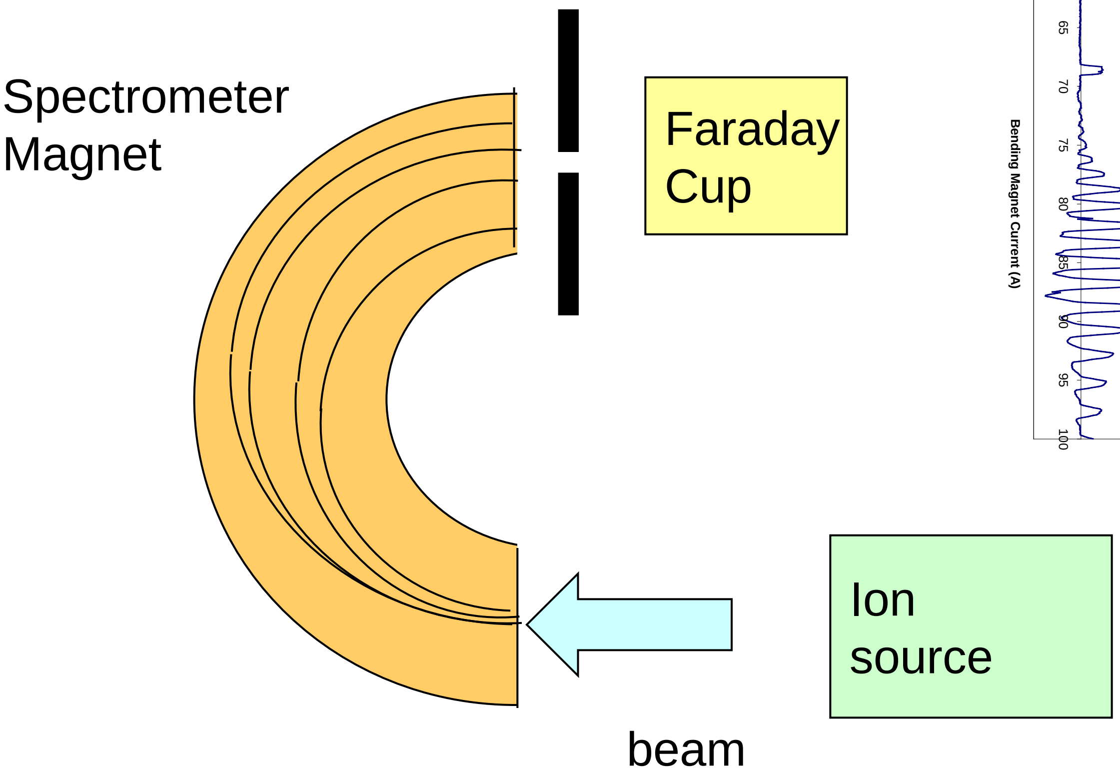
Energy Spread

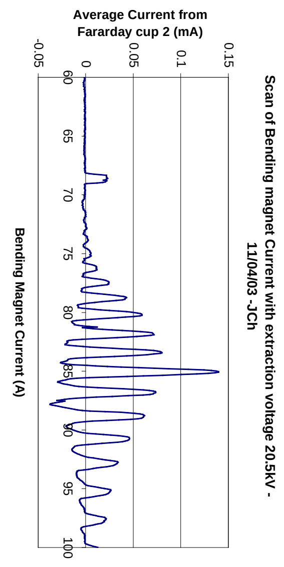
- Slit: reduces space charge effects and beam divergence
- Slit and wire grid are positioned at focal points of the optics
- Calibration by modification of the source extraction voltage (50 eV/mm)
- Profile width is determined by energy spread





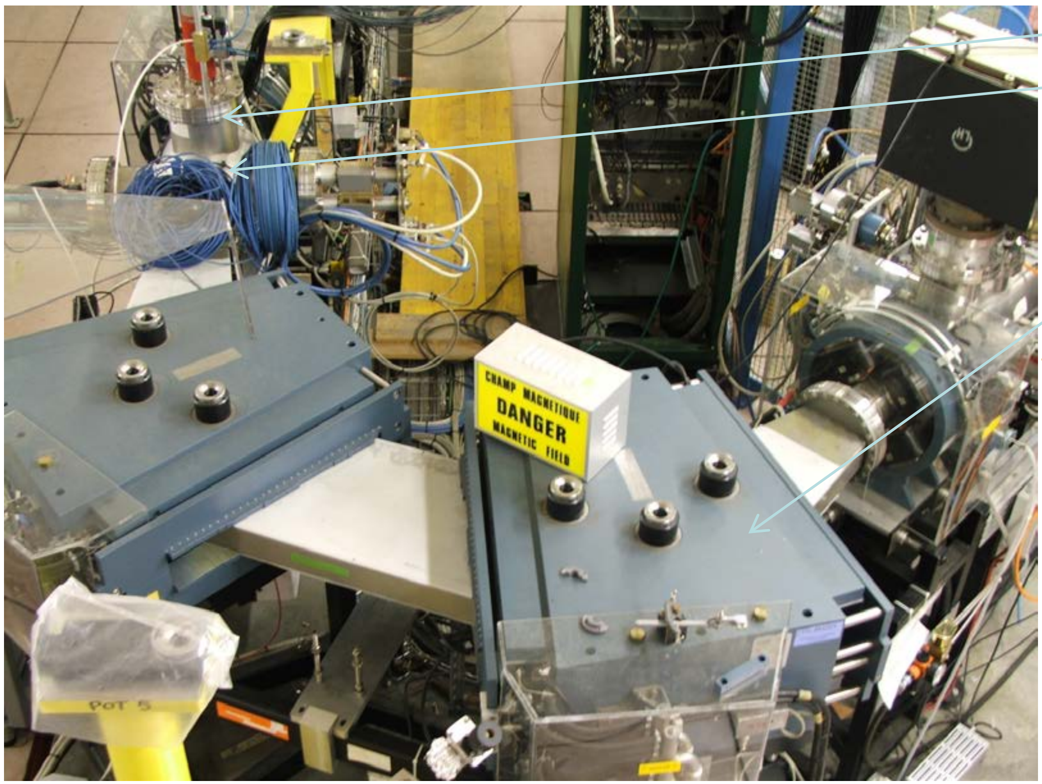
Setup for charge state measurement





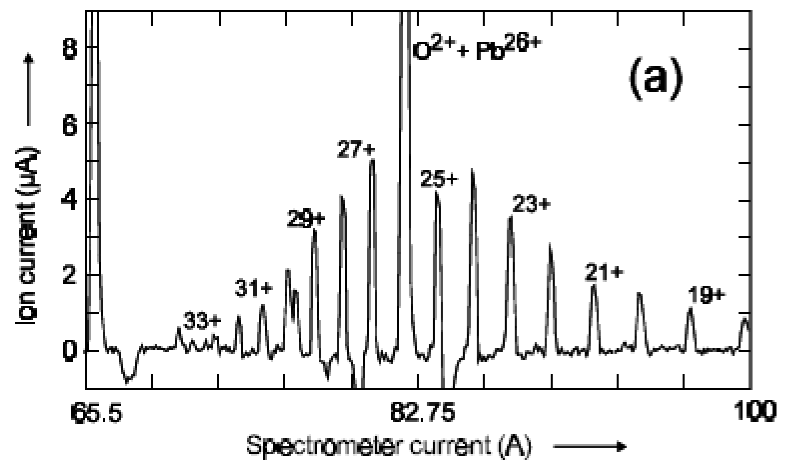
The spectrometer magnet is swept and the current passing the slit is measured

Select Charge States



Faraday Cup
Slit
Spectrometer Magnet

Charge States measured at the FaradayCup when ramping the spectrometer magnet



Conclusions

- Beam diagnostics tells you how well your ion source performs
- Needed to understand LEBT optics to adapt source beam to RFQ characteristics
- Typical measurements:
  - Beam current and total intensity (no of charges)
  - Current stability over the beam pulse
  - Transverse Profile
  - Longitudinal Profile
  - Transverse emittance