Beam Current Monitoring Tutorial

Bob Webber, Fermilab

Beam Instrumentation 2000 Workshop

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Previous Tutorials

First Workshop, 1989, BNL, Upton, NY --- *Accelerator Instrumentation*, AIP Conference Proceedings 212, New York: American Institute of Physics, 1990.

- "Longitudinal Emittance: An Introduction to the Concept and Survey of Measurement Techniques Including Design of a Wall Current Monitor", pp. 85-125.

Sixth Workshop, 1994, Vancouver, BC, Canada --- *Beam Instrumentation Workshop*, AIP Conference Proceedings 333, New York: American Institute of Physics, 1995.

- "Charged Particle Beam Current Monitoring Tutorial", pp. 3-23.

NOTE: This proceedings' paper will include bibliography of all beam current monitoring and related topic papers from all previous BIWs.

Abstract

- The tutorial begins with a look at
  - the characteristics of the beam as a signal source
  - the associated electromagnetic fields
  - the influence of the typical accelerator environment on those fields
  - the usual means of modifying and controlling that environment to facilitate beam current measurement.

•Short descriptions of three quite different types of current monitors are presented and a quantitative review of the classical transformer circuit is given.

•Since environmental noise pick-up may be a large source of error in quantitative measurements, signal handling considerations are given considerable attention using real-life examples. Options for controlling that noise are included.

•An example of a successful transport line beam current monitor implementation is presented and the tutorial concludes with a few comments about signal processing and current monitor calibration issues.

Beam Current Monitors

- Any electromagnetic beam monitor must sample the electric or magnet field of the beam to produce a useful signal
- Beam intensity monitors can be made to sense the electric field, the magnetic field, or some combination of both
- The subset of intensity monitors that rely primarily on interaction with the magnetic field component are generally termed beam current monitors
- The magnetic coupling between the beam and the monitor is usefully described with the formalism of transformer circuit theory

The Beam as a Signal Source

A charged particle beam exhibits an electric current of magnitude

$$i_b = e \cdot \lambda_N \cdot v$$

where e is the particle charge, λ_N the number of particles per unit length, and v the particle velocity.

The beam is nearly an ideal current source with a source impedance that can be described by

$$Z_b = \left(\frac{di}{dV}\right)^{-1} = \left(\frac{di}{dv}\cdot\frac{dv}{dV}\right)^{-1} = \left[(e\cdot\lambda_N)\cdot\left(\frac{d\beta c}{dE}\right)\cdot\left(\frac{dE}{dV}\right)\right]^{-1} = (e\cdot\lambda_N)^{-1}\cdot(E_o\cdot\beta\cdot\gamma^3/c)\cdot e^{-1}$$

For a 500 mA 8 GeV proton beam, this is 1.67E12 ohms!!!

The Beam Environment

- The beam and its environment communicate through the electric and magnetic fields carried with the beam
- Typically the beam travels through an evacuated chamber bounded by an electrically conducting metallic wall
- The beam, an assembly of charged particles, produces an electric field which in turn induces an image charge on the chamber wall
- The beam, charged particles in motion, produces a magnetic field that induces the image charge to flow along with it. The resulting "wall currents" are, to first order, equal and opposite to the beam current

Beam E/M Field Attenuation

- To the extent that wall currents mirror the beam current, the magnetic field outside the beam tube is cancelled
- This field strength reduction corresponds to the attenuation of electromagnetic waves propagating through a conductor
- The characteristic length in which the fields are reduced by a factor of *e* (-8.69 dB) is termed the skin depth
- The skin depth in a non-magnetic good conductor is

$$\delta = \frac{\sqrt{10} \cdot 10^3}{2\pi} \sqrt{\frac{\rho}{f}}$$

where ρ is the resistivity of the conductor and f is the frequency of interest

Energy Flows through the Dielectric

- Chart of skin depth in millimeters

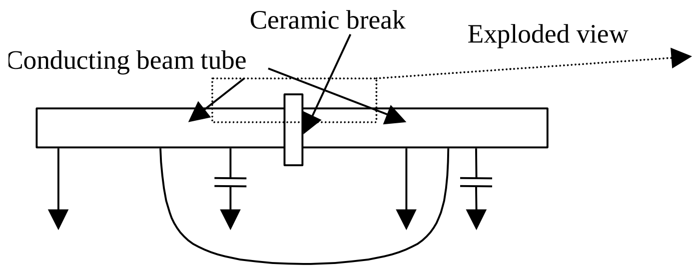
	1 KHz	10 KHz	100 KHz	1 MHz	10 MHz
Copper	2.1	0.66	0.21	0.066	0.021
302 Stainless Steel	13.3	4.2	1.3	0.42	0.13

- A typical 1/32" stainless beam tube wall, 6.1 skin depths at 10Mhz, attenuates magnetic fields propagating to the exterior by 53dB
  - Sufficient to clobber the sensitivity of a practical beam current monitor
  - Not so much as to make the beam signal invisible to a sensitive radio receiver!

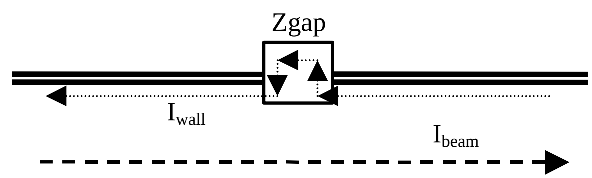
A Window to the Beam

- Since the magnetic field of the beam is severely attenuated outside a continuous conducting vacuum chamber, a practical beam current monitor must either be placed within the vacuum chamber walls or the conducting path in the chamber must be broken
- To minimize the mechanical complications of inserting a device into the vacuum, a non-conducting material, often ceramic, is typically inserted in a section of the beam tube
- This break in the beam tube conduction path forces wall currents to find a new path, potentially under the instrument designer's control, outside the vacuum chamber

The Ceramic Break



Typical Ceramic Break Installation

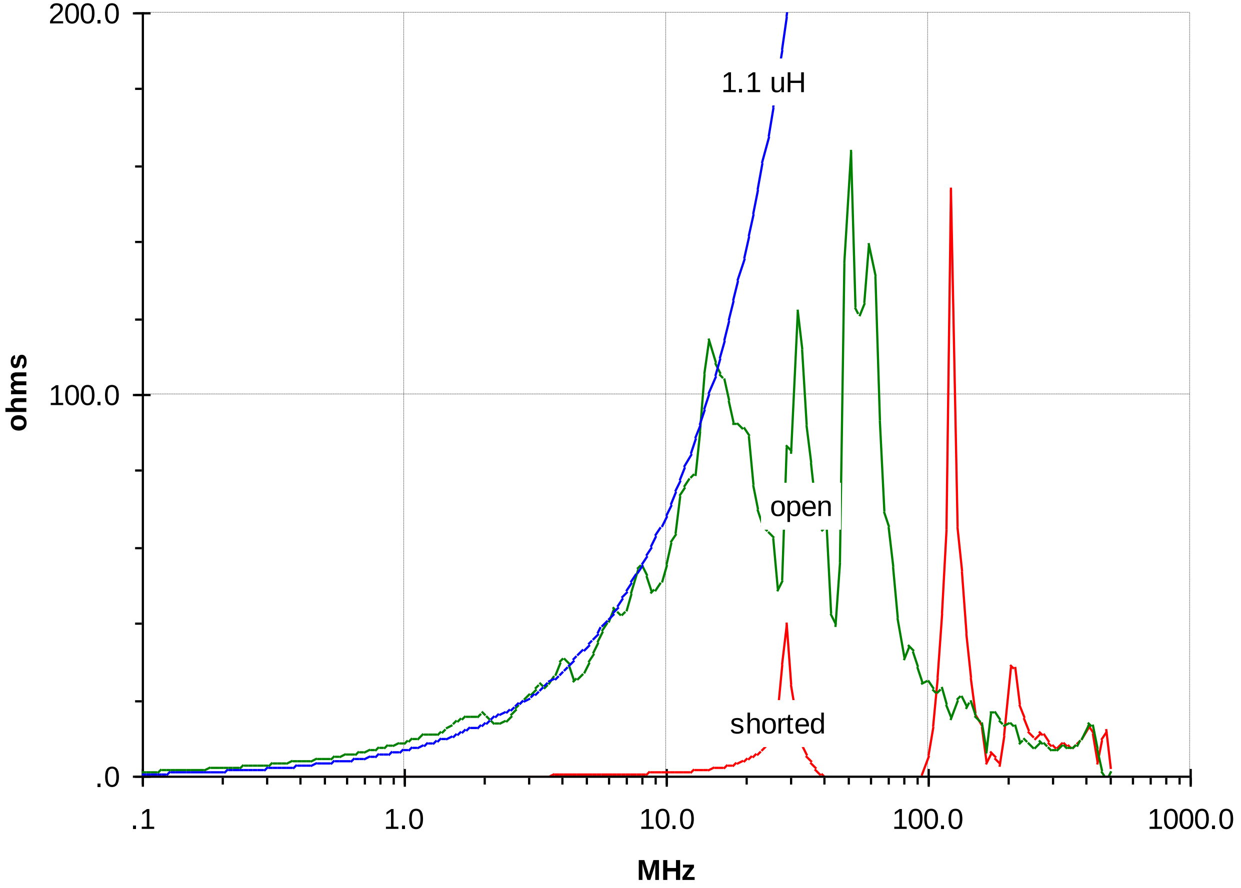


Circuit Model

- Beam tube capacitance, grounds, and ungrounded parallel connections may be intentional or incidental, local or distant, but something will always be present
- Z_{gap} is combination of the gap capacitance and all external parallel elements
- Gap voltage $V_{gap} = Z_{gap} \cdot I_{wall} = Z_{gap} \cdot I_{beam}$ will be generated

Impedance Measured Across Ceramic Gap on Beam Tube

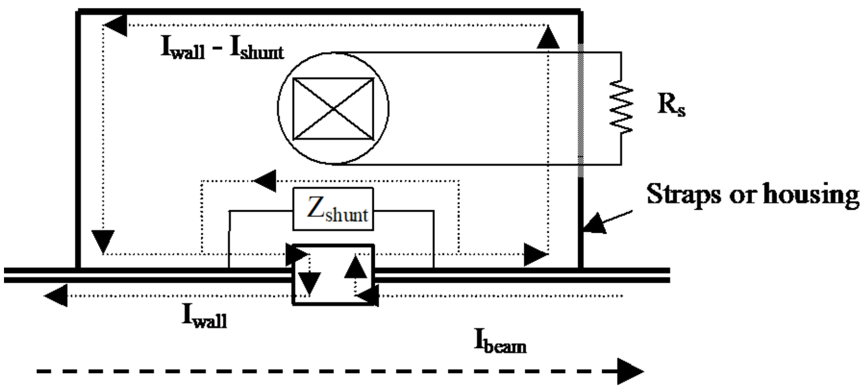
Courtesy of Jim Crisp/Mike Reid



Volts from the Beam

- The beam current typically contains a broad spectrum of frequency components
- Given the impedance as found, significant beam induced voltage across the gap will be open to the environment and be fed back on the beam itself
- A ‘noisy’ neighbor
  - for example, 500mA of 10Mhz beam current will induce about 35 volts across the gap
- Feedback to beam
  - 35 volts will not corrupt the beam in a small number of turns, but high impedance resonances can exist at higher frequencies if the gap environment is left uncontrolled

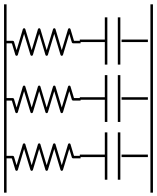
Controlling the Environment and Taming the Gap Impedance



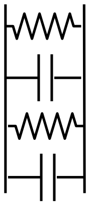
- Z_{shunt} applied to control potentially high gap impedances
- Strap or housing around the transformer and gap
  - Short circuits external currents that might flow through Z_{shunt} and therefore through the monitor
  - Shields external world from the beam current and gap voltage

Zshunt

Open circuit at DC
R/N at high frequency
Corner frequency at ω =1/RC



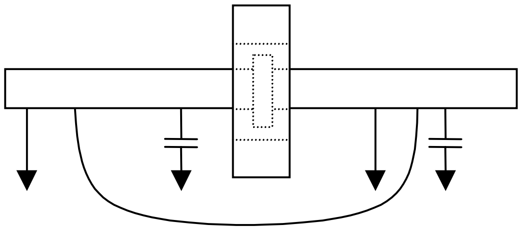
OR



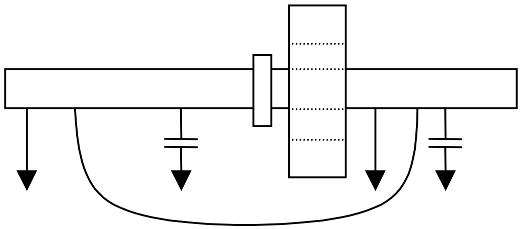
R/N at DC
1/jωNC at high frequency
Corner frequency at ω =1/RC

- Circuit elements as depicted are often used to realize Z_{shunt}
  - Multiple elements in parallel should be distributed across the gap more or less uniformly around the circumference
  - Z_{shunt} must be sufficiently high impedance at beam current frequencies to be measured so as not to short circuit the gap as seen by the current monitor, typically >10 ohms is acceptable
  - Series RC network blocks low frequency external noise currents from flowing across gap and through monitor
  - Parallel RC network exhibits lower impedance at high frequencies

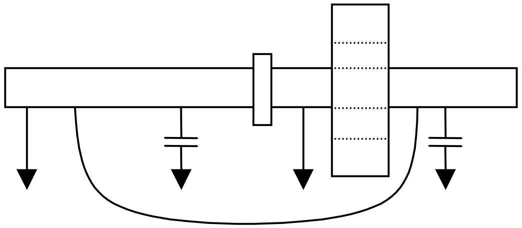
Location of Current Monitor Relative to Gap



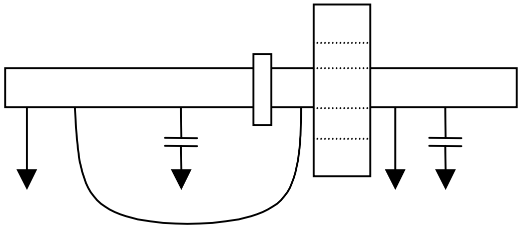
OK - only beam currents, not wall currents will pass through monitor



OK - wall currents cannot bypass gap to flow through monitor



NOT OK - wall currents bypass gap through grounds then proceed through monitor



NOT OK - wall currents bypass gap through grounds then proceed through monitor

Common Types of Beam Current Transformers

- Integrating Current Transformer (ICT)
  - Passive current transformer depending on short (< 1 nsec), isolated (±50 nsec) beam bunch to drive impulse response of transformer
  - Output pulse shape is fixed by design and independent of shape of sufficiently short beam pulse
  - Output amplitude is directly proportional to charge of beam pulse
  - Useful in synchrotrons, storage rings, and transport lines provided short isolated bunch criteria are met
  - Advantage
    - Simple, relatively inexpensive, stable passive calibration
    - Output stretched in time relative to very short beam pulse
  - Disadvantage
    - Bunch shape information is not available

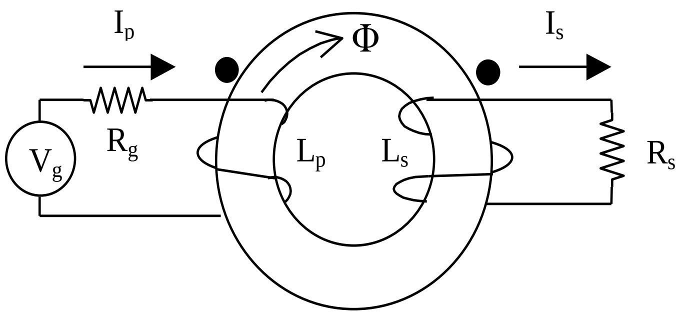
Common Types of Beam Current Transformers

- Direct Current Transformer (DCCT, PCT, etc.)
  - A strong well-controlled magnetizing force is applied to one or more toroids enabling sampling of magnetic bias imposed by beam
  - Operates in zero flux mode, a feedback current equal and opposite to the beam is driven through the toroidal cores of the device
  - Practical DCCTs for particle beams are a combination DC section and AC transformer to prevent aliasing and extend bandwidth
  - Useful in synchrotrons and storage rings, not transport lines
  - Advantages
    - Measures 0 Hz (DC) component of bunched or unbunched beams
    - Long term stability and <1 microampere DC resolution
  - Disadvantage
    - Relatively expensive for applications not requiring DC response

Common Types of Beam Current Transformers

- Classical AC Transformer
  - Beam current couples magnetic flux to toroidal transformer core inducing current in sense winding on same core
  - Output signal can provide hi fidelity representation of beam current pulse shape over wide bandwidth (10's of Hz to few MHz)
  - Passive device that can be supplemented with various active circuits to modify performance (e.g. Hereward and 'active-passive' configurations
  - Advantages
    - Simple and available in many configurations to suit application
  - Disadvantages
    - NOT DC coupled, provides NO DC output component

Classical Transformer Review



Steady state circuit equations in Laplace notation $s = j\omega$

Total magnetic flux in core $$\Phi_T = \frac{L_p \cdot i_p}{N_p} - \frac{L_s \cdot i_s}{N_s}$$

Load side current $$i_s = \frac{s \cdot \Phi_T \cdot N_s}{R_s}$$

Primary side loop $$V_g = i_p \cdot R_g + s \cdot \Phi_T \cdot N_p$$

Classical Transformer Review

Simultaneous solution and use of $\frac{L_p}{L_s} = \frac{N_p{}^2}{N_s{}^2}$, where N_p and N_s are the number of primary and secondary winding turns respectively, yields

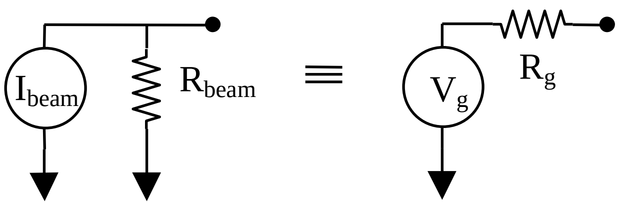
$$\frac{V_s}{V_g} = \frac{i_s \cdot R_s}{V_g} = \frac{s \cdot L_s \cdot N_p}{R_g \cdot N_s} \cdot \frac{1}{1 + s \cdot (\frac{L_p}{R_g} + \frac{L_s}{R_s})} \qquad \text{(Eqn. T1)}$$

In mid-band where $s \cdot \left(\frac{L_p}{R_g} + \frac{L_s}{R_s} \right) >> 1$ this simplifies to

$$\frac{V_s}{V_g} = R_s \cdot \frac{N_s}{N_p} \cdot \frac{1}{R_s + R_g \cdot \frac{N_s{}^2}{N_p{}^2}} \qquad \text{(Eqn. T2)}$$

Classical Transformer Review

In the case of the beam current it is appropriate to replace the voltage generator by an equivalent current generator

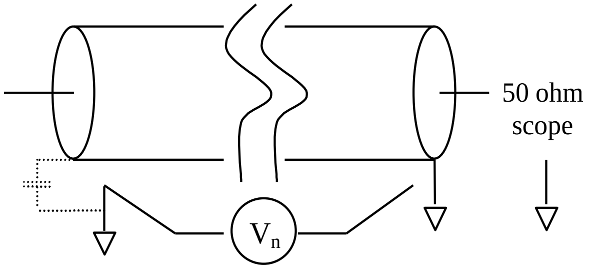


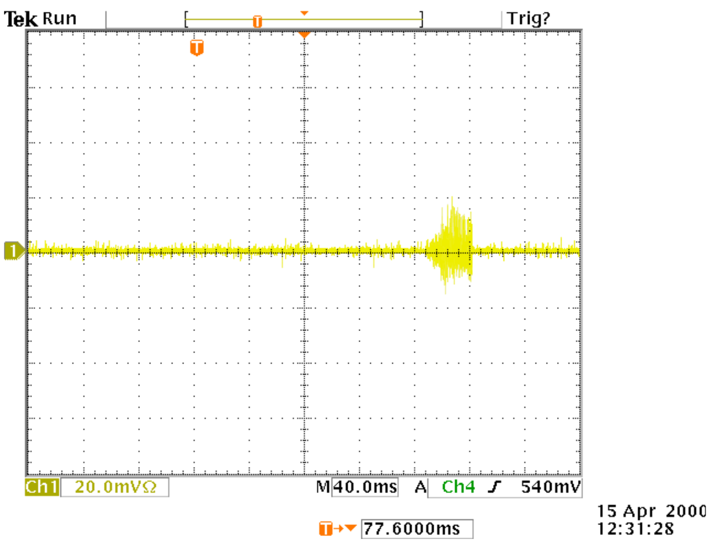
where $V_g = i_{beam} \cdot R_{beam}$ and $R_g = R_{beam}$

Substituting into Eqn. T1 with $N_p = 1$, find $\dfrac{i_s}{i_{beam}} = \dfrac{1}{N_s} \cdot \dfrac{1}{1 + \dfrac{R_s}{N_s^{\,2} \cdot R_{beam}}}$

Given that $R_{beam} >> R_s$, the familiar result $i_s = \dfrac{i_{beam}}{N_s}$ is obtained.

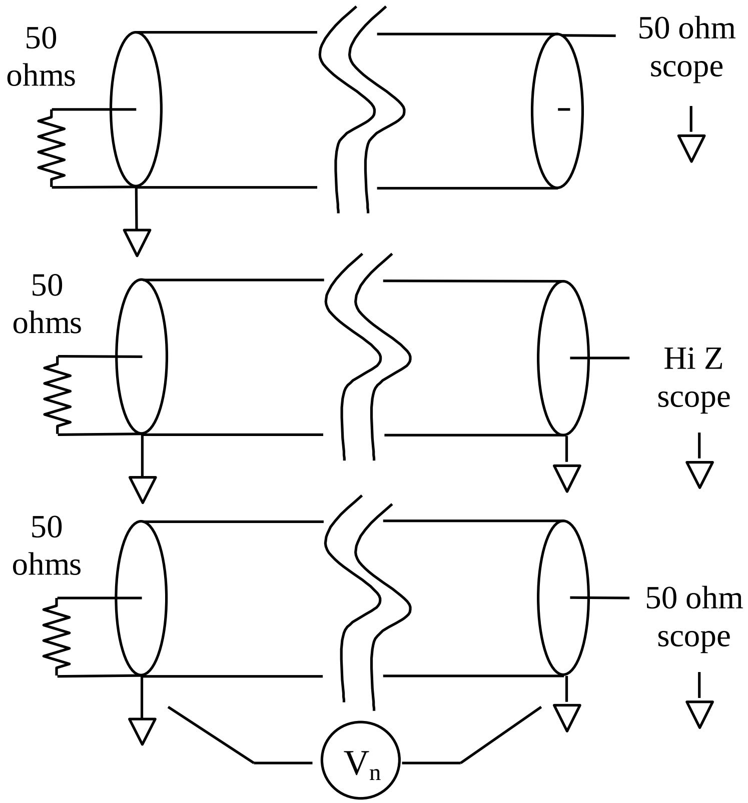
Noise on Long Coaxial Cable Far End Open and Ungrounded

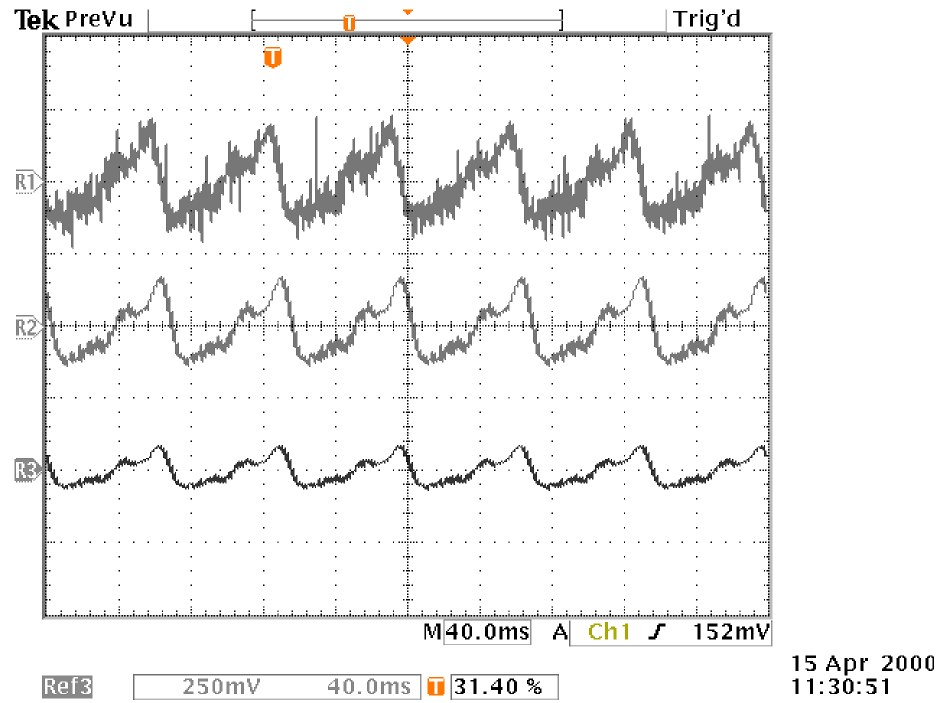




High frequency noise couples into cable via stray capacitance

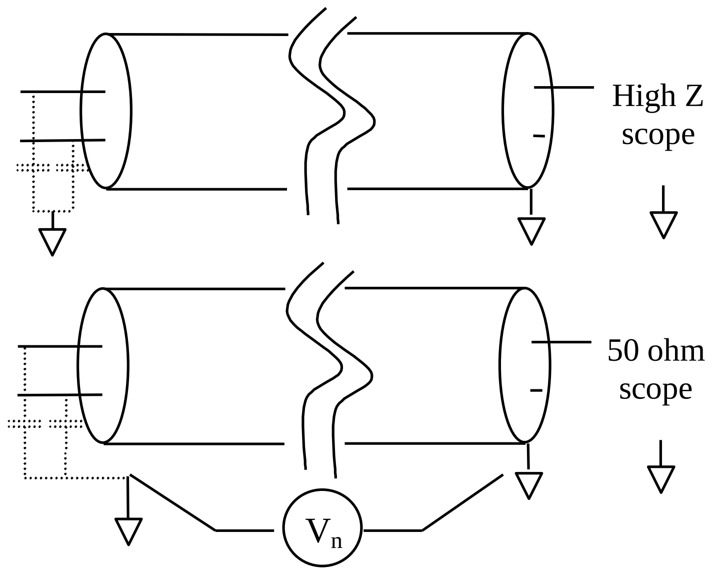
More Noise Measurement Configurations

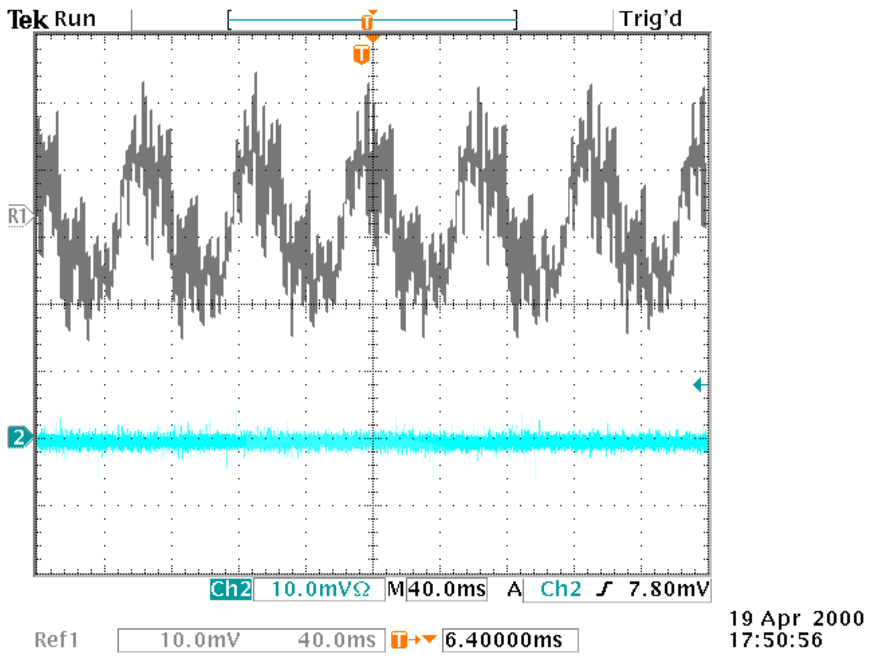




1 and 2 show noise source impedance is small compared to cable shield resistance

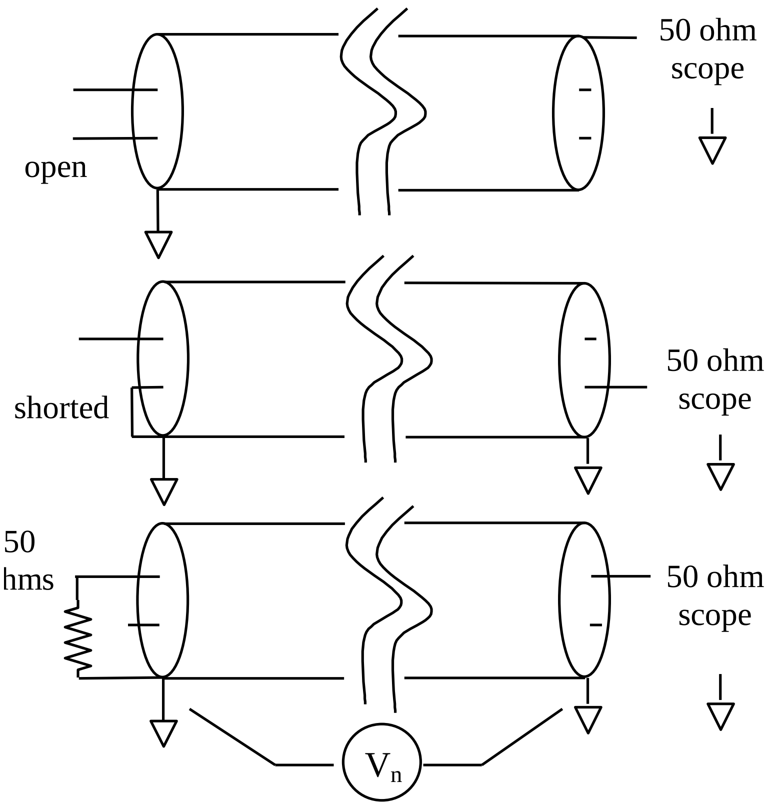
Noise on Long TwinAx Cable
Far End Open and Ungrounded

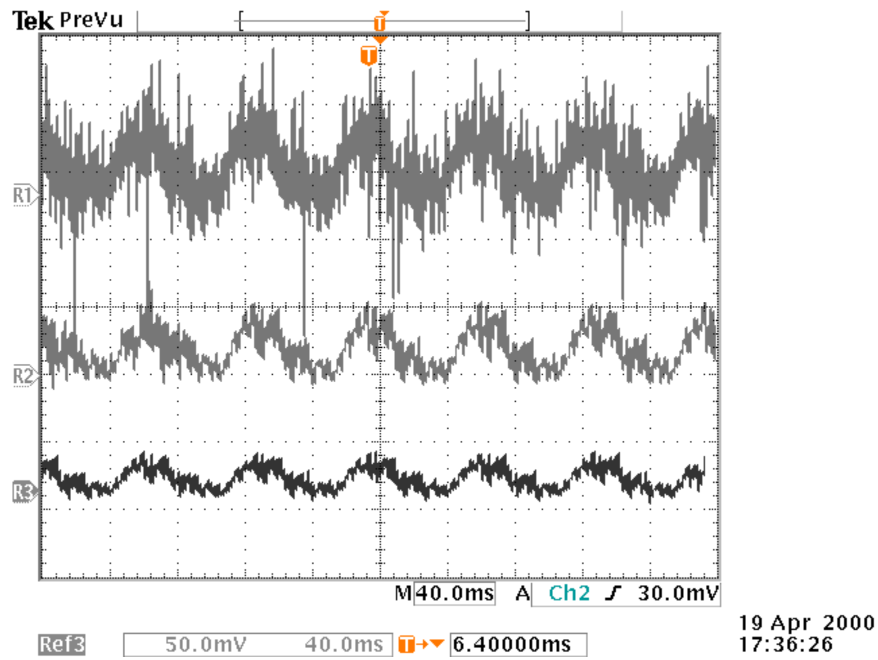




Noise, coupled to signal wires via stray capacitance,
is swamped when loaded in 50 ohms

More Noise Measurement Configurations

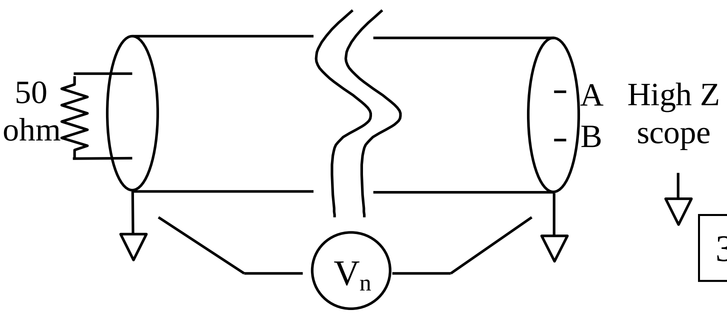




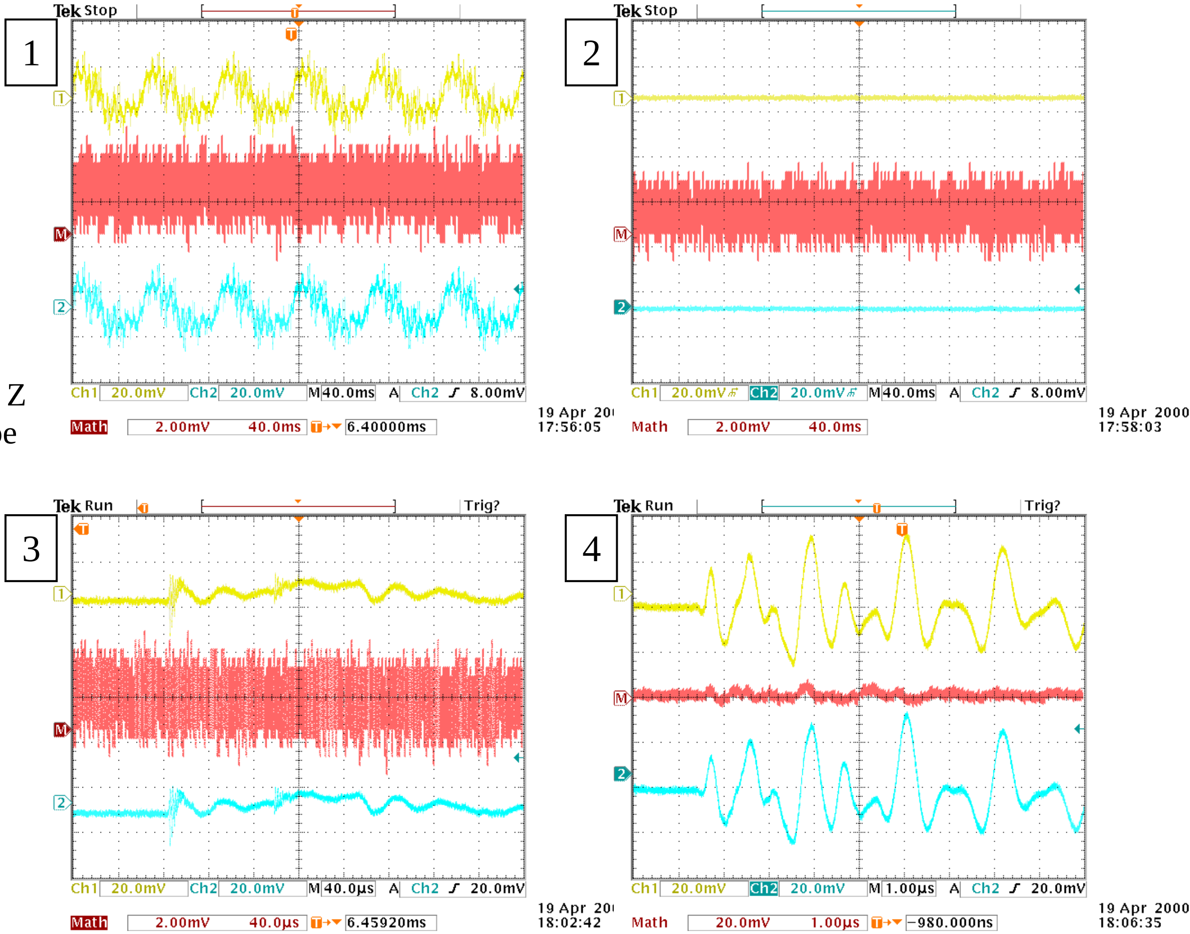
Behaves like coax two slides earlier

Long Grounded TwinAx with Floating Source

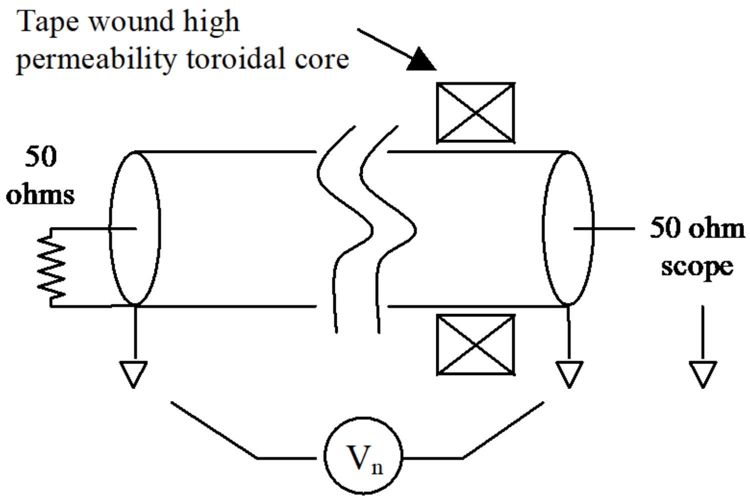
1. A, B, and A-B
2. Same w/ A & B grounded showing scope differencing noise

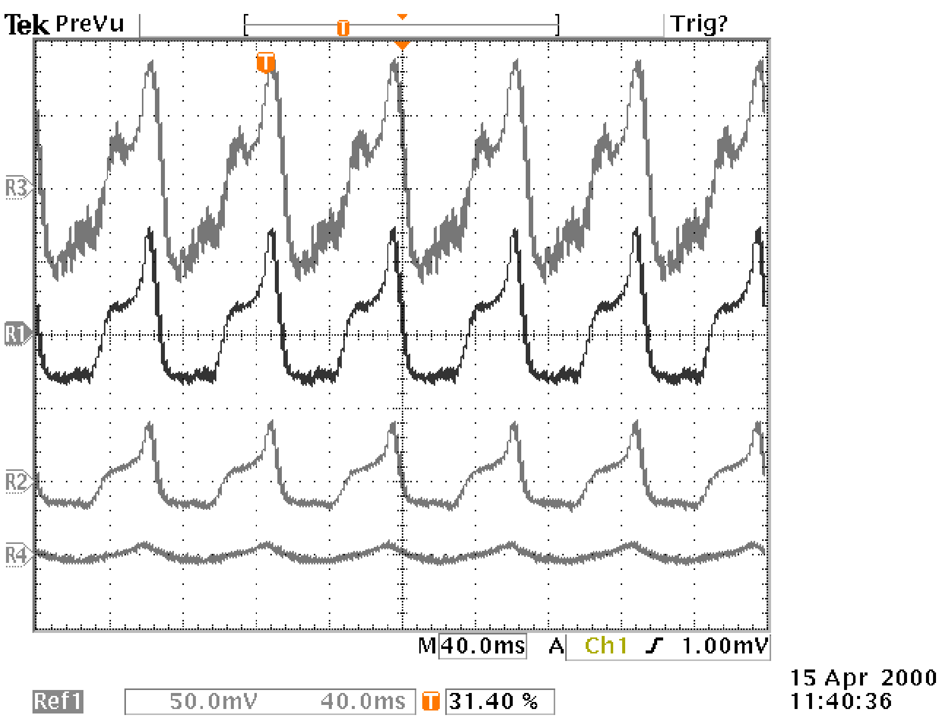


3. Same at 40 usec/div
4. Same at 1 usec/div, difference trace scale desensitized



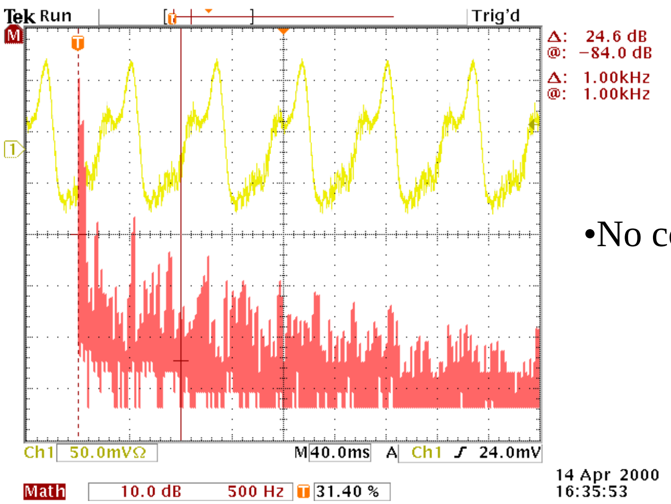
Noise Reduction Core on Coax





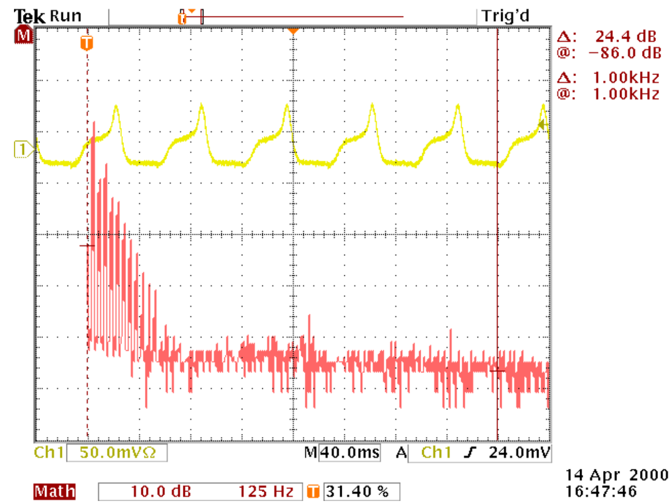
Top trace - no core
Second - 5 turns of coax through core
Third - 10 turns
Fourth - many turns

Noise Signals and Spectra w/Core

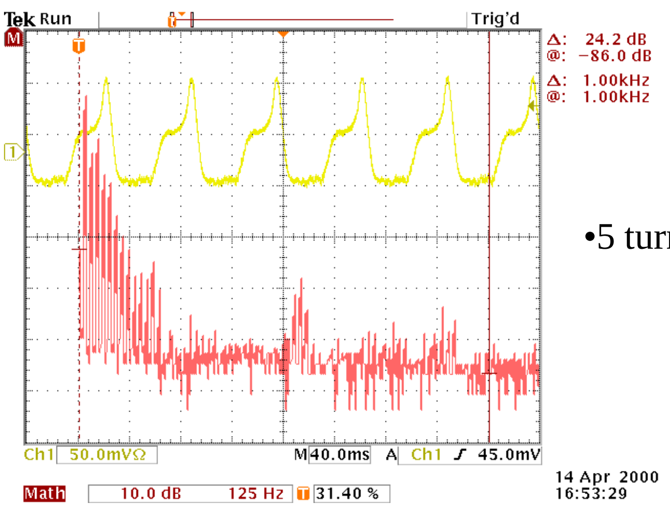


- No core

- 10 turns

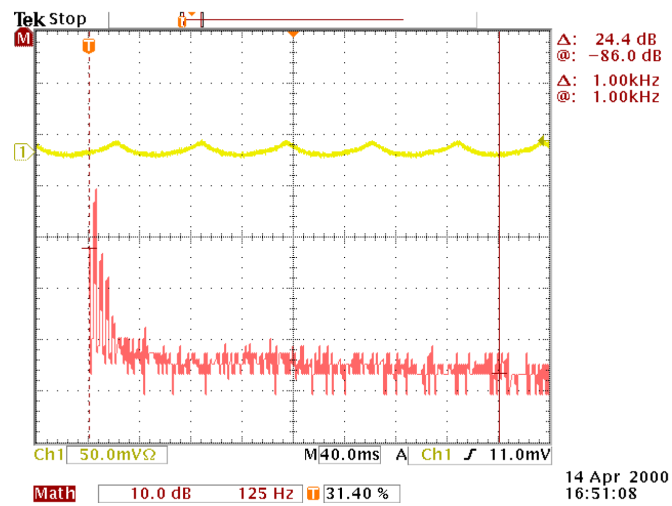


Signals at 50mV/div and 40msec/div and spectra at 10dB/div and 125 Hz/div, except no core is 500 Hz/div.



- 5 turns

- many turns



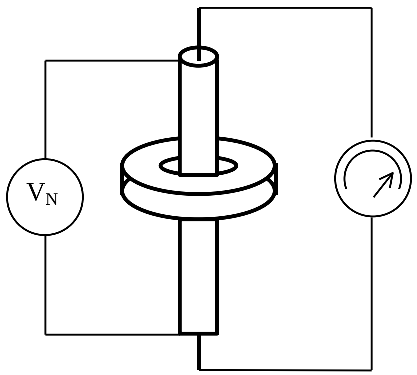
How Does the Core Help? To Z or not to Z?

- Noise measurements showed very low impedance source
- A perfectly conducting cable shield could short out the noise source, thereby eliminating the noise
- Yet apparently adding impedance to the shield in the form of a core also reduces the noise
- Dilemma -
  - Increase shield impedance to reduce noise currents?
  - Reduce shield impedance to attenuate noise source voltage?
- Solution -
  - Low impedance noise is not completely overcome, core acts as transformer coupling equal voltage to shield and center conductor

Toroid on a Coaxial Cable

Shield and center conductor circuits, each looping core N times, link same magnetic flux in core and will therefore experience same induced voltage.

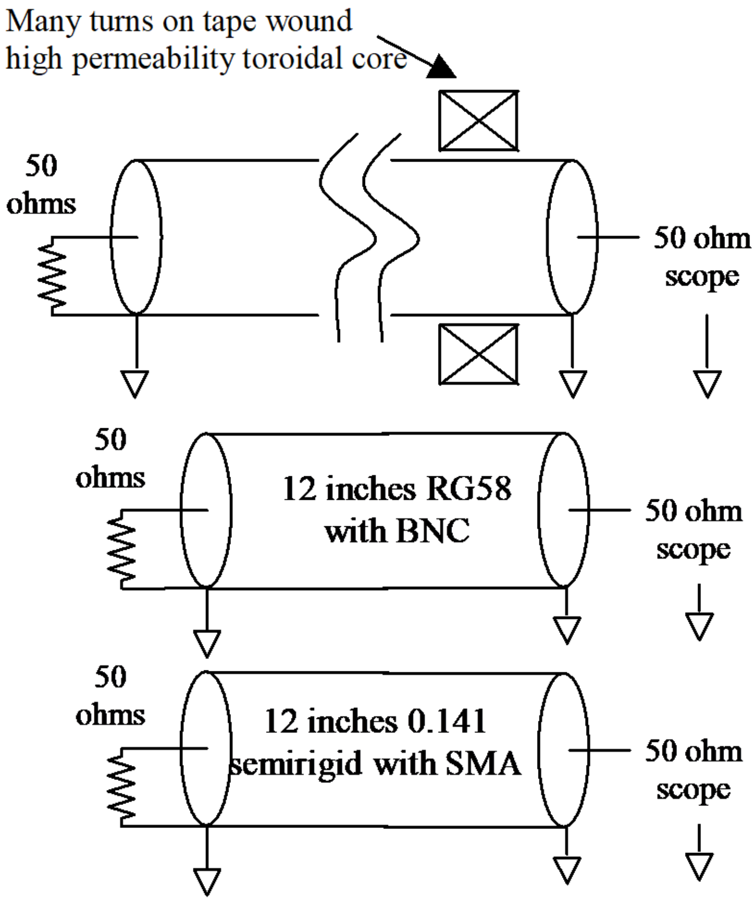
At frequencies above $\omega = R/L$, where R is the shield resistance and L is the inductance of the shield winding on the core, the end-to-end center conductor voltage will be identically equal to the shield voltage, in this case V_{noise}!

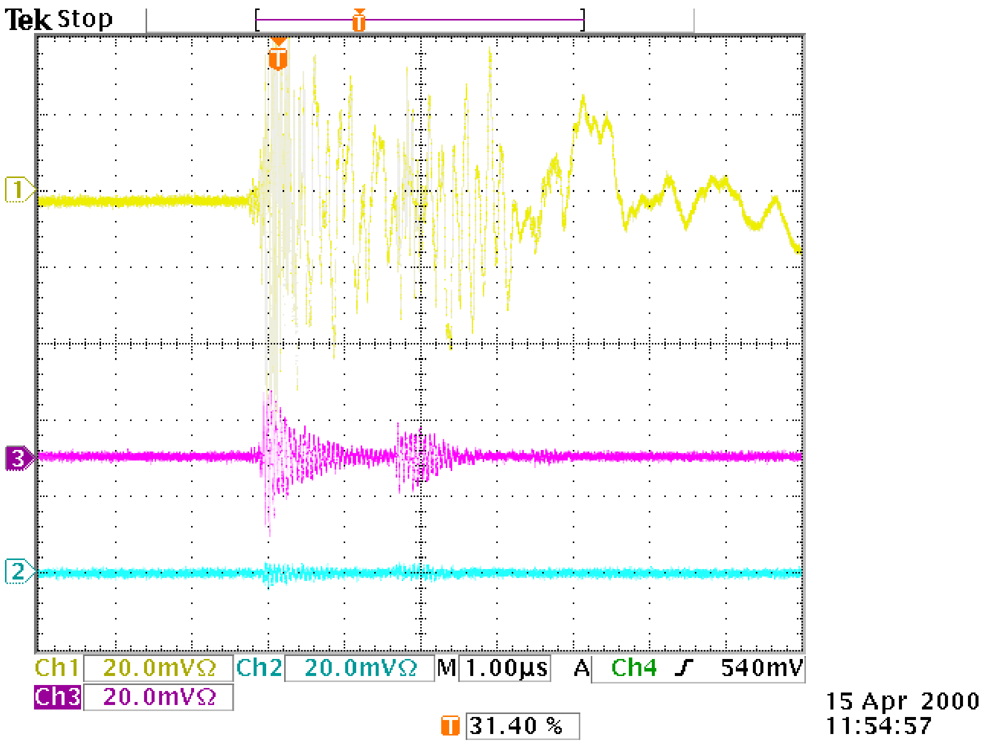


Therefore the differential shield-to-center voltage at both ends can be independent of the noise voltage Note that low shield resistance is still a good thing. It reduces the corner frequency at which the transformer action becomes effective! Dilemma resolved!

The core cannot influence desired signals propagating inside coax. With equal and opposite in shield and center conductor currents, these signals present no net current to core, effectively removing the it from the picture.

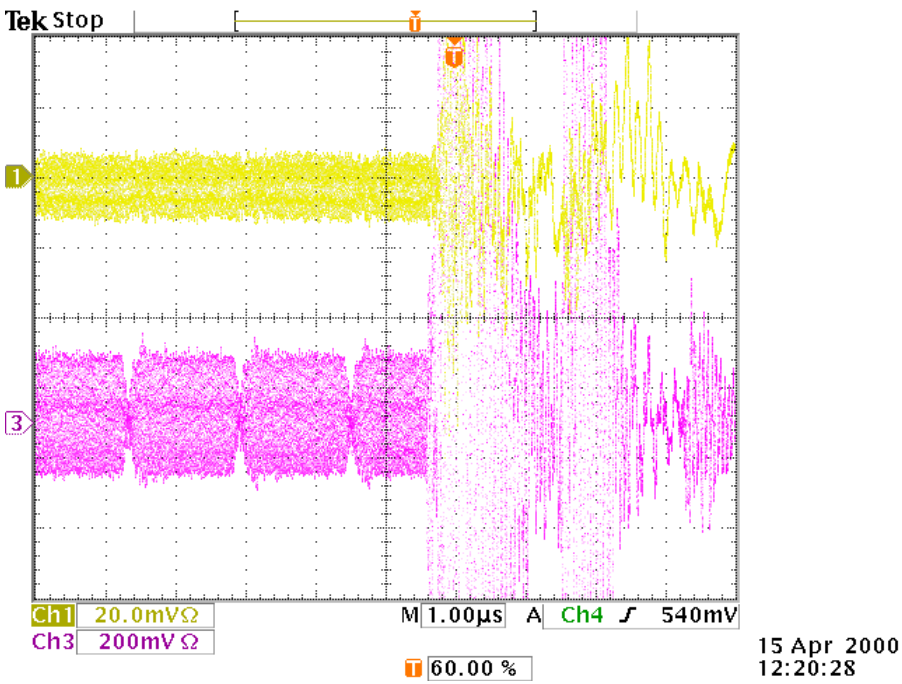
Local Fast Kicker Noise





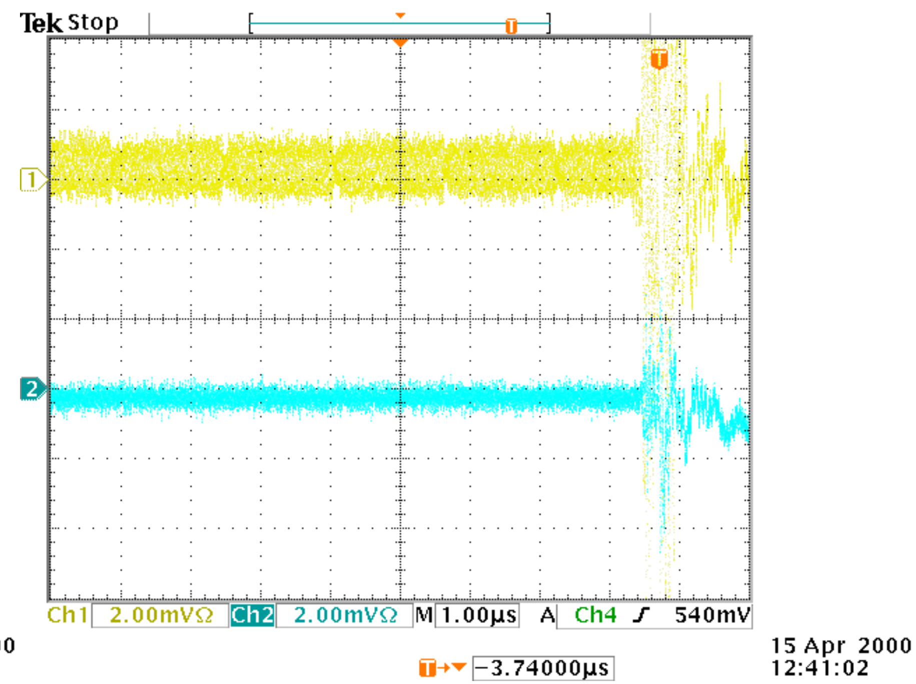
Local noise can be large also! Good cable and solid connections are necessary to win the battle.

Even the Beam Makes Noise!
Notice 1.6 usec Revolution Period



Top - Long Foam RG8 coax w/many turn noise core, 20mV/div

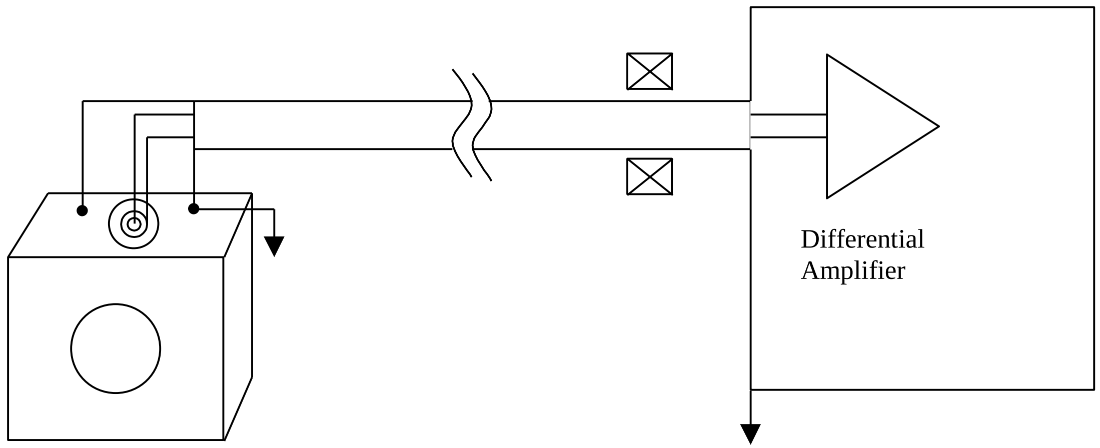
Bottom - open 12” wire, 200mV/div



Top - 12” RG58 with BNC terminated in 50 ohms, 2mV/div

Bottom - 12” 0.141 semirigid , 2mV/div

Successful Installation



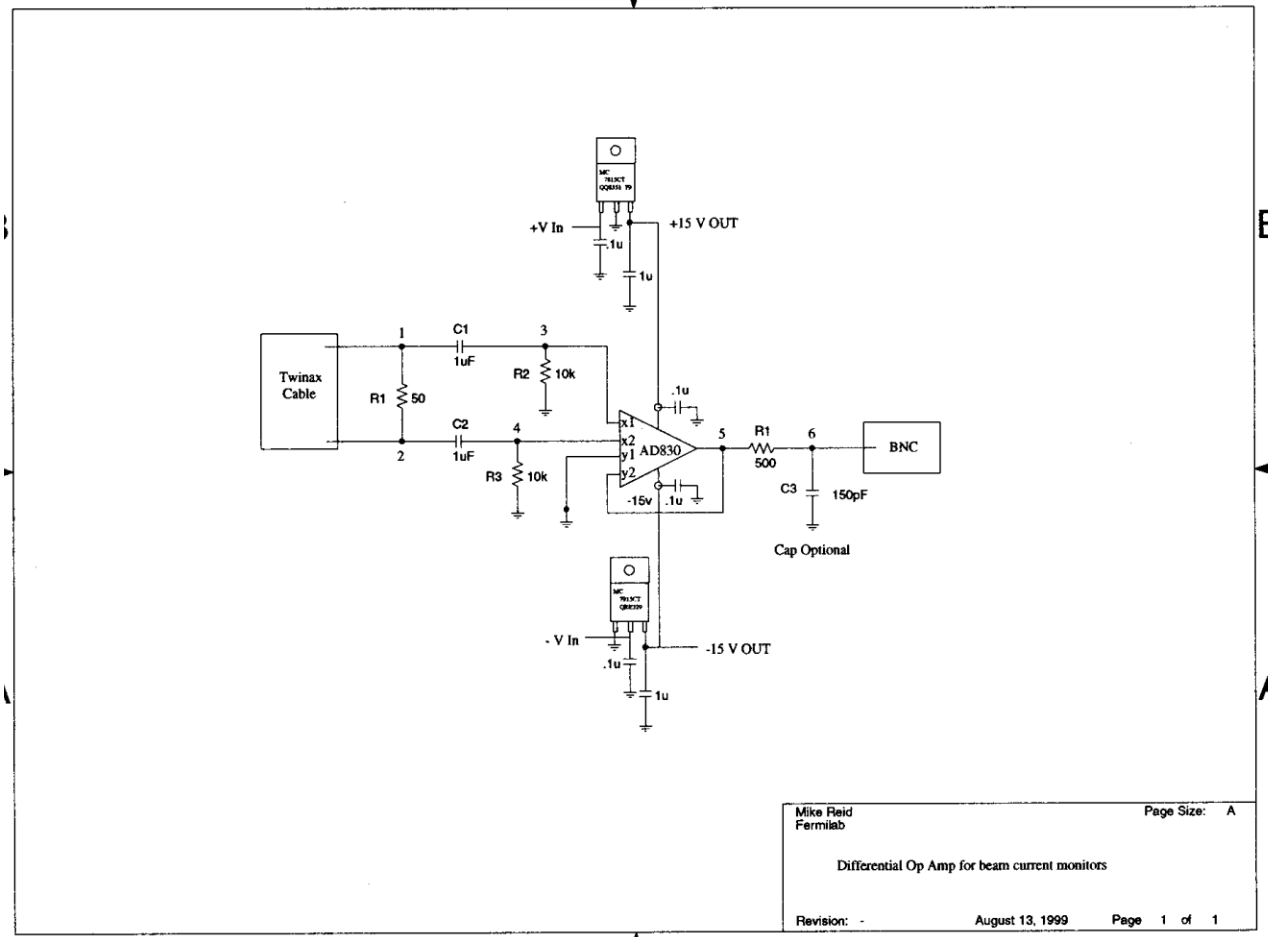
- Beam current transformer with grounded case and isolated pick-up winding
- TwinAx cable with shield grounded only to transformer case and to metal electronics chassis. Optional noise reduction core.
- Signal conductors totally enclosed by transformer case, cable shield, and metal chassis.
- Differential receiving amplifier with suitable bandwidth and common mode rejection to further attenuate

Processing the NOW CLEAN signal

- Signal processing requirements will depend on application
  - for relatively flat pulse current pulse or fixed signal shape (e.g. long bunch train down transport line or for ICT output) sampling the signal a known time may be sufficient
  - to record time shape of pulse fast digitization may be appropriate
  - to obtain total charge for beam pulses of variable shape or duration pulse integration is required
  - often need amplification as first stage of processing
- Goal --- Acquire and preserve desired information with credible and reliable accuracy

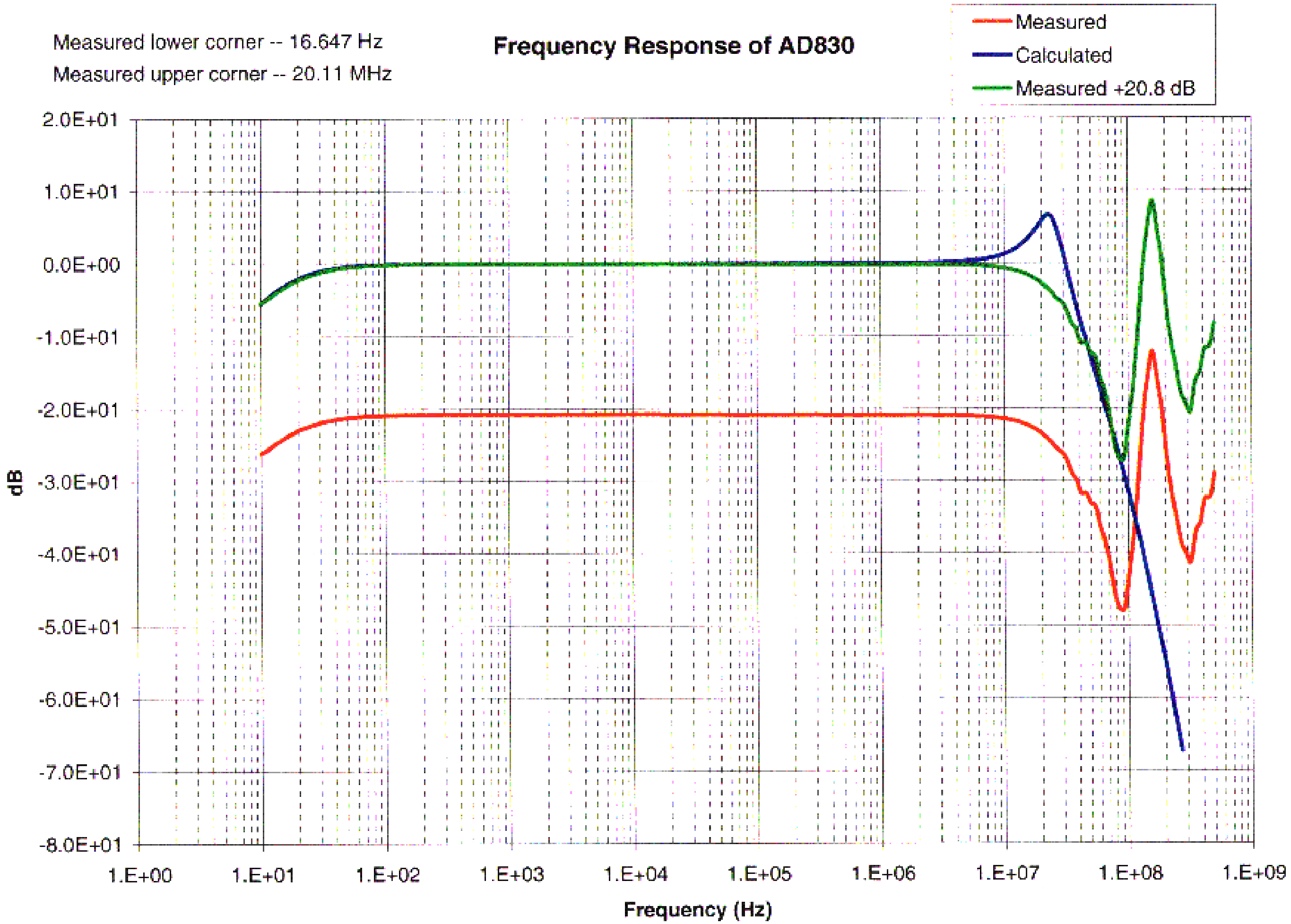
Successful Differential Receiver/Amplifier Circuit

Courtesy of Jim Crisp/Mike Reid



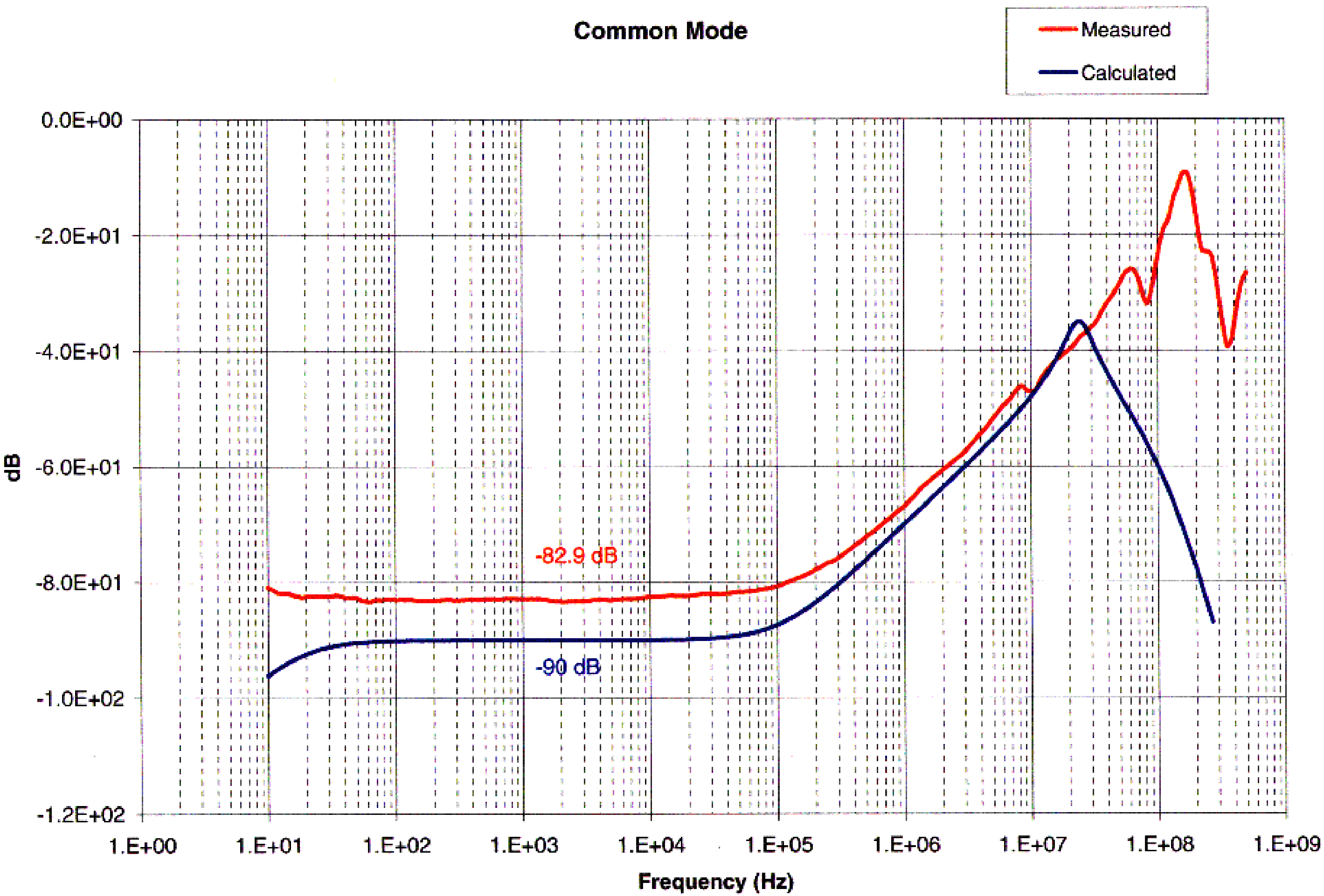
AD830 Frequency Response

Courtesy Jim Crisp/Mike Reid



AD830 Amplifier CMMR

Courtesy of Jim Crisp/Mike Reid



Sampling and Integrating

- Signal is NOT DC COUPLED!
  - Baseline level and slope is dependent on previous beam pulses for times up to several beam current transformer L/R time constants
  - Integration of the signal for an indefinite length of time yields zero
  - Timing of some sort will be important in determining accuracy of any static output
  - Active baseline restoration can re-establish a DC reference at a single point in time, but baseline slope may remain a problem

Calibration Windings

- A single turn calibration winding is usually included in a beam current monitoring system
- Calibration winding will have minimal incidental effect on instrument accuracy
  - A typical Pearson 1 volt/amp transformer has a 50 turn winding and an internal 50 load. This reflects back as R/N^2 = 0.02 ohms to the primary side of the transformer. Therefore a single turn calibration winding even terminated in 50 ohms is a 1:2500 effect.
- To calibrate for fast pulses, must consider other effects
  - resistive termination of calibration cable
  - leakage inductance of the calibration winding through transformer
  - capacitance of calibration winding to transformer and case

Calibration Windings

- Advisable, if possible, to provide return cable to bring calibration current back to source to measure the current that actually passed through monitor
- Noise coupling into calibration winding will appear as real signal to the current monitor!