Beam Instrumentation

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HIT Betriebs GmbH am
Universitätsklinikum Heidelberg

http://www.hit-centrum.de

Outline

- Beam Instrumentation for Medical Accelerators – some general remarks as introduction
- Variety of beam parameters of Linac-Synchrotron and Cyclotron Facilities
- Overview of beam characteristics and linked diagnostic equipment
- Current measurement devices
- Profile monitors
- Embedding of Beam Diagnostics devices
- Conclusion and Acknowledgements

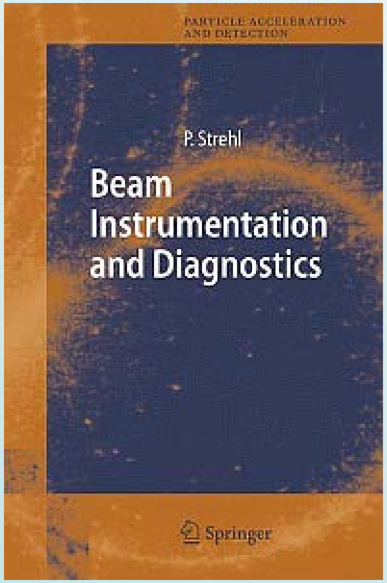
Introduction

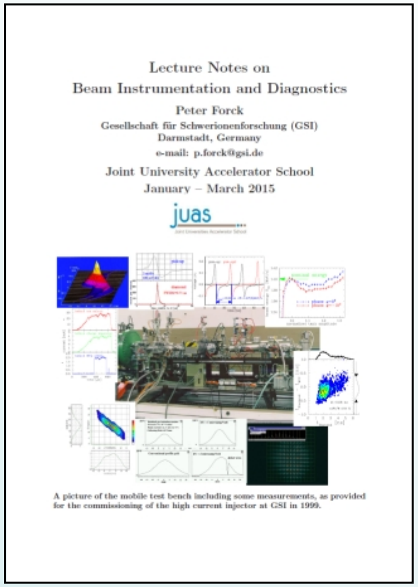
- This talk will “only” address ***Particle Accelerators*** used for Medical Applications – although most accelerators for radio oncology are small electron linacs in the MeV-region to produce X-rays
- Proton and Ion Accelerators for this purpose are today **Cyclotrons** and **Linac-Synchrotron**-Combinations with HEBTs and Gantries
- Beam Instrumentation for such accelerators is the same as used for research machines
- Thus you can find more information about ***Beam Instrumentation*** in a lot of sources, here some hints…

Introduction

- Literature:

https://indico.cern.ch/event/356897/other-view?view=standard





Lecture Notes on
Beam Instrumentation and Diagnostics
Peter Forck
Gesellschaft für Schwerionenforschung (GSI)
Darmstadt, Germany
e-mail: p.forck@gsi.de
Joint University Accelerator School
January – March 2015

A picture of the mobile test bench including some measurements, as provided for the commissioning of the high current injector at GSI in 1999.

- 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*
- …. 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:

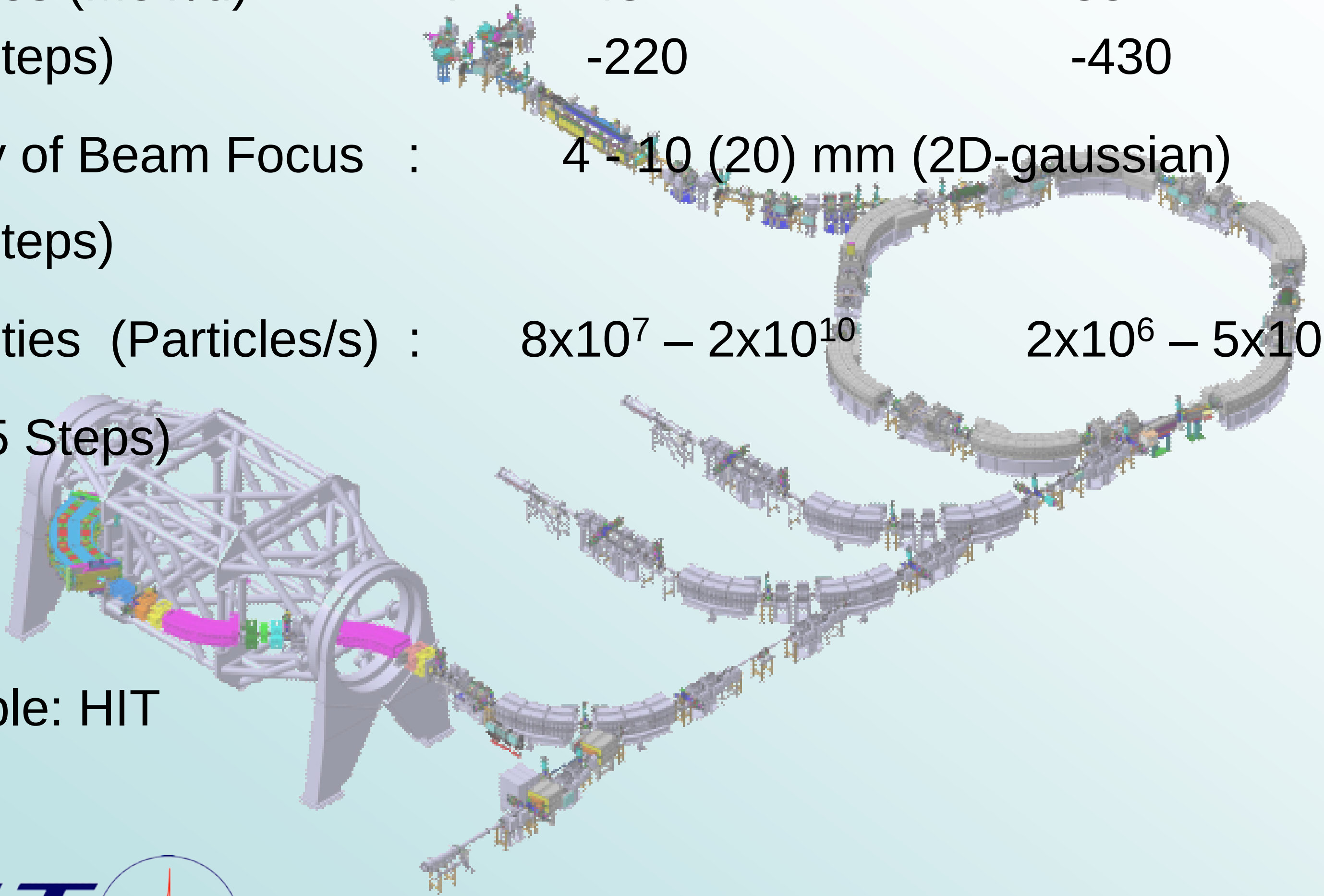
I. Non-destructive diagnostic systems that will work online during the patient treatment and in all other cases

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.

Variety of beam parameters – Linac-Synchrotron-based Facilities

Ions	p	$^{12}C^{6+}$
• Energies (MeV/u) (255 Steps)	48 -220	88 -430
• Variety of Beam Focus (4/6 Steps)	4 - 10 (20) mm (2D-gaussian)	
• Intensities (Particles/s) (10/15 Steps)	$8x10^7 – 2x10^{10}$	$2x10^6 – 5x10^8$



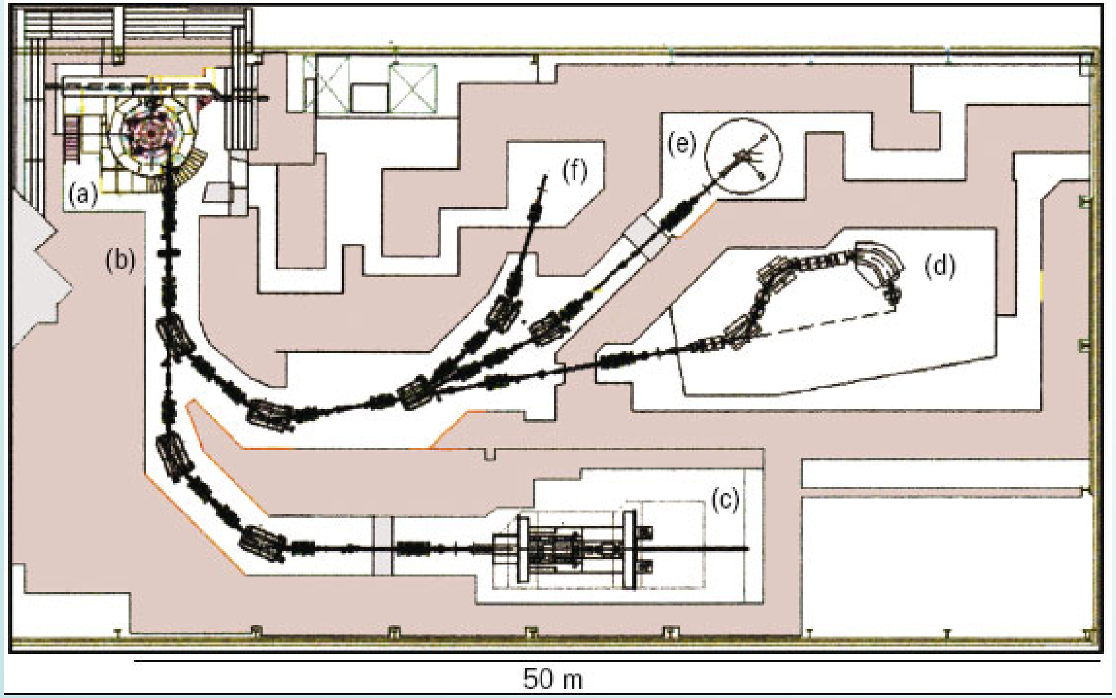
Example: HIT

Heidelberger Ionenstrahl-Therapiezentrum

Variety of beam parameters – Cyclotron-based Facilities

- Particles: protons
- Energy: up to 250 MeV
- Current: 1 – 850 nA c.w. (= 6×10^{9} – 5×10^{12} particles/s)

Degrader (b): overall transmission down to 1%



Example:
PSI ProScan

Overview of beam characteristics and linked diagnostic equipment

Beam parameter	**Measurement systems**
Current	AC and DC transformers, Faraday cups, Scint. Counters, Ionization Chambers, SEMs
Position	Capacitive and button pick-ups, “Shoe-box” pick-ups, Stripline p.u., Resonant p.u.
Transversal profile	Scintillation Screens, SEM grids, Wire scanner, MWPCs, RGMs, BIF monitor, OTR
Longitudinal profile	Coaxial FCs, Resistive wall monitors, ….
Beam energy/spread	TOF with phase probes, Schottky method
Emittance	Slit-Grid devices, Pepperpot devices, Quadrupole variation method
Beam loss	Scint. Counters, ICs, PIN diodes, optical fibers

Beam Current Measurement

The beam 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
- Important for transmission measurement and to prevent for beam losses.

Different devices are used:

- **Transformers:** Measurement of the beam's **magnetic field**

  They are non-destructive. No dependence on beam energy

  They have a limited detection threshold (~ µA).

- **Faraday cups:** Measurement of the beam's **electrical charges**

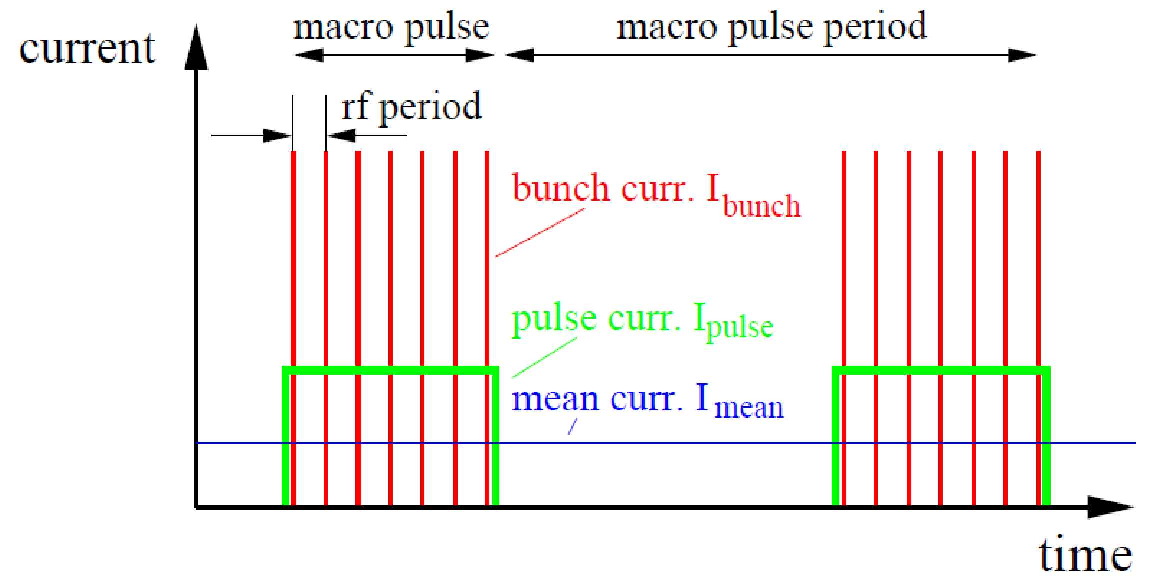
  They are destructive. For "low" energies only.
  Low currents can be determined.

- **Particle detectors:** 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.

Current Measurement – Pulsed Beams

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



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}

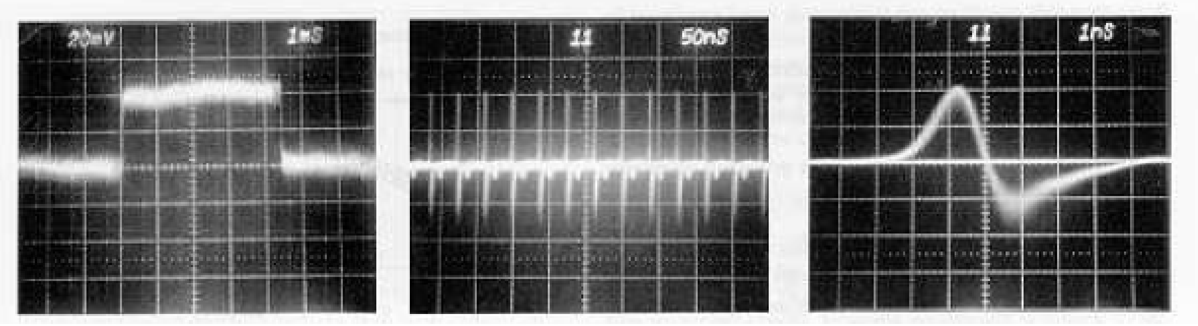
→ during the bunch in [C/bunch]

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

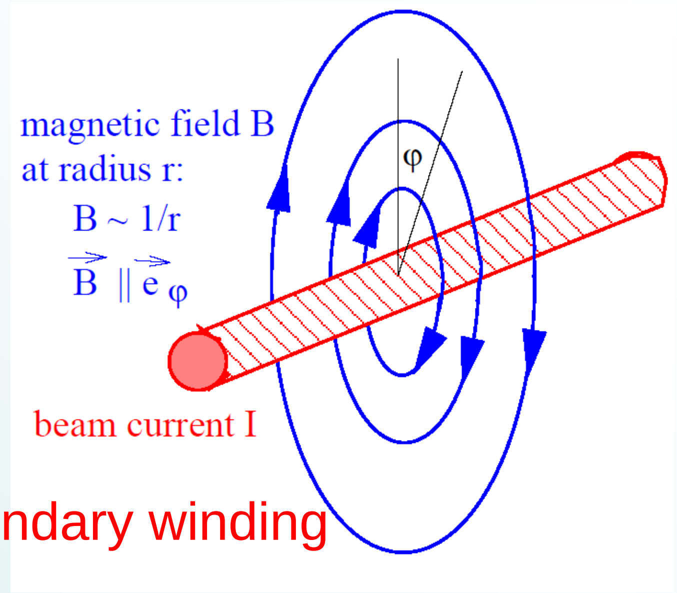
- Beam current of *N* charges with velocity β:

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

- 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

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

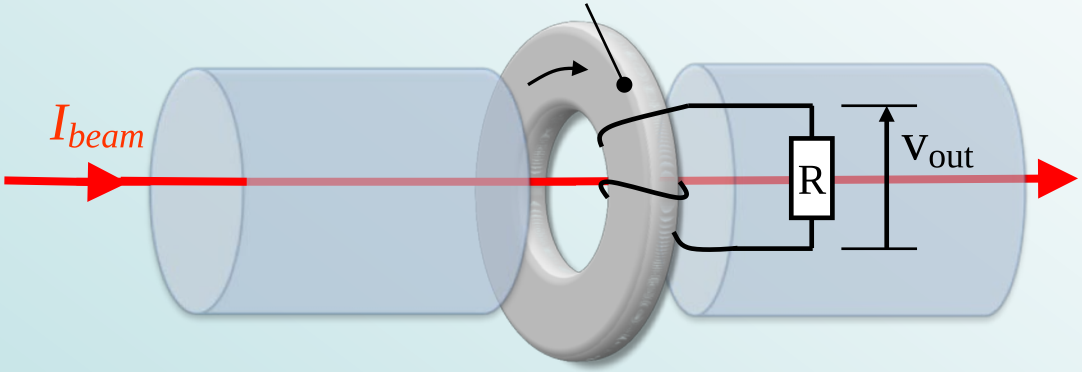
- Inductance of a torus of ***μ***$\boldsymbol{\mu_r}$

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

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

Definition: ***U = L · dI/dt***

Torus to guide the magnetic field



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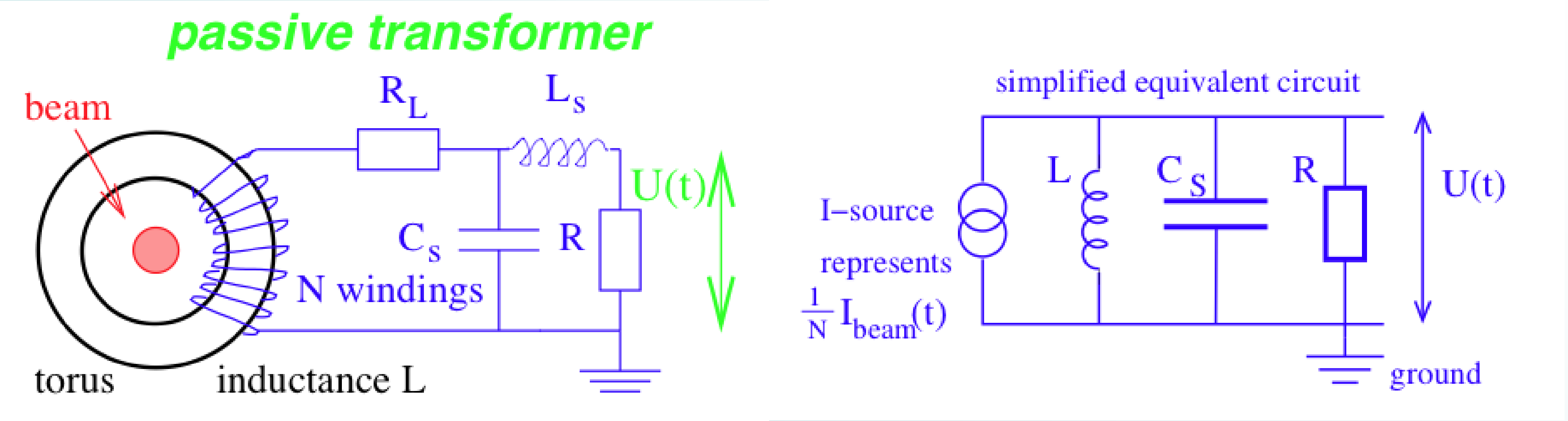
Passive Transformer / Fast Current Transformer (FCT)

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

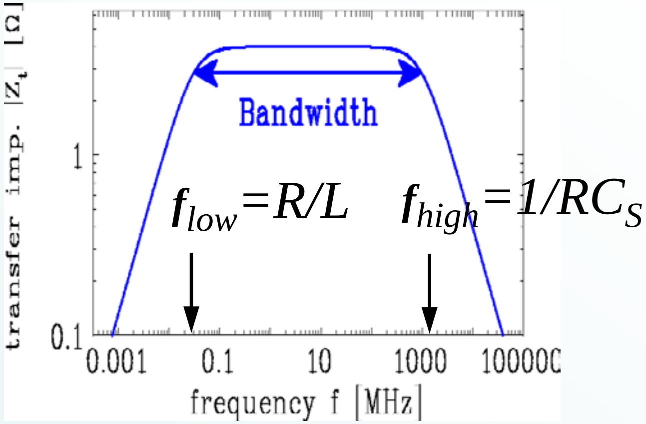
Rise time: $t_{rise} = 1/3f_{high} = 1/RC_S$ (ideal without cables)

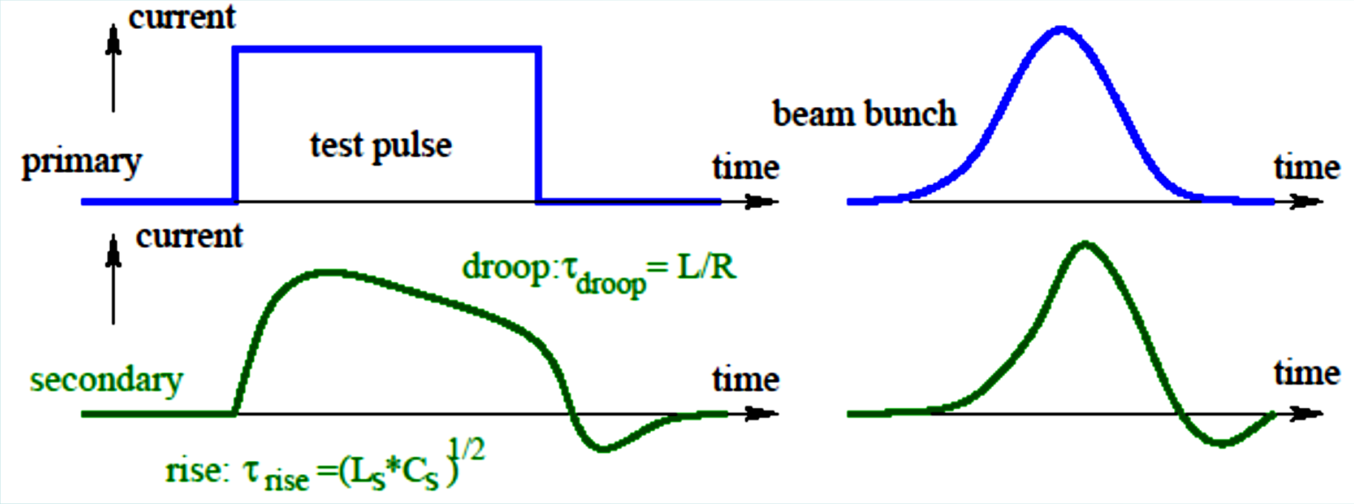
Rise time: $t_{rise} = 1/3f_{high} = \sqrt{L_S C_s}$ (with cables)

R_L: loss resistivity, **R**: for measuring.

For the working region the voltage output is

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



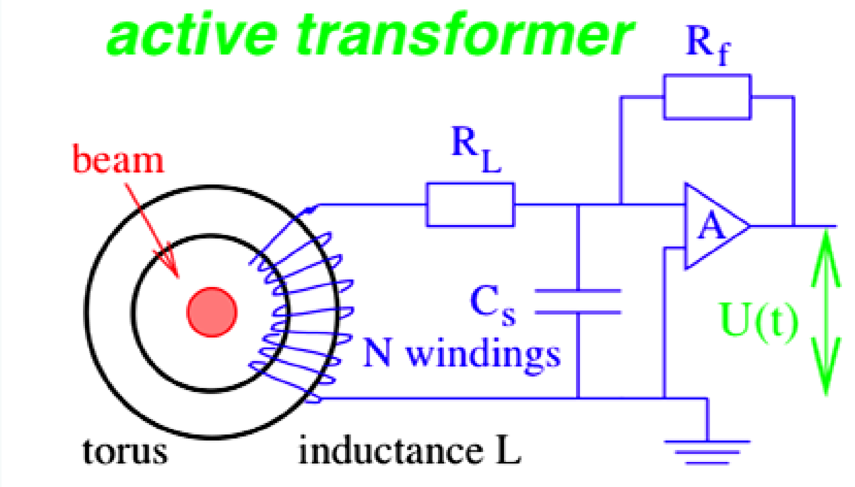


“Active” Transformer with longer Droop Time

An Active Transformer or Alternating Current Transformer **ACT** uses a trans-impedance amplifier (I/U converter) to a ***R*** $\approx$ **0 Ω** 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:

$R_f/A \ll R_L$

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

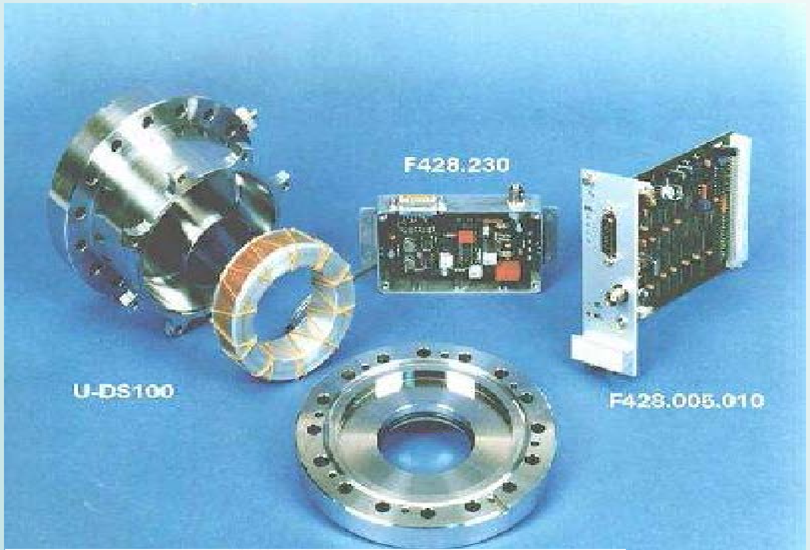
Droop time constant can be up to 1 s!

The feedback resistor is also used for range switching.

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

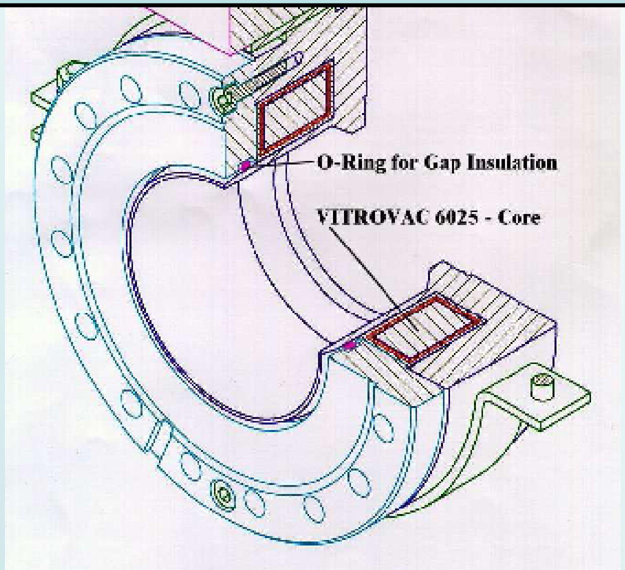
"Active" Transformer Realization

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

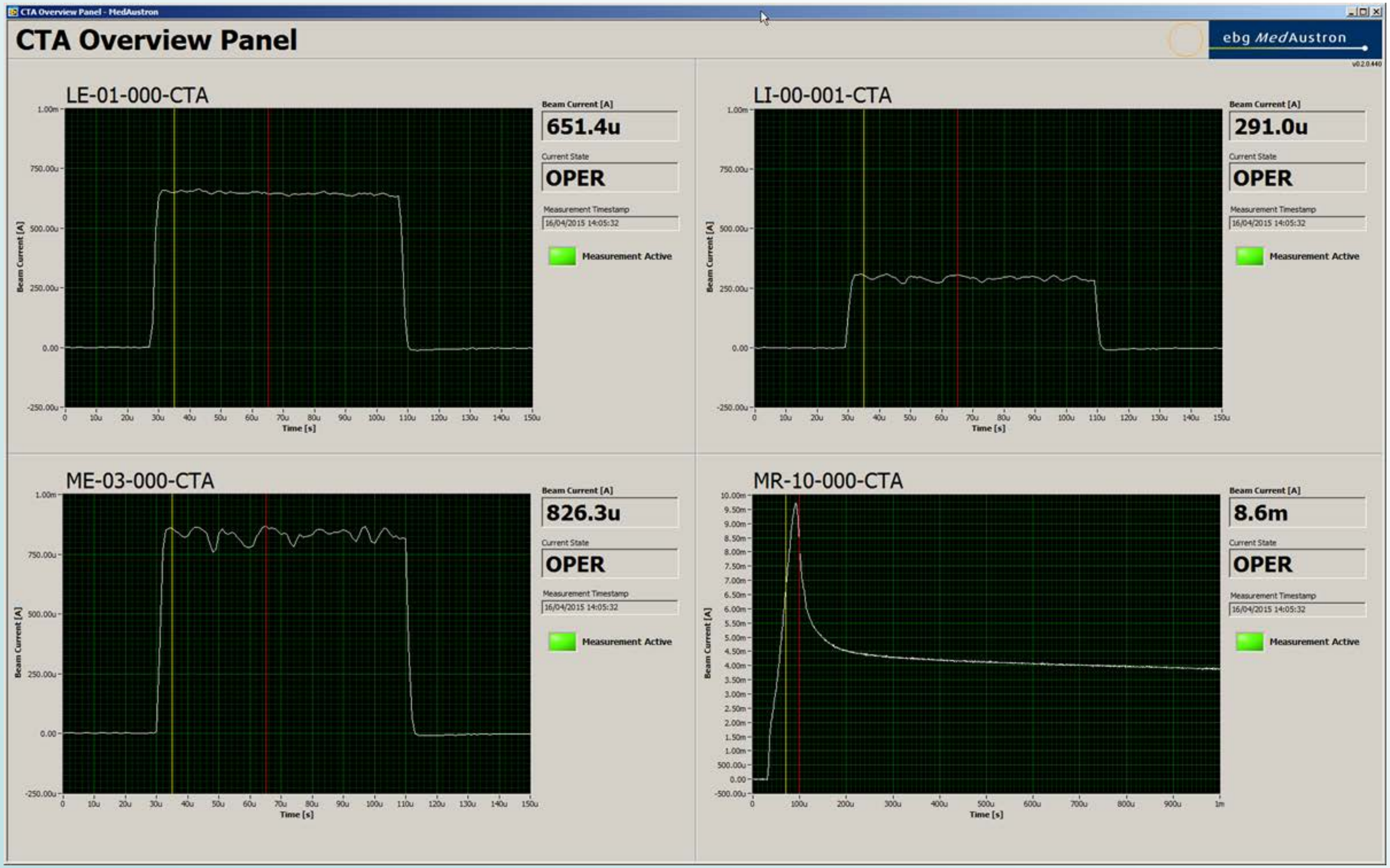


Torus inner radius	r_i=30 mm
Torus outer radius	r_o=45 mm
Core thickness	l=25 mm
Core material	Vitrovac 6025 $(CoFe)_{70\%}(MoSiB)_{30\%}$
Core permeability	μ_r=10^5
Number of windings	2x10 crossed
Max. sensitivity	10^6 V/A
Beam current range	10 µA to 100 mA
Bandwidth	1 MHz
Droop	0.5 % for 5 ms
rms resolution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

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



“Active” Transformer Measurements



CTA Overview Panel

LE-01-000-CTA
Beam Current [A]: 651.4u
Current State: OPER
Measurement Timestamp: 16/04/2015 14:05:32
🟩 Measurement Active

LI-00-001-CTA
Beam Current [A]: 291.0u
Current State: OPER
Measurement Timestamp: 16/04/2015 14:05:32
🟩 Measurement Active

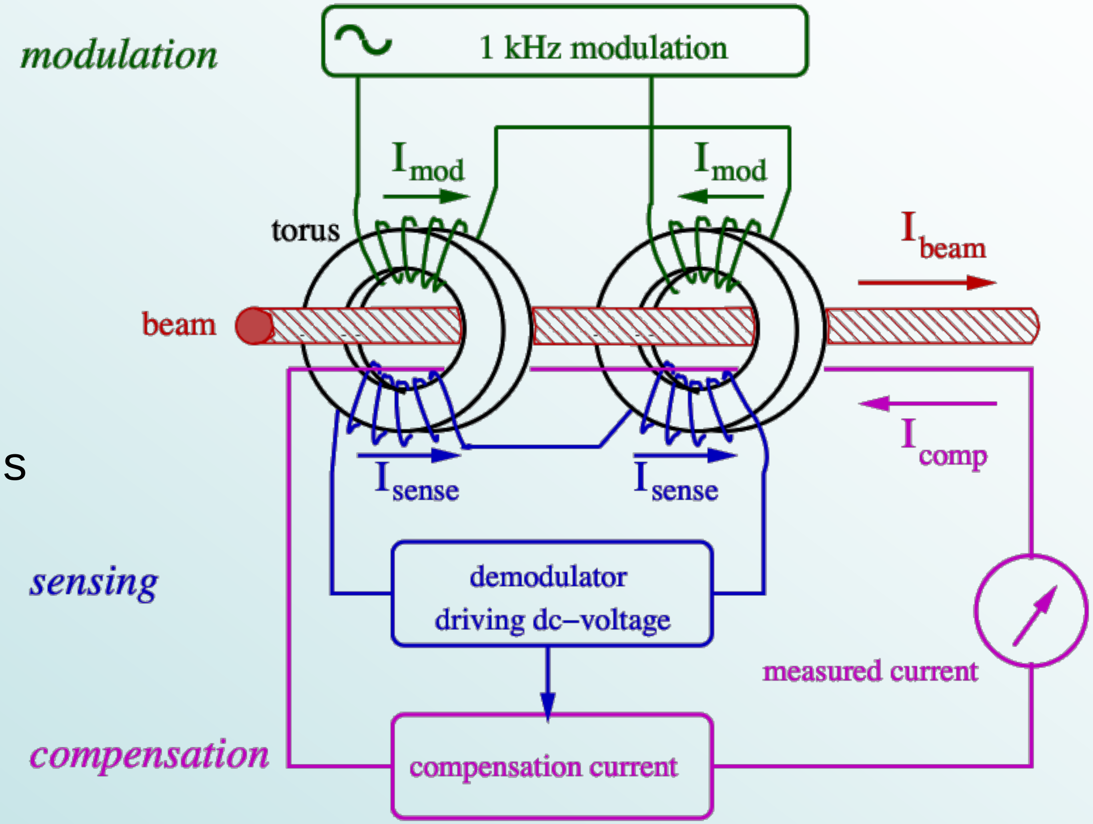
ME-03-000-CTA
Beam Current [A]: 826.3u
Current State: OPER
Measurement Timestamp: 16/04/2015 14:05:32
🟩 Measurement Active

MR-10-000-CTA
Beam Current [A]: 8.6m
Current State: OPER
Measurement Timestamp: 16/04/2015 14:05:32
🟩 Measurement Active

MedAustron: ACCT overview panel during commissioning

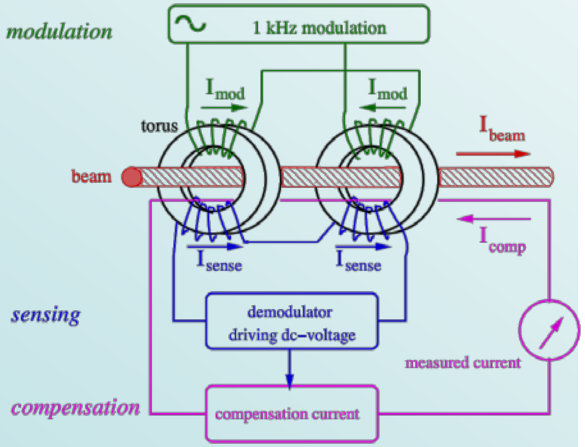
Current Measurement of DC beams

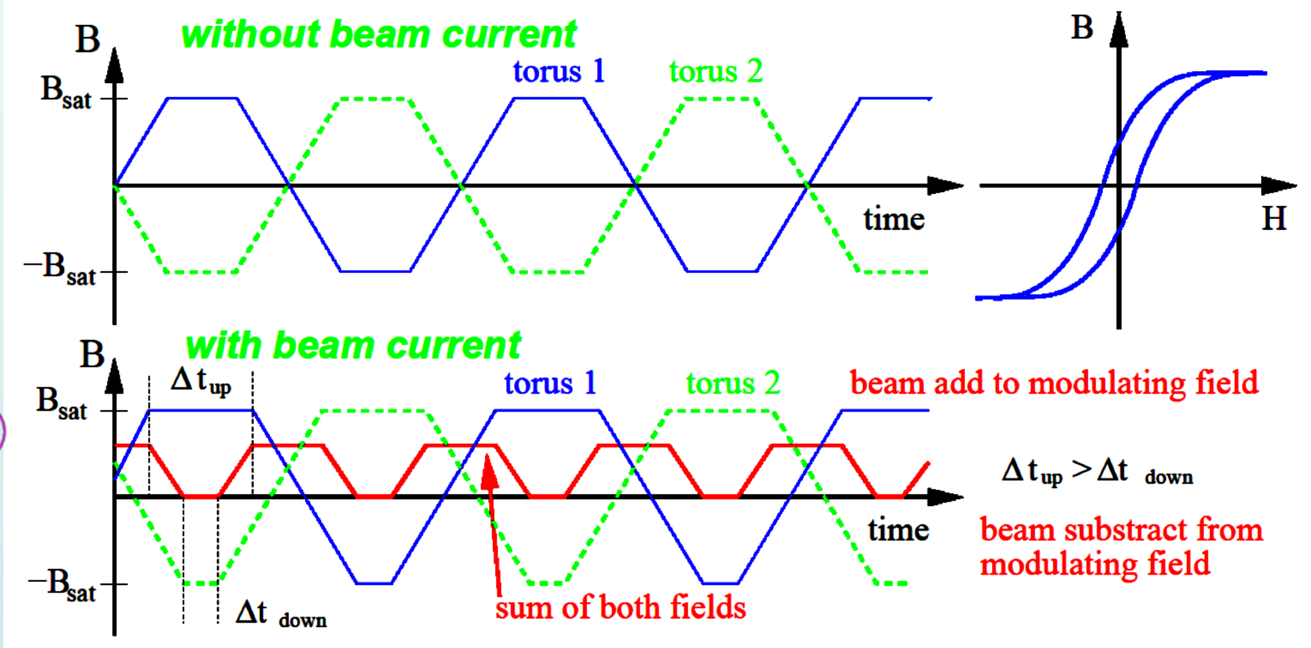
- The current transformer discussed above sees only **B-flux *changes*.**
- For measuring DC beams non-destructively the DC Current Transformer (DCCT) is the solution – method: look at the magnetic saturation of two tori.



- **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.

DCCT Function Schematics

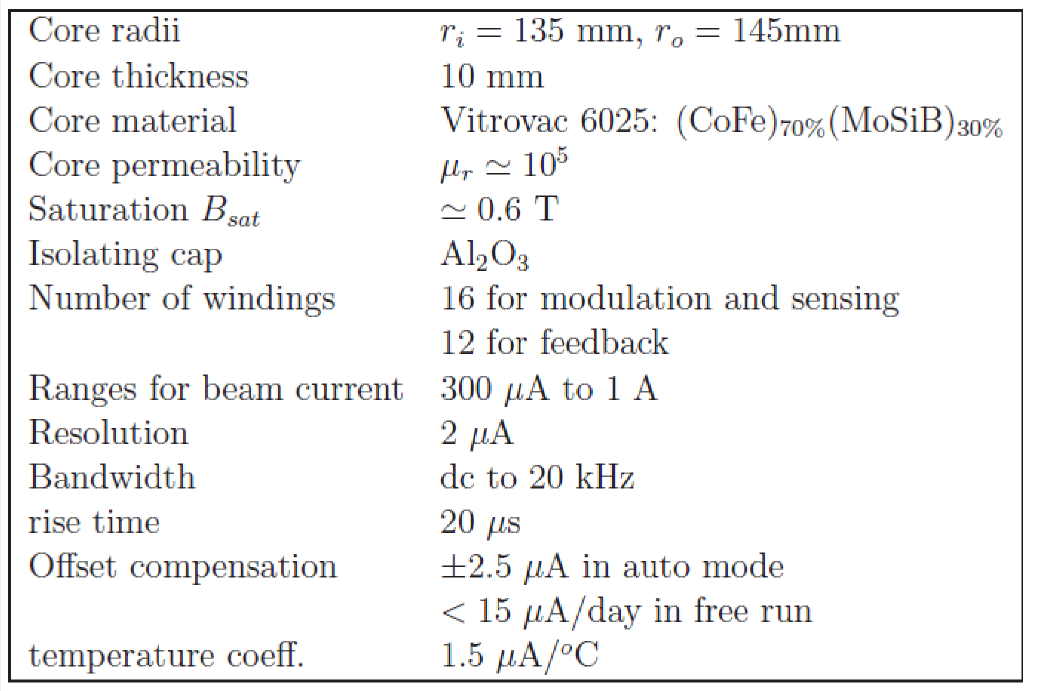




- **Modulation without beam:** typically about 1 kHz to saturation → **no** net flux
- **Modulation with beam:** saturation is reached at different times, → net flux
- **Net flux:** double frequency than modulation,
- **Feedback:** Current fed to compensation winding for larger sensitivity
- **Two magnetic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

DCCT Realizations

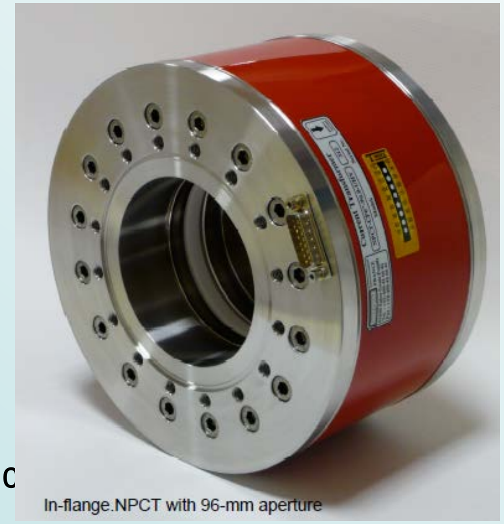
Example: The DCCT at GSI synchrotron (designed 1990 at GSI):



Core radii	$r_i = 135$ mm, $r_o = 145$mm
Core thickness	10 mm
Core material	Vitrovac 6025: $(\mathrm{CoFe})_{70\%}(\mathrm{MoSiB})_{30\%}$
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

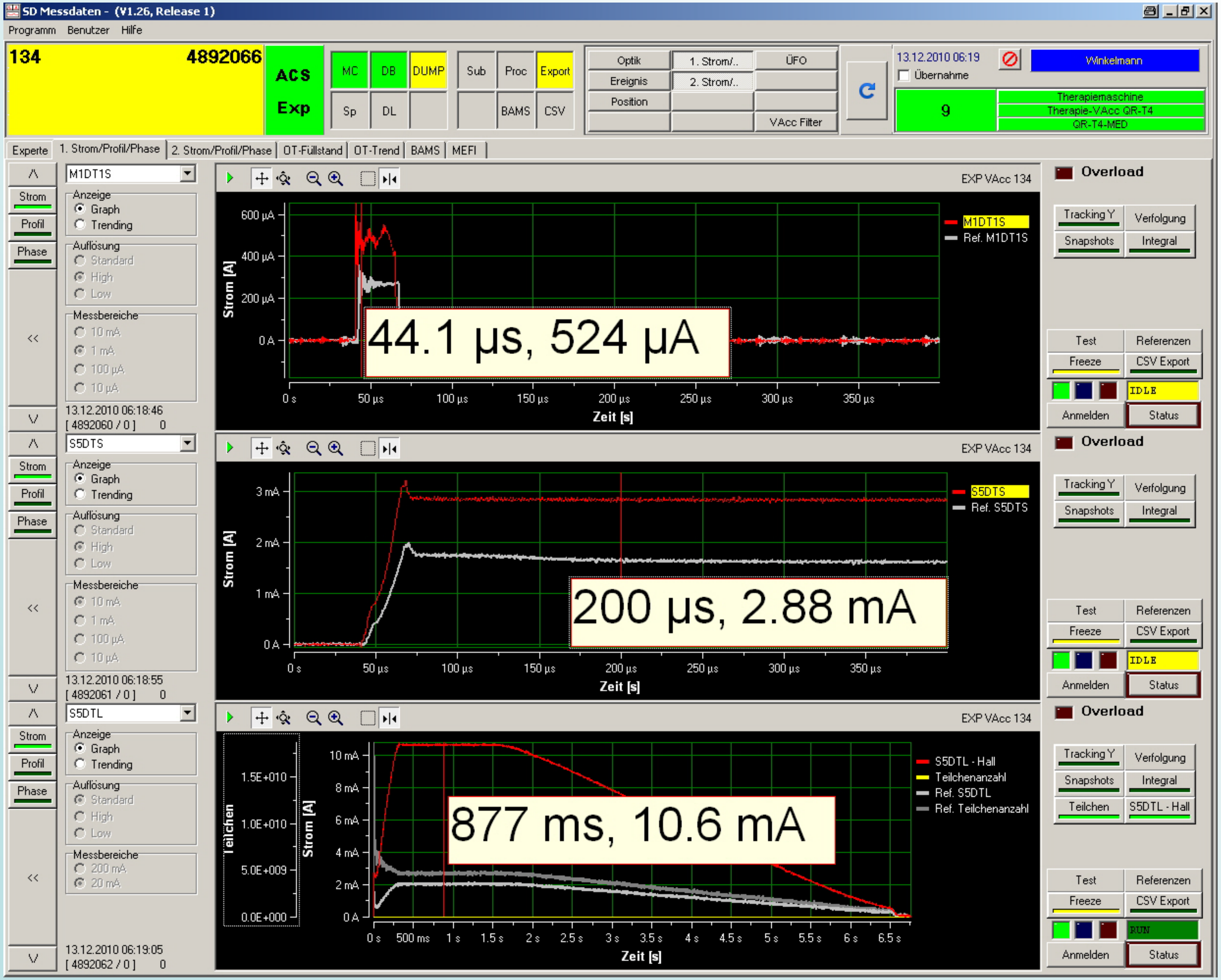
Commercial product specification (Bergoz NPCT):

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



44.1 µs, 524 µA

200 µs, 2.88 mA

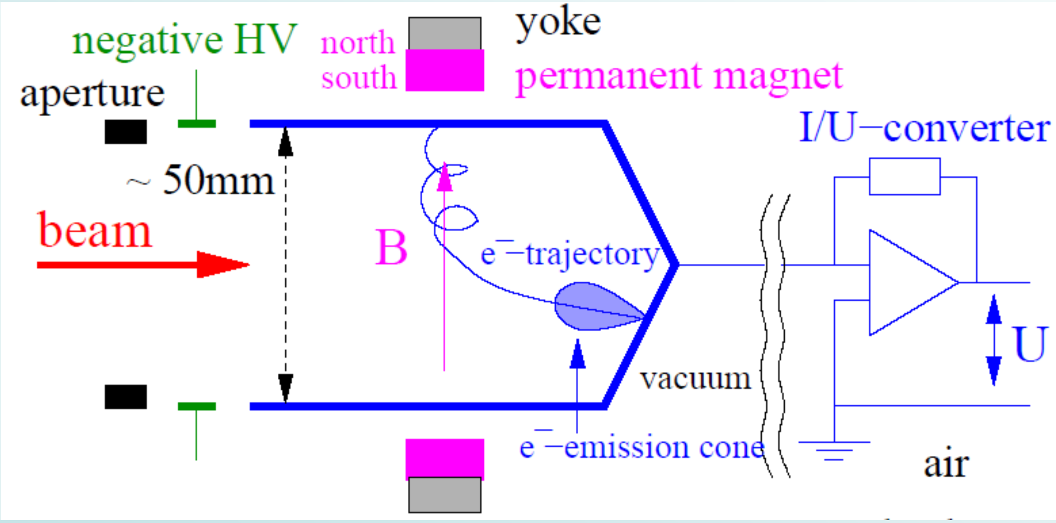
877 ms, 10.6 mA

Example:
Injection and acceleration at the HIT facility

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!

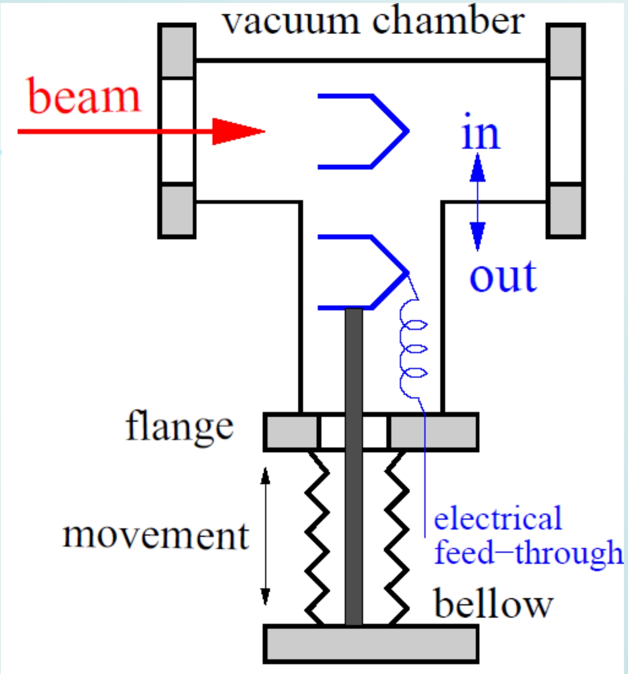
Magnetic field:
To prevent for secondary electrons leaving the cup

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.

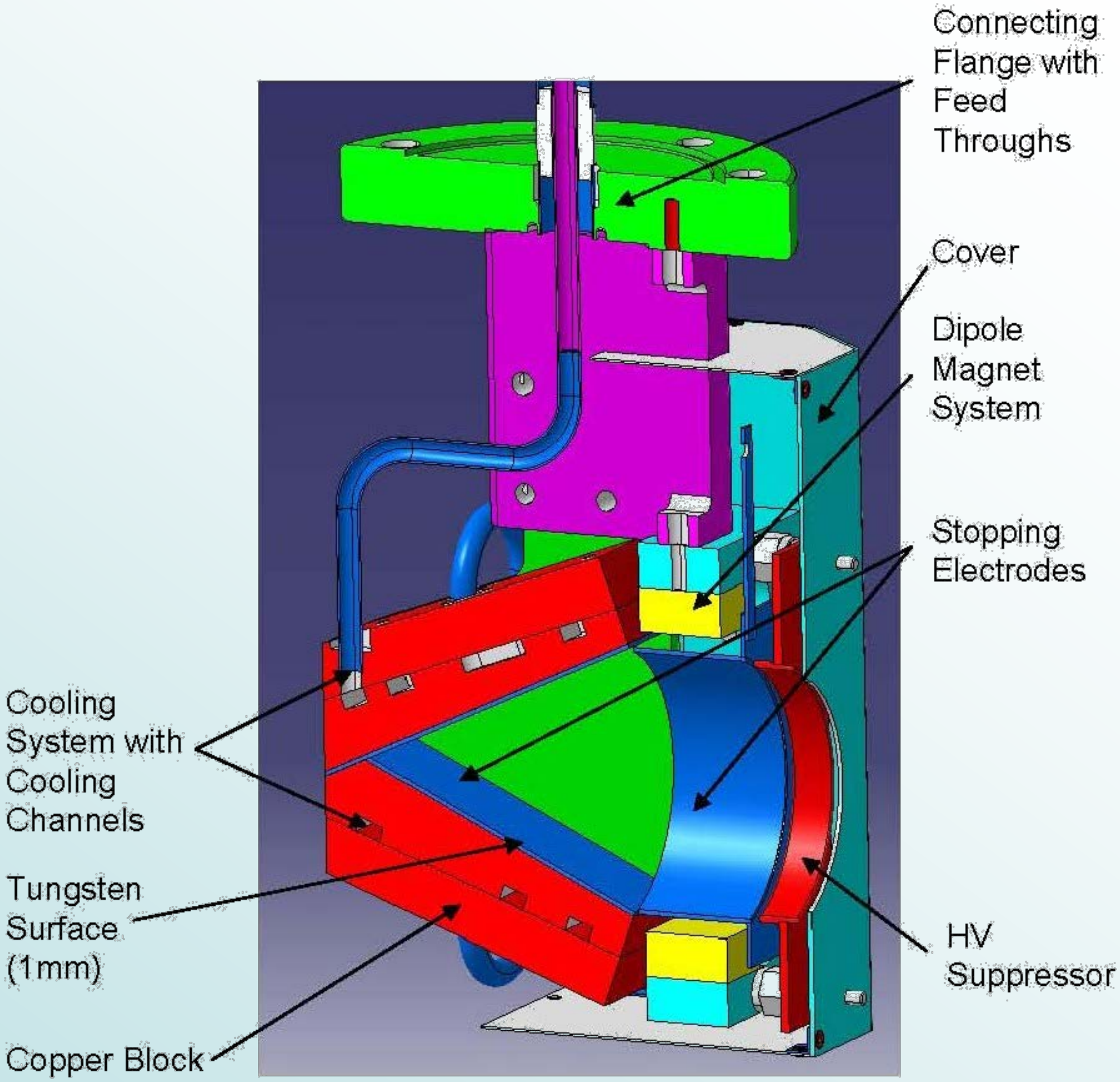


Example from HIT – uncooled FC for the MEBT section

Realizations of Faraday Cups

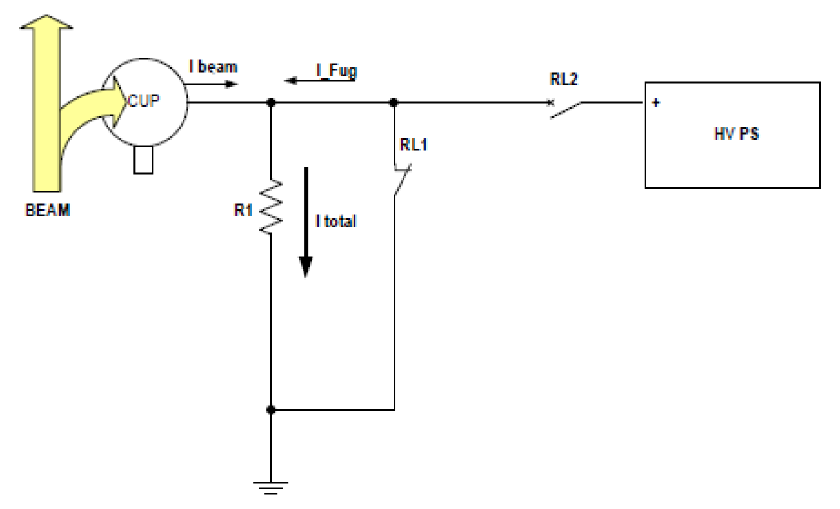
High Power Version needed e.g. for beams from ECR Ion Sources (**up to 20 mA** overall DC current possible) at low energies (**keV/u**)
→ very small penetration depth of only **some ten nm**!

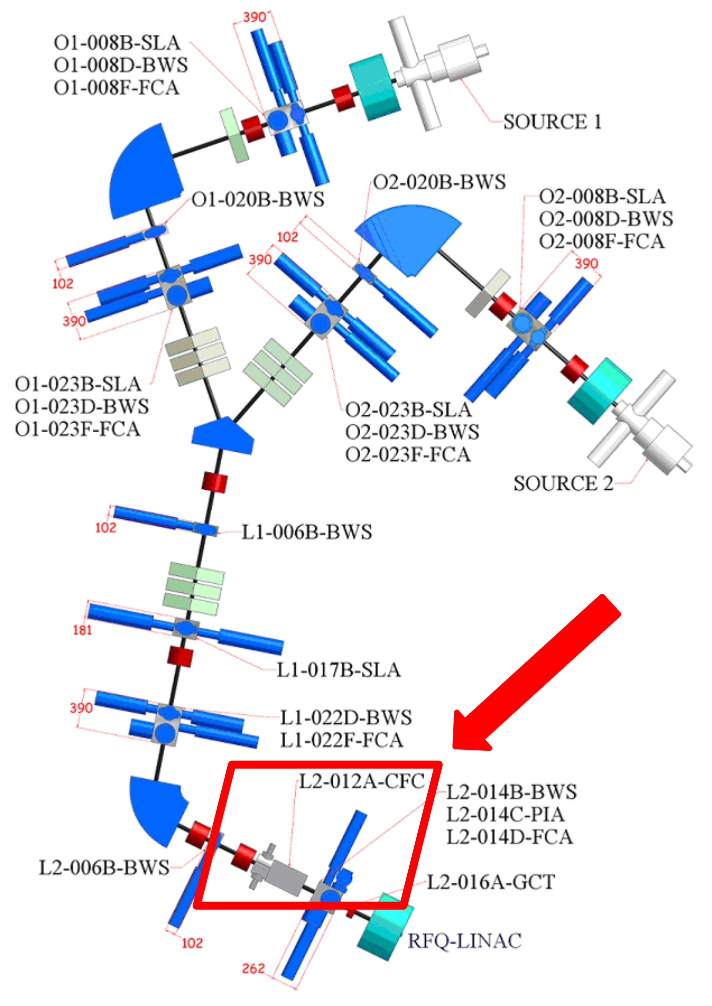
Material with high melting point needed: Tungsten, Tantalum,…



A “non-interceptive” Faraday Cup

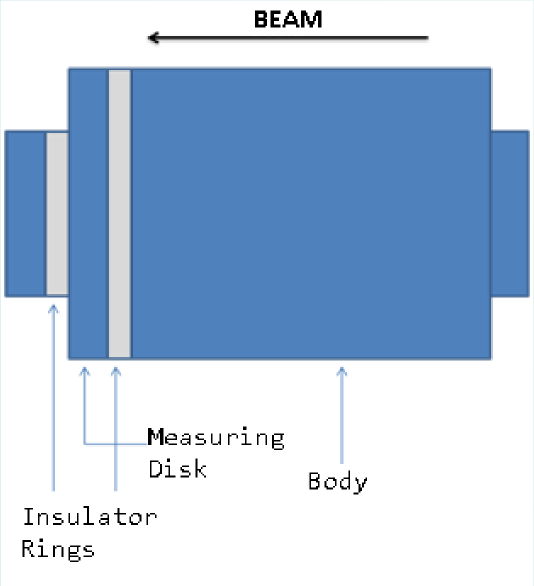
A Chopper faraday Cup (CFC) was designed and is presently in use on the CNAO machine. It measures the chopped beam, namely the beam (8keV/u energy) deviated by the Chopper deflector (installed at the end of the LEBT line) towards the vacuum chamber wall.

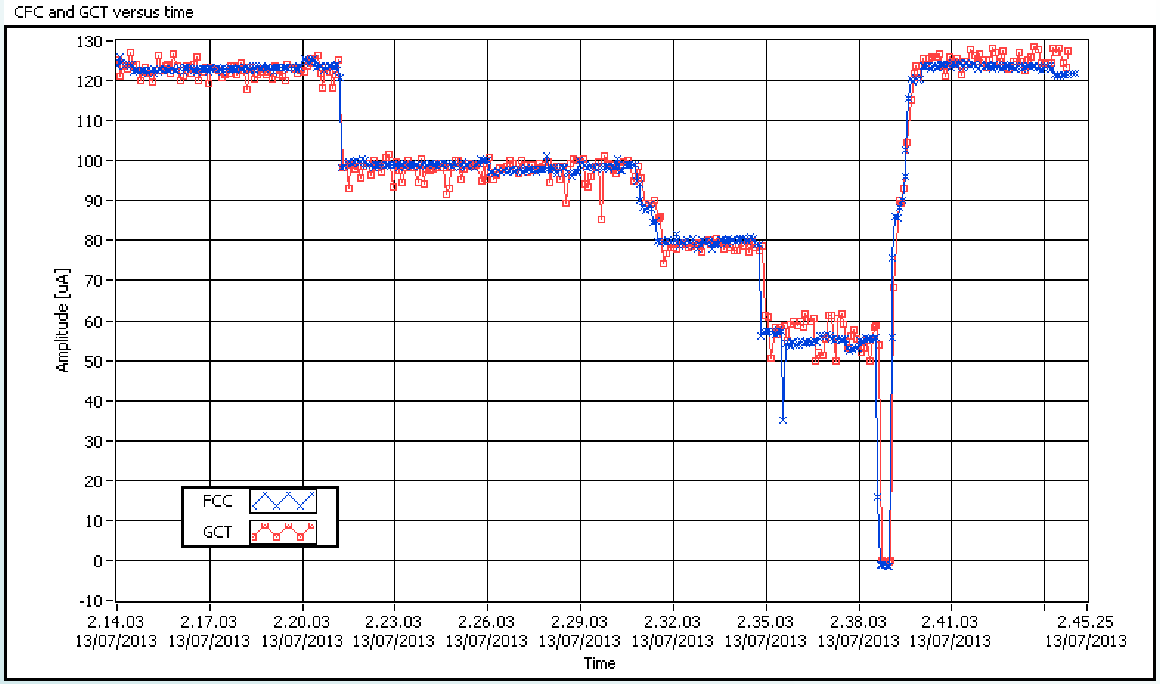




CNAO Low Energy Beam Transfer (LEBT) line

A “non-interceptive” Faraday Cup





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

[By courtesy of CNAO]

Faraday Cups for High Energy Beams

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

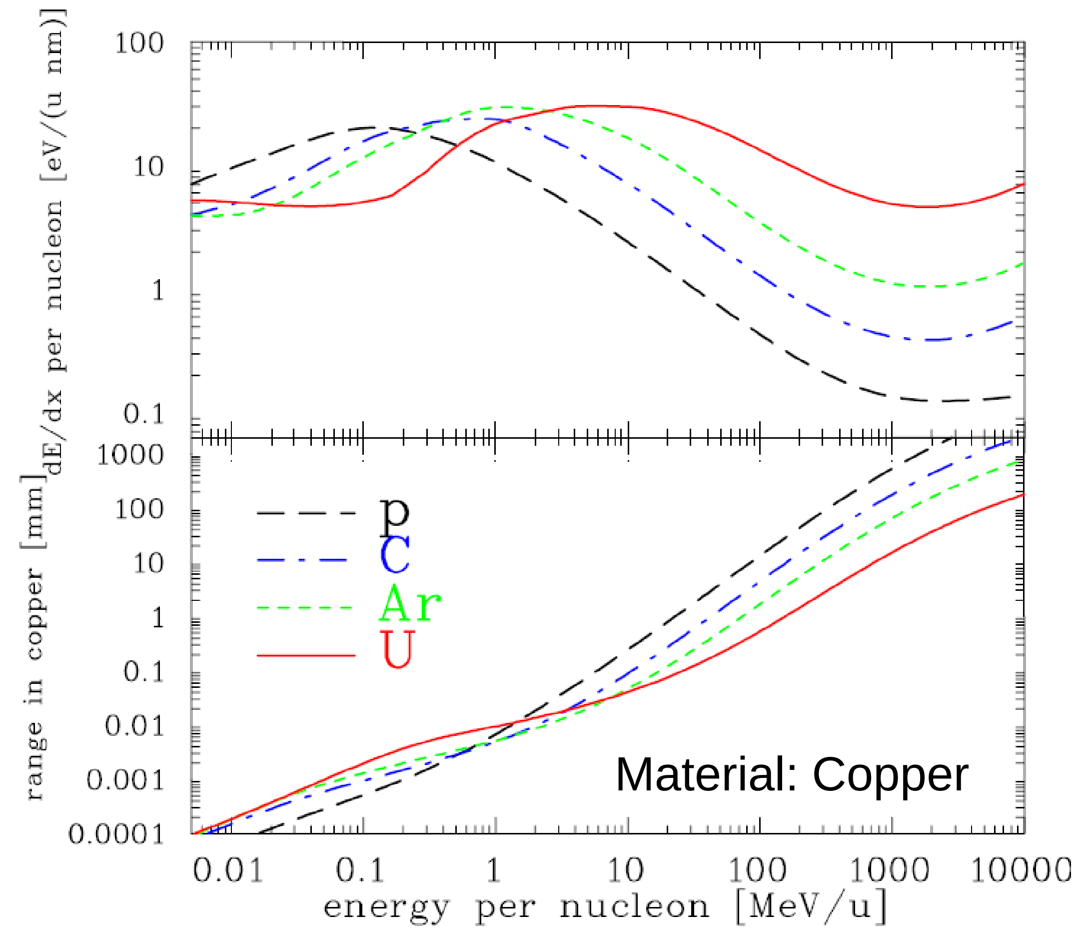
Range: $$R = \int_0^{E_{\max}} \left(\frac{dE}{dx}\right)^{-1} dE$$

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

→ Faraday Cups only for

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

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



Scintillation Counters

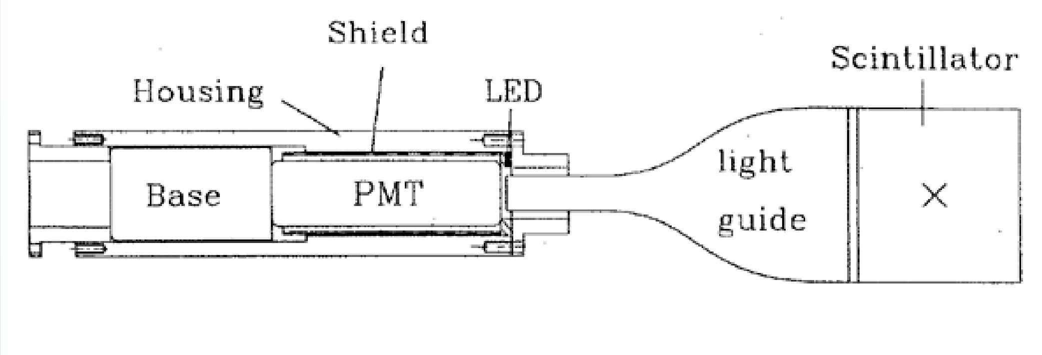
Plastic Scintillator i.e. organic fluorescence molecules in a plastic matrix

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

Disadvantage: not radiation hard

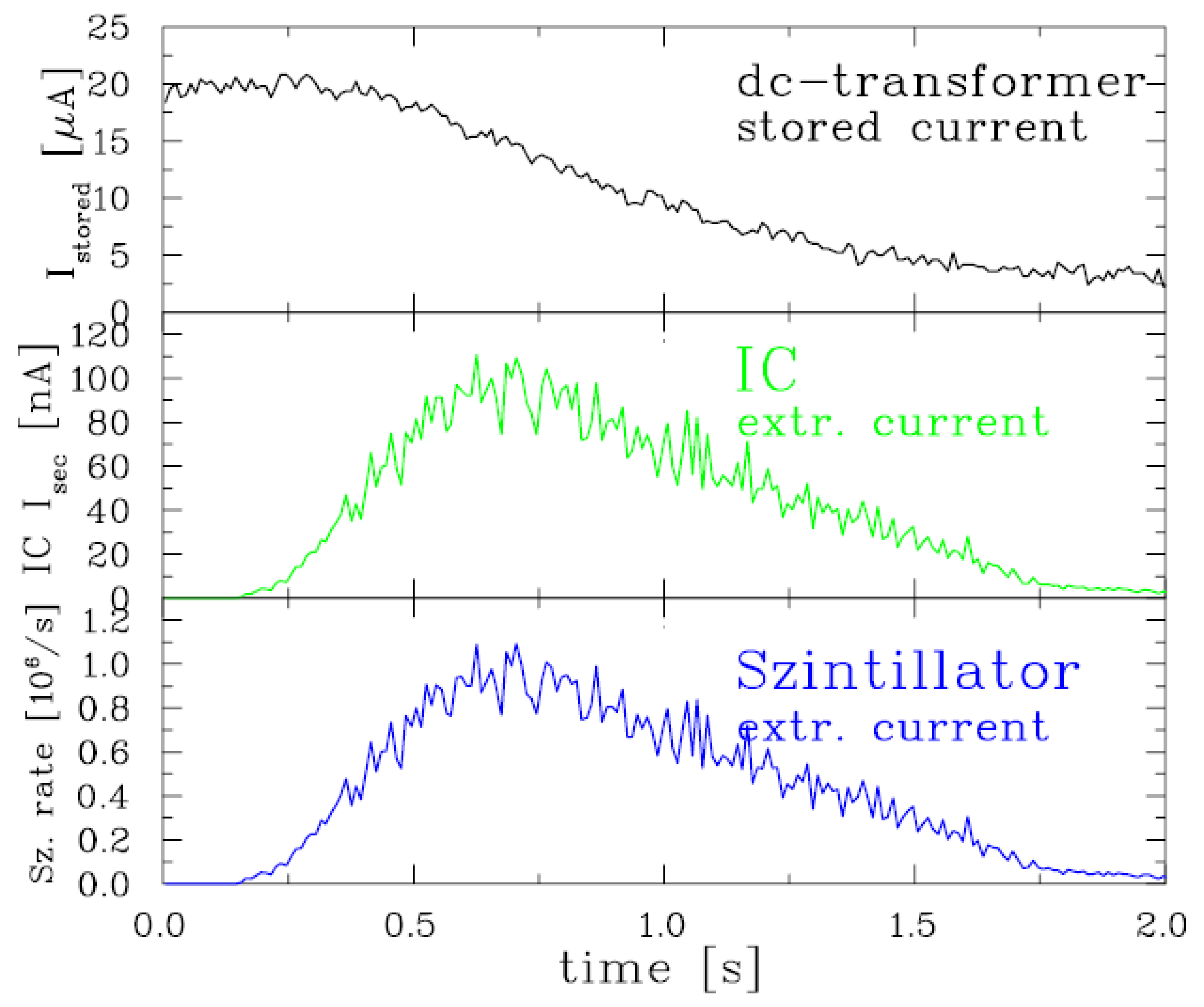
Particle counting: PMT → discriminator → scaler → computer

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:

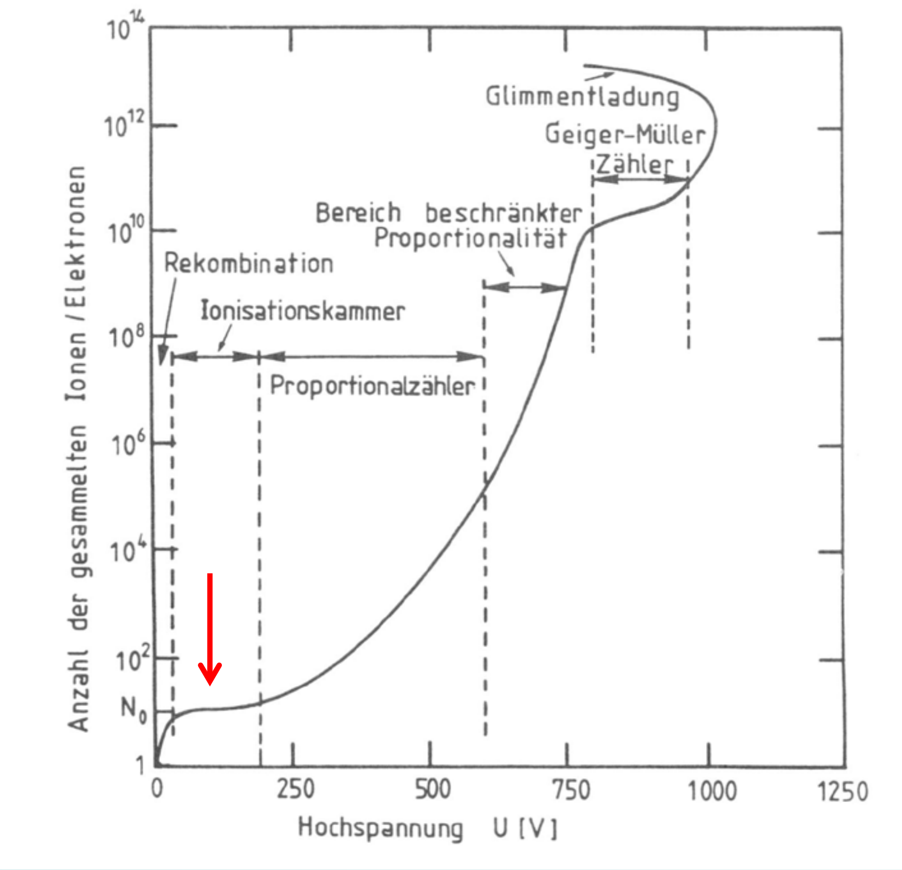
$$-\frac{dE}{dx} = 4\pi N_A r_e^2 m_e c^2 \cdot \boxed{\frac{Z_t}{A_t}\rho}\,\boxed{\frac{Z_p^2}{\beta^2}}\left[\ln\frac{2m_e c^2\gamma^2\beta^2}{I} - \beta^2\right]$$

Target:

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

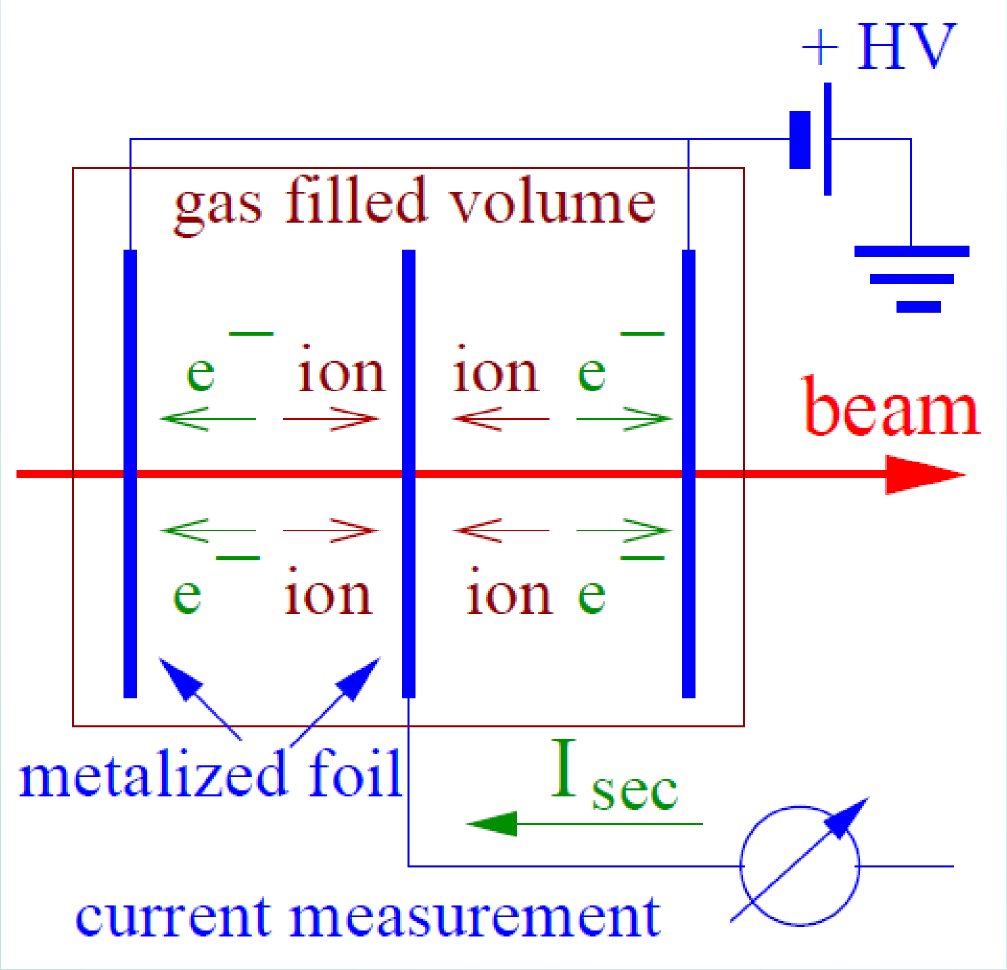
Projectile:

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



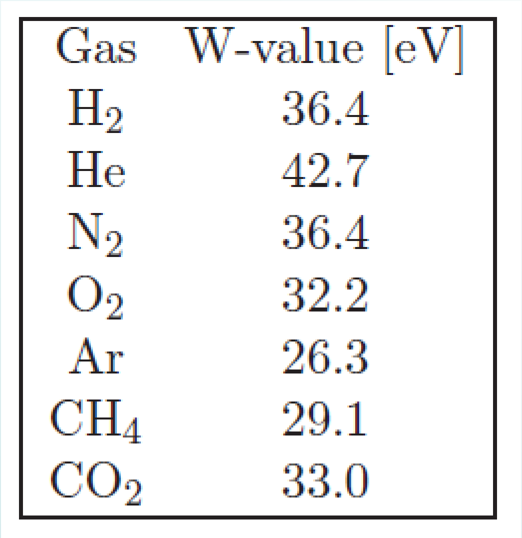
Operating ranges of gas detectors

Ionization Chambers



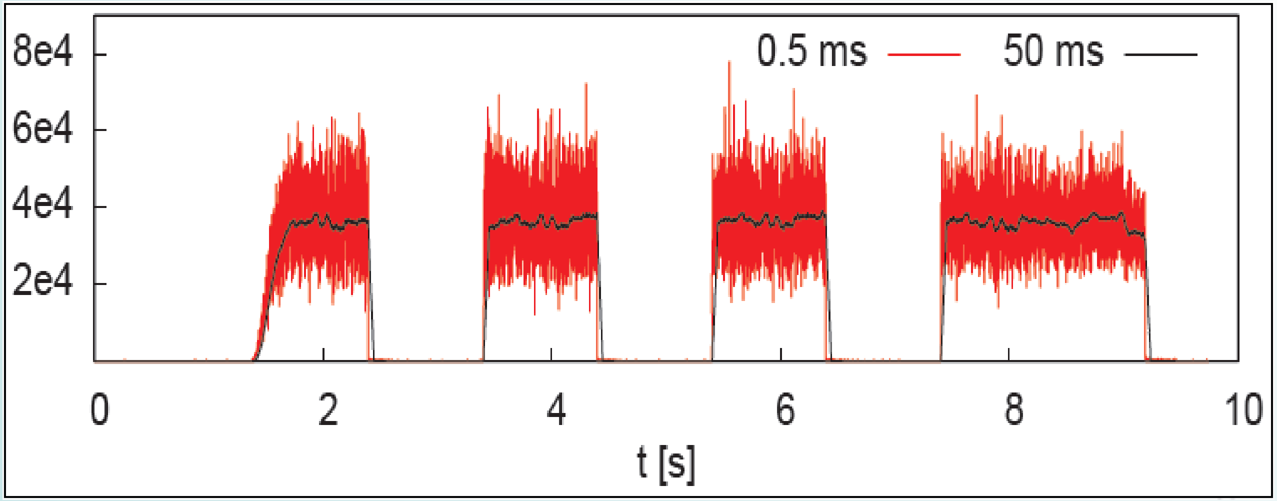
$$\boxed{I_{sec} = \frac{1}{W} \cdot \frac{dE}{dx} \Delta x \cdot I_{beam}}$$

Output vs. response velocity

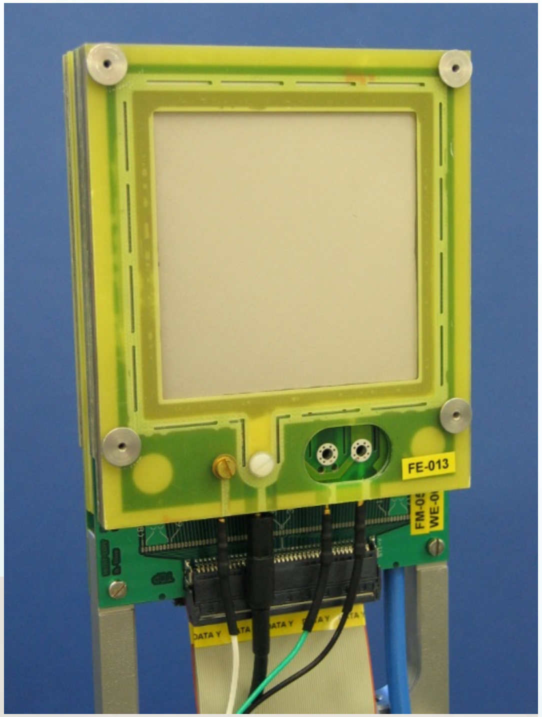


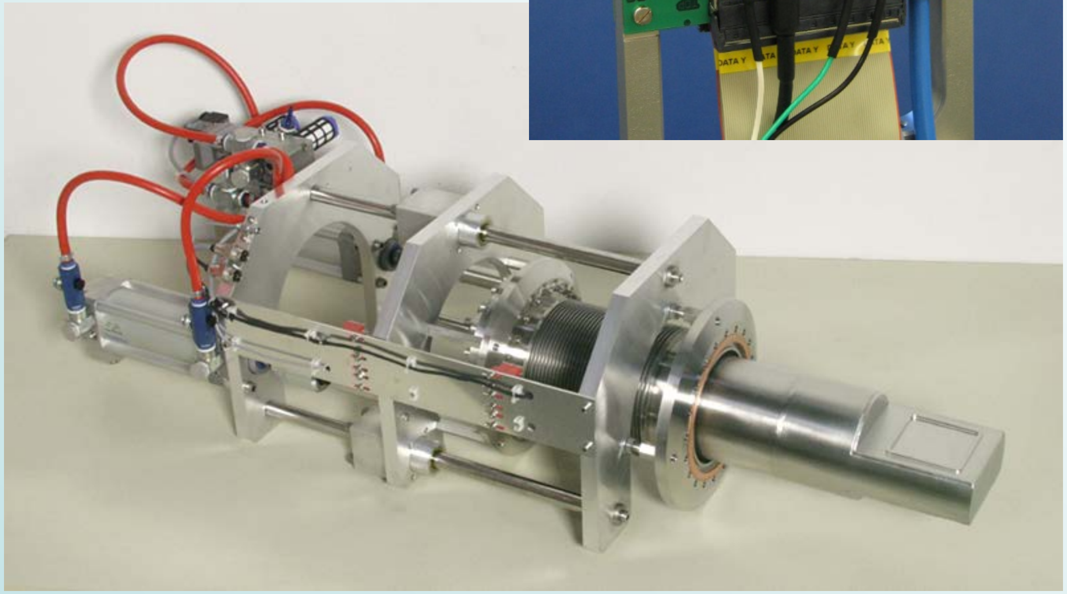
Gas	W-value [eV]
H_2	36.4
He	42.7
N_2	36.4
O_2	32.2
Ar	26.3
CH_4	29.1
CO_2	33.0

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)

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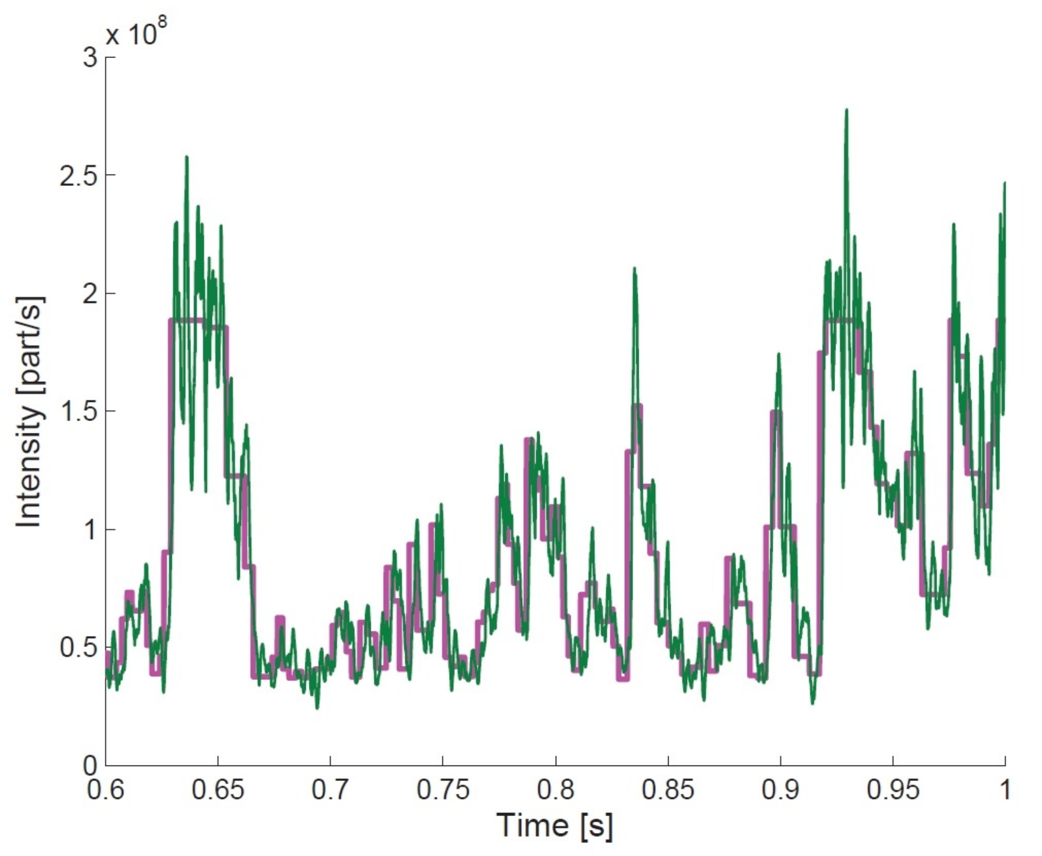
Dynamic Intensity Control with Ionization Chambers

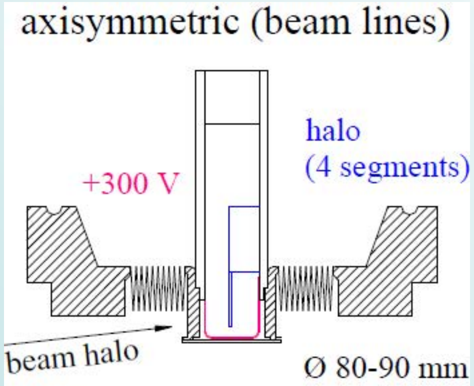
- If scanning technique is used voxel by voxel is irradiated.
- Adjustable but predefined amplitude curves drive the transverse RF-knockout excite [illegible] ed spills.
- A feedback loop has been implemented to avoid imperfections
  → Aim: rectangular spill
- Second step: A dynamic intensity adaptation during one spill with respect to the particular treatment plan. (In use at HIT since 2014.)

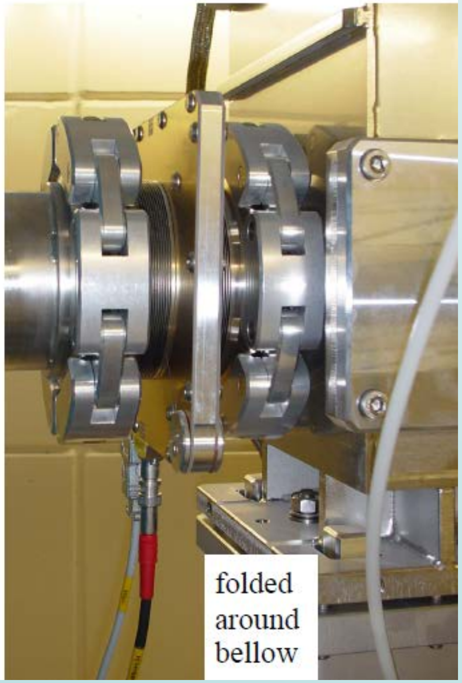
Treatment ti

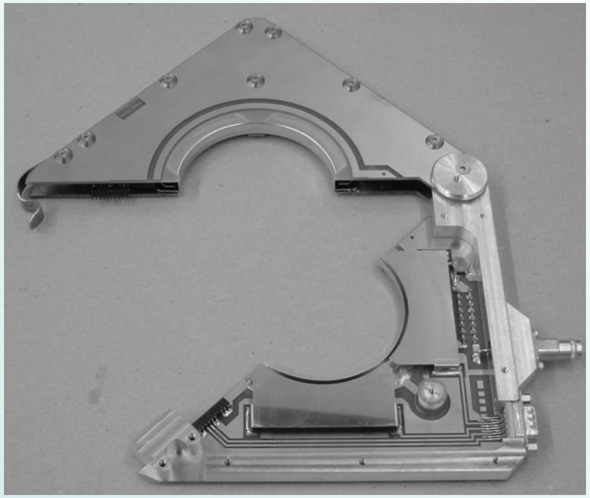
(Animation by co



Ionization Chambers

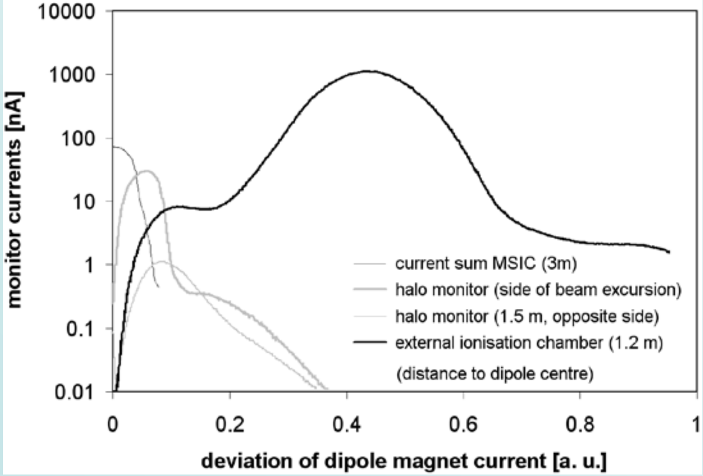






Ionization chambers as halo monitors around the beam pipe for online monitoring of beam displacements

[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

Beam Profile Measurement

The beam width can be changed by focusing via quadruples.

Transverse matching between ascending accelerators is done by focusing.

→ Profiles have to be controlled at many locations.

Synchrotrons:

Lattice functions ***β(s)*** and ***D(s)*** are fixed ⇒ width σ and emittance ε are:

$$\sigma_x^2(s) = \varepsilon_x \beta_x(s) + \left(D(s) \frac{\Delta p}{p} \right)^2 \quad \text{and} \quad \sigma_y^2(s) = \varepsilon_y \beta_y(s)$$

LINACs: Lattice functions are 'smoothly' defined due to variable input emittance.

Different techniques are suited for different beam parameters:

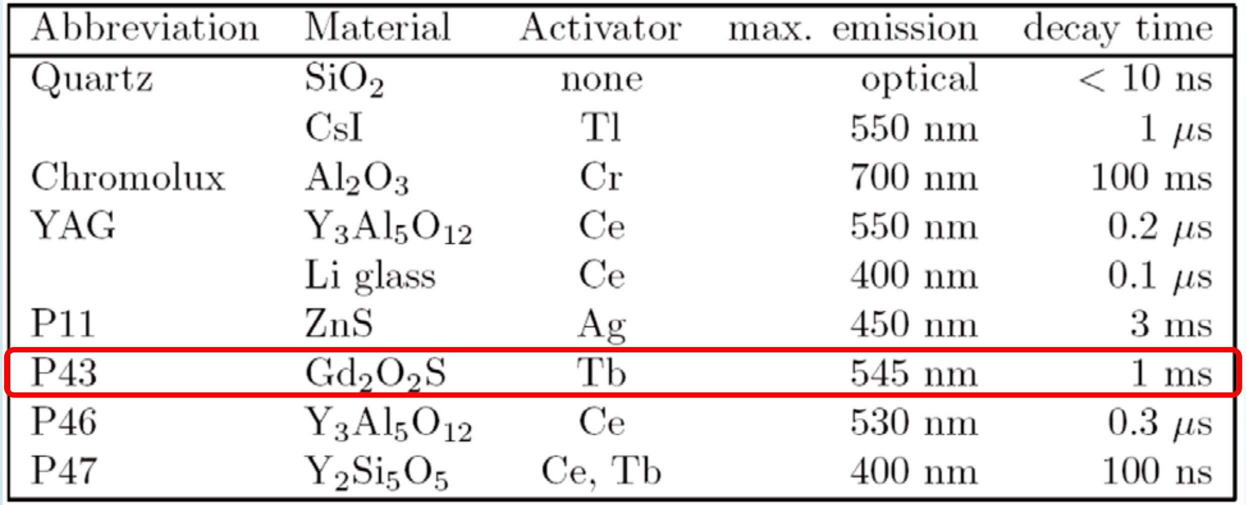
e⁻-beam: typically Ø 0.3 to 3 mm, protons/ions: typically Ø 3 to 30 mm

A great variety of devices are used, especially for protons/ions:

- ***Optical techniques***, e.g. Scintillating screens (all beams)
- ***Electronics techniques***, e.g. Secondary electron emission (SEM) grids, grids with gas amplification → MWPC (protons/ions)

Detectors for Beam monitoring – Screens

Some scintillating materials and their basic properties:



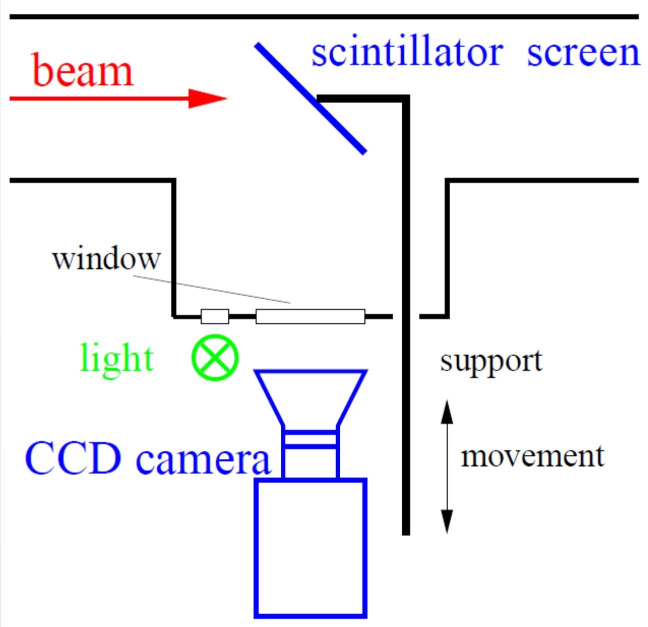
Abbreviation	Material	Activator	max. emission	decay time
Quartz	SiO_2	none	optical	< 10 ns
	CsI	Tl	550 nm	1 μs
Chromolux	Al_2O_3	Cr	700 nm	100 ms
YAG	$Y_3Al_5O_{12}$	Ce	550 nm	0.2 μs
	Li glass	Ce	400 nm	0.1 μs
P11	ZnS	Ag	450 nm	3 ms
P43	Gd_2O_2S	Tb	545 nm	1 ms
P46	$Y_3Al_5O_{12}$	Ce	530 nm	0.3 μs
P47	$Y_2Si_5O_5$	Ce, Tb	400 nm	100 ns

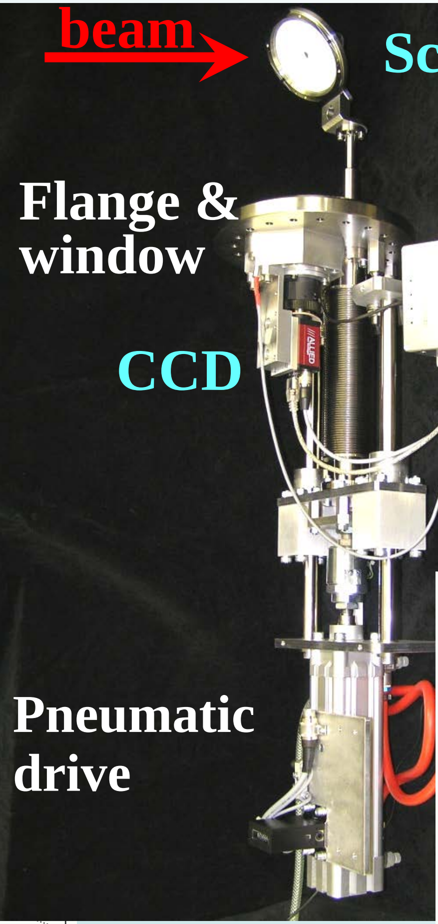
Properties of a good scintillator for beam profiling:

- Large light output at optical wavelength → standard CCD camera can be used
- Large dynamic range → no deformation due to saturation or self-absorption
- Short decay time → observation of time variations
- Radiation hardness → long lifetime
- Good mechanical properties → typical size up to Ø 10 cm

(Phosphor Pxx grains of Ø ~ 10 µm on glass or metal)

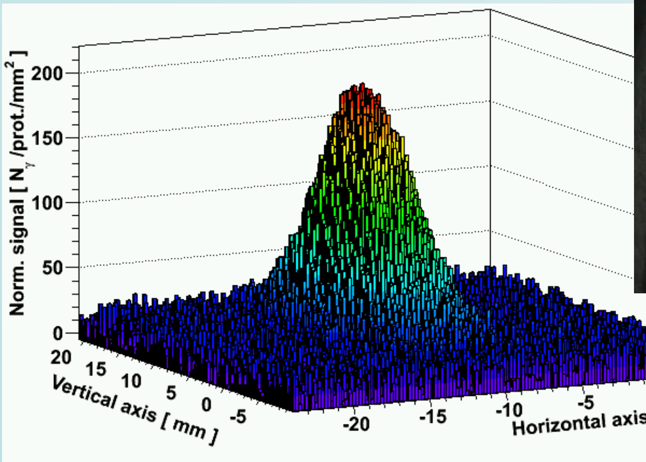
Scintillating Screens



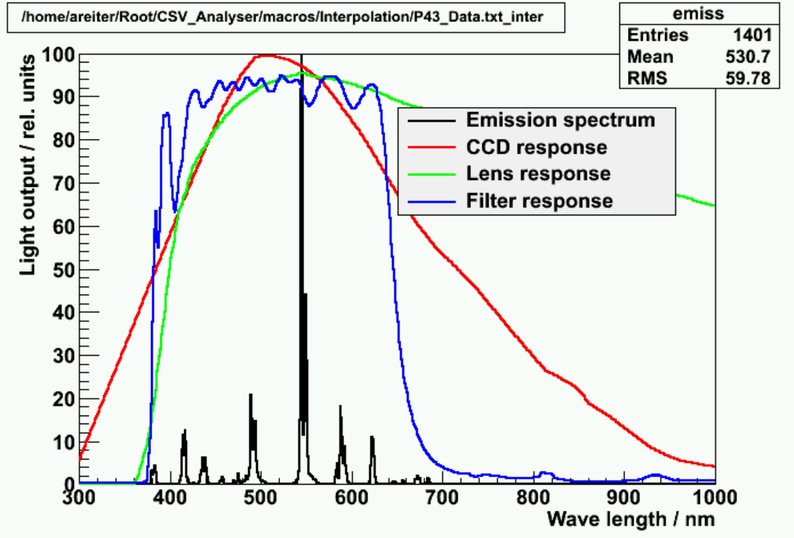


Devices for 2D profiling: Scintillating Screens

Used material: P43 (or P46)



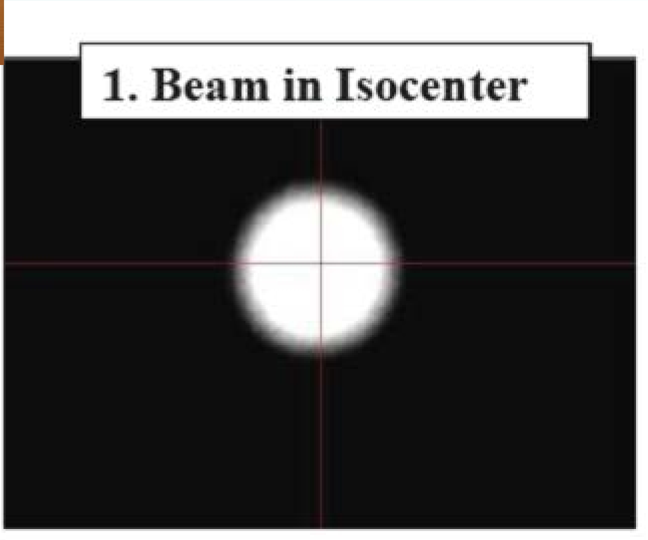
Beamline version



Scintillating Screens

Megapixel CCD camera inside

Different versions of Screens for the Iso-centre Diagnostics – fixation on robot or at Gantry nozzle (HIT)



Beam Profile Measurement – SEM Grids

When particles of the proton/ion beam hit a surface, secondary electrons are liberated, escaping form the surface → measurement of current.

Example from HIT:

Detector Parameters:

Active Area:	$80\times80\ \mathrm{mm}^2$
Wire ø:	0.1 mm
Wire distance:	1.2 mm
Wires:	64 horizontal, 64 vertical
Wire material:	W or W-Re alloy

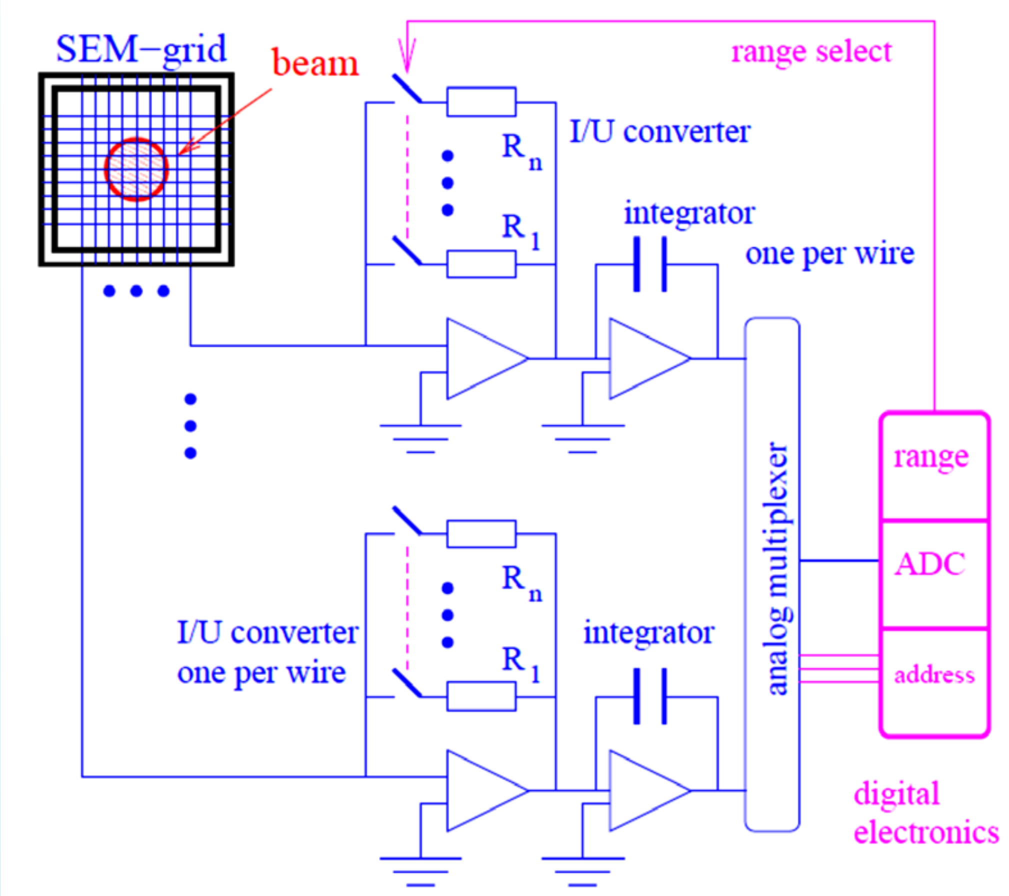
Beam Profile Measurement – SEM Grids

Multi-Channel Electronics for SEM grids, e.g. (HIT)

- I/U-converter for each channel
- 16 Measurement ranges

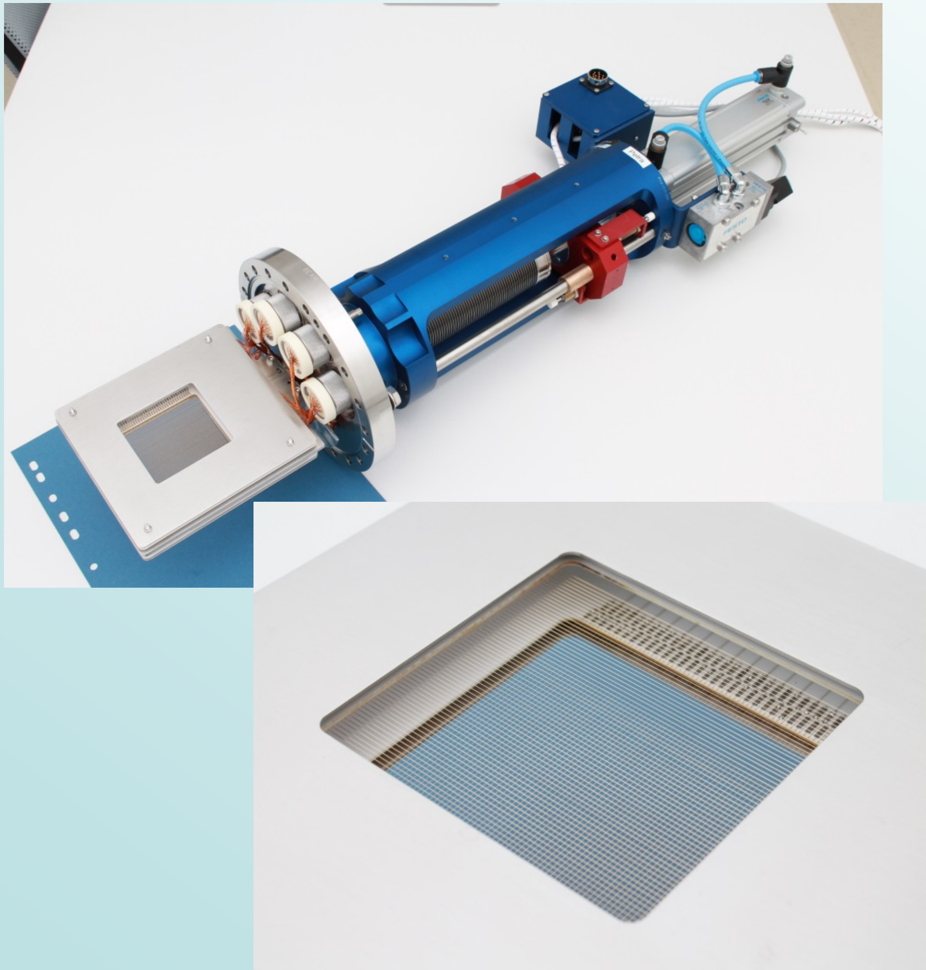
  (5 nA-500 µA) → very large

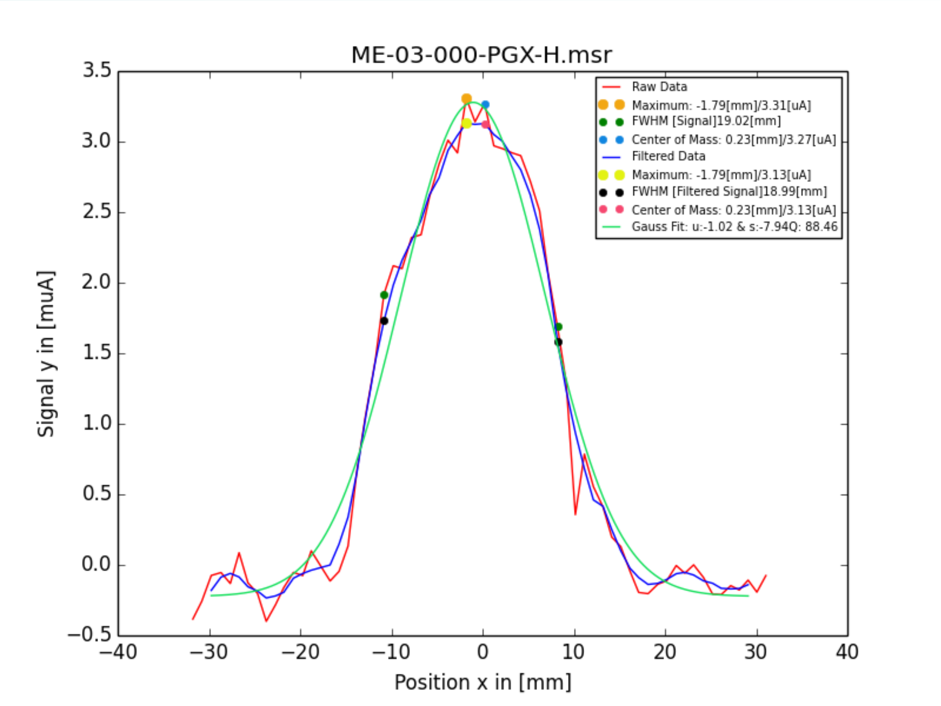
  dynamic range of 10^6
- 32 (64) channels hor. /vert.
- Switchable test signal



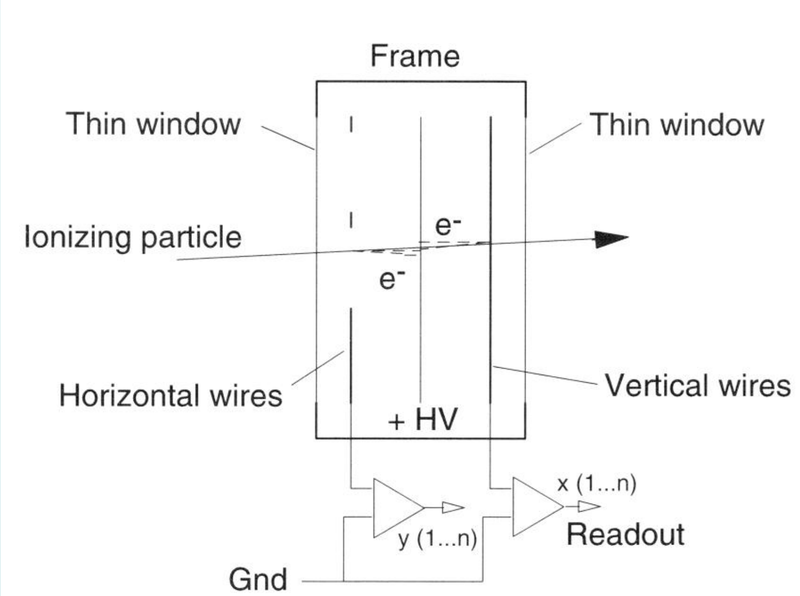
Beam Profile Measurement – SEM Grids

Profile monitor for MEBT in use at CNAO and MedAustron



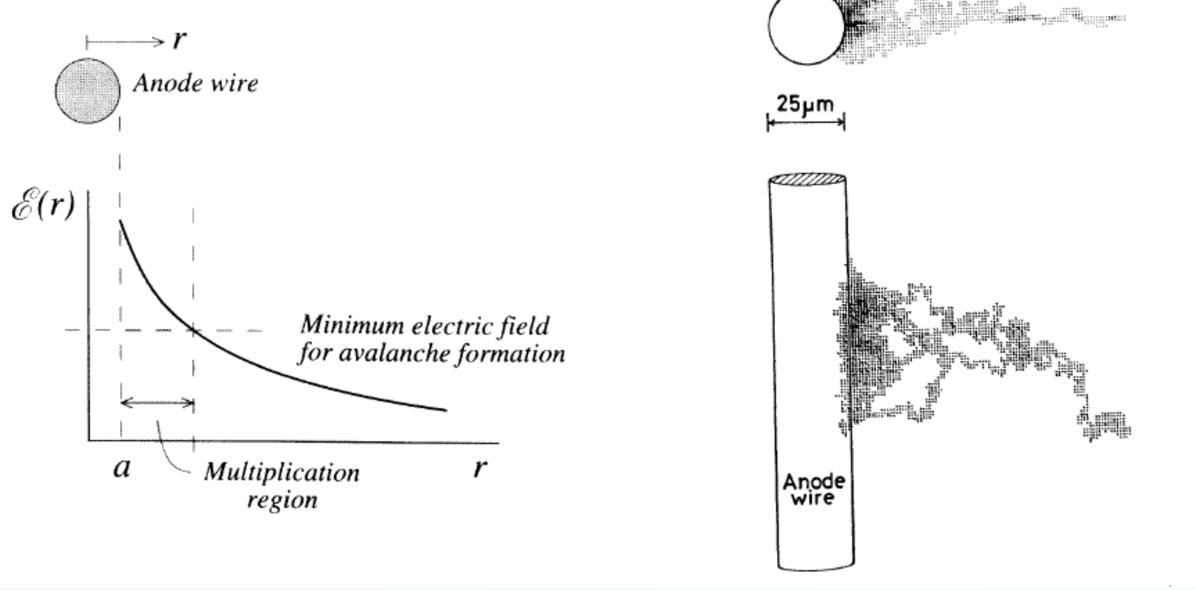


Beam Profile Measurement - MWPCs



Principle layout of a Multi-wire proportional chamber (MWPC)
- used at higher energies -

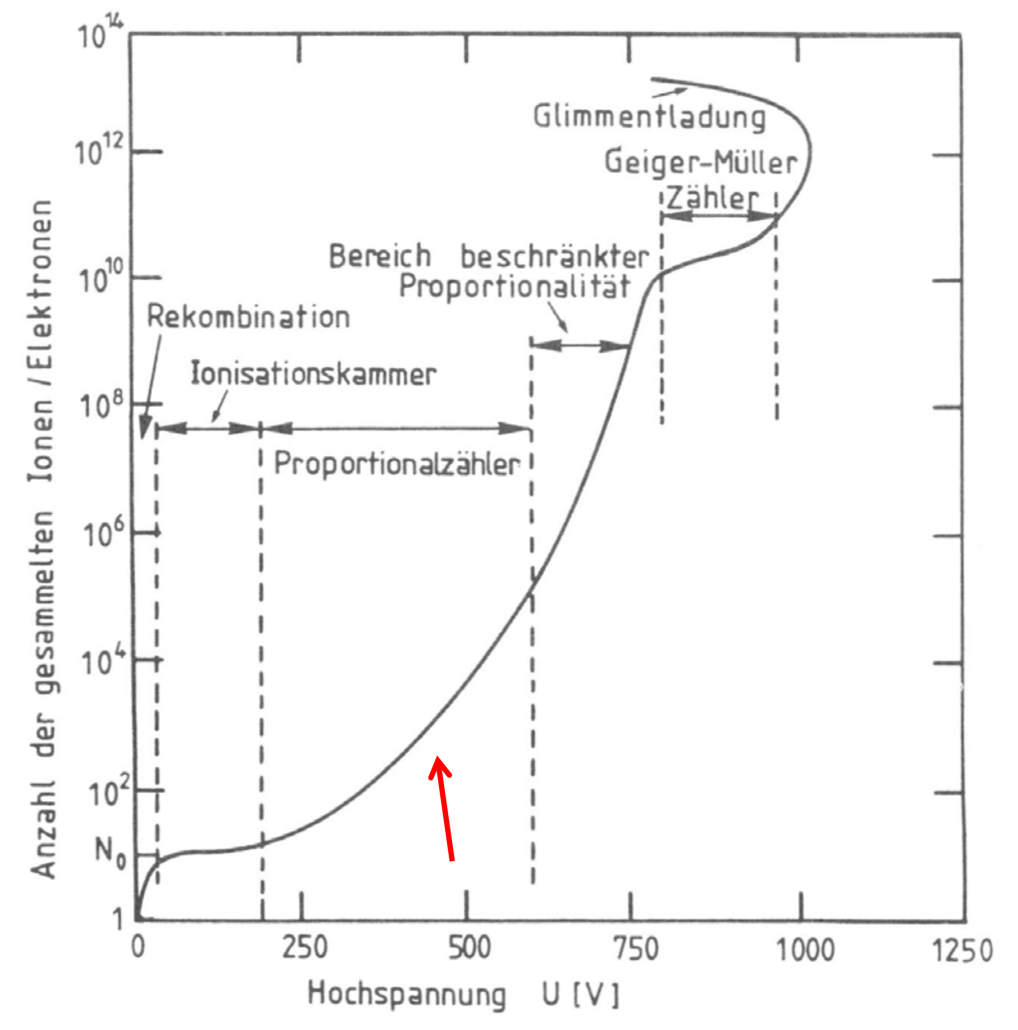
Electric field close to the anode wires with region of amplification (up to 10^3 possible)



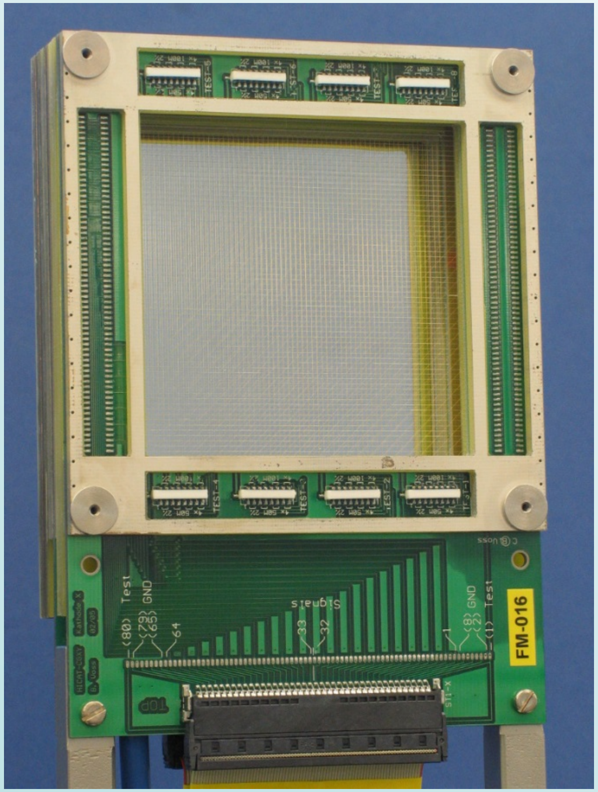
Beam Profile Measurement

Operating ranges of gas detectors

Variable amplification of the anode wire signal by changing the high voltage possible – no absolute calibration needed in a profile monitor

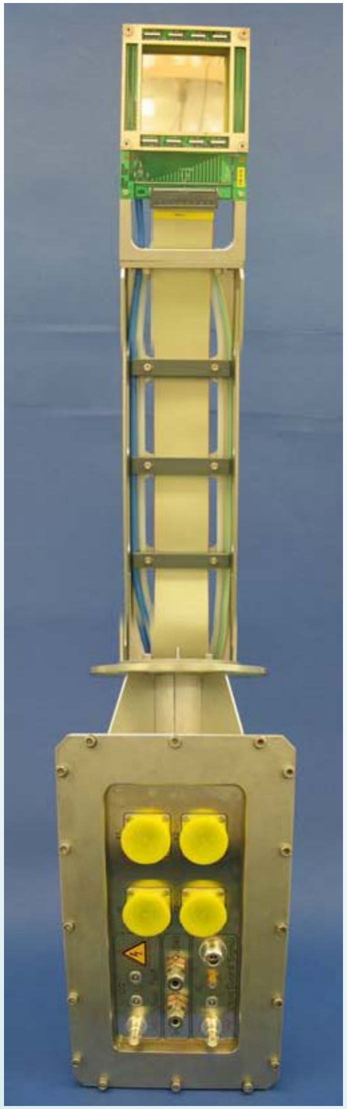


Beam Profile Measurement

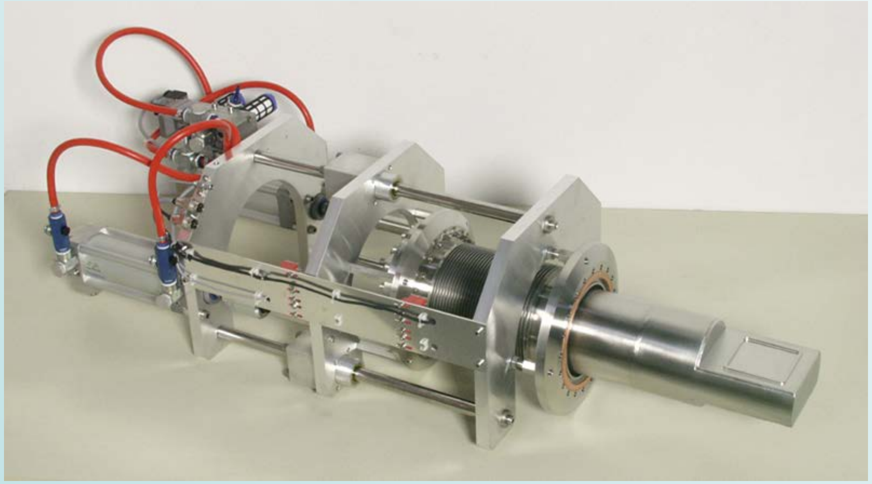


Compact detector system (combined with IC in one stack) working at HIT in the HEBT; feed-through with detector bag – windows to vacuum consist of 50 µm stainless steel; used gas: Ar/CO_2

(MWPC/IC manufactured by B. Voss & team at GSI Detector Laboratory)

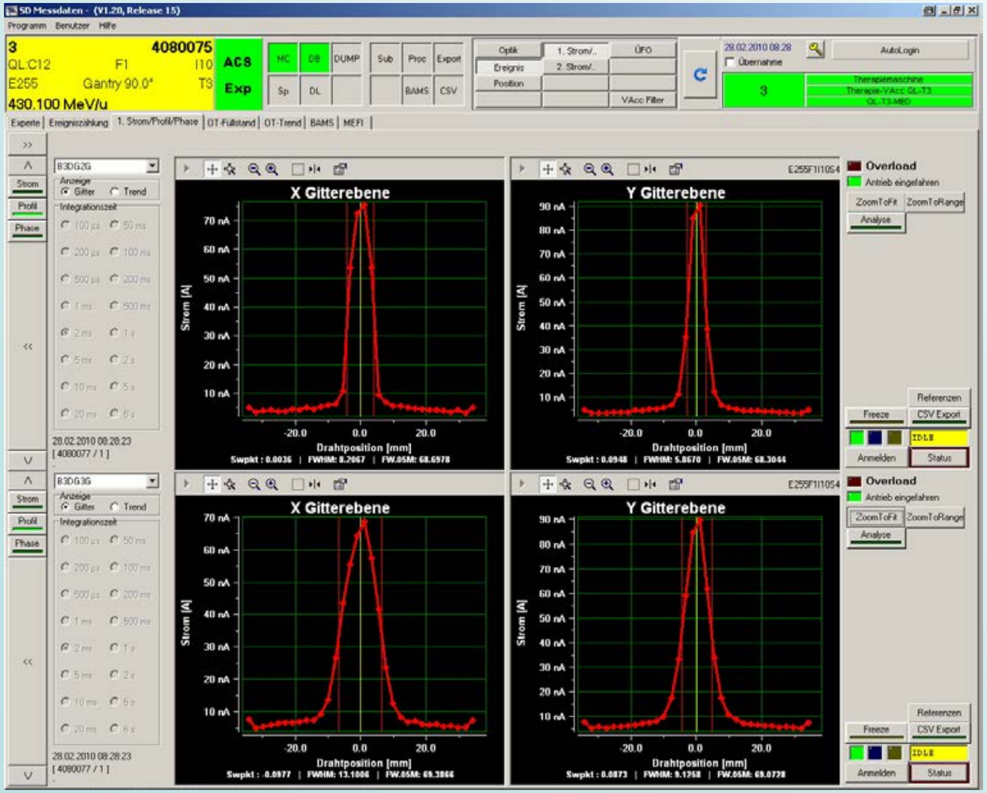


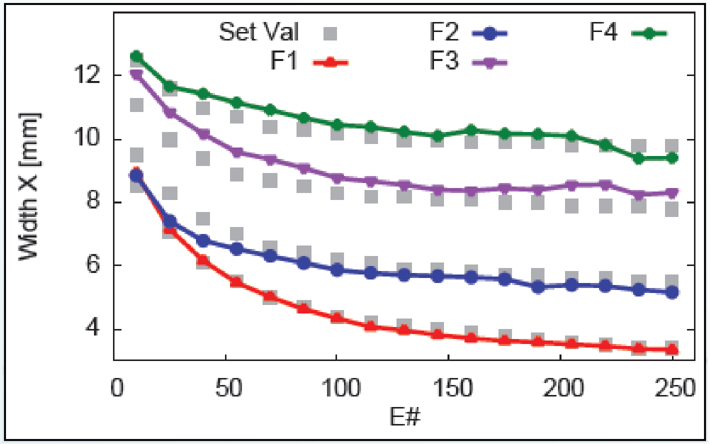
MWPC detector:
Active Area: 70x70mm^2
Wires: 2x64
Wire spacing: 1.1 mm



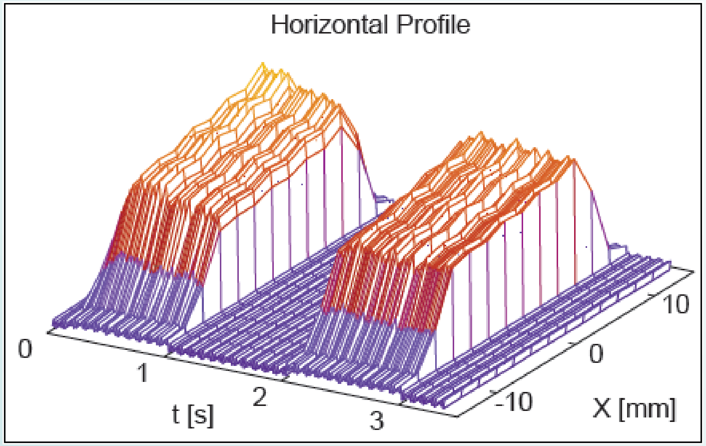
Beam Profile Measurement

Measurements with MWPCs at HIT





Profile width of $^{12}C^{6+}$ near isocenter position



Profile measurements versus time ($^{12}C^{6+}$, 250 MeV/u, with spill pause)

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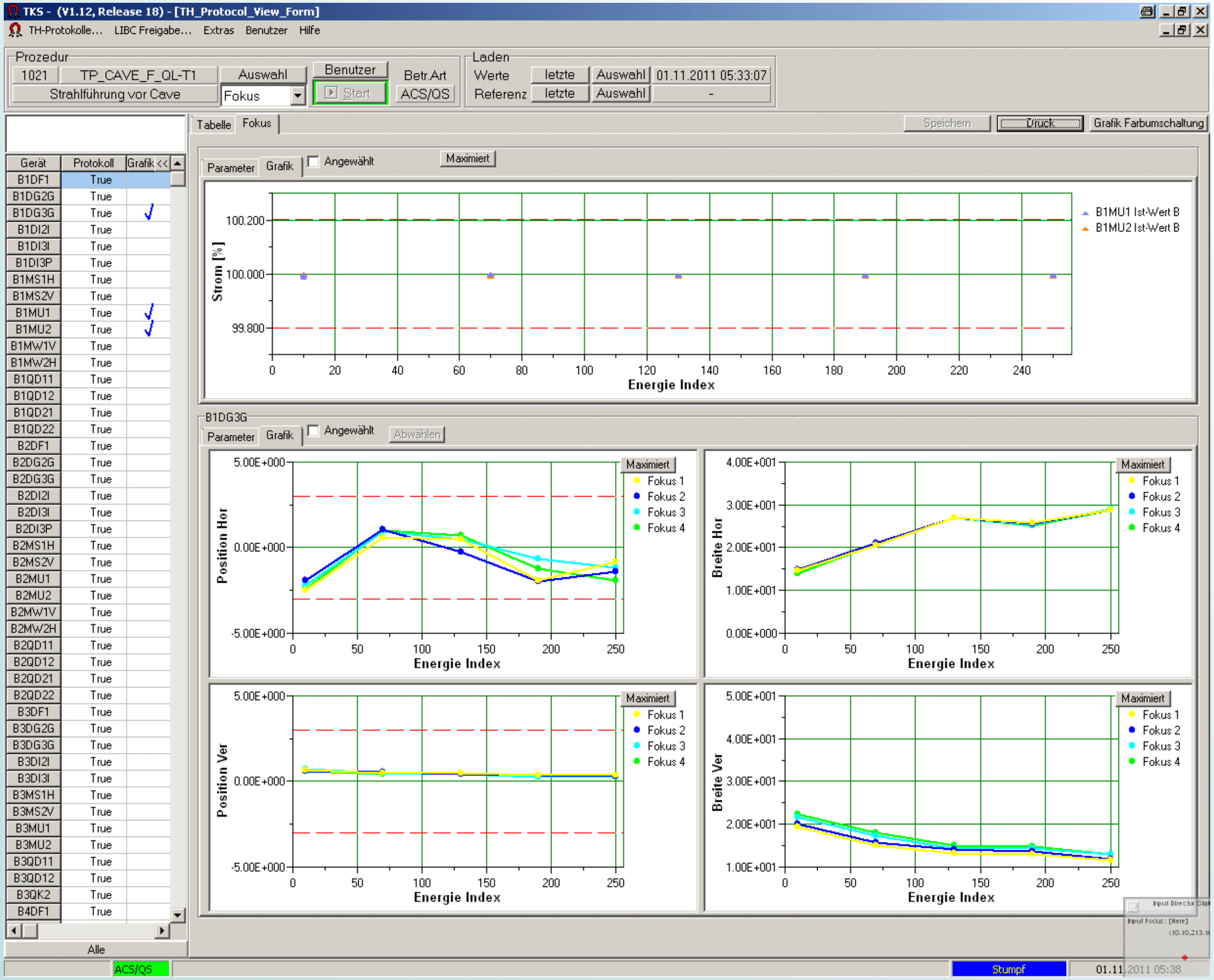
Daily Performance Checks with MWPCs



Prozedur: 1021 TP_CAVE_F_QL-T1
Strahlführung vor Cave
Fokus
Betr.Art: ACS/QS
Werte: 01.11.2011 05:33:07
Referenz: -

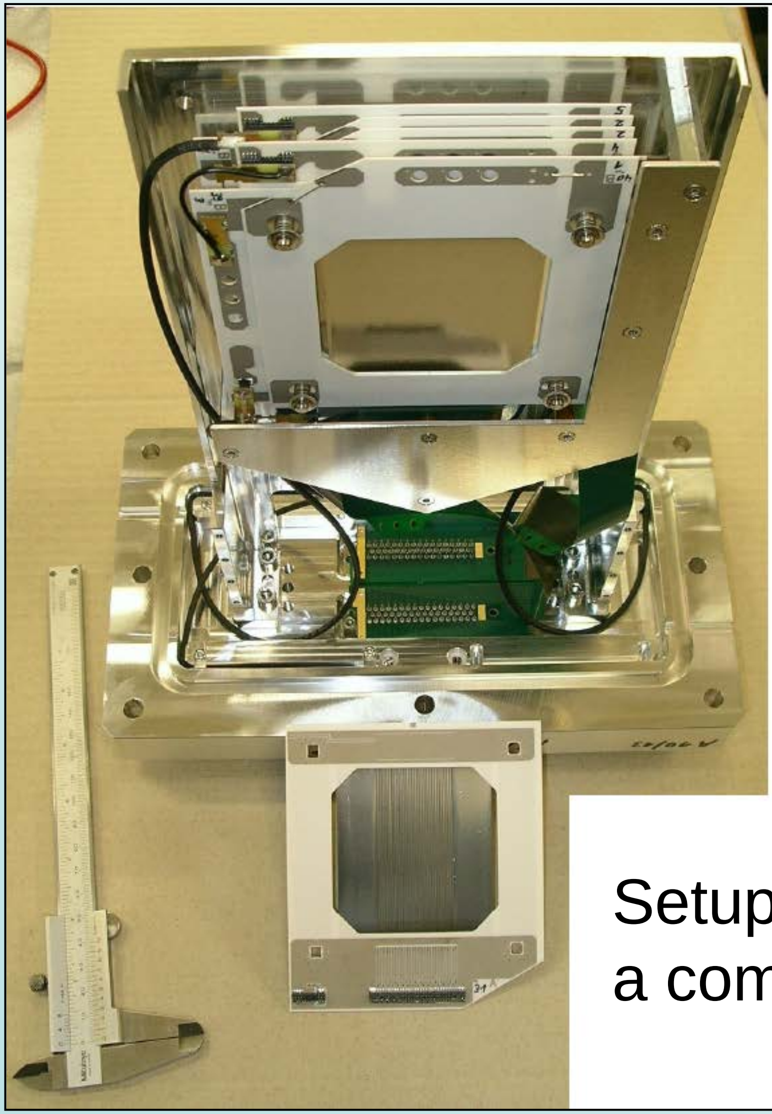
Gerät	Protokoll	Grafik
B1DF1	True	
B1DG2G	True	
B1DG3G	True	✓
B1DI2I	True	
B1DI3I	True	
B1DI3P	True	
B1MS1H	True	
B1MS2V	True	
B1MU1	True	✓
B1MU2	True	✓
B1MW1V	True	
B1MW2H	True	
B1QD11	True	
B1QD12	True	
B1QD21	True	
B1QD22	True	
B2DF1	True	
B2DG2G	True	
B2DG3G	True	
B2DI2I	True	
B2DI3I	True	
B2DI3P	True	
B2MS1H	True	
B2MS2V	True	
B2MU1	True	
B2MU2	True	
B2MW1V	True	
B2MW2H	True	
B2QD11	True	
B2QD12	True	
B2QD21	True	
B2QD22	True	
B3DF1	True	
B3DG2G	True	
B3DG3G	True	
B3DI2I	True	
B3DI3I	True	
B3MS1H	True	
B3MS2V	True	
B3MU1	True	
B3MU2	True	
B3QD11	True	
B3QD12	True	
B3QK2	True	
B4DF1	True	

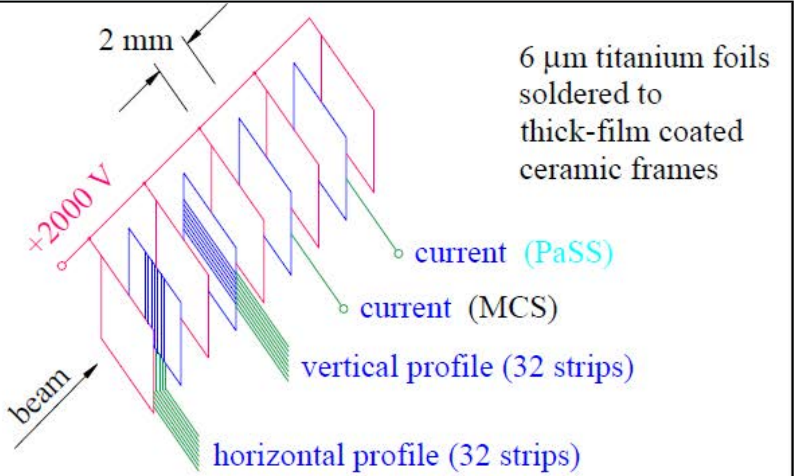
ACS/QS

Dipole currents (Actual values)

Horizontal and vertical beam positions and profile width in front of scanner magnet system

Beam Profile Measurement - MWPCs





Detector
Gas: N_2

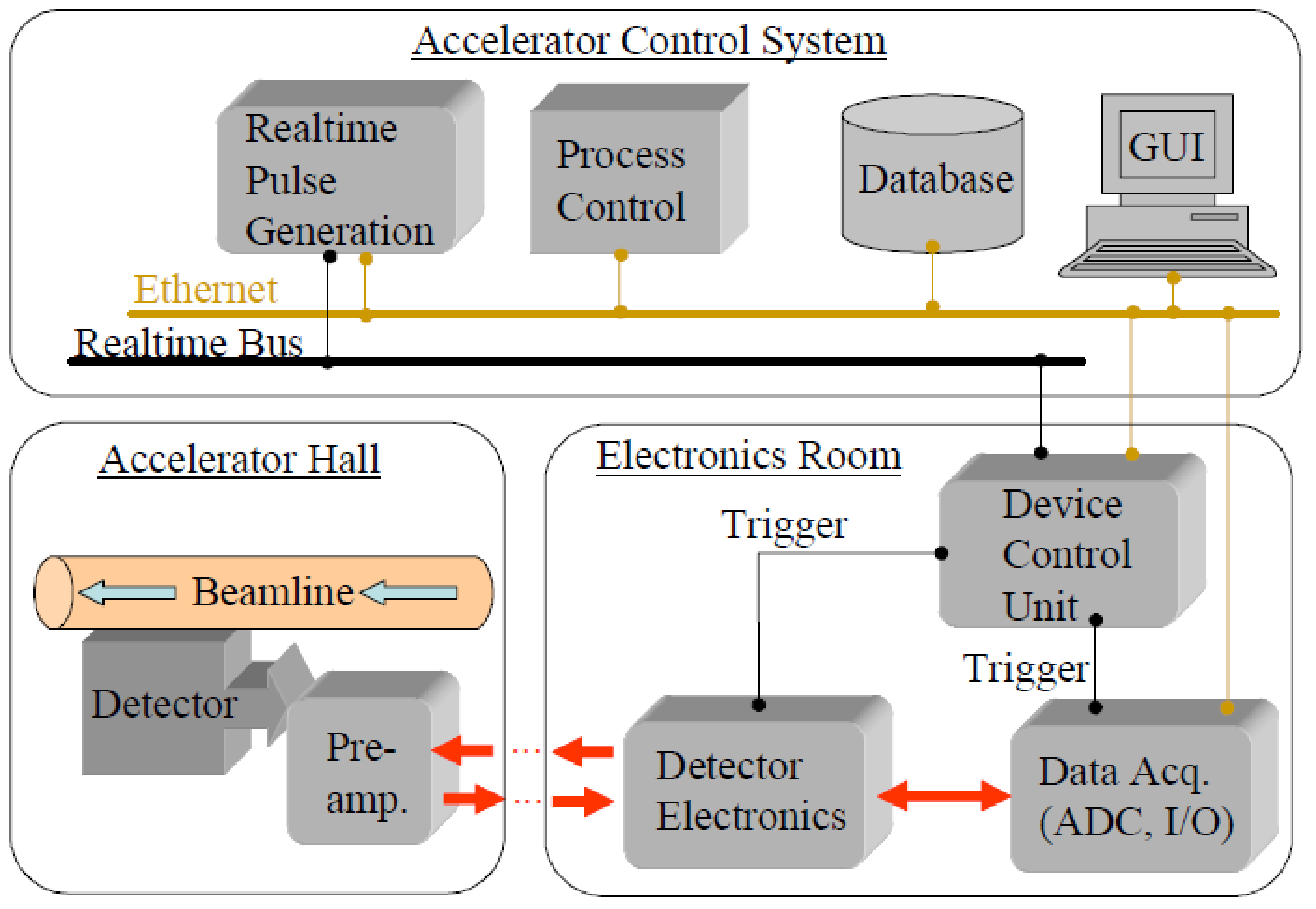
Setup at PSI at ProScan, also a combined IC/MWPC stack

Embedding of Beam Diagnostic devices

Not to forget:

- Mechanics: Compactness, easy maintenance
- Positioning: Are there environmental influences, e.g. stray fields of magnets which may disturb current measurements of transformers?
- Alignment: Which accuracy is necessary – longitudinal, transversal?
- Electronics and Cabling: Adequate sensitivity and dynamics? EMC?
- Timing system: Stable triggers with respect to machine phases are needed. Which precision is needed?
- Link of the measurement devices to the control system which should ensure consistent measurements of several devices spread over the facility in one beam pulse, e.g. online control of the transmission or in connection with ramping data from magnet power supplies or r.f.

Embedding of Beam Diagnostic devices



Conclusion and Acknowledgements

- Beam Instrumentation is the "the eyes of the operator" to the behavior of the accelerator.
- In Medical Accelerators the robustness and reliability of beam diagnostic devices is mandatory, especially for the work horses like current and profile measurement devices described in this talk.
- Beam Instrumentation needs 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 present the measurement data in the control room.

Conclusion and Acknowledgements

Many thanks to all colleagues from HIT, MIT, GSI, CNAO, PSI and MedAustron – especially to Peter Forck from GSI – for their advice and giving me interesting example measurements and photos of beam instrumentation from their facilities!

MIT
Marburger Ionenstrahl-Therapiezentrum

MedAustron

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

Thank you for your attention!