Optics Measurement Techniques for Transfer Line & Beam Instrumentation

CAS for Beam Injection, Extraction and Transfer Line
Erice, 16th and 17th of March 2017

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Acknowledgement:

- To the organizers for the invitation to this presentation
- To P. Kowina, R. Singh (GSI) and M. Schuh (KIT) for very valuable discussion
- To numerous further colleagues for versatile & enlightening discussions and providing material

Demands on Beam Diagnostics

Diagnostics is the ’sensory organs’ for the beam.

Different demands lead to different installations:

- Quick, non-destructive measurements leading to a single number or simple plots

  Used as a check for online information. Reliable technologies have to be used

  Example: Current measurement by transformers
- Complex instruments for severe malfunctions, accelerator commissioning & development

  The instrumentation might be destructive and complex

  Example: Emittance determination

General usage of beam instrumentation:

- Monitoring of beam parameters for operation, beam alignment & accelerator development
- Instruments for automatic, active beam control

  Example: *Synchrotron:* Closed orbit feedback using position measurement by BPMs
  Slow extraction: Control of extraction strength to stabilize beam $I_{beam}(t)$ at target

Non-destructive (’non-intercepting’) methods are preferred:

- The beam is not influenced ⇒ the **same** beam can be measured at several locations
- The instrument is not destroyed

Outline of the Lecture

The ordering of the subjects is oriented by the beam quantities:

- **Current measurement:** Transformers, Faraday cups, particle detectors
- **Beam loss detection:** Secondary particle detection for optimization and protection

1st lecture

- **Profile measurement:** Various methods depending on the beam properties
- **Transverse emittance measure:** Destructive devices, linear transformations

2nd lecture

- **Pick-ups for bunched beams**: Principle of rf pick-ups& relevant beam measurements
- **Measurement of longitudinal parameters:** time structure of bunches, beam energy spread energies, longitudinal emittance

3rd lecture

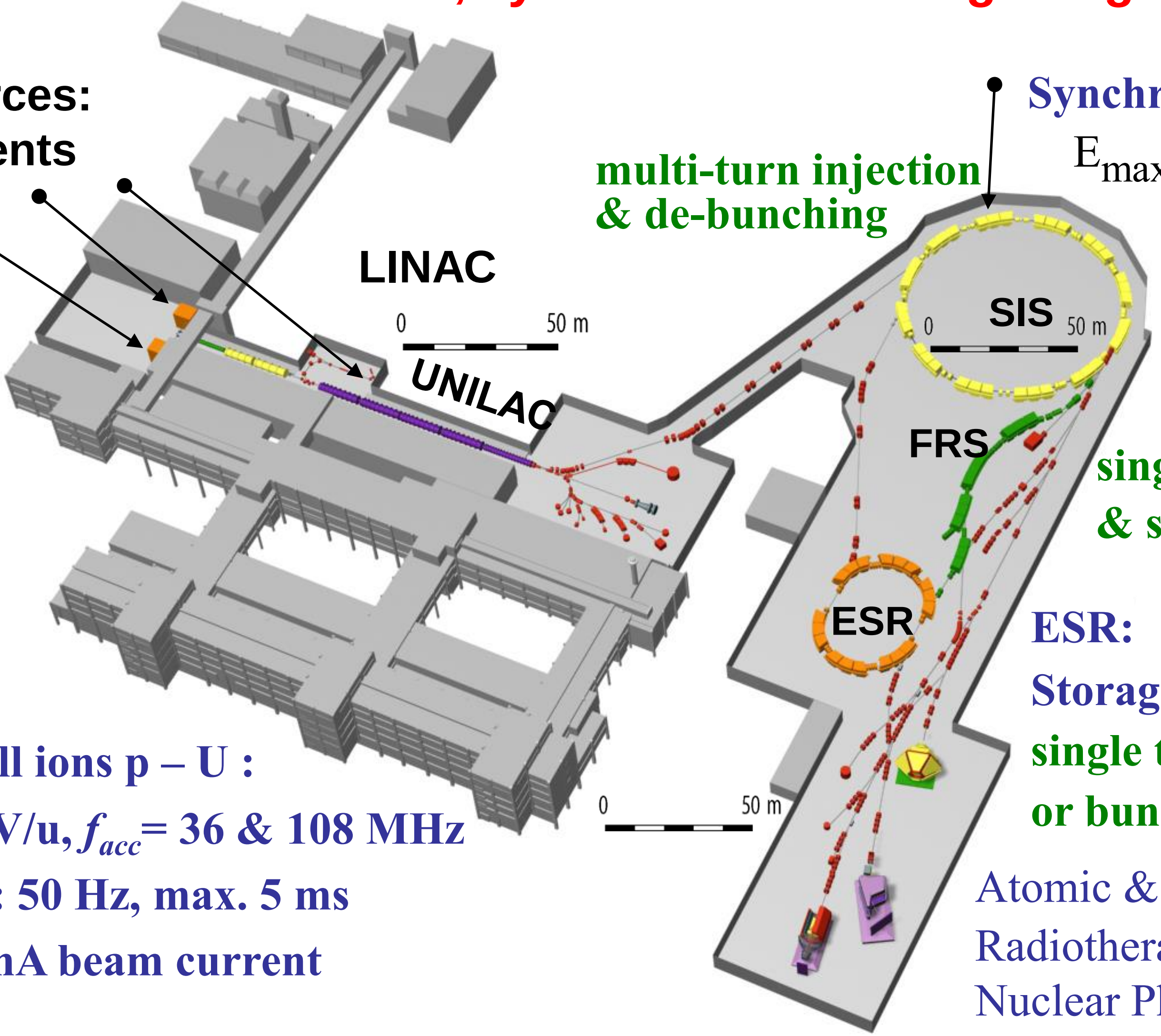
Some instruments must be different for:

- Transfer lines with single pass ↔ synchrotrons with multi-pass
- Electrons are (nearly) always relativistic ↔ protons are at the beginning non-relativistic

Remark: Most example for GSI **only** because the author is familiar with this facility!

The Accelerator Facility at GSI

The GSI linear accelerator, synchrotron & storage ring for ions



**Ion Sources:
all elements**

**multi-turn injection
& de-bunching**

Synchrotron, $B\rho$=18 Tm

E_{max} p: 4.7 GeV
U: 1 GeV/u

Achieved e.g.:

Ar^{18+}: $1 \cdot 10^{11}$

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

**single turn extraction
& slow extraction**

ESR:

Storage Ring, $B\rho$=10 Tm

**single turn injection
or bunch-to-bucket**

Atomic & Plasma Physics
Radiotherapy
Nuclear Physics

LINAC: all ions p – U :

3 – 12 MeV/u, f_{acc}= 36 & 108 MHz

repetition: 50 Hz, max. 5 ms

Up to 20 mA beam current

Measurement of Beam Current

The beam current and its time structure 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**

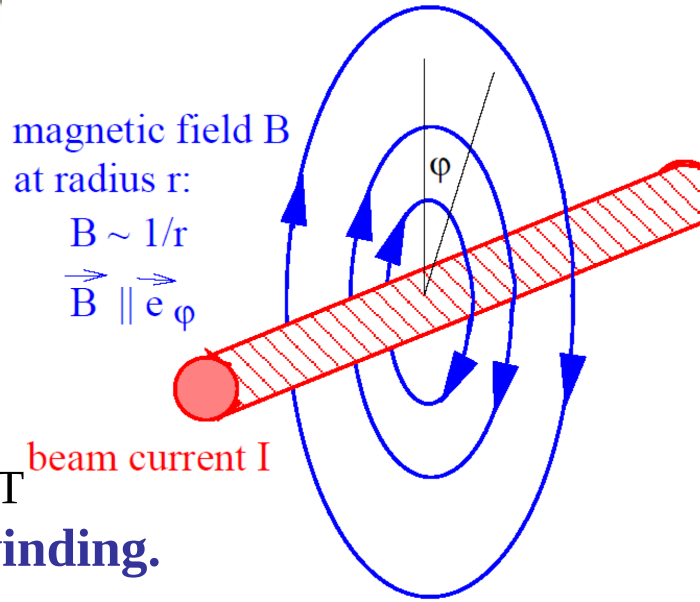
  They are non-destructive. No dependence on beam energy

  They have lower detection threshold.

- **Faraday cups:** Measurement of the beam's **electrical charges**
- **Particle detectors:** Measurement of the particle' s **energy loss** in matter

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

Magnetic field of the beam and the ideal Transformer



- 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: $I = 1\mu A$, $r = 10cm \Rightarrow B_{beam} = 2pT$, earth $B_{earth} = 50\mu T$

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

$\Rightarrow$ Loaded current transformer

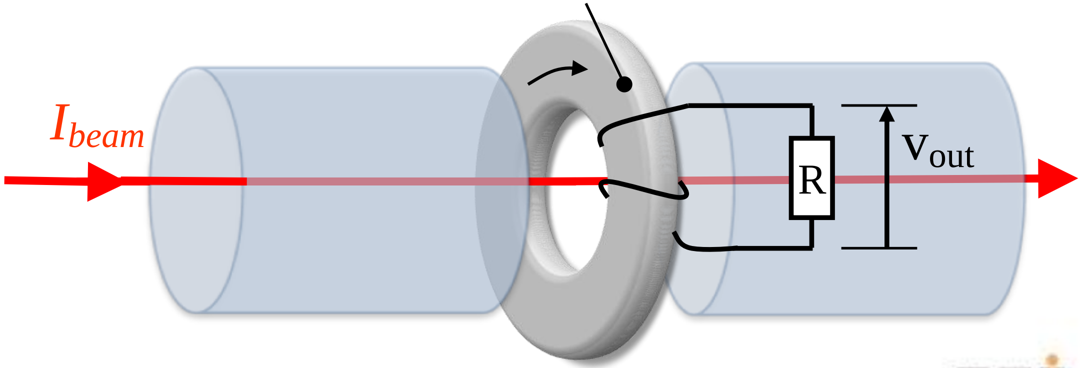
$$I_1/I_2 = N_2/N_1 \Rightarrow I_{sec} = 1/N \cdot I_{beam}$$

- Inductance of a torus of μ_r

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

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

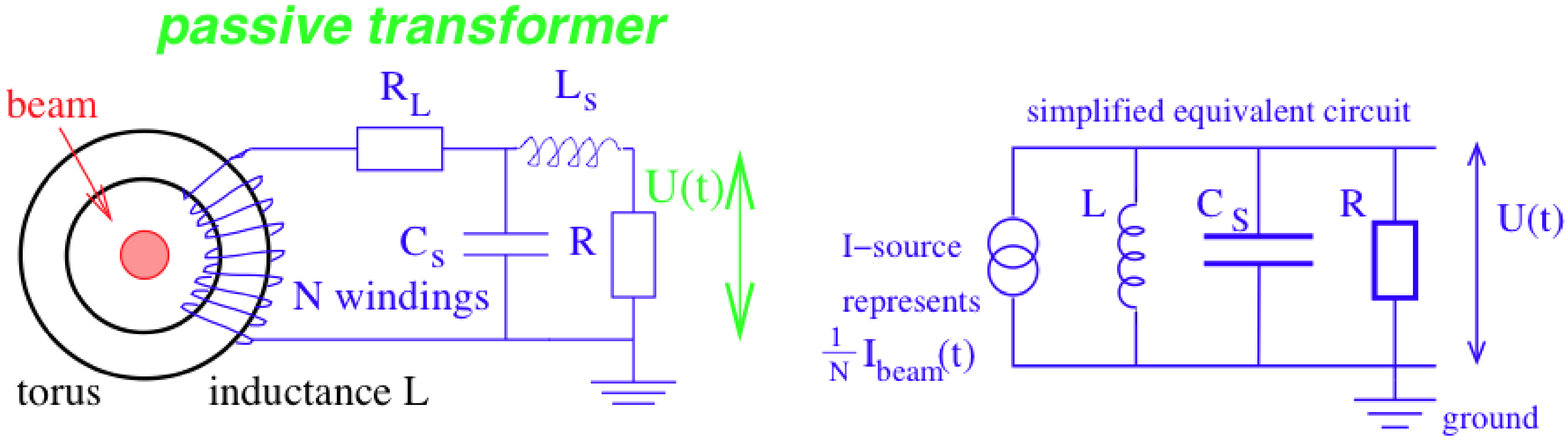
Torus to guide the magnetic field



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

Passive Transformer (or Fast Current Transformer FCT)

Simplified electrical circuit of a passively loaded transformer:



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

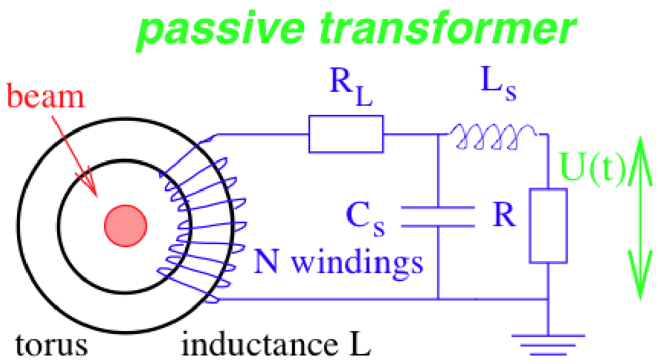
with ***S* sensitivity [V/A],** equivalent to transfer function or transfer impedance ***Z***

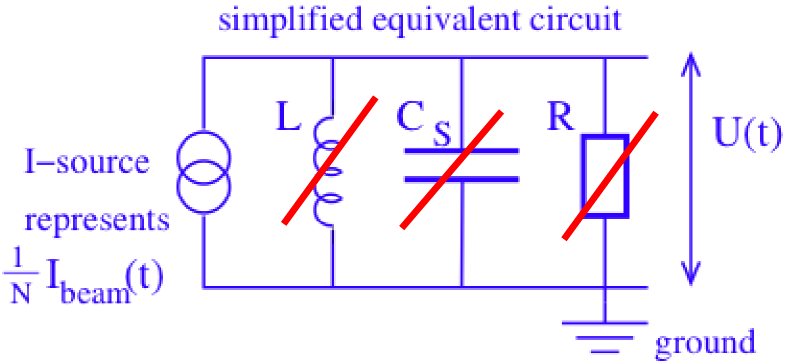
Equivalent circuit for analysis of sensitivity and bandwidth

(disregarding the loss resistivity R_L)

Bandwidth of a Passive Transformer

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





For this parallel shunt:

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

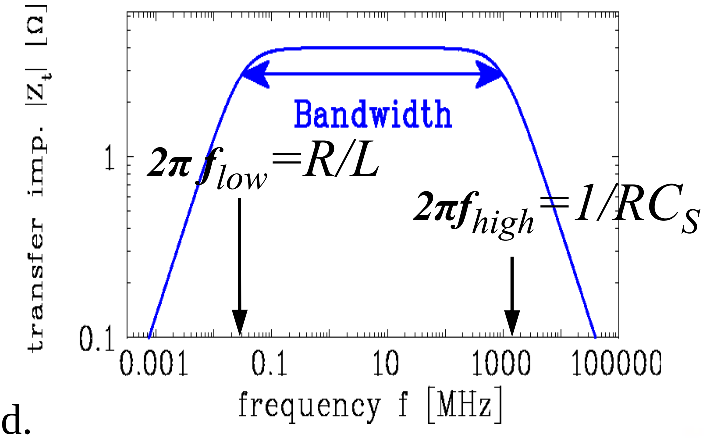
- ***Low frequency*** $\omega \ll R/L : \; Z \rightarrow i\omega L$

  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.



Response of the Passive Transformer: Rise and Droop Time

Time domain description:

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

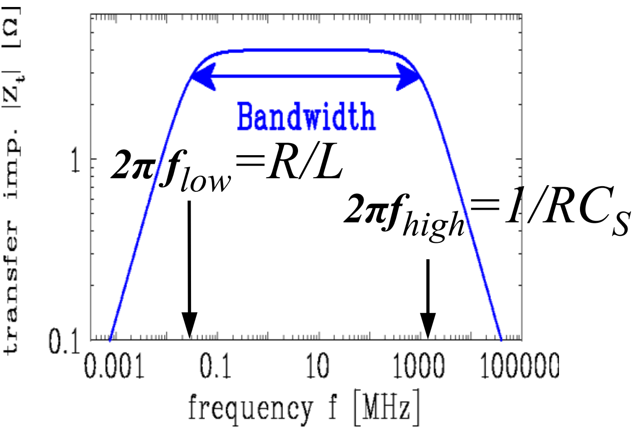
Rise time: $\tau_{rise} = 1/(2\pi f_{high}) = 1/RC_S$ (ideal without cables)

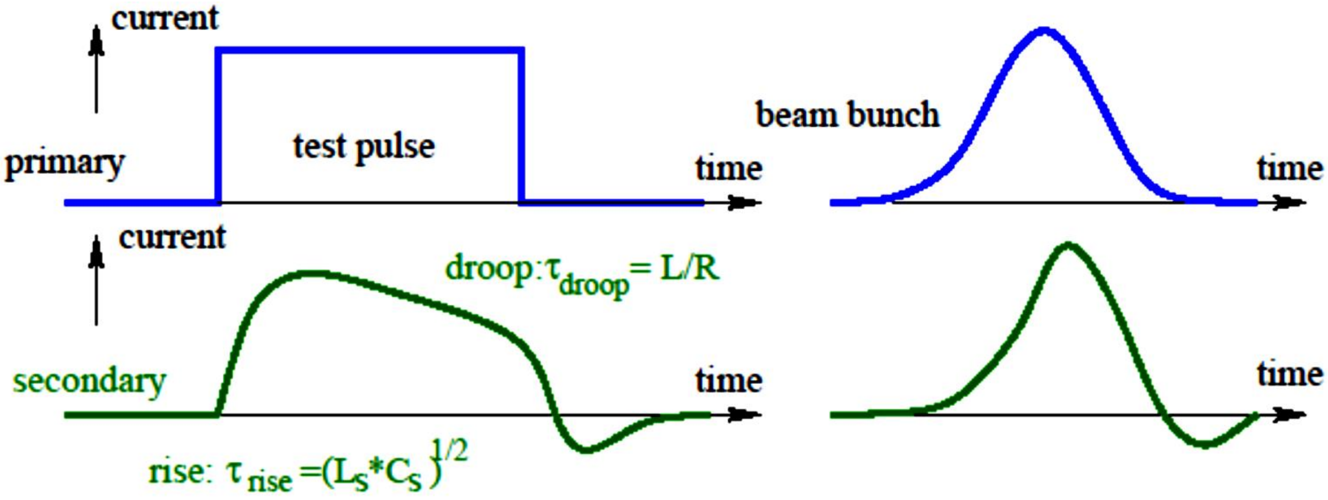
Rise time: $\tau_{rise} = 1/(2\pi f_{high}) = \sqrt{L_S C_s}$ (with cables)

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 beams e.g. transfer between synchrotrons typical bandwidth of 2 kHz < f < 1 GHz

⇔ 1 ns < $t \approx 1/f$ < 200 µs is well suited

Example GSI type:

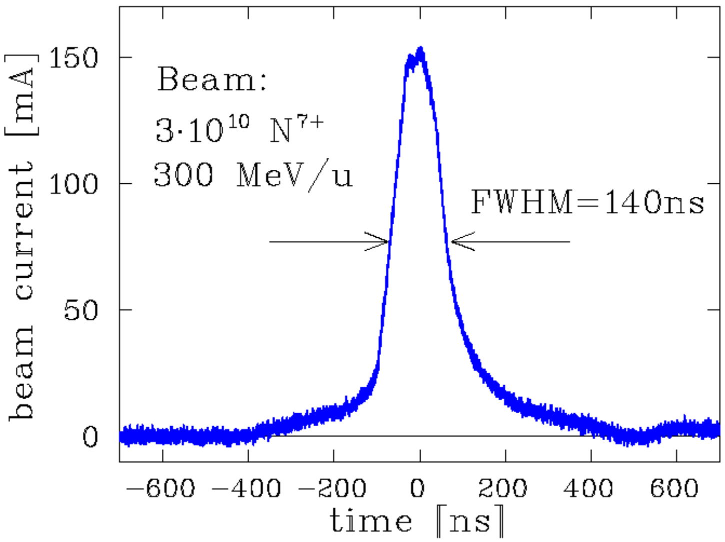
Inner / outer radius	70 / 90 mm
Torus thickness	16 mm
Torus material	$(CoFe)_{70\%}(MoSiB)_{30\%}$
Permeability	$\mu_r \approx 10^5$ for f < 100kHz $\mu_r \propto 1/f$ above
Windings	10
Sensitivity	4 V/A for R = 50 Ω
Droop time $\tau_{droop} = L/R$	0.2 ms
Rise time $\tau_{rise}=\sqrt{L_S C_S}$	1 ns
Bandwidth	2 kHz ... 300 MHz

Numerous application e.g.:

- Transmission optimization
- Bunch shape measurement
- Input for synchronization of ‘beam phase’

From Company Bergoz

Fast extraction from GSI synchrotron:



Example for passive Transformer


From Company Bergoz

For bunch beams e.g. during accel. in a synchrotron typical bandwidth of 2 kHz < ***f*** < 1 GHz

⇔ 1 ns < $\boldsymbol{t \approx 1/f}$ < 200 μs is well suited

Example GSI type:

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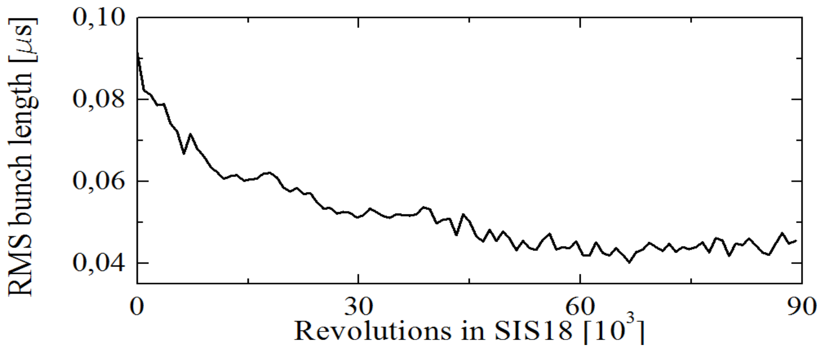
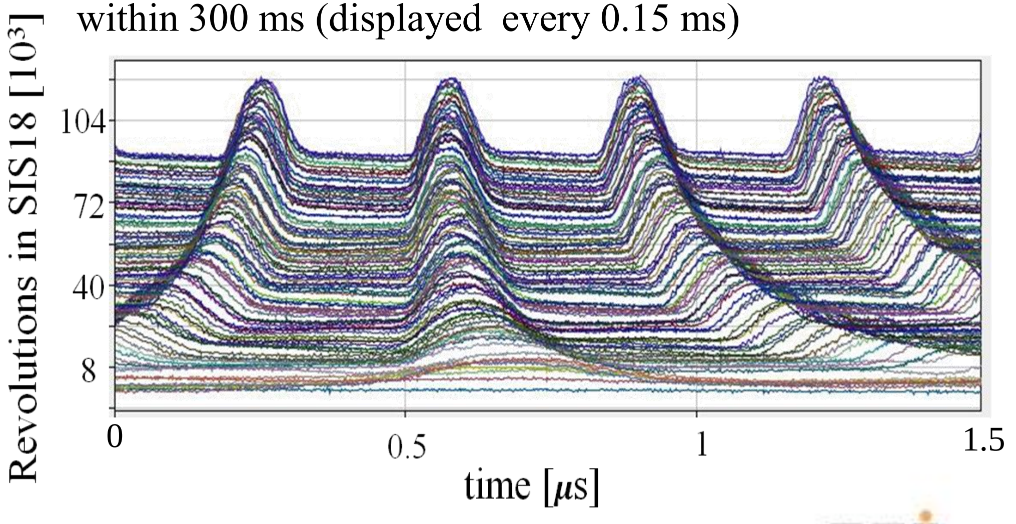


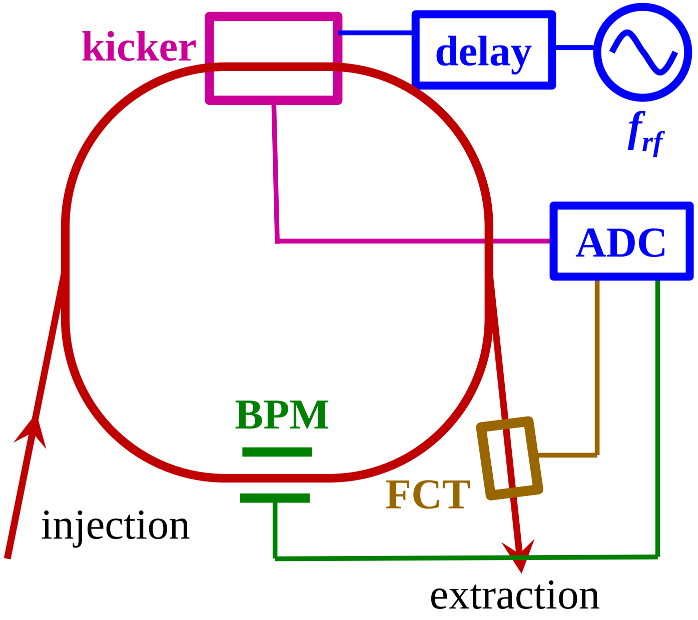
Example: U^{73+} from 11 MeV/u ($\boldsymbol{\beta}$ = 15 %) to 350 MeV/u within 300 ms (displayed every 0.15 ms)



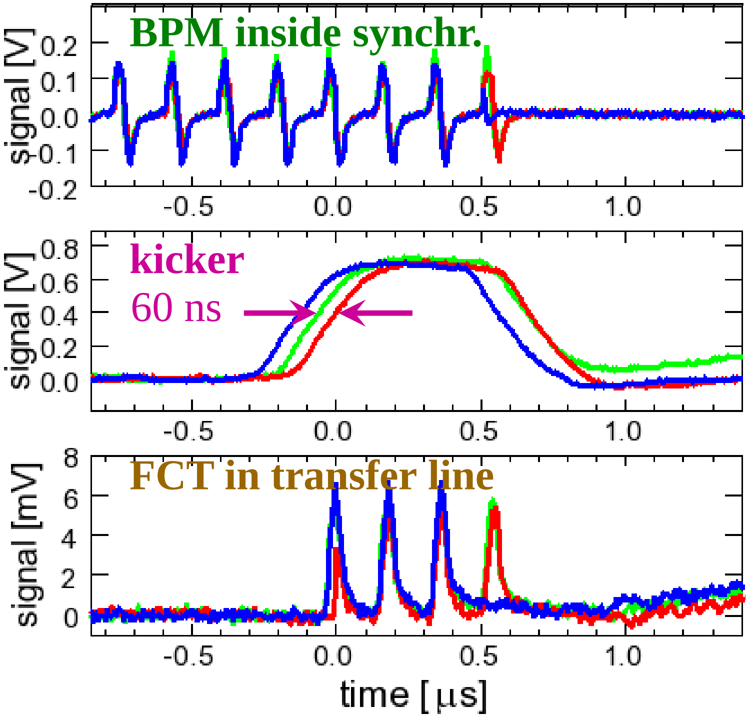
Control of extraction Kicker for 'fast' Extraction

Control of kicker timing by FCT measurement in transfer line

- **Correct timing:**
  → all bunches are extracted
- **Too late (here Δ*t* = 60 ns ≈ 120^0 @ f_{rf}):**
  → first bunch is only partly extracted
- **Too early (here Δ*t* = -60 ns ≈ -120^0 @ f_{rf}):**
  → last bunch is not extracted



Example: C^{6+} at 600 MeV/u, f_{rf}=5.46 MHz, h = 4



Longitudinal Bunch Diagnostics inside Synchrotron using FCT

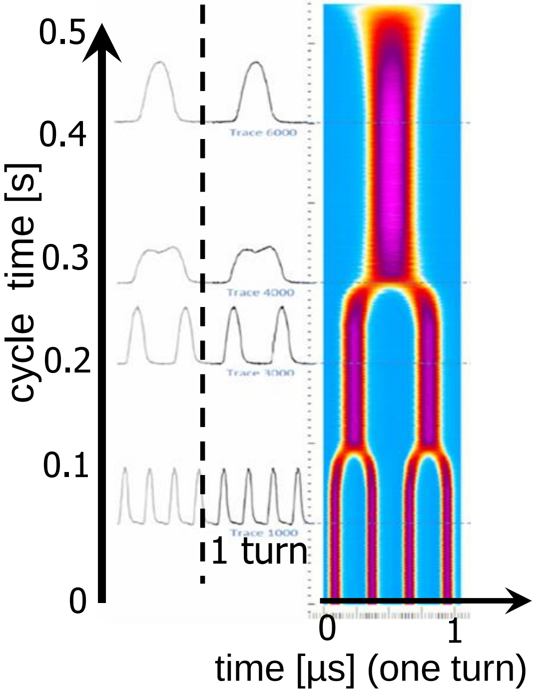
- Acceleration and bunch 'gymnastics' are performed **inside** synchrotrons
- Bunch shaping for fast, single turn extraction

Measurement within synchrotron because bunch shape is constant during transport in most cases

Example: Transfer line L=100m, β=1, $\frac{\Delta p}{p} = 2 \cdot 10^{-3} \rightarrow \Delta t = \frac{\Delta p}{p} \cdot t_{drift} = \frac{\Delta p}{p} \cdot \frac{L}{\beta c} = 0.7\text{ ns} \ll \sigma_{bunch}$

Example: Bunch merging at upper flattop using 2 cavities at GSI synchrotron

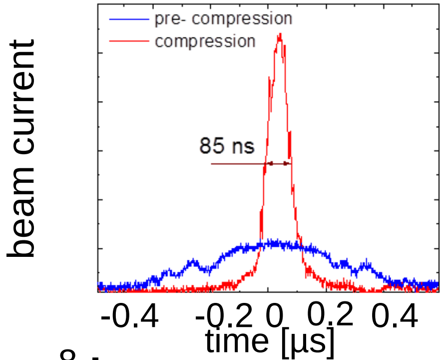
Beam: 10^9 U^{73+} at 600 MeV/u, FCT



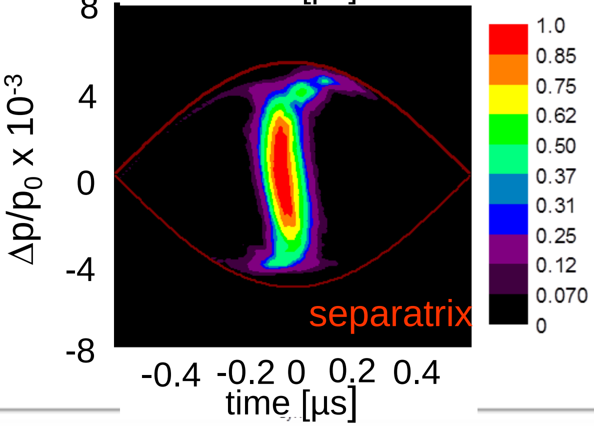
Courtesy H. Klingbeil, U. Hartel, et al. GSI

Example: Bunch shape for 'bunch compression' prior to extr.

Beam: U^{73+} at 300 MeV/u at GSI synchrotron



After acceleration before & after bunch compression



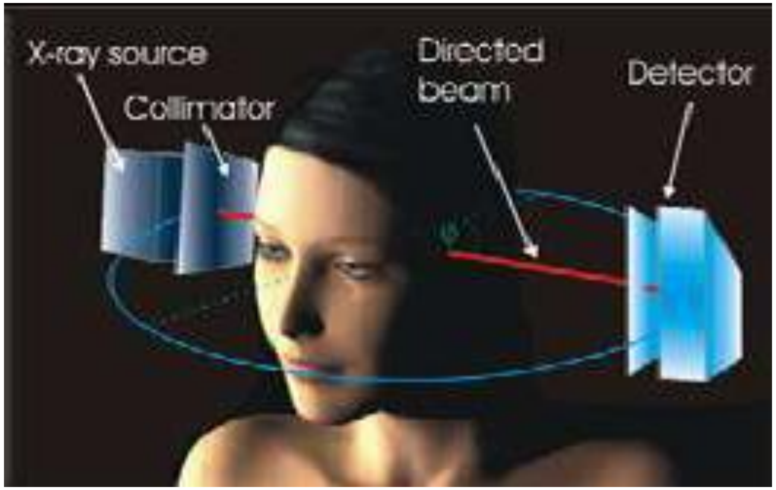
Tomographic reconstruction of longitudinal phase space depicted for min. bunch width

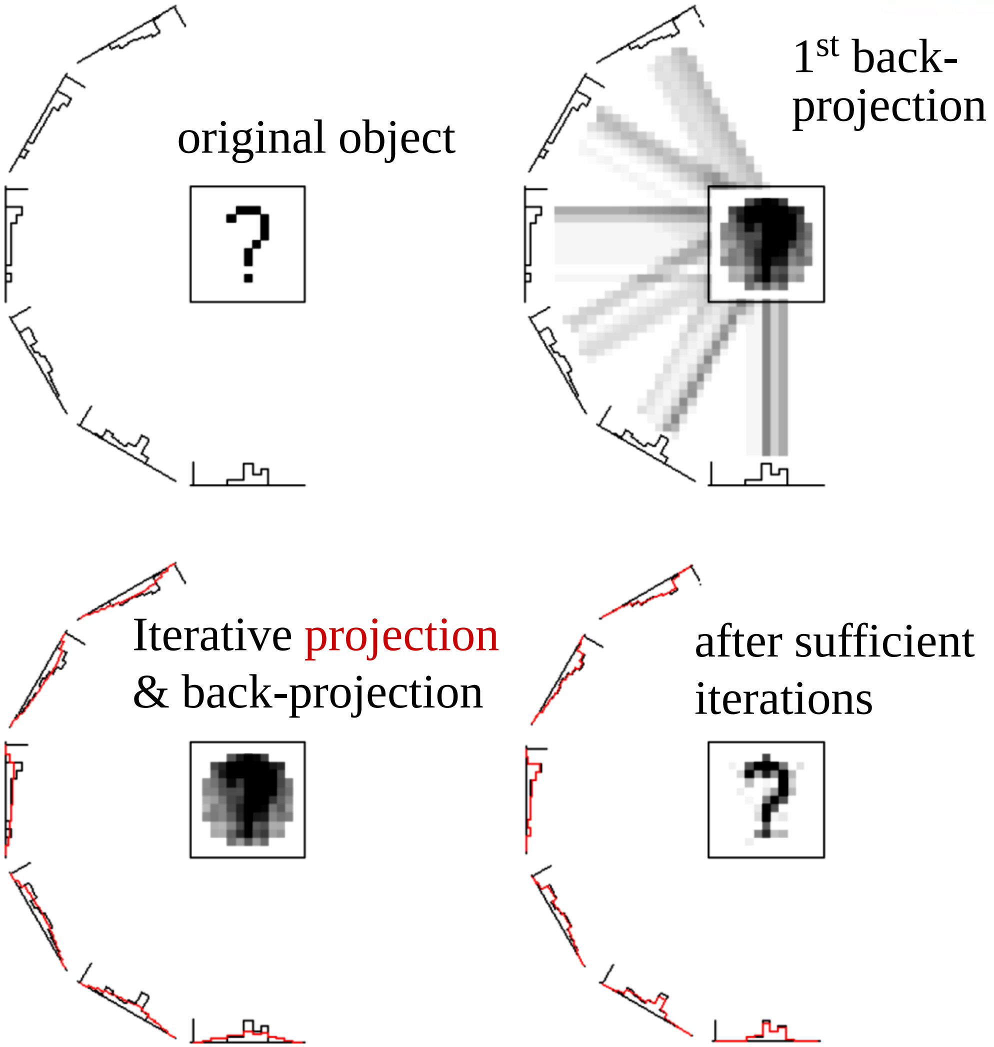
Courtesy O. Chroniy, GSI

Longitudinal Emittance using tomographic Reconstruction

Tomography is medical image method

Tomography:
2-dim reconstruction of
sufficient 1-dim projections




original object

1st back-projection

Iterative projection & back-projection

after sufficient iterations

Algebraic back projection:

Iterative process by redistributing the 2-dim image and considering the differences to the previous iteration step.

Longitudinal Emittance using tomographic Reconstruction

Tomography is medical image method

Tomography:

2-dim reconstruction of
sufficient 1-dim projections

Application at accelerators:

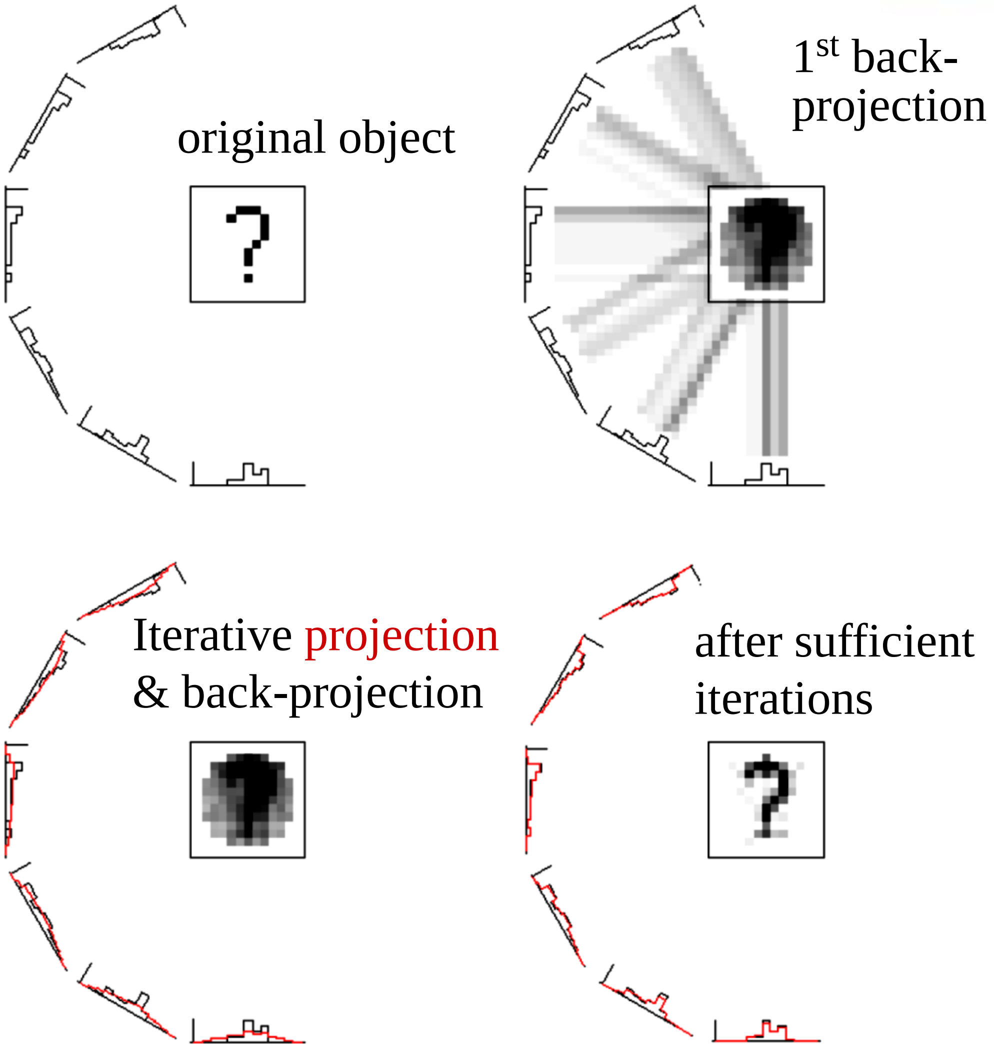
Longitudinal emittance
evolution in synchrotrons.

Bunch observation:

Each revolution,
the bunch shape changes a bit
due to synchrotron oscillations.
Fulfilled condition: $f_{synch} << f_{ref}$.

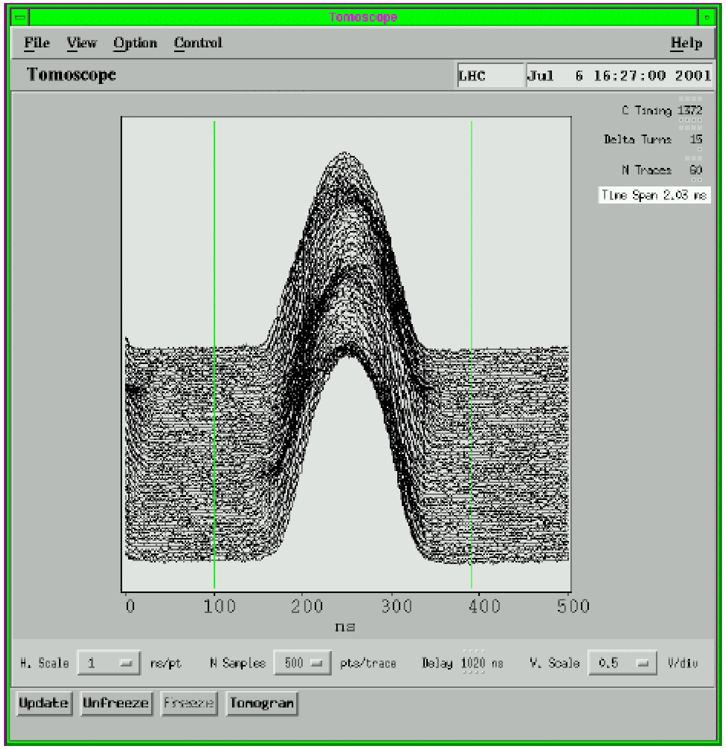
Algebraic back projection:

Iterative process by redistributing
the 2-dim image and considering the
differences to the previous iteration step.



Results of tomographic Reconstruction at a Synchrotron I

Bunches from 500 turns at the CERN PS and the phase space for the first time slice, measured with a wall current monitor:



LHC Jul 6 16:27:00 2001

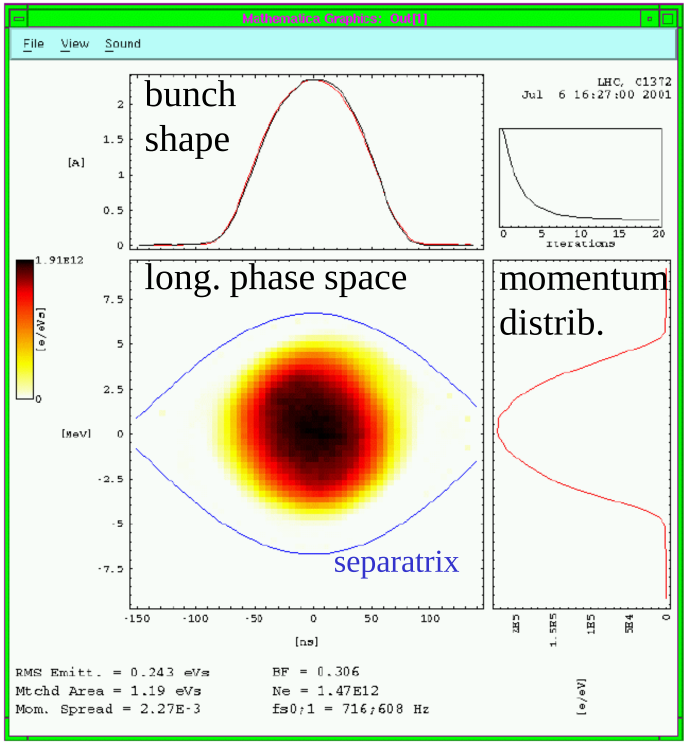
C Timing 1372

Delta Turns 15

N Traces 60

Time Span 2.03 ns

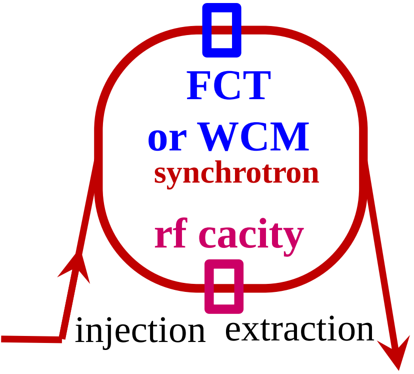
H. Scale 1 ns/pt N Samples 500 pts/trace Delay 1020 ns V. Scale 0.5 V/div



RMS Emitt. = 0.243 eVs
Mtchd Area = 1.19 eVs
Mom. Spread = 2.27E-3

BF = 0.306
Ne = 1.47E12
fs0;1 = 716;608 Hz

Courtesy S. Hancock,
J.L. Sanchez Alvarez:
http://cern.ch/tomography



FCT or WCM

synchrotron

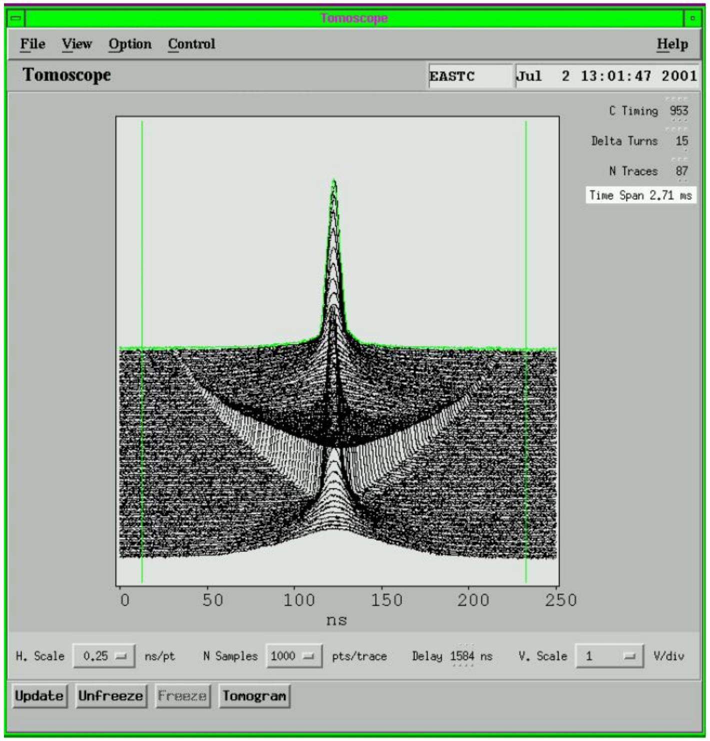
rf cacity

injection extraction

Typical bucket filling. Important knowledge for bunch 'gymnastics'.

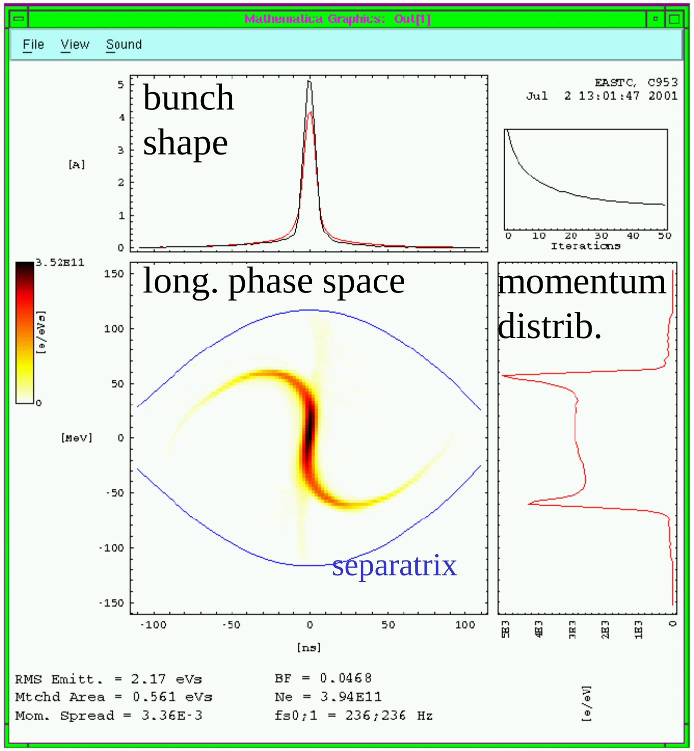
Results of tomographic Reconstruction at a Synchrotron II

Bunches from 500 turns at the CERN PS and the phase space for the first time slice, measured with a wall current monitor:



C Timing 953
Delta Turns 15
N Traces 87
Time Span 2.71 ms

H. Scale 0.25 ns/pt
N Samples 1000 pts/trace
Delay 1584 ns
V. Scale 1 V/div

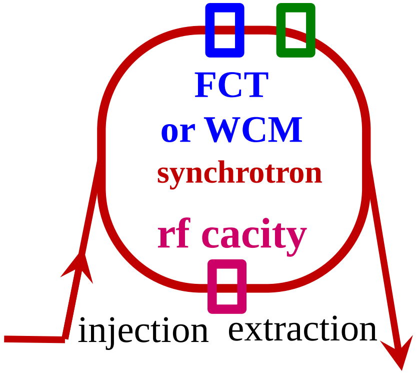


RMS Emitt. = 2.17 eVs
Mtchd Area = 0.561 eVs
Mom. Spread = 3.36E-3

BF = 0.0468
Ne = 3.94E11
fs0;1 = 236;236 Hz

Courtesy S. Hancock, J.L. Sanchez Alvarez: http://cern.ch/tomography

kicker control by beam



Mismatched bunch shown oscillations and filamentation due to ‘bunch-rotation’.

Application: Bunch rotation for short bunch extraction for experiments, alignment of kicker timing

Remark: For typical proton synch with ***E*** > 1 GeV.: negligible change of bunch shape in transfer line

⇒ measurement often done using synchrotron diagnostics.

'Active' Transformer with longer Droop Time

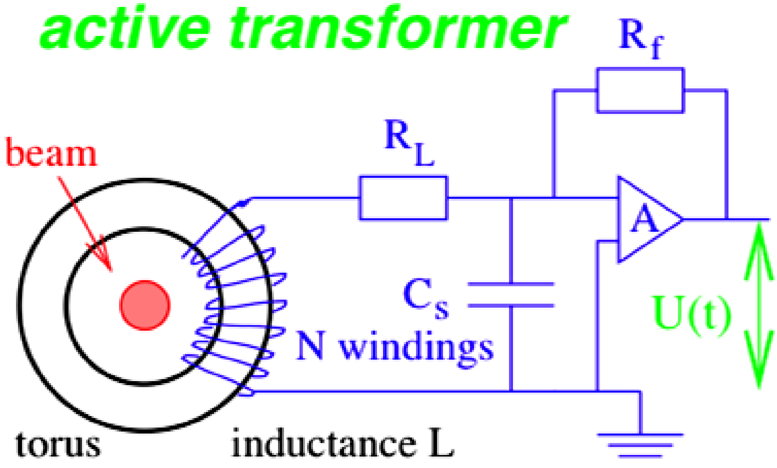
Active Transformer or Alternating Current Transformer ACCT:

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!

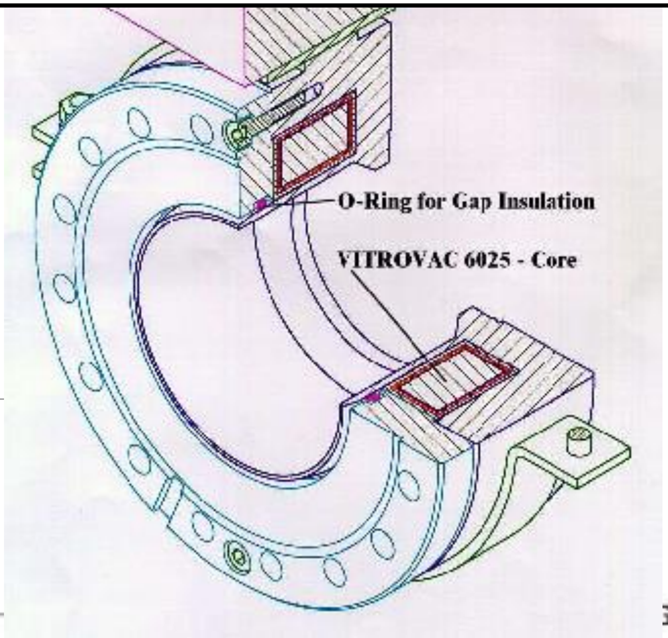
The feedback resistor is also used for range switching.

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

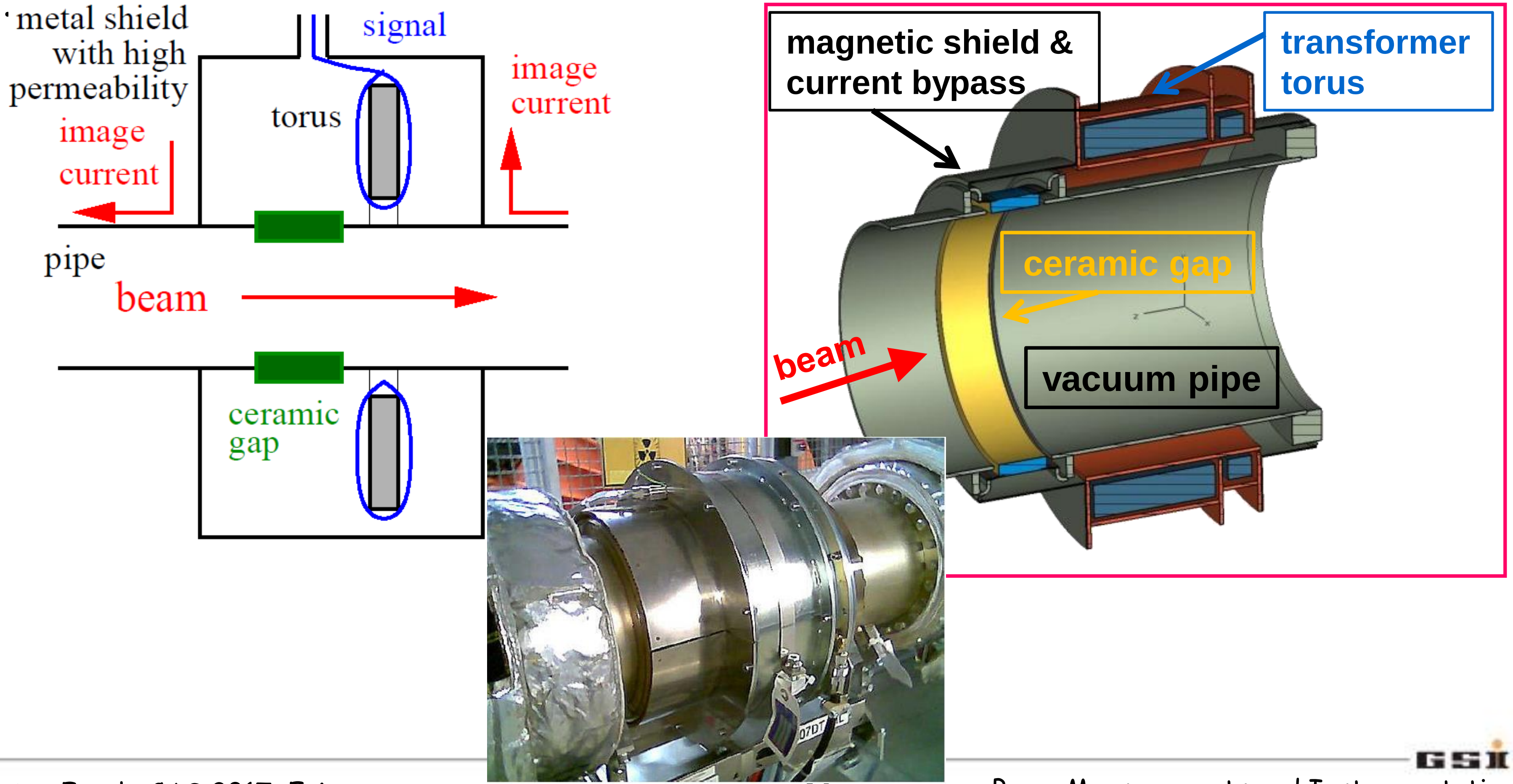
Torus inner radius	**r_i=30 mm**
Torus outer radius	**r_o=45 mm**
Core thickness	**l=25 mm**
Core material	**Vitrovac 6025** **$(CoFe)_{70\%}(MoSiB)_{30\%}$**
Core permeability	**u_r=10^5**
Number of windings	**2x10 crossed**
Max. sensitivity	**10^6 V/A**
Beam current range	**10 µA to 100 mA**
Bandwidth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



Shielding of a Transformer

Task of the shield:

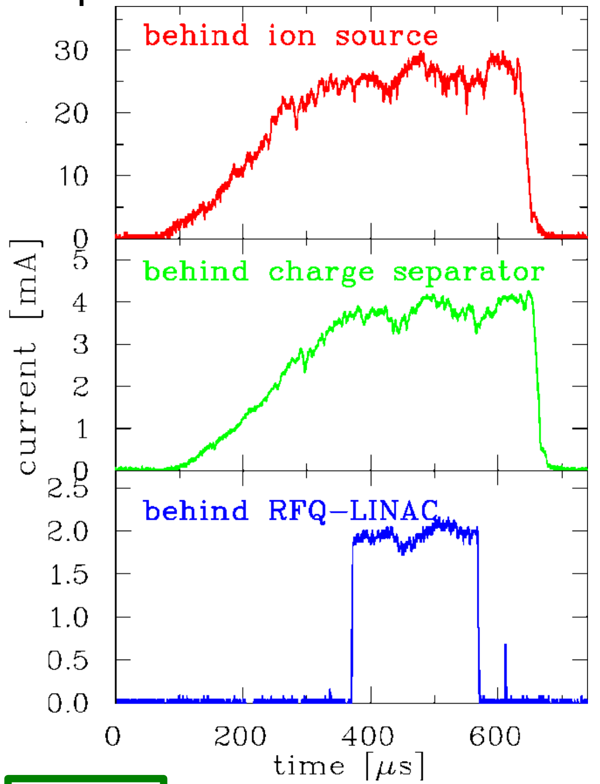
- The image current of the walls have to be bypassed by a gap and a metal housing.
- This housing uses µ-metal and acts as a shield of external B-field
  (remember: $I_{beam} = 1\ \mu A$, $r = 10$ cm $\Rightarrow B_{beam} = 2$pT, earth field $B_{earth} = 50\ \mu T$)



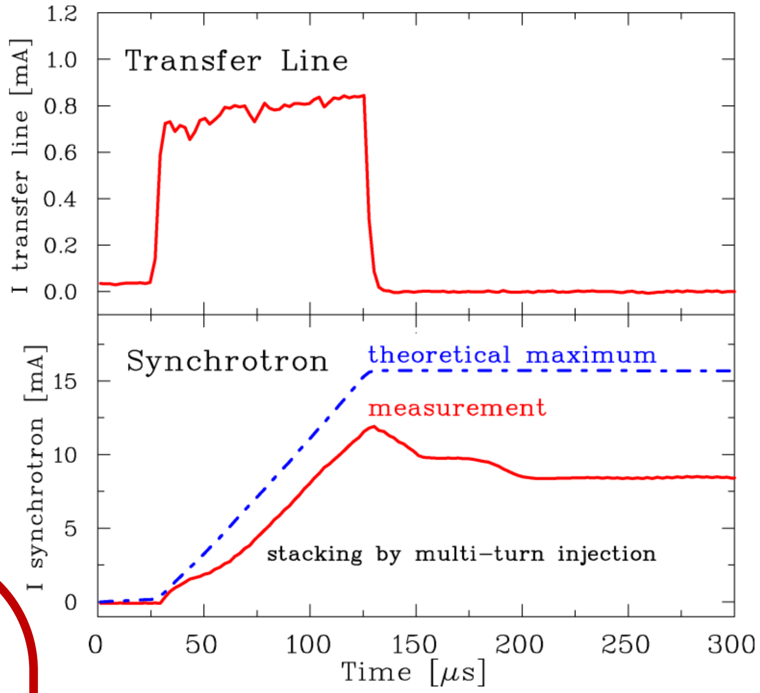
'Active' Transformer Measurement

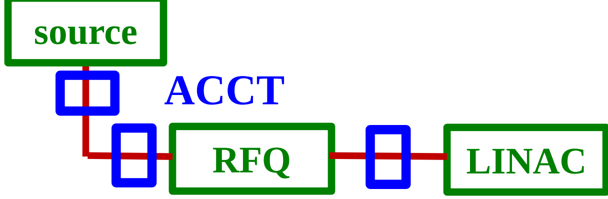
Active transformer for the measurement of long ***t*** > 10 µs pulses e.g. at pulsed LINACs

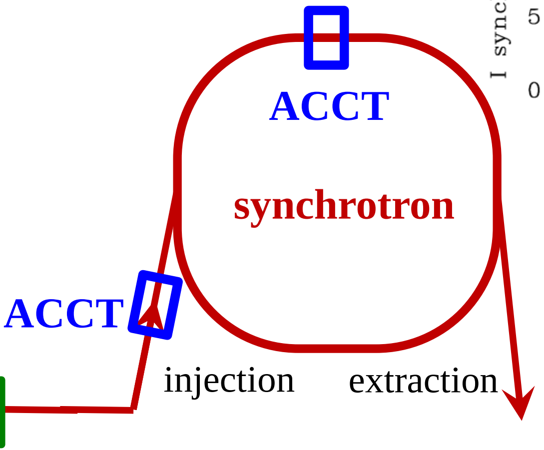
Example: Transmission and macro-pulse shape for Ni^{2+} beam at GSI LINAC



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





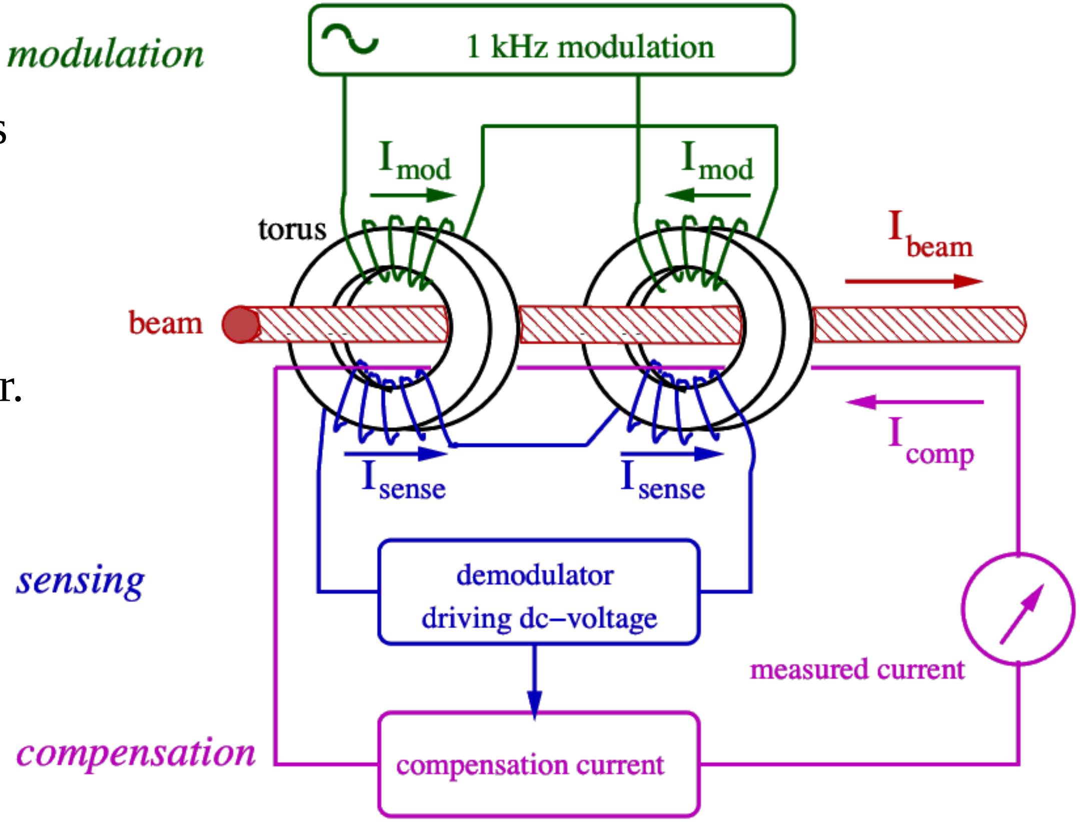


→ Transformer are frequently used for operation.

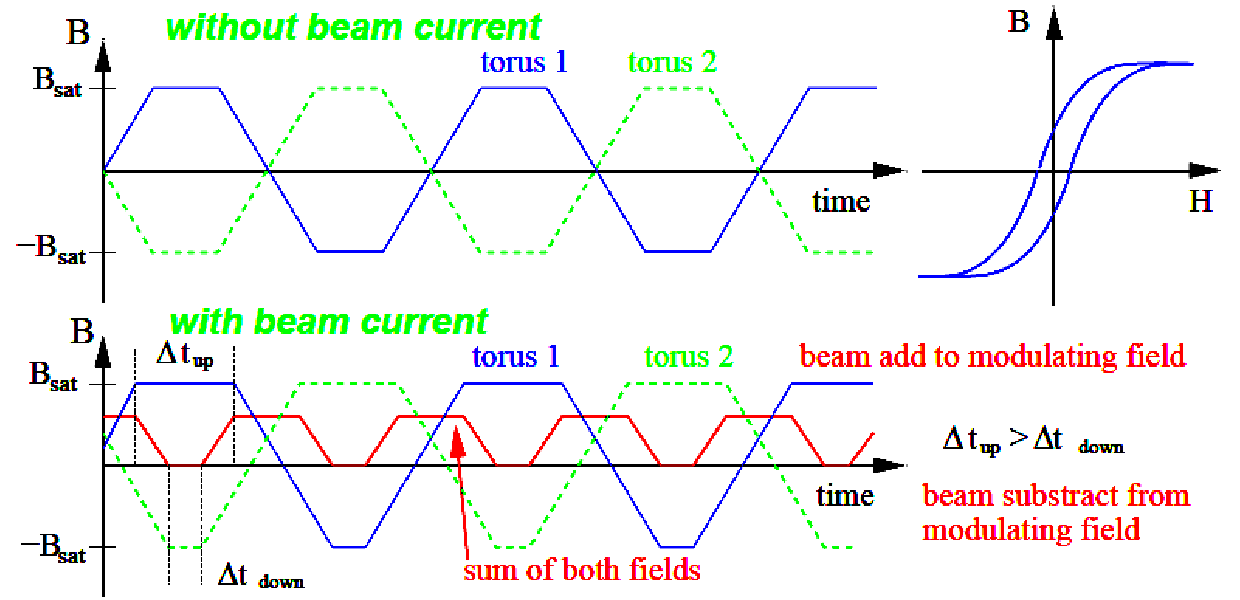
The dc Transformer

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.

- **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

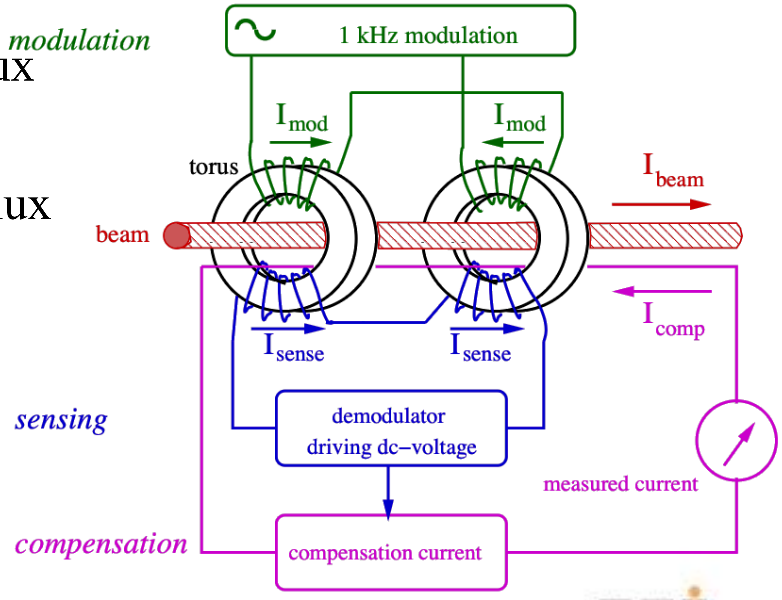


- **Modulation without beam:**

  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

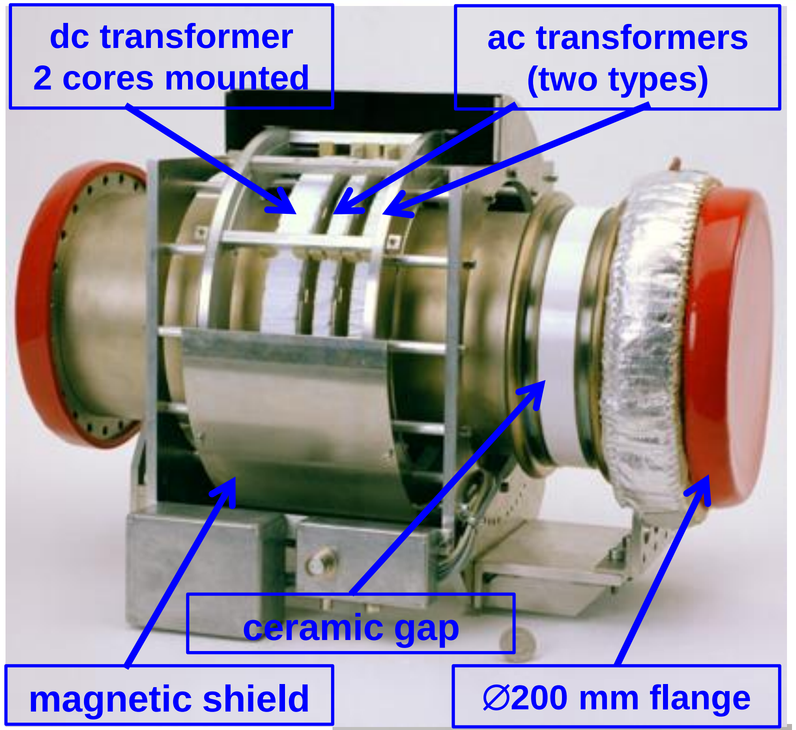
  for larger sensitivity
- **Two magnetic cores:** Must be very similar.



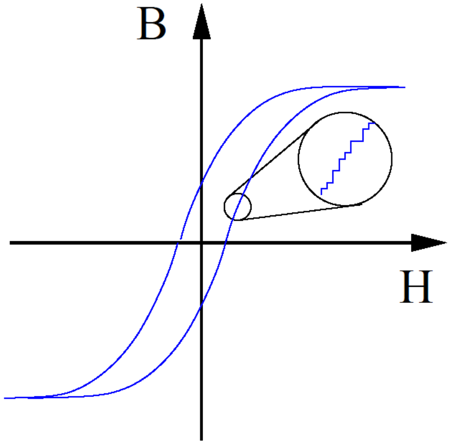
The dc Transformer Realization

Example: The DCCT at GSI synchrotron

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	$\tau_{rise} = 10$ µs
Temperature coefficient	1.5 µA/°C



Resolution limit of ≈ 1 µA caused by Barkhausen noise due to changes of Weiss domains



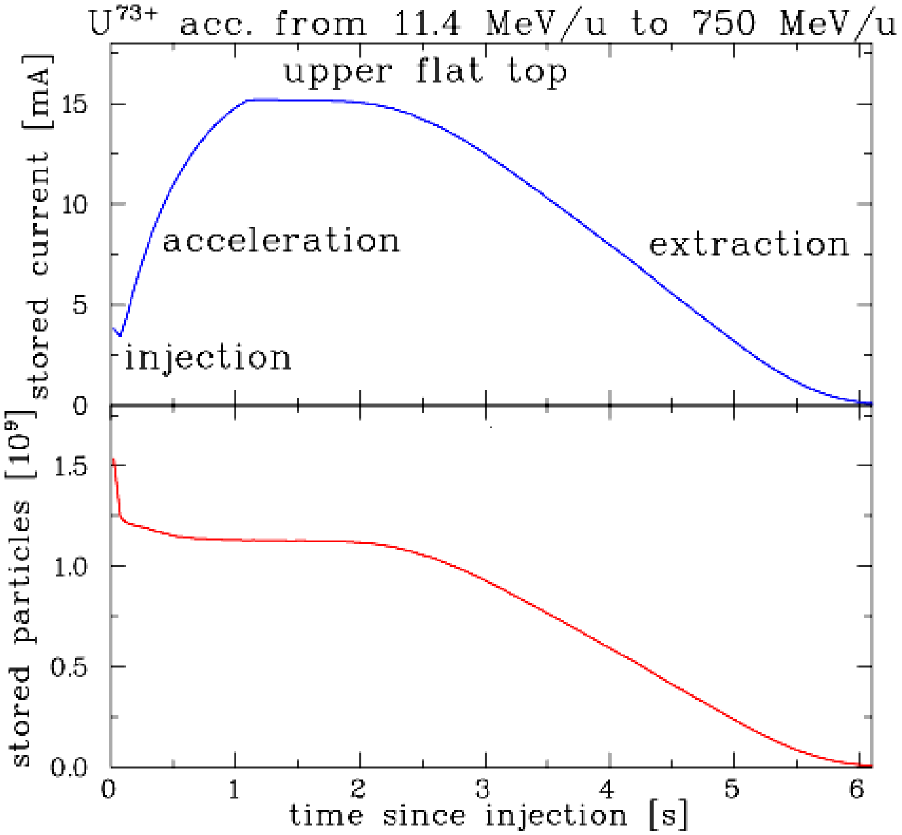

In-flange.NPCT with 96-mm aperture

Measurement with a dc Transformer

***Application for dc transformer*:**

⇒ Observation of beam behavior with typ. 20 μs time resolution → **the** basic operation tool.

Example: The DCCT at GSI synchrotron:



Important parameter:

Detection threshold: ≈ 1 μA

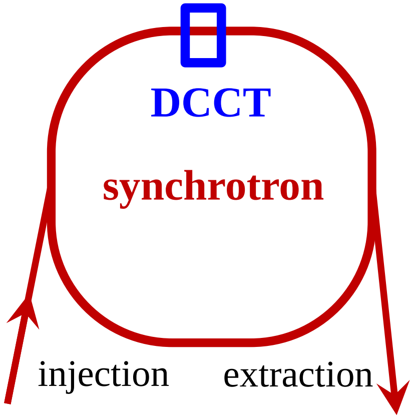
(= resolution)

Bandwidth: **Δ*f*** = dc to 20 kHz

Rise-time: t_{rise} = 20 μs

Temperature drift: 1.5 μA/^{0}C

⇒ compensation required.



Measurement of Beam Current

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

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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

Energy Loss of Ions in Copper

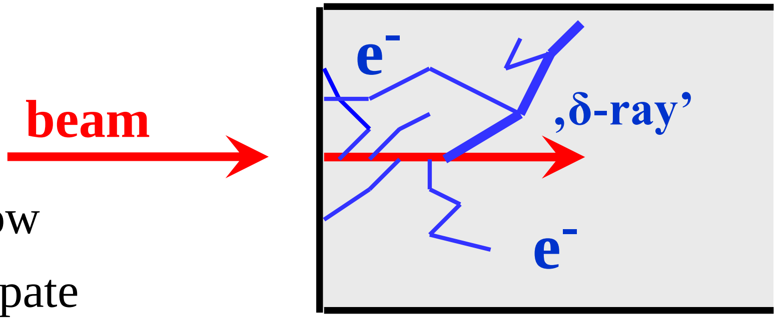
Bethe Bloch formula:
(simplest formulation)

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

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 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

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

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

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

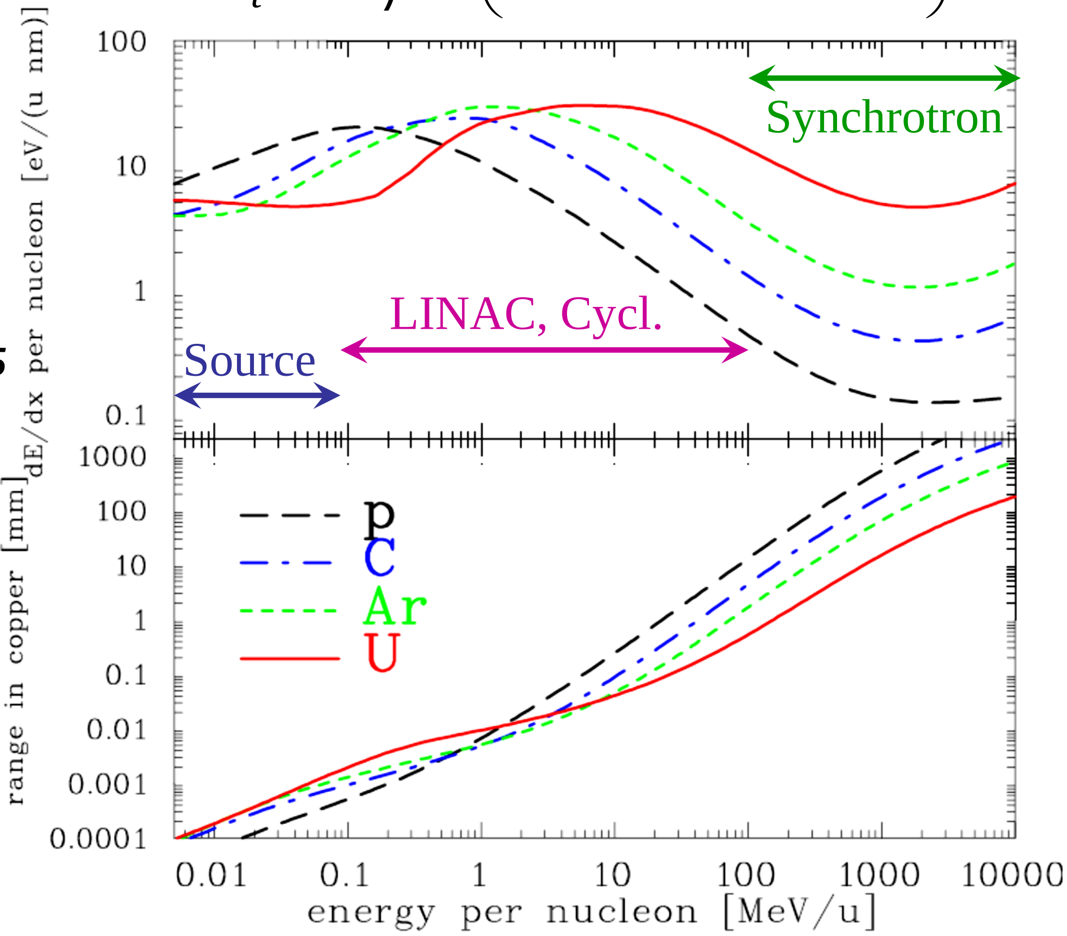
Numerical calculation

with semi-empirical model e.g. SRIM

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

⇒ Cups only for

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



Secondary Electron Emission caused by Ion Impact

Energy loss of ions in metals close to a surface:

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

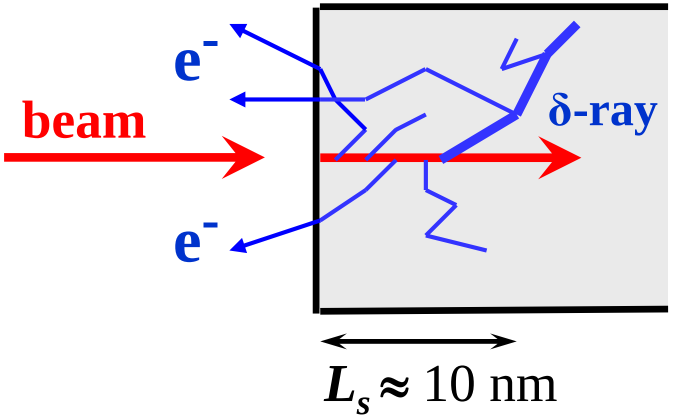
Distant collision with low energy transfer → slow e$^-$ with $E_{kin} \leq$ 10 eV

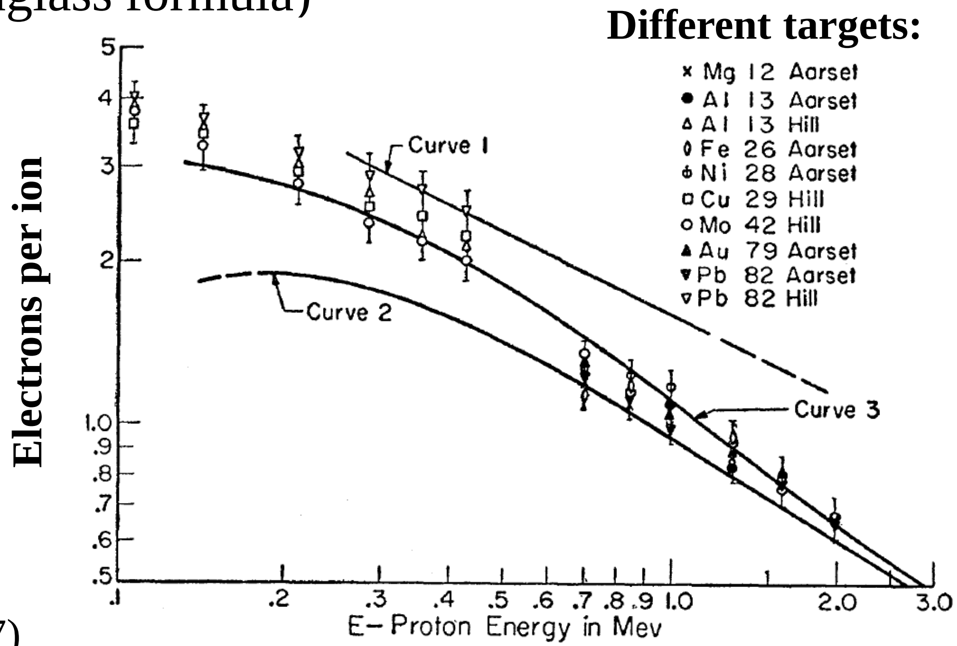
→ ‘diffusion’ & scattering with other e$^-$: scattering length $L_s \approx$ 1 - 10 nm

→ at surface ≈ 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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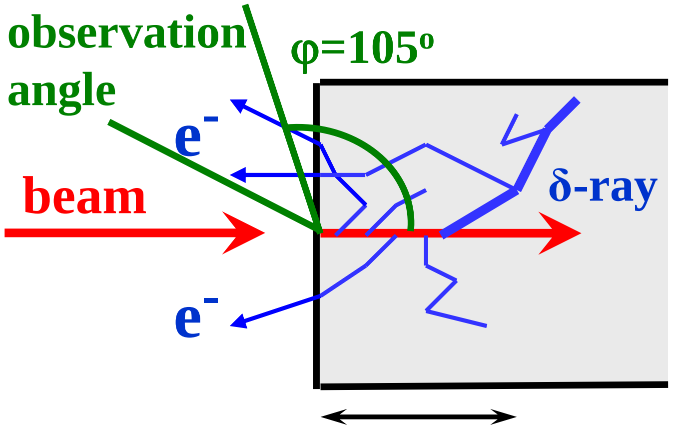
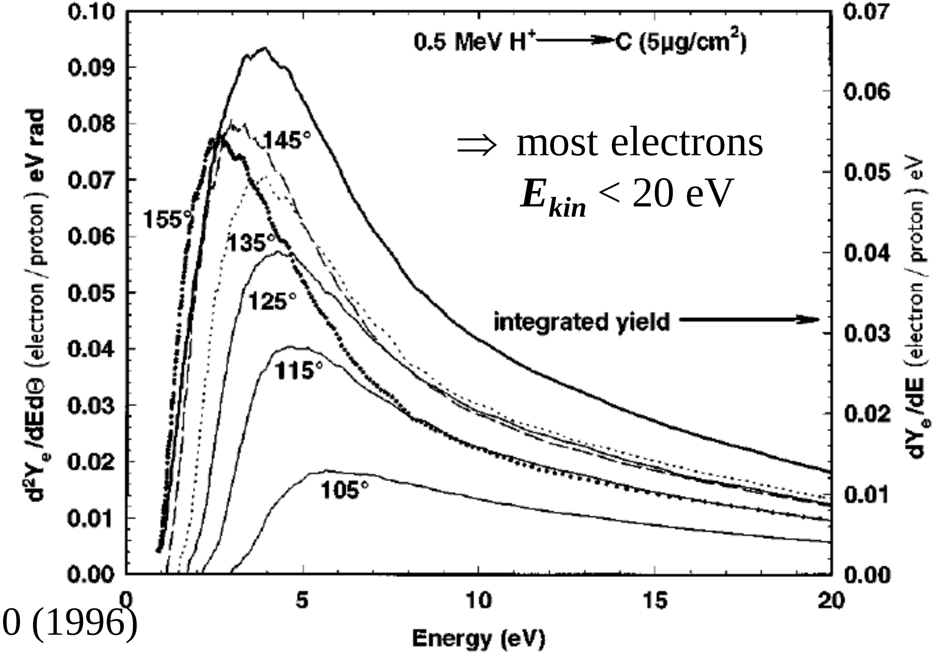


$L_s \approx 10$ nm



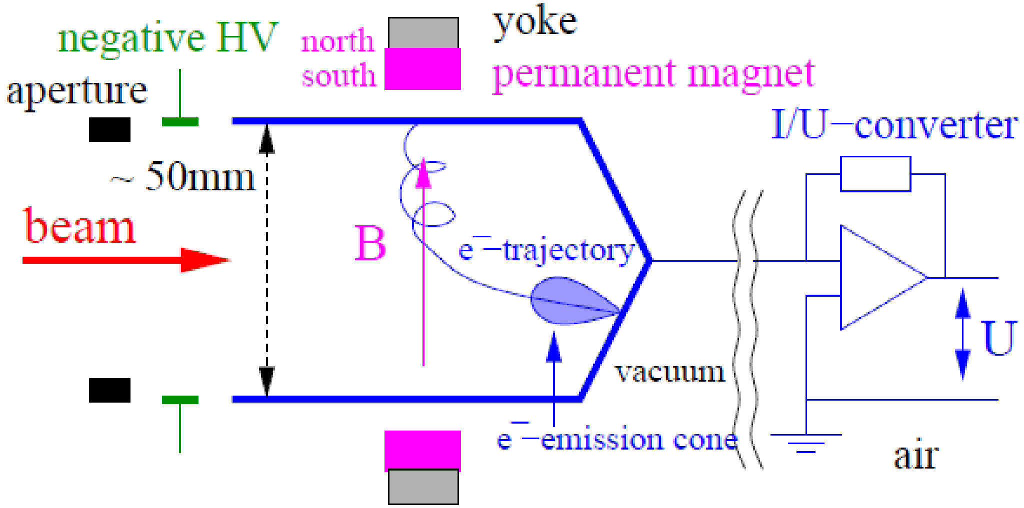
⇒ most electrons $E_{kin} < 20$ eV

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.



Currents down to 10 pA with bandwidth of 1 kHz!

Magnetic field:

To prevent for secondary electrons leaving the cup

and/or

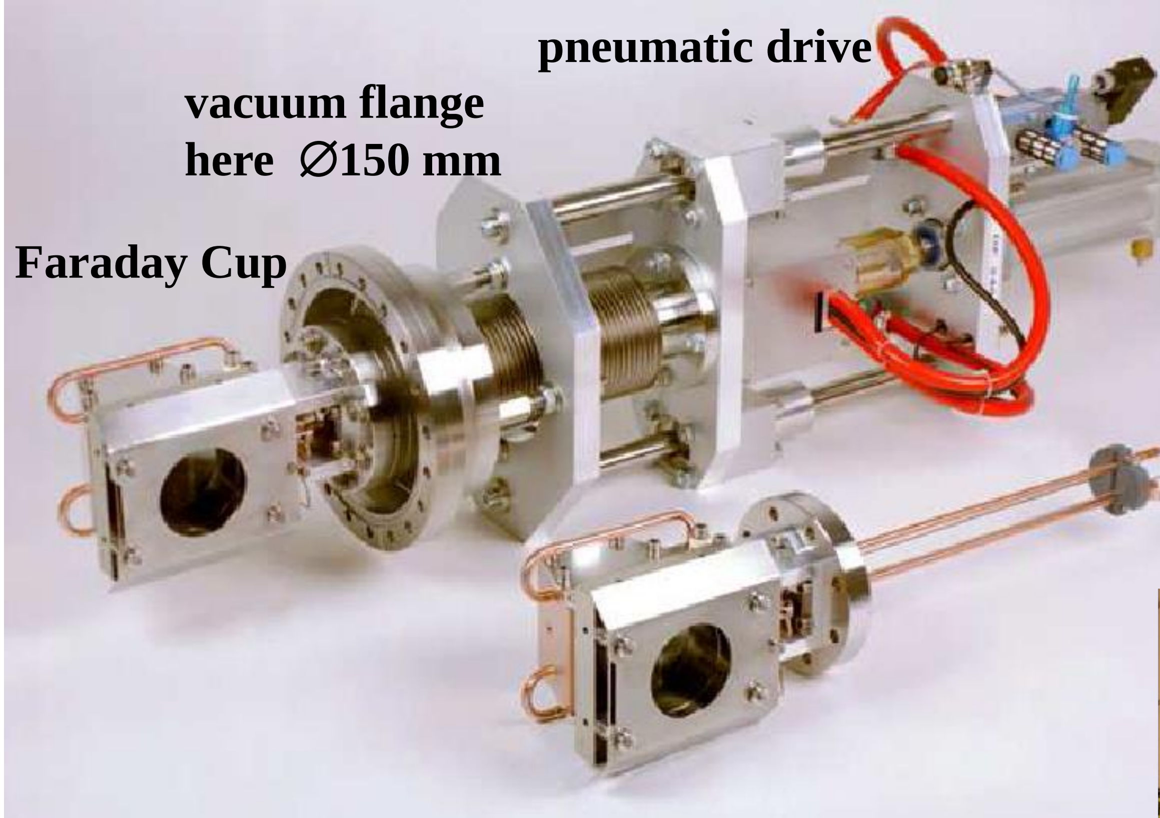
Electric field:

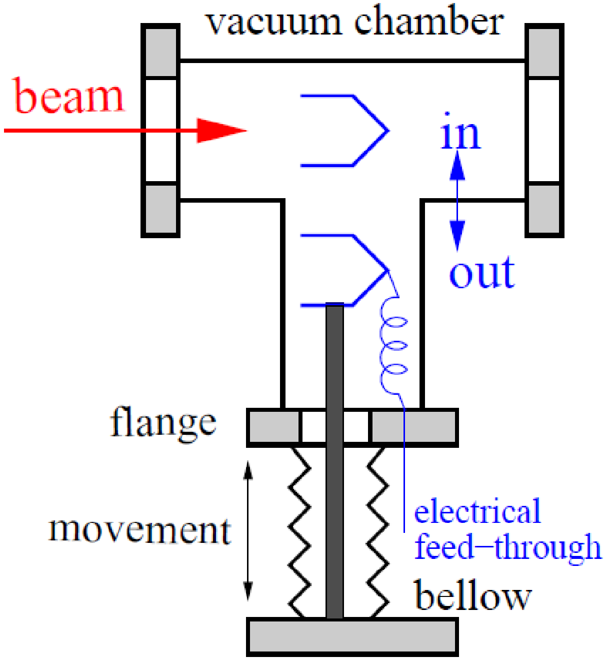
Potential barrier at the cup entrance.

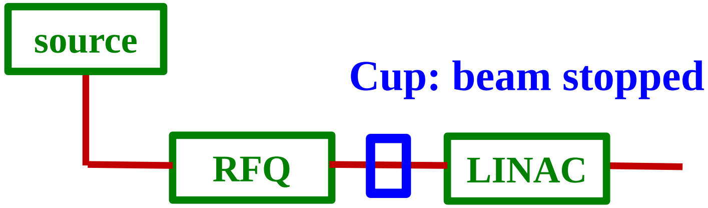
The cup is moved in the beam pass → destructive device

Realization of a Faraday Cup at GSI LINAC

The Cup is moved into the beam pass.



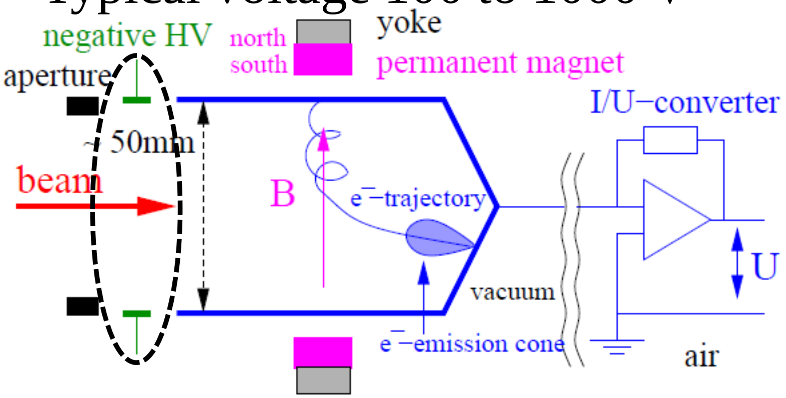


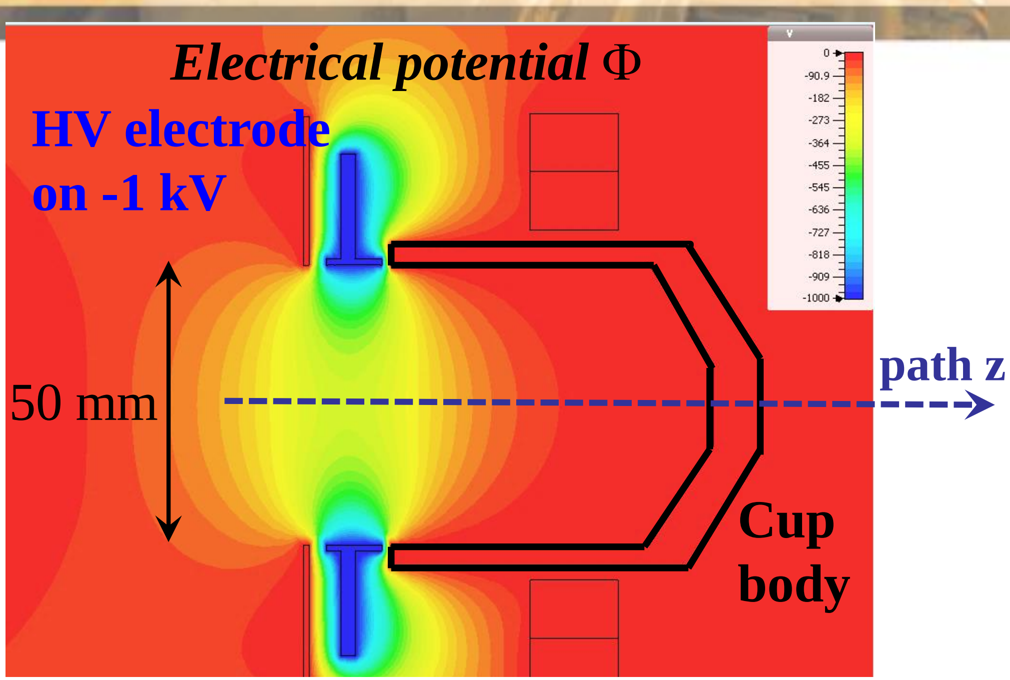


Secondary Electron Suppression: Electric Field

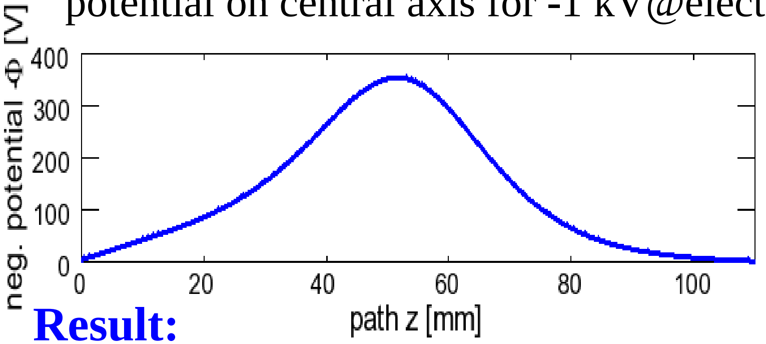
A ring shaped electrode is used at the entrance of Faraday Cup:

Typical voltage 100 to 1000 V





potential on central axis for -1 kV@electrode



Result:

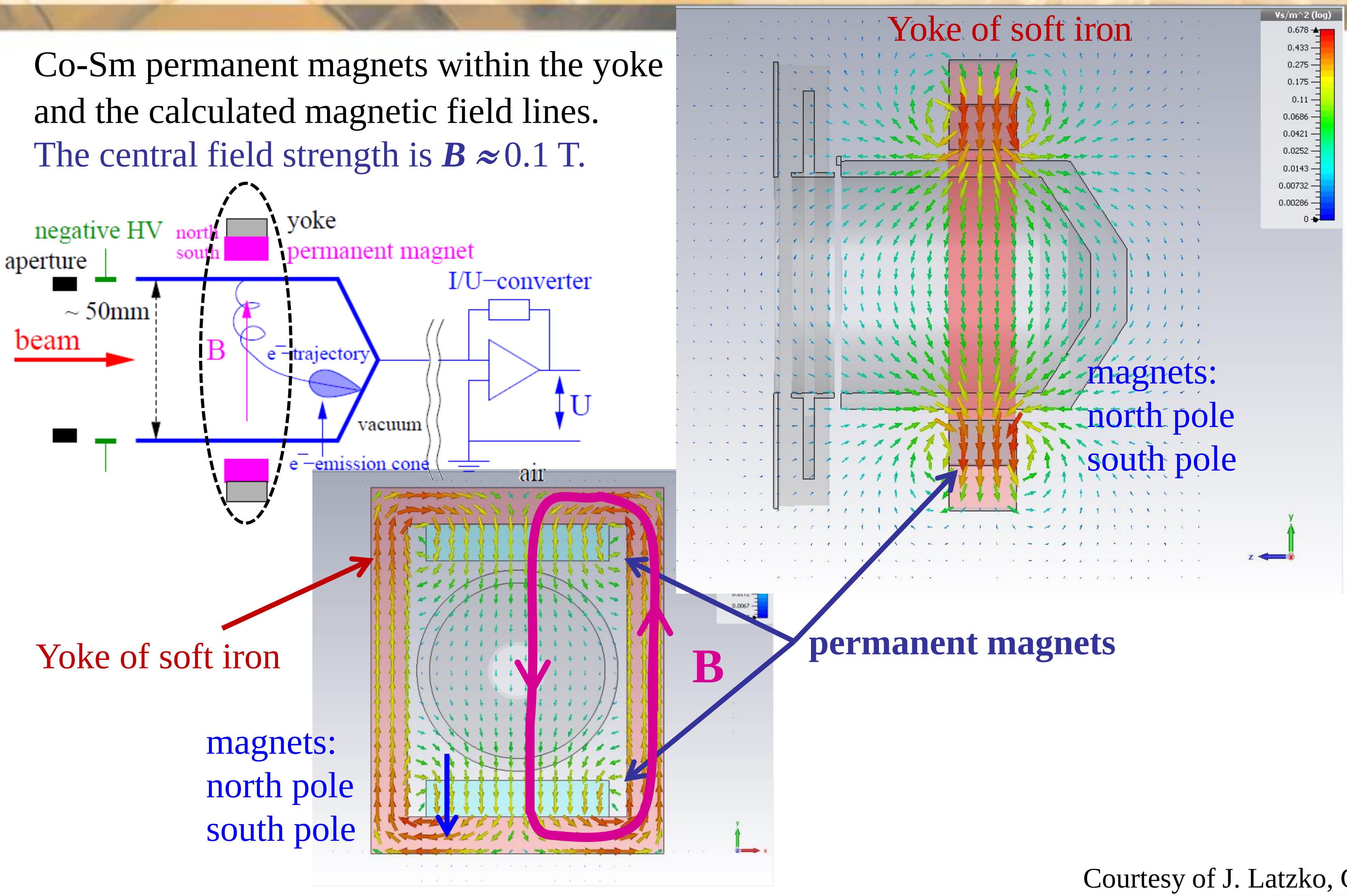
here: potential at center ≈ 35 % of applied voltage

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 $B \approx 0.1$ T.



Yoke of soft iron

magnets:
north pole
south pole

Yoke of soft iron

permanent magnets

magnets:
north pole
south pole

Courtesy of J. Latzko, GSI

Measurement of Beam Current

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  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.

Low Current Measurement for slow Extraction

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

Extracted current $I_{beam} = qe\frac{N_{part}}{t}$:

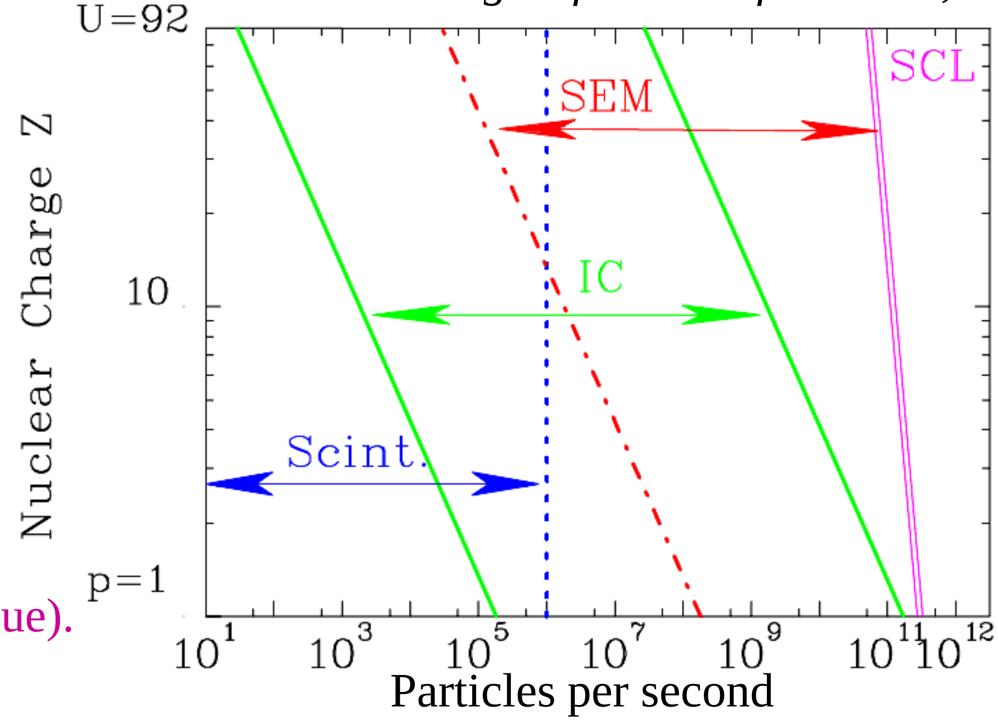
- Slow extraction: e.g. $N_{part} = 10^{12}$ protons per $t = 10$ s = 1.6 µA i.e. below DCCT threshold
- Fast extraction: e.g. $N_{part} = 10^{12}$ protons per $t = 100$ ns = 1.6 A

Detector types:

- **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, typ. value).

Particle detector technologies for ions of 1 GeV/u, A = 1 cm²:



Example of Scintillator Counter

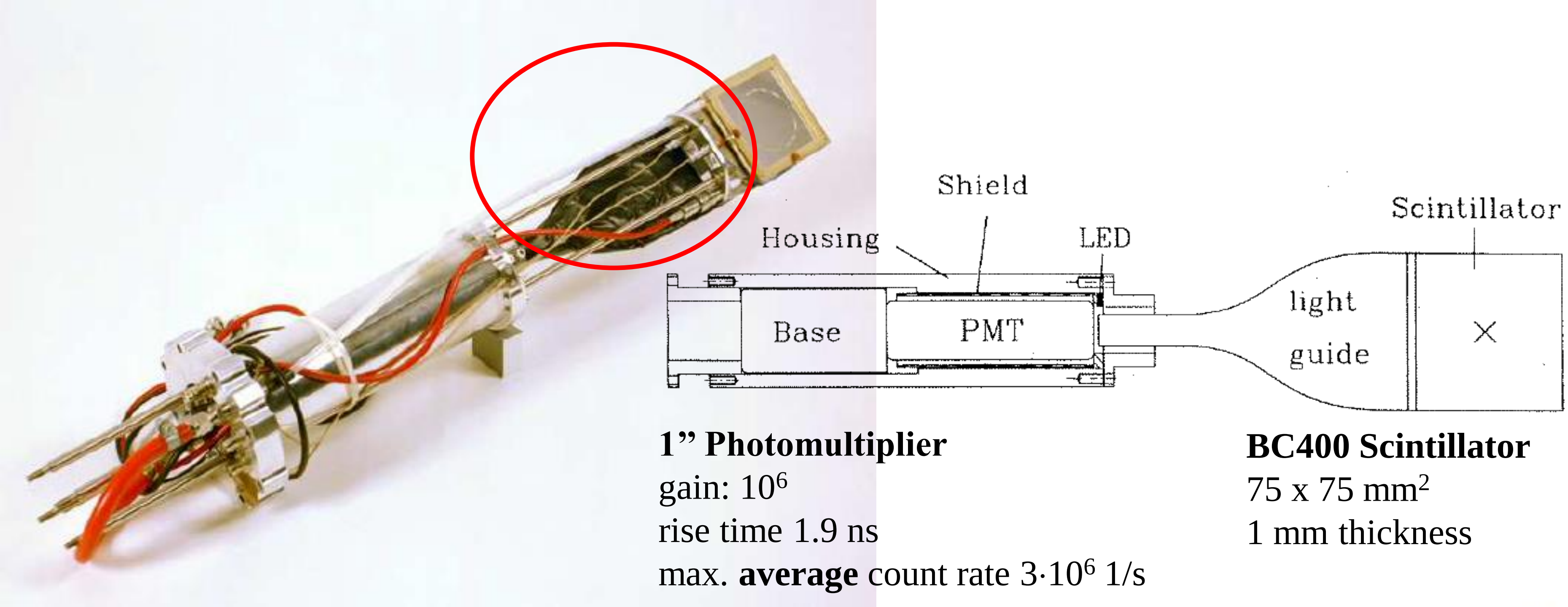
Example: Plastic Scintillator i.e. organic fluorescence molecules in a plastic matrix

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

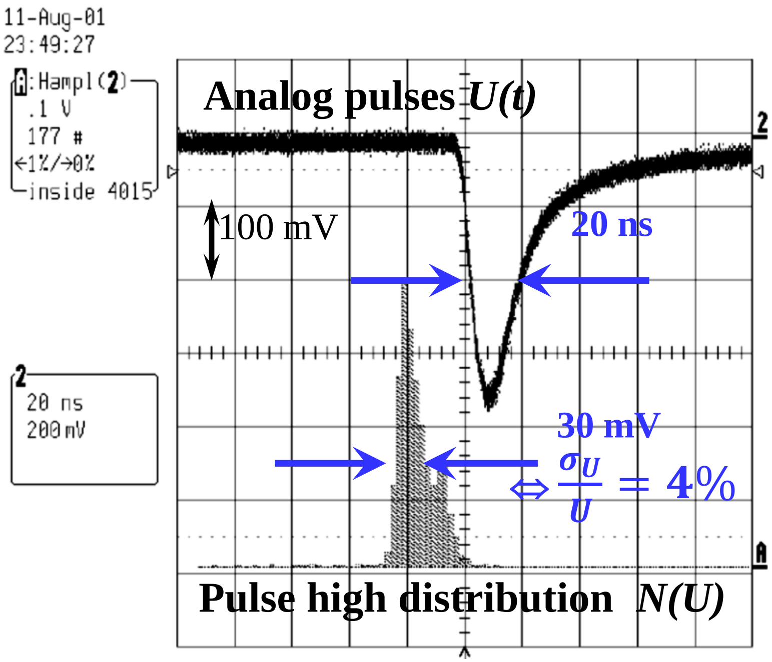
BC400 Scintillator
$75 \times 75\ \text{mm}^2$
1 mm thickness

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.



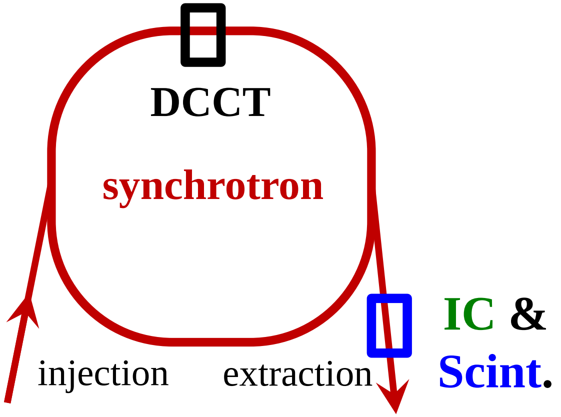
The scaling is 20 ns/div and 100 mV/div.

Monitoring of Slow Extraction

Slow extraction from a synchrotron delivers countable currents.

Usage for:

- Optimization of extraction efficiency
- If possible transmission active control
- Alignment of coarse time dependent $I_{beam}(t)$
- Determination & optimization of fine $I_{beam}(t)$
- Calibration of different detectors


DCCT

synchrotron

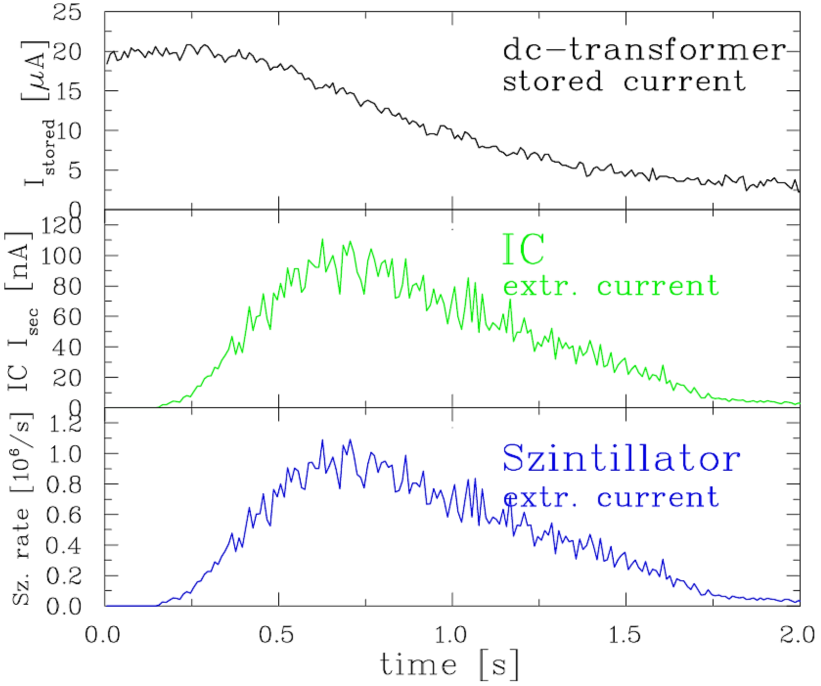
injection

extraction

IC &

Scint.

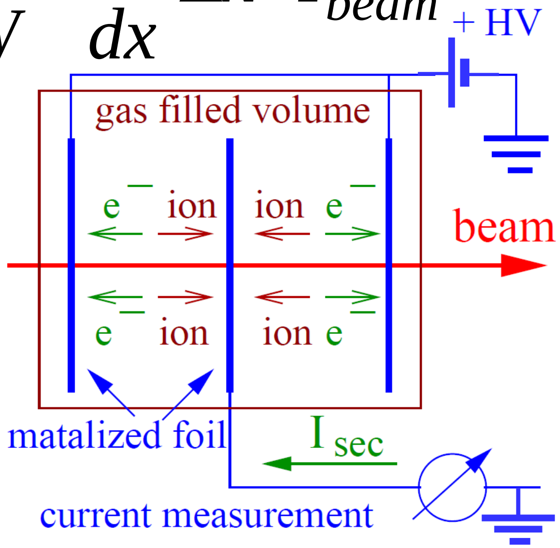
Example: Comparison for different detector types: dc-transformer DCCT inside synchrotron., ionization chamber and scintillator for 250 MeV/u Pb^{67+} beam with 10^6 particles.



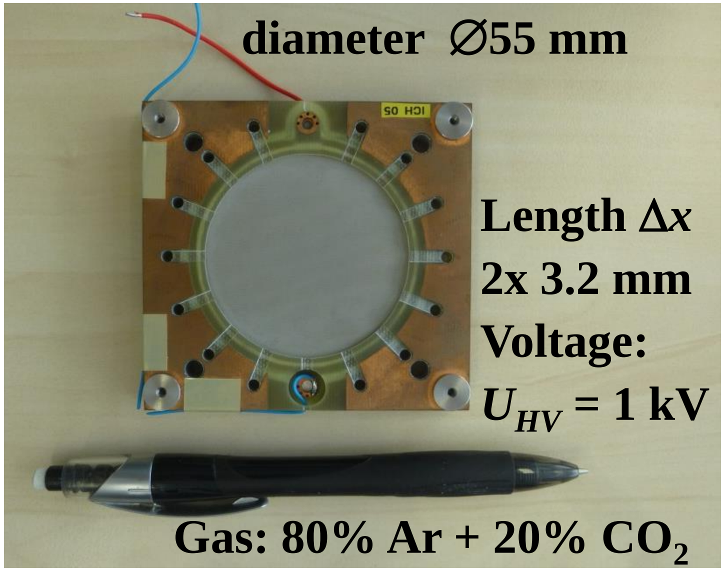
Ionization Chamber (IC): Electron Ion Pairs

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

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



Example: GSI type:


diameter ∅55 mm

Length Δ*x*
2x 3.2 mm
Voltage:
U_{HV} = 1 kV

Gas: 80% Ar + 20% CO_2

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

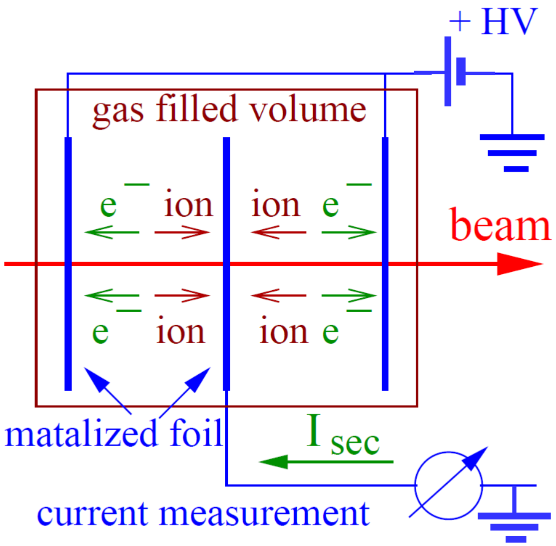
GSI realization:

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

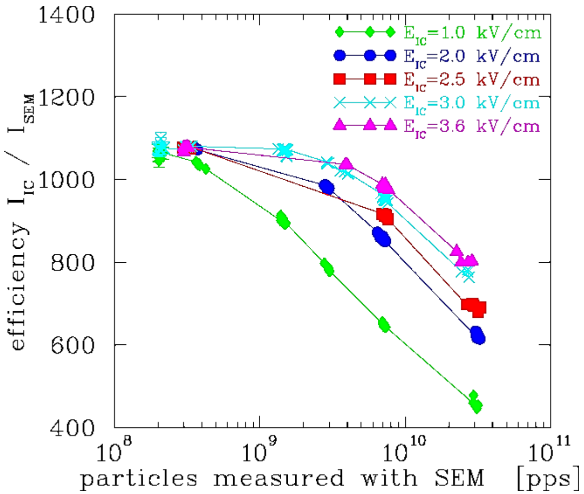
Lower and upper Limit of IC Current

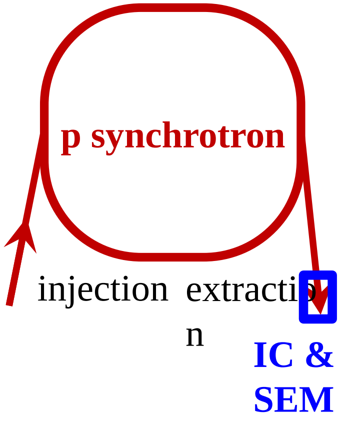
Lower limit of a IC is given by the most sensitive current measurement:

typically min. $\boldsymbol{I_{sec}} \approx$ 10 pA with 1 ms time resolution ⇔ bandwidth 0.3 kHz (note $U_{noise} \propto \sqrt{\Delta f}$)



Example: GSI slow extraction of 2 s,300 MeV/u Ne^{10+}





Upper limit of a IC is related to the recombination of gas ions e.g. Ar$^+$ with e$^-$: Ar$^+$ + e$^-$ → Ar

- The density of Ar$^+$ and is $\boldsymbol{n_{Ar} \propto I_{beam}}$ and of e$^-$ $\boldsymbol{n_e \propto I_{beam}}$
- Recombination: Ar$^+$ + e$^-$ → Ar leads to loss of sec. charges $\boldsymbol{I_{REC} \propto \alpha \cdot n_{Ar} \cdot n_e \propto I^2_{beam}}$
- Drift time Ar: $\boldsymbol{t_{drift} \propto E_{IC} \approx}$ 50μs & e$^-$: $\boldsymbol{t_{drift} \propto E_{IC} \approx}$ 0.1μs; rate coefficient $\boldsymbol{\alpha}$ = 10^{-9} cm^3/s
- Effect remarkable for secondary current $\boldsymbol{I_{sec}}$ > 1 μA or dose rate of $\boldsymbol{D_{IC}}$ > 30 Gy/s

  e.g. max $\boldsymbol{I_{beam}}$ for 1 GeV/u, t$_{ex}$=1 s, ∅ 0.5 cm: p → 10^{11} 1/s, Ne → 10^9 1/s, U → 10^7 1/s

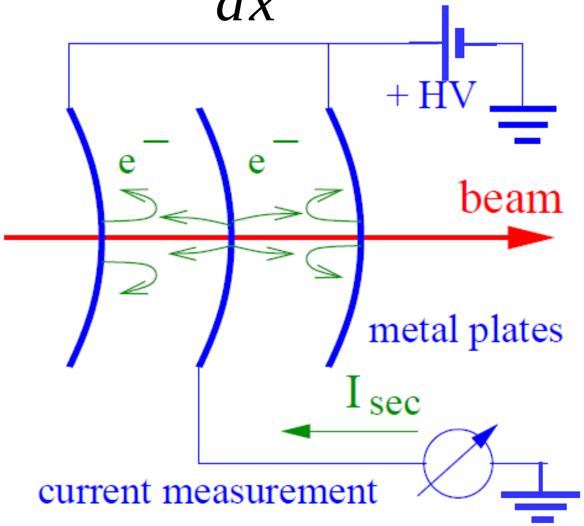
Secondary Electron Monitor (SEM): Electrons from Surface

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 electrode	3
Active surface	80 x 80 mm^2
Distance between electrodes	5 mm
Applied voltage	+ 100 V

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%.

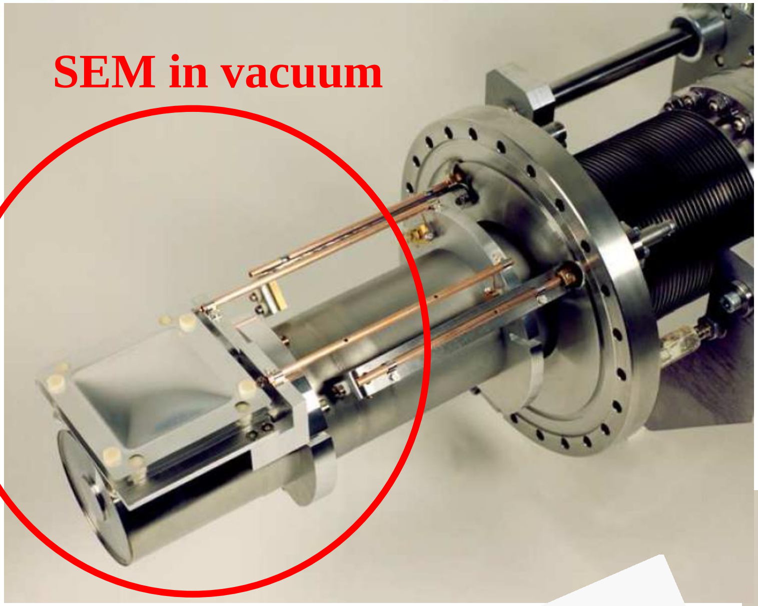
It is a ***surface*** effect:

→ Sensitive to cleaning procedure

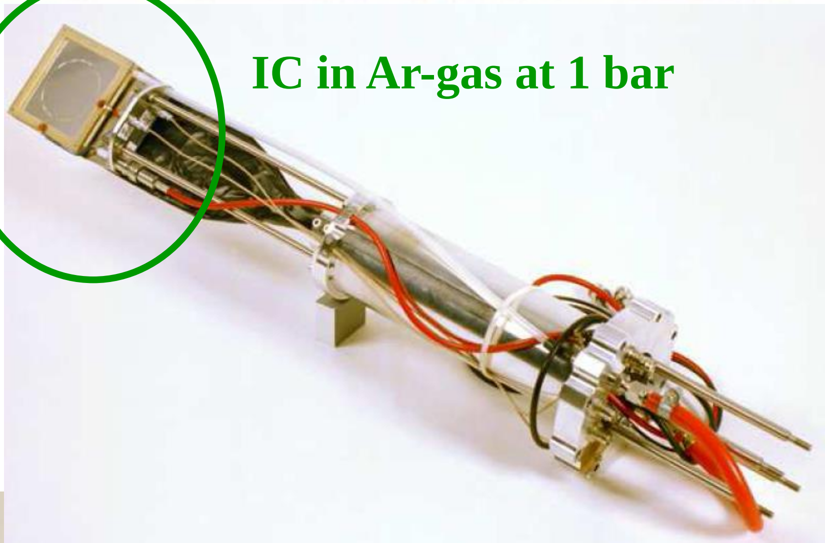
→ Possible surface modification by radiation

Sometimes they are installed permanently in front of an experiment.

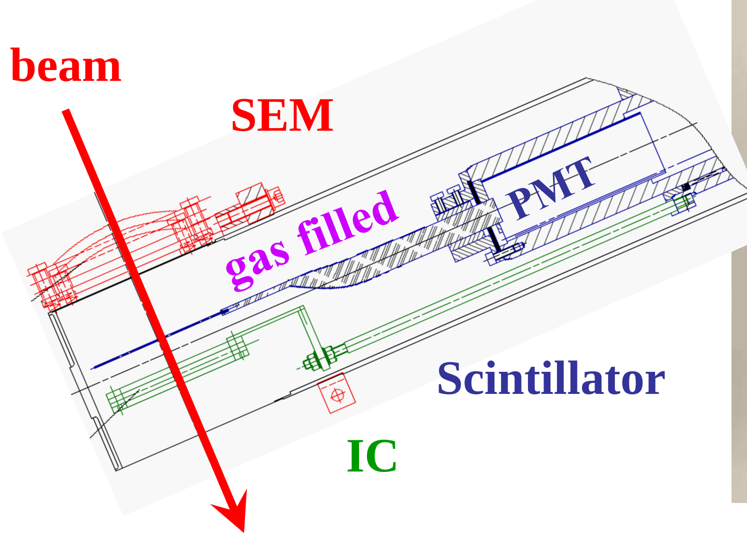
GSI Installation for SEM, IC and Scintillator

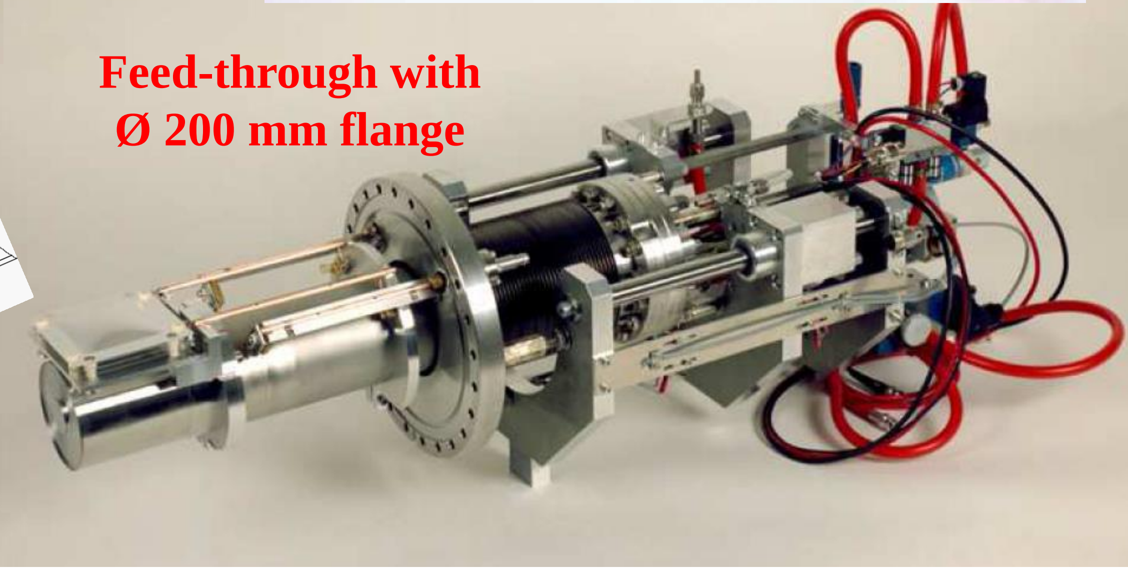


SEM in vacuum



IC in Ar-gas at 1 bar





Feed-through with
Ø 200 mm flange

P. Forck et al., DIPAC'97

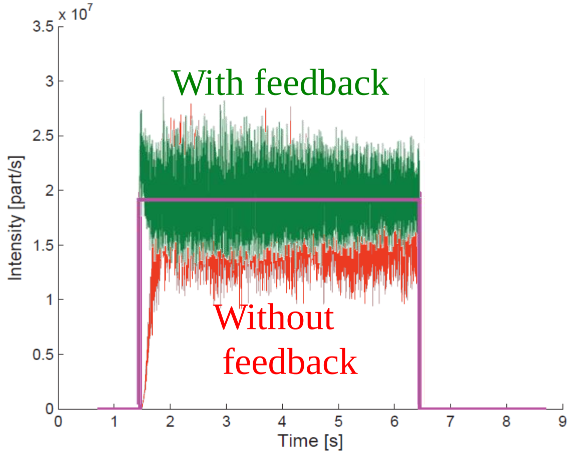
Current Control for slow Extraction using the Signal from IC

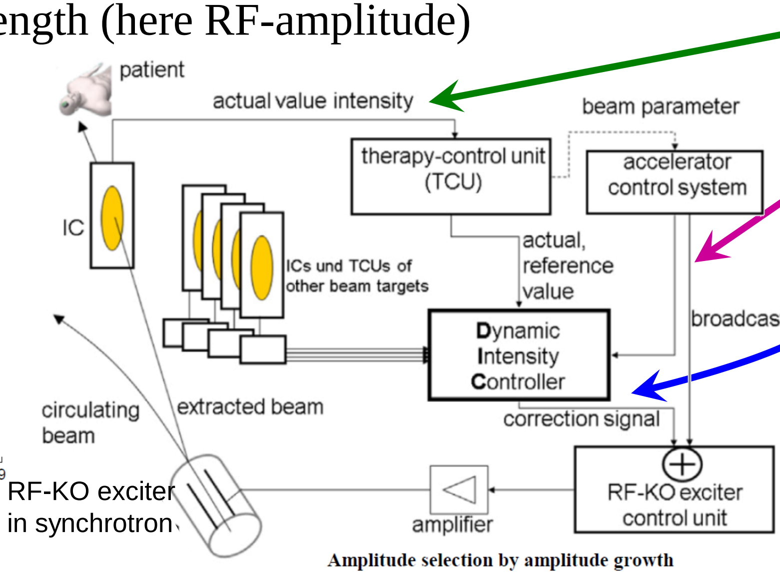
Slow extraction: A constant beam delivery ***I***$I_{beam}(t)$ at experiment is desired

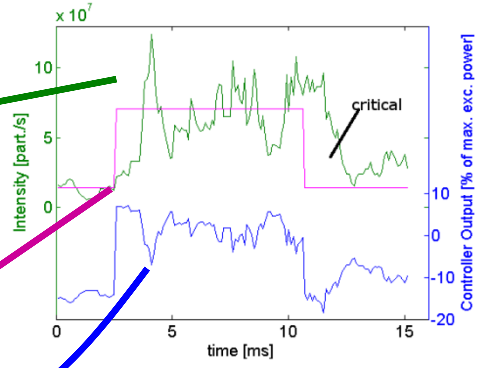
→ feedback: ***Input*** IC monitor for the *extracted* beam on target, ***Output:*** extraction strength in sychr.

Example from medical facility HIT: C^{6+} at 250 MeV/u

- ➢Beam current measurement by IC with Δt = 100 µs readout time
- ➢Regulation of extraction strength (here RF-amplitude)

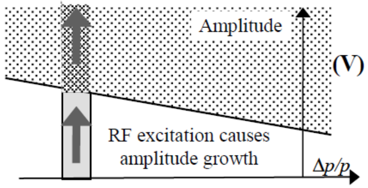


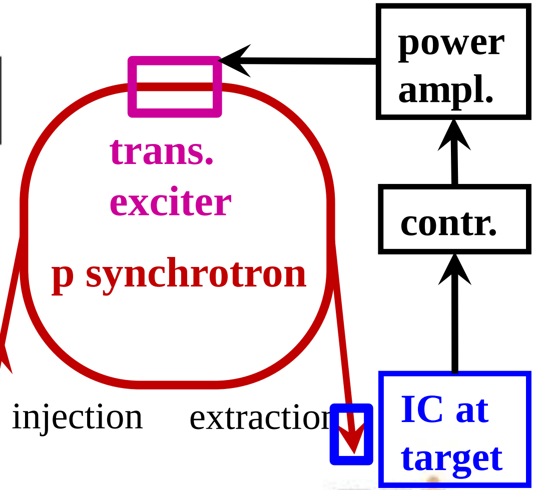




Regulation achievements: ≈ 10 ms
limited by latency from crossing separatrix
until reach the electro-static septum

Amplitude selection by amplitude growth





Courtesy C. Schömers (HIT) et al.,
NIM A 795, 92 (2015) and IPAC'11 & '13

'Waiting' beam : Large E_x, small $\Delta p/p$.
Extracted beam: Constant p, small $\Delta p/p$ and constant spiral step

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, $I_{min} \approx$ 30 µA, BW = 10 kHz ... 500 MHz),
  active (low droop, $I_{min} \approx$ 0.3 µA, BW = 10 Hz .... 1 MHz)
  dc (two toroids + modulation, $I_{min} \approx$ 1 µA, BW = dc ... 20 kHz)
- 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

Beam Loss Monitors

When energetic beam particles penetrates matter, secondary particles are emitted:
this can be e^-, γ, protons, neutrons, excited nuclei, fragmented nuclei...
⇒ Spontaneous radiation and permanent activation is produced.
⇒ Large variety of Beam Loss Monitors (**BLM**) depending on the application.

Protection: Sensitive devices e.g. super-conducting magnets to prevent quenching (energy absorption by electronic stopping)

→ **interlock signal for fast beam abortion.**

Beam diagnostics: Alignment of the beam to prevent for activation

→ **optimal transmission to the target.**

- Several devices are used, depending on particle rate and required time resolution
- Some applications for usage

Basic Idea of Beam Loss Monitors

Basic idea for Beam Loss Monitors B LM:

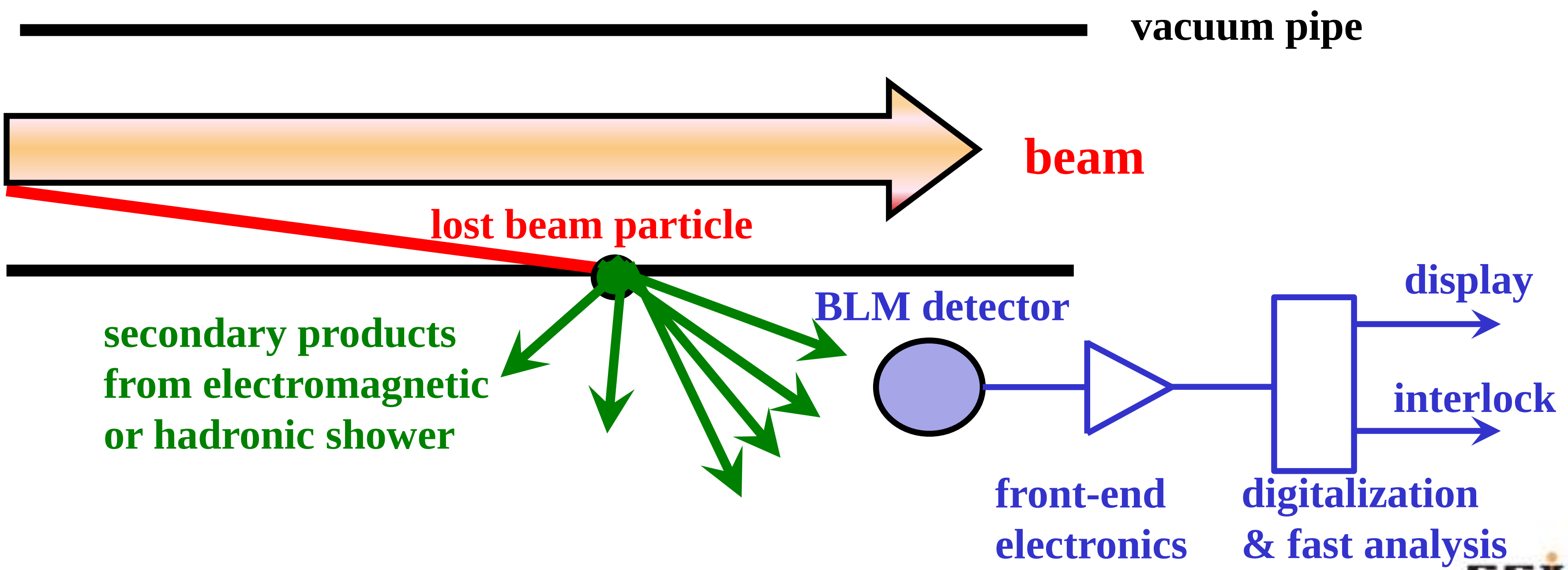
A loss beam particle must collide with the vacuum chamber or other insertions

⇒ Interaction leads to some shower particle:

e^-, γ, protons, neutrons, excited nuclei, fragmented nuclei

→ detection of these secondaries by an appropriate detector outside of beam pipe

→ relative cheap detector installed at many locations



Secondary Particle Production for Electron Beams

Processes for interaction of electrons

For E_{kin}> 100 MeV:

Bremsstrahlungs-photon dominated

$\Rightarrow \gamma \rightarrow e^+ + e^-$ or $\mu^\pm$, $\pi^\pm$ ....

$\rightarrow$ electro-magnetic showers

$\Rightarrow$ excitation of

nuclear giant resonances $E_{res} \approx 6$ MeV

via (γ, n), (γ, p) or (γ, np)

$\rightarrow$ fast neutrons emitted

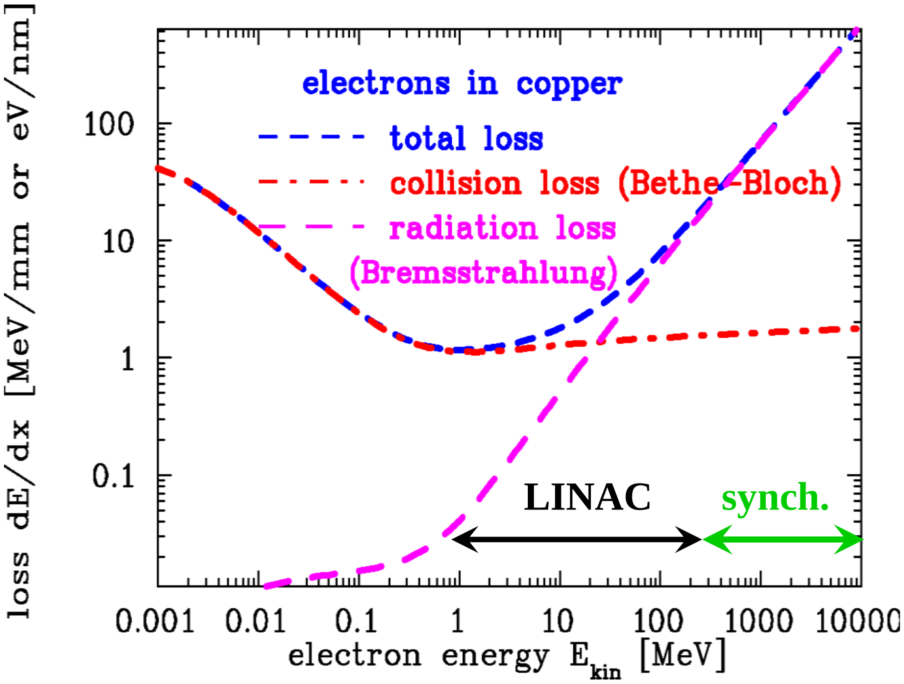
$\rightarrow$ neutrons: Long ranges in matter

due to lack of ele.-mag. interaction.

For E_{kin} < 10 MeV:

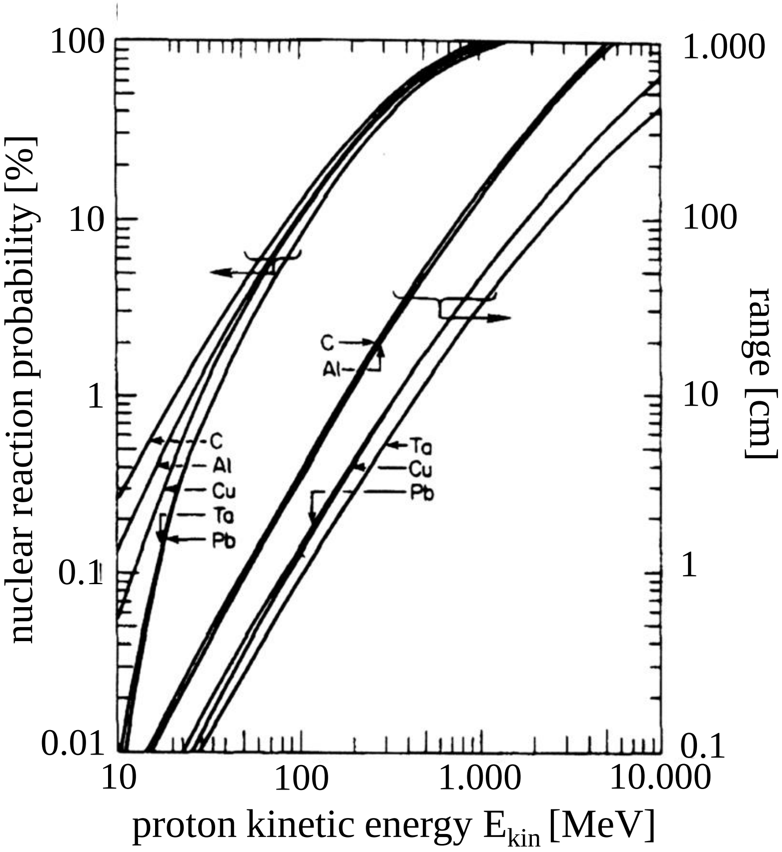
$\Rightarrow$ only electronic stopping

(x-rays, slow e^-).

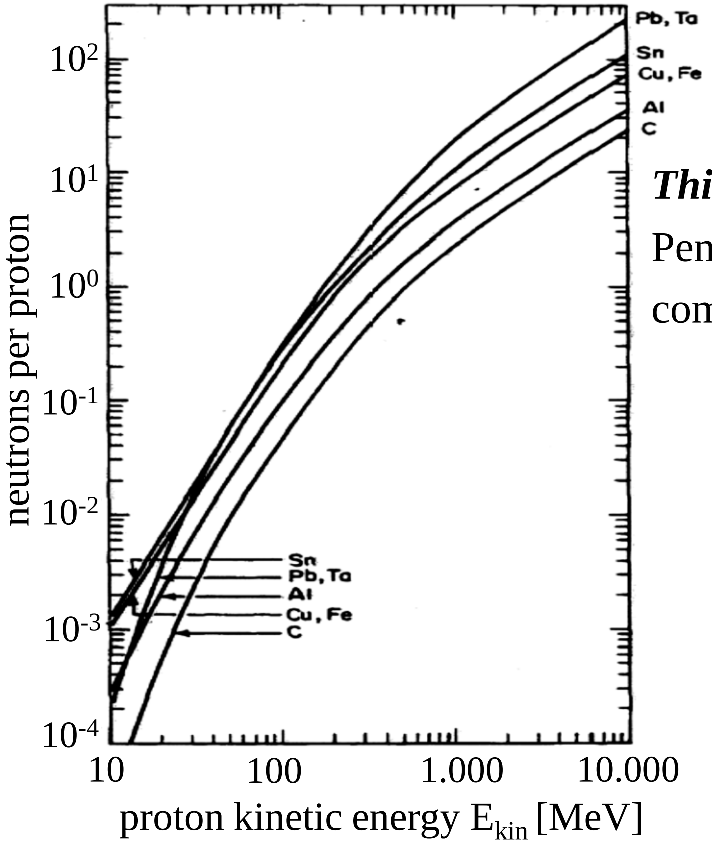


Secondary Particle Production for Proton Beams

Nuclear reaction probability:



Neutron yield per proton:



Thick target:

Penetration depth comparable to range

⇒ **High rate of neutron with broad energy & angular distribution**

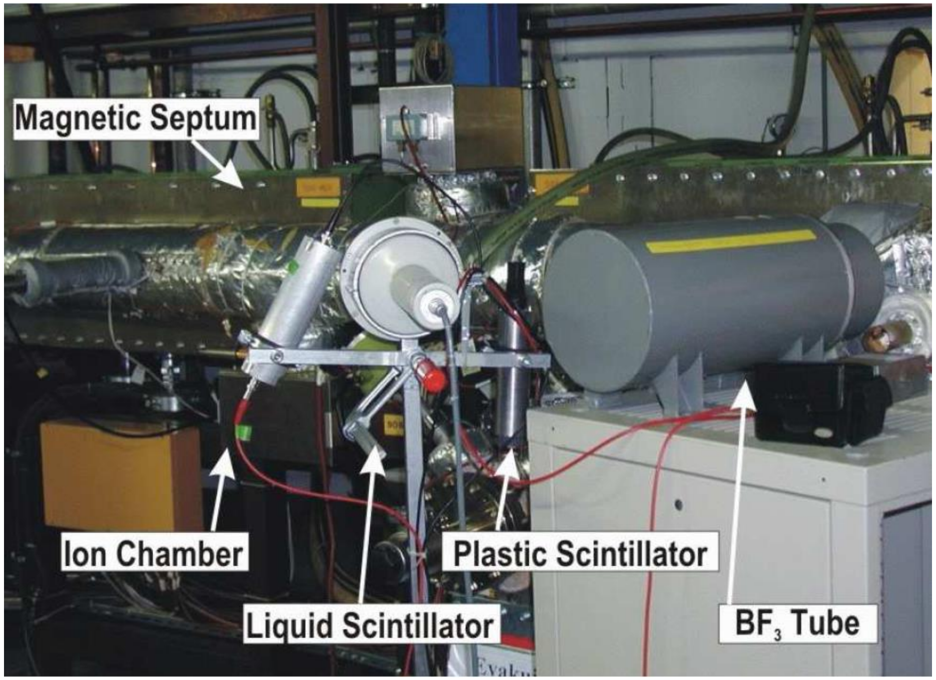
⇒ **Role of thumb for protons: Sufficient count rate for beam loss monitoring only for $E_{kin} \geq 100$ MeV**

Courtesy R.H. Thomas, in Handbook on Acc. Phy. & Eng. (ed. A.W. Chao, et al.)

Outline:

- Physical process from beam-wall interaction
- **Different types of Beam Loss Monitors**

  different methods for various beam parameters
- **Machine protection using BLMs**
- **Summary**



Scintillators as Beam Loss Monitors

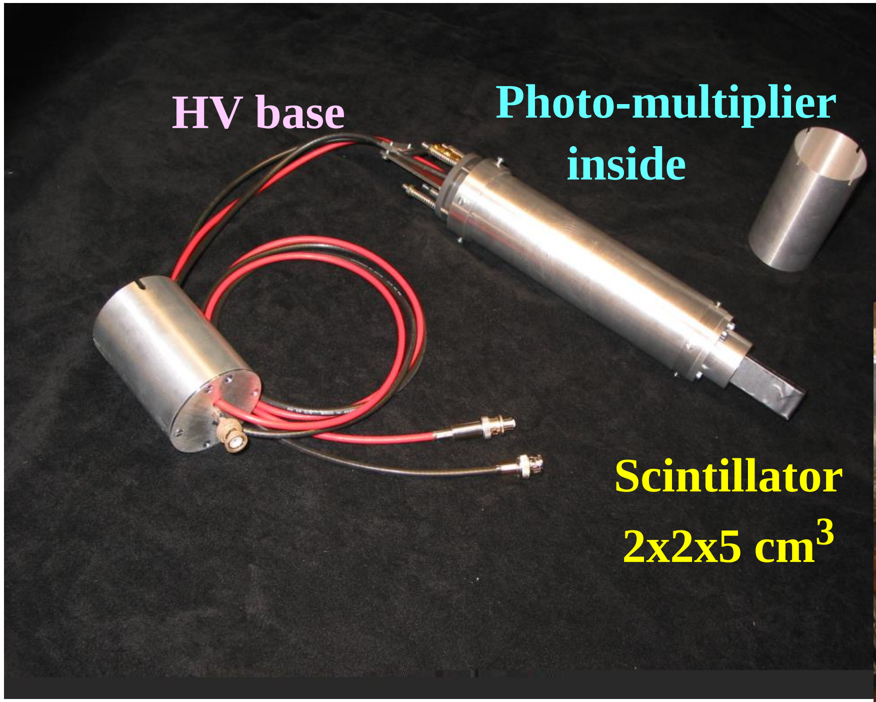
Plastics or liquids are used:

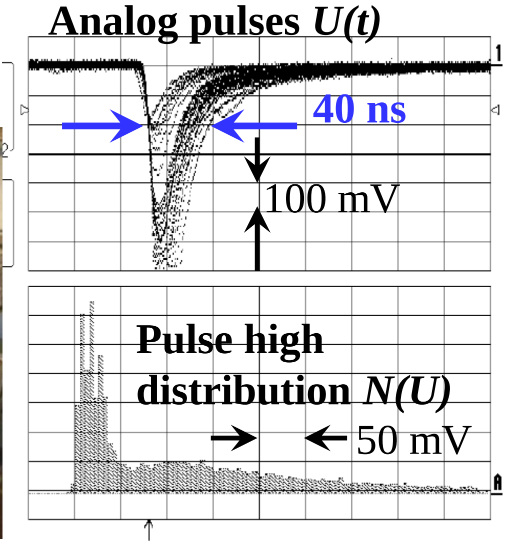
- detection of **charged particles**
  by electronic stopping
- detection of **neutrons**
  by elastic collisions n on p in plastics
  and fast p electronic stopping.

Scintillator + photo-multiplier:

counting (large PMT amplification)
or analog voltage ADC (low PMT amplification)
Radiation hardness:
plastics 1 Mrad = 10^4 Gy
liquid 10 Mrad = 10^5 Gy

Example: Analog pulses of plastic scintillator:
⇒ broad energy spectrum
due to many particle species and energies.





20 ns/div and 100 mV/div

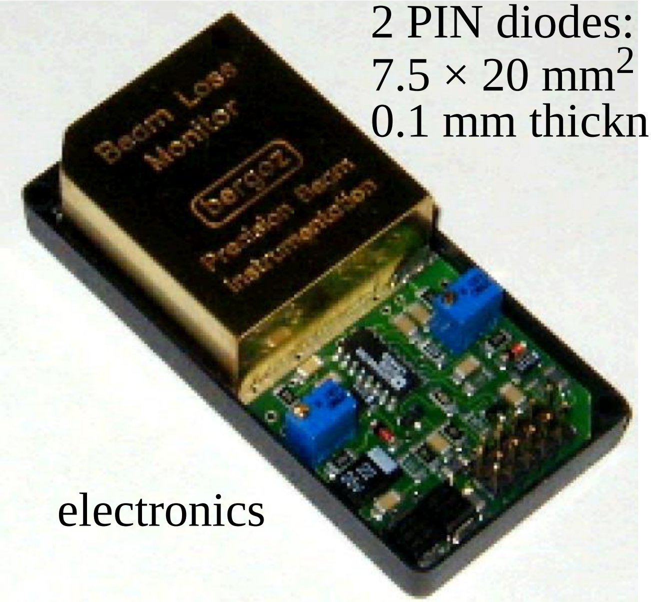
PIN-Diode (Solid State Detector) as BLM

Solid-state detector: Detection of charged particles.

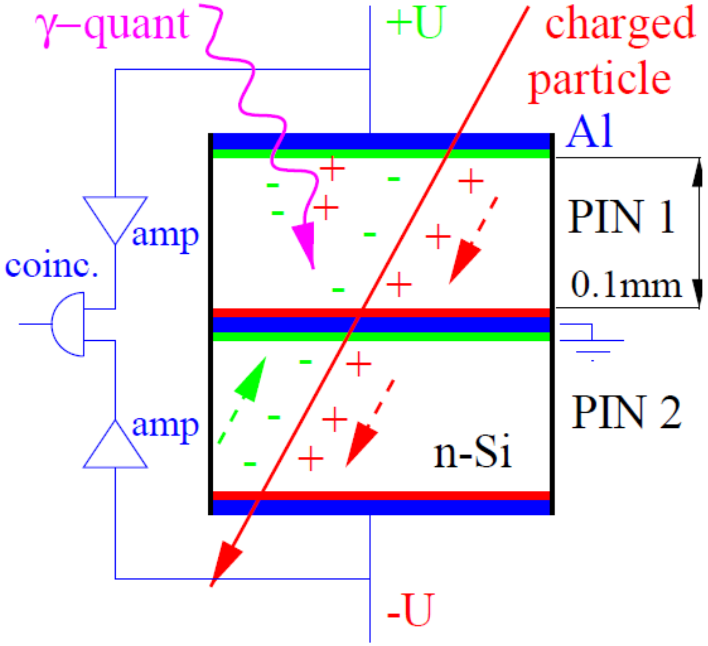
Working principle

- ➢ About 10^4 e^--hole pairs are created by a Minimum Ionizing Particle (MIP).
- ➢ A coincidence of the two PIN reduces the background due to low energy photons.
- ➢ A counting module is used with threshold value comparator for alarming.

→ small and cheap detector.



2 PIN diodes:
7.5×20 mm^2
0.1 mm thickness.



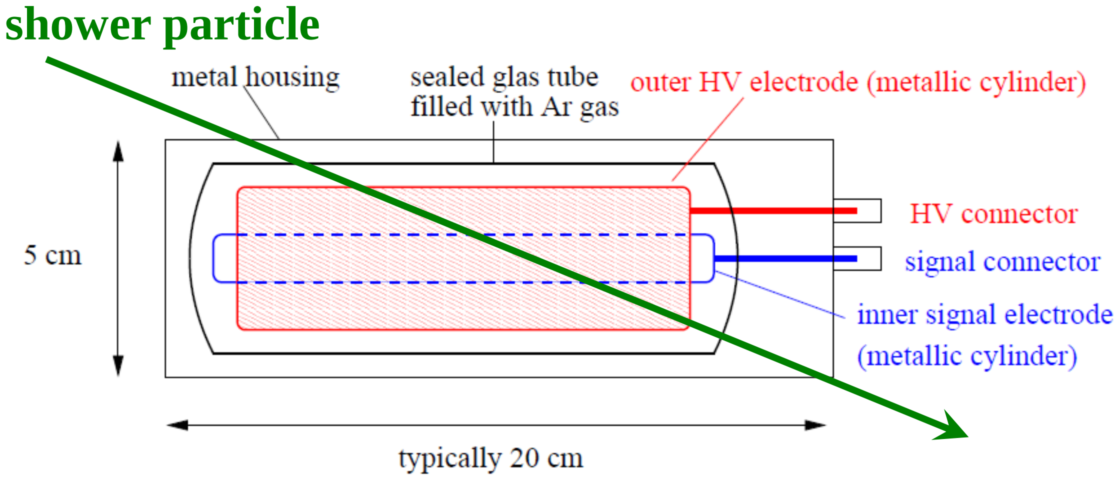
Excurse: Ionization Chamber (IC)

Energy loss of charged particles in gases → electron-ion pairs → current measurement

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

W is average energy for one e¯ -ion pair:

Gas	Ionization Pot. [eV]	W-Value [eV]
Ar	15.7	26.4
N_2	15.5	34.8
O_2	12.5	30.8
Air		33.8

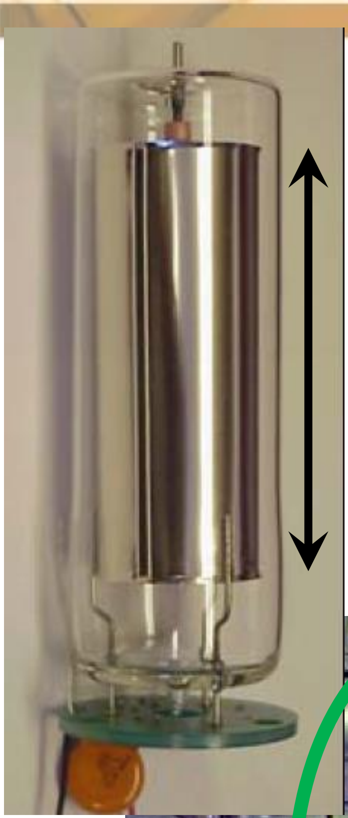


Sealed tube Filled with Ar or N_2 gas:

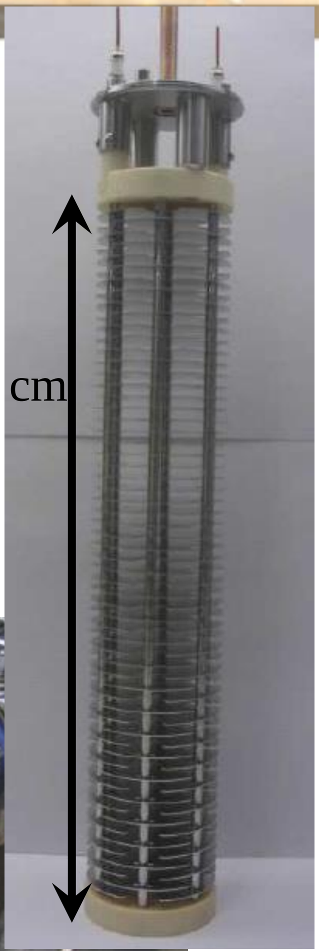
- Creation of Ar^+-e^- pairs, average energy ***W***=32 eV/pair
- measurement of this current
- Slow time response due to 100 μs drift time of Ar^+.

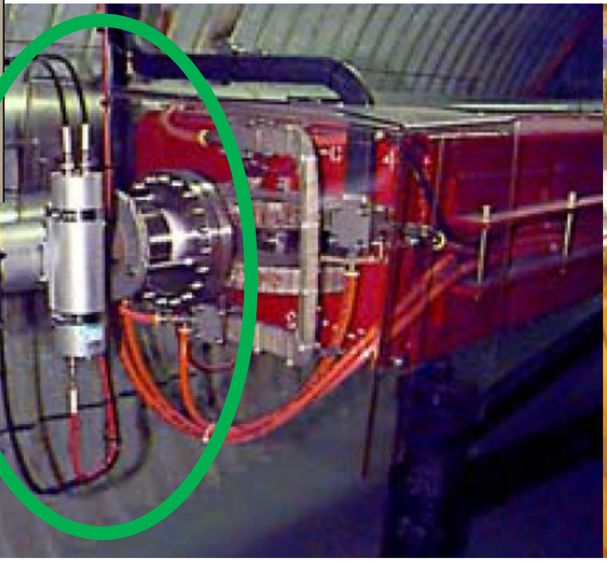
Per definition: direct measurement of dose.

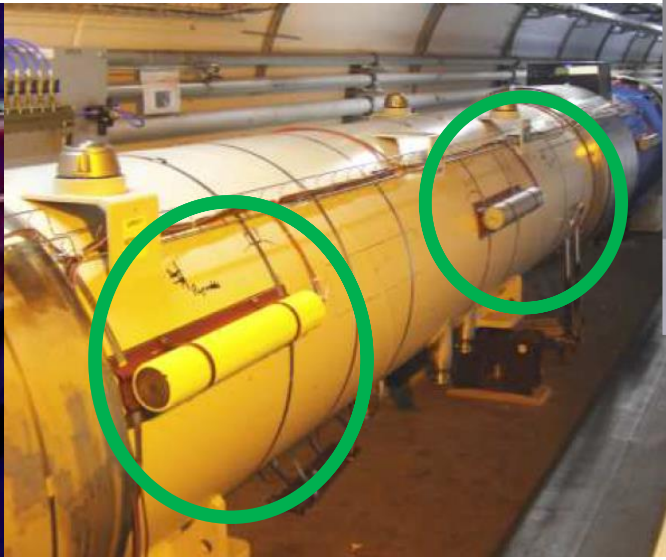
Ionization Chamber as BLM: TEVATRON and CERN Type



TEVATRON, RHIC type		CERN type
15cm, ∅ 6 cm	**size**	50 cm, ∅ 9 cm
Ar at 1.1 bar	**gas**	N_2 at 1.1 bar
three	**# of electrodes**	61
1000 V	**voltage**	1500 V
3 μs	**reaction time**	0.3 μs
	# at the synchr.	≈ 4000 at LHC
	aver. distance	1 BLM each ≈ 6 m





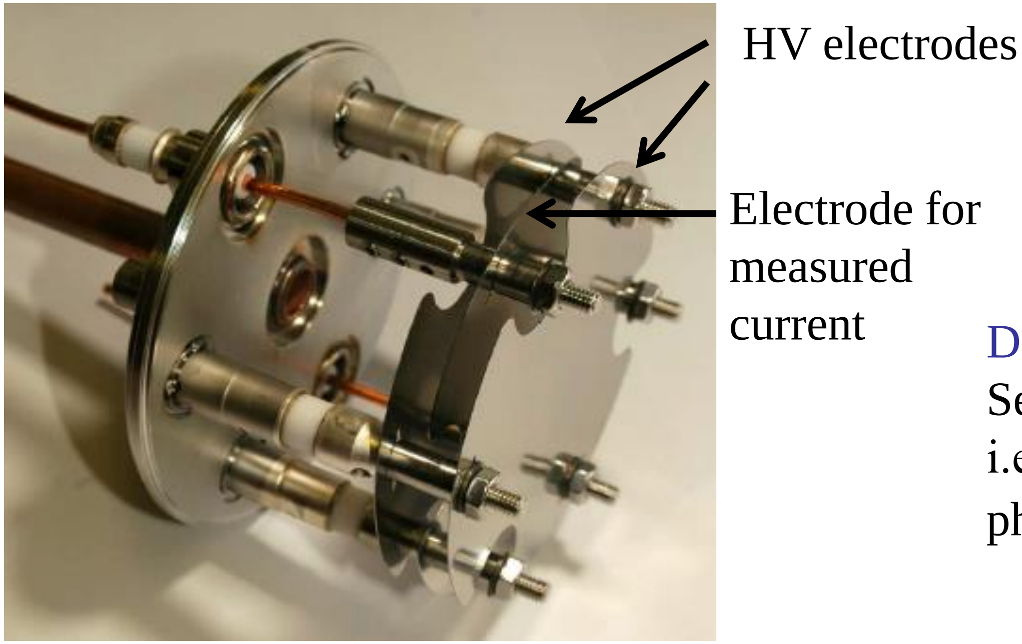


Secondary Electron Monitor as BLM

Ionizing radiation liberates secondary electrons from a surface.
Working principle:

- Three plates mounted in a vacuum vessel (passively NEG pumped)
- Outer electrodes: biased by ***U*** ≈ +1 kV
- Inner electrode: connected for current measurement (here current-frequency converter)

→ small and cheap detector, very insensitive.



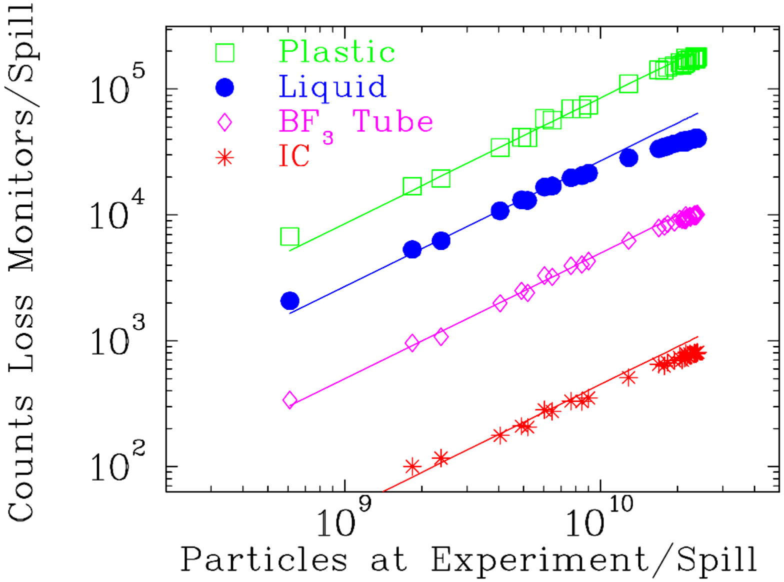
Detector with intrinsic amplification:
Secondary electron multiplier
i.e. a ‘photo-multiplier without photo-cathode’

Comparison of different Types of BLMs

Different detectors are sensitive to various physical processes
very different count rate, but basically proportional to each other

⇒ Linear behavior for all detectors
but quite different count rate:
$r_{IC} < r_{BF3} < r_{liquid} < r_{plastic}$

Example: Beam loss for 800 MeV/u O^{8+}
determined different BLMs at GSI-synchr.:



Choice of the detector type:

- IC:
  measurement of absolute dose
  low signal, sometimes slow
- PIN-diode, scintillator or diamond detector:
  fast due to particle counting
  might need calibration

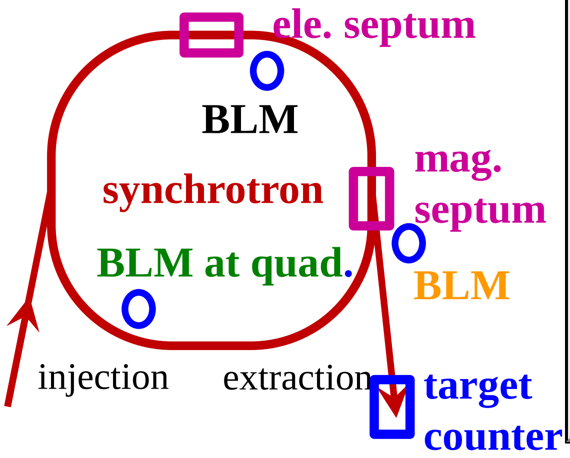
Application of BLMs for slow Extraction: Time Dependence

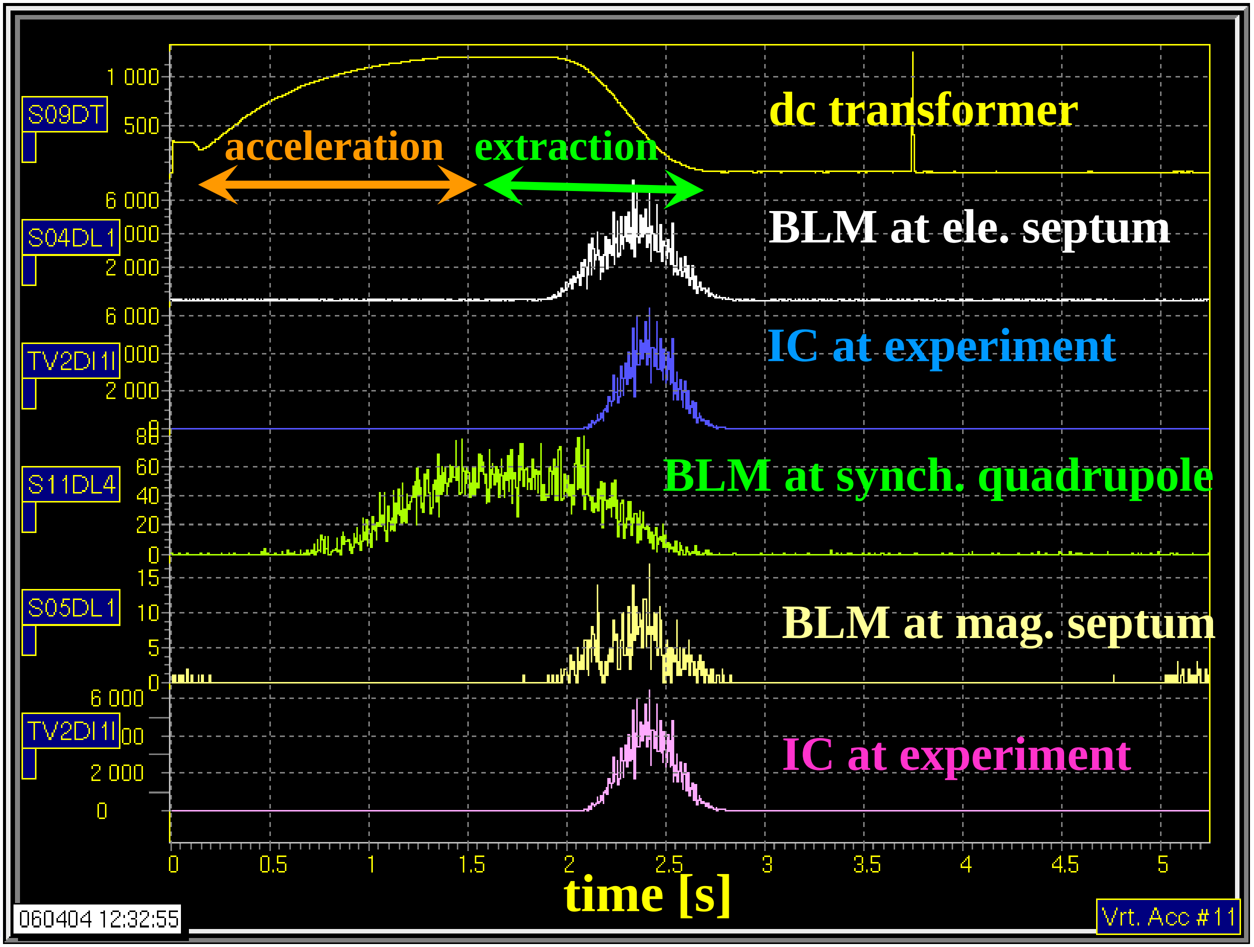
BLM are cheap and can be installed at several locations and determine local loss:

Example at SIS synchr. using quadrupole variation for slow extraction:

- Losses during acceleration
- Losses at ele. septum
- Momentum dependent extraction current
  ⇒change of extraction angle
  ⇔ time-dependent losses at mag. septum

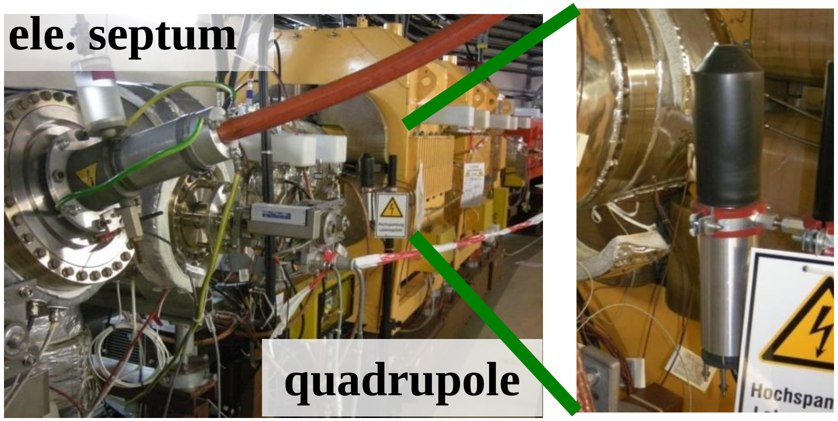
⇒ used for optimization of time-dep. extraction angle

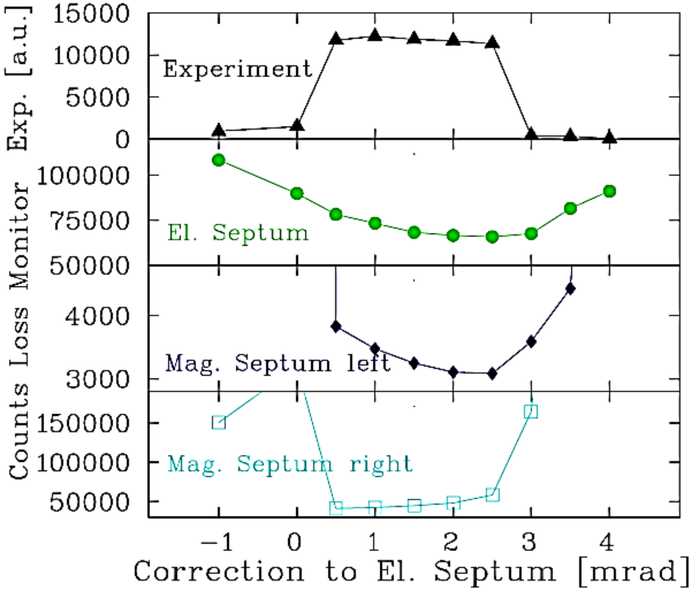


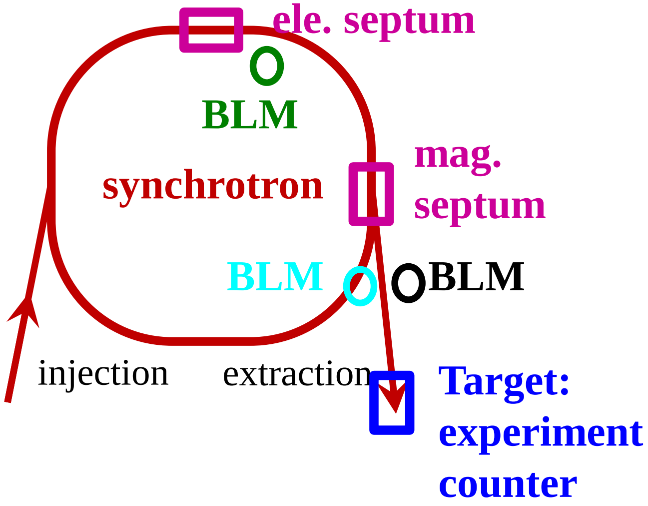


Application of BLMs for slow Extraction: Transfer Line Alignment

Example: Counts per spill from scintillators
at different location for optimization of extraction efficiency and transmission to target:







ele. septum

BLM

synchrotron

mag. septum

BLM

BLM

injection

extraction

Target: experiment counter

Advantage:

- very sensitive device for optimization
- cheap monitors
  mounted at many locations outside the vacuum pipe

Machine Protection Issues for BLM

Losses lead to permanent activation ⇒ maintenance is hampered

and to material heating (vacuum pipe, super-cond. magnet etc.) ⇒ destruction.

Types of losses:

- ***Irregular*** or fast losses by malfunction of devices (magnets, cavities etc.)
  → BLM as online control of the accelerator functionality and **interlock generation**.
- ***Regular*** or slow losses e.g. at collimator, by lifetime inside synchrotron or slow extraction
  → BLM used for alignment

Demands for BLM:

- **High sensitivity** to detect behavior of beam halo e.g. at collimator
- **Large dynamic range**:
  → low signal during normal operation, but large signal in case of malfunction
  → detectable without changing the full-scale-range
  e.g. scintillators from 10^2 1/s up to 10^7 1/s in counting mode.

Monitoring of loss rate in control room ***and*** as interlock signal for beam abortion.

Summary Beam Loss Monitors

Measurement of the lost fraction of the beam:

- detection of secondary products
- sensitive particle detectors are used outside the vacuum
- cheap installations used at many locations

Used as interlock in all high current machines for protection.

Additionally used for sensitive ‘loss studies’.

Depending on the application different types are used:

Frequently used:

- **Scintillators:** very sensitive, fast response, largest dynamics, not radiation hard
- **PIN diode:** insensitive, fast response, not radiation hard, cheap
- **IC:** medium sensitive, slow response, radiation hard, cheap, **absolute measurement of dose**
- **SEM:** very in-sensitive, i.e. suited for high radiation area, fast radiation hard, cheap

Further types are used: electron multiplier, BF_3 neutron counter, cable-based IC, optical fibers....

Thank you for your attention!