Intensity Measurements

Andreas Peters

(HIT, Head Accelerator Operations)

HIT Betriebs GmbH am
Universitätsklinikum Heidelberg

http://www.hit-centrum.de

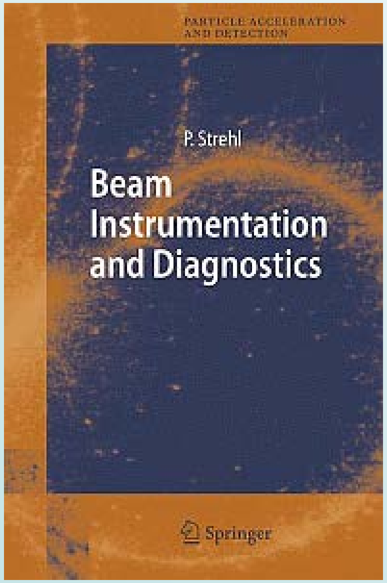
Outline

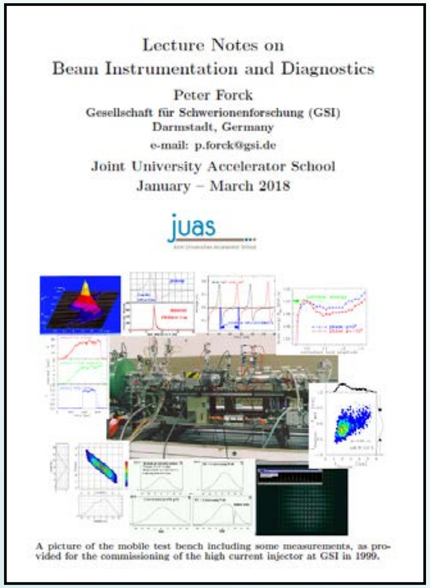
- Classification of intensity/current measurement devices
- Beam destructive/scattering monitors:
  - Stopping the Beam, e.g. Faraday cups
  - Interaction of the beam with matter, e.g. ionization chambers
- Non-destructive current monitors → current transformers (ac, dc)

- Conclusion and Acknowledgements

Introduction

- Literature: https://indico.cern.ch/event/683638/contributions/2801669/attachments/1563566/2540684/juas_script.pdf





- See: http://cas.web.cern.ch/cas/CAS%20Welcome/Previous%20Schools.htm
  - *Beam Diagnostics* from U. Raich, CERN in *CAS, Small Accelerators, 2005*
  - *CERN Accelerator School on Beam Diagnostics, 2008, Talk of J.-C. Denard*
- …. and much more sources as e.g. www.jacow.org!

Introduction

Beam diagnostic devices are necessary as *"the eyes of the operator"* to the accelerator for:

- Observation and Logging
- Measuring feedback on parameter setting/tuning
- Searching for errors in the machine, e.g. a temperature drift effect, a short in a coil, etc.

The different beam diagnostics systems can be classified in three groups:

I. Non-destructive diagnostic systems that will work online during experiments and in all other cases.

II. Destructive measurement devices that will be used for the daily checks of the machine and the beam stability, and in addition for machine tuning and solving simpler machine problems.

III. Special devices that will be necessary during the commissioning and in case of serious machine problems.

Beam Intensity/Current Measurement

Definitions:

- The **Intensity** is the power transferred per unit area, where the area is measured on the plane perpendicular to the direction of propagation of the energy.
- An **electric current** is a flow of electric charge (in accelerators mostly electrons, protons and ions).

The beam intensity/current is the basic quantity of the beam:

- It is the first check of the accelerator functionality.
- It has to be determined in an absolute manner.
- It is important for transmission measurement and to prevent for beam losses.

Beam Intensity/Current Measurement

Different devices are used:

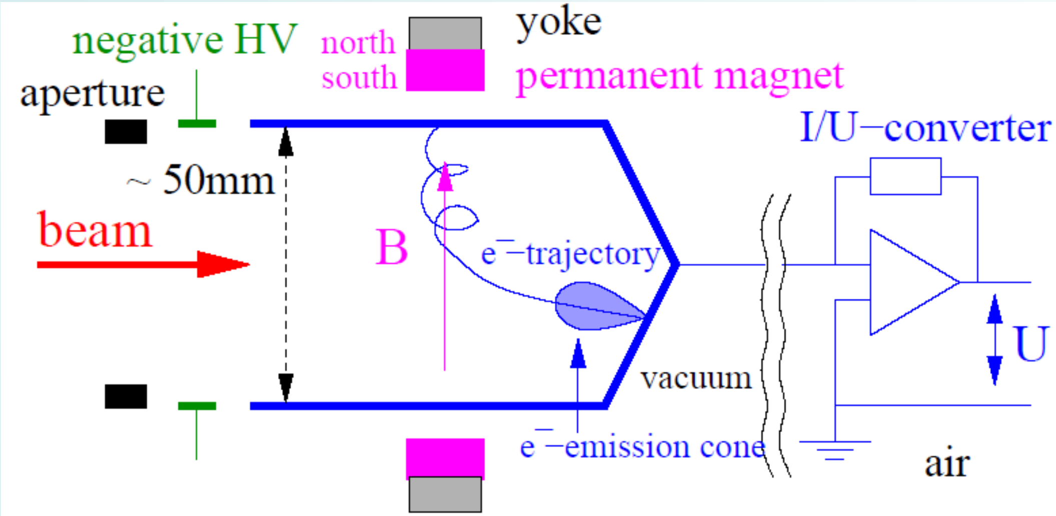
- **Faraday cups (beam is stopped):**
  - Measurement of the beam's **electrical charges.**
  - They are destructive.
  - For "low" energies only.
  - Low currents can be determined.
- **Particle detectors (beam is scattered):**
  - Measurement of the particle's **energy loss** in matter.
  - Examples are scintillators, ionization chambers, secondary e− emission monitors, …
  - Used for low currents at high energies e.g. for slow extraction.
- **Transformers (beam is not disturbed):**
  - Measurement of the beam's **magnetic field.**
  - They are non-destructive and can measure ac- and dc-beams
  - No dependence on beam energy.
  - They have (normally) a limited detection threshold (~ µA).

Faraday Cups

Faraday Cups for Beam Charge Measurement

The beam particles are collected inside a metal cup
⇒ The beam's charge is recorded as a function of time.

The cup is moved in the beam pass → destructive device!



Currents **down to 10 pA** with bandwidth of 100 Hz!

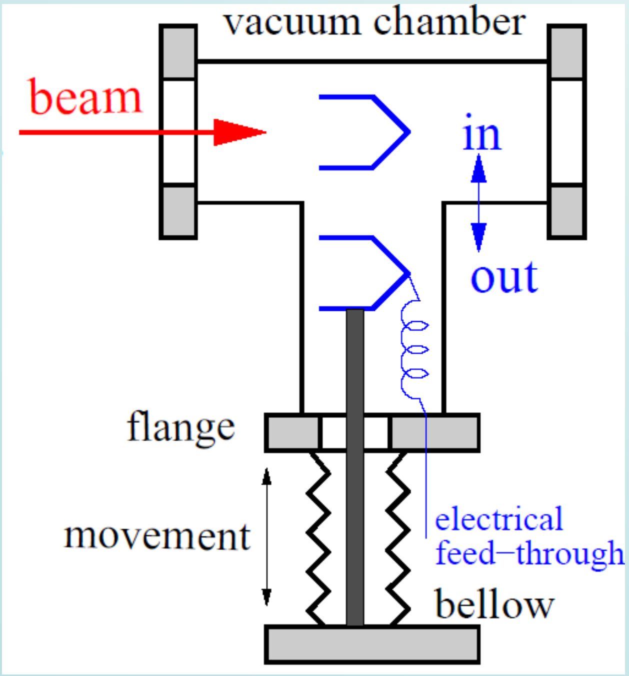
Magnetic field:
To prevent for secondary electrons leaving the cup

And / Or

Electric field:
Potential barrier at the cup entrance

Realizations of Faraday Cups

The Faraday Cup is moved into the beam pipe using an air-pressured actuator.



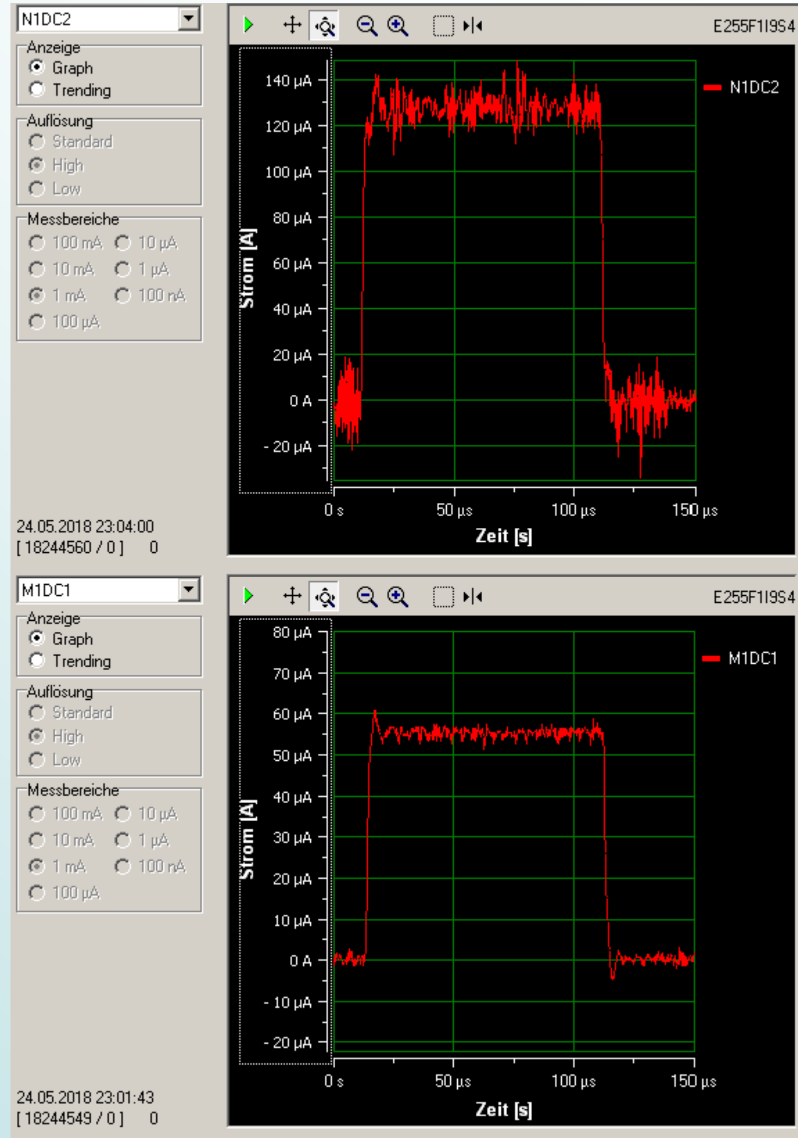
Example from HIT – uncooled FC for the MEBT section

Realizations of Faraday Cups

Example measurements with Faraday cups shown on the previous slide (HIT):

Carbon beam ($^{12}C^{4+}$) with 8 keV/u from an ECR ion source after the chopper directly in front of the RFQ

Carbon beam ($^{12}C^{6+}$) with 7 MeV/u after the Linac (RFQ and IH-DTL) and the foil stripper

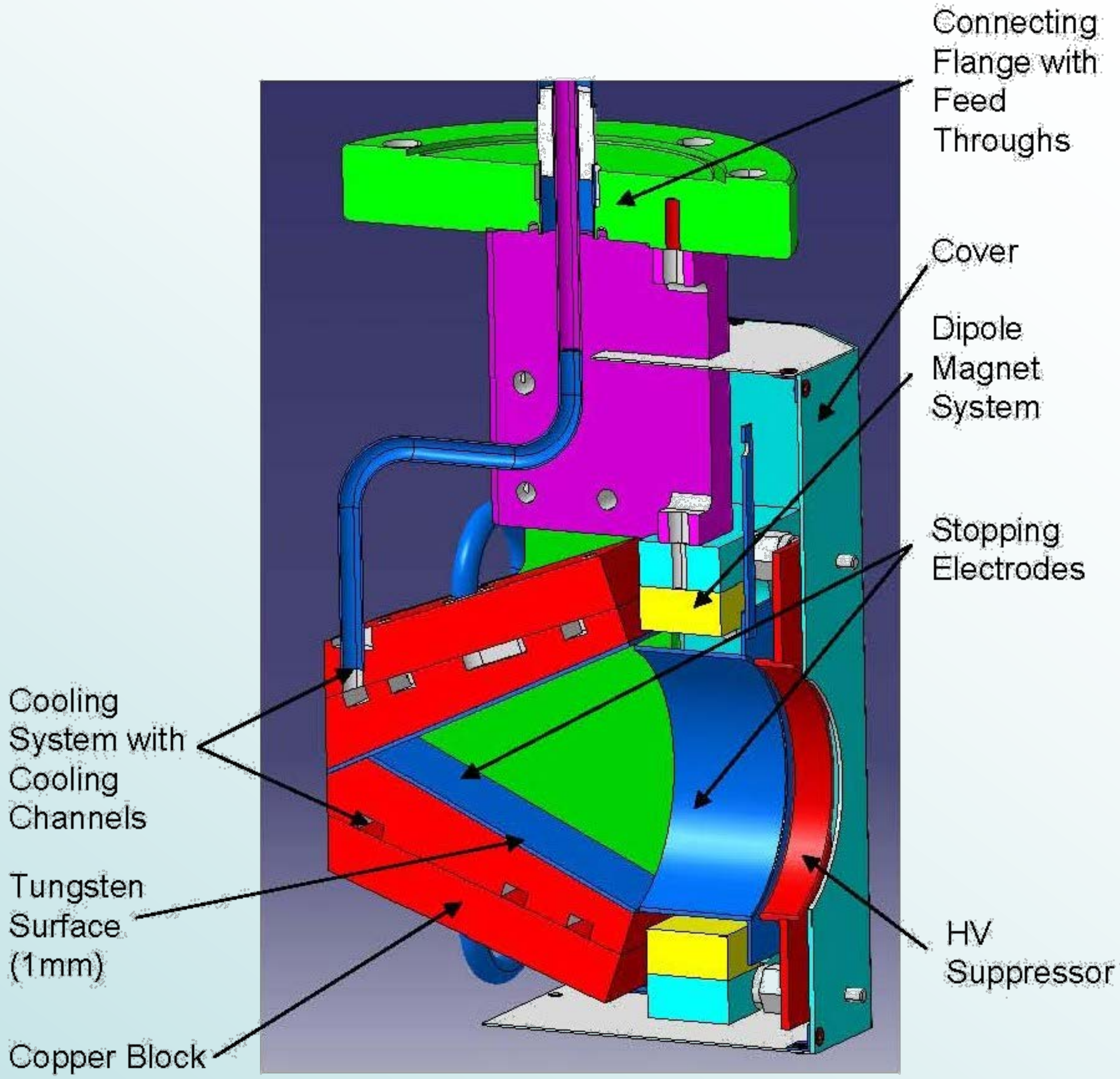


Heidelberger Ionenstrahl-Therapiezentrum

Realizations of Faraday Cups

High Power Version needed e.g. for beams from ECR Ion Sources (**up to 20 mA** overall DC current possible) at low energies (**keV/u**)
→ very small penetration depth of only **some ten nm**!

Material with very high melting point needed, e.g. Tungsten or Tantalum with cone shape



Realizations of Faraday Cups

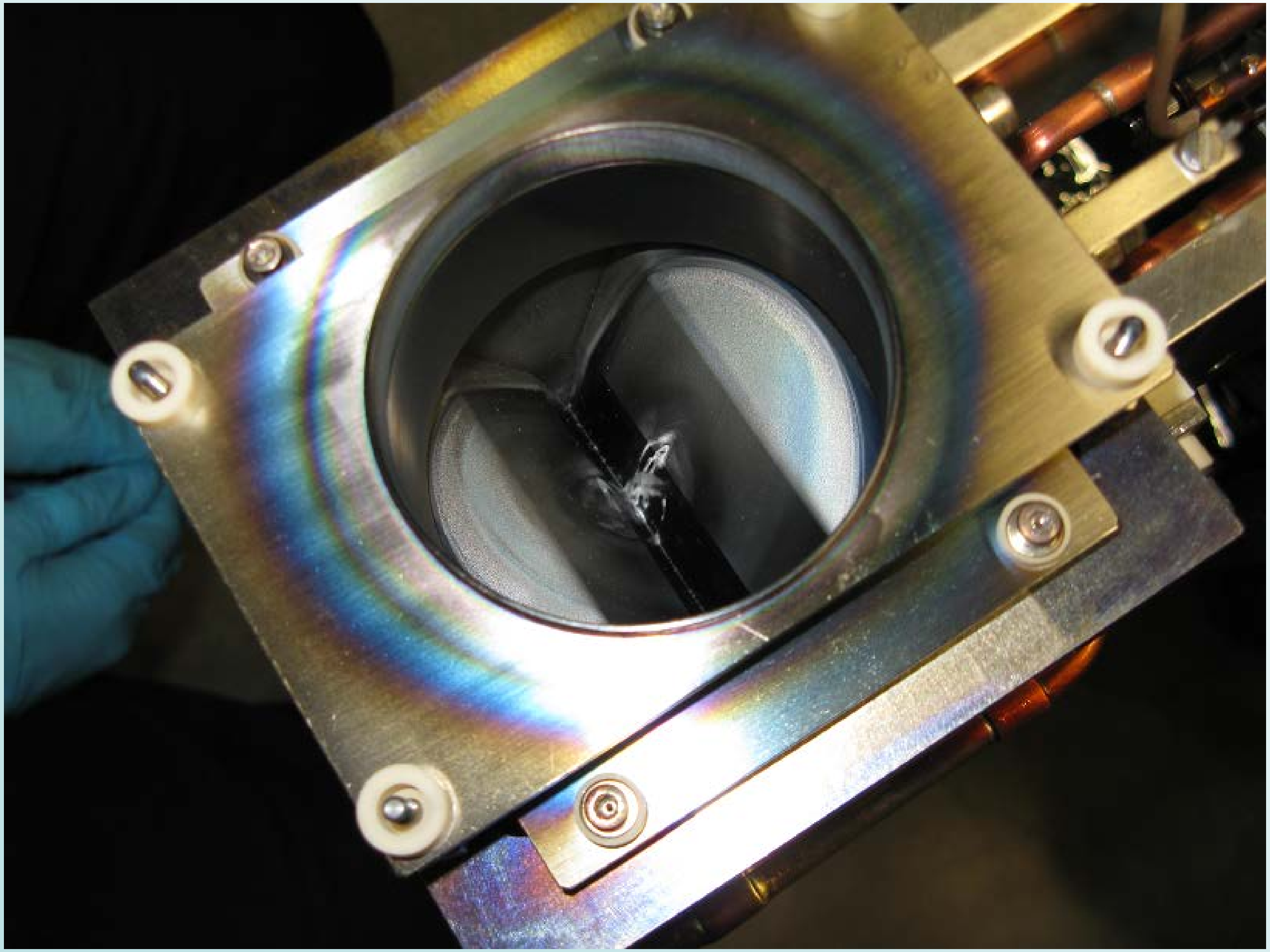
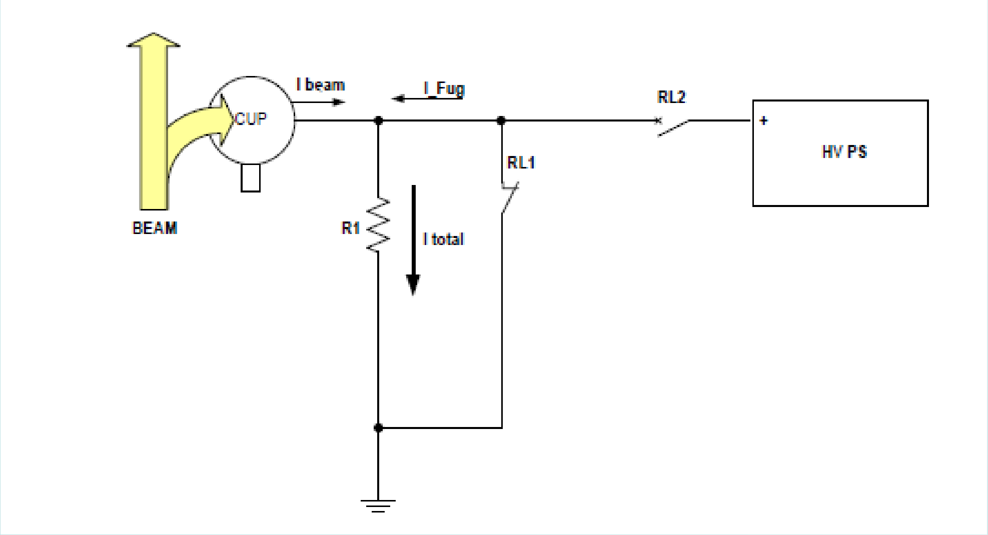
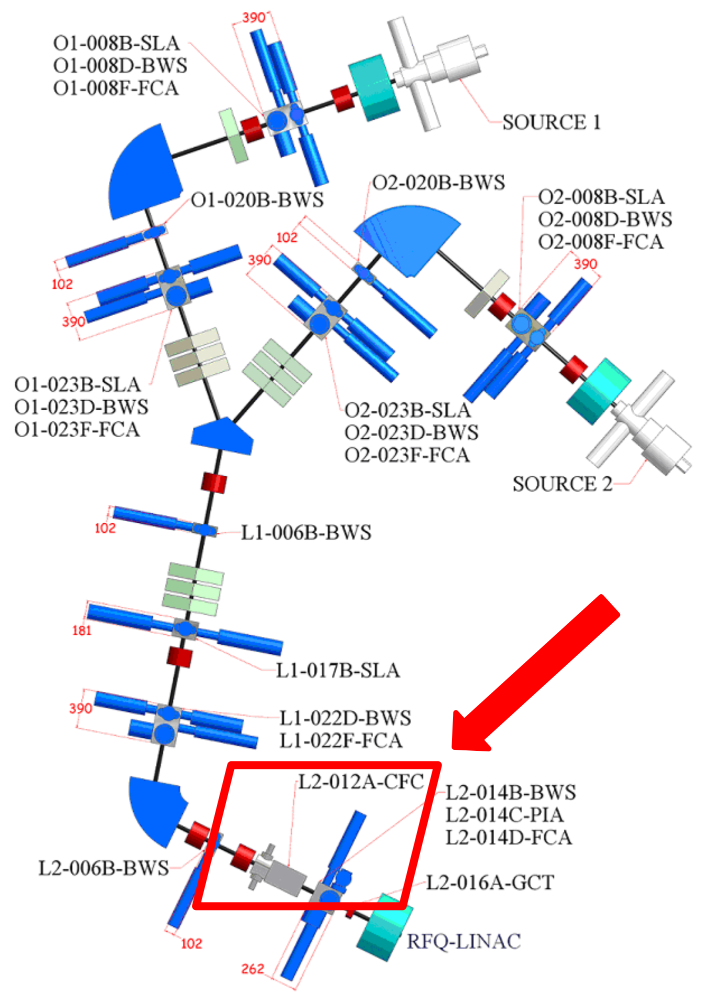


Photo of a used **Faraday cup** at the HIT LEBT, mounted closely behind the ECR ion sources, showing the **funnel-shaped geometry**
→ Obvious influences of **heating** and **sputtering** can be seen.

A “non-interceptive” Faraday Cup

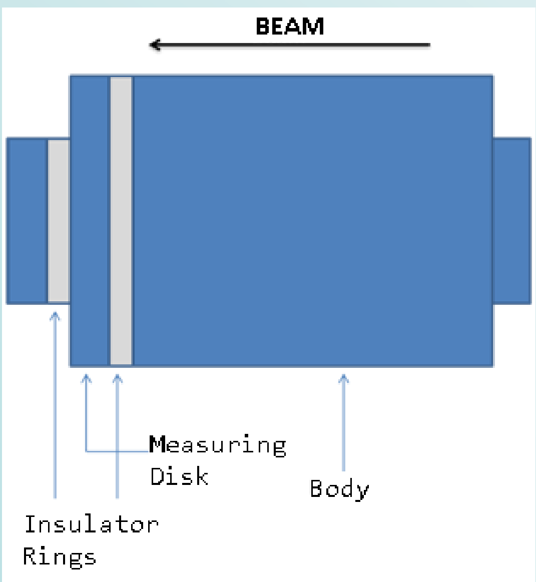
A Chopper faraday Cup (CFC) was designed and is presently in use on the CNAO machine. It measures the chopped beam, namely the beam (8keV/u energy) deviated by the Chopper deflector (installed at the end of the LEBT line) towards the vacuum chamber wall.

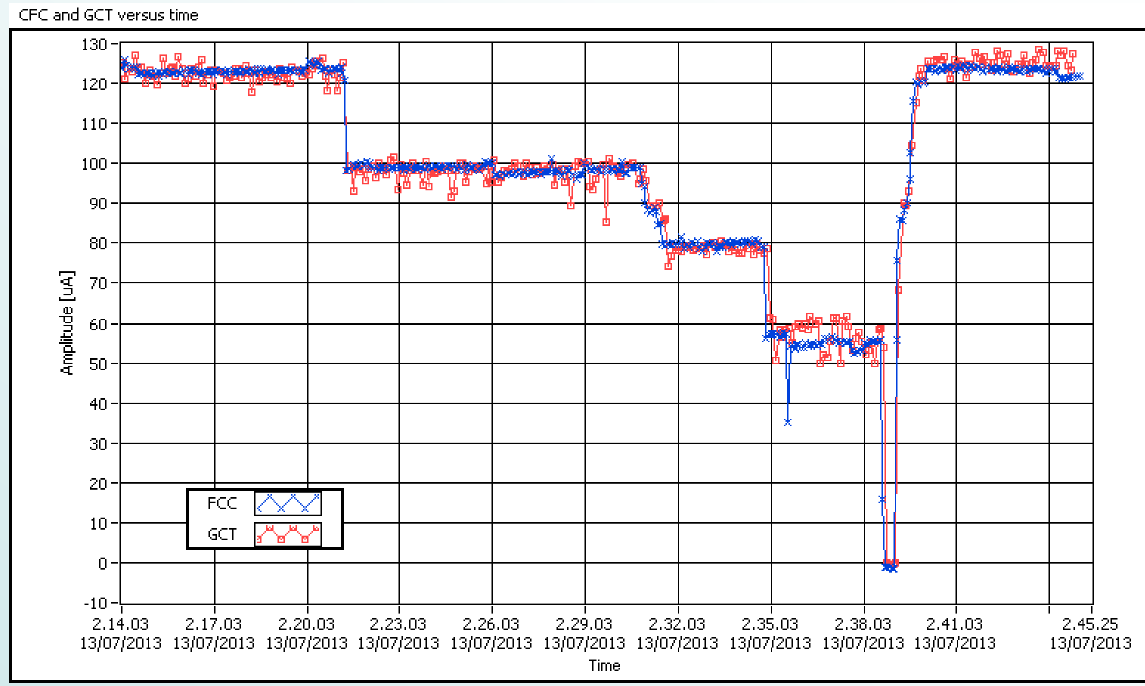




CNAO Low Energy Beam Transfer (LEBT) line

A “non-interceptive” Faraday Cup





Current intensity vs. acquisition time for carbon ion beam: comparison of CFC and AC Current Transformer (at the entrance of the Linac) performances.

[By courtesy of CNAO]

HIT Heidelberger Ionenstrahl-Therapiezentrum

Faraday Cups for High Energy Beams

Bethe Bloch formula: $-\frac{dE}{dx} = 4\pi N_A r_e m_e c^2 \cdot \frac{Z_t}{A_t}\rho_t \cdot \frac{Z_p^{\,2}}{\beta^2}\left(\ln\frac{2m_e c^2\gamma^2\beta^2}{I} - \beta^2\right)$

Range: $R = \int_0^{E_{max}} \left(\frac{dE}{dx}\right)^{-1} dE$

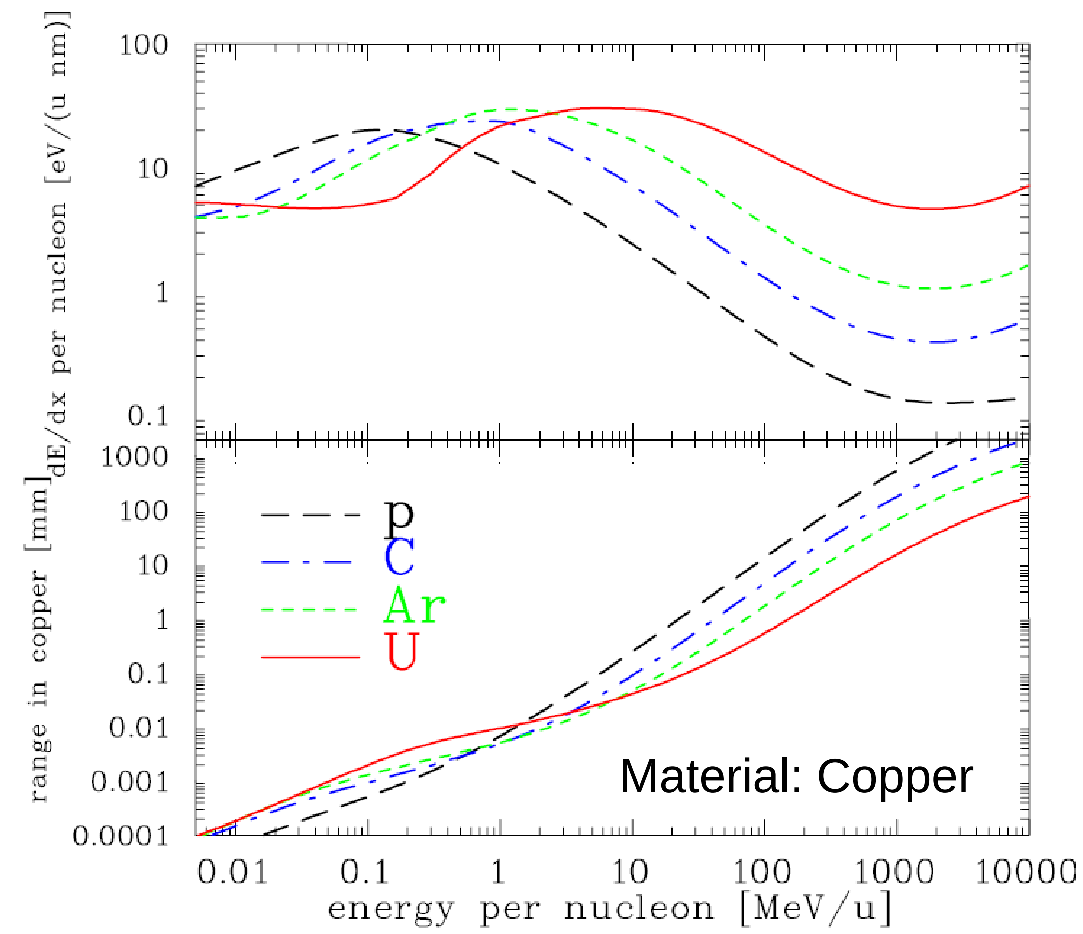
with approx. scaling $R \propto E_{max}^{1.75}$

→ Faraday Cups for **ion beams**

only for

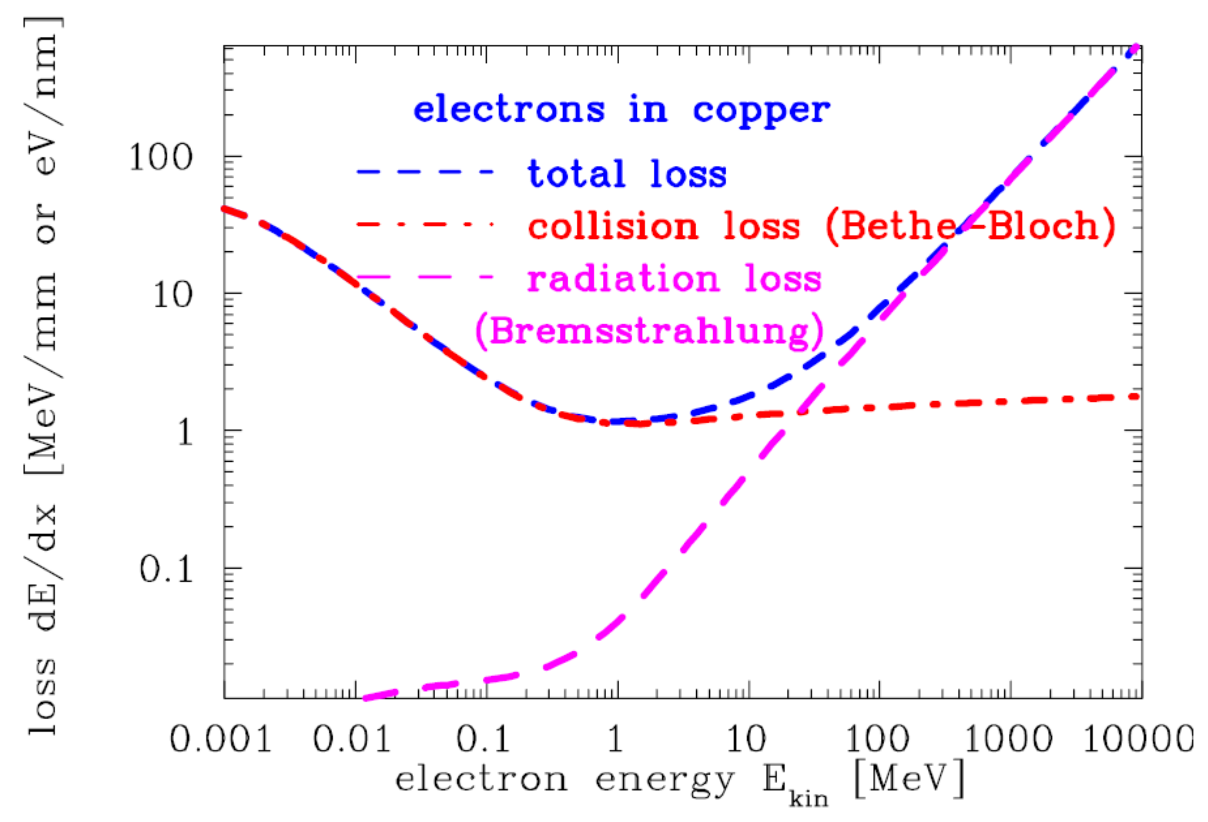
E_{kin} < 100 MeV/u with R < 10 mm!

For higher energies more material is necessary (mechanics!), but nuclear reactions and fragments must be taken into account!



Faraday Cups for High Energy Beams

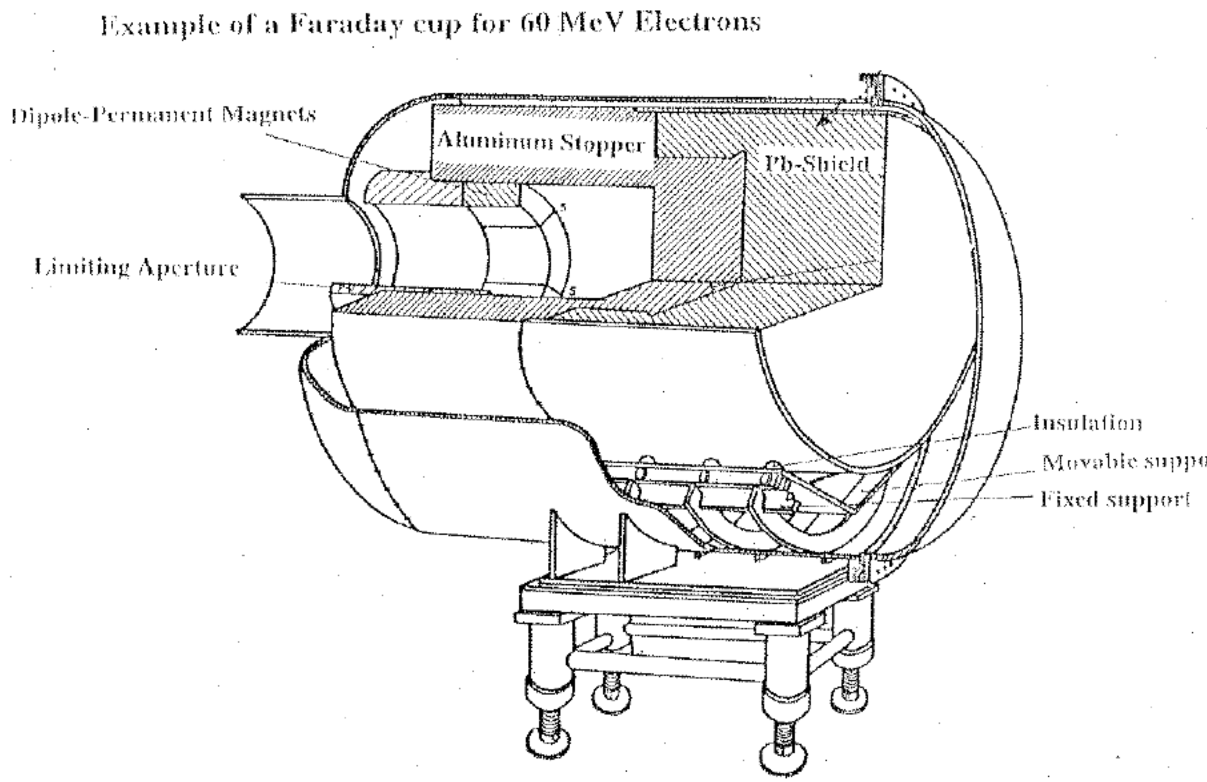
The stopping of **electrons** in matter differs from protons and ions → here the sum of the two relevant processes of collisional loss $dE/dx_{|col}$ (modified Bethe-Bloch formula for electrons) and radiation loss $dE/dx_{|rad}$ have to be added.



In addition: Electrons have much larger lateral straggling than ions and also the longitudinal straggling is larger resulting in a wider range distribution, thus Faraday cups for stopping electrons are seldom used at electron accelerators.

Heidelberger Ionenstrahl-Therapiezentrum

Faraday Cups for High Energy Beams



Left: A drawing of a Faraday cup used for **60 MeV electrons**.
Right: The installation of a Faraday cup used as a beam dump at ALBA, Barcelona.

Particle Counters

Particle Counters

- Used for **low current measurements of high-energetic particles** e.g. for slow extracted proton and ion beams from synchrotrons for atomic or nuclear physics experiments.
- Overview of the typical dynamic range of detectors:

→ For an ion rate below 10^6 s^{-1}, the individual particles can be counted by **scintillators**.

→ For the medium range from about 10^4 to 10^9 s^{-1} the energy loss in a gas is measured by an **ionization chamber (IC)**.

→ For the higher range from about 10^8 s^{-1} the emission of secondary electrons from a metal surface forced by the primary ion's energy loss is determined by **secondary electron monitors (SEM)**.

Scintillation Counters

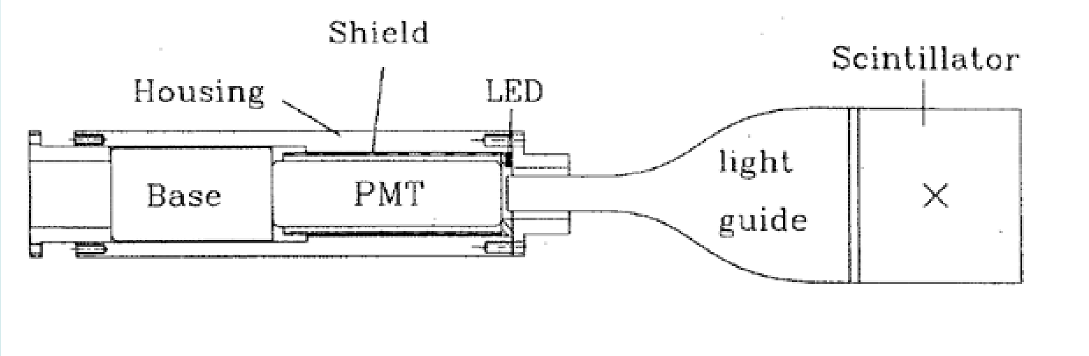
Plastic Scintillator i.e. organic fluorescence molecules in a plastic matrix

Advantage: easily machinable, cheap, blue wave length, fast decay time

Disadvantage: not radiation hard

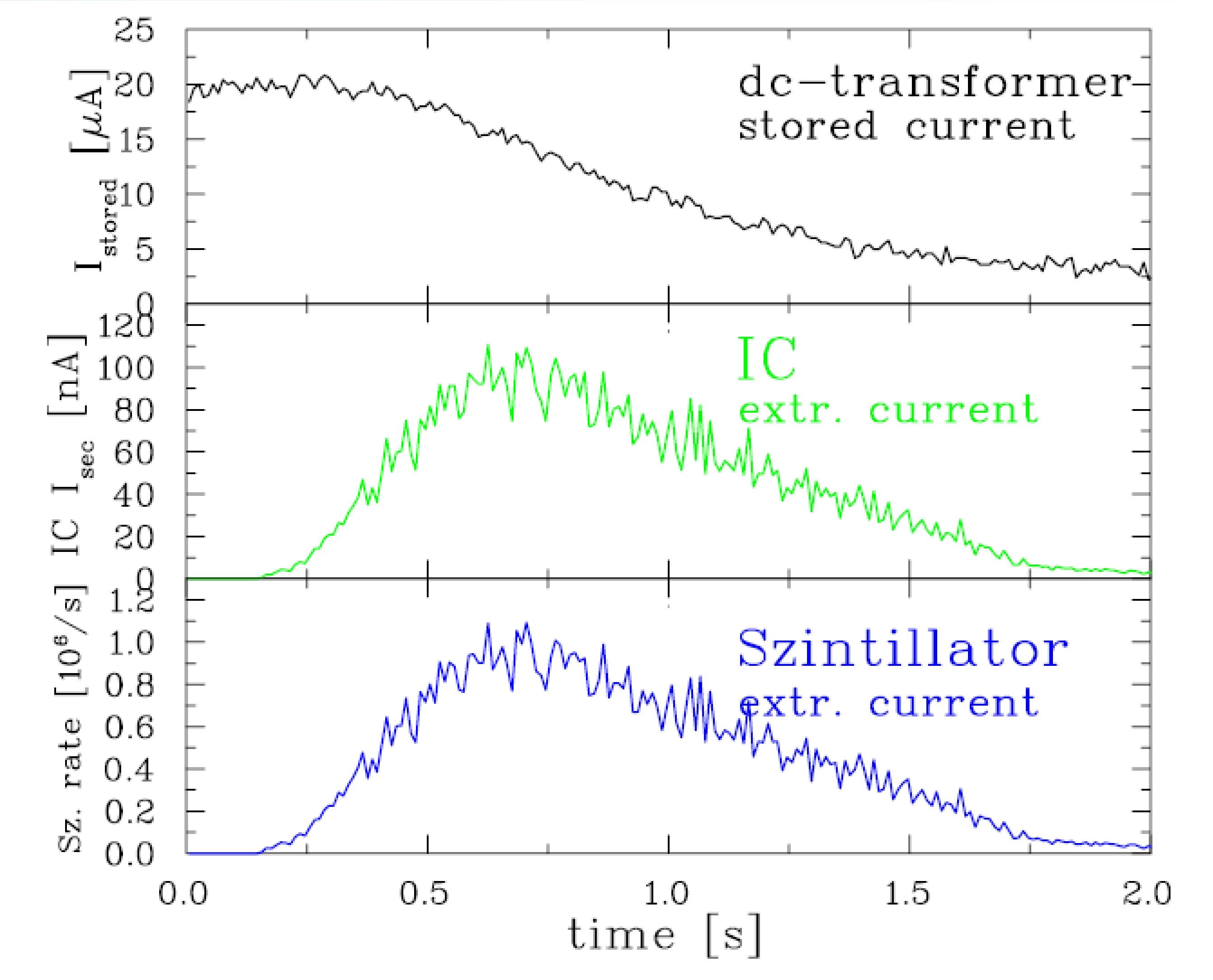
Particle counting: PMT → discriminator → scaler → computer

Example from HIT (HEBT section)



Active Area:	75×75 mm^2
Thickness:	3 mm
Scintillation material:	BC400
Measurement rate:	$<10^6$ Particles/s

Scintillation Counters



Example of extracted beam (250 MeV/u $^{208}Pb^{67+}$) from GSI´s SIS18 Heavy Ion Synchrotron showing the maximum dynamics of **Scintillation Counters** → for higher currents the use of **Ionization Chambers** is necessary.

Ionization Chambers

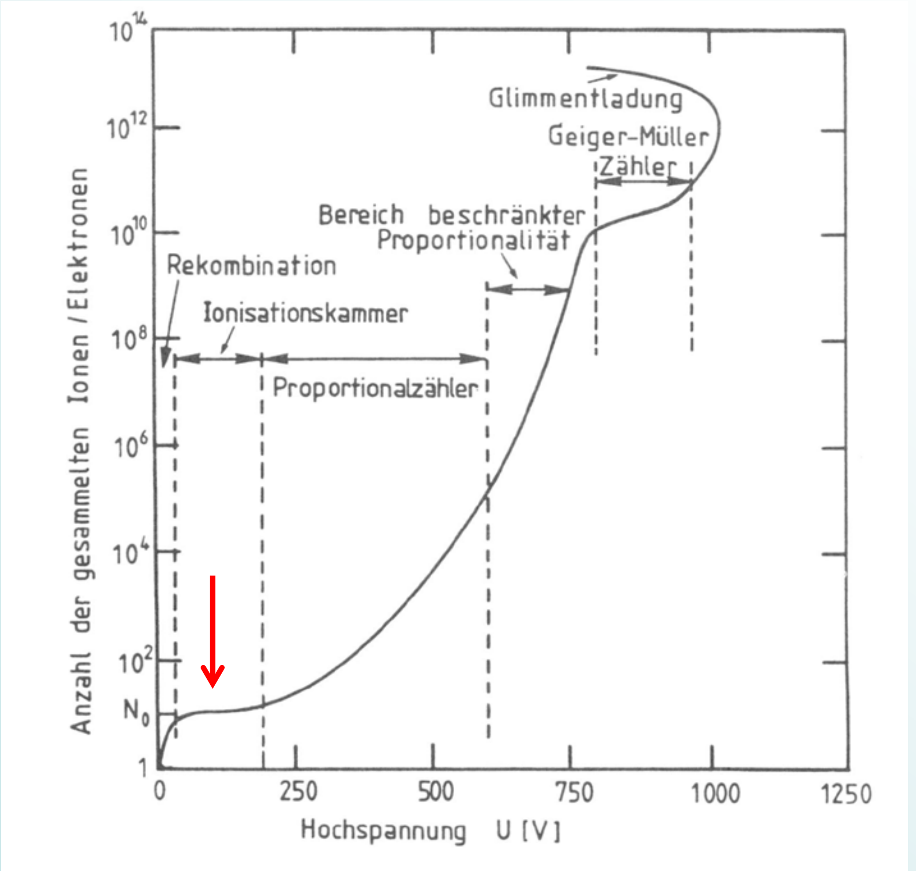
Energy loss in matter (mainly gases) → electronic stopping:

Bethe Bloch-Equation:

$$-\frac{dE}{dx} = 4\pi N_A r_e^2 m_e c^2 \cdot \frac{Z_t}{A_t}\rho \frac{Z_p^2}{\beta^2}\left[\ln \frac{2m_e c^2\gamma^2\beta^2}{I} - \beta^2\right]$$

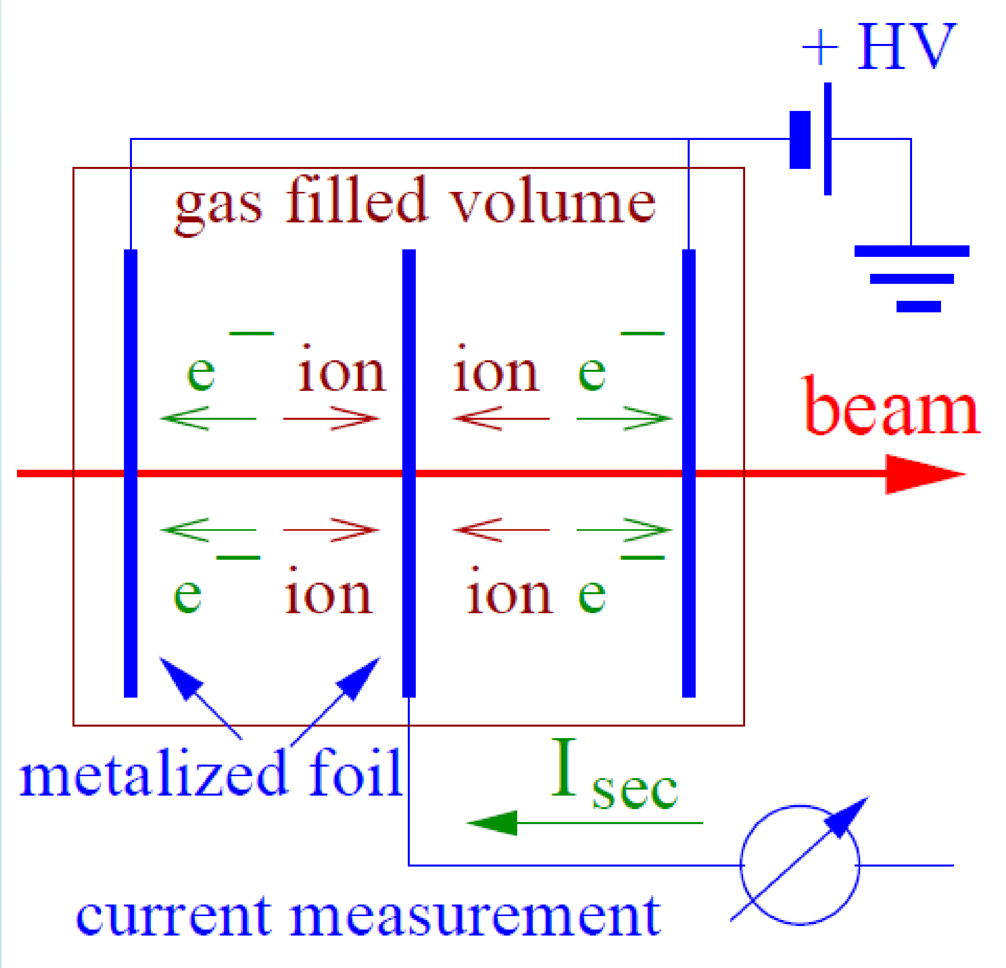
Target:
Charge & Mass (Z_t, A_t), Density (ρ), Ionization Potential (I)

Projectile:
effective charge (Z_p), Velocity (γ, β)



Operating ranges of gas detectors

Ionization Chambers

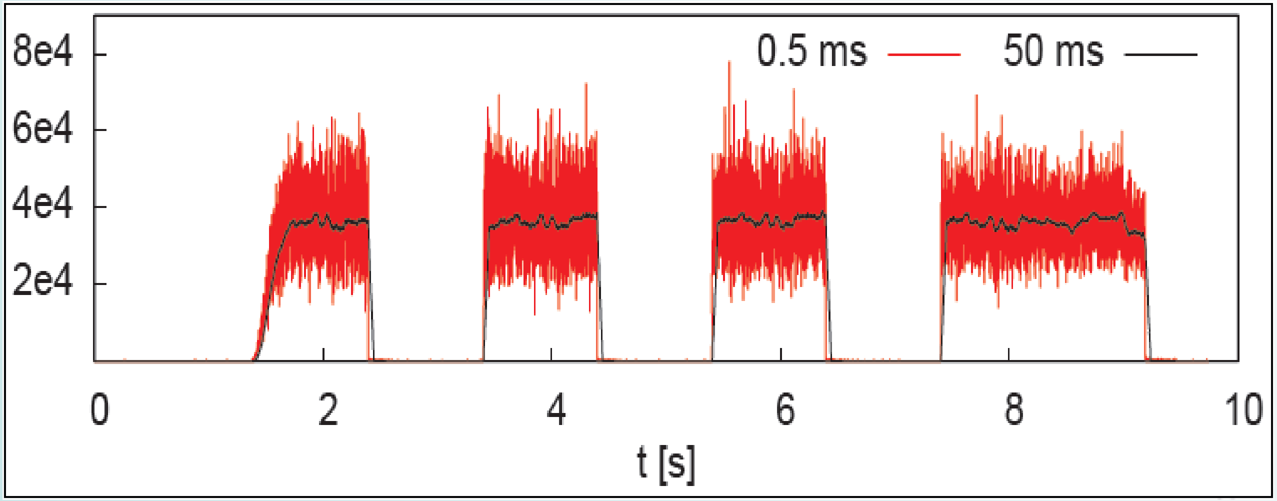


$$I_{sec} = \frac{1}{W} \cdot \frac{dE}{dx} \Delta x \cdot I_{beam}$$

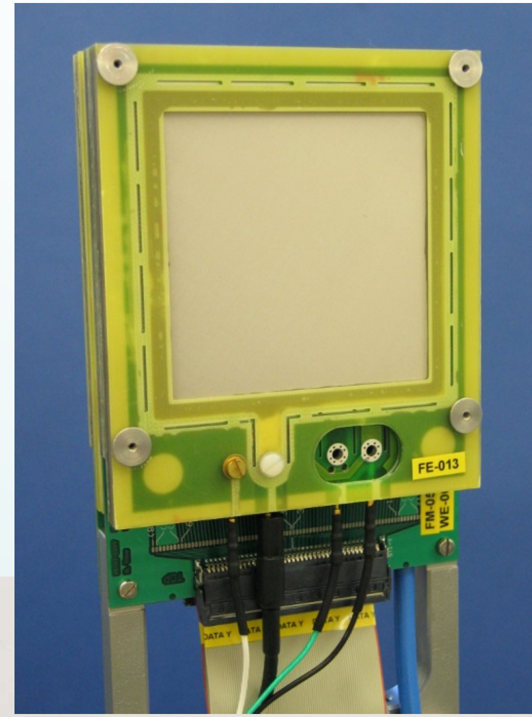
Choice of output signal strength vs. response velocity

Gas	W-value [eV]
H_2	36.4
He	42.7
N_2	36.4
O_2	32.2
Ar	26.3
CH_4	29.1
CO_2	33.0

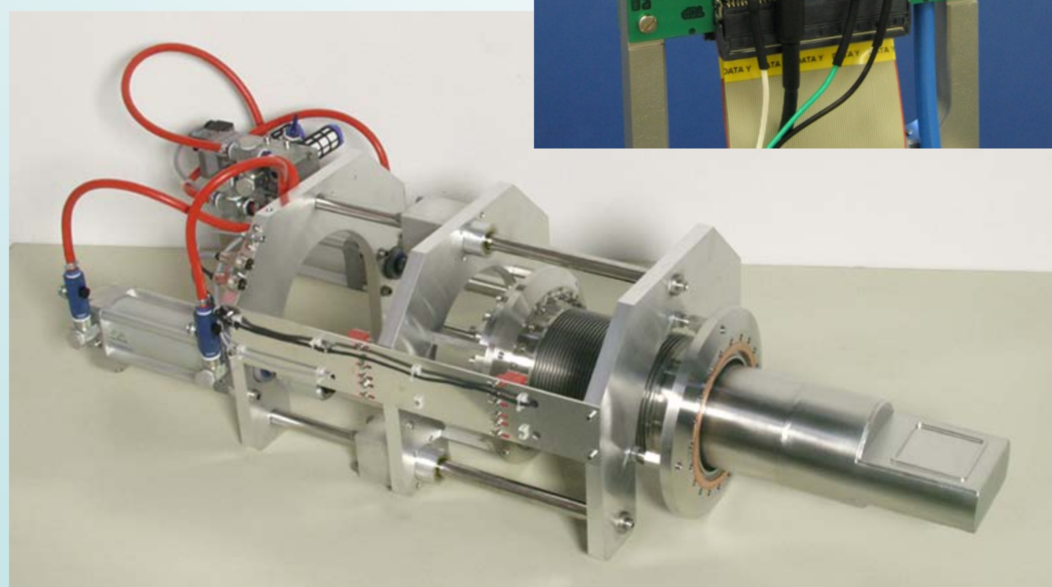
Ionization Chambers



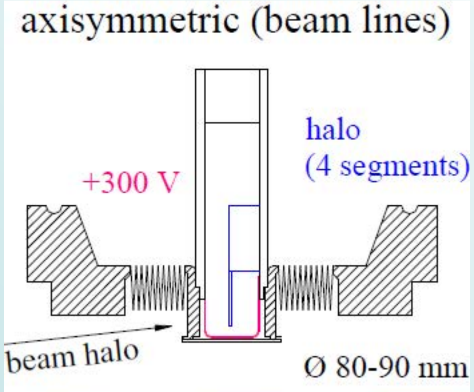
Intensity of extracted beam from HIT synchrotron („spill” with pauses)

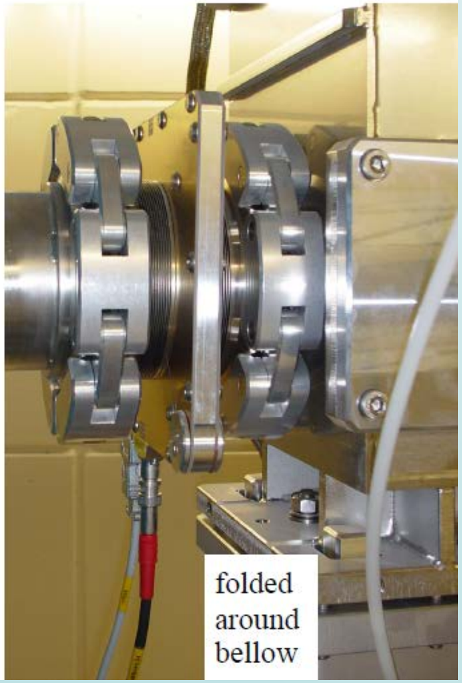


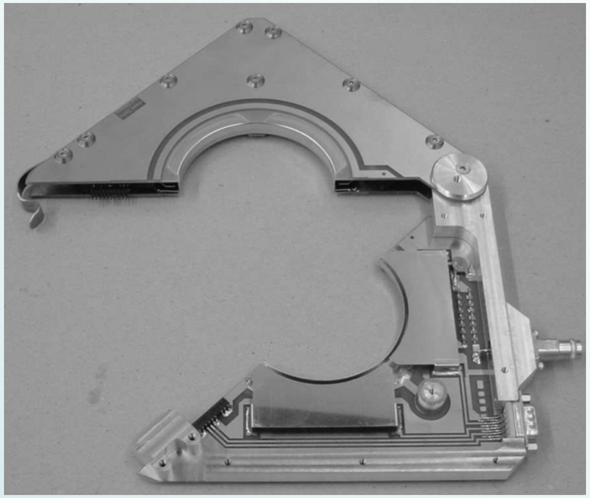
IC detector (upper right):
70x70 mm^2 active area, Δx=3 mm, with Ar/CO_2 gas mixture;
air-pressured actuator with stainless steel windows (50 µm)



Ionization Chambers

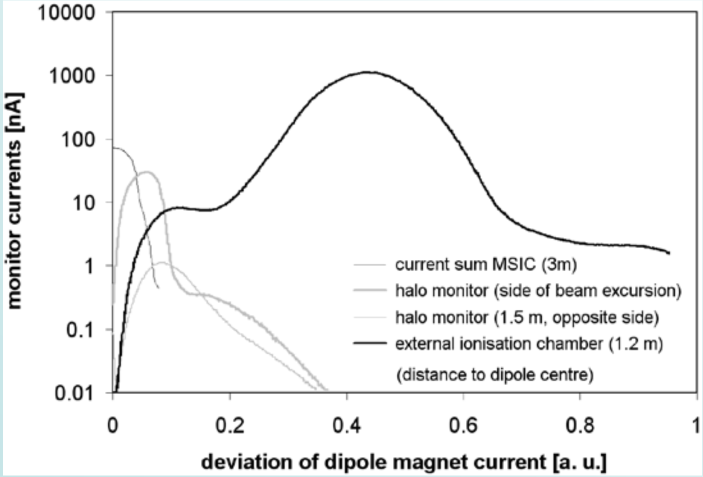






Ionization chambers as halo monitors around the beam pipe for online monitoring of beam displacements

[By courtesy of PSI]



Signal levels of several monitors when the beam is steered far off-axis

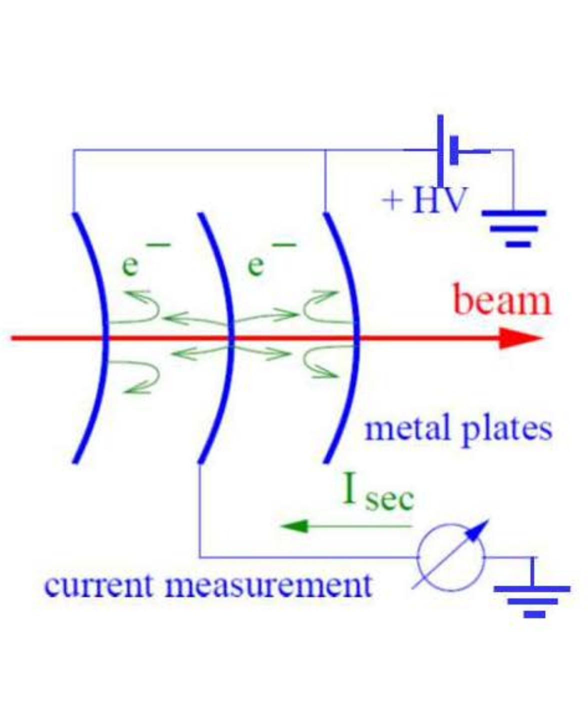
Beam current: 1.4 nA
Beam energy: 230 MeV

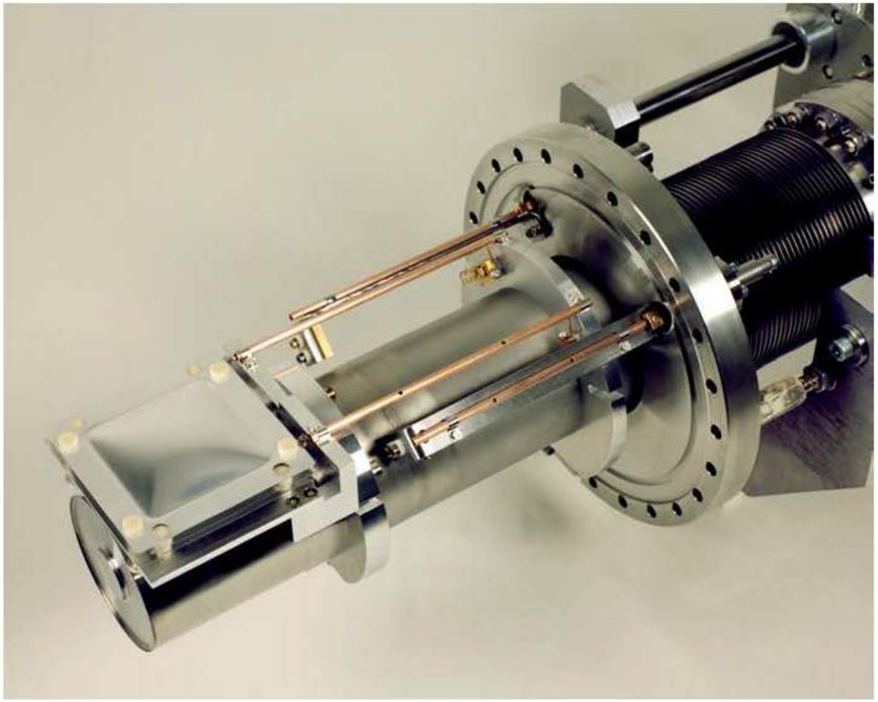
Secondary Electron Monitors (SEM)

The secondary emission current depends on the energy loss at the surface dE/ρdx, it is given by the Sternglass formula:

$$I_{sec} = Y \cdot dE/\rho dx \cdot I_{beam}$$

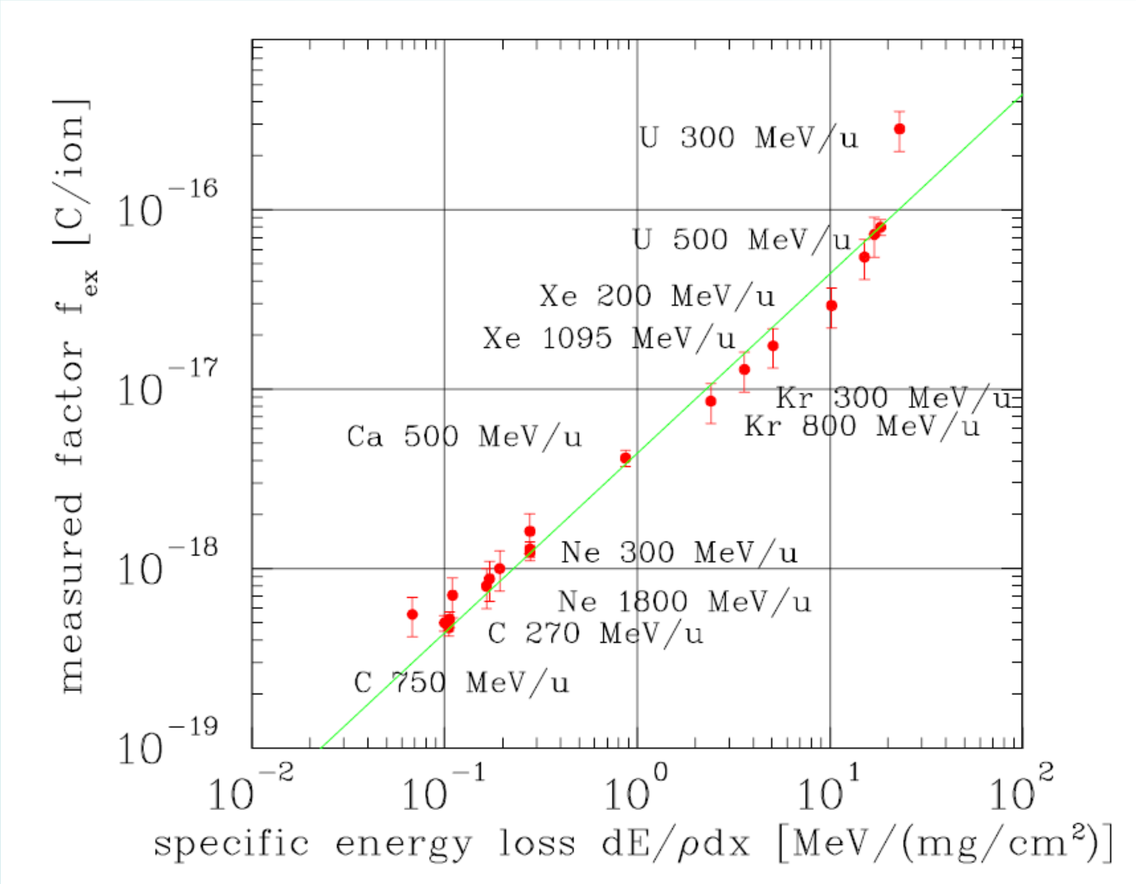
with Y being the yield factor describing the amount of secondary emission per unit of energy loss at the surface.





Left: **Scheme of a SEM** made of three metal foils.
Right: **Photo of the SEM** part made of 3 Al foils with thickness of 100 μm used for slow extraction meas. at GSI

Secondary Electron Monitors (SEM)



Calibration curve of a SEM with 3 Al foils – the yield factor value was fitted to

Y = 27.4 e^-/(MeV/mg/cm^2)

for various slowly extracted ions from the GSI synchrotron.

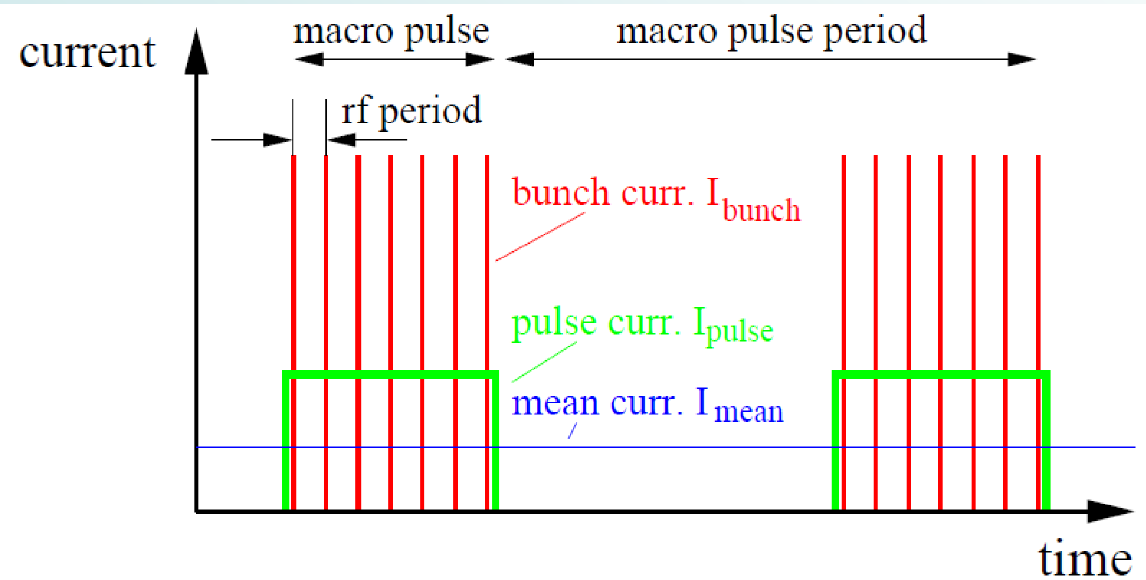
Value may depend on surface properties , e.g. material production and cleaning method.

The emission yield Y might change with irradiation, caused by modifications of the surface. A degradation by a factor of two was measured after 10^{18} protons/cm^2 (beam of 450 GeV at CERN SPS) → Ti-foils show a much lower sensitivity to radiation.

Current Transformers

Current Measurement – Pulsed Beams

Pulsed LINACs and cyclotrons used for injection to synchrotrons with $t_{pulse} \approx 100$ µs:

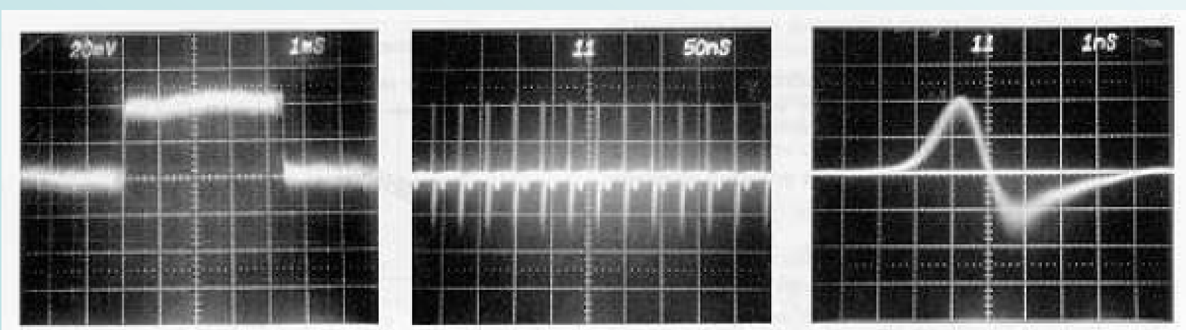


One distinguish between:

- Mean current I_{mean}
  → long time average in [A]
- Pulse current I_{pulse}
  → during the macro pulse in [A]
- Bunch current I_{bunch}
  → during the bunch in [C/bunch] or [particles/bunch]

Remark: ECR ion sources:
→ no bunch structure / DC

Example:
Pulse and bunch structure at GSI LINAC



Magnetic field of the beam and the ideal transformer

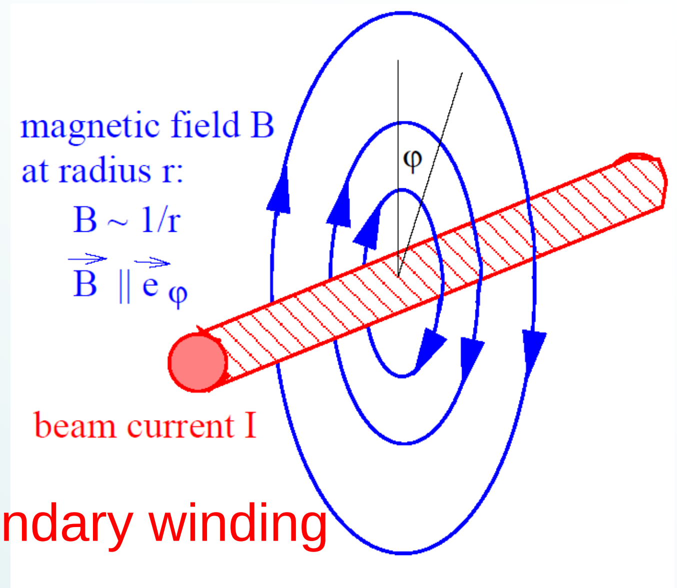
- Beam current of *N* charges with velocity β:

$$I_{beam} = qe \cdot \frac{N}{t} = qe \cdot \beta c \cdot \frac{N}{l}$$

- Cylindrical symmetry → only azimuthal component

$$\vec{B} = \mu_0 \frac{I_{beam}}{2\pi r} \cdot \vec{e_\varphi}$$

(Example: 1 μA, r = 10cm → 2 pT)



Idea: Beam as primary winding and sense by secondary winding

⇒ Loaded current transformer

$I_1/I_2 = N_2/N_1 \rightarrow I_{sec} = 1/N \cdot I_{beam}$

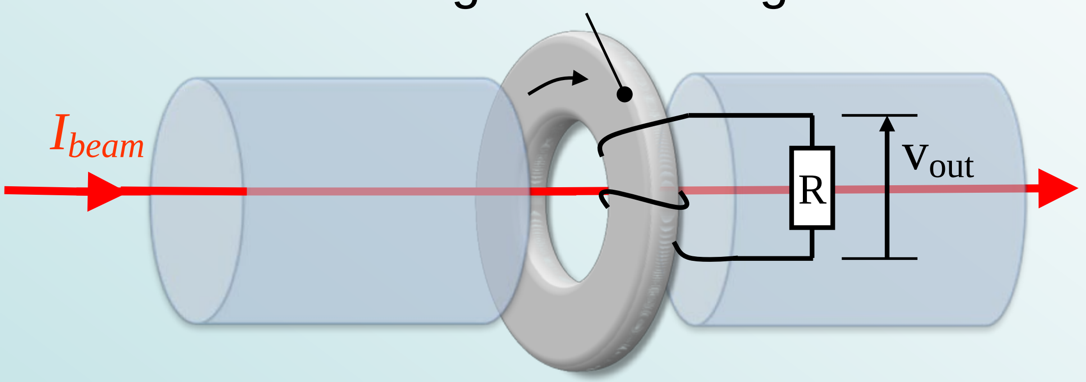
- Inductance of a torus of μ_r

$$L = \frac{\mu_0 \mu_r}{2\pi} \cdot l N^2 \cdot \ln \frac{r_{out}}{r_{in}}$$

- Goal of Torus: Large inductance ***L*** ***and*** guiding of field lines.

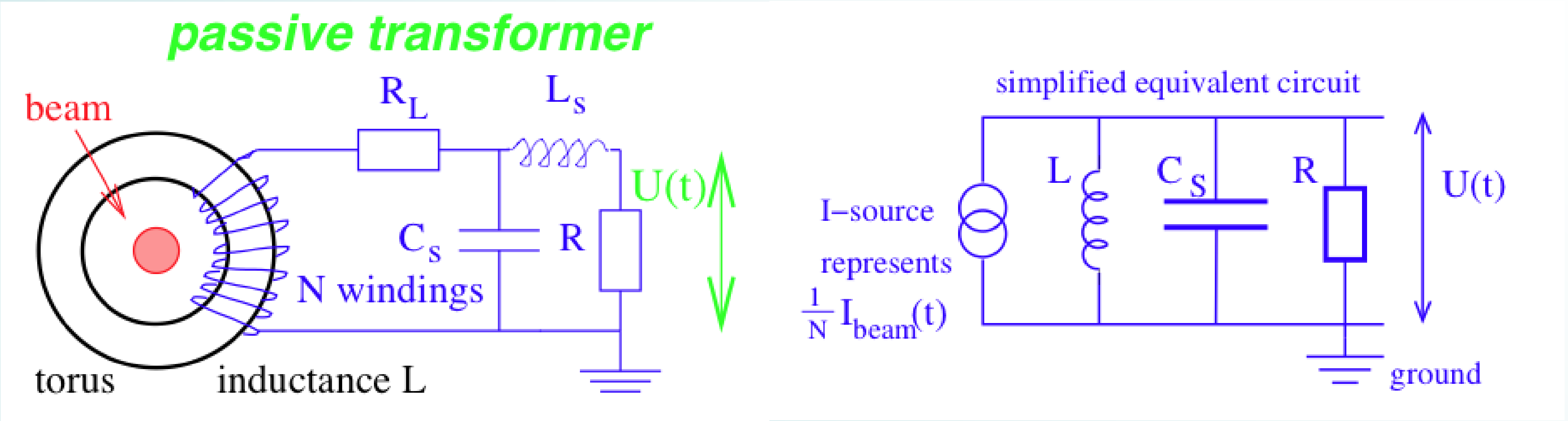
Definition: ***U = L · dI/dt***

Torus to guide the magnetic field



Passive Transformer / Fast Current Transformer (FCT)

Simplified electrical circuit of a passively loaded transformer:



A voltage is measured: $U = R \cdot I_{sec} = R/N \cdot I_{beam} \equiv S \cdot I_{beam}$

with **S sensitivity [V/A],** equivalent to transfer function or transfer impedance ***Z***.

Equivalent circuit is used for analysis of sensitivity and bandwidth

(disregarding the loss resistivity R_L)

Passive Transformer: Rise and Droop Time

Time domain description:

Droop time: $t_{droop} = 1/3f_{low} = L/R$

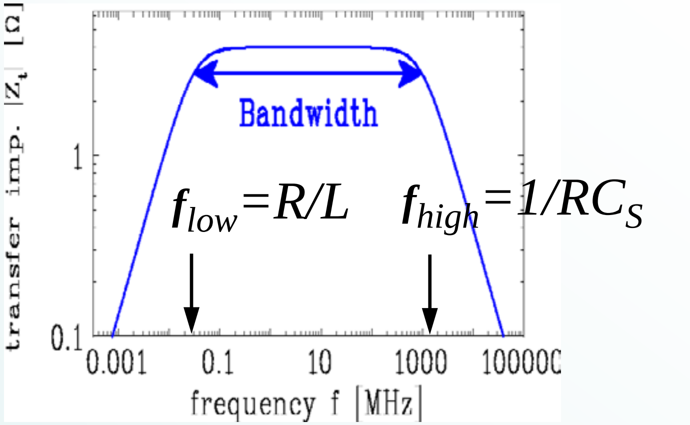
Rise time: $t_{rise} = 1/3f_{high} = 1/RC_S$ (ideal without cables)

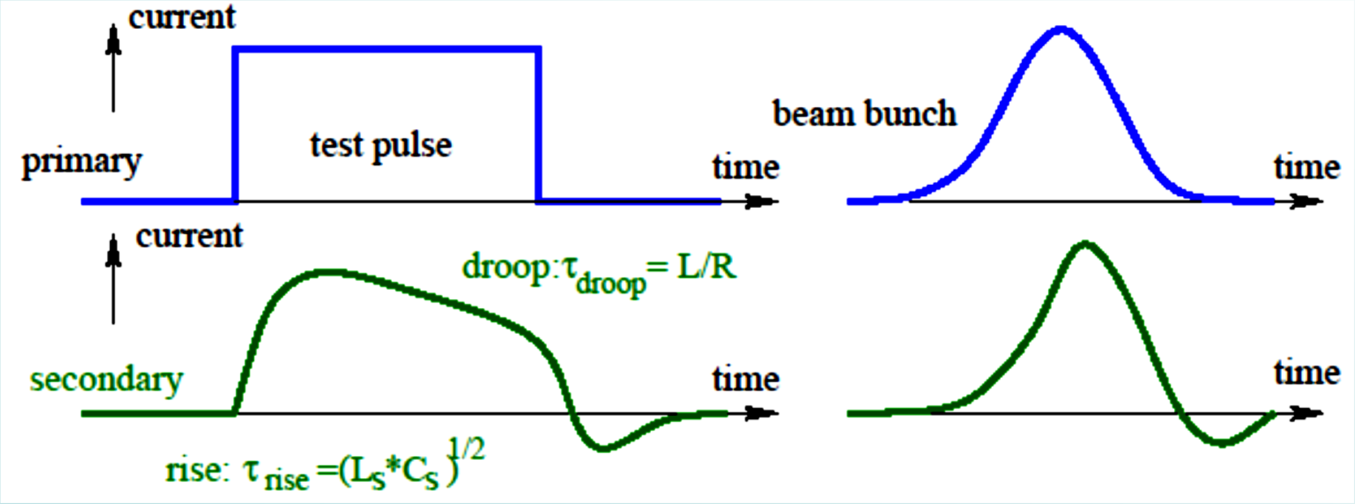
Rise time: $t_{rise} = 1/3f_{high} = \sqrt{L_S C_S}$ (with cables)

R_L: loss resistivity, R: for measuring.

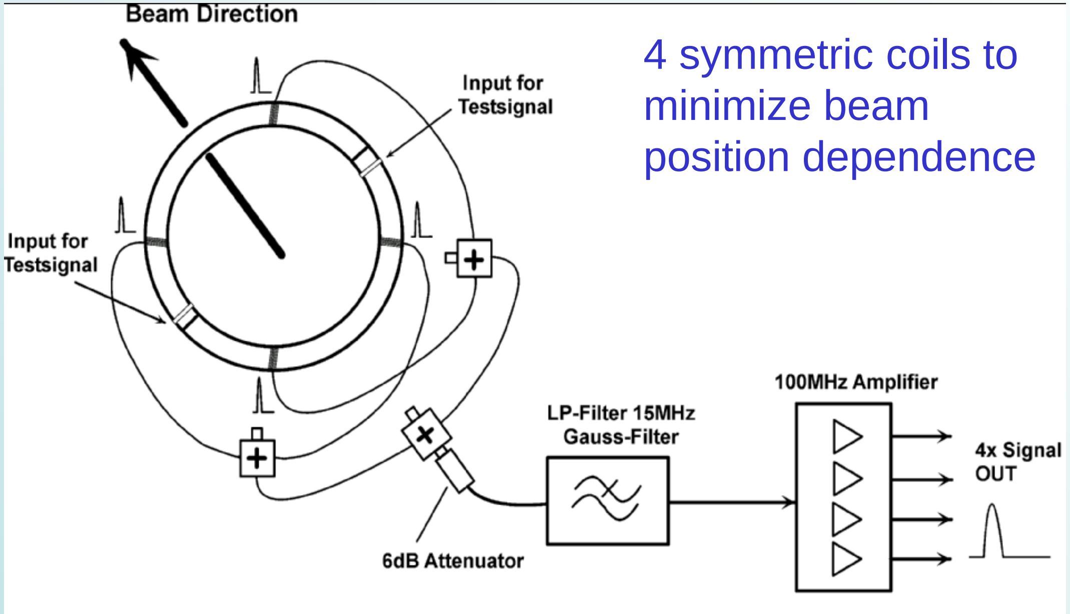
For the working region the voltage output is

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

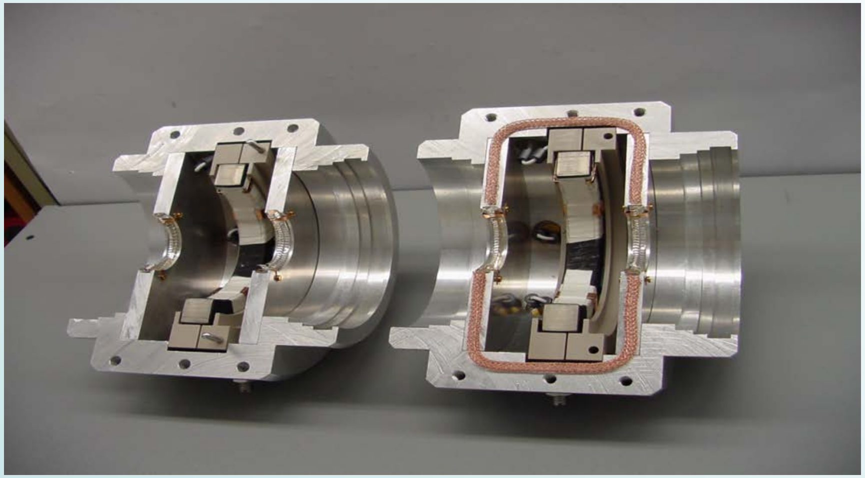




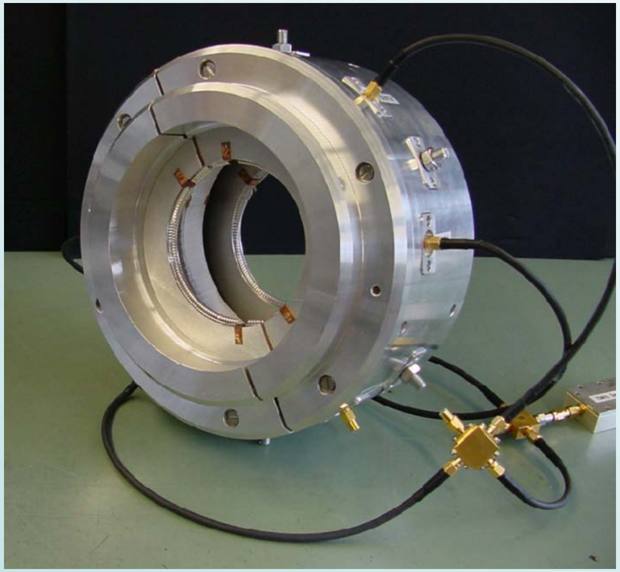
Passive Transformer / Fast Current Transformer (FCT)



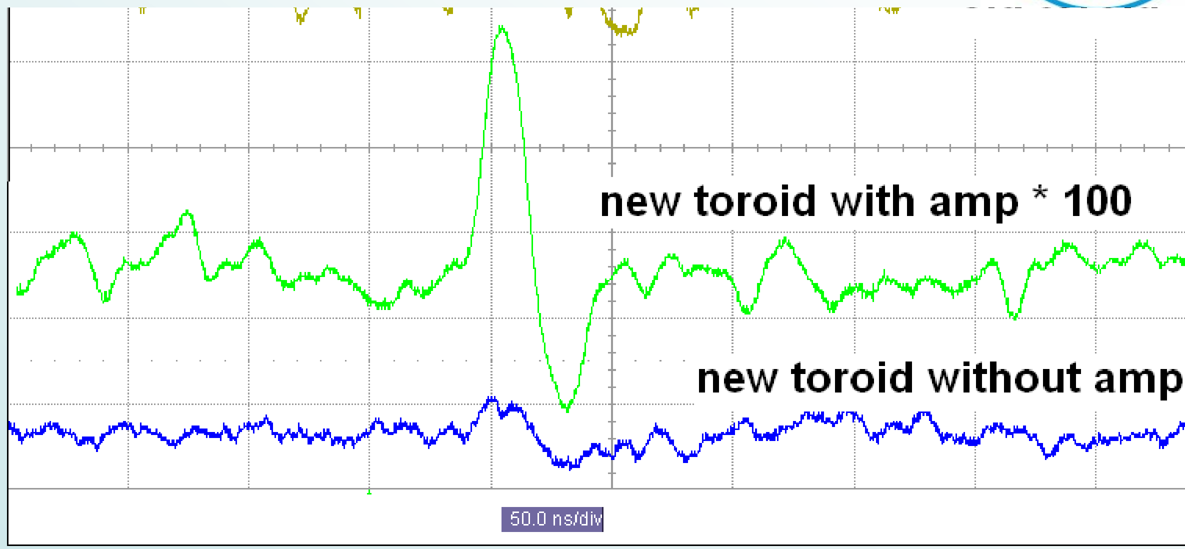
Standard Beam Current Monitors for XFEL and FLASH II (with split core for easier mounting)

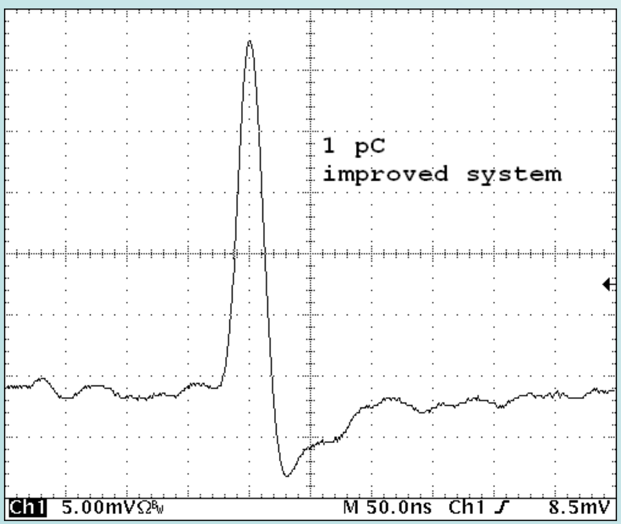


Passive Transformer / Fast Current Transformer (FCT)



Complete FCT setup





Left: Measurement in the lab → achieved resolution of **< 0.02 pC RMS**

Above: Operation in FLASH with 8 pC bunches, estimated resolution **~ 0.6pC RMS** (BW=20MHz, non-averaged).

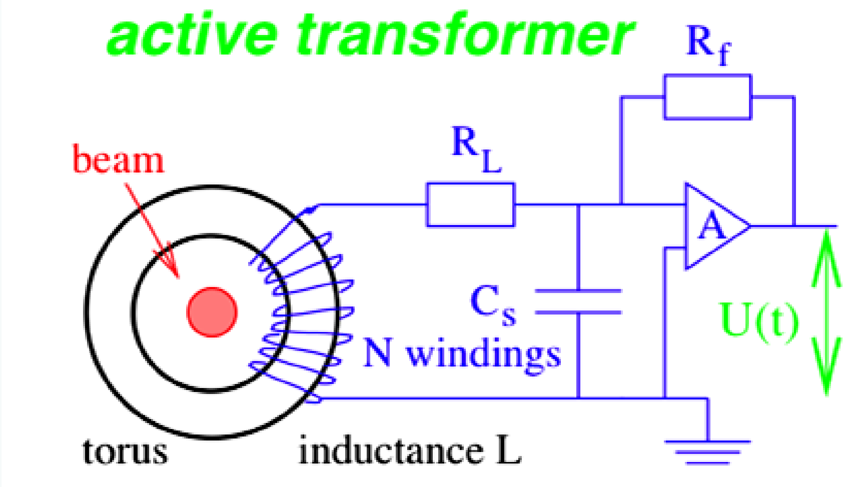
Heidelberger Ionenstrahl-Therapiezentrum

"Active" Transformer with longer Droop Time

An Active Transformer or Alternating Current Transformer **ACT** uses a trans-impedance amplifier (I/U converter) to a $R \approx 0\ \Omega$ load impedance i.e. a current sink + compensation feedback

$\Rightarrow$ longer droop time t_{droop}

Application: measurement of longer pulses with t > 10 µs e.g. at LINACs



The input resistor is for an op-amp:
$R_f/A \ll R_L$

$\Rightarrow t_{droop} = L/(R_f/A+R_L) \simeq L/R_L$

Droop time constant can be up to 1 s!

The feedback resistor is also used for range switching.

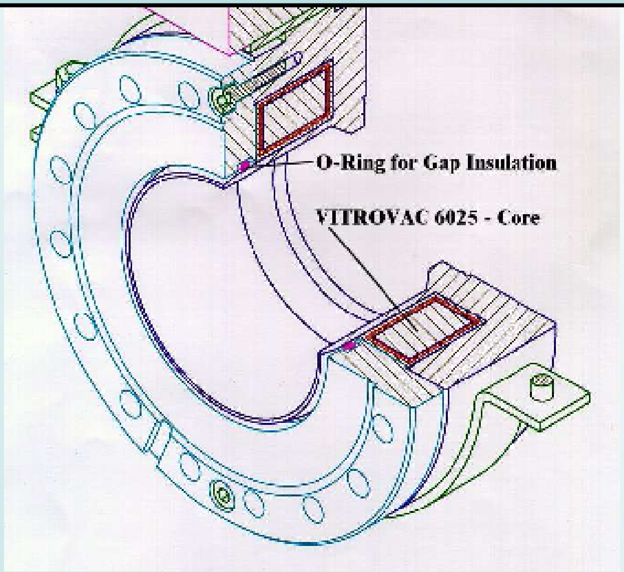
→ An additional active feedback loop is used to compensate the droop.

“Active” Transformer Realization

Active transformer system used at GSI Linacs and for the HIT and CNAO injectors

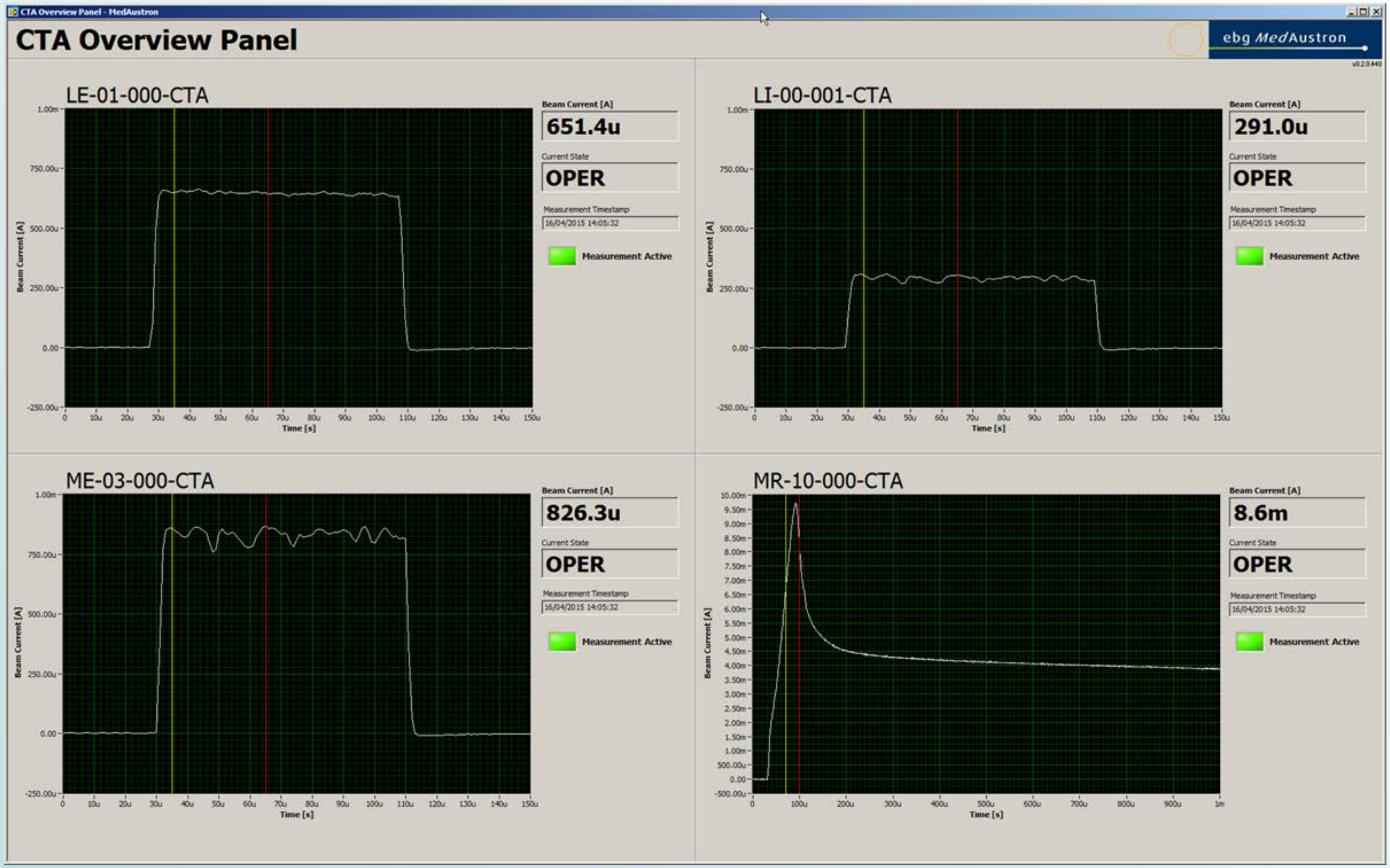
Torus inner radius	r_i=30 mm
Torus outer radius	r_o=45 mm
Core thickness	l=25 mm
Core material	Vitrovac 6025 $(CoFe)_{70\%}(MoSiB)_{30\%}$
Core permeability	$\mu_r=10^5$
Number of windings	2x10 crossed
Max. sensitivity	10^6 V/A
Beam current range	10 µA to 100 mA
Bandwidth	1 MHz
Droop	0.5 % for 5 ms
rms resolution	0.2 µA for full bw

System offered by Bergoz, used at MedAustron, MIT and SHPIC (Shanghai)



Heidelberger Ionenstrahl-Therapiezentrum

"Active" Transformer Measurements

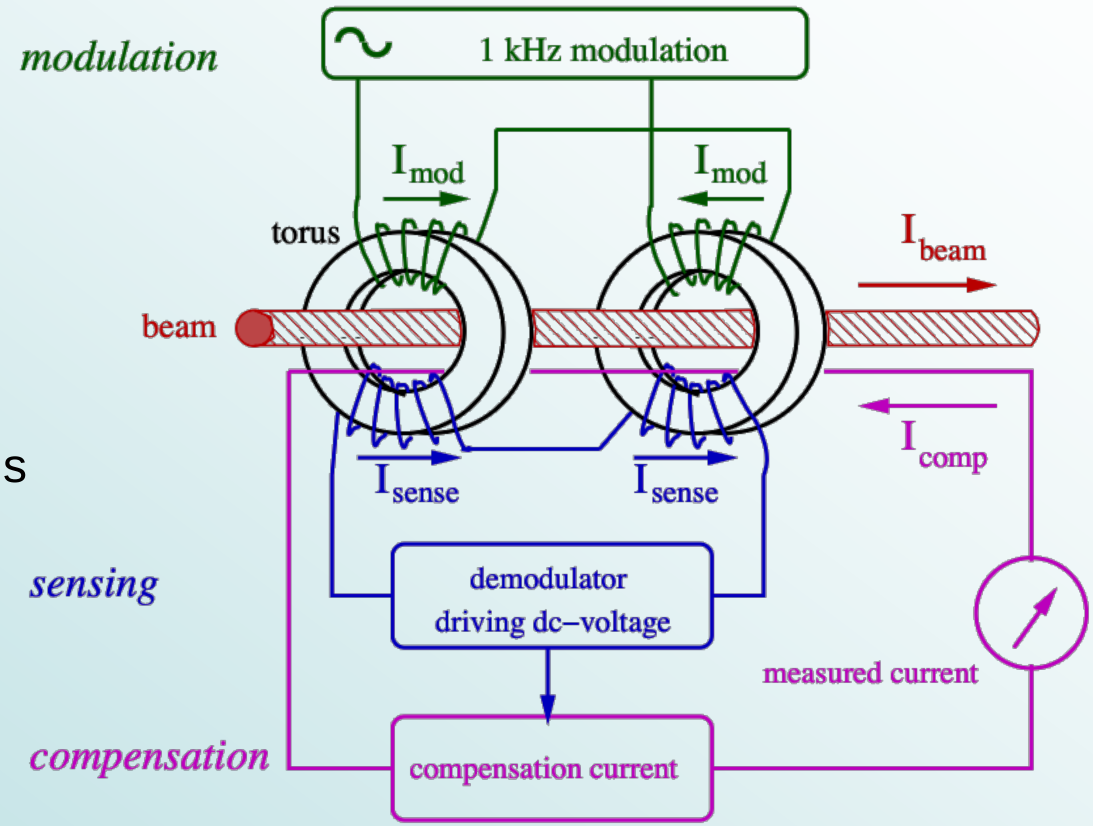


MedAustron: ACCT overview panel during commissioning

Current Measurement of DC beams

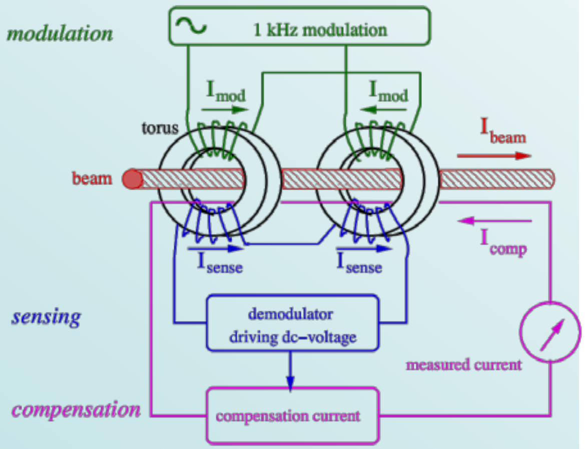
- The current transformer discussed above sees only **B-flux** ***changes*****.**
- For measuring DC beams non-destructively the DC Current Transformer (DCCT) is the solution – method: look at the magnetic saturation of two tori.

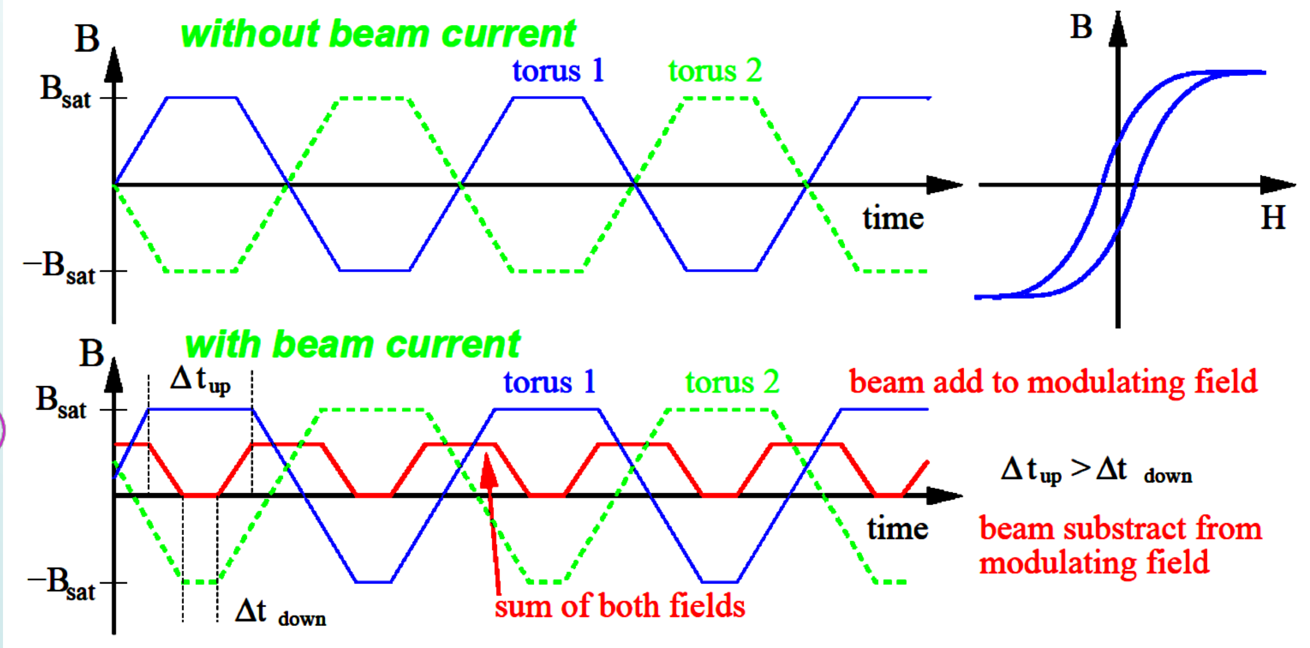
- **Modulation** of the primary windings forces both tori into saturation twice per cycle.
- **Sense windings** measure the modulation signal and cancel each other.
- But with the I_{beam}, the saturation is shifted and I_{sense} is not zero
- **Compensation current** adjustable until I_{sense} is zero once again.



Heidelberger Ionenstrahl-Therapiezentrum

DCCT Function Schematics





- **Modulation without beam:** typically about 1 kHz to saturation → **no** net flux
- **Modulation with beam:** saturation is reached at different times, → net flux
- **Net flux:** double frequency than modulation,
- **Feedback:** Current fed to compensation winding for larger sensitivity
- **Two magnetic cores:** Must be very similar.

DCCT Realizations

Example: The DCCT at GSI synchrotron (designed 1990 at GSI):

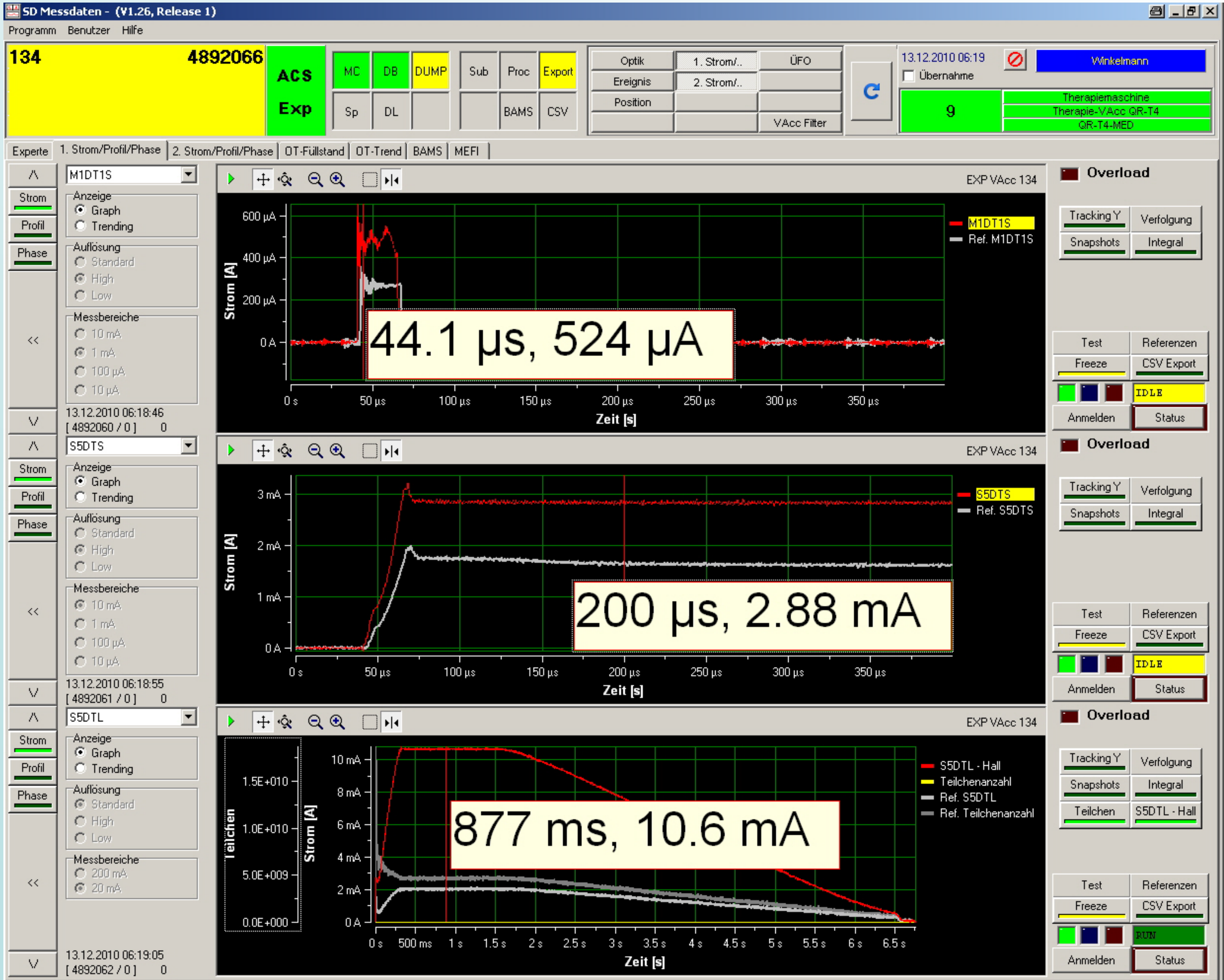
Core radii	$r_i = 135$ mm, $r_o = 145$mm
Core thickness	10 mm
Core material	Vitrovac 6025: $(CoFe)_{70\%}(MoSiB)_{30\%}$
Core permeability	$\mu_r \simeq 10^5$
Saturation B_{sat}	$\simeq 0.6$ T
Isolating cap	Al_2O_3
Number of windings	16 for modulation and sensing 12 for feedback
Ranges for beam current	300 μA to 1 A
Resolution	2 μA
Bandwidth	dc to 20 kHz
rise time	20 μs
Offset compensation	± 2.5 μA in auto mode $<$ 15 μA/day in free run
temperature coeff.	1.5 μA/^{o}C

Commercial product specification (Bergoz NPCT):

Most parameters: comparable the GSI-model
Temperature coeff. 0.5 µA/^{o}C
Resolution several µA (b.w. dependent)

In-flange.NPCT with 96-mm aperture

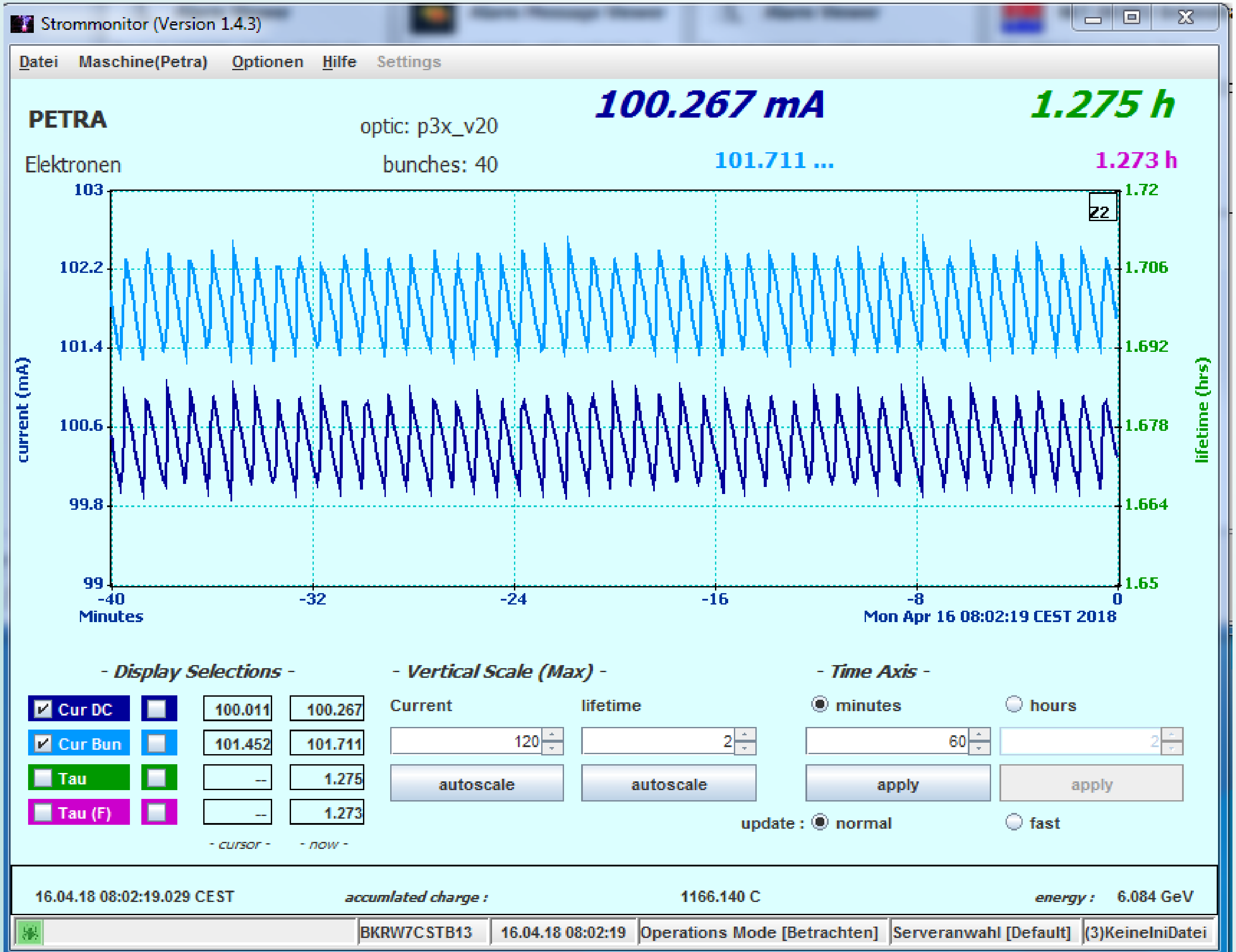
AC/DC Beam Current Measurement



Example:
Injection and acceleration at the HIT facility

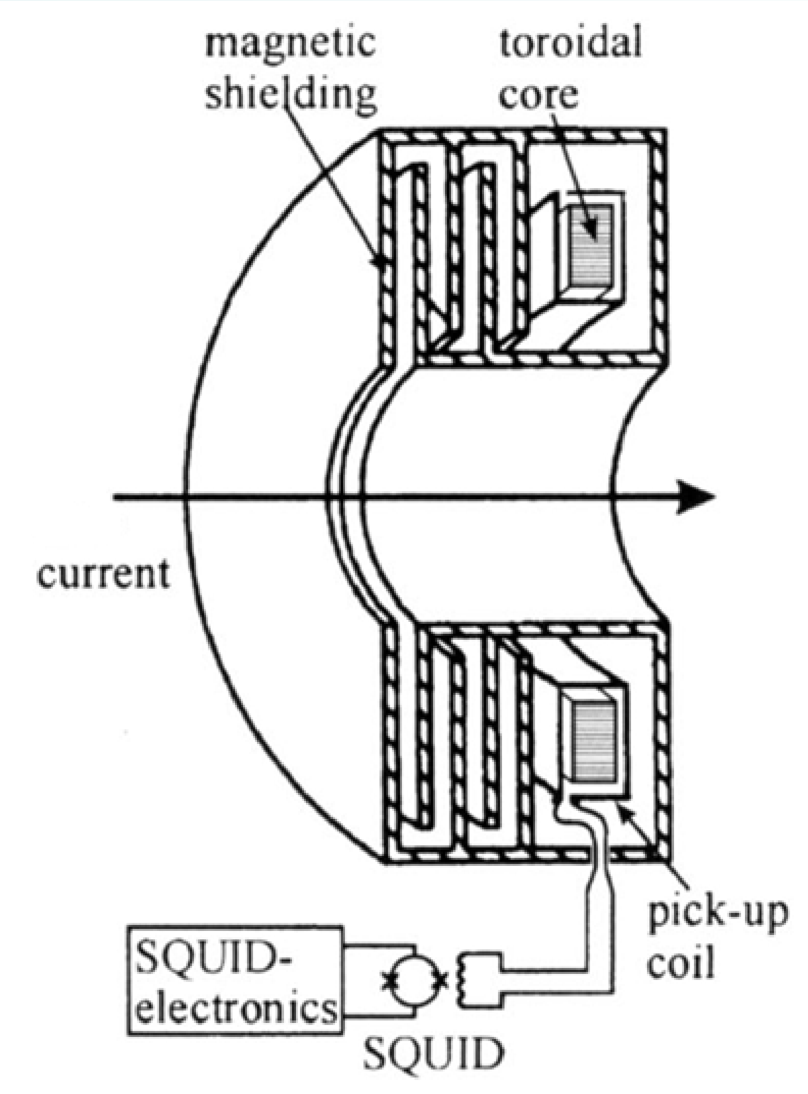
HIT
Heidelberger Ionenstrahl-Therapiezentrum

DC Beam Current Measurement



Top-Up Operation at PETRA synchrotron (upper trace → Bergoz PCT)

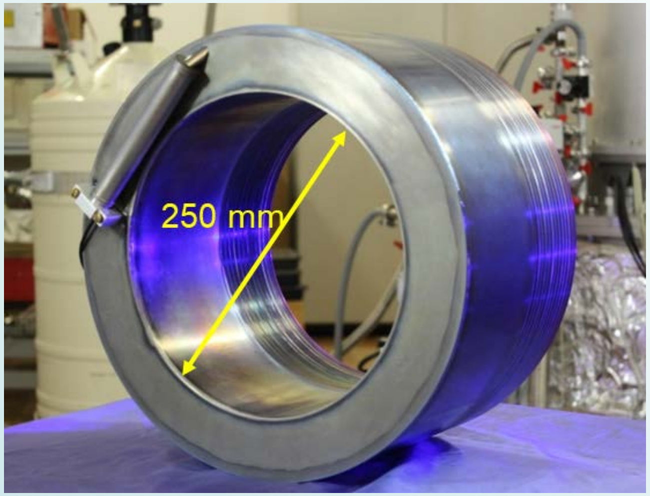
The CCC – a "nA dc transformer"



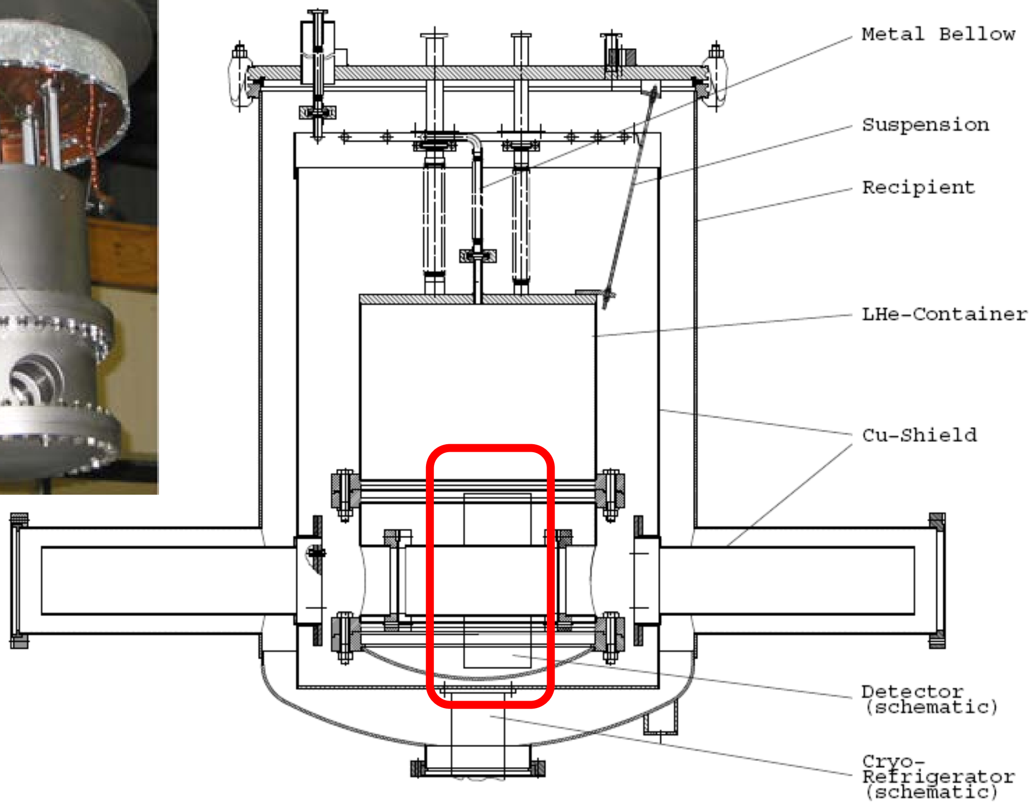
Non-destructive measurement device for low intensity beams (between 1 nA an 10 µA)

Cryogenic Current Comparator: Precise measurement of azimuthal magnetic field (fT-range) using DC-SQUIDS

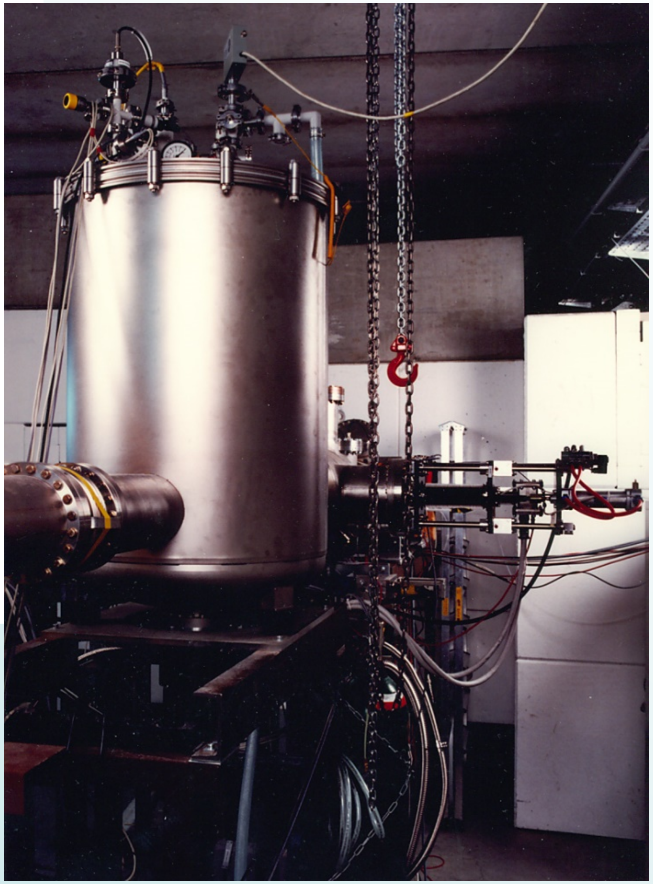
Toroid version for FAIR with big bore (from GSI)



The CCC – a "nA dc transformer"

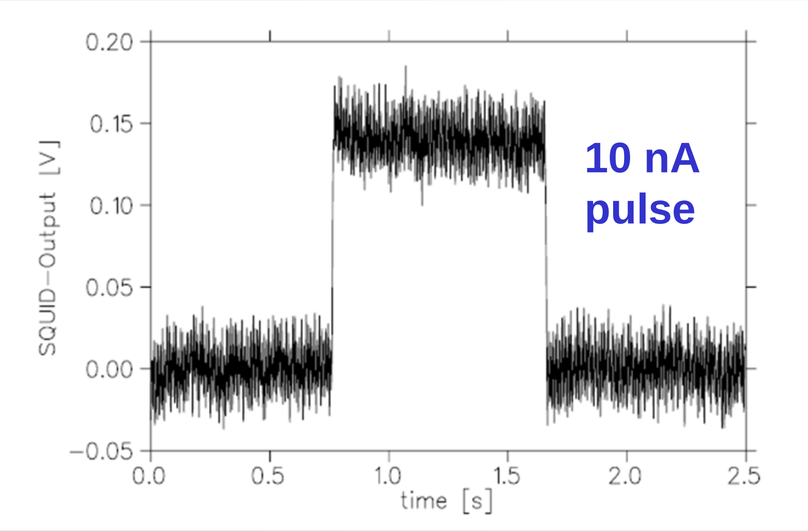


Schematic Setup of a CCC device including cryostat



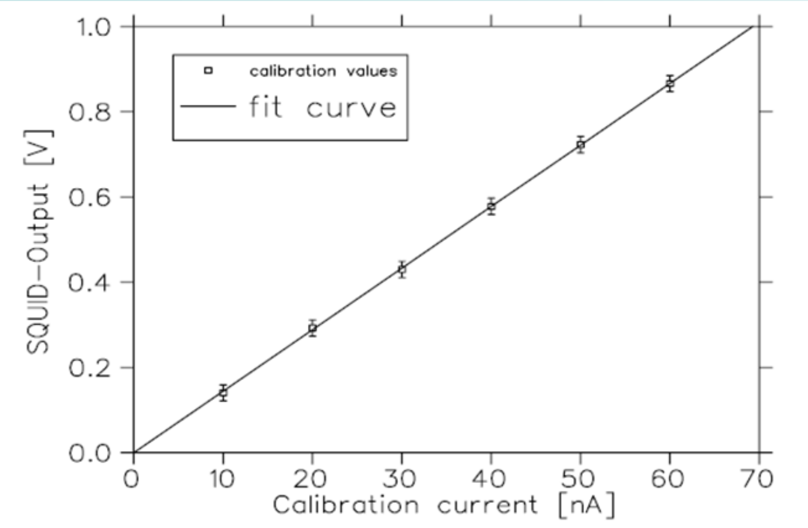
CCC measurement device in a GSI beamline behind SIS18 synchrotron (in front of a beam dump)

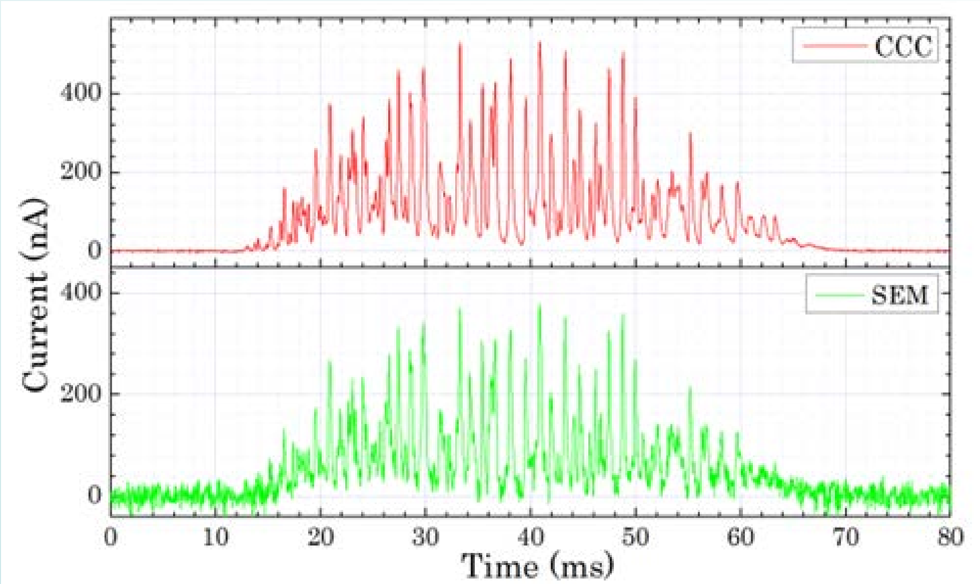
The CCC – a "nA dc transformer"



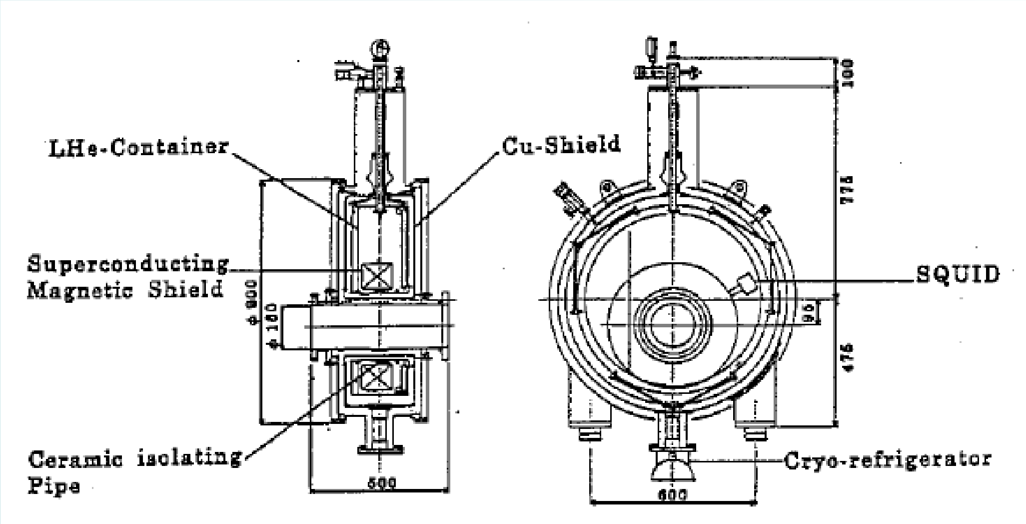
Left: CCC calibration data; current resolution: 60 pA/√Hz

Below: Slowly extracted beam, 600 MeV/u Ni^{26+}; upper trace: CCC, lower trace: SEM signal

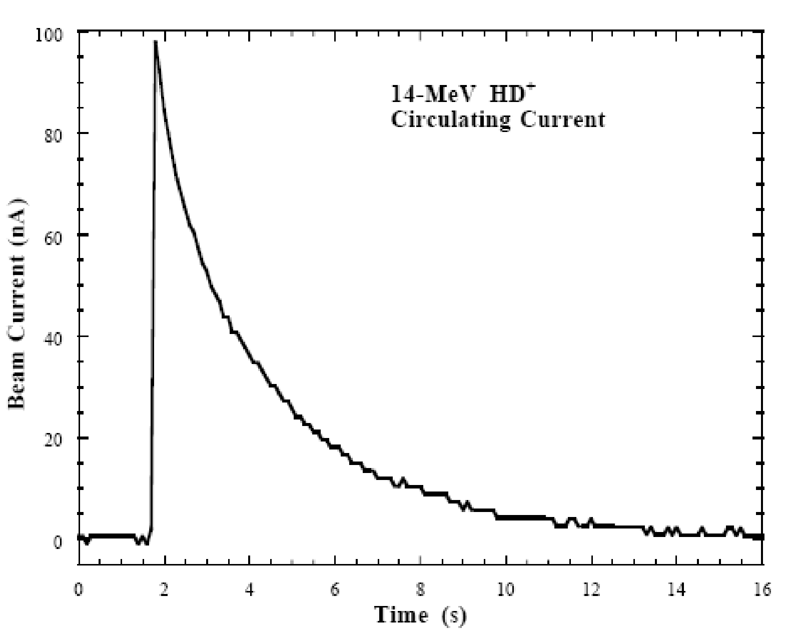


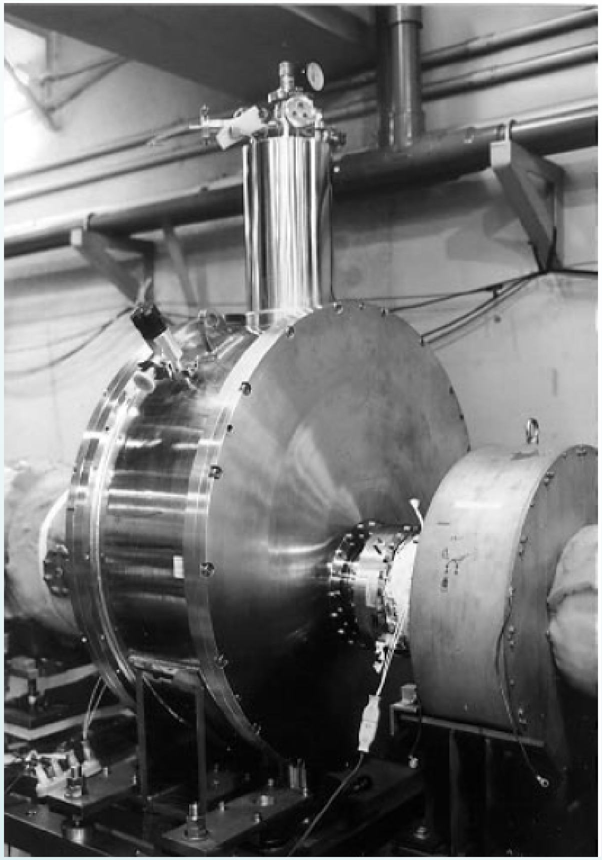


The CCC – a "nA dc transformer"



University of Tokyo, TARN-II storage ring





Lifetime measurements on stored molecules (HD^+, 14 MeV)

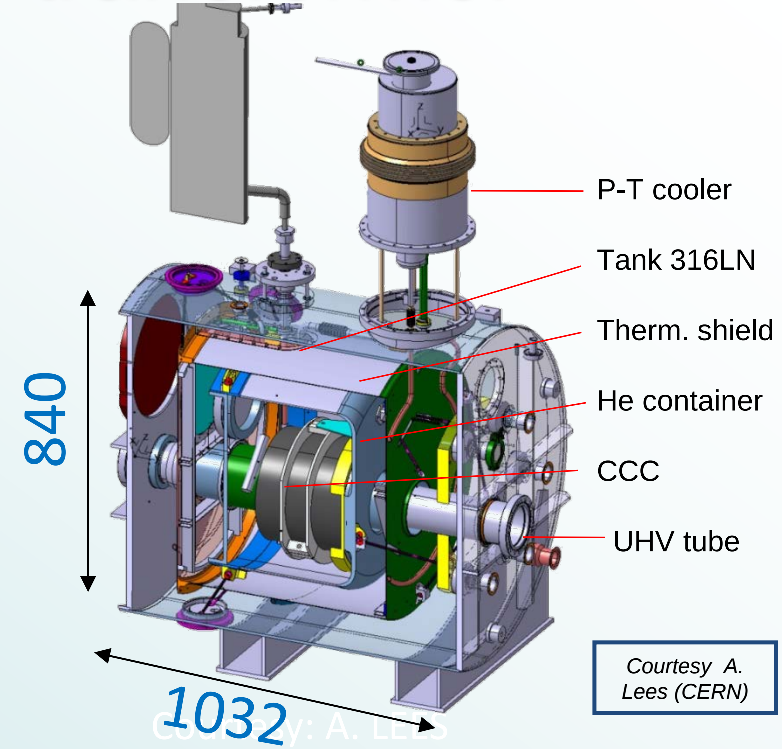
The CCC – a “nA dc transformer”

Installation at CERN-AD

<u>Requirements:</u>

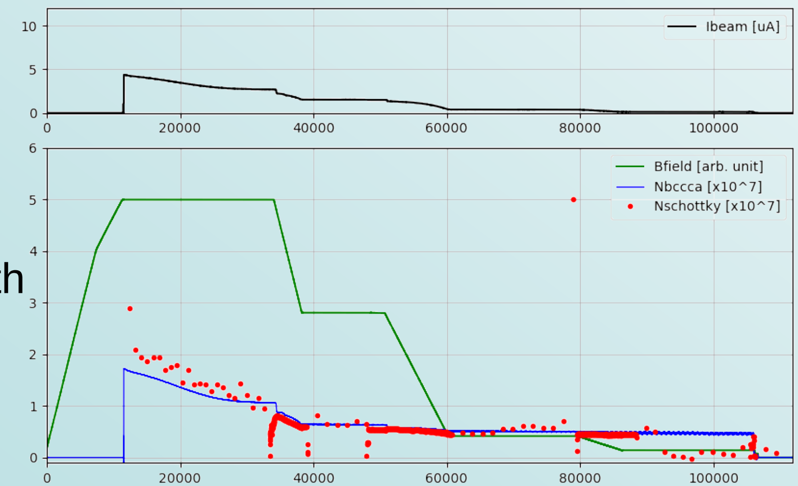
- Intensity measurement alternative to Schottky
- Current resolution: 10 nA,
  intensity resolution: $5x10^5$ pbar
- Bandwidth DC - 1 kHz

(Collaboration between CERN, FSU/HIJ/IPHT Jena, TU DA and GSI since 2014)

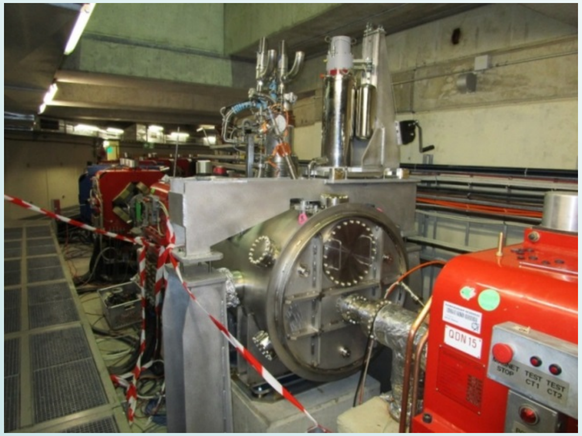


Courtesy A. Lees (CERN)

AD cycle measured with Schottky PU and CCC



	3.5 GeV/c	2.0 GeV/c	300 MeV/c	100 MeV/c R	100MeV/c E
Schottky vistar	7.3861e+06	5.3801e+06	4.4613e+06	4.4324e+06	n.a.
Schottky plot	7.3861e+06	5.3801e+06	4.4613e+06	4.4324e+06	-1.0000e+00
BCCCA plot	8.5654e+06	5.6582e+06	4.9809e+06	4.7068e+06	4.4330e+06
Ratio	+13.8%	+4.9%	+10.4%	+5.8%	+100.0%



Courtesy R. Jones, M. Fernandes (CERN)

Conclusion and Acknowledgements

- Beam Instrumentation is the "the eyes of the operator" to the behavior of the accelerator, thus robustness and reliability of beam diagnostic devices is mandatory, especially for the work horses like ac/dc beam transformers described in this talk.
- Current measurement devices need excellent maintenance, e.g. calibration to always guarantee reliable measurement results within the specifications.
- Nowadays a strong link to the accelerator control system is a must for beam instrumentation to filter and post-work the raw signal and to present the measurement data in the control room, fill longtime archives for later data evaluation, etc.

Conclusion and Acknowledgements

Many thanks to all colleagues from HIT, MedAustron, CNAO, PSI, ALBA, DESY, CERN, Bergoz, Univ. of Tokyo and GSI/FAIR – especially to Peter Forck – for their advice and giving me interesting example measurements and photos of beam instrumentation from their facilities!

PAUL SCHERRER INSTITUT PSI

MedAustron

DESY.

bergoz INSTRUMENTATION

ALBA

GSI Helmholtzzentrum für Schwerionenforschung GmbH

FAIR

fondazione CNAO Centro Nazionale di Adroterapia Oncologica per il trattamento dei tumori

CERN

THE UNIVERSITY OF TOKYO

Thank you for your attention!