Beam Current Monitors

Accelerator Beam Diagnostics
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USPAS and University of New Mexico
Albuquerque NM, June 23-26, 2009

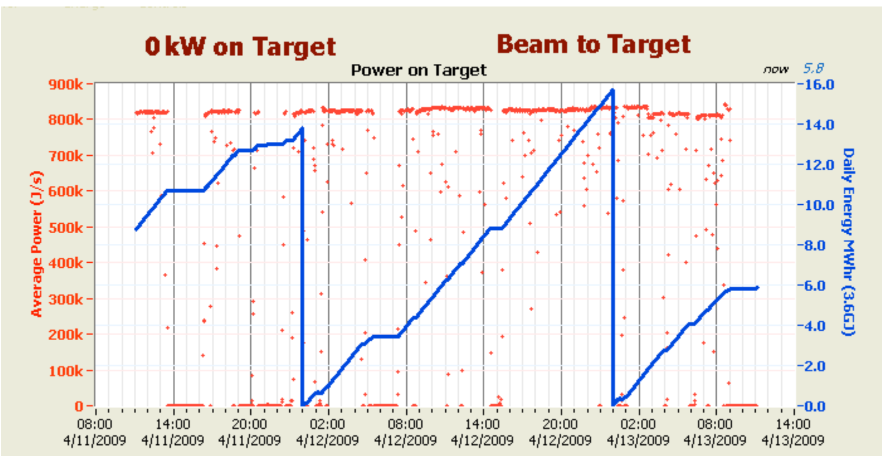
Beam Current Monitors

- Why use Beam Current Monitors?
- How to couple to the beam
  - Transformer
  - Resistive Wall Current monitor
  - Faraday Cups
- Limitations: Noise, bandwidth
- Lab

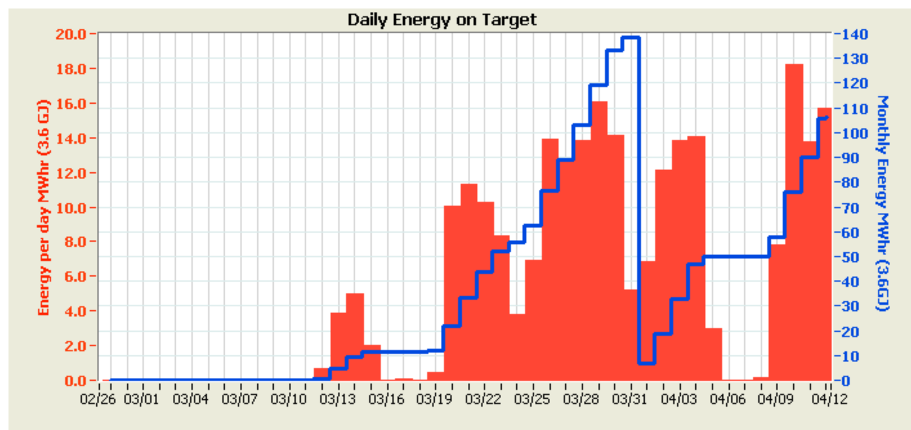
Particle Accelerators

One measure of performance: Power

- The amount of particles delivered at a certain energy.



SNS Power on target



SNS Energy delivered to target

Particle Accelerators

- How well do you accelerate beam?
  - What percent of the particles make it to the end
    - Effectiveness of acceleration process. E.g. stripping losses 3-5% of beam
  - What percent of time are you operational?
    - Damage to accelerator
  - What is the quality of your beam?
    - Emittance (collider)
    - Density profile (target)
    - Position stability
    - Radio-activation

Charged Beam

- What is the beam current?

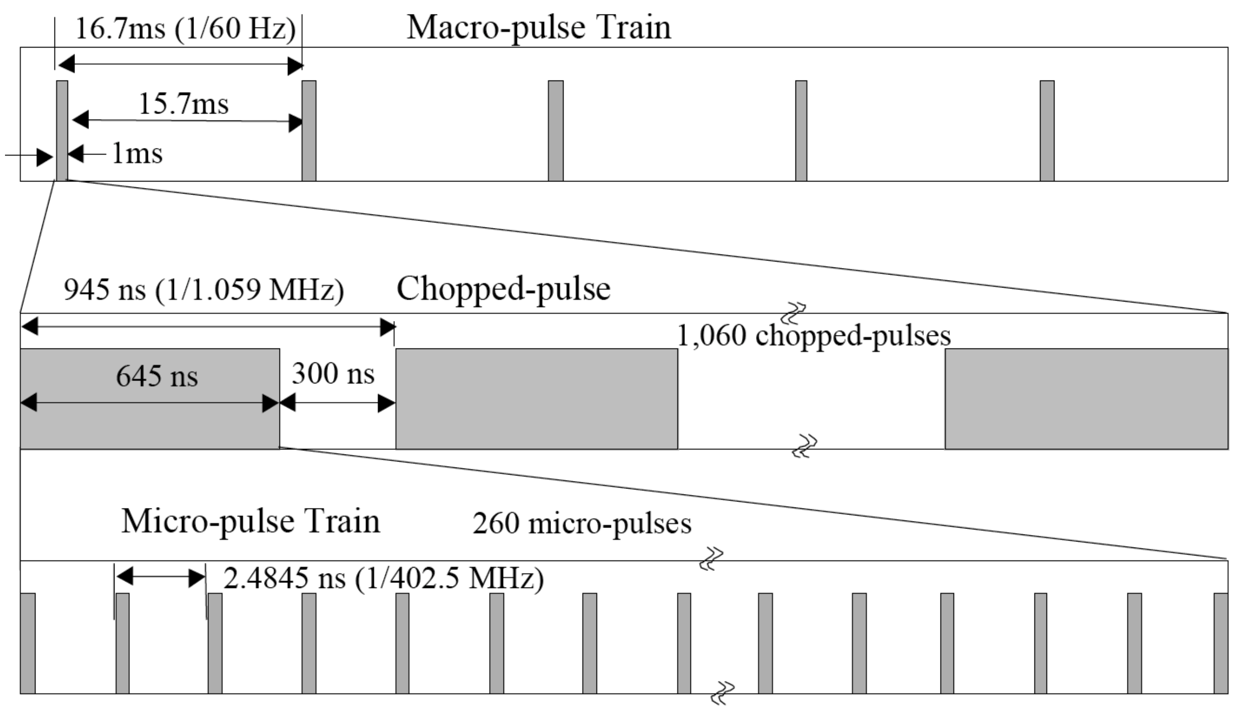
$$I_{beam} = \frac{qeN}{t} = \frac{qeN}{l} \cdot \beta c$$

In an accelerator the current is formed by N particles of charge state q per unit of time t or unit of length l and velocity $\beta = v/c$.

The beam is nearly an ideal current source with a very high source impedance

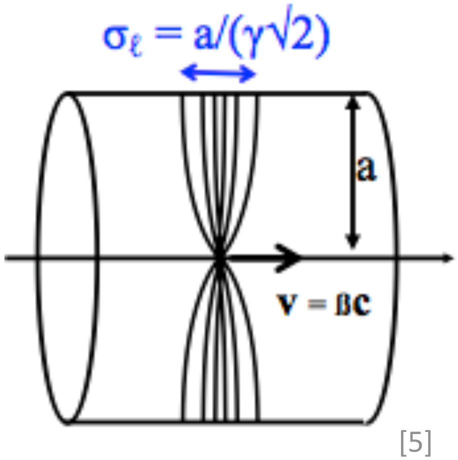
- We can measure the beam through the electric and magnetic fields created by the beam.

Beam Current Structure

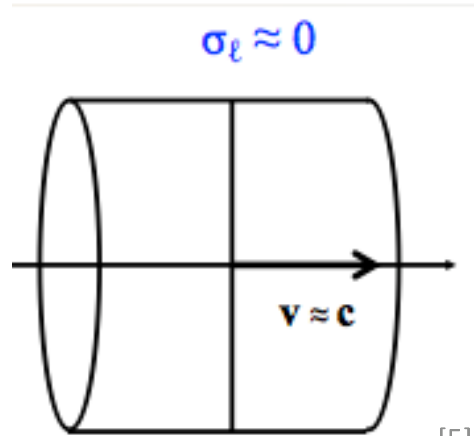


SNS Beam Structure

Beam Image currents



Moving charge



Fast moving charge

- Fast moving particles (moving E-field) create an H field. The H field moves the E-field induced image charges.
- At high velocities the wall current spectrum is an image (opposite sign) of the beam spectrum: at at a speed of 0.5c, approx RMS length is 90ps or 1.8GHz

Beam Image currents

If the wall current mirrors the beam current then the magnetic field outside the beam pipe is cancelled:

$$\text{Ampere's Law}: \oint H \bullet dl = I \quad \text{and with } I_{beam} \;=\; -\; \mathrm{I}_{image}$$

$$\text{then} \oint H \bullet dl = I_{beam} + I_{image} = 0 \rightarrow H = 0$$

Is it completely cancelled?

- Skin depth: the length in which the fields are reduced by a factor of *e* (-8.7 dB). At 10Mhz, a typical 0.794mm stainless pipe attenuates 53dB.

$$\delta = \frac{\sqrt{10} \cdot 10^3}{2\pi} \sqrt{\frac{\rho}{f}} \quad \text{with } \rho \text{ the resistivity and } f \text{ the frequency}$$

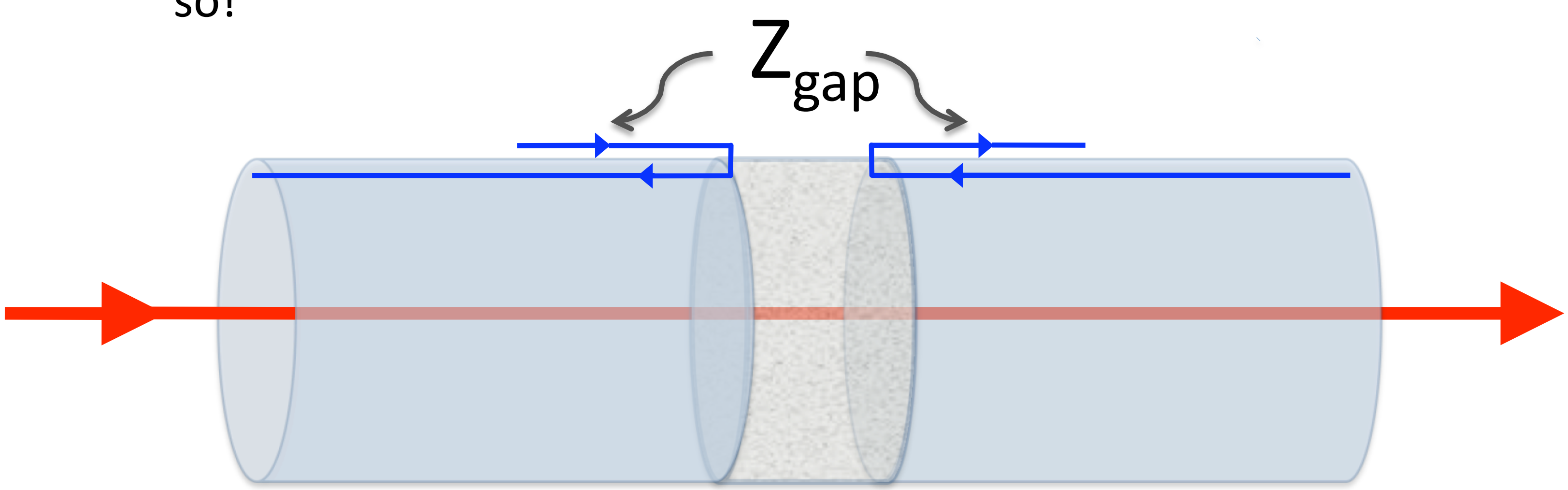
Skin depth (mm)	**1 KHz**	**10 KHz**	**100 KHz**	**1 MHz**	**10 MHz**
Copper	2.1	0.66	0.21	0.066	0.021
302 Stainless Steel	13.3	4.2	1.3	0.42	0.13

From [2] Webber.

Beam Pipe Break

No field outside of beam pipe. Either:

- install detector inside beam pipe or
  - Inside beam pipe means installation in vacuum
- use a ceramic break
  - Ceramic break forces image current to find another path and it will do so!

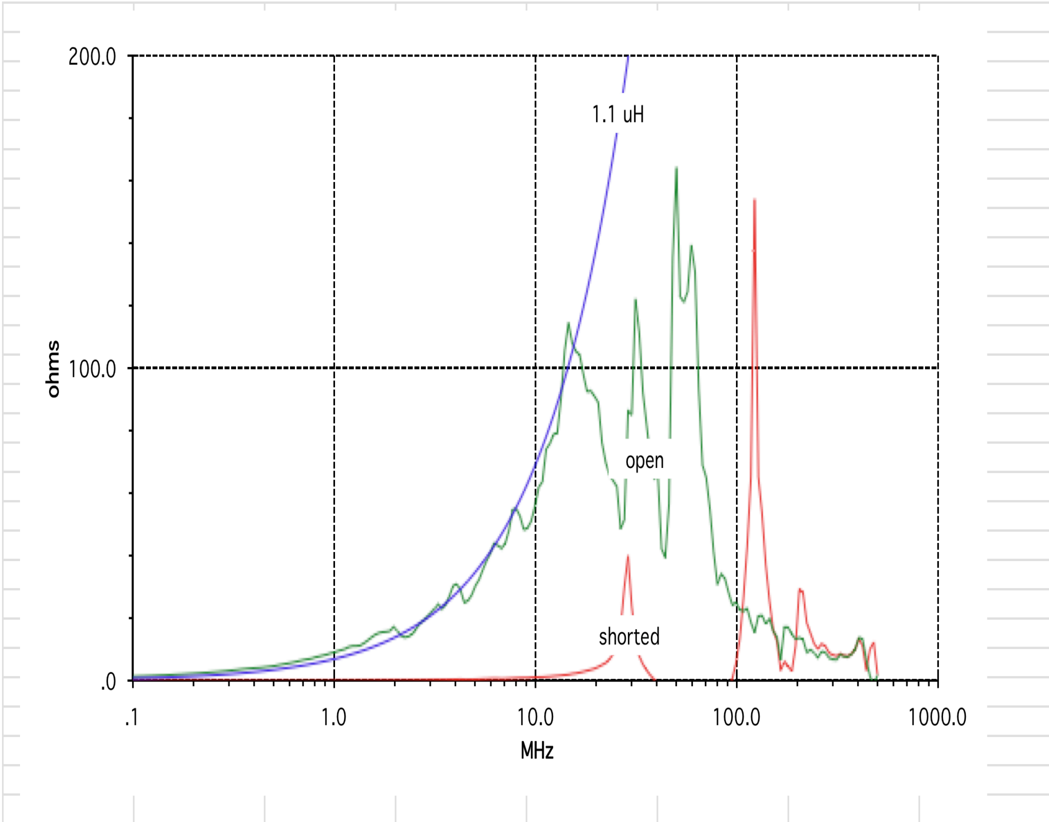


Gap Impedance

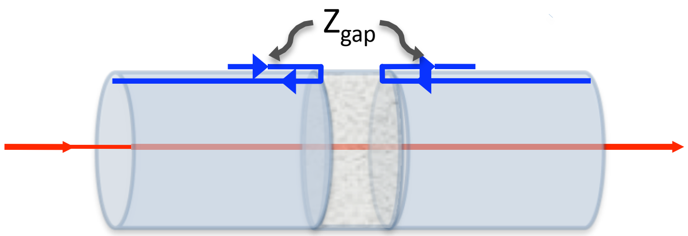
- You better define your gap impedance. Something will always be present, such as a path to ground and capacitance.
- Z_{gap} is combination of the gap capacitance and all external parallel elements
- Gap voltage

$$V_{gap} = Z_{gap} \cdot I_{wall} = Z_{gap} \cdot I_{beam}$$

can be generated up to beam voltage



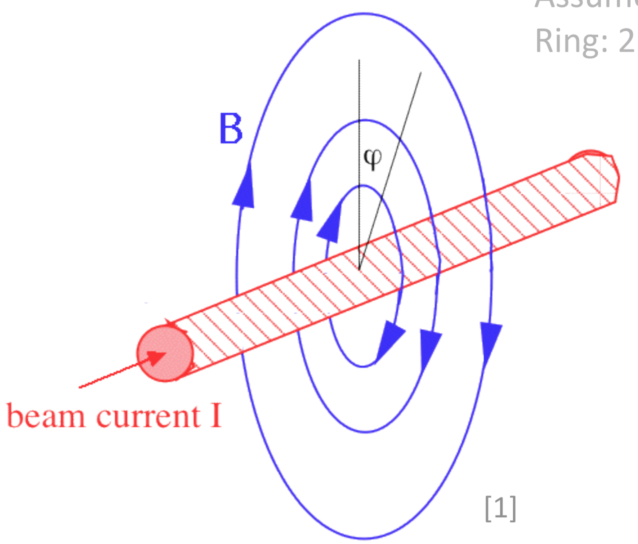
Courtesy of Jim Crisp & Mike Reid @FNAL



Current transformer

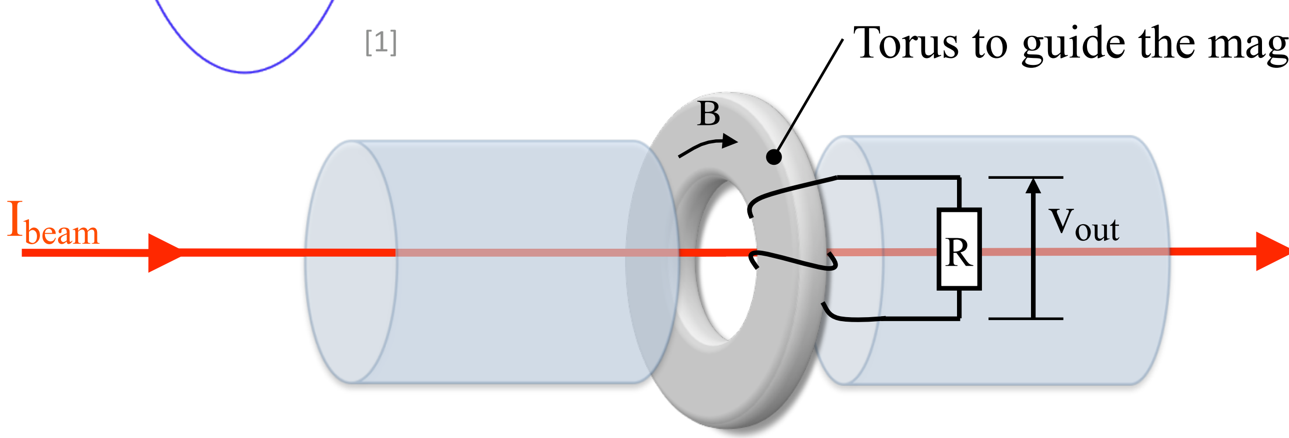
Measure the beam current through the magnetic field of the beam.

Assume the beam is long enough to be regarded as a line current. E.g. SNS Ring: 250 meters for 1usec

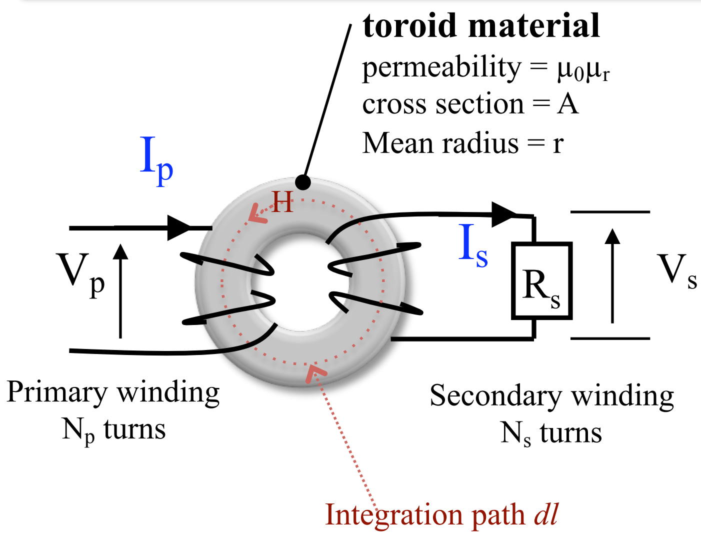


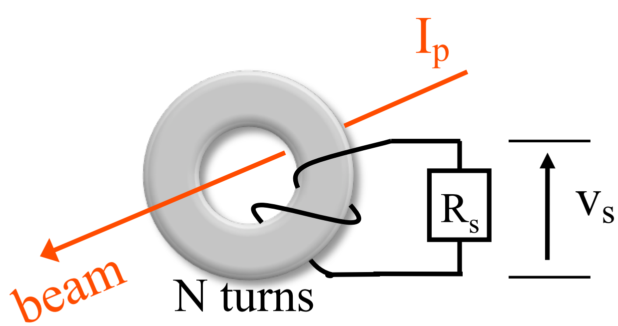
[1]

$$\text{Line current field:} \quad \vec{B} = \mu \cdot \frac{I_{beam}}{2\pi r} \vec{a}_{\varphi}$$



Current transformer





Ampere's Law:

$$\oint H \cdot dl = N_p I_p + N_s I_s = I_p + N_s I_s \quad \text{with } N_p = 1 \quad \Rightarrow$$

$$H = (I_p + N_s I_s)/2\pi r \tag{1}$$

Flux: (thin toroid approximation)

$$\Phi = \int_S B\, dS = \mu HA = \mu A(I_p + N_s I_s)/2\pi r \quad \text{with } A \text{ as area} \tag{2}$$

Faraday's Law:

$$V_s = -N_s \cdot \frac{d\Phi}{dt} = I_s \cdot R_s \tag{3}$$

Combine (2) and (3):

$$I_s \cdot R_s = -N_s \cdot \frac{\mu A}{2\pi r} \cdot \frac{d(I_p + N_s I_s)}{dt} \quad \text{with} \quad L_s = \frac{N_s^2 \mu A}{2\pi r} \Rightarrow$$

Differential equation:

$$\frac{dI_s}{dt} + \frac{R_s}{L_s} I_s = -\frac{1}{N_s} \cdot \frac{dI_p}{dt} \tag{4}$$

Laplace rewrite:

$$\frac{I_s(i\omega)}{I_p(i\omega)} = -\frac{1}{N_s} \cdot \frac{i\omega}{(i\omega + R_s/L_s)}$$

Current transformer

Great, we got our transfer function and now we can figure out what the behavior is of our current transformer:

$$\frac{I_s(i\omega)}{I_p(i\omega)} = \frac{1}{N_s} \cdot \frac{i\omega}{(i\omega + R_s / L_s)}$$

When $\quad i\omega >> R_s / L_s \longrightarrow \quad I_s = \frac{I_p}{N_s}$

Power: $\quad P_s = I_s^2 R_s = \frac{I_p^2}{N_s^2} R_s \quad$ (transferred from beam)

Current transformer

The inductance plays an important role in the design of transformer. Note that in the calculation for inductance, the geometry of the setup plays and important role as well as the μ and windings.

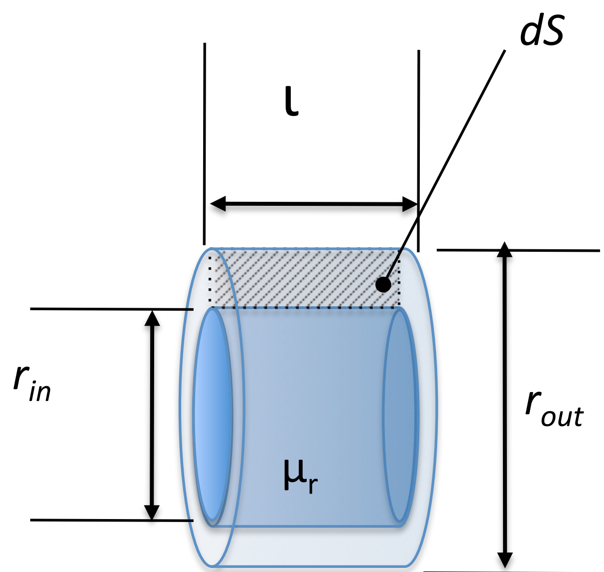
Inductance of a torus with a square cross section:

$$\Phi = \int_S B\,dS = \int_S \mu H dS = \int_{r_{in}}^{r_{out}} \frac{\mu I}{2\pi r} l dr = \frac{\mu I}{2\pi} l \ln\left(\frac{r_{out}}{r_{in}}\right)$$

with $L = \frac{N\Phi}{I}$ then

$$L = \frac{\mu N^2 l}{2\pi} \ln\left(\frac{r_{out}}{r_{in}}\right) \text{ and } \mu = \mu_0 \mu_r$$

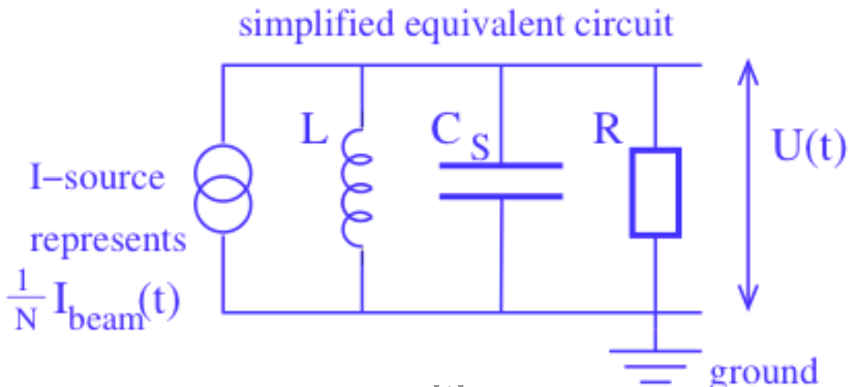
μ_r can be > 10000.



$$L_s = N_s^2 L_p$$

Current transformer

Too bad there is also a capacitance: we get an LCR circuit:



[1]

$$\frac{1}{Z} = \frac{1}{R} + \frac{1}{i\omega L} + i\omega C \Rightarrow$$

$$Z = \frac{i\omega L}{1 + i\omega L/R - (\omega L/R)\cdot(\omega RC)}$$

LRC Properties

What are properties of an LRC circuit?

$$Z = \frac{i\omega L}{1 + i\omega L/R - (\omega L/R)\cdot(\omega RC)}$$

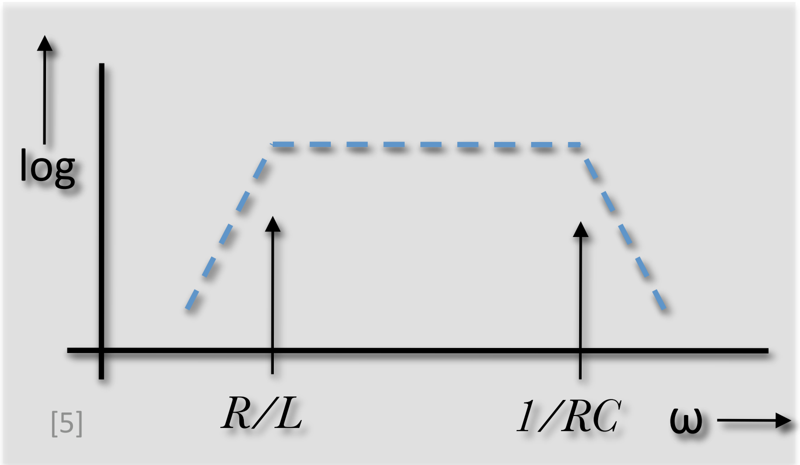
$$\text{For low frequency}\;:\quad \omega << R/L \rightarrow Z = i\omega L$$

$$\text{For high frequency}:\quad \omega >> 1/RC \rightarrow Z = 1/i\omega C$$

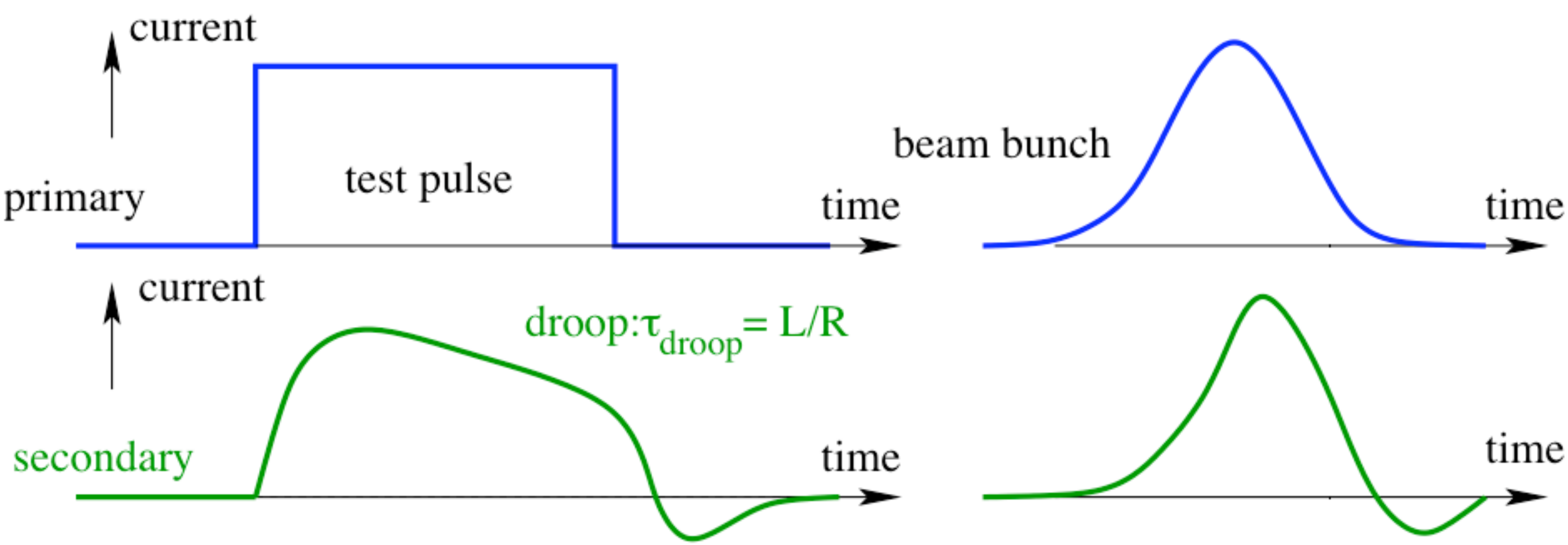
$$\text{For mid frequency}\;:\quad R/L << \omega << 1/RC \rightarrow Z \approx R$$

It's a band pass with a:

- droop time t_{droop}
- rise time t_{rise}



Bandpass effects on pulse shape



Rise-time and droop-time

- Rise time t_{rise}: defined as the time it takes the amplitude to go from 10% to 90%.
- Rise time constant τ_{rise} : $A \propto (1 - e^{-t/\tau_{rise}})$ and τ_{rise} corresponds to the time for an increase by e^{-1} = 37 %.

$$t_{rise} = \frac{\ln 0.9 - \ln 0.1}{\omega_{high}} = \frac{2.197}{\omega_{high}} = \frac{2.197}{2\pi f_{high}} \approx \frac{1}{3 f_{high}}$$

$$\omega_{high} = 1/RC \Rightarrow$$

$$t_{rise} \approx 2RC \quad \text{or} \quad t_{rise} \approx 2\tau_{rise} \quad \text{with} \quad \tau_{rise} = RC$$

- Droop time

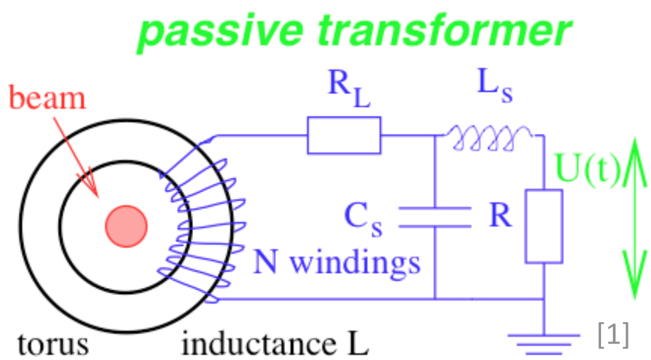
$$t_{droop} = \frac{\ln 0.9 - \ln 0.1}{\omega_{low}} = \frac{2.197}{\omega_{low}} = \frac{2.197}{2\pi f_{low}} \approx \frac{1}{3 f_{low}}$$

$$\omega_{low} = R/L \Rightarrow$$

$$t_{low} \approx 2L/R \quad \text{or} \quad t_{low} \approx 2\tau_{low} \quad \text{with} \quad \tau_{low} = L/R$$

Current Transformer

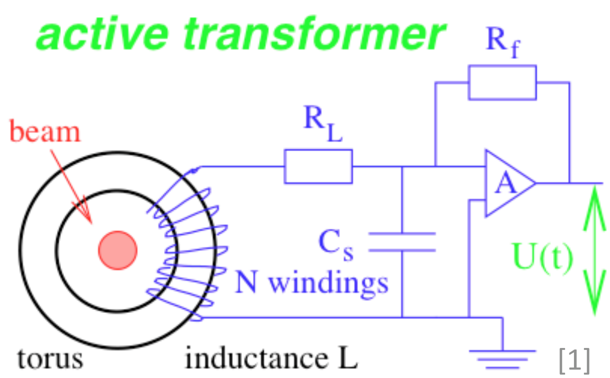
Add (long) cable to current transformer: add cable resistance, capacitance and inductance:



$$\tau_{rise} = \sqrt{L_s C_s}$$

$$\tau_{droop} = L/(R + R_L)$$

Active Transformer: use a trans-impedance circuit to lower the load impedance.



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

Design of Current Transformer

How to design a current transformer:

- High sensitivity -> low number of turns, low N_s

$$V_s = I_s R_s = \frac{I_b}{N_s} R_s$$

- High droop time -> high L -> high μ, high N_s

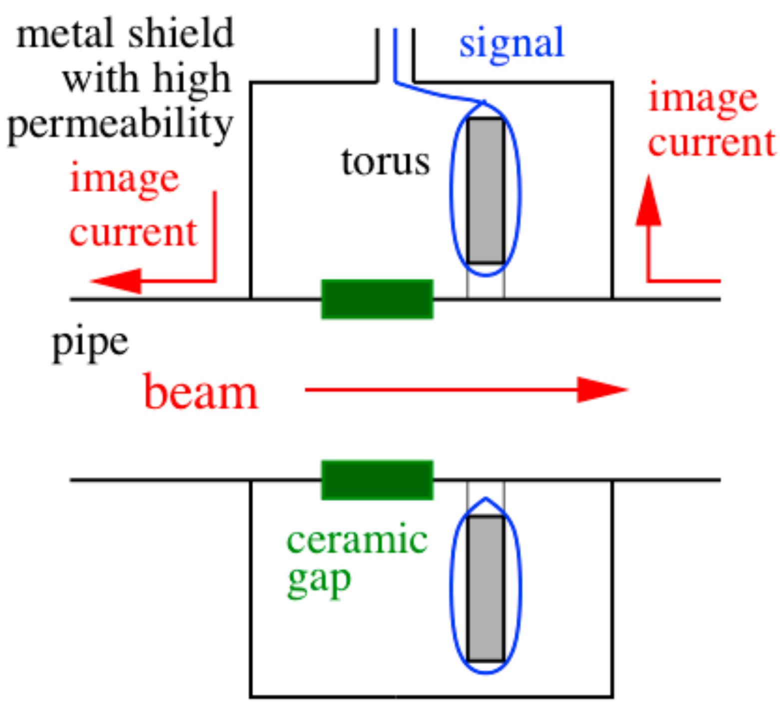
$$\tau_{droop} = L_s / R_s \qquad \mathrm{L}_s = \frac{l}{2\pi} \ln\left(\frac{r_{out}}{r_{in}}\right) \cdot \mu \cdot N_s^2$$

- Fast rise time -> low stray capacitance

$$\tau_{rise} = \sqrt{L_s C_s}$$ with cable

$$\tau_{rise} = RC$$ without cable

Design of Current Transformer



Passive transformer

Torus radii	$r_i = 70$ mm, $r_o = 90$ mm
Torus thickness	$l = 16$ mm
Torus material	Vitrovac 6025: $(\mathrm{CoFe})_{70\%}(\mathrm{MoSiB})_{30\%}$
Torus permeability	$\mu_r \simeq 10^5$ for $f < 100$ kHz, $\mu_r \propto 1/f$ above
Number of windings	10
Sensitivity	4 V/A at $R = 50\ \Omega$, 10^4 V/A with amplifier
Resolution for $S/N = 1$	40 μA_{rms} for full bandwidth
$\tau_{droop} = L/R$	0.2 ms
$\tau_{rise} = \sqrt{L_S C_S}$	1 ns
Bandwidth	2 kHz to 300 MHz

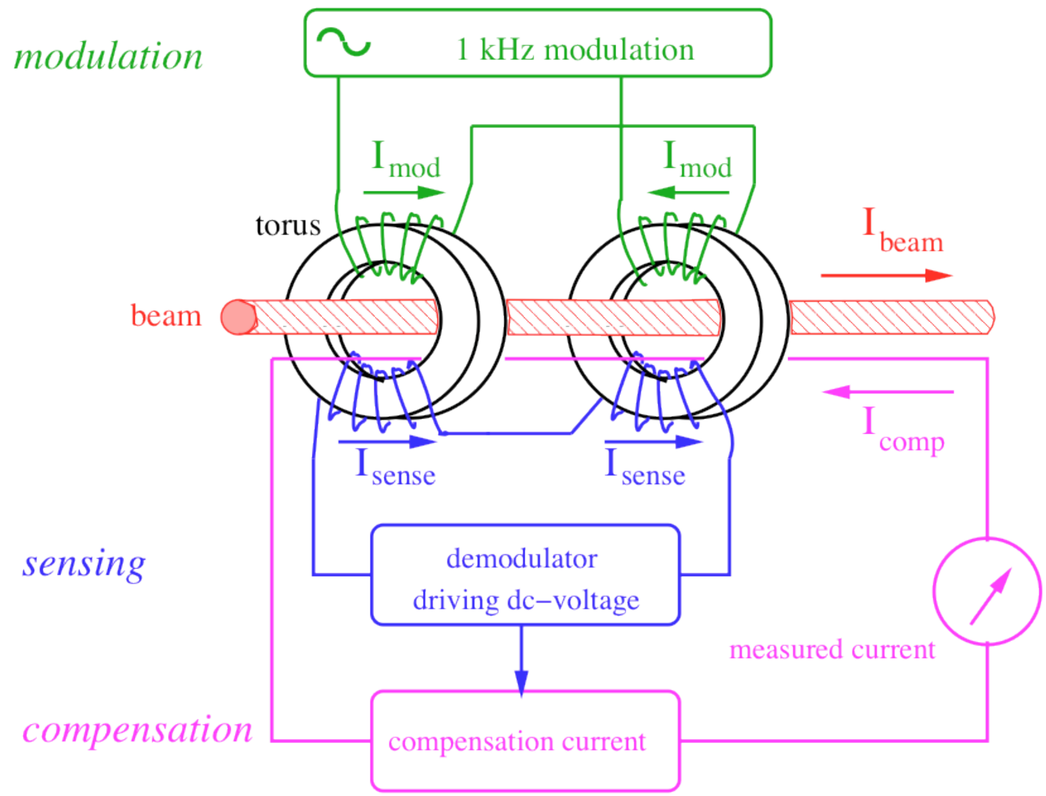
Active transformer

Torus radii	$r_i = 30$ mm, $r_o = 45$ mm
Torus thickness	$l = 25$ mm
Torus material	Vitrovac 6025: $(\mathrm{CoFe})_{70\%}(\mathrm{MoSiB})_{30\%}$
Torus permeability	$\mu_r \simeq 10^5$
Number of windings	2×10 with opposite orientation
Maximal sensitivity	10^6 V/A
Ranges of the beam current	10 μA to 100 mA
Resolution for $S/N = 1$	0.2 μA_{rms} for full bandwidth
Droop	< 0.5 % for 5 ms pulse length
Maximum pulse length	8 ms

DC Current Transformer

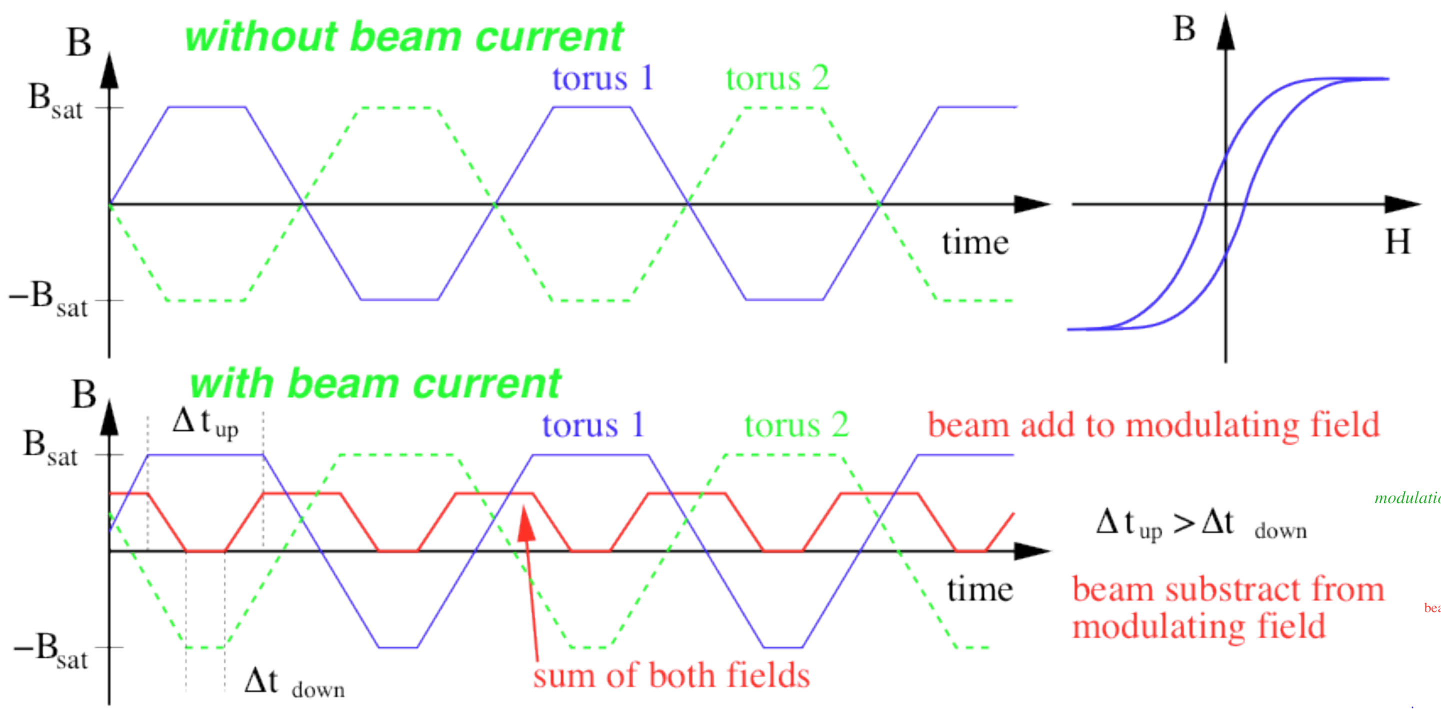
How to measure the DC current? The current transformer discussed sees only changes in the flux.
The DC Current Transformer (DCCT): look at the magnetic saturation of the torus.

- Modulation of the primary windings forces the torus into saturation twice per cycle.
- Secondary windings sense modulation signal and cancel each other.
- But with the I_{beam}, the saturation is shifted and I_{sense} is not zero
- Adjust compensation current until I_{sense} is zero once again.



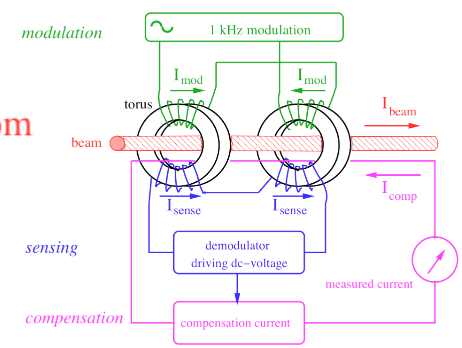
DC Transformer Operation, see [1]

DC Current Transformer



Example bandwidth:
DC to 20kHz,
resolution 2µA

[1]



- Modulation of the primary windings forces the torus into saturation twice per cycle.
- Secondary windings sense modulation signal and cancel each other.
- But with the I_{beam}, the saturation is shifted and I_{sense} is not zero
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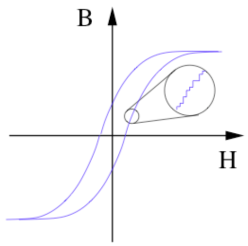
Current Monitor Limitations

Limitation to transformers:

- The permeability of a core can be saturated: specs of max B field or max current time product I*t,
- Thermal noise: $V_n \approx \sqrt{4k_b T f_{high} R}$ -> µA range lower limit
- Weiss domains lead to Barkhausen noise if terminating with high impedance (limit for DC-type)



- Avoid external magnetic fields
- Torus material has dependency of μ_r on temperature or on mechanical stress (micro-phonic pickup)
- Avoid secondary electrons from being measured

BCM Testing Fixture

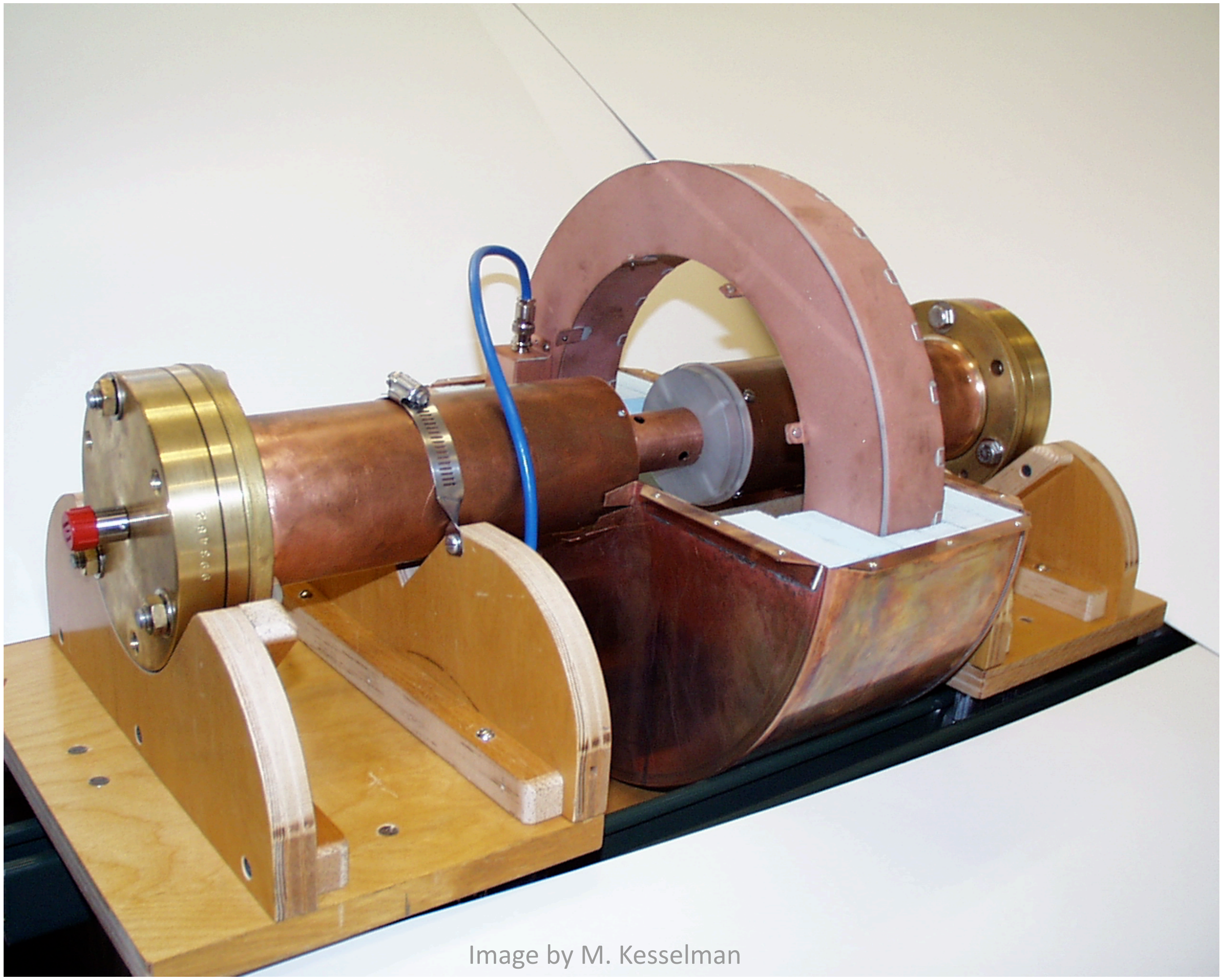
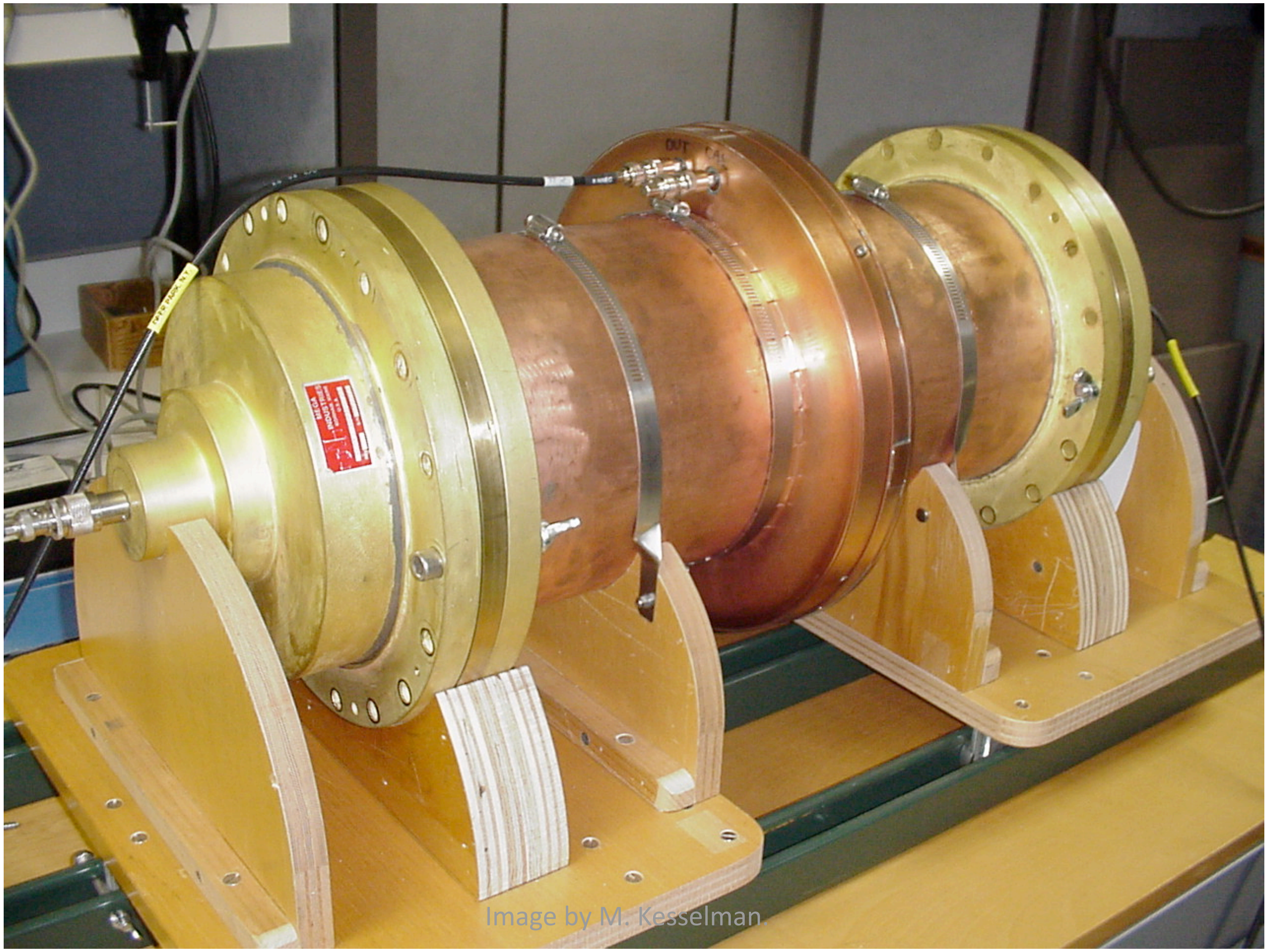
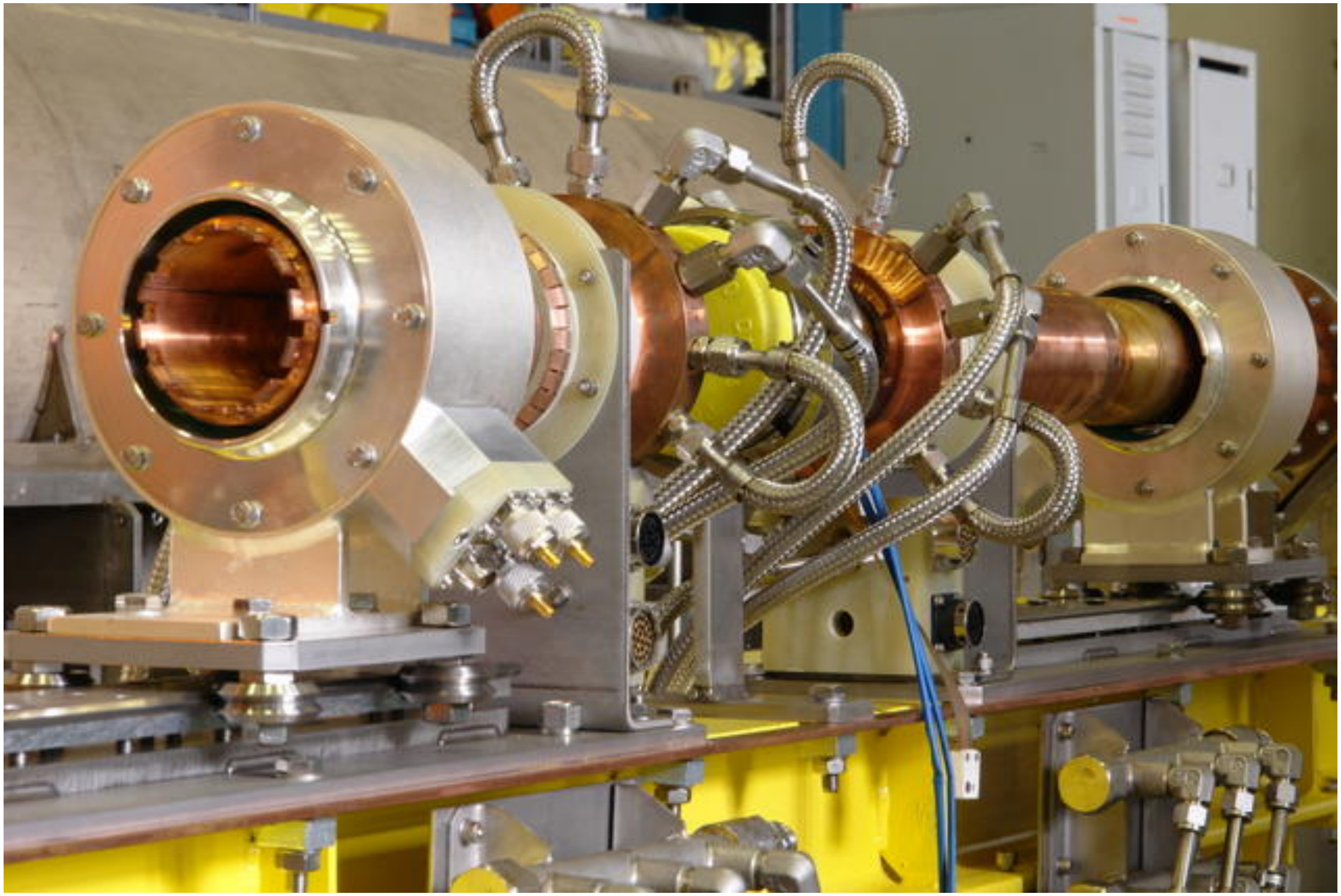


Image by M. Kesselman

SNS Current Transformer

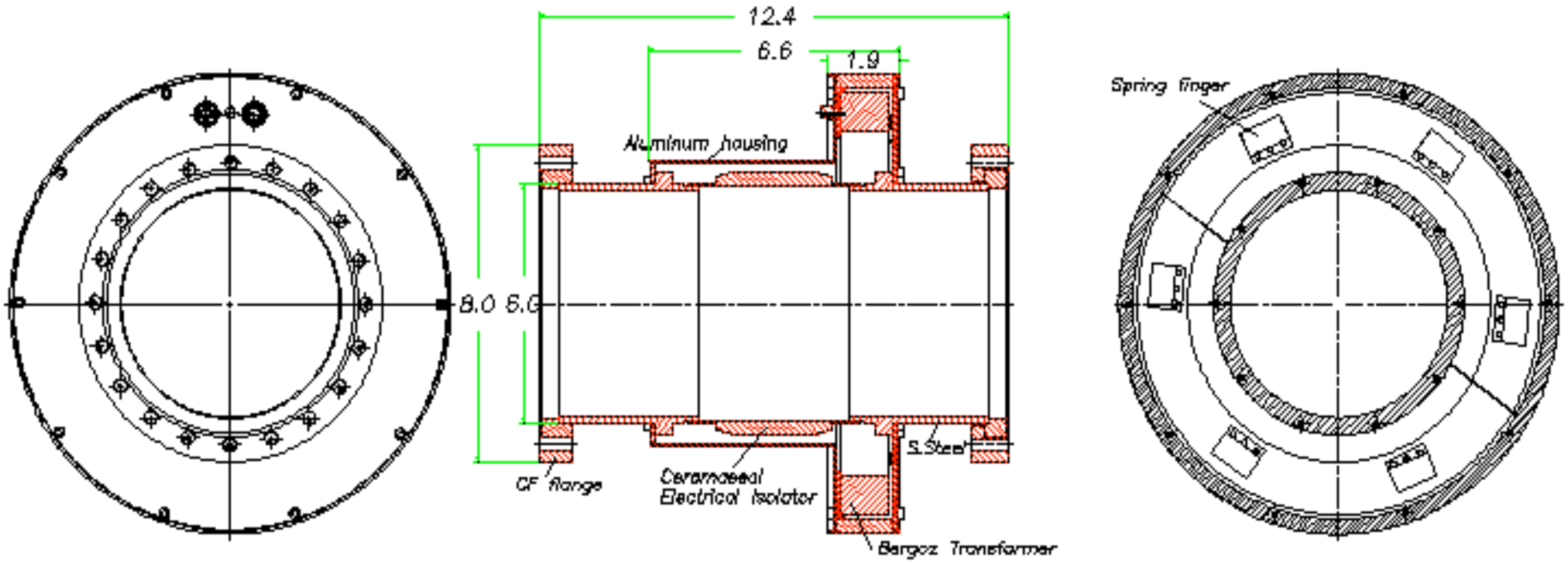


LHC Fast Current Transformer



U. Raich CAS Frascati 2008 Beam Diagnostics

COMPONENTS INSIDE HEBT BCM ASSEMBLY

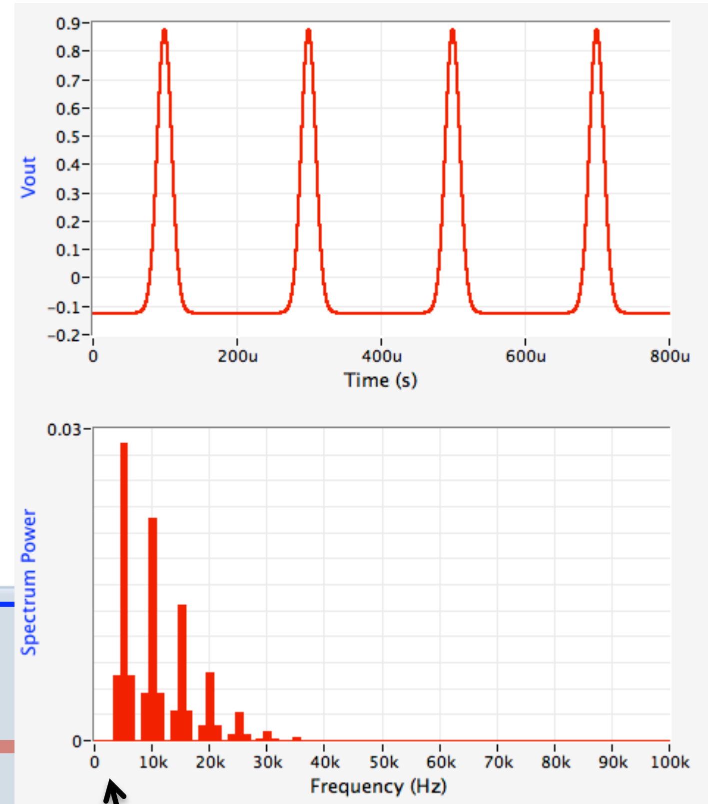


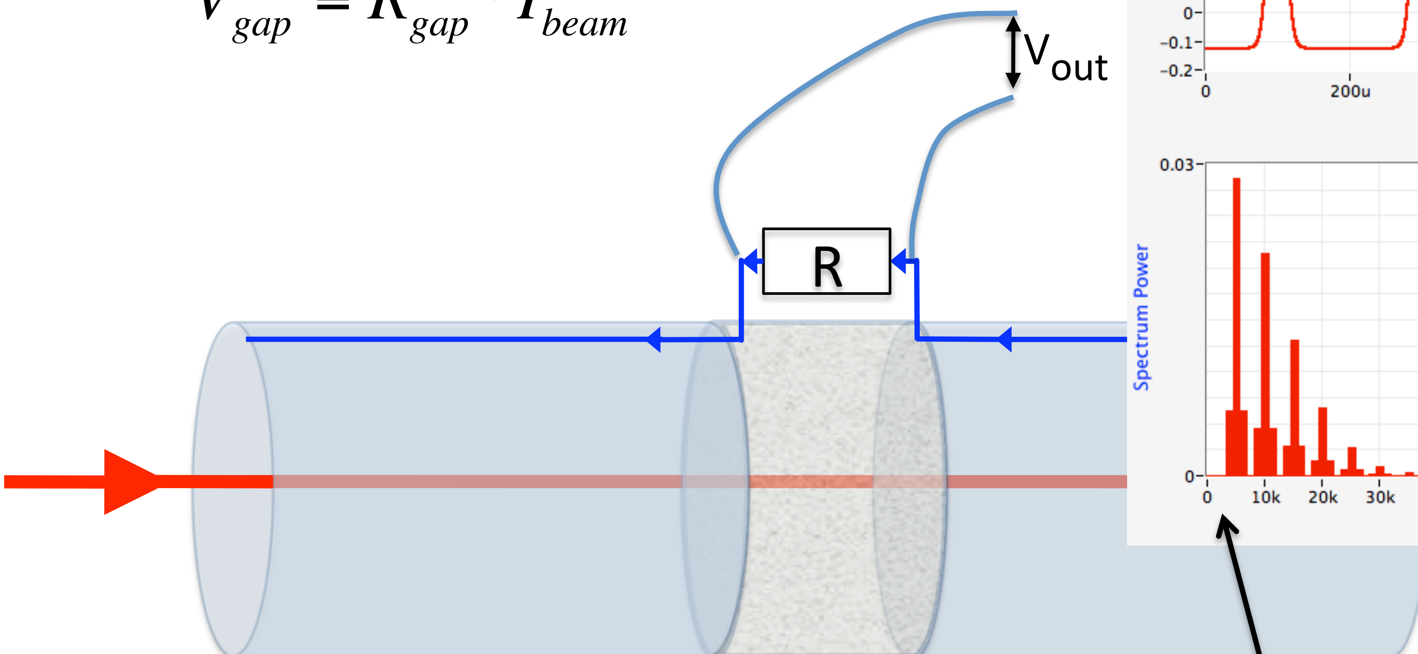
Design by BNL for SNS

Wall Current Monitor

- Put a resistor over the gap and measure its voltage.

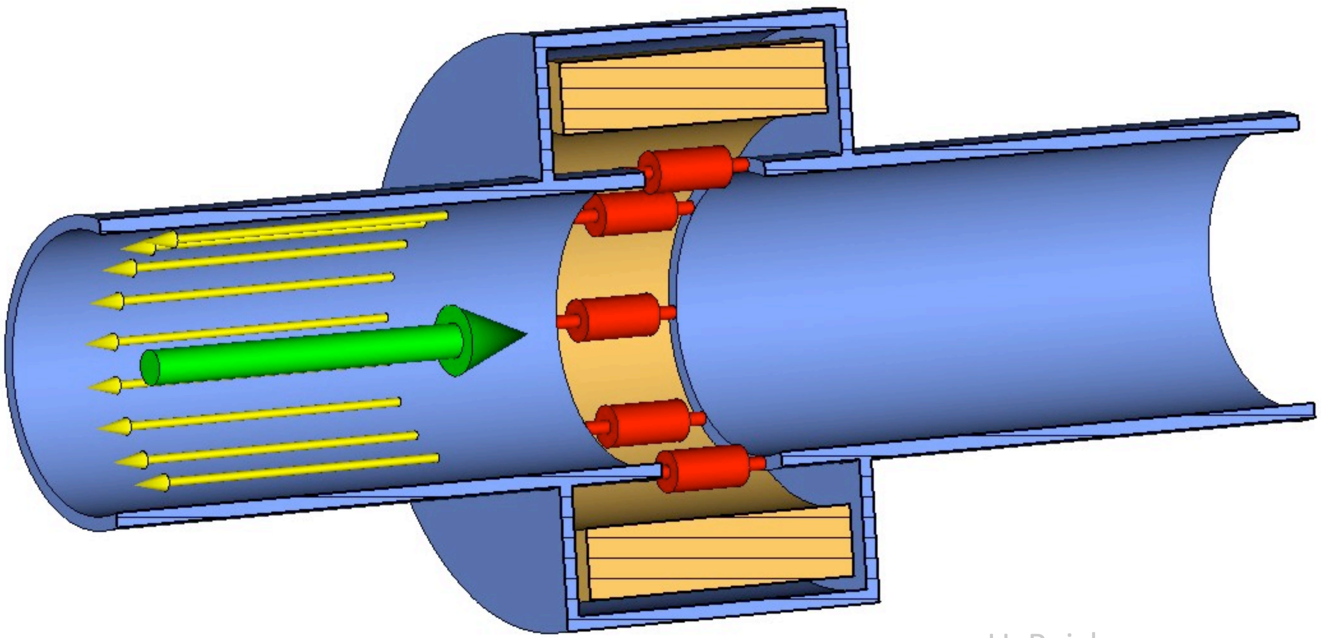
$$V_{gap} = R_{gap} \cdot I_{beam}$$





No DC in image current

Wall Current Monitor



U. Raich

The **BEAM** current is accompanied by its **IMAGE** current

A voltage proportional to the beam current develops on the **RESISTORS** in the beam pipe gap

The gap must be closed by a box to avoid floating sections of the beam pipe

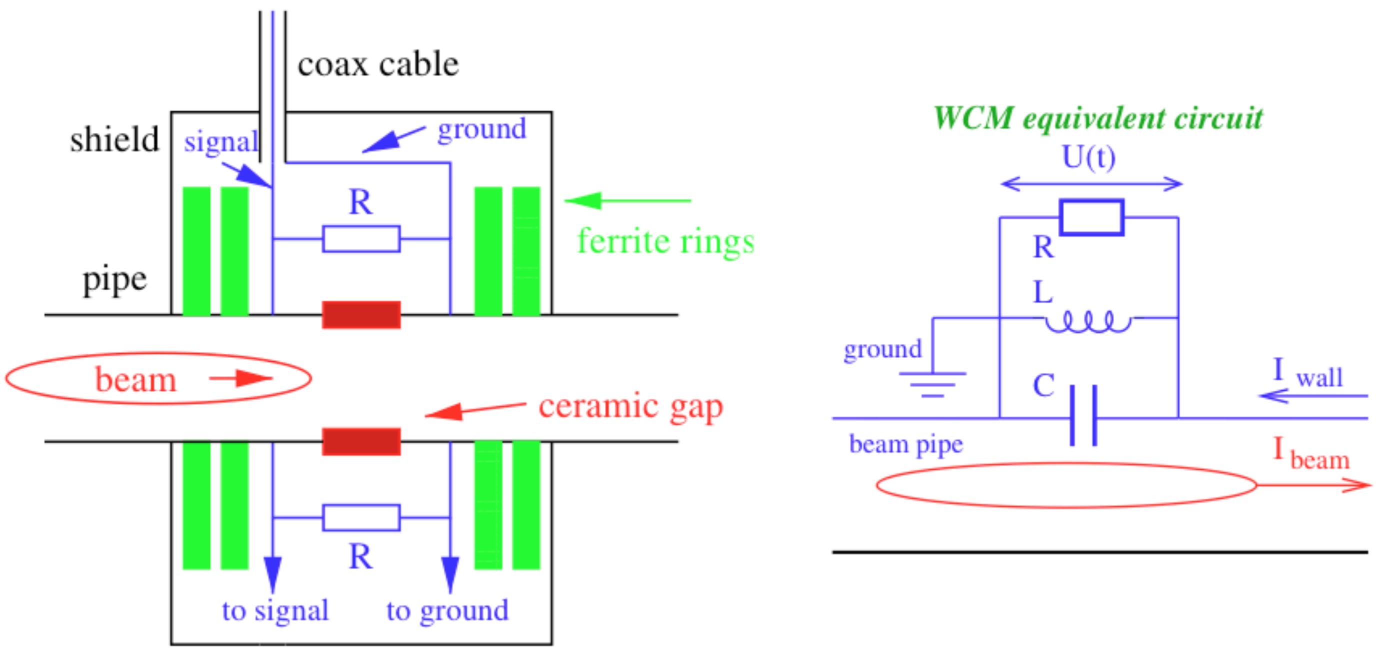
The box is filled with the **FERRITE** to force the image current to go over the resistors

The ferrite works up to a given frequency and lower frequency components flow over the box wall

Wall Current Monitor

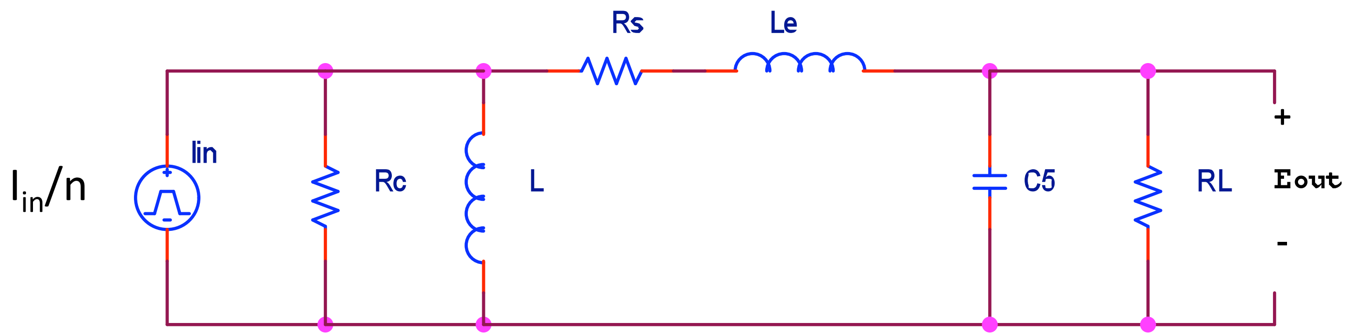
Now for the details:

- Ceramic gap to avoid working in vacuum
- Distributed resistors (30 to 100) for beam position independency
- Ferrite rings for low frequency response
- Shield for ground currents and noise protection



Schematics of a wall current monitor and its equivalent circuit [1]

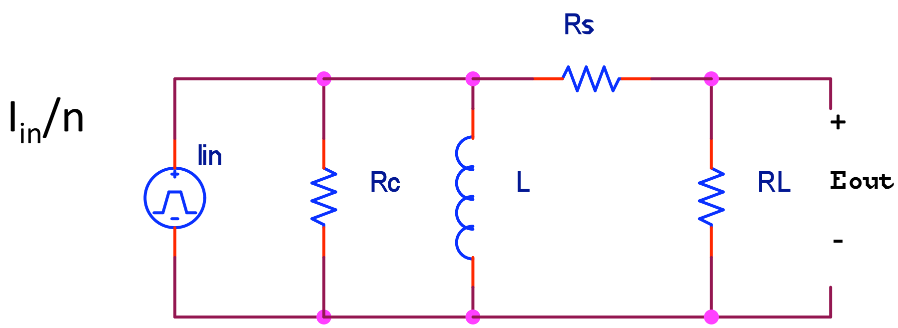
Wait, there is more



Broadband Model [4]

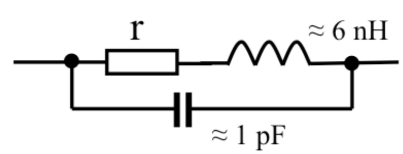
$$2\zeta=\sqrt{(R_L/R_L+R_s)}((R_s\sqrt{C/L_e}+(1/R_L)\sqrt{L_e/C})$$

$$\omega_o=\sqrt{1/(R_L/R_L+R_s)\,L_eC}$$

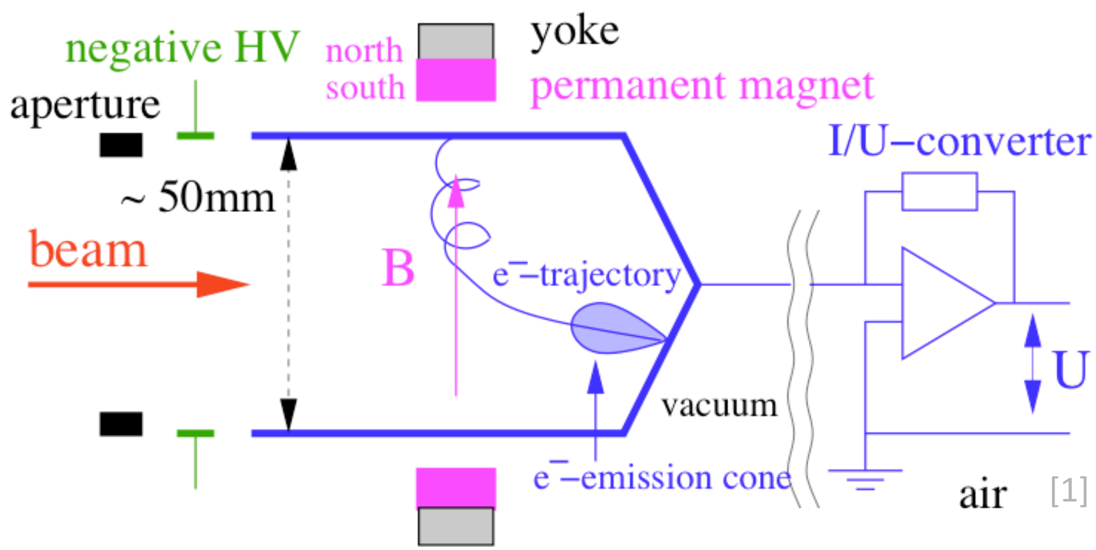


Low to Midband Model [4]

Even a resistor is not a resistor:



Faraday Cups

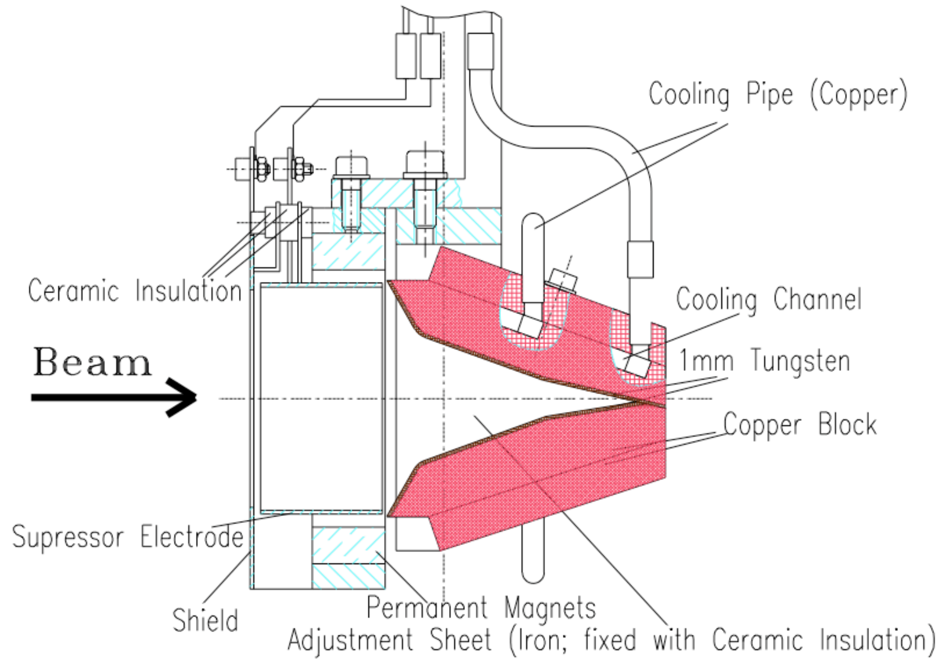


The Faraday Cup destructively intercepts the beam

- DC coupled! (With just a resistor the signal is $V_{out} = I_{beam} * R$)
- Low current measurements possible e.g., 10pA
- Problem with secondary electrons:
  - Use long cup or voltage suppression or magnetic field
- If not properly terminated -> very high voltage (beam potential)
- Must process beam power (SNS full power 1.4MW)

Faraday Cups

Low power Faraday Cup [1]



High power (1MW) Faraday Cup [1]

Noise Issues

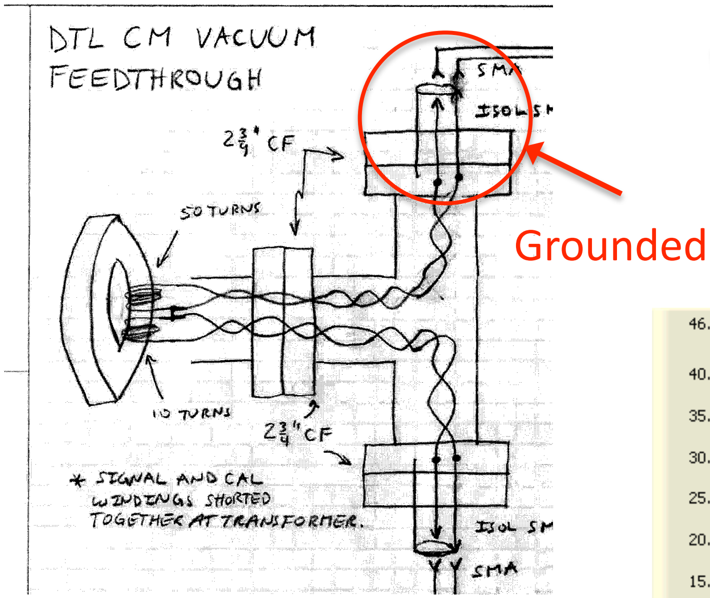
Noise can be a problem!

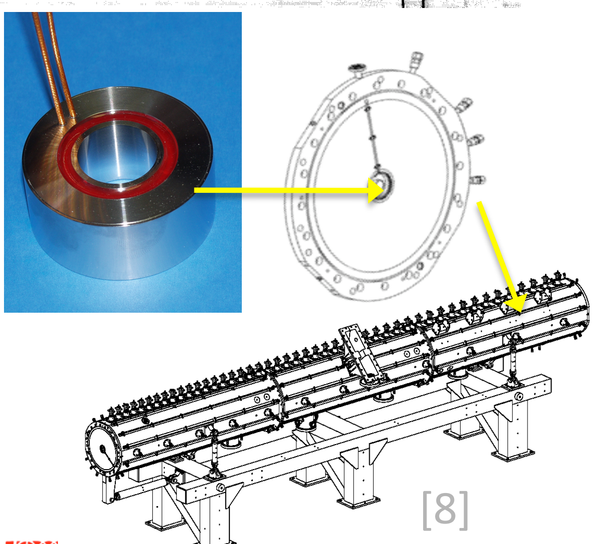
- There are many powerful noise sources in Accelerators:
  - Switching power supplies
  - Accelerating RF
  - Source RF

Case in point:

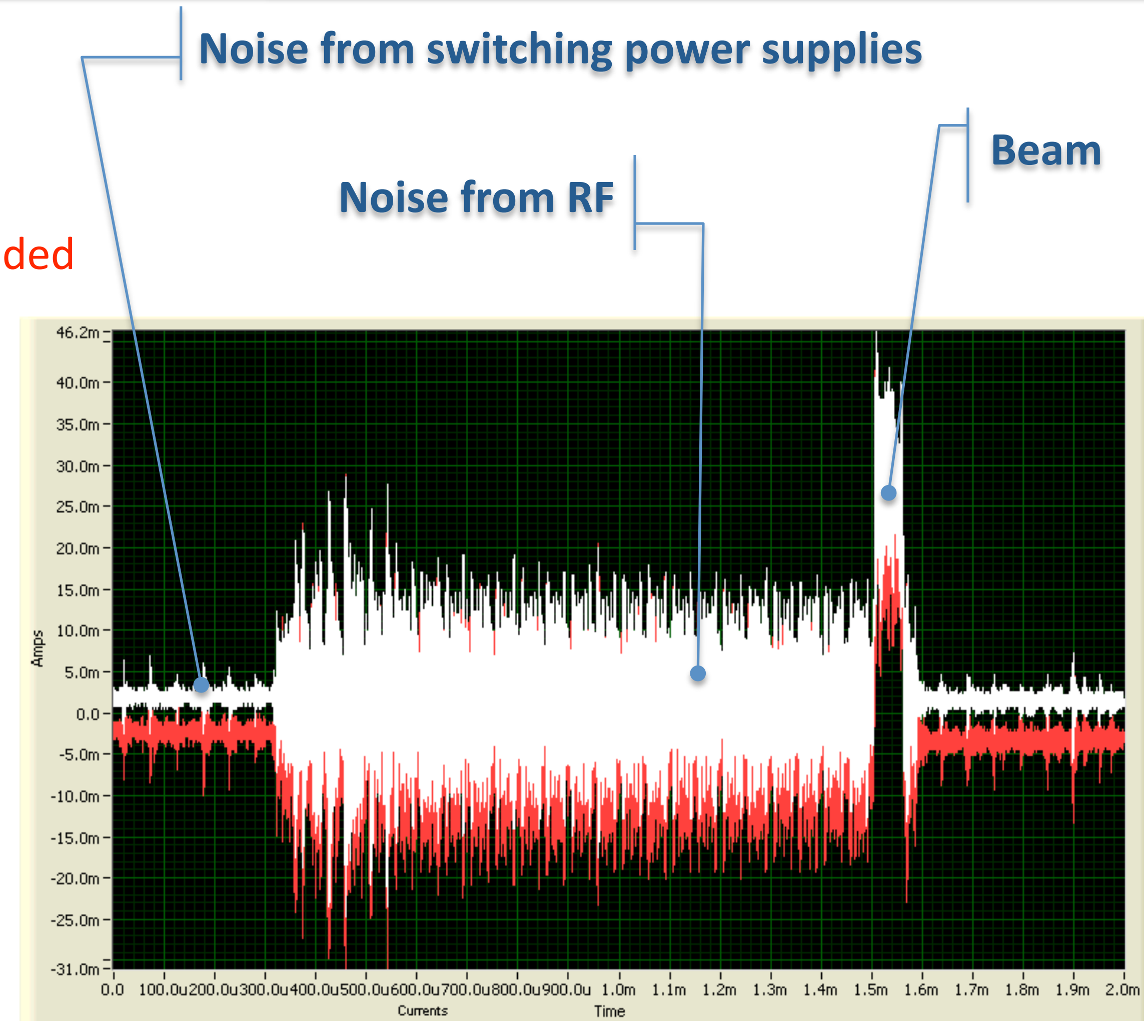
– SNS DTL BCM -> single ended and inside a cavity (due to space limitations)

Noise Issues



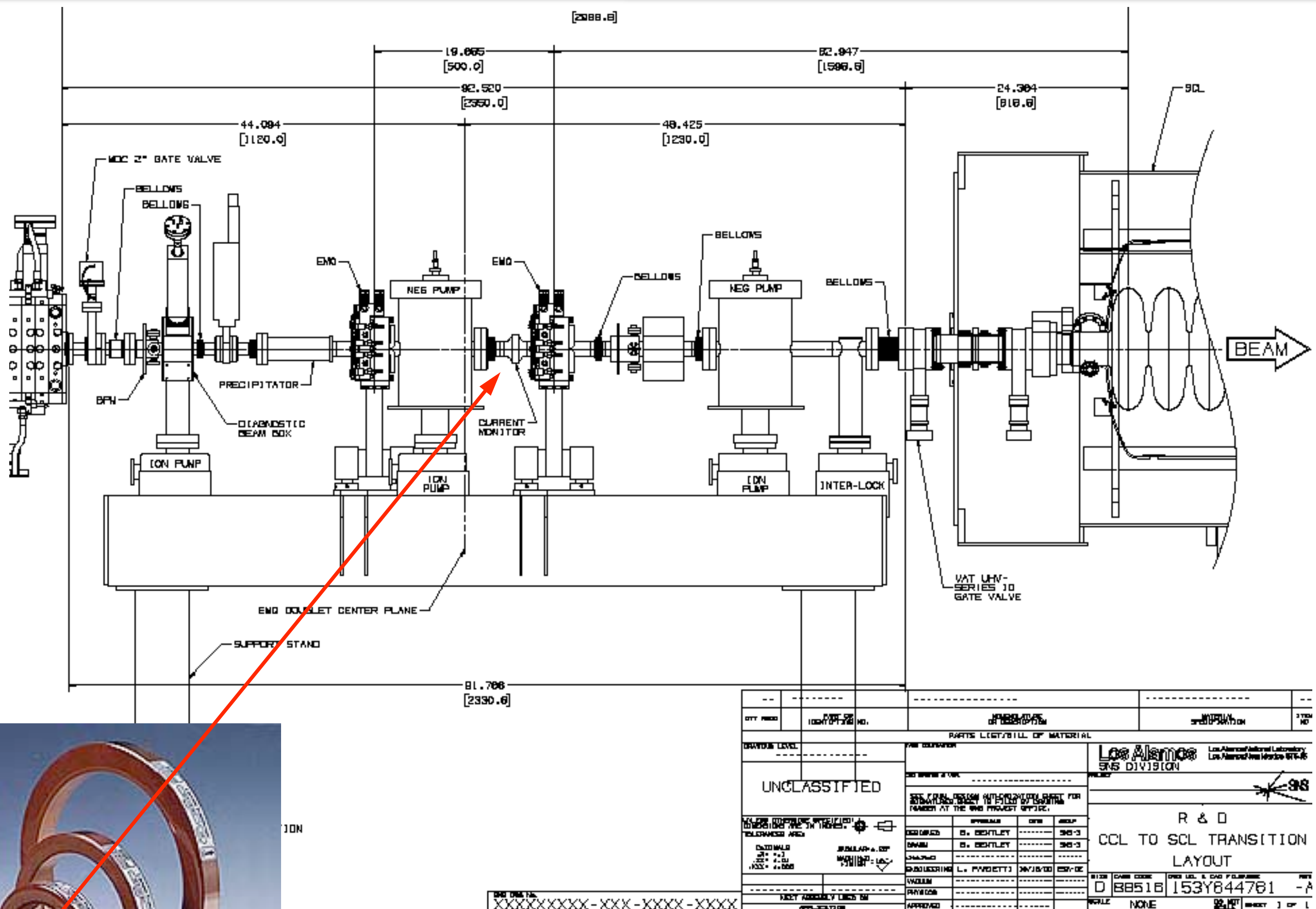


[8]



Noise of DTL current transformer (inside cavity, single ended)

Noise Issues

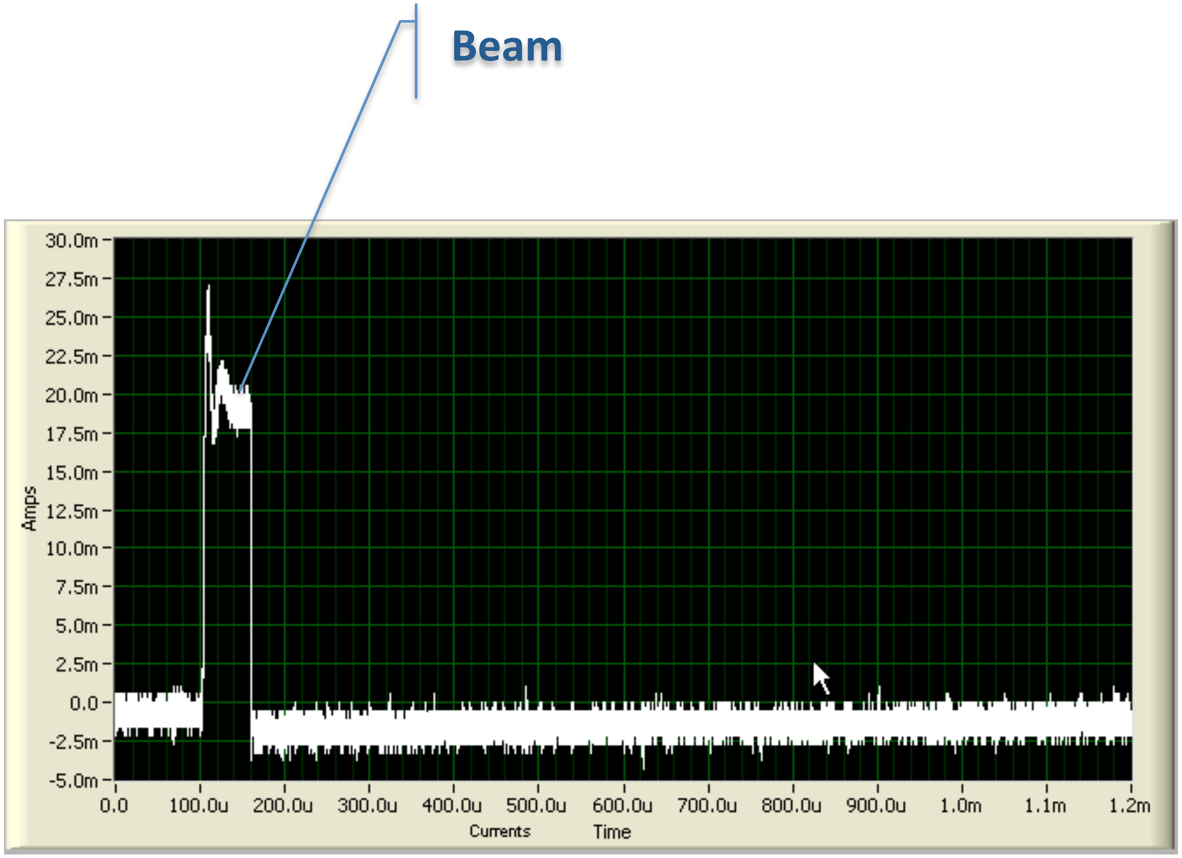


SCL Beam Current Monitor (single ended)

[8]

Noise Issues

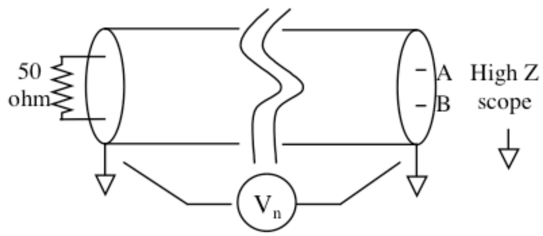
Better:
CCL BCM outside of cavity but still single ended.

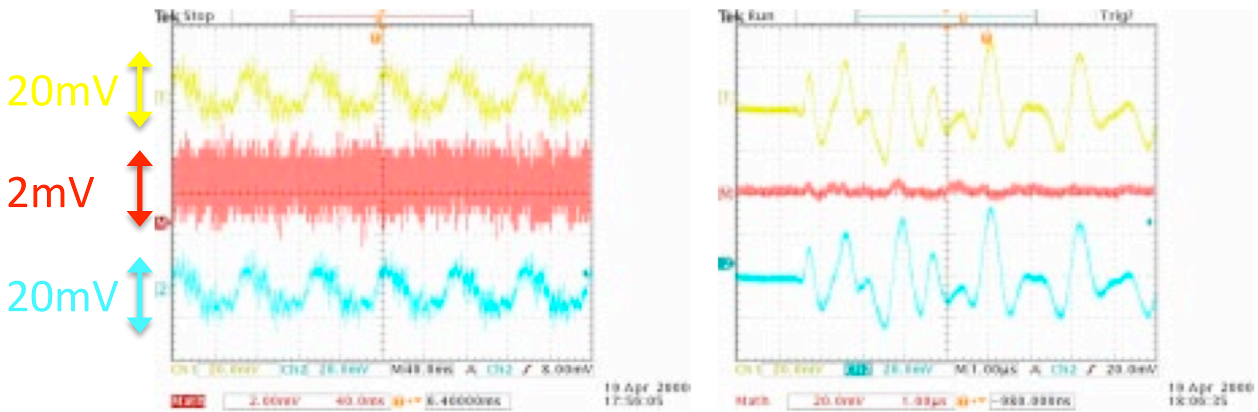


CCL Beam Current Monitor (single ended)

Noise Issues: Common Mode

If noise is coupled into both wires, we can reject it! ->
common mode noise rejection by taking the difference.
You will do this as a lab experiment.





Differential noise on long twinax with far end shield grounded. Left: top and bottom, noise on either center conductor into 50 ohms (each 20mV/div); center, difference (2mV/div); (most of residual signal due to digital scope subtraction). Right: same signals faster time scale (each 20mV/div and 1uS/div). From [2] Webber.

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