# The beam current is the basic quantity of the beam.

- It this 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 lower detection threshold.

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

  They are destructive. For low energies only

  Low currents can be determined.

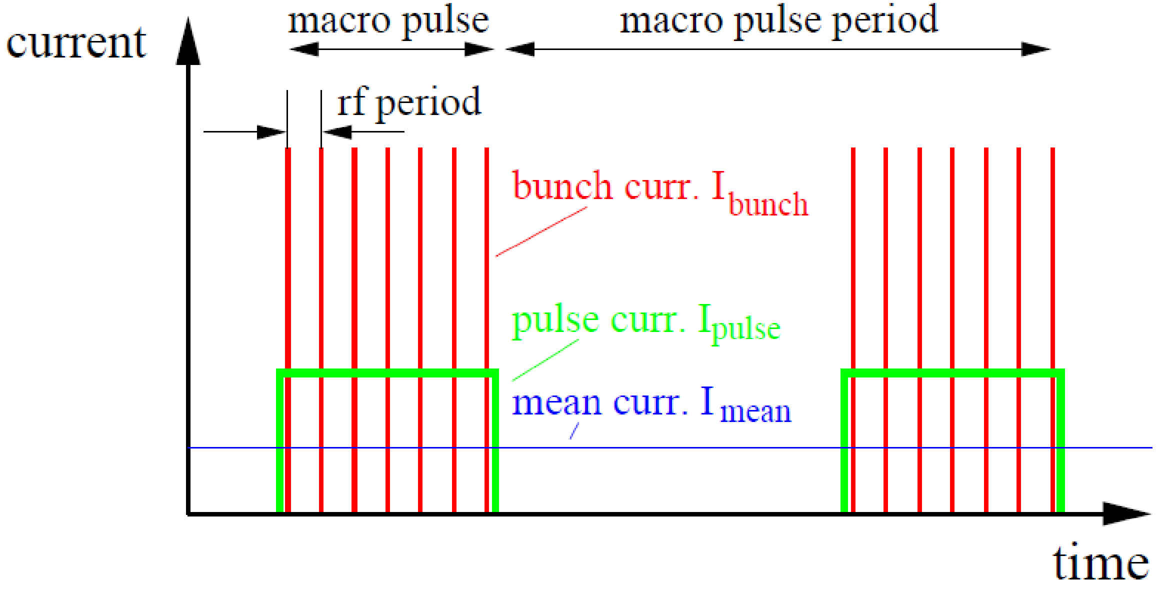
- **Particle detectors:** Measurement of the particle's **energy loss** in matter

  Examples are scintillators, ionization chambers, secondary e– emission monitors

  Used for low currents at high energies e.g. for slow extraction.

# Beam Structure of a pulsed LINAC

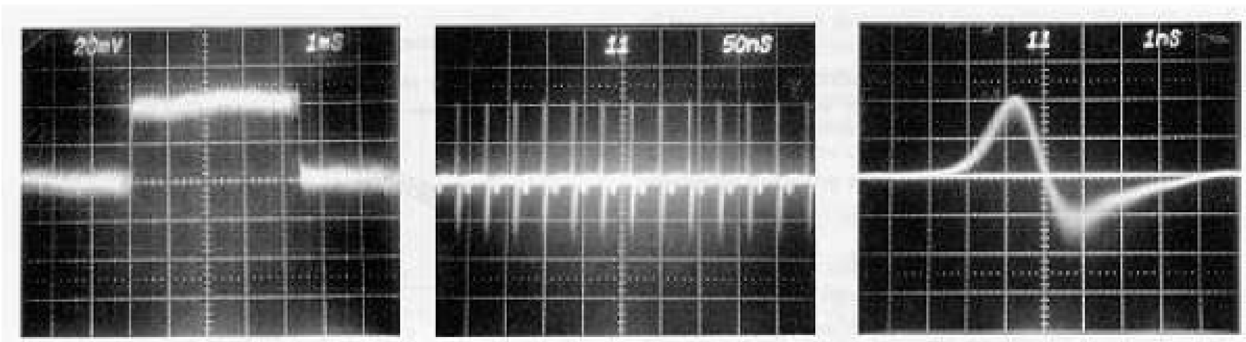
Pulsed LINACs and cyclotrons used for injection to synchrotrons with $t_{pulse} \approx 100$ µs:



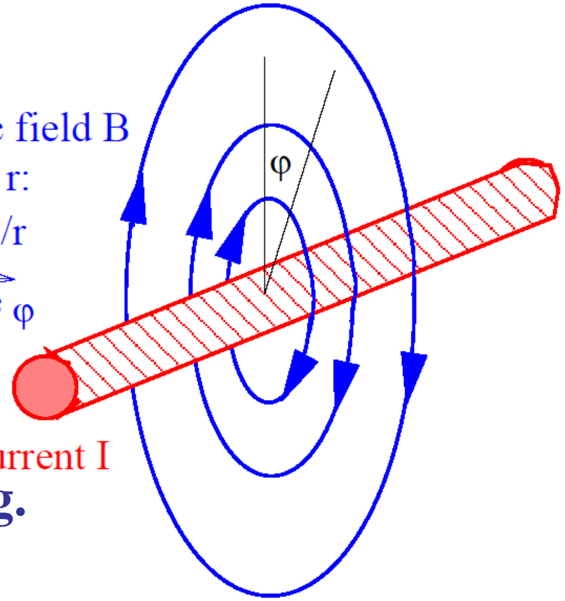

One distinguish between:

- 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: Van-de-Graaff (ele-static):
→ no bunch structure




***Example:***
Pulse and bunch structure at GSI LINAC:




- Beam current of $N$ charges with velocity $\beta$

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

- 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 sec. winding.**

⇒ Loaded current transformer

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

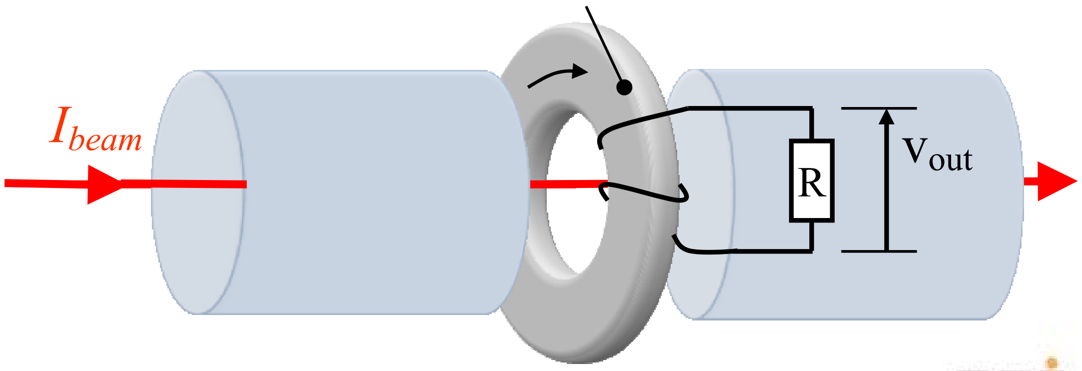
- Inductance of a torus of $\mu_r$

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

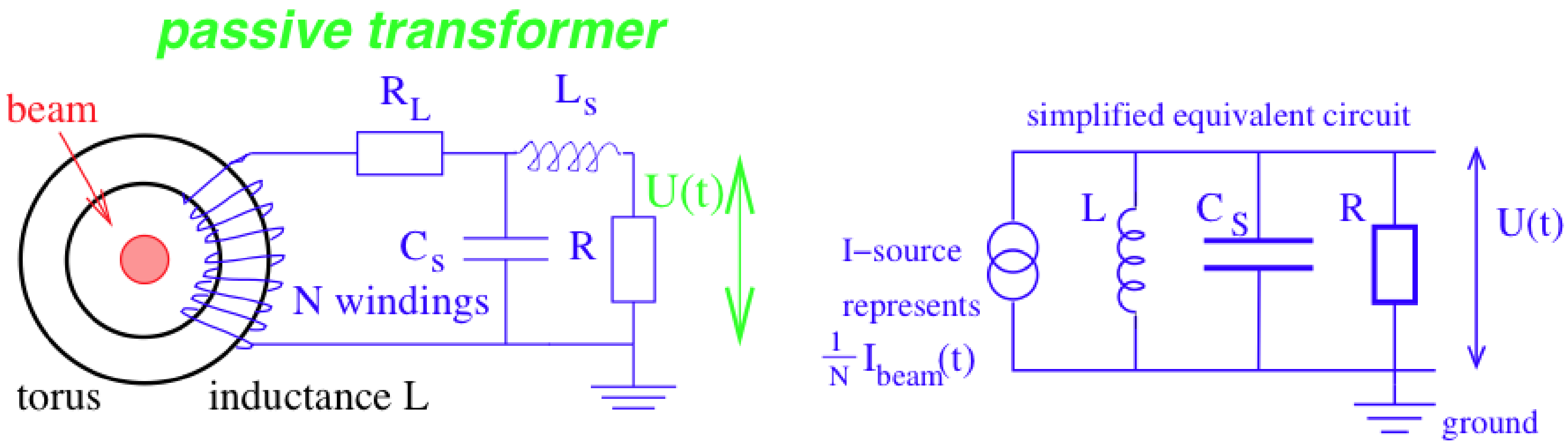
- Goal of Torus: Large inductance ***L*** ***and*** guiding of field lines.

Definition: $U = L \cdot dI/dt$

Torus to guide the magnetic field



## Simplified electrical circuit of a passively loaded transformer:



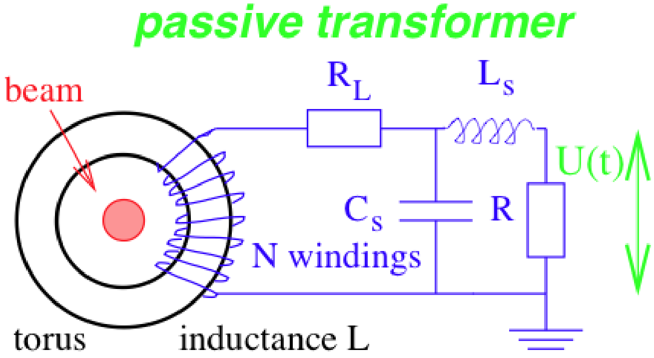

A voltages is measured: $\boldsymbol{U = R \cdot I_{sec} = R/N \cdot I_{beam} \equiv S \cdot I_{beam}}$

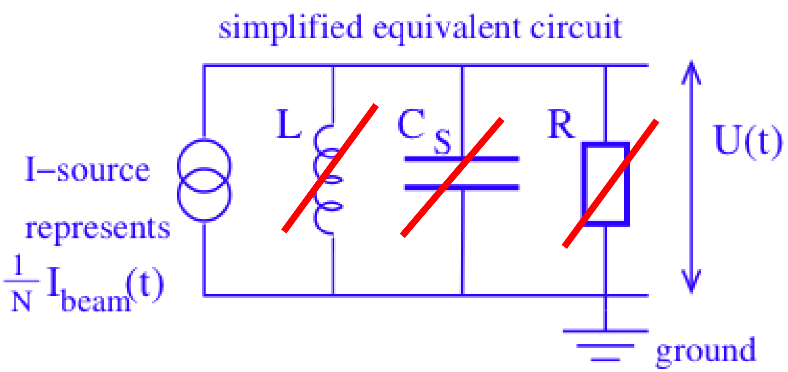
with ***S* sensitivity [V/A]**, equivalent to transfer function or transfer impedance ***Z***.

Equivalent circuit for analysis of sensitivity and bandwidth

(disregarding the loss resistivity $R_L$)

## Analysis of a simplified electrical circuit of a passively loaded transformer:




For this parallel shunt:

$$\frac{1}{Z} = \frac{1}{i\omega L} + \frac{1}{R} + i\omega C_S \Leftrightarrow Z = \frac{i\omega L}{1 + i\omega L / R + \omega L / R \cdot \omega R C_S}$$

- ***Low frequency*** $\omega \ll R/L$ **:** $Z \rightarrow i\omega L$

  i.e. no dc-transformation

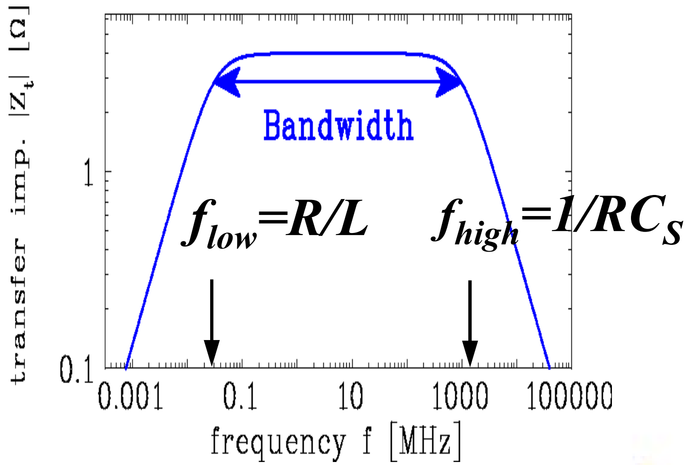
- ***High frequency*** $\omega \gg 1/RC_S$**:** $Z \rightarrow 1/i\omega C_S$

  i.e. current flow through $C_S$

- ***Working region*** $R/L \ll \omega \ll 1/RC_S$**:** $Z \simeq R$

  i.e. voltage drop at R and sensitivity $S=R/N$.

No oscillations due to over-damping by low R = 50 Ω to ground.



*Time domain description:*

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

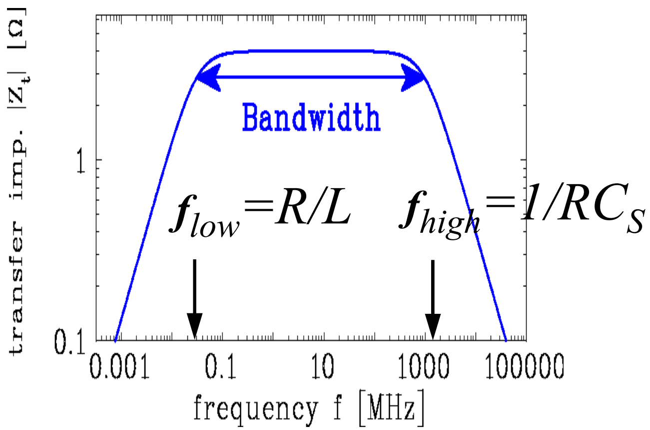
Rise time: $t_{rise} = 1/3f_{high} = 1/RC_S$ (ideal without cables)

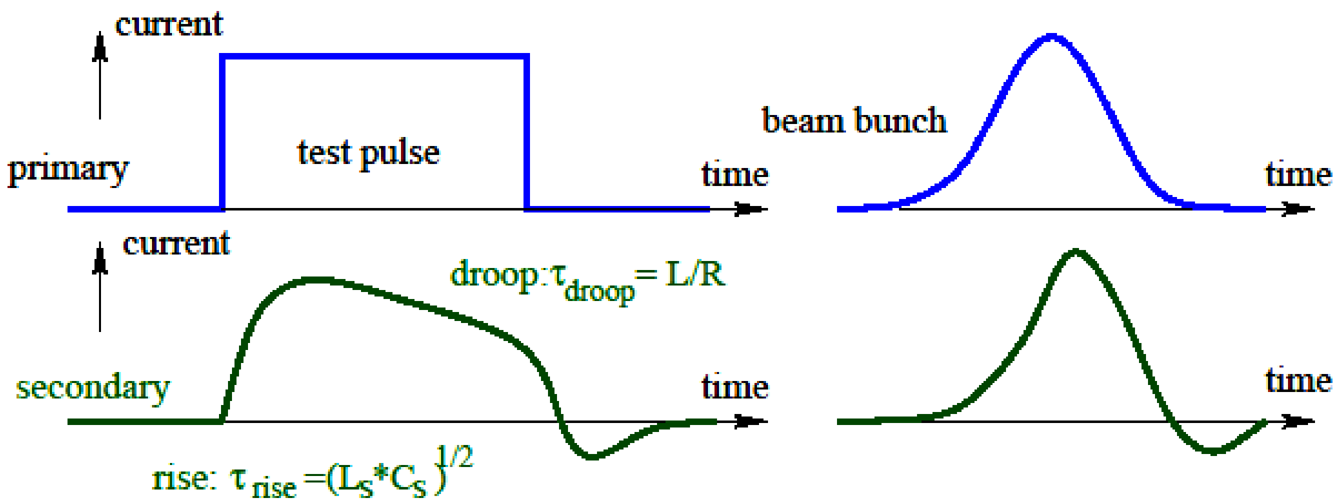
Rise time: $t_{rise} = 1/3f_{high} = \sqrt{L_S C_s}$ (with cables)

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

For the working region the voltage output is

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



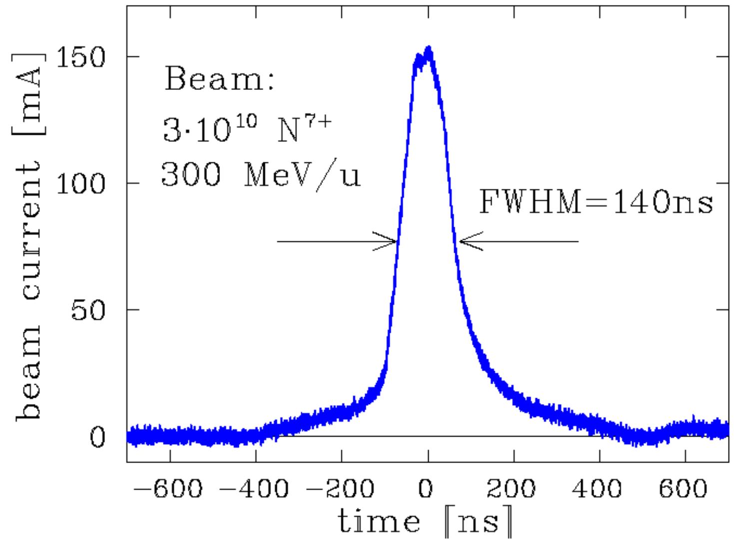
# Example for passive Transformer


For bunch observation
e.g. transfer between synchrotrons
a bandwidth of 2 kHz < ***f*** < 1 GHz
⇔ 1 ns < ***t*** < 200 µs is well suited.

*Example GSI type:*

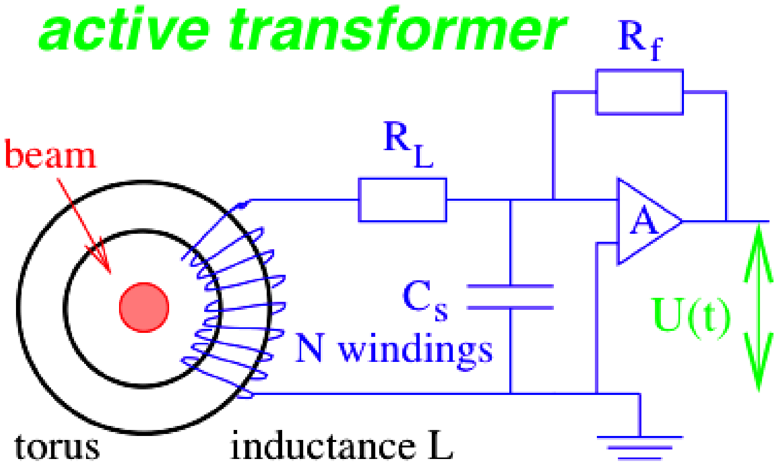
| | |
|---|---|
| Inner radius | $r_i = 70$ mm |
| Outer radius | $r_o = 90$ mm |
| Torus thickness | $l = 16$ mm |
| Torus material | Vitrovac 6025: $(CoFe)_{70\%}(MoSiB)_{30\%}$ |
| Permeability | $\mu_r \simeq 10^5$ for $f < 100$ kHz, $\mu_r \propto 1/f$ above |
| Windings | 10 |
| Sensitivity | 4 V/A at $R = 50\ \Omega$, $10^4$ V/A with ampl. |
| Resolution | 40 $\mu A_{rms}$ |
| $\tau_{droop} = L/R$ | 0.2 ms |
| $\tau_{rise} = \sqrt{L_S C_S}$ | 1 ns |
| Bandwidth | 2 kHz to 300 MHz |

Fast extraction from GSI synchrotron:



**Active Transformer or Alternating Current Transformer ACT:**
uses a trans-impedance amplifier (I/U converter) to $\boldsymbol{R \approx 0\ \Omega}$ load impedance i.e. a current sink
+ compensation feedback
⇒ longer droop time $\tau_{droop}$

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




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

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

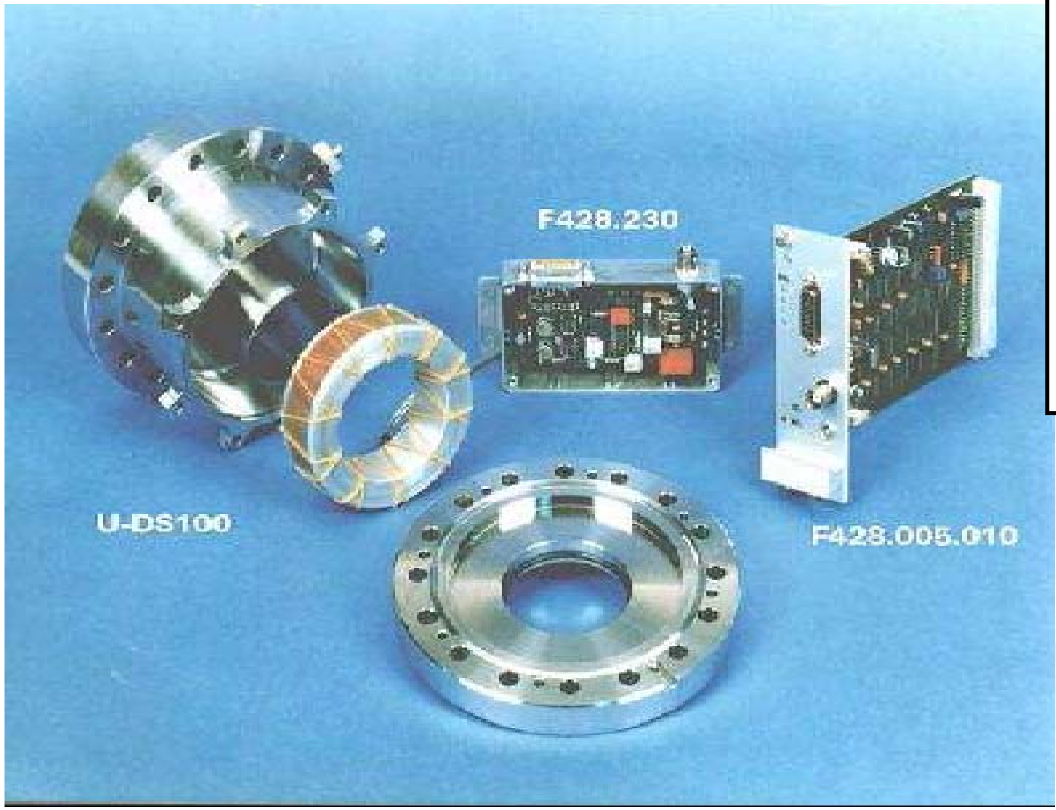
Droop time constant can be up to 1 s!

The feedback resistor is also used for range switching.

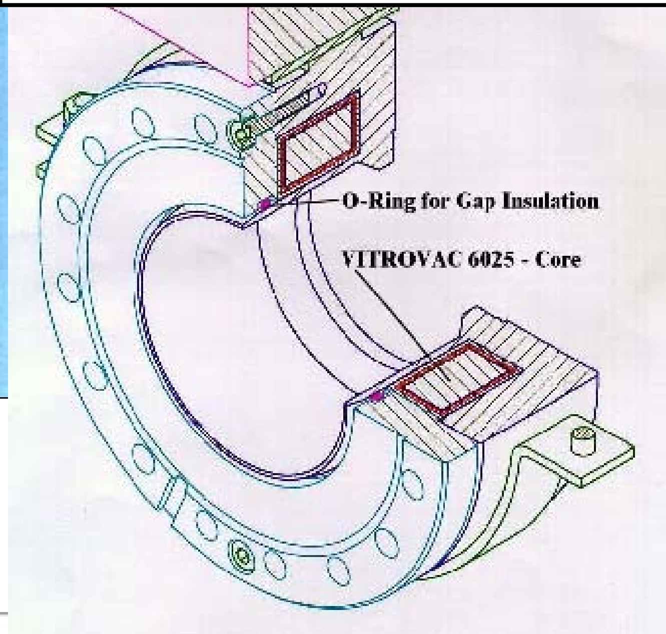
An additional active feedback loop is used to compensate the droop.

# 'Active' Transformer Realization

Active transformer for the measurement of long $t > 10$ µs pulses e.g. at pulsed LINACs



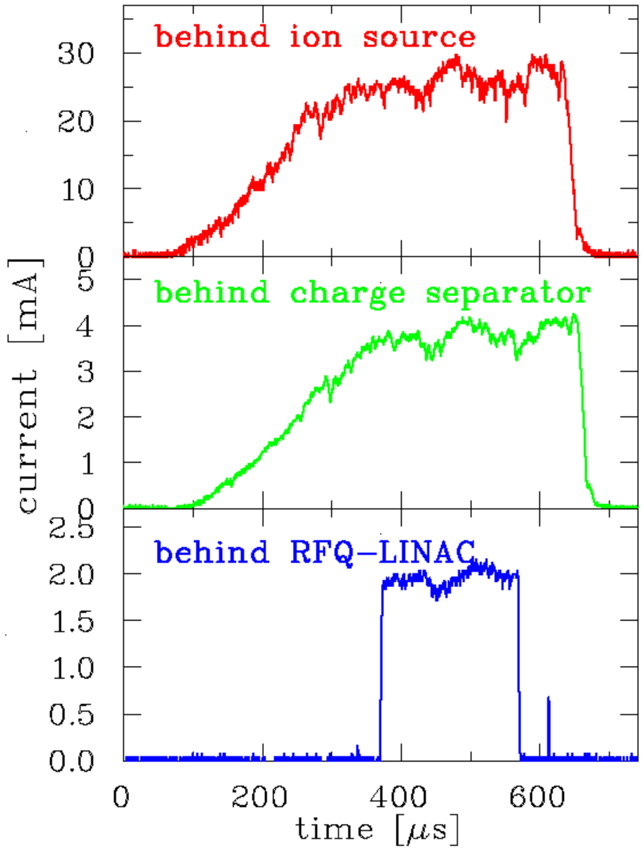

| | |
|---|---|
| **Torus inner radius** | $r_i$**=30 mm** |
| **Torus outer radius** | $r_o$**=45 mm** |
| **Core thickness** | $l$**=25 mm** |
| **Core material** | **Vitrovac 6025** $(CoFe)_{70\%}(MoSiB)_{30\%}$ |
| **Core permeability** | $u_r=10^5$ |
| **Number of windings** | **2x10 crossed** |
| **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** |



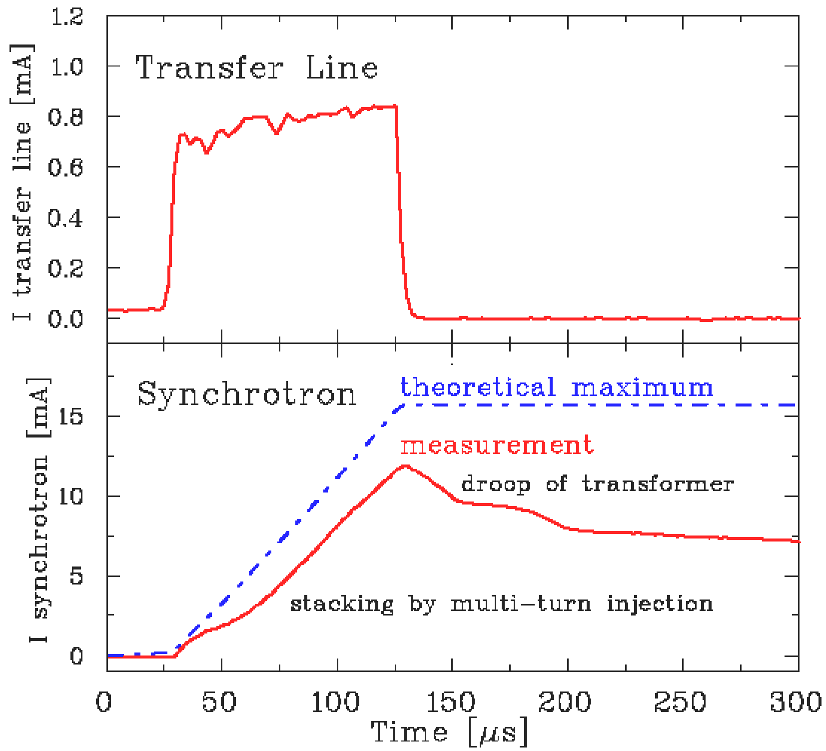
# 'Active' Transformer Measurement

Active transformer for the measurement of long $t$ > 10 µs pulses e.g. at pulsed LINACs

***Example:*** Transmission and macro-pulse shape for $Ni^{2+}$ beam at GSI LINAC

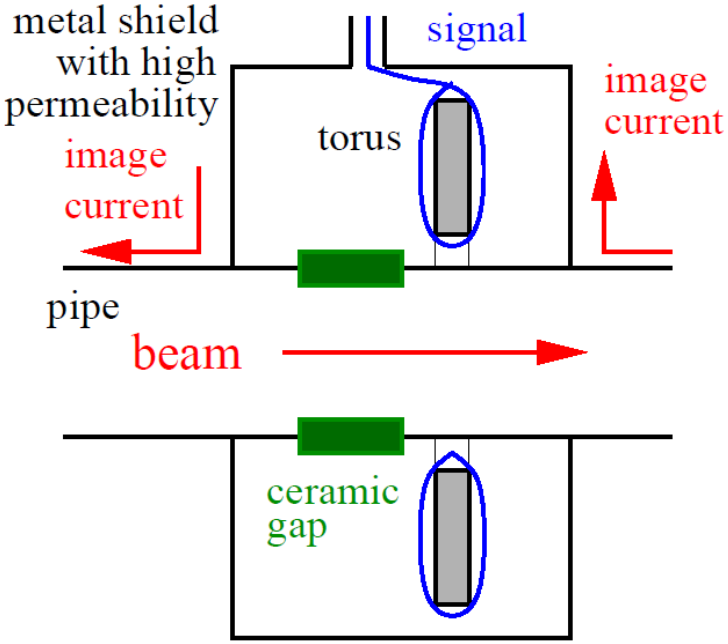



***Example***: Multi-turn injection of a $Ni^{26+}$ beam into GSI Synchrotron, 5 µs per turn



# Shielding of a Transformer

The image current of the walls have to be bypassed by a gap and a metal housing.
This housing uses μ-metal and acts as a shield of external B-fields as well.




# Design Criteria for a Current Transformer

**Criteria:**

1. The output voltage is $U \propto 1/N \Rightarrow$ low number of windings for large signal.
2. For a low droop, a large inductance $L$ is required due to $\tau_{droop} = L/R$:

   $L \propto N^2$ and $L \propto \mu_r$ ($\mu_r \approx 10^5$ for amorphous alloy).
3. For a large bandwidth the integrating capacitance $C_s$ should be low $\tau_{rise} = \sqrt{L_s C_s}$.

**Depending on applications the behavior is influenced by external elements:**

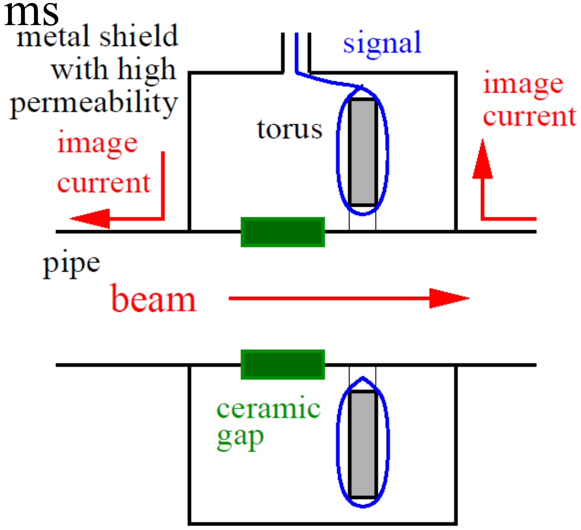
- **Passive transformer:** $R = 50\ \Omega$, $\tau_{rise} \approx 1$ ns for short pulses.

  ***Application:*** Transfer between synchrotrons : 100 ns < $t_{pulse}$ < 10 μs
- **Active transformer:** Current sink by I/U-converter, $\tau_{droop} \approx 1$ s for long pulses.

  ***Application:*** macro-pulses at LINACs : 100 μs < $t_{pulse}$ < 10 ms

**General:**

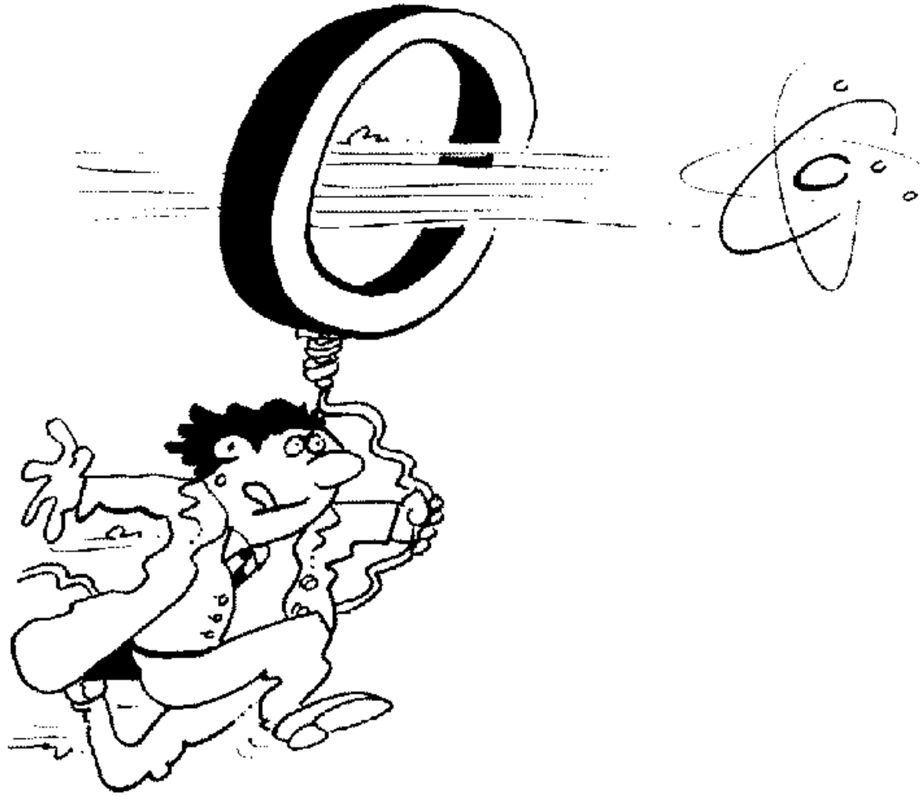
- The beam pipe has to be intersected to prevent the flow of the image current through the torus.
- The torus is made of 25 μm isolated flat ribbon spiraled to get a torus of ≈15 mm thickness, to have large electrical resistivity.
- Additional winding for calibration with current source.



# The Artist' View of Transformers

The active transformer ACCT

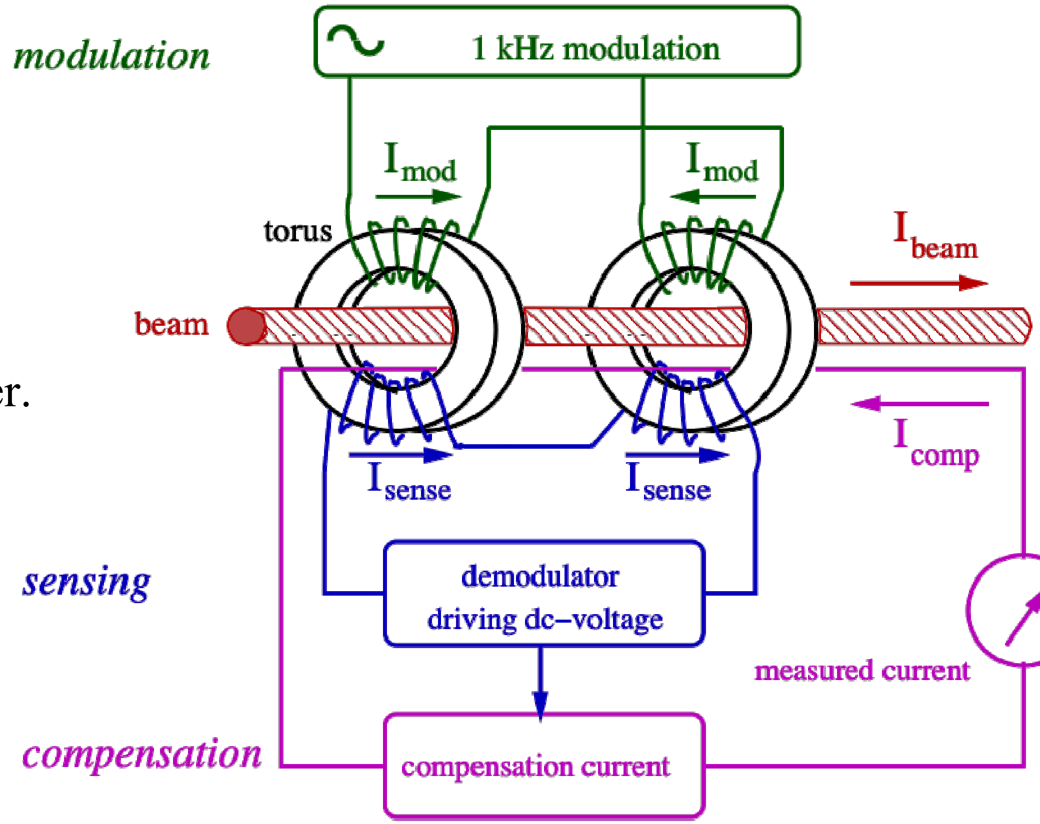

The passive, fast transformer FCT



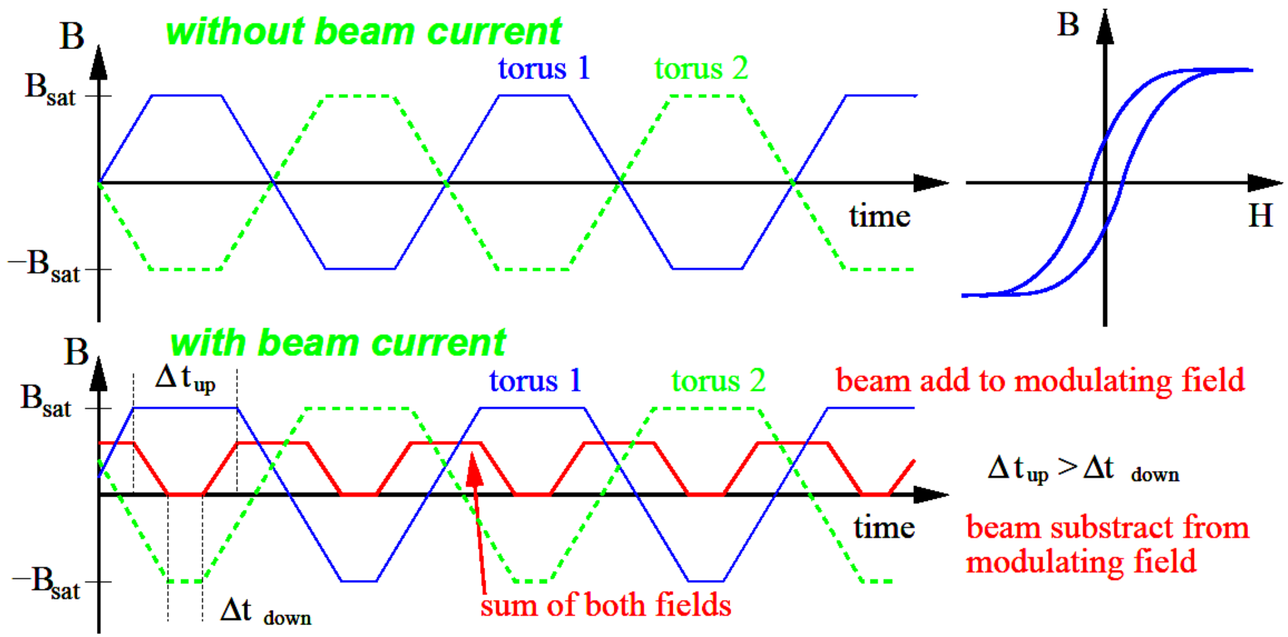
Cartoons by Company Bergoz, Saint Genis

How to measure the DC current? The current transformer discussed sees only B-flux ***changes.***
The DC Current Transformer (DCCT) → look at the magnetic saturation of two torii.

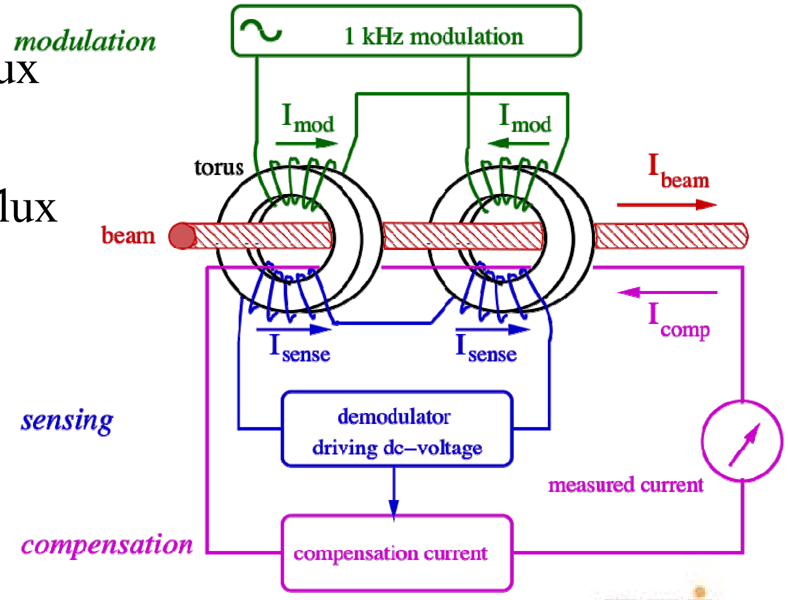
- ➢**Modulation** of the primary windings forces both torii into saturation twice per cycle.
- ➢**Sense windings** measure the modulation signal and cancel each other.
- ➢But with the $I_{beam}$, the saturation is shifted and $I_{sense}$ is not zero
- ➢**Compensation current** adjustable until $I_{sense}$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



# The dc Transformer




- **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.



# The dc Transformer Realization

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

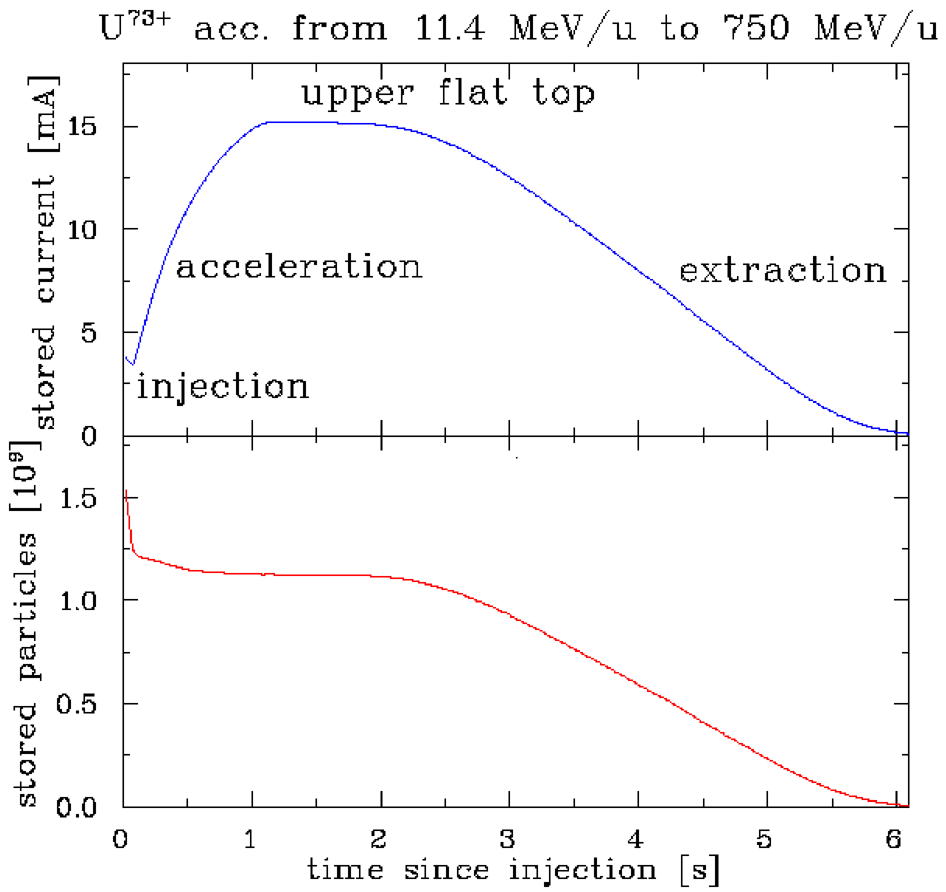
| | |
|---|---|
| Core radii | $r_i = 135$ mm, $r_o = 145$mm |
| Core thickness | 10 mm |
| Core material | Vitrovac 6025: $(CoFe)_{70\%}(MoSiB)_{30\%}$ |
| Core permeability | $\mu_r \simeq 10^5$ |
| Saturation $B_{sat}$ | $\simeq 0.6$ T |
| Isolating cap | $Al_2O_3$ |
| Number of windings | 16 for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

Recent commercial product specification (Bergoz NPCT):

| | |
|---|---|
| Most parameters | comparable the GSI-model |
| Temperature coeff. | 0.5 µA/$^o$C |
| Resolution | several µA (i.e. not optimized) |

***Example:*** The DCCT at GSI synchrotron:

⇒ Observation of beam behavior with 20 μs time resolution → important operation tool.




**Important parameter:**

**Detection threshold: 1 μA**

**(= resolution)**

Bandwidth: dc to 20 kHz

Rise-time: 20 μs

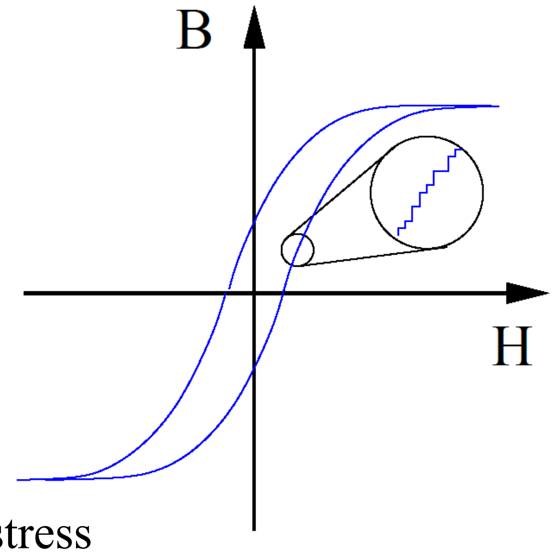
Temperature drift: 1.5 μA/$^0$C

⇒ compensation required.

# Design Criteria and Limitations for a dc Transformer

Careful shielding against external fields with $\mu$-metal.

- High resistivity of the core material to prevent for eddy current
  ⇒ thin, insulated strips of alloy.
- Barkhausen noise due to changes of Weiss domains
  ⇒ unavoidable limit for **DCCT**.
- Core material with low changes of $\mu_r$ due to temperature and stress
  ⇒ low micro-phonic pick-up.
- Thermal noise voltage $U_{eff} = (4kBT \cdot R \cdot \Delta f)^{1/2}$
  ⇒ only required bandwidth $\Delta f$, low input resistor $R$.
- Preventing for flow of secondary electrons through the core
  ⇒ need for well controlled beam centering close to the transformer.




**⇒ The current limits are: ~ 1 µA for DCCT**

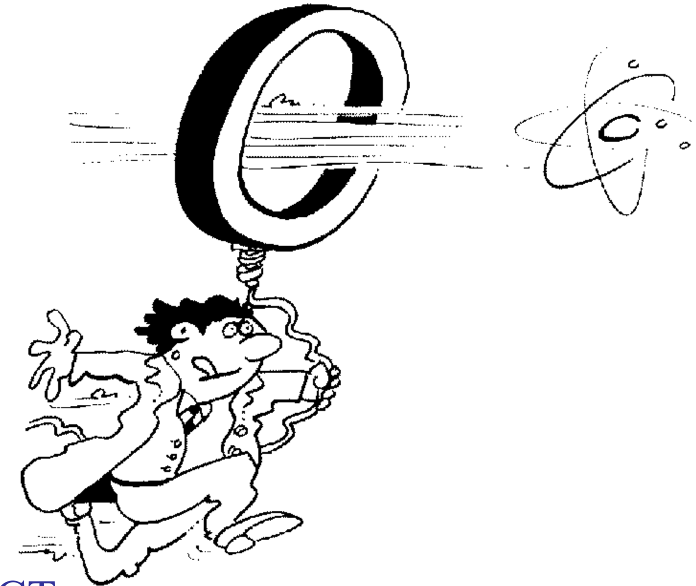
**~ 30 µA for FCT with 500 MHz bandwidth**

**~ 0.3 µA for ACT with 1 MHz bandwidth.**

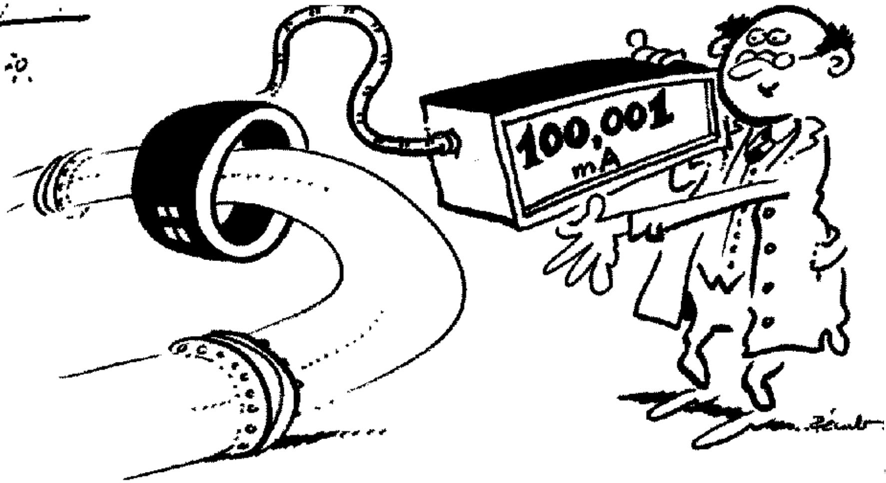
# The Artist' View of Transformers

The active transformer ACCT


The passive, fast transformer FCT



The dc transformer DCCT

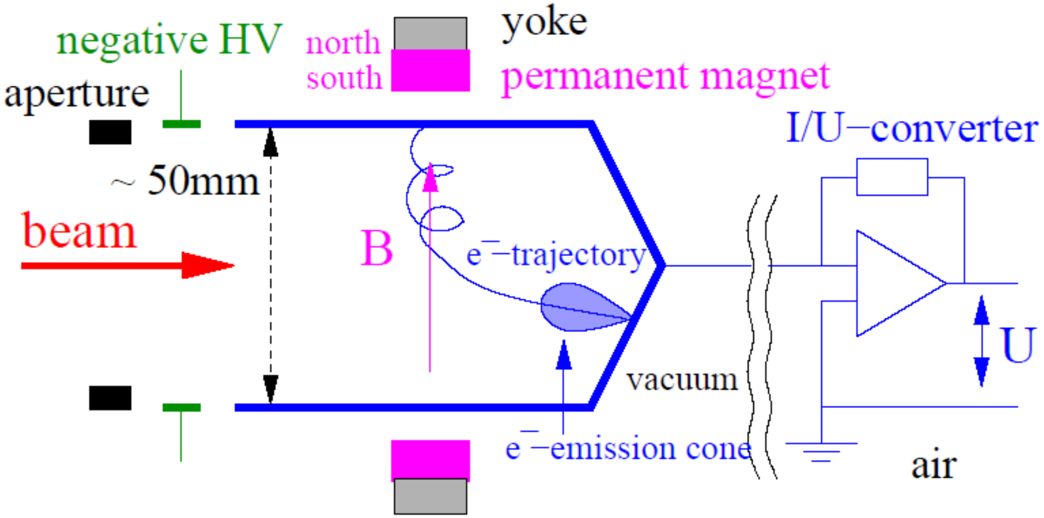



Company Bergoz

# Faraday Cups for Beam Charge Measurement

The beam particles are collected inside a metal cup
⇒ The beam's charge are 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

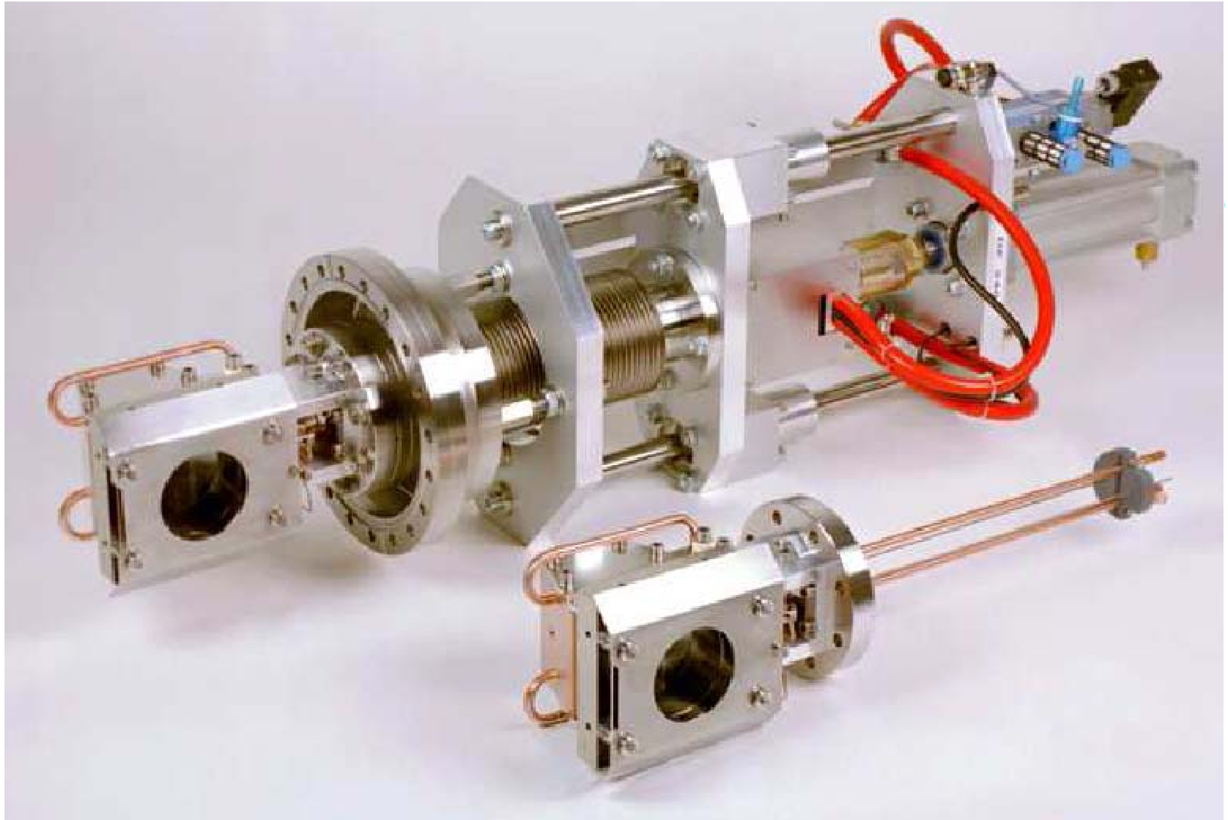
***And/or***

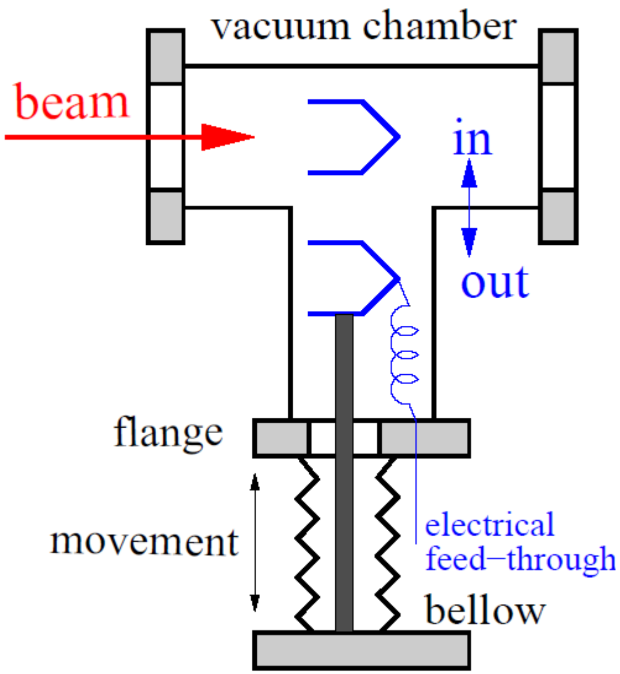
**Electric field:**

Potential barrier at the cup entrance.

# Realization of a Faraday Cup at GSI LINAC

The Cup is moved into the beam pass.

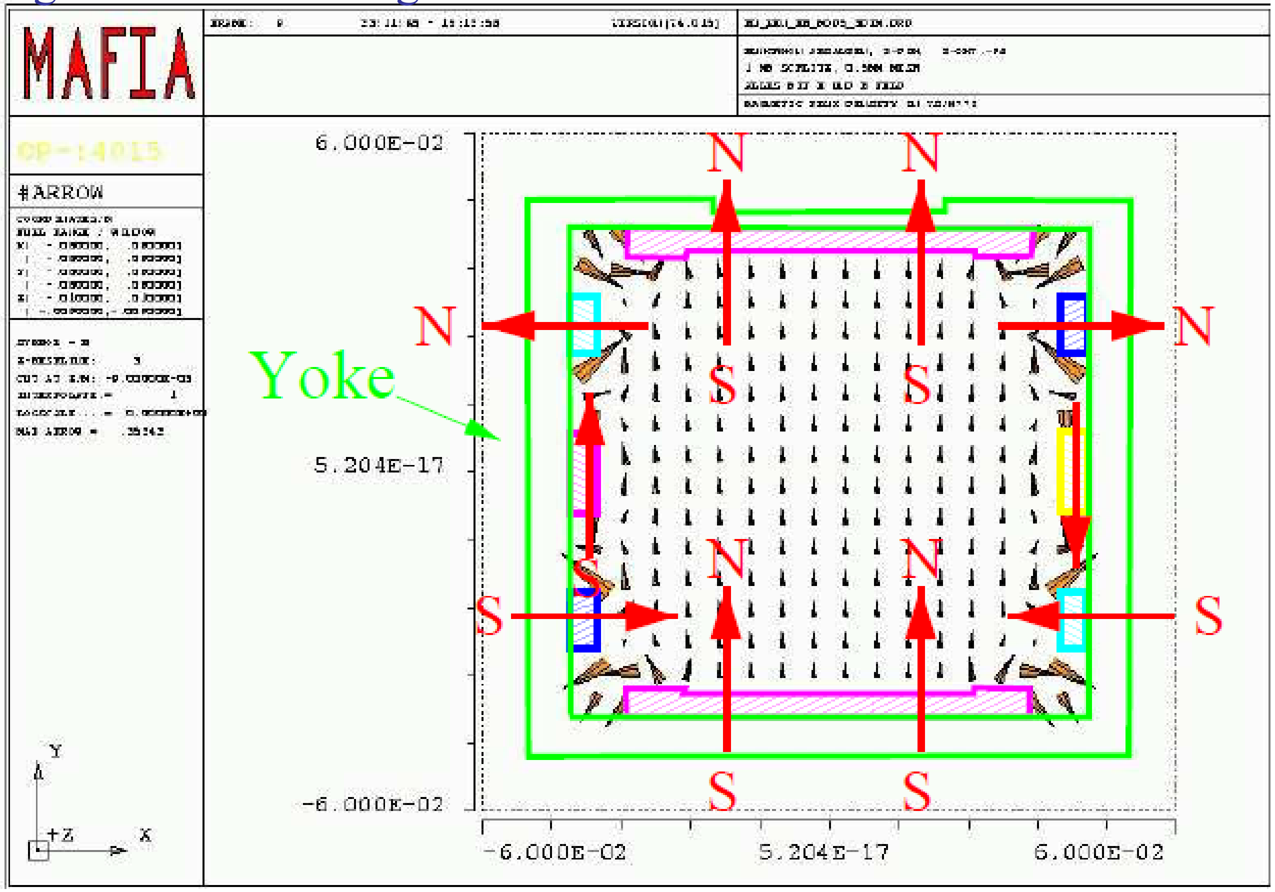




# Magnetic Field formed by permanent Magnets

Arrangement of Co-Sm permanent magnets within the yoke and the calculated magnetic field lines.

The homogeneous field strength is B ~ 0.1 T.



# Energy Loss of Ions in Copper

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 $\boldsymbol{R \propto E_{max}^{1.75}}$

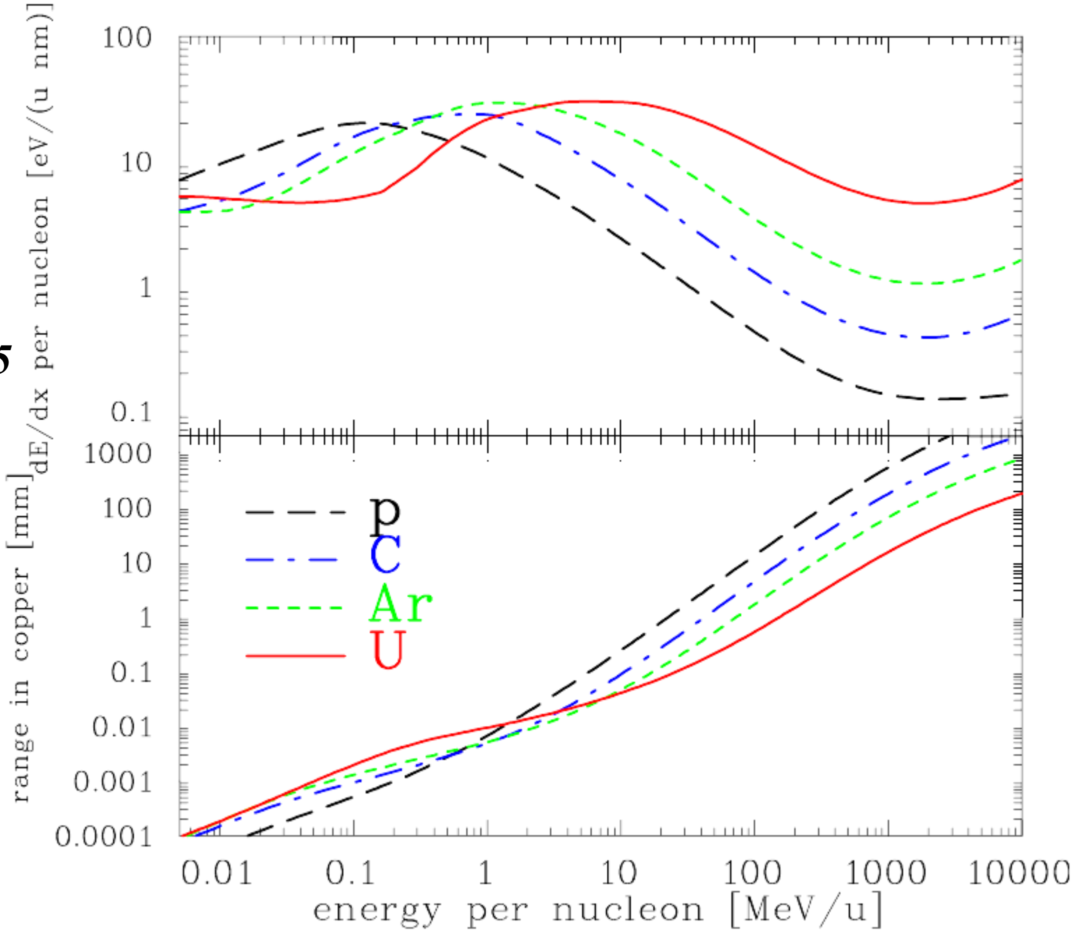
Numerical calculation

with semi-empirical model e.g. SRIM

Main modification $\boldsymbol{Z_p \rightarrow Z^{eff}_p(E_{kin})}$

⇒ Cups only for

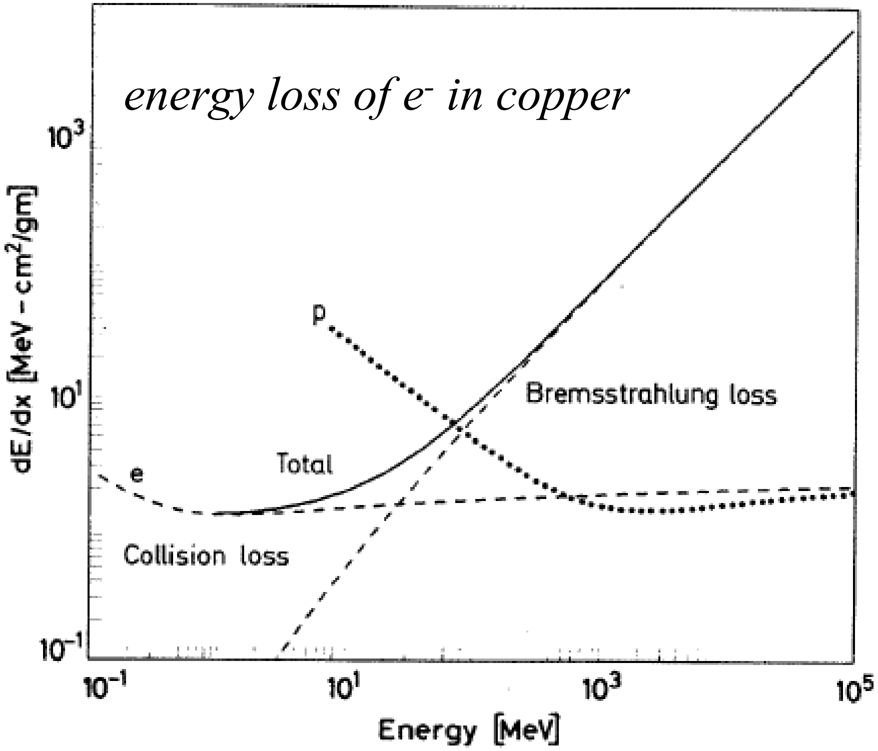
$\boldsymbol{E_{kin}}$ < 100 MeV/u due to $\boldsymbol{R}$ < 10 mm

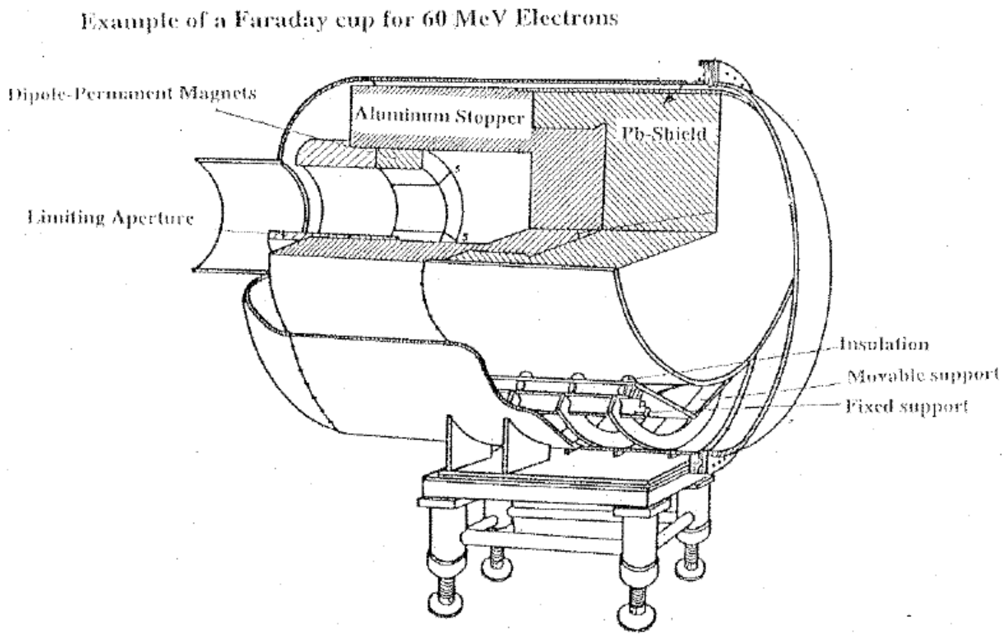


Bethe Bloch formula is valid for all charged particles.

However, Bremsstrahlung dominates for energies above 10 MeV.

e- shows much larger longitudinal and transverse straggling




Al stopper: Stopping of e- gently in low-Z material

Pb-shield: Absorption of Bremstrahlungs-$\gamma$

$\Rightarrow$ Used as beam dump

# Faraday Cups for high Intensity Ion Beam → Surface Heating

The heating of material has to be considered, given by the energy loss.
The cooling is done by radiation due to Stefan-Boltzmann: $P_r = \varepsilon\sigma T^4$

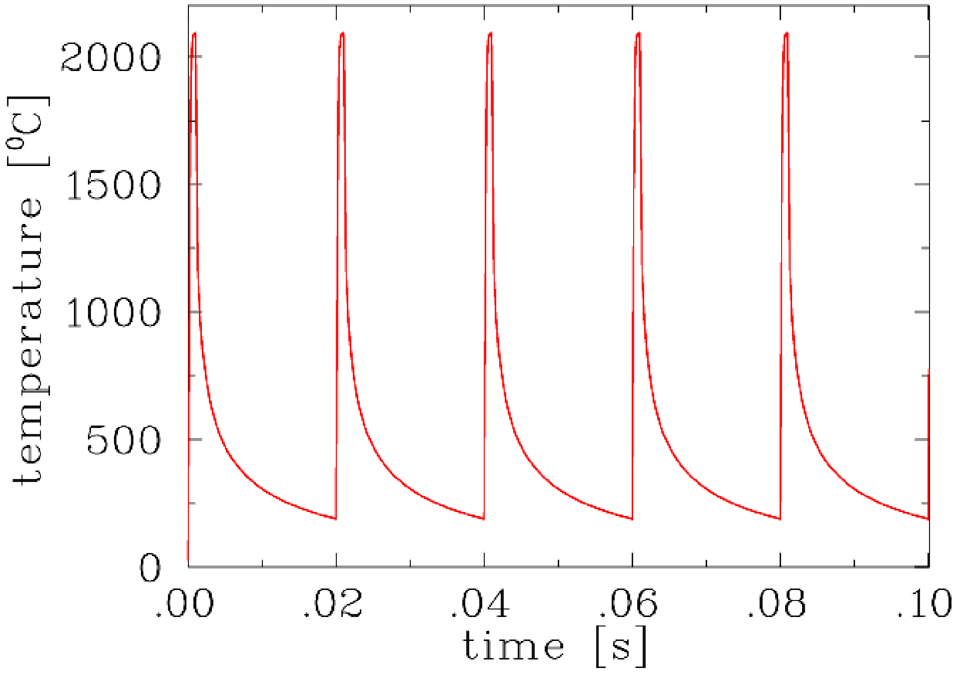
***Example:*** Beam current: 11.4 MeV/u $Ar^{10+}$ with 10 mA and 1 ms

Beam size: 5 mm FWHM → 40 kW/mm², 1 MW toal power

Foil: 1 µm Tantalum, emissivity $\varepsilon = 0.49$

Temperature increase:

T > 2000 $^0$C during beam delivery




Even for low average power,

the material should

survive the peak power!

Numerical calculation of temperature dist. ***T(x,t)*** using spec. heat ***c*** and conduct. $\lambda$:

$$\frac{\partial T(\vec{x},t)}{\partial t} = \frac{\lambda}{\rho c} \cdot \Delta T + \frac{1}{\rho c} \eta(\vec{x},t)$$

With spec. heat ***c*** and heat conduct. $\lambda$

$\rho$ density and $\eta$ heat source by beam

***Example:*** Beam current:

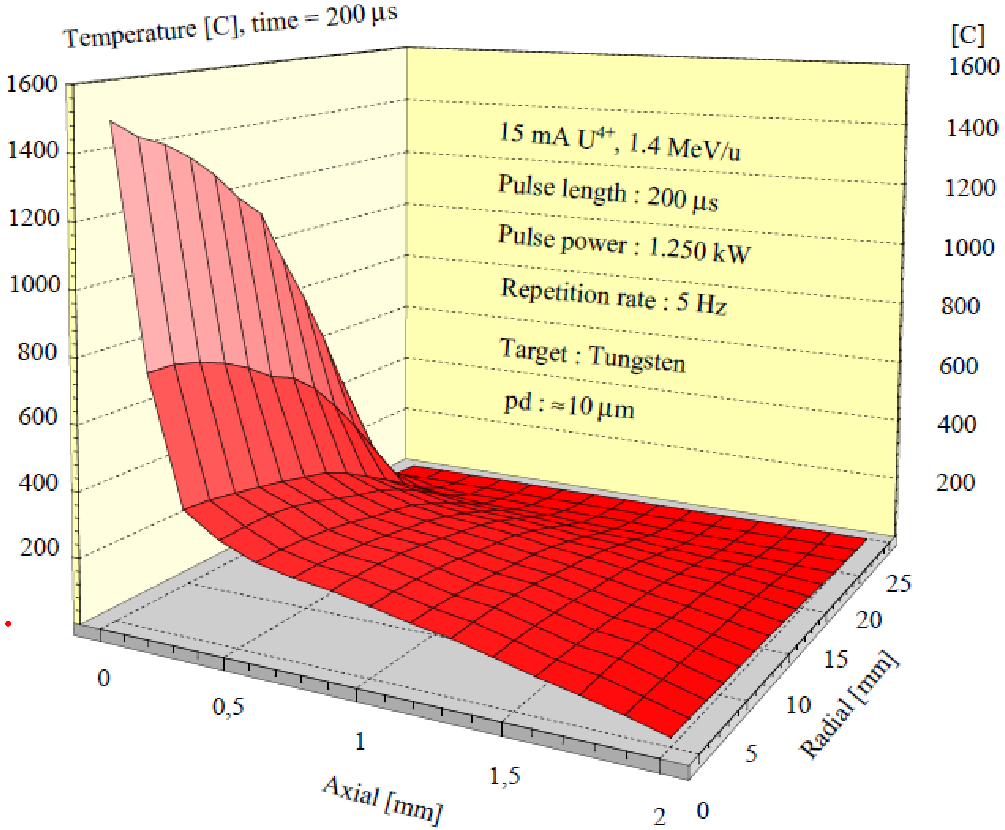
1.4 MeV/u $U^{4+}$ with 15 mA and 0.1 ms

with water cooling at side

Heat conductivity is slow

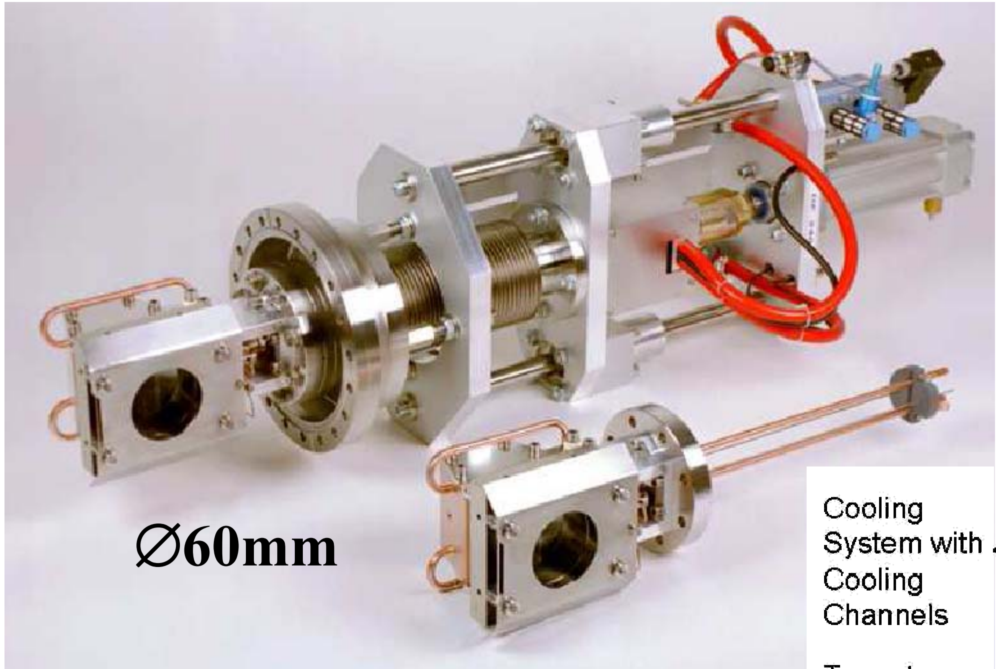
⇒only the average heating is cold

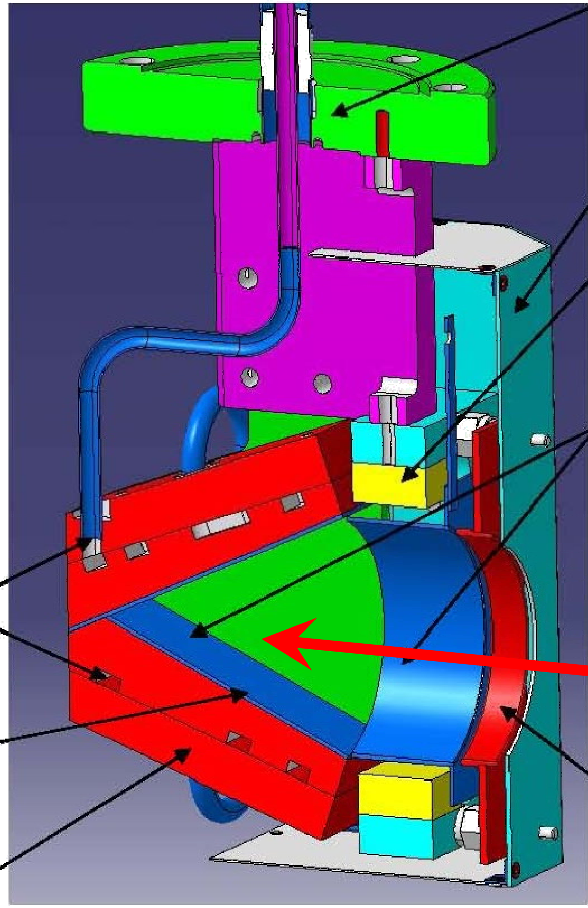
and **not** the power during short pulses.



Cups designed for 1 MW, 1 ms pulse power → cone of Tungsten-coated Copper

Bismuth for high melting temperature and copper for large head conductivity.



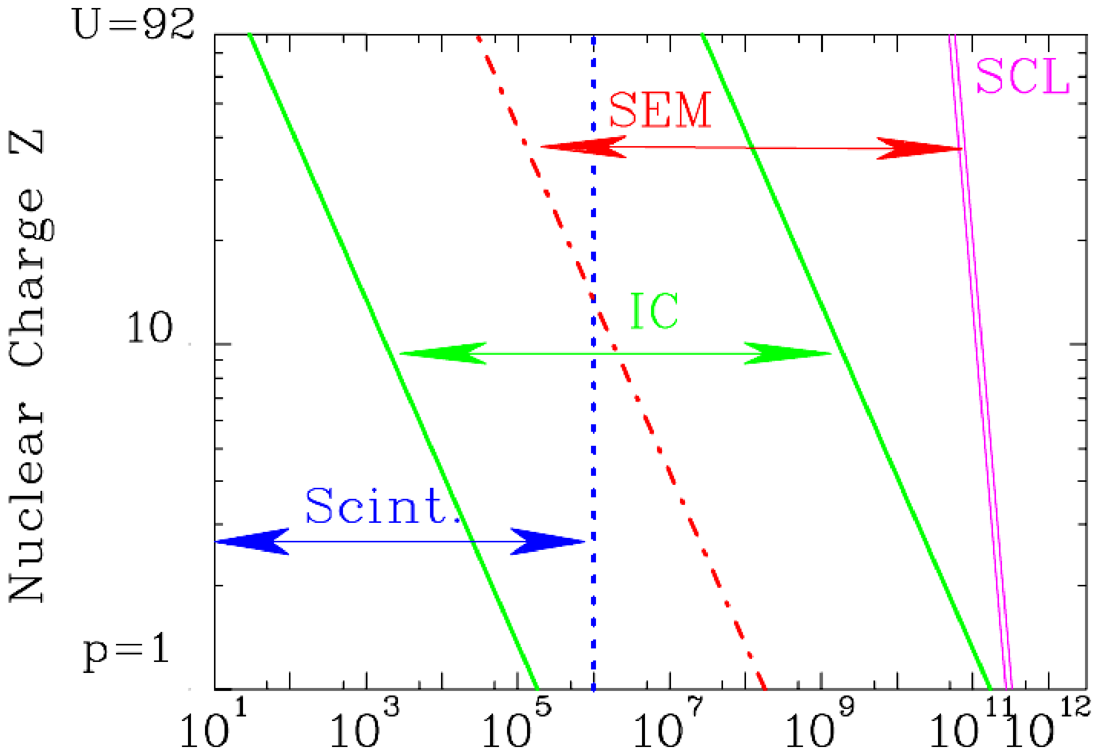



# Low Current Measurement for slow Extraction

Slow extraction from synchrotron: lower current compared to LINAC, but higher energies and larger range $R \gg 1$ cm.

- **Particle counting:**
  max: $r \simeq 10^6$ 1/s
- **Energy loss in gas (IC):**
  min: $I_{sec} \approx 1$ pA
  max: $I_{sec} \approx 1$ µA
- **Sec. e– emission:**
  min: $I_{sec} \approx 1$ pA
- **Max. synch. filling:**
  Space Charge Limit (SCL).

*Particle detector technologies for ions of 1 GeV/u, $A = 1$ cm$^2$:*



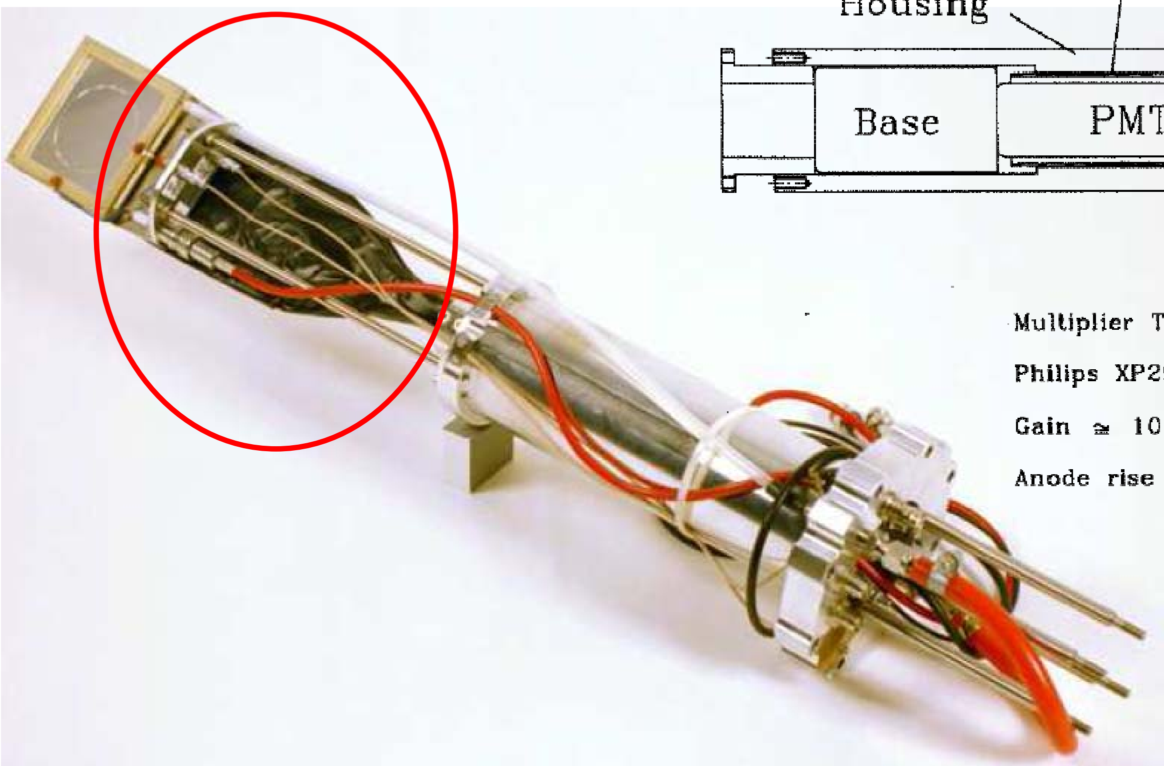
# Example of Scintillator Counter

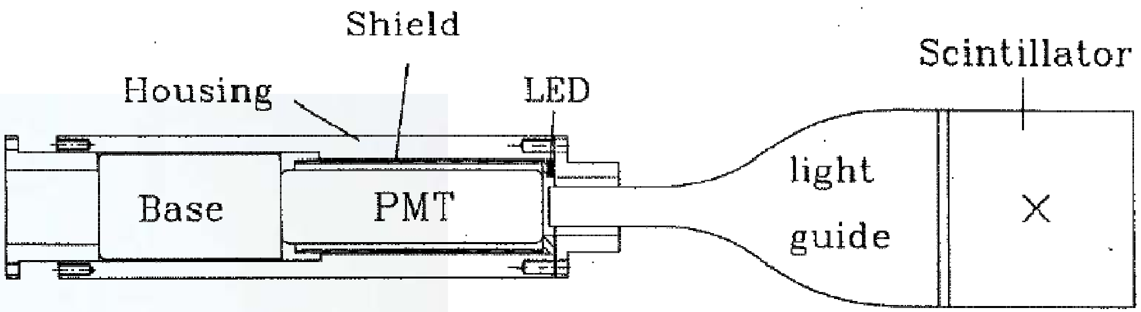
Example: Plastic Scintillator i.e. organic fluorescence molecules in a plastic matrix

**Advantage:** any mechanical from, cheap, blue wave length, fast decay time

**Disadvantage**: not radiation hard

Particle counting: PMT → discriminator → scalar → computer






Multiplier Tube:
Philips XP2972 (1")
Gain ≅ $10^4 ... 10^6$
Anode rise time < 2 ns

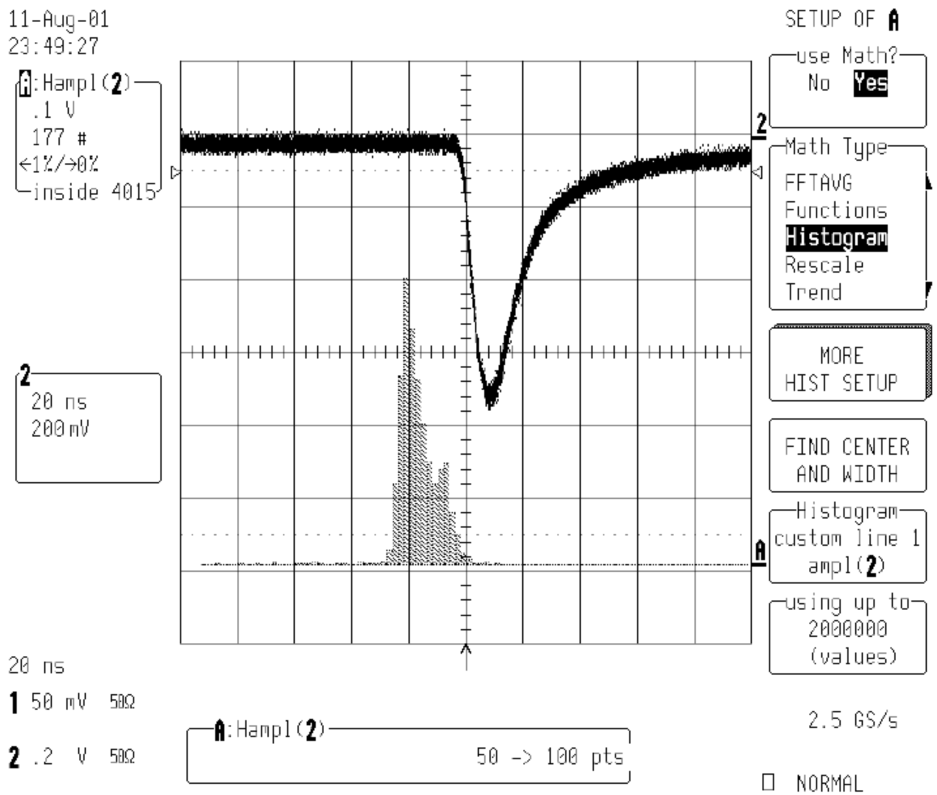
Scintillator:
Pilot U
75 x 75 x 1.0 $mm^3$
Pulse Width 1.2 ns

# Properties of a good Scintillator

Properties of a good scintillator:

- Light output linear to energy loss
- Fast decay time → high rate
- no self-absorption
- wave length of fluorescence
  350 nm < $\lambda$ < 500 nm
- index of refractivity $n \approx 1.5$
  → light-guide
- radiation hardness
  e.g. Ce-activated inorganic
  are much more radiation hard.

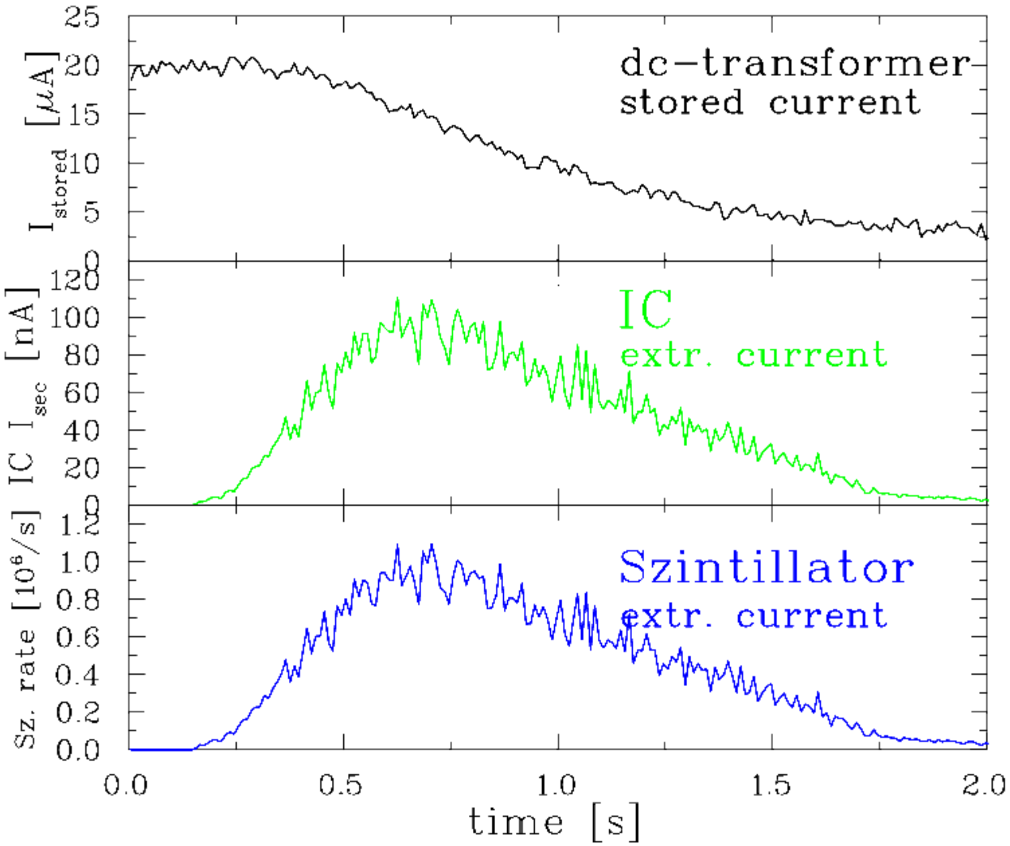
Analog pulses from a plastic sc. with a low current 300 MeV/u Kr beam.




The scaling is 20 ns/div and 100 mV/div.

Slow extraction from a synchrotron delivers countable currents

***Example:*** Comparison for different detector types:

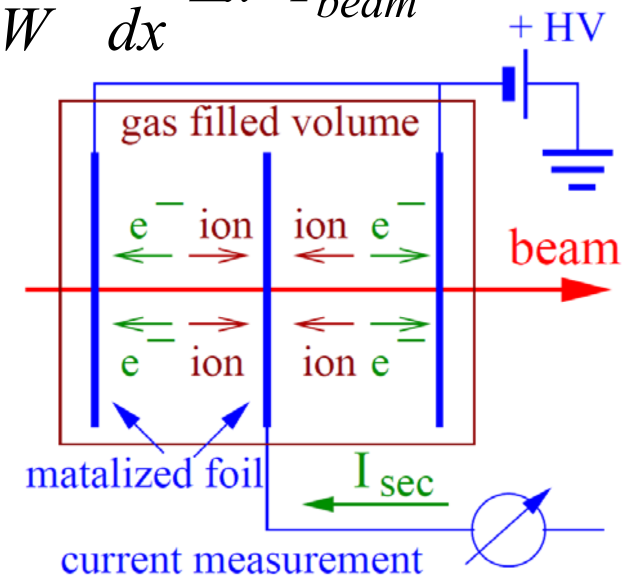



Parameters: dc-transformer inside the synch., ionization chamber and scintillator for a 250 MeV/u $Pb^{67+}$ beam with a total amount of $10^6$ particles.

# Ionization Chamber (IC): Electron Ion Pairs

Energy loss of charged particles in gases → electron-ion pairs → low current meas.

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

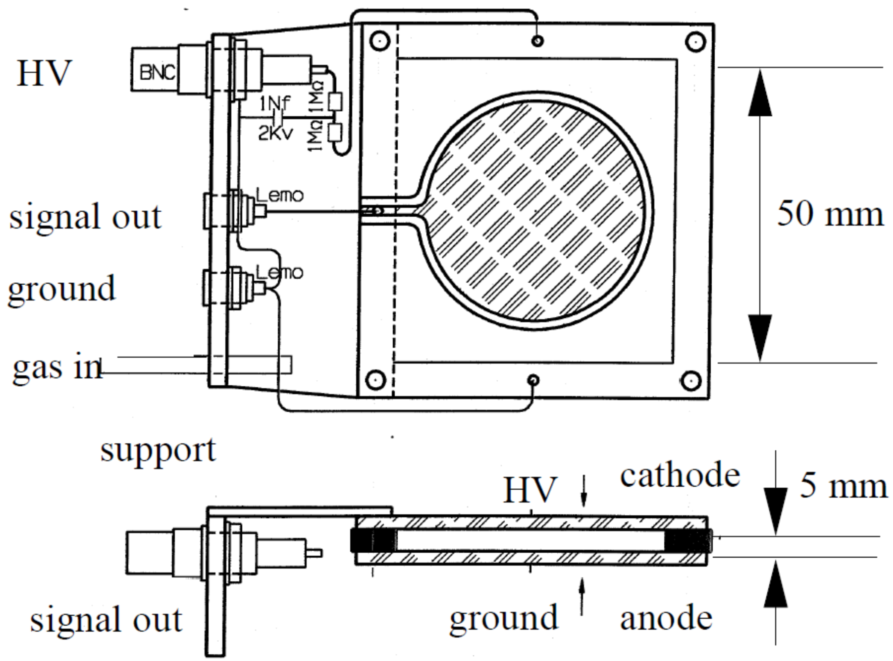



*W* is average energy for one e⁻ -ion pair:

| Gas | ioni. pot. [eV] | W-value [eV] |
|---|---|---|
| He | 24.5 | 42.7 |
| $O_2$ | 12.5 | 32.2 |
| Ar | 15.7 | 26.3 |
| $CH_4$ | 14.5 | 29.1 |
| $CO_2$ | 13.7 | 33.0 |

*Example: GSI type*

| | |
|---|---|
| active surface | $64 \times 64$ mm$^2$ |
| active length $\Delta x$ | 5 mm |
| electrode material | 1.5 $\mu$m Mylar |
| coating | 100 $\mu$g/cm$^2$ silver |
| gas (flowing) | 80 % Ar + 20 %$CO_2$ |
| pressure | 1 bar |
| voltage | 500 ... 2000 V |



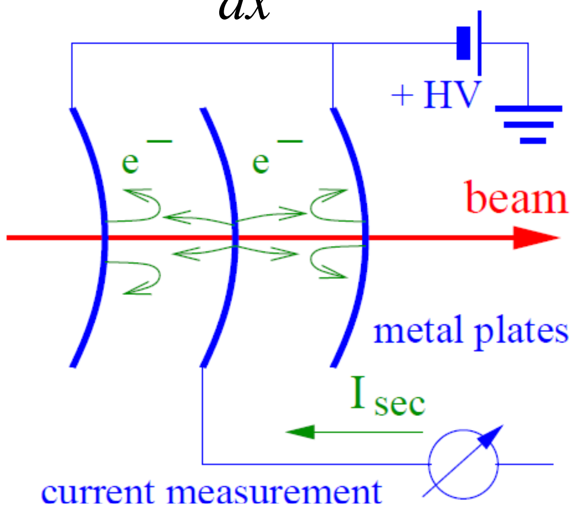
# Secondary Electron Monitor (SEM): Electrons from Surface

For higher intensities SEMs are used.

Due to the energy loss, secondary $e^-$ are emitted from a metal surface.

The amount of secondary $e^-$ is proportional to the energy loss

$$I_{\text{sec}} = Y \cdot \frac{dE}{dx} \cdot I_{beam}$$




*Example: GSI SEM type*

| | |
|---|---|
| material | pure Al (≃99.5%) |
| # of electrodes | 3 |
| active surface | 80 × 80 mm$^2$ |
| distance | 5 mm |
| voltage | 100 V |

It is a ***surface*** effect:

→ Sensitive to cleaning procedure

→ Possible surface modification by radiation

**Advantage for Al**: good mechanical properties.

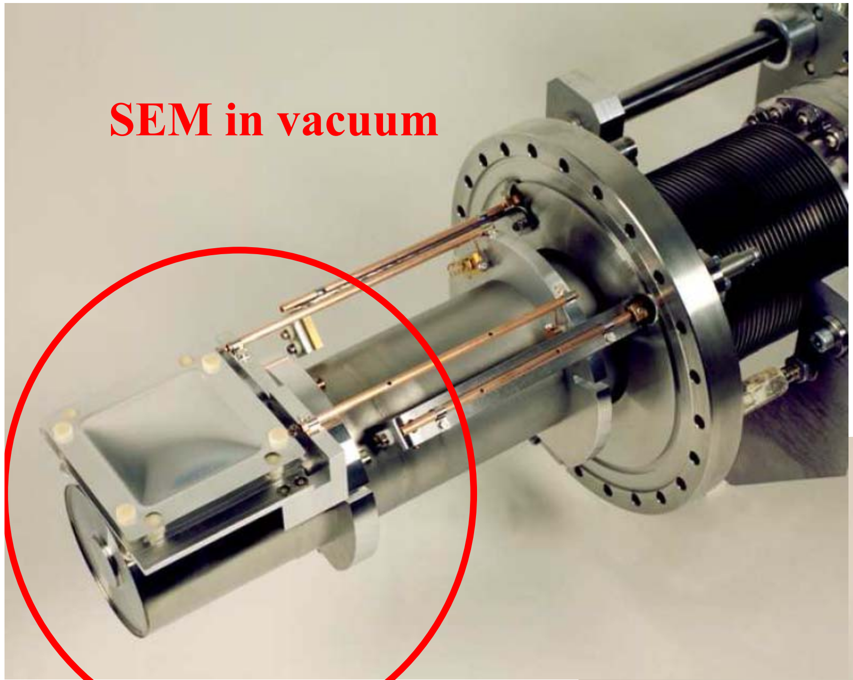
**Disadvantage:** Surface effect!

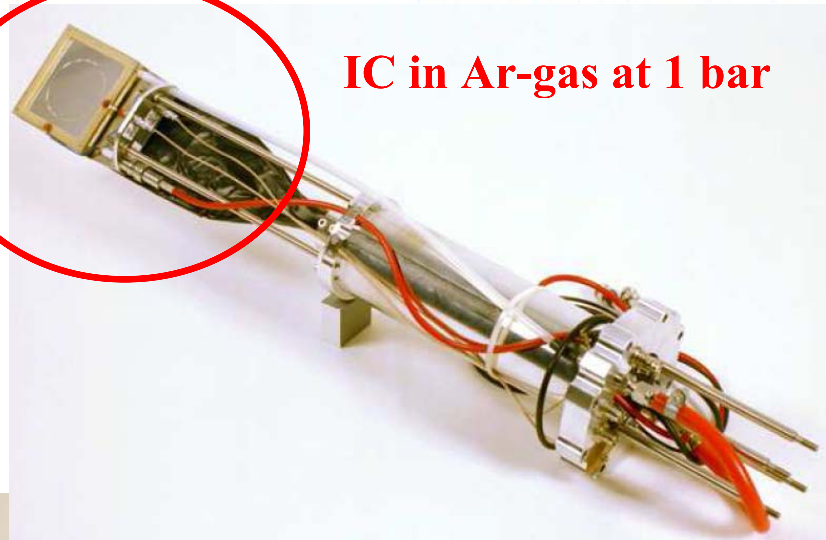
e.g. decrease of yield *Y* due to radiation

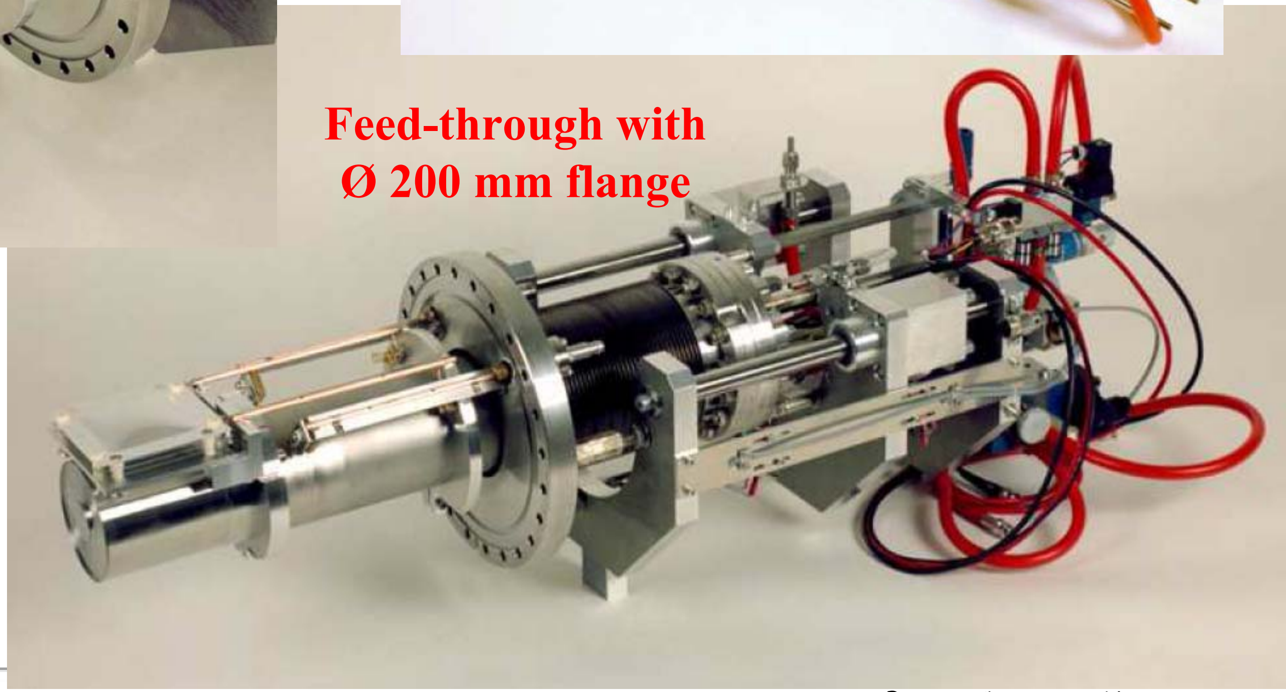
⇒ For a permanent insertion Ti.

Sometimes they are installed permanently in front of an experiment.

# Example: GSI Installation for SEM and iC

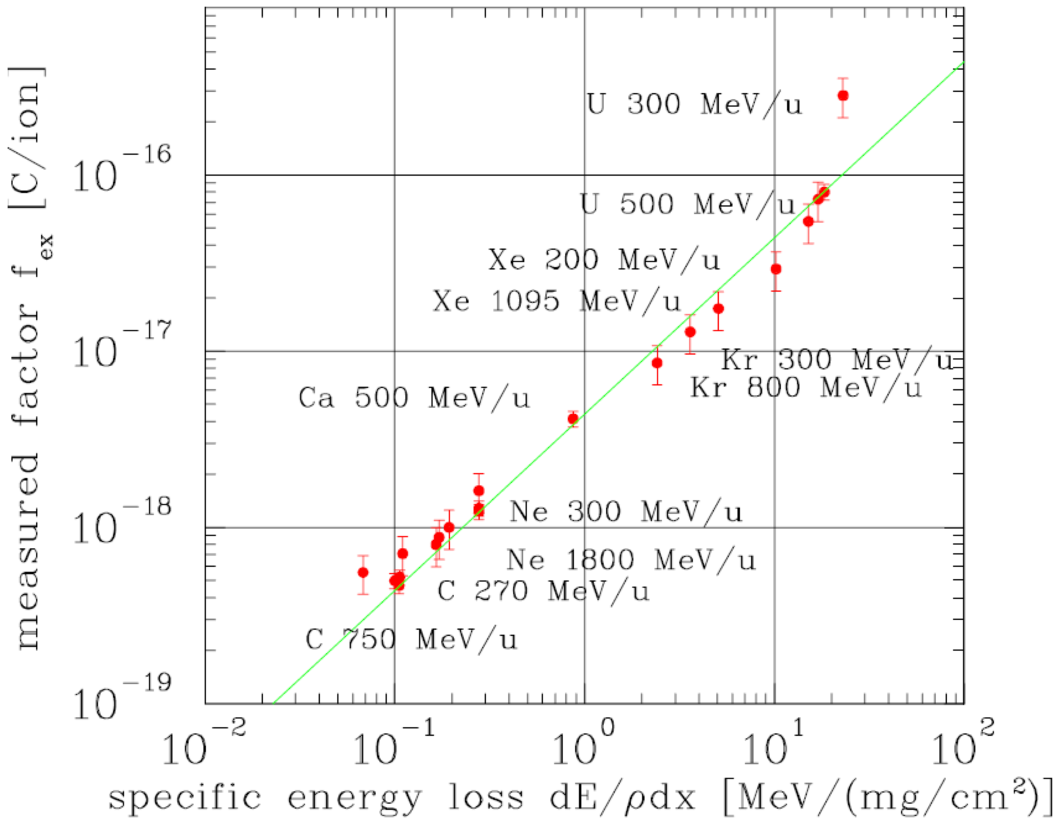


SEM must be calibrated to achieve 10 % accuracy → comparison to an IC

*Example: GSI installation for various ion beams*




Result: Secondary electron yield: $Y = e^{-}/(\rho \cdot dE/dx) = 27 e^{-}/(\text{MeV/mg/cm}^2)$.

**Current is the basic quantity for accelerators!**

***Transformer:*** **→ measurement of the beam's magnetic field**

- magnetic field is guided by a high μ toroid
- types: passive (large bandwidth), active (low droop) and dc (two toroids + modulation)
- lower threshold by magnetic noise: about $I_{beam}$ > 1 μA
- non-destructive, used for all beams

***Faraday cup:*** **→ measurement of beam's charge**

- low threshold by I/U-converter: $I_{beam}$ > 10 pA
- totally destructive, used for low energy beams

***Scintillator, IC, SEM:*** **→ measurement of the particle's energy loss**

- particle counting (Scintillator)
- secondary current: IC→gas or SEM→surface
- no lower threshold due to single particle counting
- partly destructive, used for high energy beams