High electric field development for the SNS nEDM experiment

Takeyasu Ito
Los Alamos National Laboratory

For the LANL nEDM Collaboration

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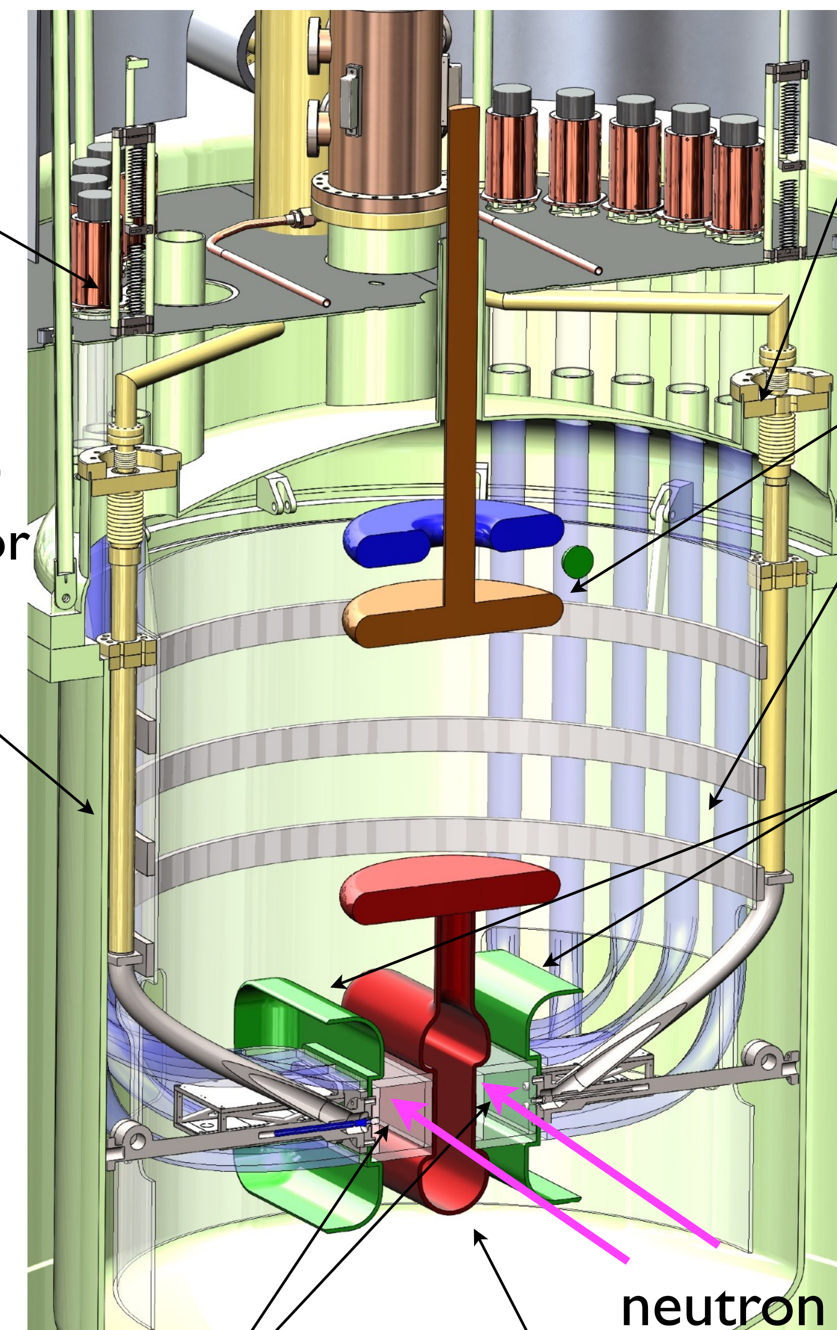
Requirements

- 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 Ω/□ < Rs < 10^8 Ω/□
  - Robust to thermal cycling and sparking
  - Minimal activation due to exposure to neutron beam
  - Non-magnetic
  - Fabrication technique scalable to large (10x40x80 cm^3) complicated 3D shape



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HV multiplier

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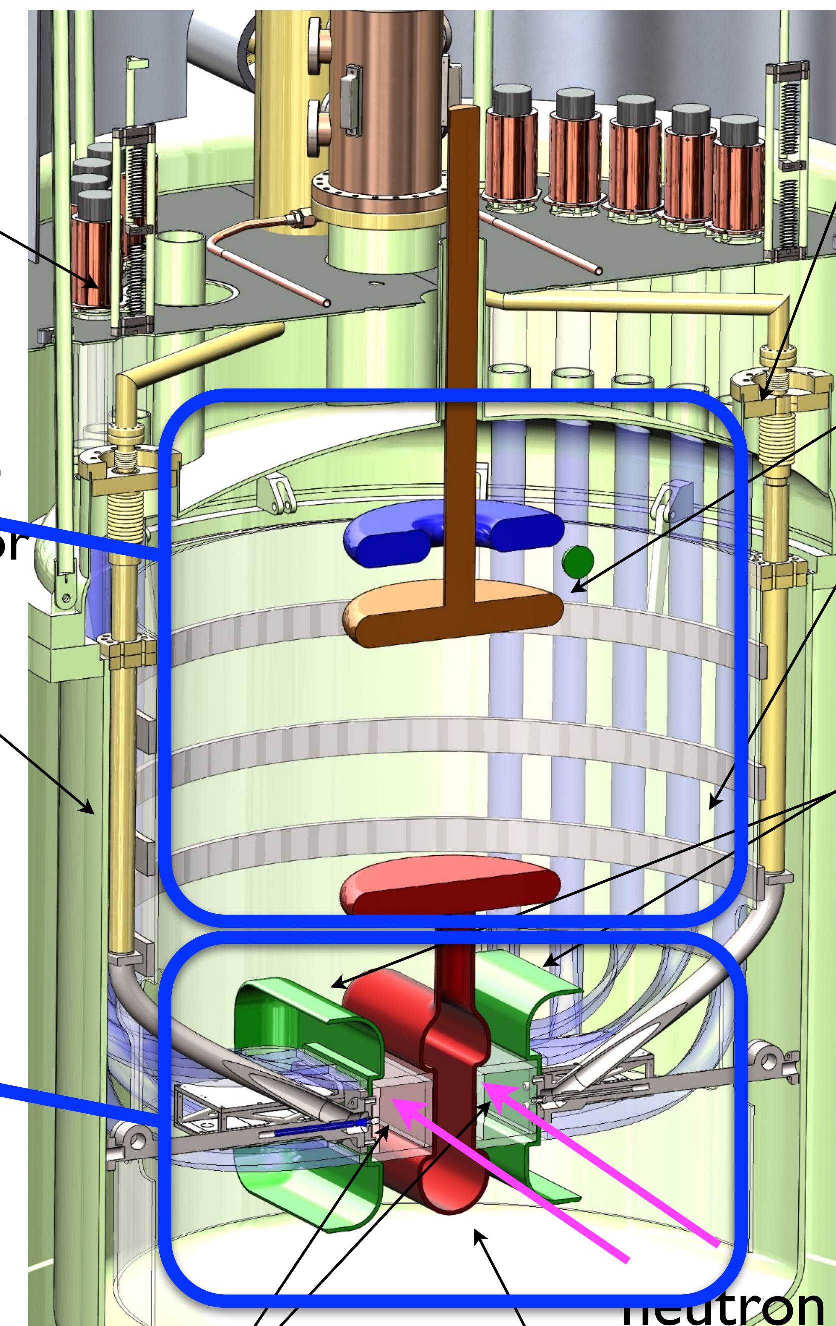

Overview of the high electric field R&D

- **HV breakdown R&D: study breakdown dependence on electrode, material, temperature, pressure, and scale**
  - ✦ Medium Scale High Voltage (MSHV) system (current system)
    - 6 L LHe volume, temperature down to 0.4 K, variable pressure, 12 cm electrodes, HV up to 100 kV
    - Study electrode materials, the effects of dialectic object placed between electrodes, the leakage currents (up to 50 kV)
    - Also used to study LHe scintillation in an electric field
  - ✦ Half Scale High Voltage (HSHV) system (next HV testing system)
    - 40 L LHe volume (45 cm ID), temperature down to 0.4 K, variable pressure, 1/2 scale measurement cell electrodes, HV up to 200 kV
    - Study damages on electrodes, effects of the presence of light guides/fibers, and leakage currents
  - ✦ Small Scale High Voltage (SSHV) system
    - Temperature down to 1.5 K, variable pressure, 2 cm diameter electrodes, HV up to 40 kV
    - Study distribution of breakdown voltage, time before breakdown, and material dependence
- **Cavallo R&D:**
  - ✦ Crude room temperature demonstration
  - ✦ Room temperature demonstration
  - ✦ Small cryogenic prototype
  - ✦ Large cryogenic prototype

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See N. Phan's talk

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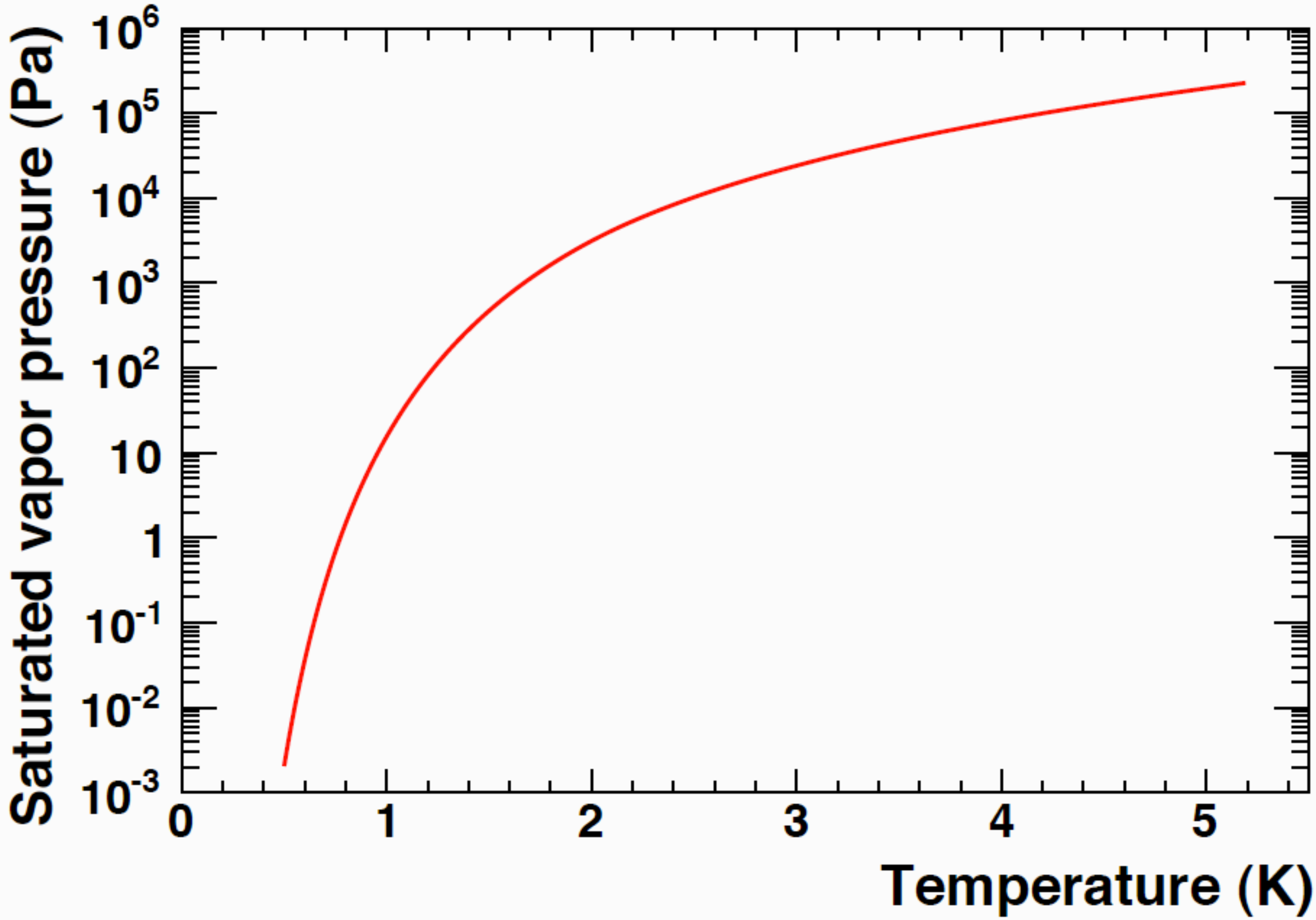
See S. Clayton's talk

Electrical breakdown in LHe

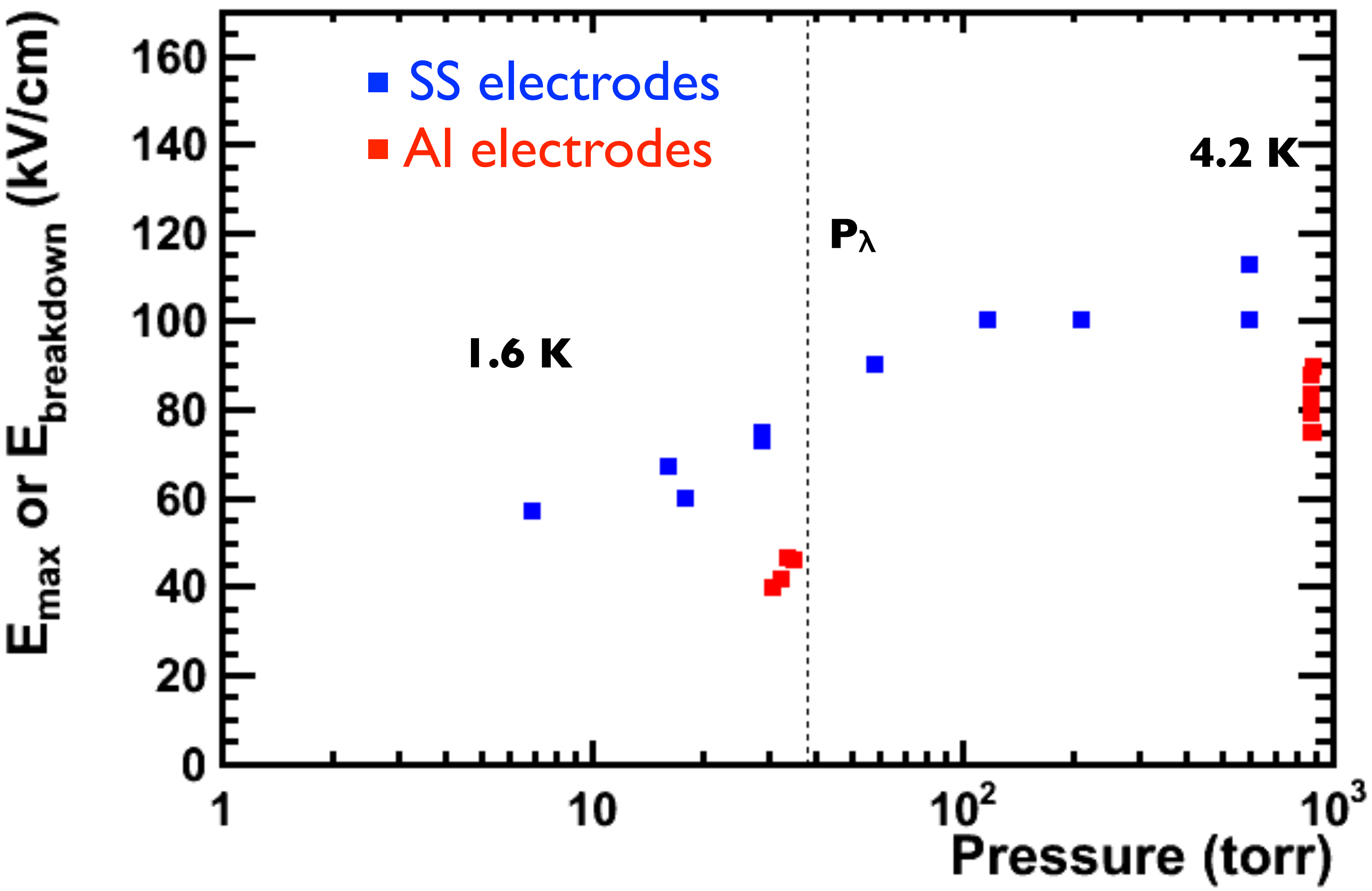
- Prior to recent LANL and Sussex efforts, data had existed for 1.2 - 4.2 K, mostly at SVP (bulk of the data were taken at 4.2 K)
  - For varying geometries (plane-plane,sphere-plane, sphere-sphere)
  - In general, very little consistency
- No models or theories
- However, a consideration of mean free 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 include:
  - Electrode material and surface quality
  - Electrode area and gap size
  - Temperature and pressure

LHe saturated vapor pressure



Breakdown field vs pressure?

Old results from the Large Scale Apparatus

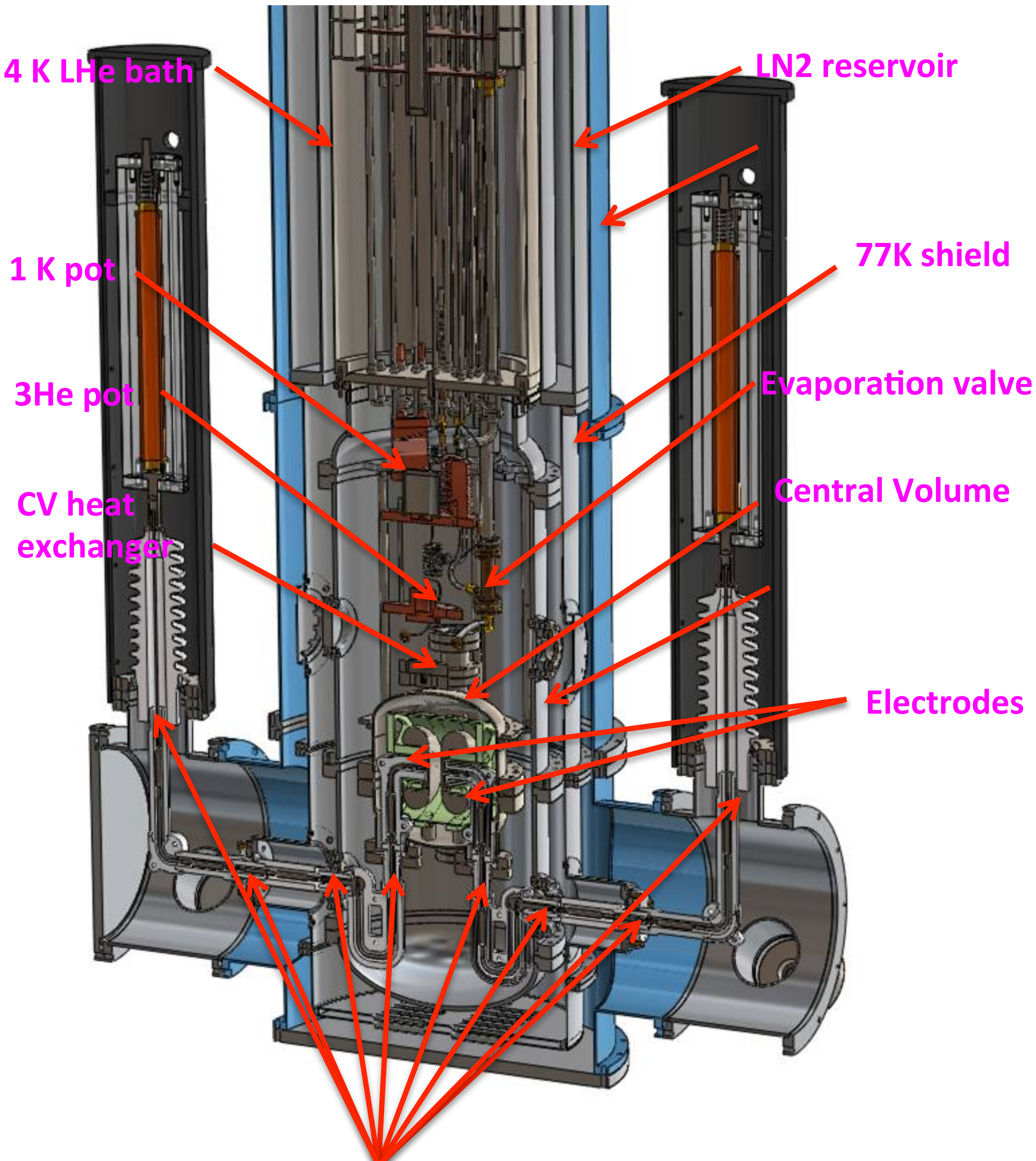


- Electrode size ~ 50 cm in diameter
- Gap ~ 3-4 mm
- Data taken at SVP
- LHe evaporatively cooled

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 High Voltage (MSHV) Test Apparatus



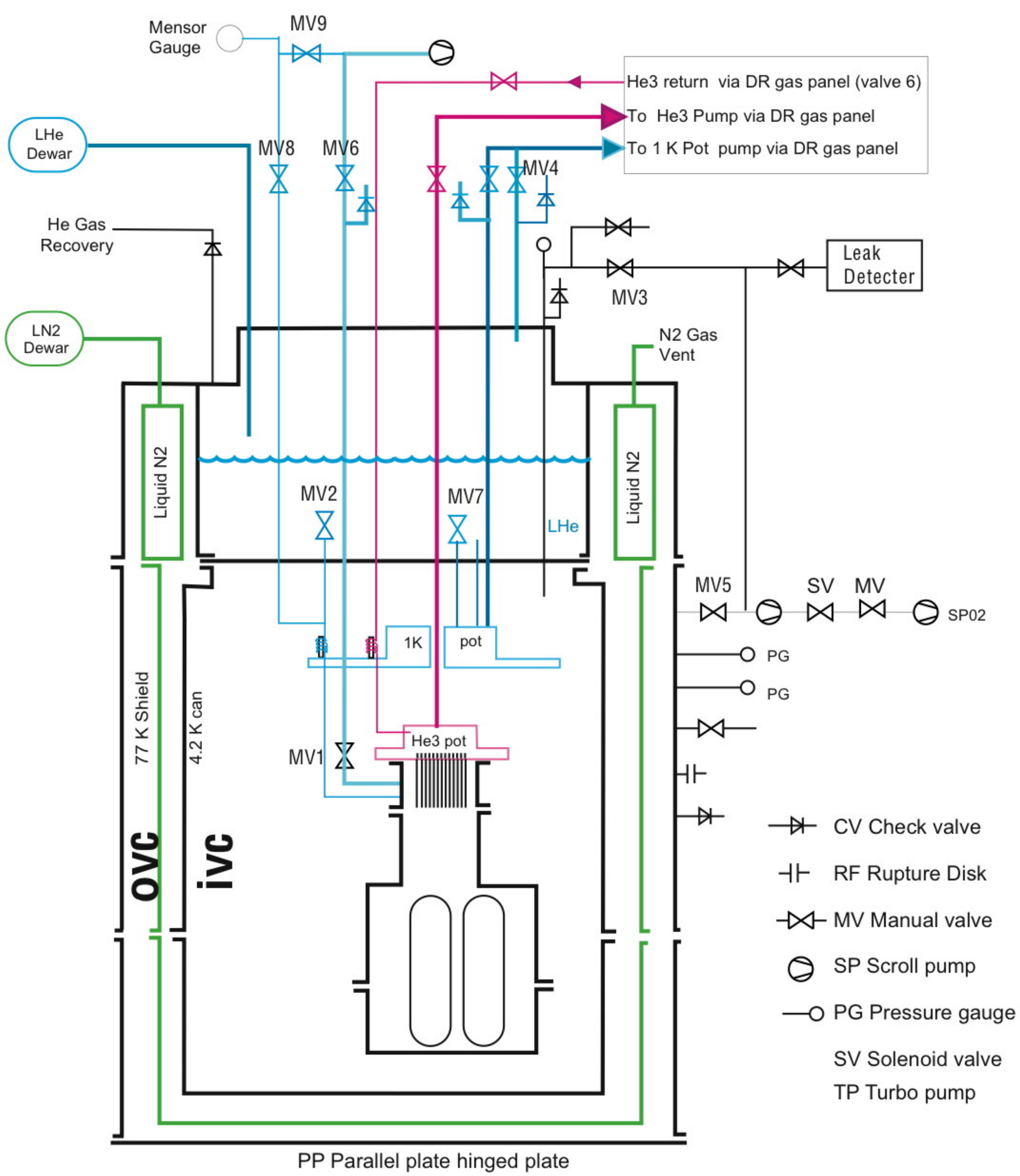
Purpose

- To study breakdown field dependence on
  - Temperature
  - Pressure
  - Gap size
  - Electrode material
  - Presence of dielectric object

Features

- 6 liter LHe volume cooled by a 3He fridge
- Electrode size ~ 12 cm in diameter (~1/5 scale)
- Electric field: up to 100 kV/cm in 1 cm gap
- Gap size: adjustable
- Lowest temperature ~ 0.4 K
- Pressure: variable between SVP and 1 atm
- Turn around time ~ 2 weeks

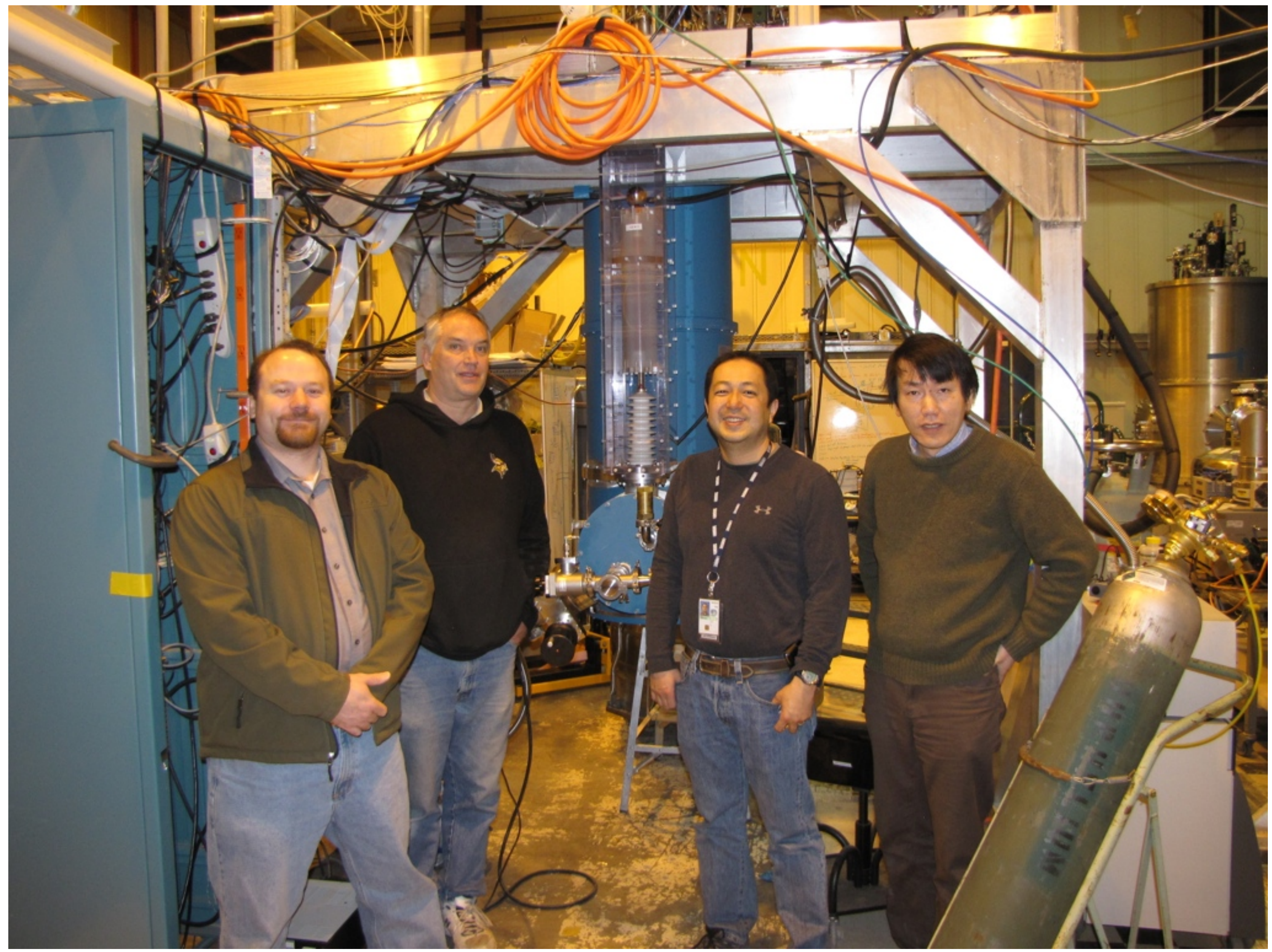
MSHV flow diagram



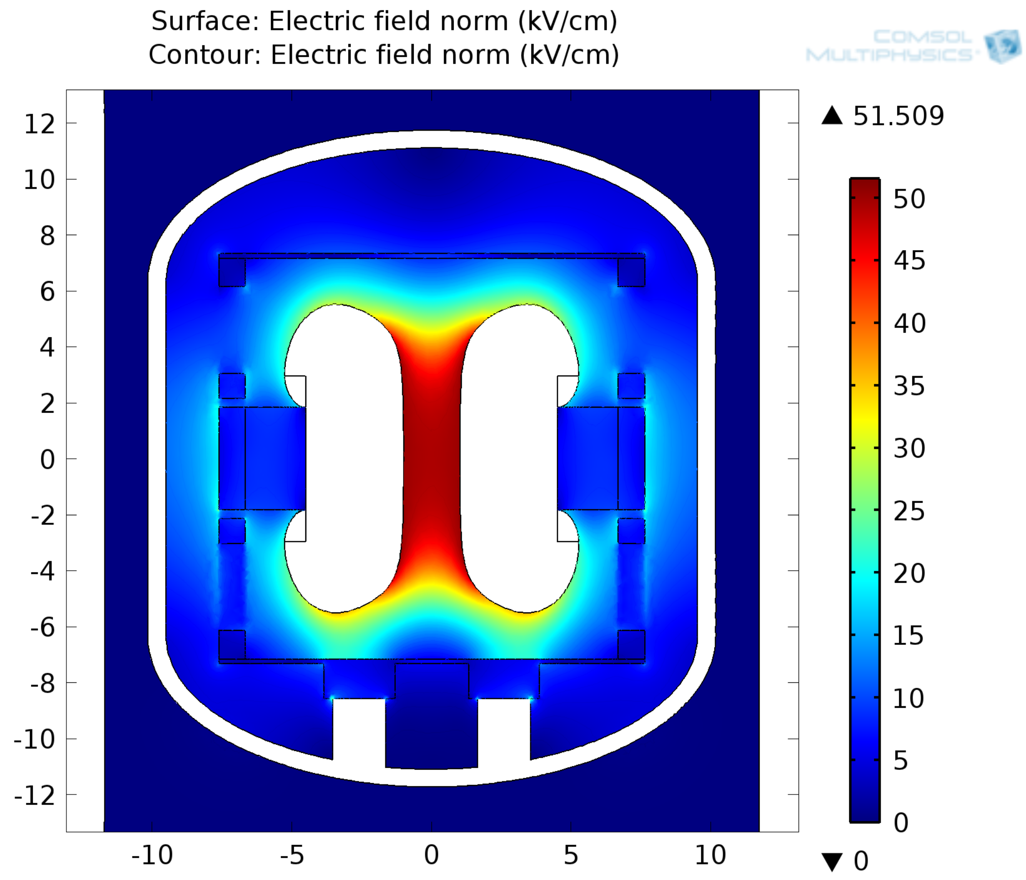
Notes:

- 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



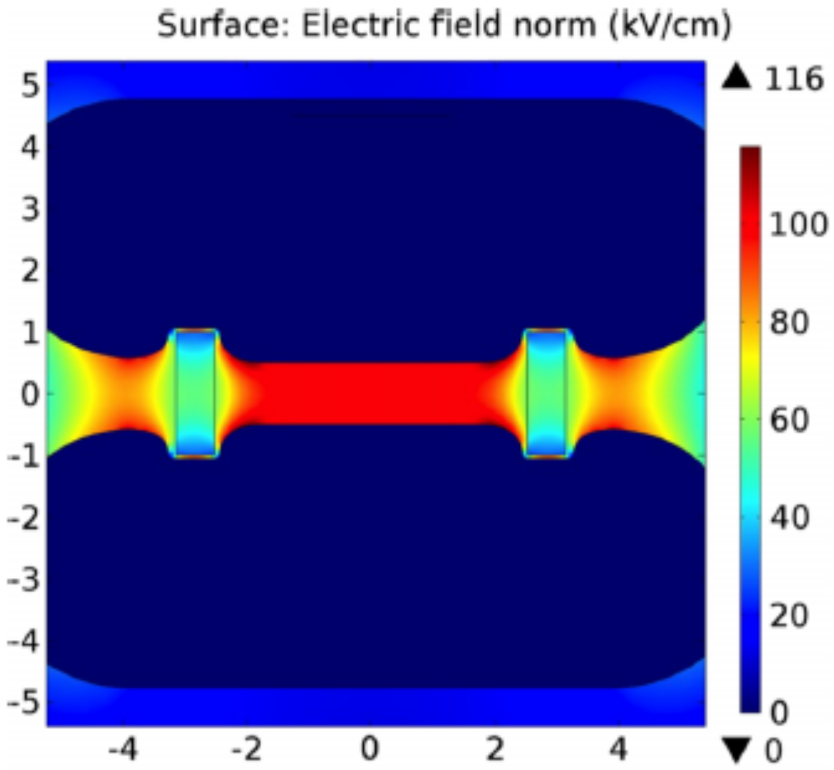
Electrodes

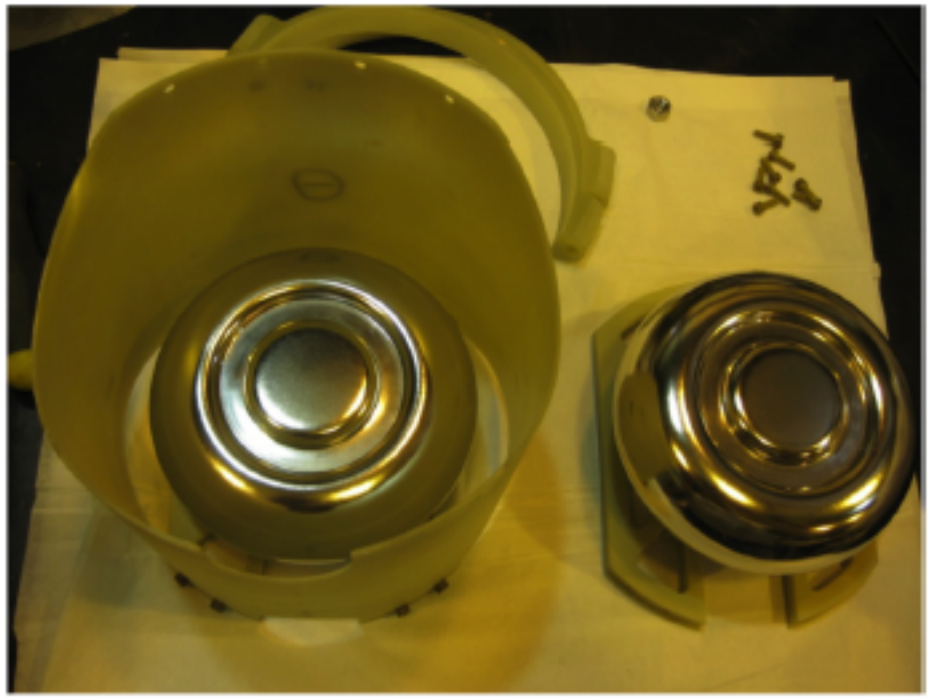


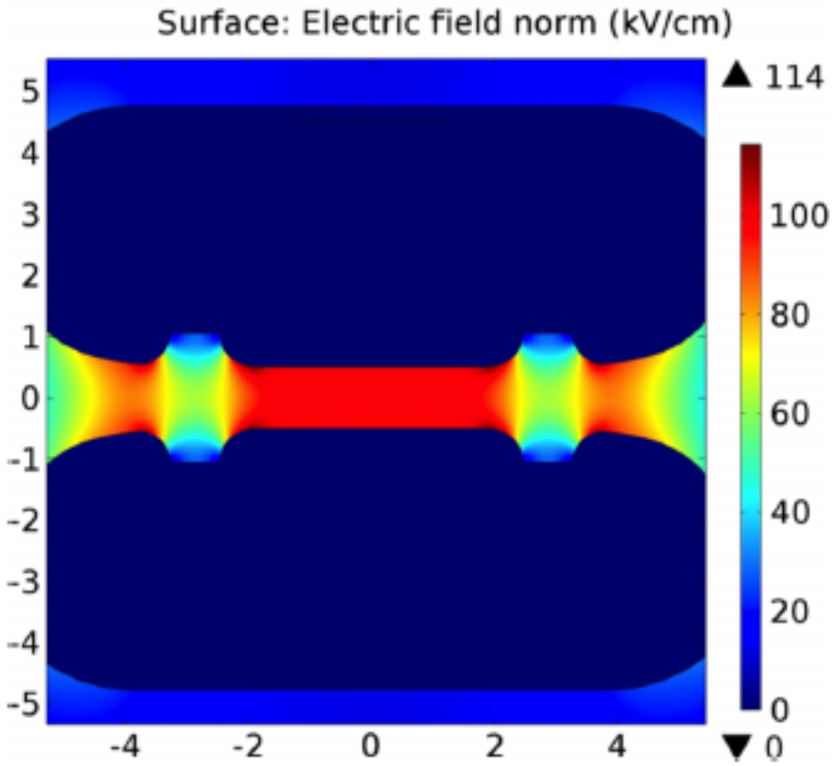
Rogowski electrodes (uniform field electrodes)

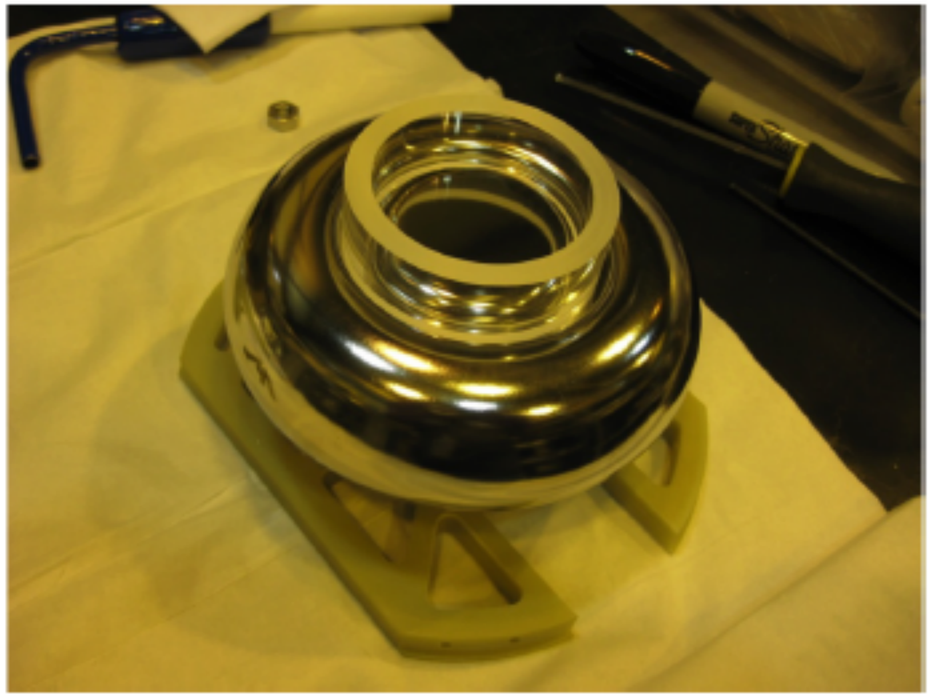
- Electropolished stainless steel
- PMMA with copper ion implantation

Electrodes with grooves and a ring



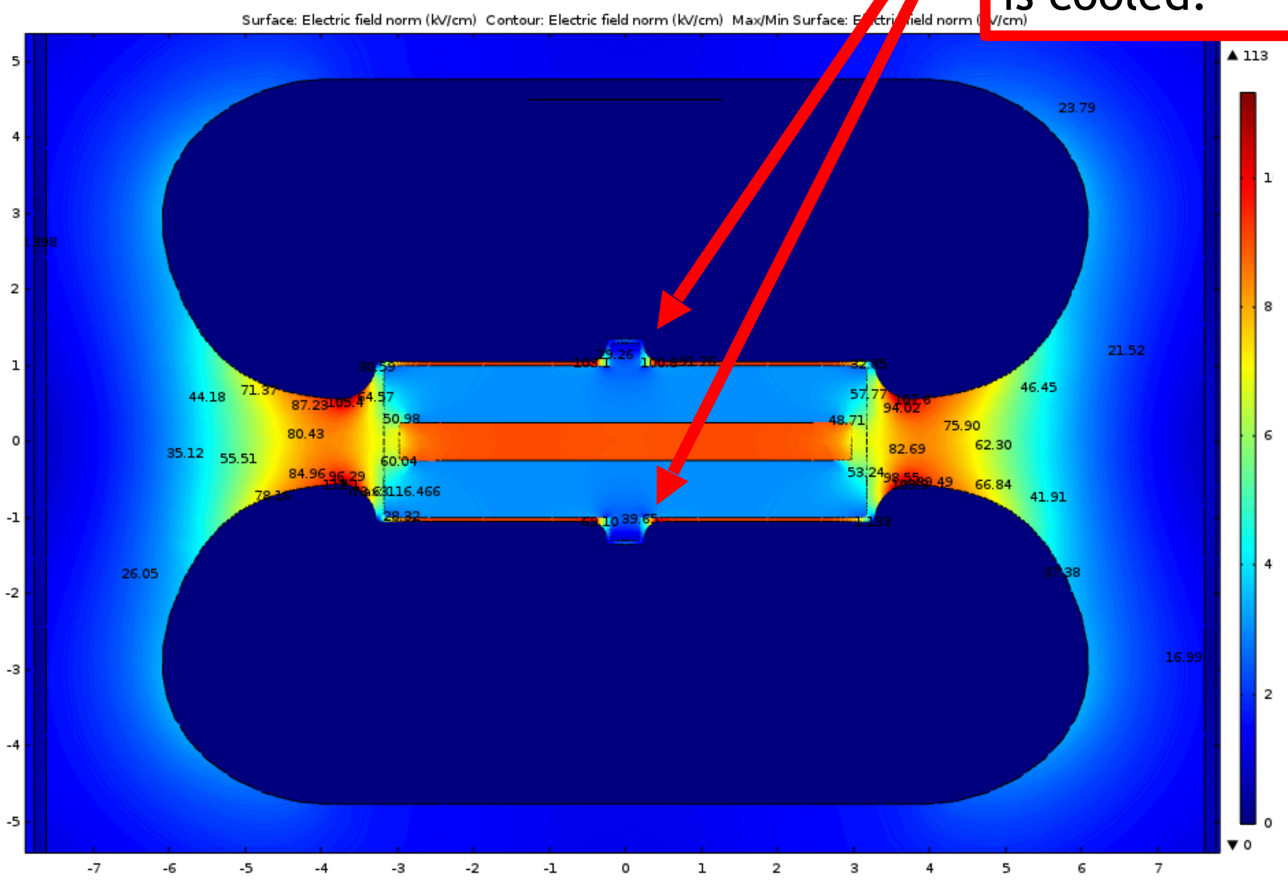






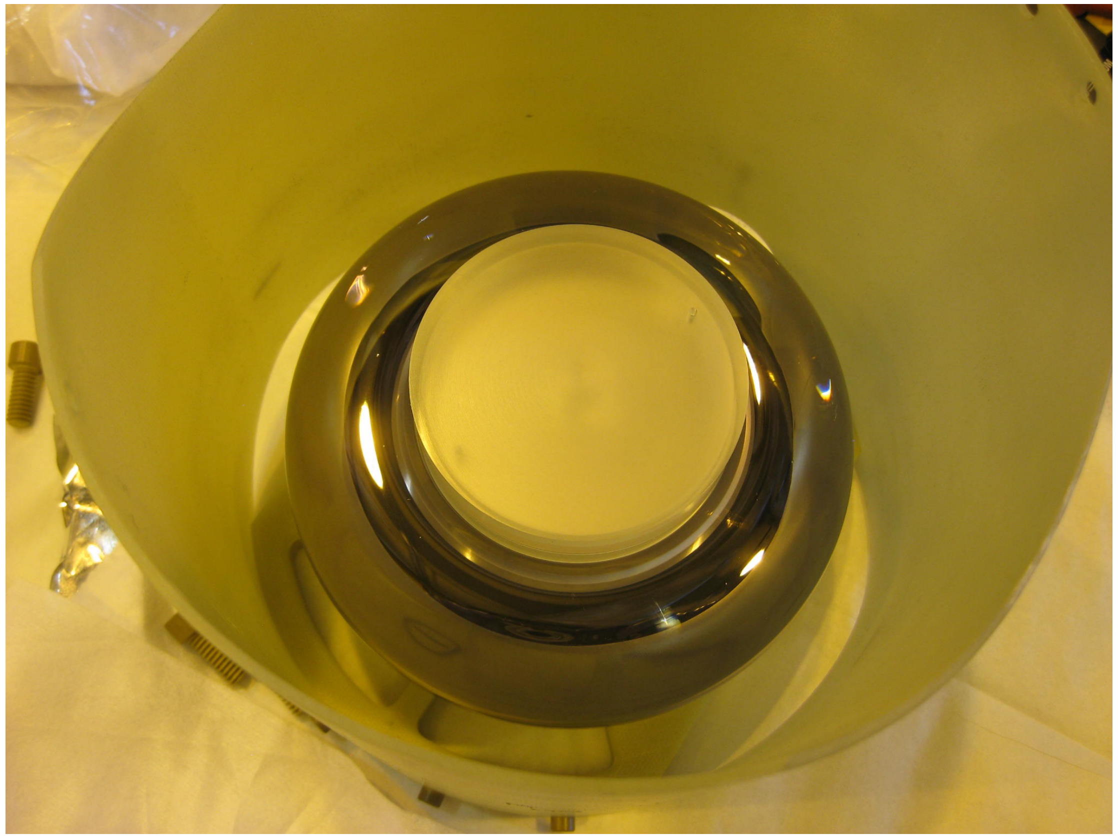
Electrodes with a mockup cell

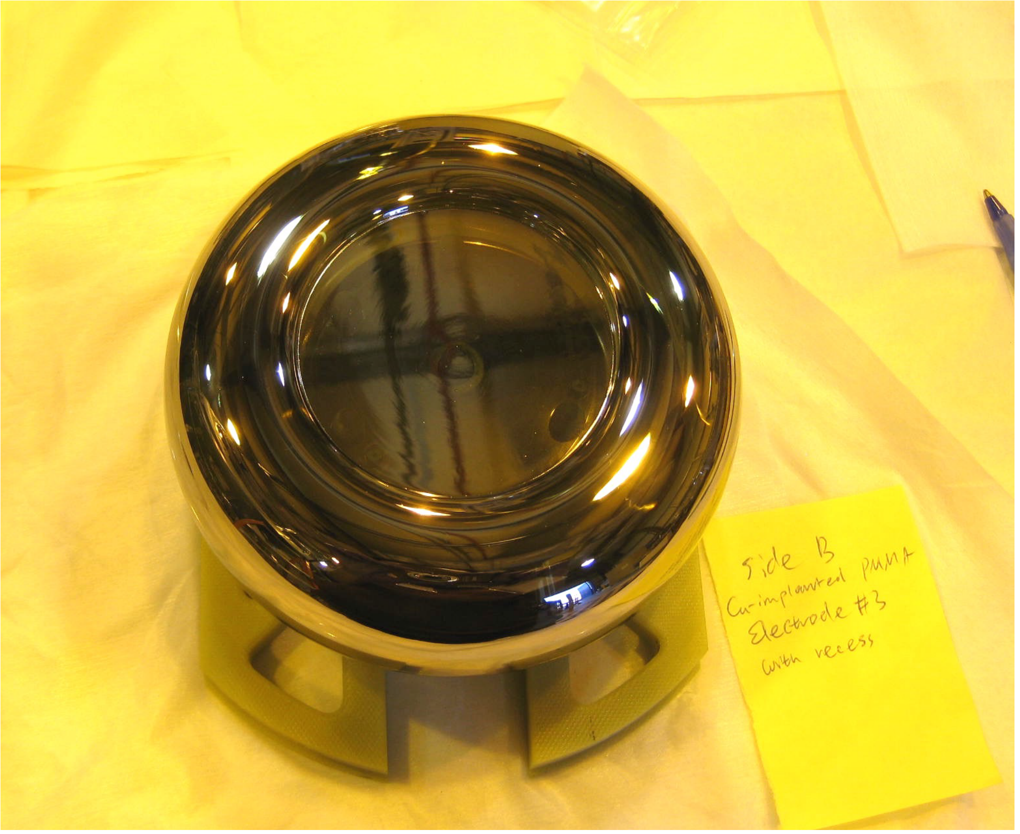
These locator pins kept the cell in position even after the system is cooled.



- Electrode-electrode distance = 2.1 cm
- PMMA wall thickness = 0.75 cm
- Gap size = 0.6 cm
- E field = V/(1.1 cm) for ε = 3.0

PMMA electrodes with Cu ion implantation





Cu ion implanted PMMA electrodes with a mockup cell.

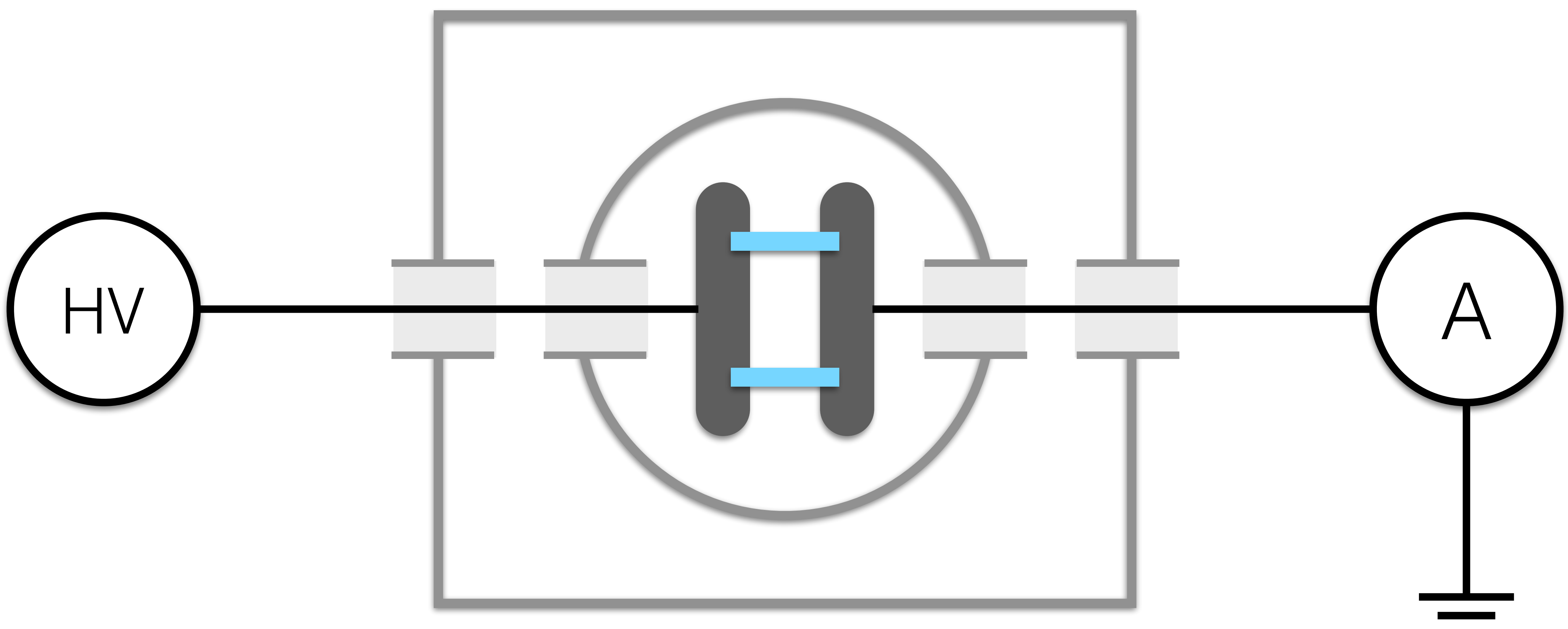
Leakage current requirements

Effects	Limit	Comments
Magnetic field generated by leakage currents	1 nA	50 pA without comagnetometer
Voltage reduction due to leakage current	100 pA	100 pA current in each cell changes the HV by 10% over 6 hours

Leakage current measurement

- Leakage currents between the two electrodes were measured by directly connecting a picoammeter to one of the electrodes in order to avoid the effect of leakage currents through HV cable insulation and feedthrough insulators.

- The applicable HV is 50% of the full voltage.

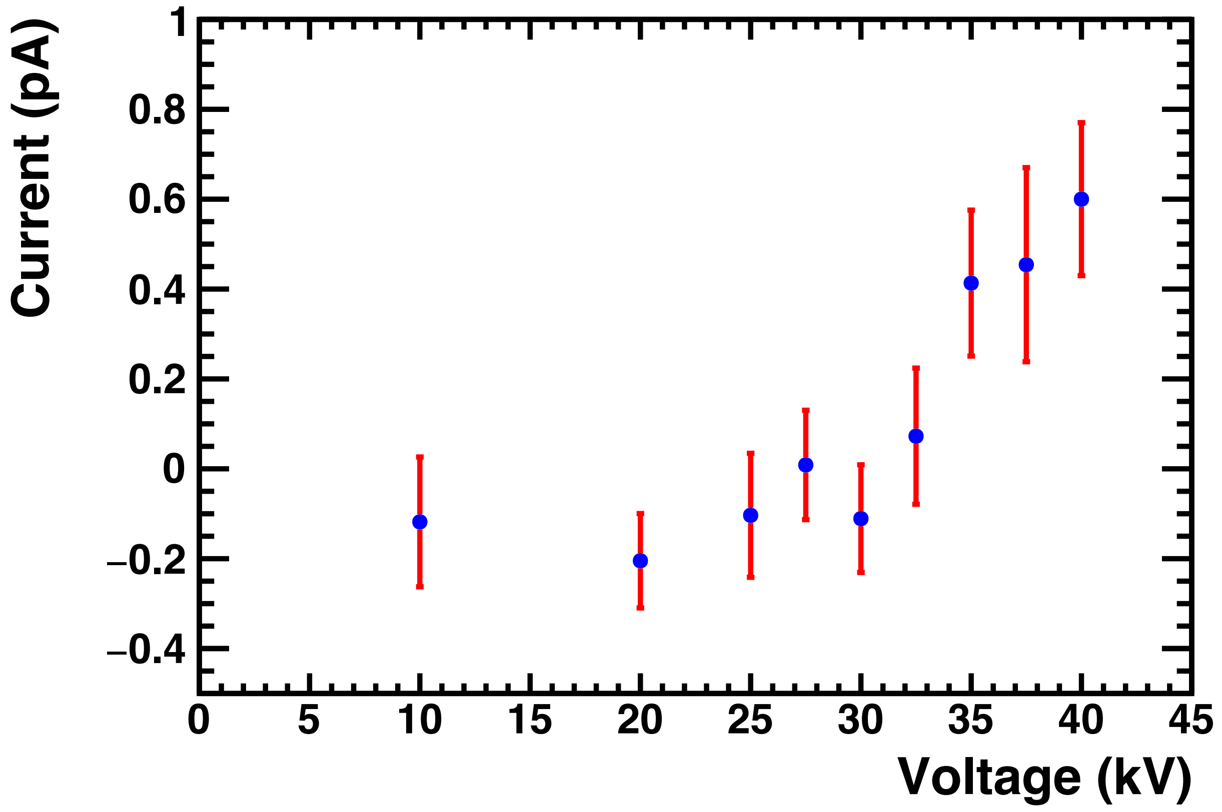


MSHV summary

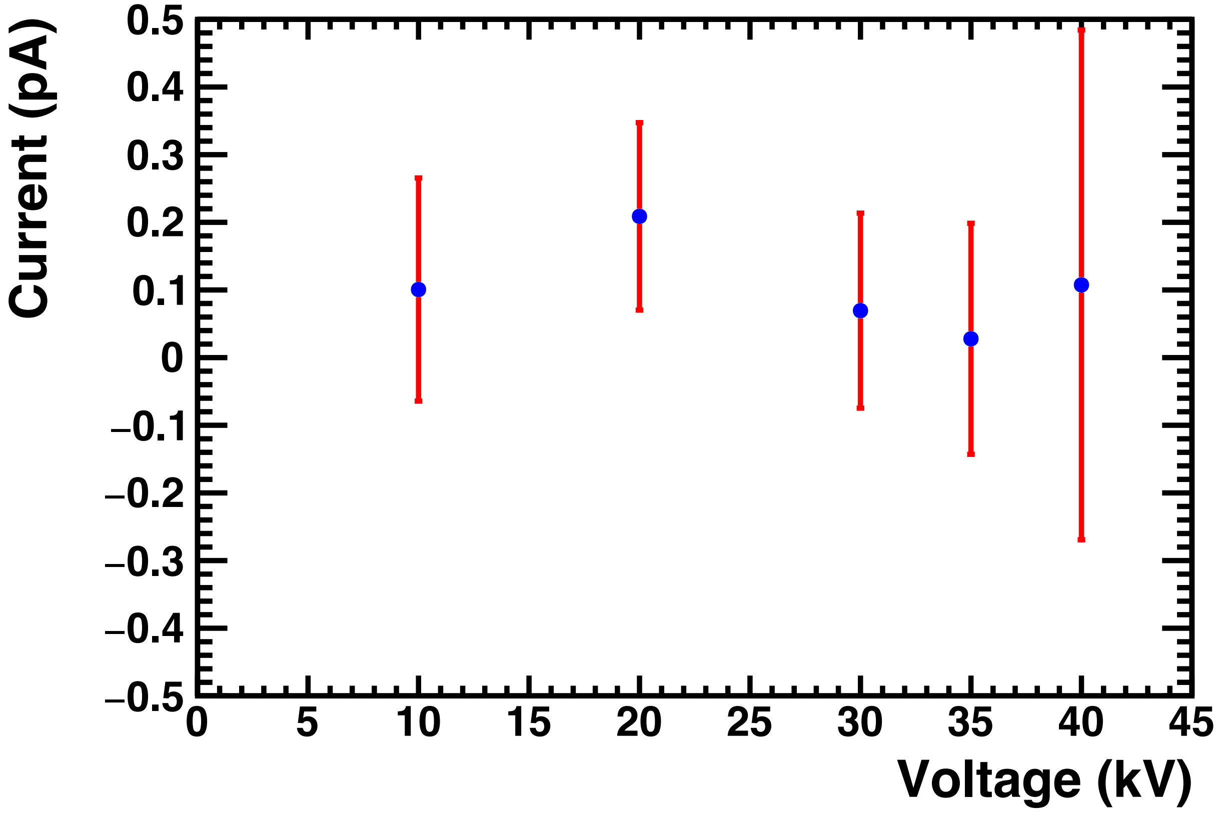
- The June 2017 cooldown concludes the MSHV HV program.
- Main findings:
    - Stable electric field ≳ 75 kV/cm at 0.4 K for a wide range of pressures in:
        - Gap between SS electrodes and Cu implanted PMMA electrodes
        - Volume inside a closed cell made of PMMA sandwiched between SS electrodes and Cu implanted PMMA electrodes
    - Leakage current ≲ 1 pA at 40 kV voltage difference with and without PMMA cell inserted between electrodes.
- The design of the MSHV system, operational experience, and initial findings can be found in T. M. Ito et al., Rev. Sci. Instrum. 87, 045113 (2016).

Leakage current vs voltage with a closed cell at 0.4K

600 torr



11 torr



Next step for MSHV
E-field dependence of LHe scintillation

- Goals:
  - Measure the E-field dependence of LHe scintillation produced by 3He(n,p)3H reactions
  - Measure the E-field dependence of LHe scintillation produced by electrons, which is important for understanding the possible suppression of signal due to neutron beta decay.
- Concept:
  - Replace one of the electrode with a grid-electrode with a light collection system behind it.
  - Radioactive source(s) will be electroplated on the remaining electrode
  - Thermal neutrons will be generated by moderating neutrons from AmBe source.

Our previous work

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

Measurement on LHe scintillation due to alpha particles

Model calculation on LHe scintillation due to n-3He capture events based on the measurement on α

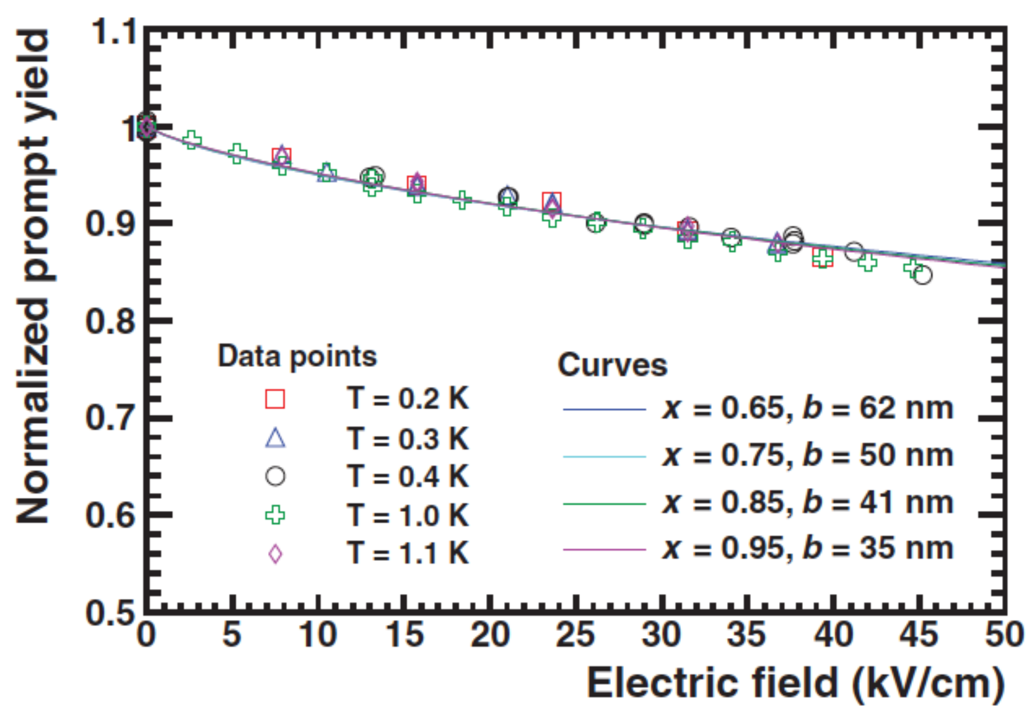


FIG. 15. (Color online) Kramers's theory fit to the electric-field–strength dependence of prompt scintillation yield measured by the current work. The prompt scintillation yield is normalized to the value at $E = 0$. The curves are calculated using Eq. (9) of Ref. [29].

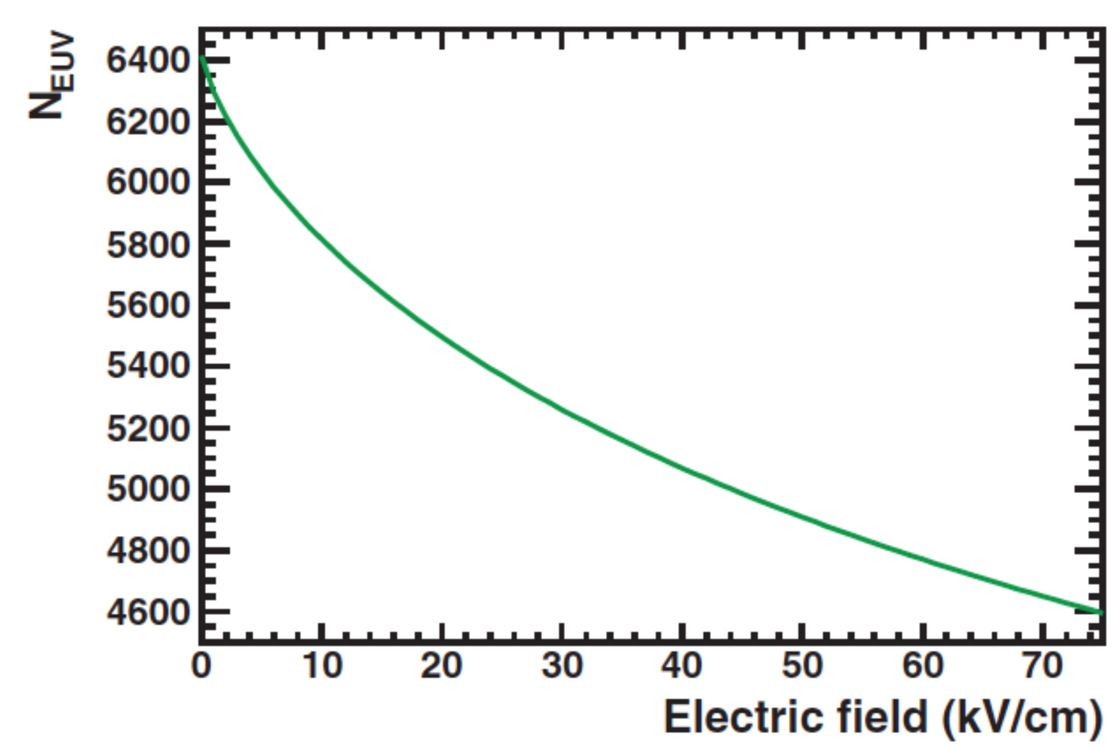
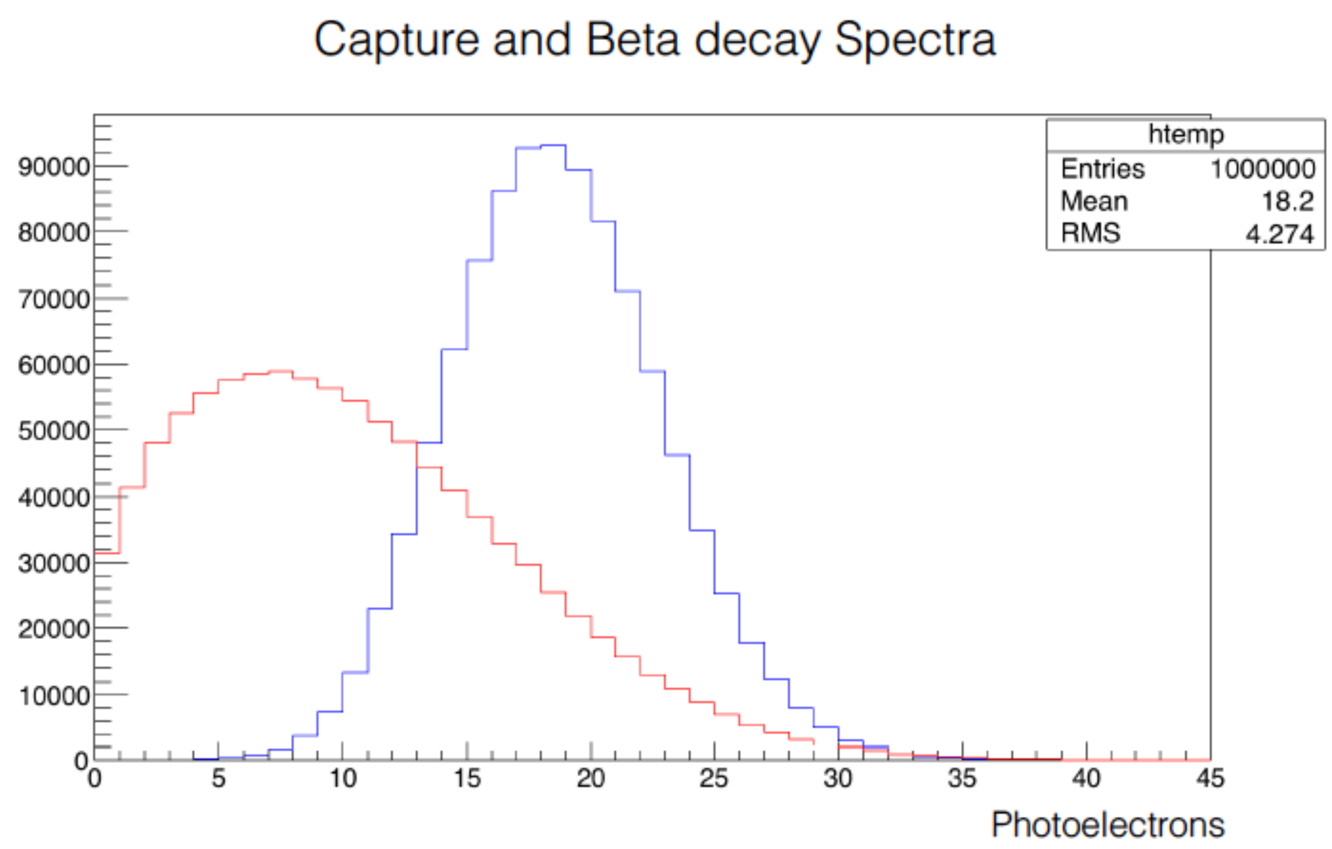


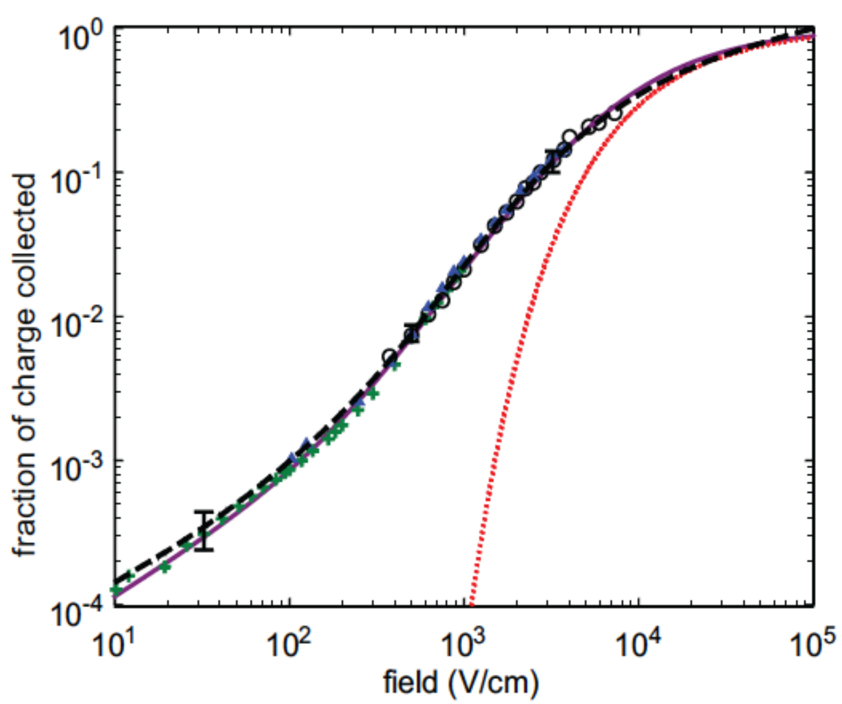
FIG. 21. (Color online) Predicted number of prompt EUV photons for LHe scintillation produced by products of $^3He(n,p)^3H$ reaction with $x = 0.65$ and $b = 62$ nm.

Motivation for electron measurement



The simulated plot on the left assumes the predicted E-field dependence on capture signal on the previous slide and the ionization current measured for beta source below with an assumption that 1/3 of beta induced LHe scintillation is E-field independent.

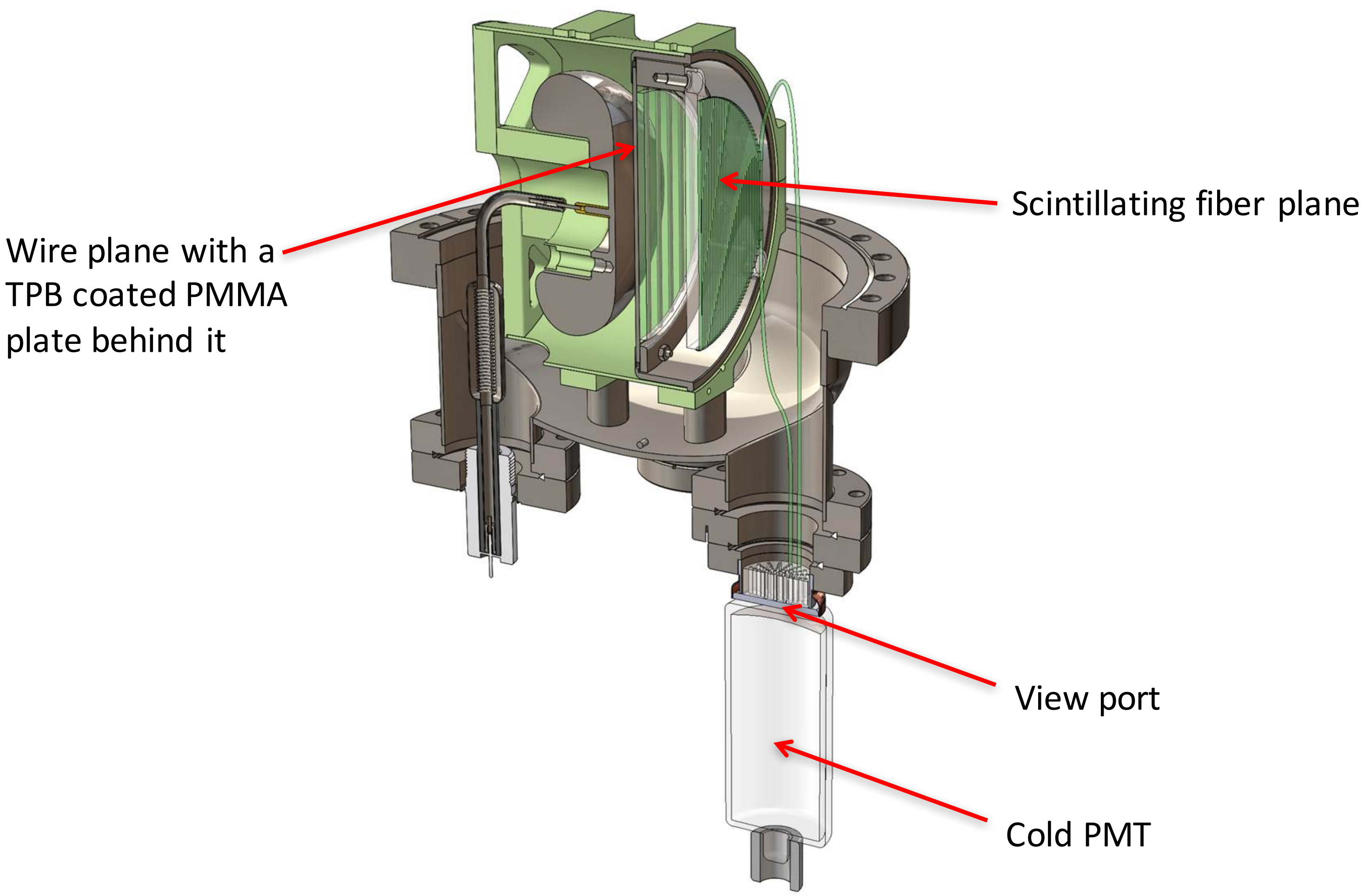
Charge collection from β source in LHe

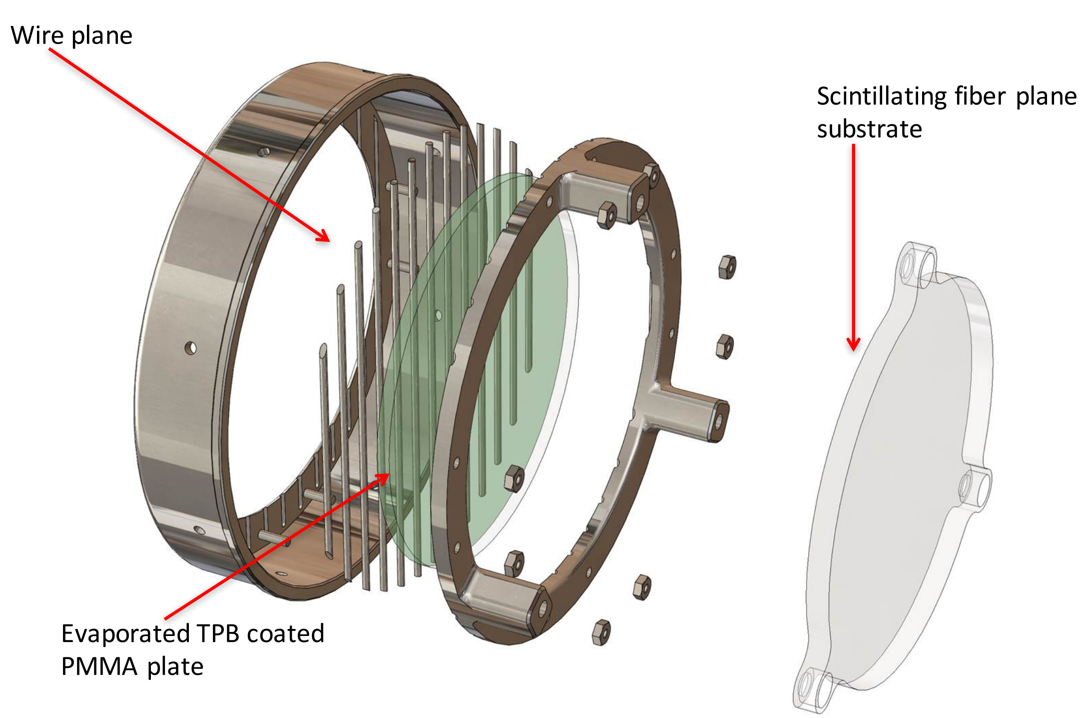


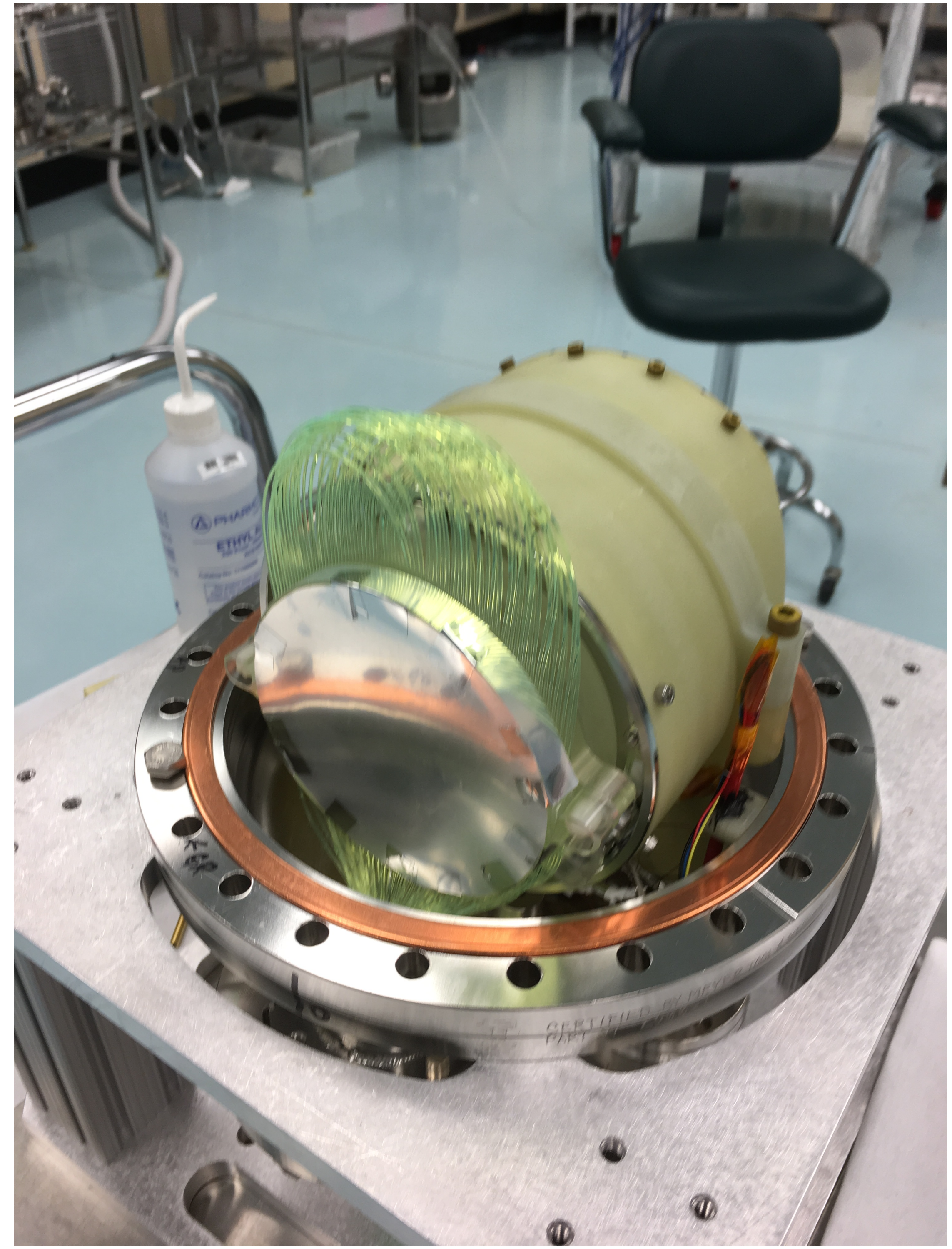
Seidel, Ito, Ghosh, Sethumadhavan, Phys. Rev. C 89, 025808 (2014)

The amount of background due to beta decay at the location of the capture signal depends on the suppression of the scintillation yield from betas due to electric field as well as that for capture signal.

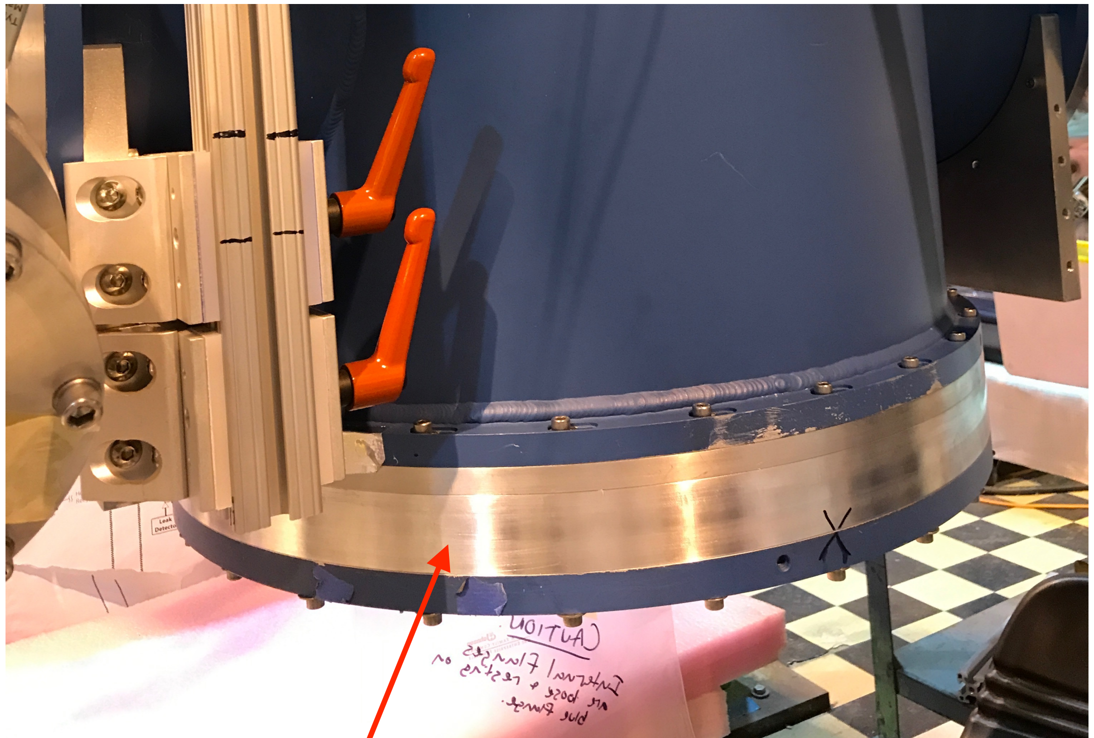
Design inside the CV



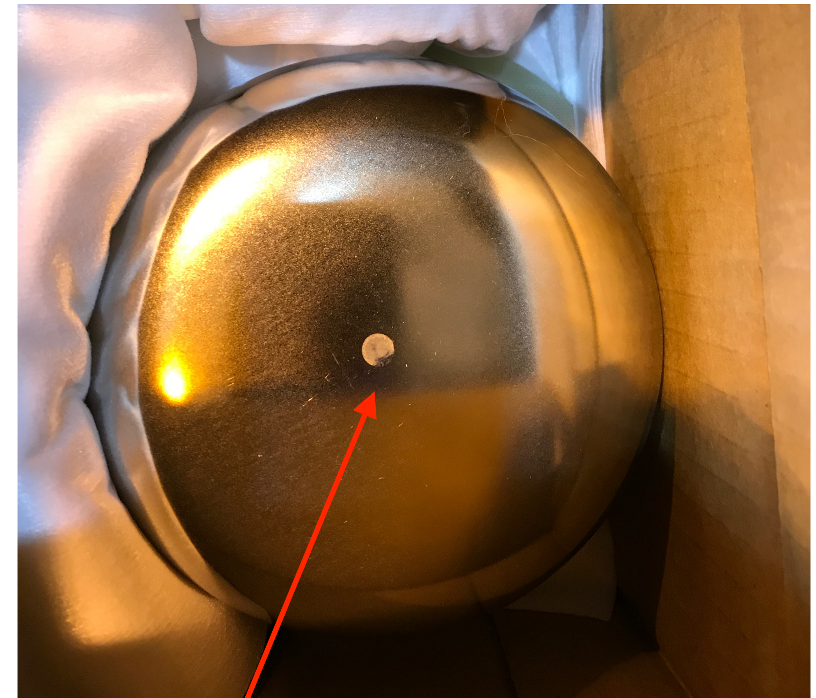




Status of other components



MSHV extension



Radioactive source
electroplated on an electrode

3He gas

Status and plans

Status

- All of the parts for modifying the MSHV apparatus have been fabricated.
- Extensions for IVC, 77K shield, and OVC have been test fitted and leak tested.
- Electrode with 241Am source and electrode with 113Sn and 241Am have been made.
- Neutron moderation simulation and radiation shielding calculation completed. Currently under review by health physics and radiation engineers.
- DAQ system being tested using Argon gas scintillation and to be tested with LHe using a small Dewar setup.
- 3He gas procured
- Light collection system fabricated and tested.
- Clean room identified at LANL to install the light collection system and electrodes into the CV.
- DAQ system tested with LHe scintillation with alpha source in a small Dewar
- The light collection system installed into the MSHV system

Plans

- Measurement of LHe scintillation from 113Sn and 241Am in MSHV — mid- to late October or early November.
- Measurement of LHe scintillation from neutron capture in the MSHV — **late November or December.**

HSHV system

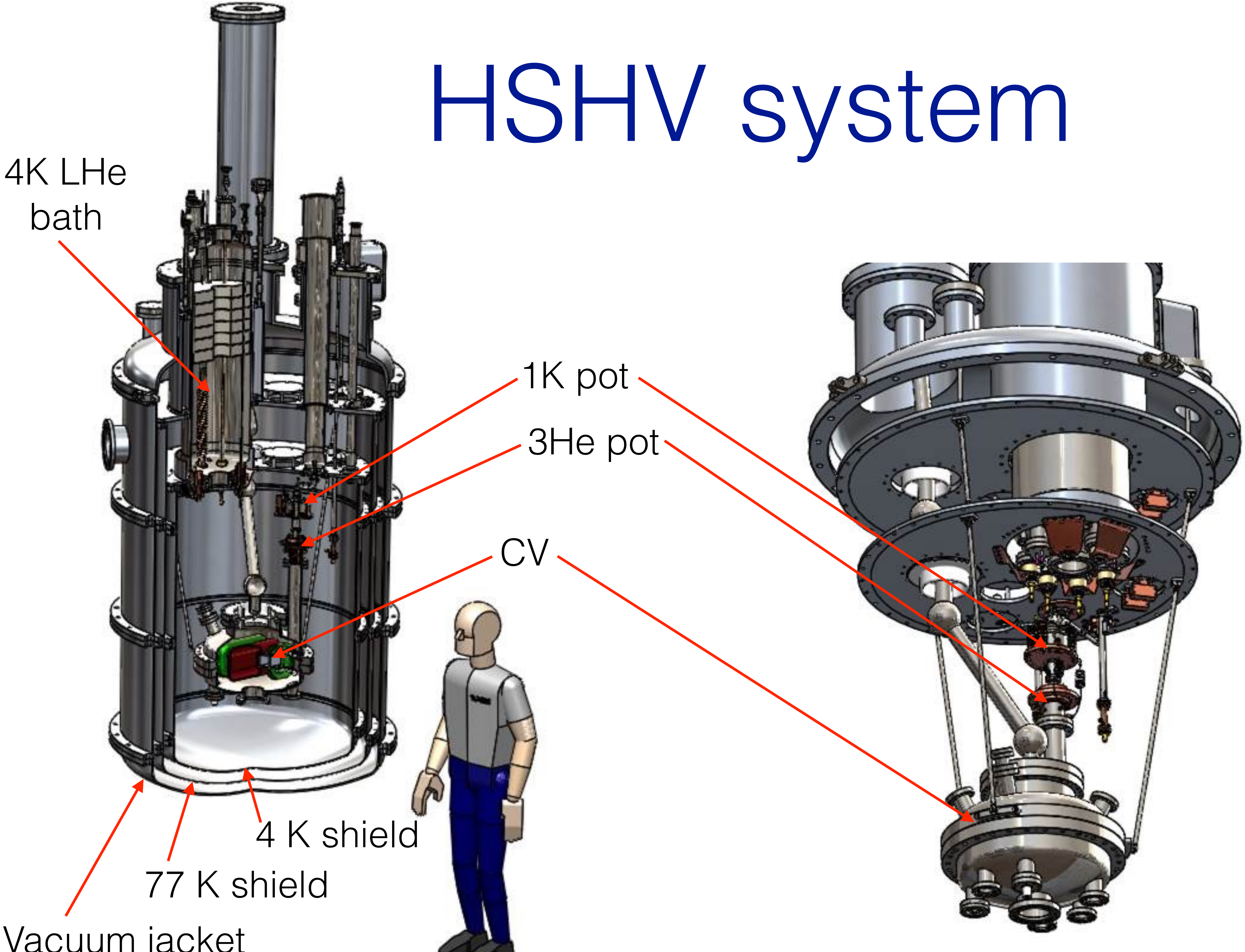
Questions that the HSHV system is expected to address:

- How to bring HV into the CV?
- What is the achievable field?
    - Do we need to pressurize?
- How do the leakage currents scale with voltage, gap size, and cell size?
- What are the damages on electrodes due to breakdown like?
- What is the effect of light guide/fibers?
- How best can we construct and assemble the system?
- Can the SQUIDs survive near HV?

HSHV system design principle

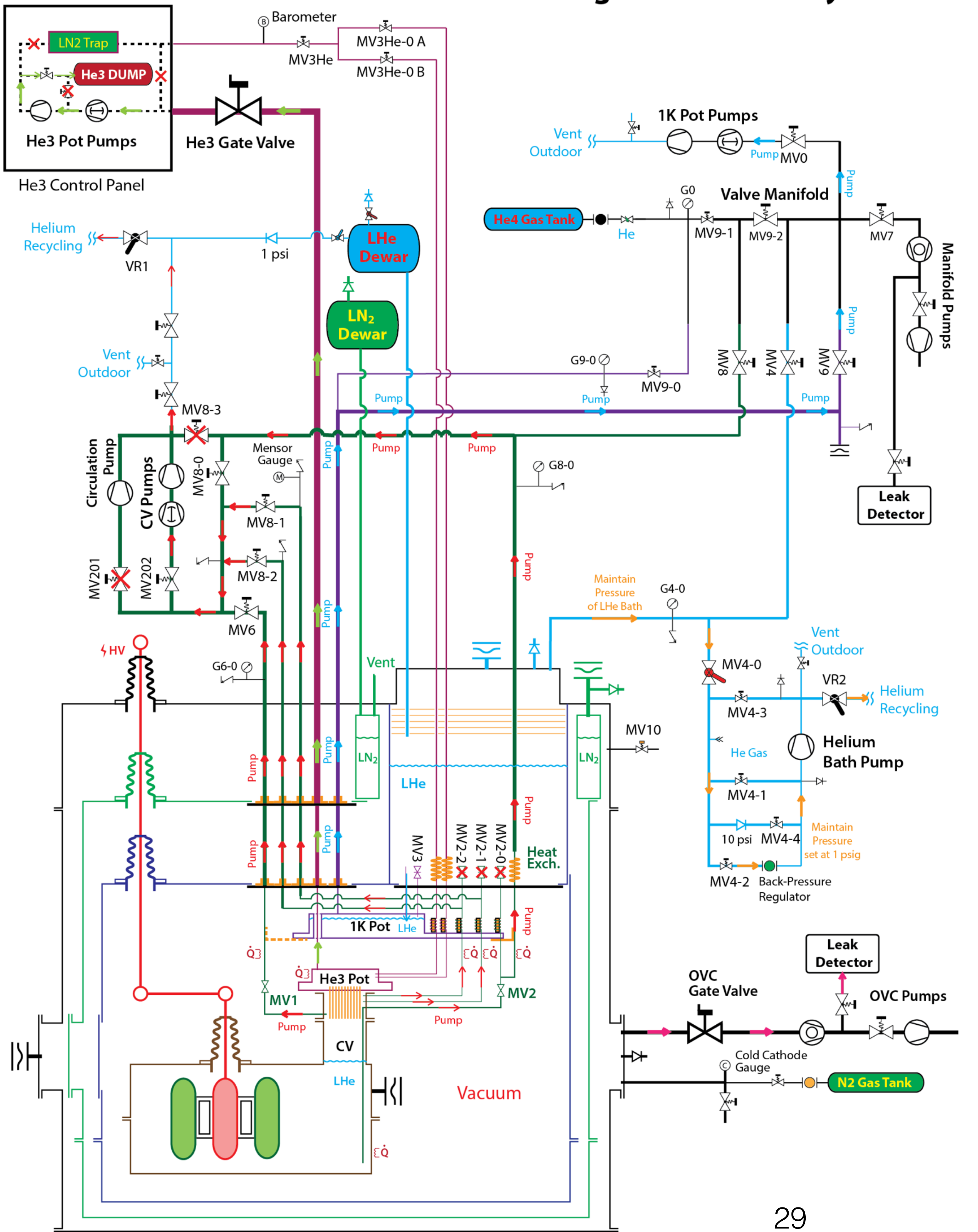
- CV just big enough to accommodate half-scale measurement cell electrodes
  - CV volume ~ 40 liters (~45 cm in ID)
  - No room for V1 valve, SQUIDs, light collection system
- Direct HV feed up to 200 kV
  - Can create sufficiently high electric fields
- Sufficient room in the system to allow various HV chain designs
- Use a 3He fridge identical to the MSHV system

HSHV system



4K LHe
bath
1K pot
3He pot
CV
4 K shield
77 K shield
Vacuum jacket

Diagram for HSHV System

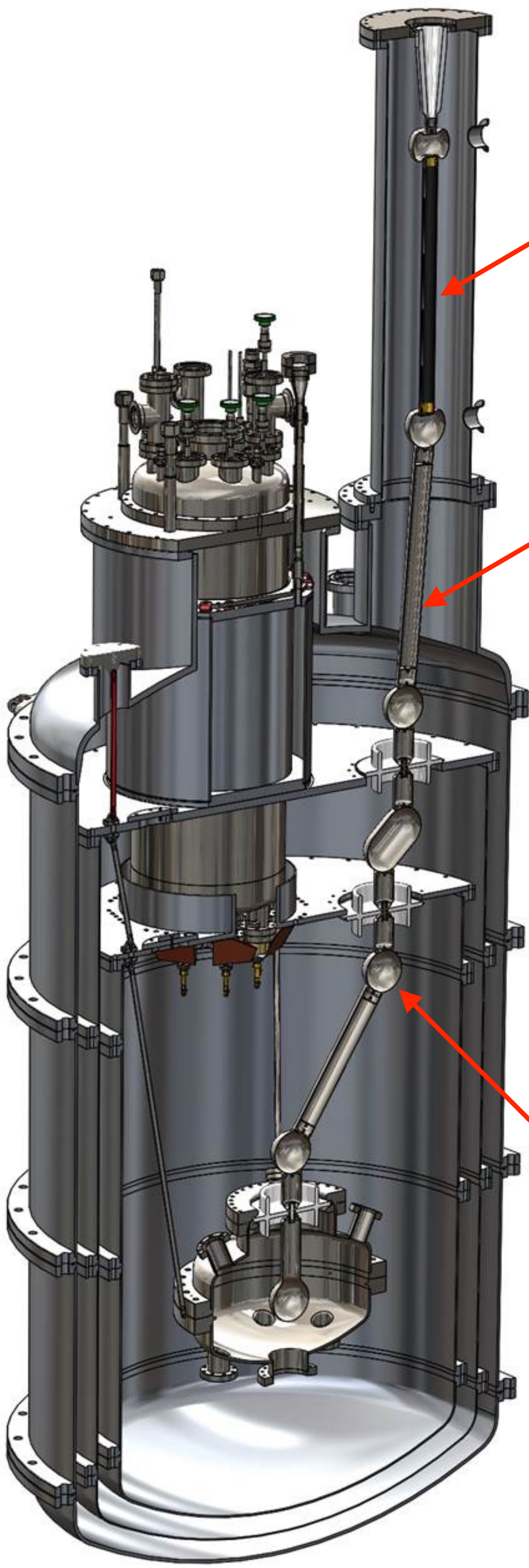


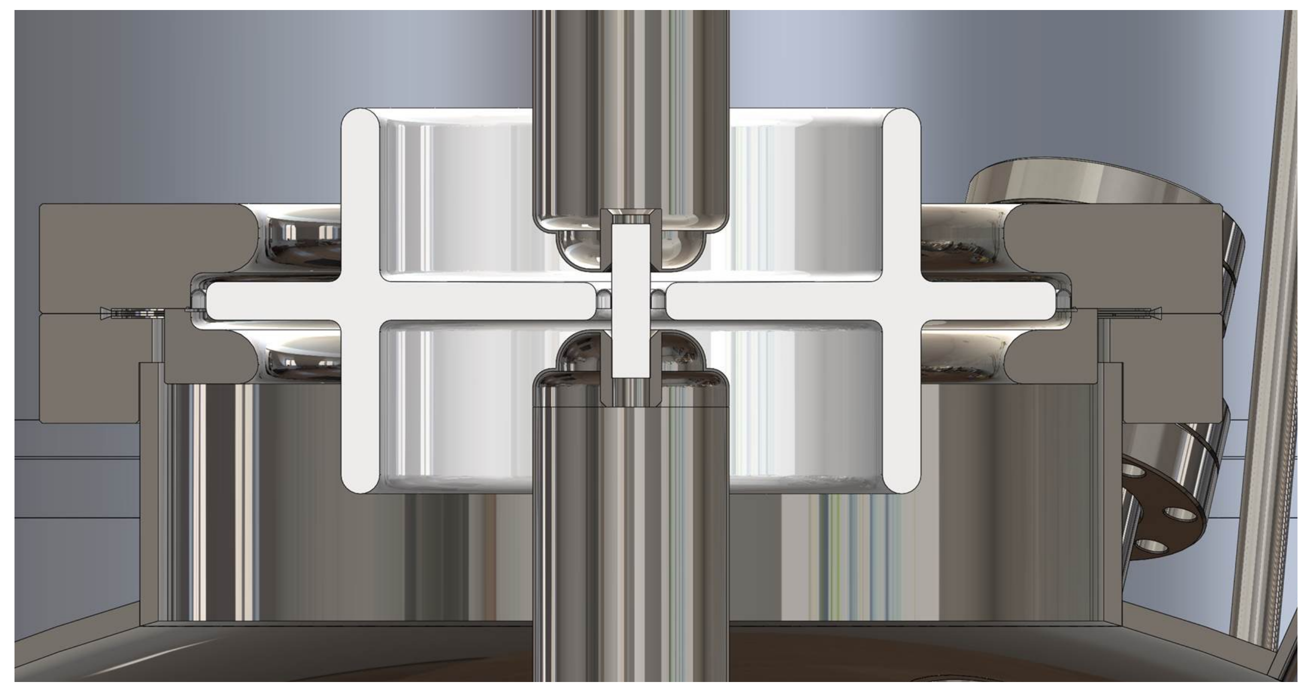
Largely based on the MSHV system. One large improvement is multiple CV fill lines with different impedances. This will allow efficient filling and cooling of the CV.

HSHV HV design

- HV PS to the apparatus:
  - Commercially available 200 kV cable (x ray industry)
- RT 200 kV feedthrough:
  - Ceramic feedthrough developed by SCT-Jlab collaboration
- HV resistor:
  - Placed inside the cryostat vacuum
- HV wire inside the cryostat:
  - Baseline:
    - Vacuum insulated thin wall stainless steel tubing
    - Use a ball joint for flexibility
  - Alternative:
    - Use commercial HV cable that use carbon loaded plastic as conductor (tested down to 1.5 K)
- HV feedthrough (SF tight) and HV thermal anchors inside the cryostat:
  - Custom design ceramic feedthroughs to be fabricated by SCT.

HSHV HV design





Custom 200 kV SF tight feedthrough being fabricated by SCT and to be delivered to LANL in October.

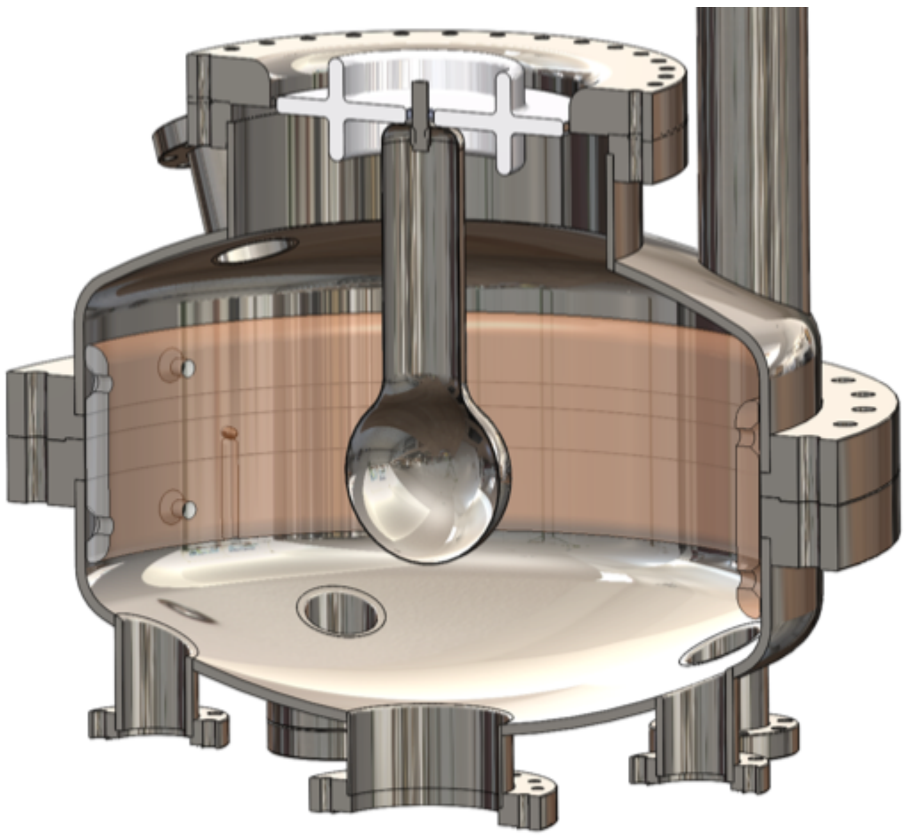
HV parts R&D

- HV parts for connections in vacuum will be prototyped and tested in a RT HV test chamber.
- The test chamber is currently being commissioned with a 100 kV PS.
- We have a 200 kV PS in hand.
- Need electrical and radiation safety approval.

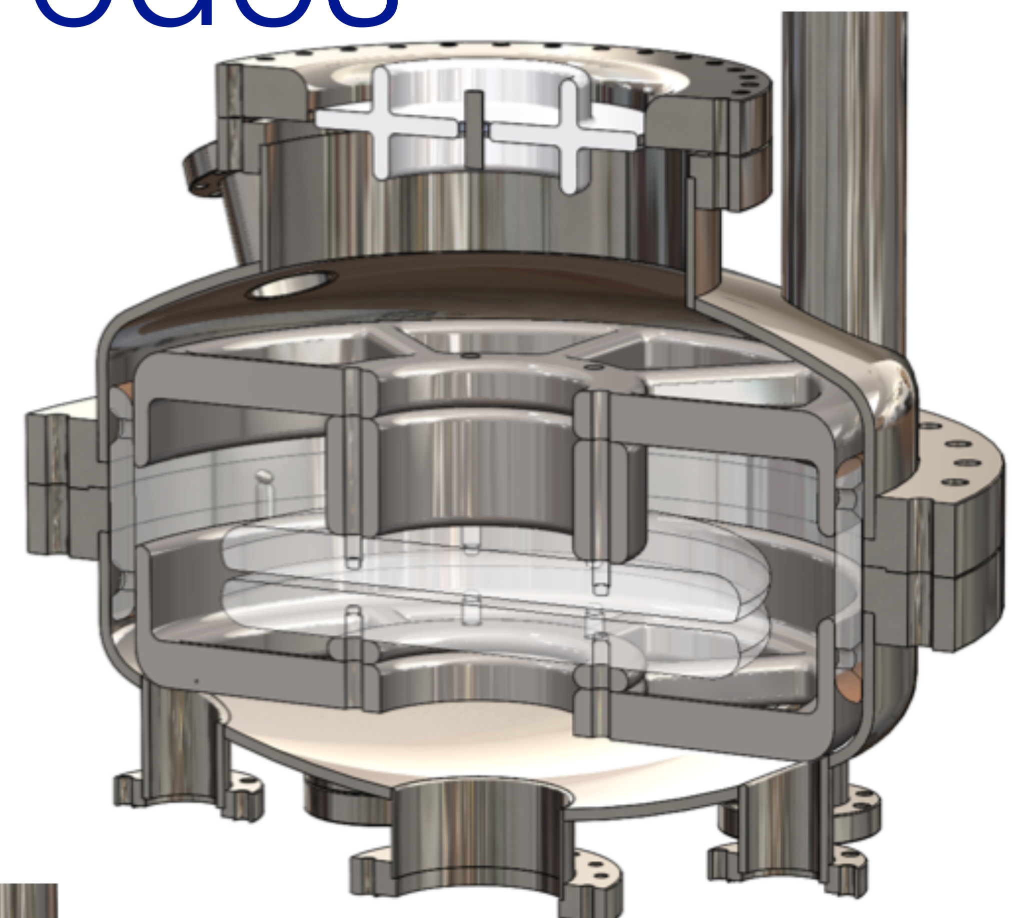
HSHV measurement program

1. Test the HV feed line with a terminating ball at the end of the HV feed line inside the CV to test for the HV performance and measure the heat load.
2. HV test with sets of Rogowski electrodes (two parallel plate electrodes) to study the area scaling.
3. Test with half-scale measurement cell electrodes with measurement cells to study:
    1. Breakdown field/voltage
    2. Damage due to breakdown
    3. Leakage current
4. Add optical fiber/light guide to study its effect on breakdown
5. Add SQUIDs to study the effect of HV breakdown on SQUIDs

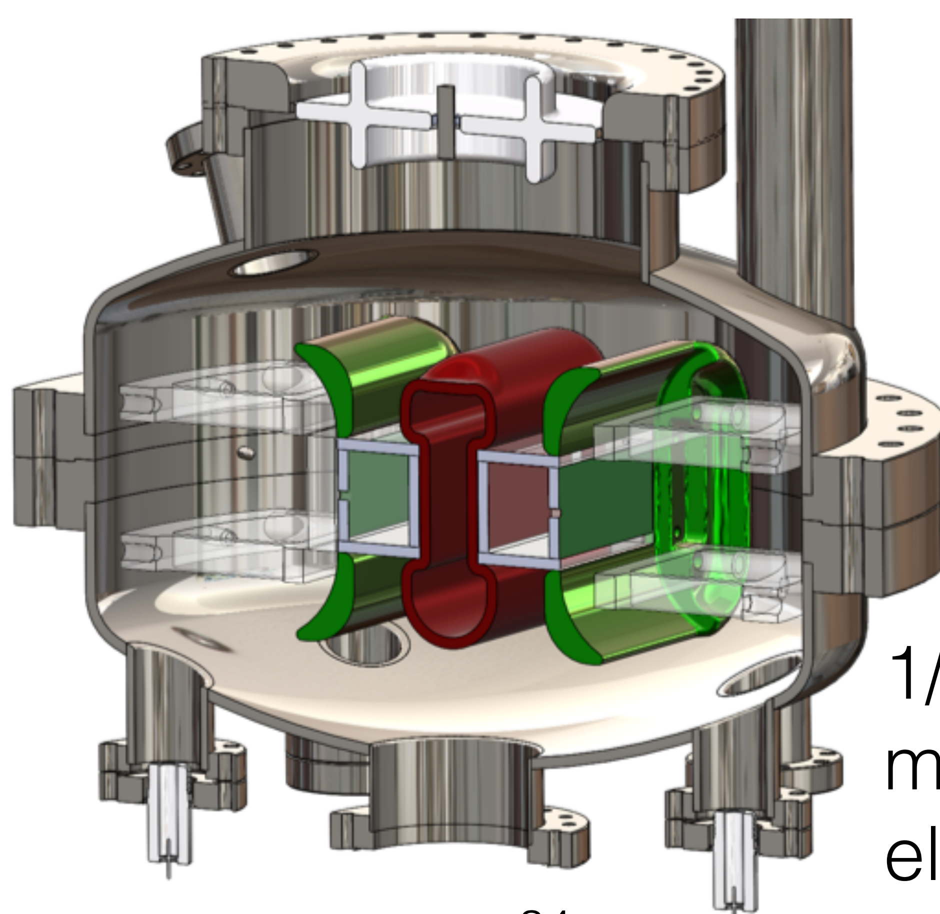
HSHV electrodes



Ball terminator



Uniform field electrodes



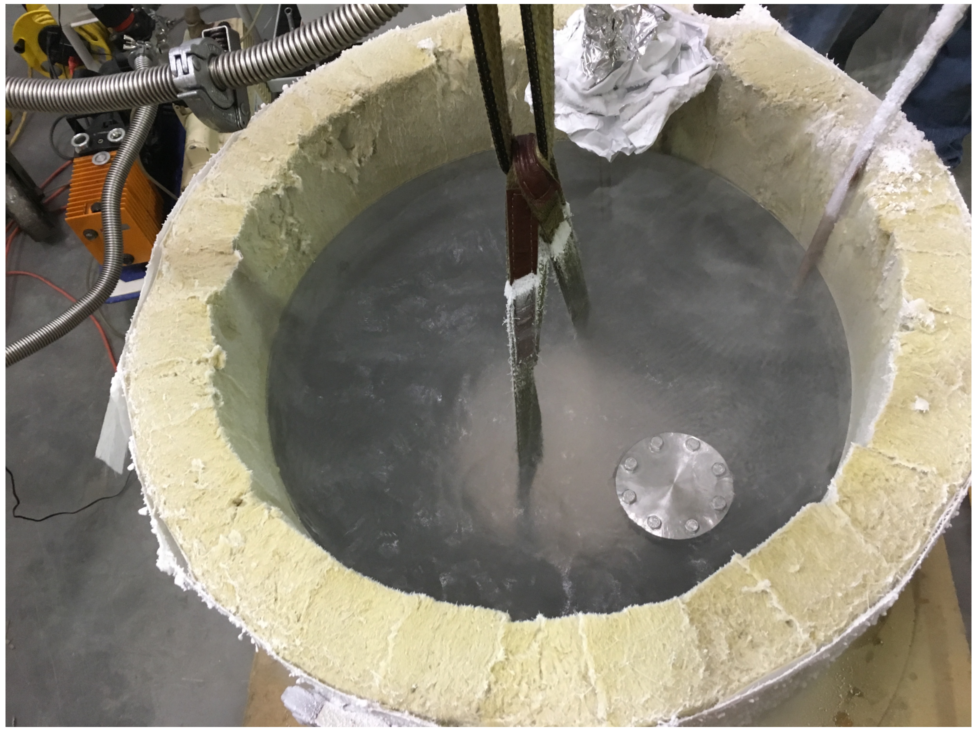
1/2-scale measurement cell electrodes

HSHV stand at LANL

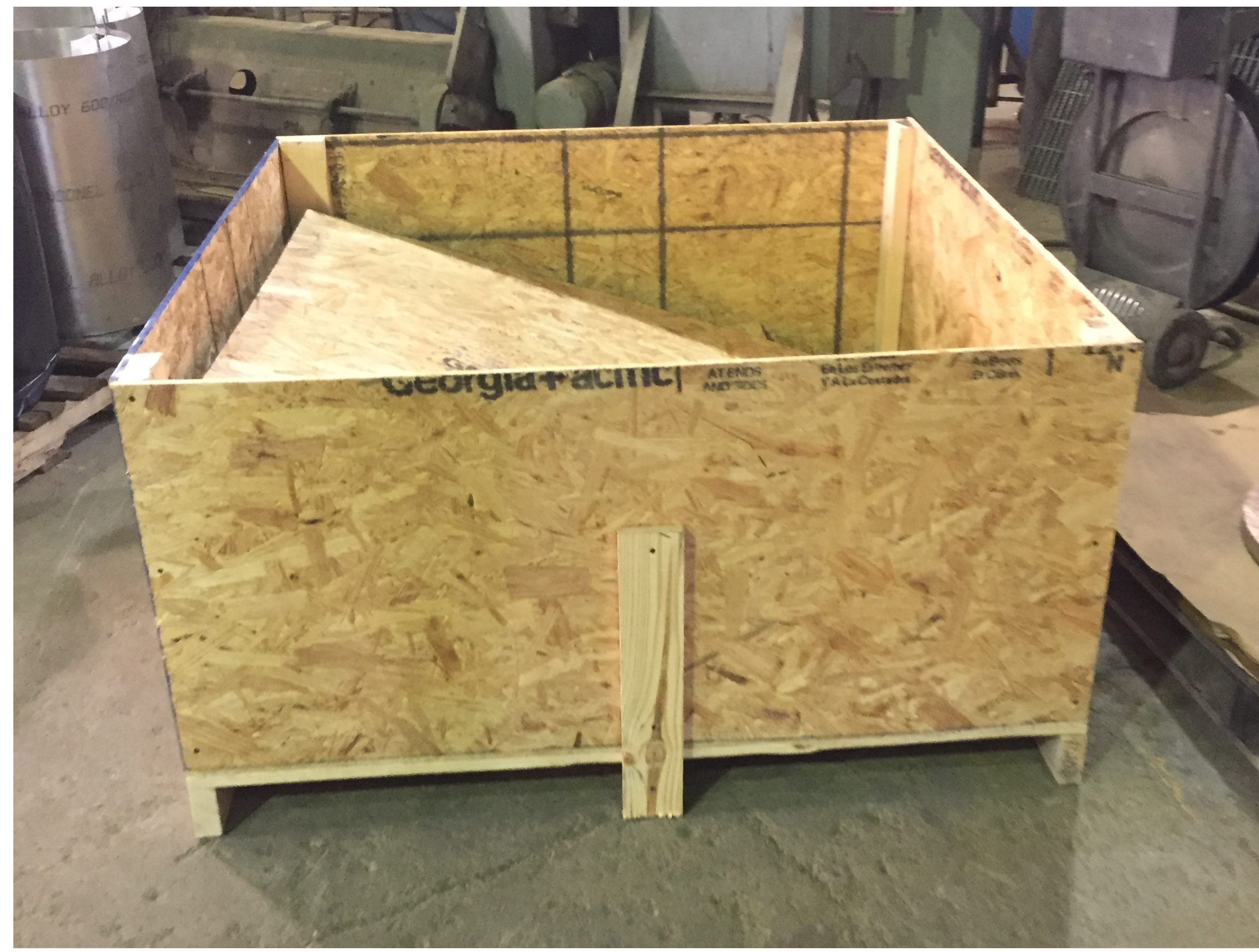
- Purchased from SafeSmart Access

- Assembled and placed in LANL Area A Staging Area read to accept the HSHV cryostat.

Photos from Alloy Fab



More photos from Alloy Fab



HSHV cryostat at LANL

Summary

- The MSHV HV R&D program has shown that:
  - Desired electric field (75 kV/cm) is possible in a 1/5-scale system.
  - Small leakage current (< 1 pA) at 40 kV in a 1/5-scale system.
- The MSHV system is being modified to perform measurements of LHe scintillation in an electric field.
- The HSHV system, the next HV test apparatus, is being assembled and tested at LANL.

Team

- LANL: Steven Clayton, Scott Currie, Clark Griffith, Takeyasu Ito, Steve MacDonald, Mark Makela, Chris O'Shaughnessy, Nguyen Phan, Erick Smith, Wanchun Wei
- ORNL: Vince Cianciolo, Seppo Penttila, John Ramsey, Weijun Yao
- UIUC: Doug Beck, John Blackburn, Eric Thorsland, Steve Williamson
- Kentucky: Chris Crawford, Daniel Wagner
- Caltech: Riccardo Schmid
- Brown: George Seidel
- Indiana: Josh Long