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.

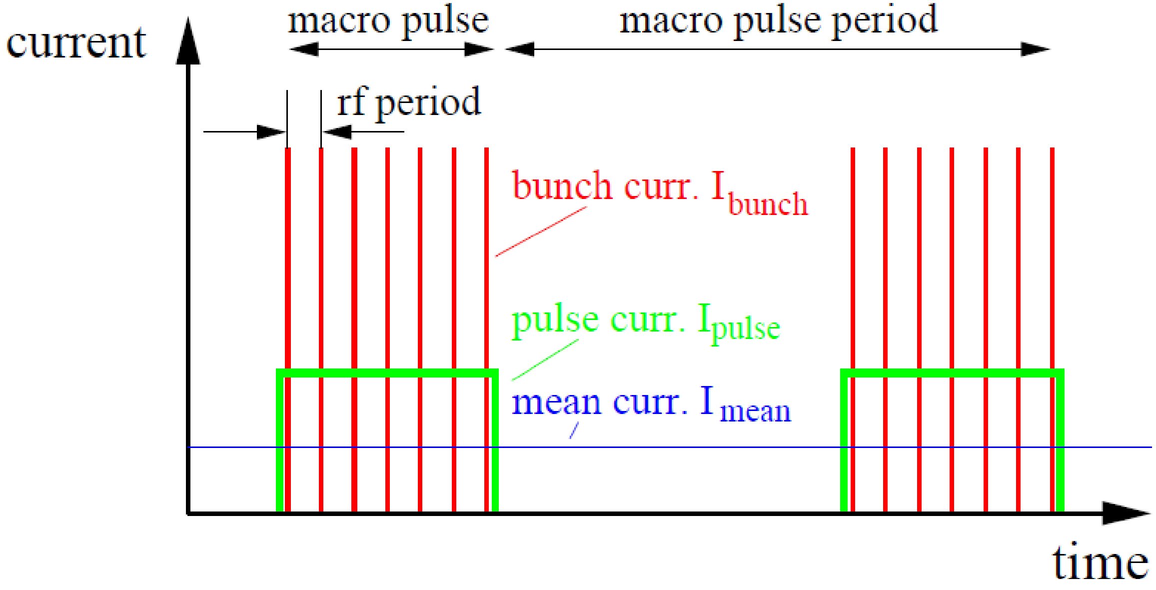
- **Particle detectors:** Measurement of the particle's **energy loss** in matter

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

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

Beam Structure of a pulsed LINAC

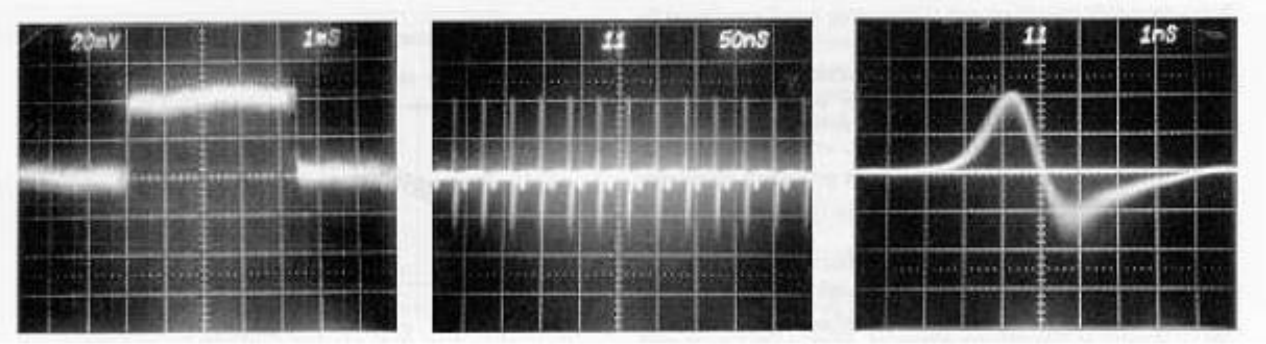
Pulsed LINACs and cyclotrons used for injection to synchrotrons with $t_{pulse} \approx 100$ µs:



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:

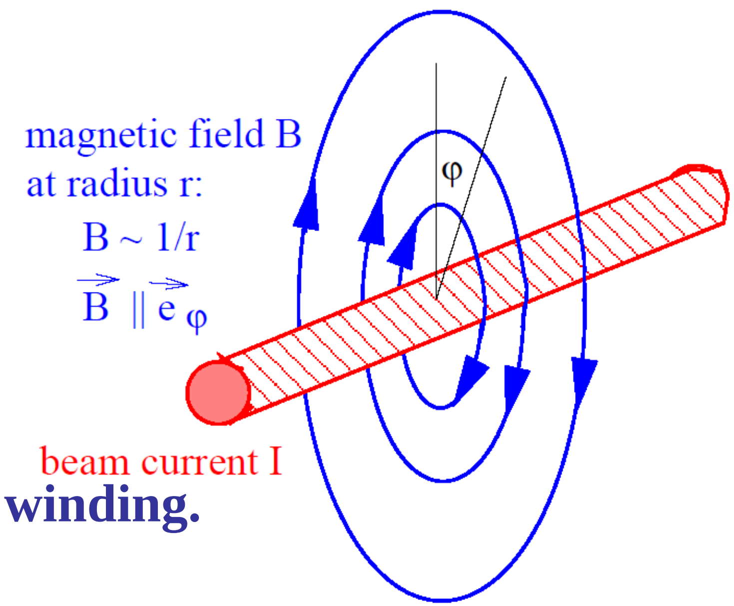
- Beam current of N charges with velocity β

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

- 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, earth B = 50 μT

Idea: Beam as primary winding and sense by sec. winding.

⇒ Loaded current transformer

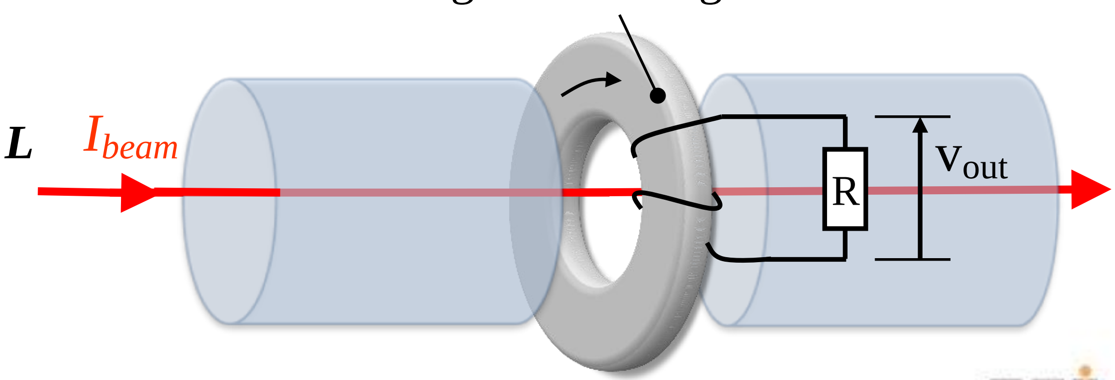
$$\boldsymbol{I_1/I_2 = N_2/N_1 \Rightarrow I_{sec} = 1/N \cdot I_{beam}}$$

- Inductance of a torus of μ_r

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

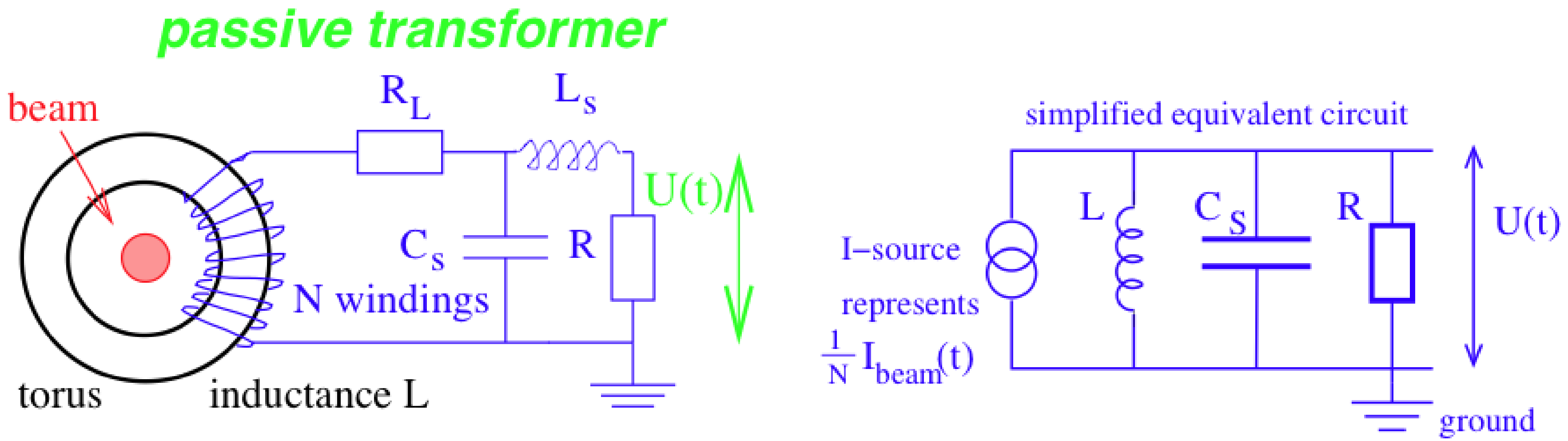
- Goal of Torus: Large inductance ***L*** ***and*** guiding of field lines.

Torus to guide the magnetic field



Definition: ***U = L · dI/dt***

Simplified electrical circuit of a passively loaded transformer:



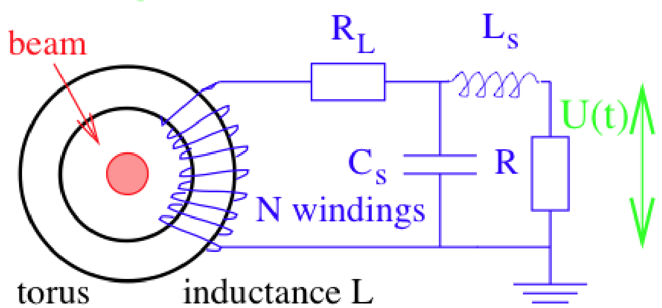
A voltages is measured: $\boldsymbol{U = R \cdot I_{sec} = R/N \cdot I_{beam} \equiv S \cdot I_{beam}}$

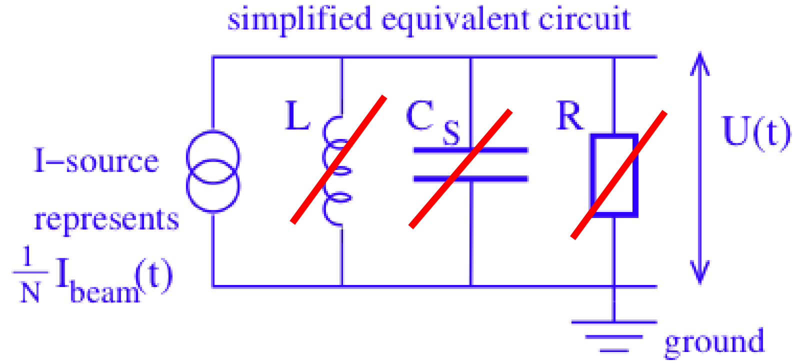
with ***S* sensitivity [V/A],** equivalent to transfer function or transfer impedance ***Z***

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:

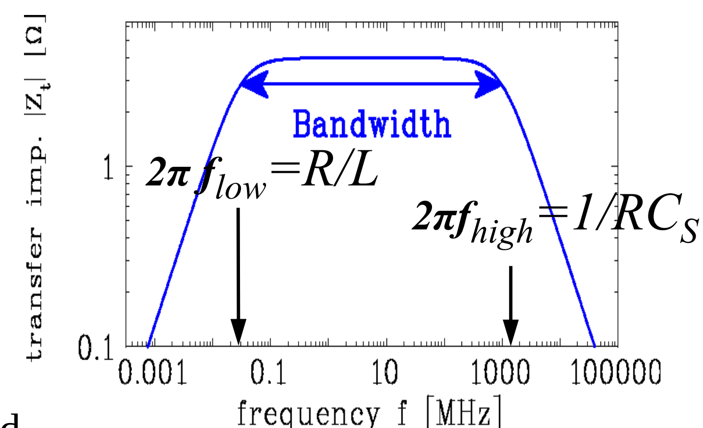
$$\frac{1}{Z} = \frac{1}{i\omega L} + \frac{1}{R} + i\omega C_S \Leftrightarrow Z = \frac{i\omega L}{1 + i\omega L / R + \omega L / R \cdot \omega R C_S}$$

- ***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*** $R/L < \omega < 1/RC_S$: $Z \simeq R$

  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: $\tau_{droop} = 1/(2\pi f_{low}) = L/R$

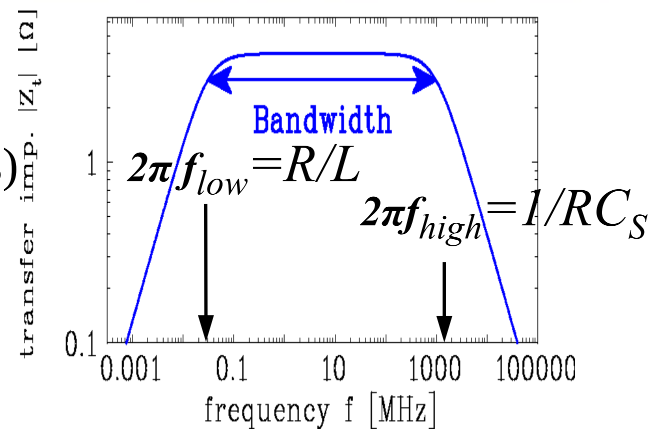
Rise time: $\tau_{rise} = 1/(2\pi f_{high}) = 1/RC_S$ (ideal without cables)

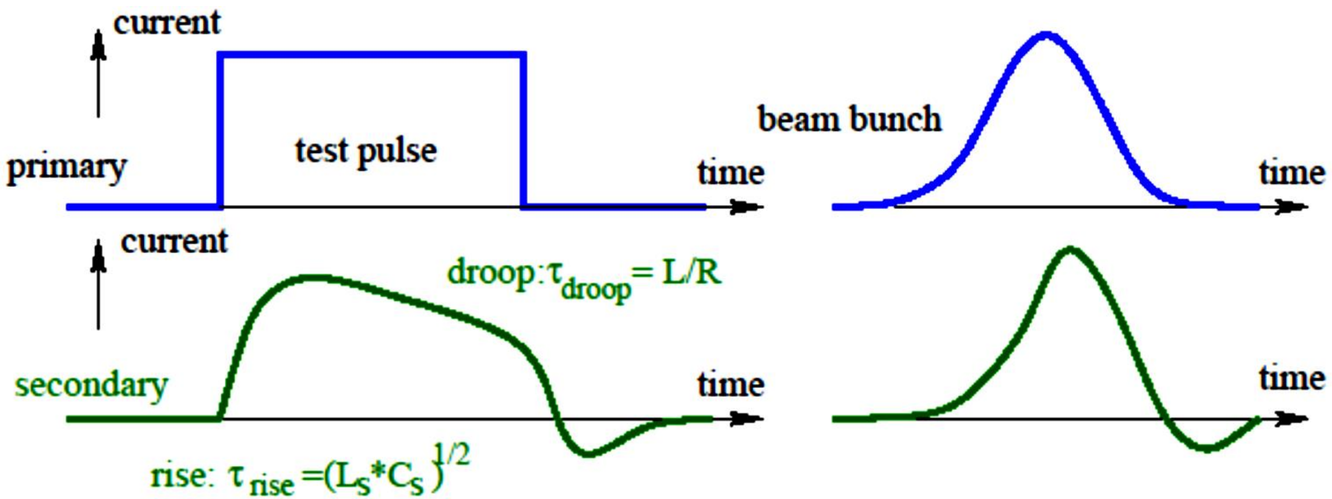
Rise time: $\tau_{rise} = 1/(2\pi f_{high}) = \sqrt{L_S C_s}$ (with cables)

R_L: loss resistivity, R: for measuring.

For the working region the voltage output is

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





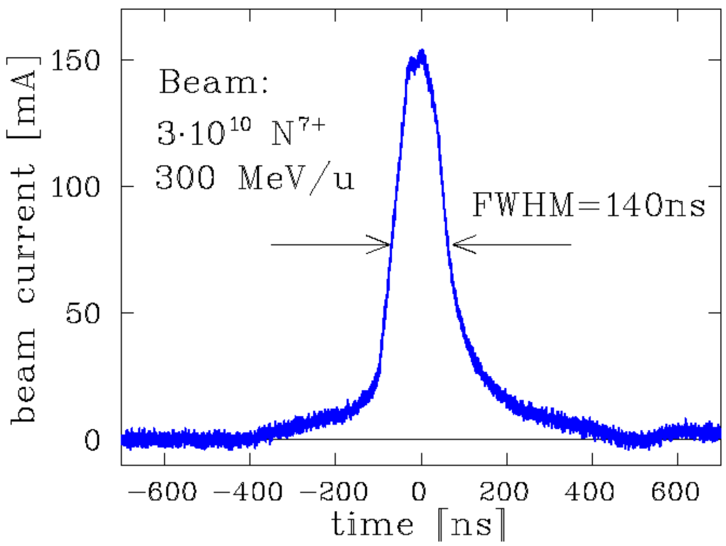
Example for passive Transformer

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:

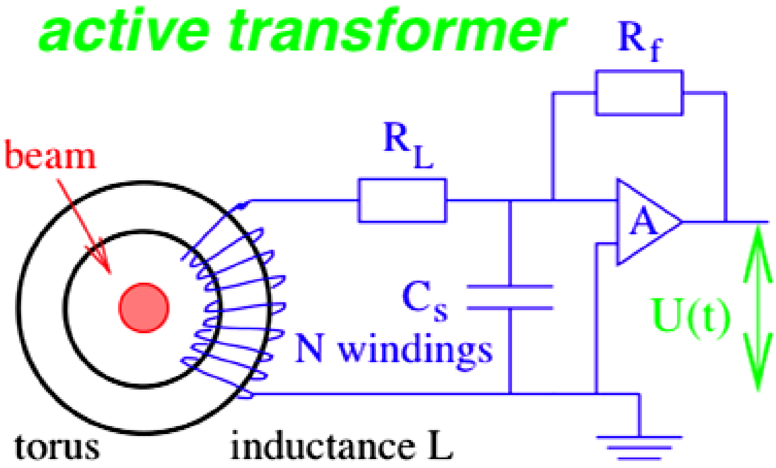
Inner radius	$r_i = 70$ mm
Outer radius	$r_o = 90$ mm
Torus thickness	$l = 16$ mm
Torus material	Vitrovac 6025: $(CoFe)_{70\%}(MoSiB)_{30\%}$
Permeability	$\mu_r \simeq 10^5$ for $f < 100$ kHz, $\mu_r \propto 1/f$ above
Windings	10
Sensitivity	4 V/A at $R = 50\ \Omega$, 10^4 V/A with ampl.
Resolution	40 μA_{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 $R \approx 0\ \Omega$ load impedance i.e. a current sink
+ compensation feedback
$\Rightarrow$ longer droop time τ_{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!

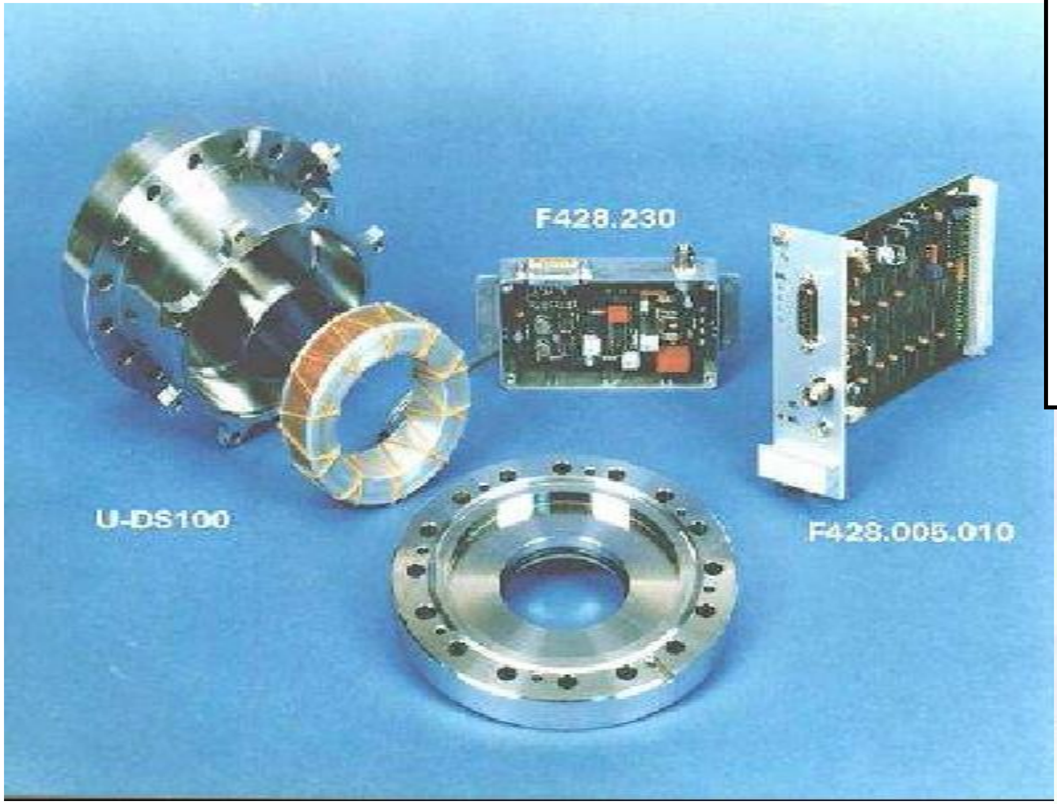
The feedback resistor is also used for range switching.

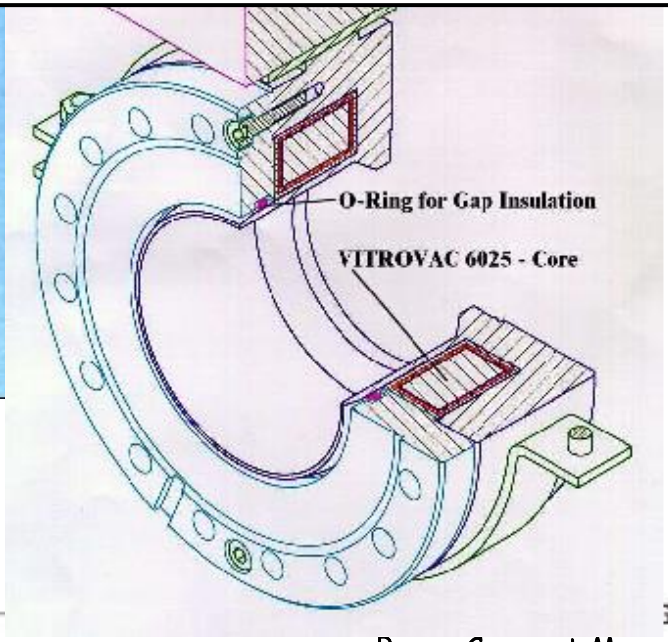
An additional active feedback loop is used to compensate the droop.

'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

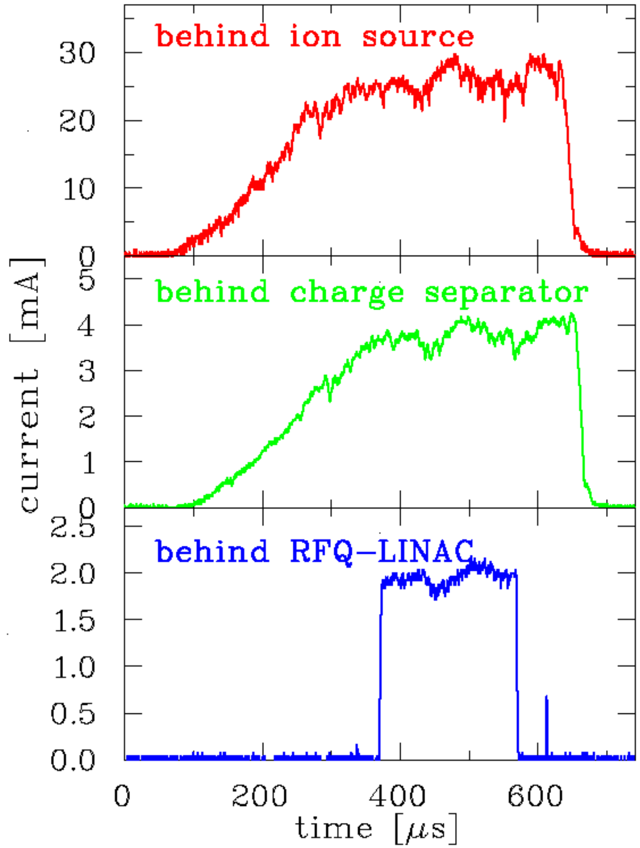




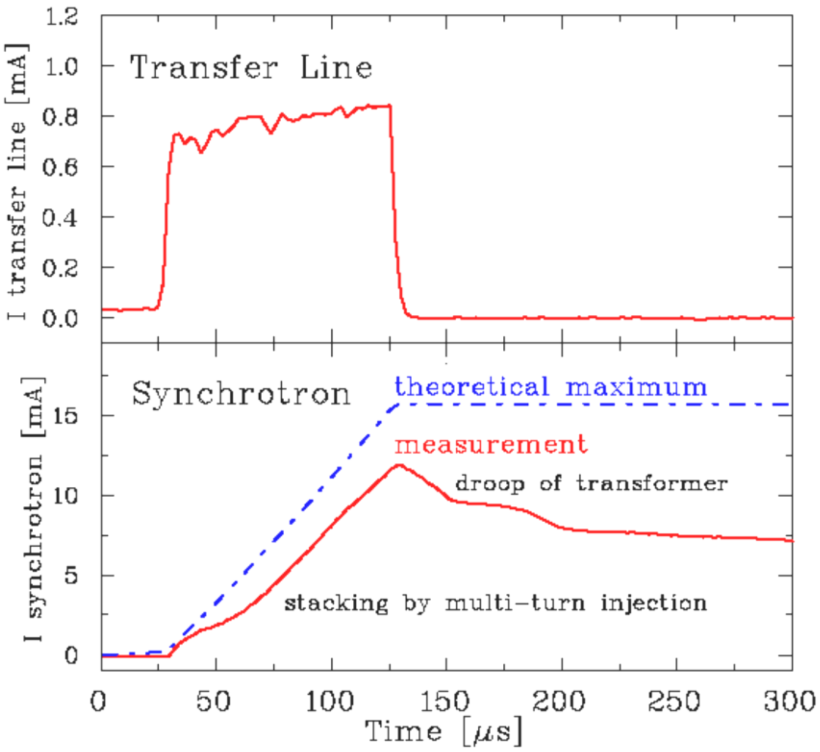
'Active' Transformer Measurement

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

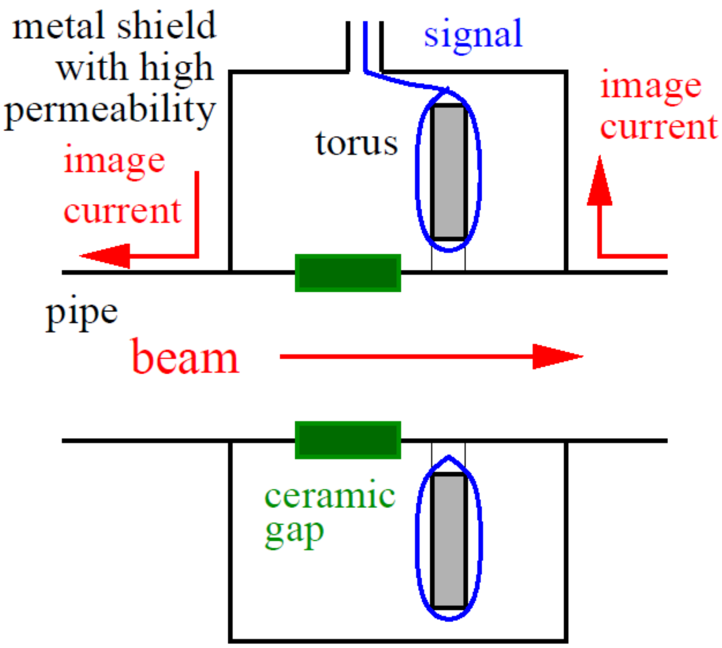


***Example*:** Multi-turn injection of a Ni^{26+} beam into GSI Synchrotron, 5 µs per turn



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:

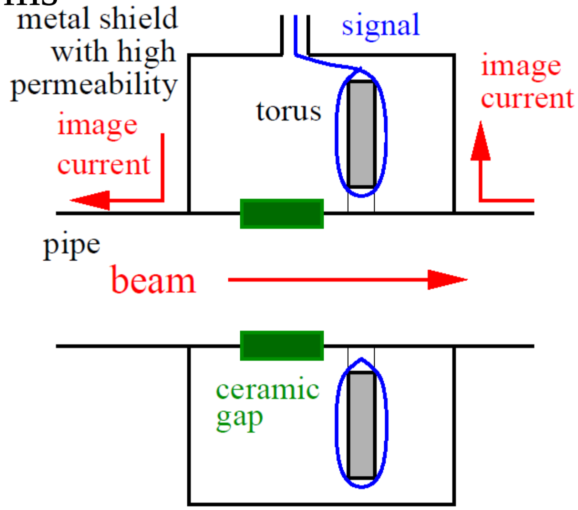
- **Passive transformer:** $R = 50\ \Omega$, $\tau_{rise} \approx 1$ ns for short pulses

  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:

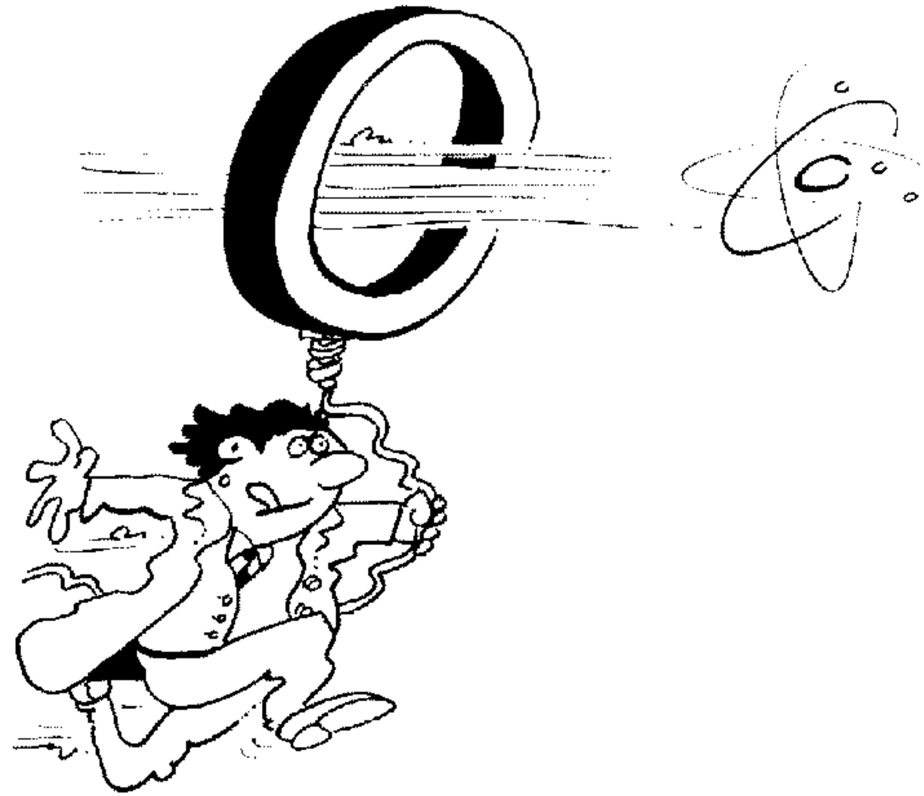
- The beam pipe has to be intersected to prevent the flow of the image current through the torus
- The torus is made of 25 µm isolated flat ribbon spiraled to get a torus of ≈15 mm thickness, to have large electrical resistivity
- Additional winding for calibration with current source



The Artist' View of Transformers

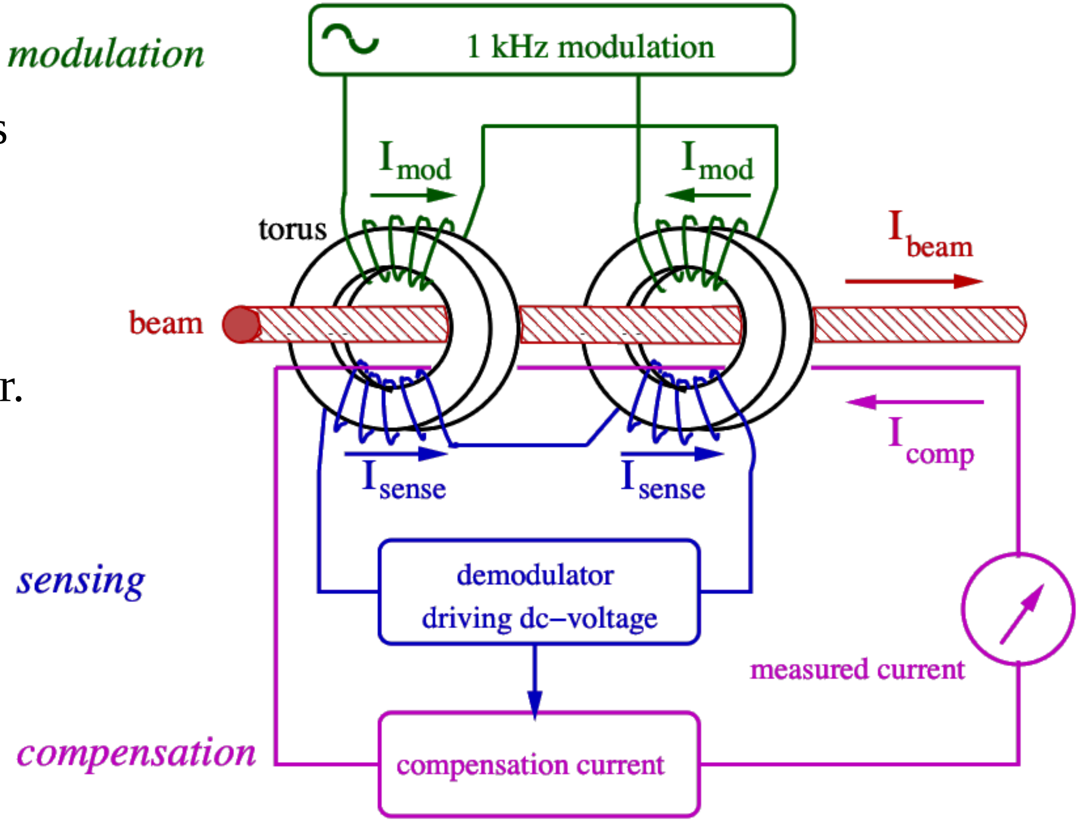
The active transformer ACCT

The passive, fast transformer FCT



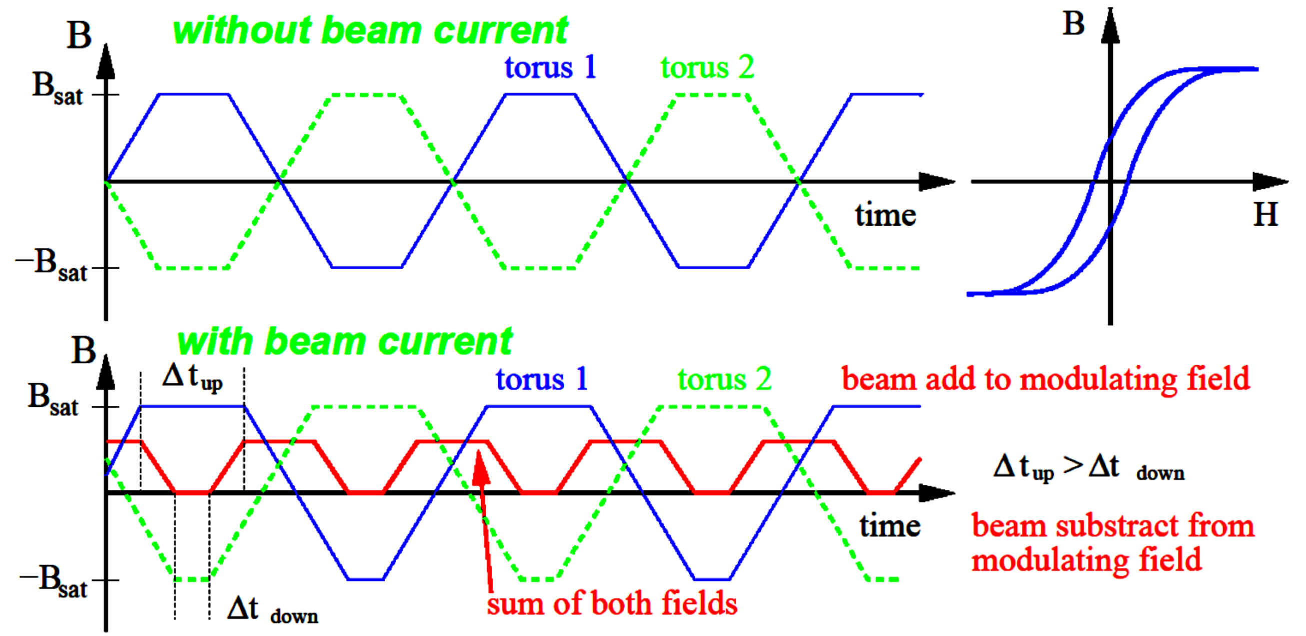
Cartoons by Company Bergoz, Saint Genis

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.

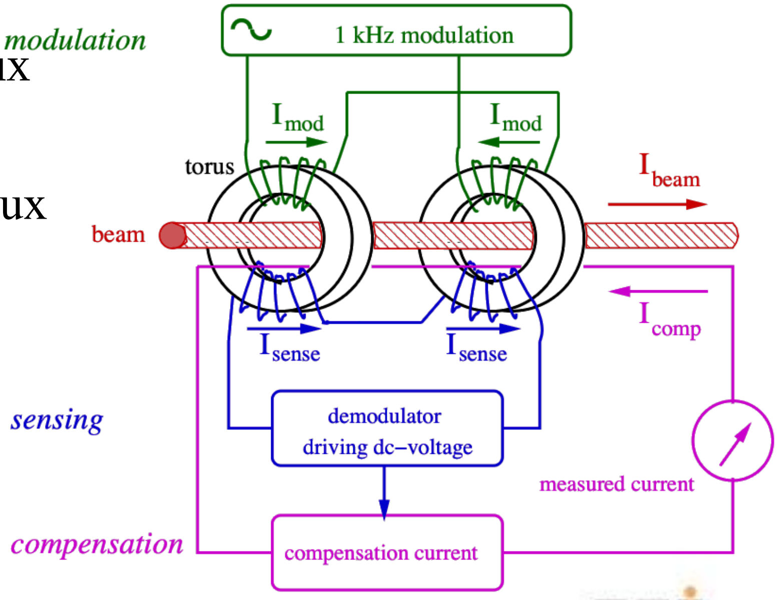


- **Modulation** of the primary windings forces both torii into saturation twice per cycle
- **Sense windings** measure the modulation signal and cancel each other.
- But with the I_{beam}, the saturation is shifted and I_{sense} is not zero
- **Compensation current** adjustable until I_{sense} is zero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



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

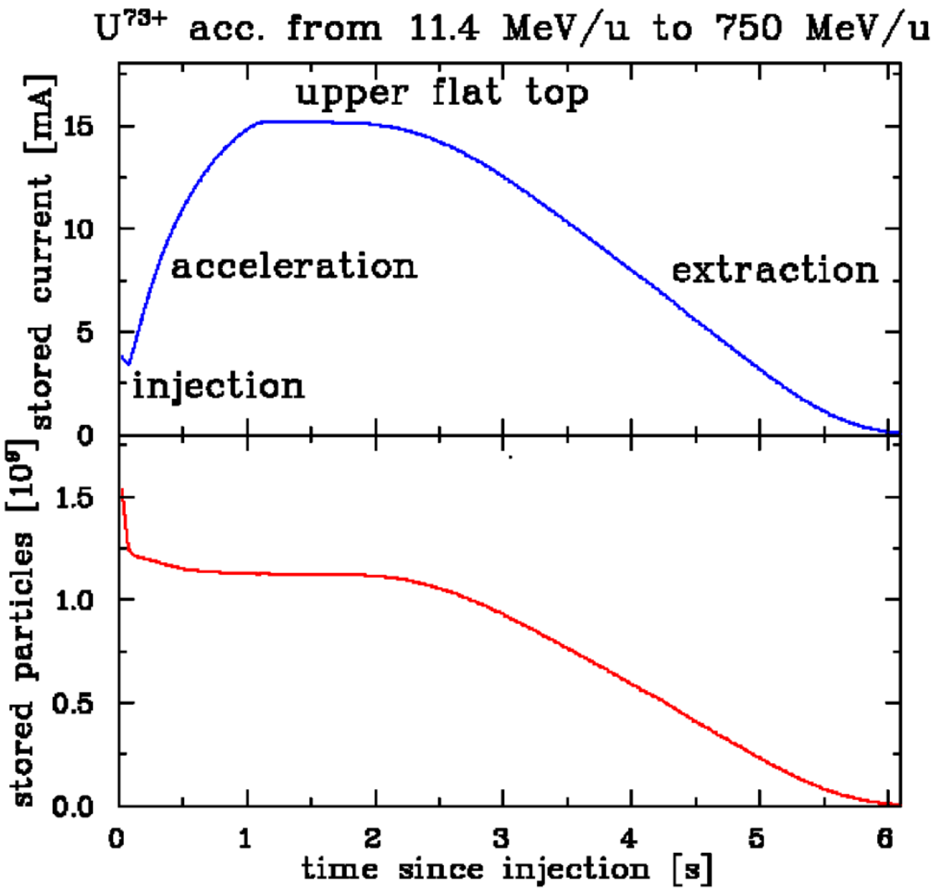
Core radii	$r_i = 135$ mm, $r_o = 145$mm
Core thickness	10 mm
Core material	Vitrovac 6025: $(CoFe)_{70\%}(MoSiB)_{30\%}$
Core permeability	$\mu_r \simeq 10^5$
Saturation B_{sat}	$\simeq 0.6$ T
Isolating cap	Al_2O_3
Number of windings	16 for modulation and sensing
	12 for feedback
Ranges for beam current	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

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

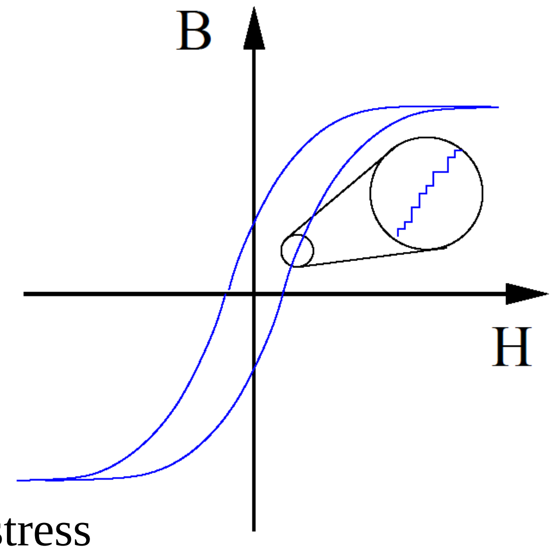
(= resolution)

Bandwidth: dc to 20 kHz

Rise-time: 20 μs

Temperature drift: 1.5 μA/^{0}C

⇒ compensation required.



Careful shielding against external fields with μ-metal.

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

$\Rightarrow$ **The current limits are: $\approx$ 1 µA for DCCT**

$\approx$ 30 µA for FCT with 500 MHz bandwidth

$\approx$ 0.3 µA for ACT with 1 MHz bandwidth.

The Artist' View of Transformers

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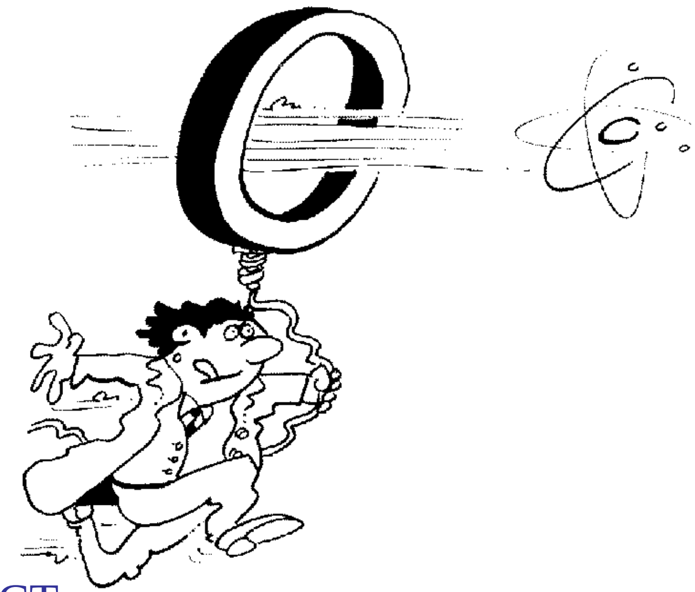
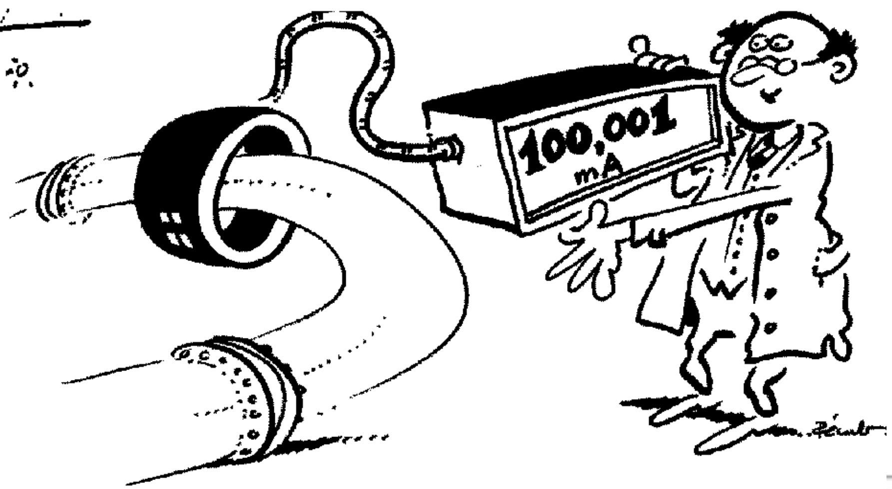
The passive, fast transformer FCT



The dc transformer DCCT



Company Bergoz

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  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 from a synchrotron.

Energy Loss of Ions in Copper

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

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

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

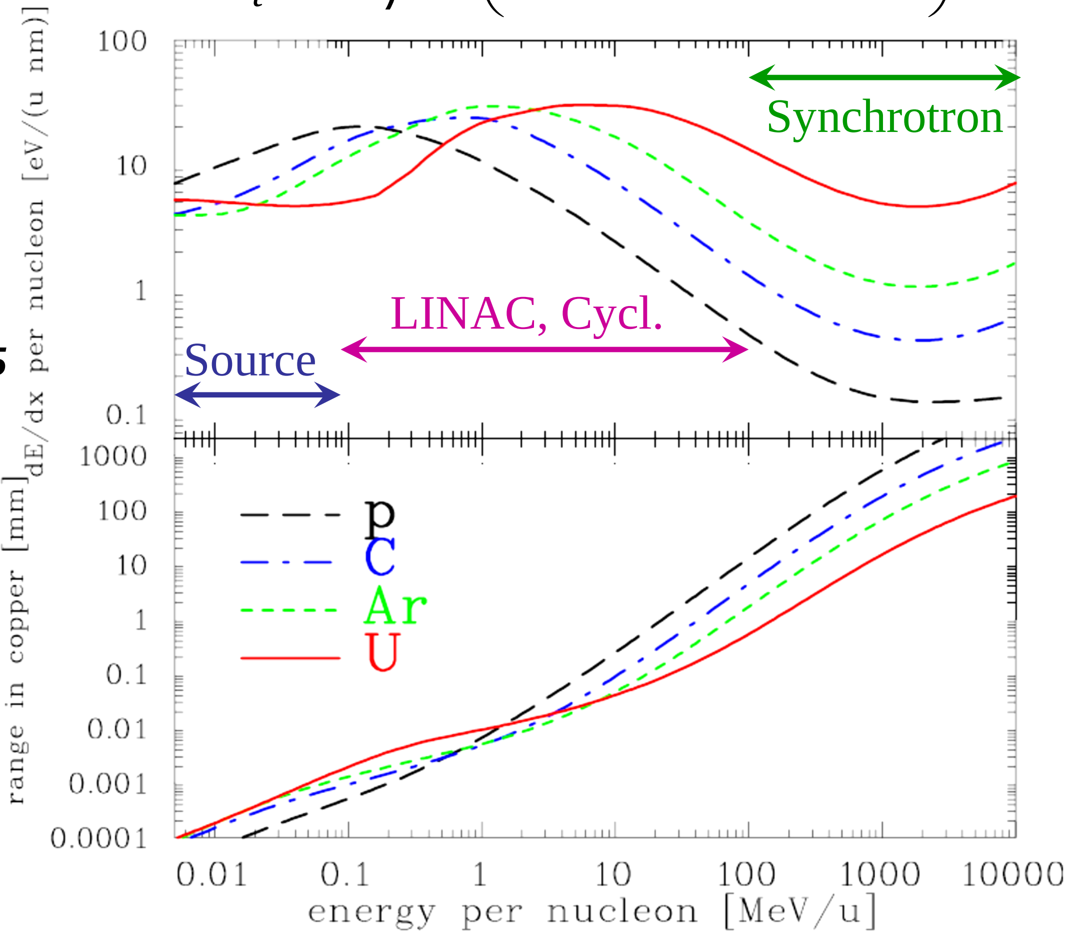
Numerical calculation

with semi-empirical model e.g. SRIM

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

⇒ Cups only for

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



Energy loss of ions in metals close to a surface:

Distant collisions → slow e^- with $E_{kin} \lesssim$ 10 eV

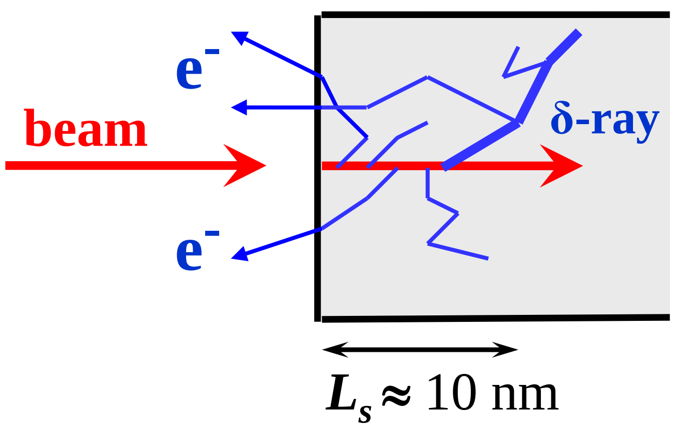
→ 'diffusion' & scattering wit other e^-: scattering length $L_s \approx$ 1 - 10 nm

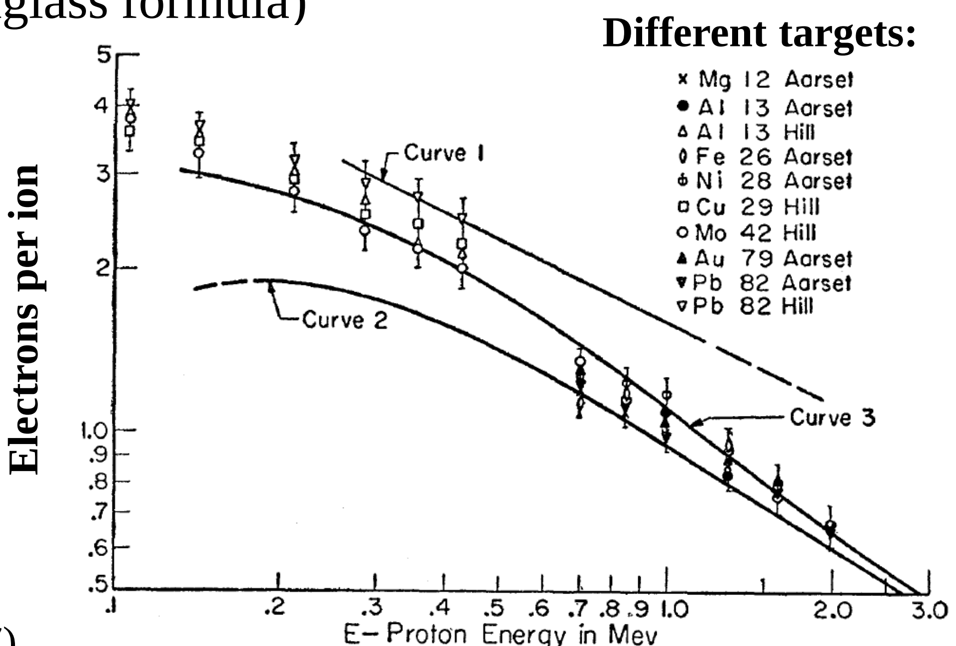
→ at surface ≈ 90 % probability for escape

Closed collision: → slow e^- with E_{kin}>> 100 eV inelastic collision and 'thermalization'

Secondary **electron yield** and energy distribution comparable for all metals!

$\Rightarrow$ $Y = const. * dE/dx$ (Sternglass formula)





From E.J. Sternglass, Phys. Rev. 108, 1 (1957)

Secondary Electron Emission by Ion Impact

Energy loss of ions in metals close to a surface:

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→ 'diffusion' & scattering wit other e$^-$: scattering length $L_s \approx$ 1 - 10 nm

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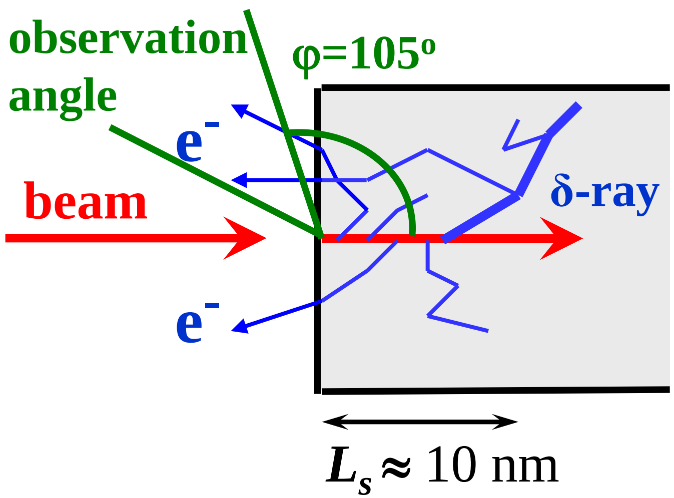
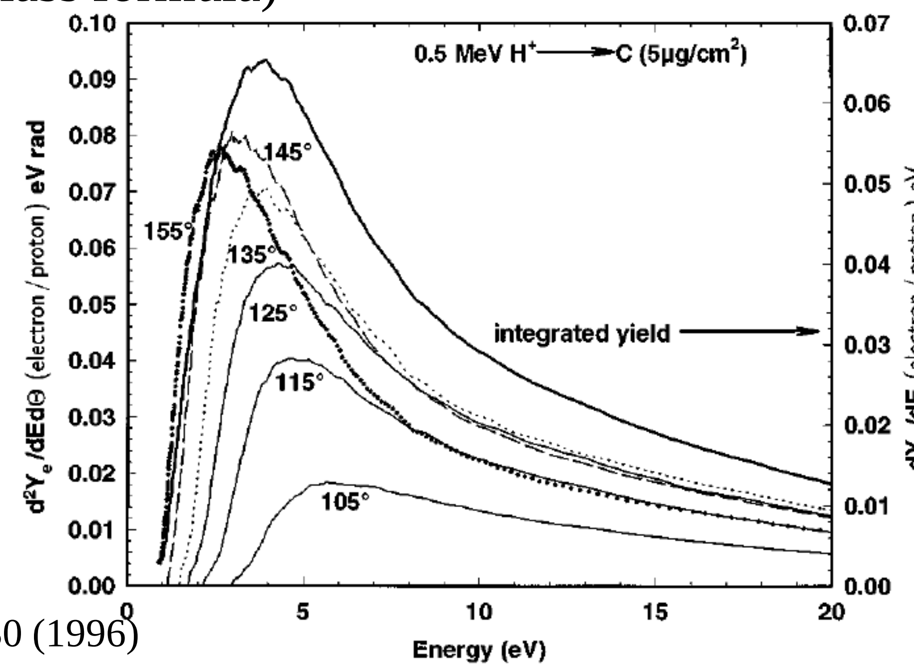
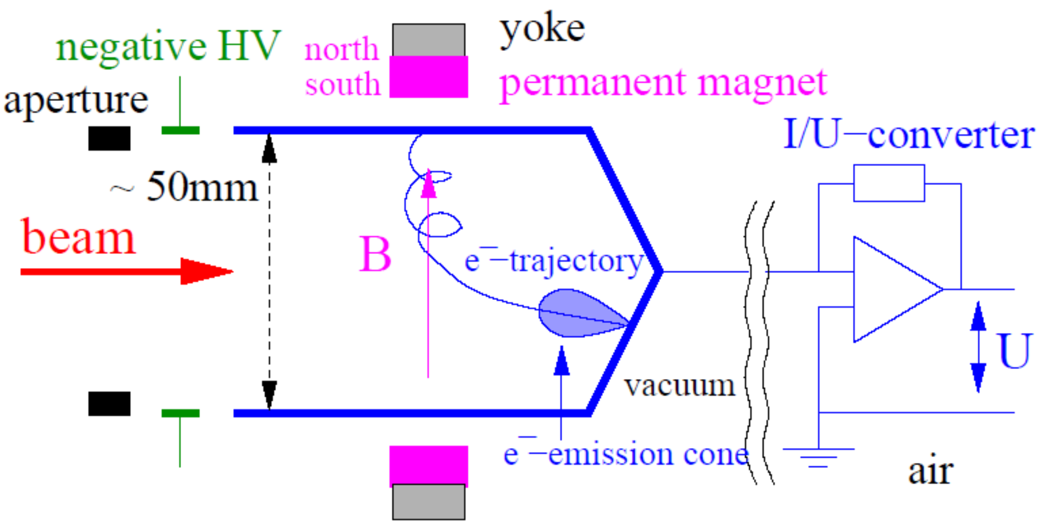




From C.G. Drexler, R.D. DuBois, Phys. Rev. A 53, 1630 (1996)

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!

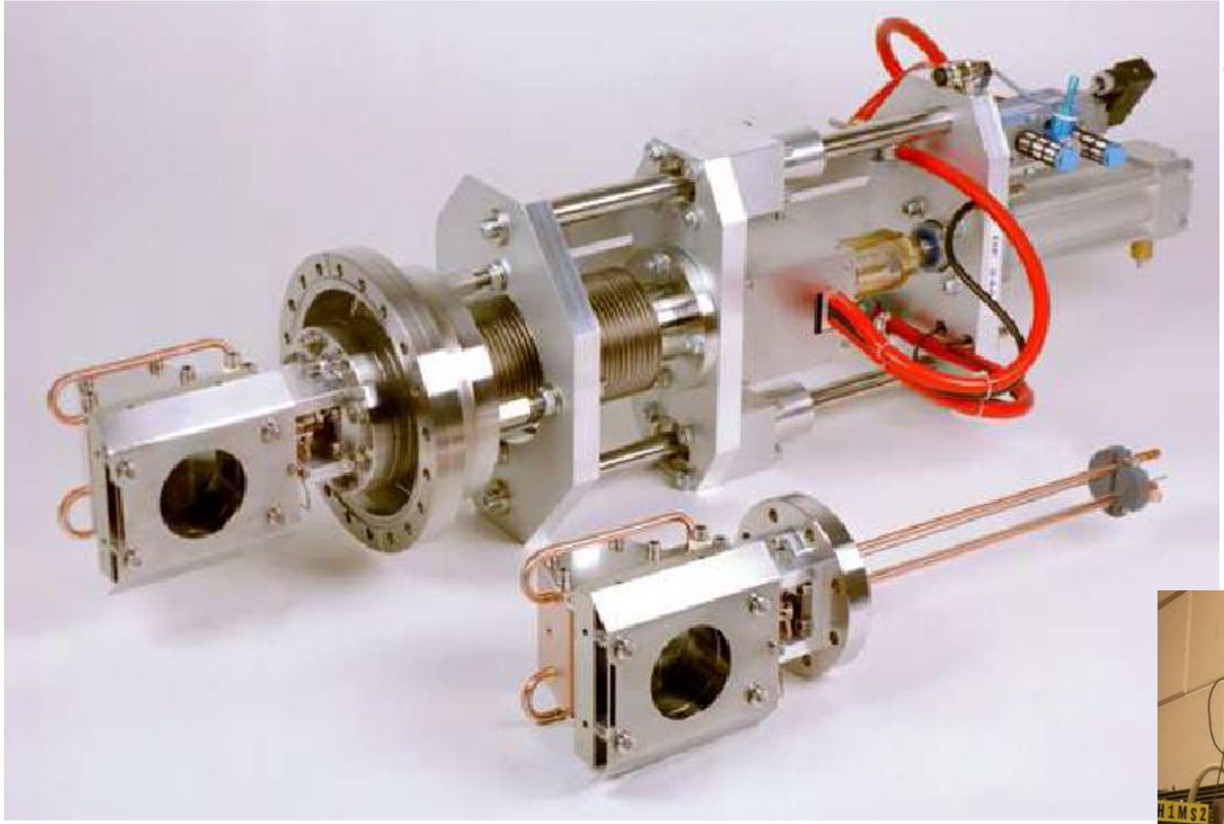
Magnetic field:
To prevent for secondary electrons leaving the cup

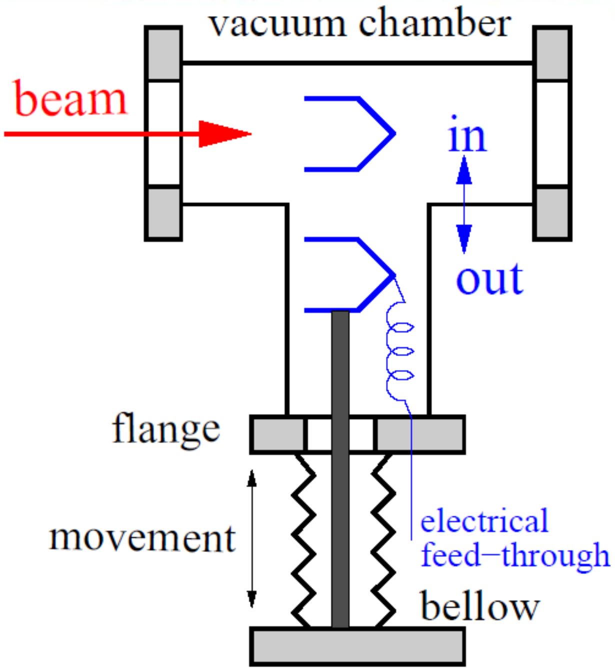
and/or

Electric field:
Potential barrier at the cup entrance.

Realization of a Faraday Cup at GSI LINAC

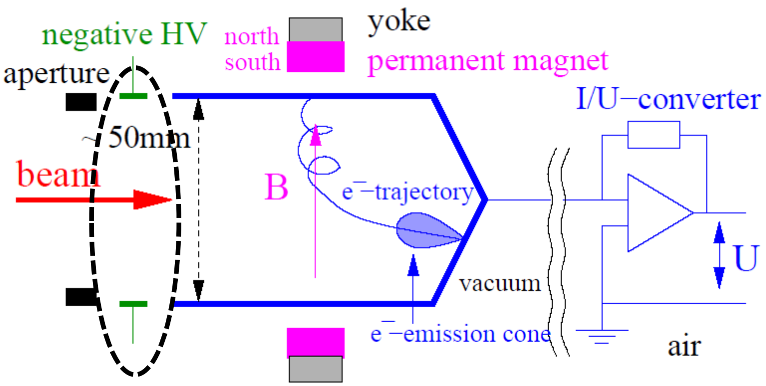
The Cup is moved into the beam pass.

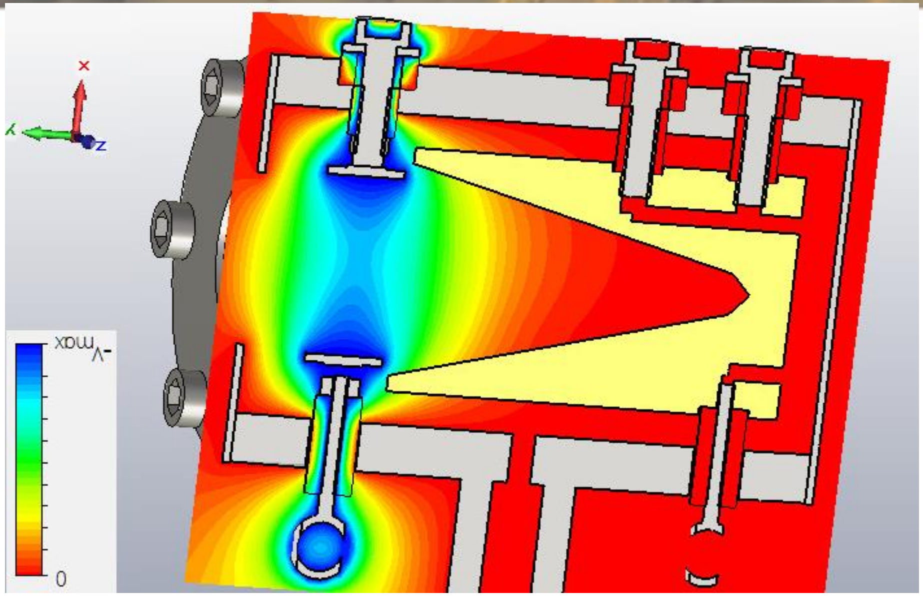


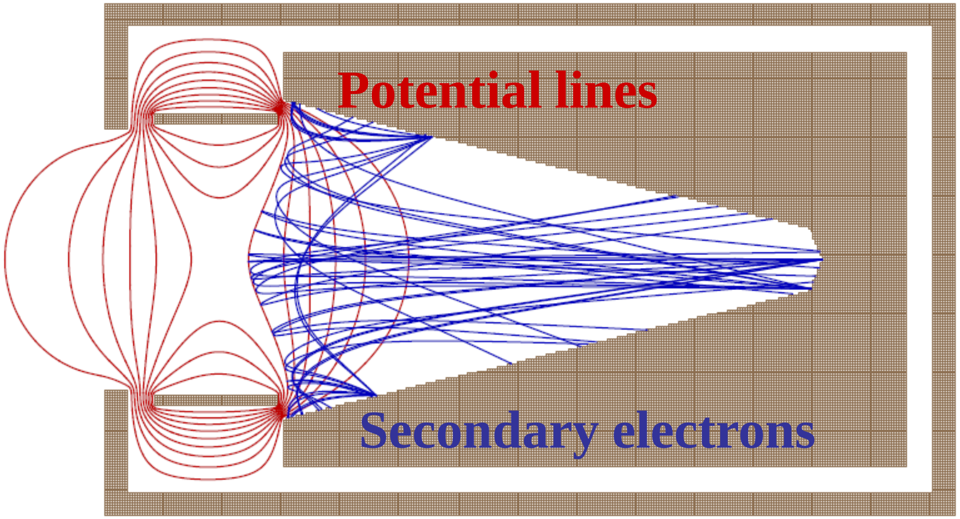


A ring shaped electrode is used at the entrance of Faraday Cup:

Typical voltage 100 to 500 V





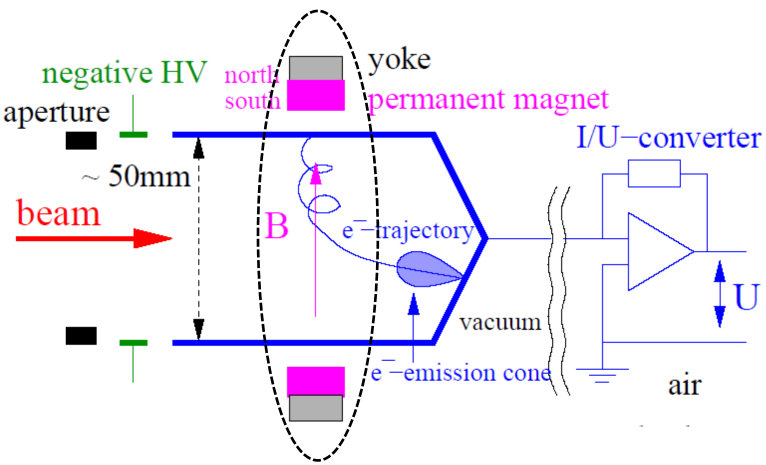


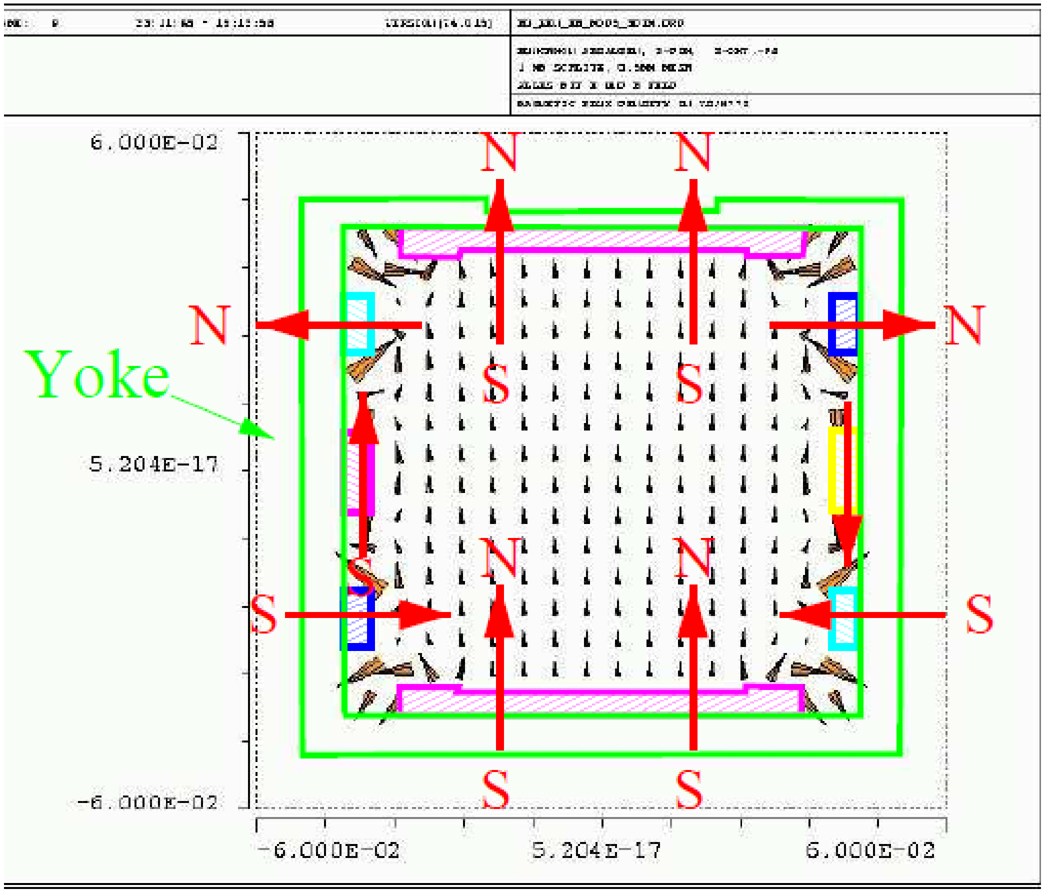
Field calculation and secondary electron trajectories
J. Harasimowicz et al. BIW 2010

Secondary Electron Suppression: Magnetic Field

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

The homogeneous field strength is $\boldsymbol{B} \approx 0.1$ T.





Energy Loss of Ions in Copper

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

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

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

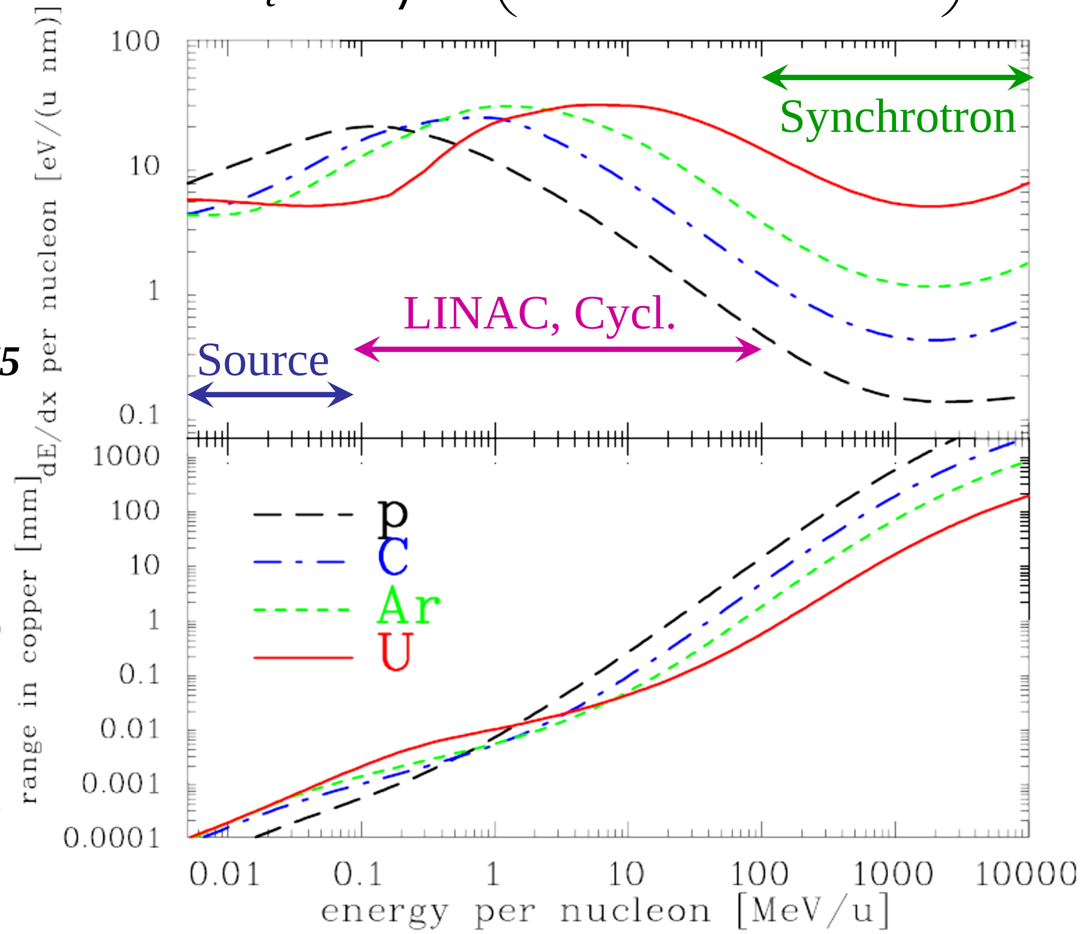
Numerical calculation

with semi-empirical model e.g. SRIM

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

⇒ Cups only for

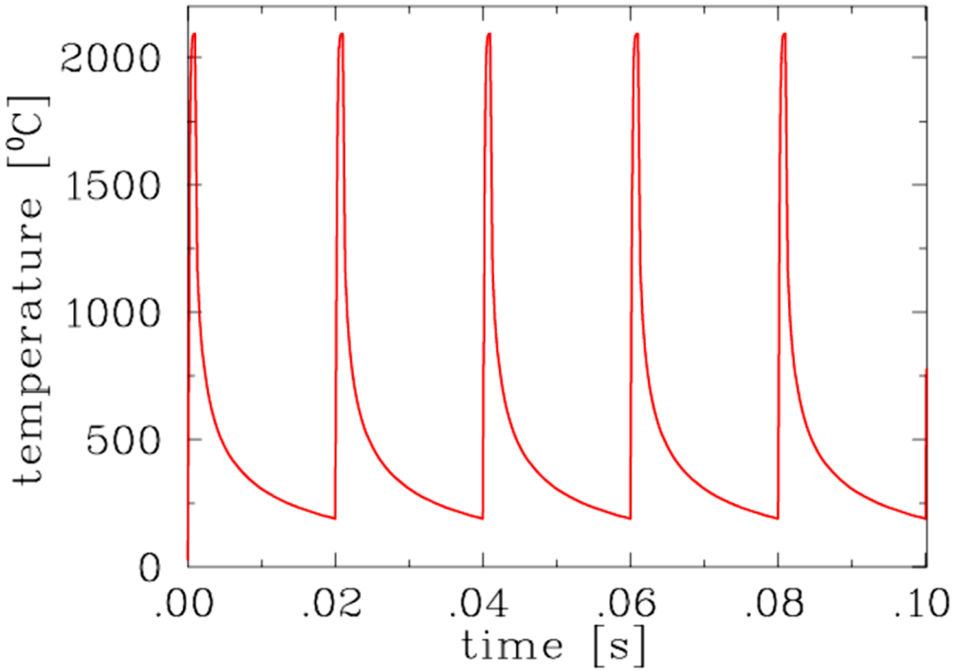
$\boldsymbol{E_{kin}}$ < 100 MeV/u due to $\boldsymbol{R}$ < 10 mm



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 delivery
Beam size: 5 mm FWHM → 23 kW/mm^2 , P_{peak} = 450 kW total power during 1ms delivery
Foil: 1 μm Tantalum, emissivity $\varepsilon = 0.49$
Temperature increase:
T > 2000 ^{0}C during beam delivery

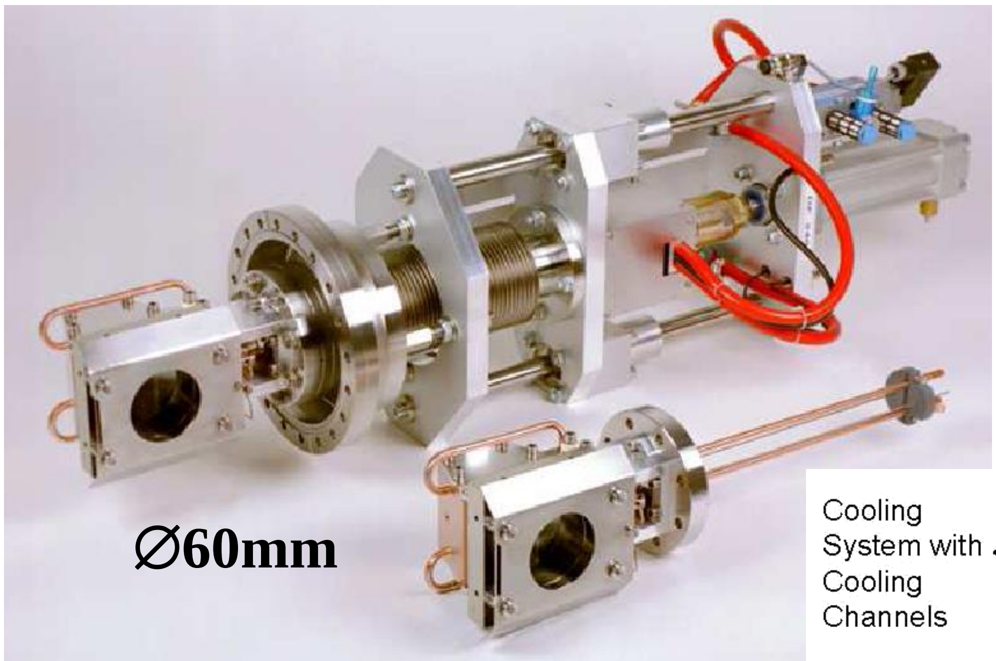


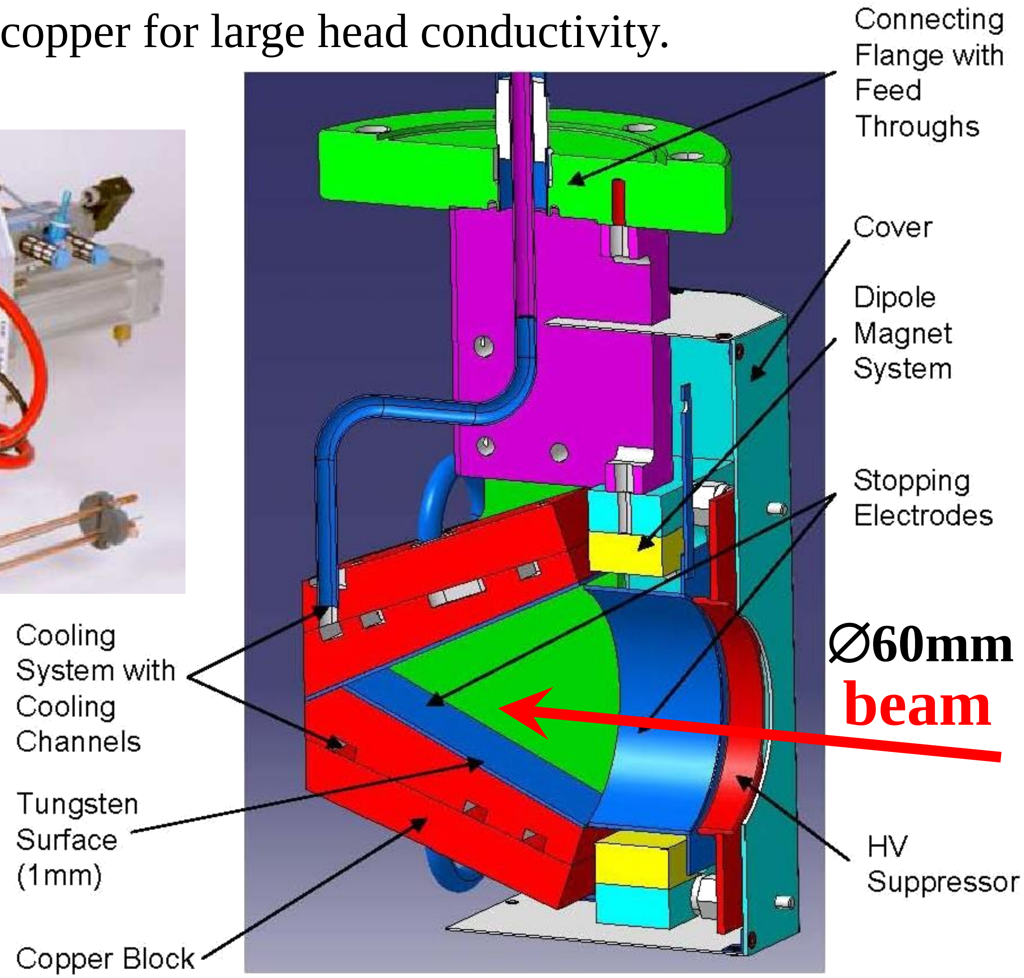
Even for low average power,
the material should
survive the peak power!

High Power Faraday Cups

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.

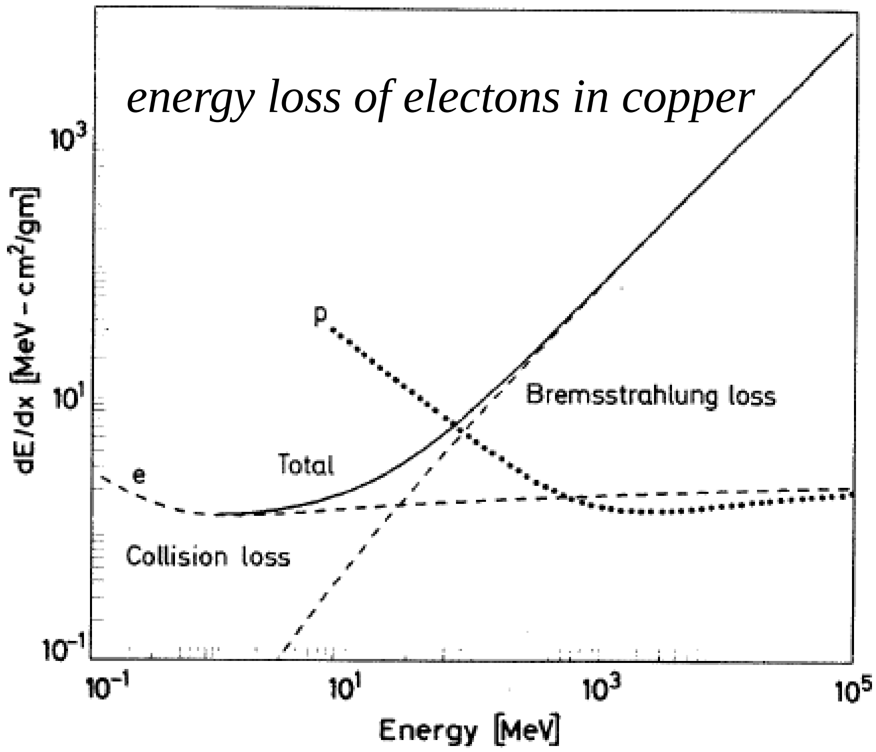


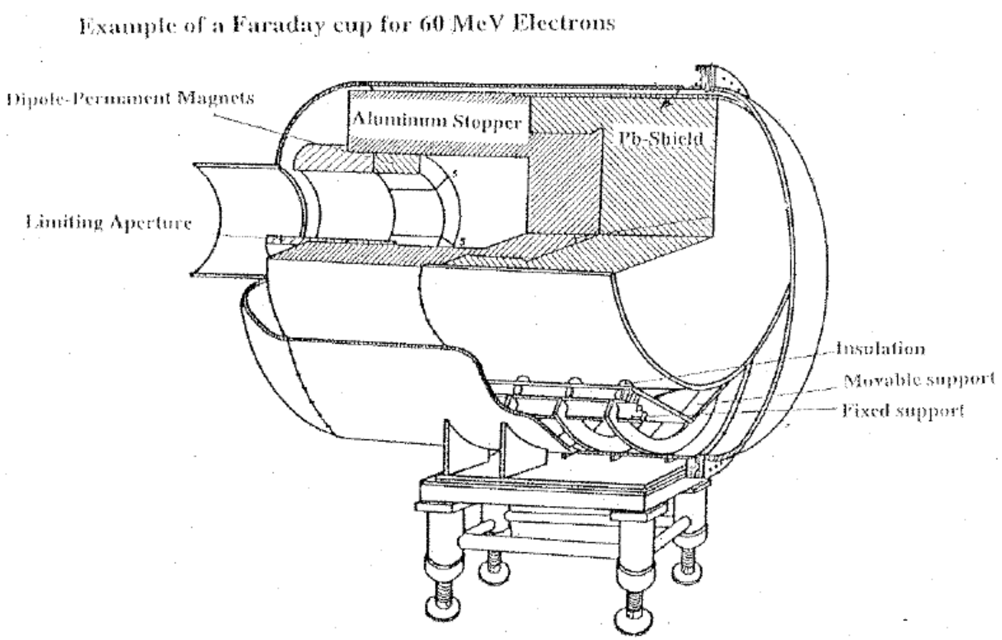


Bethe Bloch formula is valid for all charged particles.

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-γ

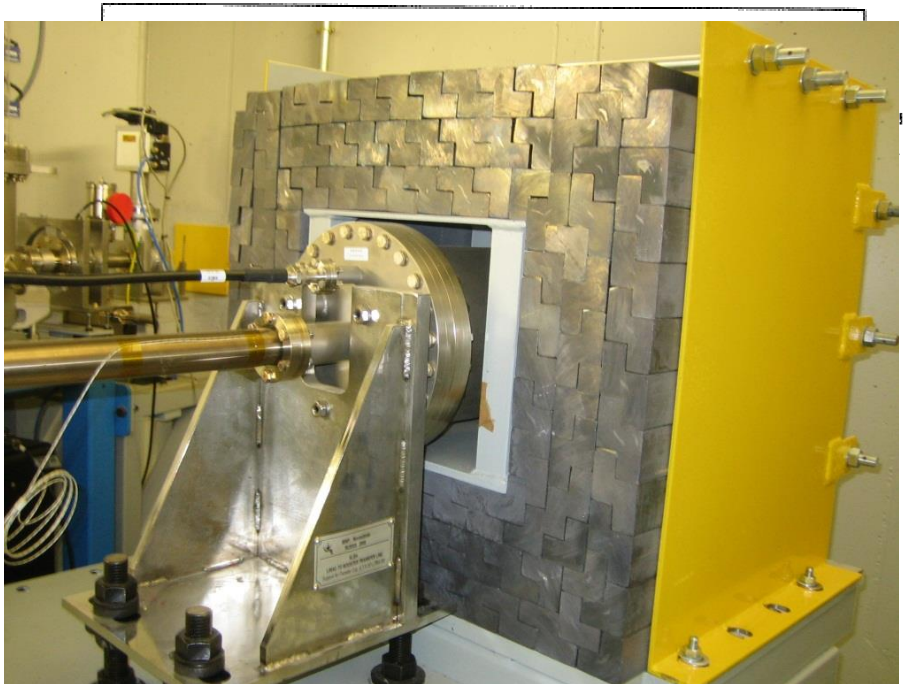
$\Rightarrow$ Used as beam dump

Energy Loss of Electrons in Copper & Faraday Cups of e^-

Bethe Bloch formula is valid for all charged particles.

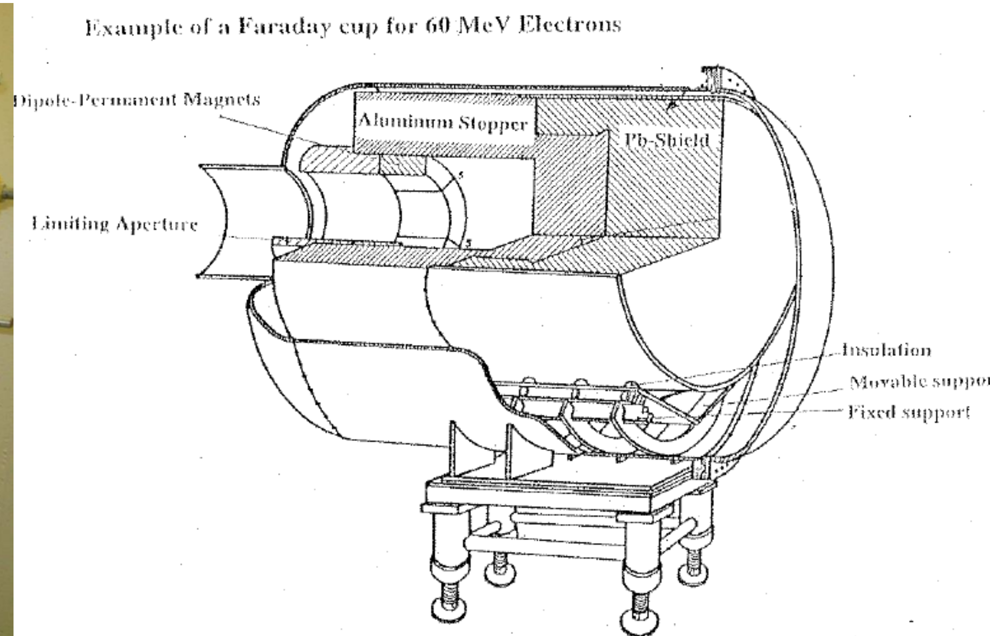
However, Bremsstrahlung dominates for energies above 10 MeV.

e^- shows much larger longitudinal and transverse straggling



Faraday Cup at ALBA used as beam dump

From U. Iriso (ALBA)



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

Pb-shield: Absorption of Bremstrahlungs-γ

$\Rightarrow$ Used as beam dump

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

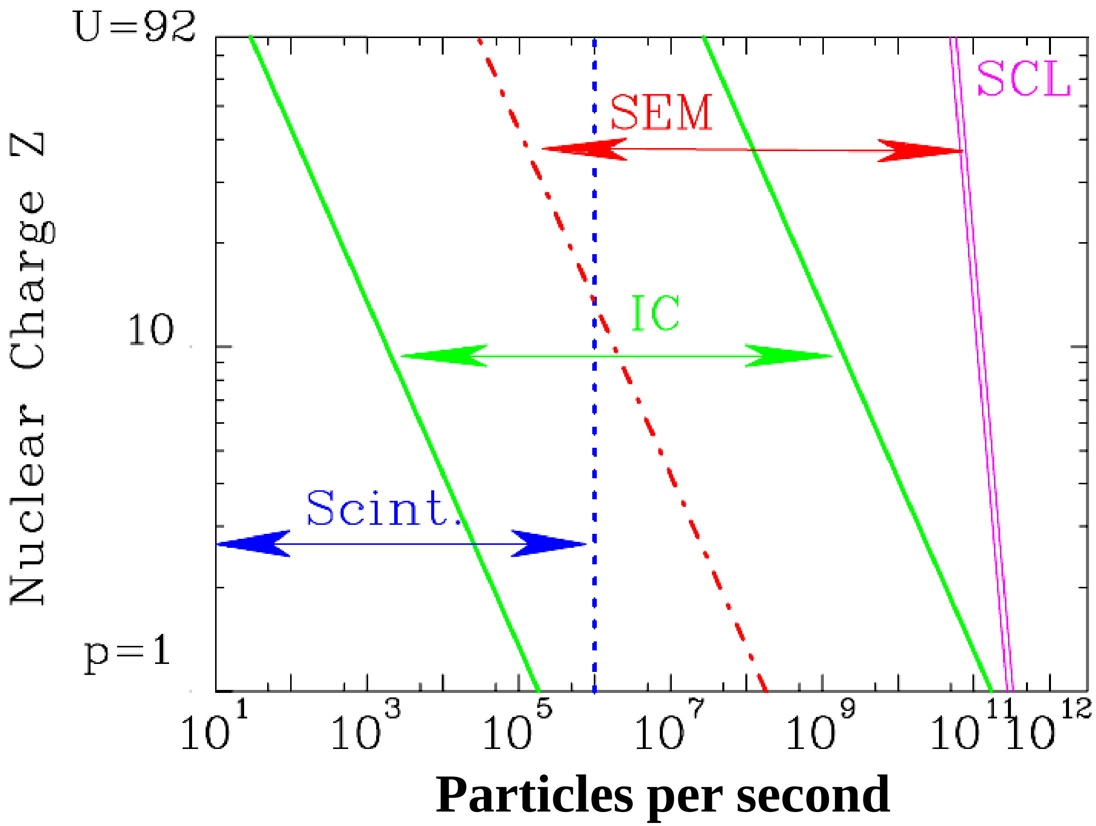
  Examples are scintillators, ionization chambers, secondary e− emission monitors

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

Slow extraction from synchrotron: lower current compared to LINAC,
but higher energies and larger range ***R*** >> 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 cm²:



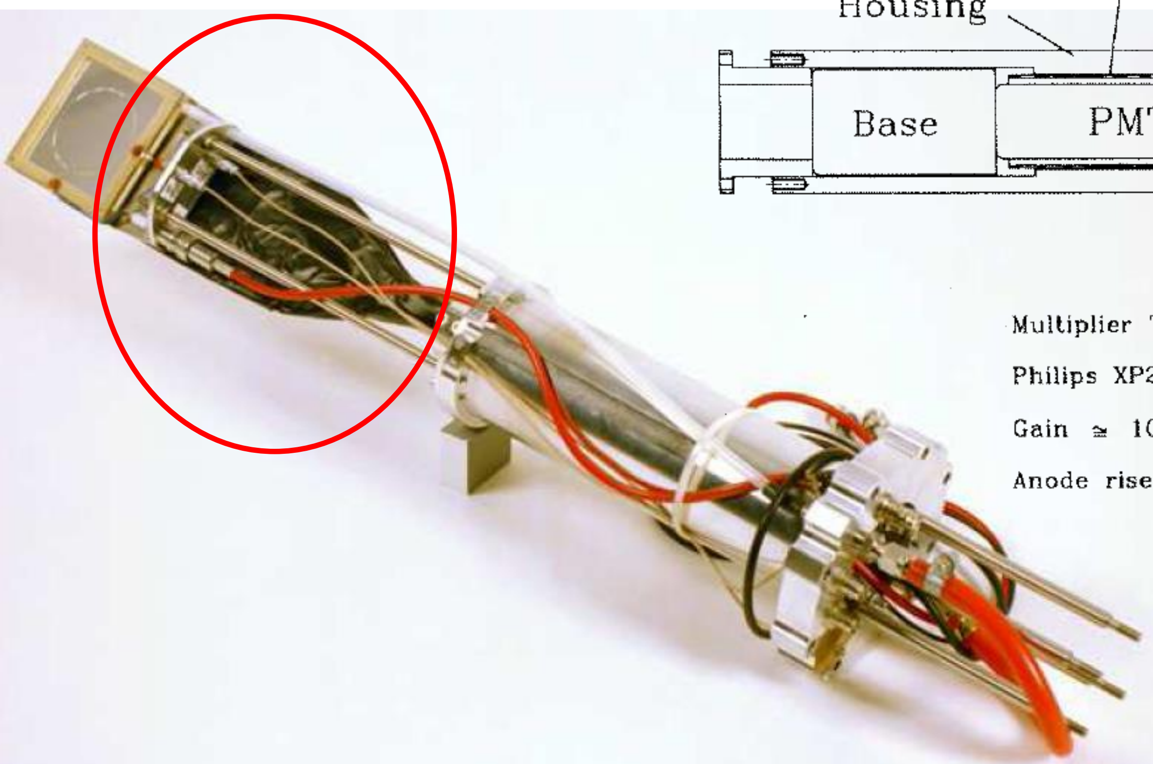
Example of Scintillator Counter

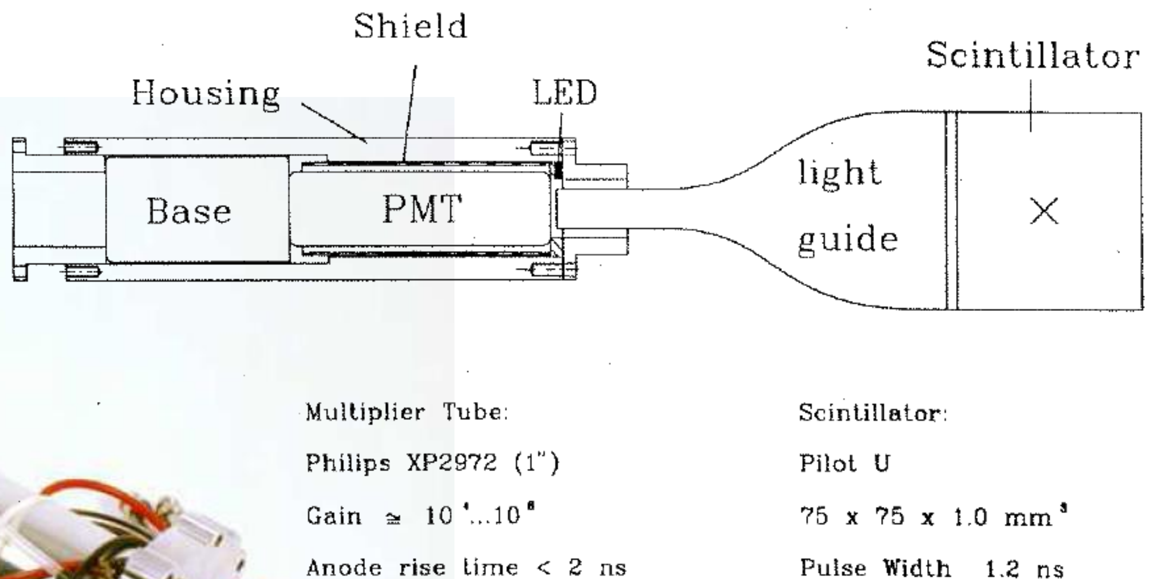
Example: Plastic Scintillator i.e. organic fluorescence molecules in a plastic matrix

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

Disadvantage: not radiation hard

Particle counting: PMT → discriminator → scalar → computer





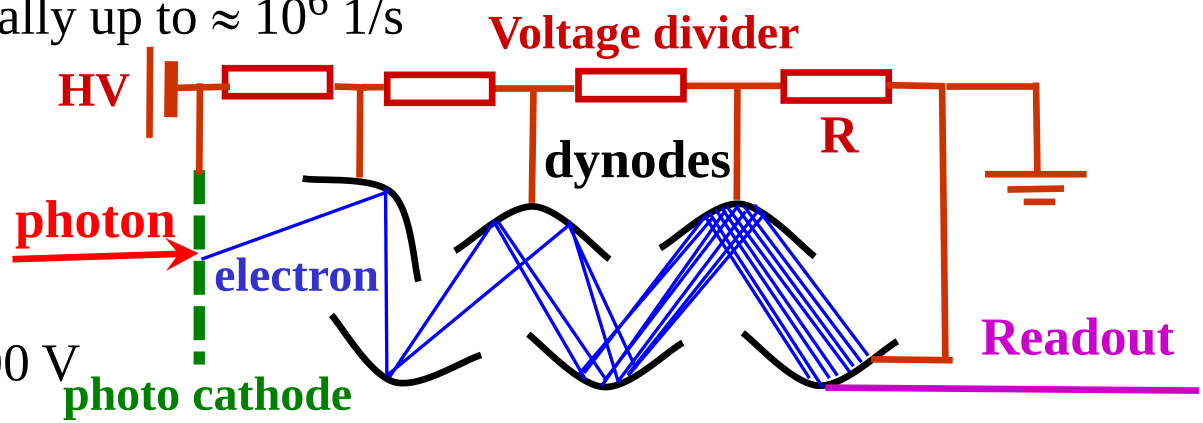
Electronic solid state amplifier have finite noise contribution

Theoretical limit: $U_{eff} = \sqrt{4k_B \cdot R \cdot \Delta f \cdot T}$

Signal-to-Noise ratio limits the minimal detectable current

Idea: Amplification of single particles with photo-multiplier, sec. e^- multiplier or MCPs and particle counting typically up to $\approx 10^6$ 1/s

Scheme of a photo-multiplier:



- Photon hits photo cathode
- Secondary electrons are acc. to next dynode $\Delta U \approx 100$ V
- Typ. 10 dynodes $\Rightarrow 10^6$ fold amplification

Advantage: no thermal noise due to electro static acceleration

Typical 1 V signal output

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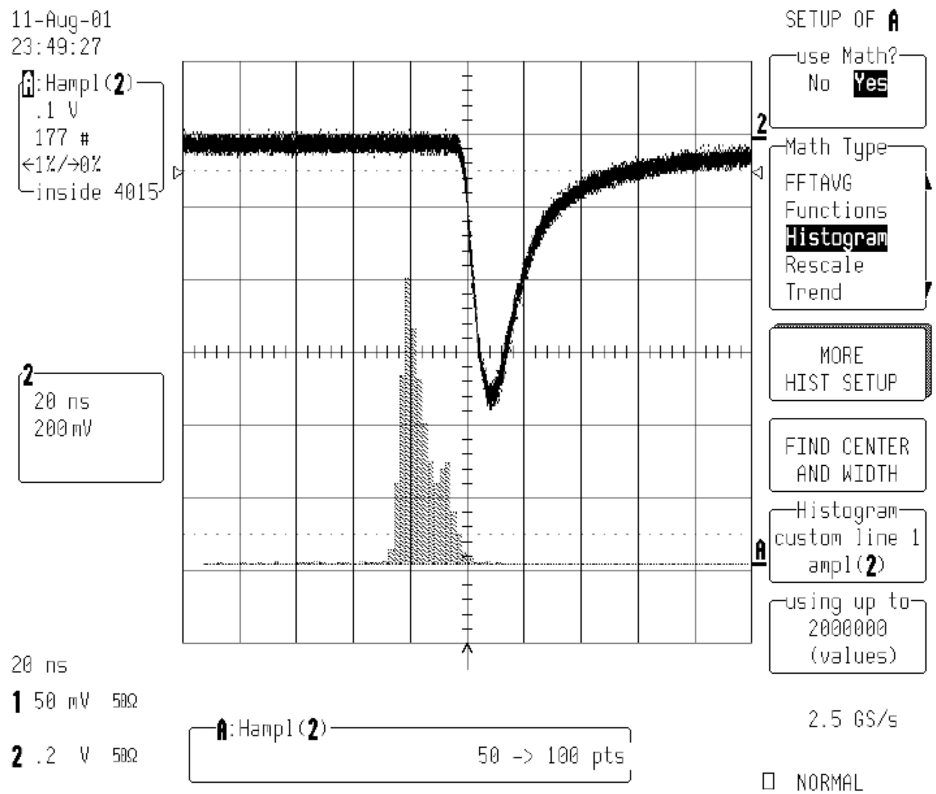
Properties of a good Scintillator

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.

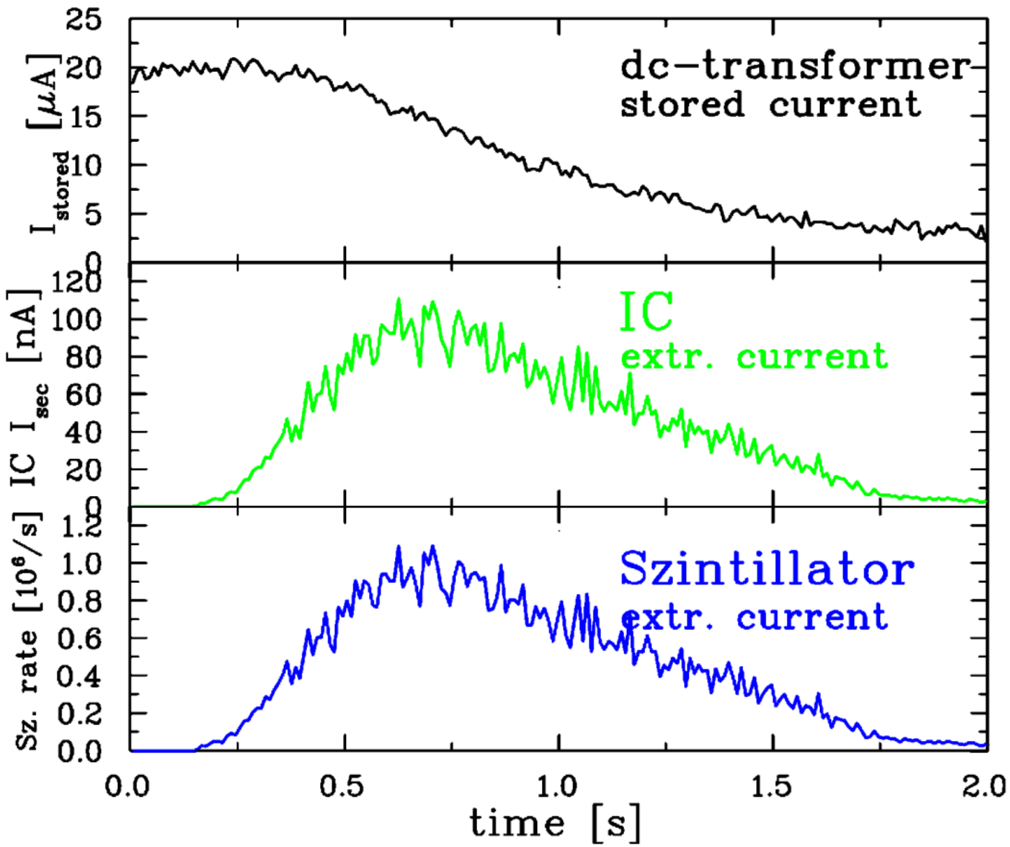
Properties of a good scintillator:

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

Slow extraction from a synchrotron delivers countable currents

Example: Comparison for

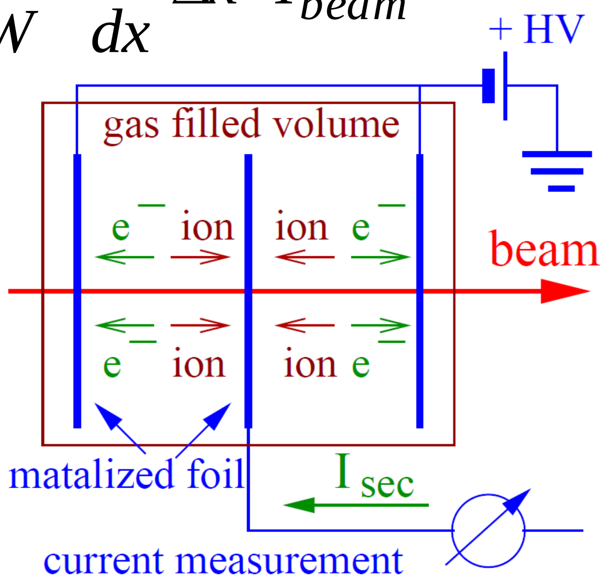
different detector types:



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.

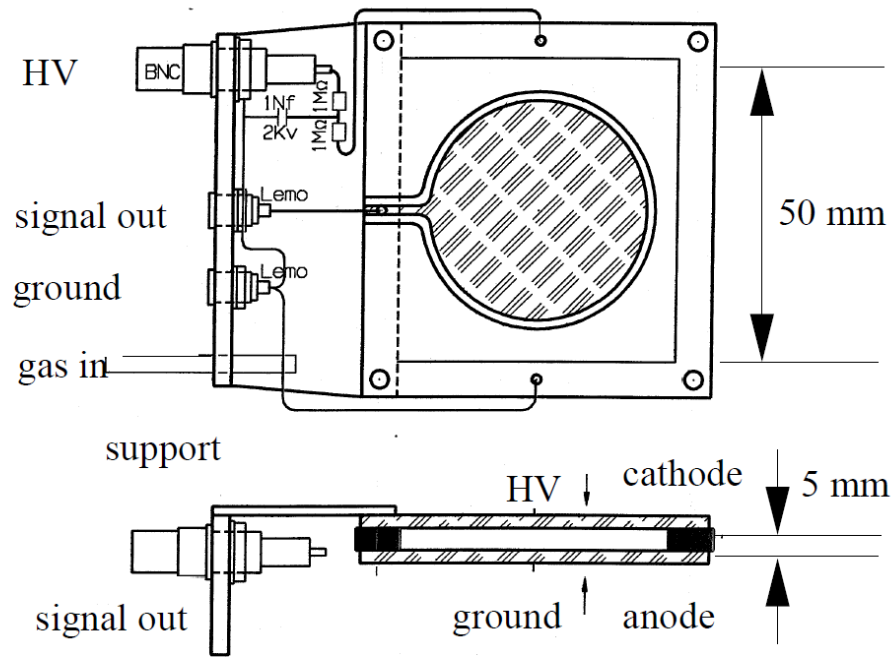
Energy loss of charged particles in gases → electron-ion pairs → low current meas.

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



Example: GSI type

active surface	64×64 mm^2
active length Δx	5 mm
electrode material	1.5 μm Mylar
coating	100 μg/cm^2 silver
gas (flowing)	80 % Ar + 20 %CO_2
pressure	1 bar
voltage	500 ... 2000 V



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

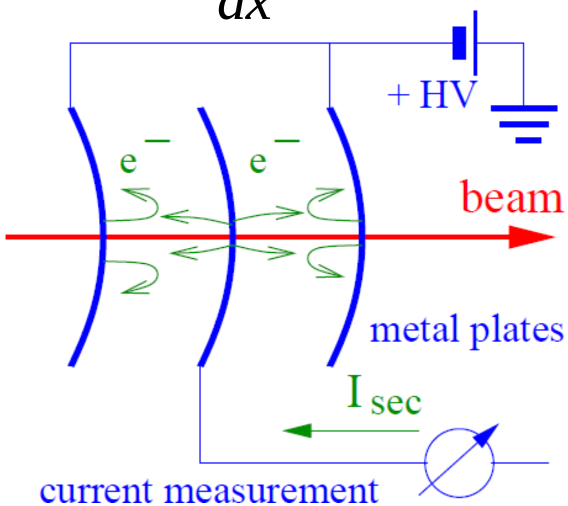
Secondary Electron Monitor (SEM): Electrons from Surface

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

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



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.

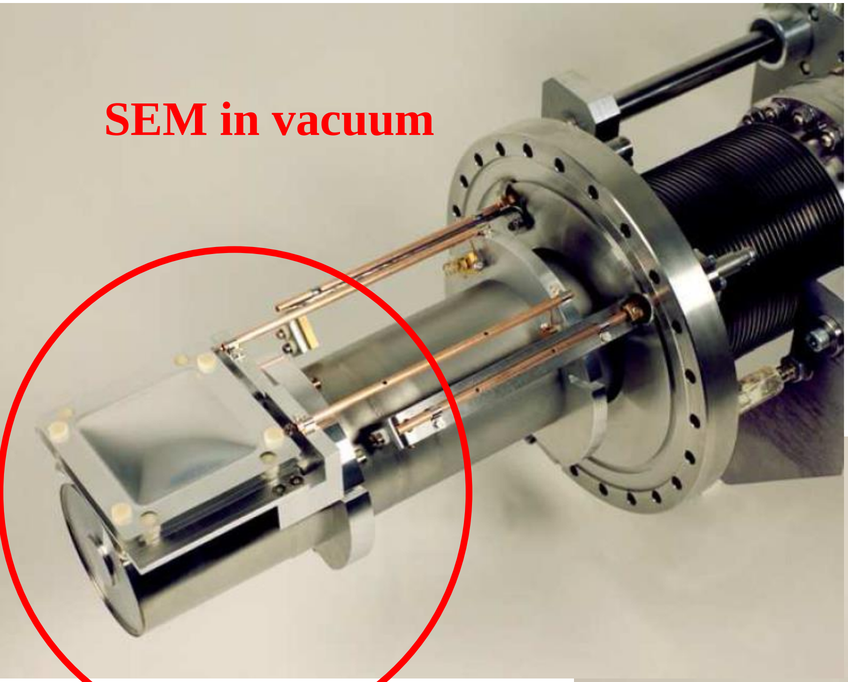
Disadvantage: Surface effect!

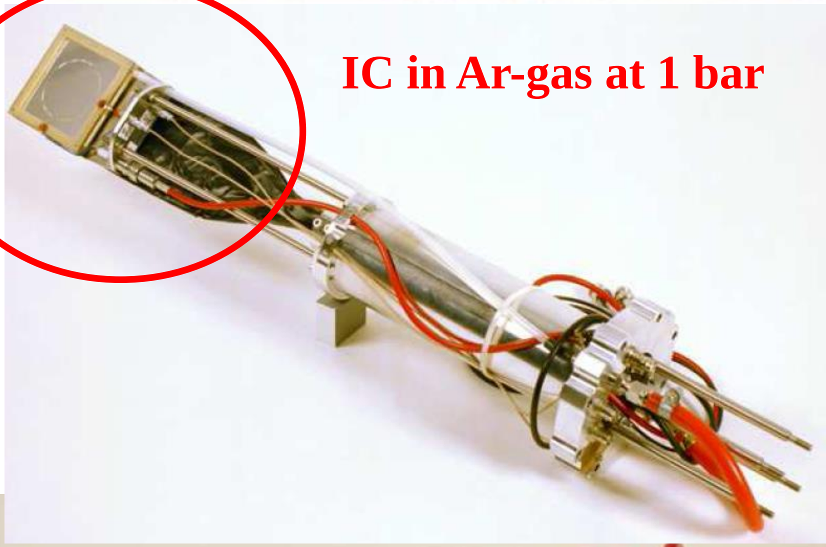
e.g. decrease of yield *Y* due to radiation

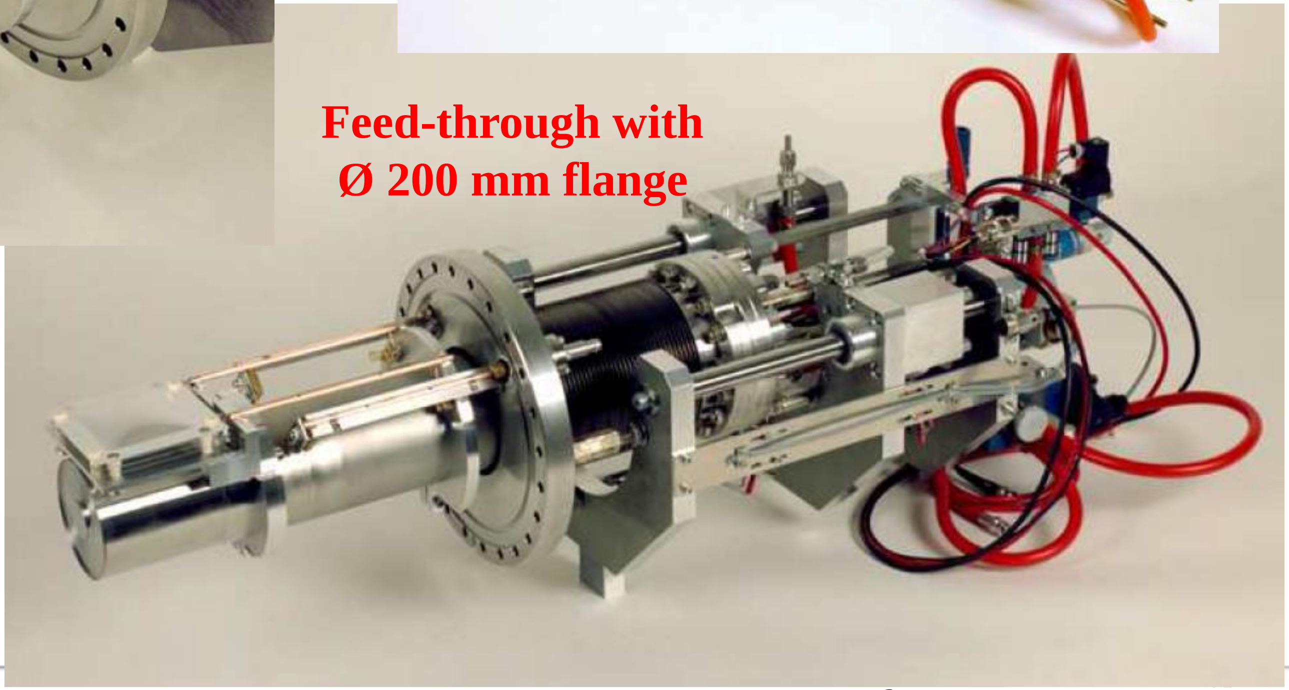
⇒ Ti foils for a permanent insertion.

Sometimes they are installed permanently in front of an experiment.

Example: GSI Installation for SEM and iC







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** from gas ionization or **SEM** sec. e^- emission surface
- no lower threshold due to single particle counting
- partly destructive, used for high energy beams