High voltage in liquid helium for the SNS nEDM experiment

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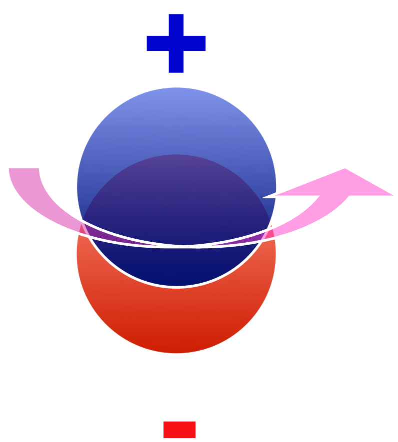
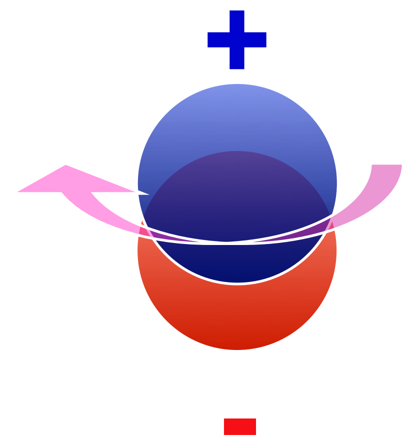
The work presented in this talk performed by many individuals including:
Scott Currie (LANL), John Ramsey (LANL), Weijun Yao (ORNL), George Seidel, (Brown), Josh Long (Indiana)

Outline

- Introduction
- R&D with Large Scale HV Test System
- R&D with Medium Scale HV Test System
- Effect of HV on LHe scintillation
- Summary

Electric dipole moment





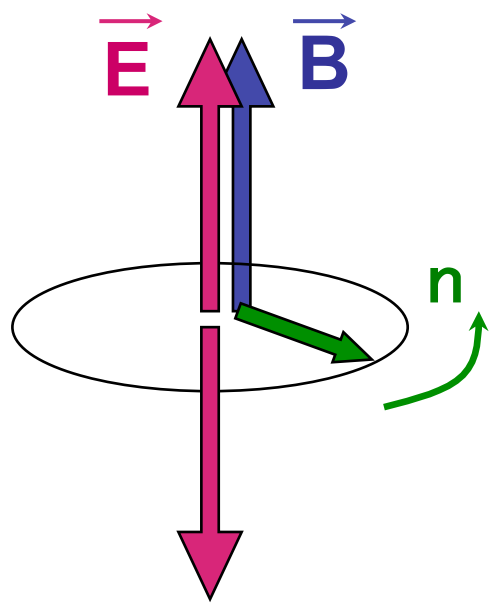
P or T reversed state

- Nonzero EDM violates both P and T (therefore CP) symmetries.
- Standard model value: $d_n \sim 10^{-32}$-10^{-31} e-cm.

  (Small! ⇒ Ideal probe for new physics)

- Present limit: dn < 2.9×10^{-26} e-cm (PRL 97, 131801 (2006))

Principle of the measurement



$$\nu = \left(2\mu_n B \pm 2 d_n E\right) / h$$

$$\Delta\nu = 4 d_n E / h$$

$$\delta d_n = h \frac{\delta \Delta \nu}{4E}$$

For B = 10 mG, ν ~ 30 Hz

For E = 50 kV/cm and $d_n = 4 \times 10^{-27}$ e-cm, Δν~ 0.2 μHz.

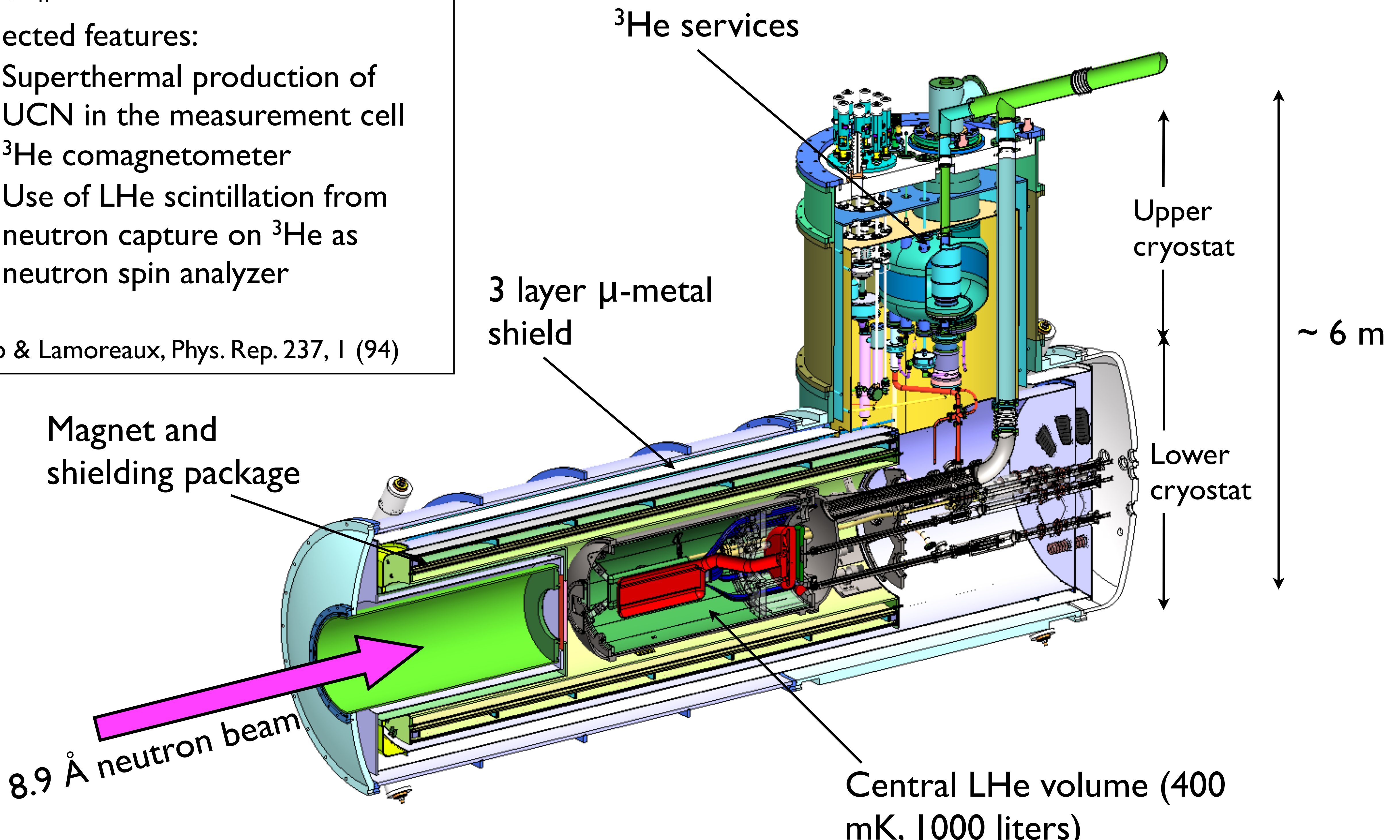
For each such measurement, the statistical sensitivity goes as

$$\delta d_n \propto \frac{1}{\left|\vec{E}\right| T \sqrt{N_{UCN}}}$$

SNS nEDM Experiment

- Goal:
  - $\delta d_n \sim 5 \times 10^{-28}$ e·cm
- Selected features:
  - Superthermal production of UCN in the measurement cell
  - ^{3}He comagnetometer
  - Use of LHe scintillation from neutron capture on ^{3}He as neutron spin analyzer

Golub & Lamoreaux, Phys. Rep. 237, 1 (94)

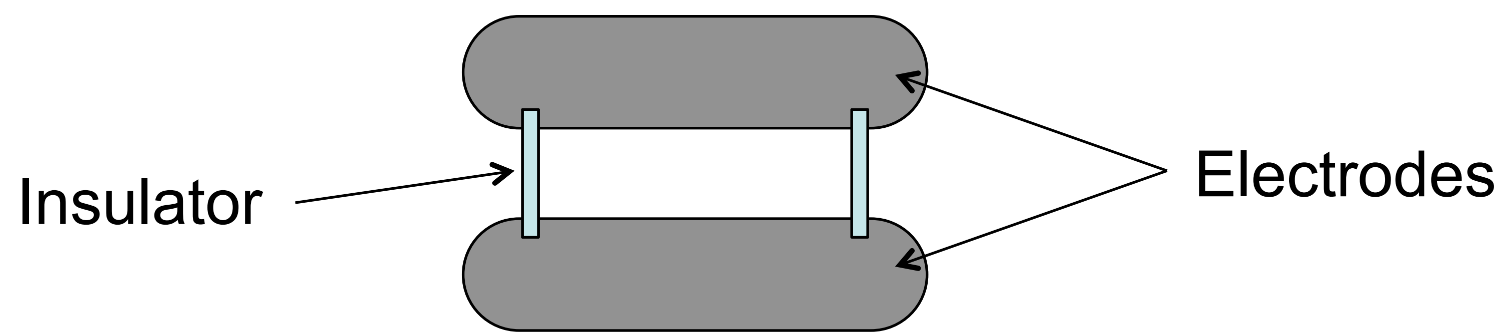


Electric field for nEDM experiments

- Sensitivity goes as

$$\delta d_n \propto E^{-1}$$

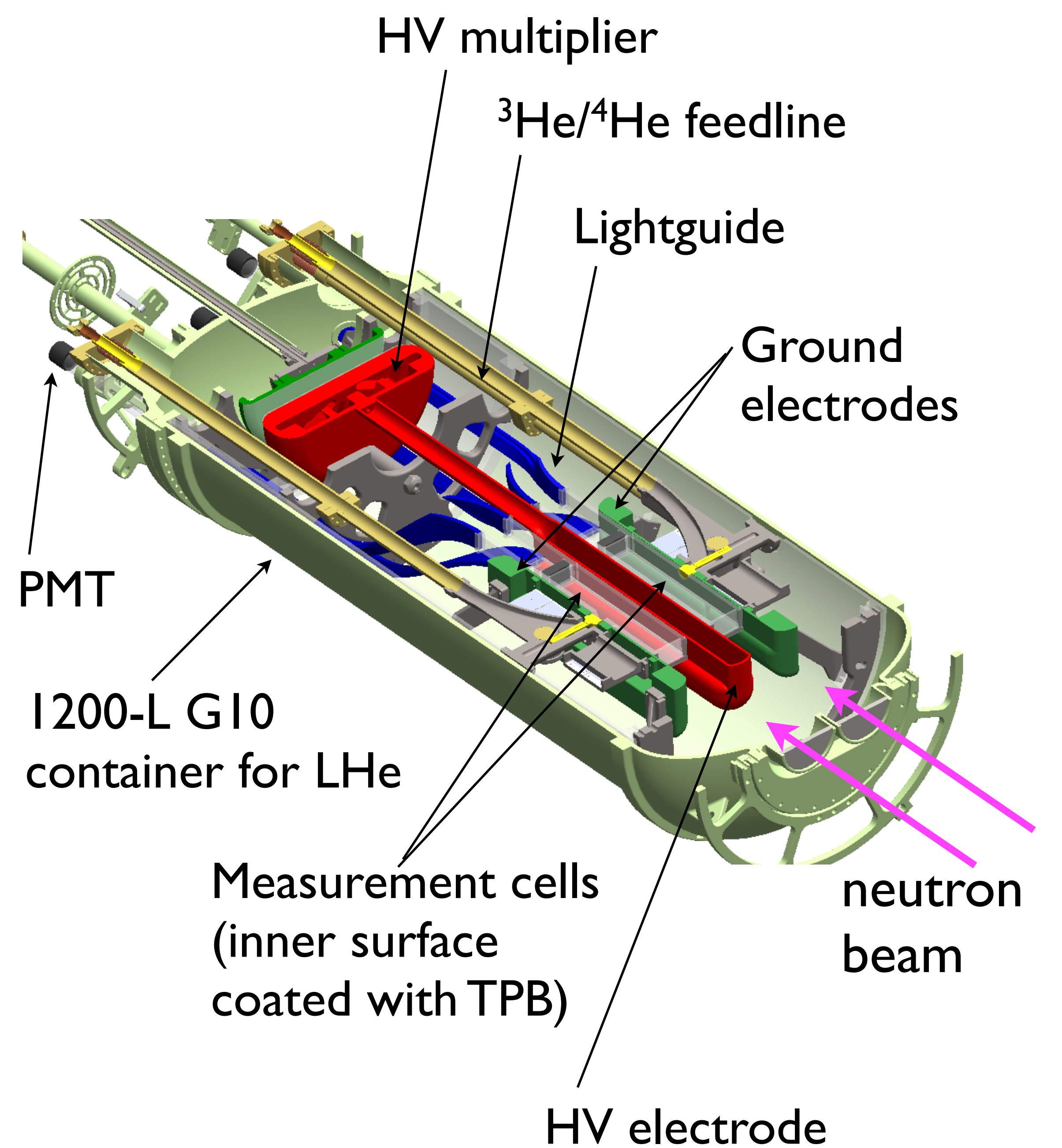
- The electric field strength for the previous room temperature experiments limited to ~ 10 kV/cm.
  - Problem: field emission electrons at the insulator-cathode junction.



- It is expected that a higher electric field can be used in nEDM experiments in which the measurement cell is immersed in LHe.
  - How high a field can be applied stably?
  - What is the effect of an insulator between the electrodes?
  - What is the dependence on temperature, pressure, electrode material and properties, etc?

Requirements/goals for HV in the SNS nEDM experiment

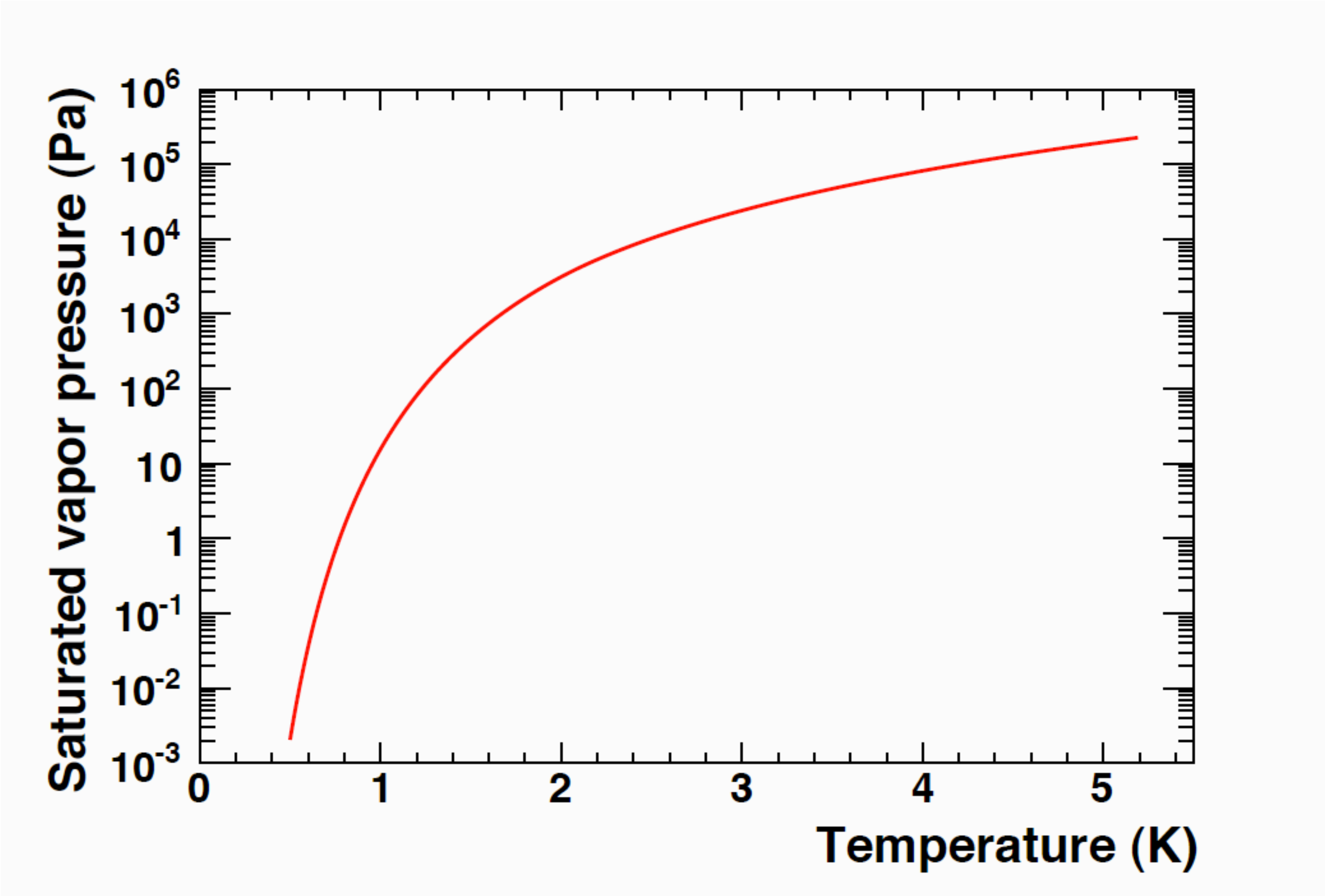
- Electric field goal:
  - 70kV/cm inside the measurement cells
    - Inner dimension: 40 x 7.62 x 10.16 cm^3
    - Wall thickness: 1.27 cm
  - Minimum leakage current between the electrodes
- Electrode material requirements:
  - Electrodes made of PMMA coated with conductive material
  - Electrical resistivity: $10^2\ \Omega/\square < Rs < 10^8\ \Omega/\square$
  - Robust to thermal cycling and sparking
  - Minimal activation due to exposure to neutron beam
  - Non-magnetic
  - Fabrication technique scalable to large ($10 \times 40 \times 80\ cm^3$) complicated 3D shape



Electrical breakdown in LHe

- Prior to recent LANL and Sussex efforts, data existed for 1.2 - 4.2 K, mostly at SVP (bulk of the data were taken at 4.2 K)
  - For varying geometries (plane-plane, sphere-plane, sphere-sphere)
  - In general, very little consistency
- No models or theories
- However, a consideration mean free path of ions in LHe suggests a very high intrinsic breakdown field (>10 MV/cm)
- Generally accepted picture:
  1. A vapor bubble is formed on the surface of the electrode e.g. by field emission from roughness on the cathode
  2. The vapor bubble grows by some mechanism and forms a column of gas reaching from one electrode to the other
  3. Electrical breakdown occurs through the gas
- Parameters that may affect the breakdown field
  - Electrode material and surface quality
  - Electrode area (Weber and Endicott, Trans. AIEE 75, 371 (1956))
  - Gap size
  - Temperature and pressure

LHe saturated vapor pressure

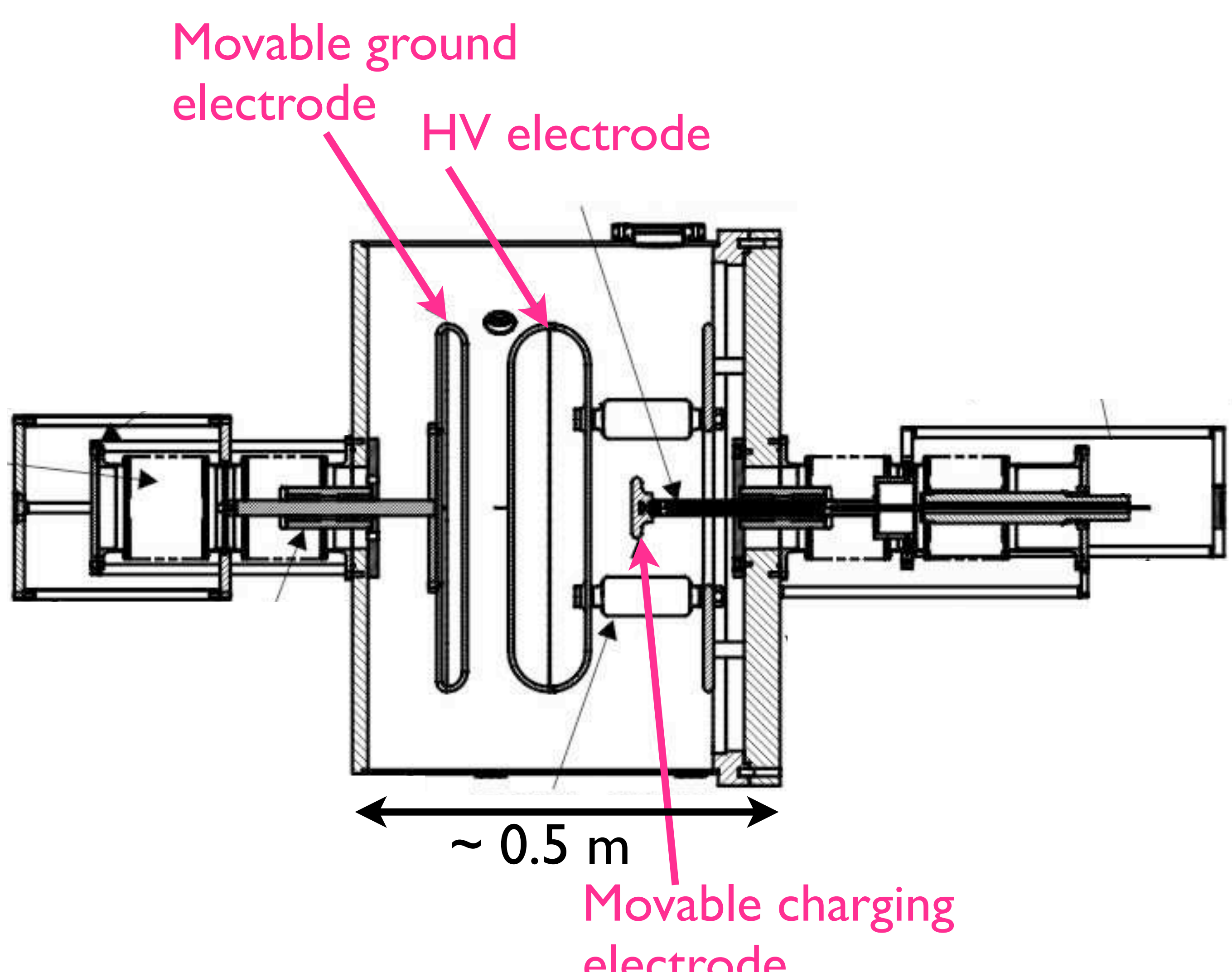


R&D performed so far

- Large Scale HV Test at LANL (electrode size ~ 50 cm in diameter)
  - HV generation
  - Temperature/pressure dependence of breakdown field by evaporative cooling to down to 1.6 K
- Medium Scale HV Test at LANL (electrode size ~ 12 cm in diameter)
  - Temperature dependence down to 0.4 K
  - Pressure dependence between SVP and 1 atm
  - Electrode material dependence
  - Gap dependence
- Small Scale HV Test at IU (electrode size ~ 2 cm in diameter)
  - Temperature dependence down to 1.5K
  - Pressure dependence between SVP and 1 atm
  - Electrode material dependence

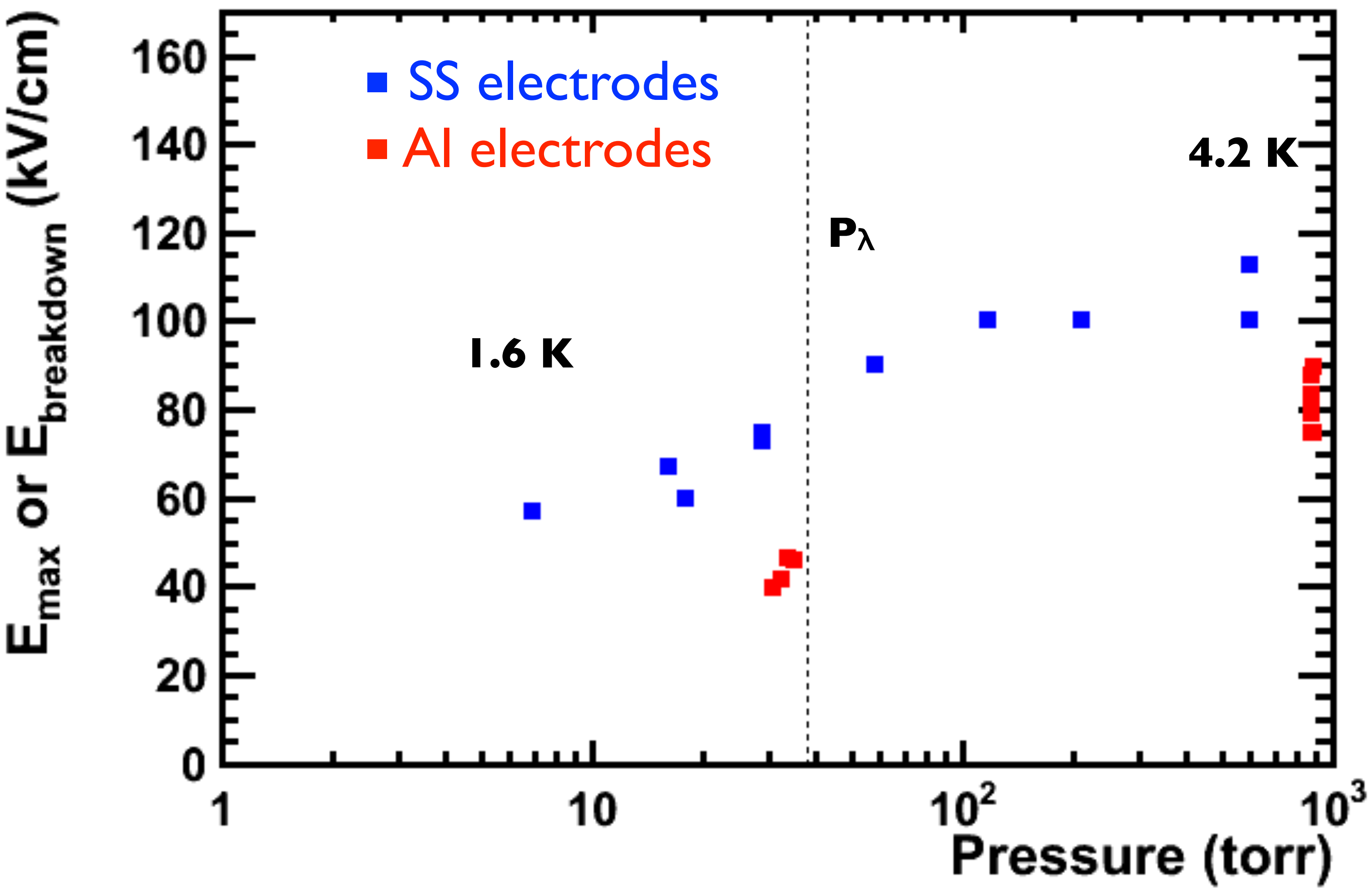
Large Scale HV Test Apparatus

- Need for potentials > 600 kV (75 kV/cm across 7 cm plus 2 cm cell walls)
- Capacitance multiplier: variable capacitor, potential increases as the spacing
- Demonstrated voltage amplification (~ 600 kV at 4.2 K).



Breakdown field vs pressure?

Old results from the Large Scale Apparatus



- Electrode size ~ 50 cm in diameter
- Gap ~ 3-4 mm
- Data taken at SVP
- LHe evaporatively cooled

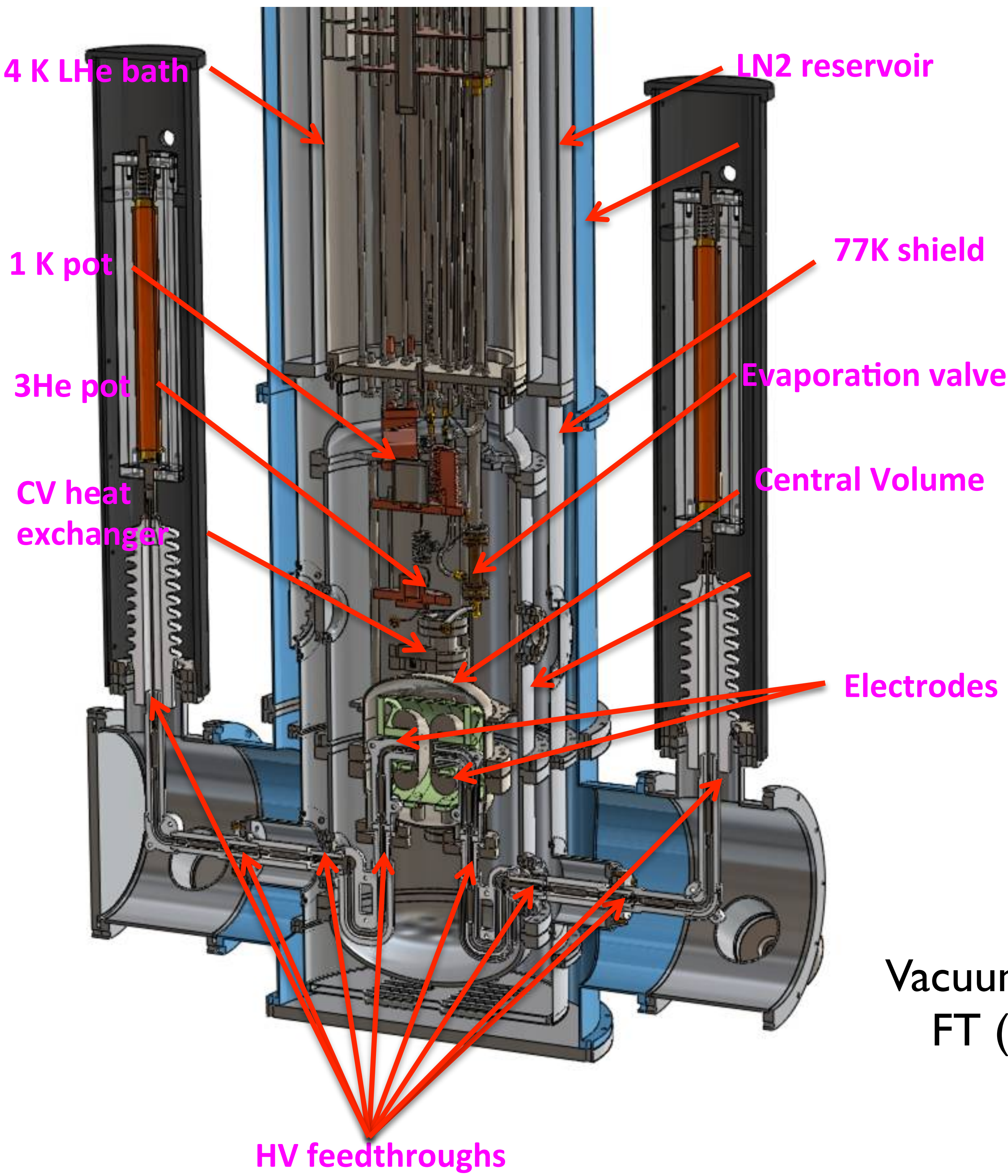
Note: the field strength plotted is simply V/d. The actual highest field in the system is higher because the electrode shape was simply a flat plate with a rounded edge.

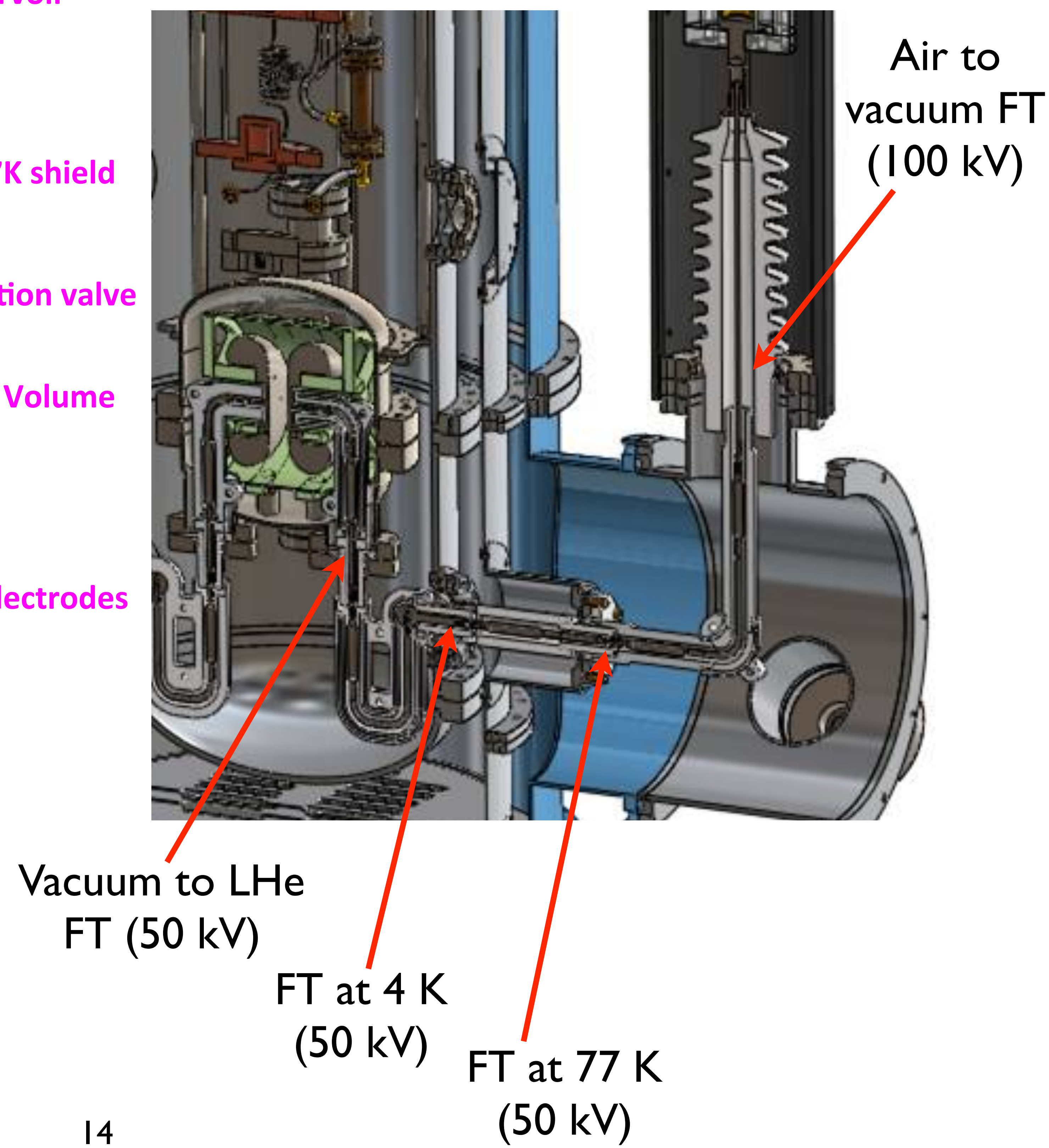
Based on our observation made later in other systems, it is possible that the observed pressure dependence was due to bubbles formed on the electrode surface due to heat flowing into the electrodes because of insufficient thermal anchoring.

Medium Scale HV (MSHV) Test Apparatus

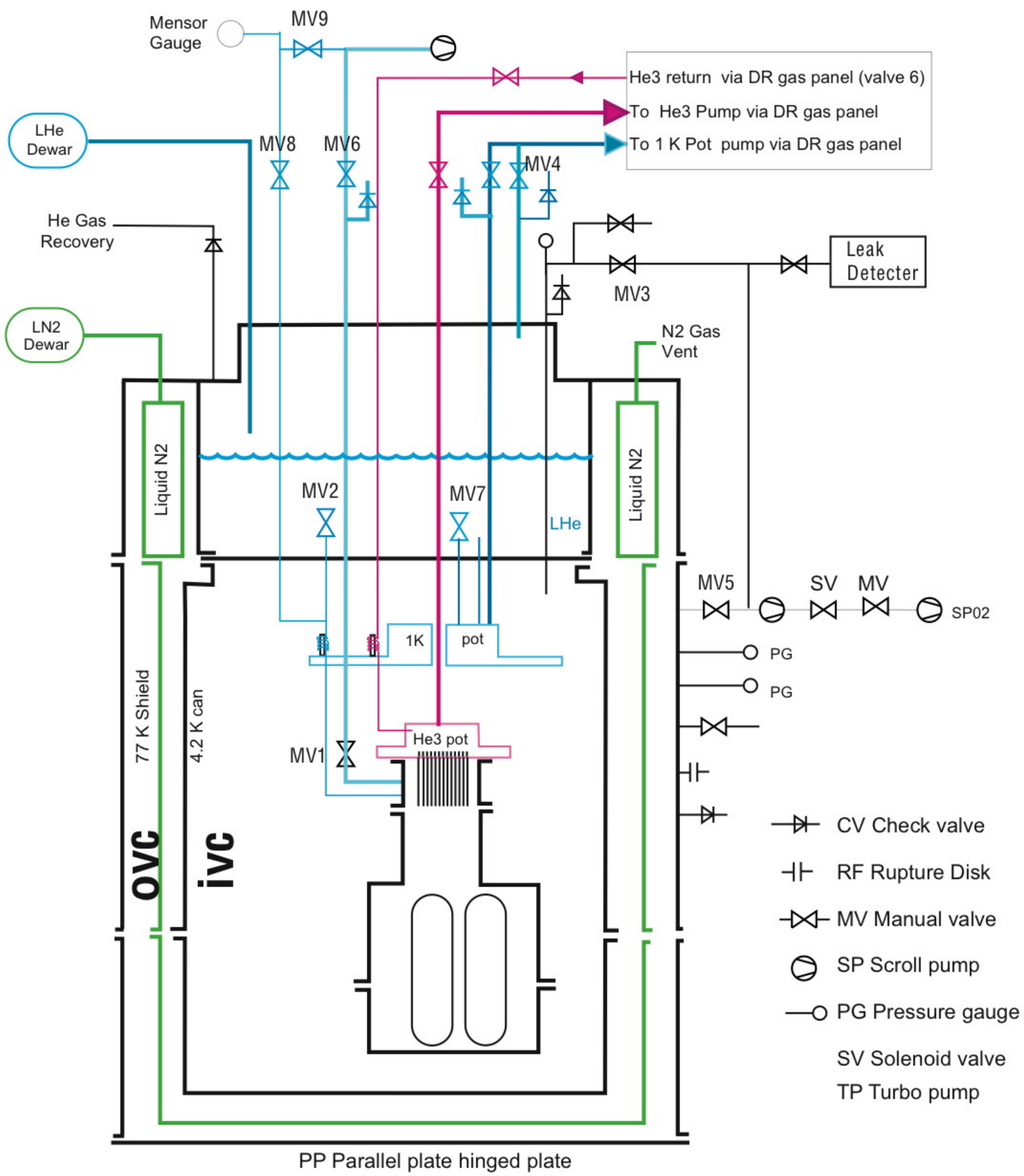
- Purpose
  - To study breakdown field dependence on various parameters in a system that can be cooled and warmed up in a relatively short turn around time (~ 2 weeks)
  - These parameters include: Temperature, pressure, gap size, electrode material
- Features
  - 6 liter LHe volume is cooled by a 3He fridge
  - Electrode size: ~ 12 cm in diameter
  - Electric field: currently up to ~ 100 kV/cm in a 1 cm gap (design goal: 75 kV/cm in a 2 cm gap)
  - Gap size adjustable between 0.5 cm and 2.0 cm
  - Lowest temperature: 400 mK
  - Pressure: variable between SVP and 1 atm
  - Turn around time: ~ 2 weeks

MSHV Design


4 K LHe bath
LN2 reservoir
1 K pot
77K shield
3He pot
Evaporation valve
CV heat exchanger
Central Volume
Electrodes
HV feedthroughs


Air to vacuum FT (100 kV)
Vacuum to LHe FT (50 kV)
FT at 4 K (50 kV)
FT at 77 K (50 kV)

MSHV flow diagram



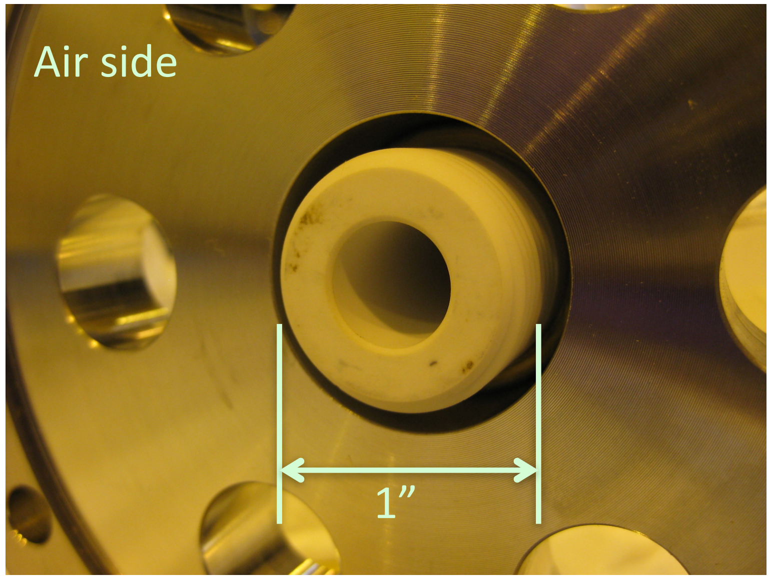
Notes:

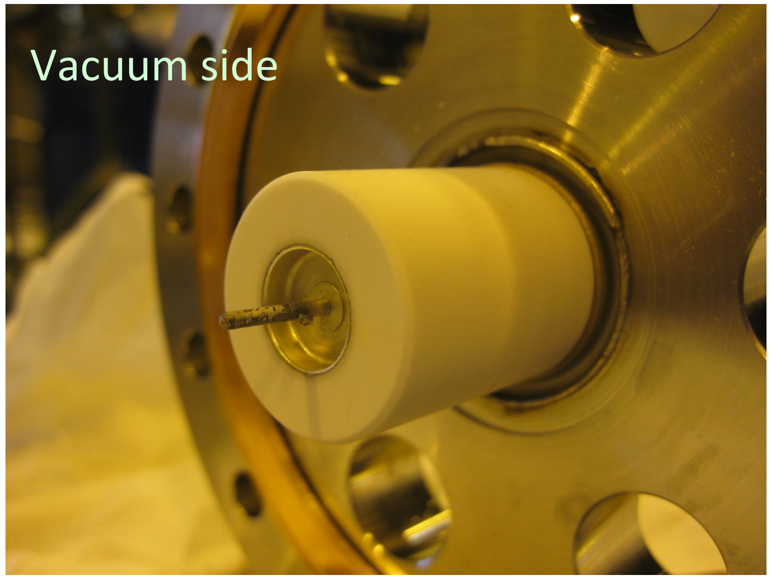
- The CV is filled through from the main LHe bath through MV2 and a capillary line.
- MV1 is a large aperture superfluid tight valve developed at UIUC.
- The CV pressure can be varied by closing MV2 and pumping on the capillary line.

MSHV system

Feedthroughs

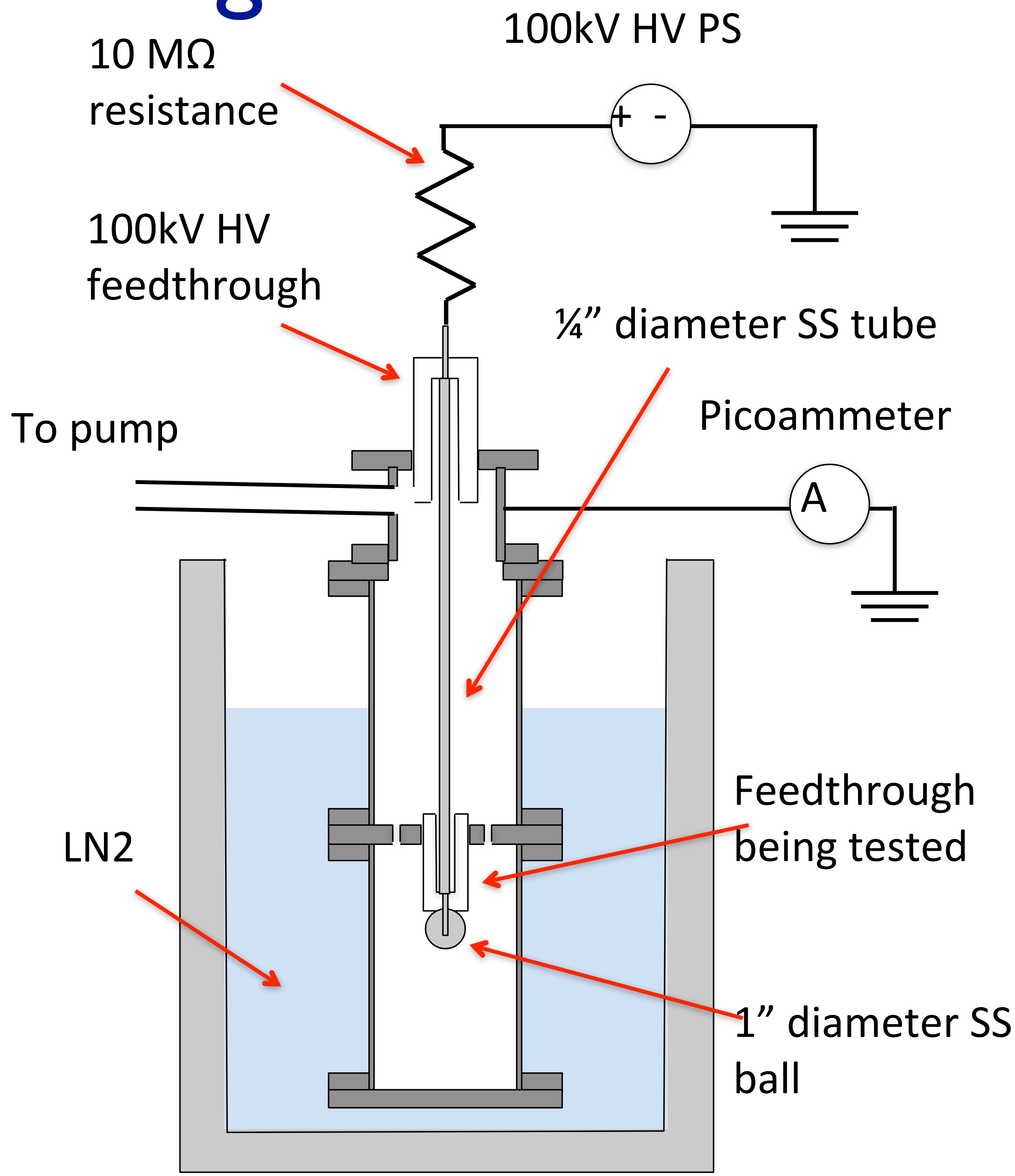
- The design goal was to apply up to 75 kV/cm in a 2 cm gap by bringing in +75 kV and -75 kV. This requires 75 kV feedthroughs.
- However, space limitation required us to use Ceramtec 50 kV feedthroughs (model 21183-01-W) inside OVC. These feedthroughs are rated for 4K operation.
- We studied how high a voltage it can withstand.





Ceramtec model 21183-01-W

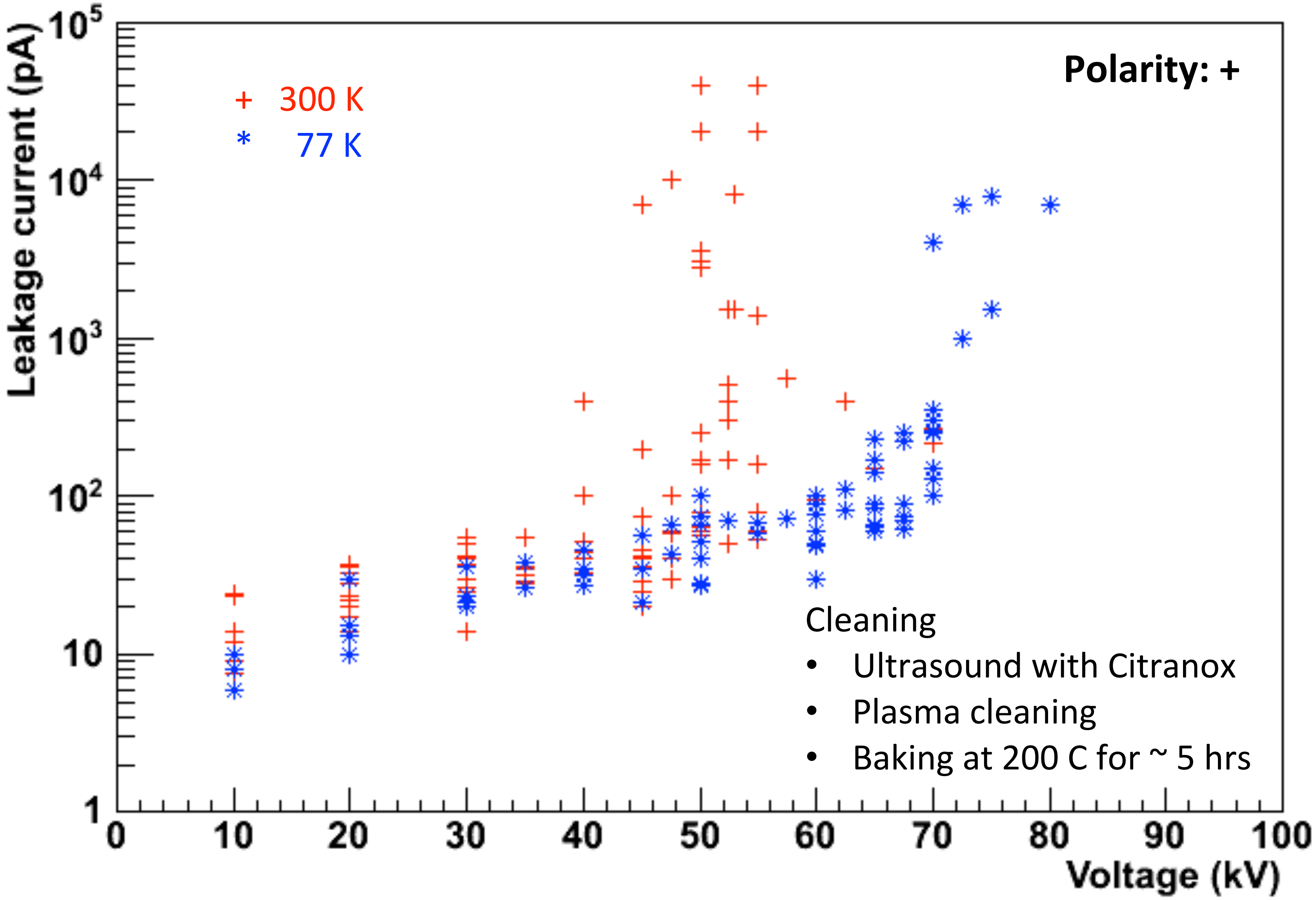
Cold feedthrough test



This apparatus was also used to test HV conductor

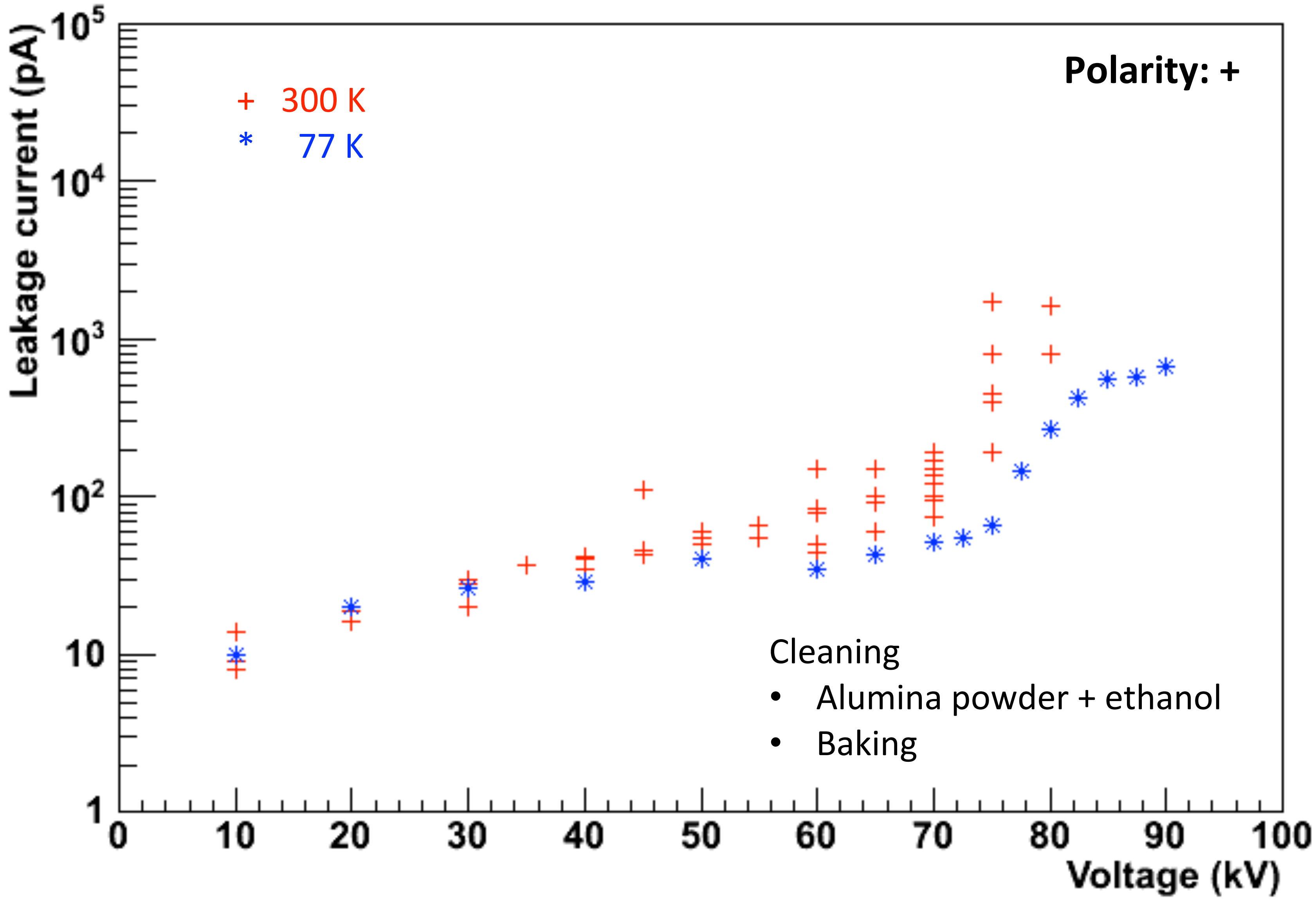
Feedthrough leakage current vs voltage

Preliminary results (FT#3)



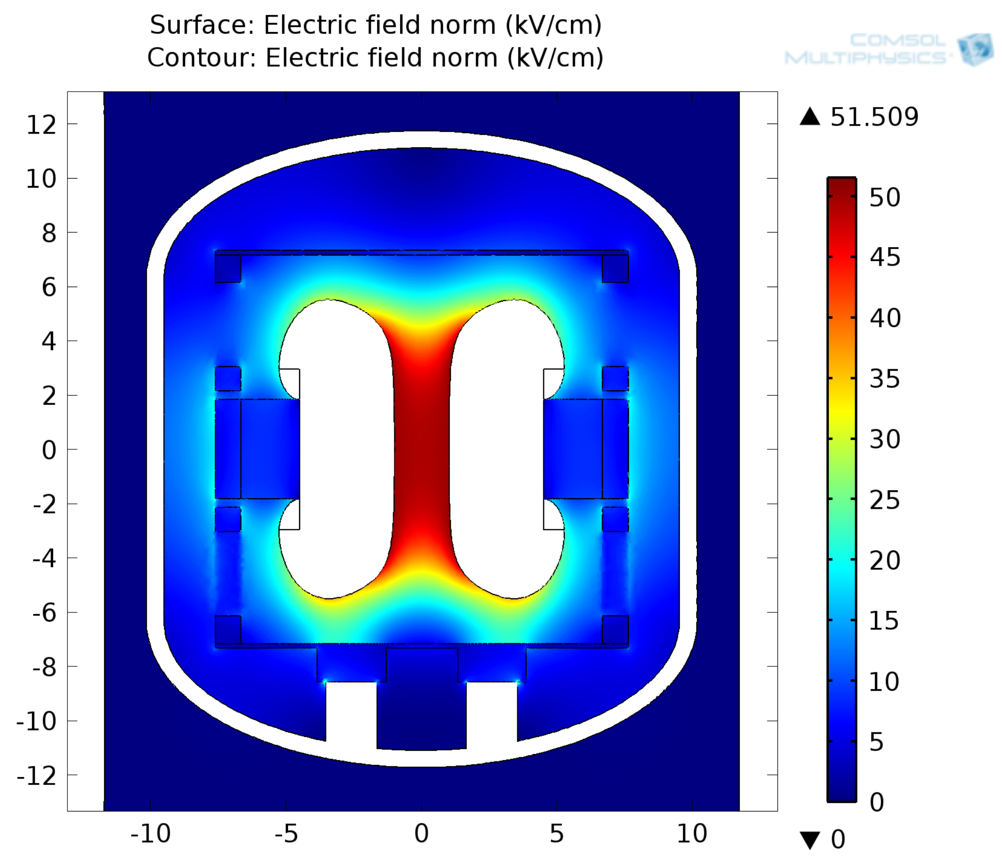
Feedthrough leakage current vs voltage

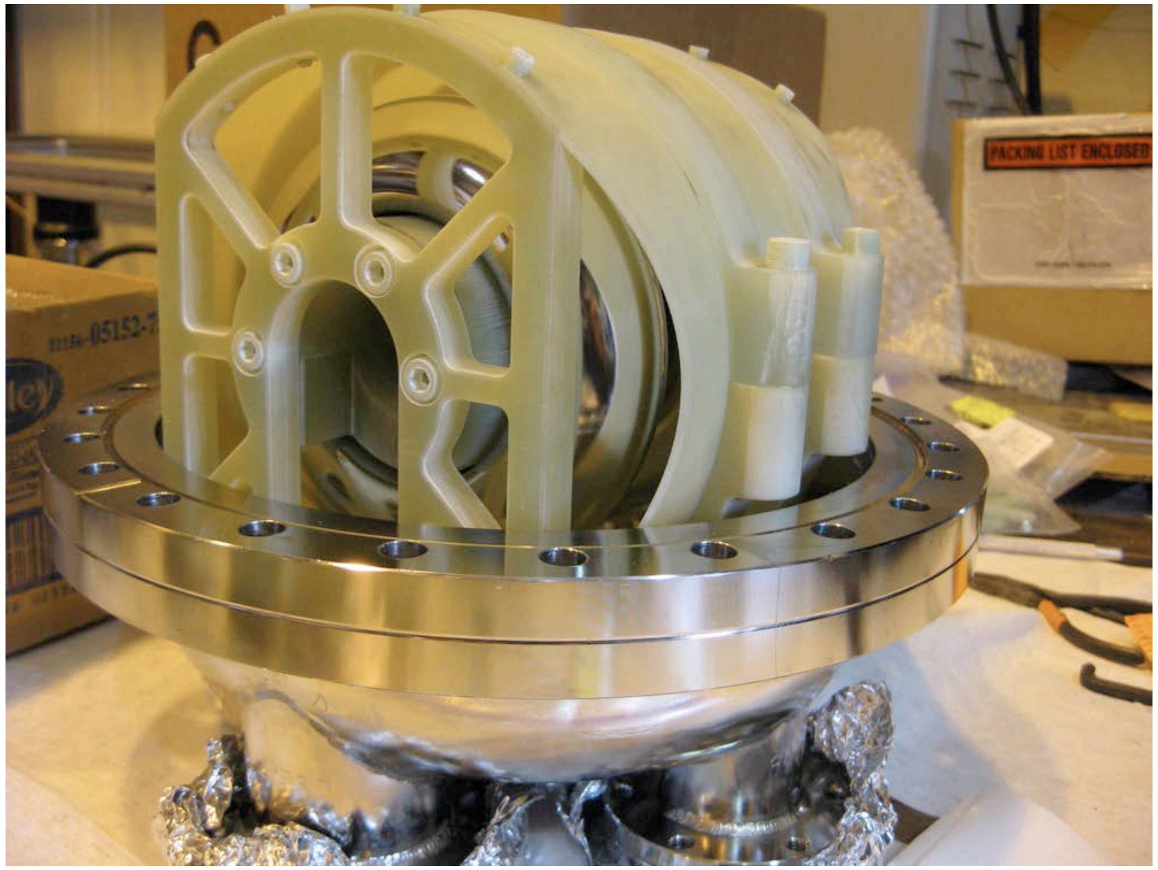
Preliminary results (FT#4)



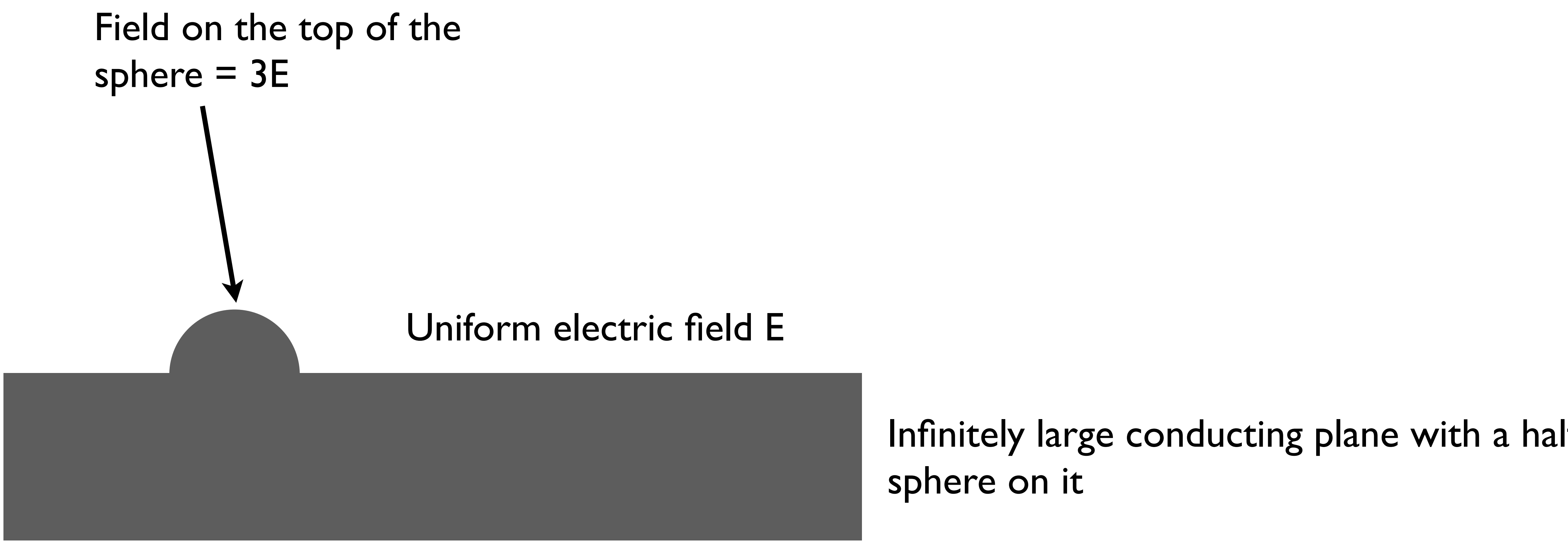
Electrodes

- For the initial test, we used electrodes that have the so-called Rogowski profile.
- The field in the gap is uniform and is the highest in the system.
- Allow us to sample a large area of the electrode surface. Note: breakdown is a random process: ball-plane and ball-ball geometries only sample a very limited surface area.
- For the first test, we used electropolished SS.





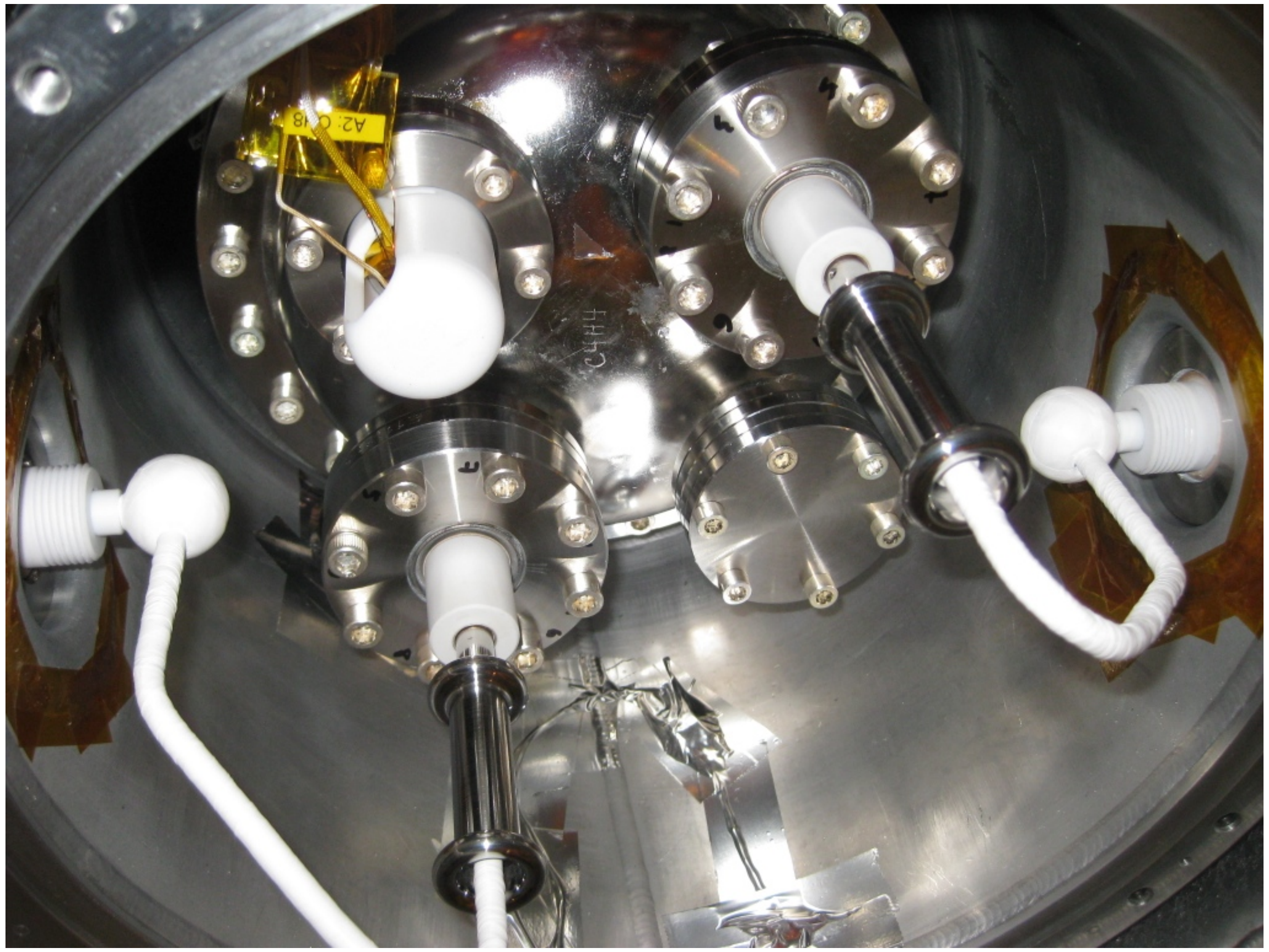
Effect of surface features



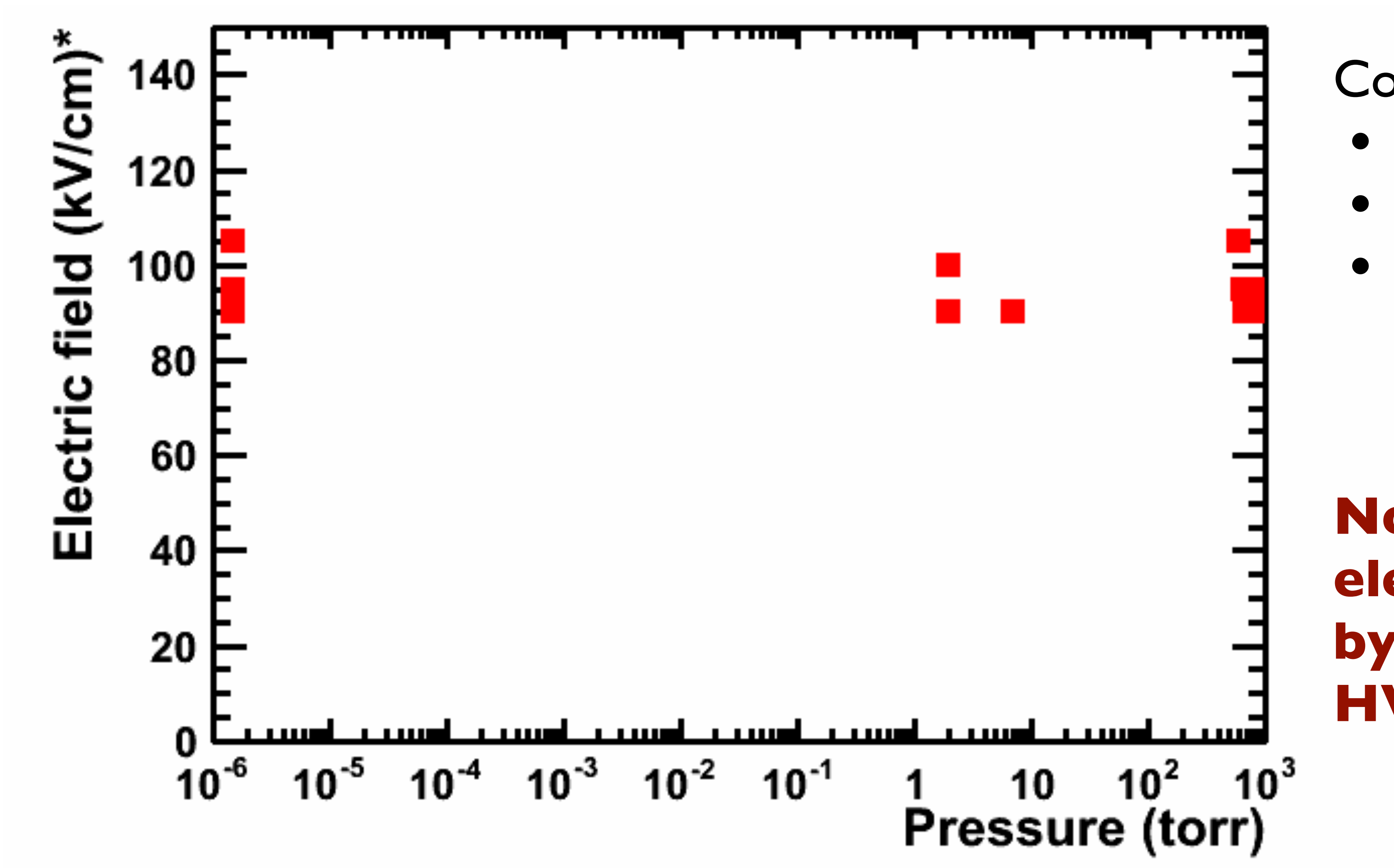
The shape of the features on the surface is more important than the size of the features.

HV conductors

- HV conductors inside the cryostat need to have low thermal conductivity.
- Parts of them need to be flexible (for assembly and thermal contraction of the system).
- Our solution is to use 1/4" thin wall SS tubing plus formed bellows, wrapped with Teflon tape. In the most recent design, the bellows are covered with a smooth metal sheath.



Preliminary results



Condition:

- Gap = 1 cm
- T = 0.4 K
- Electrodes: electropolished SS, Rogowski

Note: the achievable electric field was limited by the performance of the HV leads.

Note:

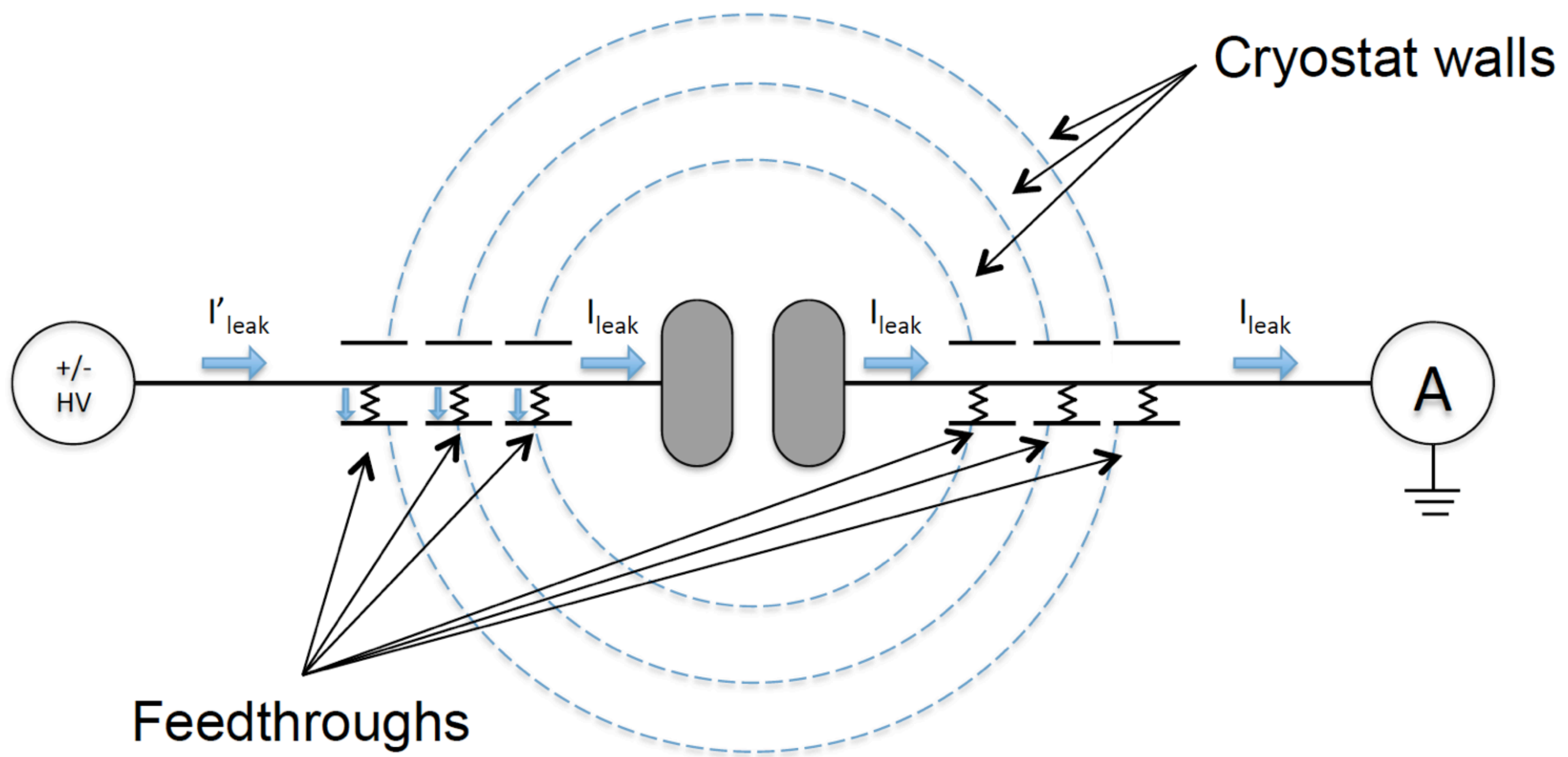
- The pressure on the horizontal axis is the lowest pressure in the system.
- The hydrostatic pressure ~ $\mathcal{O}(1)$ torr (~ 0.1 torr/cm of LHe).

Comments on bubble formation

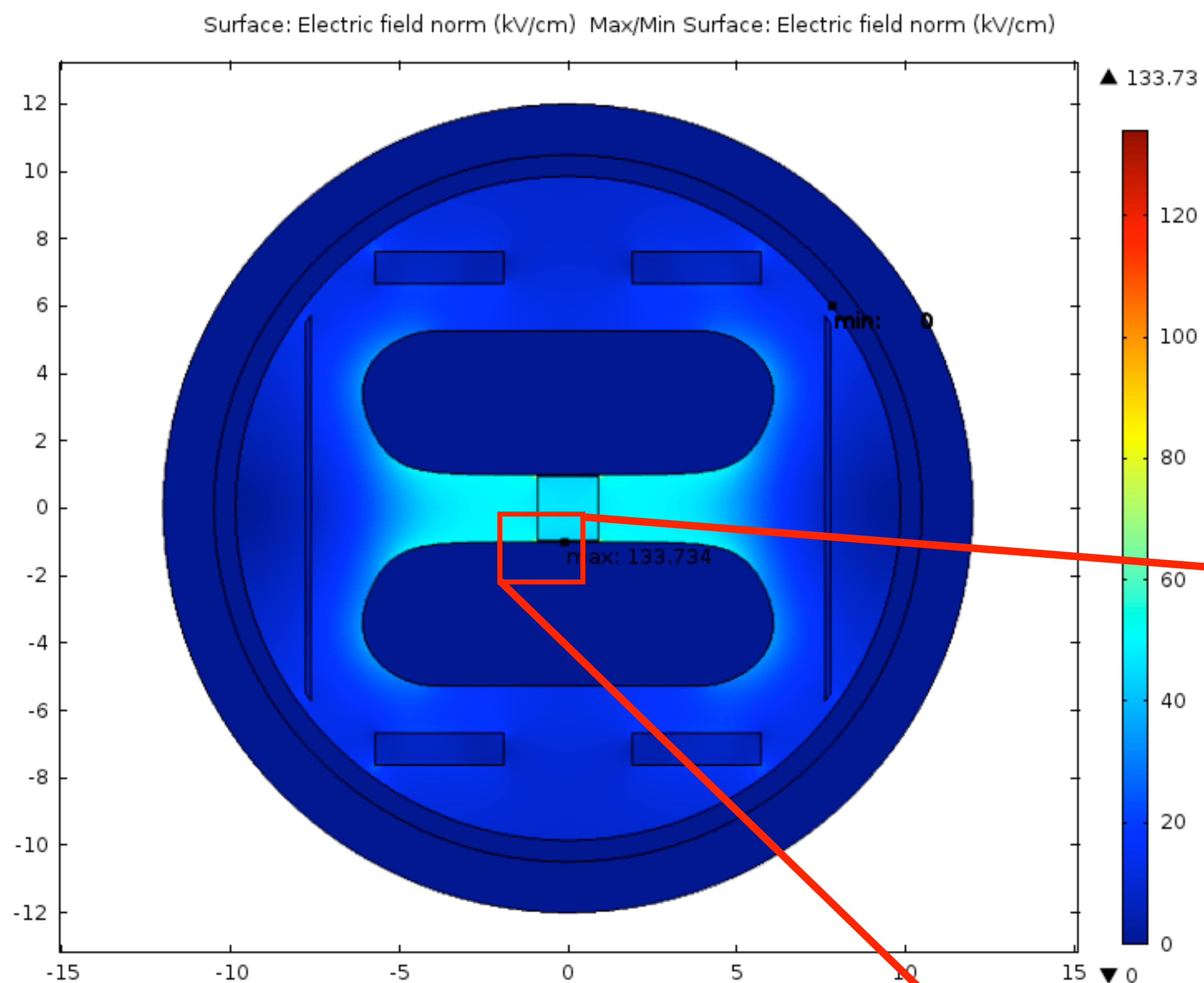
- Our results indicate suppression of surface bubble formation is important
  - Good thermal anchoring of the HV line to prevent LHe boiling on the electrode surface due to heat leak
  - Slow cooldown to ensure removal of all the heat from the electrodes

Leakage current

- Leakage currents between the two electrodes were measured by directly connecting a picoammeter to one of these electrodes.
- The measured current was < 1 pA at 45 kV voltage difference.



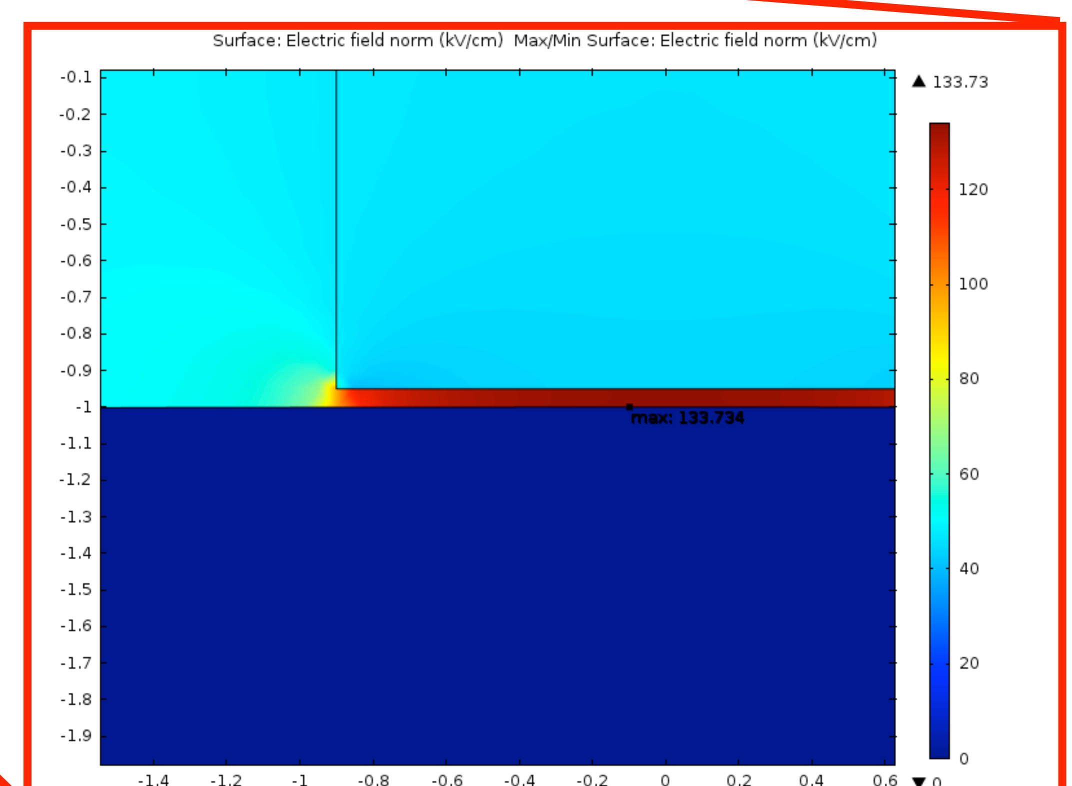
Effect of dielectric insulator inserted between electrodes



Field in the gap between the electrode and the insulator

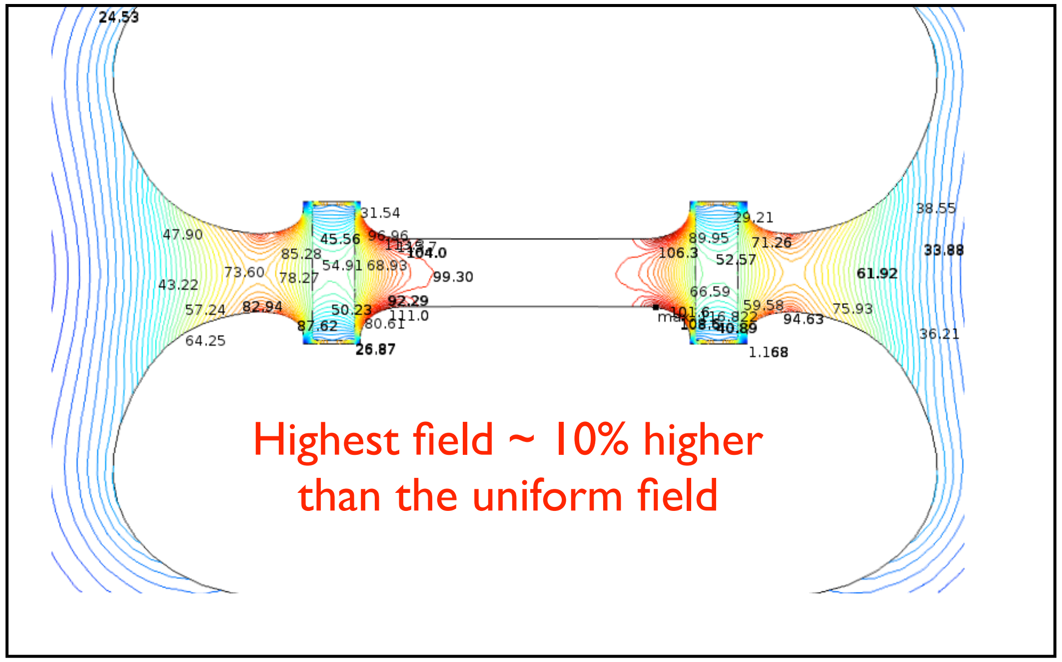
$$E_{gap} = \frac{V}{d + \frac{D-d}{\varepsilon_r}} \rightarrow \frac{V}{D}\varepsilon_r \quad (\text{ when } d << D)$$

V: voltage between the electrodes
D: gap between the electrodes
d: gap between the insulator and the electrode
ε_r: ratio of the dielectric constant $\varepsilon_r = \varepsilon_{ins}/\varepsilon_{He}$



Next step

- The next step is to study the electric breakdown with a dielectric insulator sandwiched between the electrodes. The electrode shape was optimized to minimize the field strength at "hot spots" at the electrode insulator interface. PMMA will be used as the insulator.



Results of an FEM electrostatic calculation optimizing the shape of the electrode with a dielectric insulator in between. The insulator is a PMMA cylinder

LHe scintillation in SNS nEDM exp

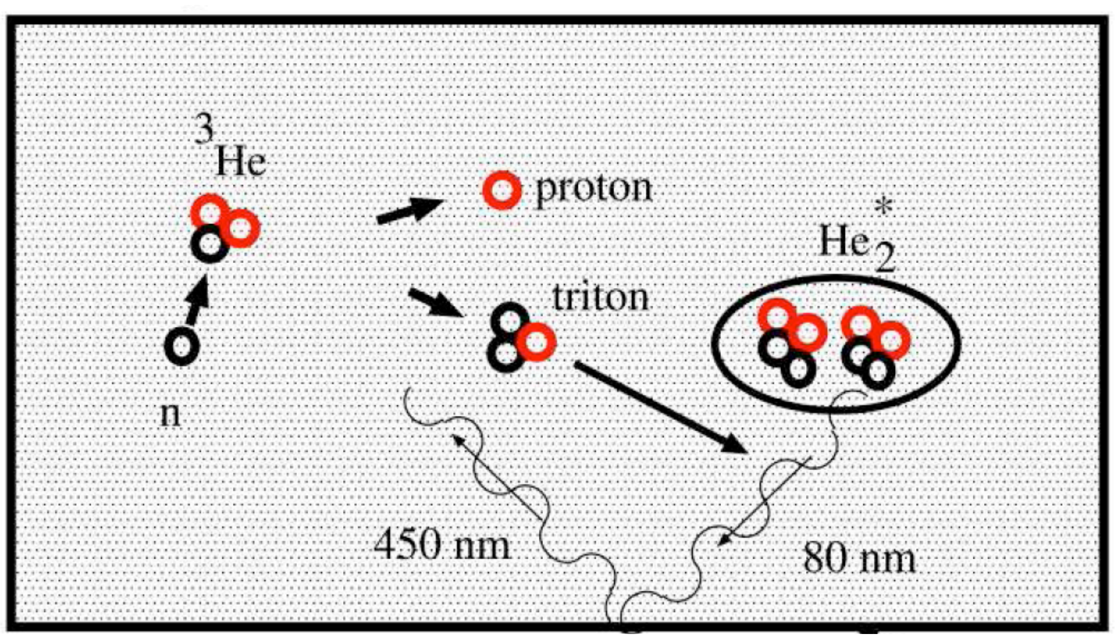
- ^{3}He-n reaction cross section

  $^3\overrightarrow{He} + \overrightarrow{n} \rightarrow t + p + 760$ keV   σ(parallel) << σ (anti-parallel)

- ^{3}He-UCN reaction rate

$$\boxed{1 - \overrightarrow{p_3} \cdot \overrightarrow{p_n} = 1 - p_3 p_n \cos[(\gamma_n - \gamma_3)Bt]} \qquad |\gamma_n - \gamma_3| = |\gamma_n|/10$$

- Detect Scintillation light from the reaction products traveling in LHe
  - Convert EUV light to blue light using wavelength shifter
  - Detect the blue light with PMTs



^{4}He superfluid filled measurement cell made of acrylic and coated with wavelength shifter

- Signature of EDM would appear as a shift in ω_3-ω_n corresponding to the reversal of ***E*** with respect to ***B*** with no change in ω_3

Liquid helium scintillation

Ionization track

$$\mathrm{He}^+ + e \rightarrow \left(\mathrm{He}_3{}^+\right)_{snawball} + \left(e^-\right)_{bubble} \rightarrow \mathrm{He}_2{}^* + \mathrm{He}$$

- Singlet state: decays within ~ 1ns emitting a 80 nm photon (prompt scintillation)

$$\mathrm{He}_2\left(A^1\Sigma_u^+\right) \rightarrow \mathrm{rad.\ decay}$$

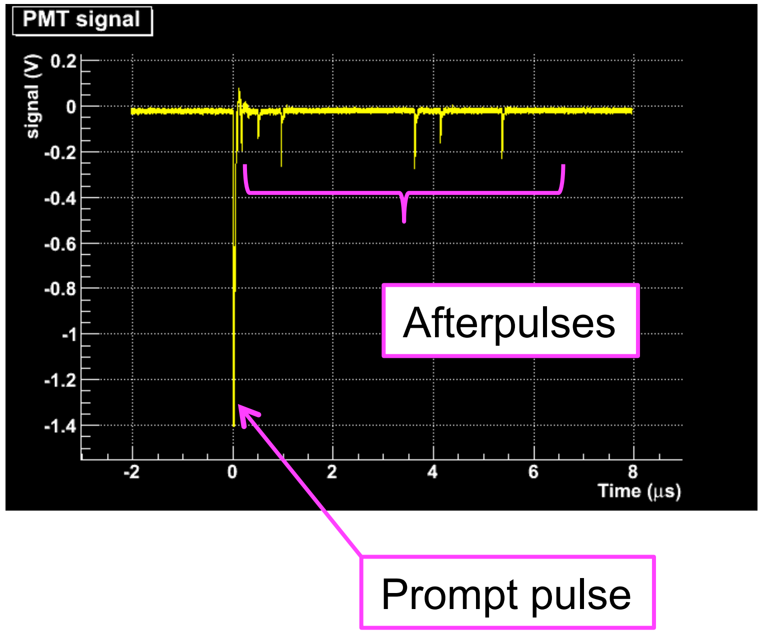
- Triplet state: has a litefime of ~ 10 s in vacuum. Gives afterpulses through Penning ionization (destructive interaction with each other)

$$\mathrm{He}_2\left(a^3\Sigma_u^+\right) + \mathrm{He}_2\left(a^3\Sigma_u^+\right) \rightarrow 3\mathrm{He} + \mathrm{He}^+ + e^-$$

or

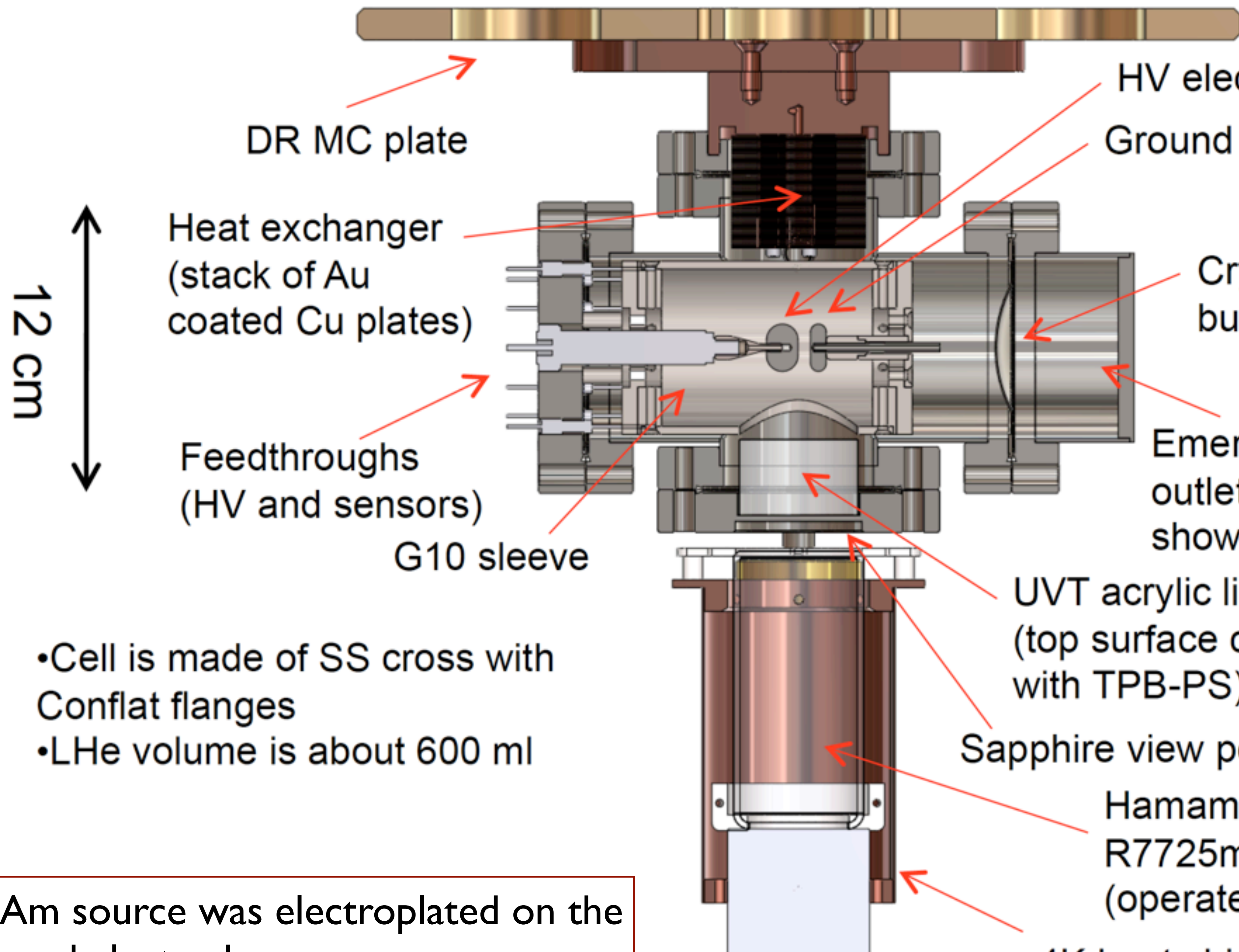
$$\mathrm{He}_2\left(a^3\Sigma_u^+\right) + \mathrm{He}_2\left(a^3\Sigma_u^+\right) \rightarrow 2\mathrm{He} + \mathrm{He}_2{}^+ + e^-$$

$$\mathrm{He}^+ + e \rightarrow \left(\mathrm{He}_3{}^+\right)_{snawball} + \left(e^-\right)_{bubble} \rightarrow \mathrm{He}_2{}^* + \mathrm{He}$$



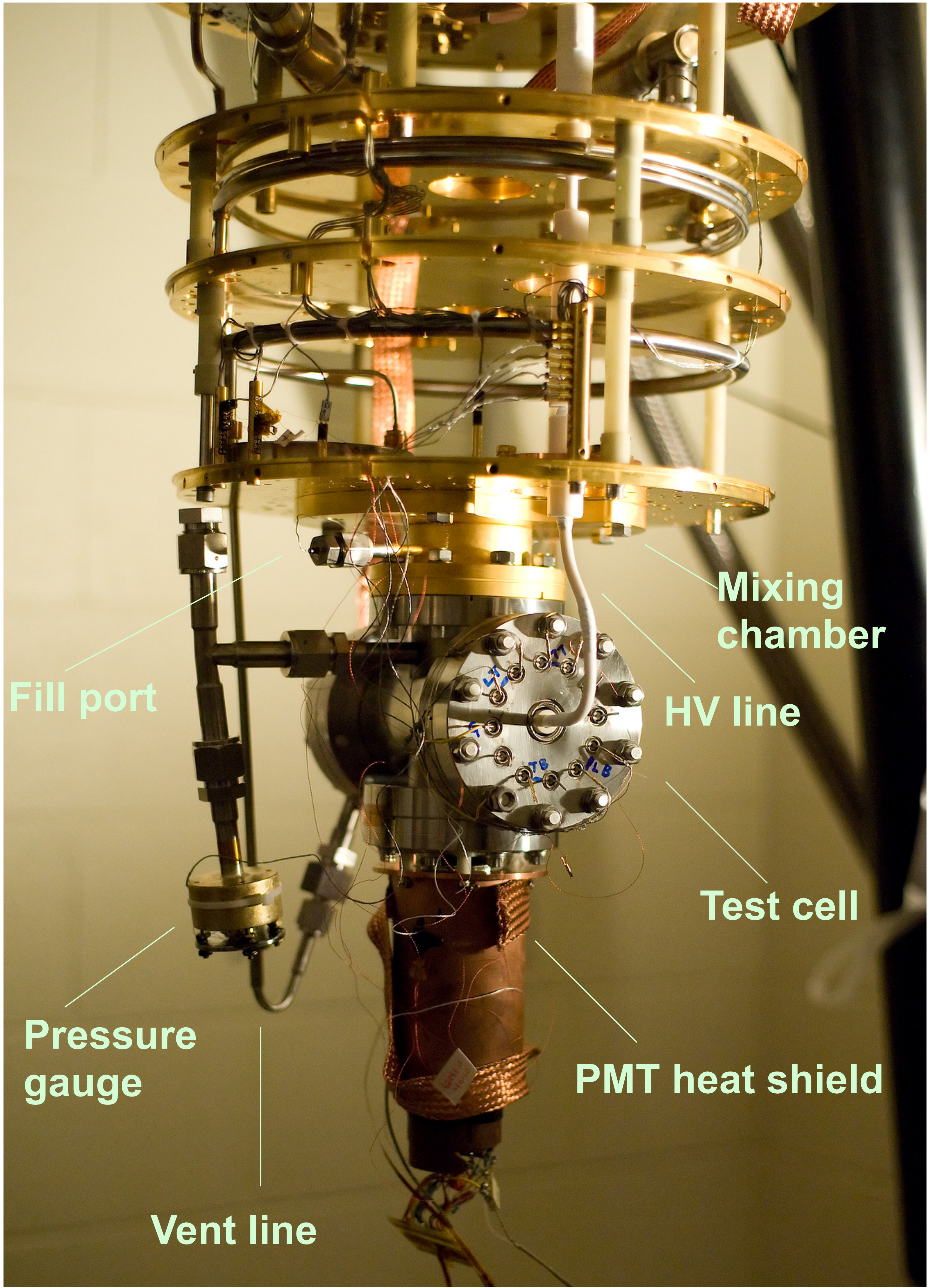
What is the effect of an electric field?

Apparatus

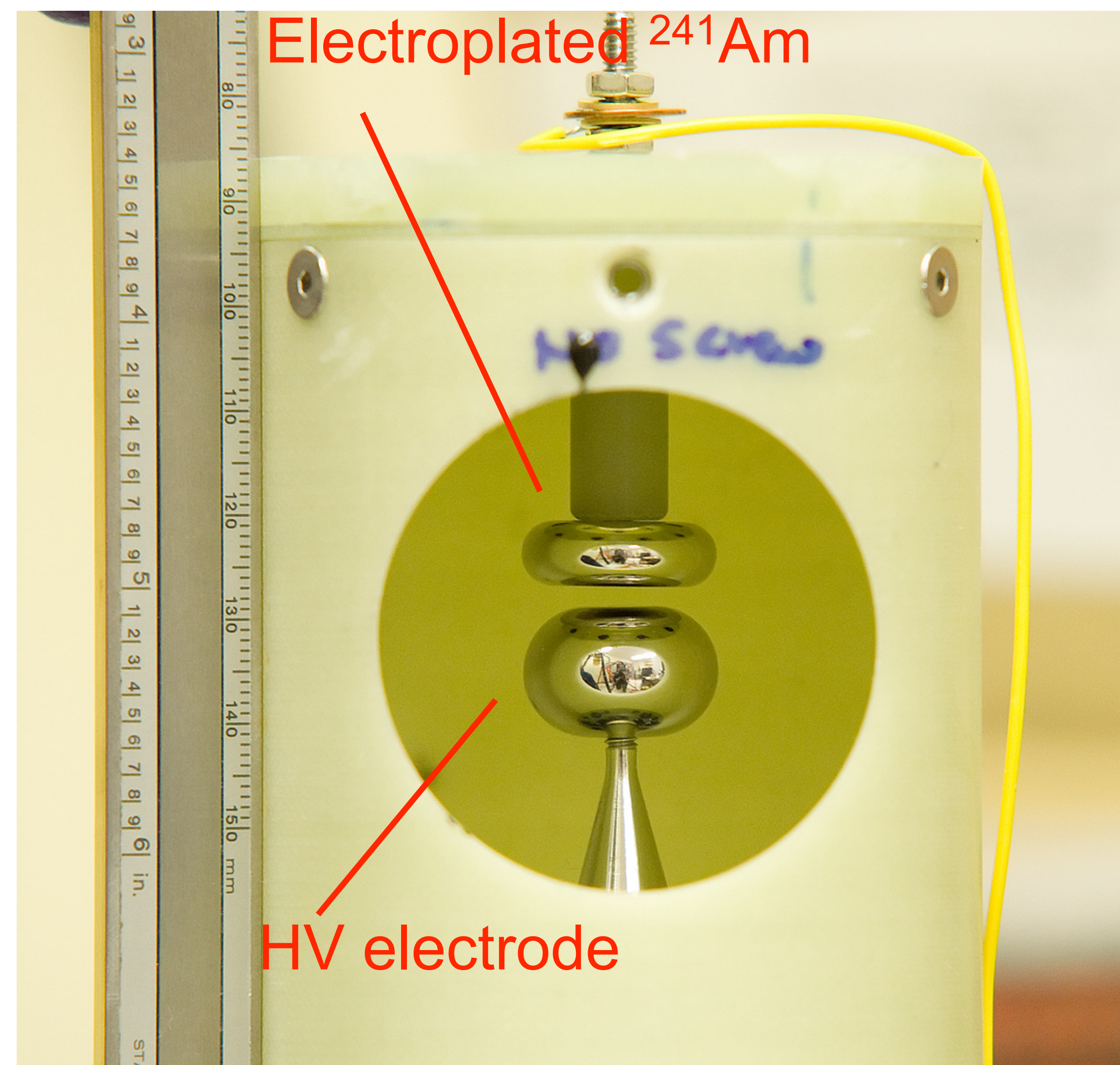


•Cell is made of SS cross with Conflat flanges
•LHe volume is about 600 ml

^{241}Am source was electroplated on the ground electrode



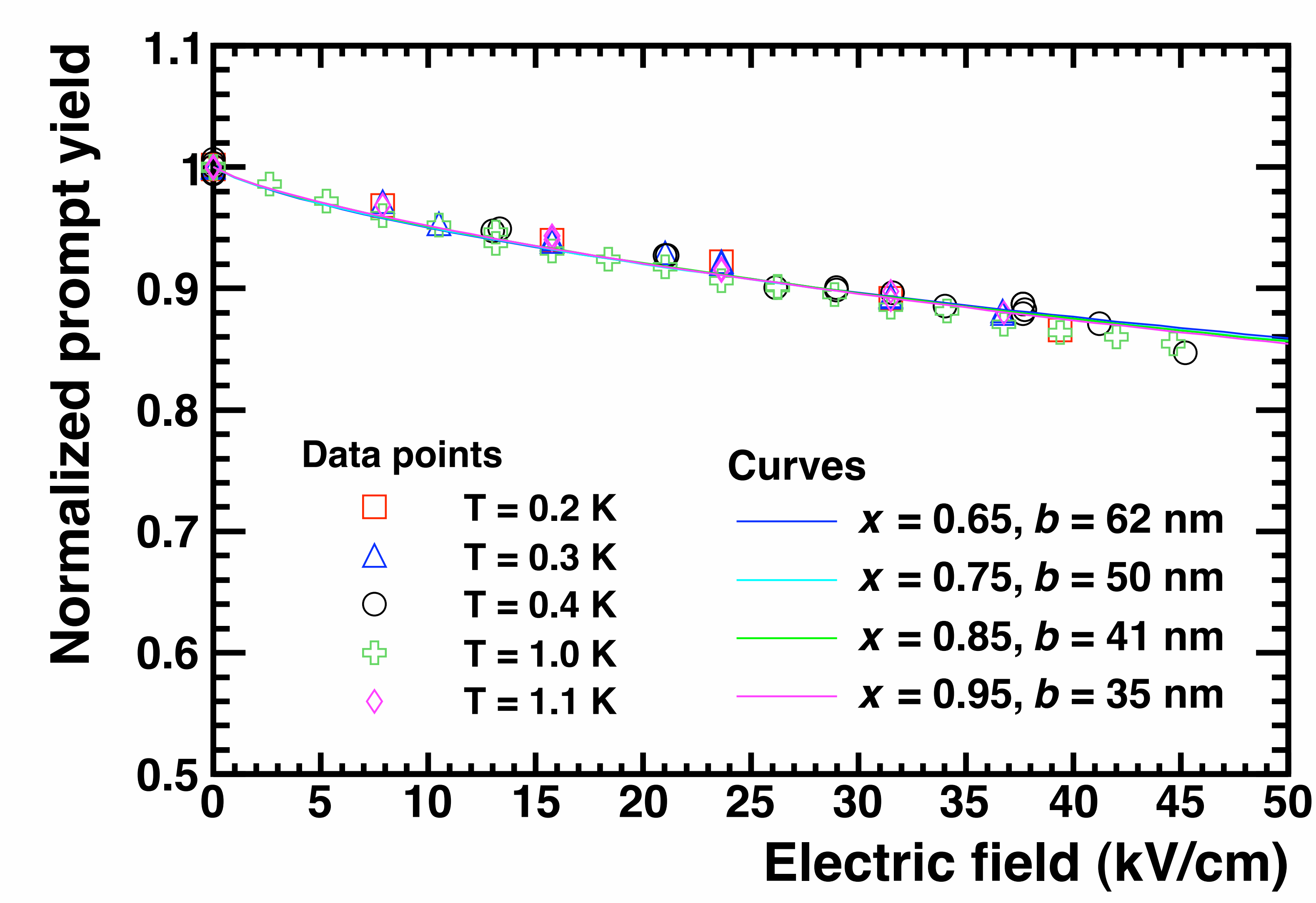
Mixing chamber
Fill port
HV line
Test cell
Pressure gauge
PMT heat shield
Vent line



Ground electrode with
Electroplated ^{241}Am
HV electrode

Prompt scintillation yield vs *E*

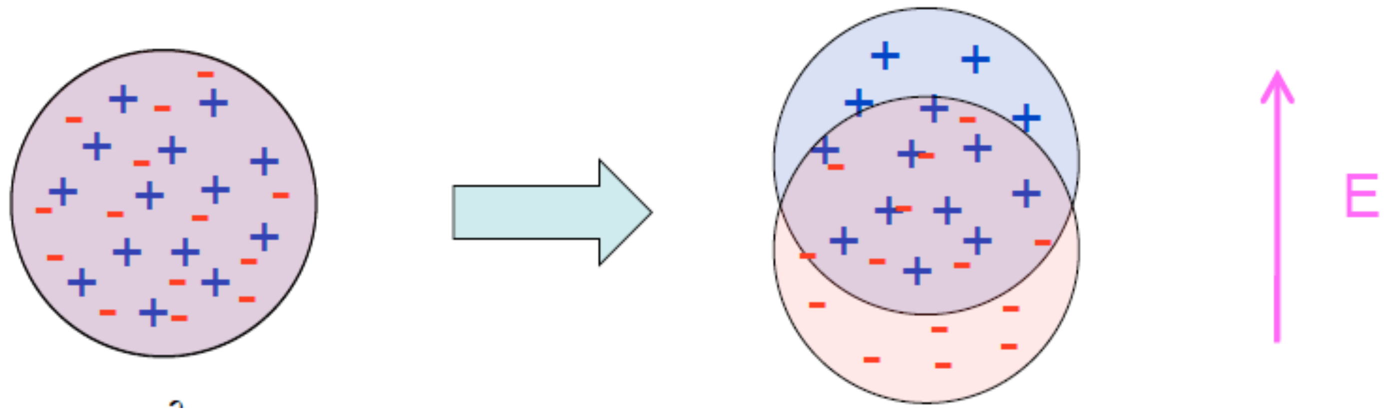
T. M. Ito *et al.*, Phys. Rev. A 85, 042718 (2012)



- The reduction was ~ 15% at 50 kV/cm.
- The effect of an electric field on prompt scintillation yield had little temperature dependence.

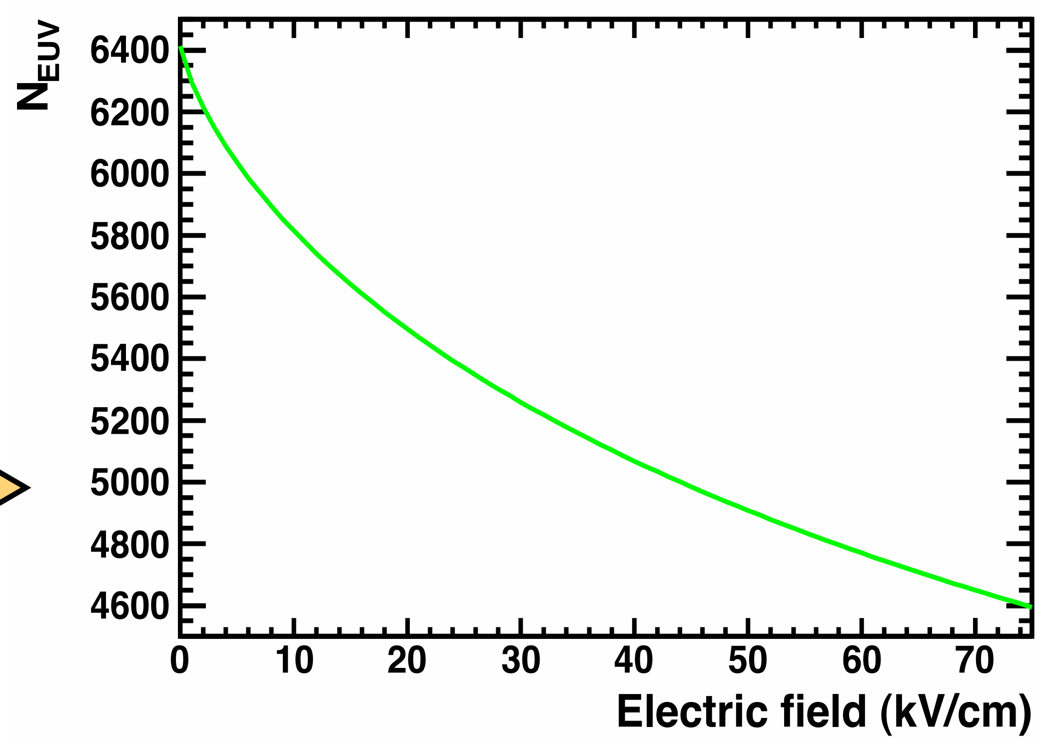
Interpretation

- The results on the prompt scintillation can be well-described by Jaffe's columnar theory of recombination (applicable for high ionization density tracks).



- The model allowed us to make a prediction for the prompt scintillation yield for the ^{3}He(n,p)t reaction.

Model prediction for the prompt LHe scintillation yield for 3He(n,p)t reaction

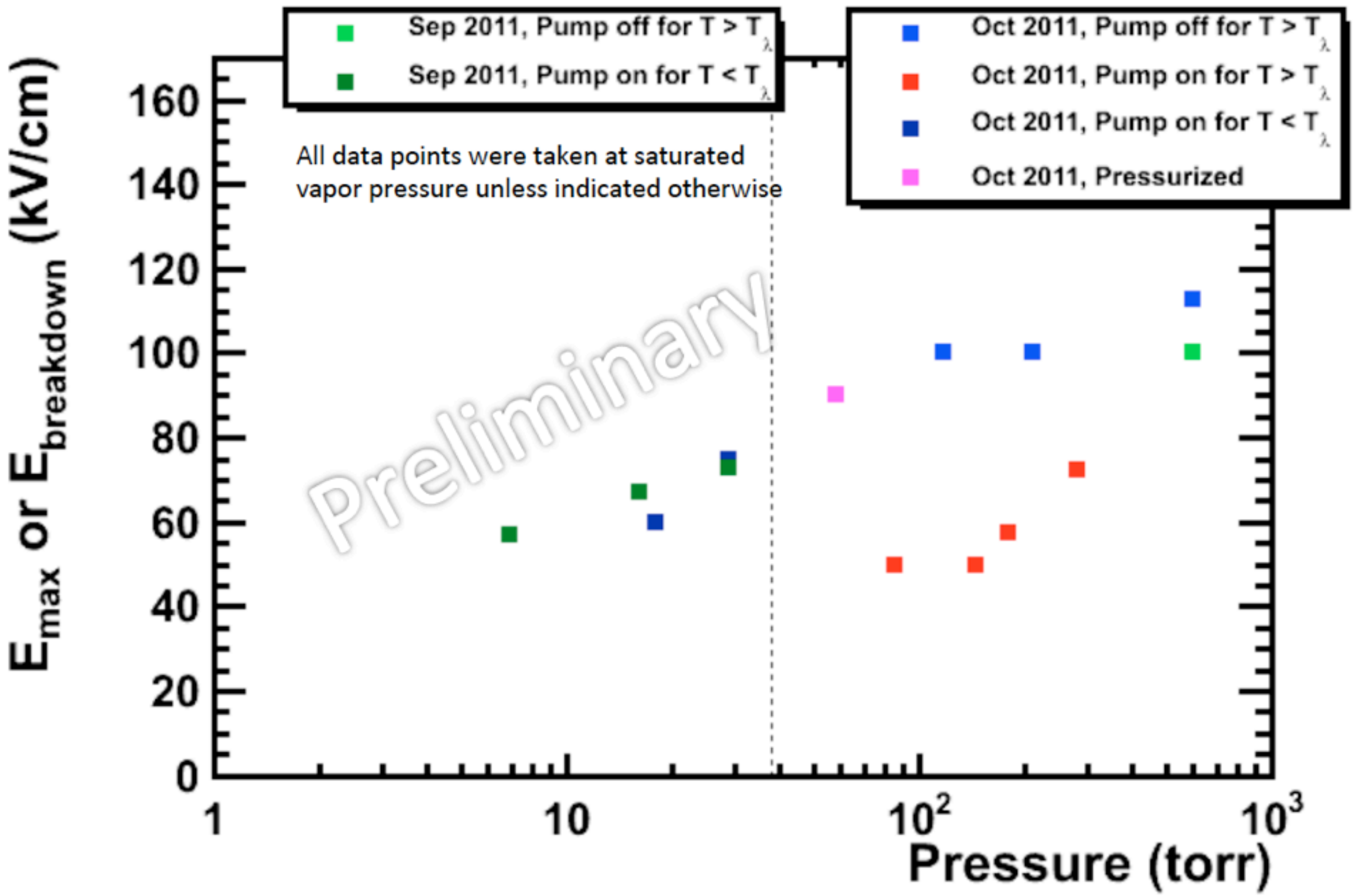


T. M. Ito *et al.*, Phys. Rev. A 85, 042718 (2012)

Summary

- HV R&D for the SNS nEDM experiment is in progress.
- Results from the recently built MSHV system demonstrated electric fields exceeding 100 kV/cm at 0.4 K for a wide range of pressures.

Effect of bulk boiling



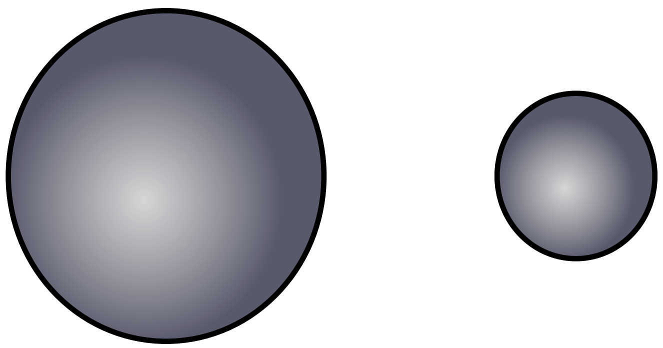
Statistics of breakdown

Area effect from transformer oil data

Weber and Endicott, Trans. AIEE 75, 371 (1956)

Direct measurement of size dependence

Electrodes with different sizes

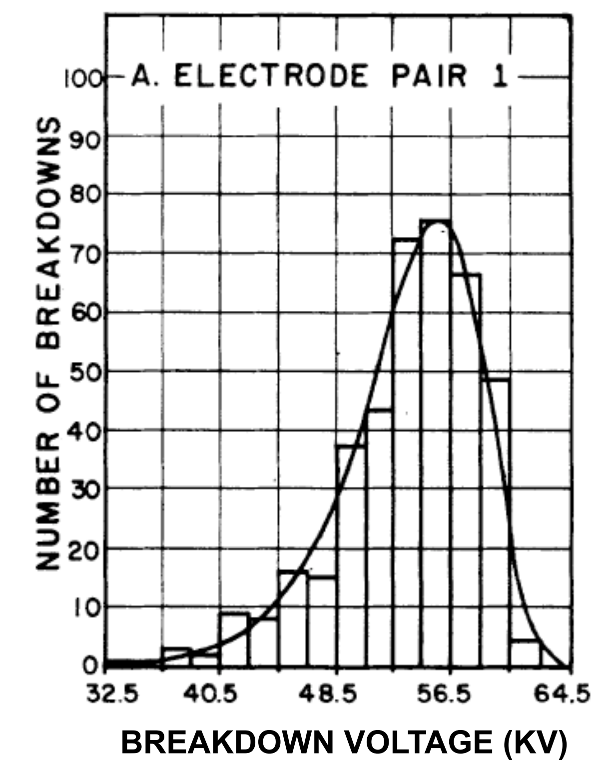


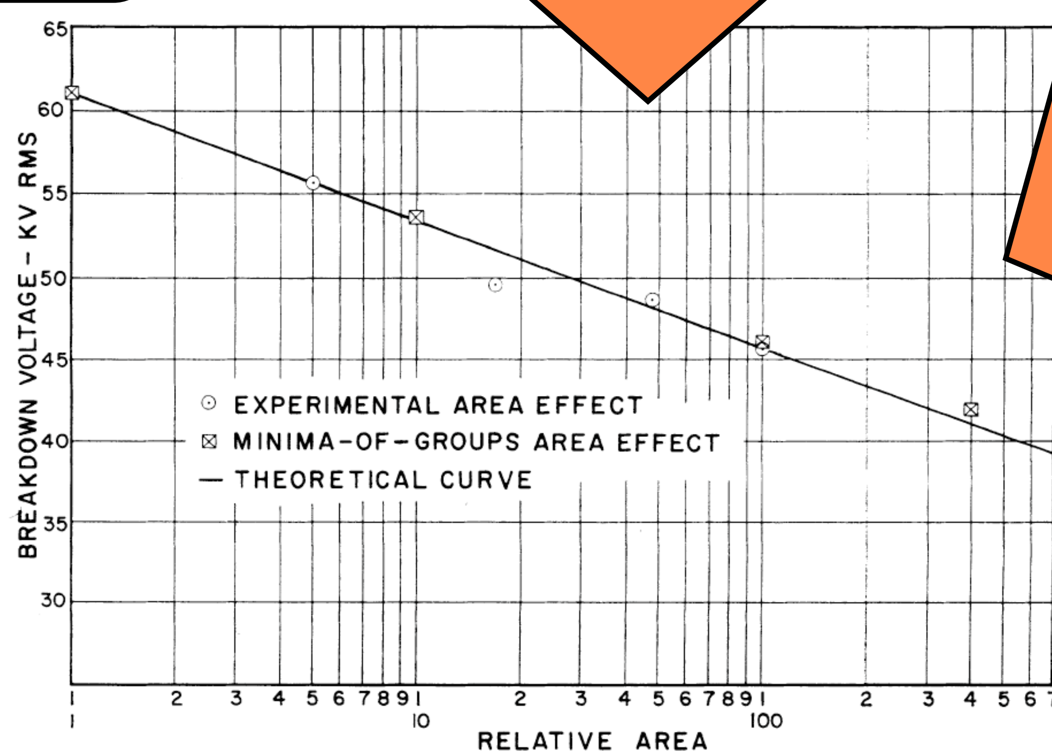
Area = A   Area = a

Minima-of-group analysis

- n×a = A
- Take the lowest breakdown value of n tests with electrodes with area a
- Compare it to the breakdown value of electrode with area A.

Breakdown distribution + Statistical theory of extreme values





Data well described by statistical theory of extreme values