Beam Current Monitors

CERN Accelerator School on Beam Diagnostics
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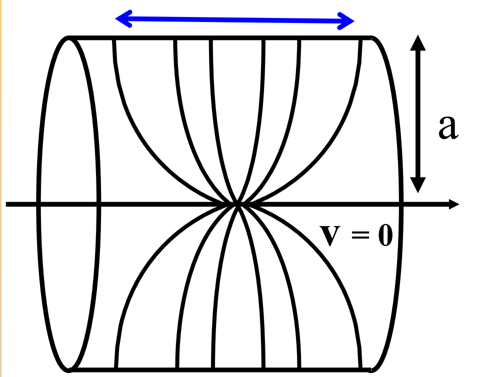
Summary

- Electromagnetic field associated to charged particle beams
- Destructive monitors: faraday cup ….
- Non destructive monitors; electromagnetic interaction
  - Electro-magnetic field → wall current monitors;
  - Magnetic field → transformers, SQUID
- References

Longitudinal E Field Distribution of a Point Charge in a Conducting Pipe

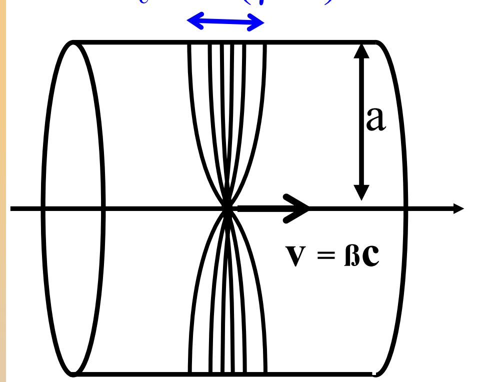
Static charge



- Charge produces E field
- E field induces image charges of opposite sign on the wall

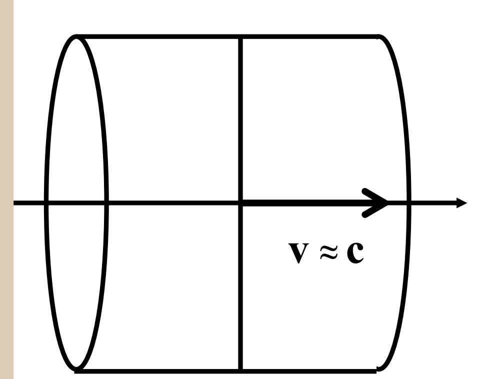
Note: there is no E field outside

Moving charge



- Moving E field creates H field inside the tube
- H field moves the image charges along with beam
- Wall + beam currents = 0. Then, Ampère's law, $\oint (H\,dl) = i$ indicates that H = 0 outside the pipe (except for DC field).

Ultra-relativistic charge



- Wall current distribution is image of beam distribution (except for DC component that is not present in wall current)
- Wall current sign is opposite to that of the beam

Wall Current Longitudinal Distribution for a Point-like Moving Charge

Numerical Examples with a 50 mm Diam. Tube = 2a

kinetic energy E	0	100 keV	1 MeV	10 MeV
Lorentz factor γ	1	1.2	3	20.6
$\beta = (1-1/\gamma^2)^{1/2}$	0	0.55	0.94	0.999
$\sigma_l = a/(\gamma\sqrt{2})$	18 mm	15 mm	6 mm	0.9 mm
rms length (ps) = $a/(\beta\gamma c\sqrt{2})$	∞	90 ps	21 ps	2.9 ps
Wall current BW (*)	0	1.8 GHz	7.5 GHz	55 GHz

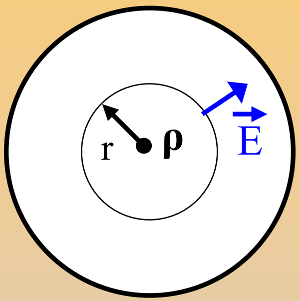
(*) The actual distribution is not gaussian, but for the sake of simplicity, its Bandwidth has been approximated to that of a gaussian distribution of same rms length

In most cases, the wall current distribution = beam distribution

Transverse Field Distribution

Static charge

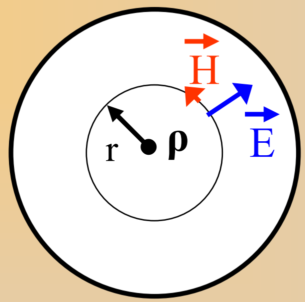
v = 0



no magnetic field inside

Moving charge

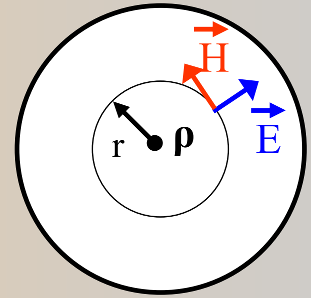
v < c



magnetic field appears

Ultra relativistic charge

v ≈ c



Ampère's Law : $\oint H.dl = i$

at radius r $\rightarrow H(r) = i / 2\pi r$

TEM wave : $\dfrac{|\vec{E}|}{|\vec{H}|} = \eta_o$

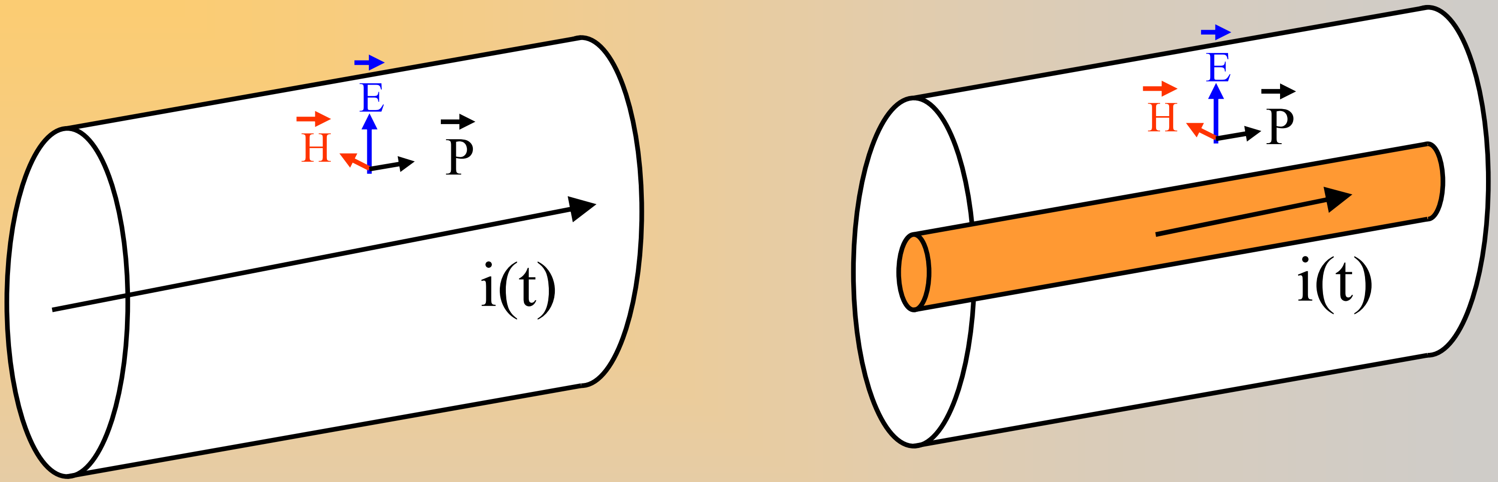
With $\eta_o = \sqrt{\mu_o / \varepsilon_o} = 377\ \Omega$ = vacuum impedance

ε_o = vacuum electric permittivity

μ_o = vacuum magnetic permeability

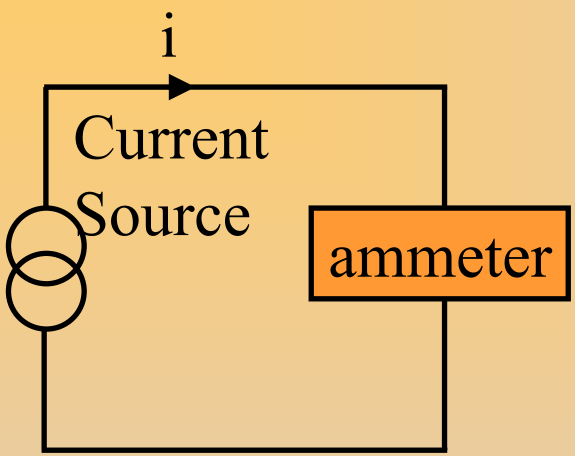
no E field outside the pipe means no magnetic field (except DC) with moving charges

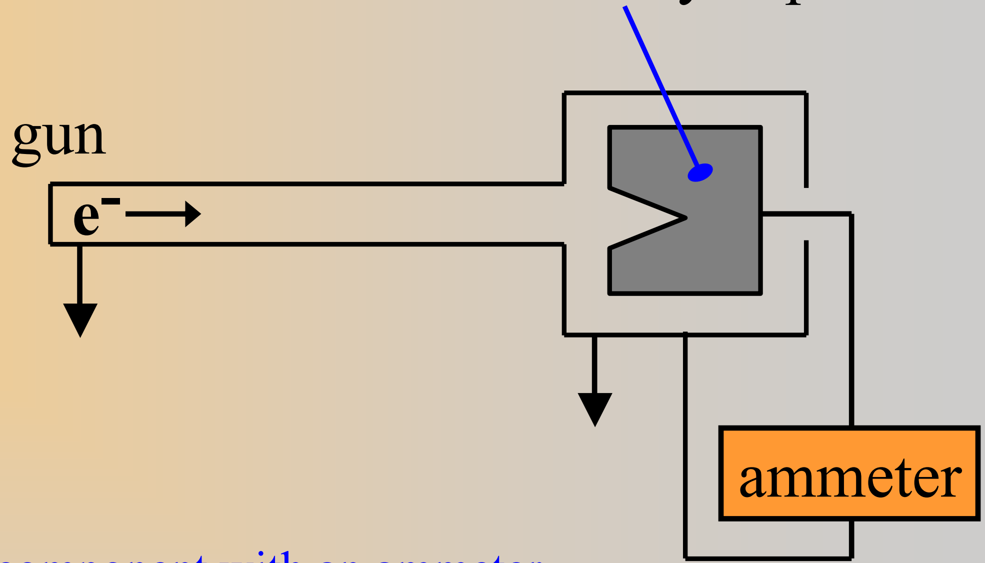
TEM Wave in Vacuum Chamber is Like in an Air Filled Coaxial Transmission Line



- **Similarities**: TEM wave carries the same EM energy (Pointing vector $\vec{P} = \vec{E} \times \vec{H}$):
- a monitor can be realistically tested in a coaxial line structure.
- **Some differences**:
  - High frequencies (cutoff frequencies are different in the two cases)
  - DC :
    - a coaxial transmission line transports the DC component
    - in a linac terminated by a dump, the charges come back to the gun through the pipe and the grounding circuit (like a coaxial line grounded on both ends)
    - in a Storage Ring there is no DC beam component on the outer conductor tube

Faraday Cup



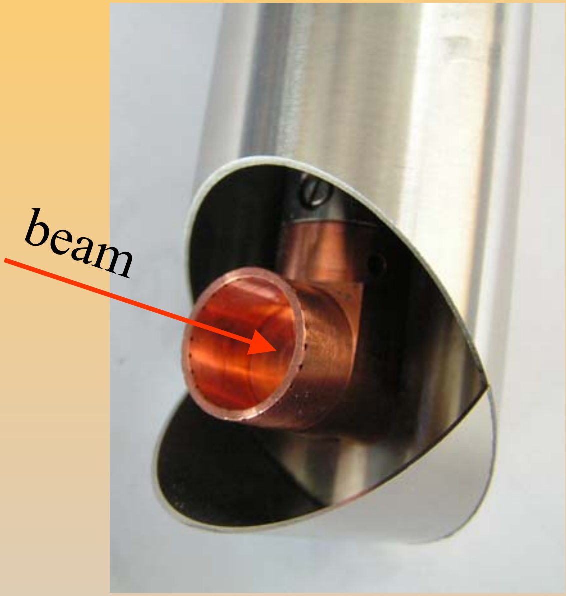


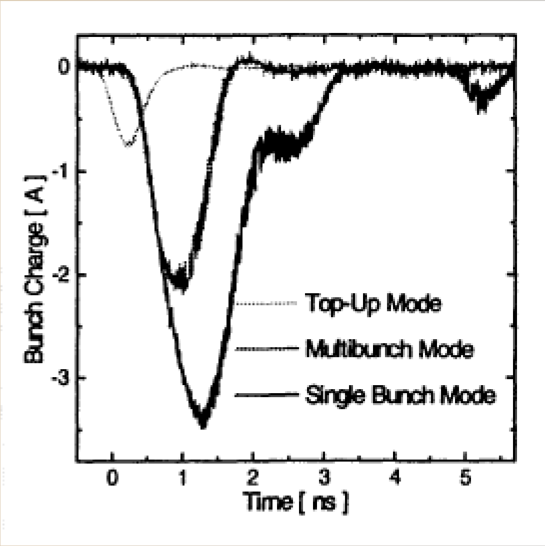
- Destructive
- Absolute measurement of DC component with an ammeter
- An oscilloscope or Sample & Hold measures the peak current in case of pulsed beam.
- Can be used for the calibration of non destructive monitors providing relative measurements. For example FC calibrates an RF cavity current monitor on CEBAF injector (CW superconducting Linac).

Faraday Cup; Design Issues

- Absolute accuracy is usually around 1%, some monitors reach 0.1%.
- Needs to absorb all the beam: block with large entrance size and thickness >> radiation length. A FC built at DESY and presently used on a low current 6 GeV beam at JLAb uses 1 m3 of lead (12 tons).
- Backscattered particles (mostly e-): narrow entrance channel, bias voltage or magnetic field redirect the backscattered e- on the FC. Accuracy evaluation requires Monte Carlo simulations (EGGS from SLAC; GEANT from CERN).
- Power (W) = E (MeV × I (µA).
  Example: 5 MeV FC in CEBAF injector with 200 µA CW beam → 1000 W. A cooling circuit takes the power out. The isolation is done with de-ionized water and insulating rubber tubes.
- Safety issues: FC needs to be always terminated by a DC circuit to avoid arcing and a potentially dangerous high voltage that would develop at cable end . A pair of high impedance diodes can be connected in parallel on the FC output.

SLS Wide Bandwidth Coaxial Faraday Cup (0-4 GHz)





M. Dach et al. (SLS) ;
BIW2000

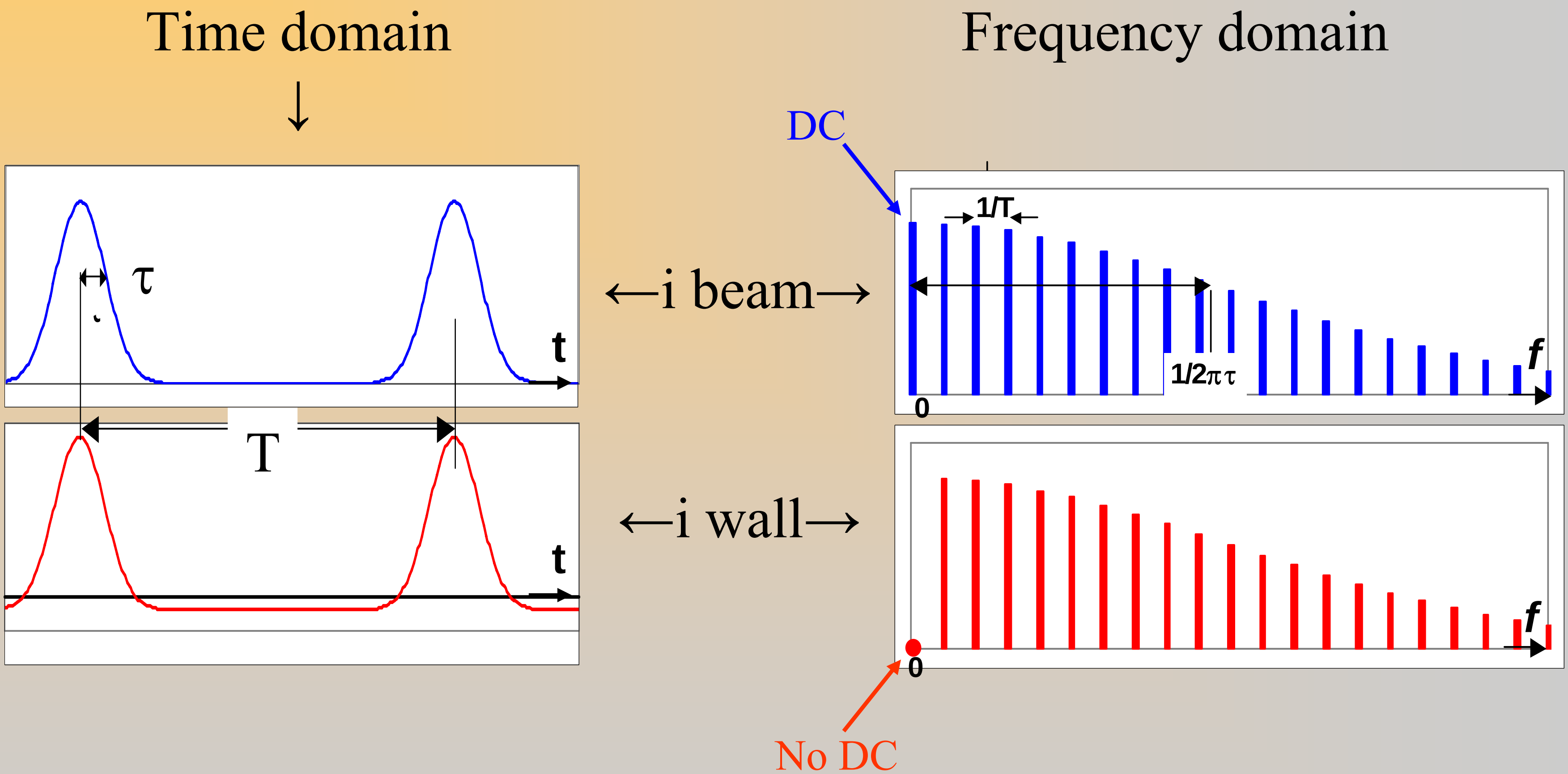
This Faraday Cup will be at the hardware display of June 3rd & 5th

Calorimeter

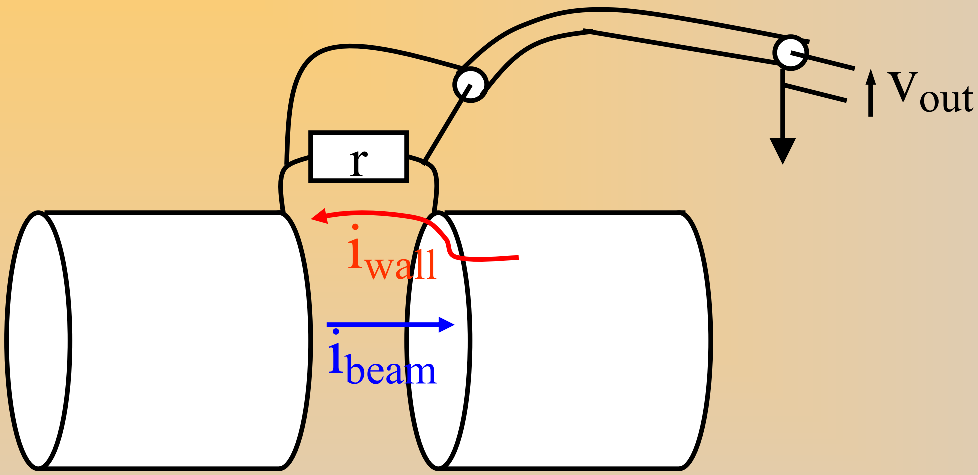
- Calorimetry refers to a direct measurement of the total energy delivered to a massive block of metal (silver or tungsten) over a period of time.
- Total energy is determined by measuring the temperature rise of the object if:
  - The average beam energy is precisely known
  - Any energy losses can be accounted for by reliable calculation or direct measurement.

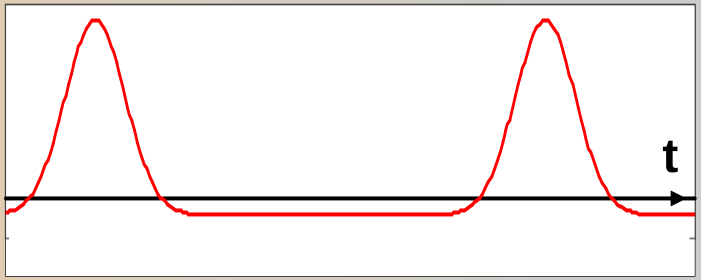
- A calorimeter has been developed for CEBAF CW beam (A. Freyberger, to be published)

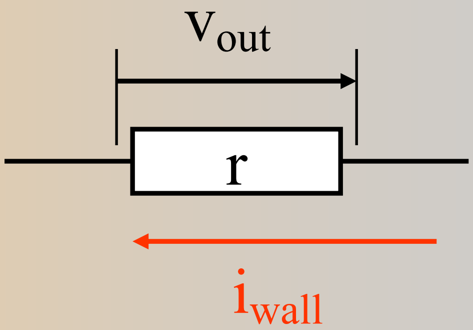
Wall Current Monitor:
Beam and Wall Current Spectra for Ultra Relativistic Beams



Wall Current Monitor: Concept



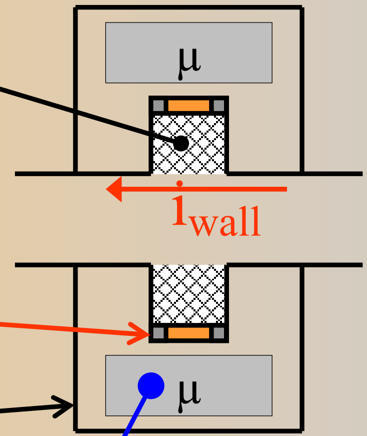


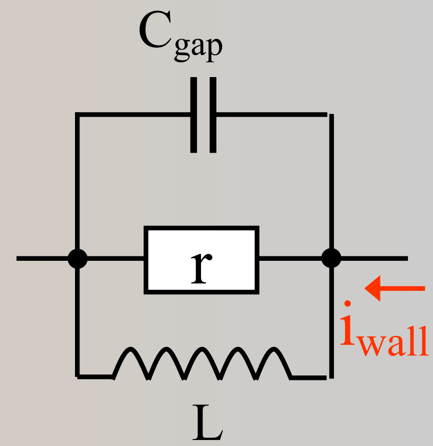


$$V_{out} = i_{wall} * r$$

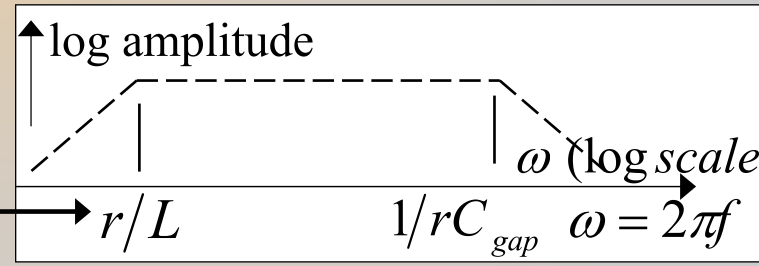
WCM: From Concept to Actual Implementation

- For vacuum quality: ceramic gap
- r is made of several resistors in parallel, distributed around the gap. Special chip resistors still behave as resistors in the GHz frequency range.
- Electrical shield: avoids parasitic external currents flowing through r, and prevents the beam EM field from escaping the monitor.
- High µ material fills the space between gap and shielding for low frequency response.



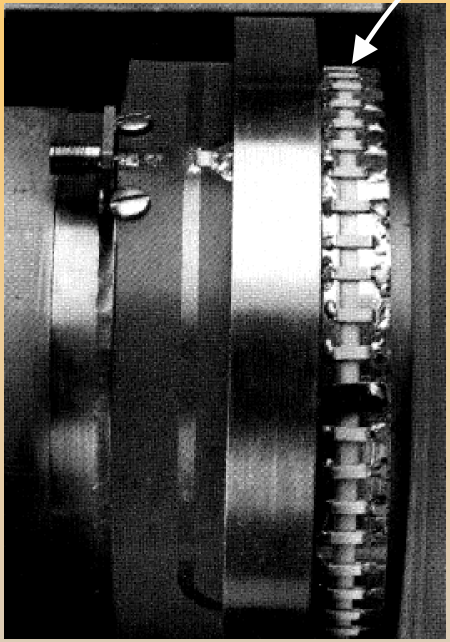


WCM response



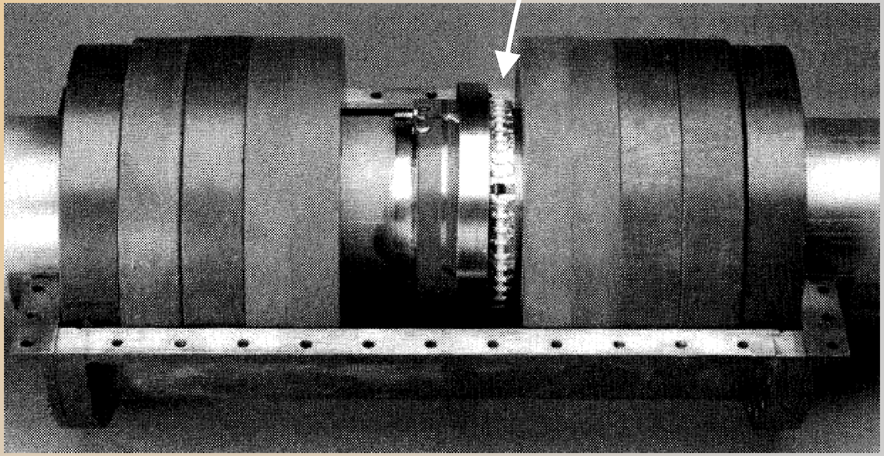
$$L = \frac{\mu_o \mu_r}{2\pi} h \; Ln\,(b/a)$$

Implementation Example: 6 kHz to 6 GHz WCM : (R. Weber BIW93)

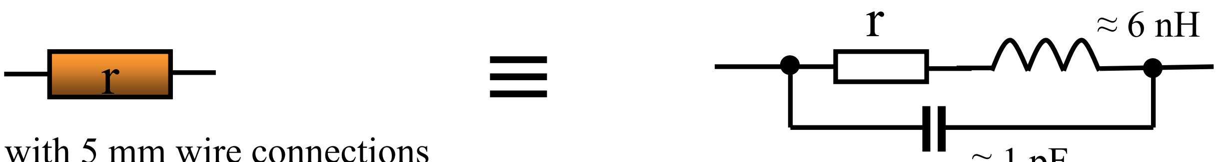


Ceramic gap and surface mounted resistors

ferrites ferrites



Resistor equivalent circuit at high frequencies



Resistor with 5 mm wire connections

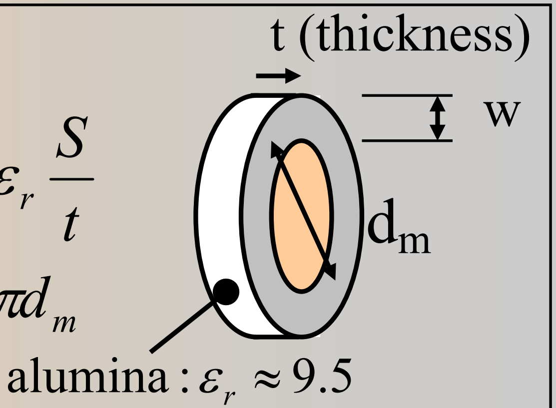
6 kHz to 6 GHz WCM : (R. Weber)

- r = 1.4 ohm (80 resistors in parallel).

- **rC$_{gap}$ circuit at high frequencies**
  - Ceramic gap considered as a lump capacitor:
    d_m= 90 mm; t = 3.2 mm; and w = 4.5mm
    => C_{gap} = 33 pF
    and $f_h = 1/2\pi r C_{gap} = 3.4\,\mathrm{GHz}$
  - Ceramic gap behaves as a radial transmission line matched to its 1.4Ω characteristic impedance: f_h > 6 GHz (measured)

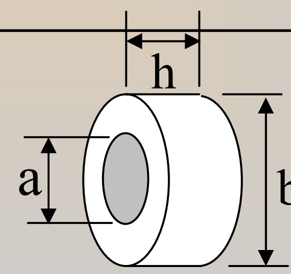
$$C_{gap} = \varepsilon_0 \varepsilon_r \frac{S}{t}$$

$$S \cong w * 2\pi d_m$$



- **rL circuit at low frequencies**

$$f_{low} = r/2\pi L = 5.6\,\mathrm{kHz} \text{ with } L = 40\mu\mathrm{H}$$



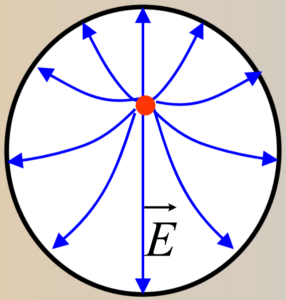
Shield = 1 turn

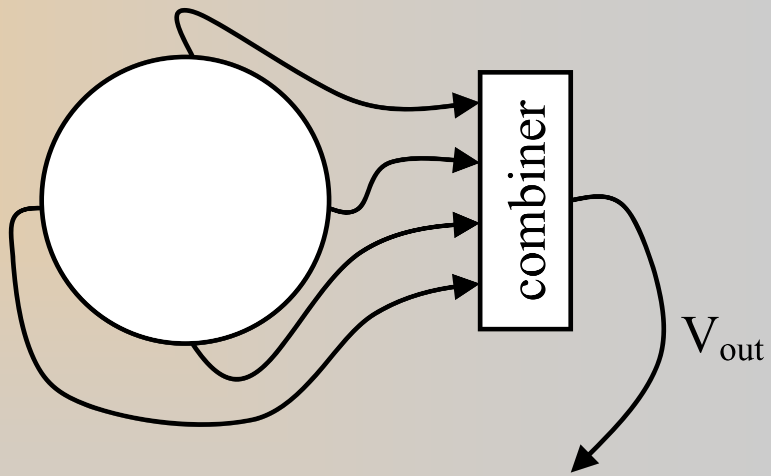
$$L = \frac{\mu_o \mu_r}{2\pi} h \; Ln(b/a)$$

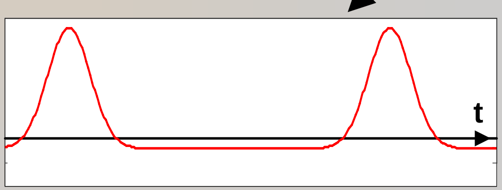
WCM: Output Connection; Beam Position Dependence

- Off-center beam yields higher wall currents near the beam.
- There is a difference signal ($i_{\text{wall top}} - i_{\text{wall bottom}}$) that propagates around the gap. The wave velocity is reduced by a factor $\sqrt{\varepsilon_r} = 3$ with alumina.
- With our example, propagation time is 2.8 ns. There is no position dependence for f <<300 MHz. We want no position dependence up to several GHz!
- A practical solution is to combine signals from four quadrants.
- A 20 GHz WCMs is in development at CERN.

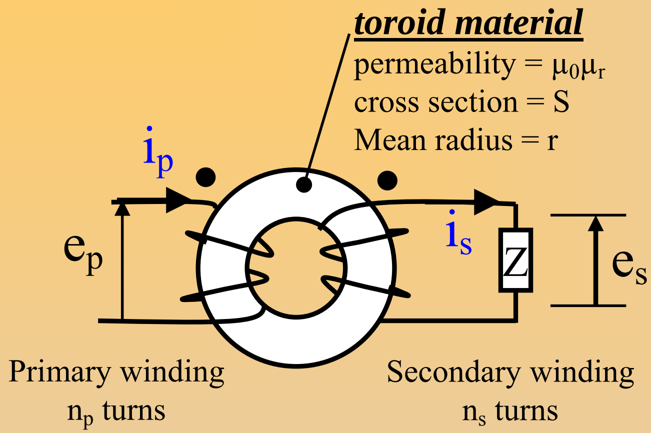
  3D electromagnetic simulation codes (MAFIA, GDFIDL, HFSS) are necessary for damping the high frequency components of the wake fields without loading significantly the useful signal (L. Soby et al., EUROTeV-Report-2006-104, 2006).







Classical Transformer Review



definition : magnetic flux $\Phi = \int \mu H \, dS$ (1)

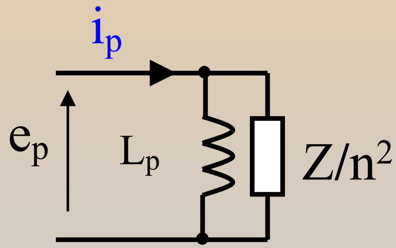
Ampère's Law ($\oint H dl = i$), with thin toroid approximation

yields: $H.2\pi r = n_p.i_p + n_s i_s$ (2)

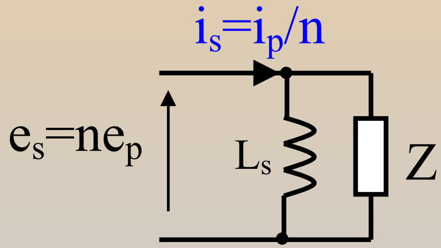
Faraday's law : $e_p = \frac{d\Phi}{dt} n_p; \quad e_s = \frac{d\Phi}{dt} n_s$ (3)

with $\frac{d\Phi}{dt} = j\omega\Phi$ and $n = \frac{n_s}{n_p}$; one obtains the following equivalent circuits in the mid range frequencies

Primary equivalent circuit



Secondary equivalent circuit



At low frequencies, the self inductance of the winding is in parallel on the load.

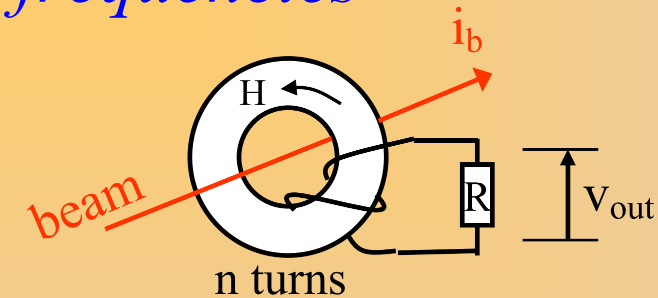
$L_s = n_s^2 L_1$; with L_1 = self inductance of a 1-turn winding

$$L_1 = \frac{\mu_o \mu_r}{2\pi} h \; Ln(b/a)$$

Note: a 3rd winding would bring its Equivalent circuit in // on the 2nd

Same power in both equivalent circuits

Beam Current Transformer; low and mid range frequencies

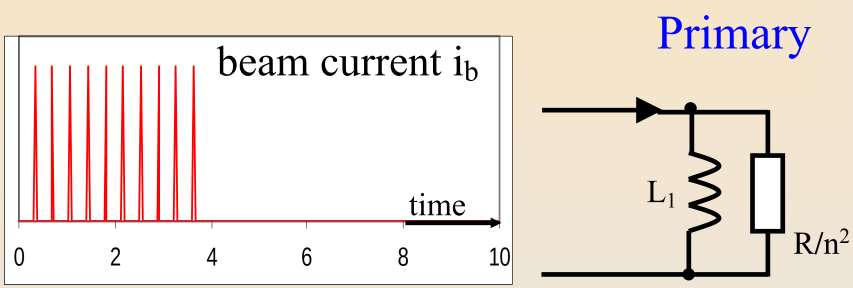


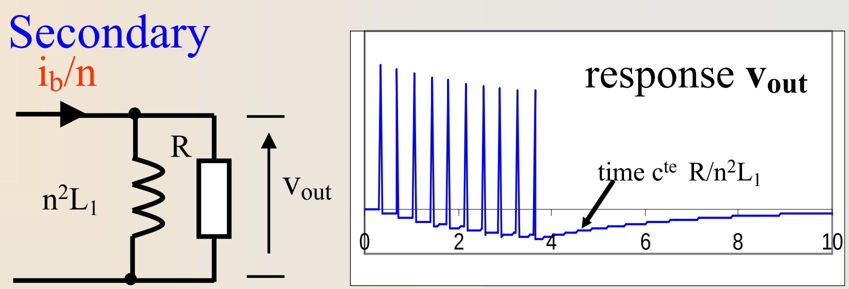
- Current through toroid ≡ current on 1-turn primary winding

The magnetic field is the same in both cases :

H = beam current / toroid circumference

- With ip = ib, n_2 = n, and Z = R, the equivalent circuits become:



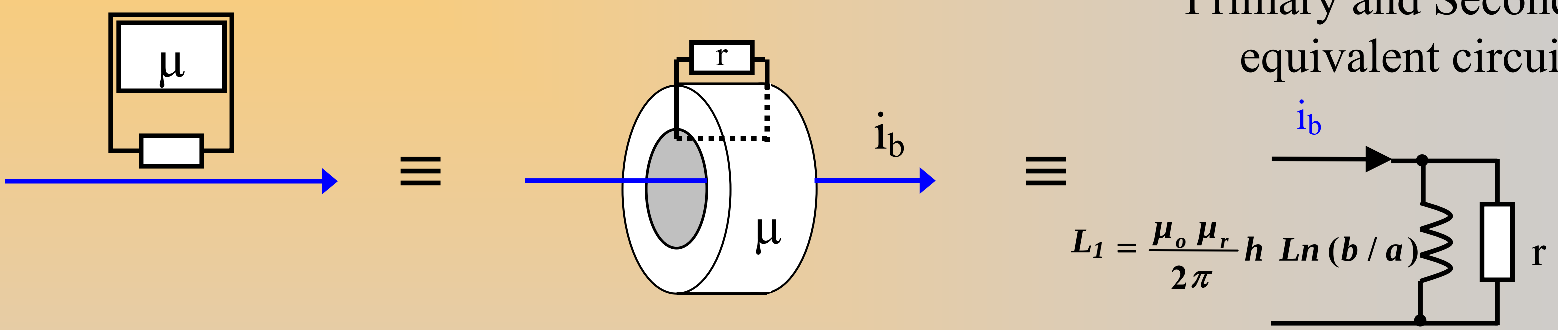


- Beam current i_b is « transformed » into i_b/n on the secondary winding.
- $V_{out} = i_b/n * [R / (1 + R / jn^2L_1\omega)]$; with L1 = one-turn self inductance
- In mid range frequencies, $L_1\omega >> R$,
  and the power transferred from the beam to the load R is $P \approx R*(i_b/n)^2$

WCM = Current Transformer with n=1

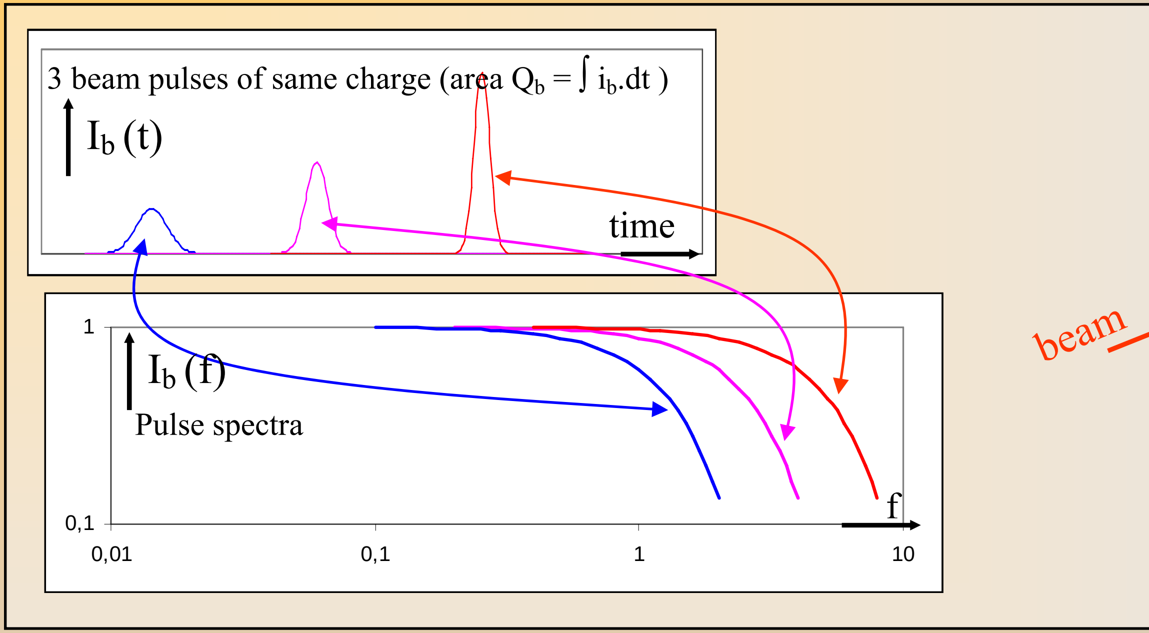
Shield cross-section

Primary and Secondary equivalent circuits

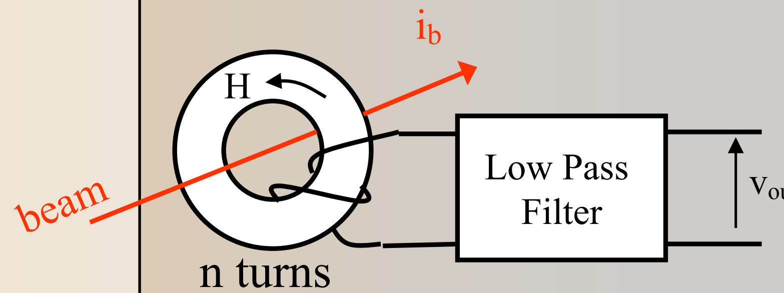


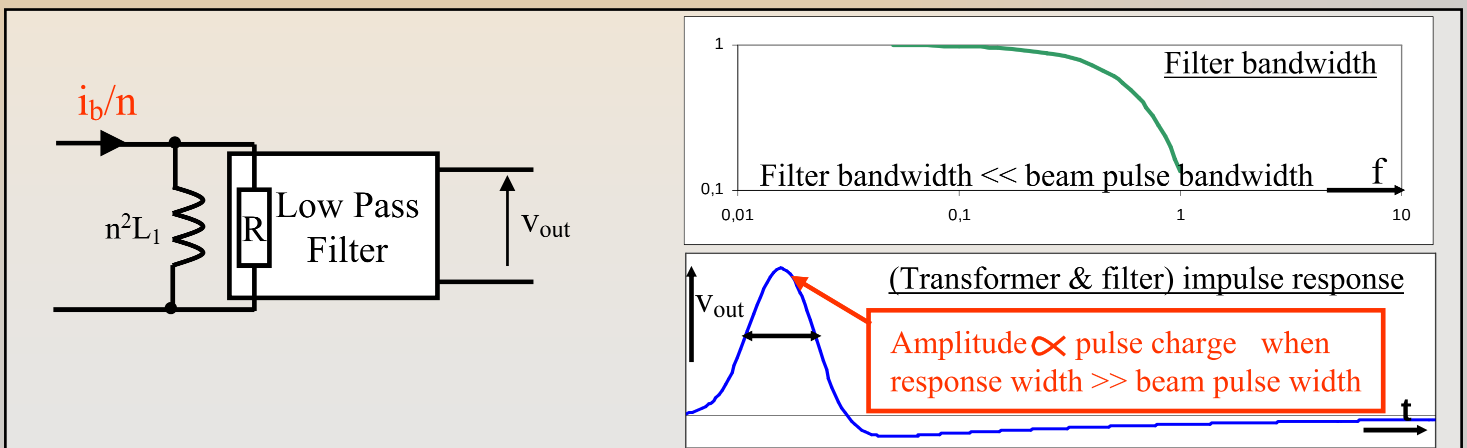
The shield is equivalent to a 1-turn winding
But the high frequency analysis is better done using the WCM concept

Integrating Current Transformer (ICT) = Beam Charge Monitor

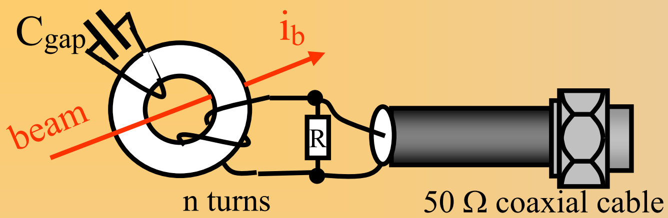


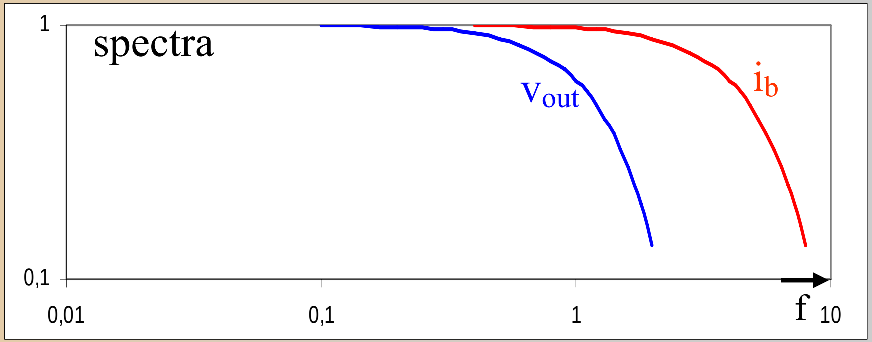
for short pulses long rep. rate:
SOLEIL Linac & transfer lines



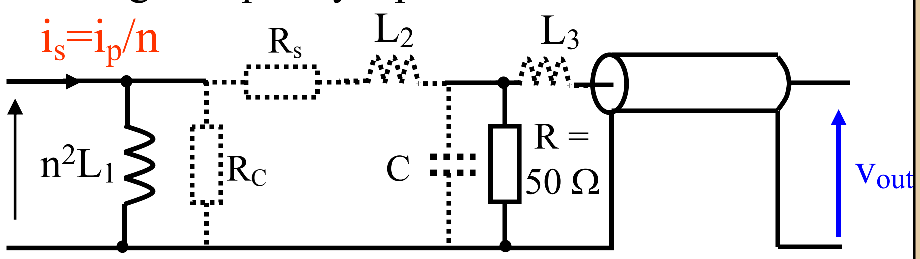


Fast Current Transformer (FCT)





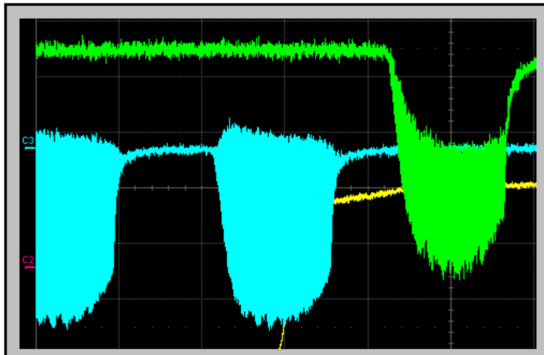
High frequency equivalent circuit



- R_C represents transformer core losses, it depends on frequency and field amplitude
- R_s is the secondary winding resistance
- L2 is the leakage inductance
- C is the addition of stray capacities and $Cgap/n^2$; a gap made of Al2O3, a few mm thick is usual ($C_{gap} \approx 30pF$).
- L3 is the inductance of the coaxial cable connection
- Coaxial cable has increasing losses with frequency
- Very high frequency losses occur into the shield cavity where the beam excites many modes.
- The high frequency equivalent circuit does not take into account the cavity mode losses. Wake field loss evaluation possible with 3D simulation codes (GDFIDL…)

Example: Soleil Booster and Tranfer Line

- **Transformer bandwidth is narrower than beam spectra.**
- **Part of the signal power is lost at high frequencies into the magnetic core.**
- **There is little power taken from the beam to affect its stability or to heat the magnetic core.**

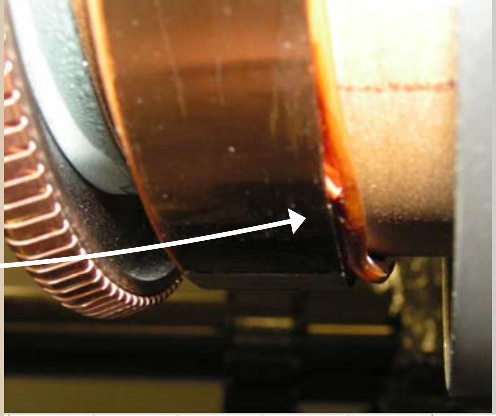


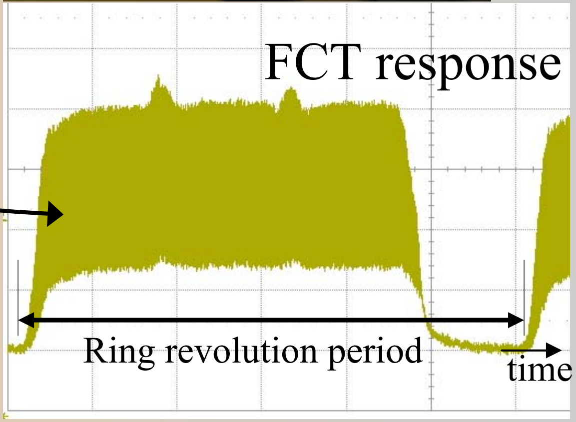
Last 2 turns in Soleil Booster and first turn in Storage Ring

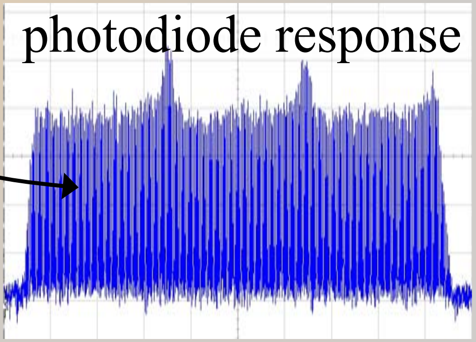
FCT Issues on a Storage Ring

Example: Soleil Storage Ring FCT

- Magnetic core heated over 110°C with a 300 mA beam (¾ Ring filling)
- The heating problem has been solved by installing additional capacitors in parallel on the gap and improving the air cooling of the toroid.
- But the reduced bandwidth affects the information: the signal does not return to zero between 2.8 ns separated bunches.
- Resistors around the gap (like in a WCM) can suppress the power entering the cavity.
- Another solution is to fill the cavity space with microwave absorbing material.
- A thorough study of these solutions would need GDFIDL and HFSS simulations and plenty of time.
- A good and cheap solution seems to use a photo-diode illuminated by the synchrotron radiation easily available in the diagnostic hut.
- Then, the gap could be removed which will reduce slightly the high order mode losses on the beam.





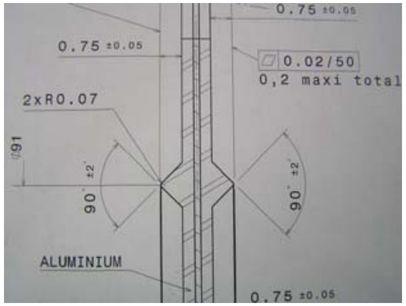


DC current Monitors: DCCTs, also called PCTs

- DCCTs are important for Storage Rings. The 1 μA resolution is usually less than 1E-5 the beam current. With a CW superconducting Linac beam of 200 μA (CEBAF), the 1 μA resolution is only 0.5 %.
- A DCCT senses the magnetic flux in a set of magnetic toroids. It feeds back a DC current in the beam current opposite direction in order to cancel the magnetic flux. A precision resistor in the feedback current path yields the output voltage.
- The DC magnetic flux into the magnetic circuits does not depend on the beam position (Ampère's law).
- DCCTs are commercially available.

Issues to address before installing a DCCT

- The zero flux sensing is affected by external magnetic fields: build good magnetic shieldings
- The zero current drifts with temperature. Avoid power losses in gap.
- Isolation gap can be very narrow and gap capacitor high (a few nF).
- Gap Example: Elettra and Soleil have a custom made seal. It is reproducing a VAT aluminum seal with a capton foil sandwiched in two half-Al seals



N. Rouvière seal design: will be on display 3 & 5 June.

Other Non Destructive DC Monitors

- Cryogenic Current Comparator (A. Peters, GSI). Used for low current ion beams. A CCC uses a SQUID as null detector for the magnetic field (SQUID = **S**uperconducting **Qu**antum **I**nterference **D**evice). The SQUID detects extremely small changes of the magnetic field. A fraction of nA resolution for 100 nA beams has been obtained. It performs an absolute measurement independent of beam position. It a very delicate instrument to implement (A. Peters. BIW1998)

- Cavity current monitor for CW beam measurement. Passive cavity in fundamental mode like an accelerating cavity. The output pick up voltage is proportional to the beam current. Like in a linac where the beam energy does not depend on its beam position, the output power of a passive cavity does not depend on beam position. It is sensitive to nA beams but needs an external calibration.
  Example: CEBAF, stainless steel low-Q cavities ($Q \leq 8000$) for low currents, calibrated against a DCCT at ≈ 100 µA.

References

- Much of the content of this lecture has been extracted from the following:

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