Cavallo high voltage multiplier for the nEDM@SNS experiment

Steven Clayton, LANL

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Feeding 650 kV into a LHe cryostat from outside is difficult

750 kV Cockcroft Walton Generator at CERN

- HV generation
  - Requires a large device
- HV vacuum feedthrough
  - It is impossible to make a HV vacuum feedthrough that meets all the nEDM@SNS requirements related to:
    - Sub-K cryogenics
    - Compatibility with SQUID operation
    - Non-magnetism
    - Limited physical size
- Note: we need very little power
  - Leakage current << 1 nA
  - Charged particles caused by n beam

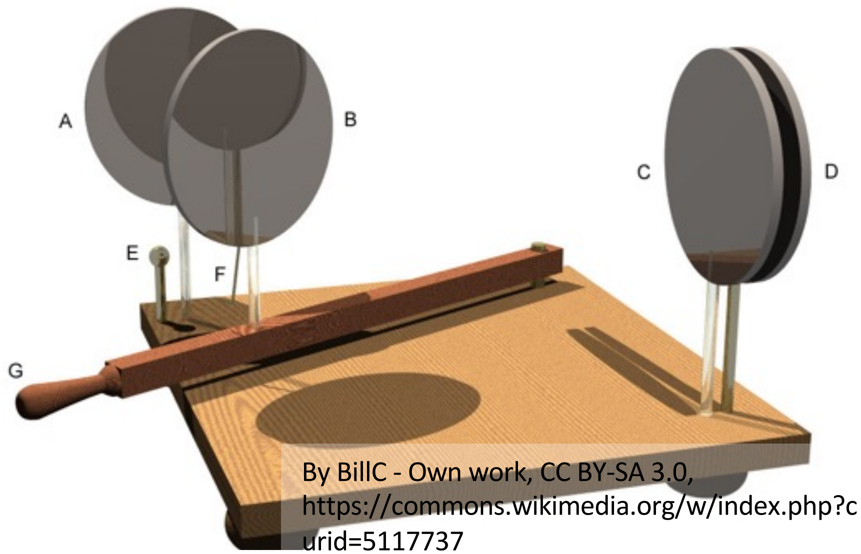
Methods to produce high voltage

- 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.



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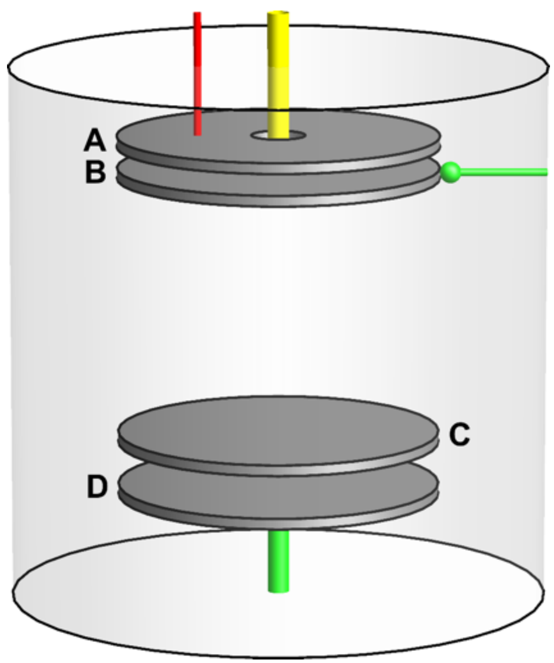
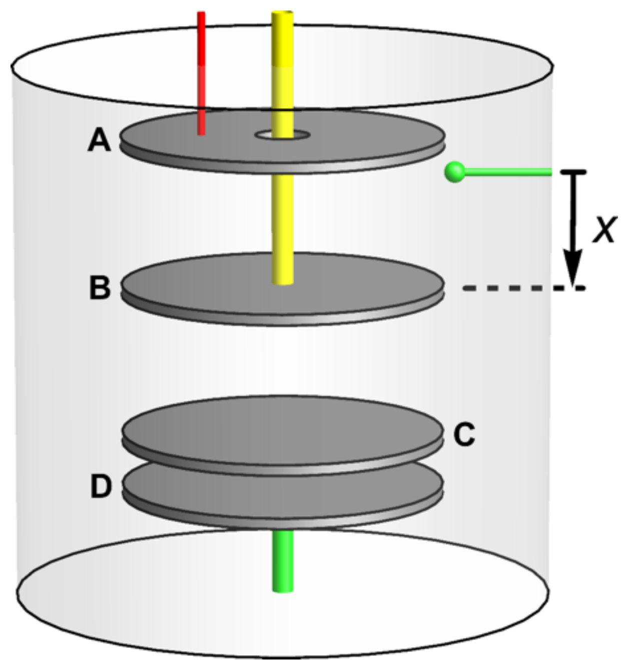
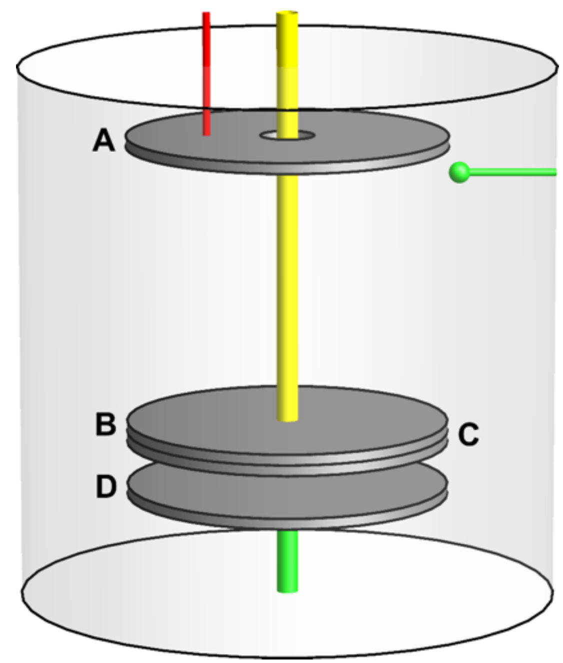
Induce charge on Plate B with $V_B = 0$

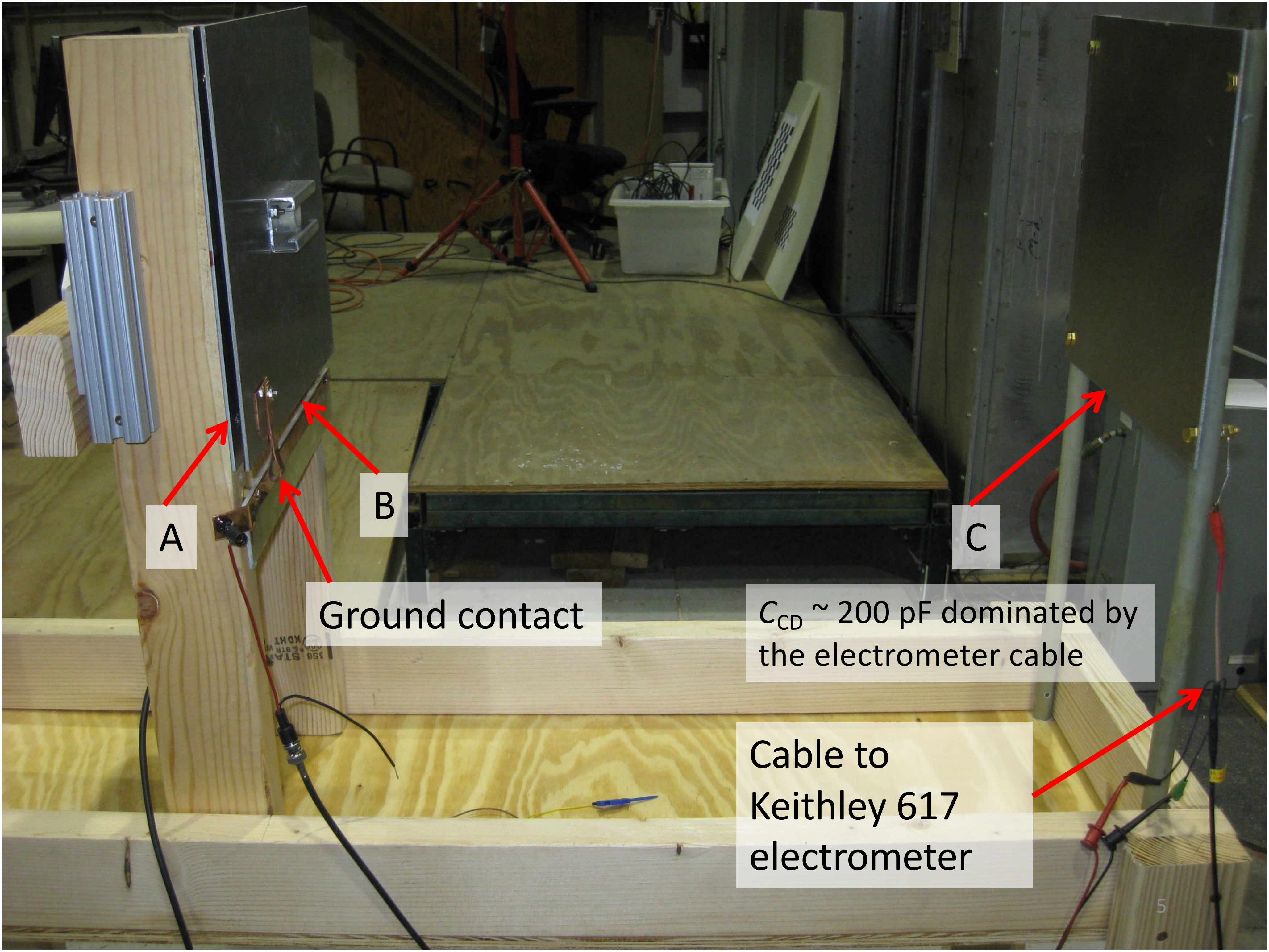


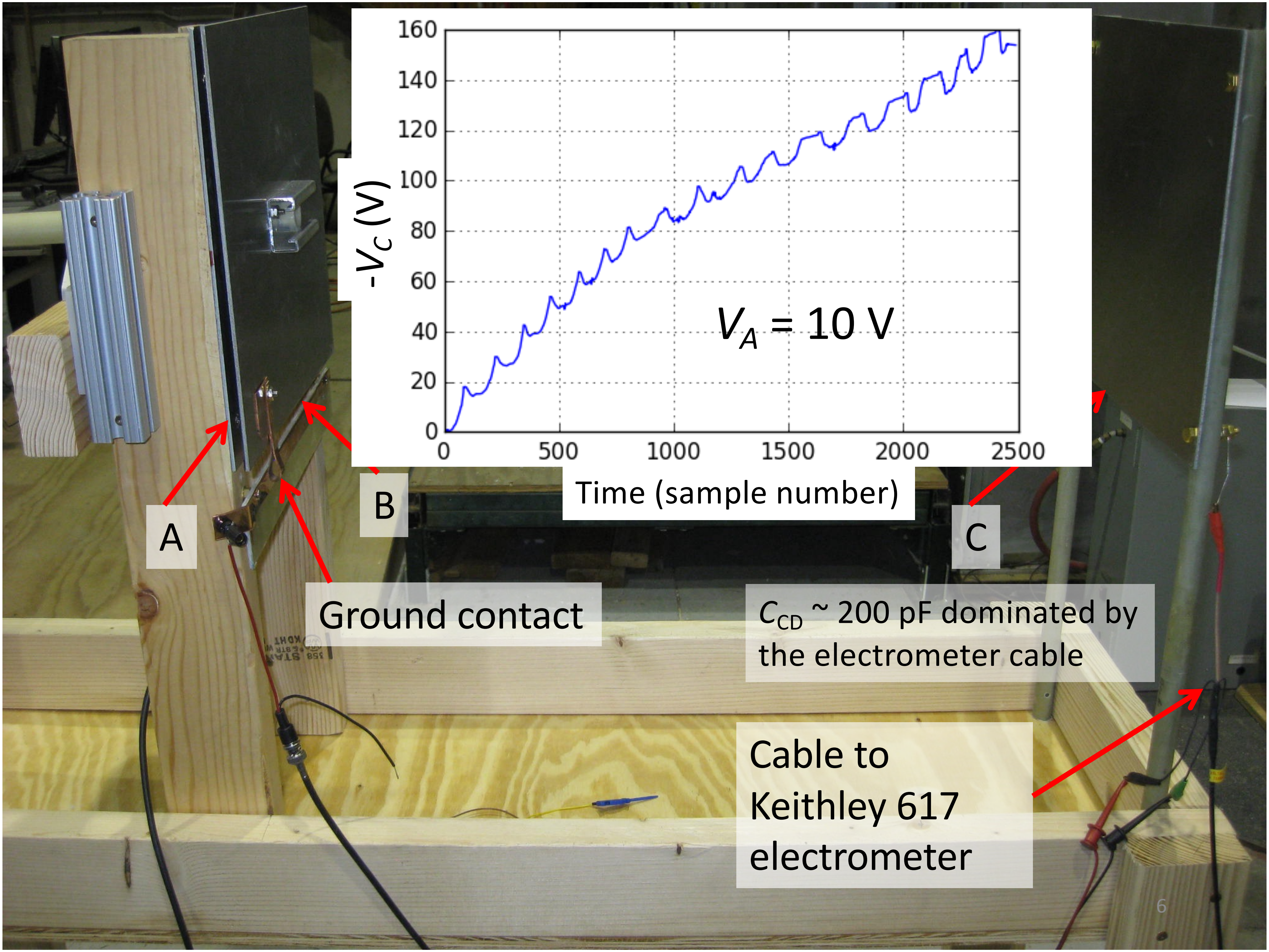
Disconnect ground from Plate B, move toward Plate C. $Q_B \sim -C_{AB} V_A$



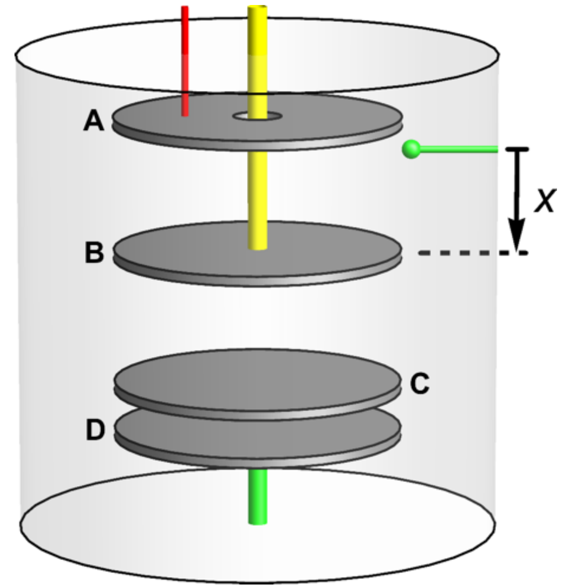
Touch Plate B to Plate C, transferring charge.




A
B
Ground contact
C
C_{CD} ~ 200 pF dominated by the electrometer cable
Cable to Keithley 617 electrometer


160
140
120
100
80
60
40
20
0
0
500
1000
1500
2000
2500
$-V_C$ (V)
V_A = 10 V
Time (sample number)
A
B
C
Ground contact
C_{CD} ~ 200 pF dominated by the electrometer cable
Cable to Keithley 617 electrometer

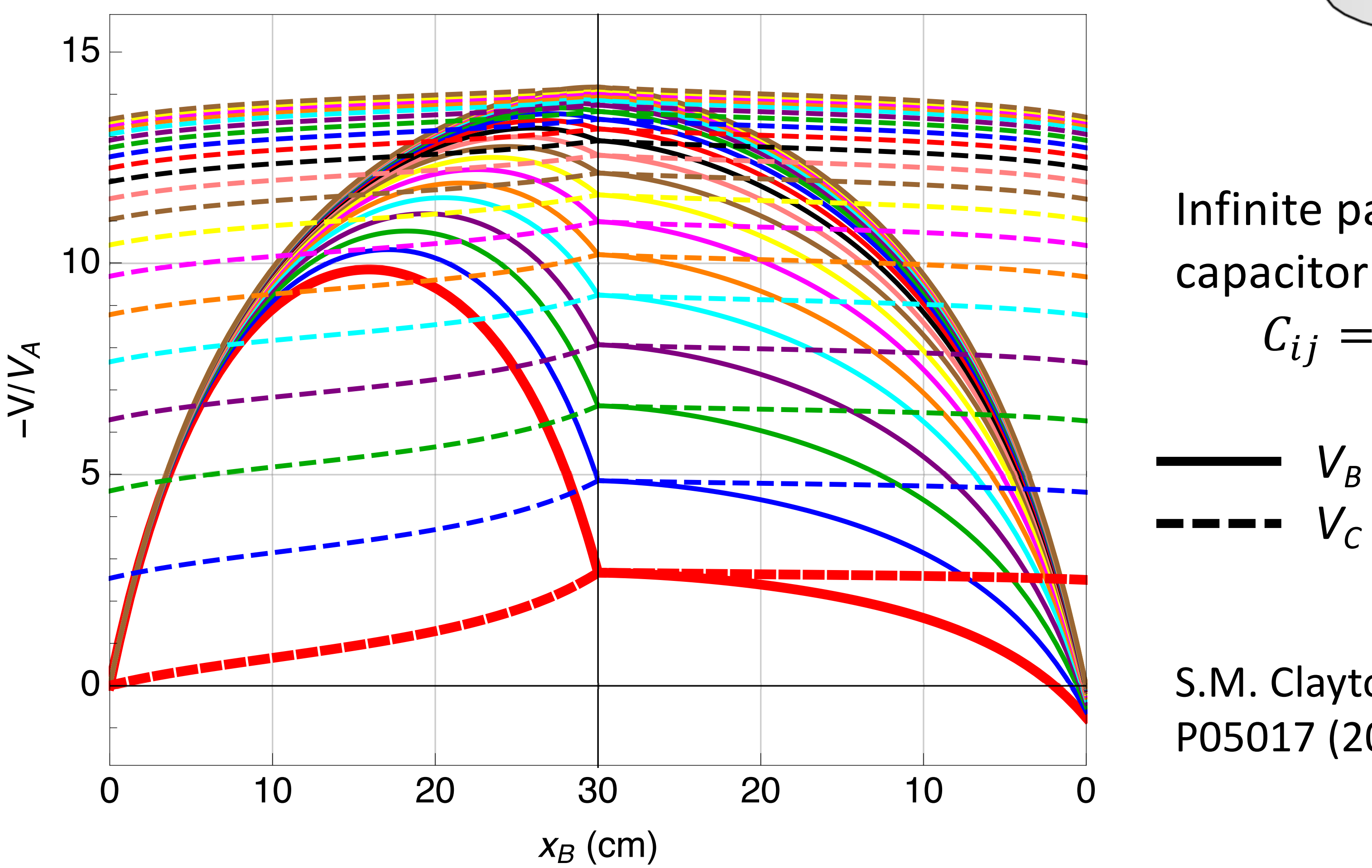
Prediction of Voltages



Expression in terms of mutual capacitances C_{ij}:

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

$$-\frac{V_C^{1,\max}}{V_A} = \frac{C_{AB}^a - C_{AB}^c}{C_{BG}^c + C_{AB}^c + \kappa C_{BC}^a} \equiv G^{\max}, \text{ where } \kappa \equiv C_{CG}^c/(C_{CG}^a + C_{BC}^a)$$



Infinite parallel plate capacitor model:

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

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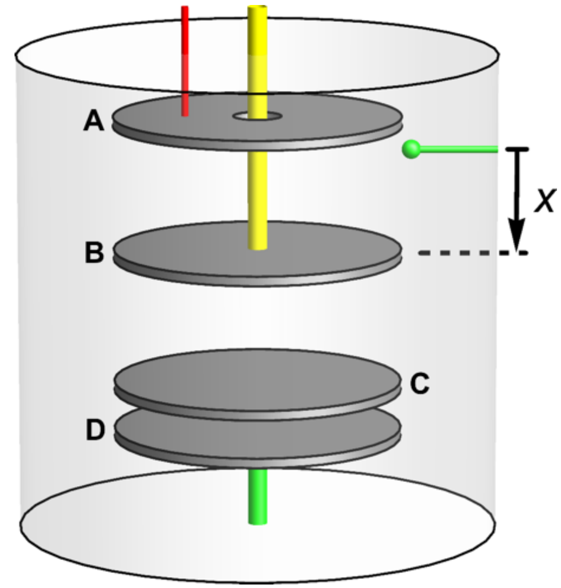
Prediction of Voltages



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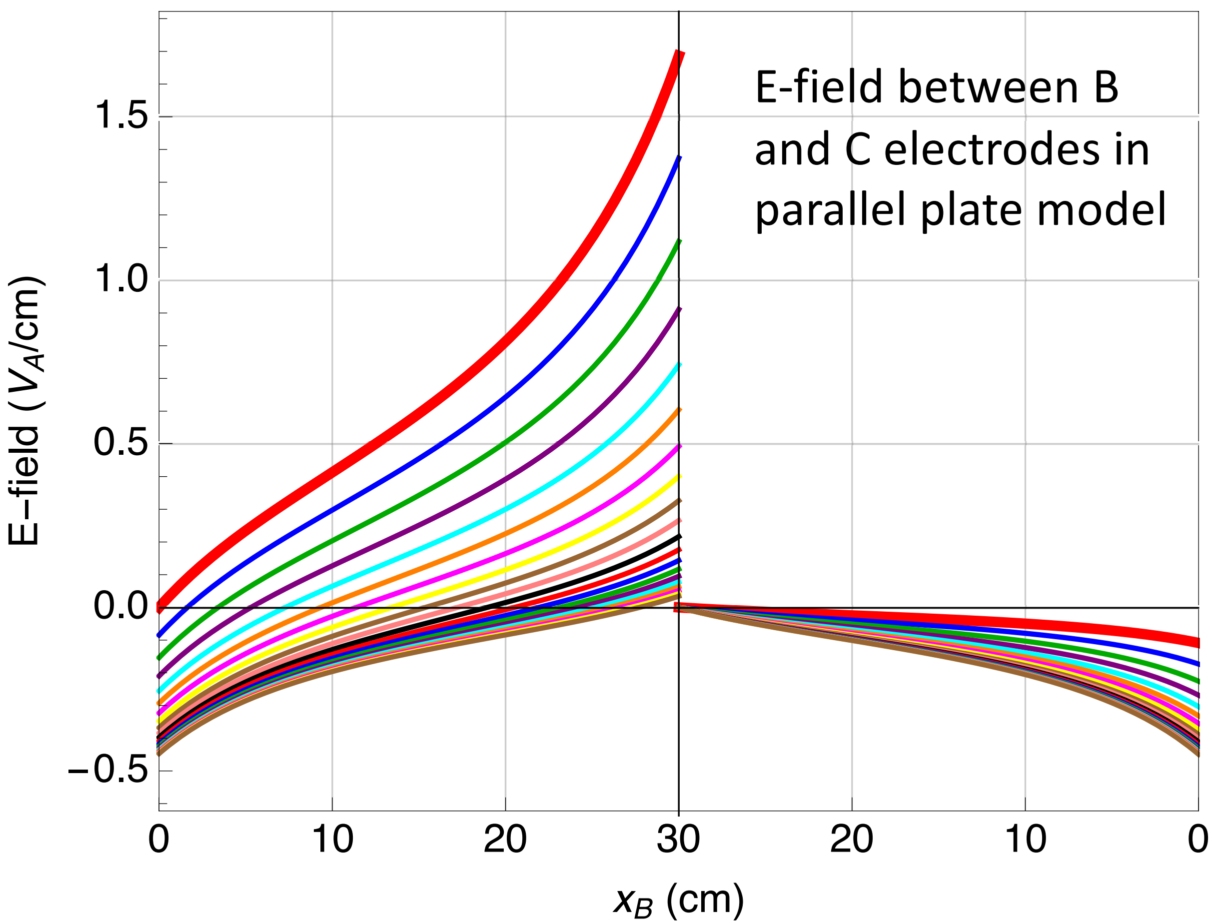
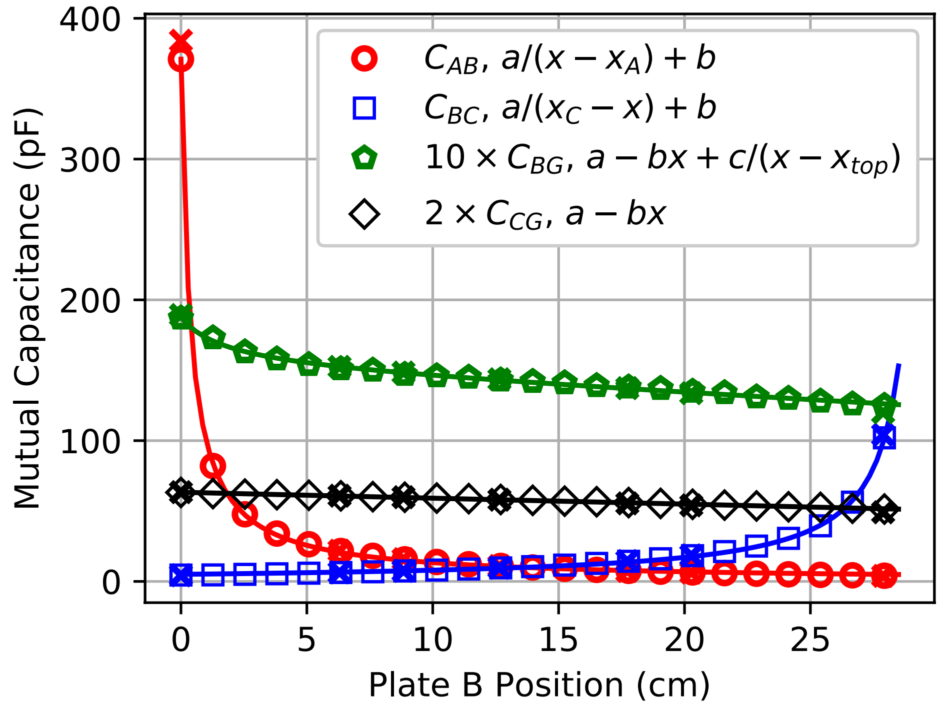


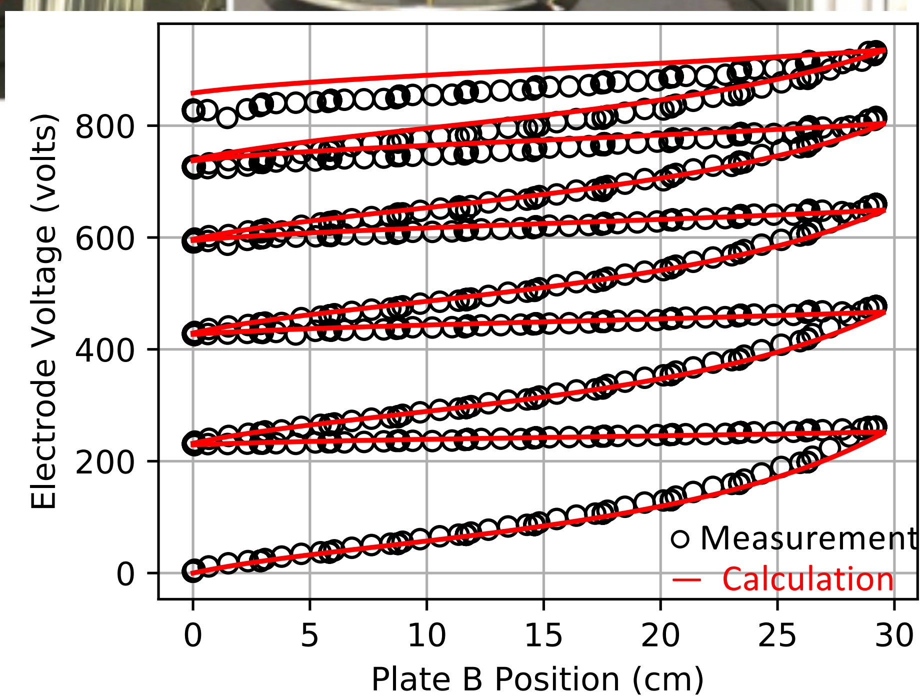
Infinite parallel plate capacitor model:

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

S.M. Clayton et al. JINST **13** P05017 (2018)

Room temperature demonstrator

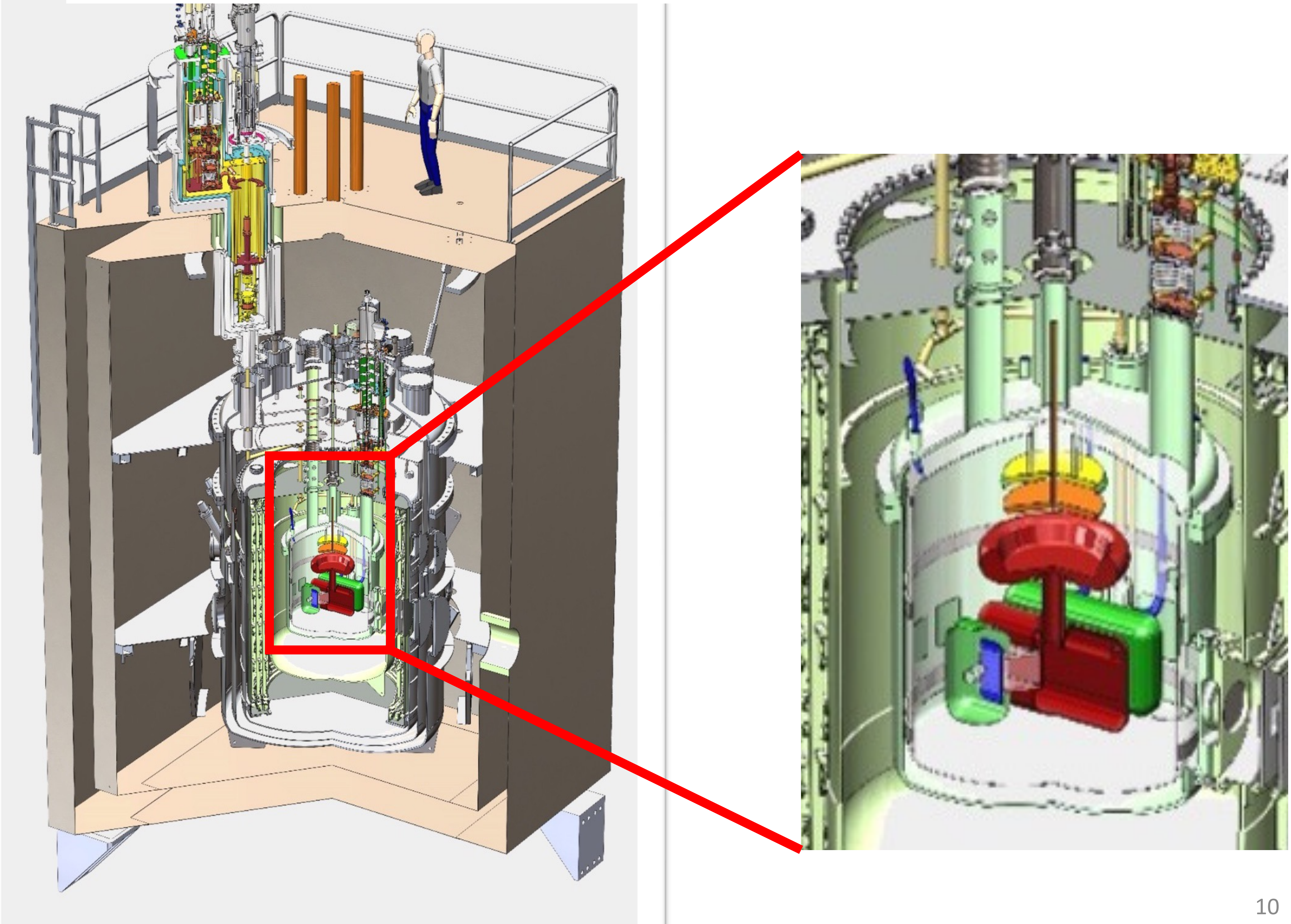




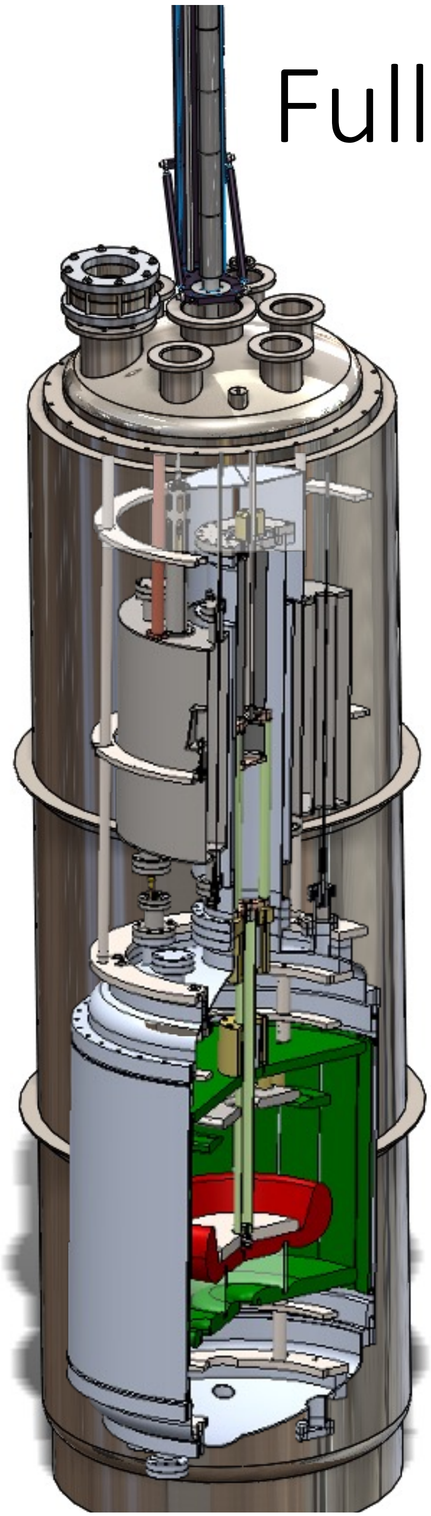
- Predicted electrode voltage is based on fits to measured capacitances (above plot).

S.M. Clayton et al. JINST **13** P05017 (2018)

nEDM@SNS experiment

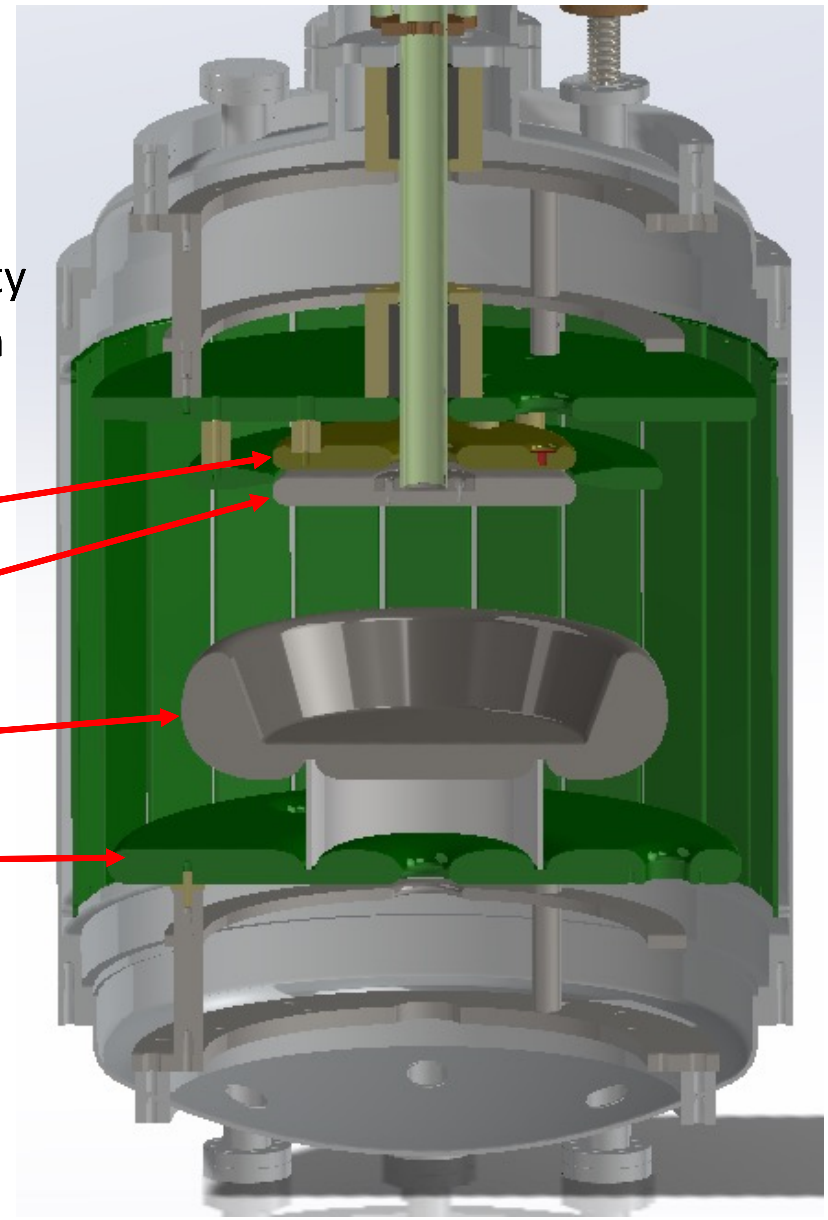


Full scale cryogenic prototype



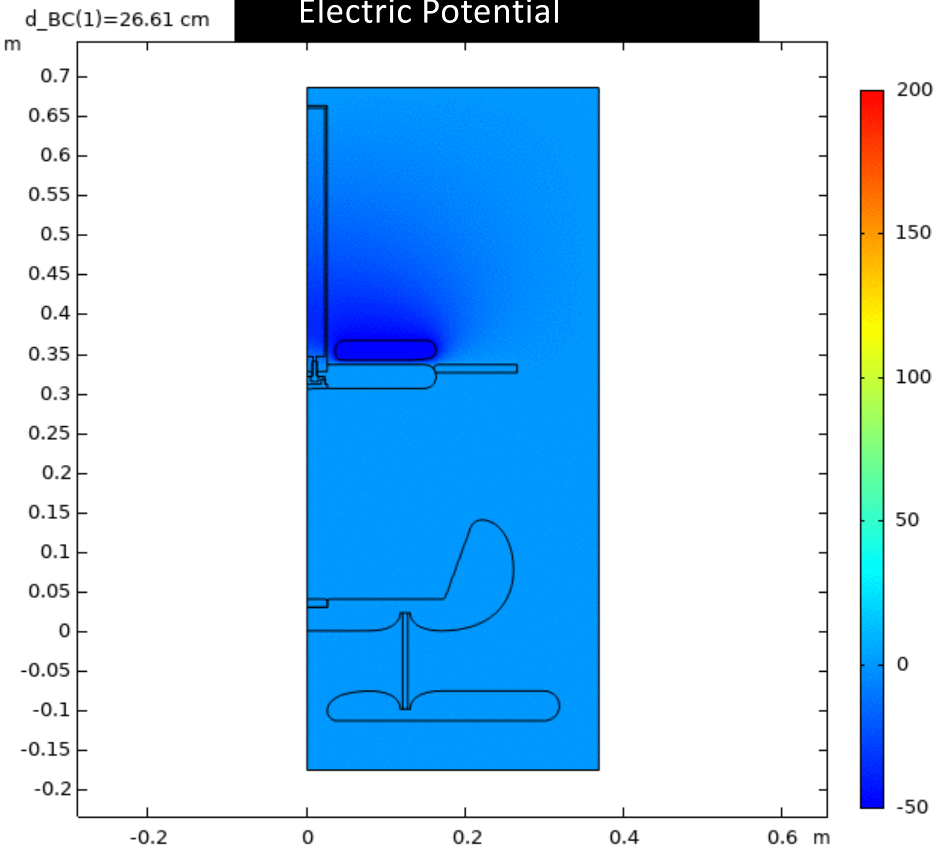
The electrode geometry was optimized to:

- Maximize the voltage gain
- Minimize the probability of electrical breakdown

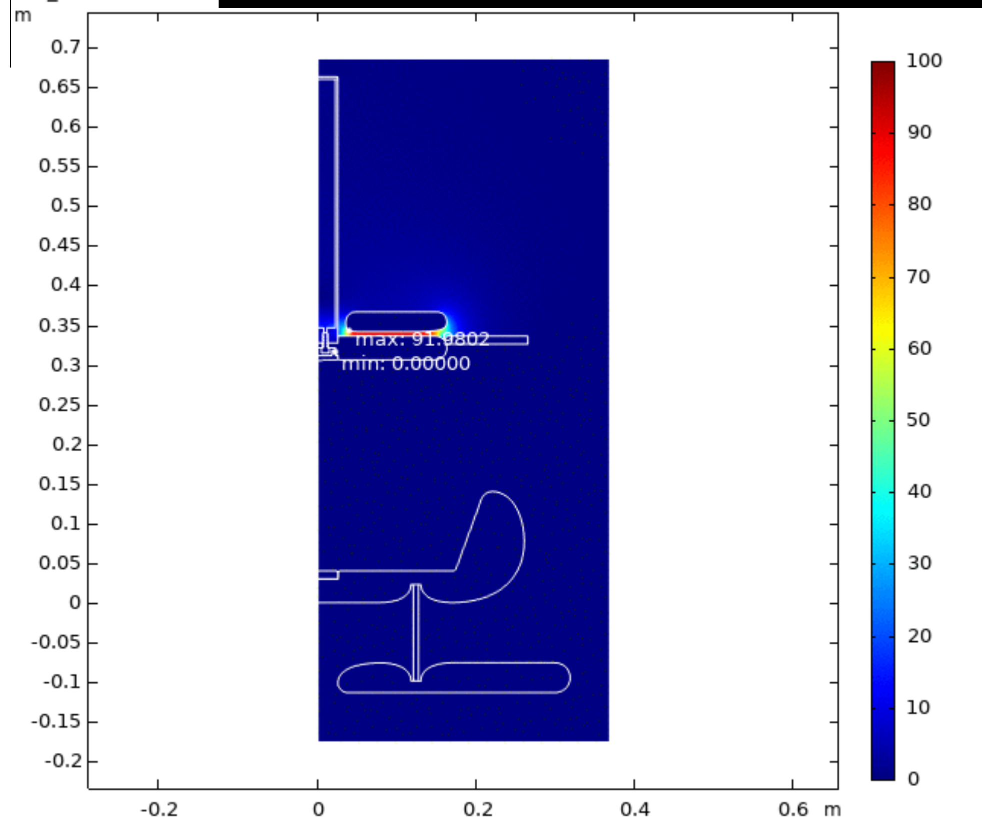


Cryogenic Cavallo Simulations

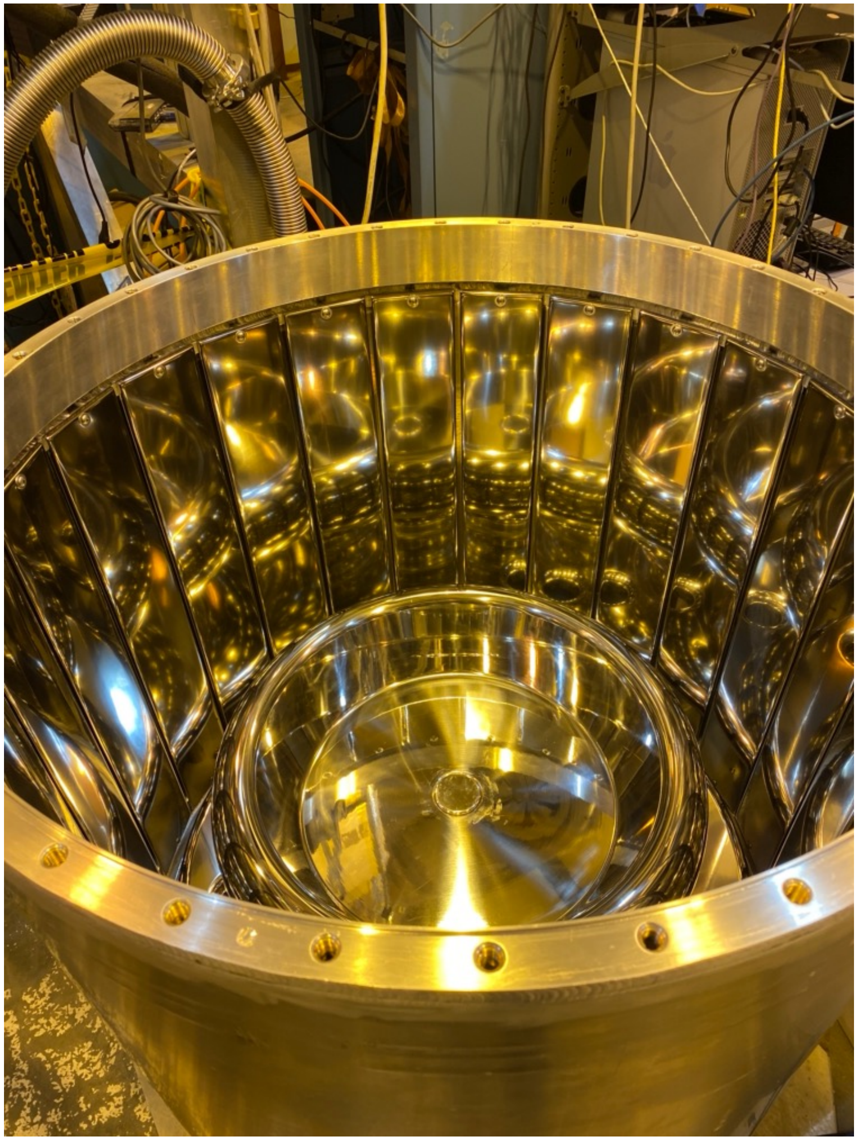
Electric Potential



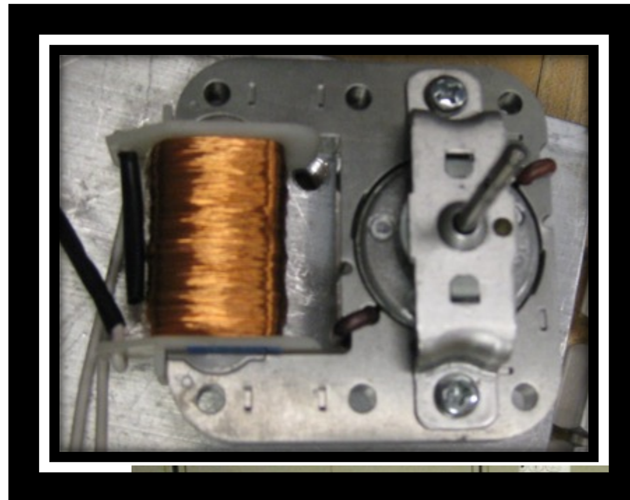
Electric Field

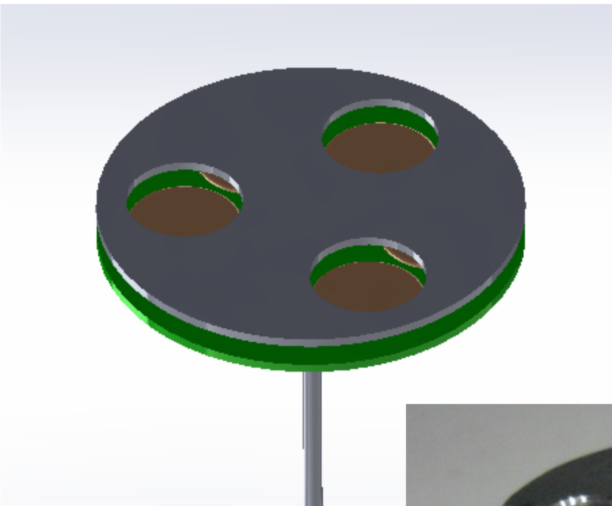


Assembly of full-scale cryogenic prototype

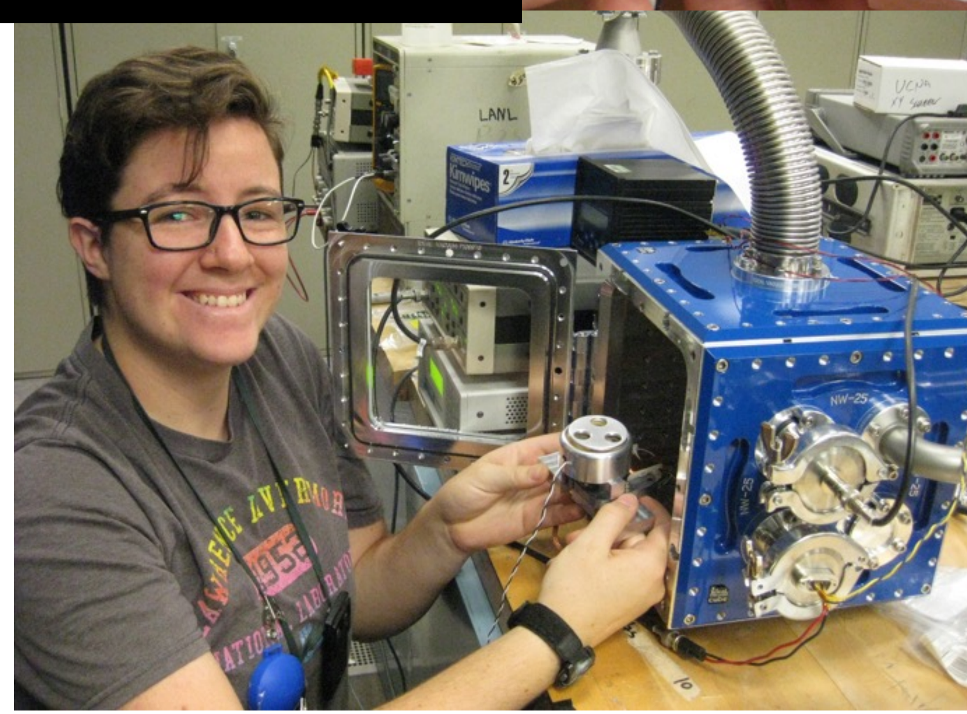


Field mill for non-contact voltage measurement in Cavallo test stand

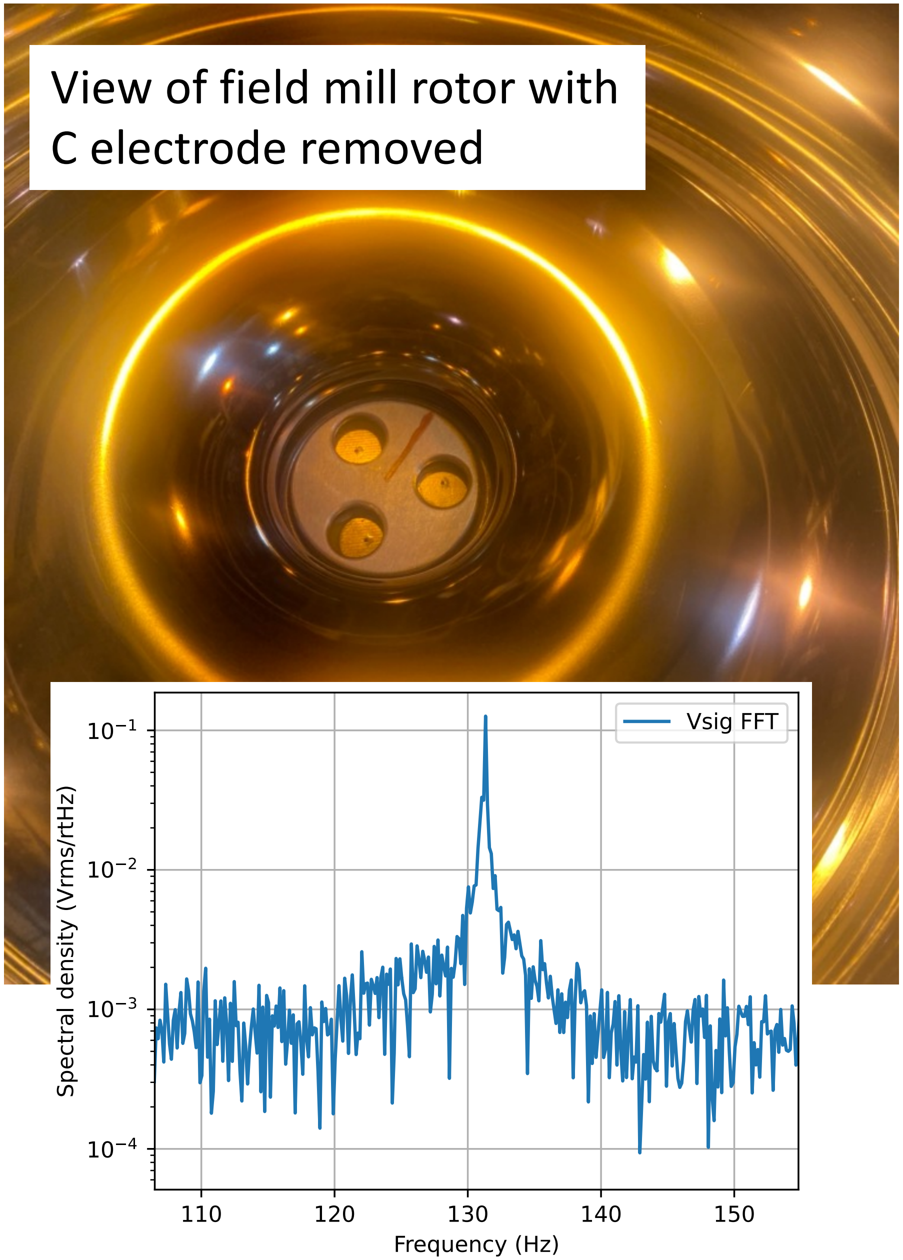


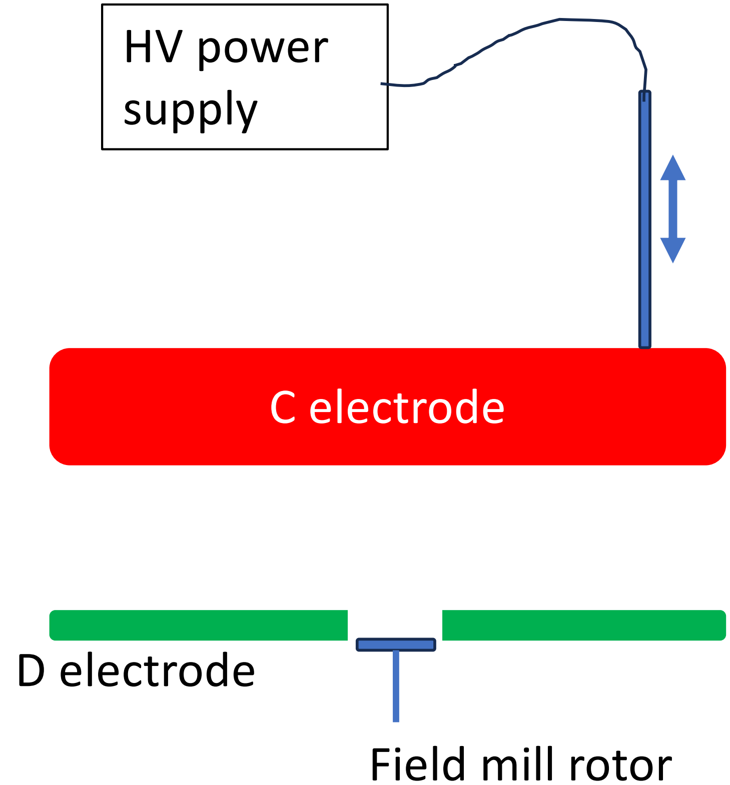


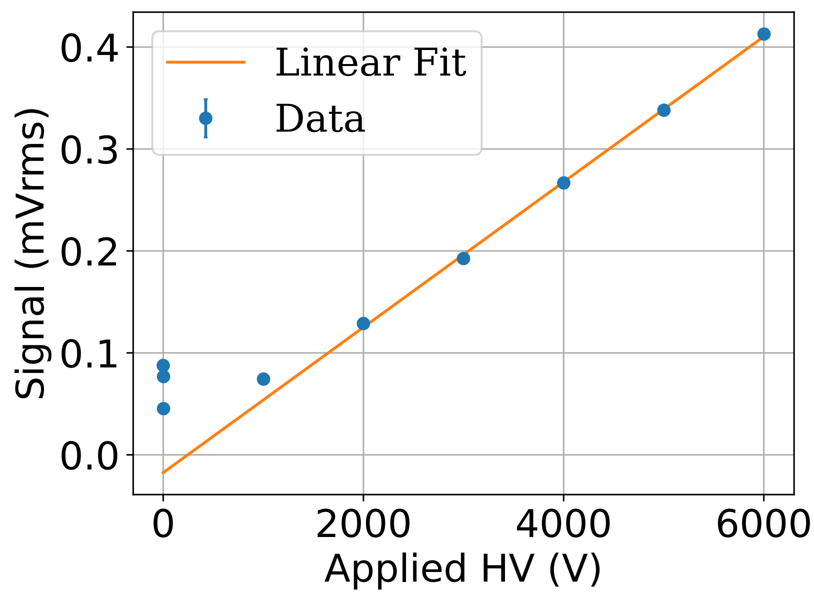
“3-Hole-Punch”



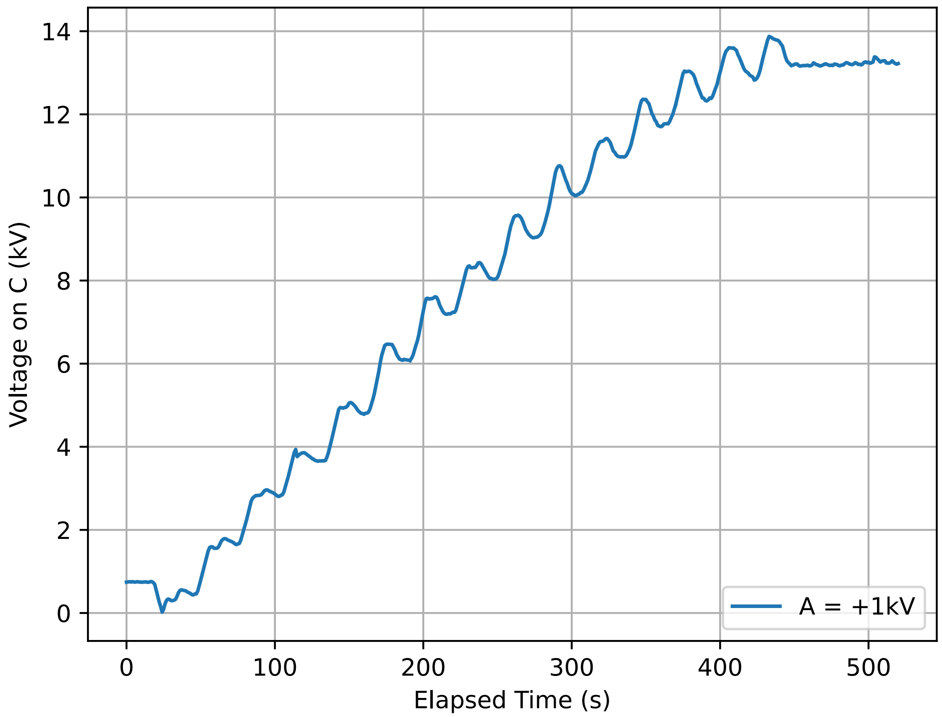
Field mill calibration



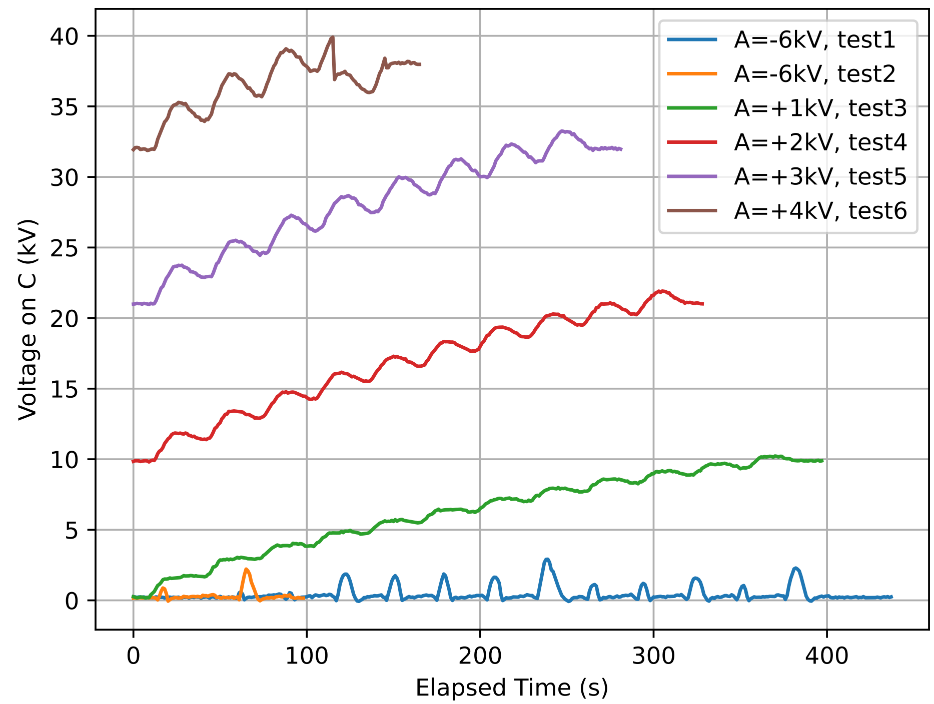




Test of the full-scale cryogenic prototype at room temperature in vacuum



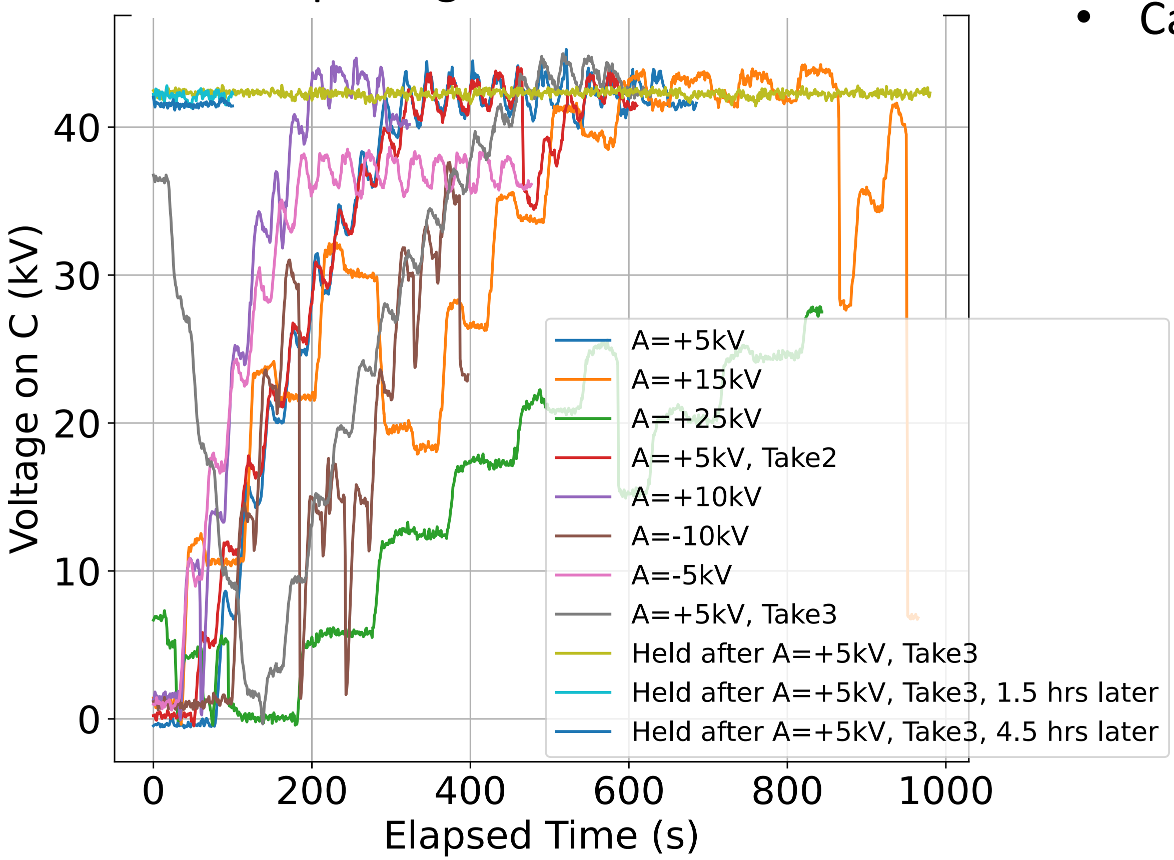
Successful demonstration of an amplification factor of 13.



A problem developed with the A electrode holding the input voltage. The problem was traced to an incorrect material used for the standoffs.

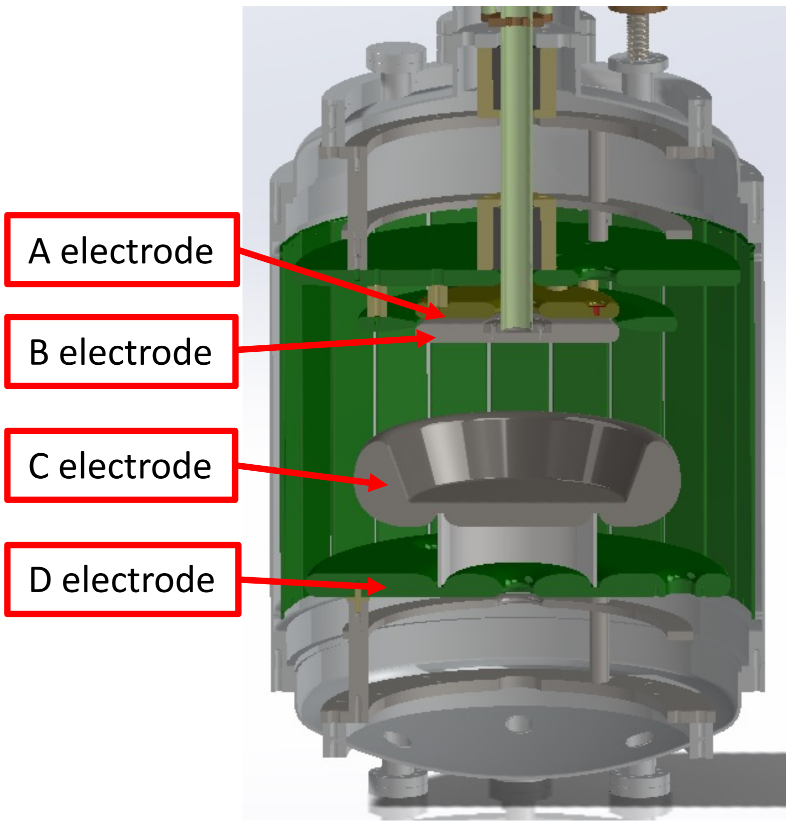
2^{nd} Test of the full-scale cryogenic prototype at room temperature in vacuum

After replacing A electrode standoffs



New problems were revealed:

- Ions created when B returns to ground
  - Can be mitigated…
- Can't seem to charge above ~45 kV
  - Caused by poor vacuum?



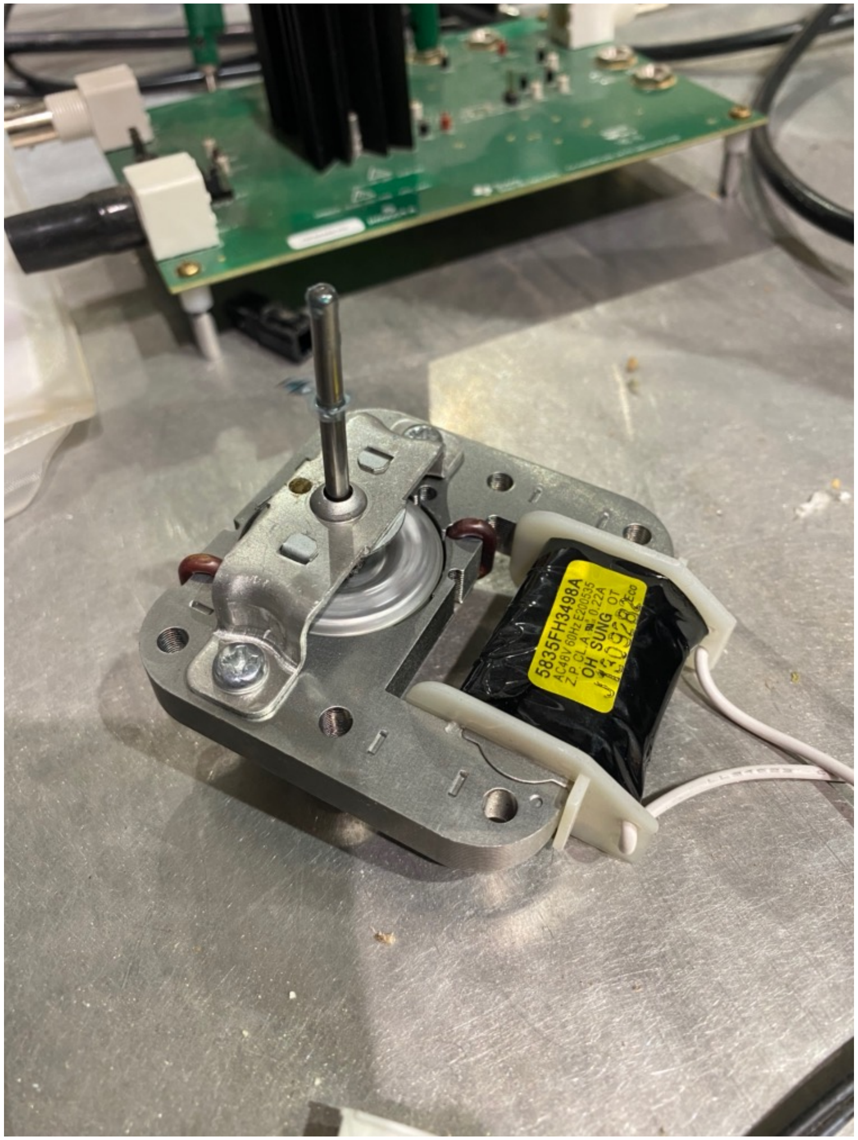
Next steps

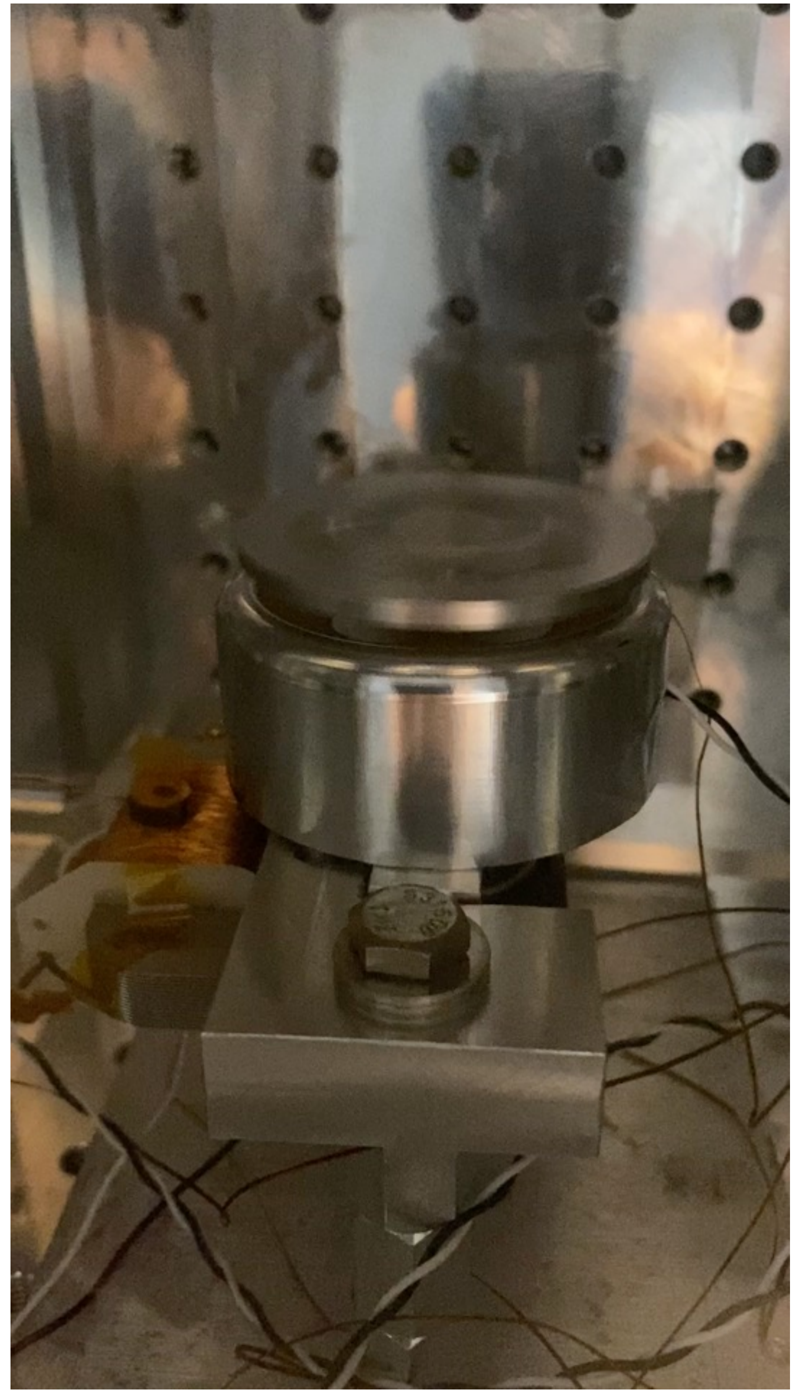
- Repeat HV amplification test in room temperature vacuum with an input voltage of up to 25 kV
  - Improve vacuum
  - Add diagnostics (monitor currents induced on ground ring and “D” electrode)
  - Also: Try SF6 environment
- Develop cryogenic field mill and alternatives
- Test cooldown of upper cryostat (1K pot)
- Install the Cavallo electrodes in the test cryostat
- Cooldown the cryostat and perform HV amplification test in liquid helium

Cavallo team and friends

- Marie Blatnik
  Caltech graduate student
  (front row, 2nd from left)
- Steven Clayton
  work package leader (back row, left)
- Takeyasu Ito
  scientist (front row, left)
- Alex Jacobs
  summer student from Santa Fe Prep
  (middle row, right)
- Anh-Thai Le
  summer student from Yale
  (middle row, 2nd from right)
- Mark Makela
  deputy group leader (not in the photo)
- Chris O'Shaughnessy
  engineer (not in the photo)
- Eric Renner
  engineer (middle row, left)
- Isaac Smythe
  post-bac (back row, right)
- Theresa Sandborn
  post-bac (front row, middle)
- T.J. Schaub
  research Technologist (not in the photo)
- Jason Surbrook
  postdoc (not in the photo)
- Wade Uhrich
  research technologist (not in the photo)

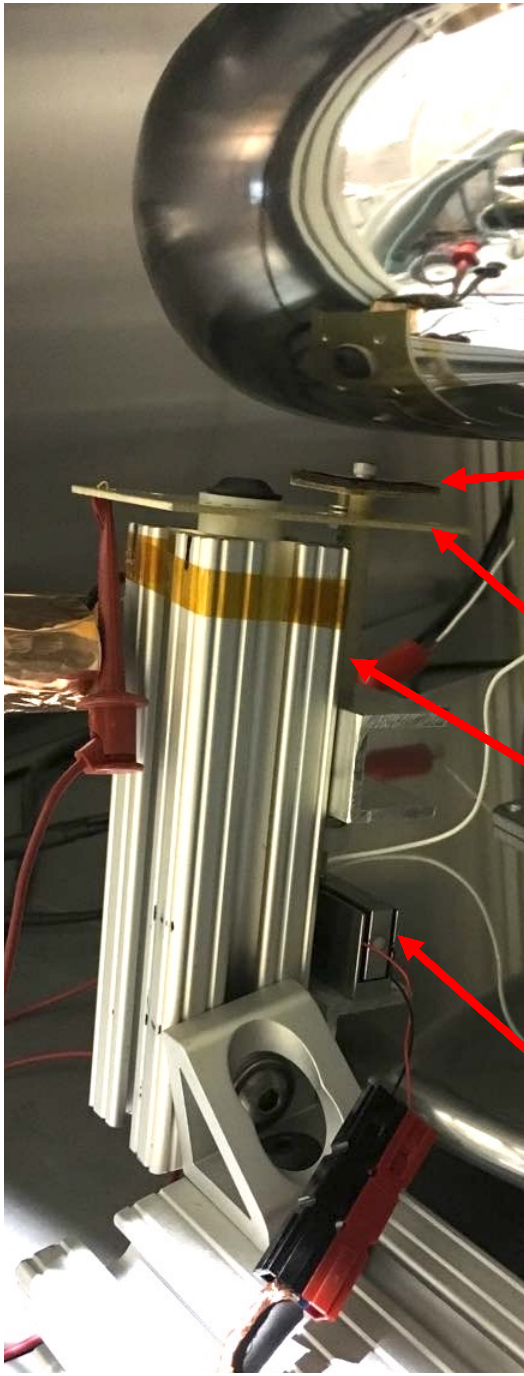
Extra Slides


5835FH3498A
AC48V 60Hz E200535
Z.P. CL.A. 0.22A
OH SUNG OT



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)

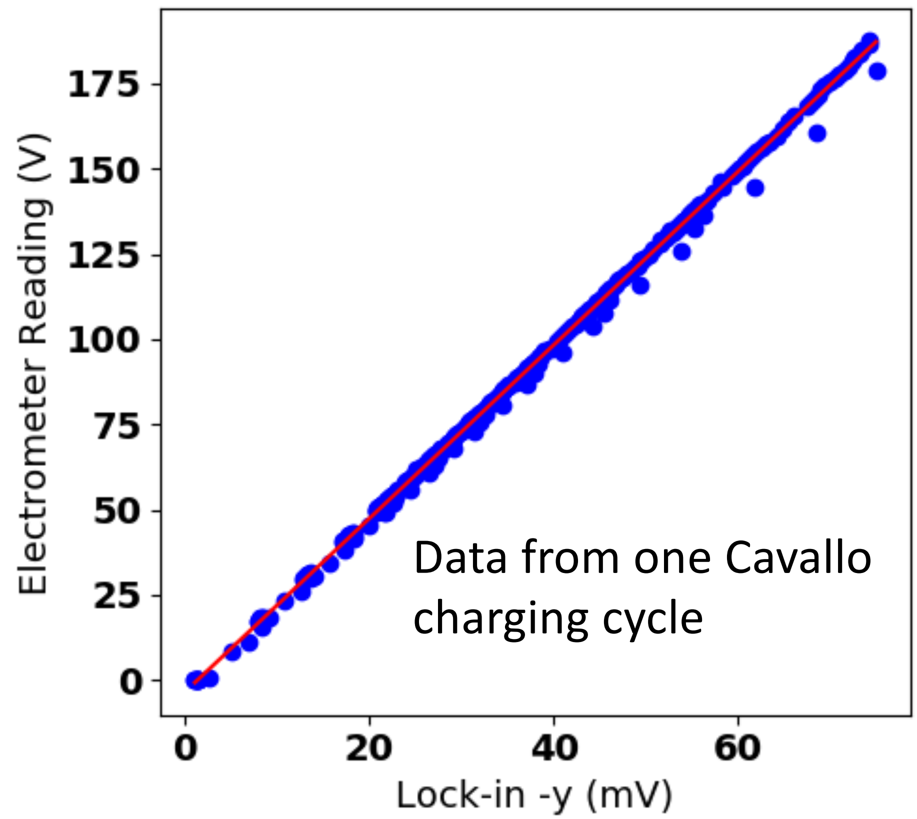


Moving plate: Cu-clad G10 (now a 1 ¼" disc; old plate shown here)

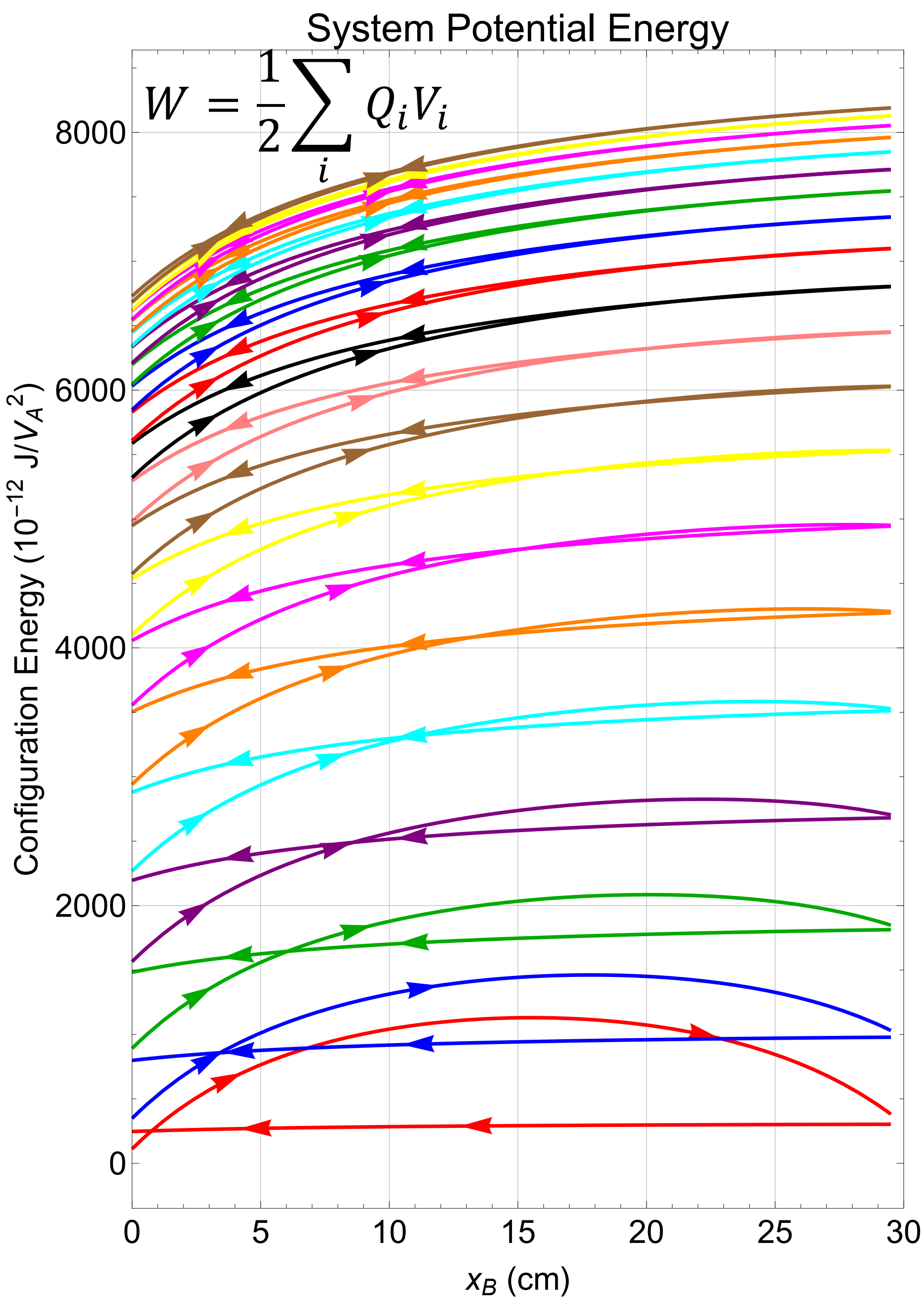
Reference plate

G10 rod down to actuator

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



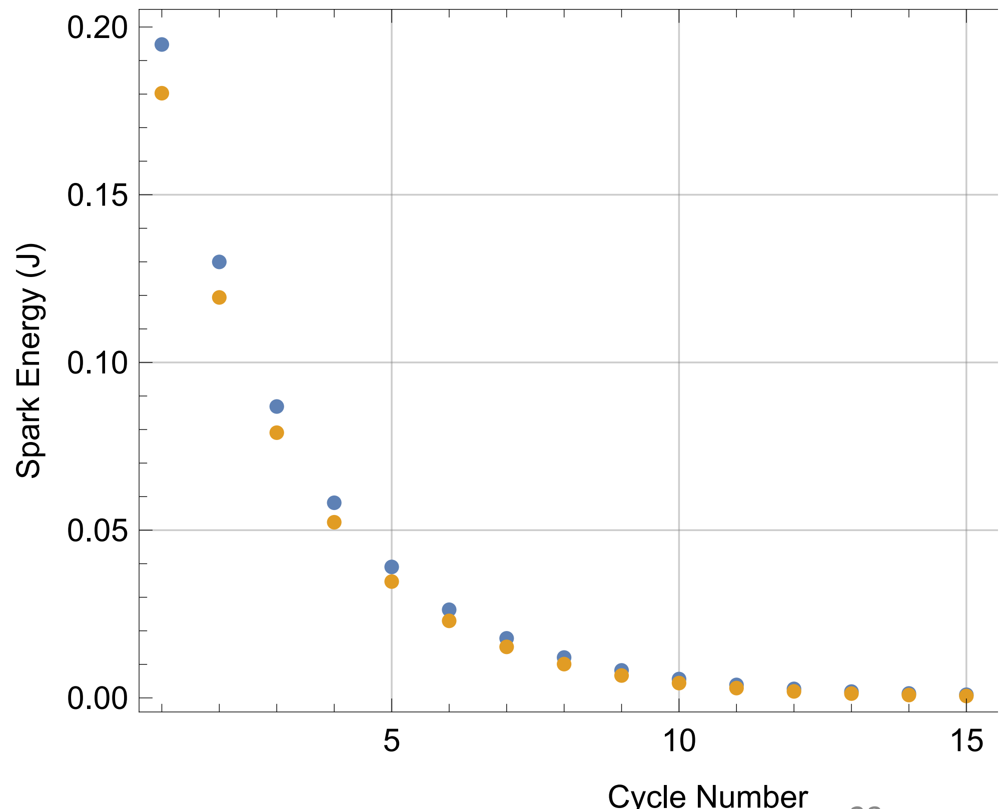
Spark Energy in Toy Model



Assumptions:

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

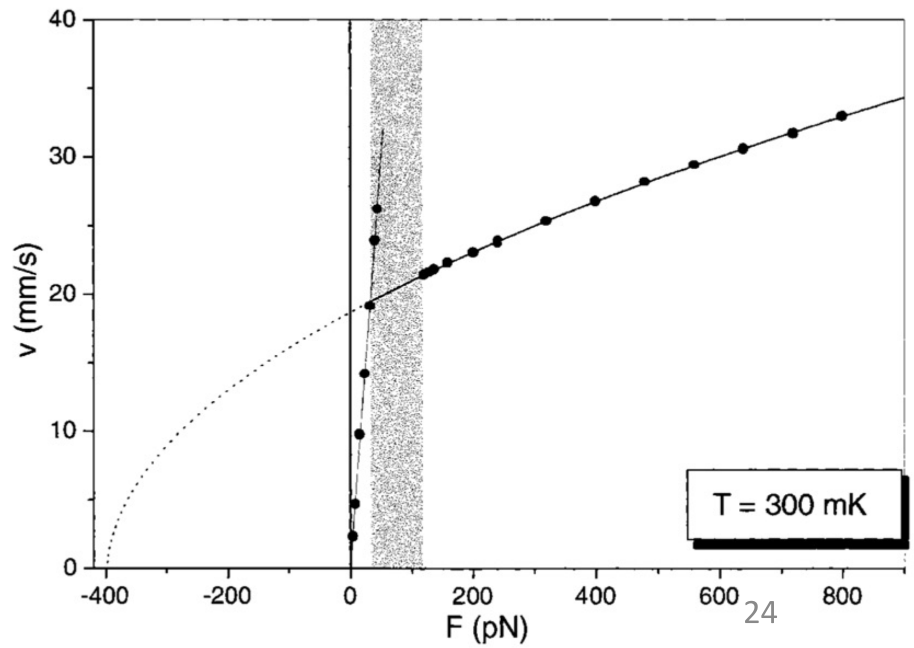
Maximum energy available to a spark: ΔW (before – after spark)



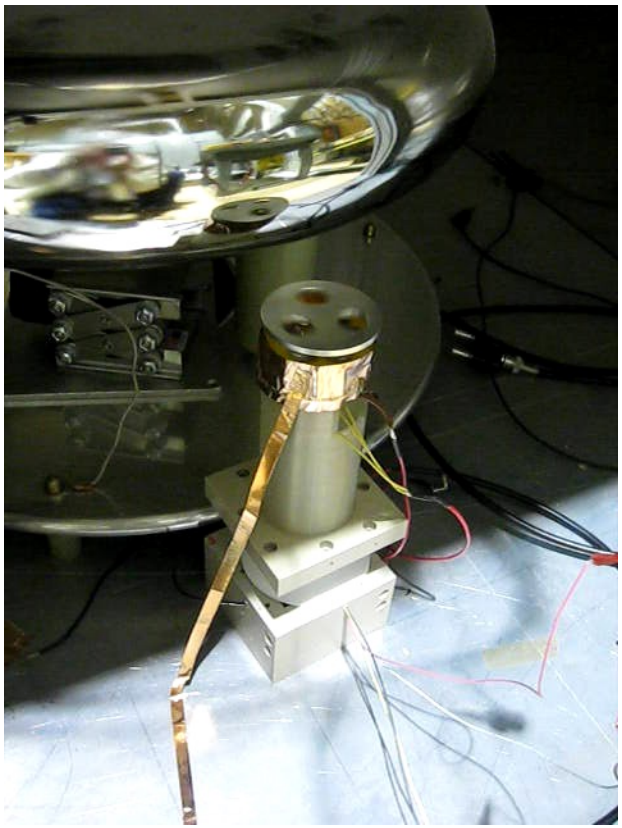
Other Sources of Heat

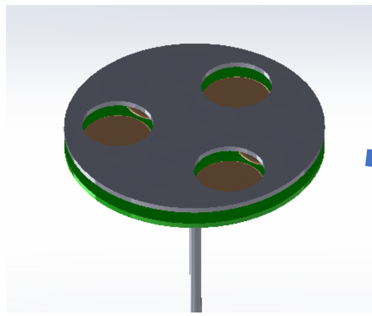
- Charge flow across resistive electrode surfaces
  - $W_q \sim \Delta t\, I^2 R \sim R Q_B^2/\Delta t$
  - If $R \sim 1$ kΩ, $Q_B \sim 1$ μC, and Δt ~ 1 s, → $W_q \sim 1$ nJ

- 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.



FIELD MILL PROGRAM:
NO-CONTACT HIGH VOLTAGE MEASUREMENT DEVICE





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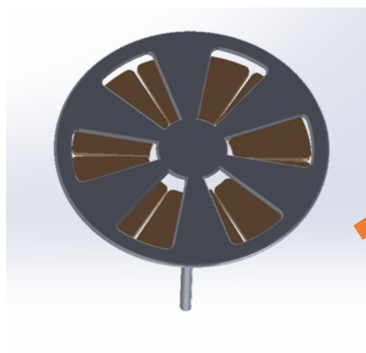

“Waffle”