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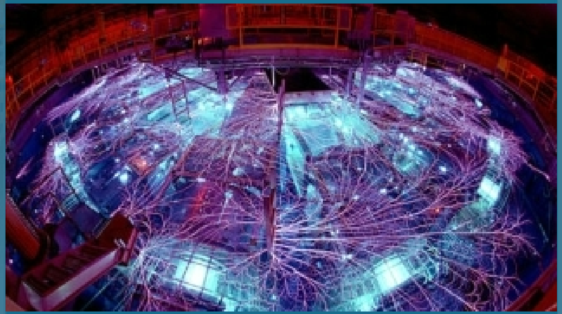
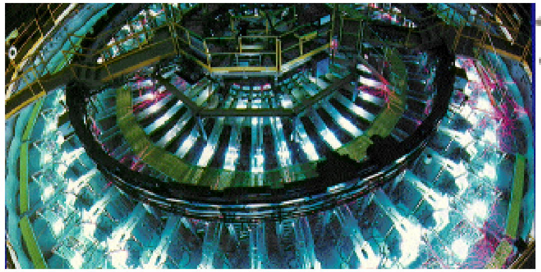
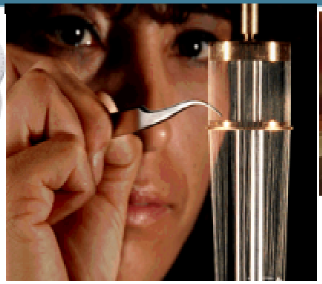
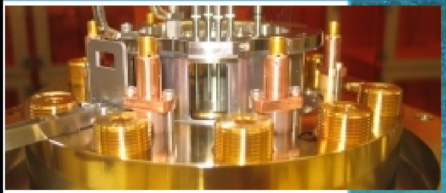
Pulsed power electrical measurements: some tips learned from the masters









Mark Savage

2021 IEEE International Pulsed Power Conference

December 13 2021

U.S. DEPARTMENT OF ENERGY NNSA

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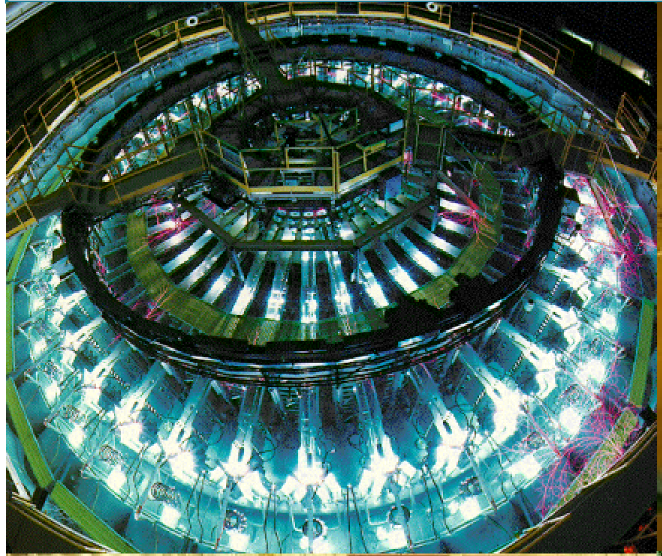
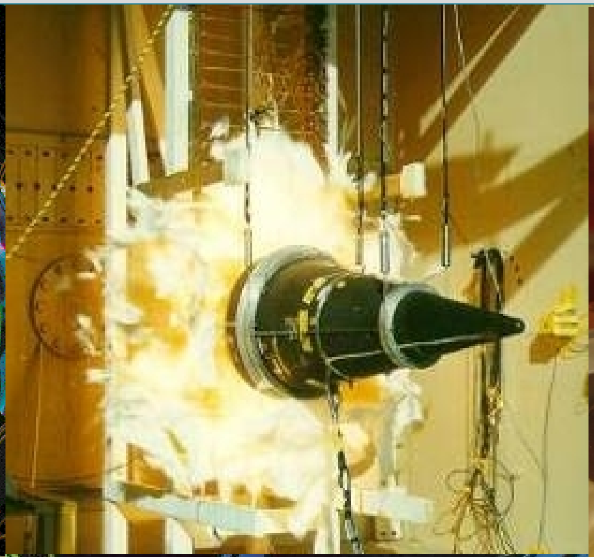
Outline

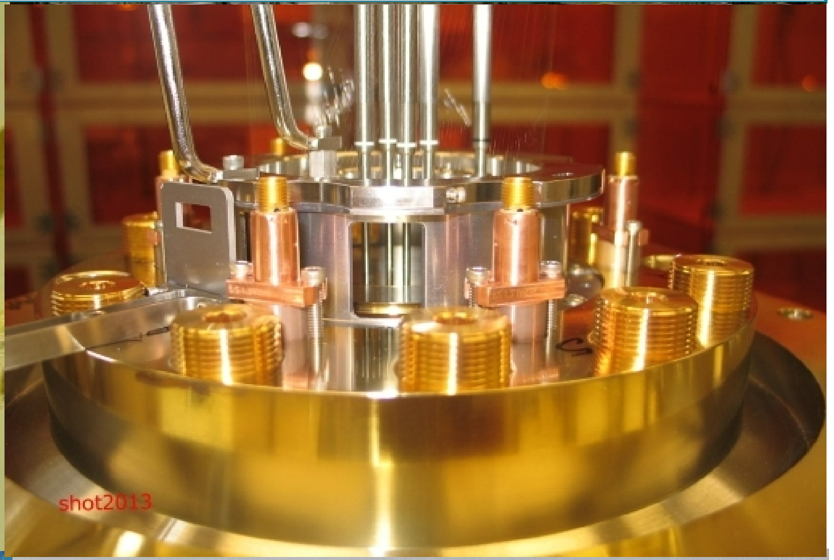
- General comments
  - Sandia's interest
  - Signals, noise, and integration
  - Numerical cable frequency response compensation
- Examples of useful post-processing of voltage and current signals
  - High-pass filter
  - General voltage divider
  - Computing voltage at the end of an open-circuit transmission line
  - Dense plasma focus current and voltage measurements, and further processing
  - Simple measurements on an explosive closure valve
  - Simple measurement of laser-created plasma dimensions for a laser-triggered gas switch

Sandia capabilities: Extreme environments

Saturn	Light Initiated High Explosives Facility	Z K-shell X-ray source







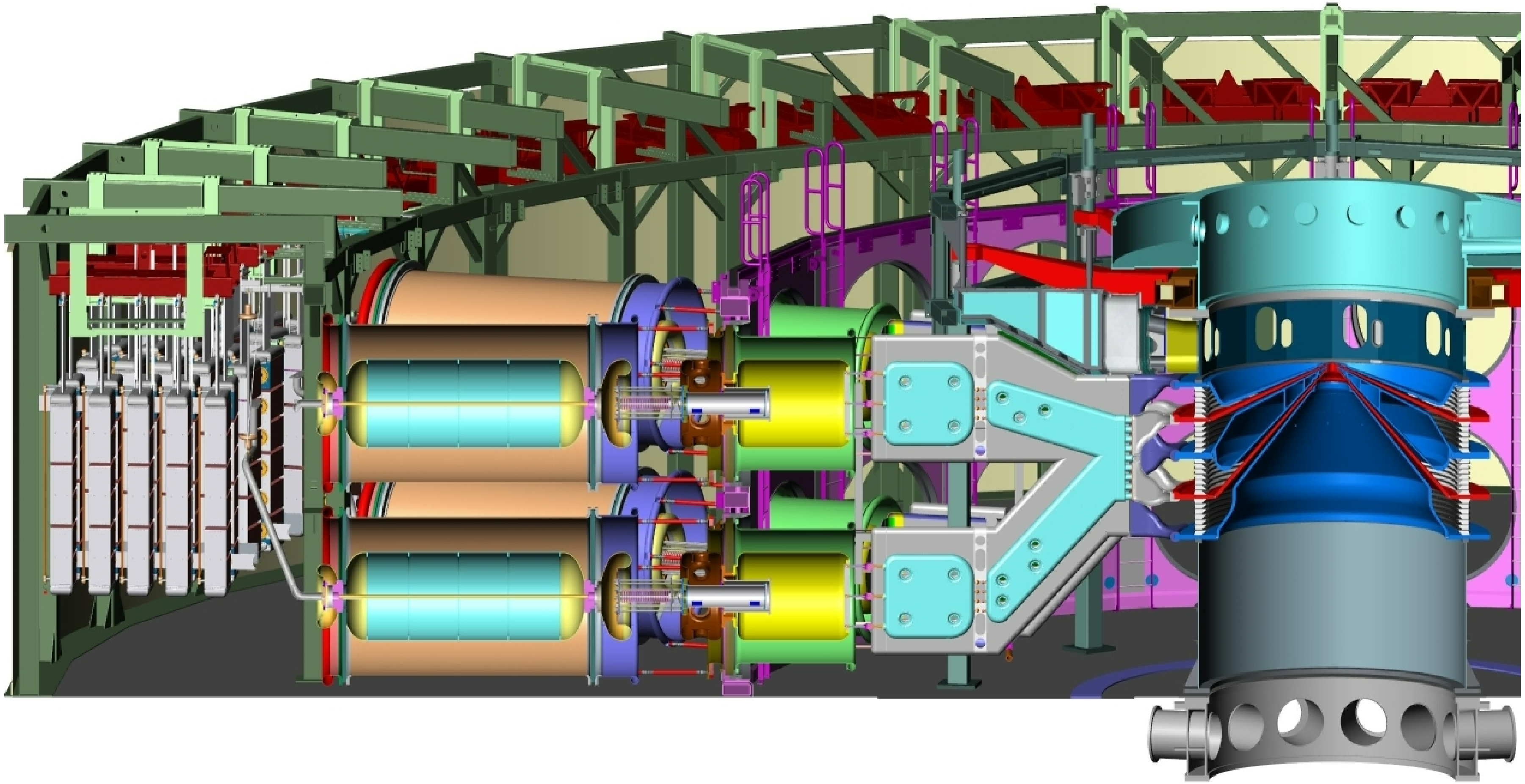
Hermes III	Annular Core Research Reactor	Blast tube

Acknowledgments

- **Operation of Z and Saturn machines is accomplished with a dedicated team of scientists, engineers, and technologists working for continual improvement**
- **The people are the key**

Electrical diagnostics are the basic measurements for a pulsed power system

- **Being electrical systems, voltage and current measurements are fundamental**
- **Circuit-model based simulations are desirable**
- **Voltage and current measurements are conceptually simple and generally cheap**



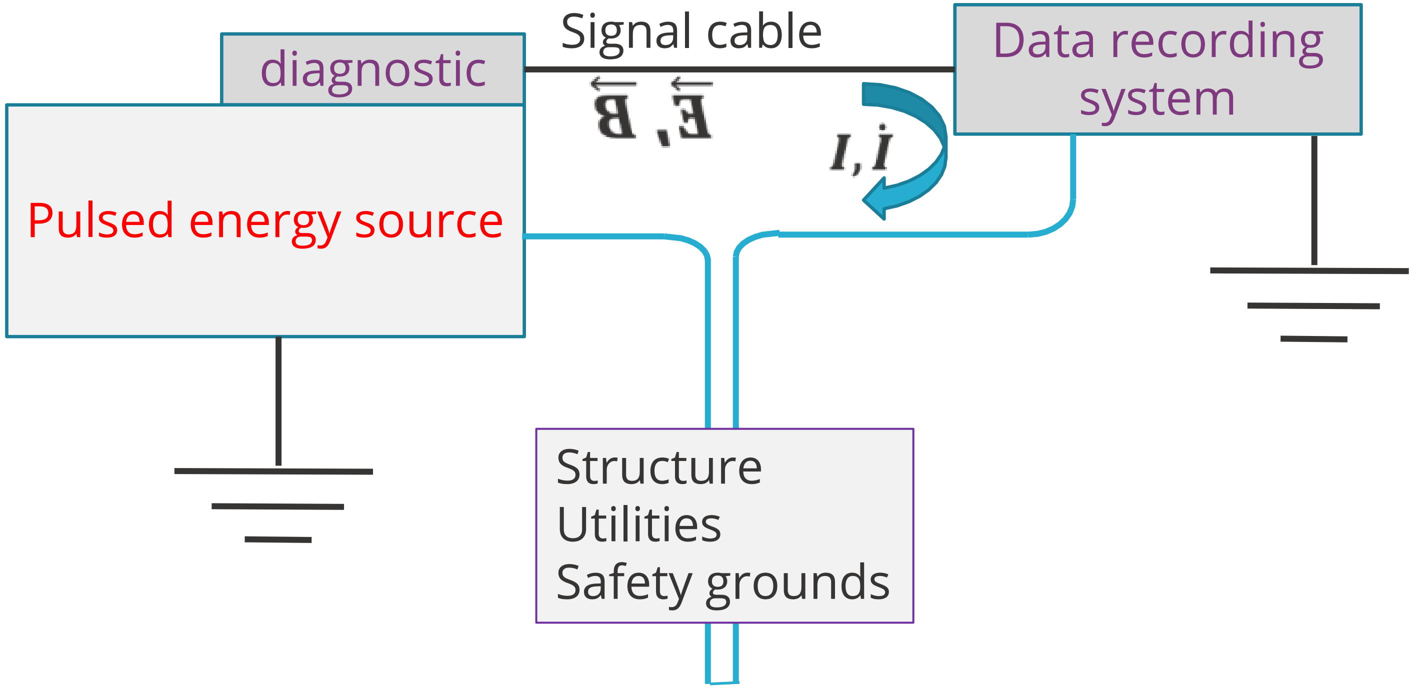
Signals, cables, noise

General comments

- In large pulsed power systems, signals generally traverse significant cable length before being recorded on a digitizer
  - Underground tests were an extreme example of long cable runs
- Even machines like Z and Saturn have hundreds of feet of coaxial cable propagating measurement signals
- What are typical effects of long cable runs?
  - Possible incursion of “noise” by extraneous electric and magnetic fields
  - Attenuation of high frequency content

A simple view of electrical diagnostics and noise

- **Eliminating ground loops in large systems is often impractical**
- **The current flowing outside the cable can be much larger than that of the actual signal**

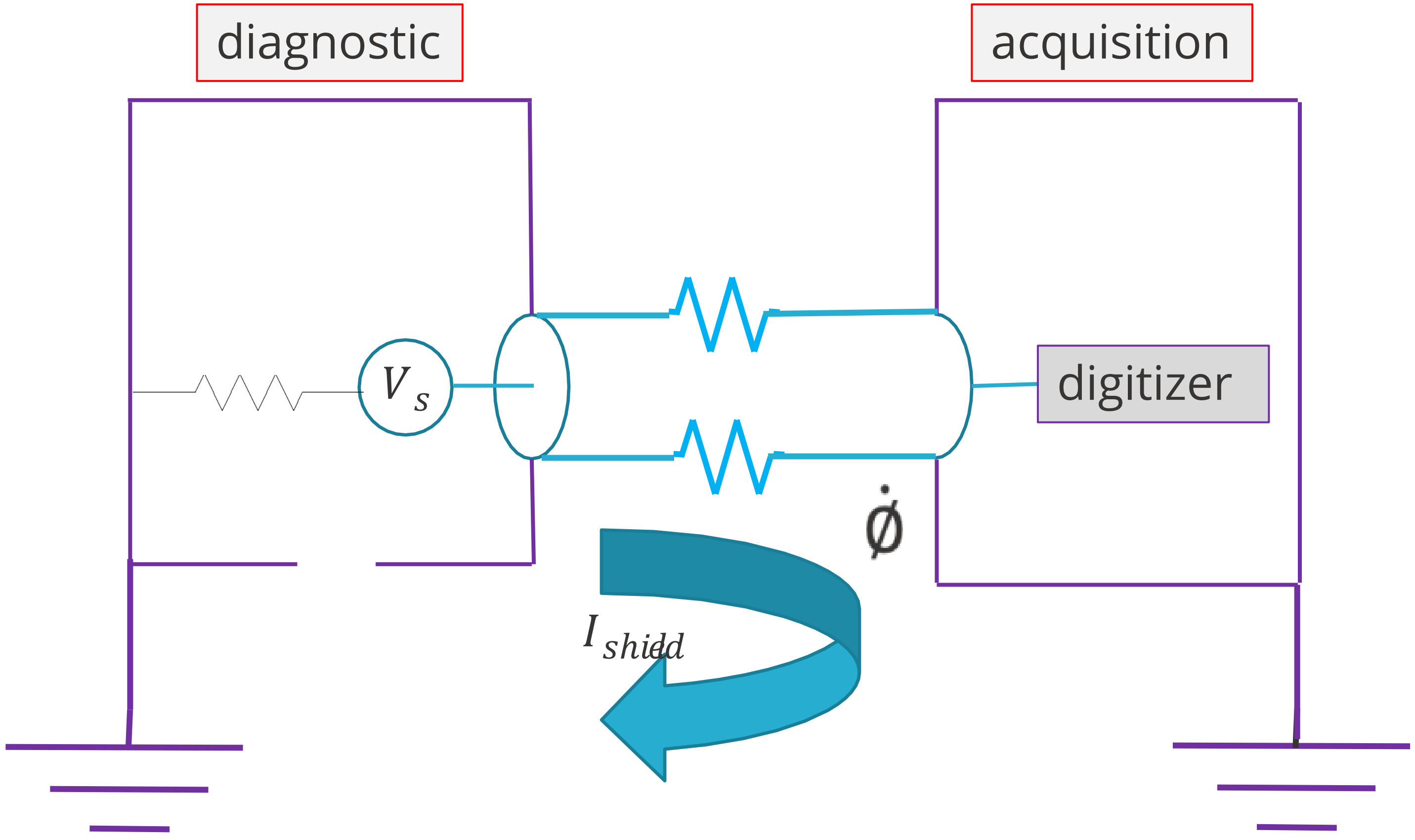


We will assume that the diagnostic and the acquisition system work as intended

- **The diagnostic, signal cable, and acquisition enclosure is an extended 'Faraday cage'**
- **If noise doesn't enter at the diagnostic or in the "screen room" the only place for spurious signals to enter is the cable run via:**
  - **capacitive coupling from the environment to the cable center conductor**
  - **Mutual inductance from a circuit outside the cable coupling to the center conductor**
  - **Flux penetration, or axial resistive voltage drop along the cable**

Resistance is usually how noise flux gets into signal cables

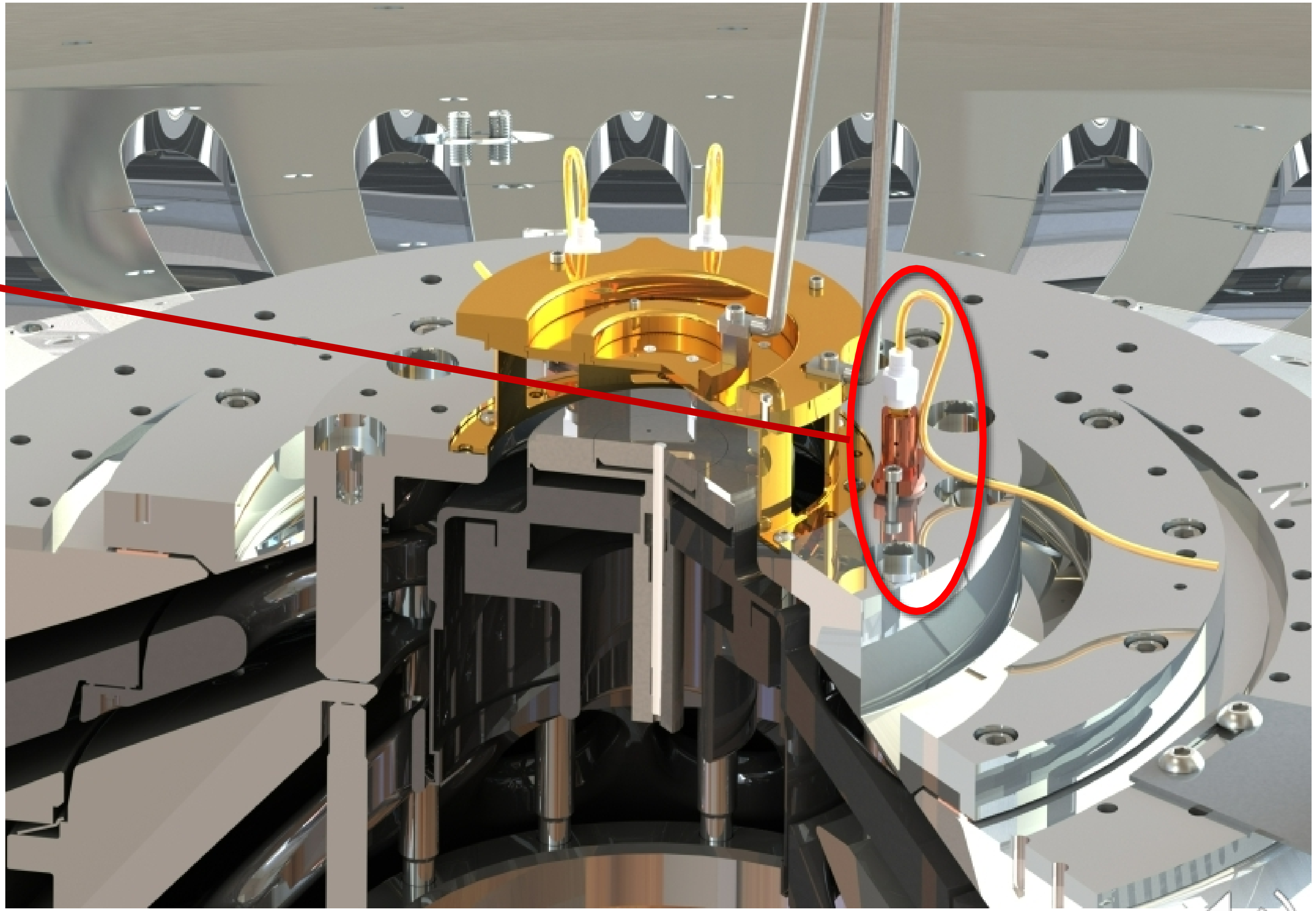
- Loop inductance and EMF difference determine the current flowing in the cable shields
- Resistance of the cable shield and connectors determines the voltage drop along the cable
- **If the cable is short and the diagnostic impedance is much higher than the cable impedance, the noise voltage can appear at the diagnostic instead of the acquisition system**



We generally don't care what the cable shield current or resistance is, but their product is important

Electrical noise issues for Z load current B-dots

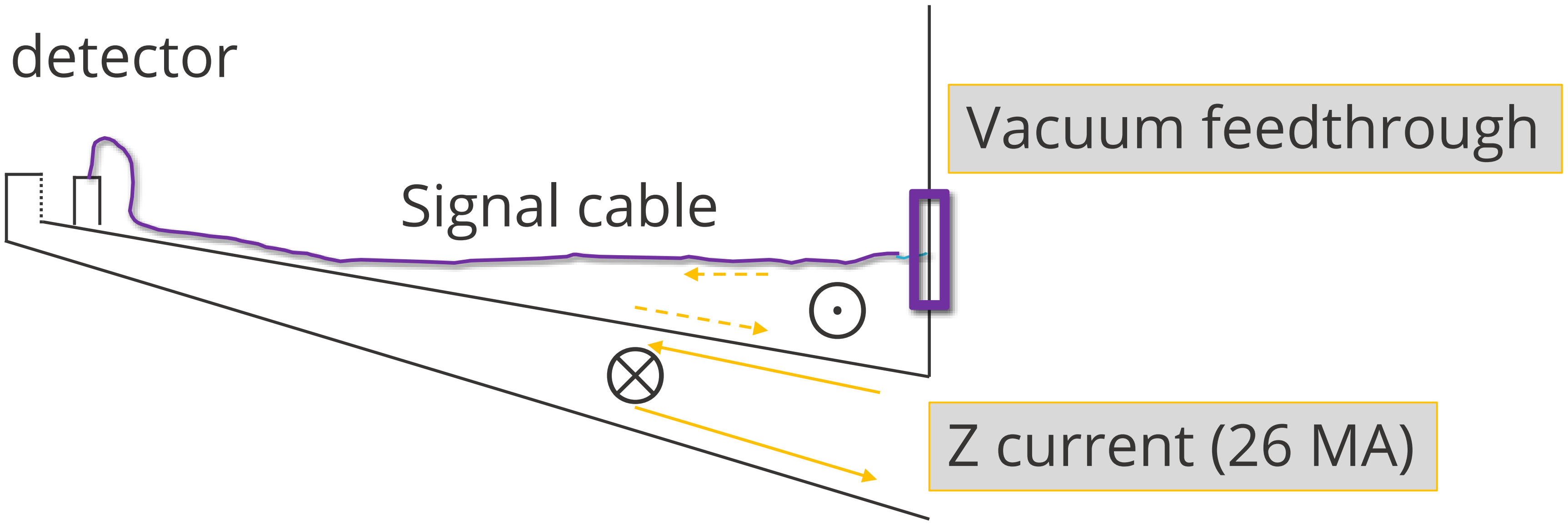
The load B-dots measure current upstream of the load and downstream of the post-hole convolute



Issues

- $\sim 65T$ and $8\times10^{8}\frac{T}{s}$ magnetic field in power feed
- X-ray flux
- Stray magnetic flux outside the load

Stray magnetic flux is the problem: Z load current monitors



Eddy current in the shield can be much higher than the signal current

Maximize signal to noise ratio: lower cable resistance

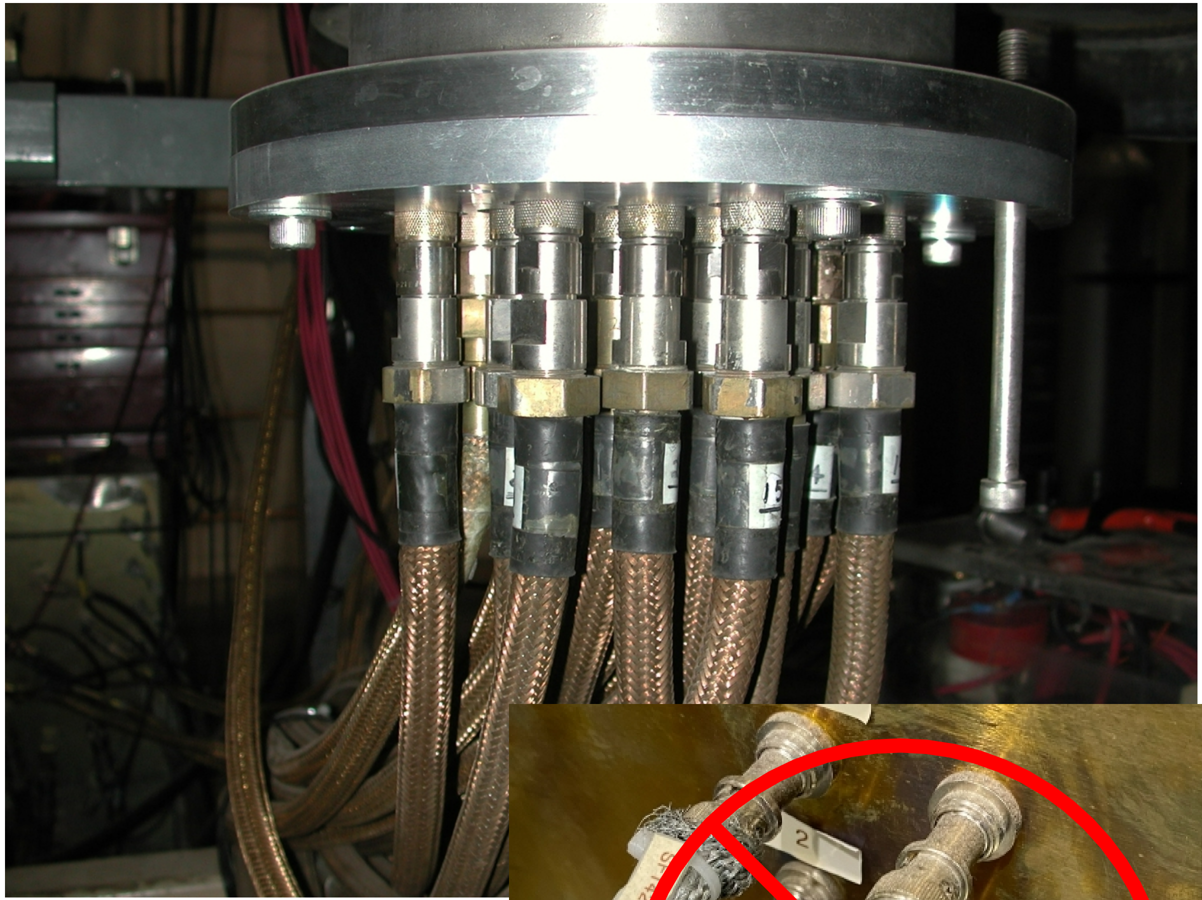
- **Reduce noise**
  - **Use coaxial cable with a low resistance shield**

	Cable type	Impedance, Ω	mΩ/foot
worst	RG-58	50-53.5	6
↓	RG-405 (.086)	50	1.5
	RG-214	50	0.7
best	LDF4.5-50 Heliax	50	0.42

Large diameter cables have both lower shield resistance and lower high frequency attenuation

Increase cable plant inductance and use low resistance connectors

- **Reduce current in the signal cables**
  - **Bundle cables together to increase cable run inductance**
  - **Ferromagnetic material (“cores”) around cables**
- **Reduce resistance**
  - **Double-shielded cable of the largest acceptable diameter**
    - **Auxiliary shields in addition: copper braid, conduit, copper pipe, etc.**
  - **Threaded connectors (N-type or HN, or SMA if space concerns)**
    - **BNC shield resistance can be 1000X higher than N-type shield resistance *and variable***
    - ***Noise issues make μΩ to mΩ shield resistance significant***



Don’t use single-braid cable or BNC connectors outside of the shielded enclosure

Bandwidth issues and signal level

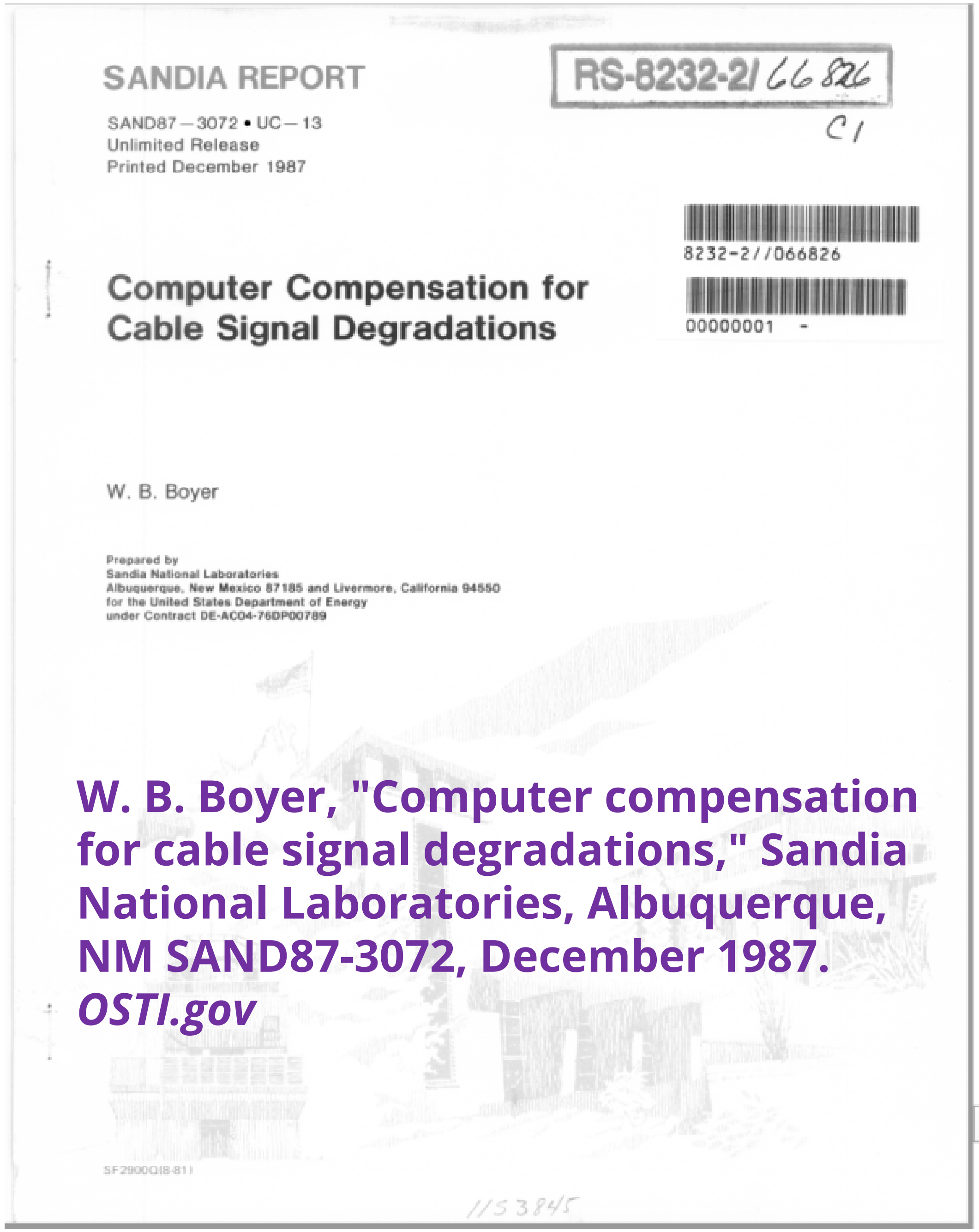
- Bandwidth is easy to characterize on individual components and combined to the whole system
- There are widely-held beliefs that:
  - ~~Time-integration of derivative-responding monitors must be done at the sensor to reduce the effect of cable high-frequency limitations~~
  - ~~Recording derivative signals requires higher bandwidth digitizers~~
- Both of those are false because integration is a linear process
  - Cable response is also linear; the order of execution of two linear processes is immaterial to the result
  - Passive ("RC") integration and numerical integration are both linear
    - We find numerical integration drastically reduces bit noise when using fast sample rates
    - Bit noise is an effective randomizer that allows little data degradation for conservative V/div settings with numerical integration

There is no advantage to passive integration at the monitor. However, the generally reduced signal level (0.01 to 0.1) of integrated signals *lowers* the signal to noise ratio

High-frequency roll-off in cables is linear, predictable, and readily compensated

- **One discussion of numerical cable compensation techniques is given by Bill Boyer in 1987**
  - **Largely based on techniques developed in support of underground testing**

All Z-machine signals are numerically compensated, typically increasing effective cable bandwidth a factor of three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Computer Compensation for
Cable Signal Degradations

W. B. Boyer

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550
for the United States Department of Energy
under Contract DE-AC04-76DP00789

SF2900Q(8-81)

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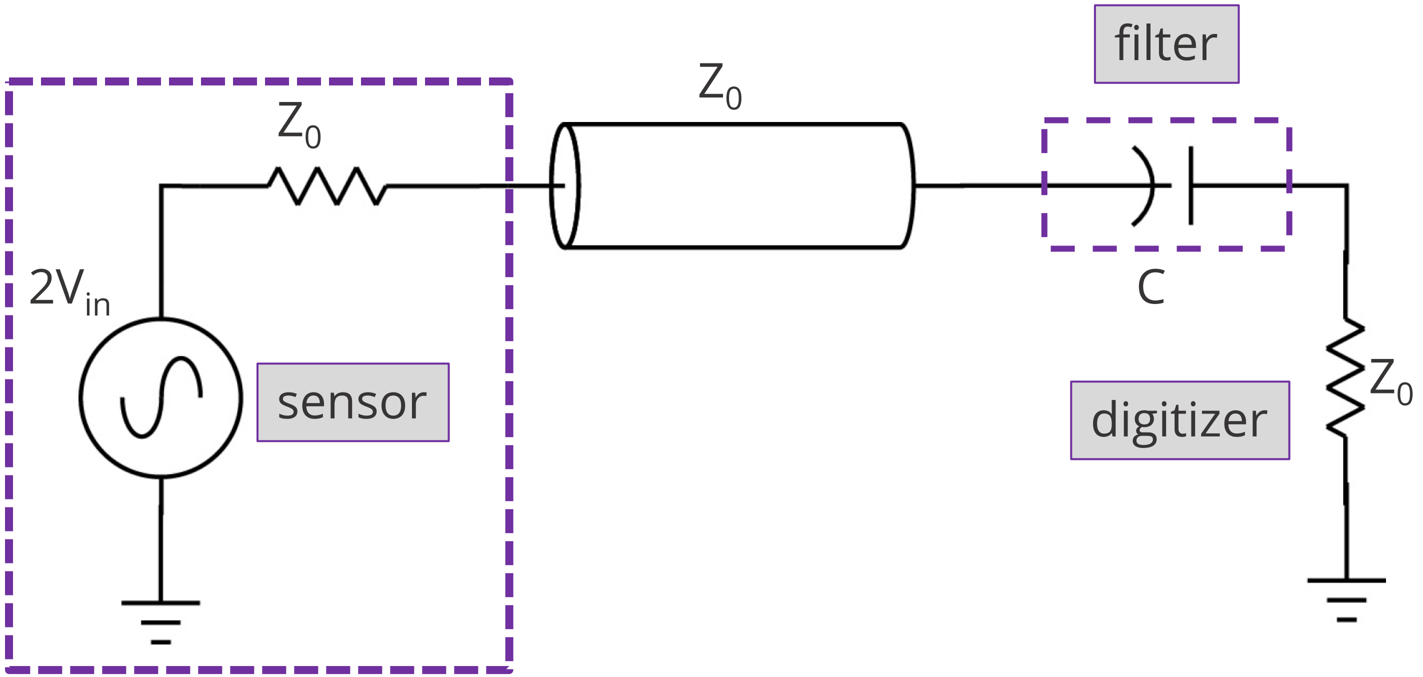
W. B. Boyer, "Computer compensation for cable signal degradations," Sandia National Laboratories, Albuquerque, NM SAND87-3072, December 1987. *OSTI.gov*

Waveform processing

Digital data: signal improvement with post calculations- a simple example

- Often a monitor or recording setup has known deficiencies due to geometric parasitics or intentional circuit changes
- Rather than modify the diagnostic to ideal (often difficult) it is easy to post-correct
- **Consider a simple high-pass filter to block DC baseline offsets from reaching the digitizer**



$$2V_{in} = Z_0 I + \frac{1}{C}\int_{-\infty}^{t} I d\tau + Z_0 I$$

$$I = \frac{V_{out}}{Z_0}$$

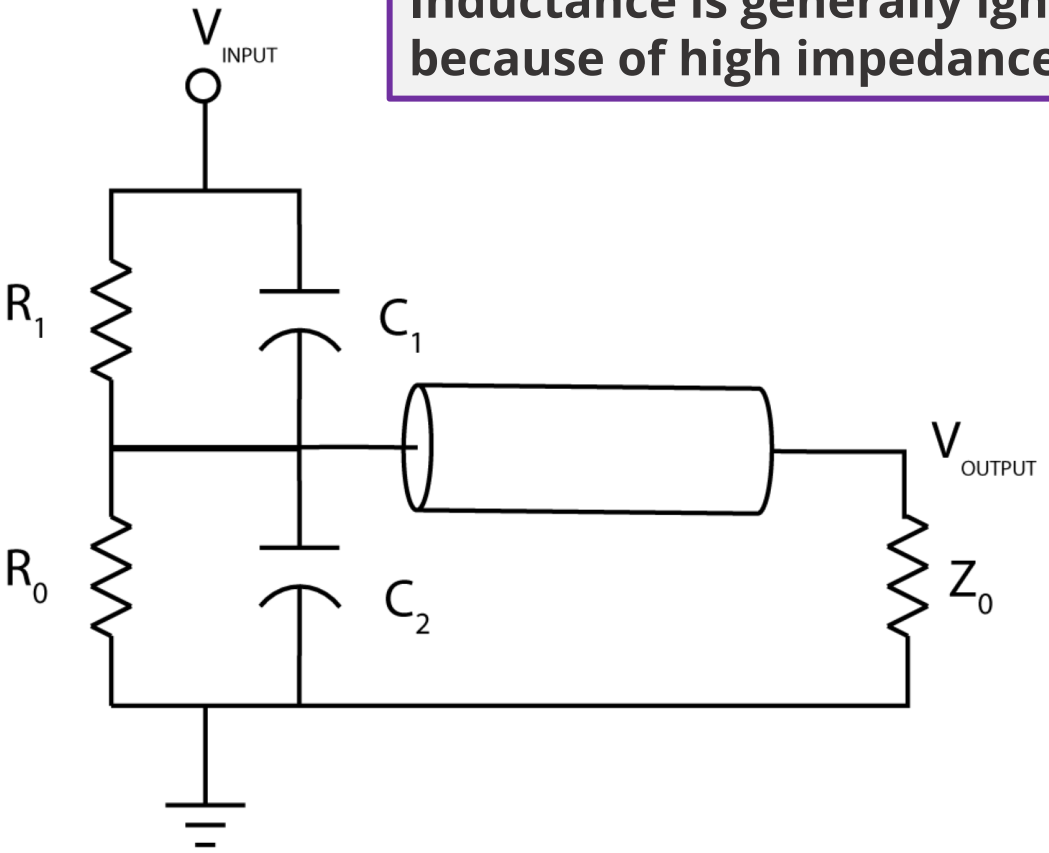
Analytically exact

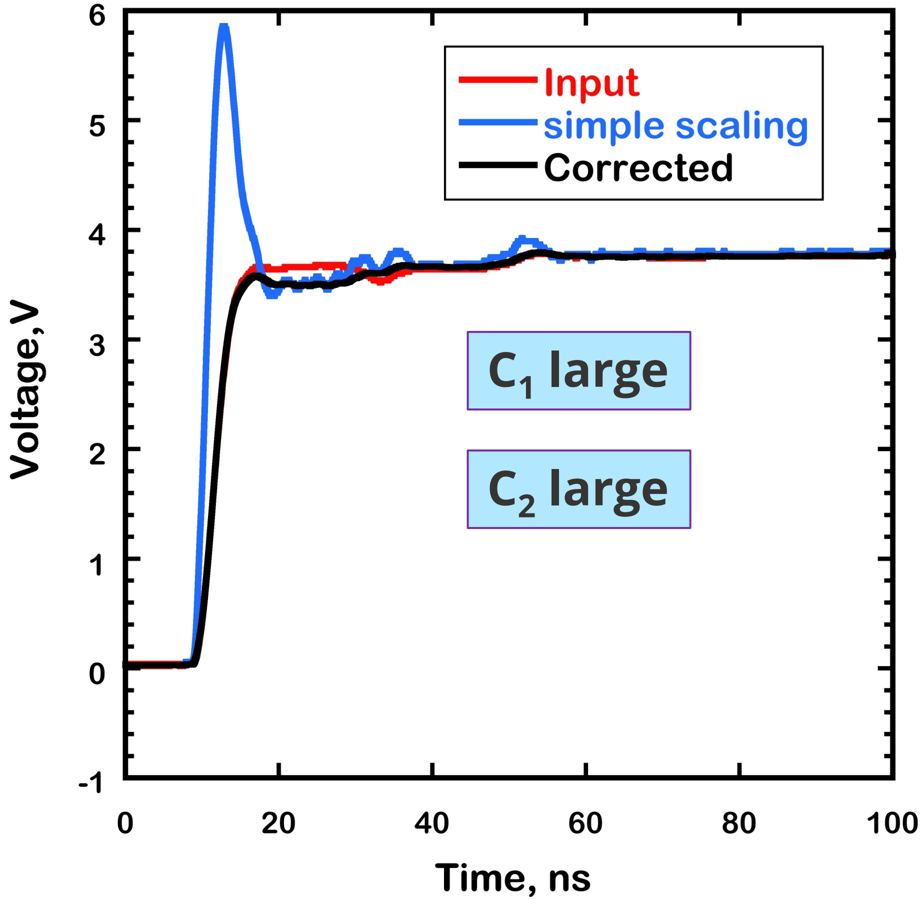
$$V_{in} = V_{out} + \frac{1}{2Z_0 C}\int_{-\infty}^{t} V_{out} d\tau$$

Solution for a general voltage divider:

$$V_{input} = \exp\left[\frac{-t}{R_1 C_1}\right]\left[\frac{1}{R_2 C_1}\int_{-\infty}^{t} V_{output} \exp\left[\frac{t}{R_1 C_1}\right] d\tau + \frac{C_2}{C_1}\int_{-\infty}^{t} \frac{dV_{output}}{dt} \exp\left[\frac{t}{R_1 C_1}\right] d\tau\right]$$

Inductance is generally ignorable because of high impedance

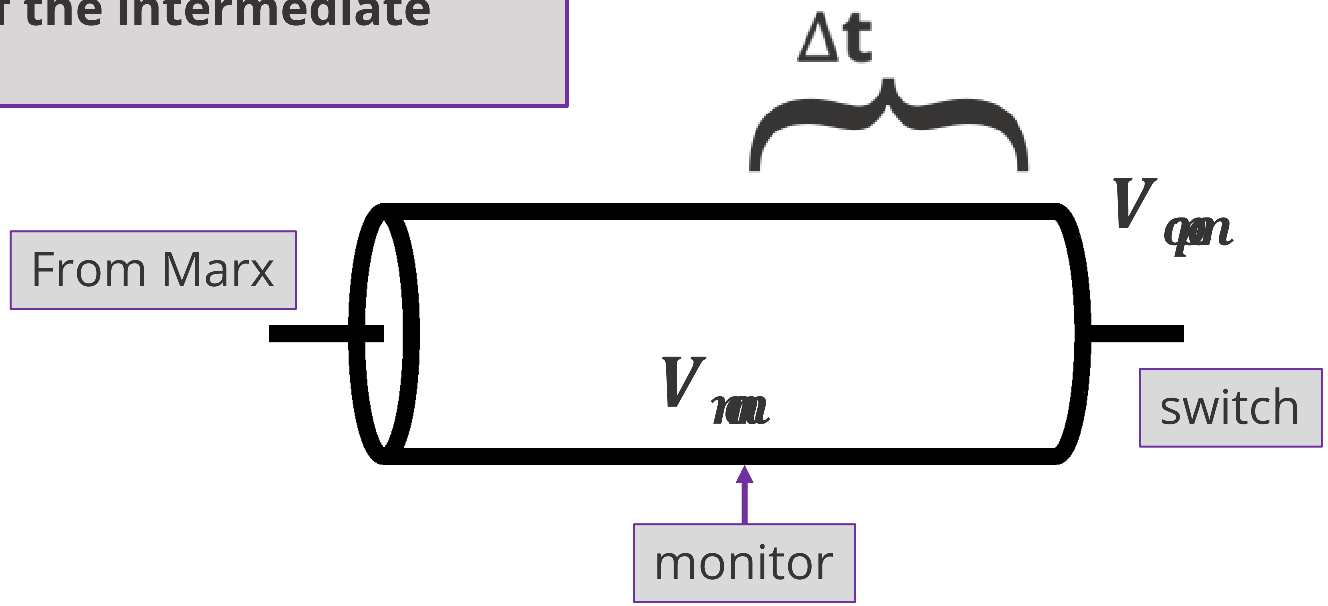




We wanted to estimate the actual laser-triggered gas switch voltage to set the pressure

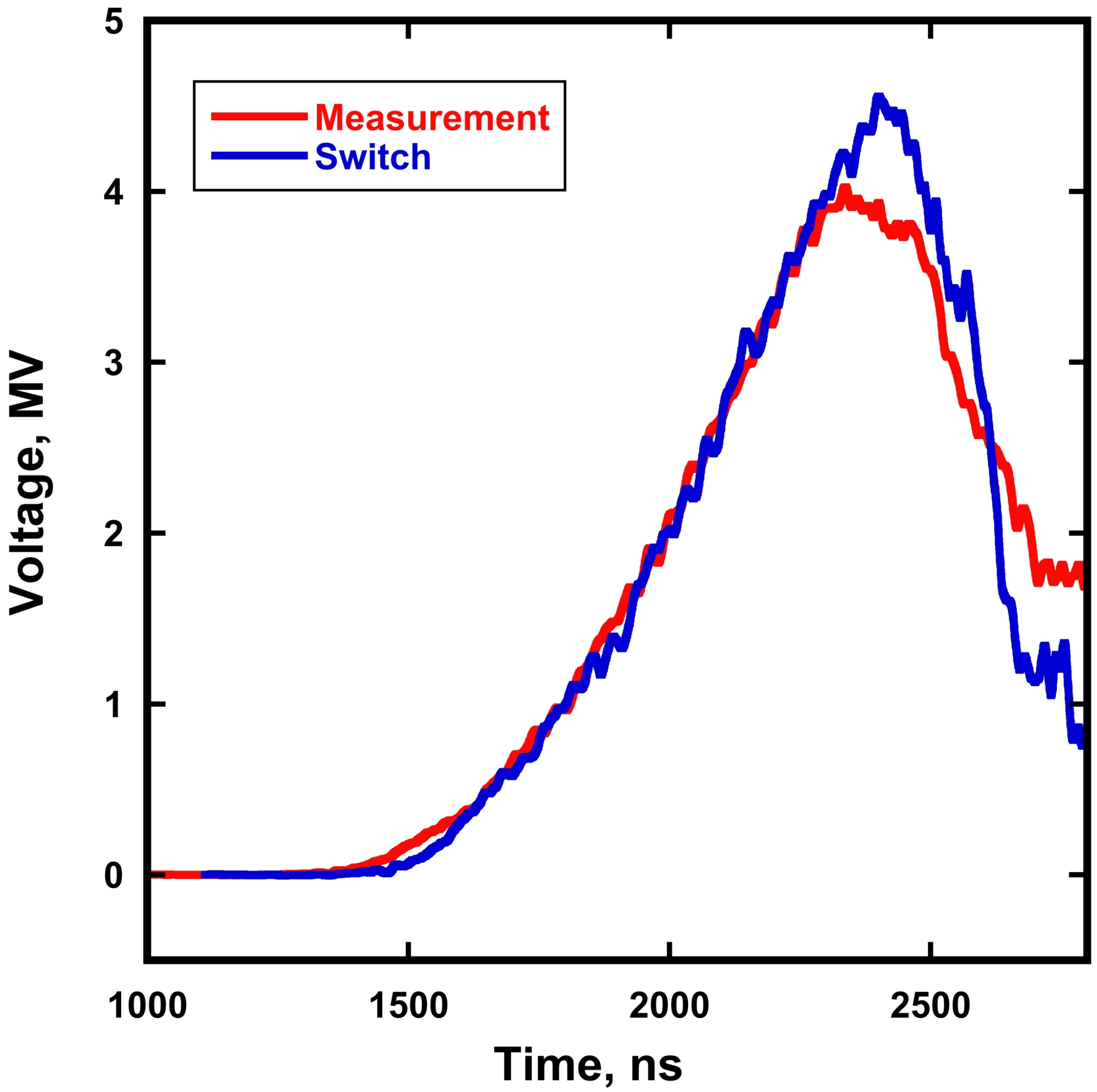
The voltage measurement is in the middle of the intermediate store capacitor, and the switch is at the end

ZR intermediate store capacitor



$$V_{open} = 2\sum_{i=0}^{\infty}(-1)^{n}\,V_{mon}(t+(2n+1)\Delta t)$$

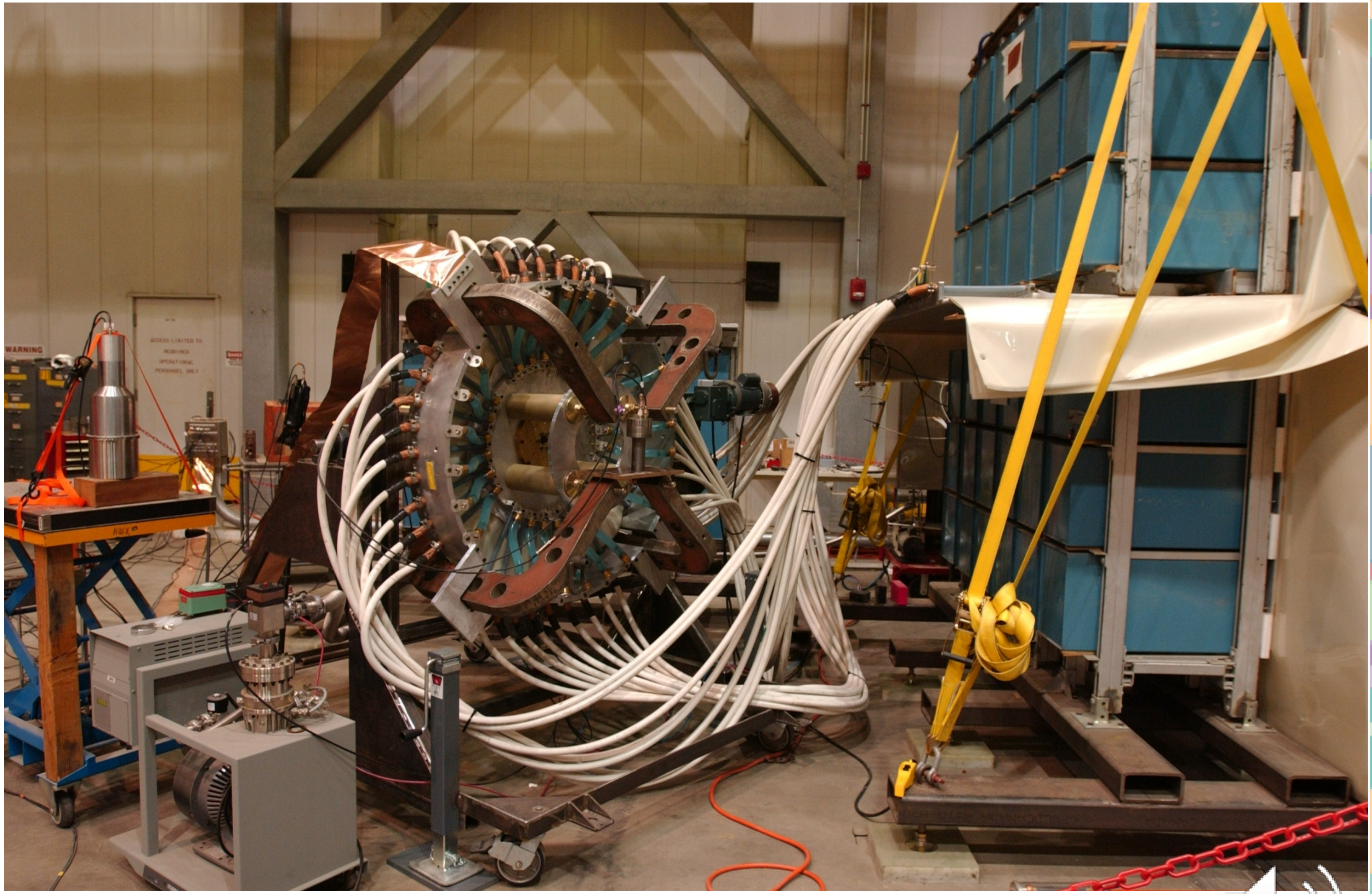
There is a difference in voltage despite the short transit time compared to the rise time



Knowing the peak switch voltage accurately is important for setting the switch pressure

Basic measurements on the NNSS dense plasma focus

- In a collaboration with NNSS, LANL, and LLNL, Sandia set out to make independent measurements of voltage and current on the DPF
  - ~2 MA
  - ~100 kV
  - ~6 μs
- Current measured with a segmented Rogowski belt
- Voltage measured with a hybrid RC divider



The plasma focus accumulates magnetic energy while a current sheet translates through a static fill gas

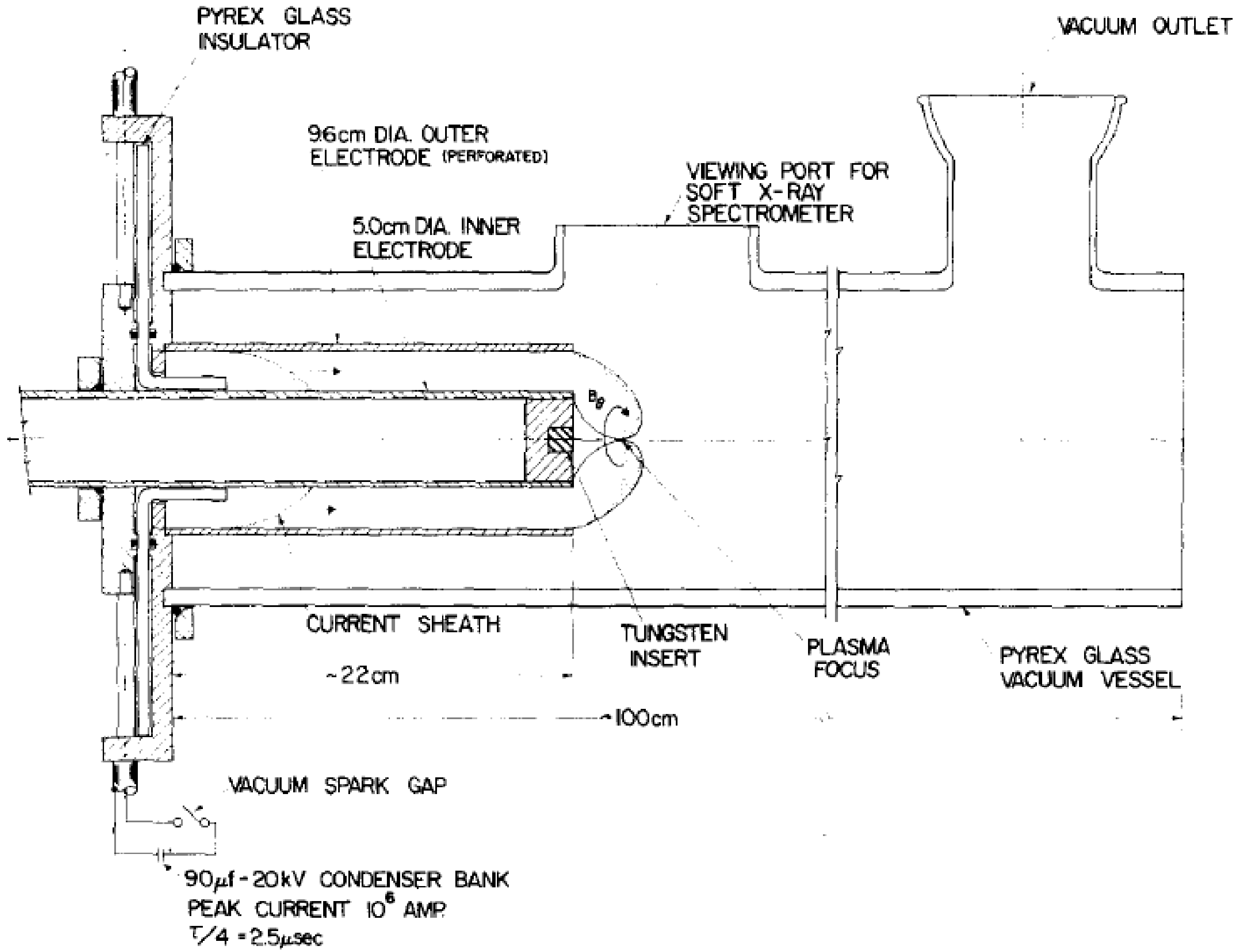
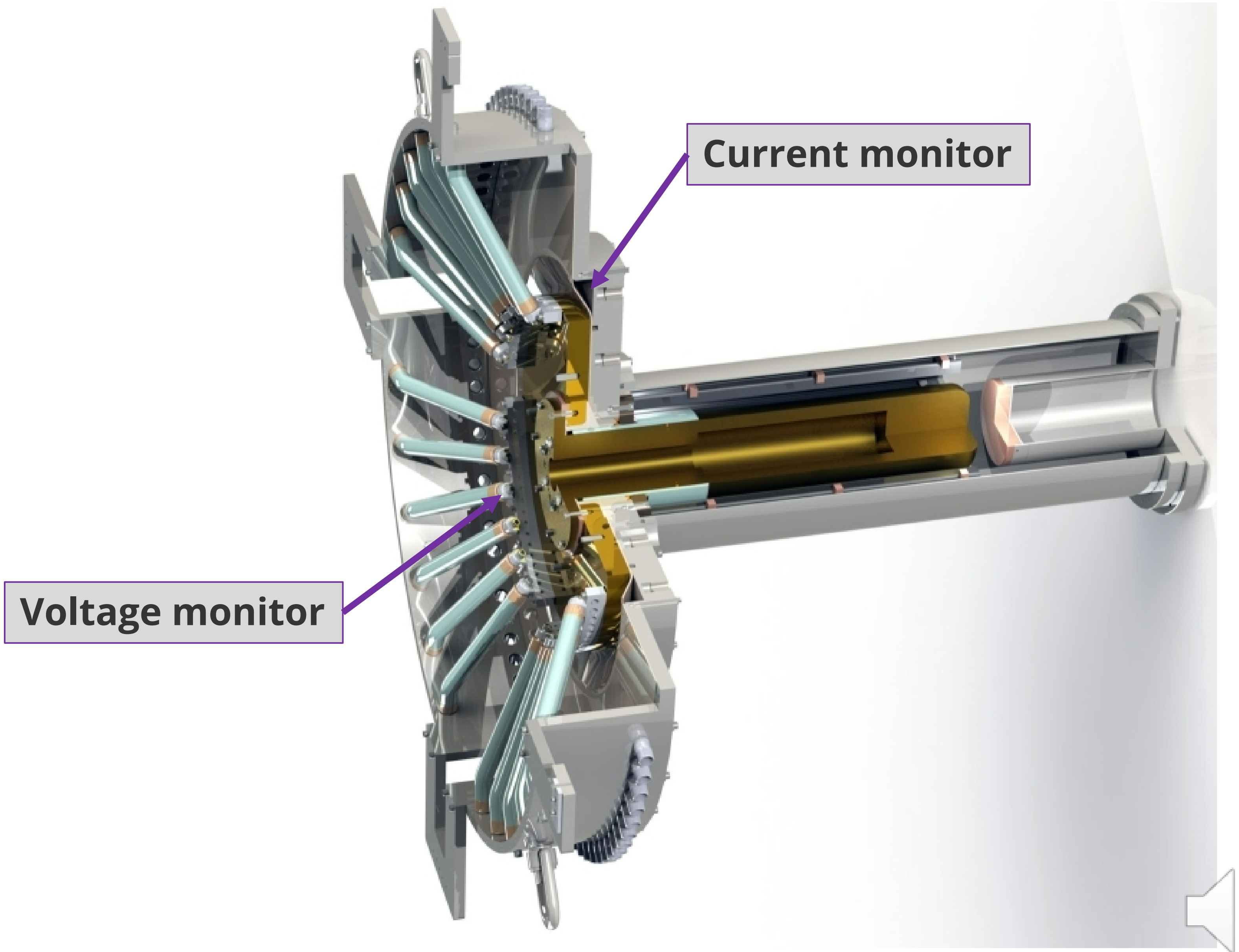


Fig. 1. Schematic representation of the dense plasma focus apparatus.

J.W. Mather in Methods of experimental physics, 1971

The dense plasma focus is a dynamic load: inductance changes significantly

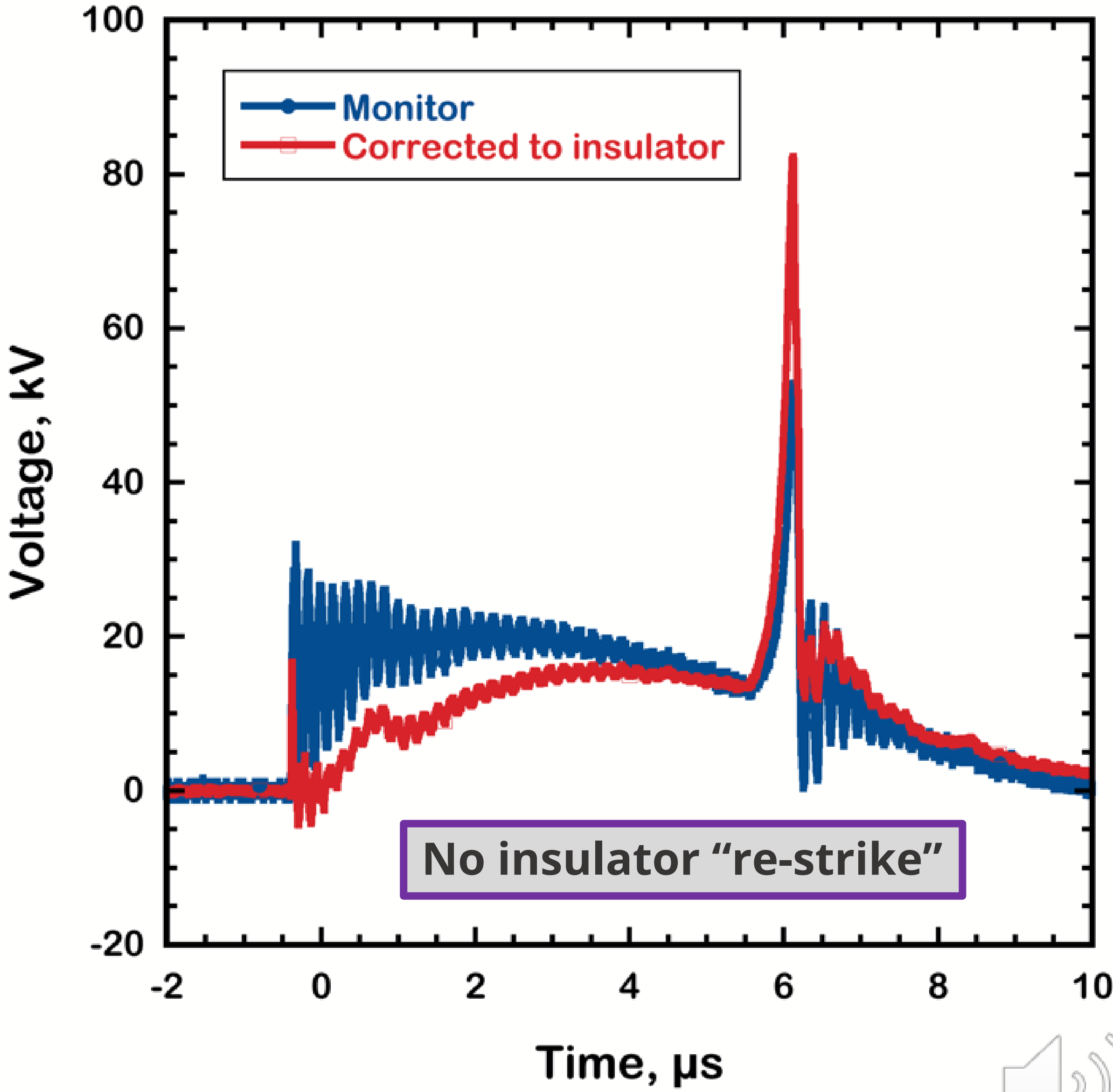
- With accurate voltage and current measurements it is simple to resolve the time-varying inductance
- The goal was investigating possible causes of variations in neutron yield



Neither a resistive divider nor a V-dot was ideal for the DPF voltage measurement

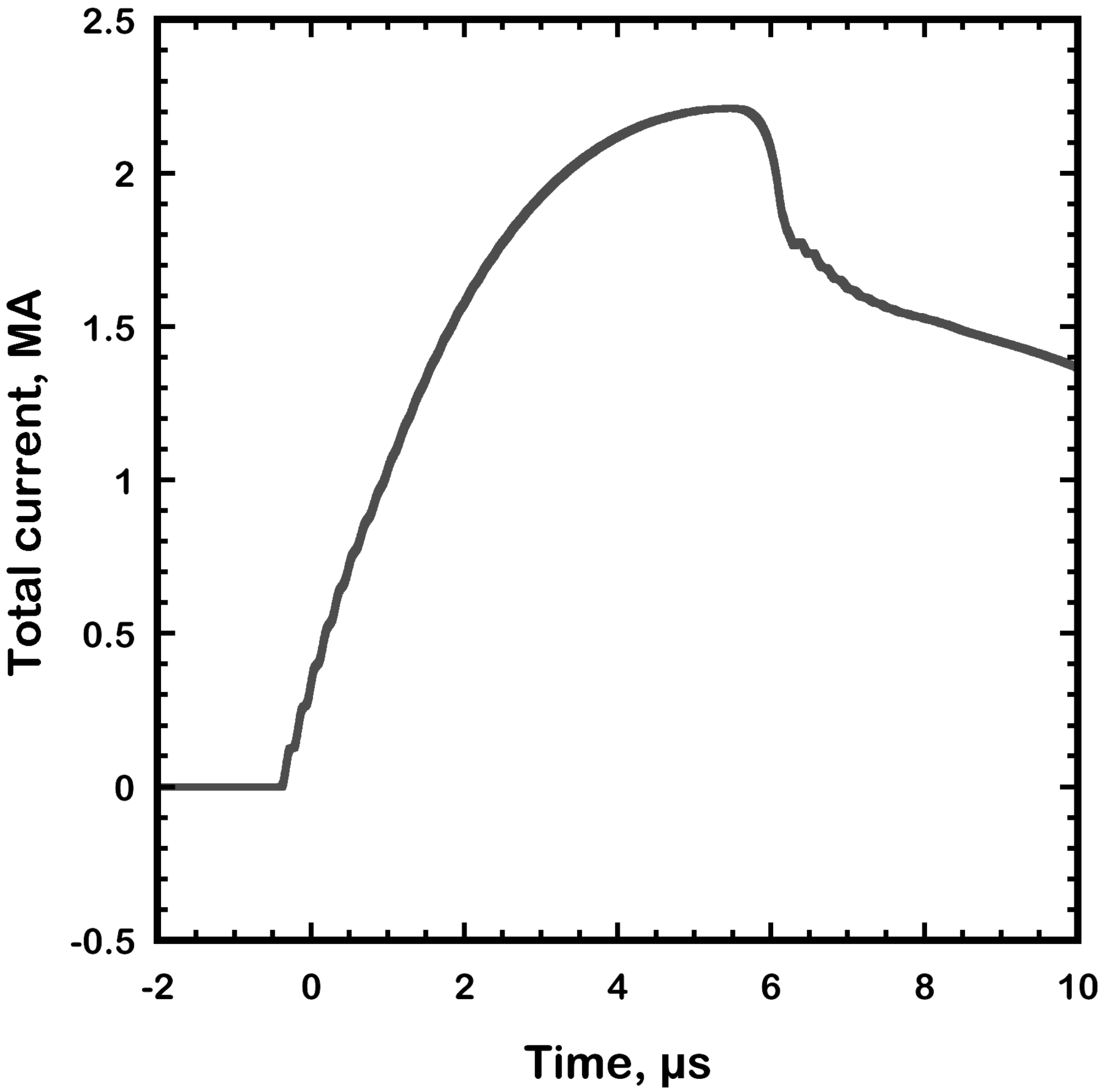
- In a resistive divider, the precision, low voltage-coefficient resistors would be damaged if DPF current were delayed a few μs
- The slow signal made monitor voltage from a pure V-dot small
- The solution for a reliable monitor was to make a divider with a series capacitor to limit resistor energy

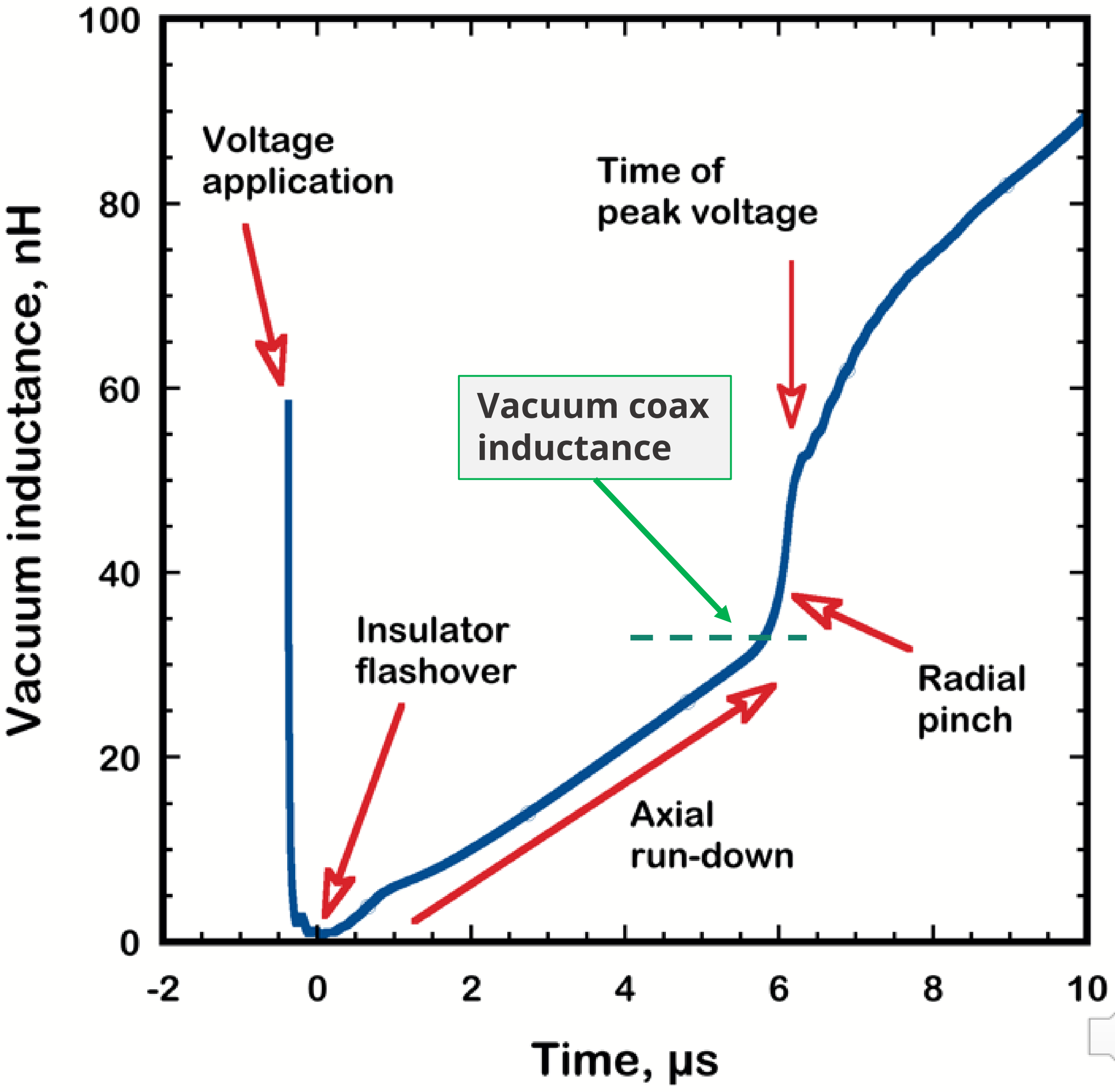
DP



$$V_{in} = V_o\left[1 + \frac{R_1}{Z_0}\right] + \frac{1}{Z_0 C}\int_{-\infty}^{t} V_o \, d\tau$$

With voltage and current at the DPF vacuum insulator, we can calculate energy delivered and inductance

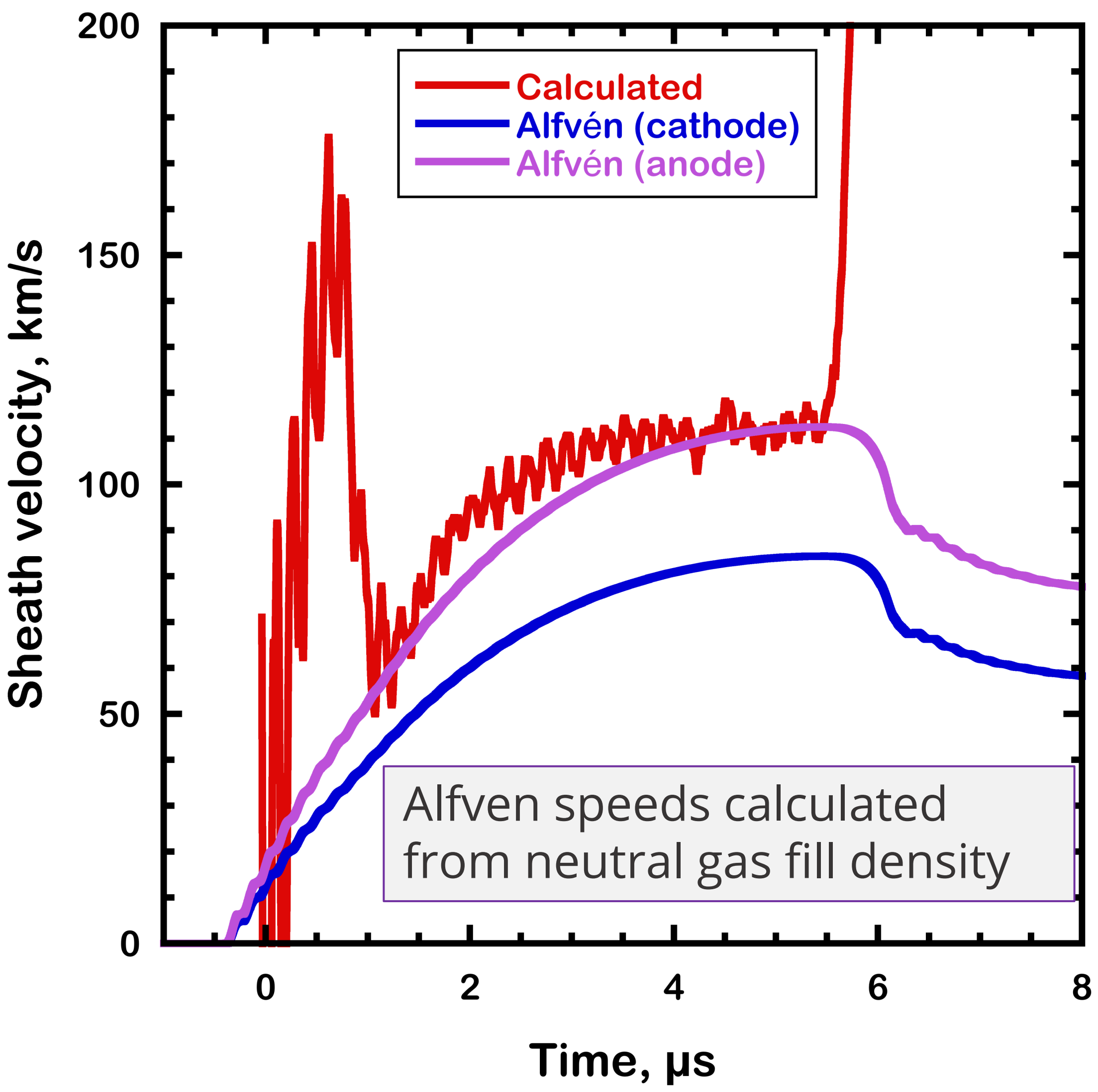




With current and inductance it is possible to calculate DPF current sheath velocity

- **Because the magnetic pressure is higher at the anode, the current sheet is angled**
- **More of the magnetic energy is near the anode, dominating the inductance**

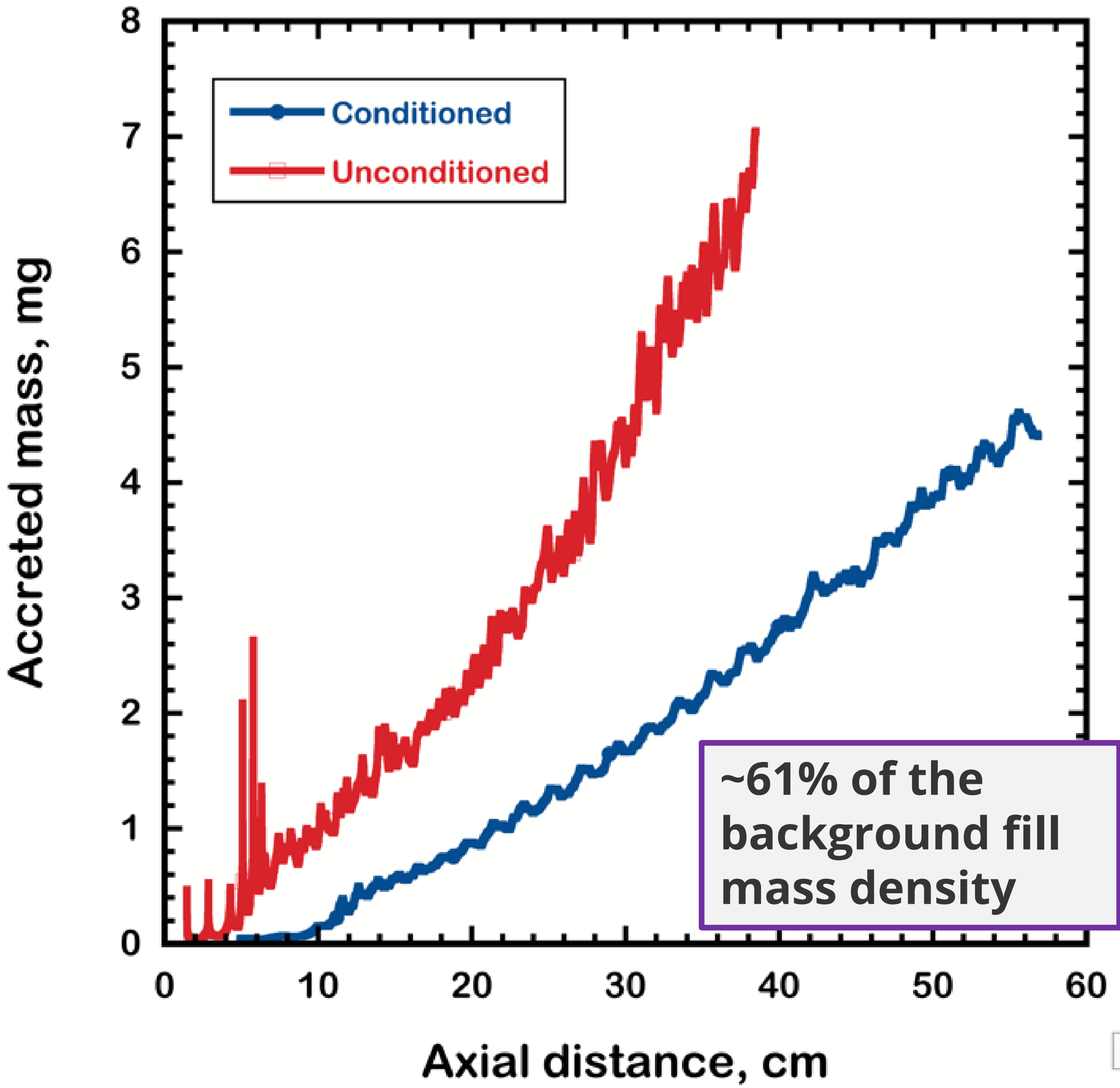
$$v = \frac{dL}{dt}\frac{c}{Z_{vacuum}}$$



And finally the accreted plasma mass

- **The calculated mass is less than the fill density but the angled sheath may eject mass radially outward**
- **Much larger accreted mass on unconditioned electrodes indicates desorbed contaminants**

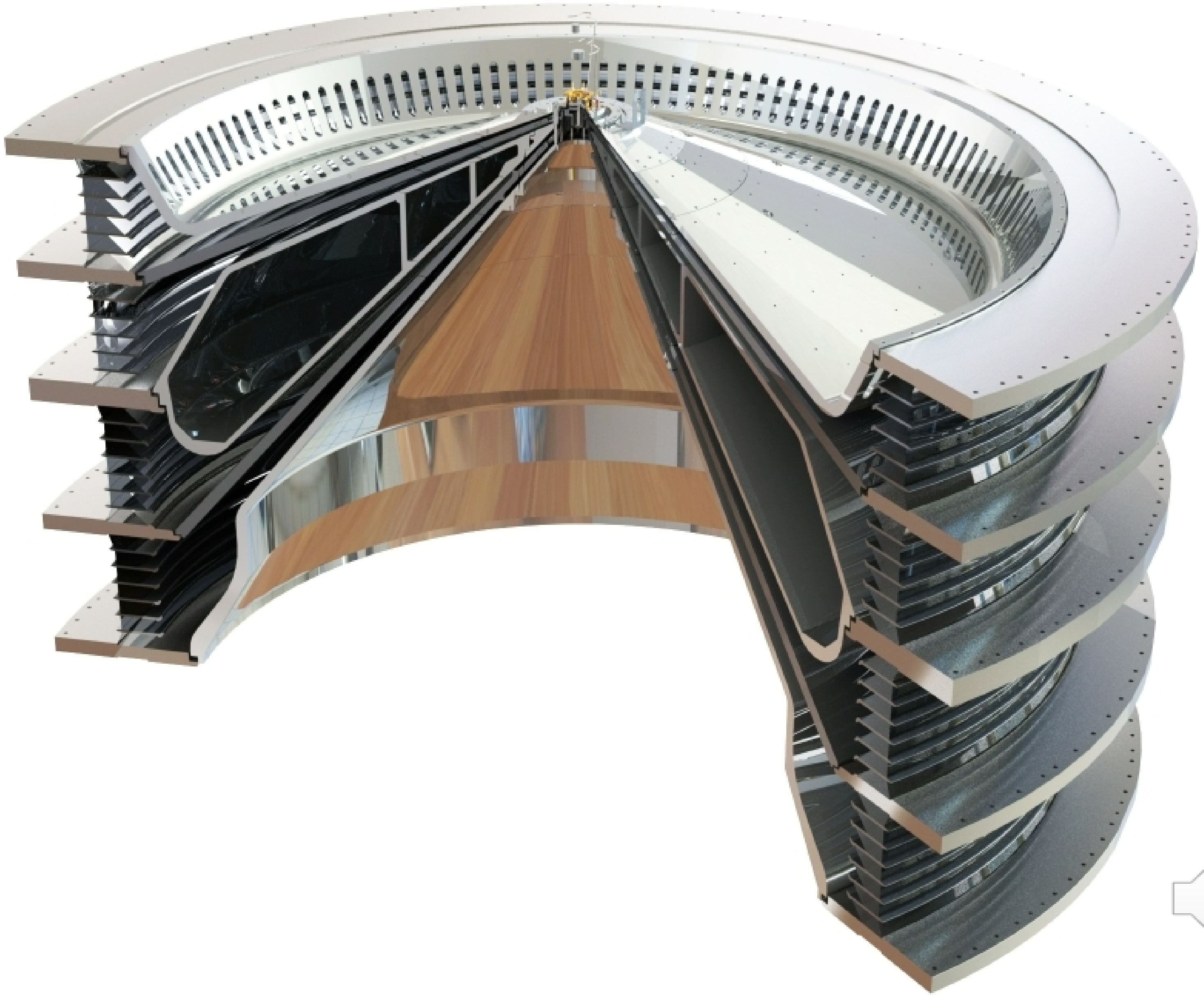
$$m(t) = \frac{{Z_{vacuum}}^2}{2c^2 \frac{dL}{dt}} \int_{-\infty}^{t} I^2 d\tau$$



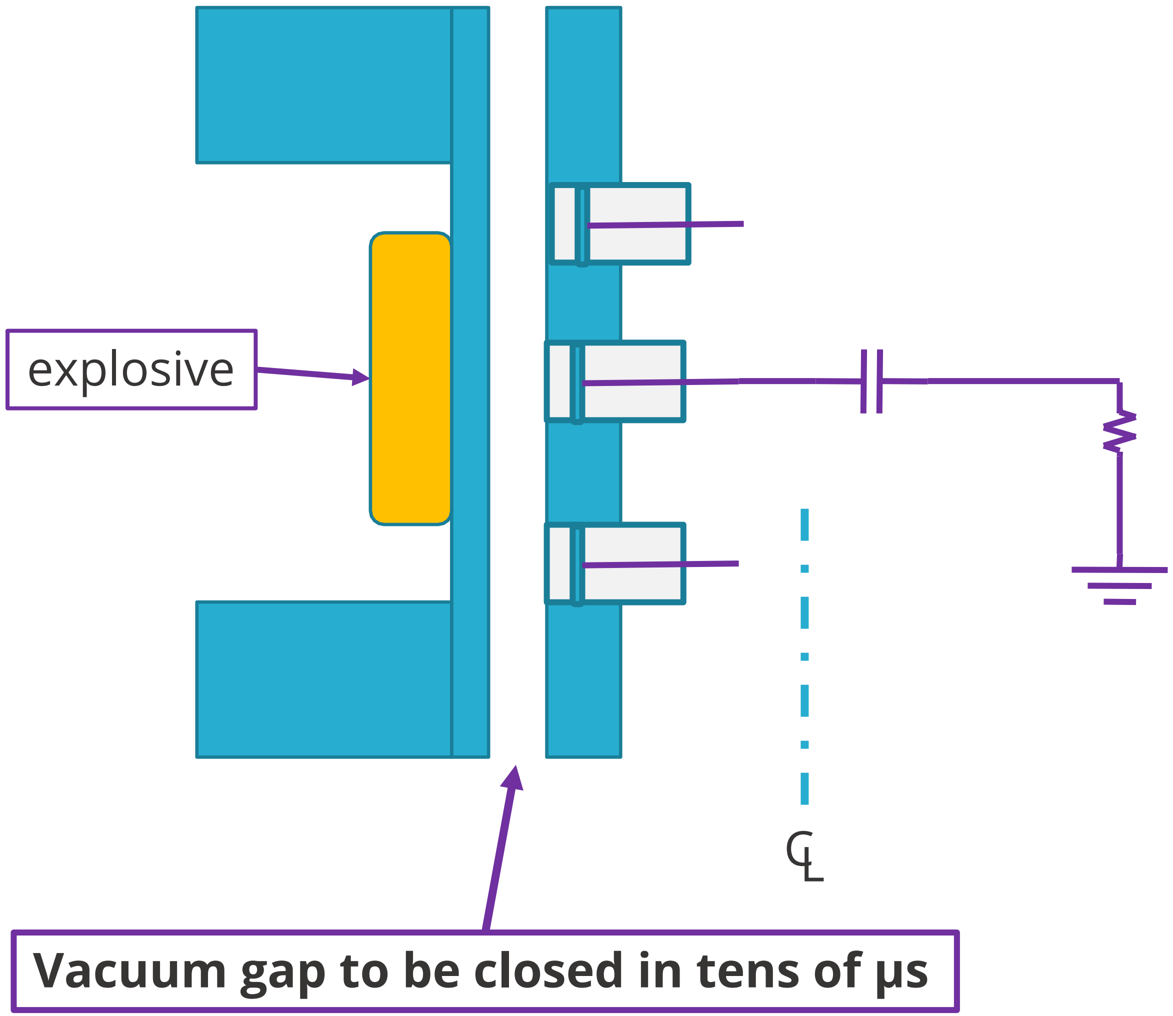
~61% of the background fill mass density

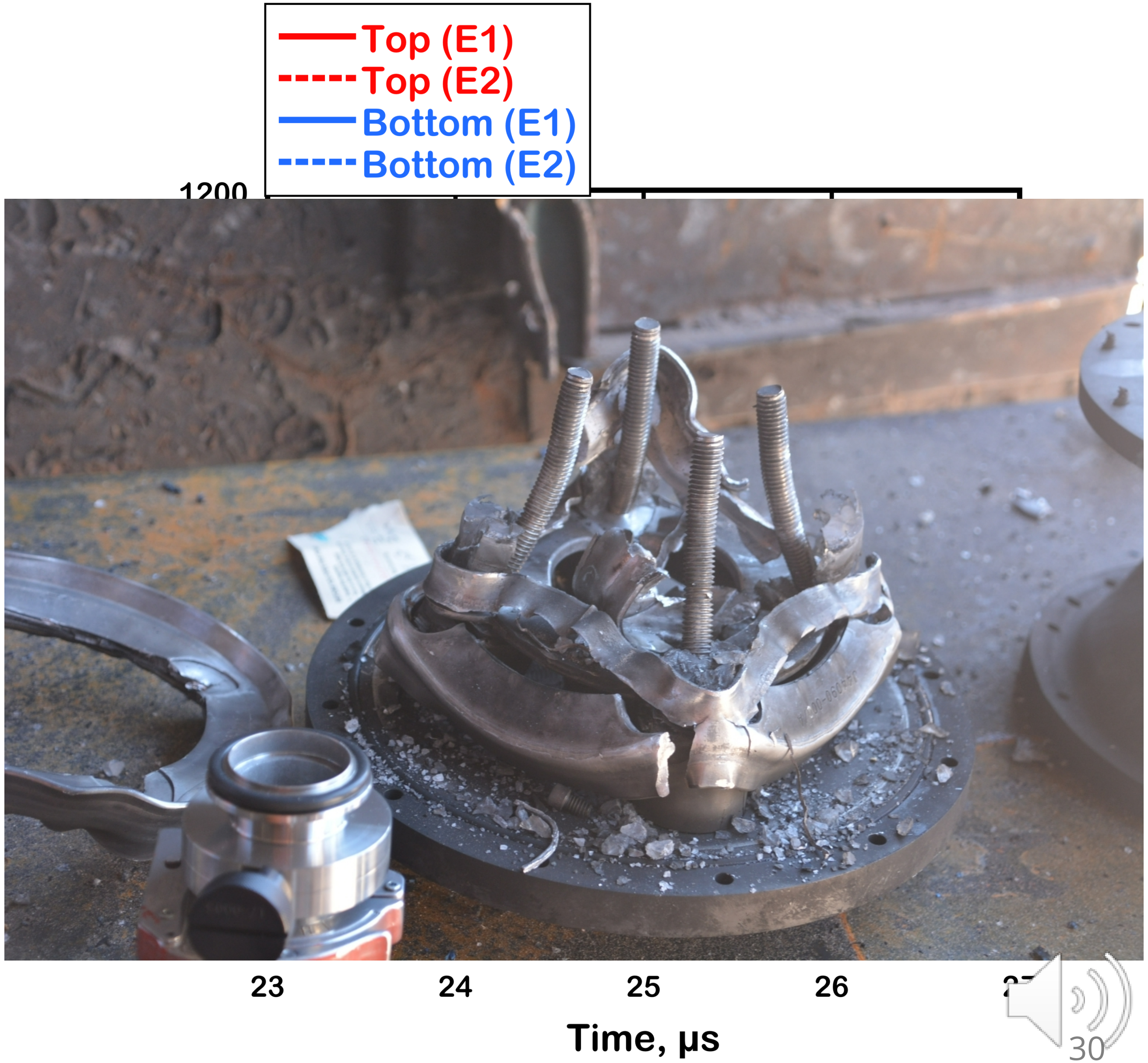
Explosive valve closure velocity measurement

- **Some material physics experiments on Z use hazardous or toxic materials**
- **To prevent contamination of the entire vacuum section, a fast closing valve is used to isolate the load region after the Z current pulse**
- **To independently detect closure and neutral gas that PDV optical diagnostics cannot see, we used a simple biased probe**



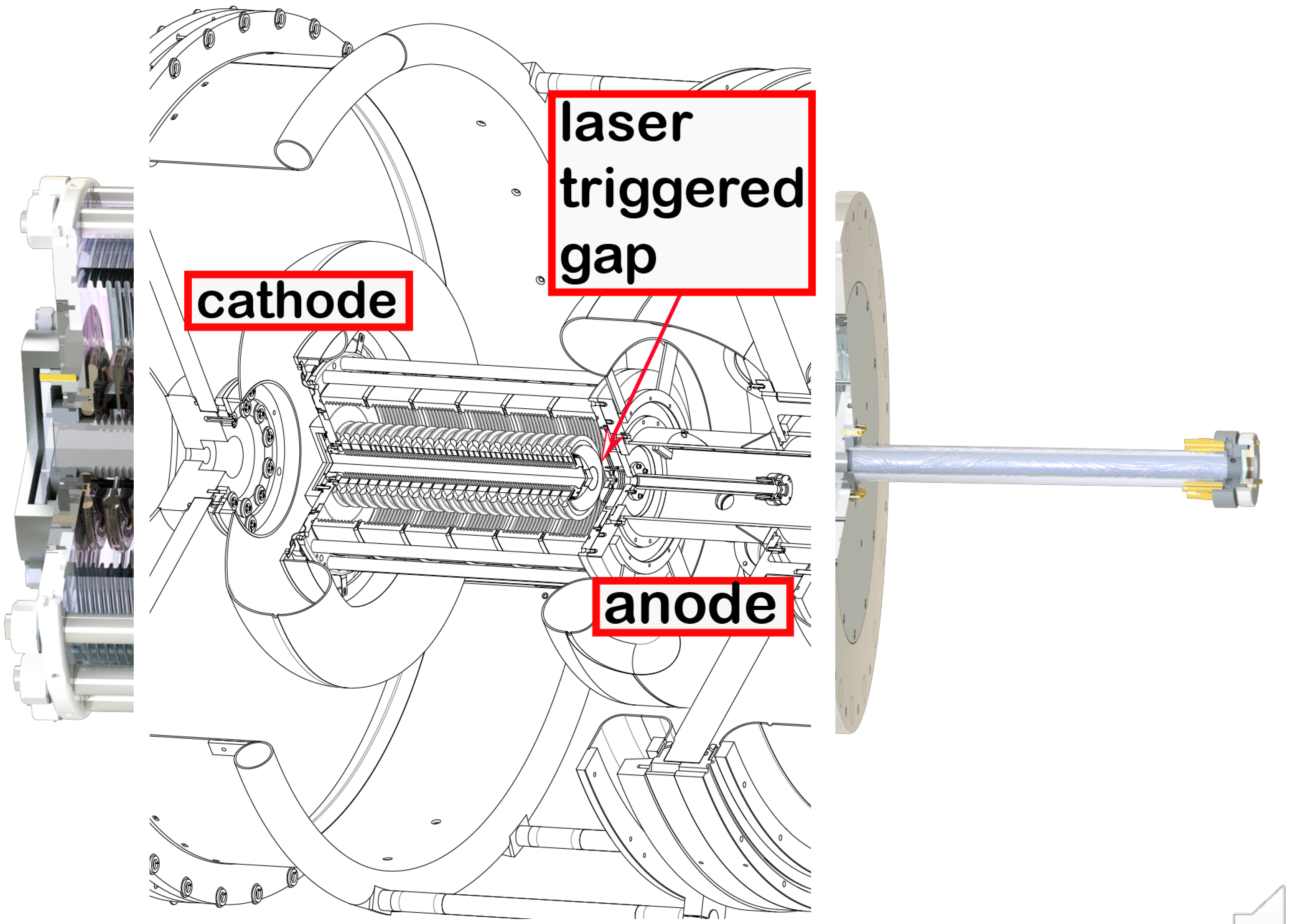
A simple probe biased to 1 kV shows electrode motion and would detect neutral gas





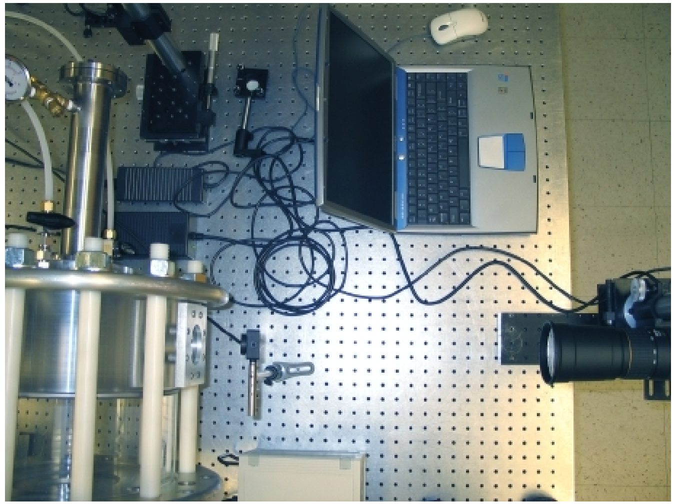
Length of laser-generated spark

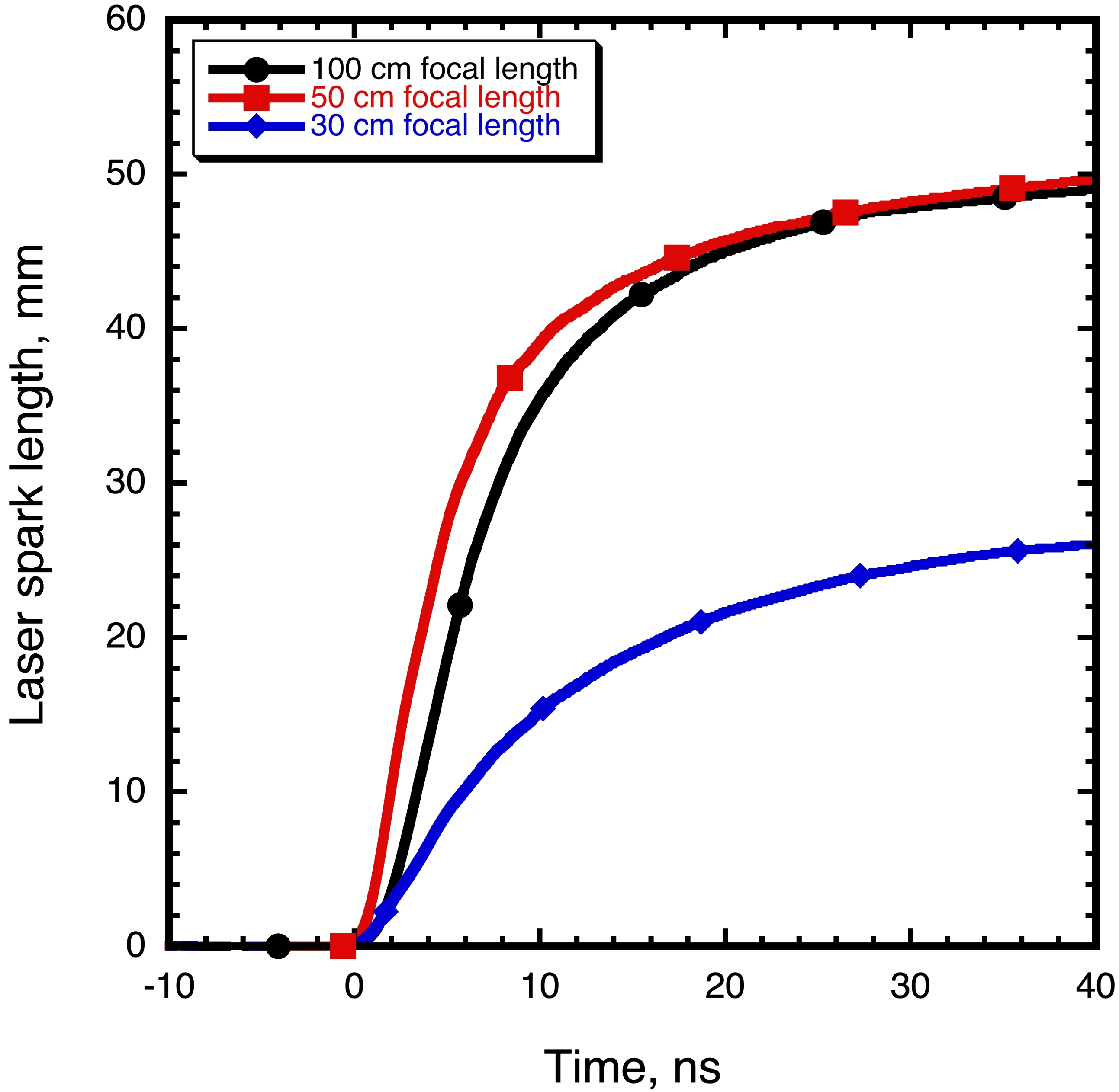
- The Z laser-triggered gas switches rely on ionization of switch gas by a UV laser
- Quantifying the axial spark length has been done by visible light emission and interferometry but both are affected by detector sensitivity
- An electrical measurement can measure the actual useful spark length



Laser triggering is an important part of precision switching

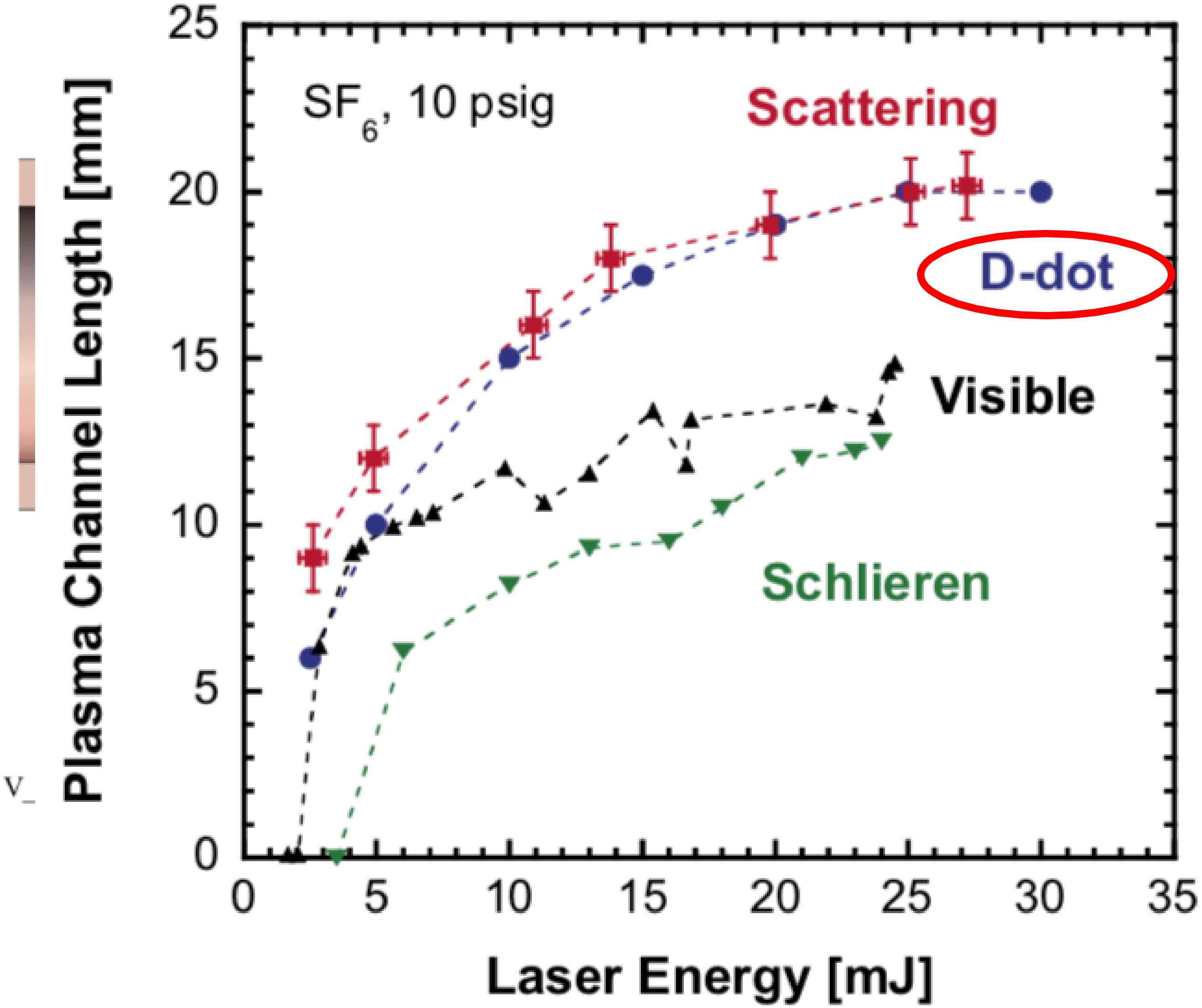
- **Characterizing and optimizing laser triggering was done with a variety of tools**
  - **Optical diagnostics (plasma self-emission, interferometry)**
  - **Electrical measurements (time-resolved spark length)**





Conductivity of laser plasma provides capacitive coupling between two cylinders

- The length of the plasma channel is the key parameter
- The capacitance measurement as well as a microwave scattering diagnostic respond to conductivity
- Laser plasma conductive length is the best predictor for switch triggering and may be a less subjective measure



Gilmore et al, 2009 IEEE Pulsed Power Conference

Summary

- Pulsed power systems are electrical devices; accurate current and voltage measurements are fundamental
- Conceptually simple steps will reduce signal noise
- Waveform integration, cable attenuation, and circuit post-processing are all linear processes; the order executed and corrected is unimportant
- Simple circuit analysis can be applied to waveform data after acquisition to correct for non-ideal monitors
- Simple electrical measurements can provide useful information about dynamic systems with minimal creativity