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

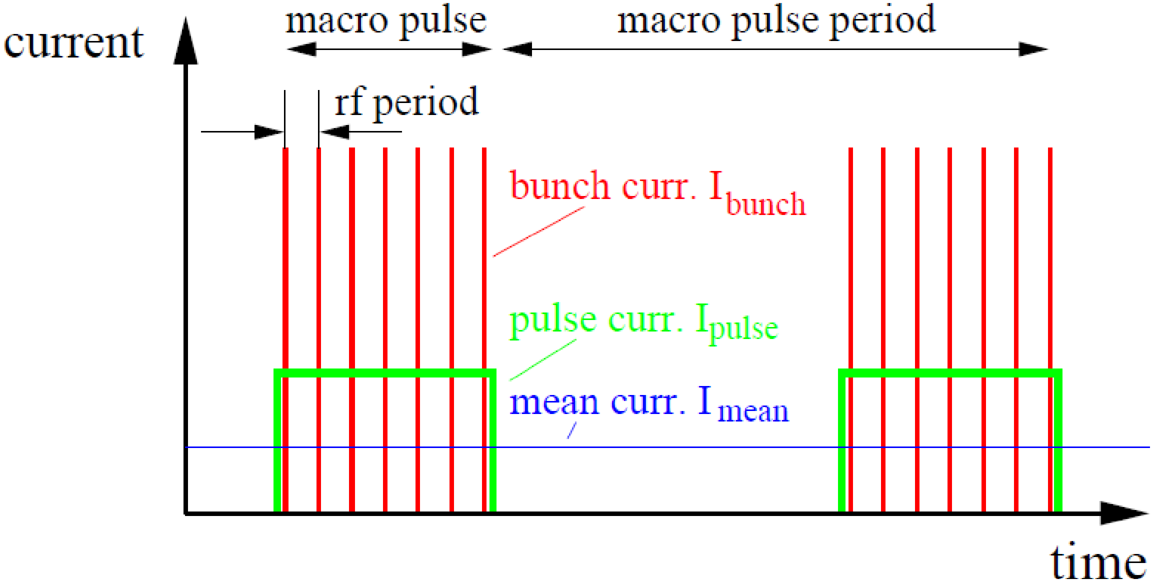
  Examples are scintillators, ionization chambers, secondary e− emission monitors

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

Generally: Beam instruments are mounted outside of rf cavities to prevent for electro-magnetic interference from the high field; only inside cyclotrons some BI.

Beam Structure of a pulsed LINAC

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

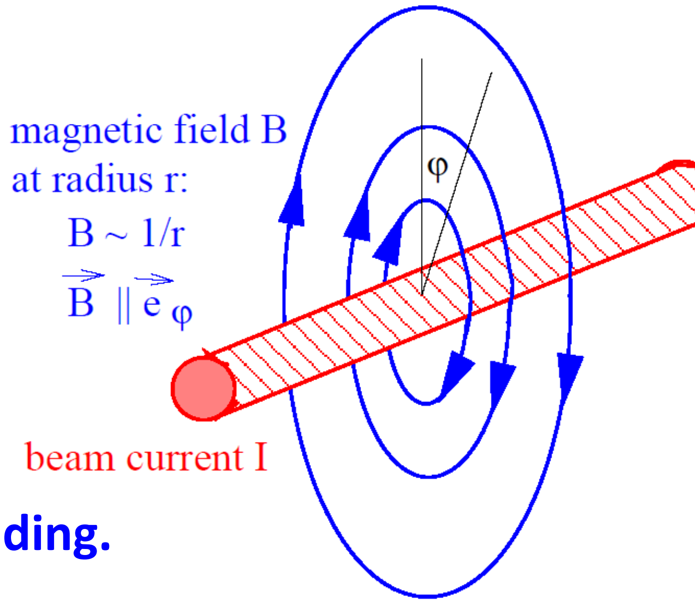
- Beam current of N_{part} charges with velocity β

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

- cylindrical symmetry

$\rightarrow$ only azimuthal component

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



Example: I =1μA, r =10cm $\Rightarrow$ B_{beam}= 2pT, earth B_{earth}= 50μT

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

$\Rightarrow$ Loaded current transformer

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

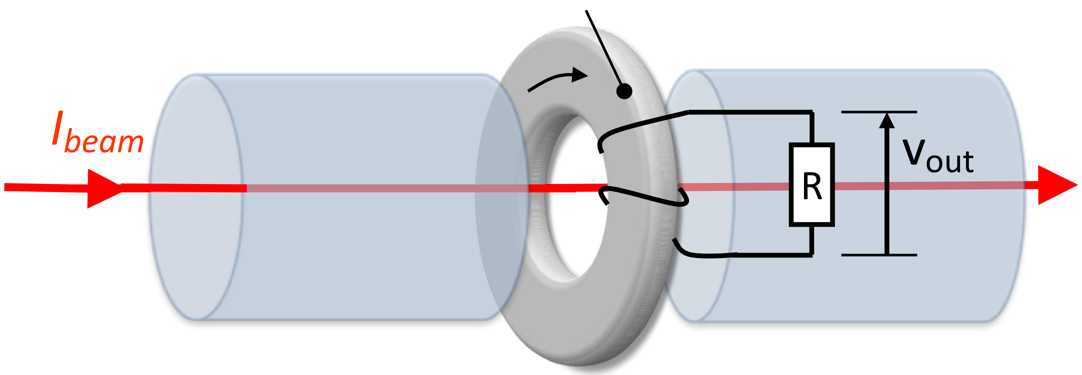
- Inductance of a torus of μ_r

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

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

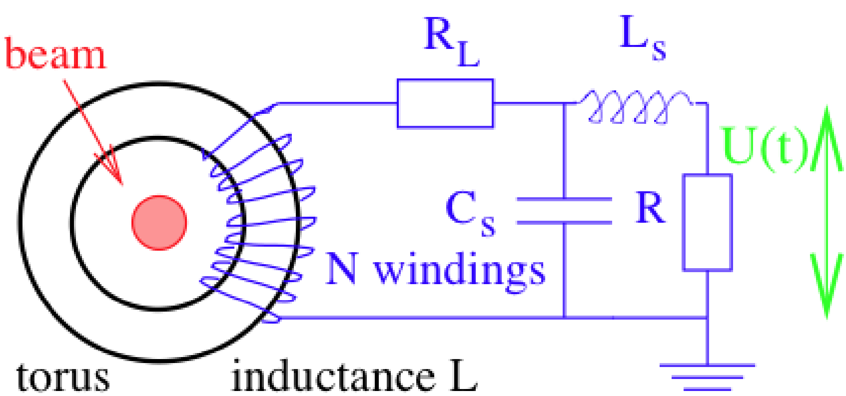
Definition: $U = L \cdot dI/dt$

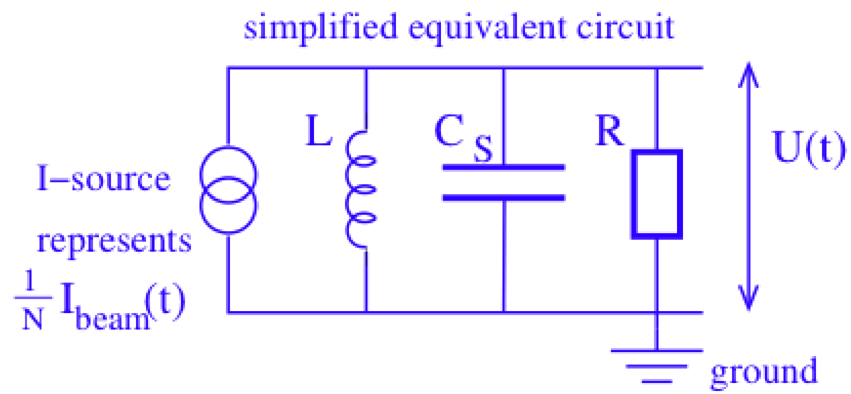
Torus to guide the magnetic field

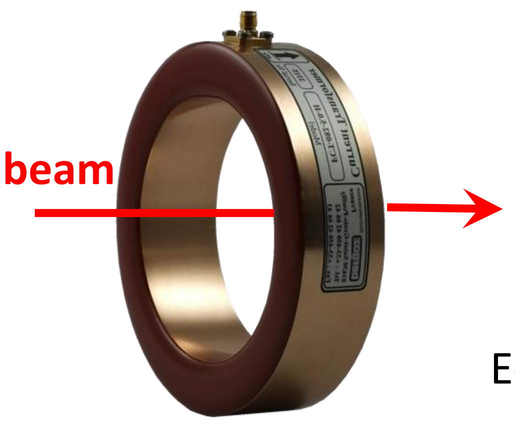


Simplified electrical circuit of a passively loaded transformer:

passive transformer







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

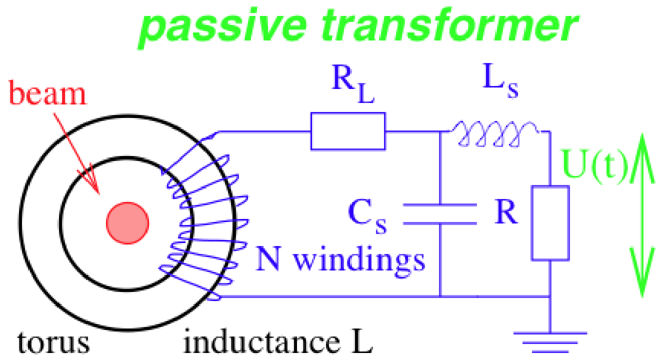
with ***S* sensitivity [V/A]**,

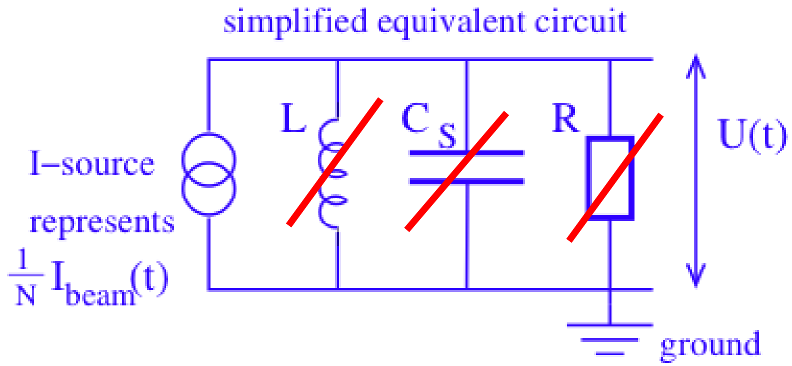
equivalent to transfer function or transfer impedance ***Z***

Equivalent circuit 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:

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

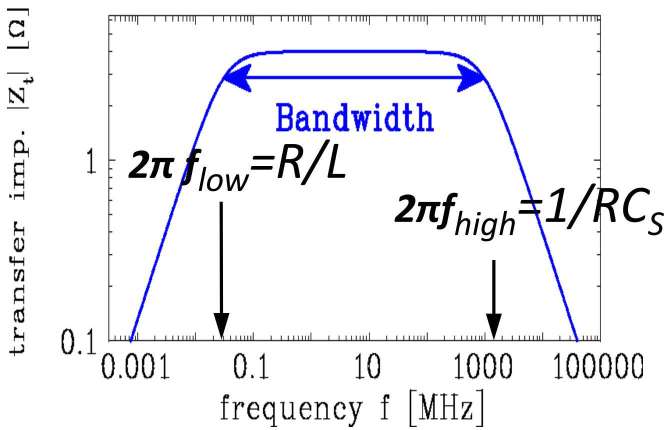
- ***Low frequency ω << R/L : Z → iωL***

  i.e. no dc-transformation
- ***High frequency ω >> 1/RC$_S$: Z → 1/iωC$_S$***

  i.e. current flow through ***C_S***
- ***Working region R/L < ω < 1/RC$_S$: Z ≃ 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.



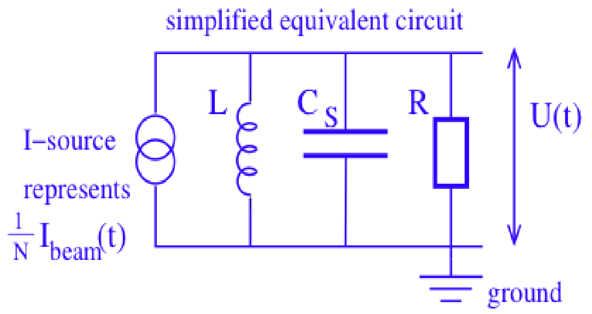
Time domain description:

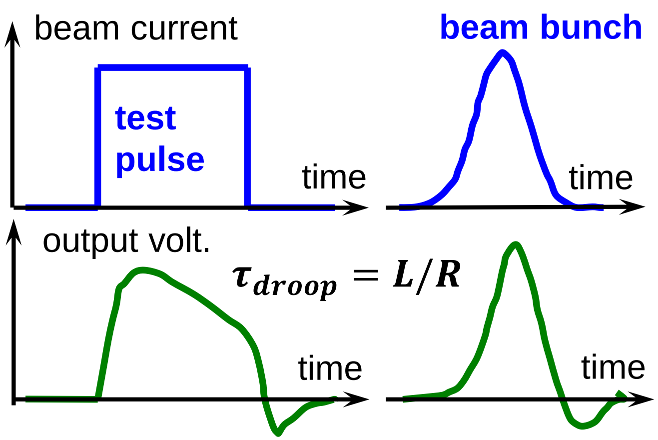
Droop time: $\tau_{droop} = 1/(2\pi f_{low}) = L/R$

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

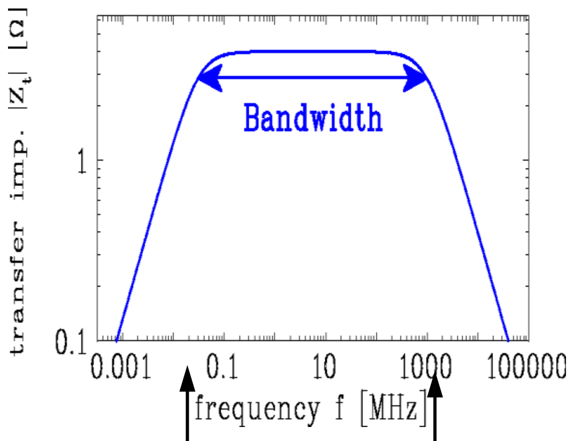
Rise time: $\tau_{rise} = 1/(2\pi f_{high}) = \sqrt{L_S C_s}$ (with cables)

R_L: loss resistivity, R: for measuring.



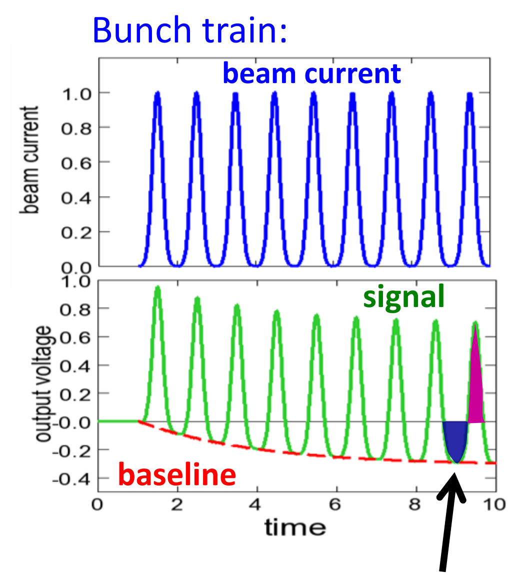


$$\tau_{rise} = \sqrt{L \cdot C_S}$$



$2\pi f_{low}$ $=R/L$

$2\pi f_{high}$ $=1/RC_S$



Baseline: $U_{base} \propto 1 - \exp(-t/\tau_{droop})$
positive & **negative areas are equal**

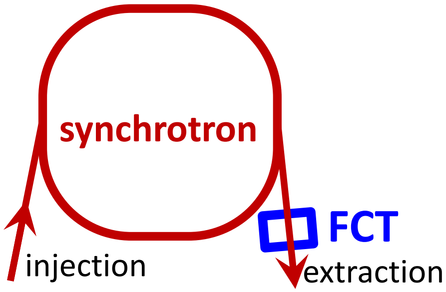
Example for Fast Current Transformer

For bunch beams e.g. transfer between synchrotrons
typical bandwidth of 2 kHz < f < 1 GHz
⇔ 1 ns < t_{batch} < 200 µs is well suited

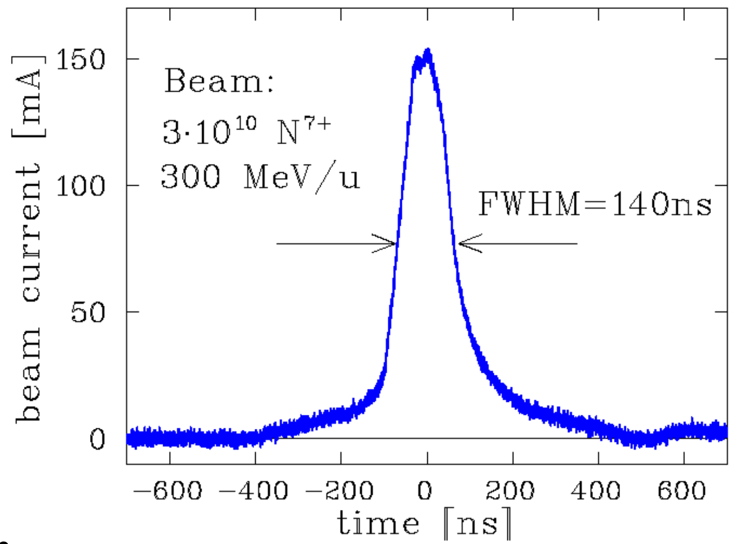
Example GSI type:

Inner / outer radius	70 / 90 mm
Permeability	$\mu_r \approx 10^5$ for f < 100kHz $\mu_r \propto 1/f$ above
Windings	10
Sensitivity	4 V/A for R = 50 Ω
Droop time τ_{droop} = L/R	0.2 ms
Rise time $\tau_{rise}=\sqrt{L_S C_S}$	1 ns
Bandwidth	2 kHz ... 500 MHz

Numerous application e.g.:
- Transmission optimization
- Bunch shape measurement
- Input for synchronization of 'beam phase'



Fast extraction from GSI synchrotron:



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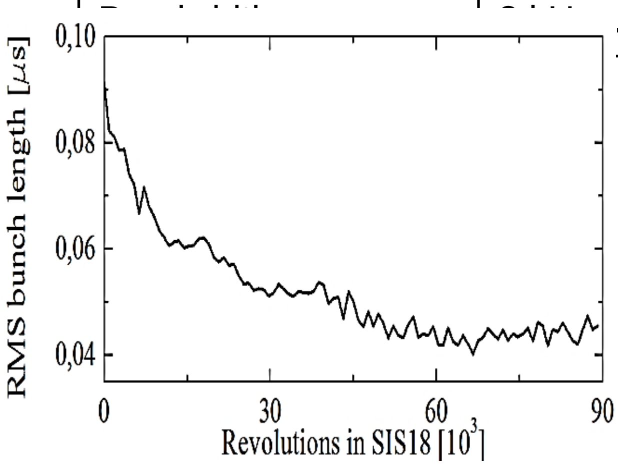
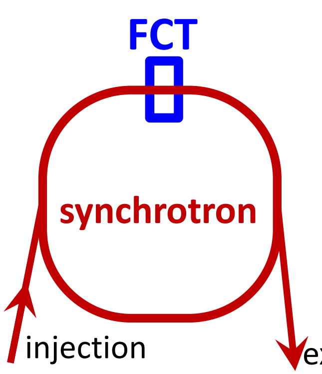
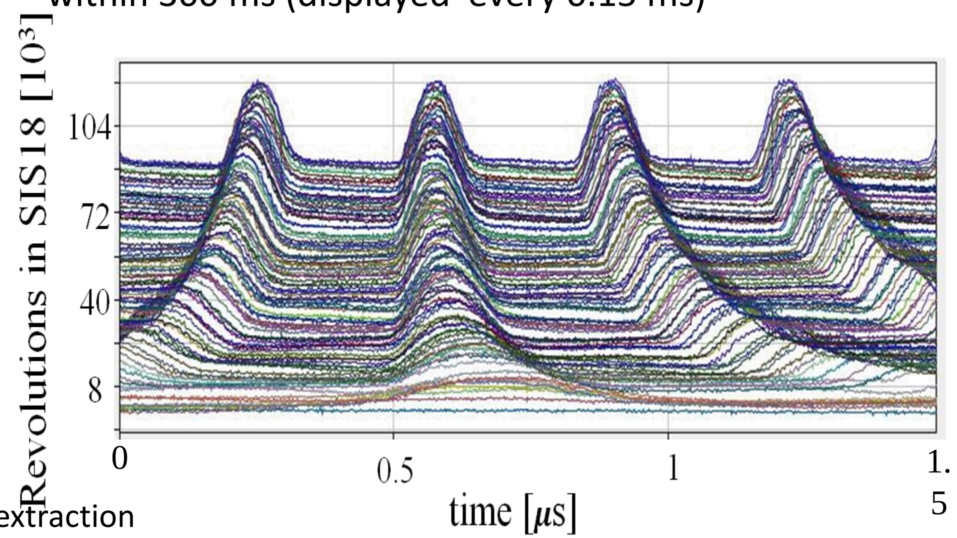
[illegible]	.. 500 MHz





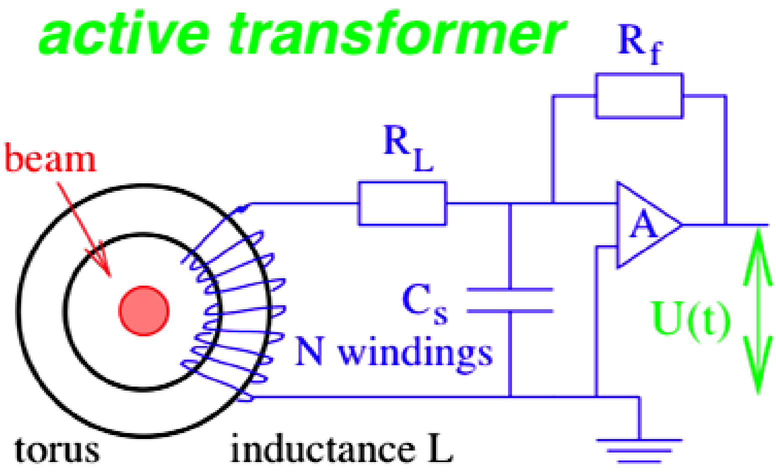
Example: U^{73+} from 11 MeV/u ($\boldsymbol{\beta}$ = 15 %) to 350 MeV/u within 300 ms (displayed every 0.15 ms)



'Active' Transformer with longer Droop Time

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
$\Rightarrow$ longer droop time $\boldsymbol{\tau_{droop}}$

Application: measurement of longer $\boldsymbol{t}$ > 10 μs e.g. at pulsed LINACs



The input resistor is for an op-amp: $\boldsymbol{R_f/A << R_L}$

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

Droop time constant can be up to 1 s!

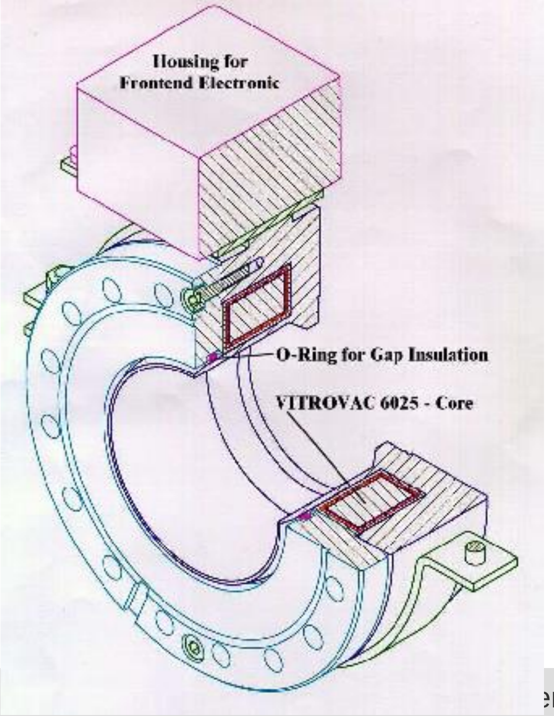
The feedback resistor is also used for range switching.

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

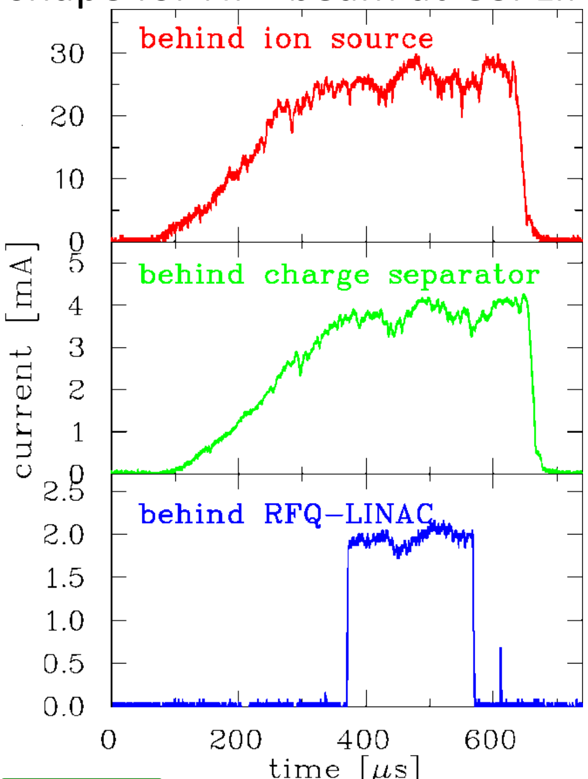
Inner / outer radius	30 / 45 mm
Permeability	$\mu_r \approx 10^5$ for f < 100kHz $\mu_r \propto 1/f$ above
Windings	2x10 crossed
Max. sensitivity	10^6 V/A with amplifier
Current resolution	0.2 μA for full BW
Droop	0.5 % per 5 ms
Rise time	200 ns
Bandwidth	2 kHz ... 1 MHz



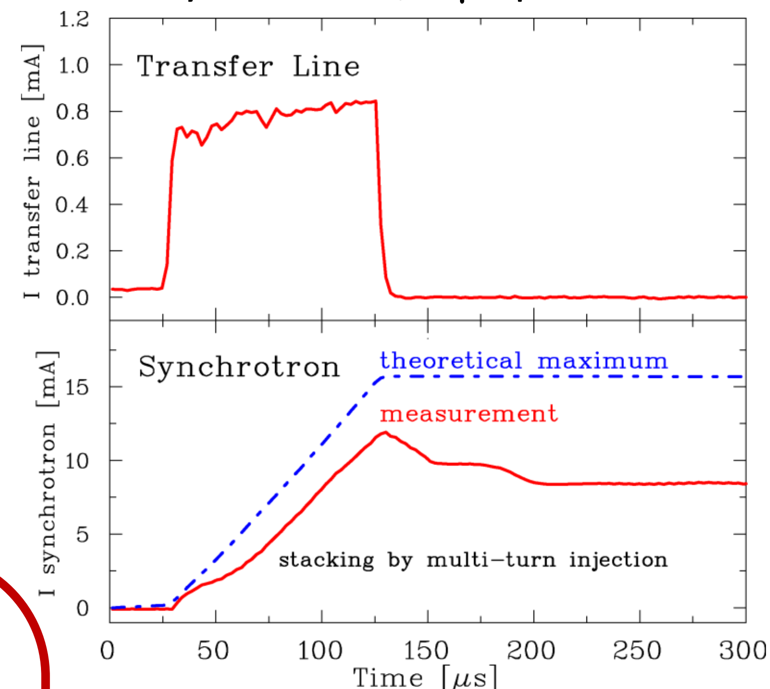
'Active' Transformer Measurement

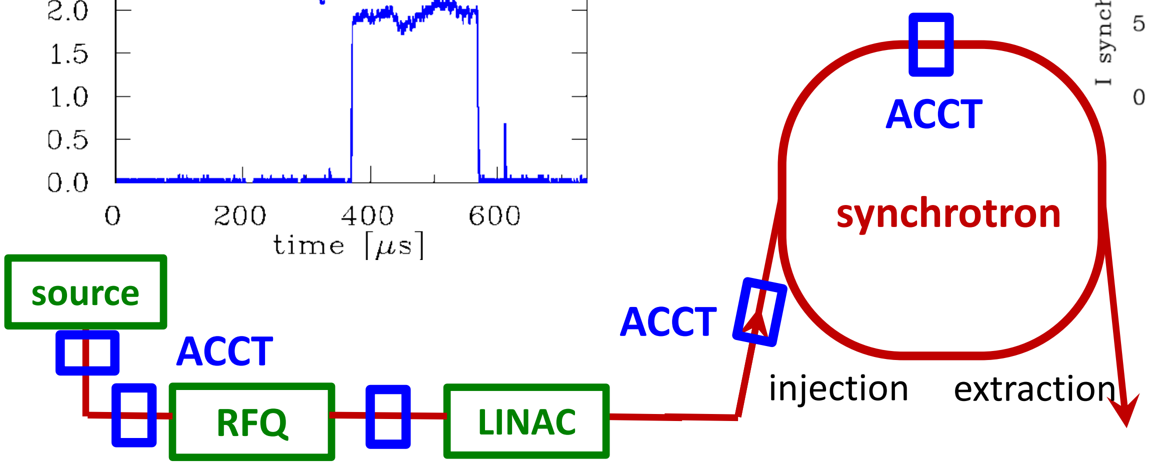
Active transformer for the measurement of long ***t*** > 10 µs pulses e.g. at pulsed LINACs

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



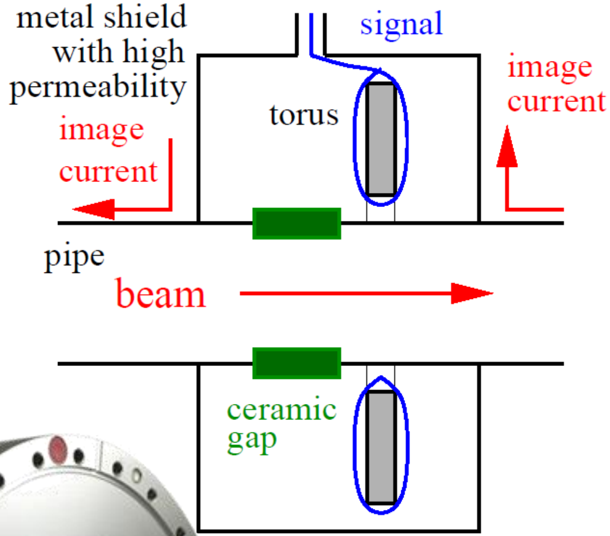


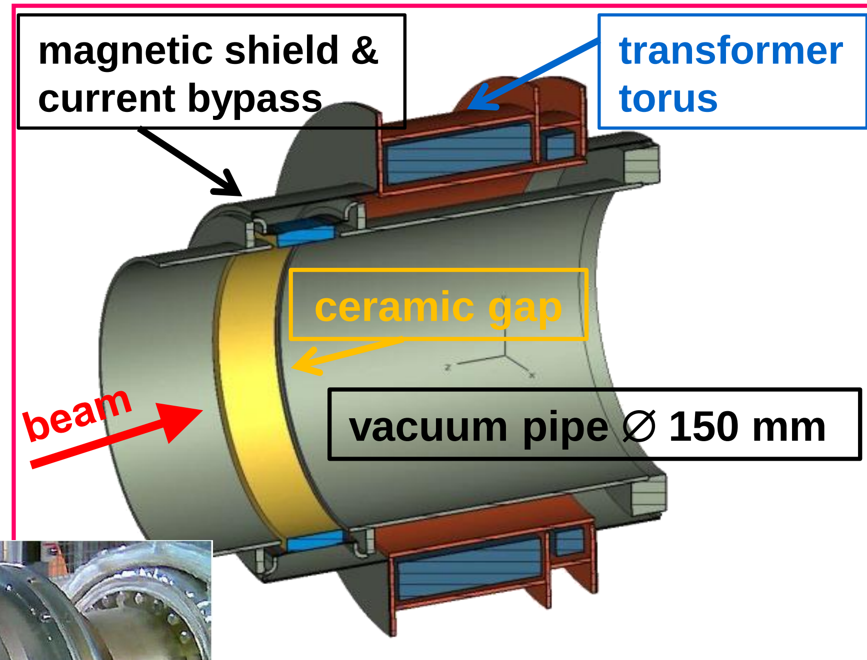
→ **Transformer are frequently used for operation.**

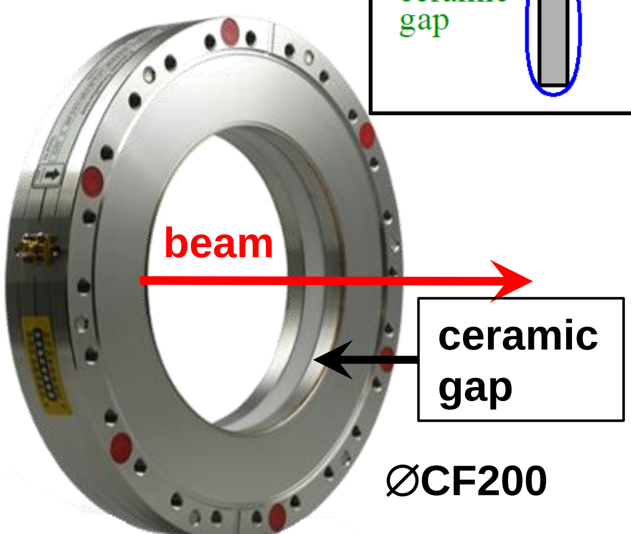
Shielding of a Transformer

Task of the shield:

- 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-field
  (remember: I_{beam} = 1 µA, r = 10 cm $\Rightarrow$ B_{beam} = 2pT, earth field B_{earth} = 50 µT)







courtesy Company Bergoz

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 longer droop time, 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:

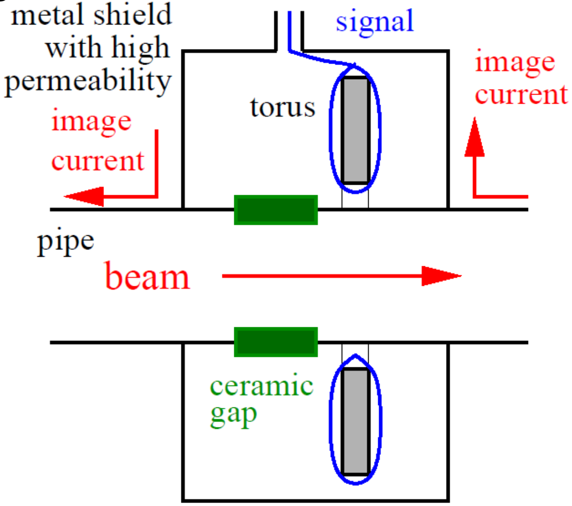
- **Passive transformer:** $R = 50\ \Omega$, $\tau_{rise} \approx 1$ ns for short pulses

  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:

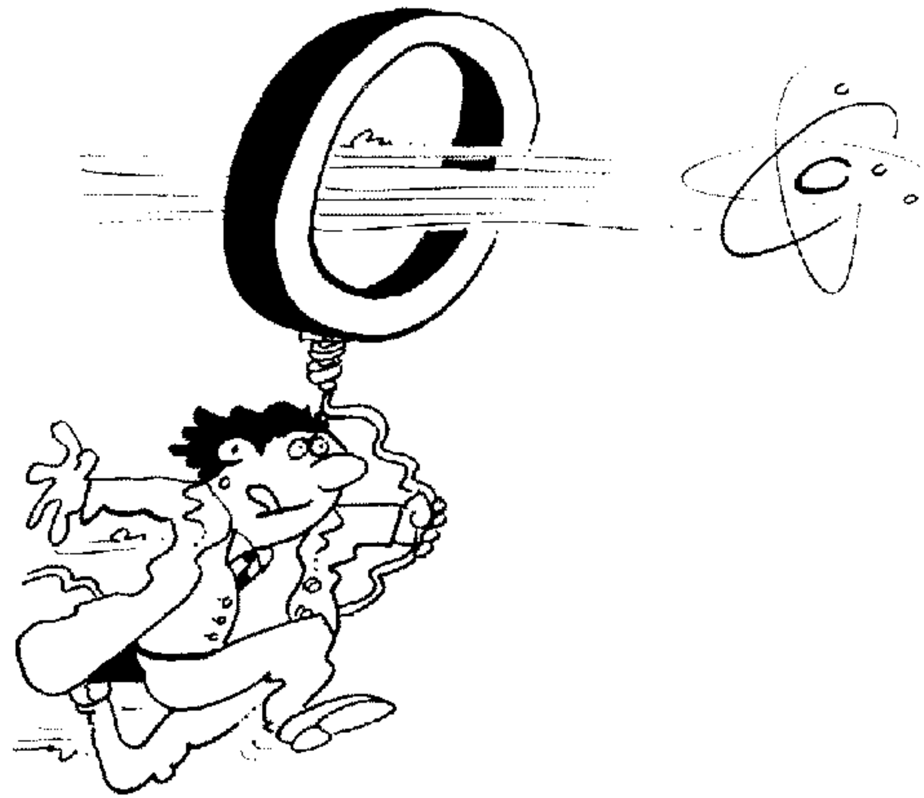
- The beam pipe has to be intersected to prevent the flow of the image current through the torus
- The torus is made of 25 µm isolated flat ribbon spiraled to get a torus of ≈15 mm thickness, to have large electrical resistivity
- Additional winding for calibration with current source



The Artists View of Transformers

The active transformer ACCT

The passive, fast transformer FCT



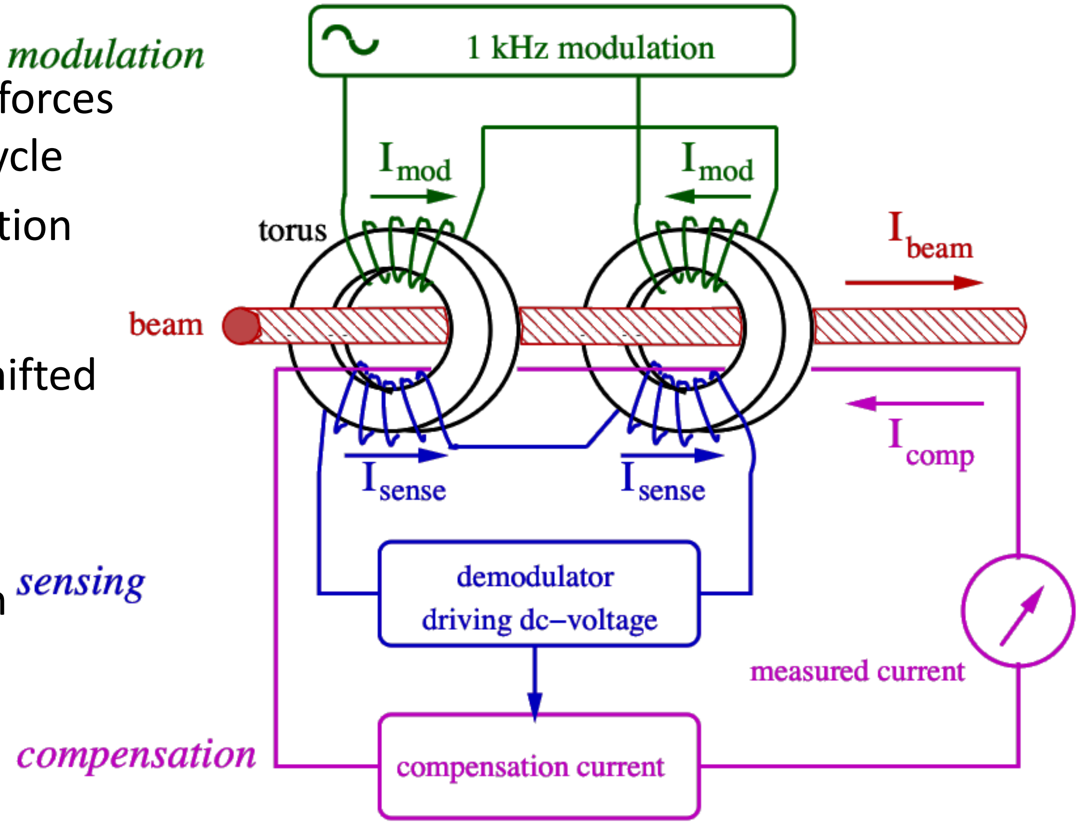
Cartoons by Company Bergoz, Saint Genis

The dc Transformer

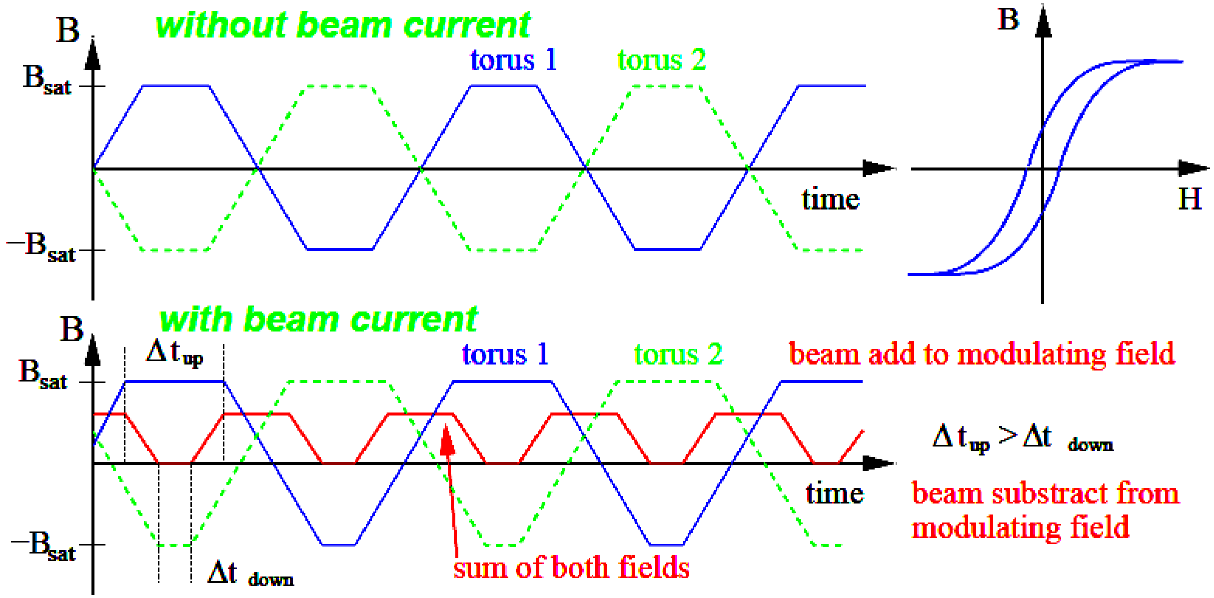
How to measure the DC current? The current transformer discussed sees only B-flux ***changes***.
The DC Current Transformer (DCCT) → look at the magnetic saturation of two torii.

Depictive statement:
A single transformer needs varying beam. The trick is to 'switch two transformers'!

- **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

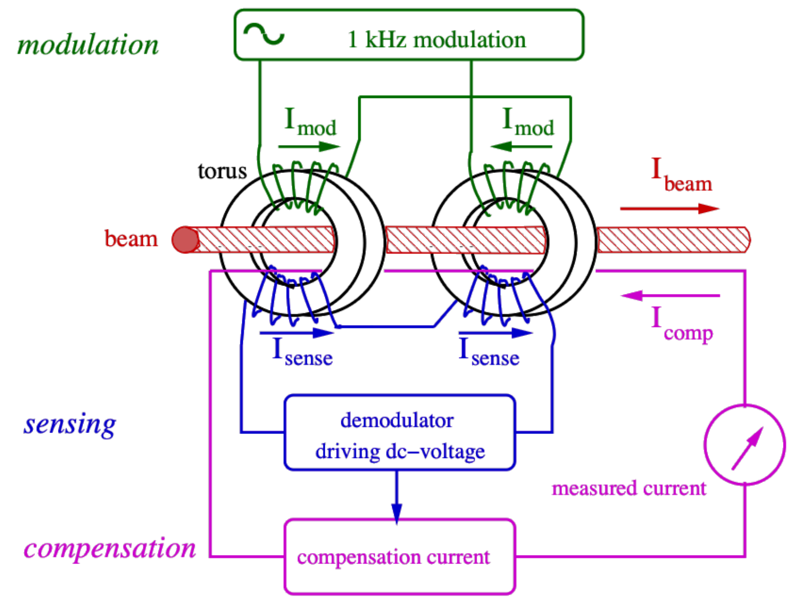


- **Modulation without beam:**

  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

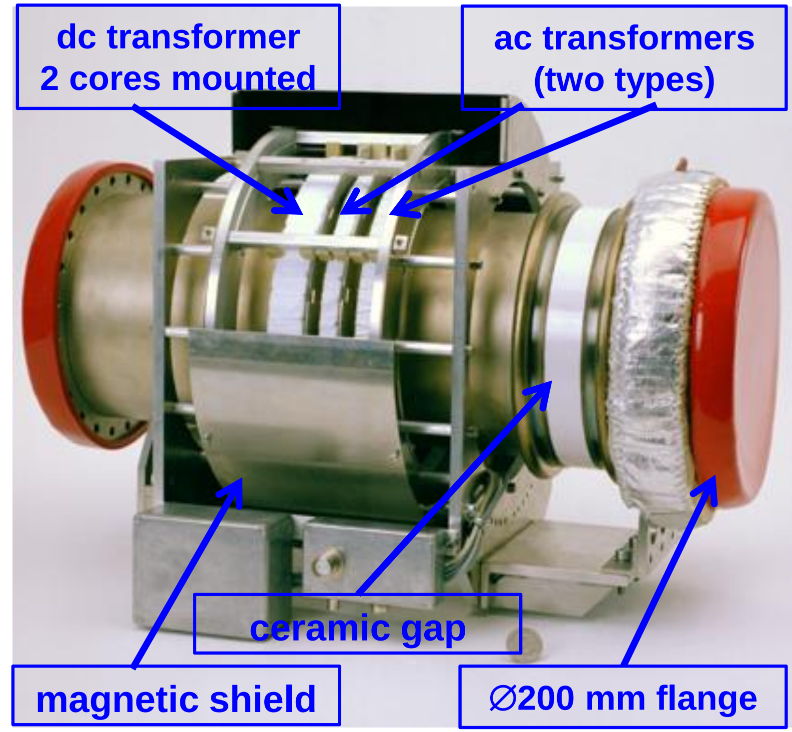
  for larger sensitivity
- **Two magnetic cores:** Must be very similar.



The dc Transformer Realization

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

Torus radii	r_i = 135 mm r_o=145 mm
Torus thickness	d = 10 mm
Torus permeability	$\mu_r = 10^5$
Saturation inductance	B_{sat} = 0.6 T
Number of windings	16 for modulation & sensing 12 for feedback
Resolution	I^{min}_{beam} = 2 μA
Bandwidth	Δf = dc .... 20 kHz
Rise time constant	τ_{rise} = 10 μs
Temperature drift	1.5 μA/°C



Recent commercial product specification (Bergoz NPCT):

Most parameters are comparable the GSI-model

Temperature coefficient: 0.5 μA/°C

Resolution: ≈ 10 μA (i.e. not optimized)


In-flange.NPCT with 96-mm aperture

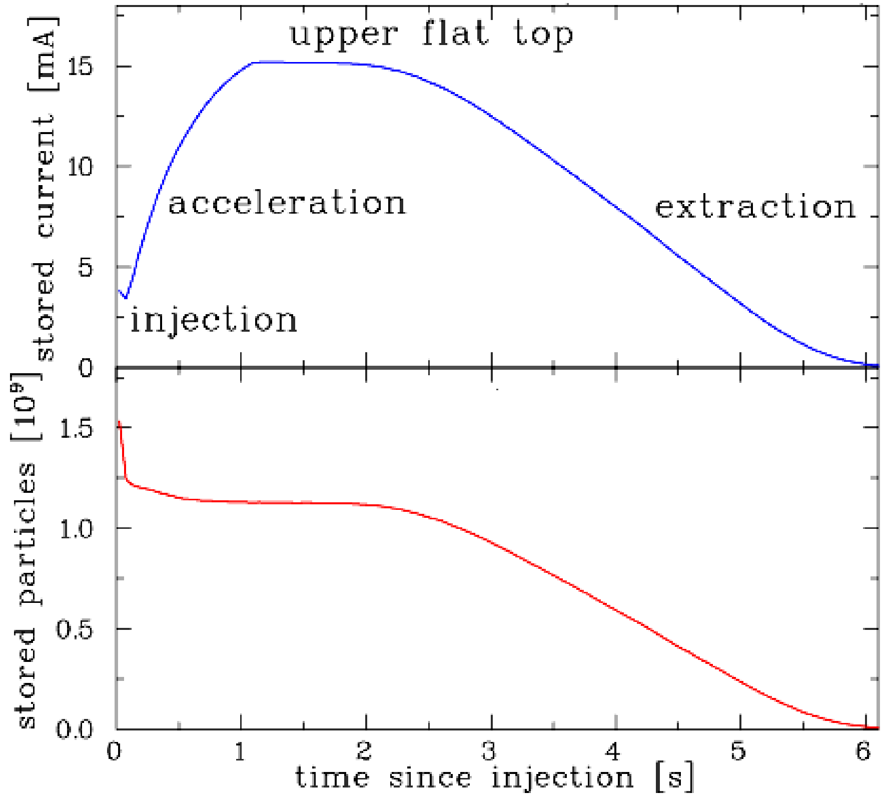
Measurement with a dc Transformer

Example: The DCCT at GSI synchrotron:

$\Rightarrow$ Observation of beam behavior with 20 μs time resolution $\rightarrow$ most important operation tool.

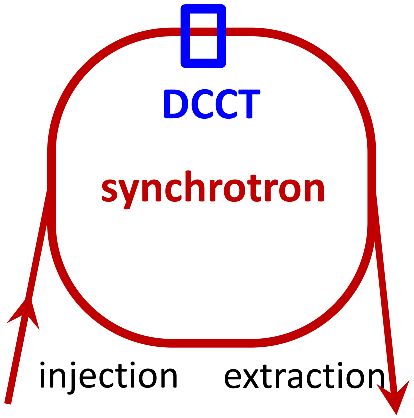
Example: U^{73+} accelerated from

11. 4 MeV/u (β = 15.5%) to 750 MeV/u (β = 84 %)

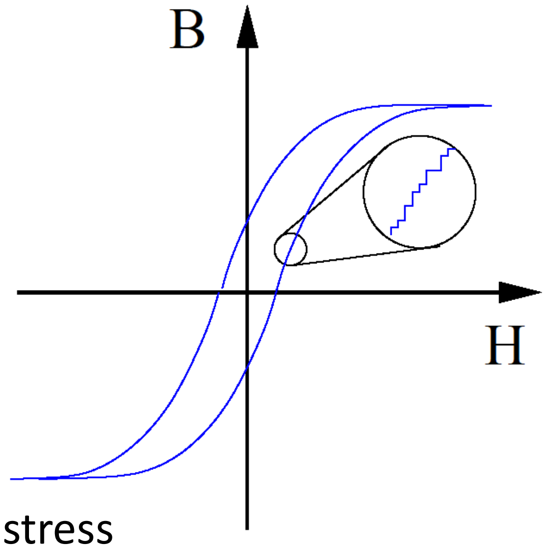


Important parameters:

- **Detection threshold: 1 μA (= resolution)**
- Bandwidth: dc to 20 kHz
- Rise-time: 20 μs
- Temperature drift: 1.5 μA/^{0}C
  $\Rightarrow$ compensation required.



Design Criteria and Limitations for a dc Transformer



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 $U_{eff} = \sqrt{4k_B T \cdot R \cdot f}$
  $\Rightarrow$ design for only required bandwidth f, low input resistor R preferred.
- Preventing for flow of secondary electrons through the core
  $\Rightarrow$ need for well controlled beam centering close to the transformer.

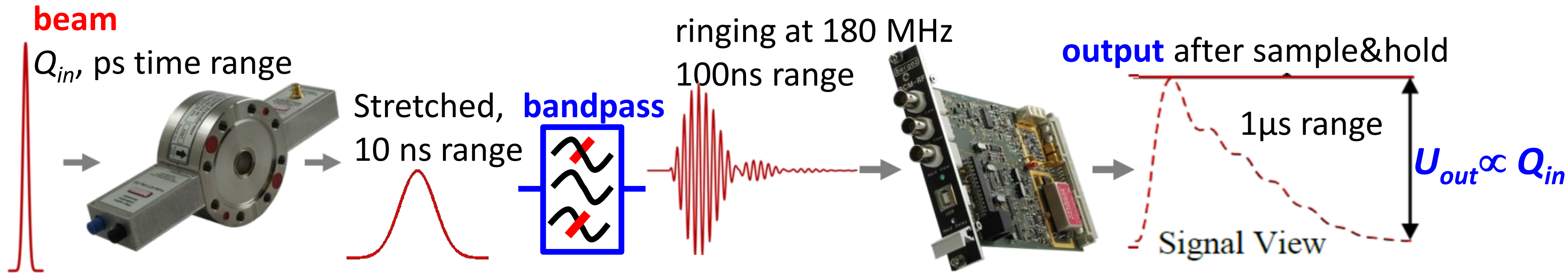
$\Rightarrow$ **The lowest measurable current: ≈ 1 µA for DCCT**
≈ 30 µA for FCT with 500 MHz bandwidth
≈ 0.3 µA for ACCT with 1 MHz bandwidth.

ICT short pulses: Image charge storage $\rightarrow$ analog pulse stretching, $Q_{min} \approx$ 10 fC, no timing

Integrating Current Transformer ICT for short Pulses

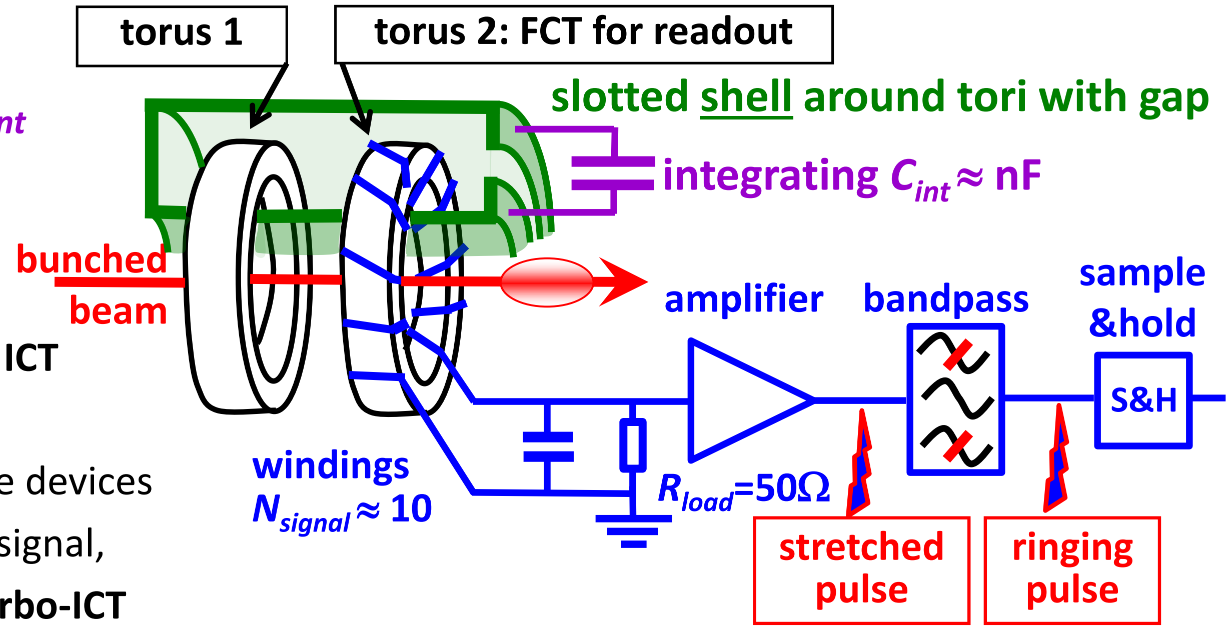
Short, single pulse at FELs: Too short to be recorded by FCT due to rise time $\tau_{pulse} \ll \tau_{rise} \approx 1ns$

$\Rightarrow$ depictive statement: 'analog stretching of signal information' yields charges per bunch



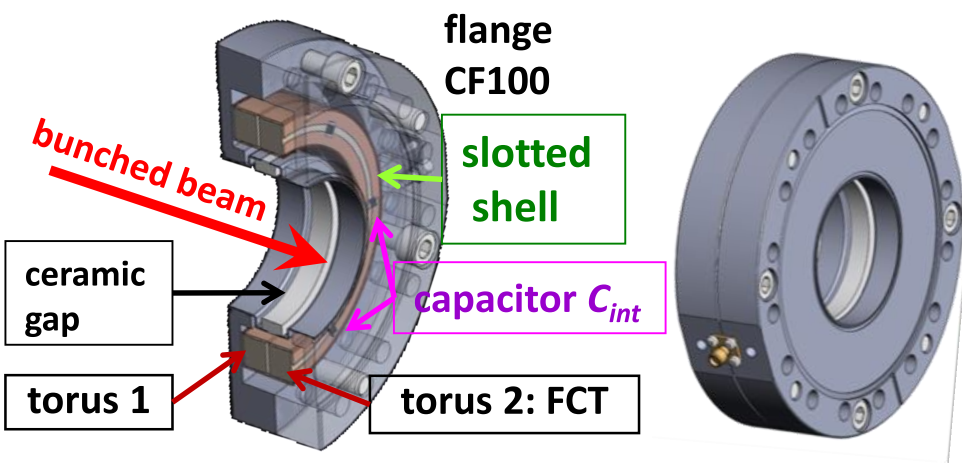
ICT operation principle for ps pulses:

- Image current on **shell with gap**
- Storage of induced charges at C_{int}
- 'Slow' recombination of charges
- Sensing this current with **FCT**
  $\Rightarrow$ **stretched pulse,** length
  independent on input $\rightarrow$ called **ICT**
- Torus1 for correct inductance:
  damped resonant circuit of entire devices
- Broad bandpass filter $\Rightarrow$ ringing signal,
  to enlarge sensitivity $\rightarrow$called **Turbo-ICT**



Typical parameter of a Turbo-ICT as used at FELs and Laser Plasma Accelerators:

Tori thickness	l = 5 mm respectively
Full scale range	500 fC ...1 nC
Resolution	**10 fC_{rms} ⇔ 10^5 e^- / bunch**
Max. pulse repetition	500 ns for single pulses
Dynamic range	80 dB by logarithmic amp.



courtesy Company Bergoz

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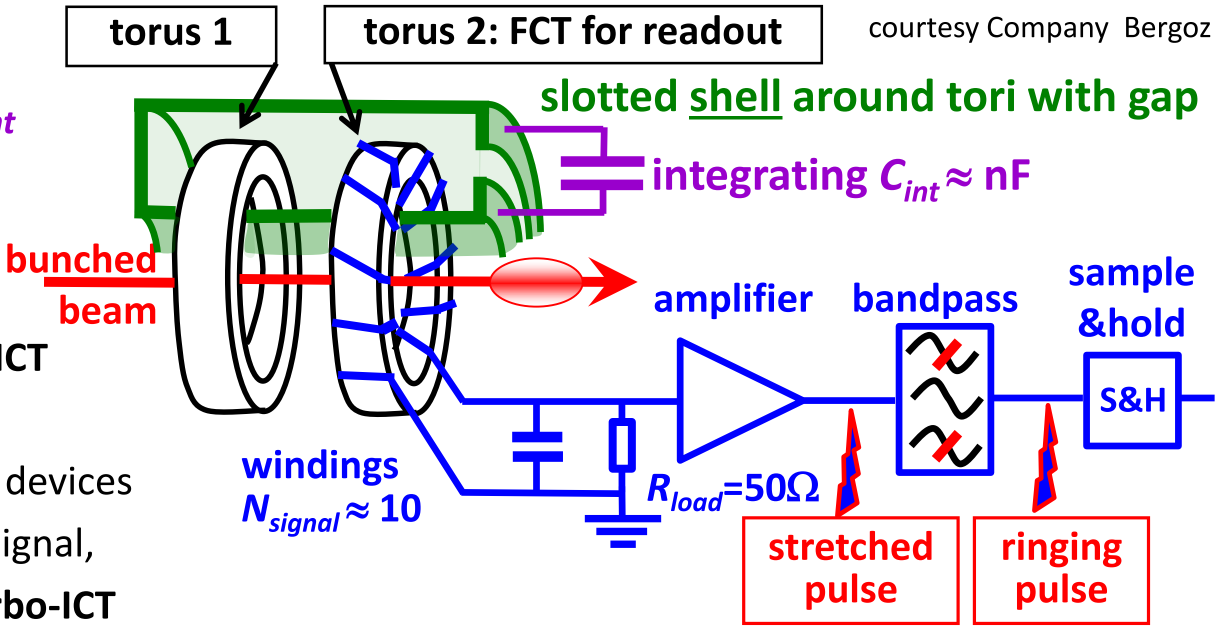
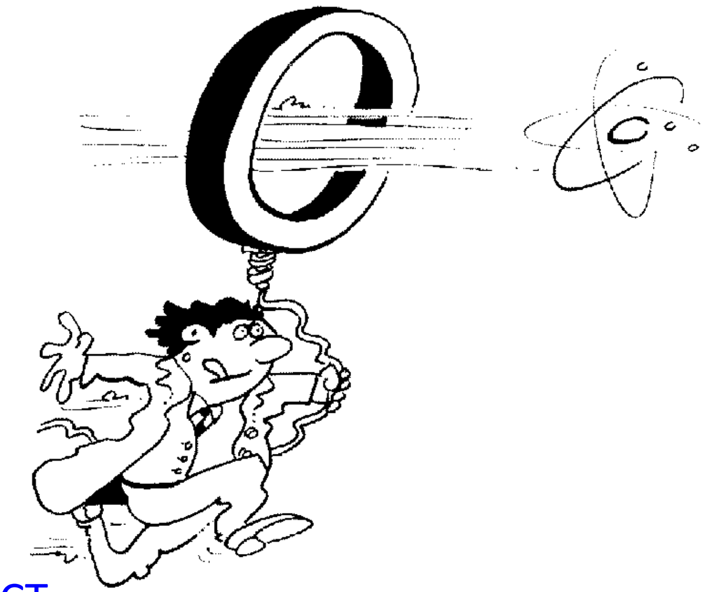


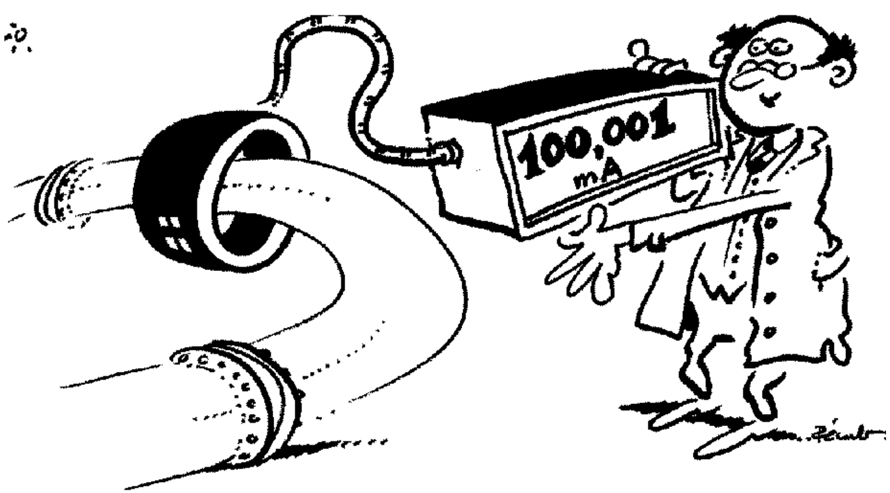
The Artists View of Transformers

The active transformer ACCT

The Fast Transformer FCT



The dc transformer DCCT



Company Bergoz

Measurement of Beam Current

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

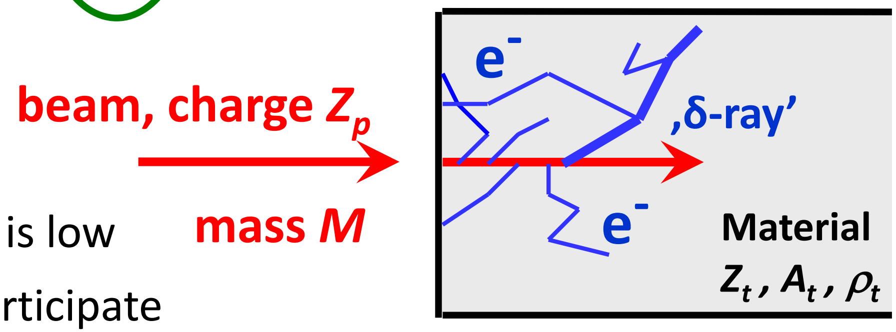
  Used for low currents at high energies e.g. for slow extraction from a synchrotron.

Excurse: Energy Loss of Ions in Matter

Bethe-Bloch formula: $-\frac{dE}{dx} = 4\pi N_A r_e^2 m_e c^2 \cdot \frac{Z_t}{A_t}\rho_t \cdot Z_p^2 \cdot \frac{1}{\beta^2}\left(\frac{1}{2}\ln\frac{2m_e c^2\beta^2\gamma^2 \cdot W_{max}}{I^2} - \beta^2\right)$

(simplest formulation)

Semi-classical approach:



- Projectiles of mass ***M*** collide

with free electrons of mass ***m***

- If ***M >> m*** then the relative energy transfer is low

⇒ many collisions required many elections participate

proportional to target electron density $n_e = \frac{Z_t}{A_t}\rho_t$

⇒ low straggling for the heavy projectile i.e. 'straight trajectory'

- If projectile velocity $\beta \approx 1$ low relative energy change of projectile (γ is Lorentz factor)
- I is mean ionization potential including kinematic corrections $I \approx Z_t \cdot 10$ ***eV*** for most metals
- Strong dependence an projectile charge Z_p as $\frac{dE}{dx} \propto Z_p^2$

Constants: N_A Advogadro number, r_e classical e⁻ radius, m_e electron mass, c velocity of light

Maximum energy transfer from projectile ***M*** to electron m_e: $W_{max} = \frac{2m_e c^2\beta^2\gamma^2}{1 + 2\gamma m_e/M + (m_e/M)^2}$

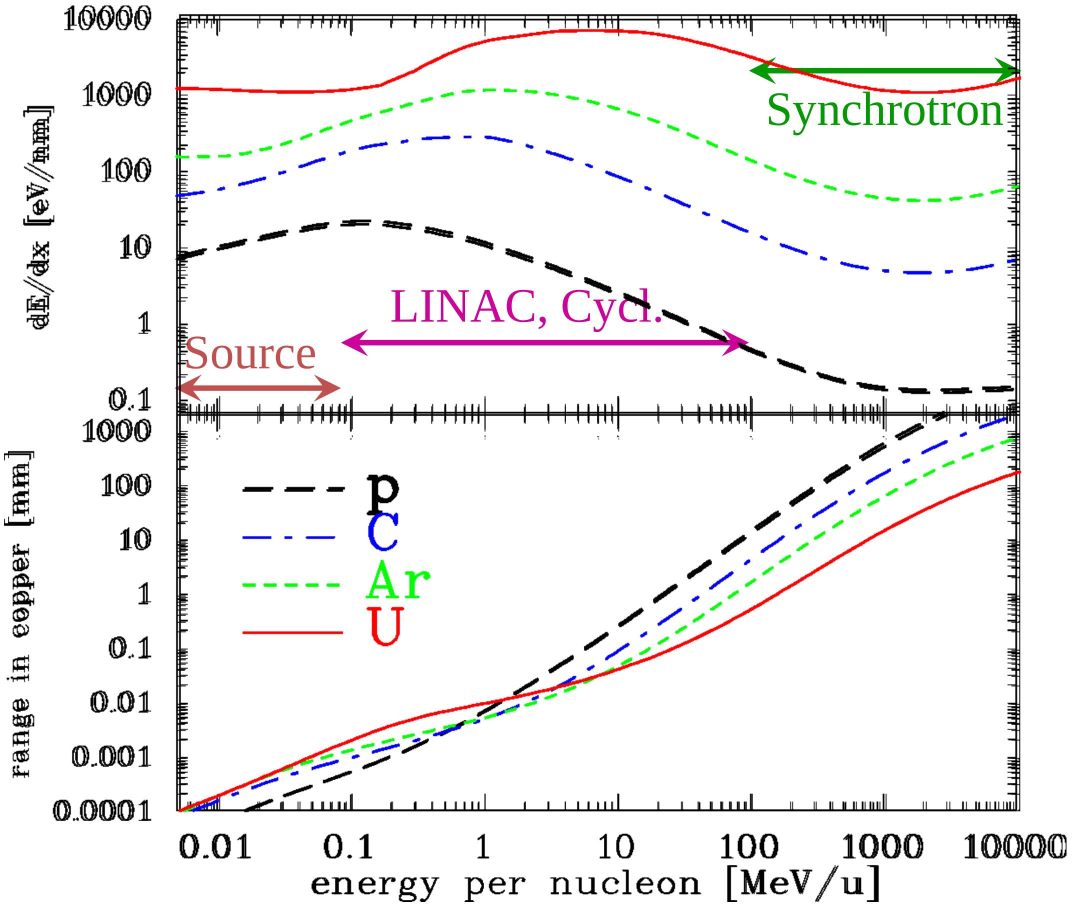
Excurse: Energy Loss of Ions in Copper

Bethe-Bloch formula: $-\frac{dE}{dx} = 4\pi N_A r_e^2 m_e c^2 \cdot \frac{Z_t}{A_t}\rho_t \cdot Z_p^2 \cdot \frac{1}{\beta^2}\left(\frac{1}{2}\ln\frac{2m_e c^2\beta^2\gamma^2 \cdot W_{max}}{I^2} - \beta^2\right)$

(simplest formulation)

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

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



Numerical calculation for **ions**

with semi-empirical model e.g. SRIM

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

$\Rightarrow$ Cups only for

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

Excurse: Secondary Electron Emission by Ion Impact

Energy loss of ions in metals close to a surface:

Closed collision with large energy transfer $\rightarrow$ fast e$^-$ with E_{kin}>> 100 eV

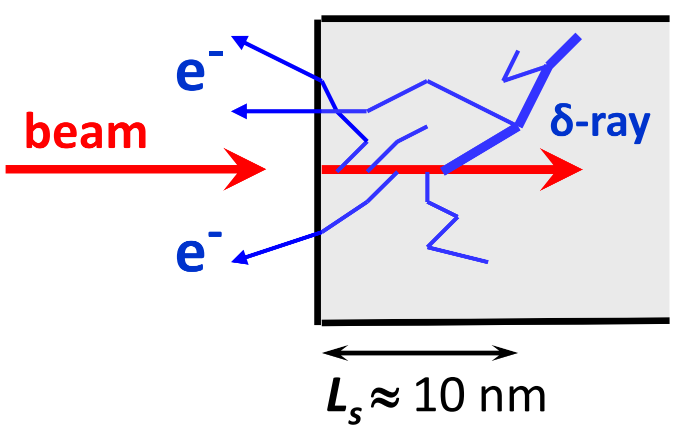
Distant collision with low energy transfer $\rightarrow$ slow e$^-$ with $E_{kin} \lesssim$ 10 eV

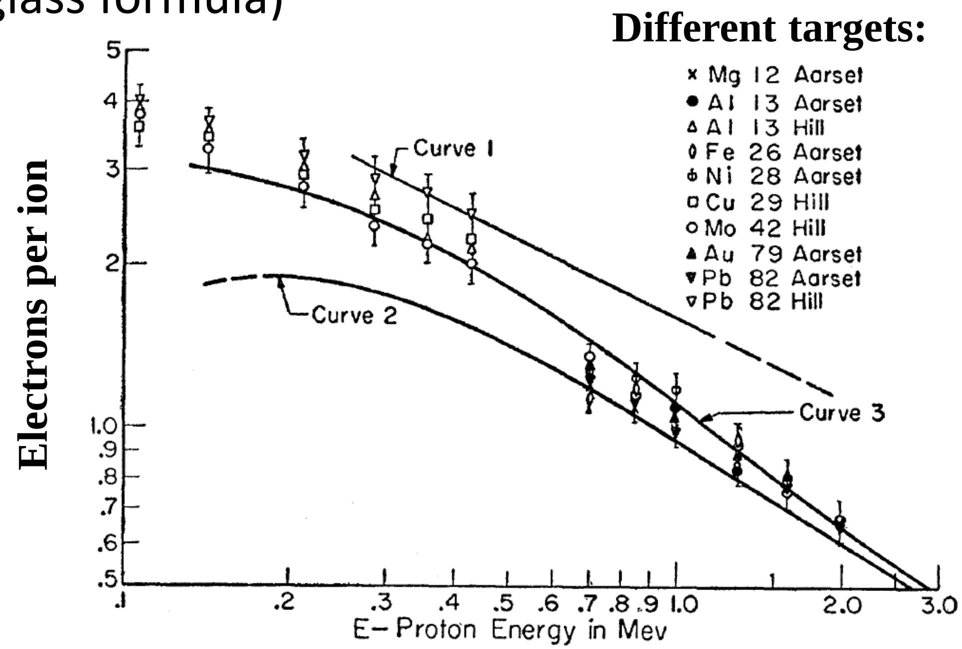
$\rightarrow$ 'diffusion' & scattering with other e$^-$: scattering length $L_s \approx$ 1 - 10 nm

$\rightarrow$ at surface $\approx$ 90 % probability for escape

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)

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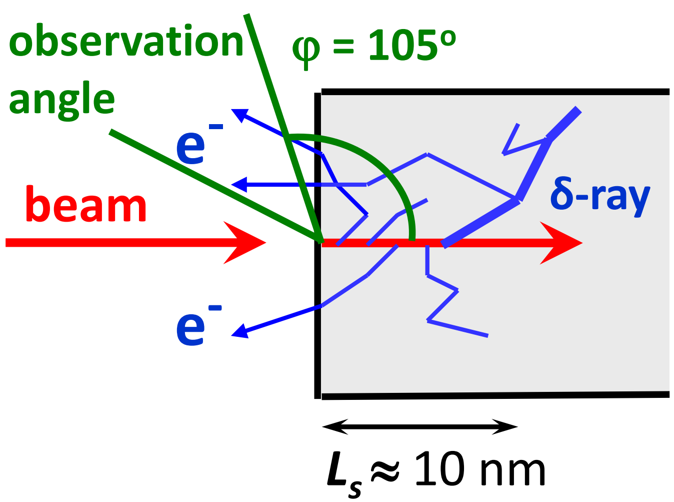
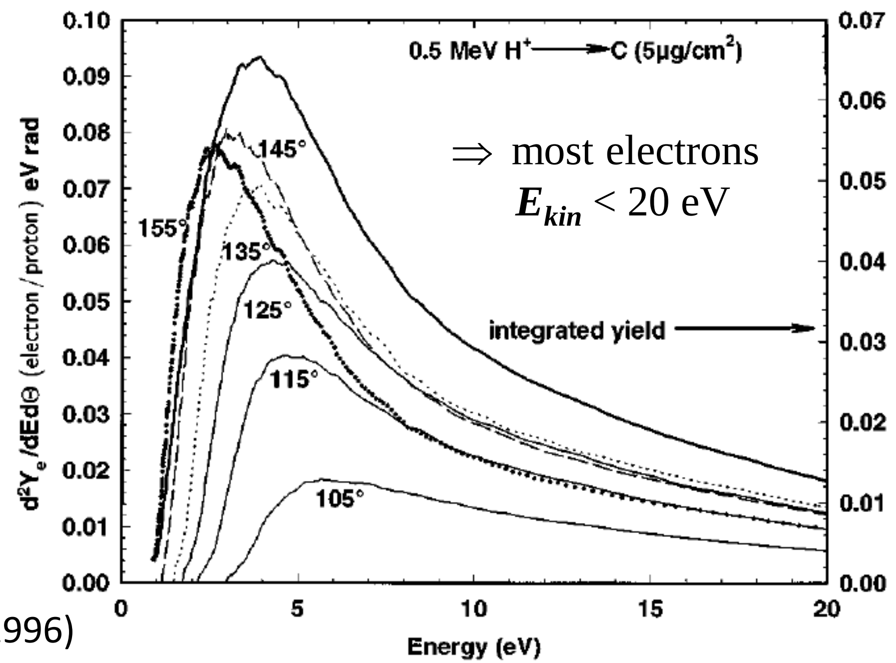


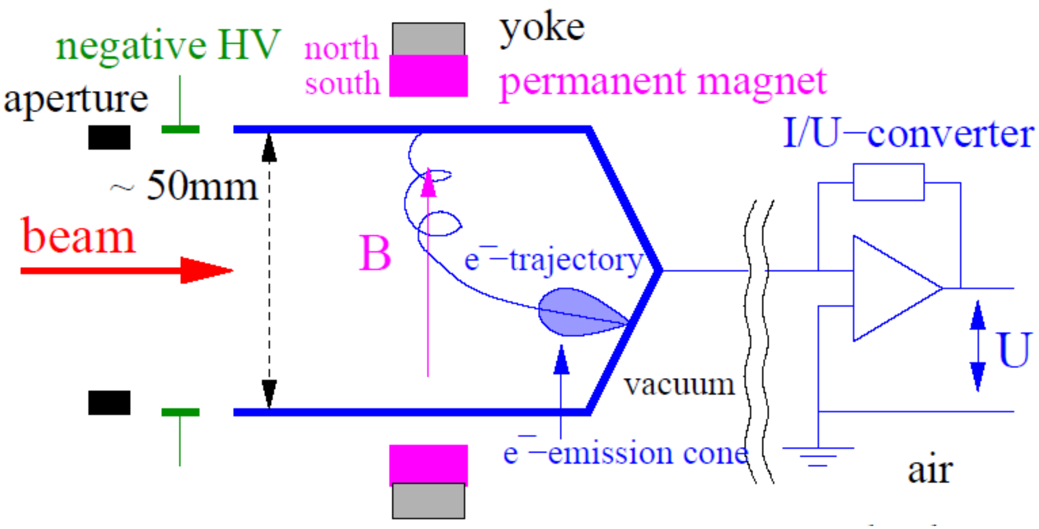


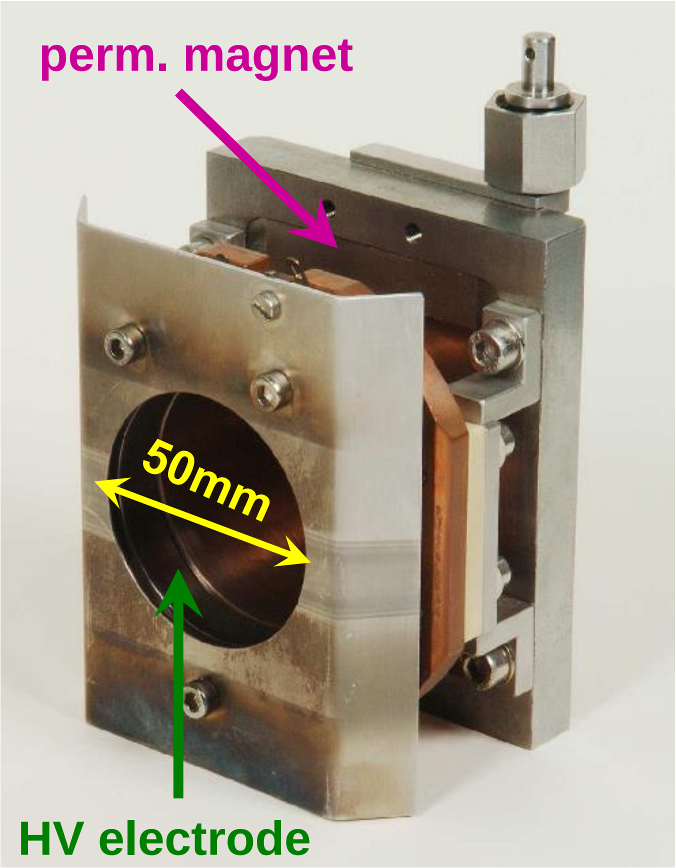
From C.G. Drexler, R.D. DuBois, Phys. Rev. A 53, 1630 (1996)

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

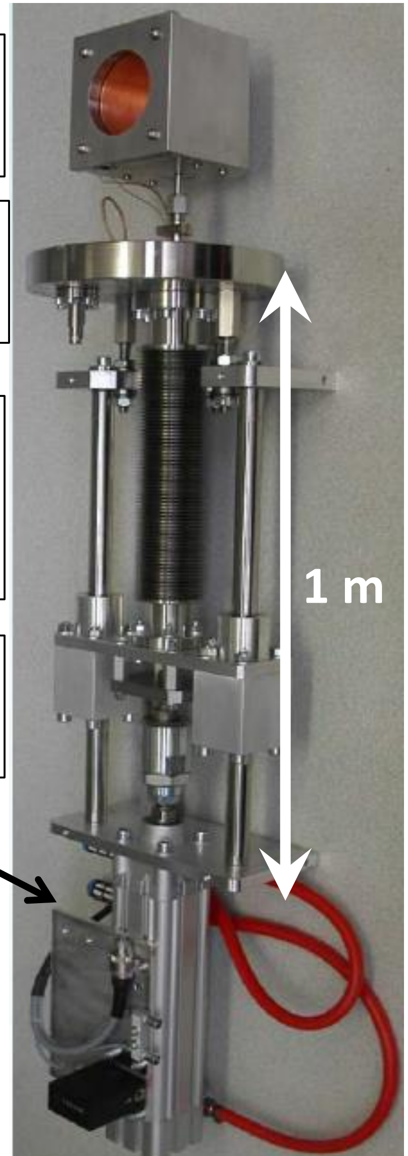
The Cup is moved
into the beam pass.

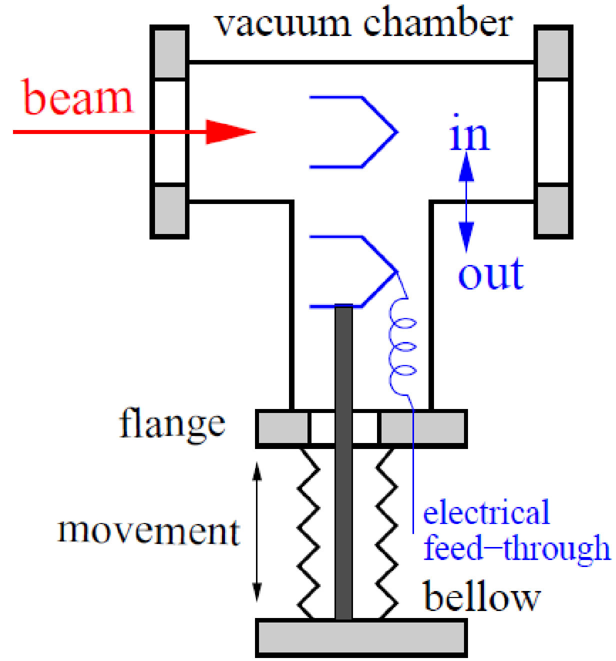
Faraday Cup
∅60 mm

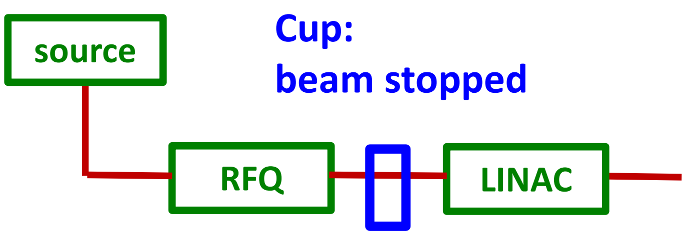
vacuum flange
here ∅150 mm

bellow
compression
for movement

pneumatic
drive





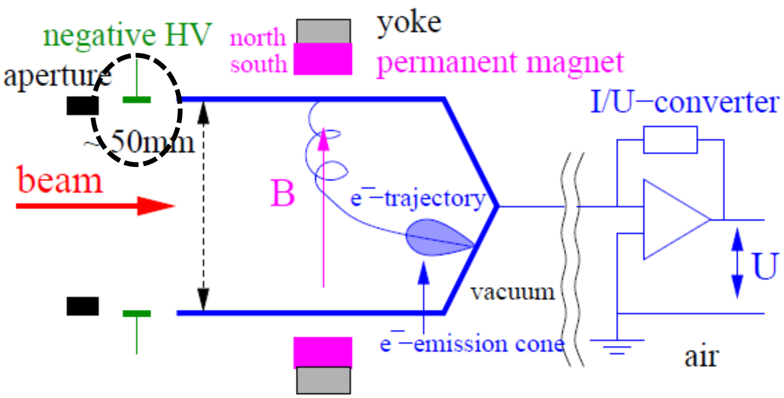


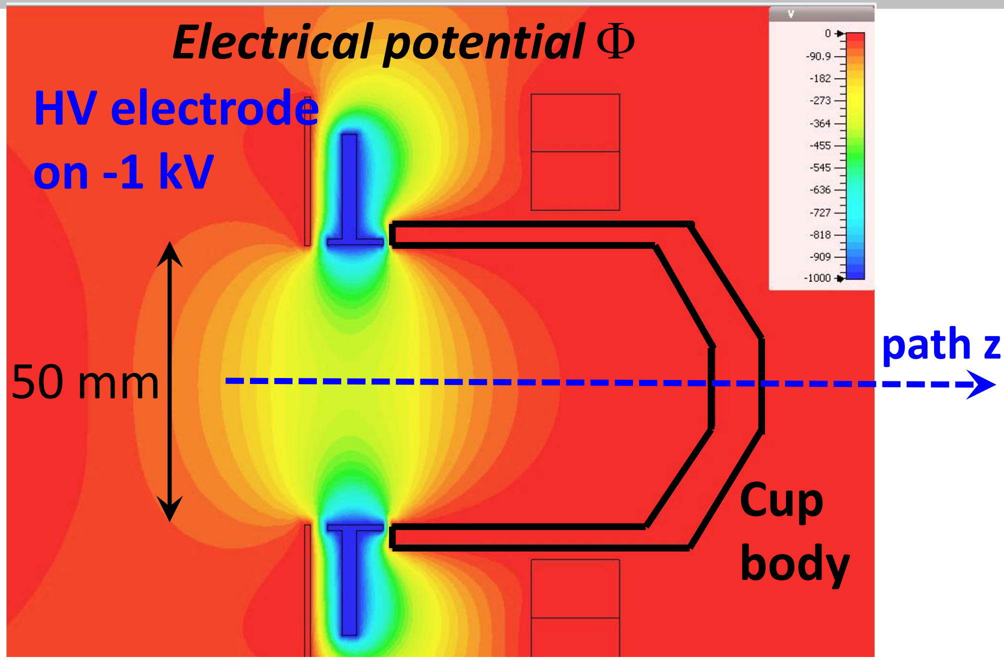
Cup:
beam stopped

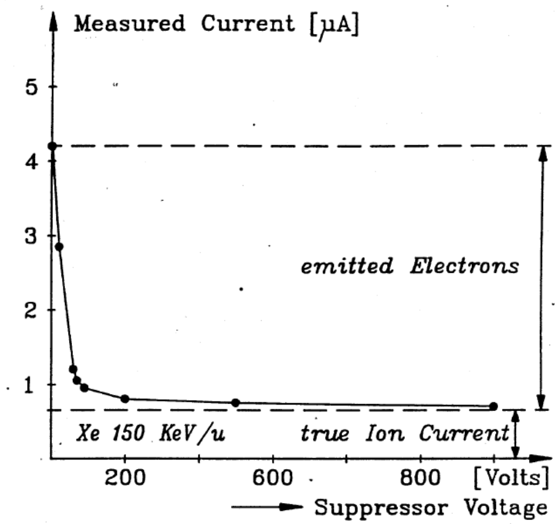
Secondary Electron Suppression: Electric Field

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

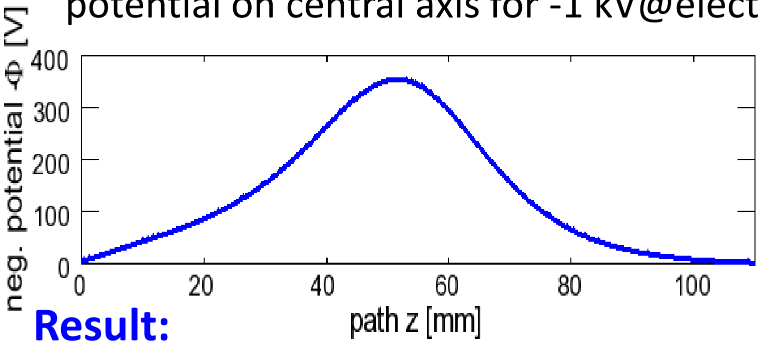
Typical voltage 100 to 1000 V







potential on central axis for -1 kV@electrode



Result:

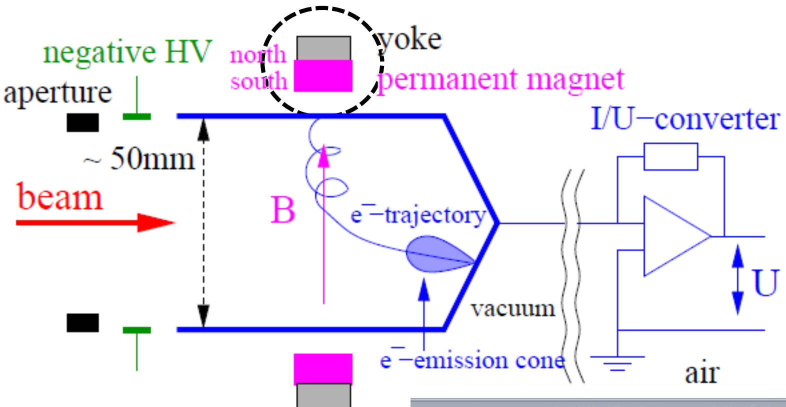
here: potential at center ≈ 35 % of applied voltage

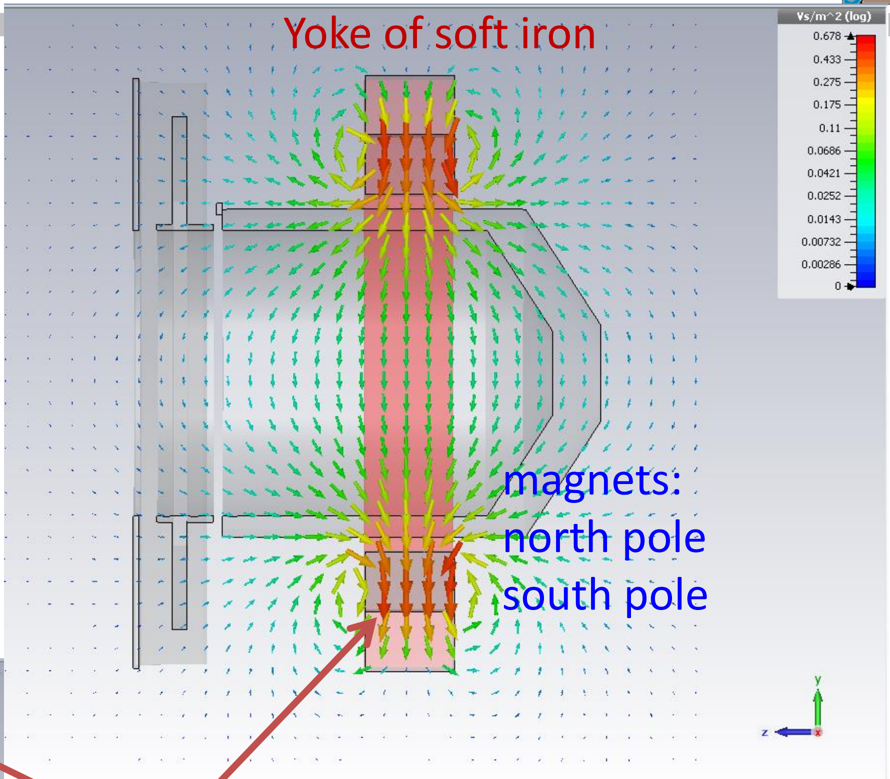
Courtesy of J. Latzko, GSI

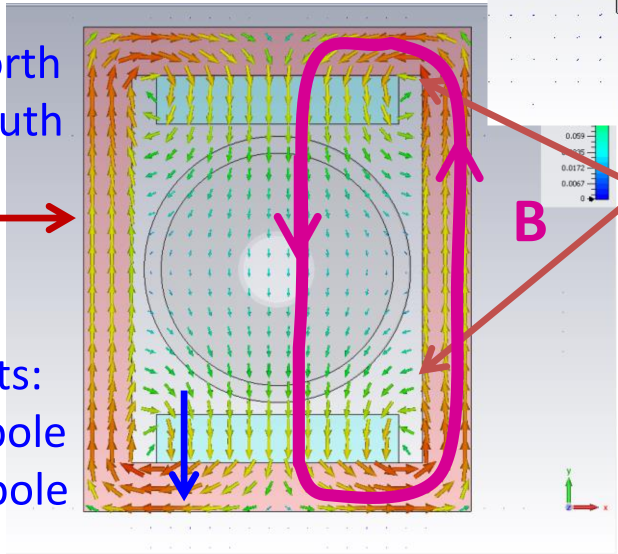
Secondary Electron Suppression: Magnetic Field

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

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

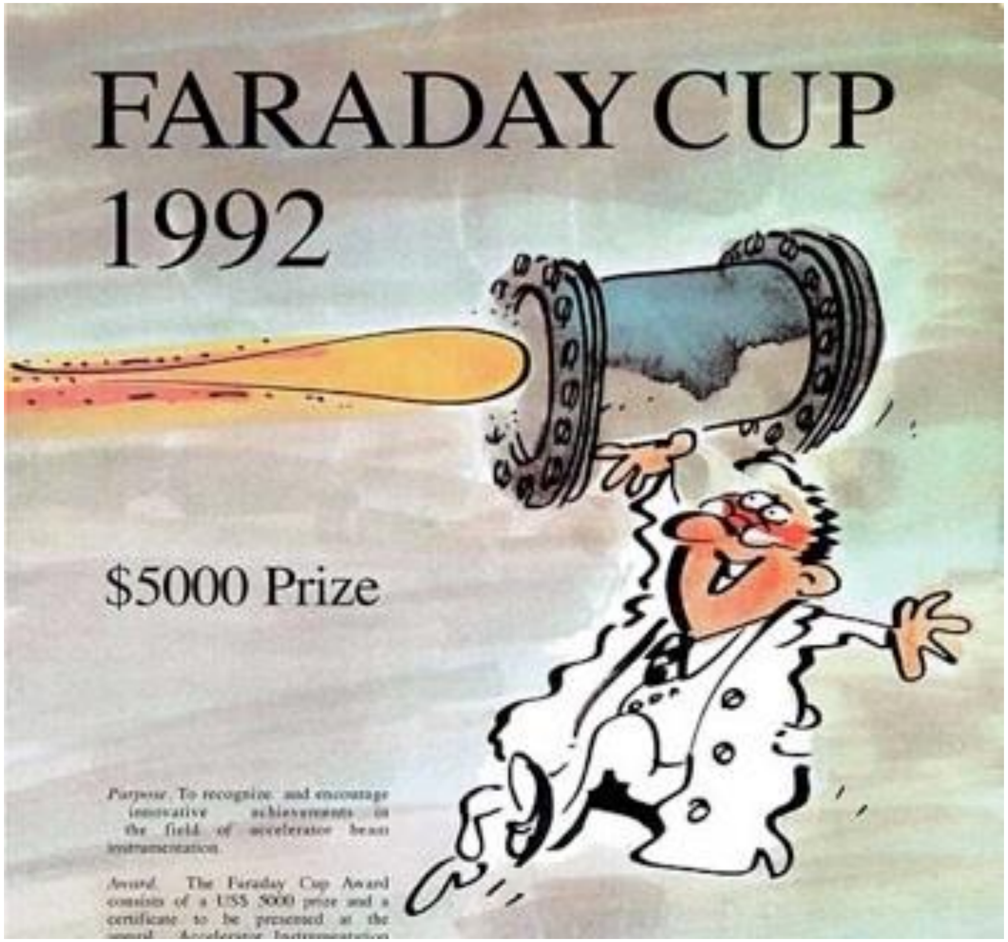






Courtesy of J. Latzko, GSI

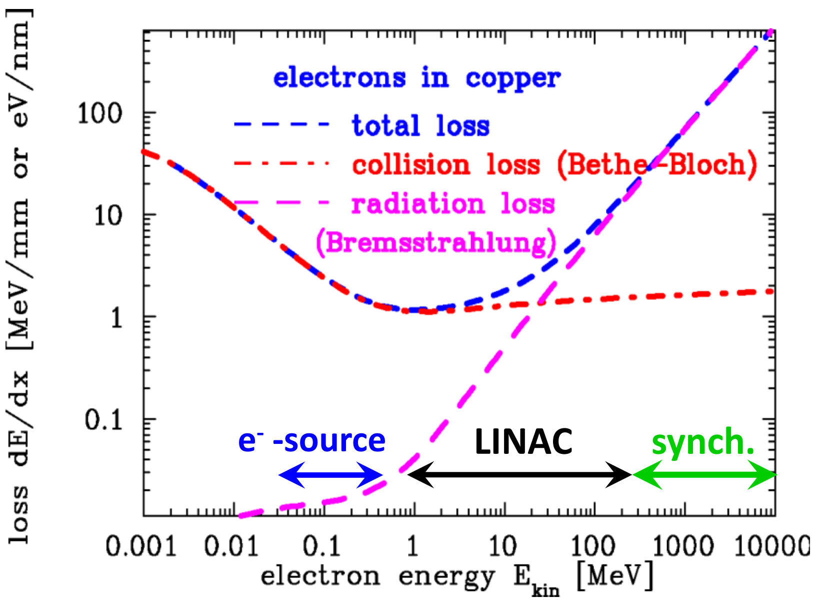
The Artists View of Faraday Cup

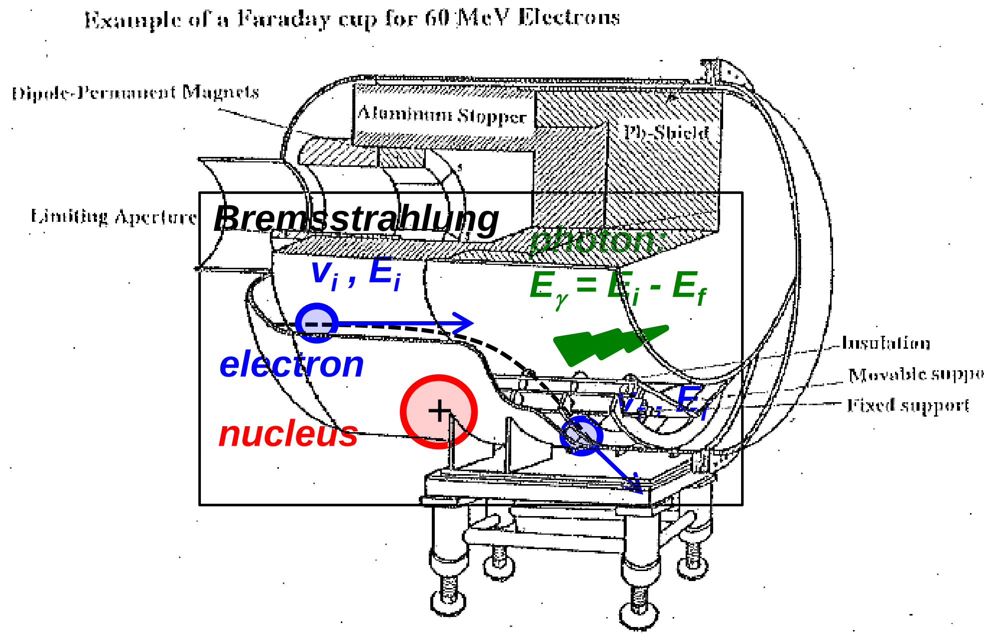


Company Bergoz

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

Collisional loss by Bethe-Bloch formula $dE/dx\,|_{col} \propto f(E_{kin}) \cdot Z_t$ is valid for all charged particles. However, radiation loss $dE/dx\,|_{rad}$ by Bremsstrahlung (i.e. γ-rays of some MeV) dominates for energies above E_{kin} > 10 MeV with the scaling $dE/dx\,|_{rad} \propto E_{kin} \cdot Z_t^2$.
Moreover, e^- shows much larger longitudinal and transverse straggling.





Minimum of Bethe-Bloch $dE/dx\,|_{col}$ roughly at $E_{kin} \approx m_0c^2$ = 511 keV (rest mass)
$\Leftrightarrow \beta \approx 90\,\%$ and $\gamma = \frac{1}{\sqrt{1-\beta^2}} \approx 2$

Al stopper: Stopping of e^- gently in low-Z material
Pb-shield: Absorption of Bremsstrahlungs-γ
⇒ Used as beam dump

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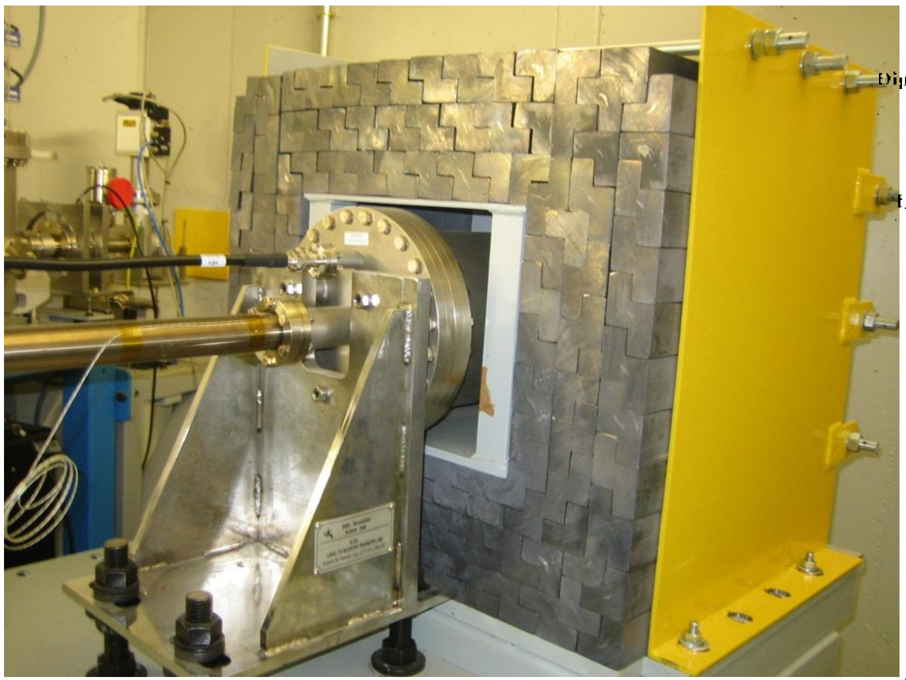
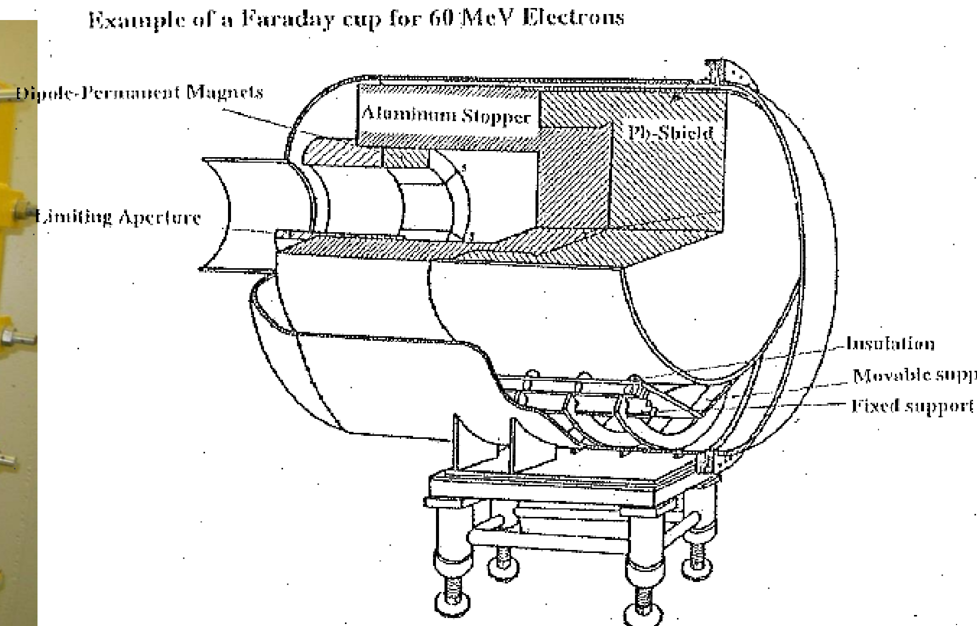


Faraday Cup at ALBA used as beam dump

From U. Iriso (ALBA)



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Pb-shield: Absorption of Bremsstrahlungs-γ
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- 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.

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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

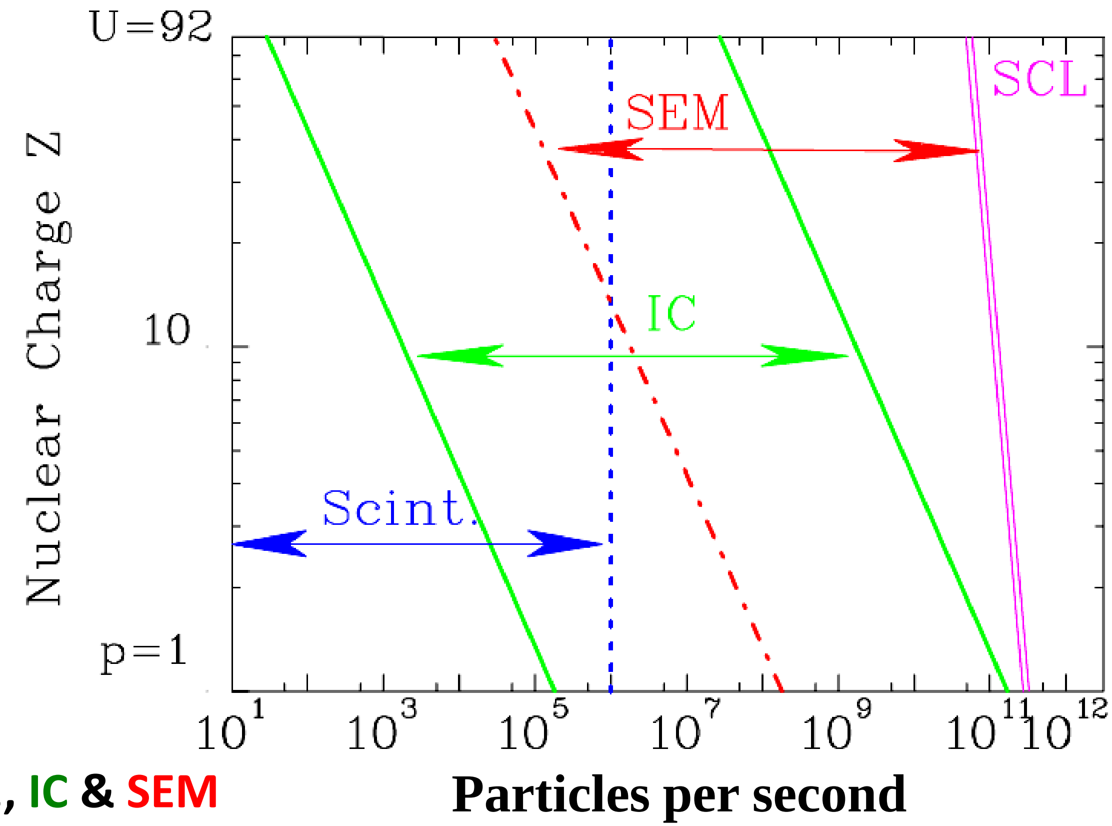
  Examples are scintillators, ionization chambers, secondary e− emission monitors

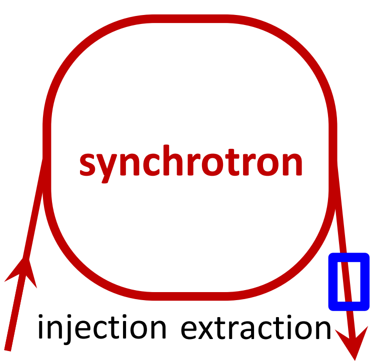
  Used for low currents at high energies e.g. for slow extraction from a synchrotron.

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:





Scint., IC & SEM

Example of Scintillator Counter

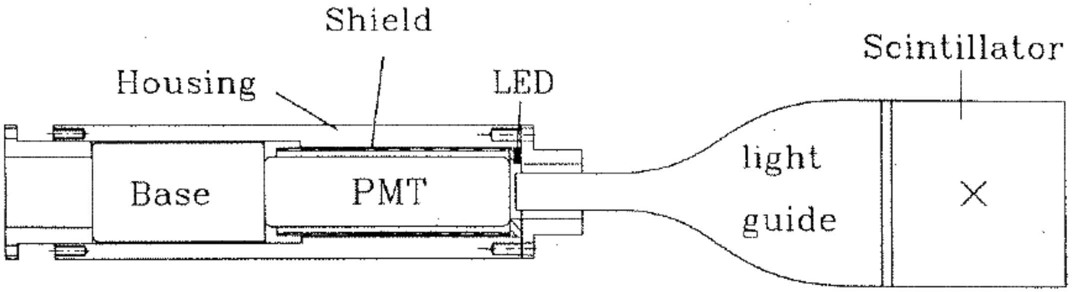
Example: Plastic Scintillator i.e. organic fluorescence molecules in a plastic matrix

Here: BC 400 (emission λ_{max} = 420 nm, pulse width ≈ 3 ns + cable dispersion, size)

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

Disadvantage: not radiation hard

Particle counting: Photomultiplier → discriminator → scalar → computer



1'' Photomultiplier
gain: 10^6
rise time 1.9 ns
max. **average** count rate $3 \cdot 10^6$ 1/s

BC400 Scintillator
75 x 75 mm^2
1 mm thickness

Low Current Measurement: Particle Detectors

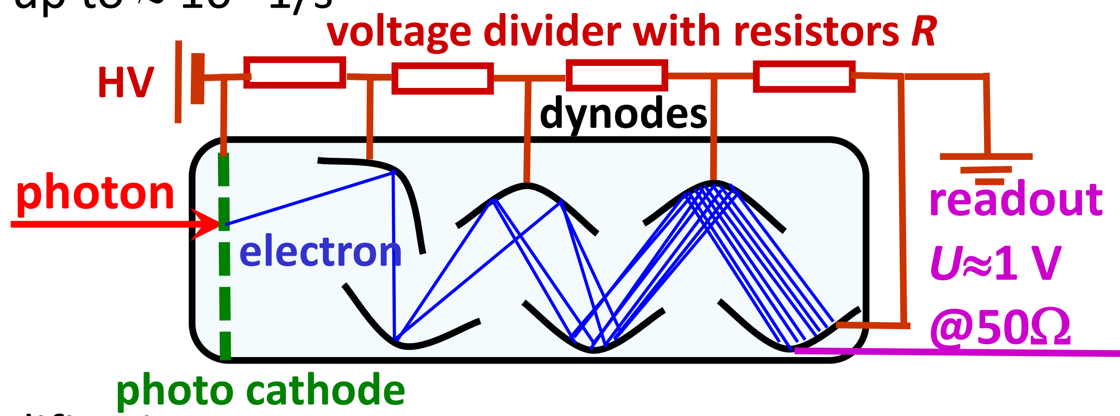
Electronic **solid state amplifier** have finite noise contribution

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

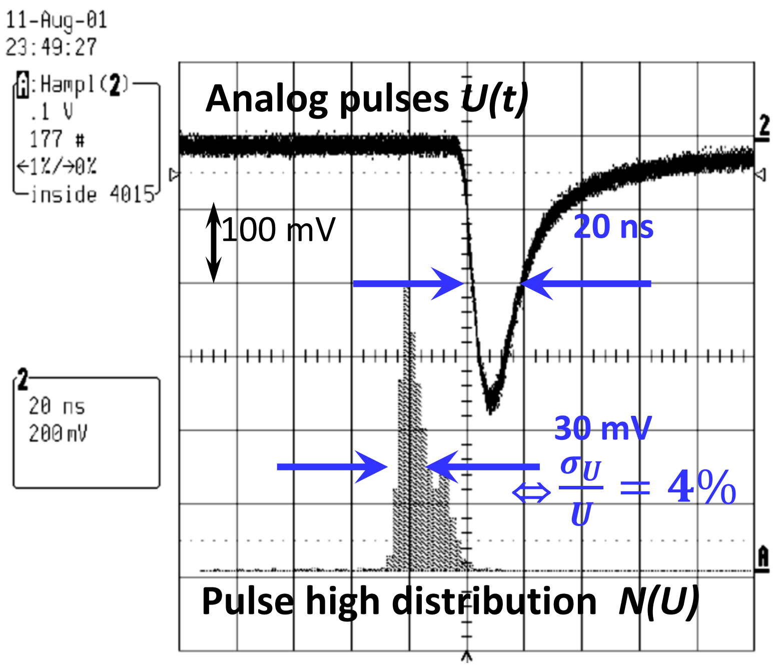
Typical 1 V signal output

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 < λ < 500 nm
- Index of refractivity $n \approx 1.5$
  → light-guide
- Radiation hardness
  e.g. Ce-activated inorganic
  are much more radiation hard.

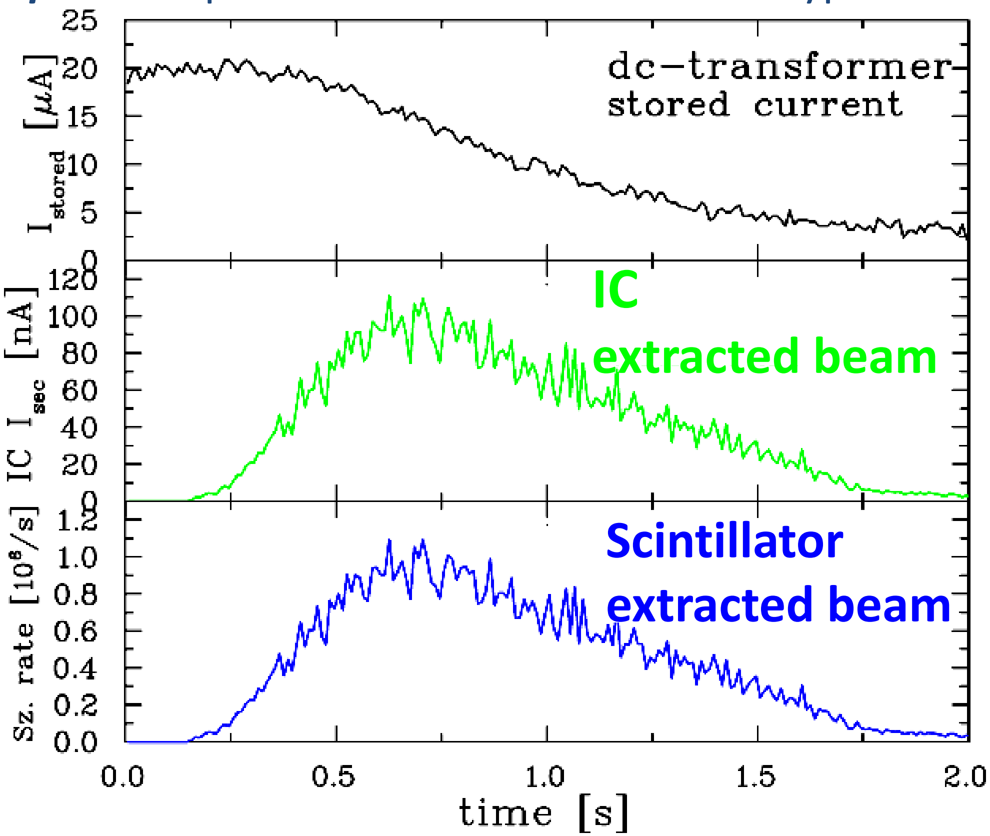
Analog pulses from a plastic sc. with a low current 300 MeV/u Kr beam.

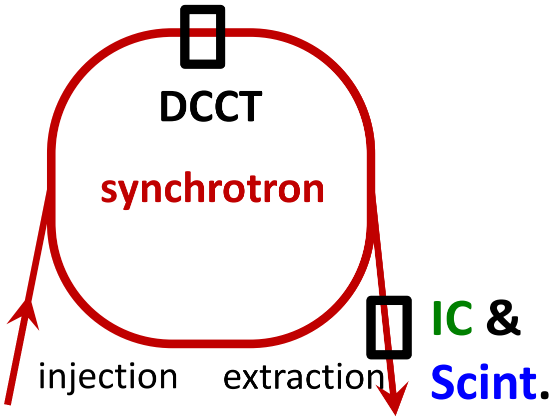


The scaling is 20 ns/div and 100 mV/div.

Slow extraction from a synchrotron delivers countable currents

Example: Comparison for different detector types:



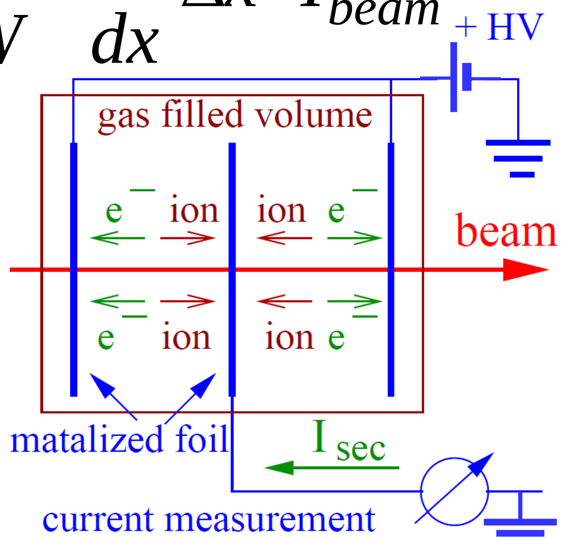


Parameters: dc-transformer inside the synch., ionization chamber and scintillator for a 250 MeV/u Pb^{67+} beam with a total amount of 10^6 particles.

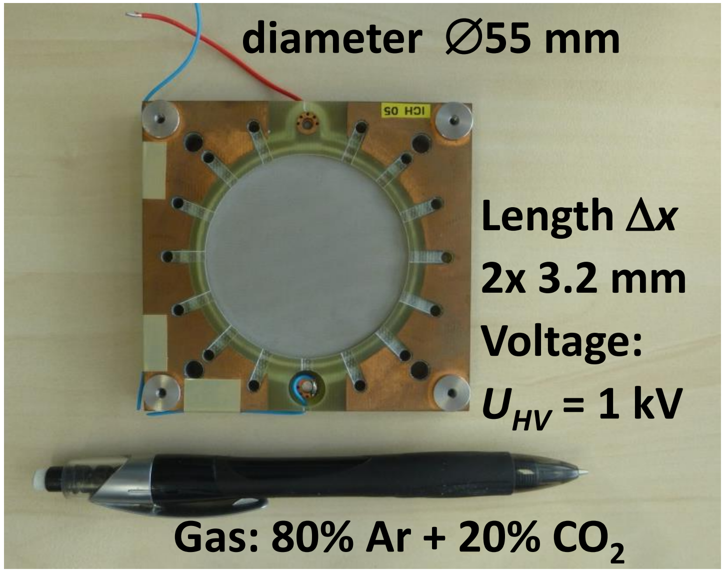
Ionization Chamber (IC): Electron Ion Pairs

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

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



Example: GSI type:



W-value

is the average energy for one e^- -ion pair:

Gas	Ionization Pot.	W-value
He	24.5 eV	42.7 eV
N_2	15.5 eV	36.4 eV
O_2	12.5 eV	32.2 eV
Ar	15.7 eV	26.3 eV
CO_2	13.7 eV	33.0 eV

GSI realization:

- Energy calculation *dE/dx* with SRIM or LISE
- Current measurement via current-to-frequency converter IFC

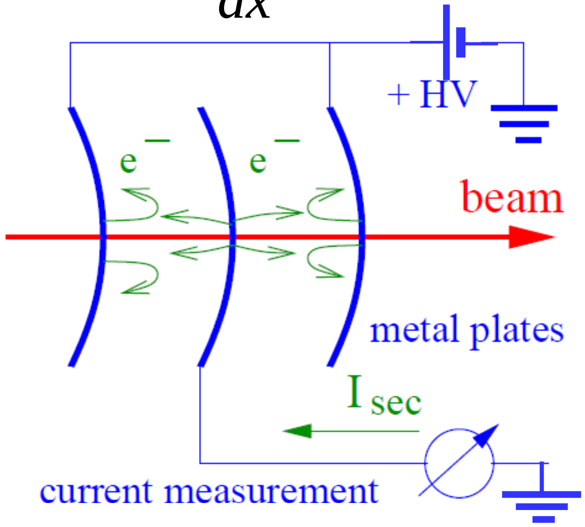
Secondary Electron Monitor (SEM): Electrons from Surface

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%)
# electrodes	3
Active surface	80 x 80 mm ^{2}
Distance between electrodes	5 mm
Applied voltage	+ 100 V
CO_2	13.7 eV

Advantage for Al: good mechanical properties.

Disadvantage: Surface effect!

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

⇒ calibration versus IC required to reach 5%.

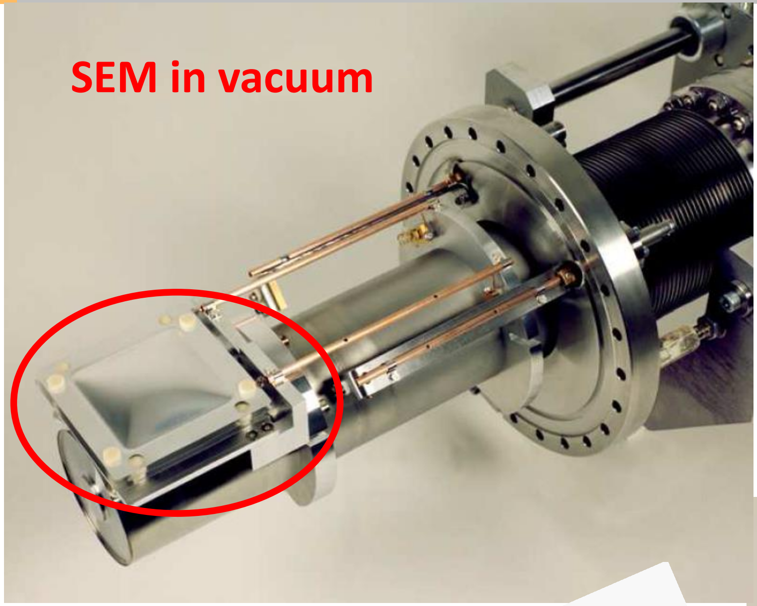
It is a ***surface*** effect:

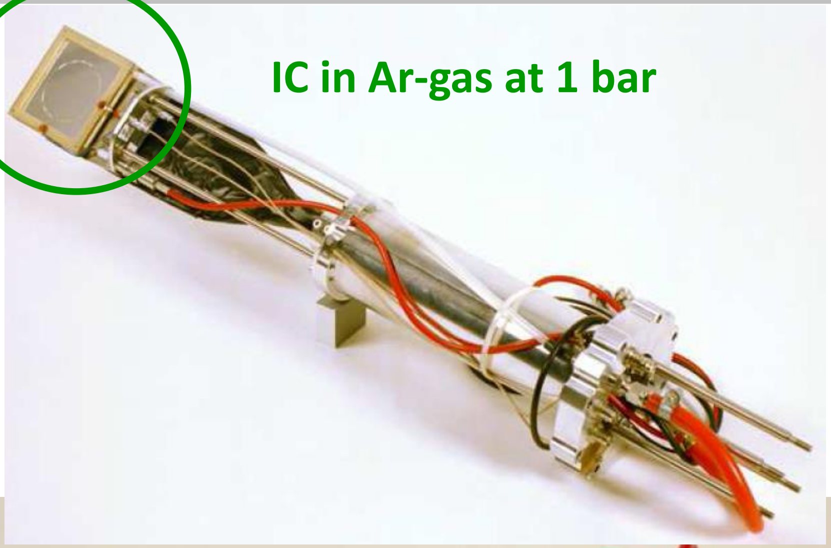
→ Sensitive to cleaning procedure

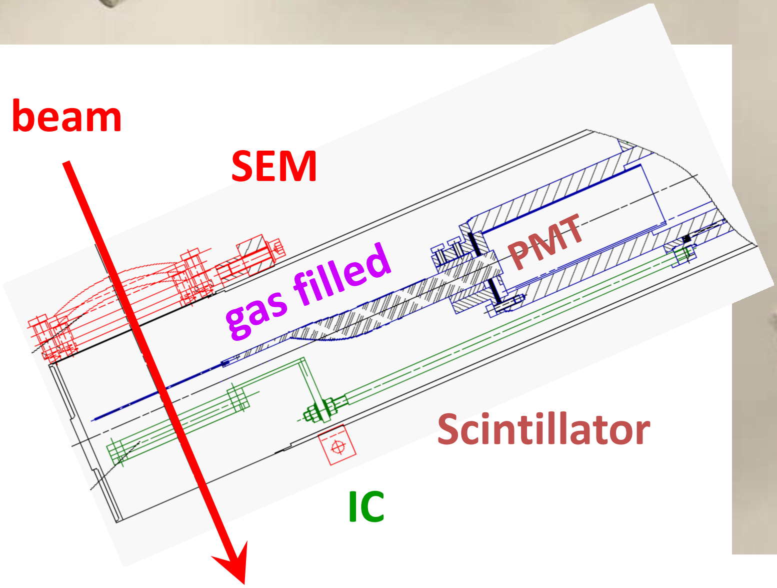
→ Possible surface modification by radiation

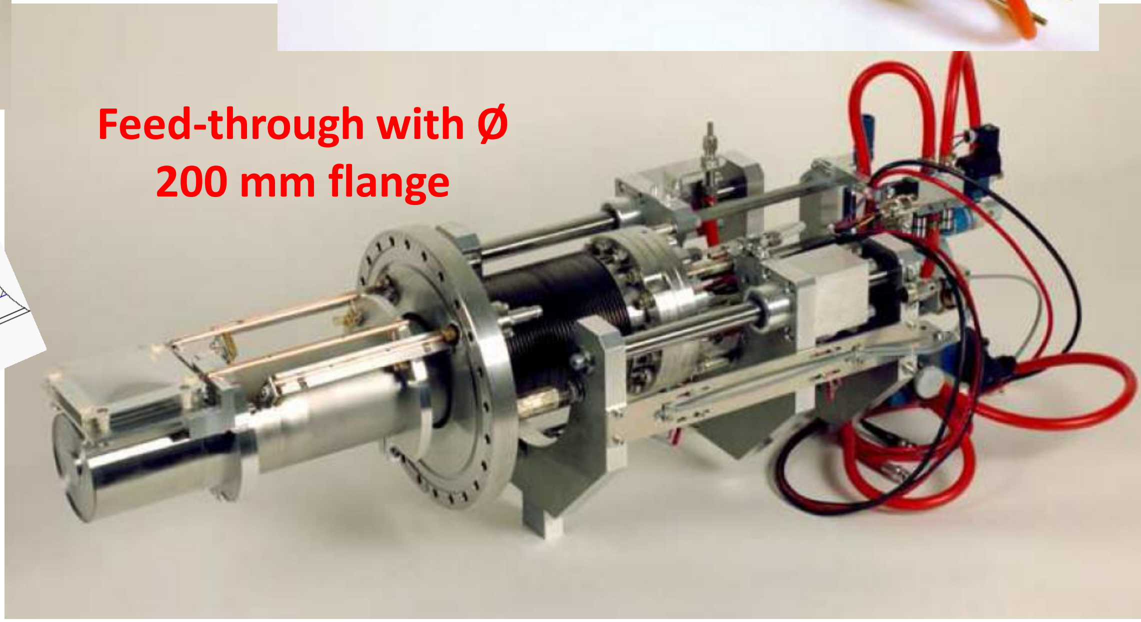
Sometimes they are installed permanently in front of an experiment.

GSI Installation for SEM, IC and Scintillator









P. Forck et al., DIPAC’97

Appendix: GSI Heavy Ion Research Center

German national heavy ion accelerator facility in Darmstadt

Accelerators:

Acceleration of all ions

LINAC: up to 15 MeV/u

Synchrotron: up to 2 GeV/u

Research area:

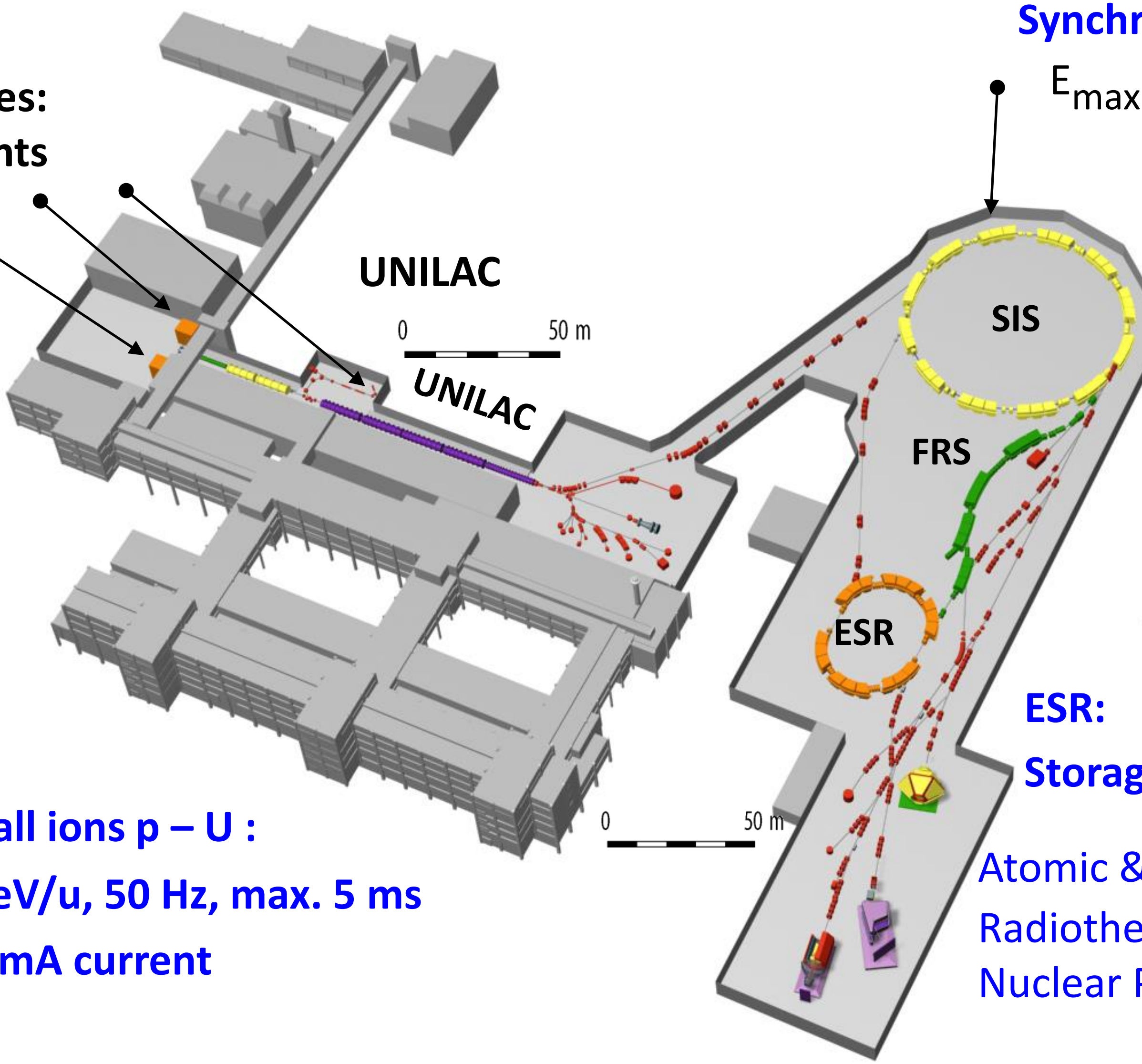
- Nuclear physics ≈ 60 %
- Atomic physics ≈ 20 %
- Bio physics (e.g. cell damage)
  incl. cancer therapy ≈ 10 %
- Material research ≈ 10 %

Extension by international FAIR facility

GSI is one of 18 German large scale research centers.

Appendix: The Accelerator Facility at GSI

Ion Sources:
all elements



Synchrotron, Bρ=18 Tm

E_{max} p: 4.7 GeV

U: 1 GeV/u

Achieved e.g.:

Ar^{18+}: $1\cdot10^{11}$

U^{28+}: $3\cdot10^{10}$

U^{73+}: $1\cdot10^{10}$

ESR:

Storage Ring, Bρ=10 Tm

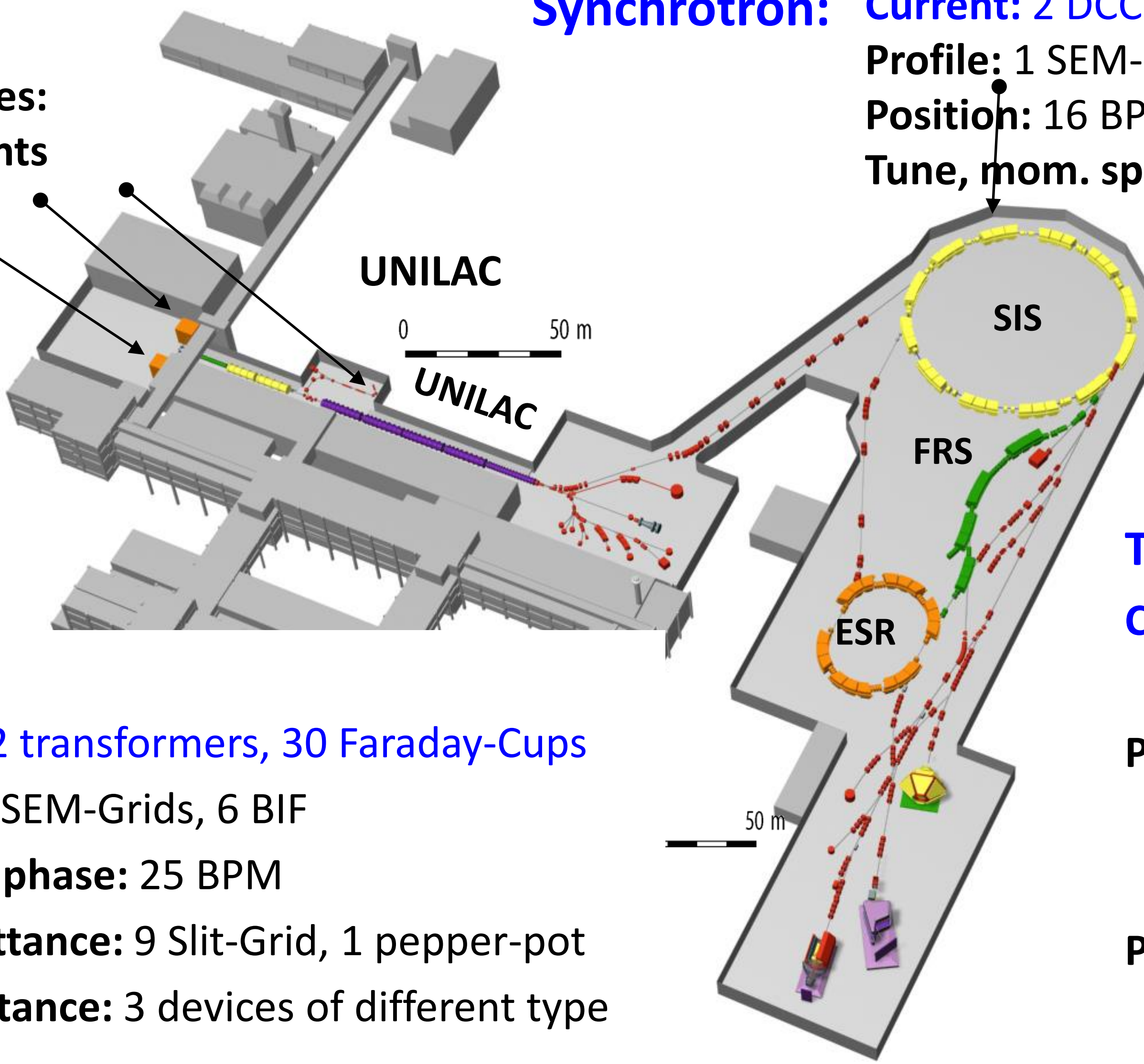
Atomic & Plasma Physics
Radiotherapy
Nuclear Physics

UNILAC: all ions p – U :

3 – 12 MeV/u, 50 Hz, max. 5 ms

Up to 20 mA current

Appendix: Beam Instruments at GSI Accelerator Facility



Ion Sources: all elements

Synchrotron:

Current: 2 DCCT, 1 ACCT, 1 FCT
Profile: 1 SEM-Grid, 1 IPM, 1 Screen
Position: 16 BPM
Tune, mom. spread: 1 Exciter + BPM
1 Schottky

Transport Lines:

Current: 8 FCT
15 Part. Detec.
Profile: 10 SEM-Grid
26 MWPC
18 Screens
Position: 8 BPM

LINAC:

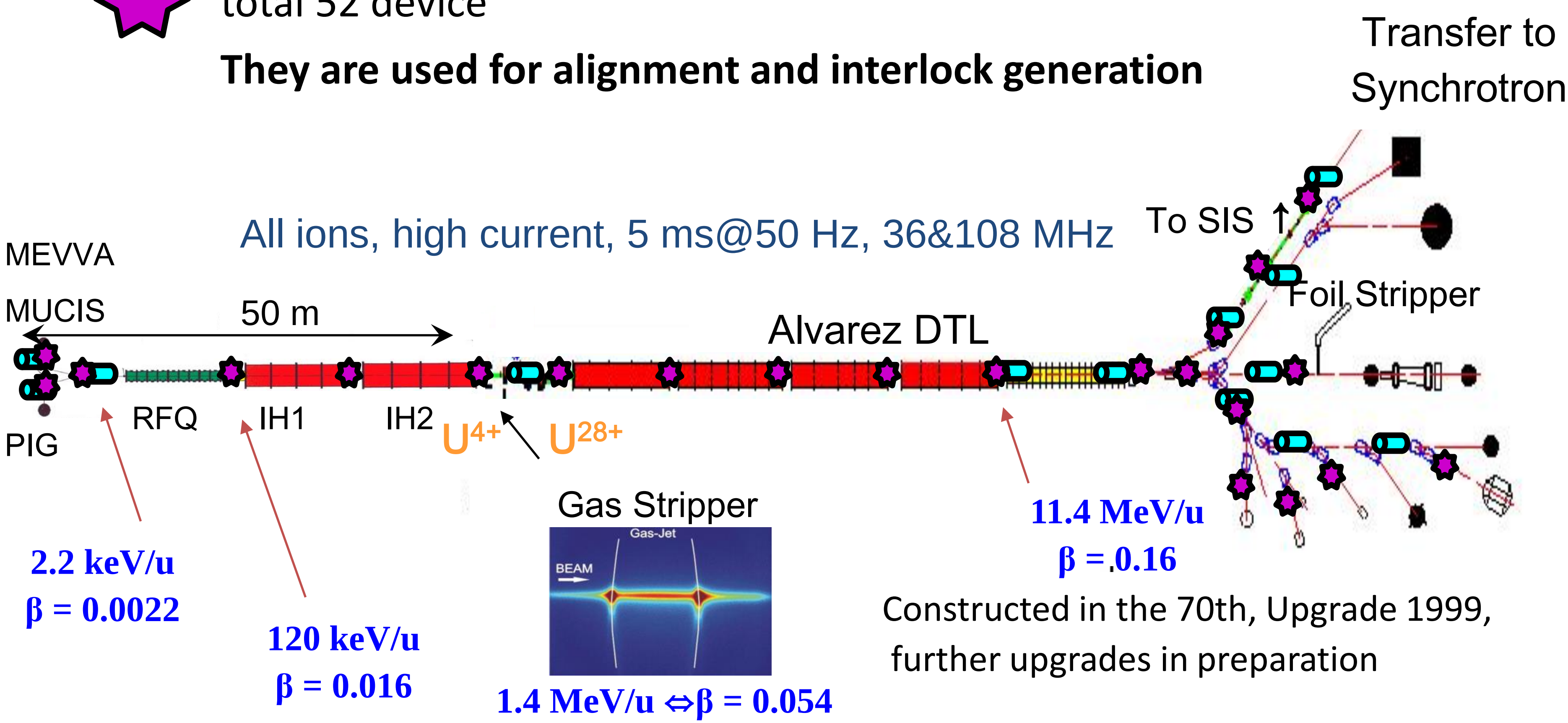
Current: 52 transformers, 30 Faraday-Cups
Profile: 81 SEM-Grids, 6 BIF
Position & phase: 25 BPM
Trans. emittance: 9 Slit-Grid, 1 pepper-pot
Long. emittance: 3 devices of different type

Appendix: UNILAC at GSI: Current Measurement

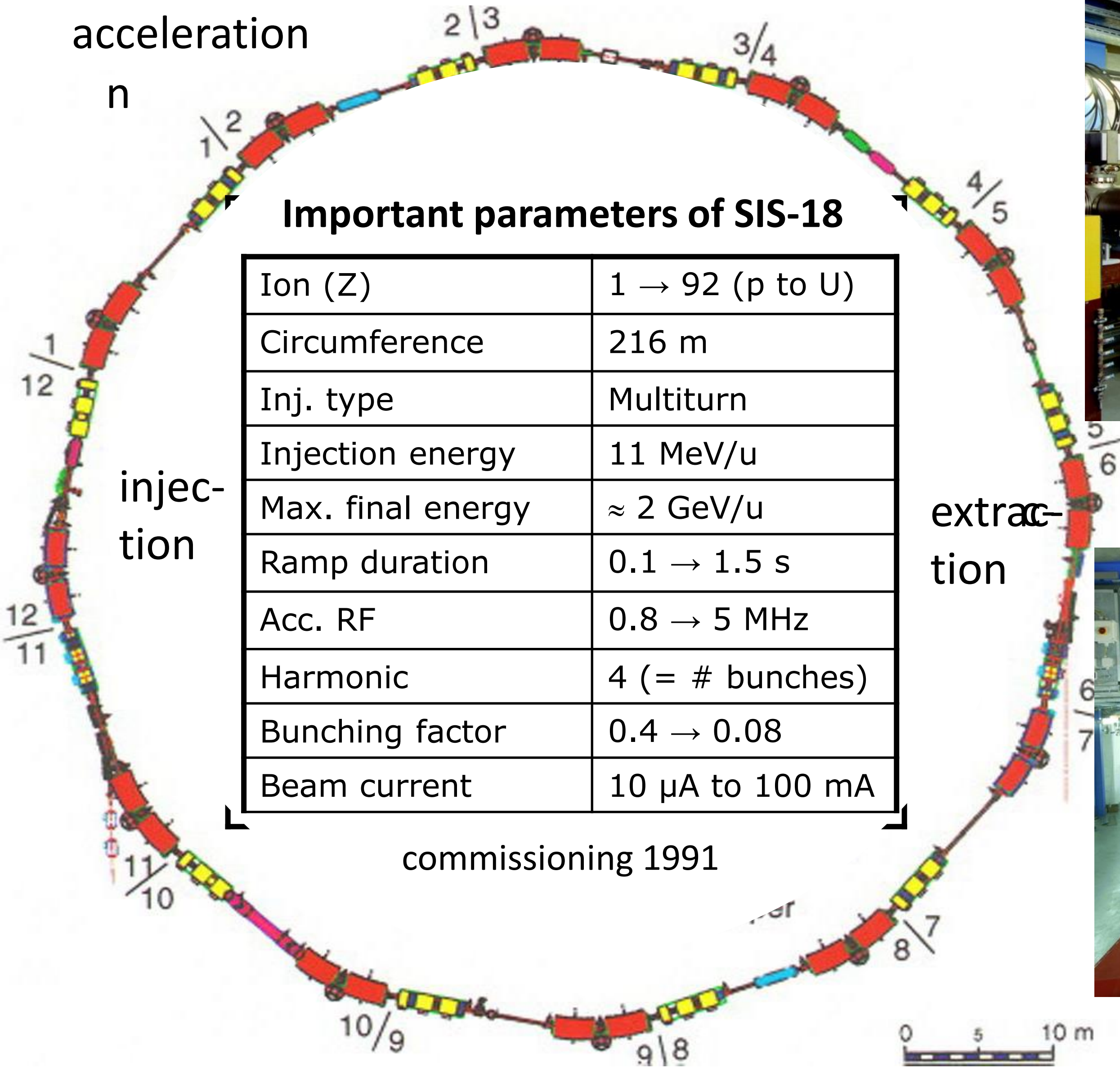
Faraday Cup: for low current measurement and beam stop, total 30

Transformer ACCT: for current measurement and transmission control total 52 device

They are used for alignment and interlock generation



Appendix: GSI Heavy Ion Synchrotron: Overview



acceleration

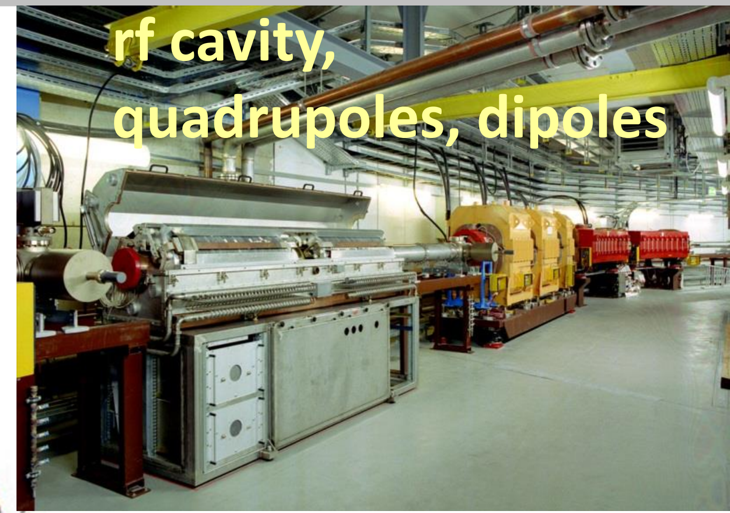
Important parameters of SIS-18

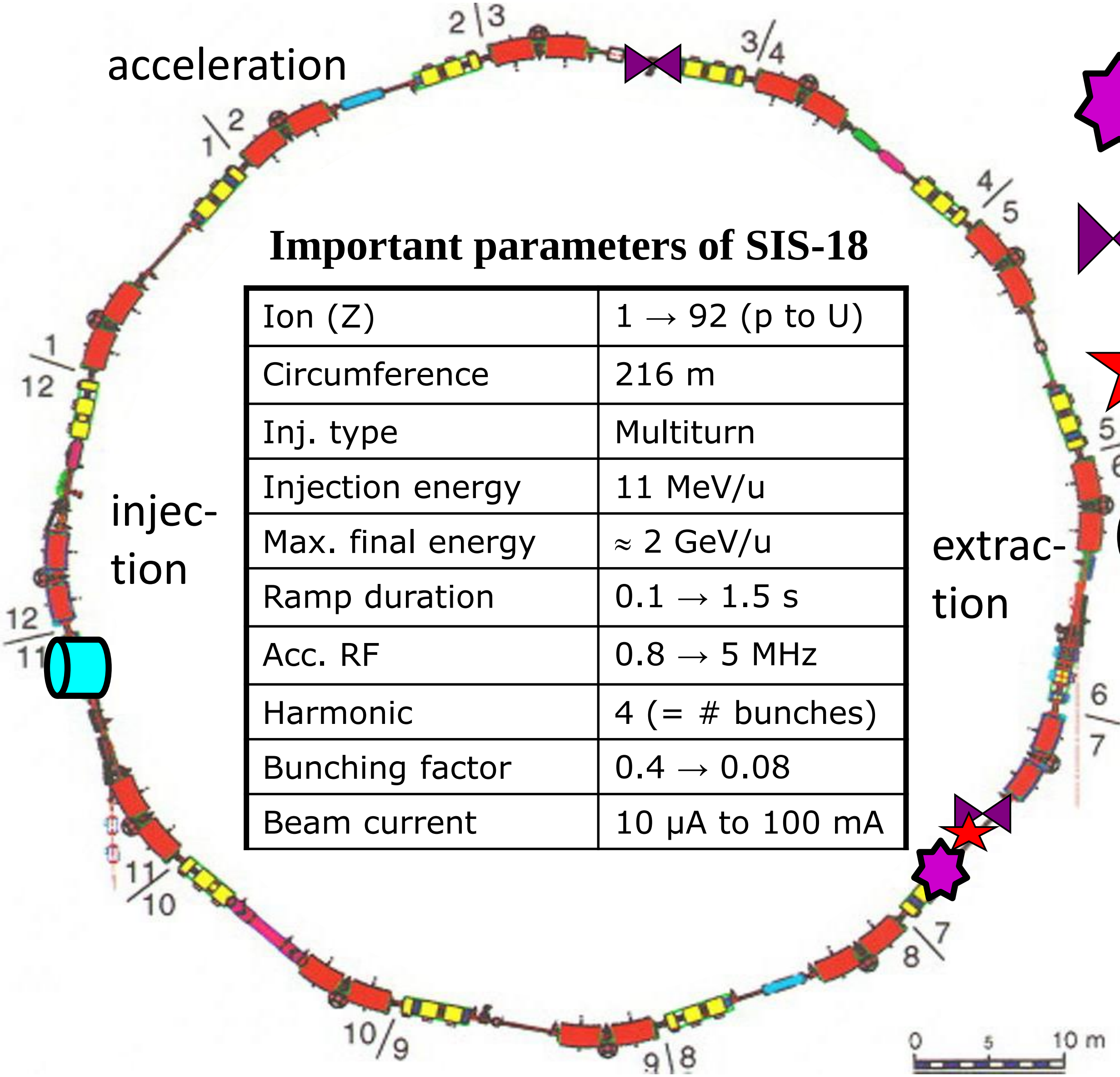
Ion (Z)	1 → 92 (p to U)
Circumference	216 m
Inj. type	Multiturn
Injection energy	11 MeV/u
Max. final energy	≈ 2 GeV/u
Ramp duration	0.1 → 1.5 s
Acc. RF	0.8 → 5 MHz
Harmonic	4 (= # bunches)
Bunching factor	0.4 → 0.08
Beam current	10 μA to 100 mA

commissioning 1991

injection

extraction





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ACCT: injected current 0.01... 1 MHz

DCCT: circulating current 0... 10 kHz

FCT: bunch structure 0.01... 500 MHz

Faraday Cup: beam dump

Appendix: 3rd Generation Light Sources

Soleil, Paris, $\boldsymbol{E_{electron}}$= 2.5 GeV, $\boldsymbol{C}$ = 354 m

3rd Generation Light Sources:

Synchrotron-based

with $\boldsymbol{E_{electron}} \approx$ 1…8 GeV

Light from undulators & wigglers, dipoles,

with $\boldsymbol{E_\gamma}$< 10 keV (optical to deep UV)

Users in:

- Biology (e.g. protein crystallography)
- Chemistry (e.g. observation of reaction dynamics)
- material science (e.g. x-ray diffraction)
- Basic research in solid state and atomic physics

Unique setting: intense, broad-band light emission (monochromator for wavelength selection)

National facilities in many counties, some international facilities.

Appendix: The Spanish Synchrotron Light Facility ALBA

3rd generation Spanish national synchrotron light facility in Barcelona

Layout:

Beam lines: up to 30

Electron energy: 3 GeV

Top-up injection

Storage ring length: 268 m

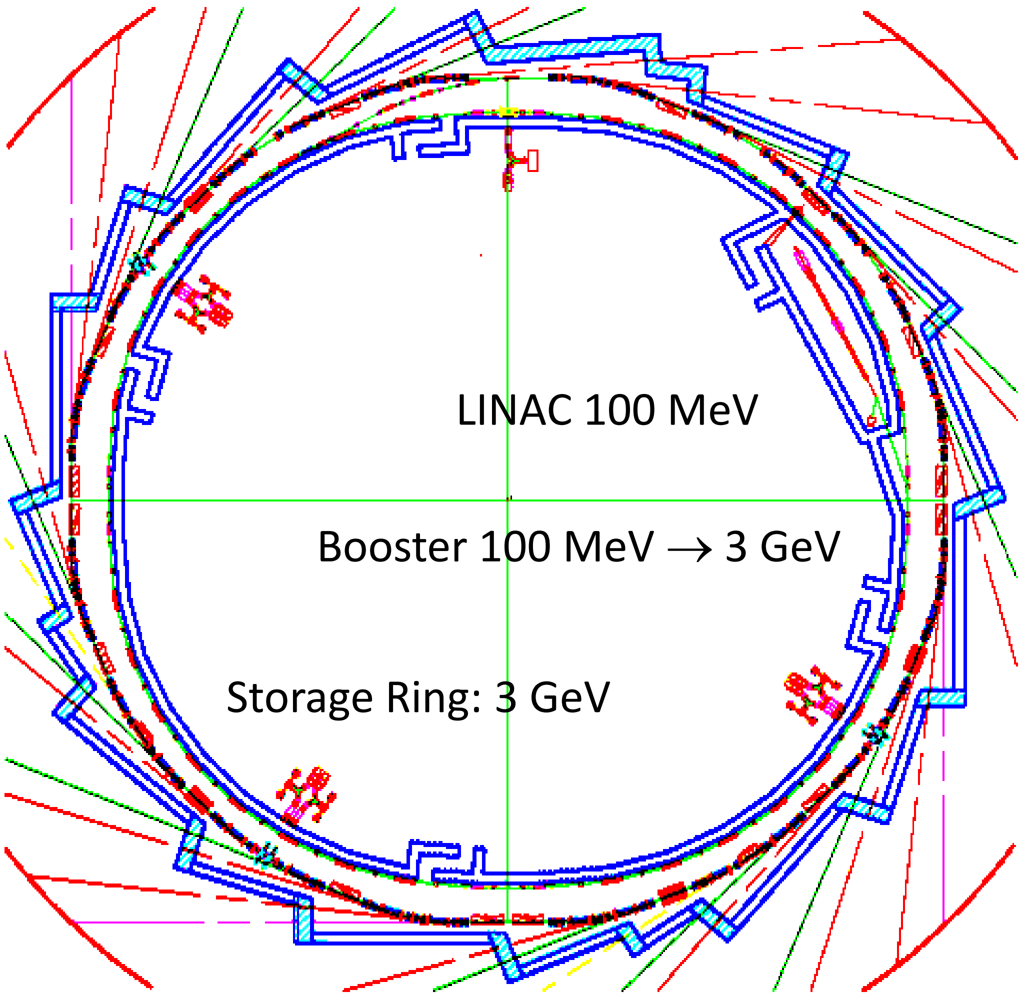
Max. beam current: 0.4 A

Commissioning in 2011

Talk by Ubaldo Iriso: at DIPAC 2011, adweb.desy.de/mpy/DIPAC2011/html/sessi0n.htm

see also www.cells.es/Divisions/Accelerators/RF_Diagnostics/Diagnostics

3rd generation Spanish national synchrotron light facility in Barcelona



From U. Iriso, ALBA

Layout:

Beam lines: up to 30

Electron energy: 3 GeV

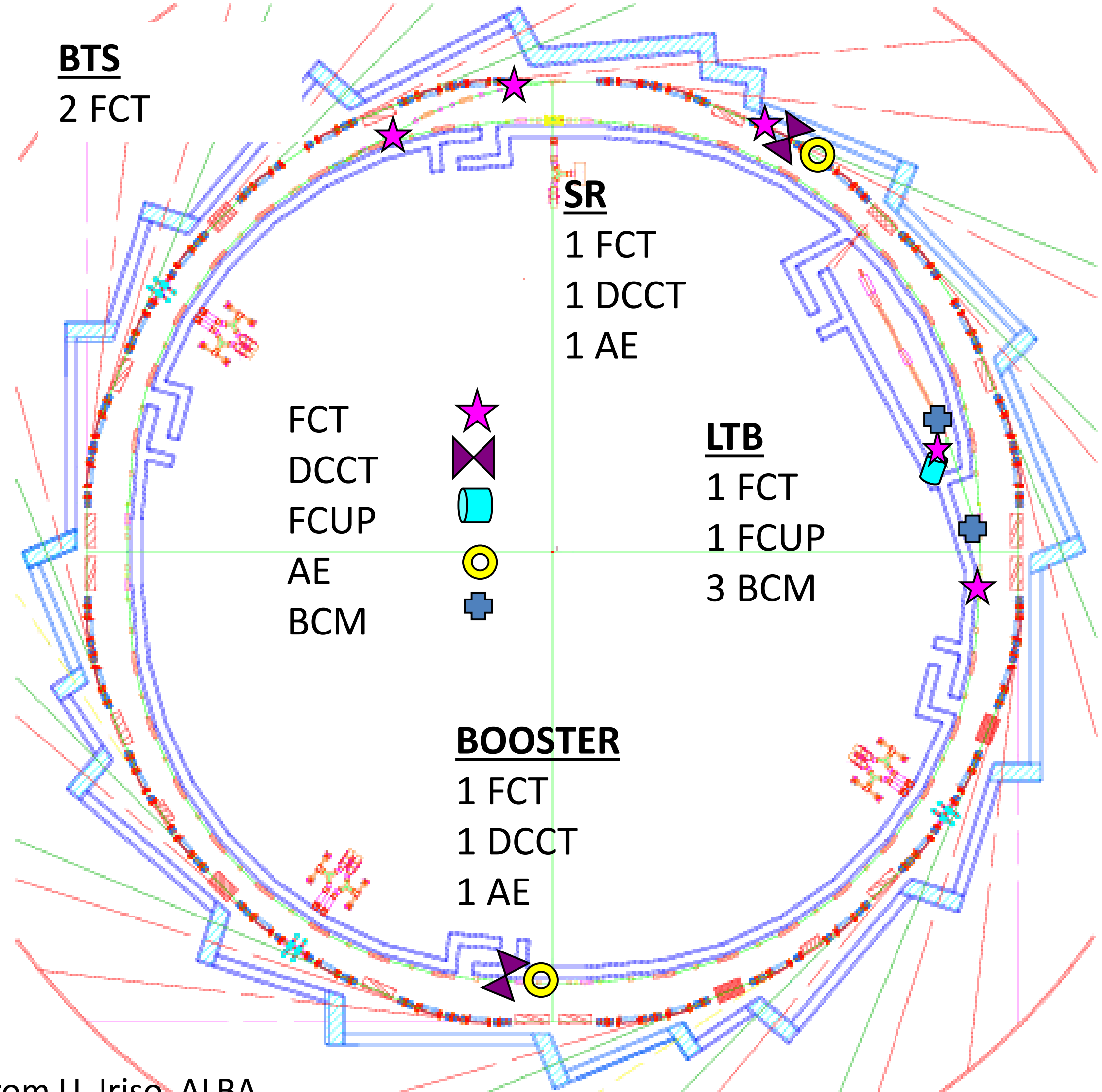
Top-up injection

Storage ring length: 268 m

Max. beam current: 0.4 A

Commissioning in 2011

Appendix: The Synchrotron Light Facility ALBA: Current Meas.



From U. Iriso, ALBA

Beam current:

Amount of electrons accelerated, transported and stored

- Several in transport lines
- One per ring

Abbreviation:

FCT: Fast Current Transformer
DCCT: dc transformer
FCUP: Faraday Cup
AE: Annular Electrode
BCM: Bunch Charge Monitor

Remark:

AE: Annular Electrode
i.e. circular electrode acting like a high frequency pick-up

Summary for Current Measurement

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**

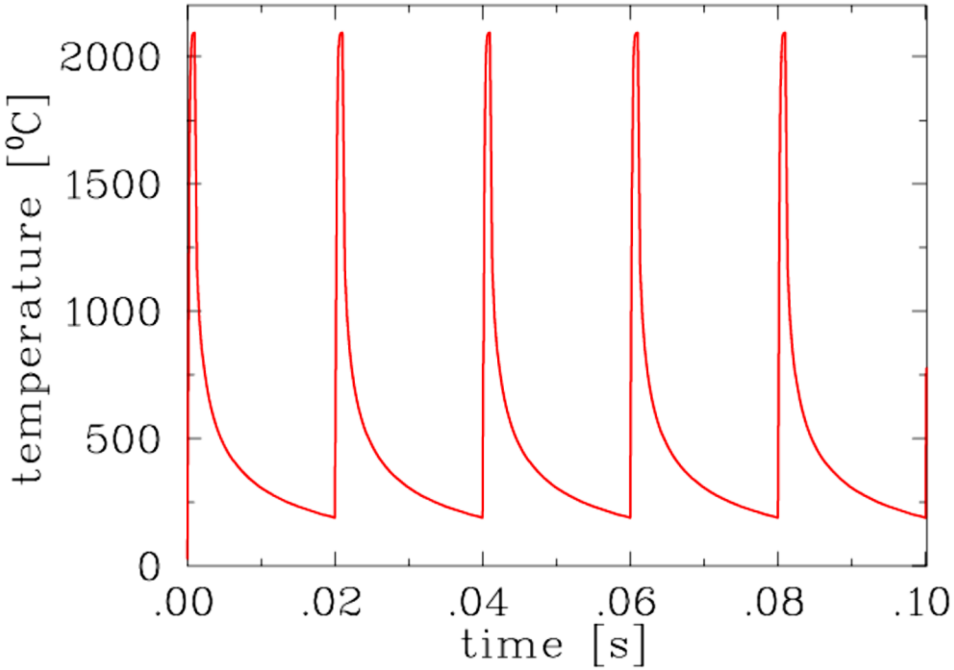
- particle counting (Scintillator)
- secondary current: **IC** from gas ionization or **SEM** sec. e^- emission surface
- no lower threshold due to single particle counting
- partly destructive, used for high energy beams

Backup slides

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 ε = 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.