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Pulsed Power Electrical Diagnostics

Techniques and Analysis

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IEEE Pulsed Power-Plasma Science Mini-course

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Purpose

- This talk is meant to provide a partial survey of techniques useful in high power experiments
- Many of the techniques are broadly useful; most of the philosophy (simple models) is beneficial in many cases

Abstract

- This talk will cover a variety of standard electrical diagnostic techniques used in pulsed power experiments. We will discuss electric and magnetic field (voltage and current) measurements in the nanosecond to millisecond regimes, including measurements in magnetically insulated transmission lines. We will also discuss straightforward numerical manipulation of data to improve accuracy and correct for non-ideal monitors and components. A discussion of low-frequency noise commonly found in pulsed power experiments will also be shown, with some simple mitigating techniques. Throughout, we'll use simple linear circuits to model monitors and components.

What we'll cover

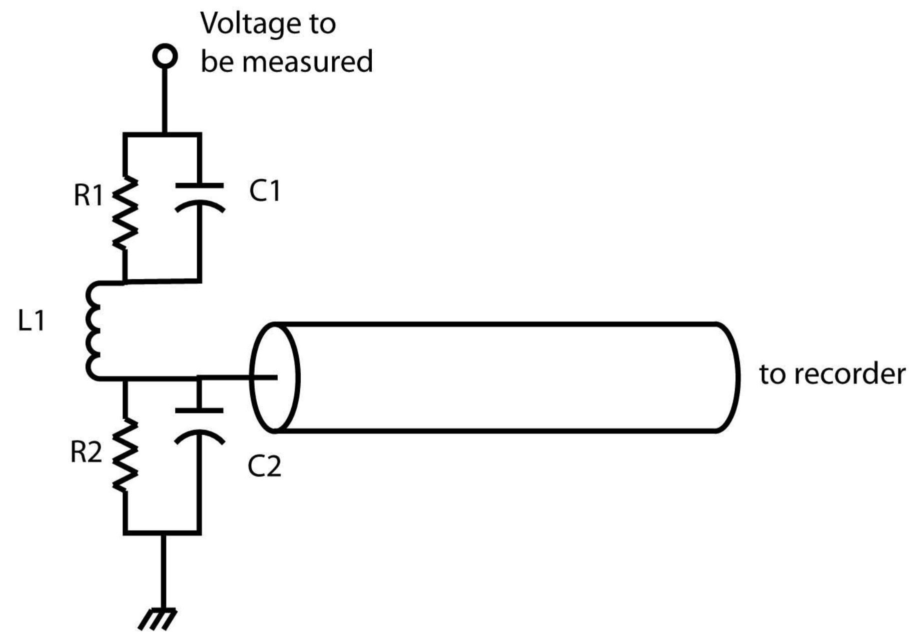
- Principles of electrical current and voltage probes
- Modeling monitors and components with simple circuits
- Correcting for non-ideal monitors
- Integration of derivative-responding monitors
- Calibration techniques
- Measurements in vacuum and in magnetically insulated transmission lines
- Noise and shielding

What we won't cover

- Electro-optic techniques
- X-ray spectral methods

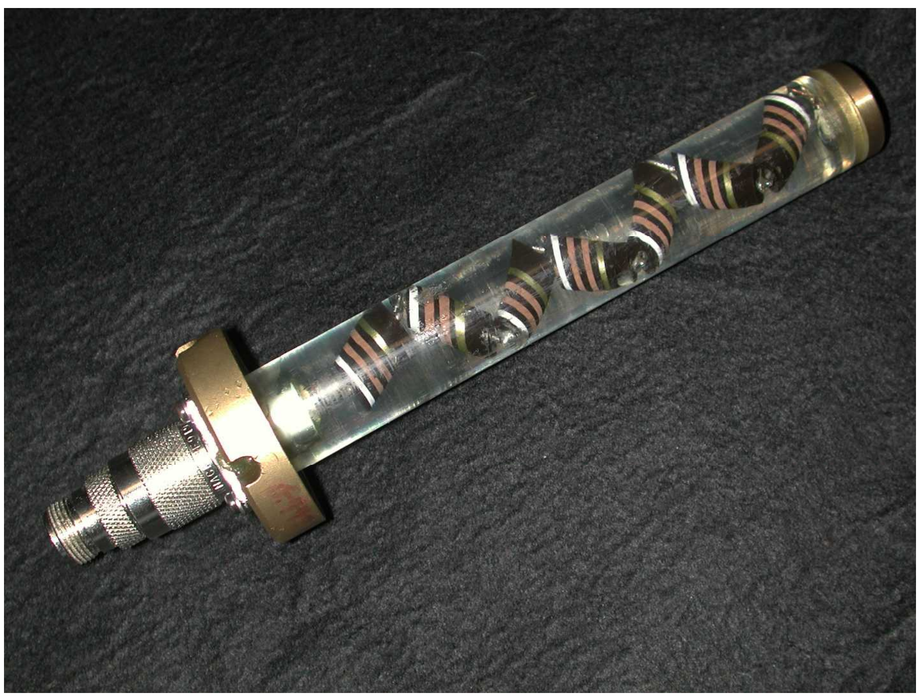
A basic passive voltage monitor

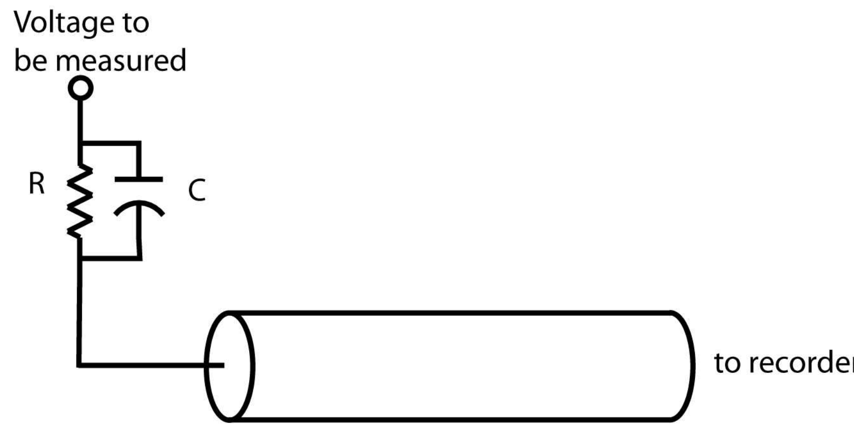
- The monitor will have lower voltage than the signal to be measured
- How it works depends on the component values



The resistive divider

- C1 is small (R1*C1 << pulse features)
- C2 is small (R2*C2 << pulse features)
  - Output is proportional to voltage





For fast signals and large division ratios, C becomes important

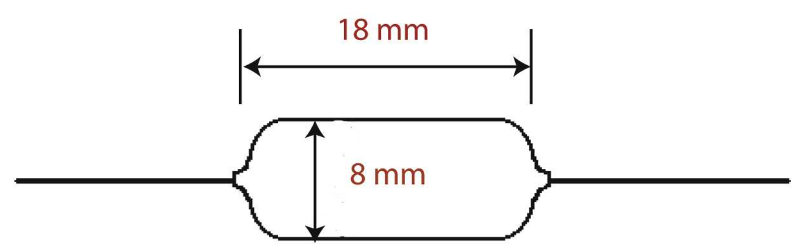
Any resistor has shunt capacitance

- For a 1kΩ resistor, RC is about 500 ps
- L is about 30 nH in a 25 mm tube-
  - L/R is 30 ps for 1kΩ
- Capacitance is more important than inductance for resistors larger than about $\frac{120\pi}{\sqrt{\varepsilon_r}}$

$$C = \frac{\varepsilon_0 A}{d}$$

$$= \frac{\varepsilon_r \varepsilon_0 (6mm)^2 \pi}{15mm}$$

$$\approx 534\, fF$$

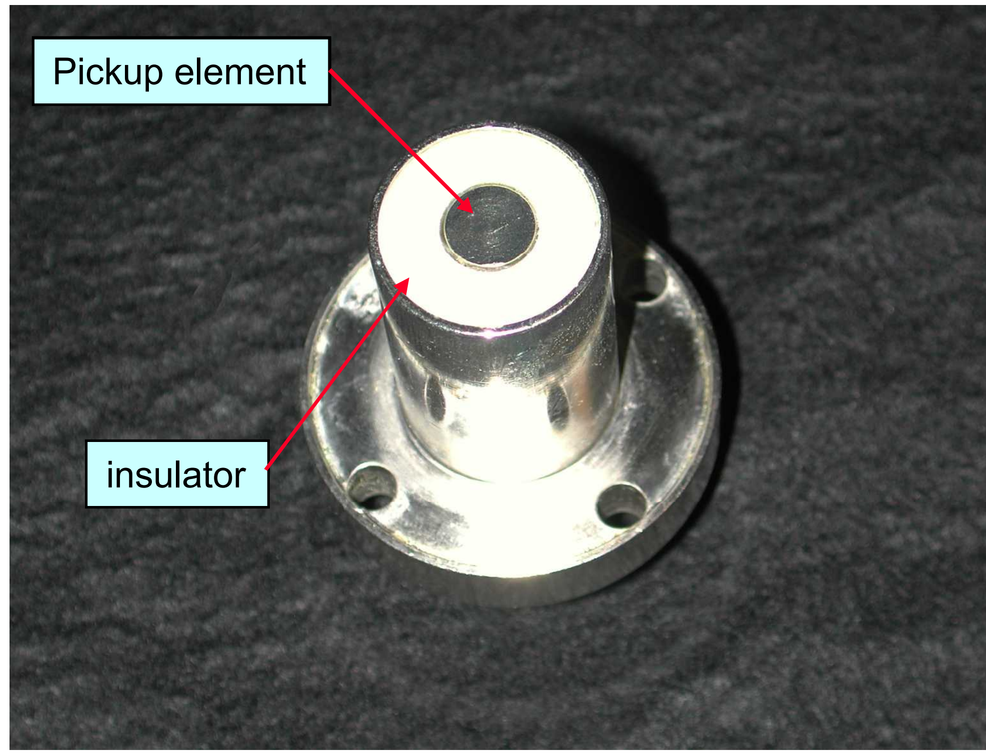


The displacement current voltage monitor

- **R1*C1 is much longer than the pulse features**
- **R2*C2 is shorter than pulse features (geometry)**
- **Output is**

$$C_1 R_2 \frac{dV_{in}}{dt}$$

$$\longrightarrow \quad V_{in} = \frac{1}{Z_0 C} \int_{-\infty}^{t} V_{in} d\tau$$



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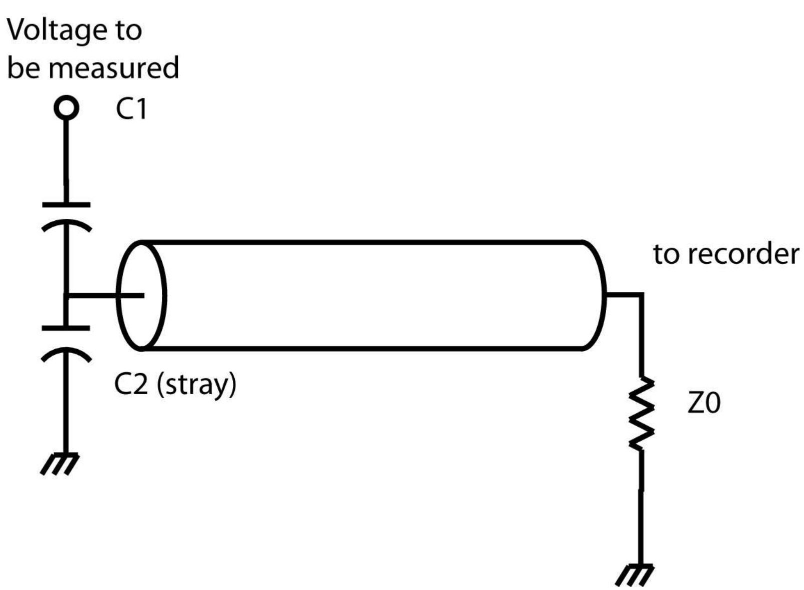
In water, stray capacitance can be a problem

- **C2 is undesirable stray capacitance**

$$C_1\left(\frac{dV_{in}}{dt}-\frac{dV_{out}}{dt}\right)=\frac{V_{out}}{Z_0}+C_2\frac{dV_{out}}{dt}$$

$$\frac{dV_{in}}{dt}=\frac{\left(C_1+C_2\right)}{C_1}\frac{dV_{out}}{dt}+\frac{V_{out}}{Z_0C_1}$$

$$V_{in}=\frac{1}{Z_0C}\int_{-\infty}^{t}V_{out}d\tau+\frac{\left(C_1+C_2\right)}{C_1}V_{out}$$

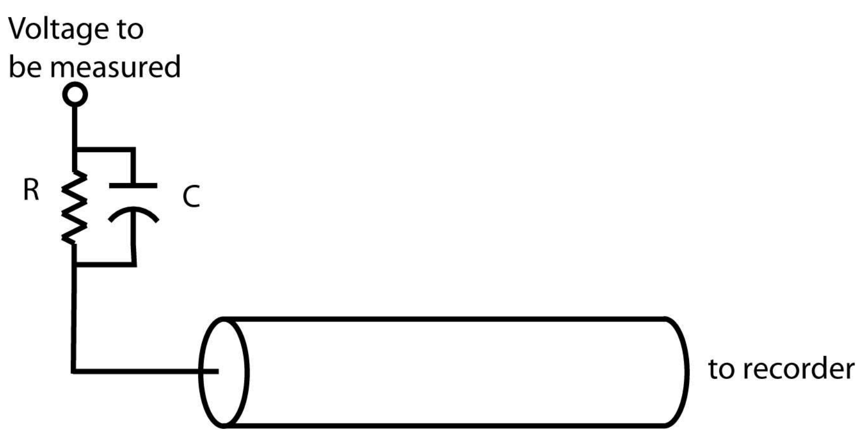


If C2=0

$$V_{in}=\frac{1}{Z_0C}\int_{-\infty}^{t}V_{out}d\tau+V_{out}$$

A general compensation for RC effects

- Shunt resistance in a V-dot probe
- Shunt capacitance in a resistive probe



Assume the resistor and capacitor are linear and the output is much smaller than the measured voltage

- This is a general solution for the circuit
- There are numerical issues for very small time constants and long windows

$$\frac{V_{in}}{R} + C\frac{dV_{in}}{dt} = \frac{V_{out}}{Z_0}$$

$$\frac{V_{in}}{RC} + \frac{dV_{in}}{dt} = \frac{V_{out}}{Z_0 C}$$

$$a = \frac{1}{RC}$$

$$g = \frac{V_{out}}{Z_0 C}$$

$$aV_{in} + \frac{dV_{in}}{dt} = g$$

$$\frac{d(Ve^{at})}{dt} = e^{at} g$$

$$V_{in} = \frac{e^{\frac{-t}{RC}}}{Z_0 C} \int_{-\infty}^{t} e^{\frac{\tau}{RC}} V_{out} \, d\tau$$

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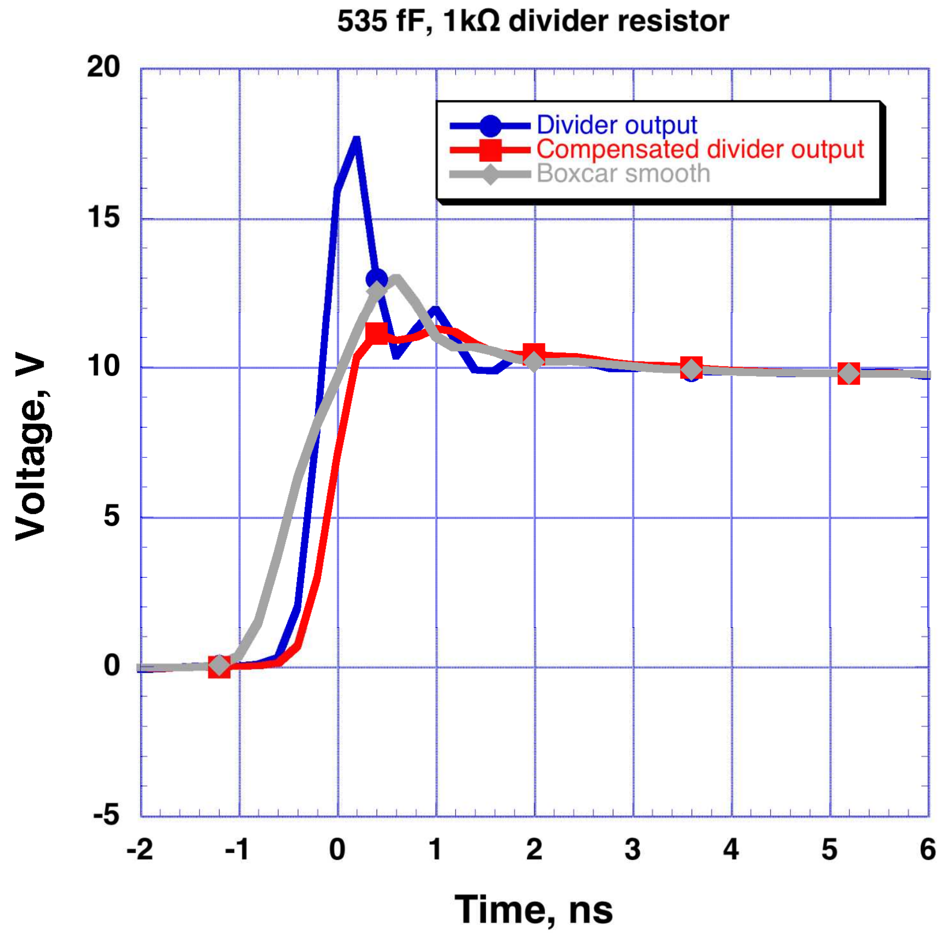
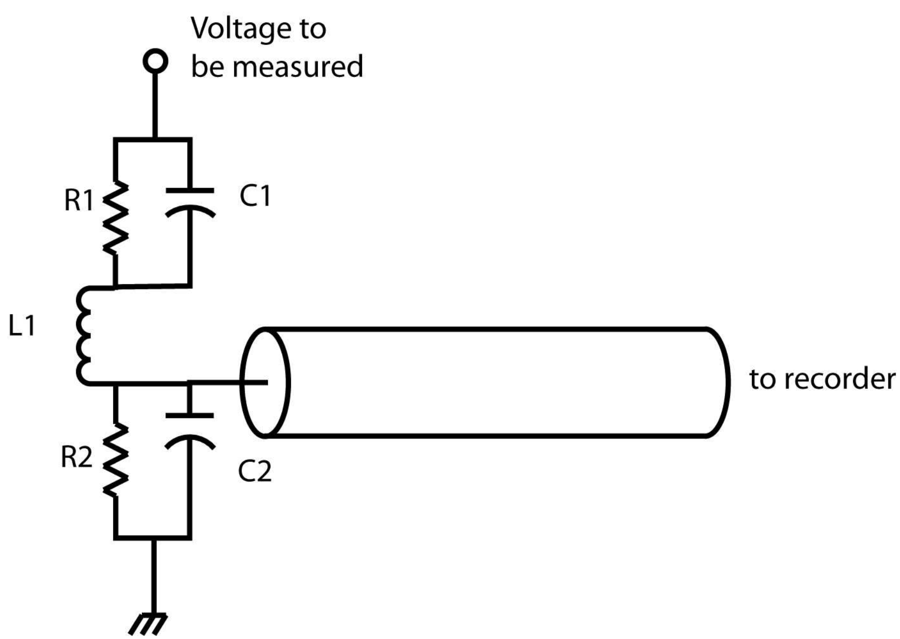
Compare uncorrected, corrected, and simple smooth

- Corrected signal is much more accurate with no loss of bandwidth
- Simple boxcar smoothing is acausal and starts before the input



The balanced divider

- R1*C1=R2*C2; L1~0
- Alleviates all compensation concerns, but proper component values can be problematic



Voltage measurements in MITLs

- **Use well-understood electron flow theory to aid in analysis**

$$V = Z_0\left(I_a^2 - I_c^2\right)^{\frac{1}{2}} - \frac{m_e c^2}{2e}\left(\frac{I_a^2}{I_c^2} - 1\right)$$

But often currents are close together

Measure electron current directly

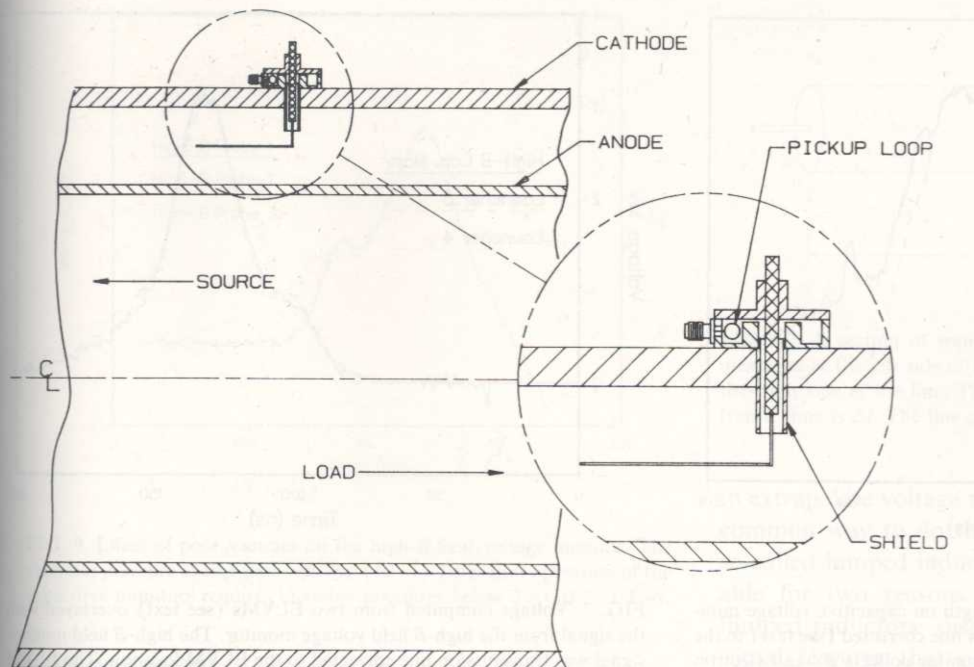
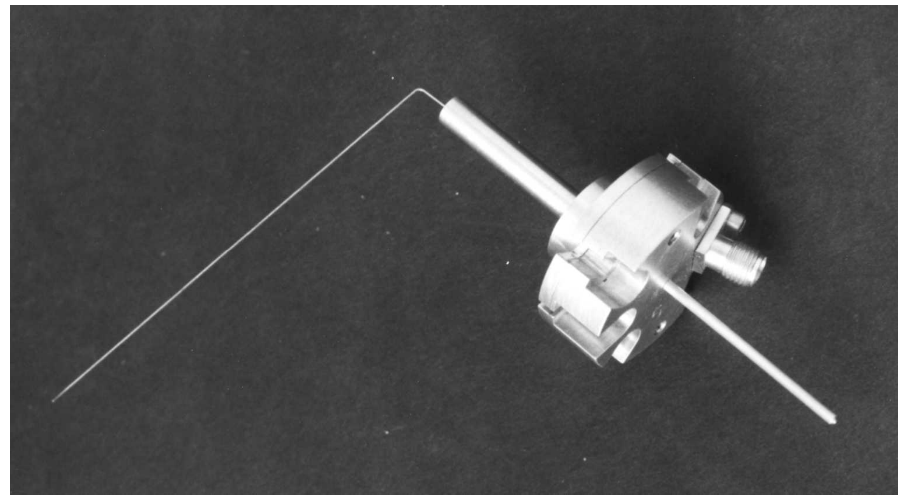


FIG. 5. The electron launching voltage monitor. Machine power flows from left to right. The small launching wire extends halfway across the transmission line gap. The launched electrons flow towards the load. No electron damage is seen on the anode near the launcher.

With readily measured currents, the volatge can be calculated

- **Cathode current should be measured close to the launcher**



$$V = Z_{gauge}\sqrt{I_c I_{launched}}$$

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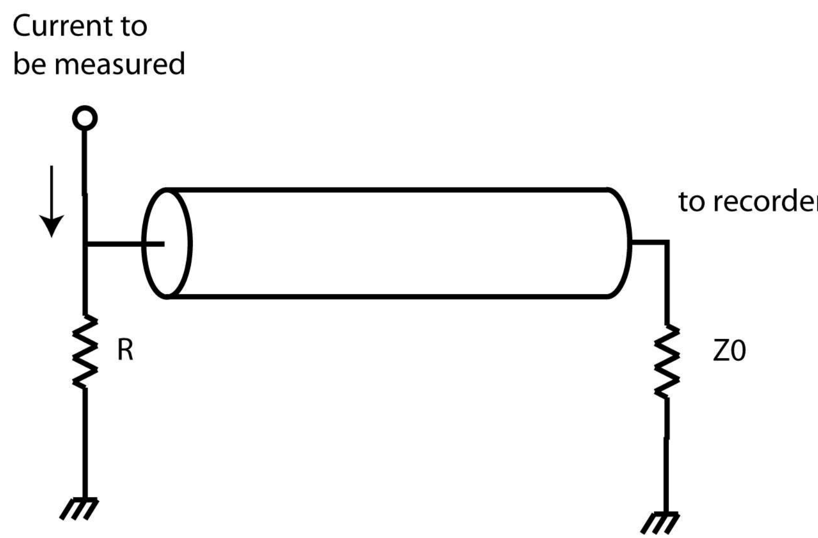
Current monitors

- **Series resistor current diagnostics ("CVRs" or "shunts")**
  - **Must be at scope ground**
  - **DC-coupled (not derivative-responding)**
  - **Not particularly geometry sensitive**
  - **Easily calibrated**

But- the fact that the signal and noise are not derivative-responding makes it hard to tell signal from noise
Also, many CVRs are mΩ and normal ground connections are mΩ, making for an inherently low signal to noise ratio

CVRs are simple in principle

- **Note that current viewing resistor is in parallel with the signal cable, so R can't exceed the cable impedance**

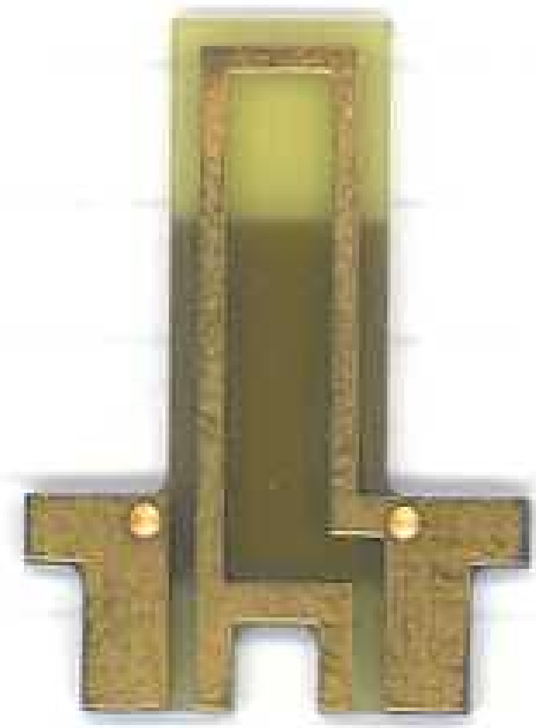


$$V = IR$$

$$I = \frac{V}{R}$$

Flux loops respond to ø-dot

- Assume a geometry scaling to convert sampled loop flux to total current
- Output proportional to the derivative of current

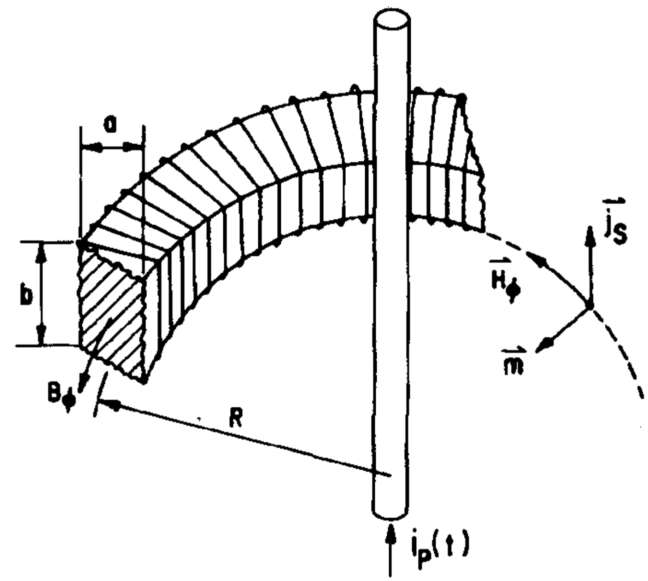


Flux loop advantages

- Can be isolated from ground (break shield current paths); signal can be inverted
- Low impedance source (charged particle collection usually a small effect)
- Time response related to transit time around loop (often ps)
- Signal out proportional to change in flux
  - Noise is usually related to current, so differences can be exploited

Flux belt (Rogovskii belt)

- **Averages flux measurement over an area typically much greater than the conductor cross-sectional area**
- **Largely removes geometry effects of current centroid**



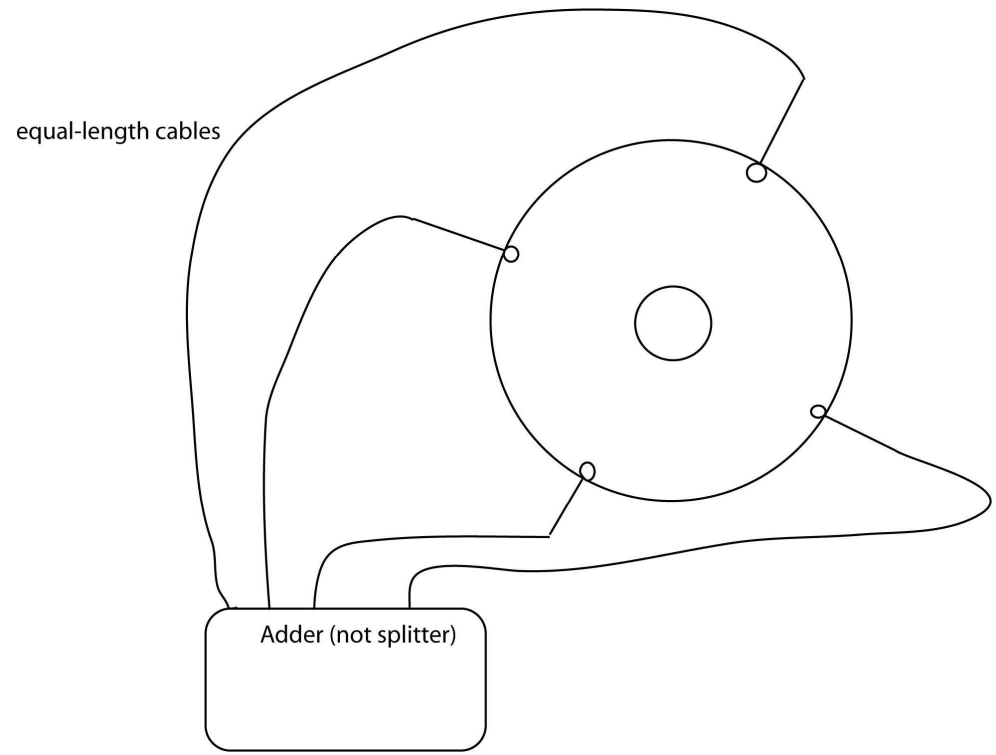
John Anderson, RSI 42,7,1971

Disadvantages of belt

- Limited time response (transit time around belt)
- Inaccurate averaging on time scales comparable to transit time
- Transit time can be appreciable

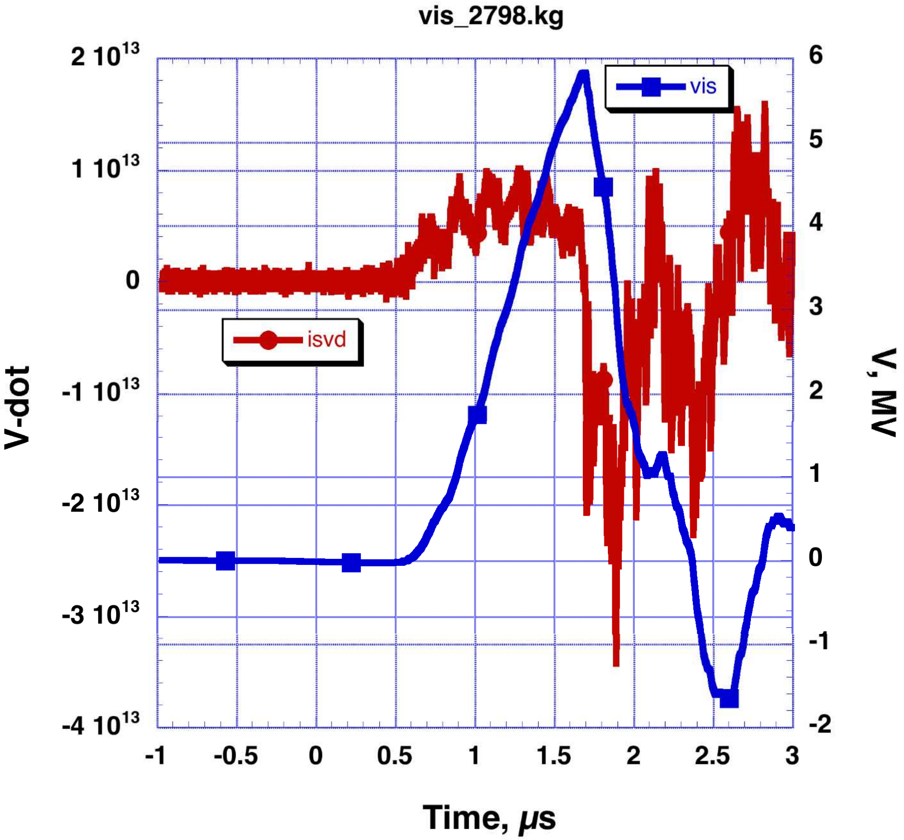
Solution to current centroid position tolerance and time limits

- **Use discrete small flux loops and average electrically or numerically**



Integration of derivative-responding monitors

- Numerical (easy)
- Passive RC (or L/R) integrators
- Active integrators



Integration is a linear process

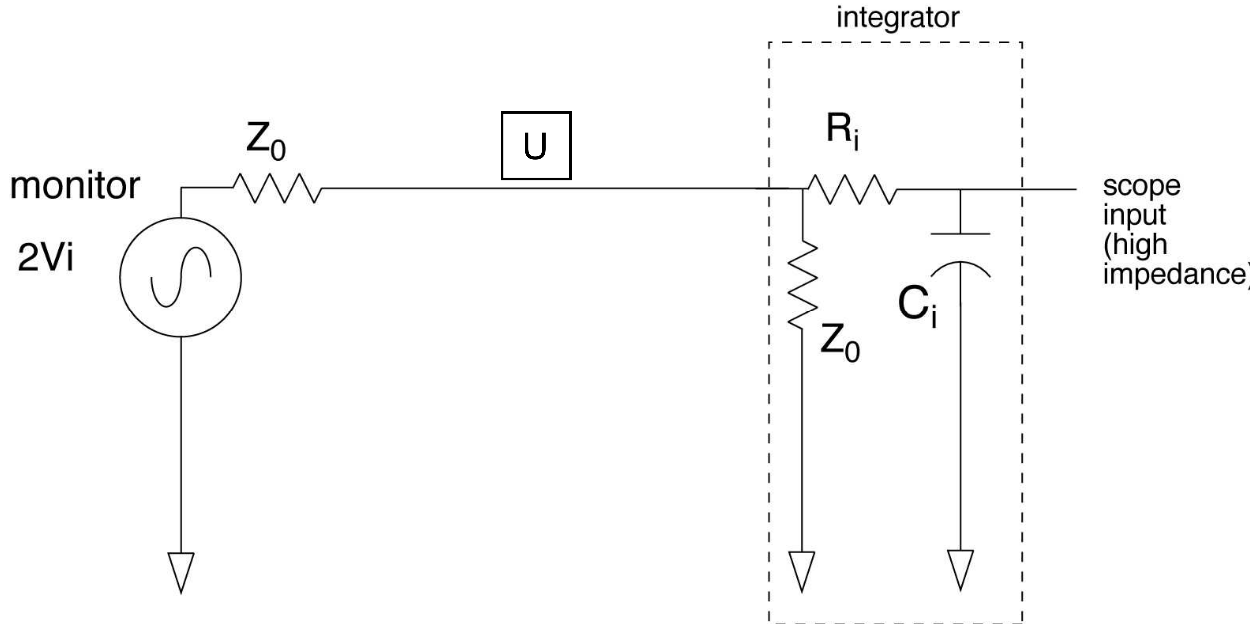
- Digitization is non-linear
  - Can alias energy into lower frequency
- While it can be difficult to build a great integrator, a passive integrator will get the right answer late in time
- Numerical integration can “miss” a point and get the final answer wrong

Integrator requirements

- Basic: integrator time constant much greater (~10 times) than the pulse duration
- Reduces recorded signal
- No droop correction needed
- Can be large capacitors for 50Ω scopes; large caps might tend to be inductive
- Note that active integrators solve these problems, but needs a fast amplifier circuit

The passive integrator

- **With a high impedance scope**



The integrator circuit is linear and simple

- **Analyze the circuit**

$$\frac{2V_i - u}{Z_0} = \frac{u}{Z_0} + \frac{u - V_0}{R_i}$$

$$u = R_i C \dot{V}_o + V_o$$

$$\int V_i dt = V_o \left[C_i \left(R_i + \frac{Z_0}{2} \right) \right] + \int V_o dt$$

$$\tau = C_i \left(R_i + \frac{Z_0}{2} \right)$$

For a system with the integrator time constant $\tau = C_i \left(R_i + \frac{Z_0}{2} \right)$ applied to the gauge factor G, the droop correction is $\frac{G}{\tau} \int V_o dt$. Thus, for a scaled signal $S(t)$, the droop-corrected data are

$$S_{corrected} = S(t) + \frac{1}{\tau} \int_{t_{start}}^{t} S(t') dt'$$

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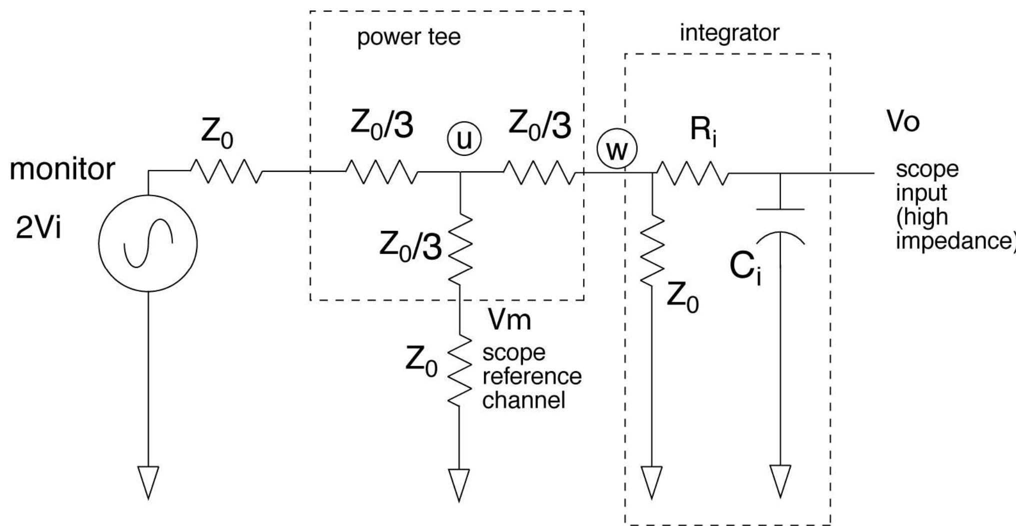
An integrator must be calibrated since it affects the signal amplitude

- Use a signal that can be numerically integrated accurately, with a window long enough for significant droop



Using the hard-integrated and numerically integrated signals to find the time constant

$$\frac{2V_i - u}{Z_0 + \frac{Z_0}{3}} = \frac{u}{Z_0 + \frac{Z_0}{3}} + \frac{u - w}{\frac{Z_0}{3}}$$

$$\frac{u - w}{\frac{Z_0}{3}} = \frac{w}{Z_0} + \frac{w - V_o}{R_i}$$

$$\frac{w - V_o}{R_i} = C_i \dot{V}_o$$

$$V_m = \frac{3u}{4}$$

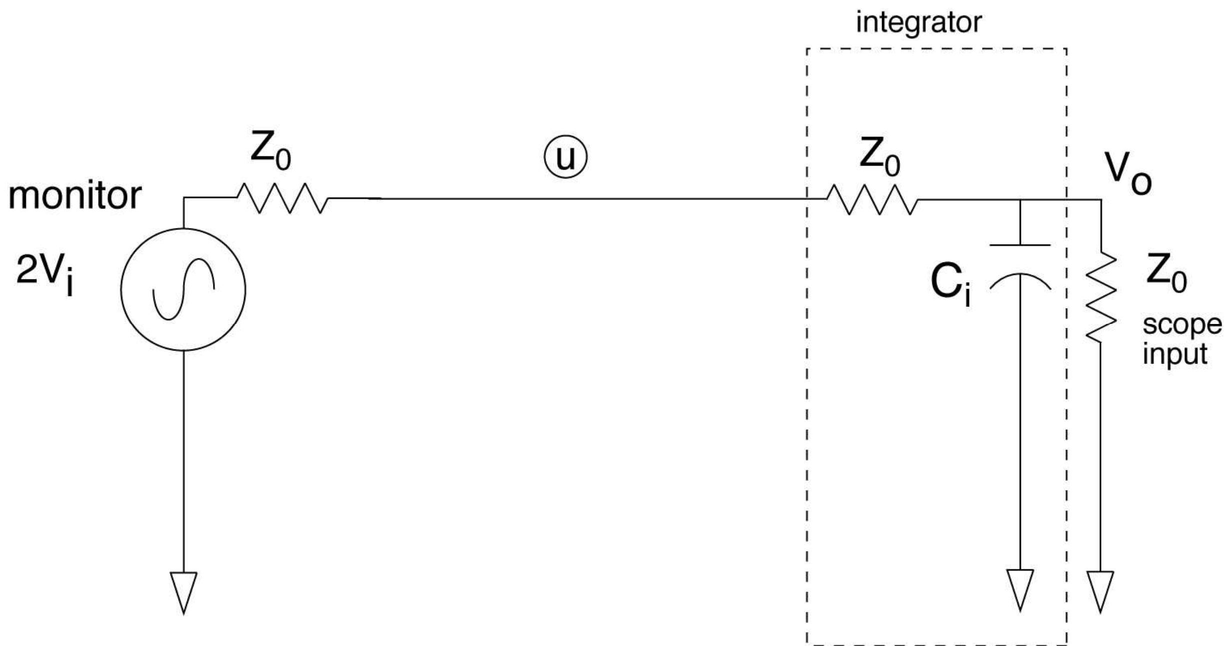
$$\frac{\int_{t_{start}}^{t} V_m dt' - \int_{t_{start}}^{t} V_o dt'}{V_o} = \left(R + \frac{Z_0}{4} \right) C_i$$

$$\tau = \left(R + \frac{Z_0}{4} \right) C$$

R must be much greater than cable impedance to maintain match

For fast signals or long cables or when high impedance scope is not available

- Same type of analysis



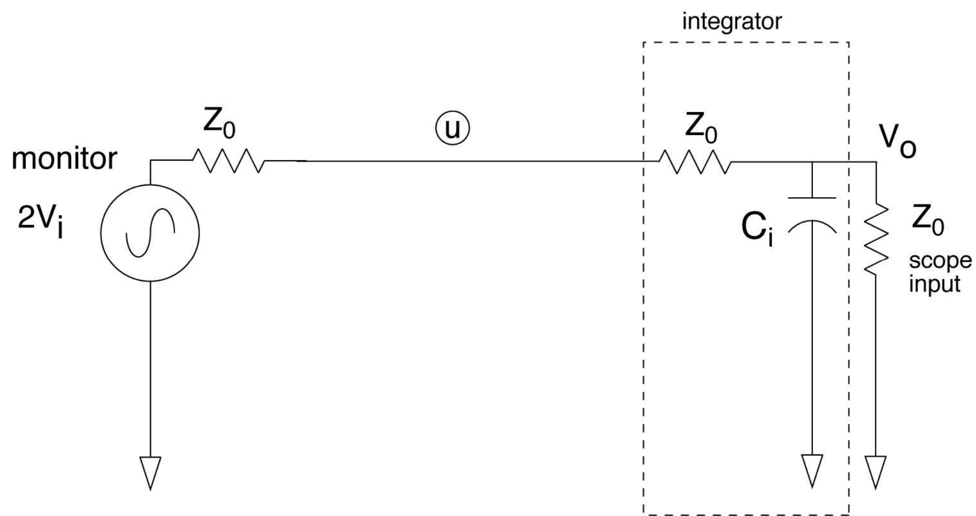
50Ω integrator droop correction

$$\frac{2V_i - V_o}{2Z_0} = \dot{V}_o C_i + \frac{V_o}{Z_0}$$

$$\int V_i dt = V_o \left[C_i Z_0 \right] + \frac{3}{2} \int V_o dt$$

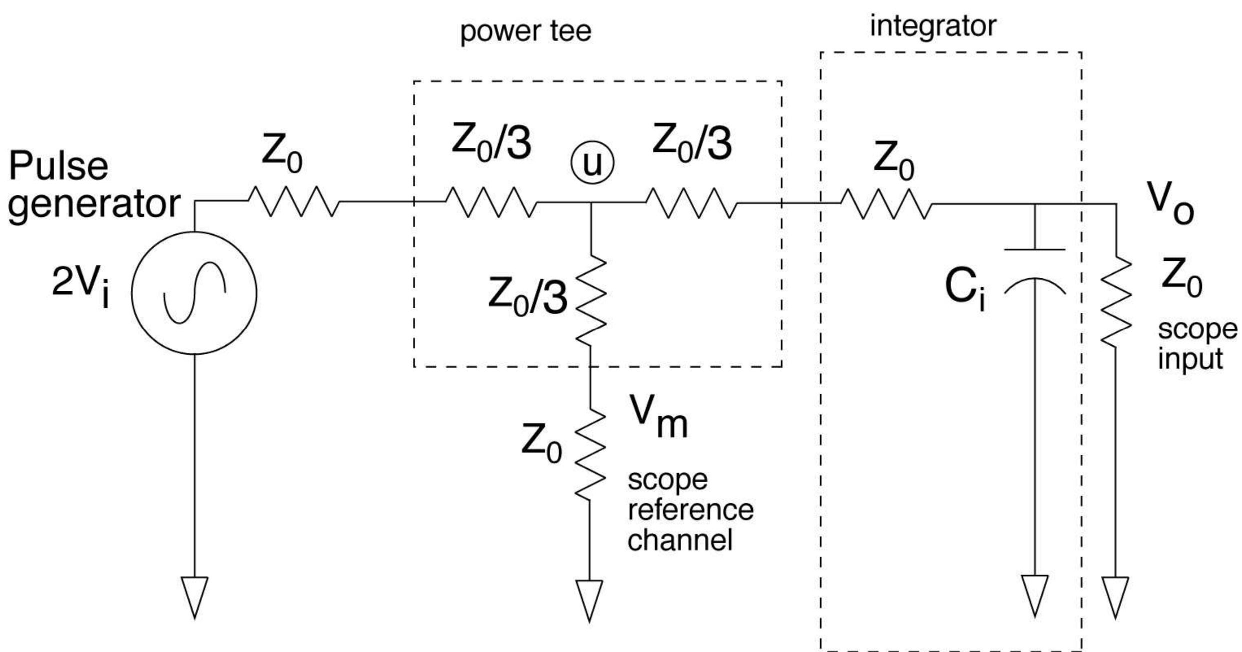
$$S_{corrected} = S(t) + \frac{3}{2\tau} \int_{t_{start}}^{t} S(t')dt'$$

$$\tau = Z_0 C_i$$



To calibrate the 50Ω integrator

- **Similarly, use a signals that can be acquired without aliasing**



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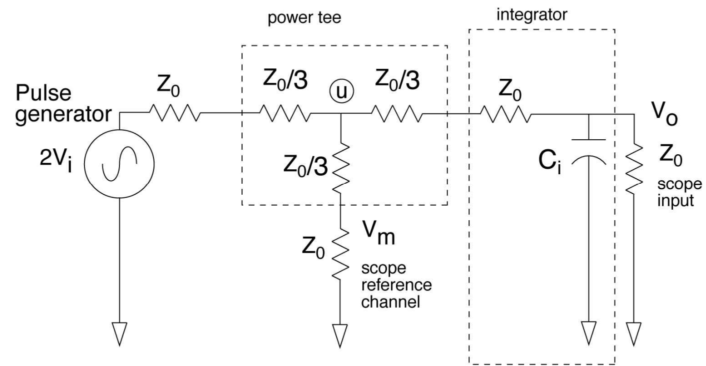
Analyze the circuit

- **The circuit is much like the high impedance integrator**



$$\frac{2V_i - u}{\frac{4Z_0}{3}} = \frac{u}{\frac{4Z_0}{3}} + \frac{u - V_o}{\frac{4Z_0}{3}}$$

$$\frac{u - V_o}{\frac{4Z_0}{3}} = \frac{V_o}{Z_0} + C_i\dot{V}_o$$

$$V_m = \frac{3u}{4}$$

$$\frac{\int_{t_{start}}^{t} V_m dt' - \frac{7}{4}\int_{t_{start}}^{t} V_o dt'}{V_o} = C_i Z_0$$

$$\frac{\int_{t_{start}}^{t} V_m dt' - k\int_{t_{start}}^{t} V_o dt'}{V_o} = \tau$$

where k is 1 for the 1 megohm integrator, $7/4$ for the 50 ohm integrator, and τ is the integrator time constant used in the gauge factor and the droop correction function

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To actually calibrate integrators

- **Align the numerically and passively integrated signals in time**
- **Do a least squares fit to get amplitudes**

$$\tau = \frac{\left\langle \left(\int V_o\right)^2 \right\rangle \langle V_o V_m \rangle - \left\langle V_o \int V_o \right\rangle \left\langle V_m \int V_o \right\rangle}{\left\langle V_o^2 \right\rangle \left\langle \left(\int V_o\right)^2 \right\rangle - \left\langle V_o \int V_o \right\rangle^2}$$

$$k = \frac{\left\langle V_o^2 \right\rangle \left\langle V_m \int V_o \right\rangle - \left\langle V_o \int V_o \right\rangle \langle V_m V_o \rangle}{\left\langle V_o^2 \right\rangle \left\langle \left(\int V_o\right)^2 \right\rangle - \left\langle V_o \int V_o \right\rangle^2}$$

where $\langle x \rangle$ is the mean value of the array x.

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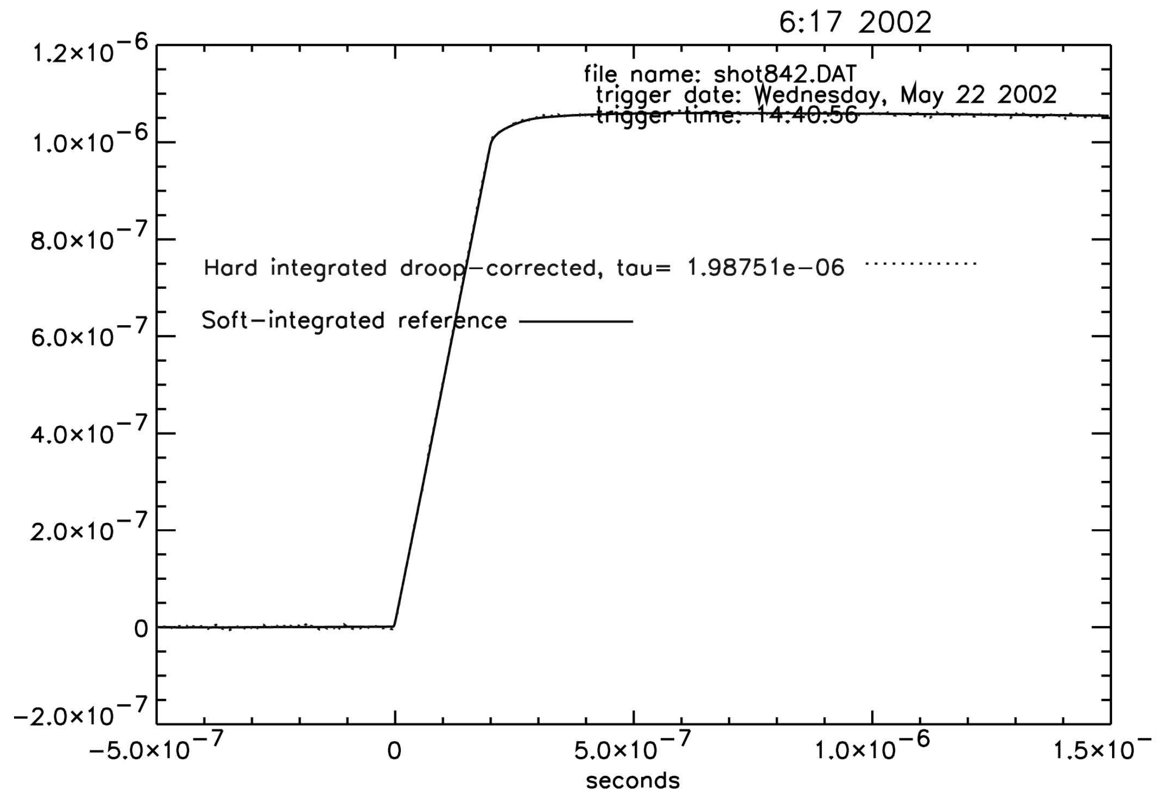
Calibration of high impedance integrator

- **Use scope averaging for noise reduction**




```
Notice:  Time-shifting data by: 2.5951761e-09 seconds
Time constant is: 1.98751e-06 seconds, B is: 0.981567
B is expected to be 1.00000 from the circuit, so you have a
-1.84327 percent error level
```

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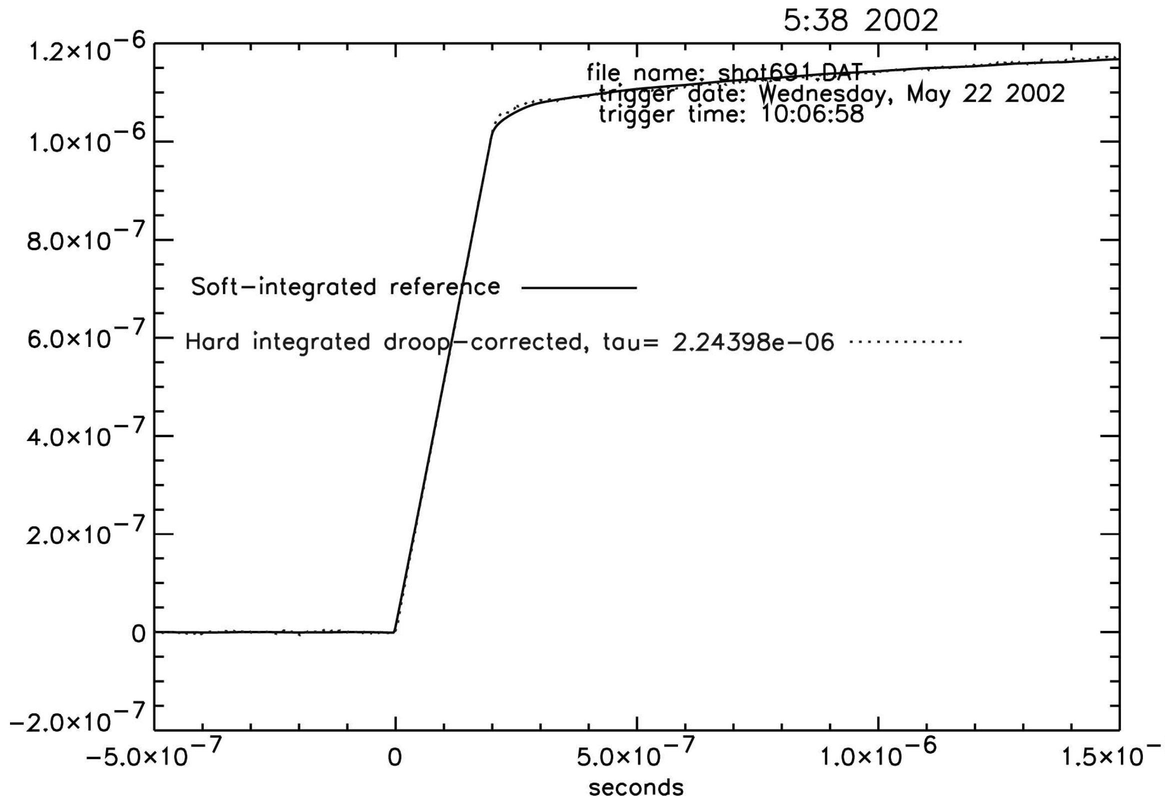
Calibration of 50Ω integrator

- The input impedance rises as the capacitor charges up; final input impedance is twice Z0



Notice: Time-shifting data by: -3.7183901e-10 seconds
Time constant is: 2.24398e-06 seconds, B is: 1.77217

B is expected to be 1.75000 from the circuit, so you have a 1.26690 percent error level

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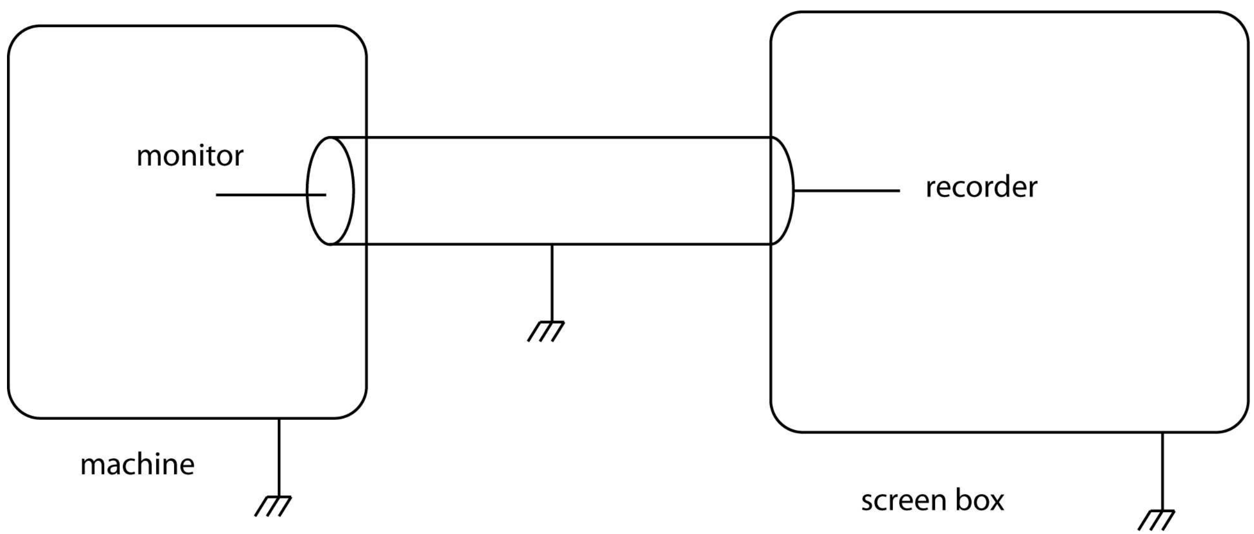
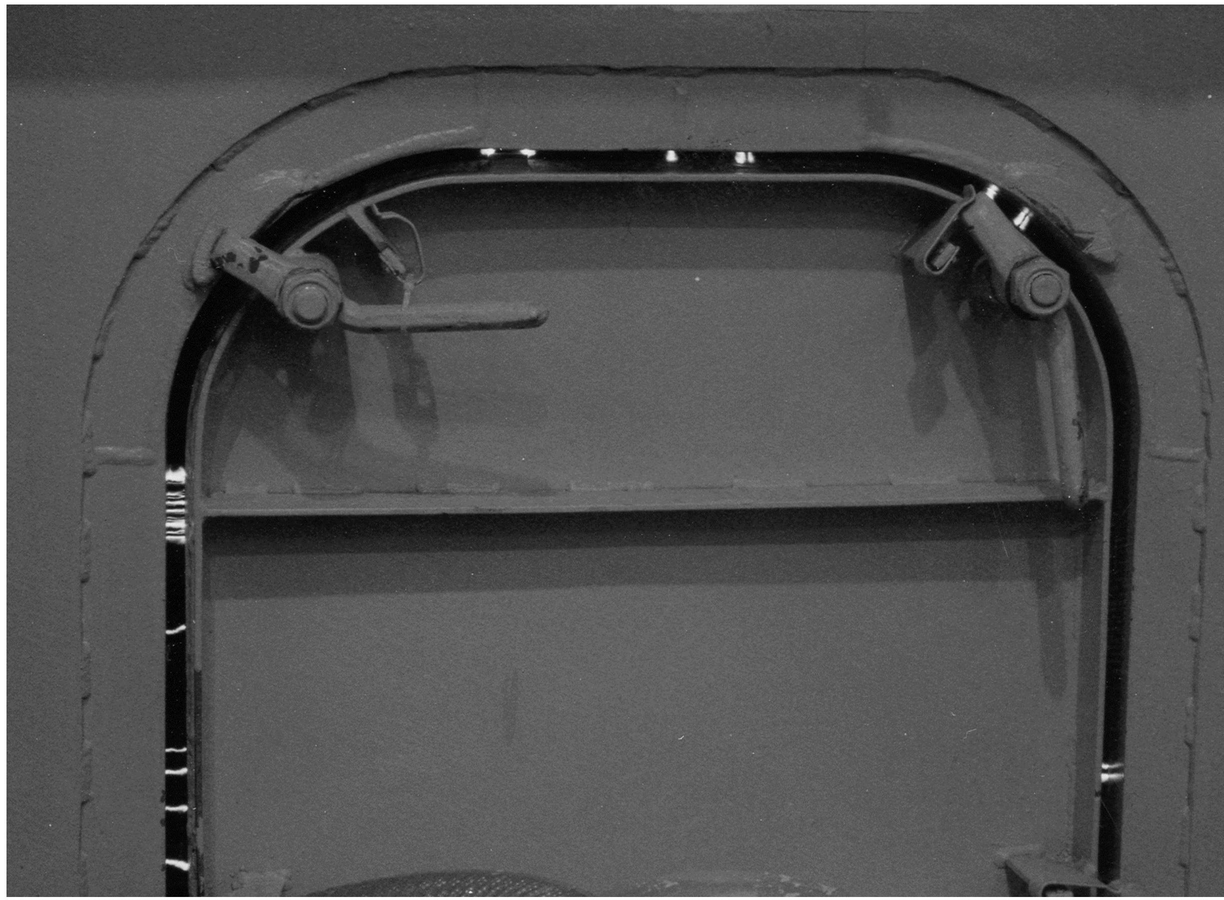
Noise in pulsed power systems

- **In low impedance, slow (dimensions smaller than wavelength) systems, often noise is caused by shield current**



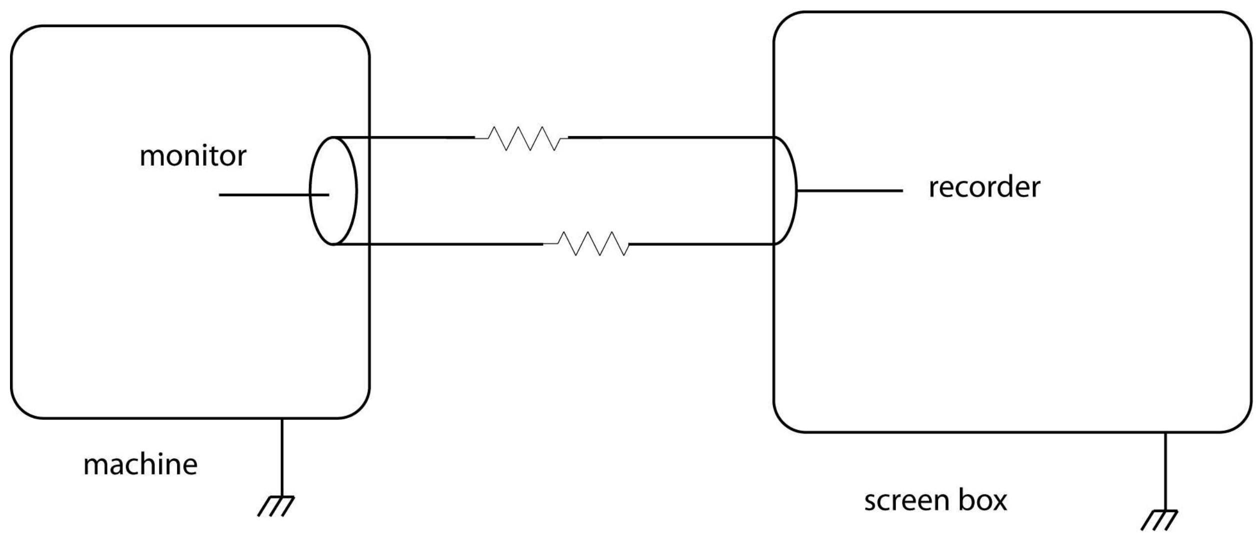
With superconducting cables, there's no noise!

Many systems have large stray currents



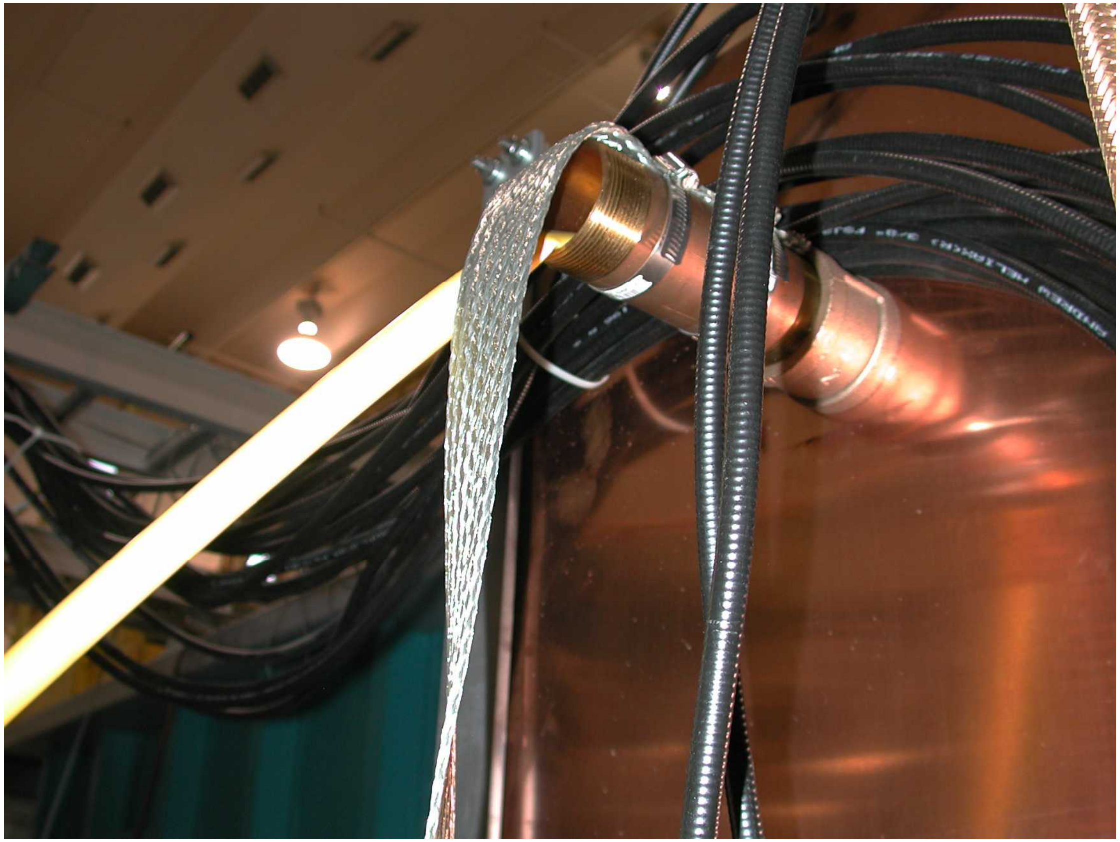
Resistance is how noise flux gets into signal cables

- **Shield current and shield resistance cause noise**



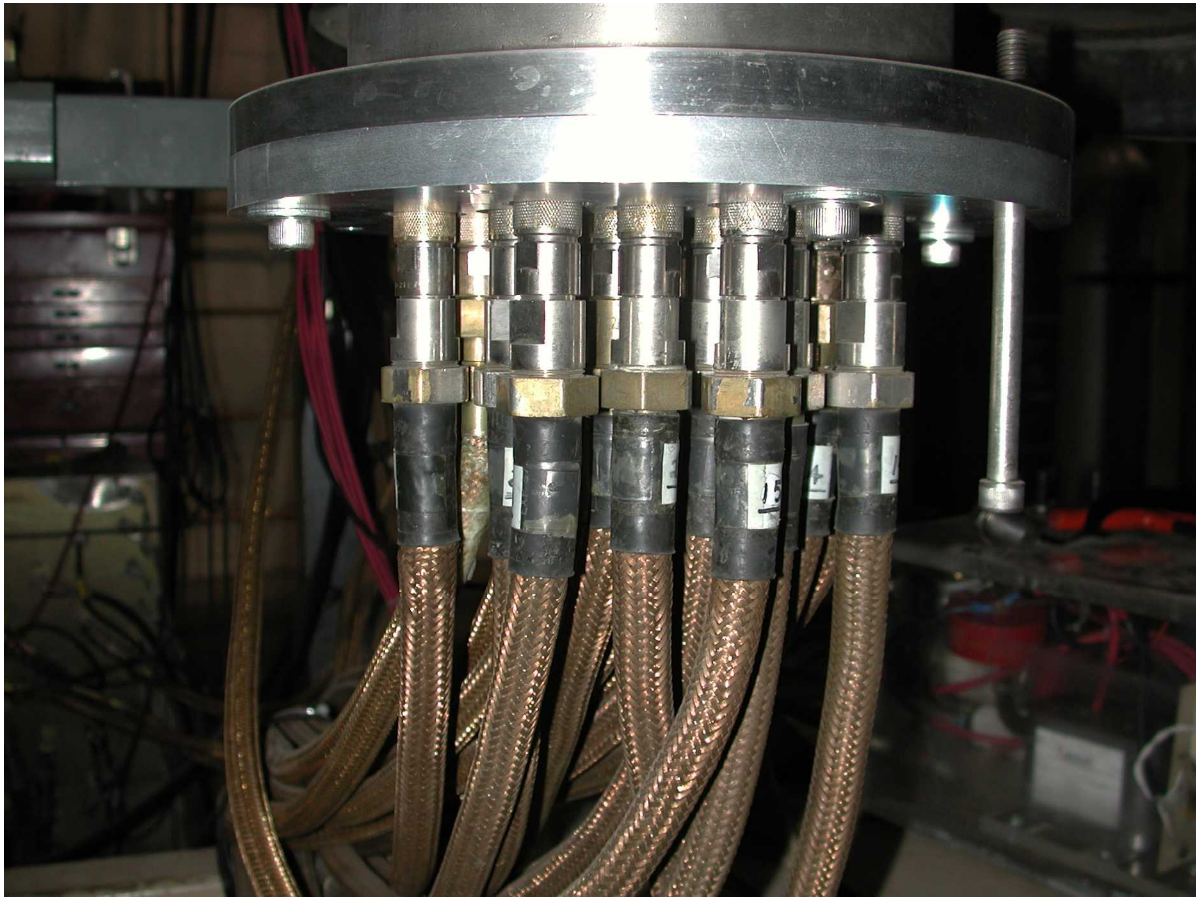
Minimize current in signal cable shields

- Low resistance straps and low resistance connections



Minimize shield resistance

- Use double-shielded cable and threaded connectors (NOT BNC)

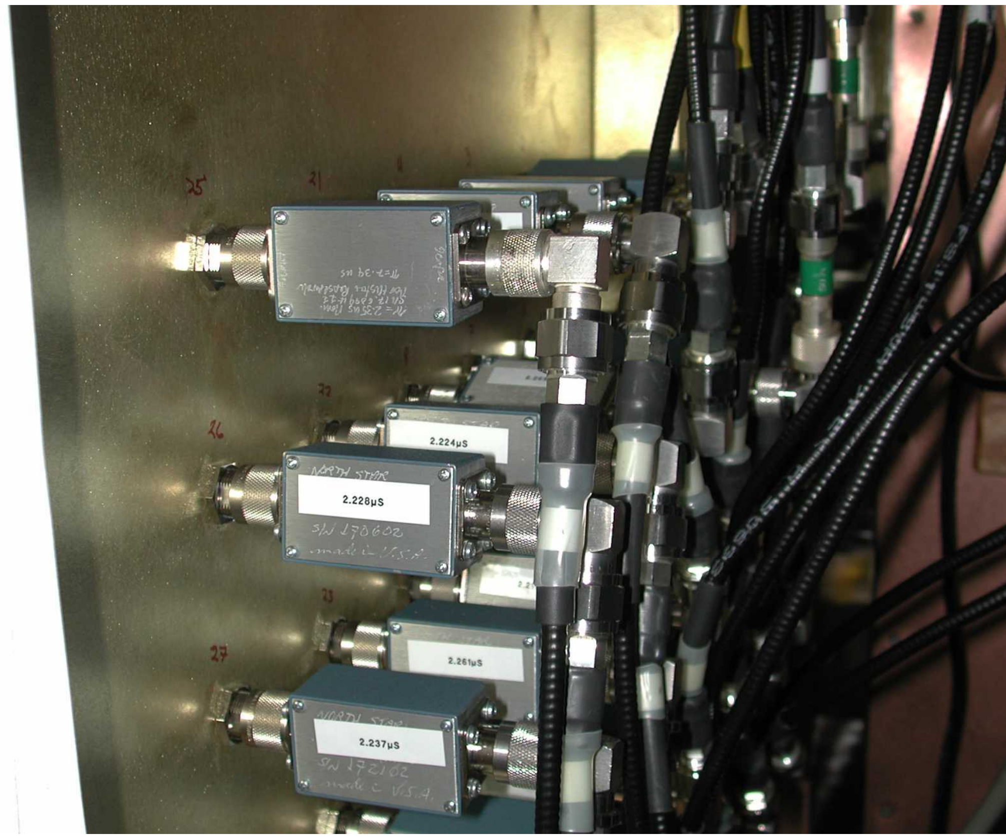


Minimize power line noise

- Use high-quality filters

Attenuate and integrate inside the shielded enclosure

- **Small signal self-integrating monitors are not ideal for noisy environments**



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Noise is often challening but rarely un-fixable

- Good cabling practices solve most noise problems

Conclusions

- **Simple analysis can improve data quality and understanding**
- **Linear circuits with one current loop describe many situations**
- **Modern data acquisition makes high-quality analysis practical and desirable**
  - **For example, digitizer trigger jitter in the 50 ps range is common**
- **Non-ideal monitor systems can be improved with simple math algorithms**

Conclusions (continued)

- **Noise is not a mystery**
- **Reduce current in shields and reduce resistance of shields to reduce noise voltage**