HV Generation, SQUID Applications in SNS nEDM

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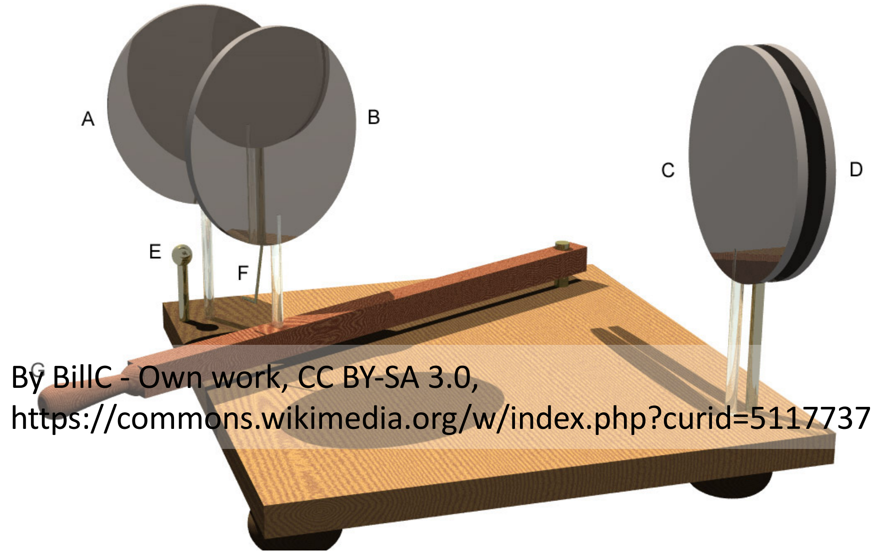
Methods to produce high voltage

- Van de Graff
- Cockcroft-Walton/Greinacher
- Marx Generator
- …

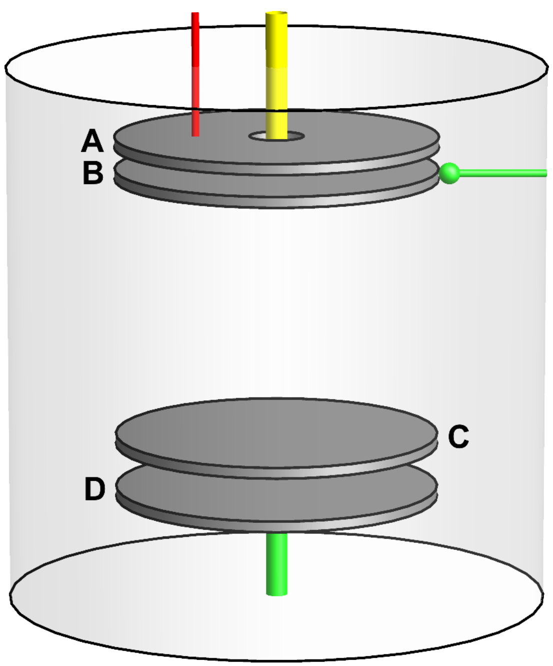
- Most are not suitable for cryogenic operation (doesn’t work, or produces too much heat)
  - Heat from friction
  - Diode operation at <1 Kelvin
  - Heat from moving charge across diode drops
  - …

Cavallo Multiplier Concept

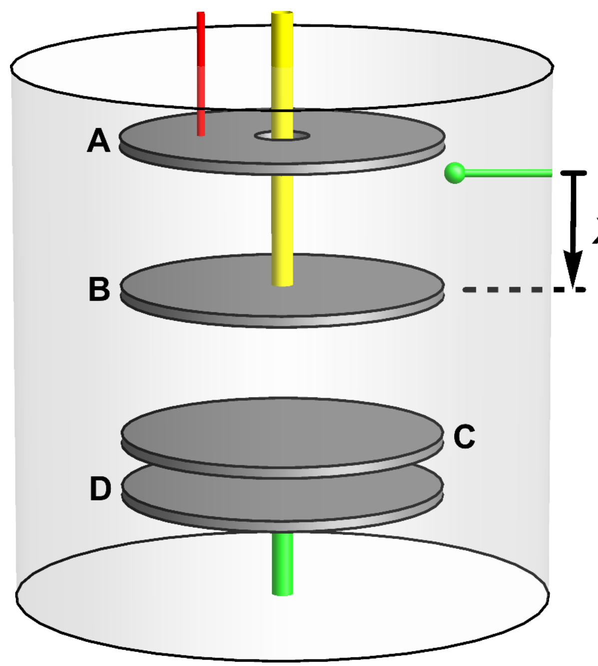
The "Cavallo Multiplier" is a 200+ year old method to amplify a voltage.



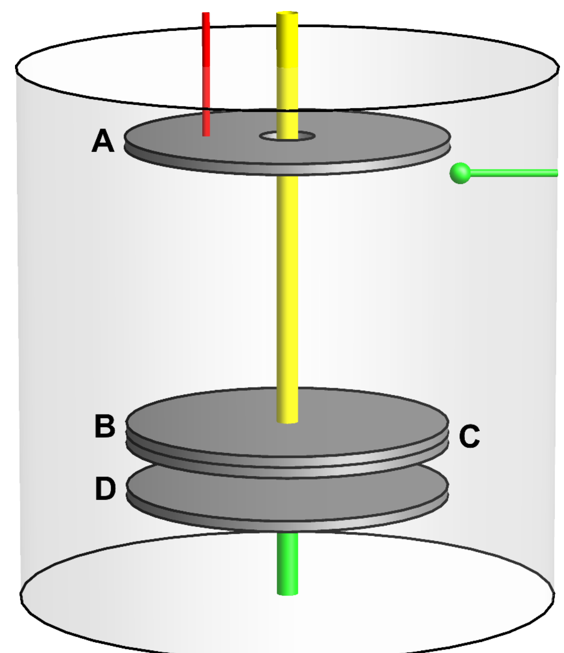
Induce charge on Plate B with $V_B = 0$



Disconnect ground from Plate B, move toward Plate C. $Q_B \sim -C_{AB} V_A$



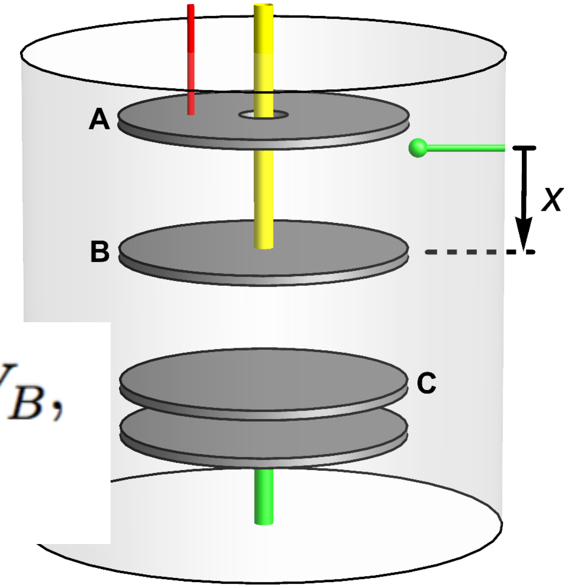
Touch Plate B to Plate C, transferring charge.

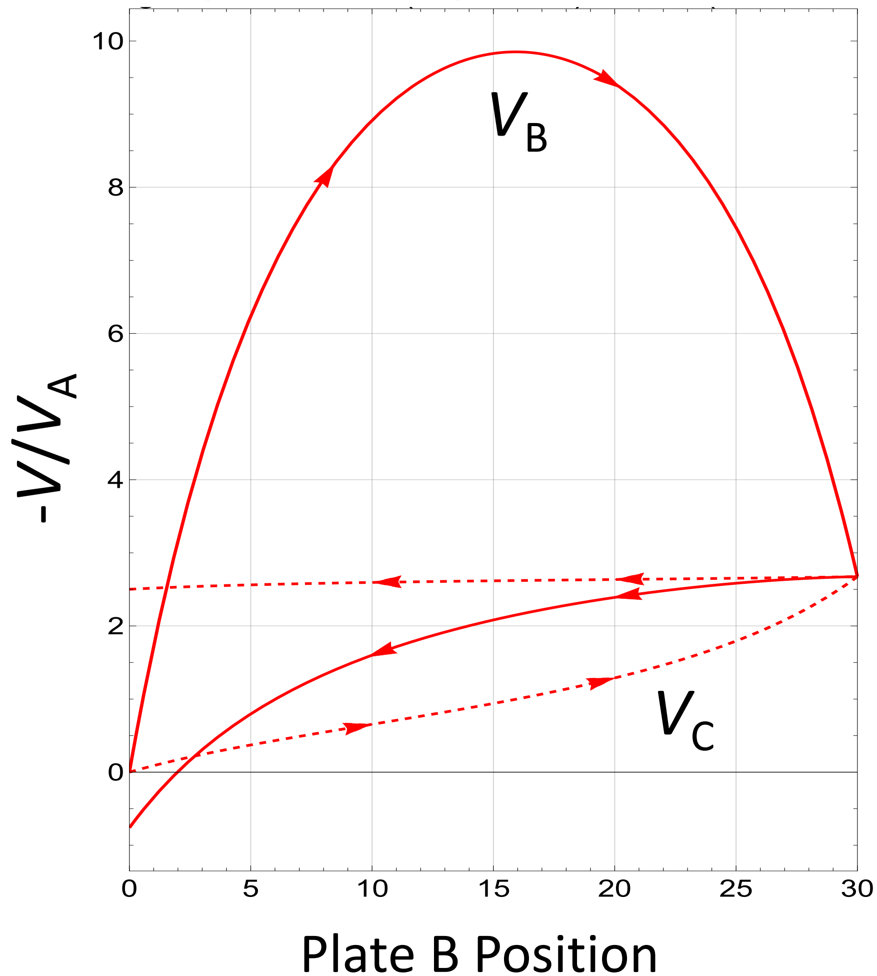


Prediction of Voltages

Expression in terms of mutual capacitances C_{ij}:

$$Q_B = C_{AB}(V_B - V_A) + C_{BC}(V_B - V_C) + C_{BG}V_B,$$
$$Q_C = C_{BC}(V_C - V_B) + C_{CG}V_C,$$

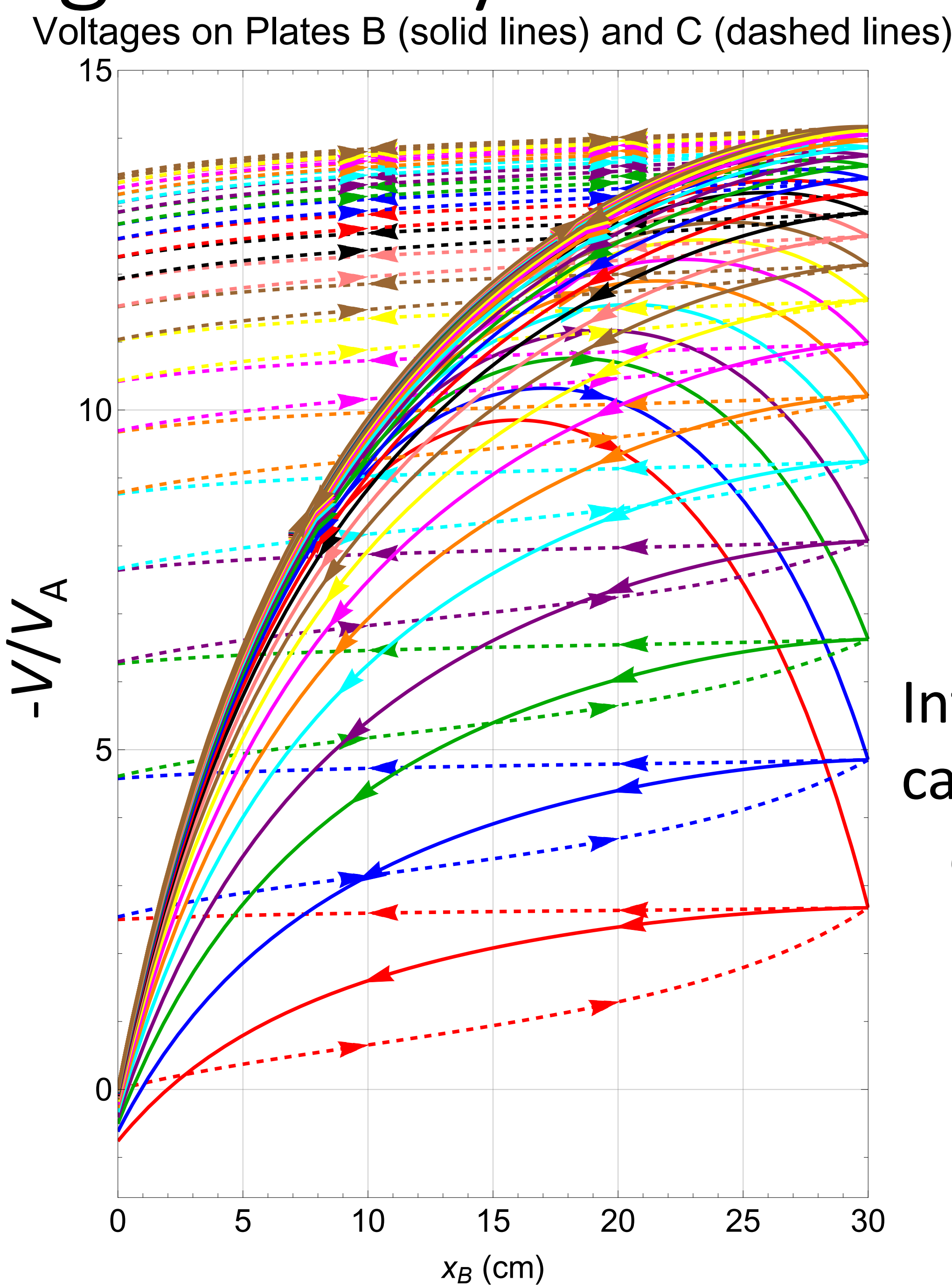


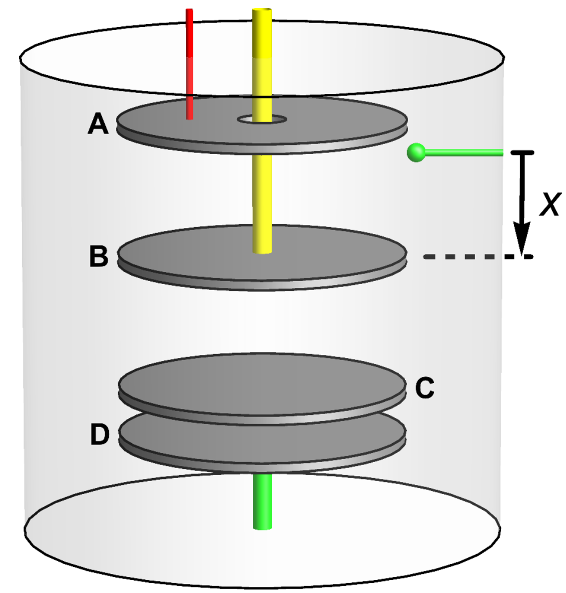


Infinite parallel plate capacitor model:

$$C_{ij} = \varepsilon_0 A / |x_i - x_j|$$

Voltages in Toy Model

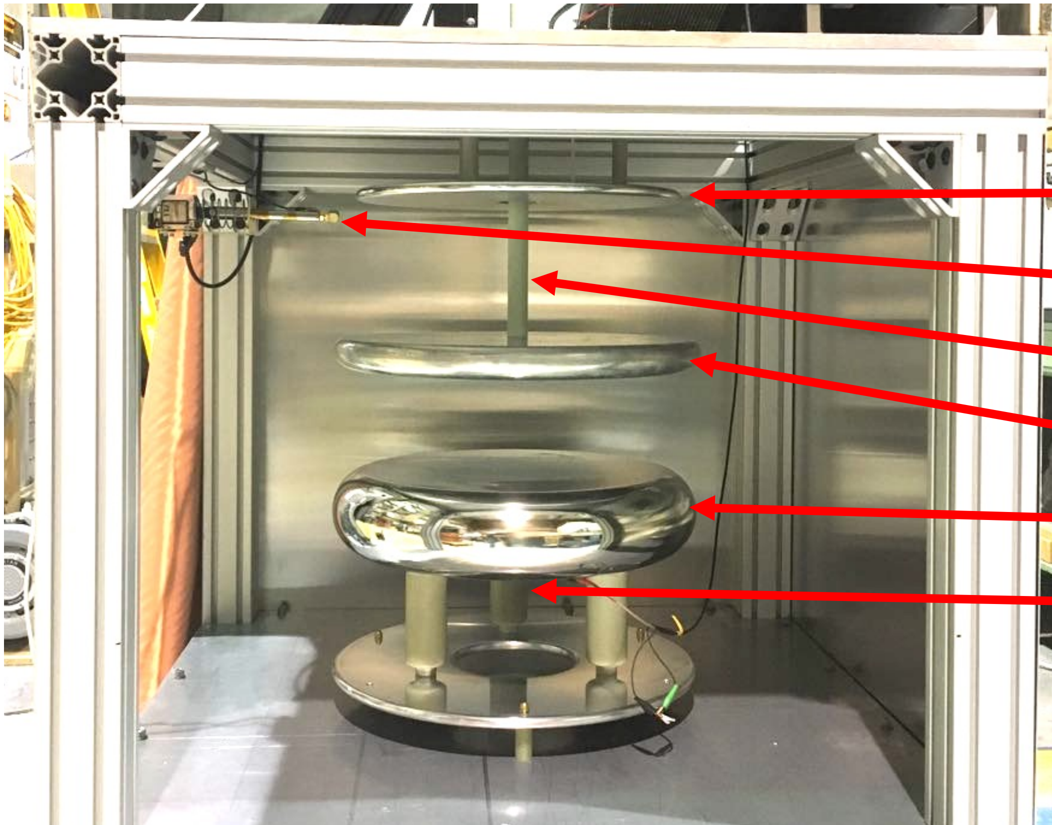




Infinite parallel plate capacitor model:

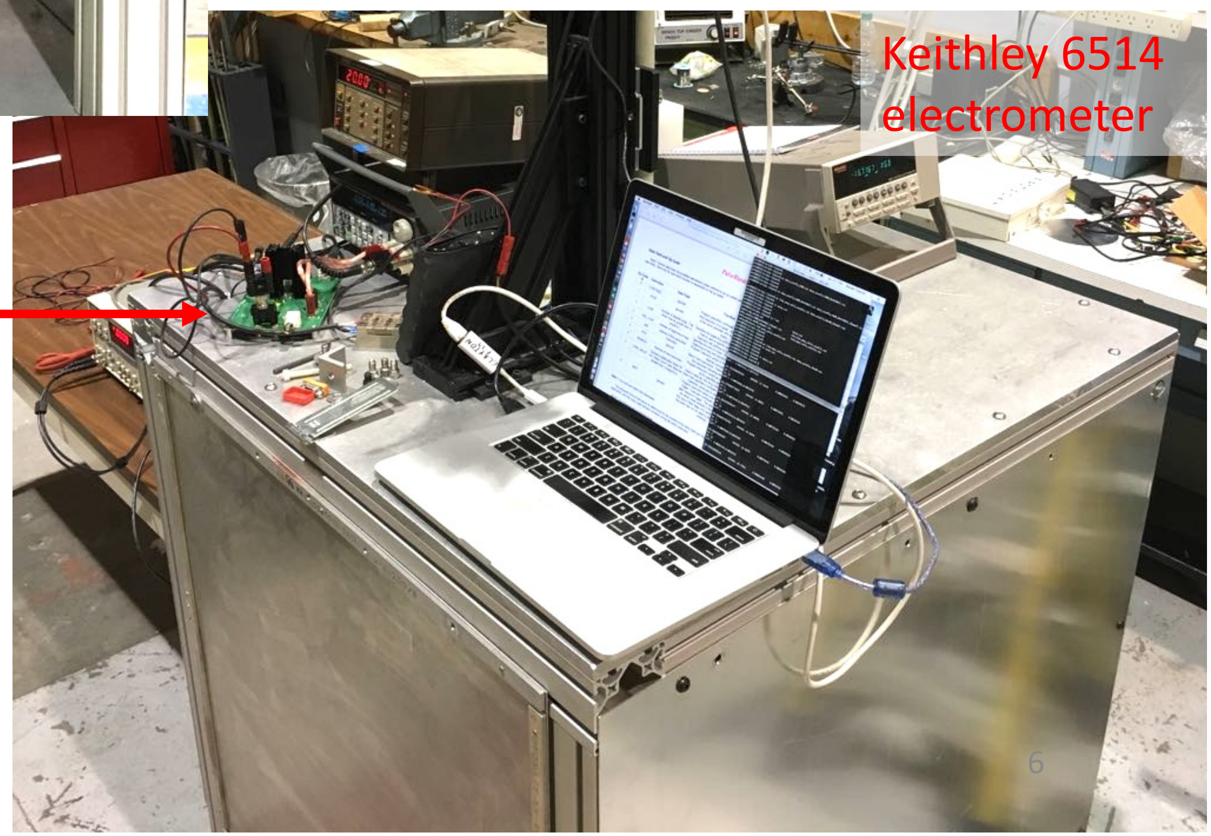
$$C_{ij} = \varepsilon_0 A/|x_i - x_j|$$

Cavallo Demo Apparatus



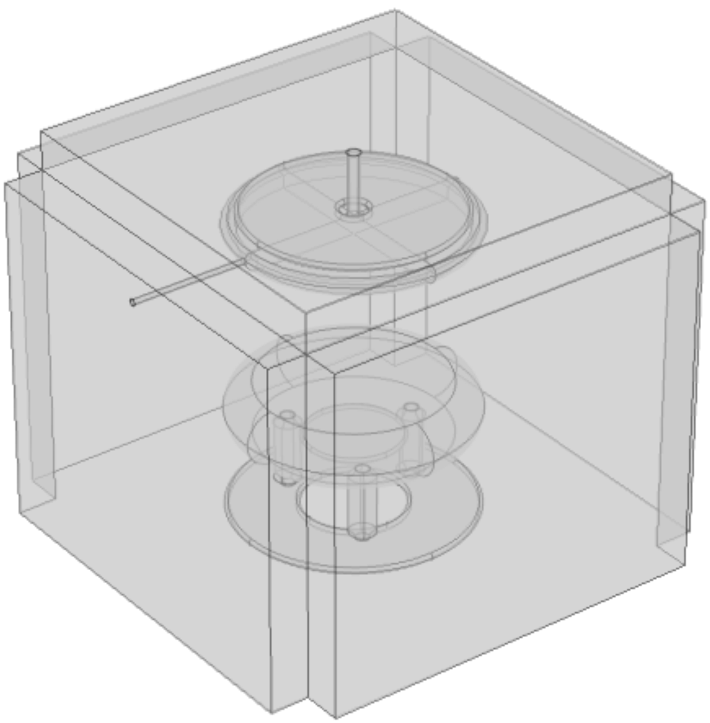
- Plate A
- Grounding pin
- G10 support rod for plate B
- Plate B
- Plate C
- Additional plate D (not shown) to increase C_{CG}

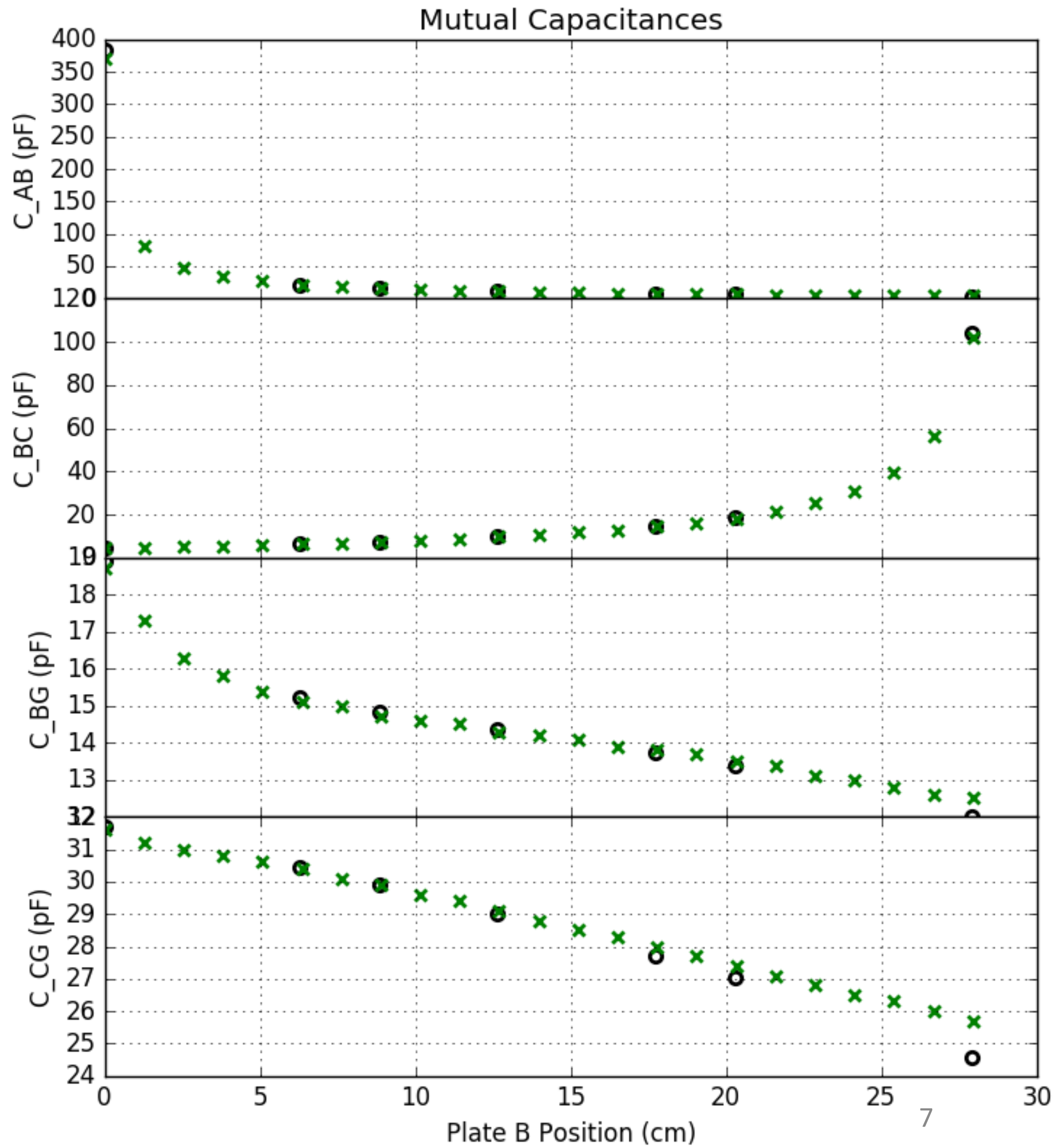
Electronics for non-contact voltage measurement: driver for piezo actuator, lock-in amplifier



Mutual Capacitances in Demo Apparatus

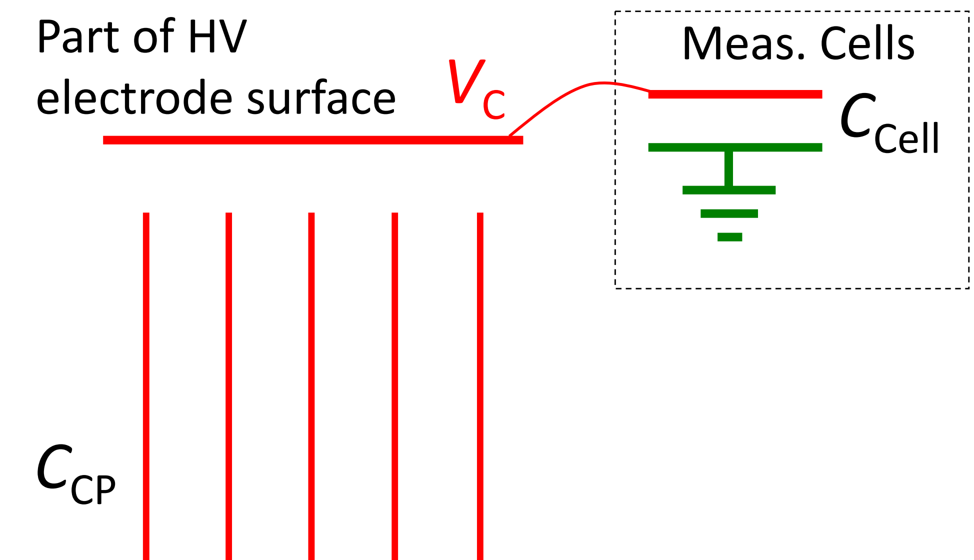
- Measurements with hand-held LCR meter, Agilent U1733C (green x's)
- COMSOL calculations (black circles)

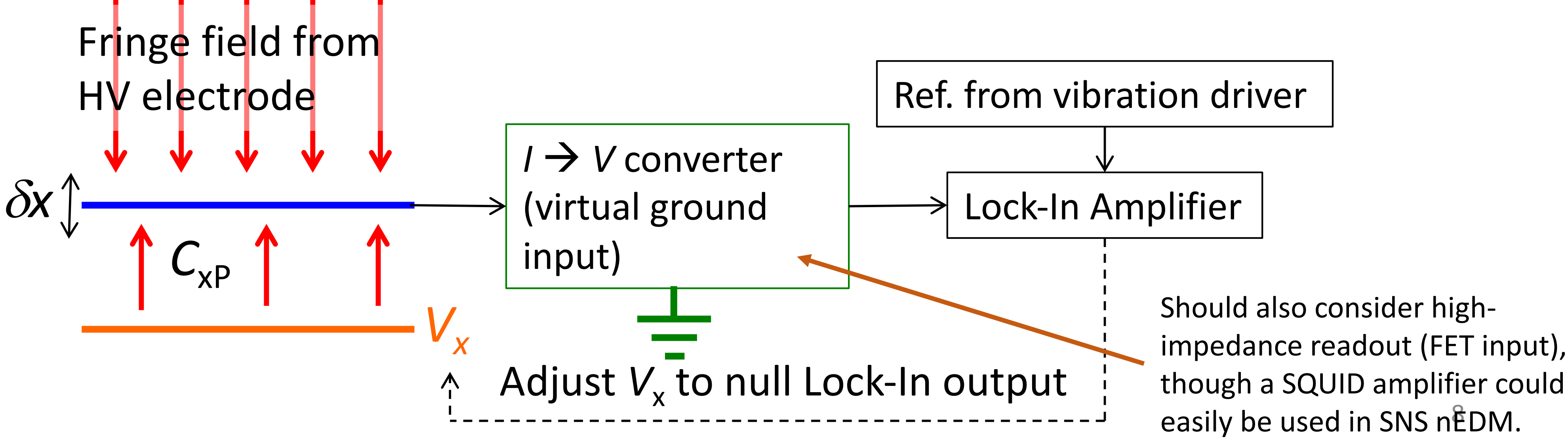




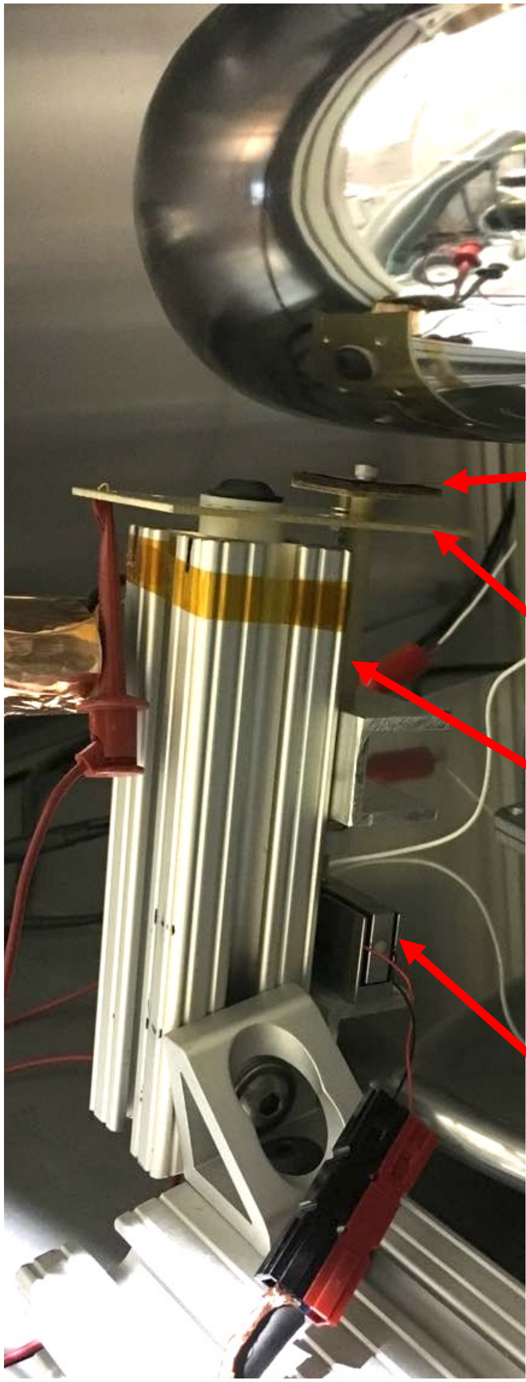
Non-Contact Voltage Measurement: Vibrating Capacitor Method

The technique is similar to the method in surface physics to measure contact potentials (see e.g. Meyerhof and Miller, Rev. Sci. Instrum. **17** (1946), p. 15, and many more recent papers).





Non-Contact Voltage Measurement



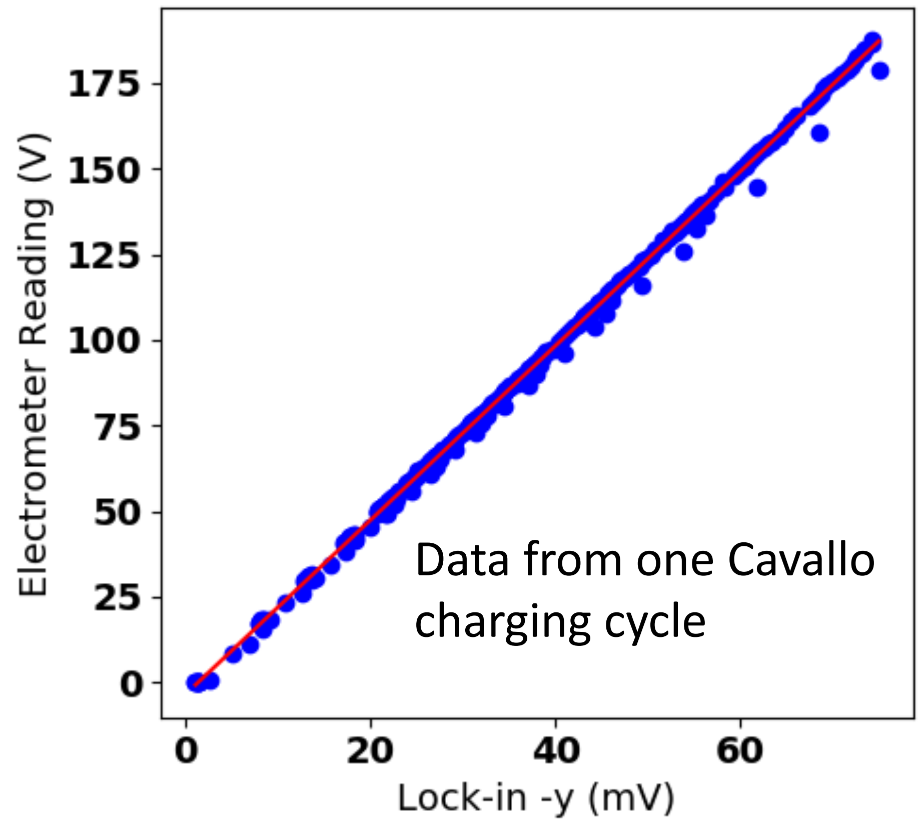
- Vibrating plate connected to current preamp (Stanford Research SR556) followed by lock-in amplifier (SR830)
- In this study, the reference plate voltage was fixed at 0 V (open-loop operation)

Moving plate: Cu-clad G10 (now a 1 ¼” disc; old plate shown here)

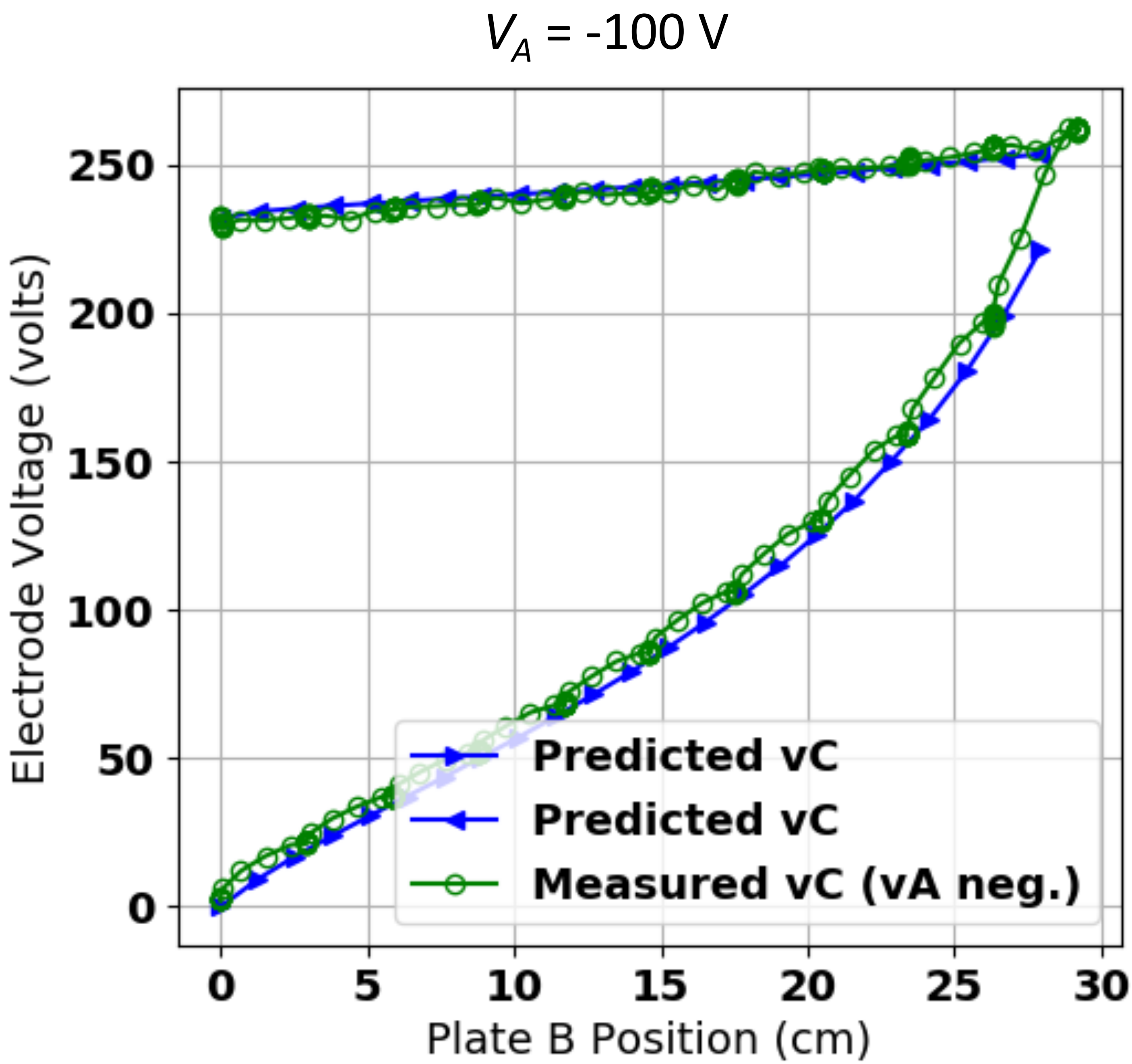
Reference plate

G10 rod down to actuator

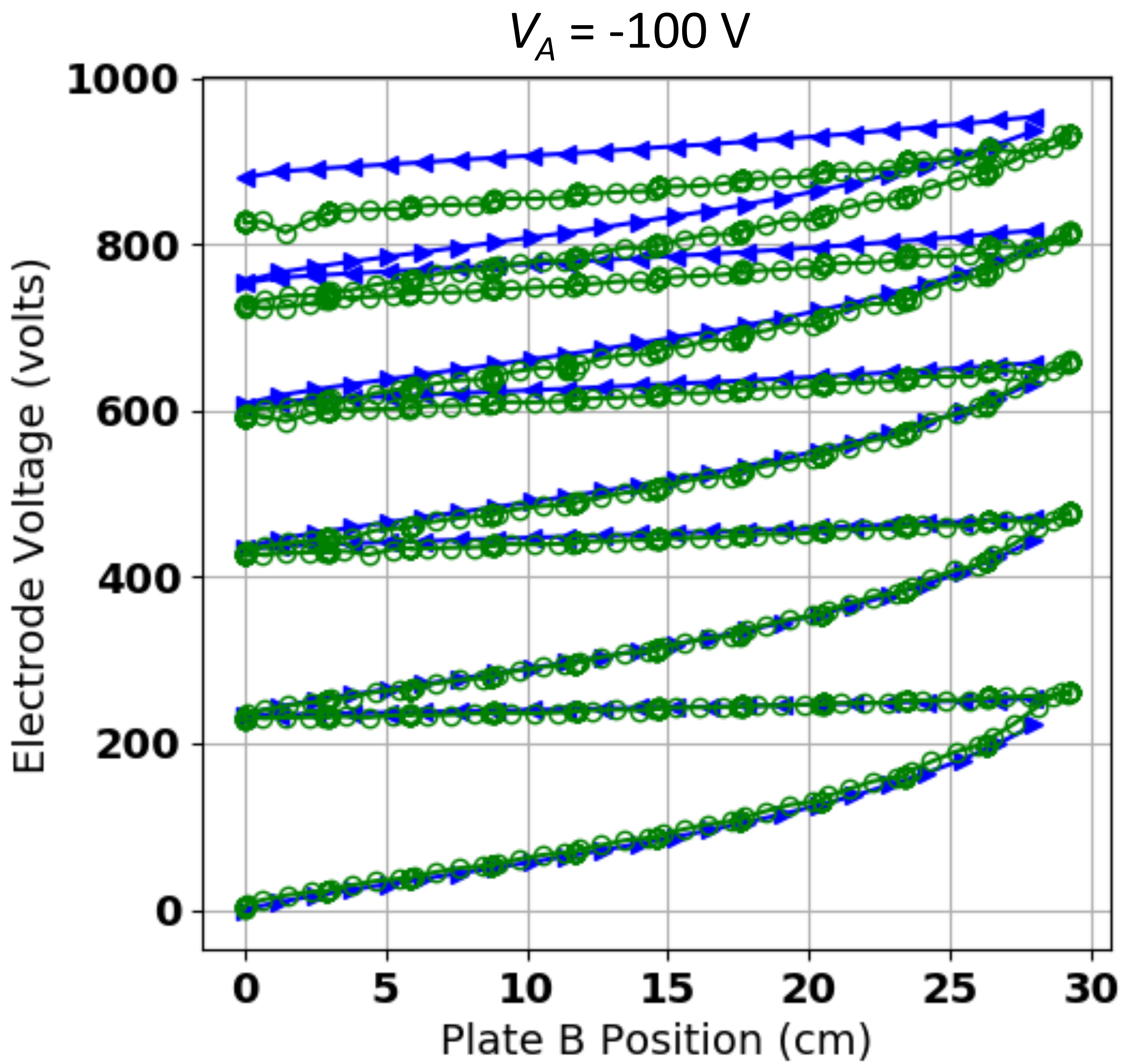
Piezo actuator (here, operated with $\approx 40\mu$m stroke, 40 Hz sine wave excitation, so $\text{Max}|v_{plate}| = 0.5$ cm/s)



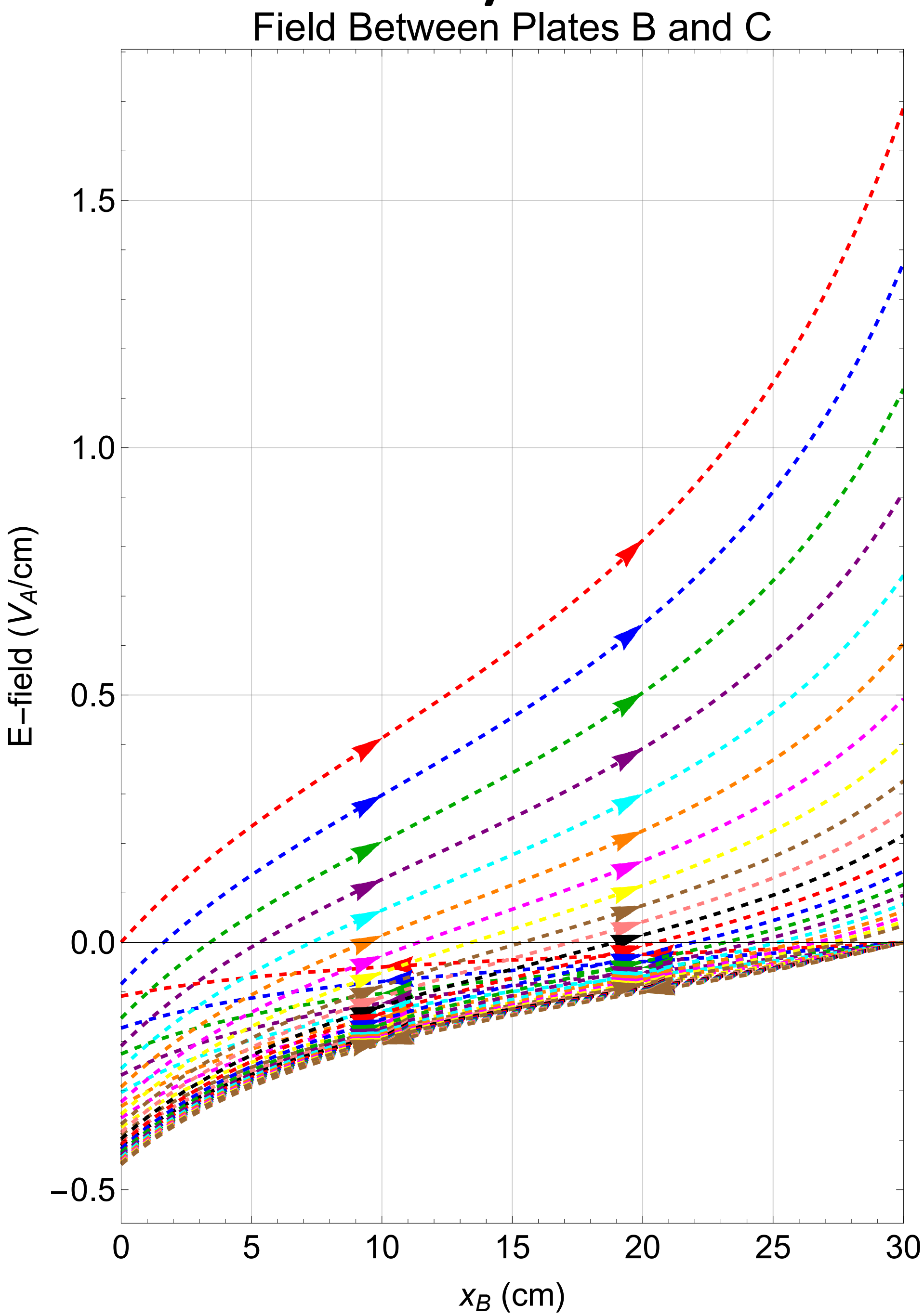
Data vs. Prediction

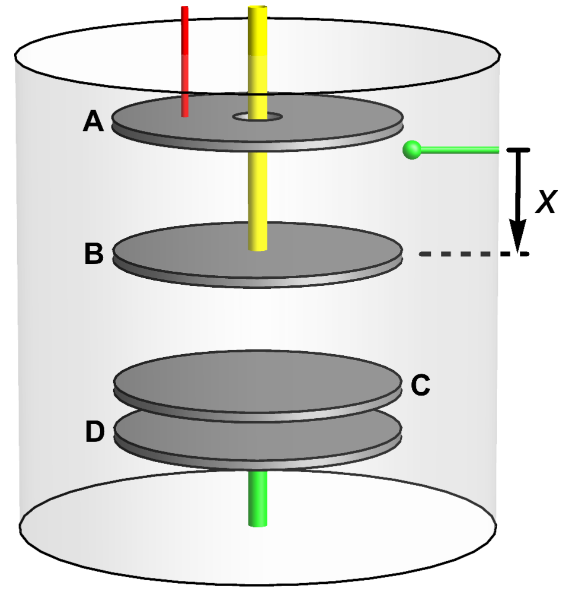


Data vs. Prediction: Multiple Cycles



E-field in Toy Model





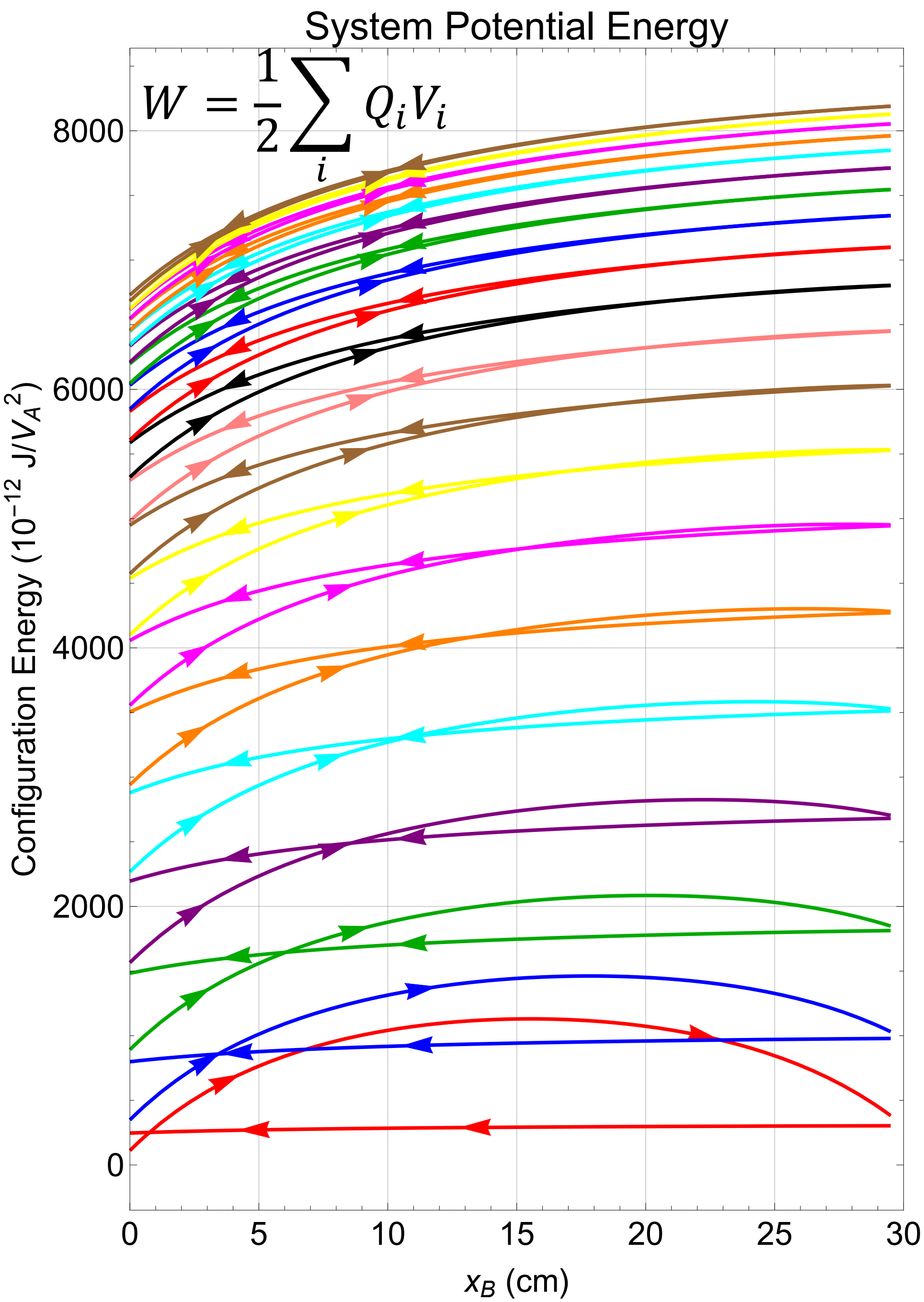
Infinite parallel plate capacitor model:

$$C_{ij} = \varepsilon_0 A / |x_i - x_j|$$

Field remains finite for perfectly flat, parallel infinite plates.

For real surfaces, we most likely get a spark before contact.

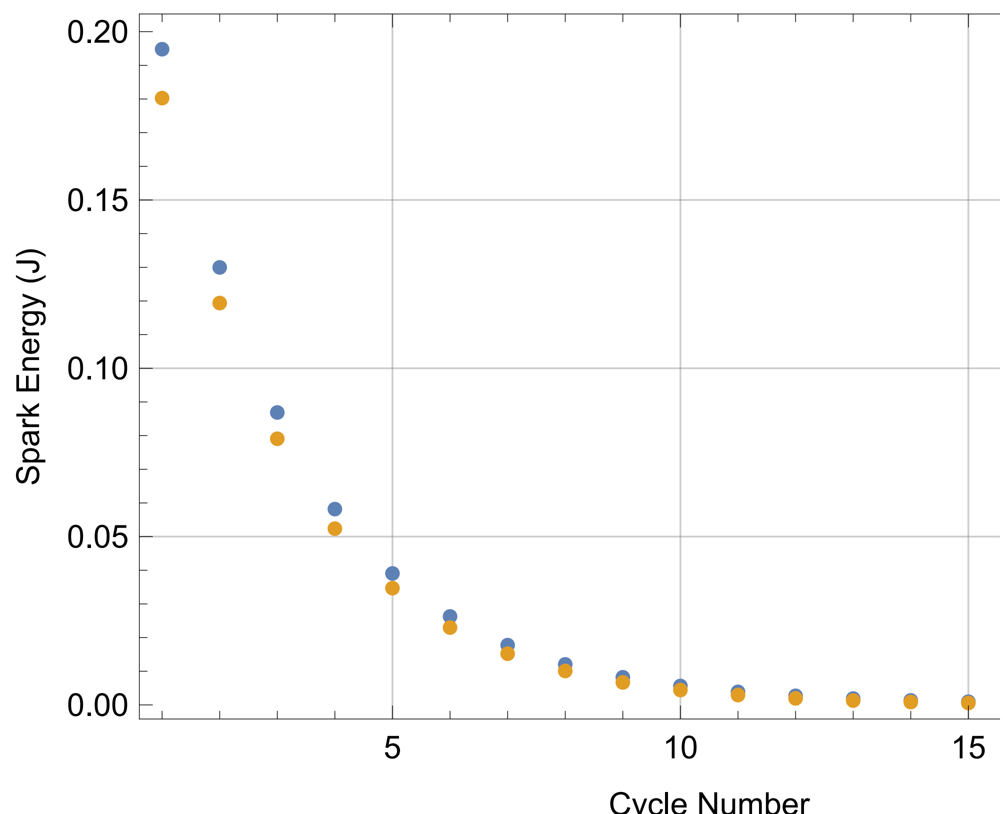
Spark Energy in Toy Model



Assumptions:

- spark at 5-mm gap
- $|V_A|$=50 kV

Maximum energy available to a spark: ΔW (before – after spark)

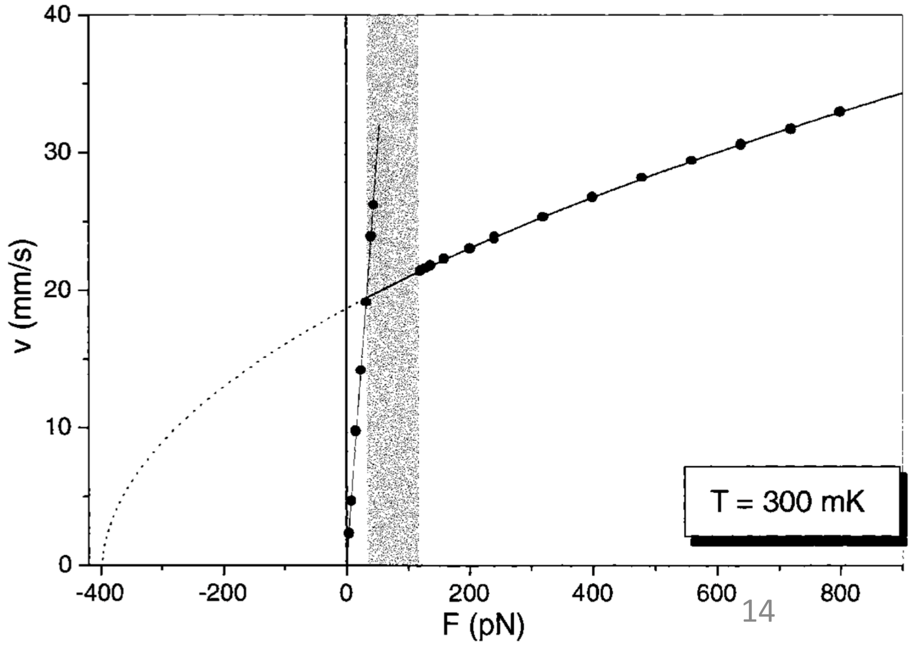


Other Sources of Heat

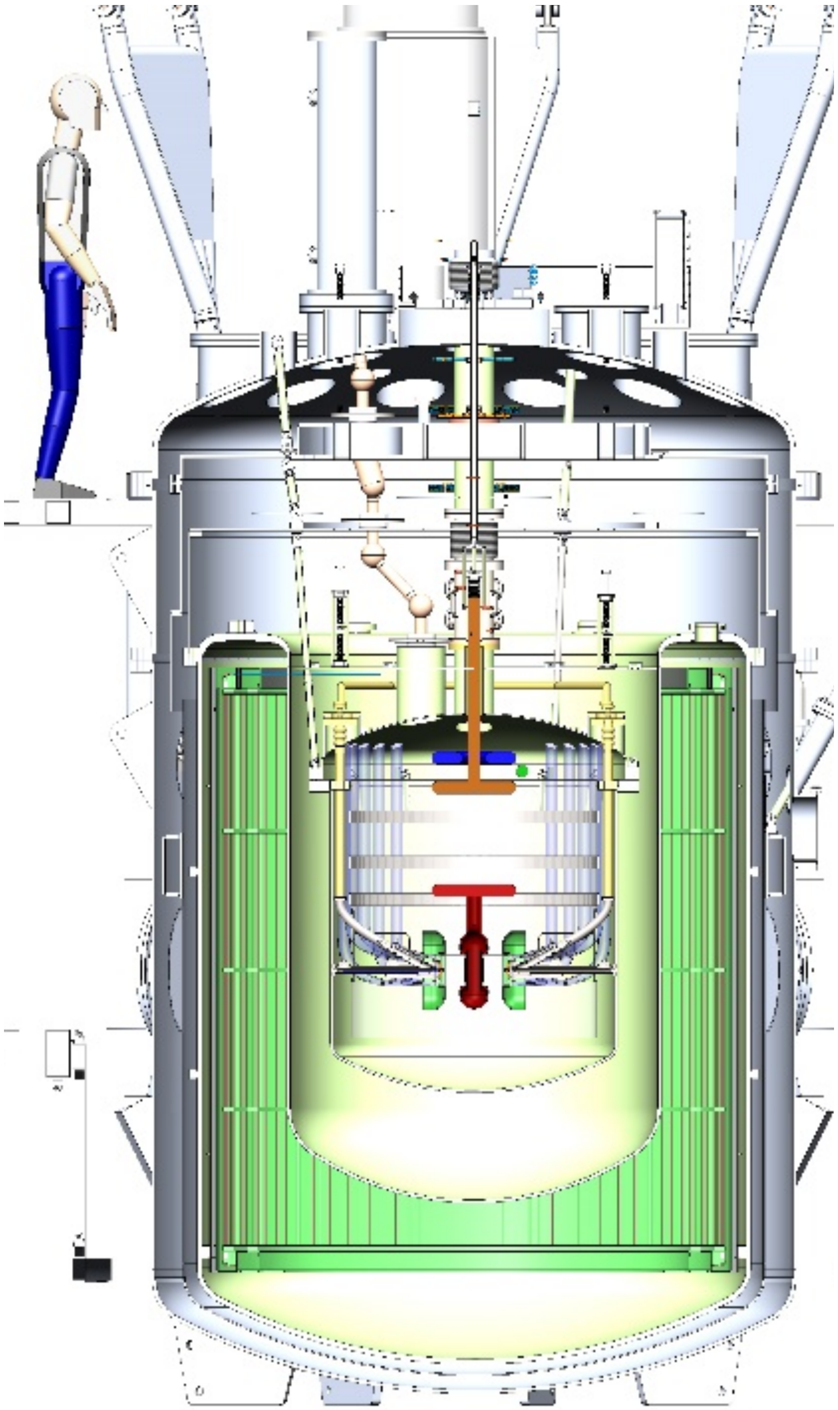
- Charge flow across resistive electrode surfaces
  - $W_q \sim \Delta t\, I^2 R \sim R Q_B^2 / \Delta t$
  - If R ~ 1 kΩ, Q_B ~ 1 μC, and Δt ~ 1 s, → W_q ~ 1 nJ

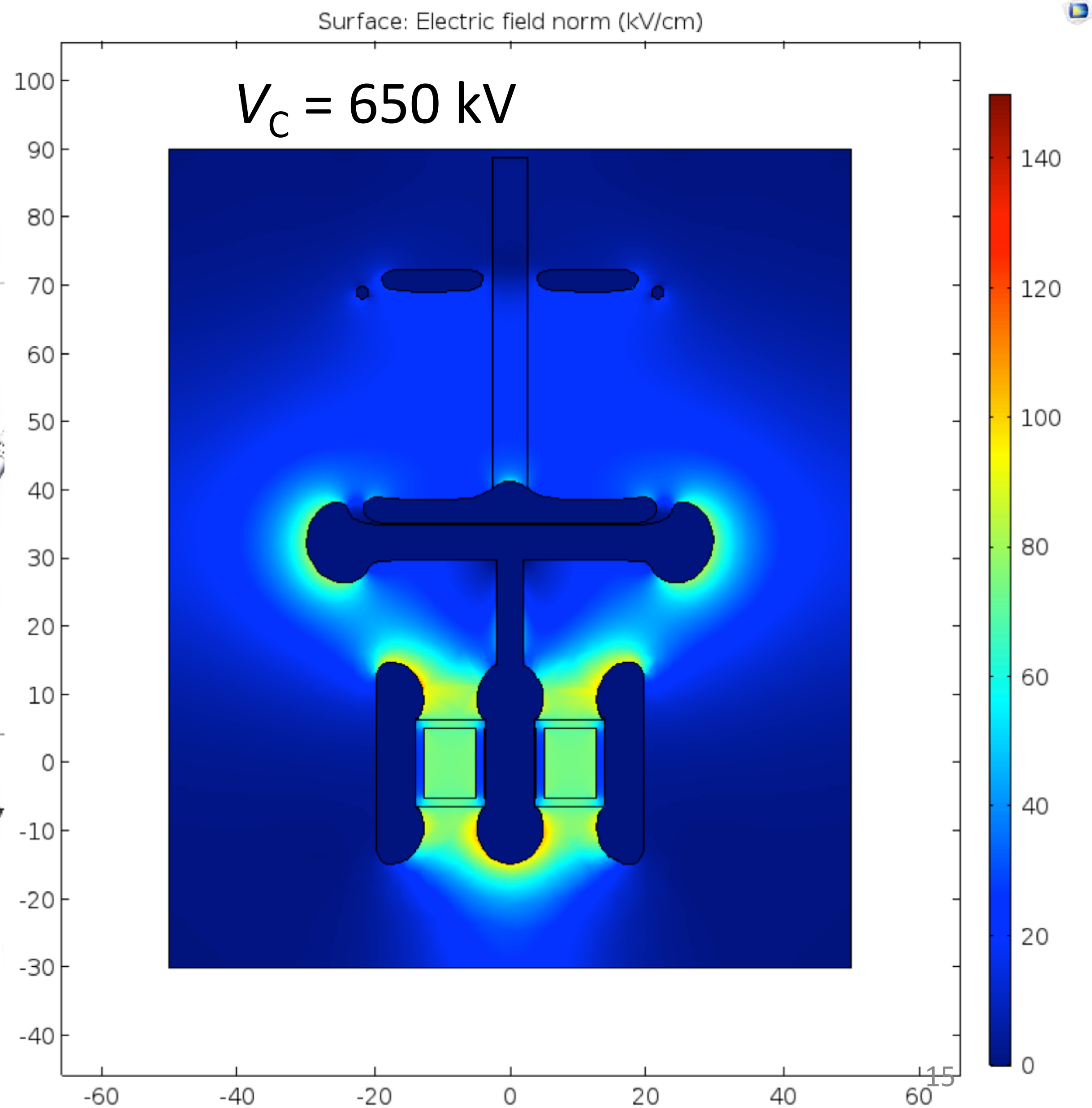
- Turbulent flow around B electrode
  - Scale experimental results of small sphere oscillating in He-II at 0.3 K, M. Niemetz and W. Schoepe, J. Low Temp. Phys. 135 447 (2004).
  - Force $F_D = (c_D \rho A/2) v^2 - F_0$
  - If v=3 cm/s, the estimate is

    P_D~0.1 mW for ~10 cm radius disc.

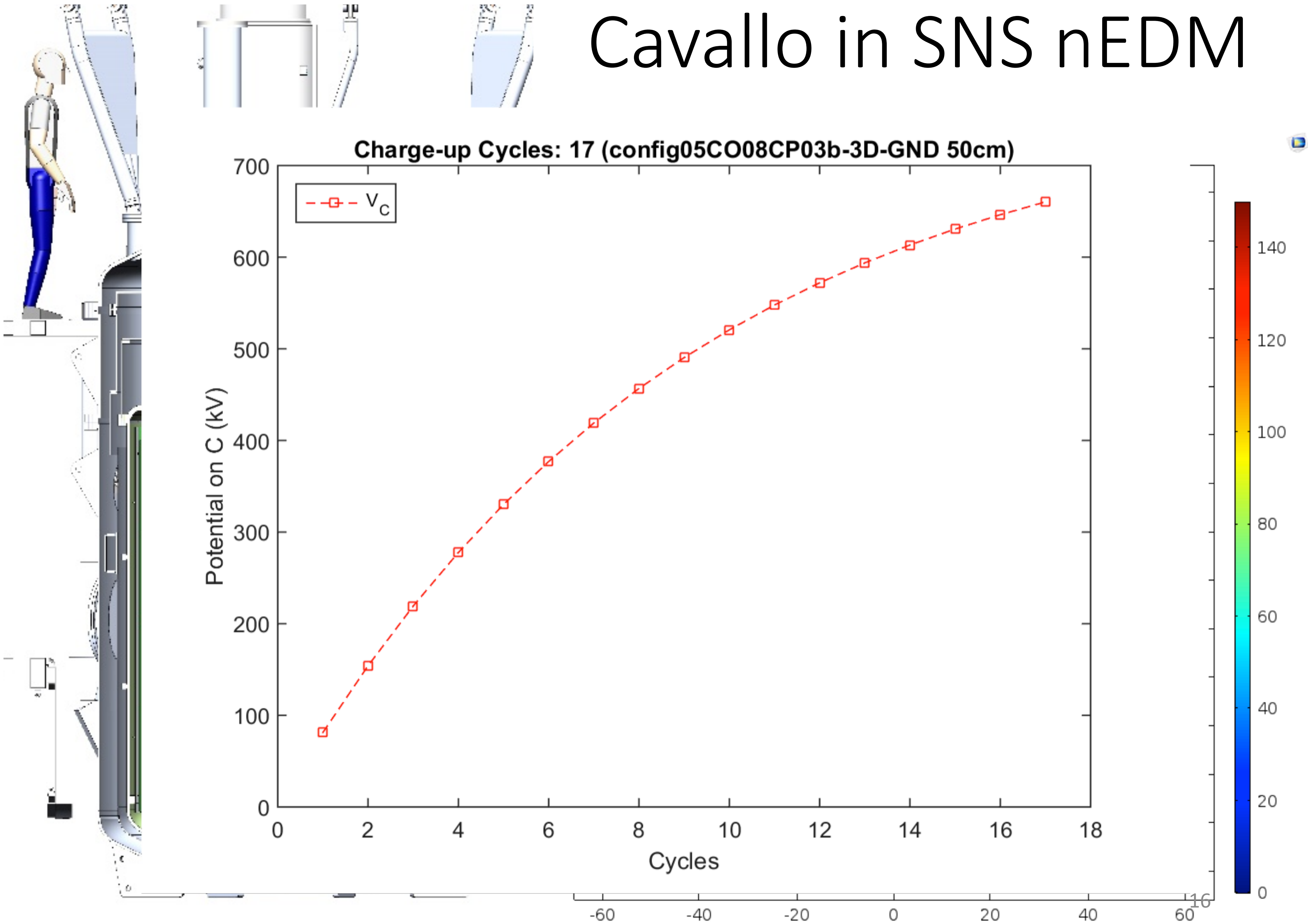


Cavallo in SNS nEDM





Cavallo in SNS nEDM



SQUIDs in SNS nEDM

- Main application: readout of ^{3}He co-magnetometer magnetization
  - ~6 fT signal amplitude outside the cell
  - Need ~10 uHz precision measurement of the ^{3}He precession frequency per 100-s storage time → noise must be ~1 fT/rtHz or better
  - SQUID pickup loops will be positioned behind the ground electrodes
- Other:
  - Monitoring polarized ^{3}He in other parts of the experiment
- Preamp for non-contact high voltage monitor (maybe)

^{3}He Co-magnetometer Readout

$$d_n = \frac{\hbar}{2E}\left[2\pi(f_s^{\uparrow} - f_s^{\downarrow}) - \frac{(\gamma_3 - \gamma_n)}{\gamma_3} 2\pi(f_3^{\uparrow} - f_3^{\downarrow})\right]$$

$\frac{(\gamma_3 - \gamma_n)}{\gamma_3} = 0.1$

scintillation signals ~10 Hz

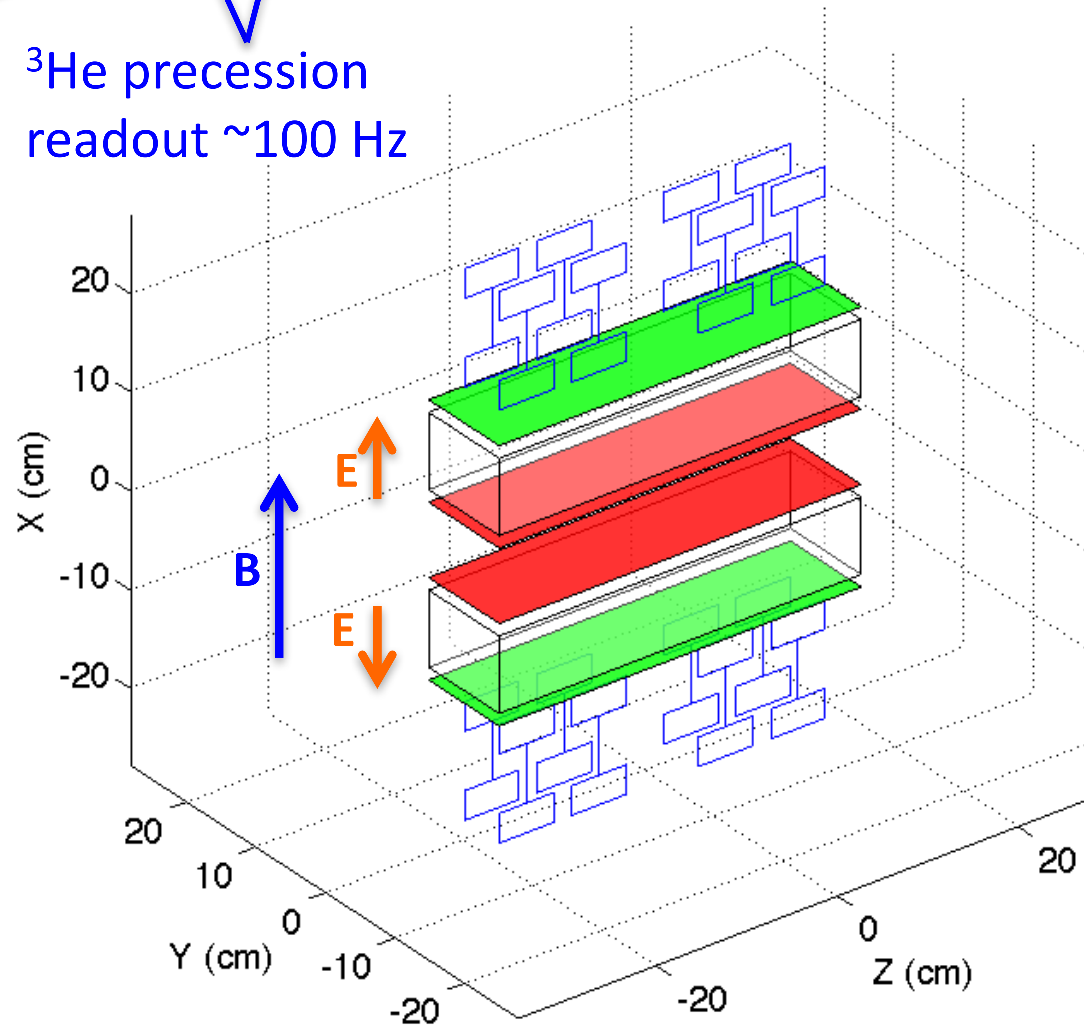
^{3}He precession readout ~100 Hz

IEEE TAS **23**, 2500104 (2013)

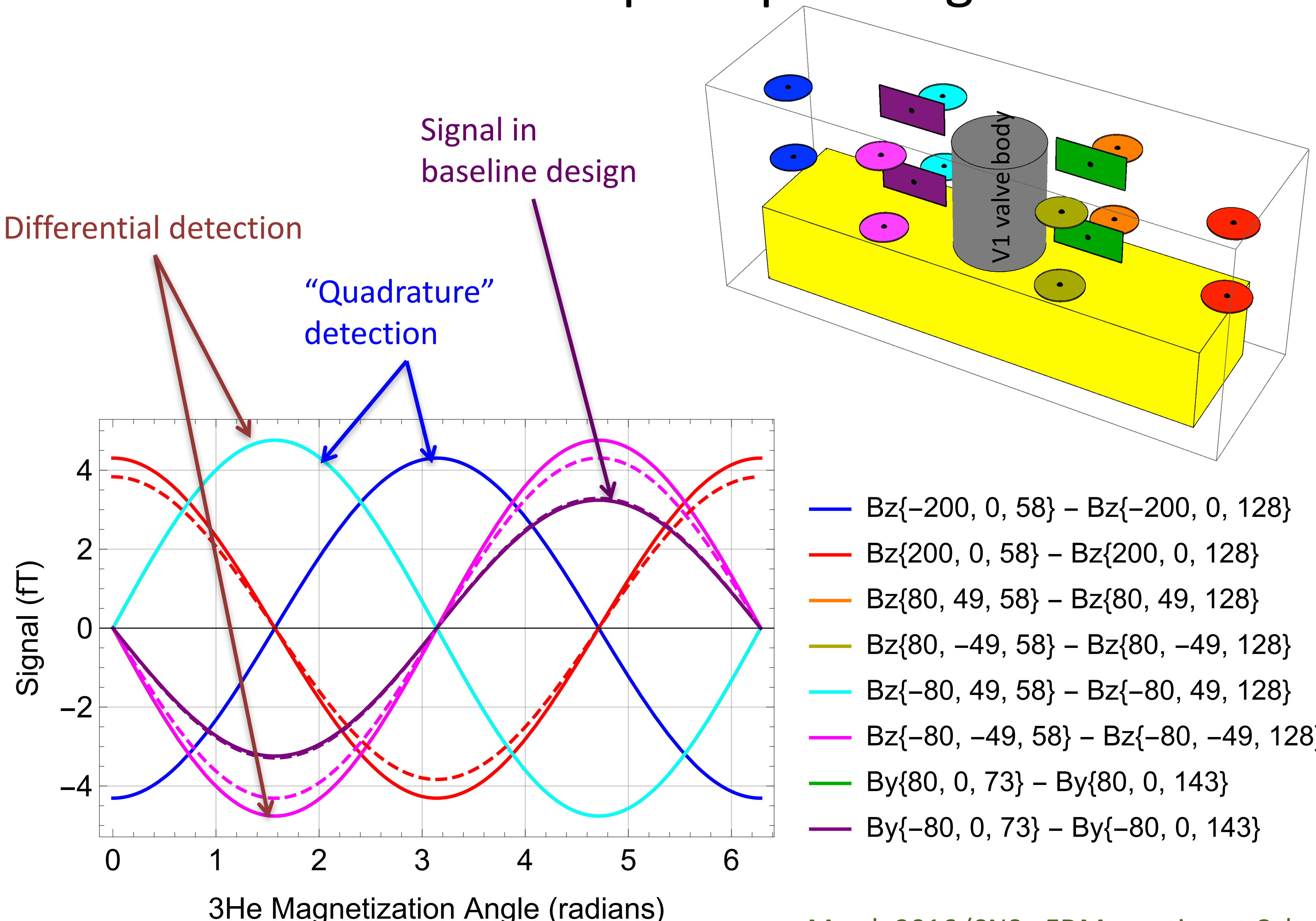
- Need SQUID signal-to-noise-density ≥2 rtHz

IEEE TAS **25**, 1600205 (2015)

- Intrinsic noise of candidate SQUID+pickup is low enough

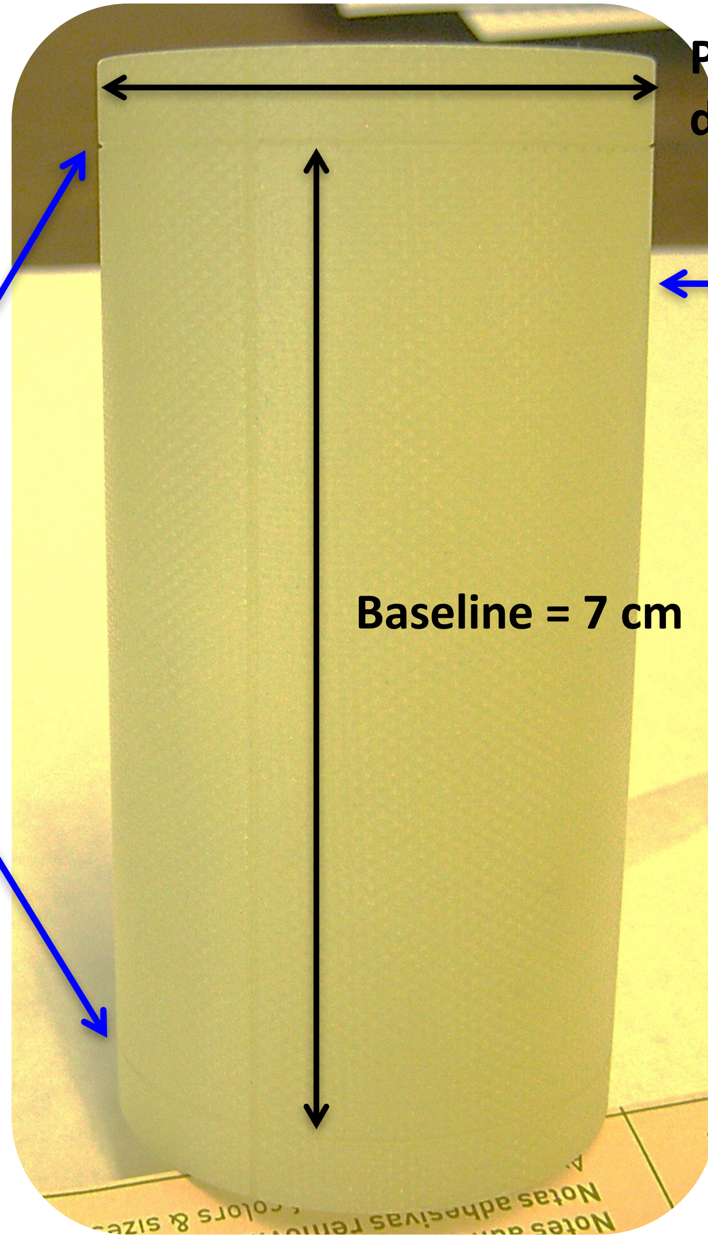


Alternative Pickup Loop Arrangement



March 2016 (SNS nEDM meeting at Caltech)

Coil form for one-turn axial gradiometer



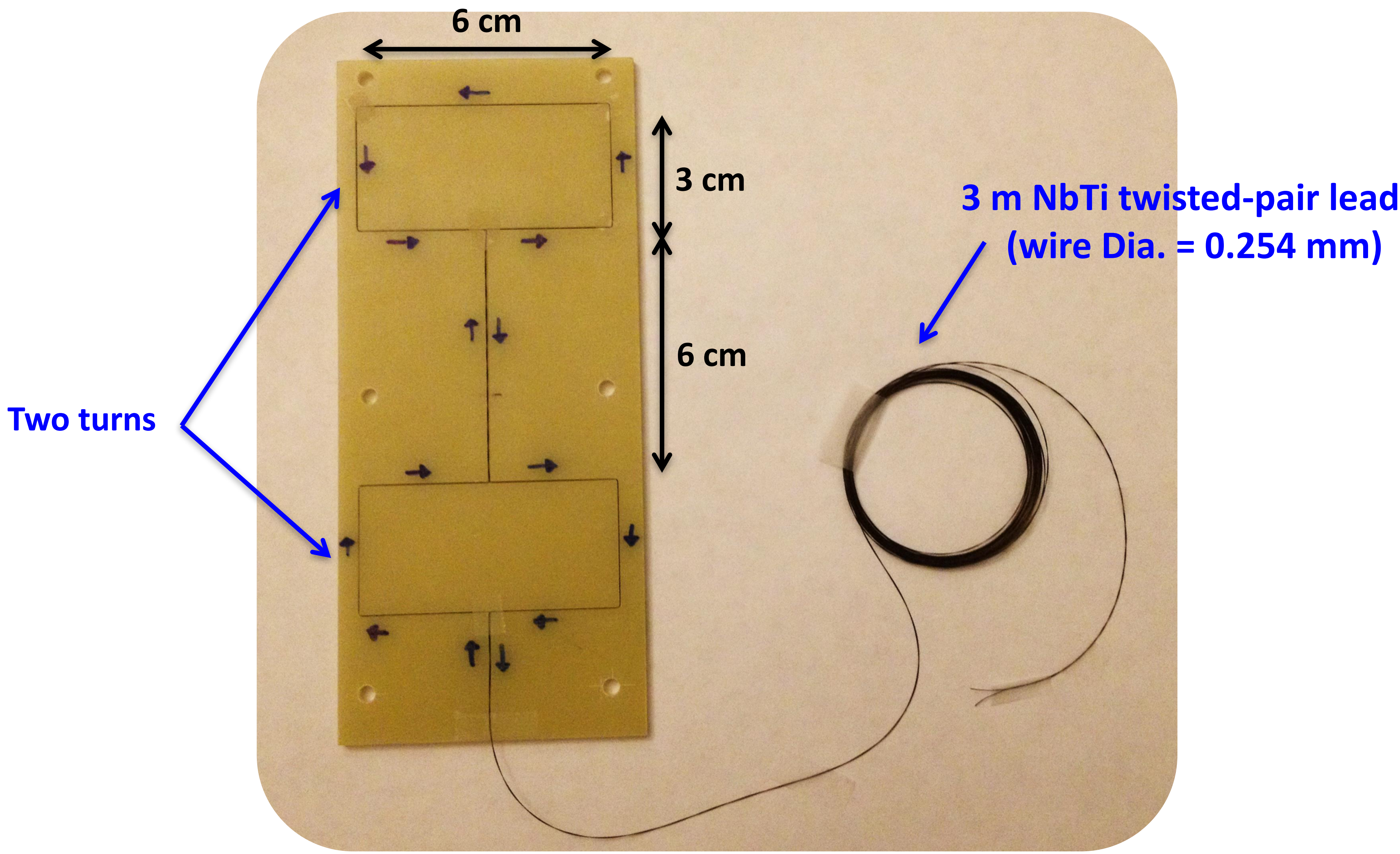
Pickup loop diameter = 4 cm

G10 cylinder

Baseline = 7 cm

Groove (size = 0.254 mm) - NbTi wire will be wound through grooves.

Handwound two-turns gradiometer



Wound NbTi wires through groove (size=0.254mm) on G10 plate

Diagram of SQUIDs & High Voltage Test Setup

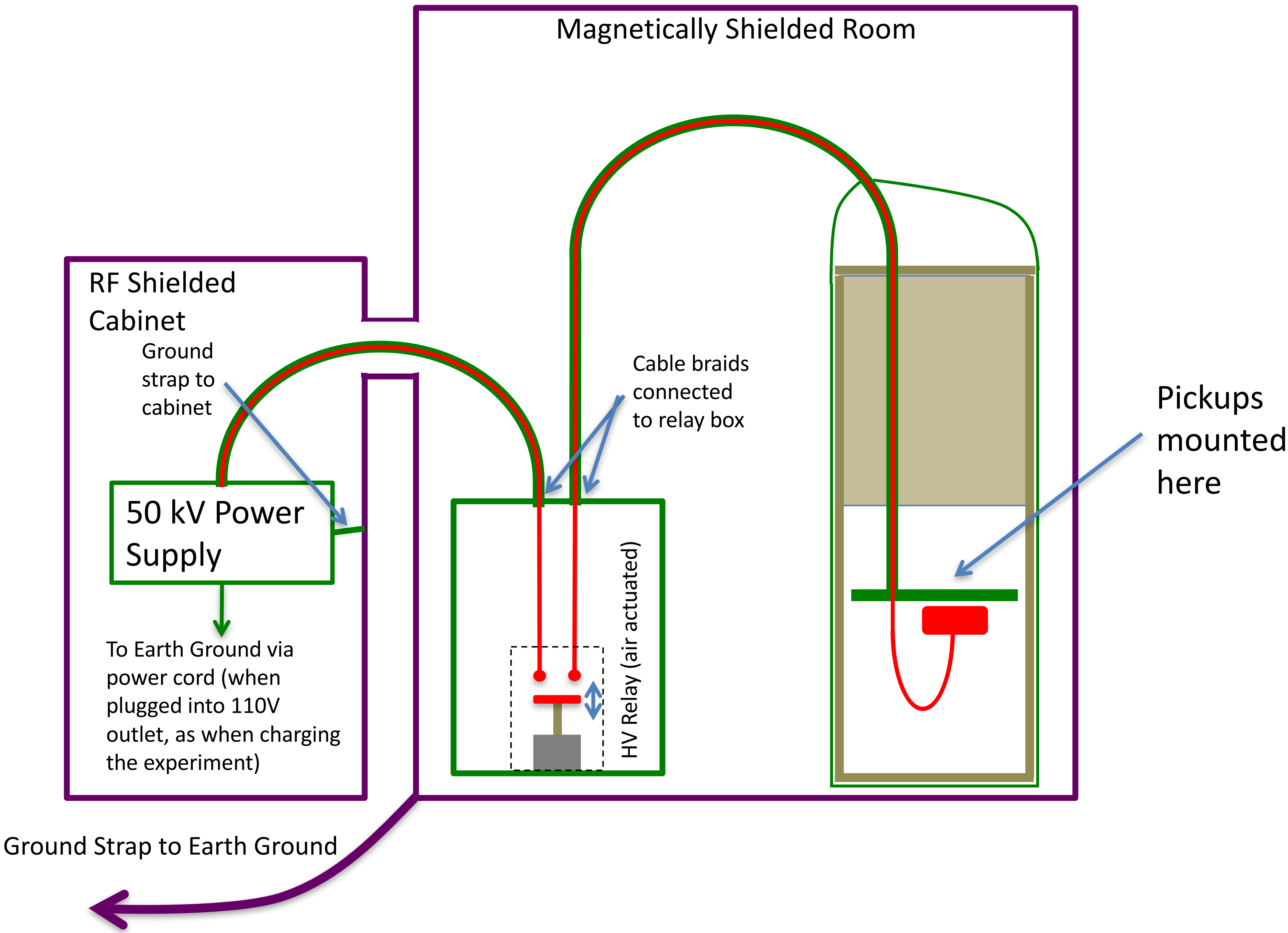


Diagram of SQUIDs & High Vo

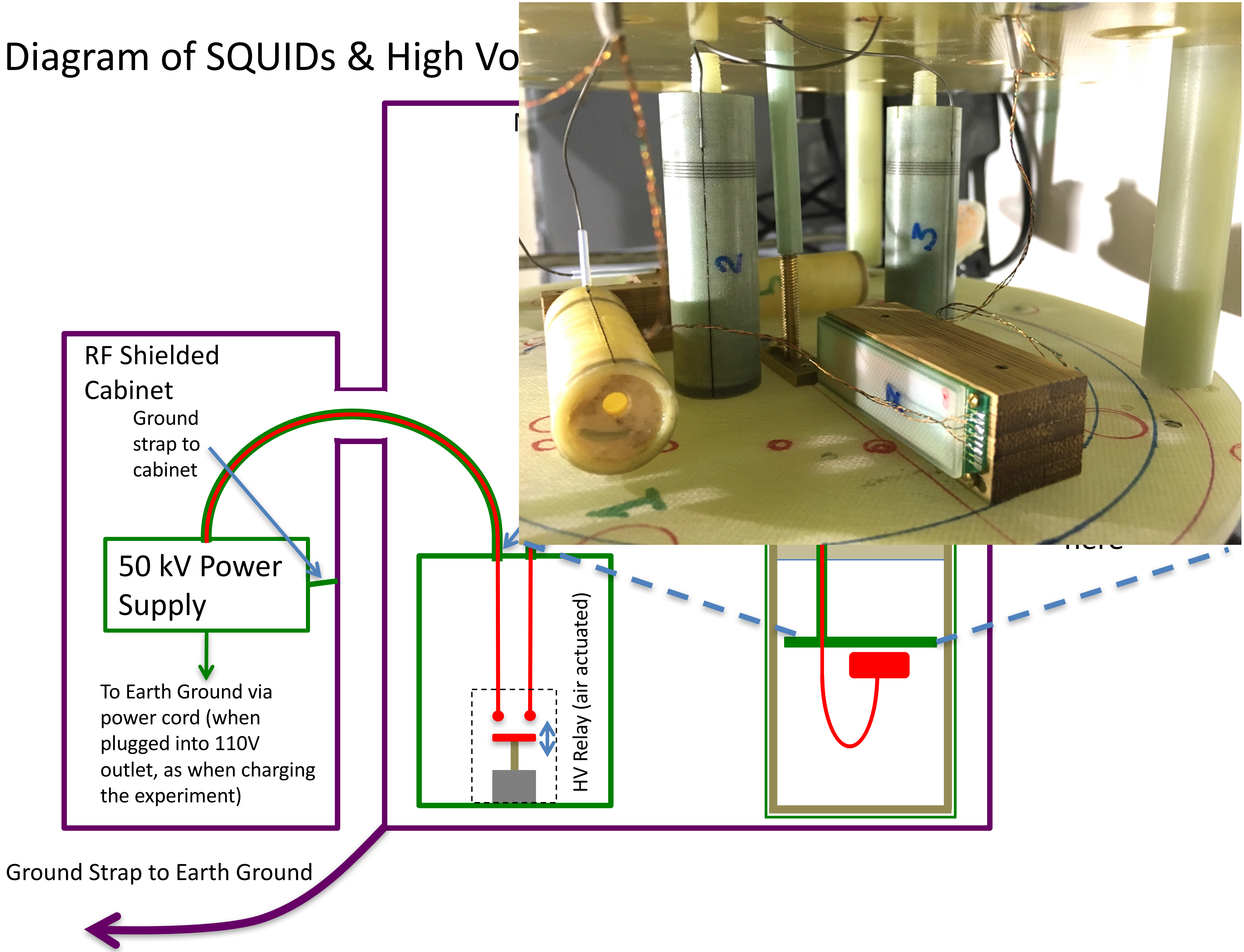
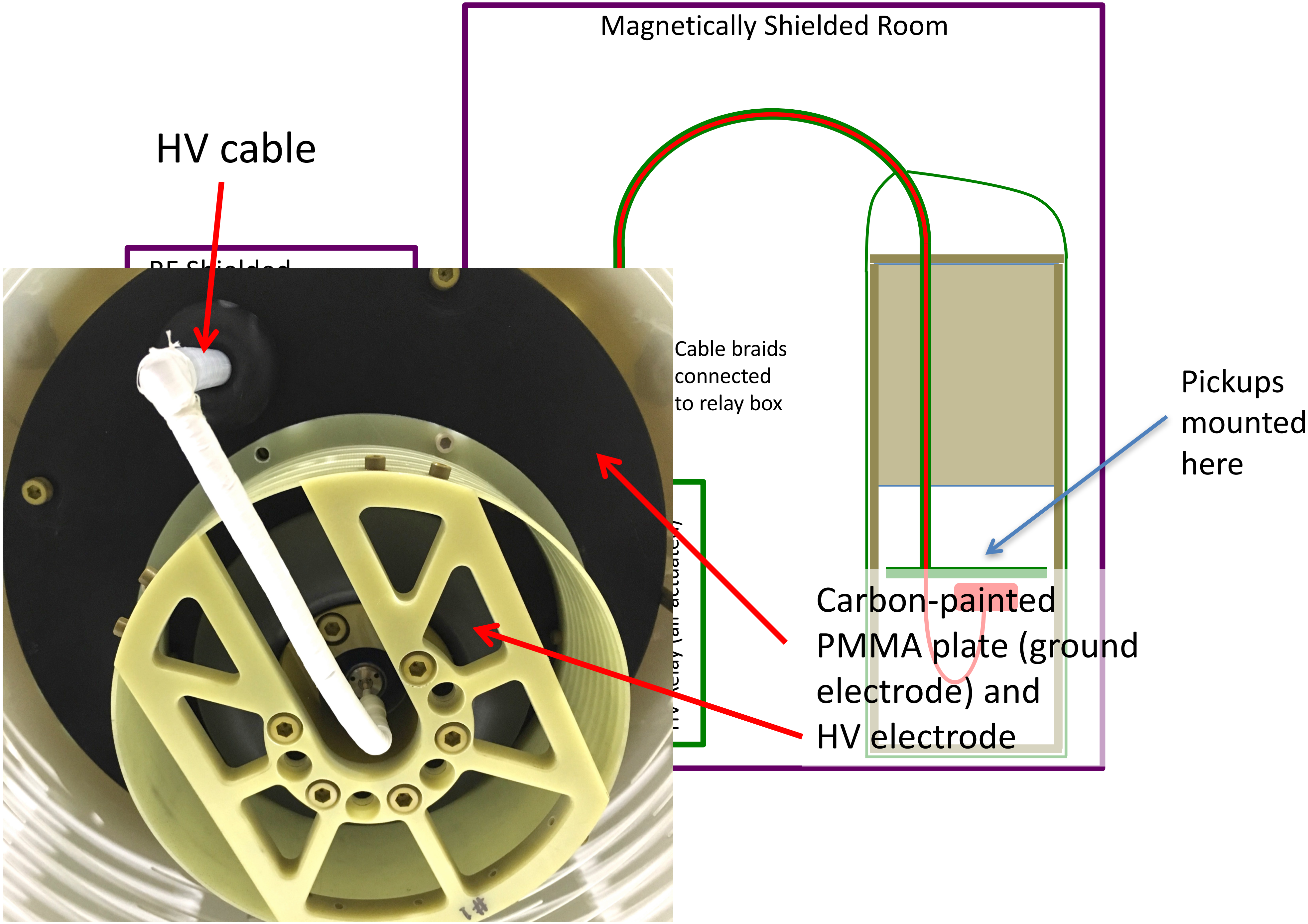
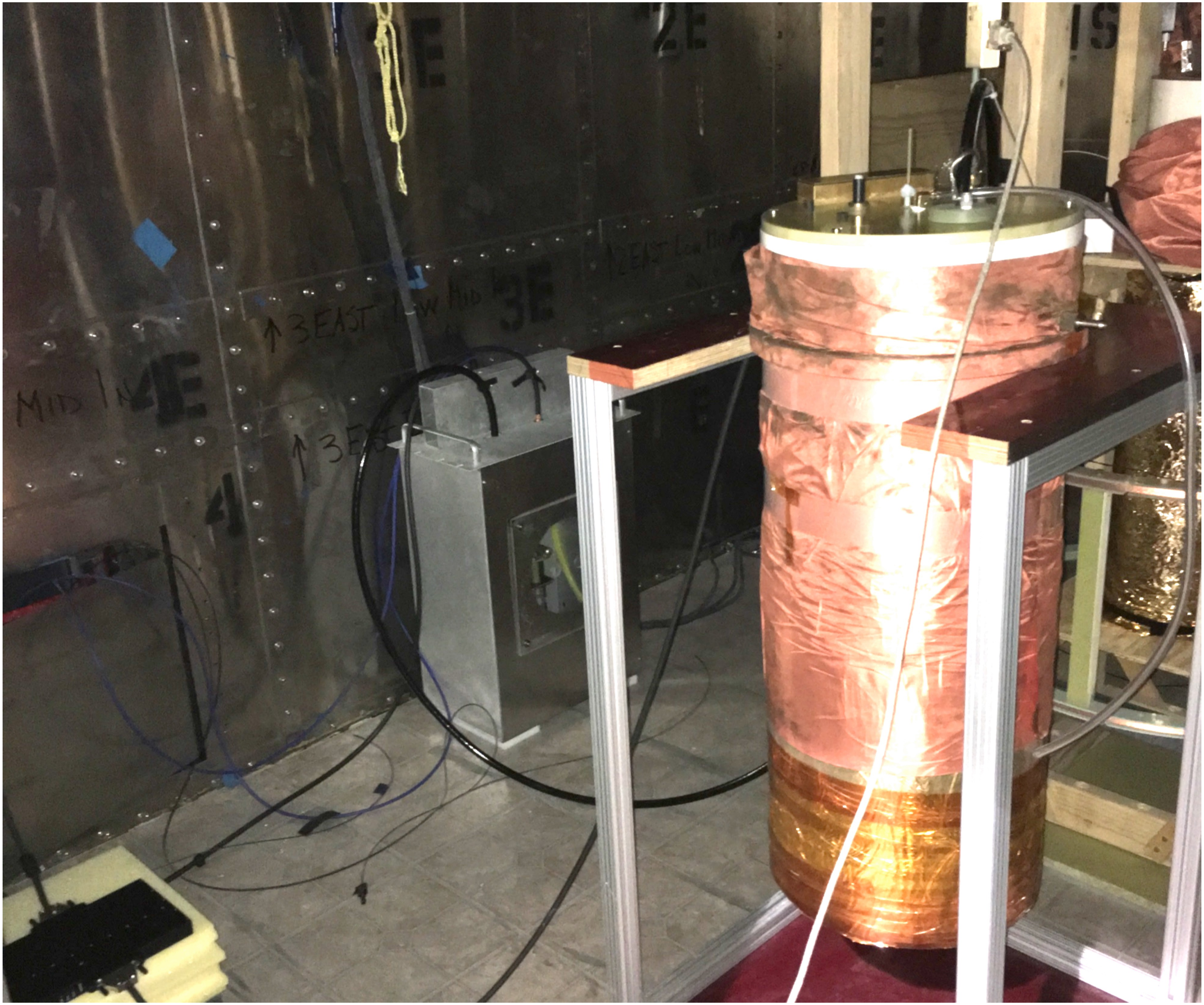


Diagram of SQUIDs & High Voltage Test Setup




3E
2E
3E
4E
↑ 3 EAST

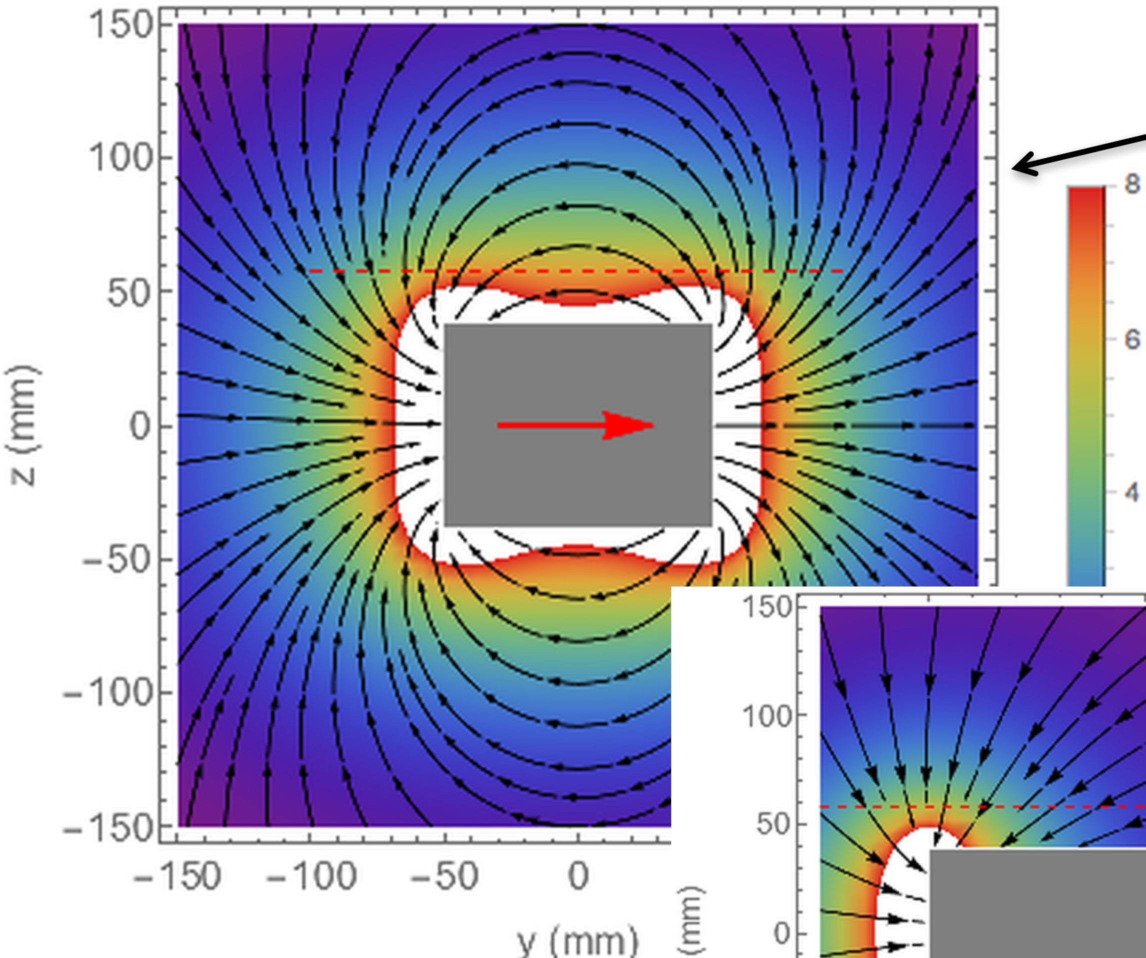
SQUIDs+HV Preliminary Observations

- Sparks sometimes trapped flux in SQUIDs; recovery by heating SQUID chip.
- No SQUIDs were killed
- Noise was somewhat high in these tests (factor of ~2), possibly due to too high conductivity ground plate.

Summary

- In situ high voltage generation with a Cavallo multiplier appears feasible for SNS nEDM.
- A new SQUID pickup loop configuration is under consideration with differential and quadrature readout.
- Preliminary studies of SQUIDs near high voltage discharges demonstrate SQUID survival, recovery by heating.

B-field from Cell Magnetization (2.2×10^{12}/cc ^{3}He)



Magnetization along shorter cell dimension

Magnetization along long cell direction