

## Measurement of Beam Current JUAS 2025, ESI-Archamps at CERN Peter Forck (GSI and University Frankfurt)





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## 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 current 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; exception for BPMs in cyclotrons











#### Analysis of a 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  $R_L$ )

## Bandwidth of a Passive Transformer or FCT



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





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



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Measurement of Beam Current





## **Example for Fast Current Transformer**

For bunch beams e.g. transfer between synchrotrons typical bandwidth of 2 kHz < f < 1 GHz  $\Leftrightarrow$  1 ns <  $t_{batch}$  < 200 µs is well suited Example: GSI Fast Current Transformer FCT:

| Inner / outer radius                     | 70 / 90 mm   |
|--|--|
| Permeability                             | $\mu_r \approx 10^5$ for f < 100kHz<br>$\mu_r \propto 1/f$ above |
| Windings                                 | 10   |
| Sensitivity                              | 4 V/A for R = 50 $\Omega$  |
| Resolution, full BW                      | 30 µA <sub>rms</sub>   |
| Droop time $\tau_{droop} = L/R$          | 0.2 ms   |
| Rise time $\tau_{rise} = \sqrt{L_S C_S}$ | 300 ps   |
| 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:



## **Example for Fast Current Transformer**

For bunch beams e.g. during accel. in a synchrotron typical bandwidth of 2 kHz < f < 1 GHz  $\Leftrightarrow$  10 ns <  $t_{bunch}$  < 1 µs is well suited

Example: GSI Fast Current Transformer FCT:

| Inner / outer radius                     | 70 / 90 mm   |
|--|--|
| Permeability                             | $\mu_r \approx 10^5$ for f < 100kHz<br>$\mu_r \propto 1/f$ above |
| Windings                                 | 10   |
| Sensitivity                              | 4 V/A for R = 50 $\Omega$  |
| Resolution, full BW                      | 30 µA <sub>rms</sub>   |
| Droop time $\tau_{droop} = L/R$          | 0.2 ms   |
| Rise time $\tau_{rise} = \sqrt{L_S C_S}$ | 300 ps   |
| Bandwidth                                | 2 kHz 500 MHz  |





*Example:* U<sup>73+</sup> from 11 MeV/u ( $\beta$  = 15 %) to 350 MeV/u within 300 ms (displayed every 0.15 ms)



![](_page_10_Figure_1.jpeg)

**Active Transformer or Alternating Current Transformer ACT:** 

uses a trans-impedance amplifier (I/U converter) to  $\mathbf{R} \approx \mathbf{0} \Omega$  load impedance i.e. a current sink

- + compensation feedback
- $\Rightarrow$  longer droop time  $\tau_{droop}$

Application: measurement of longer  $t > 10 \mu s e.g.$  at pulsed LINACs

![](_page_10_Figure_7.jpeg)

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

![](_page_11_Picture_1.jpeg)

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

![](_page_11_Picture_3.jpeg)

| Inner / outer radius | 30 / 45 mm   |
|----------------------|--|
| Permeability         | μ <sub>r</sub> ≈ 10 <sup>5</sup> for f <<br>100kHz<br>μ <sub>r</sub> ∝ 1/f above |
| Windings             | 2x10 crossed   |
| Max. sensitivity     | 10 <sup>6</sup> V/A with amplifier   |
| Current resolution   | $0.2 \mu A$ for full BW  |
| Droop                | 0.5 % per 5 ms   |
| Rise time            | 200 ns   |
| Bandwidth            | 2 kHz 1 MHz  |

![](_page_11_Figure_5.jpeg)

![](_page_12_Picture_1.jpeg)

![](_page_12_Figure_2.jpeg)

![](_page_13_Picture_1.jpeg)

- > The image current of the walls have to be bypassed by a gap and a metal housing.
- > This housing uses  $\mu$ -metal and acts as a shield of external B-field

![](_page_13_Figure_4.jpeg)

**Uas** 

![](_page_14_Picture_1.jpeg)

# The active transformer ACCT The passive, fast transformer FCT $\mathcal{P}$ 10 -0 -0

Cartoons by Company Bergoz, Saint Genis

On the 6<sup>th</sup> of March : Comparison of these types at company Bergoz

![](_page_15_Picture_1.jpeg)

![](_page_15_Picture_2.jpeg)

Enter the code

## 1208 6026

![](_page_15_Picture_5.jpeg)

![](_page_16_Picture_1.jpeg)

#### Poll 2.1:

What is the **sensitivity** for a current transformer? It is the ratio between the measurable voltage and...

- 1) the beam current
- 2) the current in the transformer windings
- 3) the beam induced current flowing in the vacuum wall

#### Poll 2.2:

Which statement is correct concerning the comparison of **FCT** versus **ACT**? An **FCT** has a ...

- 1) lower bandwidth and a lower sensitivity
- 2) higher bandwidth and a lower sensitivity
- 3) higher bandwidth and a higher sensitivity

#### Poll 2.3:

What is the correct relation between the rise time and the cut-off frequencies?

- 1)  $\tau_{rise} = \frac{1}{2\pi f_{low}}$
- 2)  $\tau_{rise} = \frac{1}{2\pi f_{high}}$
- 3) The rise time does not depend on the cut-off frequencies
- 4) For transformers the rise time and the droop time are equal

![](_page_16_Picture_18.jpeg)

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## The dc Transformer

![](_page_17_Picture_1.jpeg)

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

#### **Depictive statement:**

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

![](_page_17_Figure_5.jpeg)

![](_page_18_Figure_0.jpeg)

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

| Torus radii           | r <sub>i</sub> = 135 mm r <sub>o</sub> =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<br>12 for feedback |
| Resolution            | I <sup>min</sup> <sub>beam</sub> = 2 μA        |
| Bandwidth             | ∆f = dc 20 kHz                                 |
| Rise time constant    | $\tau_{rise} = 10 \ \mu s$                     |
| Temperature drift     | 1.5 μA/ºC                                      |

Recent commercial product specification (Bergoz NPCT): Most parameters are comparable the GSI-model Temperature coefficient:  $0.5 \ \mu A/^{\circ}C$ Resolution:  $\approx 10 \ \mu A$  (i.e. not optimized)

![](_page_19_Picture_4.jpeg)

magnetic shield

dc transformer

2 cores mounted

Ø200 mm flange

![](_page_19_Picture_7.jpeg)

![](_page_19_Picture_8.jpeg)

![](_page_19_Picture_12.jpeg)

ac transformers

(two types)

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

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

![](_page_20_Figure_3.jpeg)

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![](_page_20_Picture_7.jpeg)

## Design Criteria and Limitations for a dc Transformer

![](_page_21_Picture_1.jpeg)

Careful shielding against external fields with  $\mu$ -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**
  - $\Rightarrow$  determines the resolution of  $I_{min} \approx 1 \ \mu A$

![](_page_21_Figure_8.jpeg)

- Core material with low changes of  $\mu_r$  due to temperature and stress  $\Rightarrow$  low micro-phonic pick-up.
- > Thermal noise voltage  $U_{eff} = \sqrt{4k_BT \cdot R \cdot f}$ 
  - $\Rightarrow$  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.

#### Poll 2.4:

A DCCT can be used ...

- 1) at only electro-static accelerators such as Van-de-Graaff, TANDEM or behind an ion source
- 2) at only a synchrotron storing a coasting (= un-bunched) beam
- 3) at a synchrotron with coasting and bunched beam

#### Poll 2.5:

The principle of a dc current transformer DCCT is related to ...

- 1) direct transformation of a dc current
- 2) modulation of the particle beam in terms of on  $\leftrightarrow$  off
- 3) modulation of two transformer cores with 180<sup>0</sup> degree phase shift
- 4) modulation of two transformer cores with  $0^0$  degree phase shift

![](_page_22_Picture_12.jpeg)

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![](_page_23_Picture_1.jpeg)

#### *Transformer: M*easurement of the beam's magnetic field

 $\blacktriangleright$  Magnetic field is guided by a high  $\mu$  toroid

#### > Types of transformers:

FCT for bunches: $I_{min} \approx 30 \ \mu$ A, bandwidth  $\approx 10 \ \text{kHz} \dots 500 \ \text{MHz}$ ACT for macro-pulses: $I_{min} \approx 0.2 \ \mu$ A, bandwidth  $\approx 100 \ \text{Hz} \dots 3 \ \text{MHz}$ DCCT for dc beams: $I_{min} \approx 1 \ \mu$ A, BW  $\approx \text{dc} \dots 20 \ \text{kHz}$ , based two toroids + modulation> Non-destructive, used for all beams

![](_page_23_Figure_6.jpeg)

![](_page_24_Picture_1.jpeg)

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#### **Faraday cups:** Measurement of the beam's **electrical current**

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

![](_page_25_Picture_1.jpeg)

![](_page_25_Figure_2.jpeg)

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

- $\Rightarrow$  low straggling for the heavy projectile i.e. 'straight trajectory'
- > If projectile velocity  $\beta \approx 1$  low relative energy change of projectile ( $\gamma$  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<sup>-</sup> radius,  $m_e$  electron mass, c velocity of light

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

![](_page_26_Picture_1.jpeg)

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:

$$R = \int_{0}^{E_{\text{max}}} \left(\frac{dE}{dx}\right)^{-1} dE$$

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

Numerical calculation for ions with semi-empirical model e.g. SRIM Main modification  $Z_p \rightarrow Z_p^{eff}(E_{kin})$  $\Rightarrow$  Cups only for

*E*<sub>*kin*</sub> < 100 MeV/u due to *R* < 10 mm

![](_page_26_Figure_8.jpeg)

![](_page_27_Picture_1.jpeg)

Energy loss of ions in metals close to a surface:

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

Distant collision with low energy transfer  $\rightarrow$  slow e<sup>-</sup> with  $E_{kin} \leq 10 \text{ eV}$ 

- $\rightarrow$  'diffusion' & scattering with other e<sup>-</sup>: 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) **Different targets:** × Mg 12 Aarset AL 13 Aarset 13 Hill 26 Aarset Electrons per ion 28 Aarset 29 Hill oMo 42 Hill -ray ▲ Au 79 Aarset beam ▼Pb 82 Aarset ⊽Pb 82 Hill Curve 3 *L*<sub>c</sub> ≈ 10 nm .2 .6 2.0 3.0 E-Proton Energy in Mey

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

![](_page_28_Picture_1.jpeg)

Energy loss of ions in metals close to a surface:

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

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

![](_page_28_Figure_9.jpeg)

## Faraday Cups for Beam Charge Measurement

![](_page_29_Picture_1.jpeg)

The beam particles are collected inside a metal cup  $\Rightarrow$  The beam's charge are recorded as a function of time.

The cup is moved in the beam pass  $\rightarrow$  destructive device

![](_page_29_Figure_4.jpeg)

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.

![](_page_29_Picture_11.jpeg)

## **Realization of a Faraday Cup at GSI LINAC**

![](_page_30_Picture_1.jpeg)

![](_page_30_Figure_2.jpeg)

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## **Secondary Electron Suppression: Electric Field**

![](_page_31_Picture_1.jpeg)

A ring shaped electrode is used at the entrance of Faraday Cup: Typical voltage 100 to 1000 V

![](_page_31_Figure_3.jpeg)

![](_page_31_Figure_4.jpeg)

![](_page_31_Figure_5.jpeg)

## **Secondary Electron Suppression: Magnetic Field**

![](_page_32_Picture_1.jpeg)

## The Artists View of Faraday Cup

![](_page_33_Picture_1.jpeg)

![](_page_33_Picture_2.jpeg)

#### **Company Bergoz**

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juas

Collisional loss by Bethe-Bloch formula  $dE/dx \mid_{col} \propto f(E_{kin}) \cdot Z_t$  is valid for all charged particles. However, radiation loss  $dE/dx \mid_{rad}$  by Bremsstrahlung (i.e.  $\gamma$ -rays of some MeV) dominates for energies above  $E_{kin} > 10$  MeV with the scaling  $dE/dx \mid_{rad} \propto E_{kin} \cdot Z_t^2$ .

Moreover, e<sup>-</sup> shows much larger longitudinal and transverse straggling.

![](_page_34_Figure_4.jpeg)

Minimum of Bethe-Bloch  $dE/dx \mid_{col}$ roughly at  $E_{kin} \approx m_0 c^2 = 511 \text{ keV}$  (rest mass)  $\Leftrightarrow \beta \approx 90 \%$  and  $\gamma = \frac{1}{\sqrt{1-\beta^2}} \approx 2$ 

![](_page_34_Figure_6.jpeg)

## **Faraday Cups for Electrons**

![](_page_35_Picture_1.jpeg)

-bisulation \_ Movable suppo - Fixed support

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

![](_page_35_Picture_3.jpeg)

![](_page_35_Figure_4.jpeg)

From U. Iriso (ALBA)

Al stopper: Stopping of e<sup>-</sup> gently in low-Z material Pb-shield: Absorption of Bremsstrahlungs- $\gamma$  $\Rightarrow$  Used as beam dump

Example of a Faraday cup for 60 MeV Electrons

Aluminum Stopper

Ph-Shield

 $\rightarrow$  To questions on Faraday Cups

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## Poll concerning invasive Instrumentation and Faraday Cups

![](_page_36_Picture_1.jpeg)

#### Poll 2.7:

What mean invasive beam instrumentation?

- 1) A gas is injected in the beam path
- 2) A detector is moved in the beam path
- 3) The beam is stopped
- 4) A tip is injected at the beam halo

#### Poll 2.11:

Comparing the energy loss of protons and heavy ions of same velocity: What is correct? The energy loss of protons...

- 1) are **higher** than of ions
- 2) are lower than of ions

#### Poll 2.8:

A Faraday Cup is used to measure...

- 1) the beam's electric field
- 2) the beam voltage
- 3) the beam current
- the charge state of an ion beam

#### Poll 2.12:

Comparing the energy loss of protons and heavy ions of same velocity: What is correct for energies **above** 10 MeV/u? The range of protons are...

- 1) longer than of ions
- 2) shorter than of ions

#### Poll 2.10:

Electronic stopping is mediated by...

- 1) exchange of electrons between projectile and target
- 2) Coulomb interaction
- 3) strong interaction
- 4) weak interaction

![](_page_36_Picture_28.jpeg)

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![](_page_37_Picture_1.jpeg)

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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.

![](_page_38_Picture_1.jpeg)

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:  $I_{sec} \approx 1 \text{ pA}$ max:  $I_{sec} \approx 1 \, \mu A$ Sec. e– emission: min:  $I_{sec} \approx 1 \text{ pA}$ > Max. synch. filling: Space Charge Limit (SCL).

synchrotron

![](_page_38_Figure_6.jpeg)

![](_page_39_Picture_1.jpeg)

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

Here: BC 400 (emission  $\lambda_{max}$  = 420 nm, pulse width  $\approx$  3 ns + cable dispersion, size ) Advantage: any mechanical from, cheap, blue wave length, fast decay time Disadvantage: not radiation hard

Particle counting: Photomultiplier  $\rightarrow$  discriminator  $\rightarrow$  scalar  $\rightarrow$  computer

![](_page_39_Picture_5.jpeg)

![](_page_39_Figure_6.jpeg)

![](_page_40_Picture_1.jpeg)

readout

*U*≈1 V

@50Ω

## 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<sup>-</sup> multiplier or MCPs

electron

HV

photon

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  $\Delta U \approx 100 \text{ V}$ 

 $\blacktriangleright$  Typ. 10 dynodes  $\Rightarrow$  10<sup>6</sup> fold amplification

Advantage: no thermal noise due to electro static acceleration Typical 1 V signal output

![](_page_40_Picture_12.jpeg)

voltage divider with resistors R

dynodes

![](_page_41_Picture_1.jpeg)

## Properties of a good scintillator:

- Light output linear to energy loss
- $\succ$  Fast decay time  $\rightarrow$  high rate
- No self-absorption
- Wave length of fluorescence
  350 nm < λ < 500 nm</li>
- ▶ Index of refractivity  $n \approx 1.5$ 
  - $\rightarrow$  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.

![](_page_41_Figure_12.jpeg)

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

![](_page_42_Picture_1.jpeg)

#### Slow extraction from a synchrotron delivers countable currents

![](_page_42_Figure_3.jpeg)

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

![](_page_43_Picture_1.jpeg)

## Energy loss of charged particles in gases $\rightarrow$ electron-ion pairs $\rightarrow$ low current meas.

![](_page_43_Figure_3.jpeg)

| <i>W-value</i><br>s the average energy<br><sup>f</sup> or one e <sup>-</sup> -ion pair: | Gas            | Ionization<br>Pot. | W-value |
|---|----------------|--------------------|---------|
|   | He             | 24.5 eV            | 42.7 eV |
|   | N <sub>2</sub> | 15.5 eV            | 36.4 eV |
|   | O <sub>2</sub> | 12.5 eV            | 32.2 eV |
|   | Ar             | 15.7 eV            | 26.3 eV |
|   | $CO_2$         | 13.7 eV            | 33.0 eV |

Example: GSI type:

![](_page_43_Picture_6.jpeg)

#### GSI realization:

- Energy calculation *dE/dx* with SRIM or LISE
- Current measurement via

current-to-frequency converter IFC

![](_page_44_Picture_1.jpeg)

For higher intensities SEMs are used.

Due to the energy loss, secondary e<sup>−</sup> are emitted from a metal surface.

The amount of secondary e<sup>-</sup> is proportional to the energy loss

![](_page_44_Figure_5.jpeg)

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

- $\rightarrow$  Sensitive to cleaning procedure
- $\rightarrow$  Possible surface modification by radiation

*Example:* GSI SEM type:

| Material                       | Pure AI (99.5%)         |
|--------------------------------|-------------------------|
| # electrodes                   | 3                       |
| Active surface                 | 80 x 80 mm <sup>2</sup> |
| Distance between<br>electrodes | 5 mm                    |
| Applied voltage                | + 100 V                 |

Advantage for AI: good mechanical properties. Disadvantage: Surface effect!

e.g. decrease of yield Y due to radiation

 $\Rightarrow$  calibration versus IC required to reach 5%.

Sometimes they are installed permanently in front of an experiment.

## **GSI Installation for SEM, IC and Scintillator**

![](_page_45_Picture_1.jpeg)

![](_page_45_Picture_2.jpeg)

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Measurement of Beam Current

![](_page_46_Picture_1.jpeg)

#### Poll 2.13:

What is the basis of an ionization chamber?

- 1) It detects only ions
- 2) It contains always ions
- 3) It is based on ionizations of a gas

#### Poll 2.15:

What is a photomultiplier?

- 1) It amplifies directly photons
- 2) It only amplifies incoming electrons
- It converts photon to electrons and amplifiers the electrons
- 4) It contains active electronics (e.g. transistors)

#### Poll 2.14:

What is scintillation? It is light emitted cause by the energy loss of the particles and ...

- 1) excitation of electronic states
- 2) excitation of lattice vibration
- 3) related mechanical stress
- 4) emission of thermal photon

#### Poll 2.16:

The principle of an SEM is based

- 1) Emission of electrons from t
- 2) Emission on electrons from an intersecting metal www.menti.com
- 3) Back-scattering of beam ionsode: 1208 6026
- 4) Emission of ions form an intersecting metal

## **Appendix: GSI Heavy Ion Research Center**

![](_page_47_Picture_1.jpeg)

#### German national heavy ion accelerator facility in Darmstadt

![](_page_47_Picture_3.jpeg)

#### **Accelerators:**

Acceleration of all ions LINAC: up to 15 MeV/u Synchrotron: up to 2 GeV/u **Research area:** 

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

**Extension by** international FAIR facility

GSI is one of 18 German large scale research centers.

![](_page_48_Picture_1.jpeg)

![](_page_48_Picture_2.jpeg)

![](_page_49_Picture_1.jpeg)

![](_page_49_Picture_2.jpeg)

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

**Transformer ACCT:** for current measurement and transmission control

![](_page_49_Picture_4.jpeg)

PIG

![](_page_49_Figure_5.jpeg)

#### **Appendix: GSI Heavy Ion Synchrotron: Overview**

![](_page_50_Picture_1.jpeg)

![](_page_50_Figure_2.jpeg)

Peter Forck, JUAS Archamps

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## **Appendix: GSI Heavy Ion Synchrotron: Current Measurement**

![](_page_51_Picture_1.jpeg)

![](_page_51_Figure_2.jpeg)

## **Appendix: 3<sup>rd</sup> Generation Light Sources**

![](_page_52_Picture_1.jpeg)

## **3<sup>rd</sup> Generation Light Sources:**

Synchrotron-based

with  $E_{electron} \approx 1...8$  GeV Light from undulators & wigglers, dipoles, with  $E_{\gamma} < 10$  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.

Soleil, Paris, *E<sub>electron</sub>*= 2.5 GeV, *C* = 354 m

![](_page_52_Picture_15.jpeg)

## **Appendix: The Spanish Synchrotron Light Facility ALBA**

![](_page_53_Picture_1.jpeg)

## **3**<sup>rd</sup> generation Spanish synchr. light facility in Barcelona

![](_page_53_Picture_3.jpeg)

#### 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

![](_page_53_Figure_6.jpeg)

#### Talk by Ubaldo Iriso: at DIPAC 2011

## Example $\rightarrow$ Synchrotron Light Facility ALBA

![](_page_54_Picture_1.jpeg)

![](_page_54_Figure_2.jpeg)

#### Layout:

Beam lines: up to 30 Electron energy: 3 GeV **Top-up** injection Storage ring length: 268 m Max. beam current: 0.4 A

LINAC 100 MeV

![](_page_54_Picture_5.jpeg)

**Storage Ring:** 3 GeV

![](_page_54_Picture_7.jpeg)

![](_page_55_Picture_1.jpeg)

![](_page_55_Figure_2.jpeg)

![](_page_56_Picture_1.jpeg)

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

*Transformer:*  $\rightarrow$  measurement of the beam's magnetic field

- $\succ$  magnetic field is guided by a high  $\mu$  toroid
- types: passive (large bandwidth), active (low droop)

and dc (two toroids + modulation)

- $\succ$  lower threshold by magnetic noise: about  $I_{beam} > 1 \mu A$
- non-destructive, used for all beams

#### Faraday cup: $\rightarrow$ measurement of beam's electrical current

 $\succ$  low threshold by I/U-converter:  $I_{beam} > 10 \text{ pA}$ 

totally destructive, used for low energy beams

- Scintillator,  $\rightarrow$  measurement of the particle's energy loss
- *IC, SEM:* > particle counting (Scintillator)
  - ➤ secondary current: IC from gas ionization or SEM sec. e<sup>-</sup> emission surface
  - > no lower threshold due to single particle counting
  - > partly destructive, used for high energy beams

![](_page_57_Picture_0.jpeg)

## **Backup slides**

- What is the numerical value of the earth magnetic field?
- What is the sensitivity S of a beam current transformer?
- > What is the rise time constant  $\tau_{rise}$  and to which cut-off frequency  $f_{???}$  is it connected?
- > What is the droop time constant  $\tau_{droop}$  and to which cut-off frequency  $f_{???}$  is it connected?
- Why a single bunch of 1 ps cannot be measured by a FCT?
- What is the principle idea behind a dc current transformer?

IUas

![](_page_59_Picture_1.jpeg)

- What is the physics process of the energy loss of protons with E<sub>kin</sub> > 10 MeV in matter?
- > What is the physics process of the energy loss of *electrons* with  $E_{kin}$  > 10 MeV in matter?
- Why are secondary electrons emitted from a surface due to charge particle impact?

![](_page_59_Picture_5.jpeg)

IUas

- What happens if a particle in a transfer line loses 10 % of is kinetic energy e.g. by passing through a ionization chamber? What happens if the energy loss is 1 %?
- > To which physical processes does the word 'scintillation' refers?
- What is a photo-multiplier?
- What is an ionization chamber?
- Can ICs be used for other purposes as beam current measurement as well?
- > What is the physics process of the energy loss of *electrons* with  $E_{kin}$  > 10 MeV in matter?

![](_page_60_Picture_7.jpeg)

iuas

![](_page_61_Picture_1.jpeg)

What is an appropriate device for beam current measurements for the following parameter? (Further examples are given in Exercise #2)

#### Proton beam:

- Behind an ion source by electro-static acceleration to 100 keV and a current o 100 mA?
- Behind a electro-static TANDEM accelerator delivering 10 MeV/u protons and 100 nA?
- Behind a pulsed LINAC for 100 MeV protons with 100 mA current and 1 ms duration?
- Inside a synchrotron with protons of 100 MeV and 100 mA current?
- $\blacktriangleright$  Extracted proton beam of 1 GeV from a synchrotron with 1 µs resulting in 100 mA current?
- > Extracted proton beam of 1 GeV from a synchrotron with 1 s resulting in 100 nA current?

#### **Electron beam:**

- > What is the difference for electrons with basically the same parameter (i.e. kin. energy)?
- Inside a synchrotron with 1 GeV electrons but 10 nA current?

![](_page_62_Picture_1.jpeg)

- 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<sup>10+</sup> with 10 mA and 1 ms beam delivery Beam size: 5 mm FWHM  $\rightarrow$  23 kW/mm<sup>2</sup>,  $P_{peak}$  = 450 kW total power during 1ms delivery Foil: 1 µm Tantalum, emissivity  $\varepsilon$  = 0.49
- Temperature increase:
- T > 2000 <sup>o</sup>C during beam delivery
  - Even for low average power,
  - the material should
  - survive the peak power!

![](_page_62_Figure_9.jpeg)

## **High Power Faraday Cups**

![](_page_63_Picture_1.jpeg)

#### Cups designed for 1 MW, 1 ms pulse power $\rightarrow$ cone of Tungsten-coated Copper

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

![](_page_63_Figure_4.jpeg)

![](_page_63_Figure_5.jpeg)

![](_page_64_Picture_1.jpeg)

## 3<sup>rd</sup> generation Spanish national synchrotron light facility in Barcelona

![](_page_64_Picture_3.jpeg)

#### 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

#### LINAC 100 MeV