Liquid helium
Scintillation, application of a large electric field, and generation of HV

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Dark matter (WIMPs) direct detection
Peking University
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Outline

- LHe scintillation
  - Introduction
  - Measurements with alpha particles
  - Measurements with electrons
- Application of a large electric field in LHe
- Generation of a high electrical potential in LHe

Work presented in this talk have been performed by:
Marie Blatnik (Caltech), Vince Cianciolo (ORNL), Steven Clayton (LANL), Scott Curie (LANL), Takeyasu Ito (LANL), Stephen MacDonald (LANL), Chris O'Shaughnessy (LANL), Nguyen Phan (LANL), John Ramsey (LANL/ORNL), George Seidel (Brown), Erick Smith (LANL), Wanchun Wei (LANL), Weijun Yao (ORNL)

Thanks to Nguyen Phan for many slides.

LHe Scintillation

Liquid helium scintillation

Energy deposition from charged particles

Ionizations

Excitations (Field independent)

- Recombination leads to formation of excited molecules

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

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

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

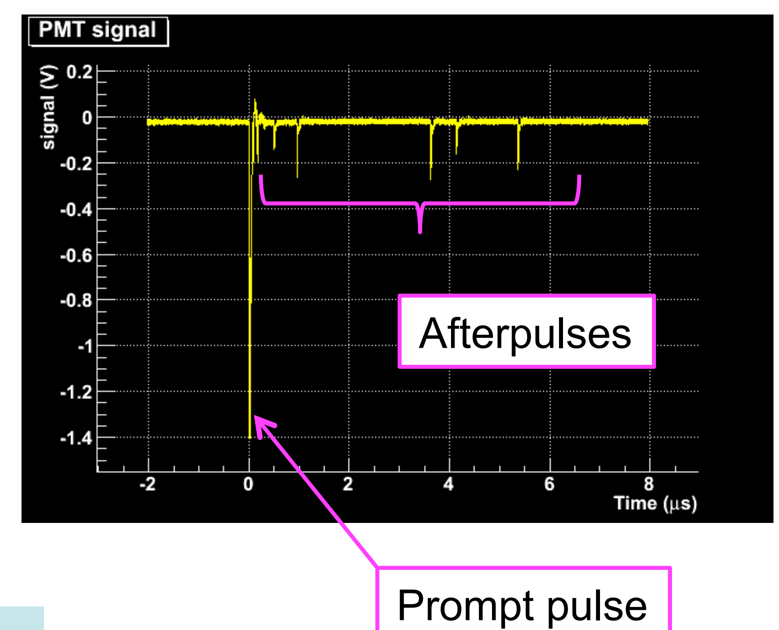
- Triplet state: has a litefime of ~ 10 s in vacuum. Gives afterpulses through Penning ionization (destructive interaction with each other)

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

or

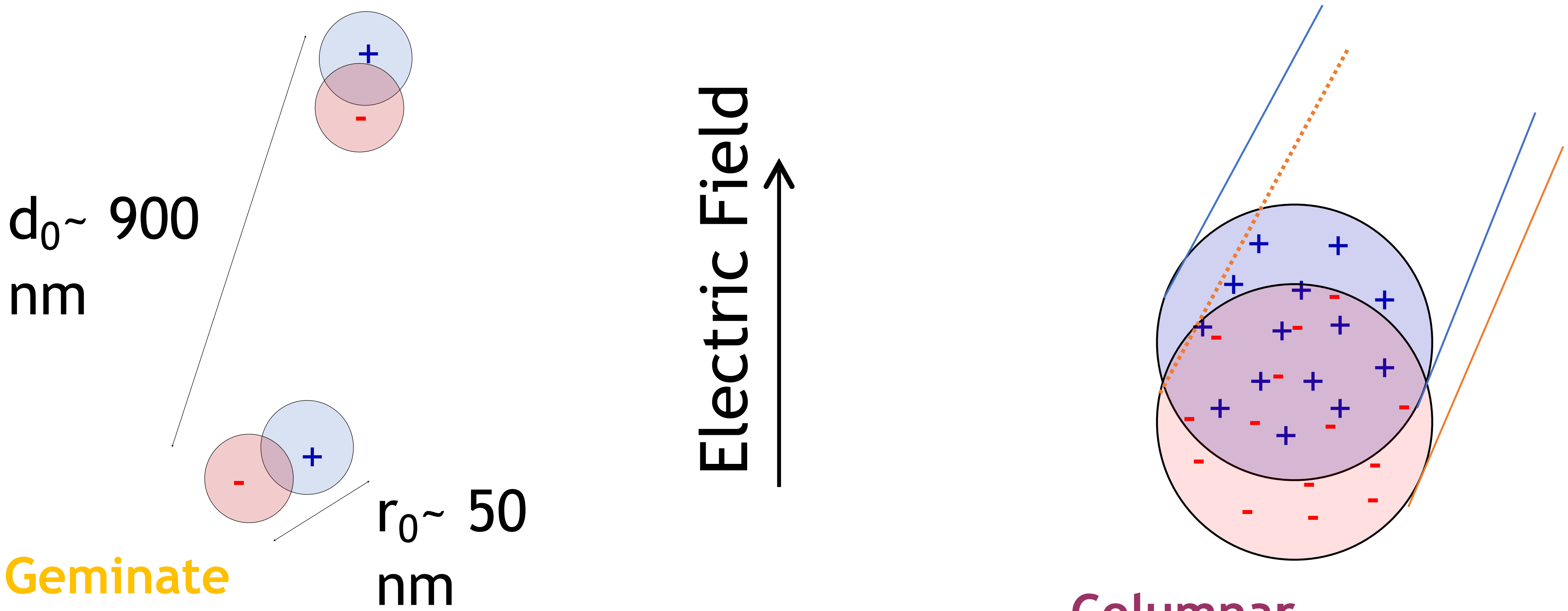
$$\mathrm{He}_2\left(a^3\Sigma_u^+\right) + \mathrm{He}_2\left(a^3\Sigma_u^+\right) \rightarrow 2\mathrm{He} + \mathrm{He}_2{}^+ + e^-$$

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



Two types of ionizing particles

Distribution of charges and recombination depends on the type of ionizing particle.



Geminate recombination (electrons)

Columnar recombination (alphas, protons, tritons, etc.)

Recombination leads to excited molecules which then decay by emitting 80 nm EUV photons. Electric field suppresses recombination, which in turn results in suppression in scintillation light production. Separated charges can be measured as ionization current.

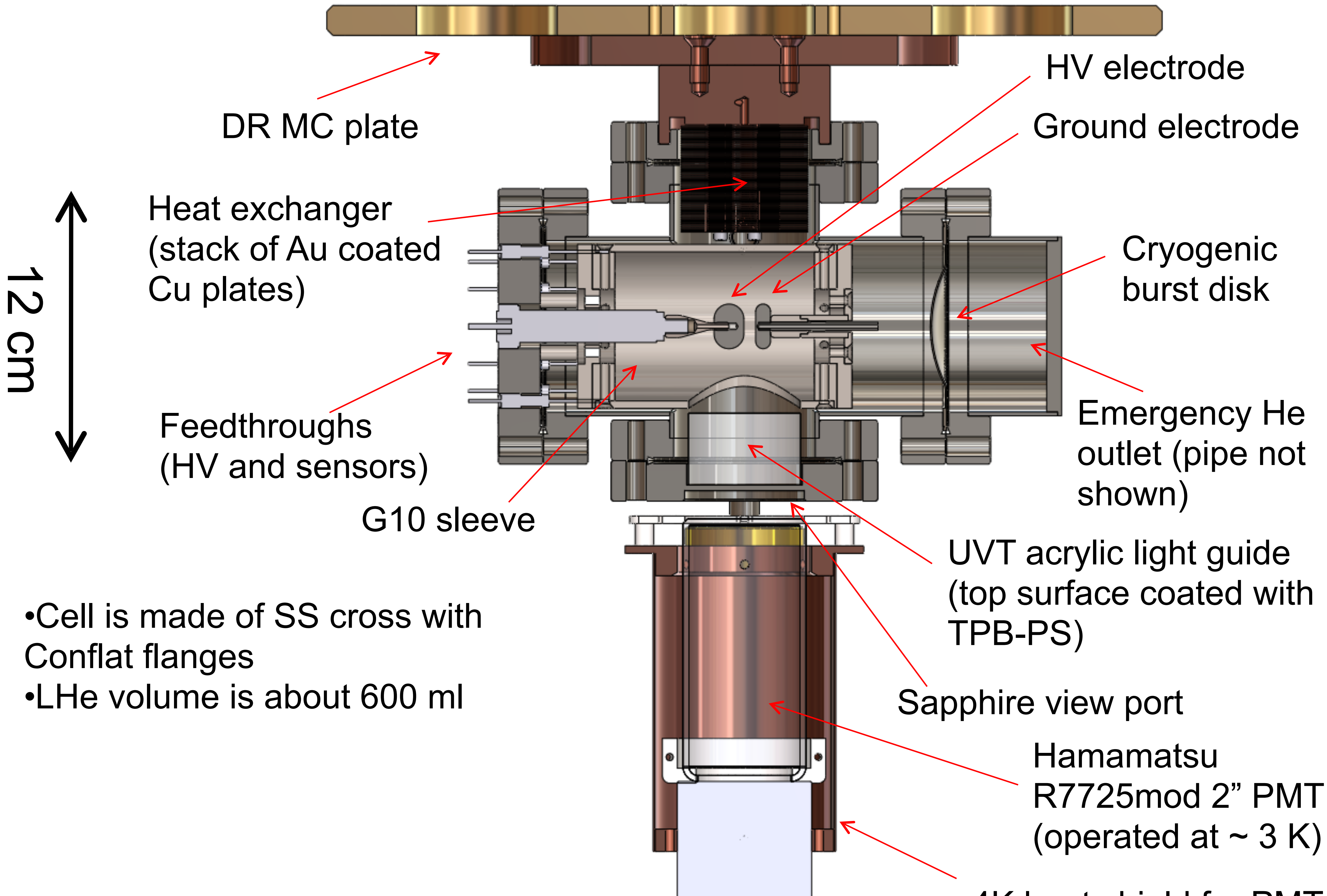
Studies done by our group

<table>
<tr><th>Year</th><th>Ionization source</th><th>Temperature (K)</th><th>Pressure (Torr)</th><th>Electric field (kV/cm)</th><th>Location</th><th>Apparatus</th></tr>
<tr><td>2009*</td><td>5.5 MeV α</td><td>0.2 — 1.1</td><td>SVP</td><td>0 — 45</td><td>Indiana U</td><td>LANL built chamber cooled by IU DR</td></tr>
<tr><td>2019</td><td>5.5 MeV α</td><td>0.44 — 3.12</td><td>600</td><td>0 — 40</td><td rowspan="3">LANL</td><td rowspan="3">MSHV** cooled by a ^{3}He fridge</td></tr>
<tr><td>2019</td><td>364 keV electron</td><td>0.44 — 3.12</td><td>600</td><td>0 — 40</td></tr>
<tr><td>2019 (To be performed)</td><td>n(^{3}He,^{3}H)p</td><td>0.44</td><td>600</td><td>0 — 40</td></tr>
</table>

* Results published in Ito et al., Phys. Rev. A 85, 042718 (2012)

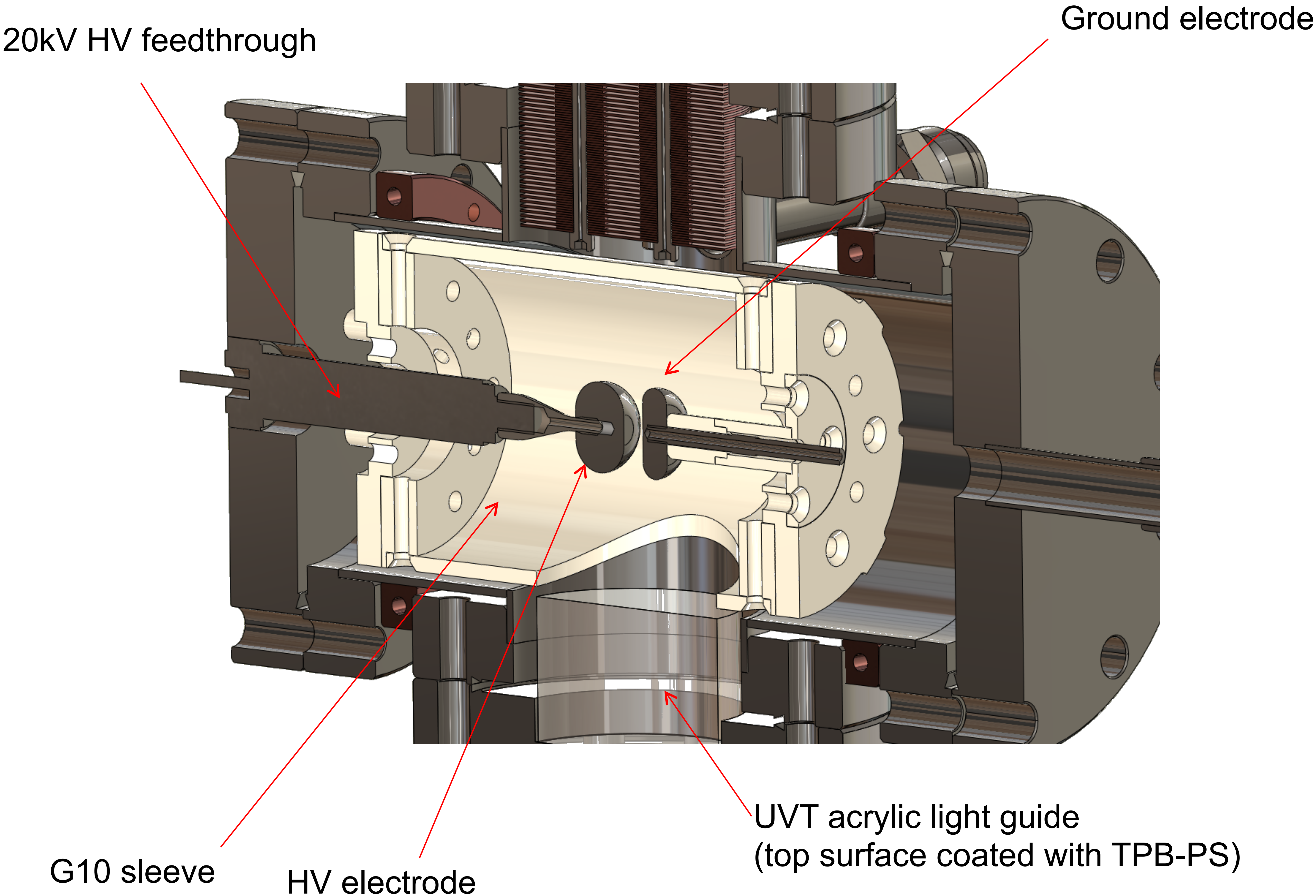
** The MSHV apparatus described in Ito et al. Rev. Sci. Instrum. 87, 045113 (2016)

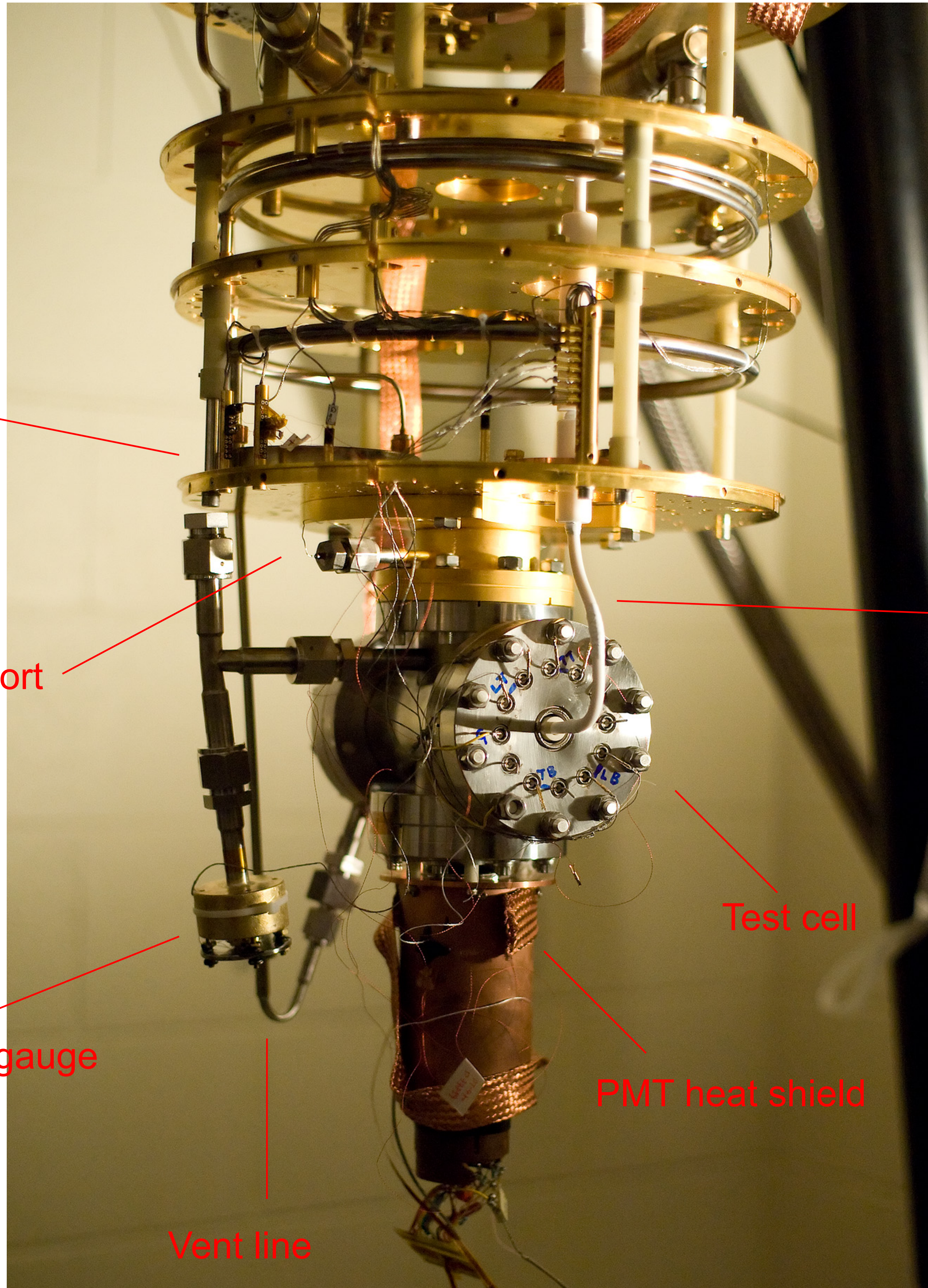
Apparatus use at IU



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

Apparatus used at IU




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

Results from the measurement at IU

Ito et al., PRA **85**, 042718 (2012).

Predicted 28% reduction in light yield at 75 kV/cm for neutron captures (Ito et al. (2012)) . We plan to measure this soon.

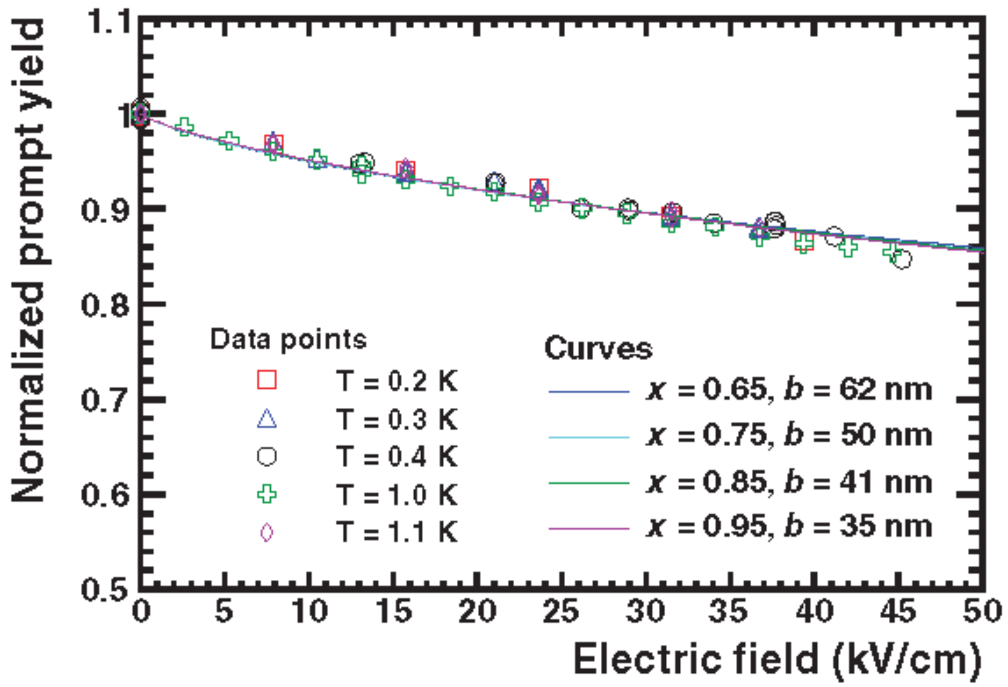


FIG. 15. (Color online) Kramers's theory fit to the electric-field–strength dependence of prompt scintillation yield measured by the current work. The prompt scintillation yield is normalized to the value at $E = 0$. The curves are calculated using Eq. (9) of Ref. [29].

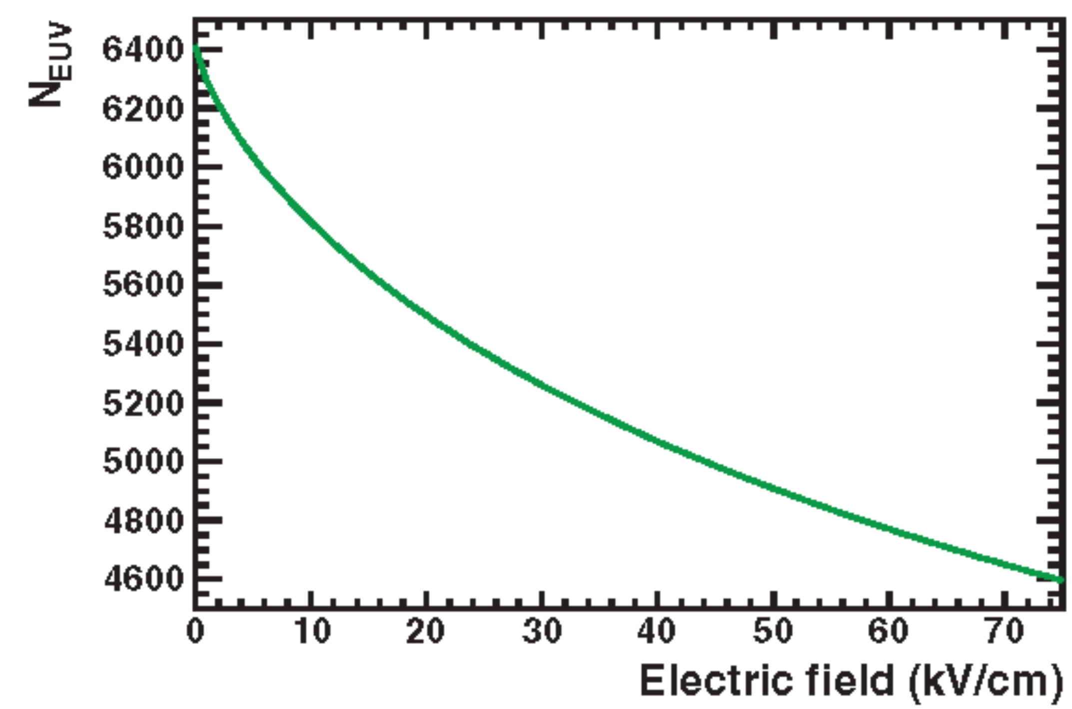
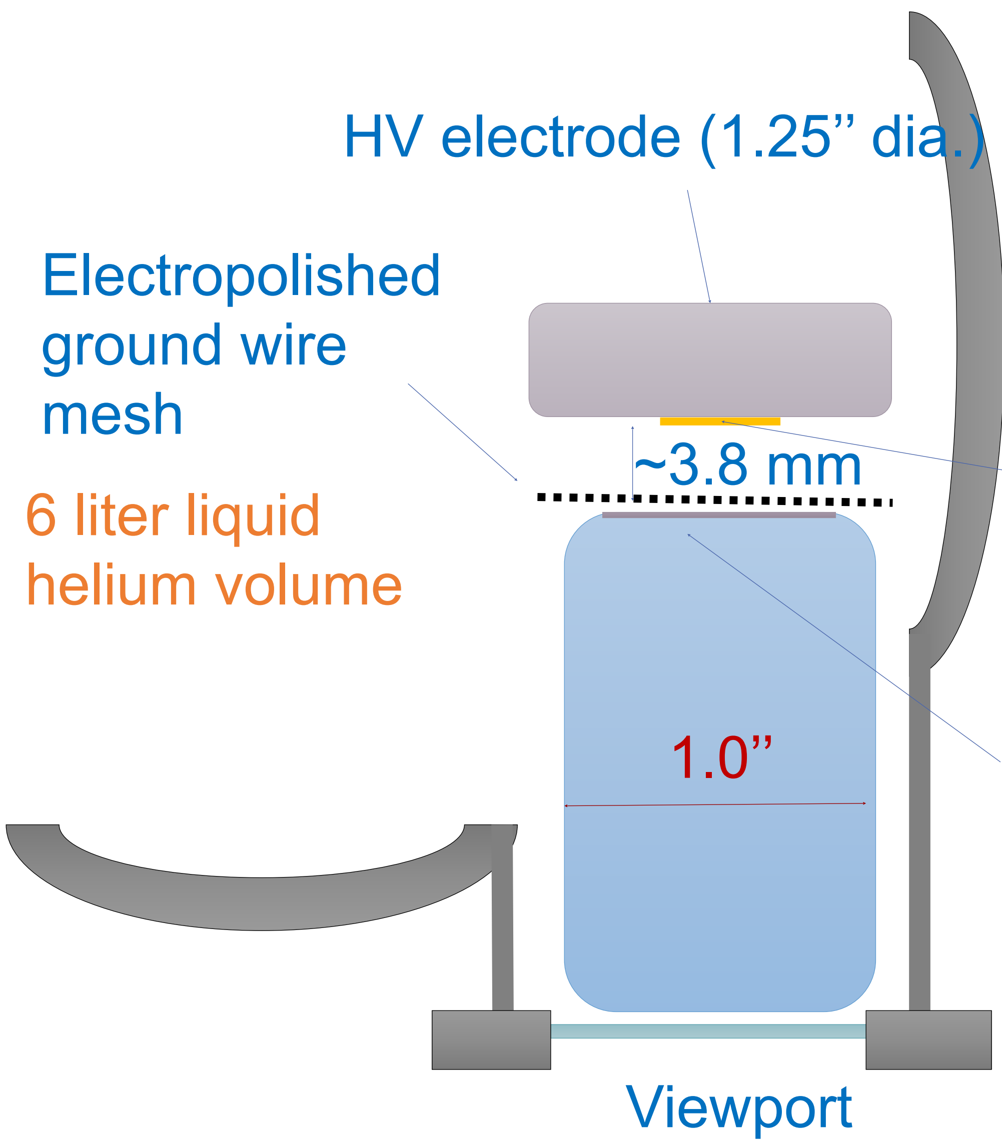
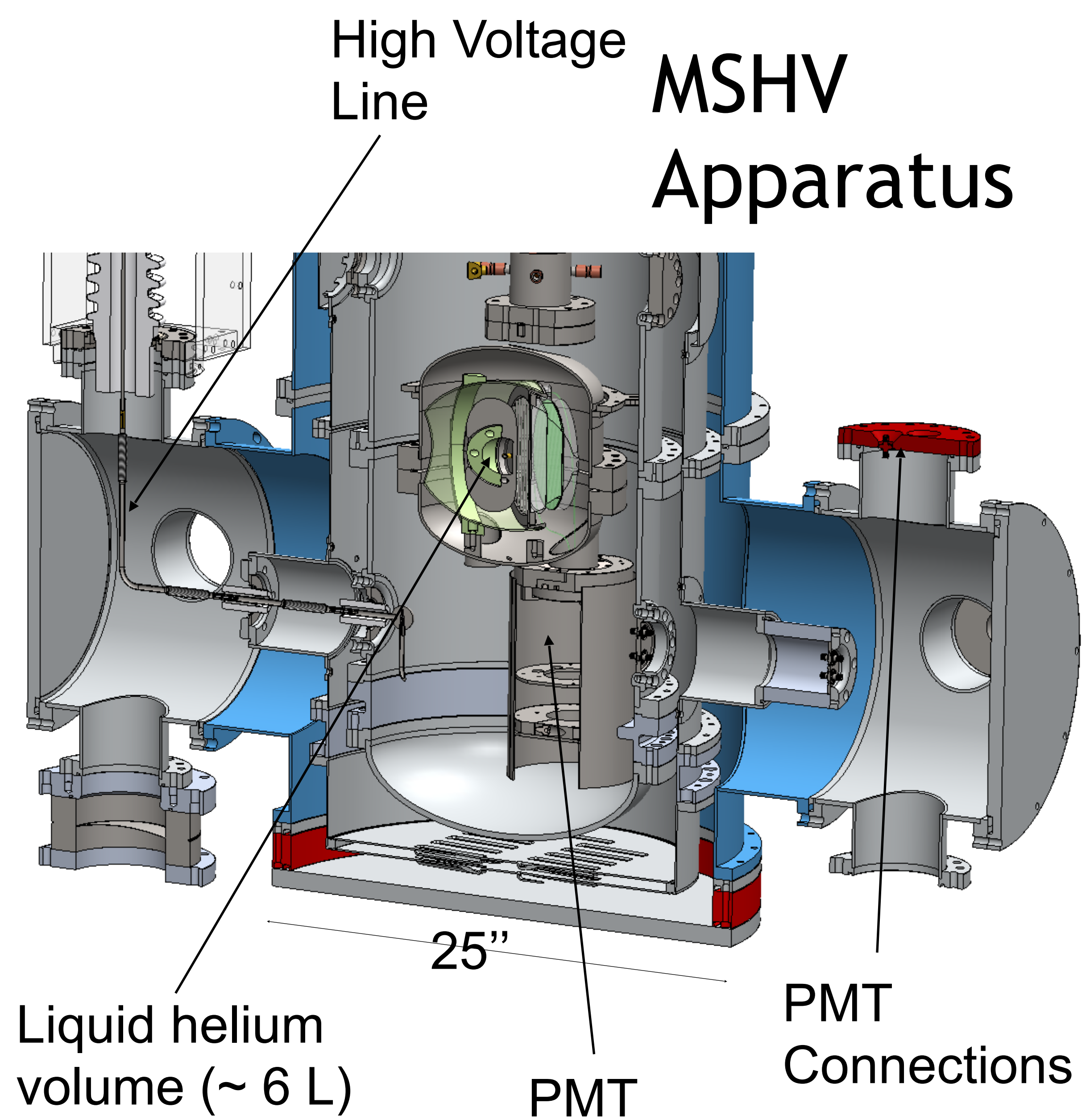


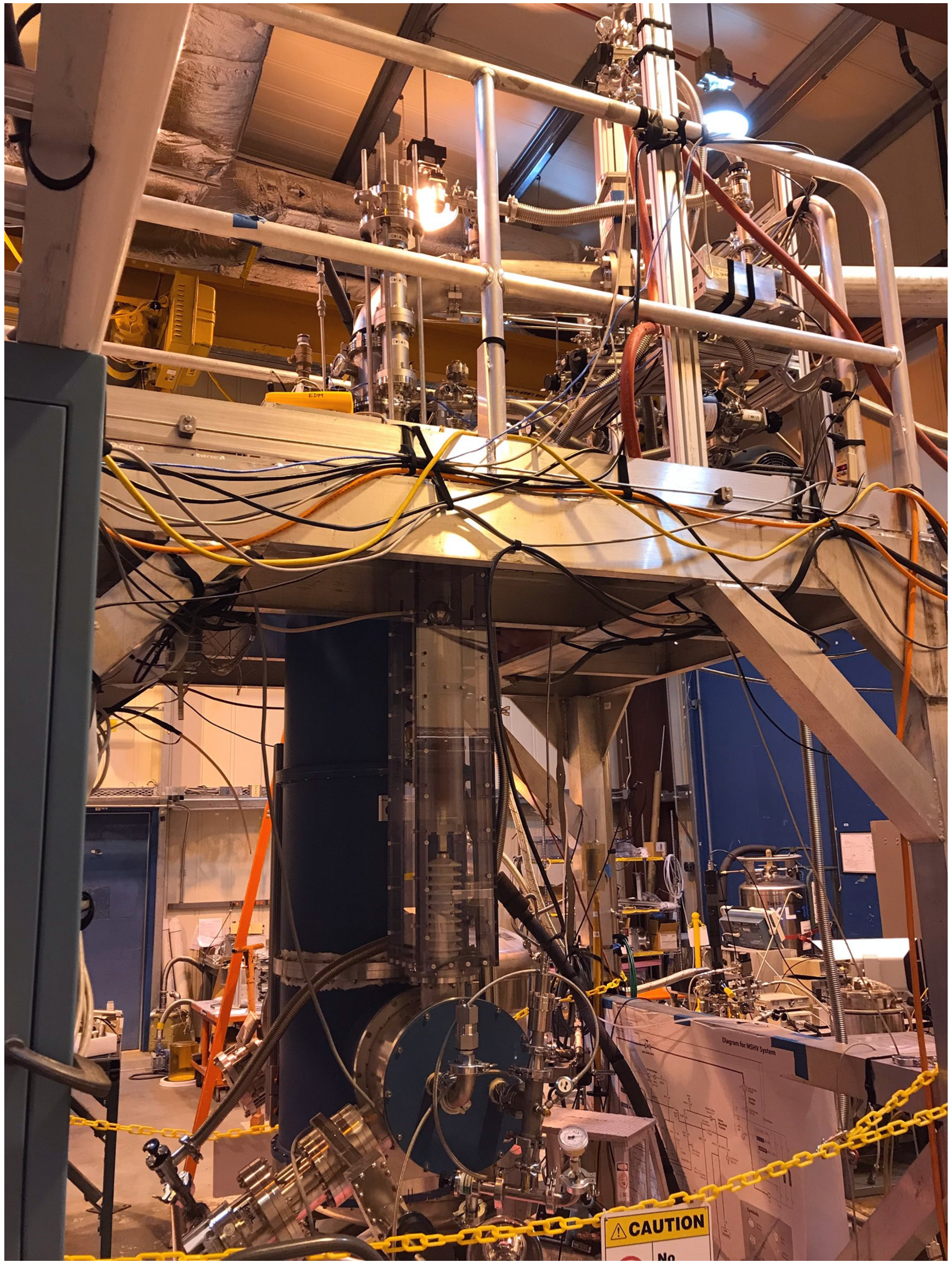
FIG. 21. (Color online) Predicted number of prompt EUV photons for LHe scintillation produced by products of $^3He(n,p)^3H$ reaction with $x = 0.65$ and $b = 62$ nm.

MSHV based apparatus to study the effect of an E field on LHe scintillation



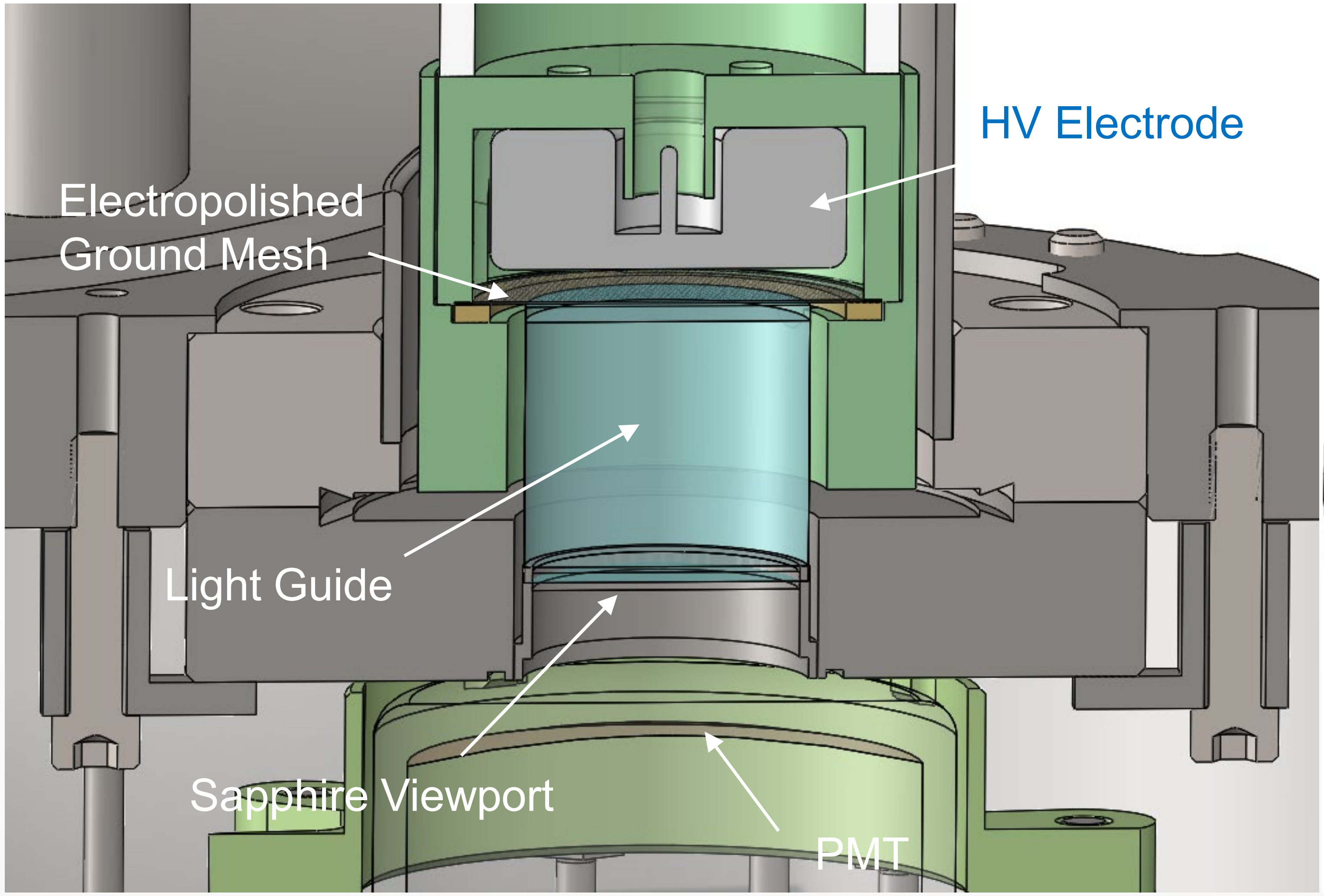


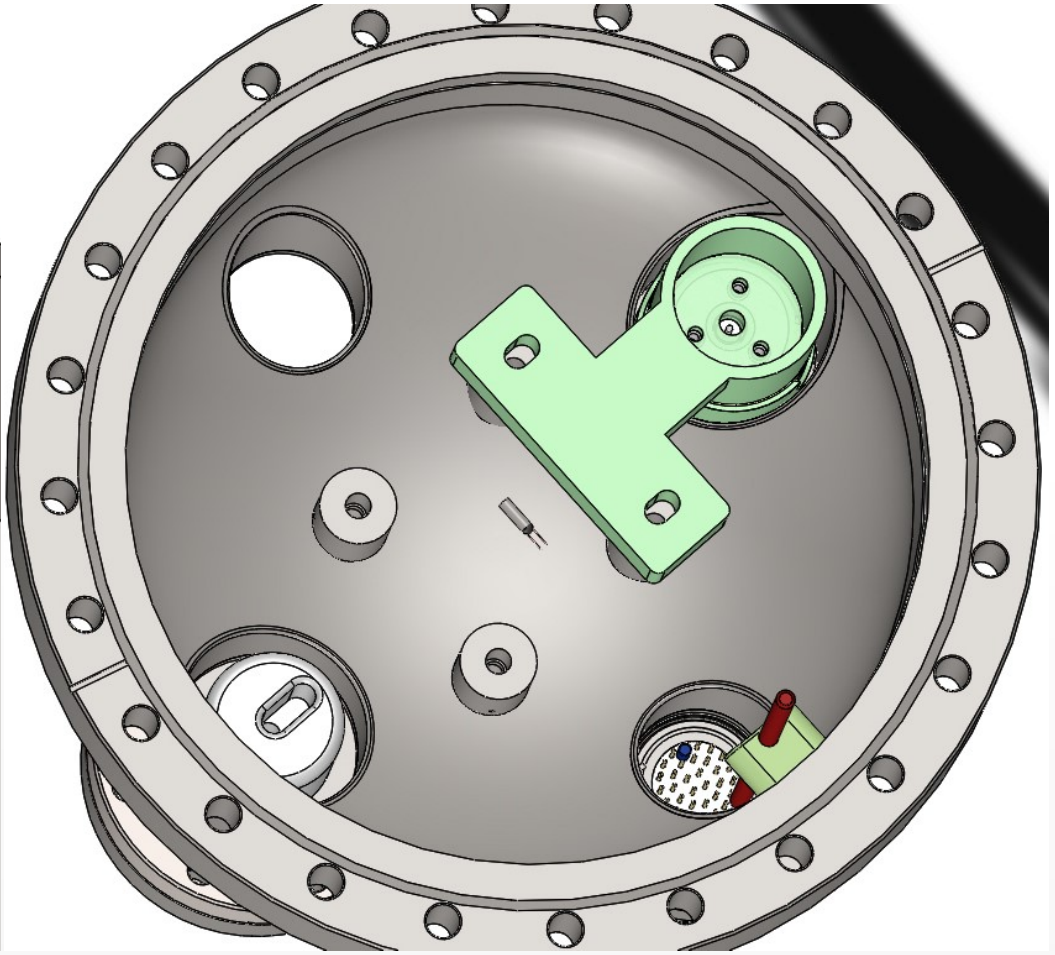
MSHV system



Model of the setup

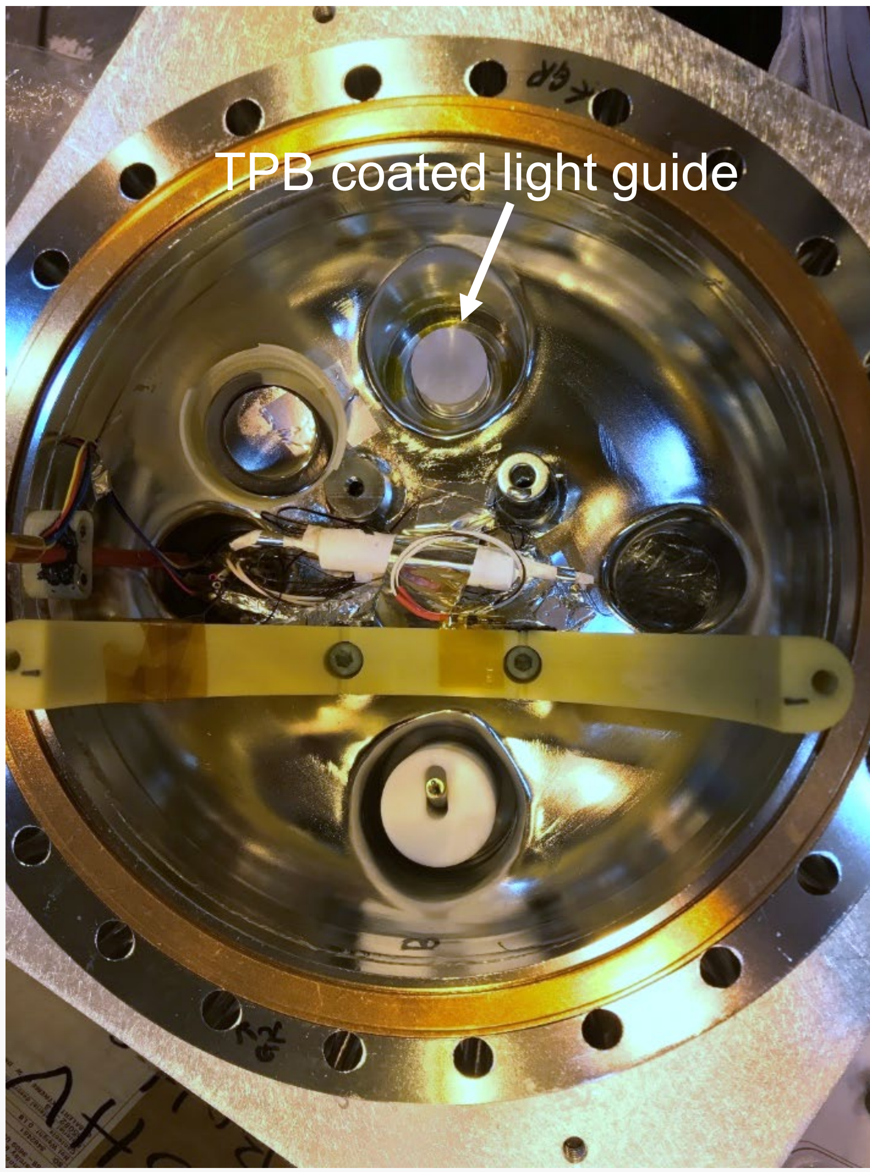
Assembly mounted inside the CV



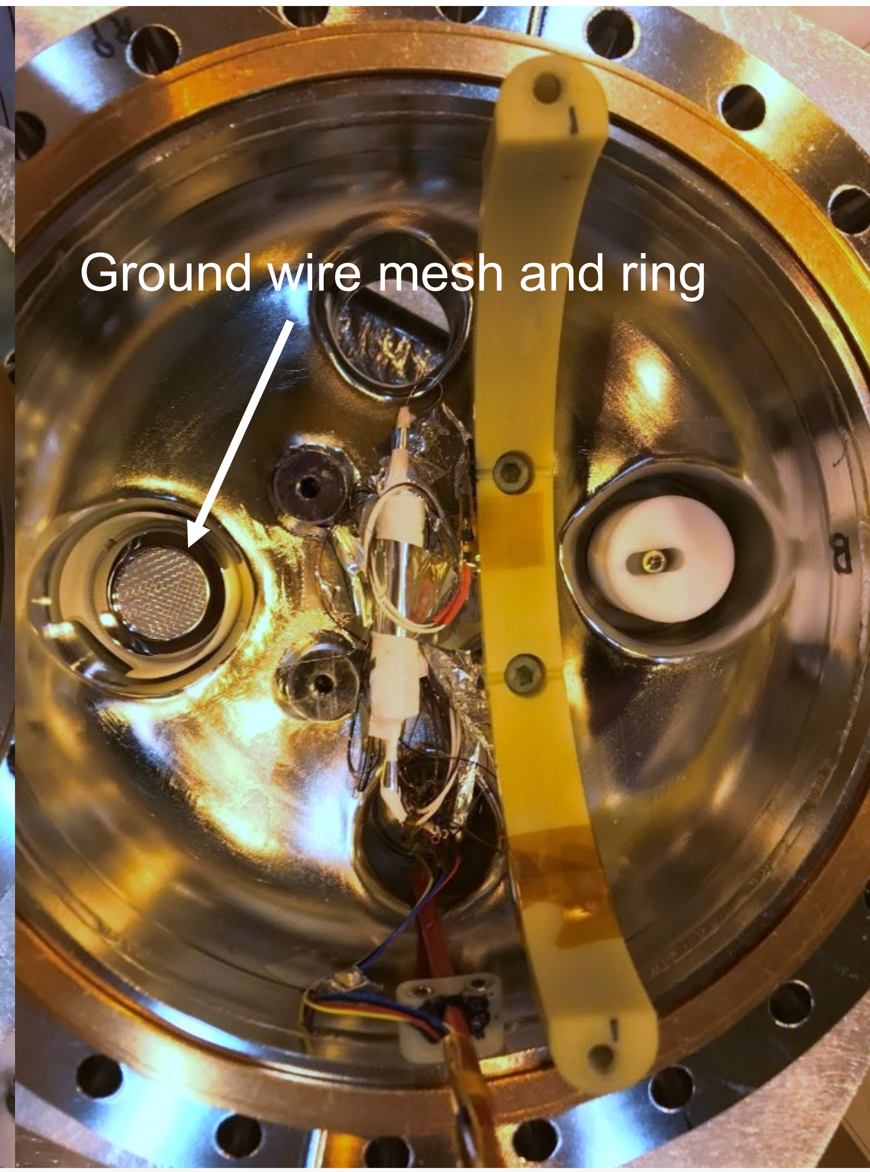


- COMSOL calculation for the geometry was made. Highest field is around the edge of the HV electrode (~60 kV/cm) & on the mesh wires (~80 kV/cm) vs 40 kV/cm in measurement gap. All measurements were made at ~ 600 torr and no breakdowns were observed.

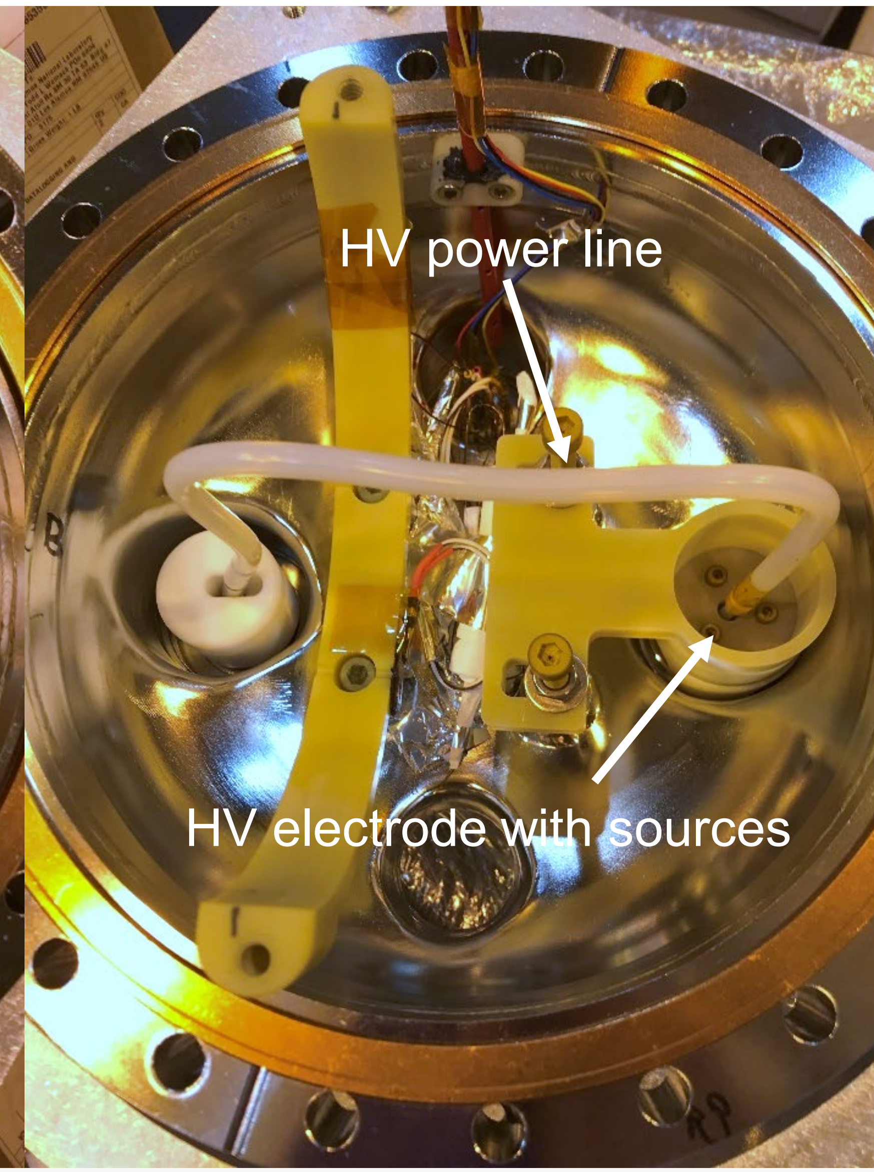
Component installation into Central Volume



TPB coated light guide installed

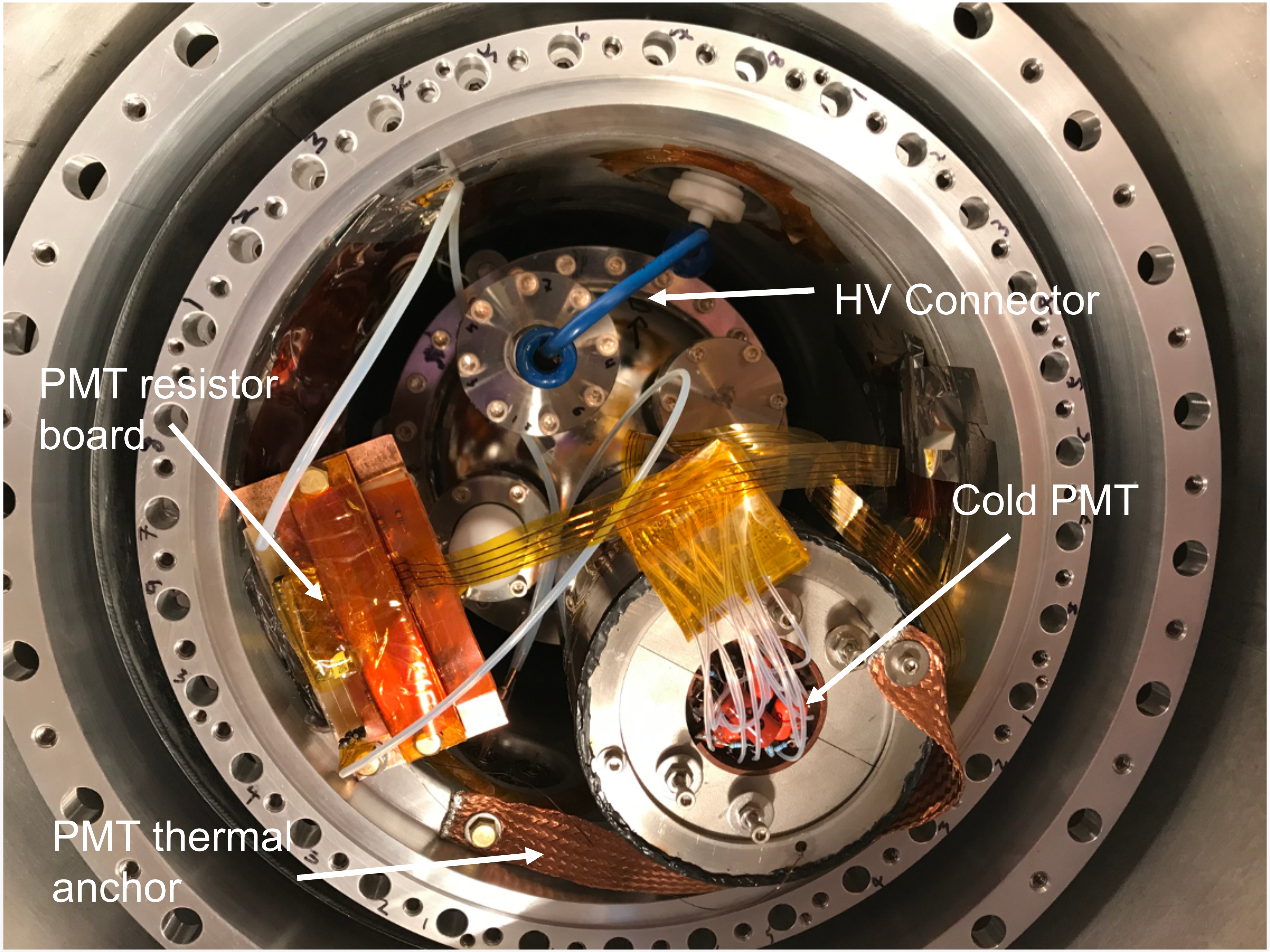


Ground mesh and ring installed

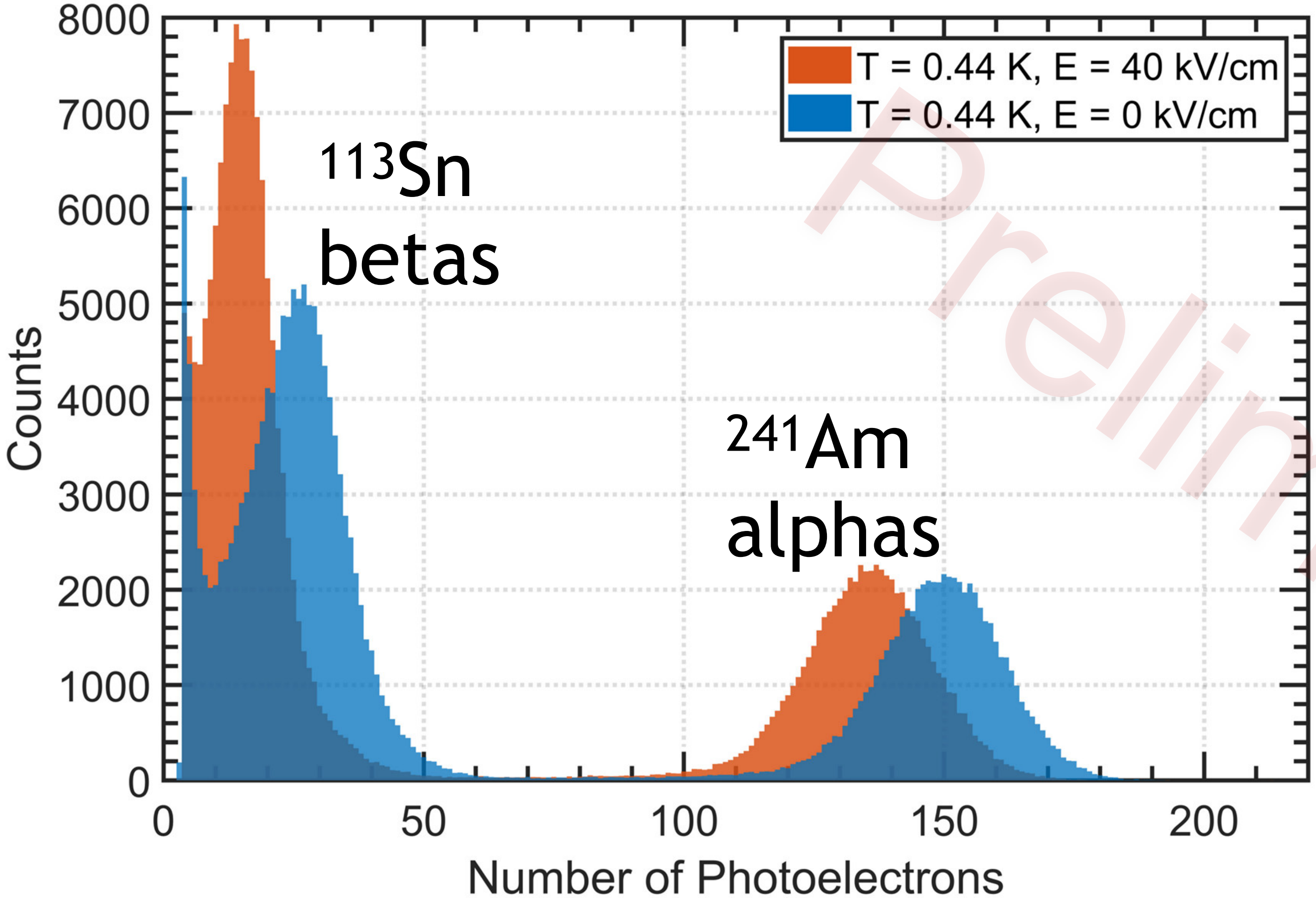


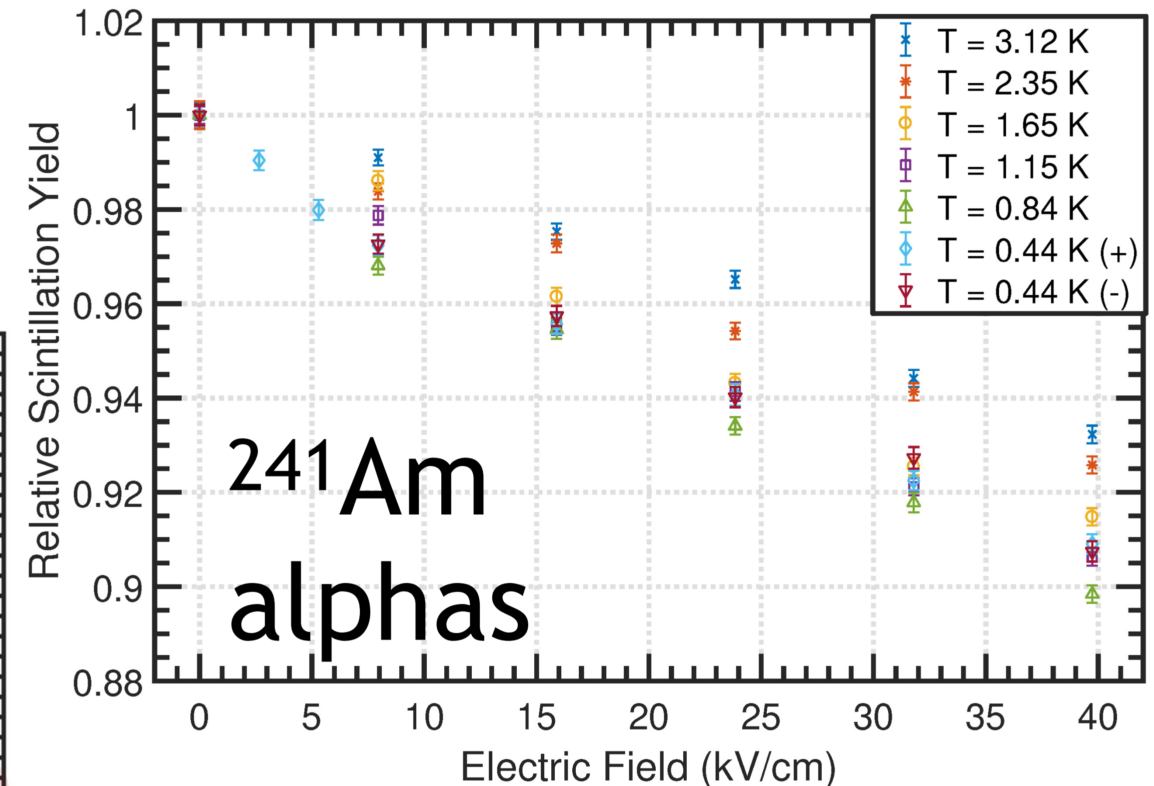
All components installed

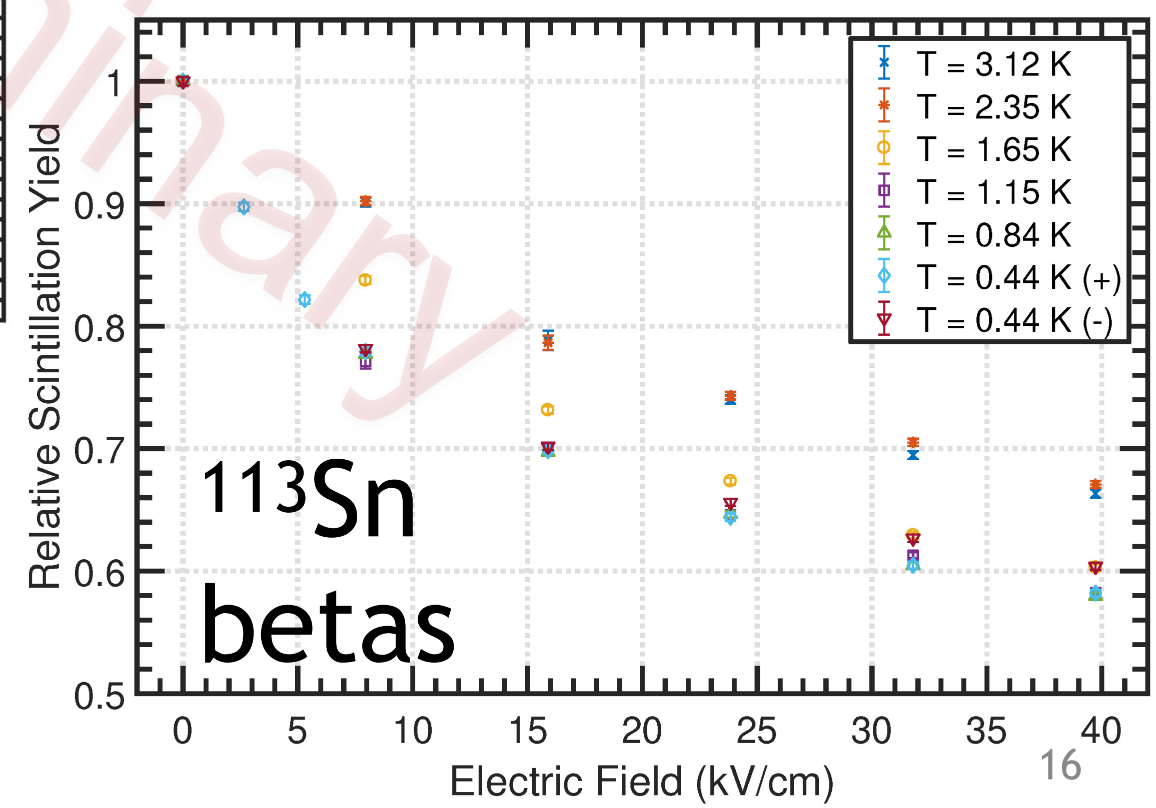
View inside the IVC



Selected results







Normalized scintillation yield vs electric field:

$$y(E,T) = \frac{N(E,\ T)}{N(E=0,\ T)}$$

A model of the electron scintillation yield

Simple model of the scintillation yield vs electric field for electrons:

a: # of electrons and ions that recombine as singlets

b: # of electrons and ions that recombine as triplets

x: ratio of number of singlet excitations to the total number of ionizations

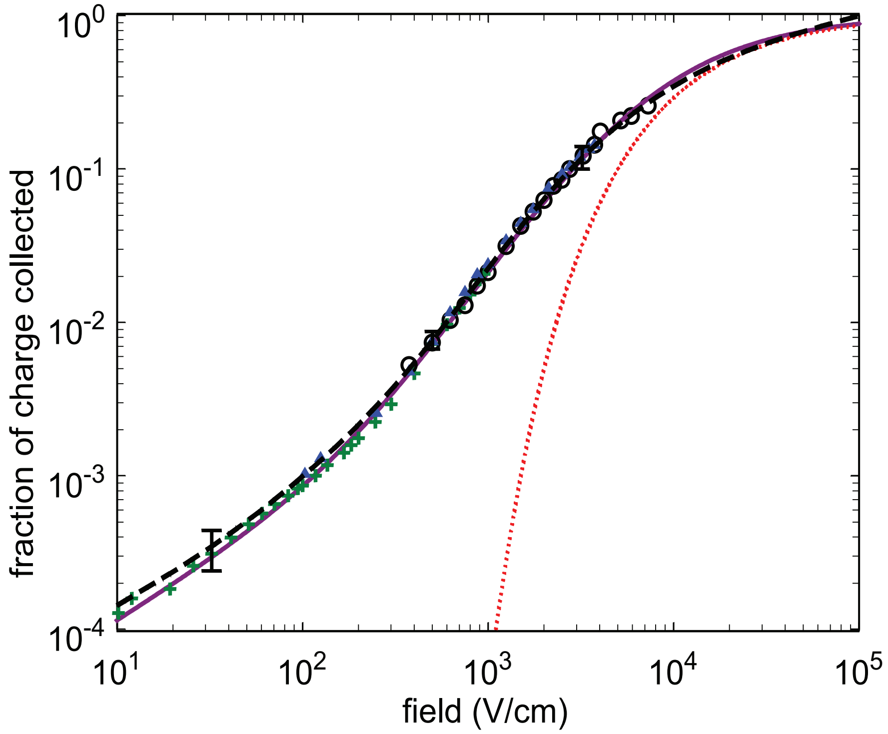
The normalized scintillation yield, $y(E)$, as a function of electric field, E, is given by:

$$y(E) = 1 - \frac{i(E)}{1 + x(1 + b/a)}$$

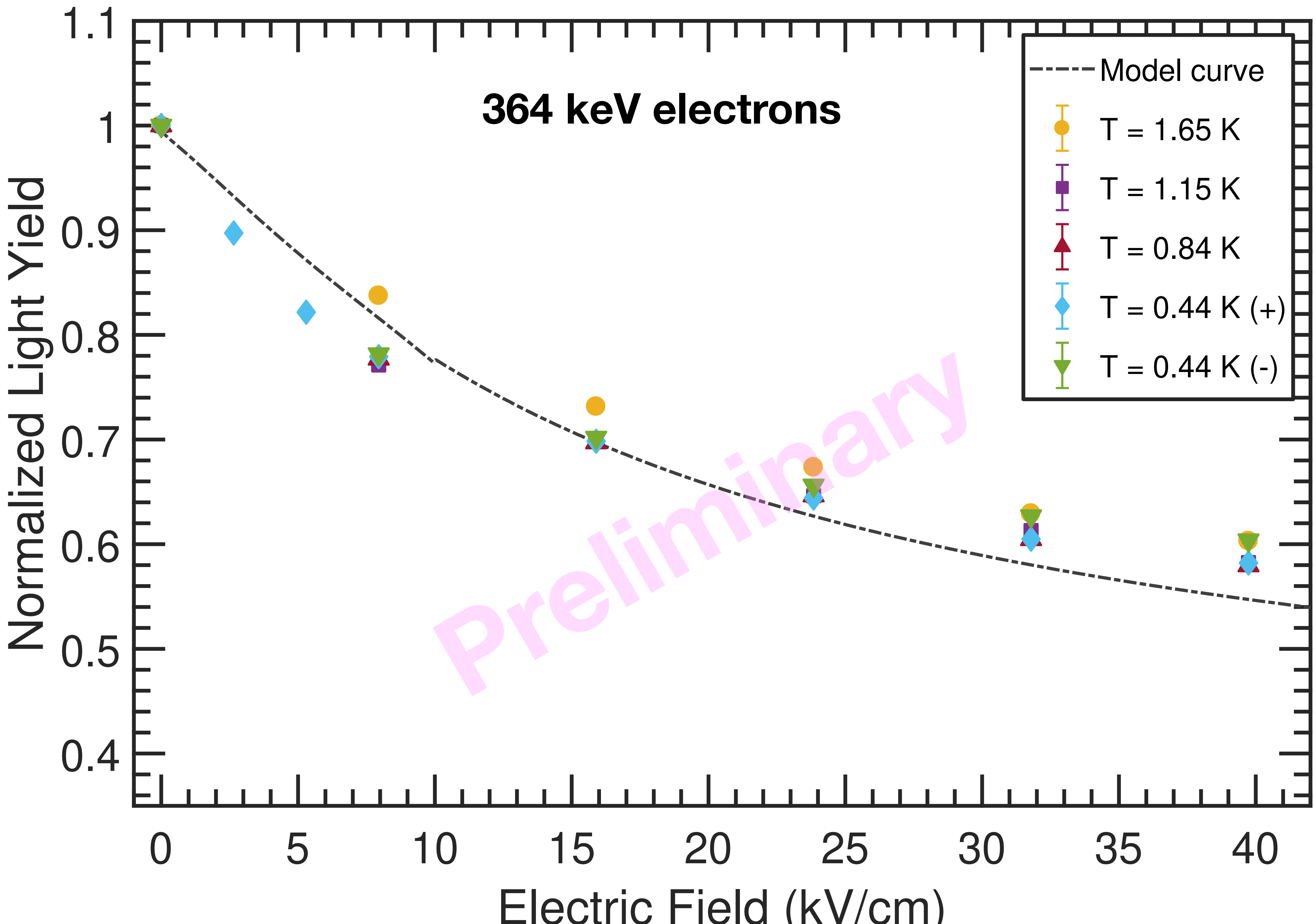
"Current", which is the fraction of charges that escape recombination as a function of applied electric field.

$$y(E) = 1 - 0.6 \times i(E)$$

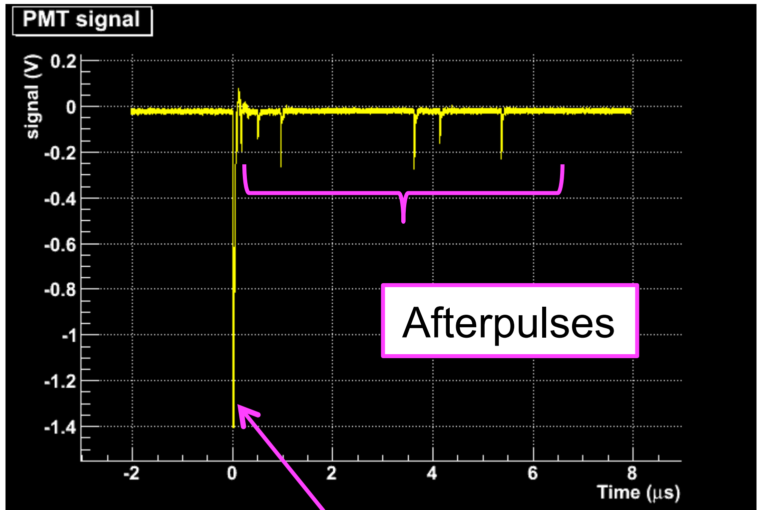
Current measurements taken from:
Seidel et al., PRC **89**, 025808 (2014).

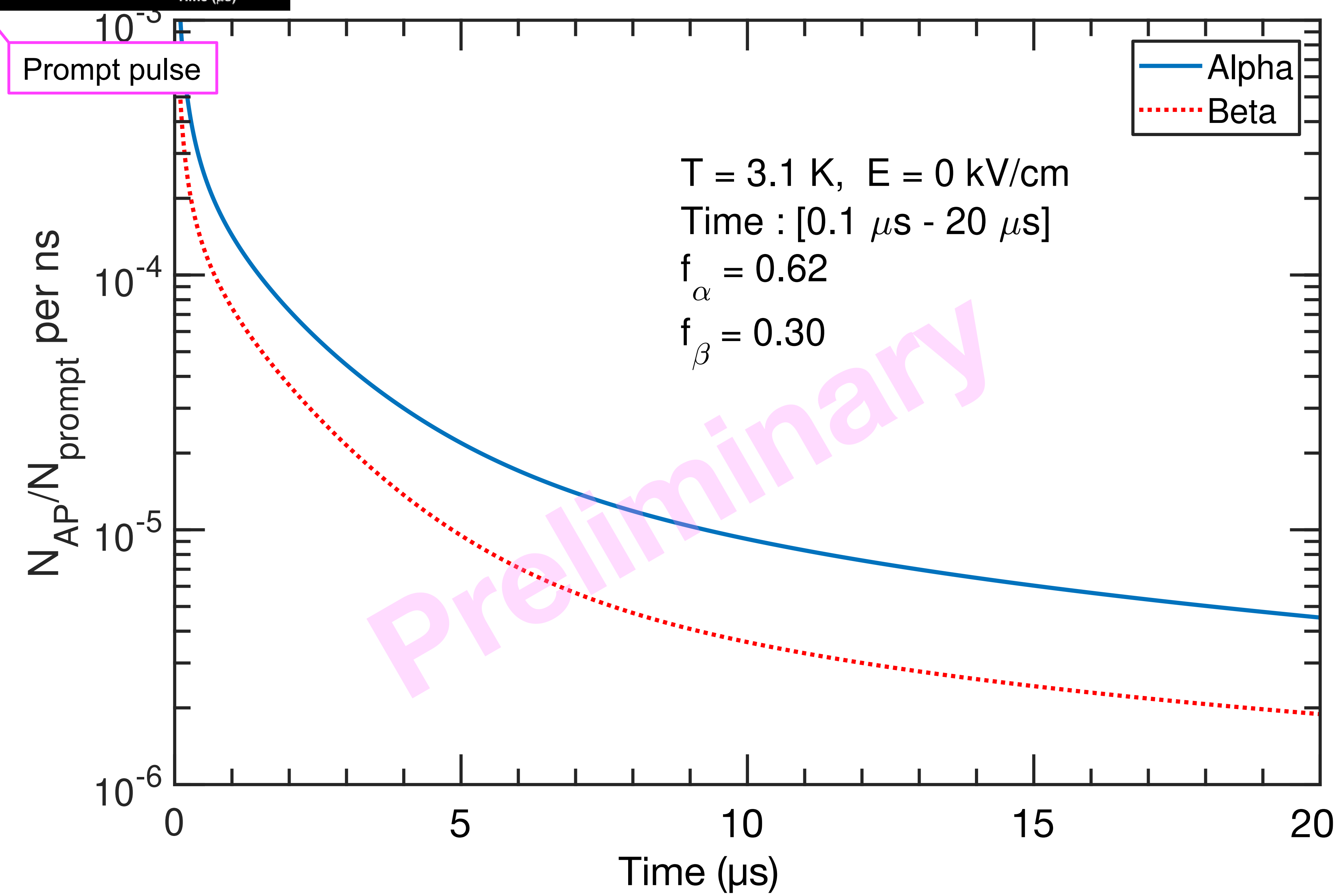


Data compared with the model

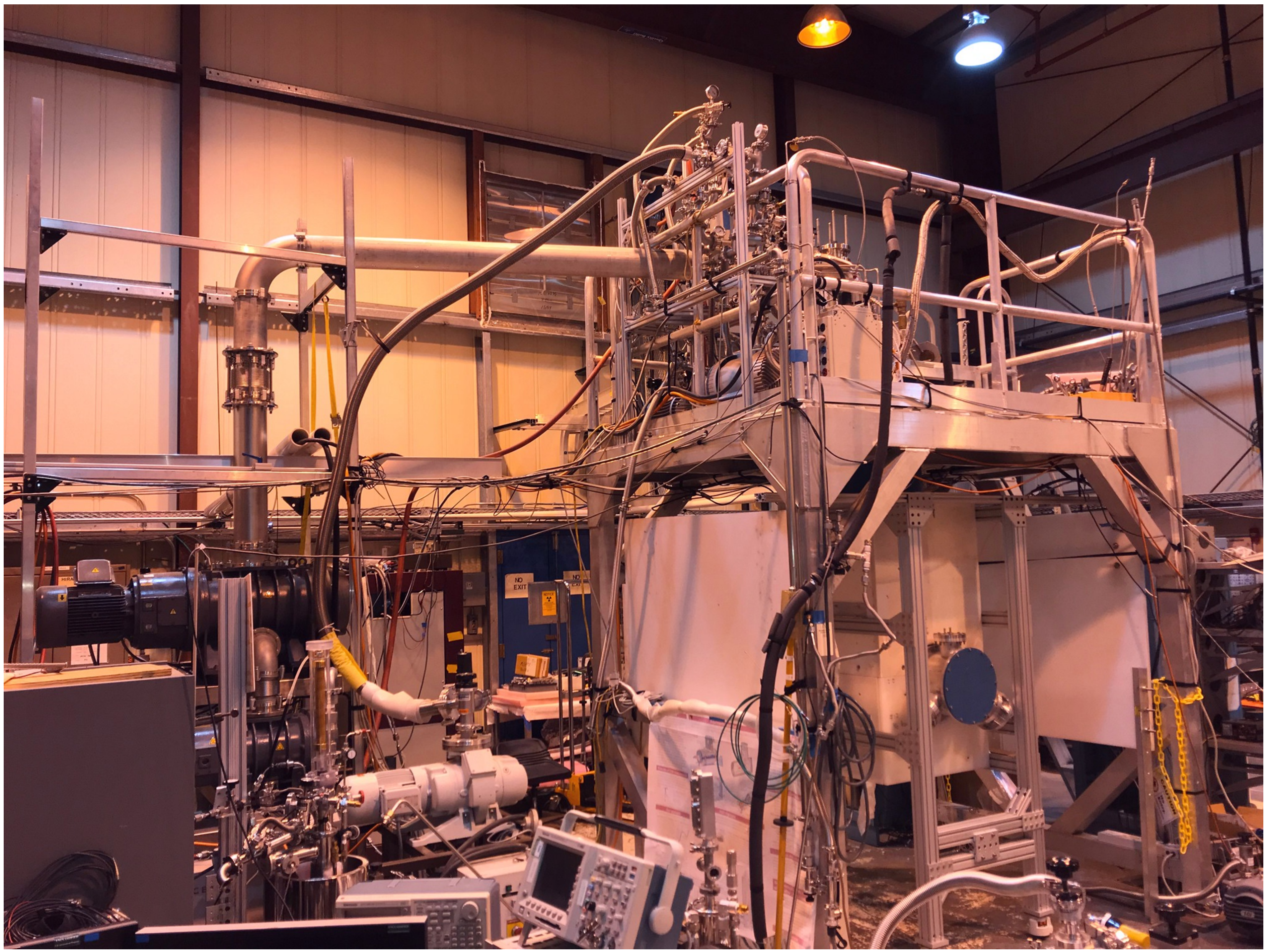


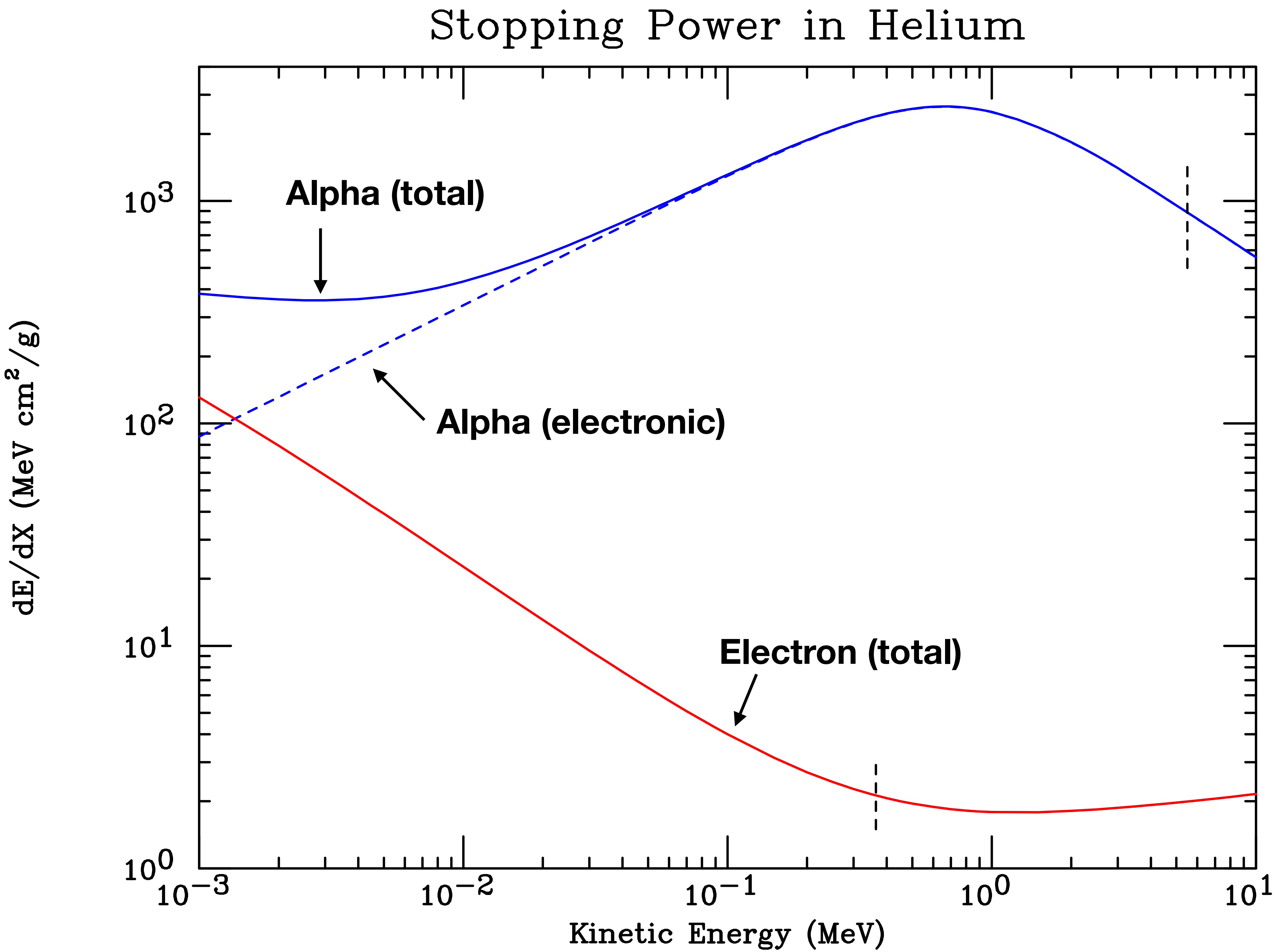
Afterpulses





MSHV with polyethylene neutron moderator for measurement with n(^{3}He, ^{3}H)p





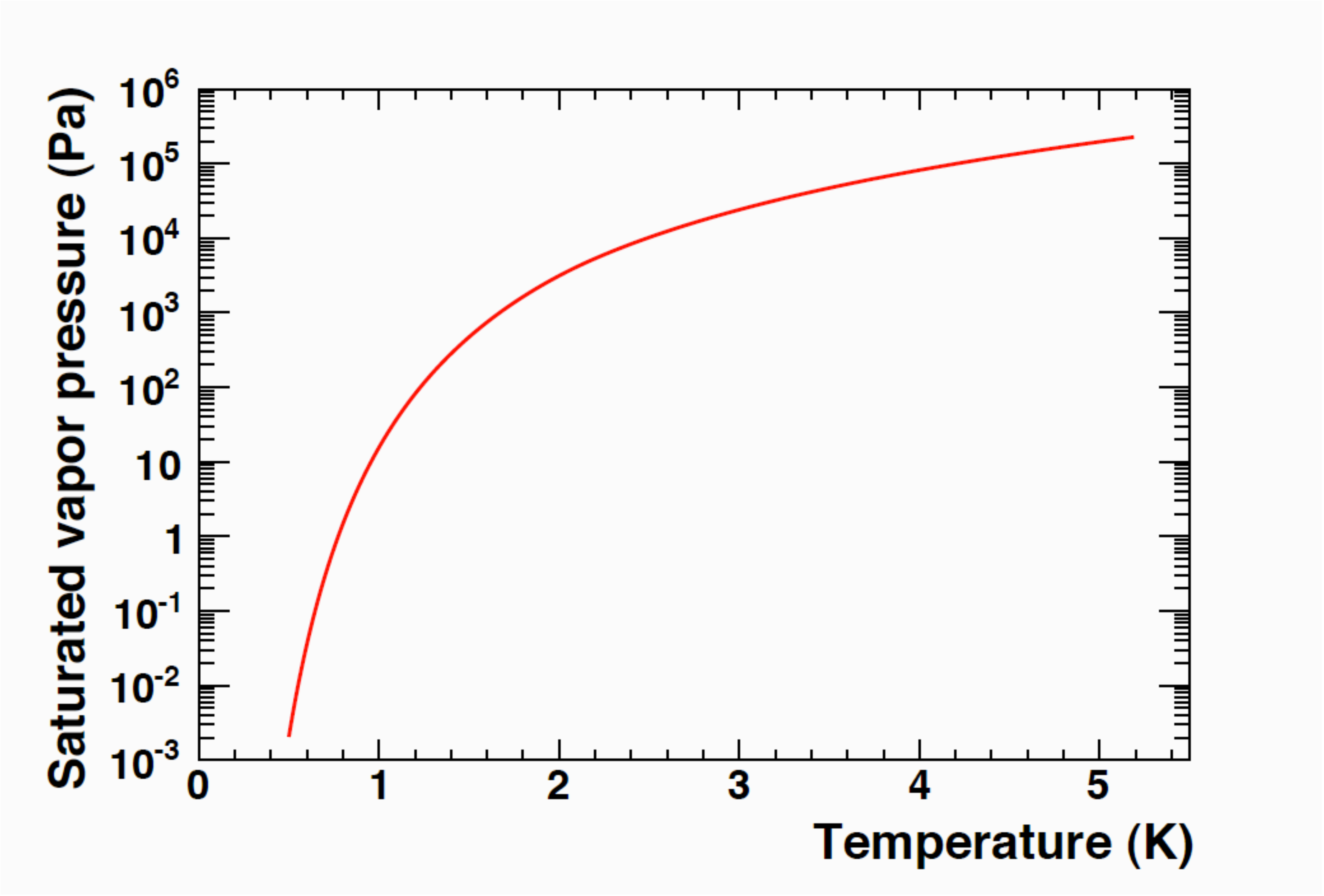
Stopping Power in Helium
Alpha (total)
Alpha (electronic)
Electron (total)
dE/dX (MeV cm^2/g)
Kinetic Energy (MeV)
10^0
10^1
10^2
10^3
10^{-3}
10^{-2}
10^{-1}
10^0
10^1

Application of a large electric field

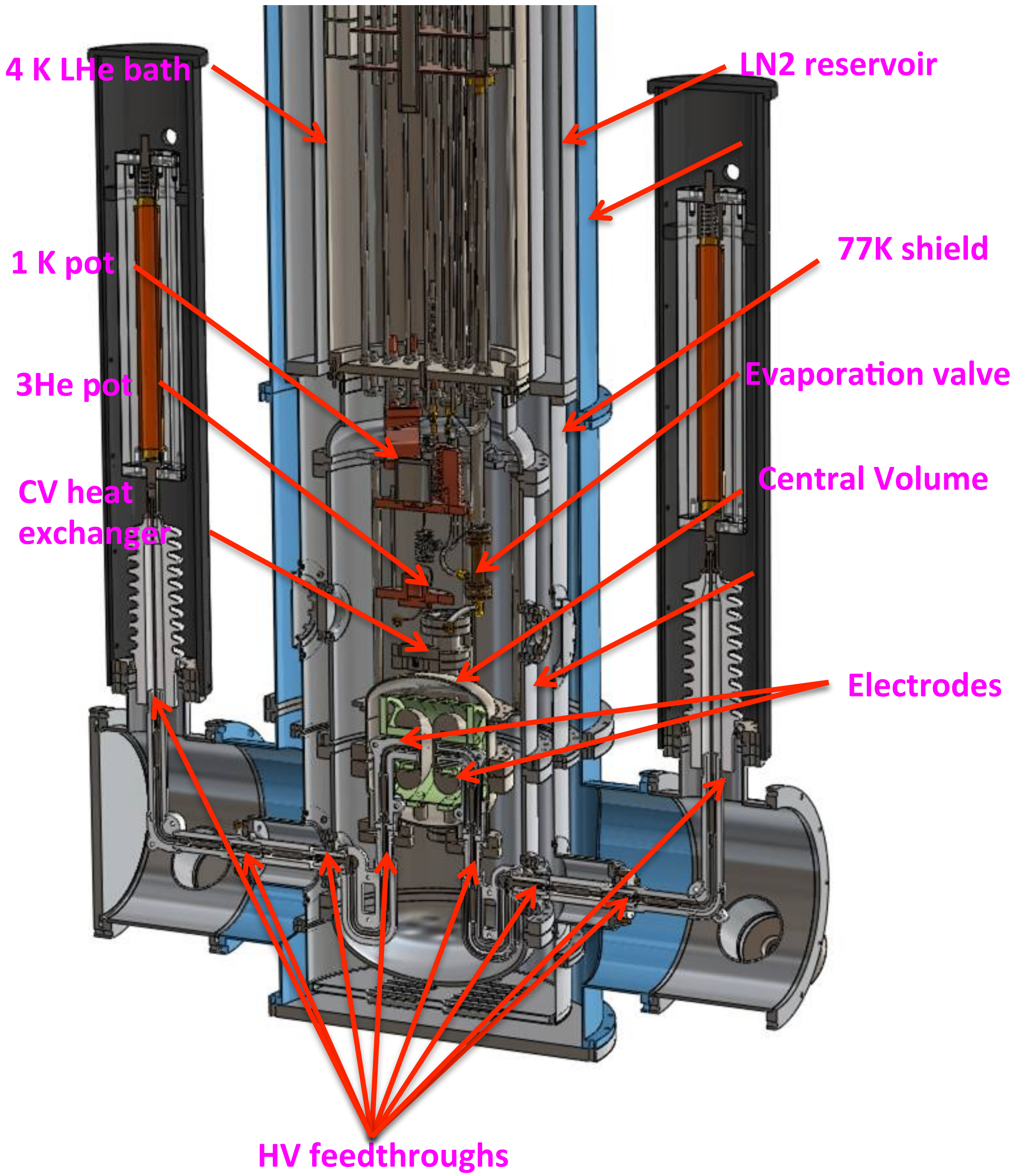
Electrical breakdown in LHe

- Data exist 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 detailed theoretical study of electron multiplication process in LHe indicates a very high intrinsic breakdown field (MV/cm), well above the observed breakdown fields (~100 kV/cm or below) (Belevtsev, NIMA 327, 18 (1993)).
- 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 include:
  - Electrode material and surface quality
  - Electrode area and/or gap size
  - Temperature and pressure

He temperature vs SVP

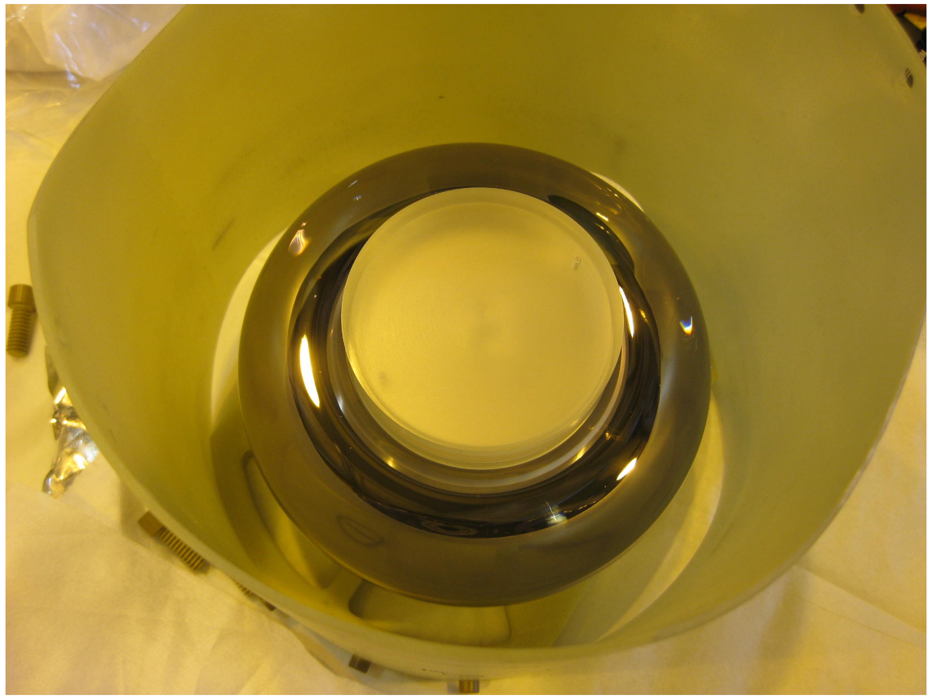


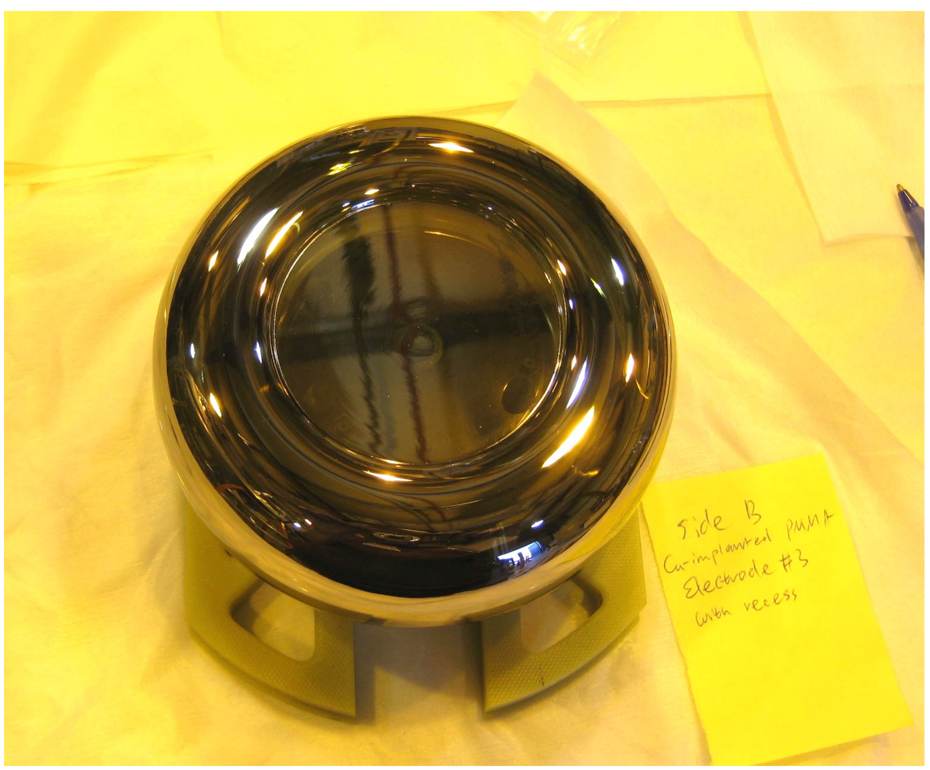
HV E-field R&D using Medium Scale HV Test System at LANL



Ito et al., Rev. Sci. Instrum. 87, 045113 (2016).

HV E-field R&D using Medium Scale HV Test System at LANL



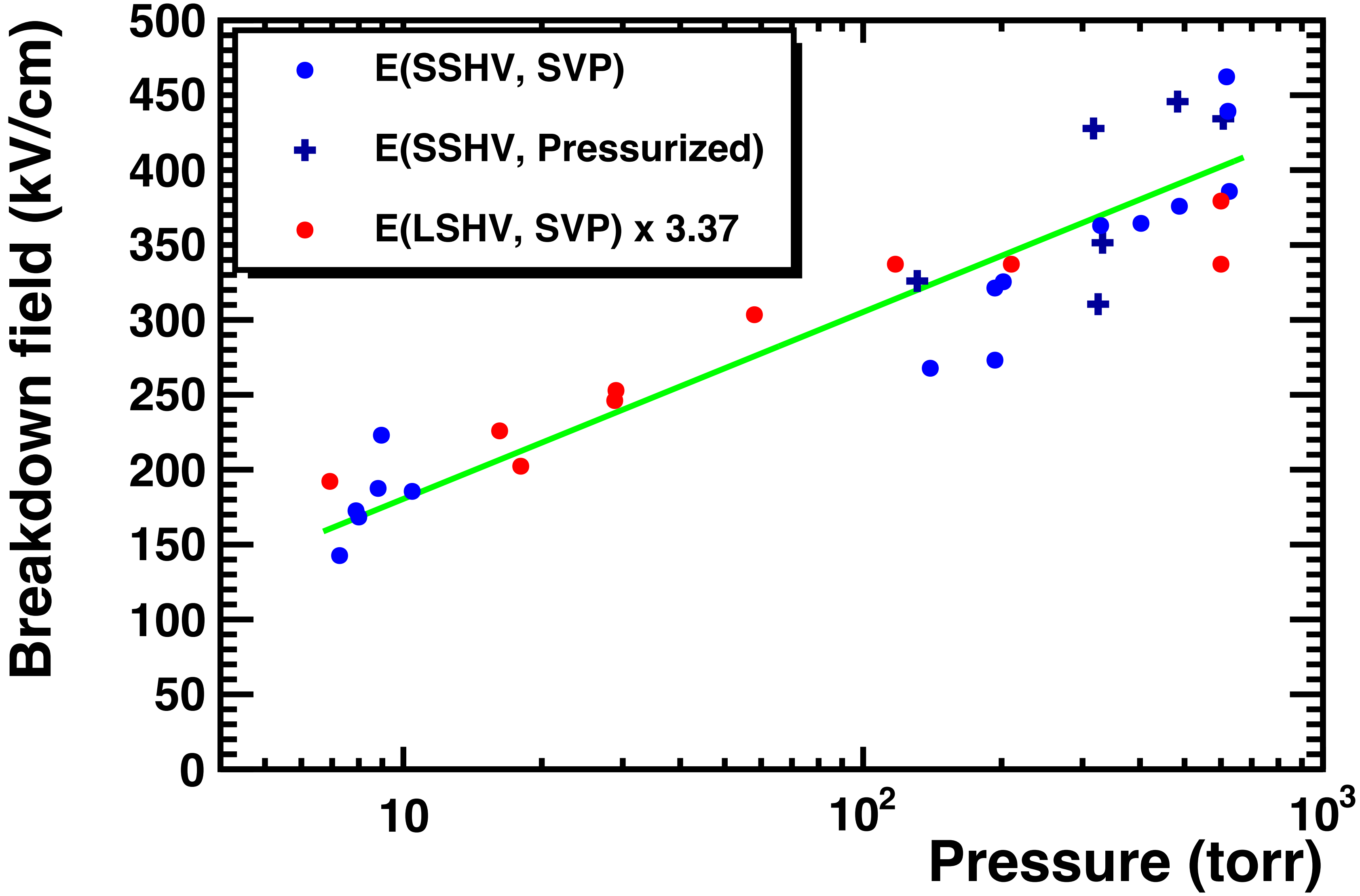


Cu ion implanted PMMA electrodes with a mockup cell.

- MSHV main 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
  - Lowest temperature ~ 0.4 K
  - Pressure: variable between SVP and 1 atm
- Main findings:
  - Stable electric field ≳ 75 kV/cm at 0.4 K for a wide range of pressures with and without PMMA cell inserted between electrodes.
  - Leakage current ≲ 1 pA at 40 kV voltage difference with and without PMMA cell inserted between electrodes.

Ito et al., Rev. Sci. Instrum. 87, 045113 (2016).

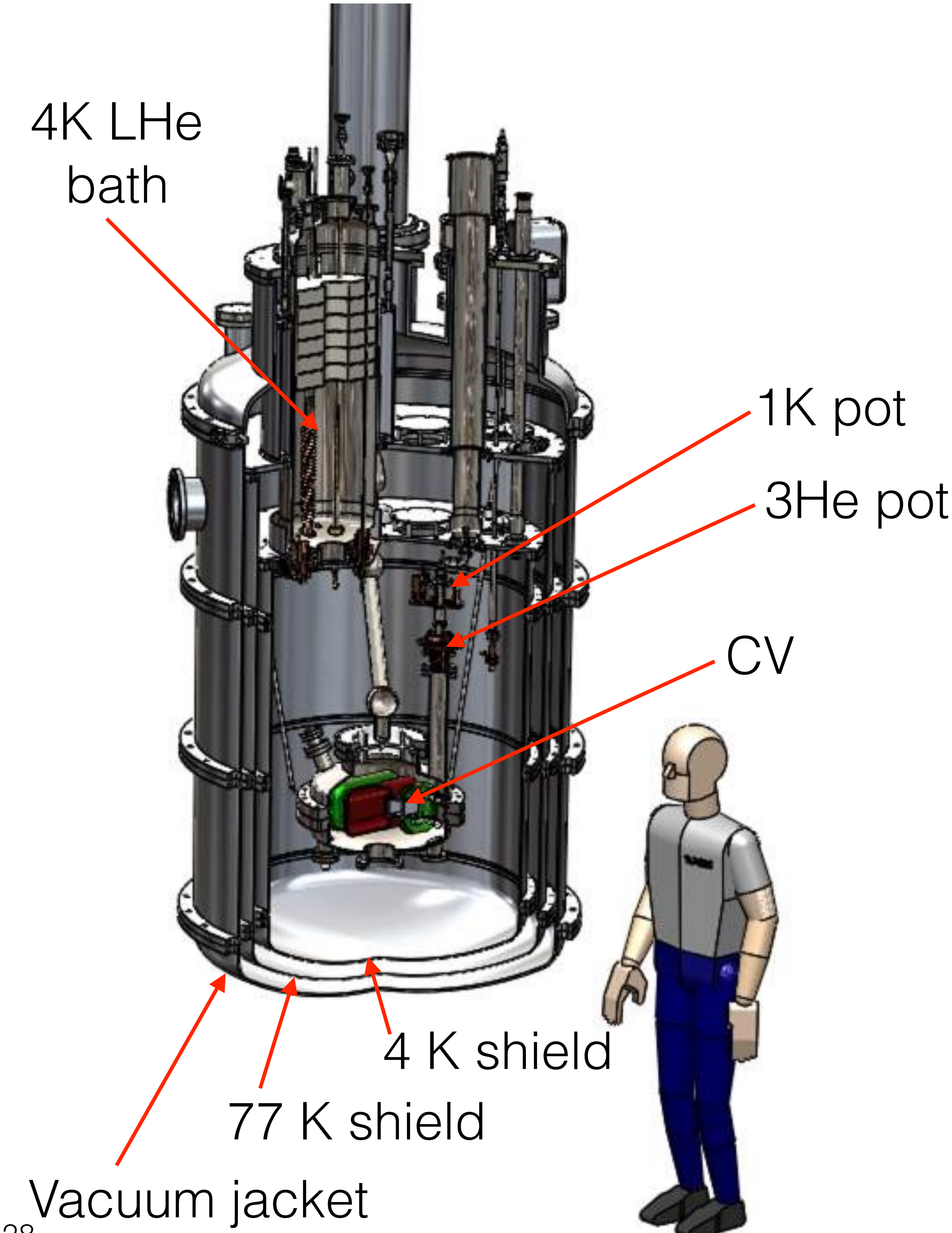
High E field R&D with the Small Scale HV apparatus



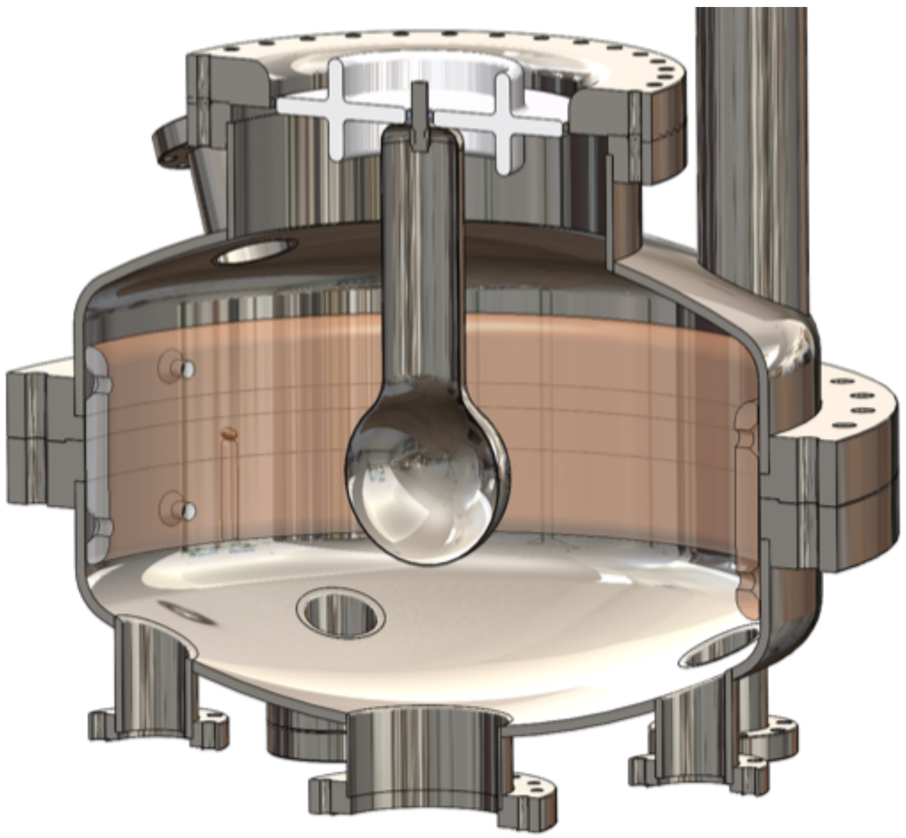
The electrode gap ~ 0.5 mm.
The stressed area ~ 0.3 cm².

Half scale HV test apparatus at LANL

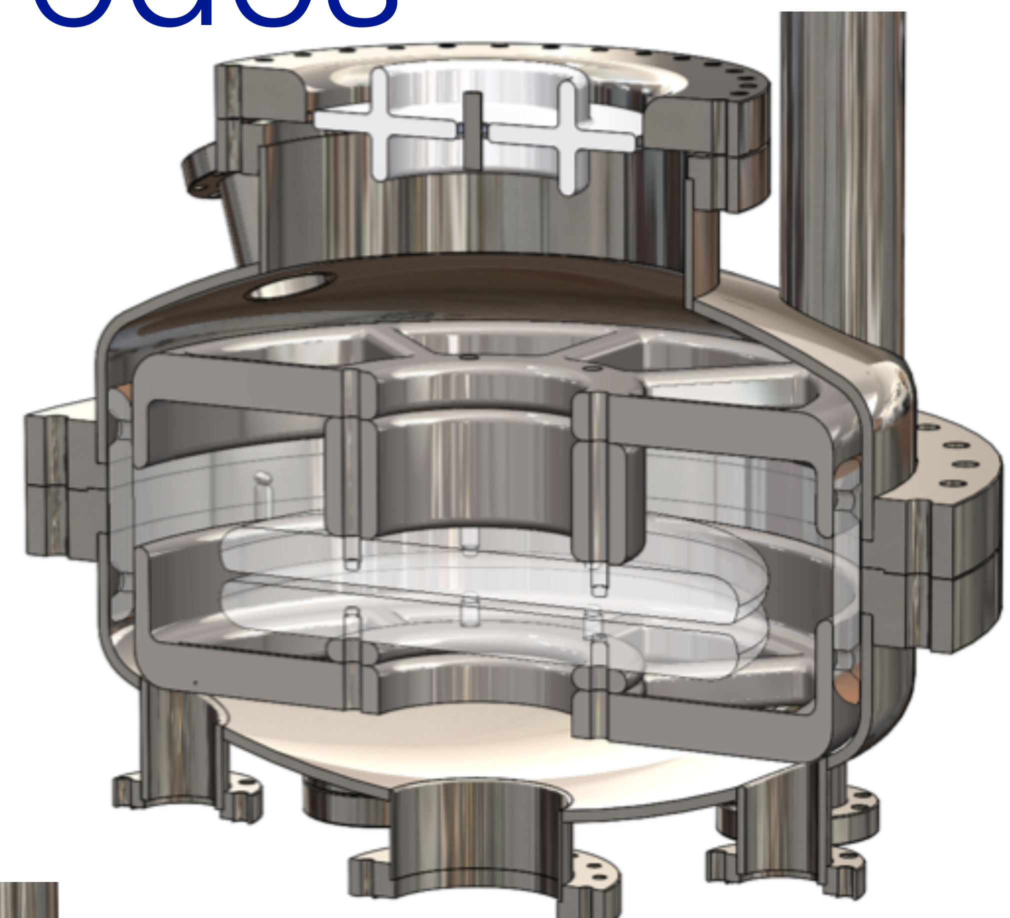
A half-scale electrode system is immersed in 40 liter LHe volume cooled to 0.4 K. HV performance test will be performed with 200 kV direct HV feed. The cryostat is currently being commissioned.



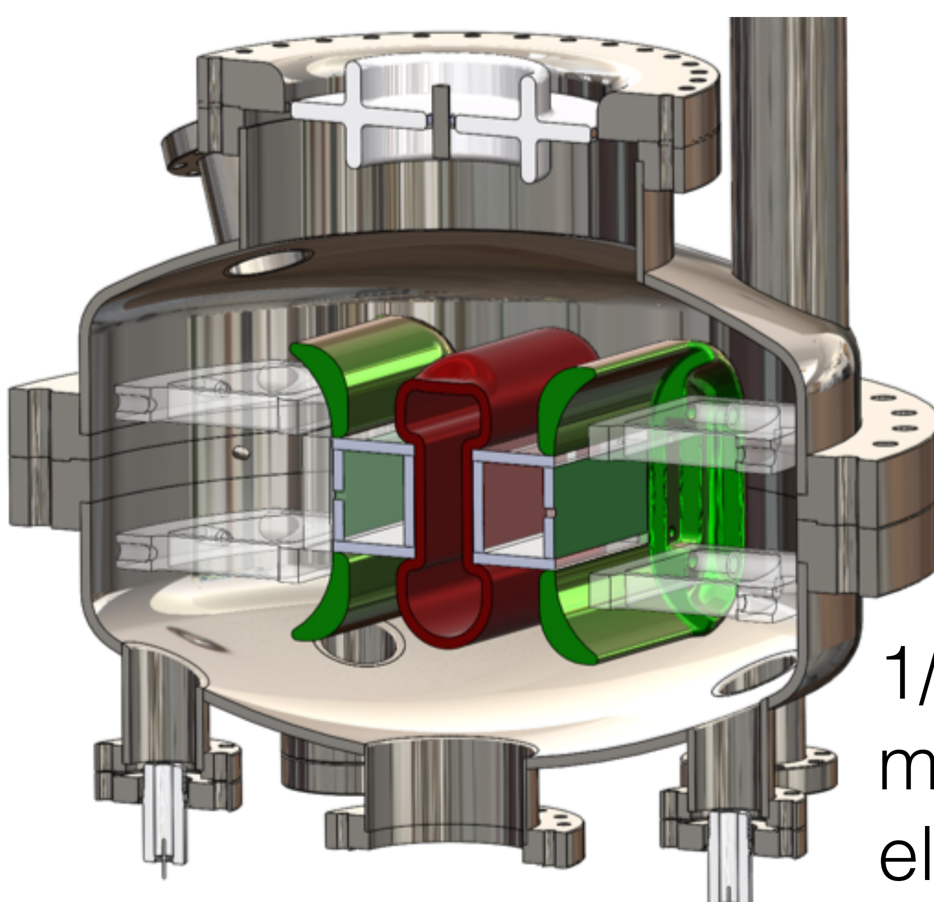
HSHV electrodes



Ball terminator



Uniform field electrodes



1/2-scale
measurement cell
electrodes

Generation of a high electric potential

Challenge with feeding HV into LHe

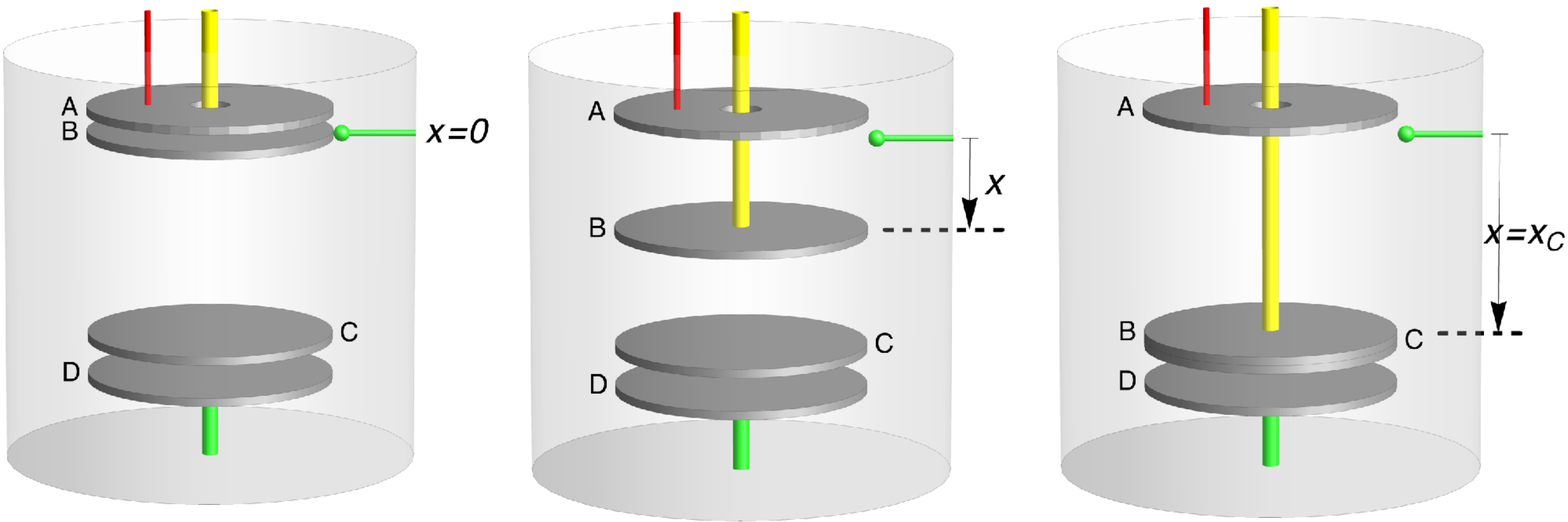
- SNS nEDM experiment requires 650 kV in LHe at 0.4 K
- Heat load through the HV conductor
  - Thermal intercept requires electrically-insulating and thermally-conducting material
- Leakage current at the insulator of the HV feedthrough
  - Additional heat load

Cavallo's Multiplier for SNS nEDM

a) Induce charge onto B

b) Move charge

c) Transfer charge to C

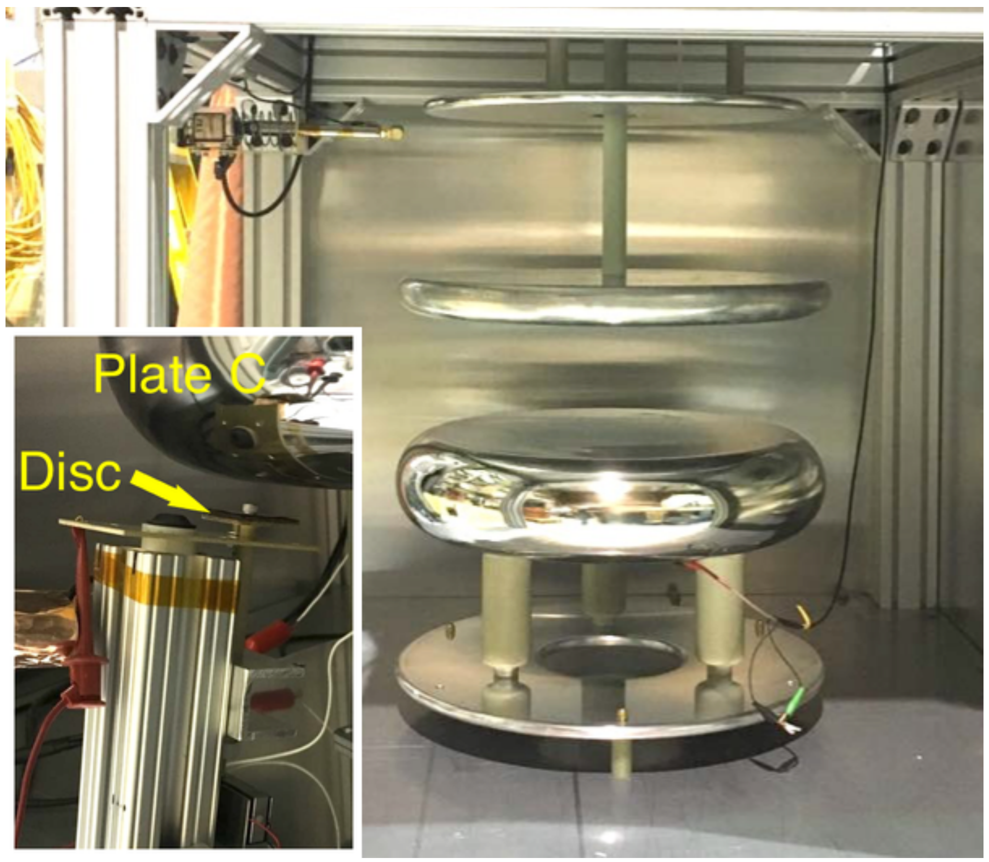


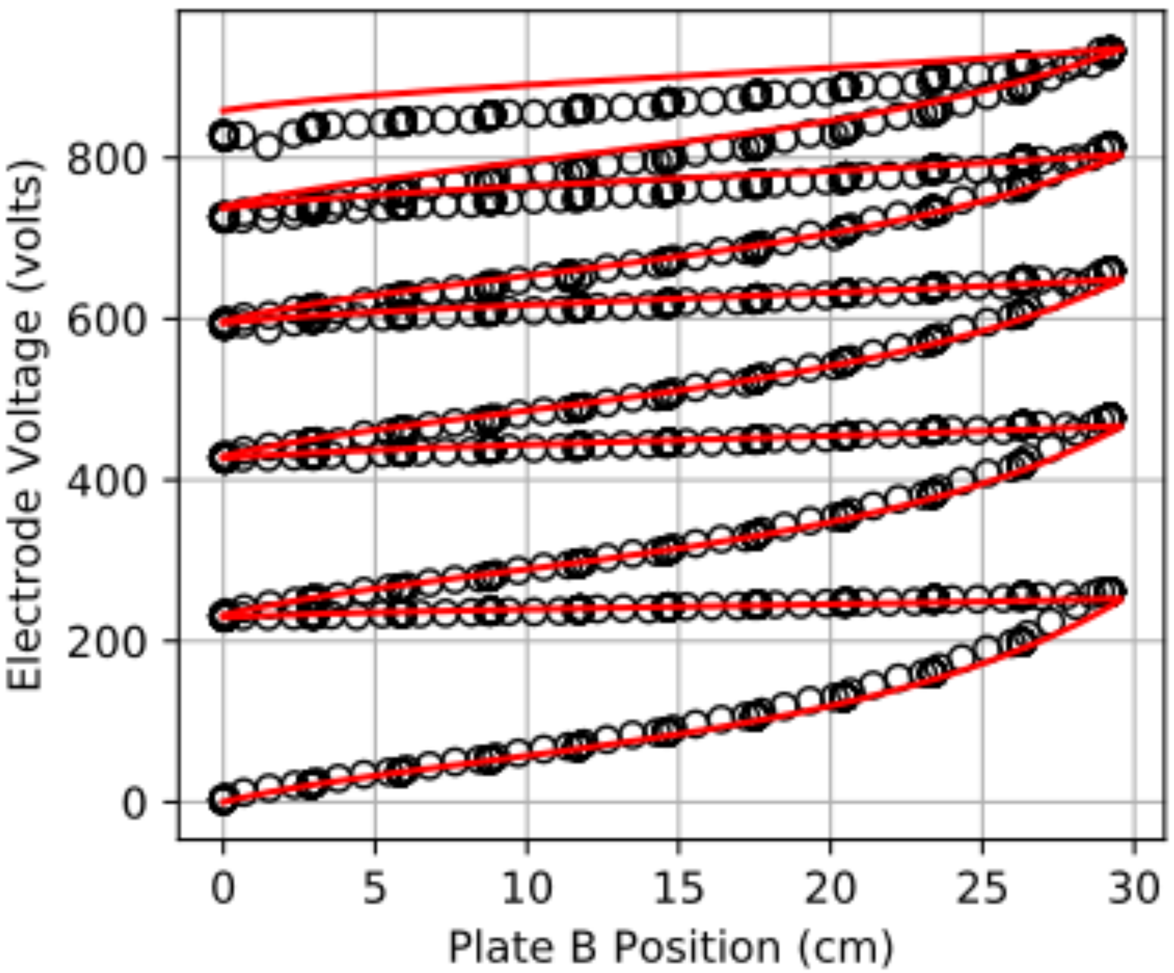
This 1795 technology will be used to generate > 700 kV inside the SNS nEDM Central Volume from 50 kV, eliminating the need for a 700-kV, superfluid-tight, low-leakage-current HV feedthrough and simplifying the design of the experiment.

Clayton *et al* 2018 *JINST* **13** P05017

Cavallo HV multiplier development at LANL

Room temperature demonstration



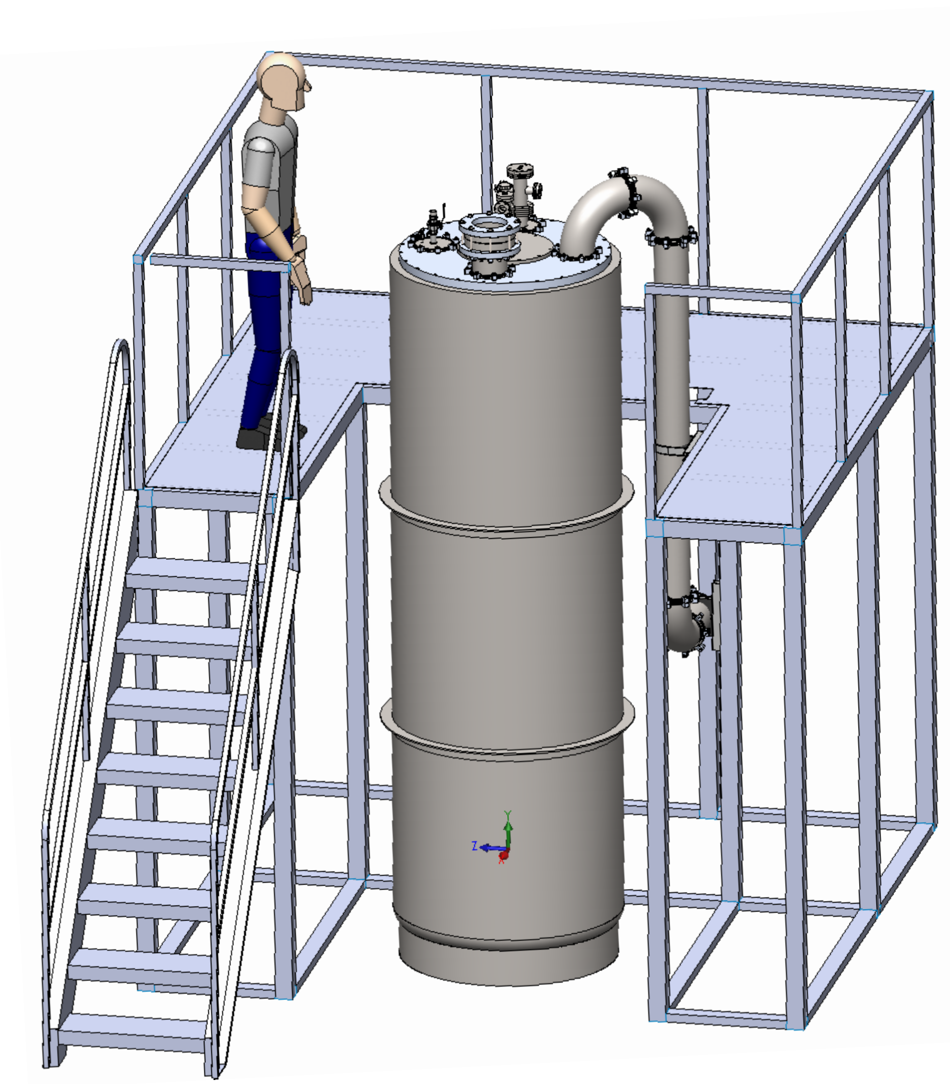


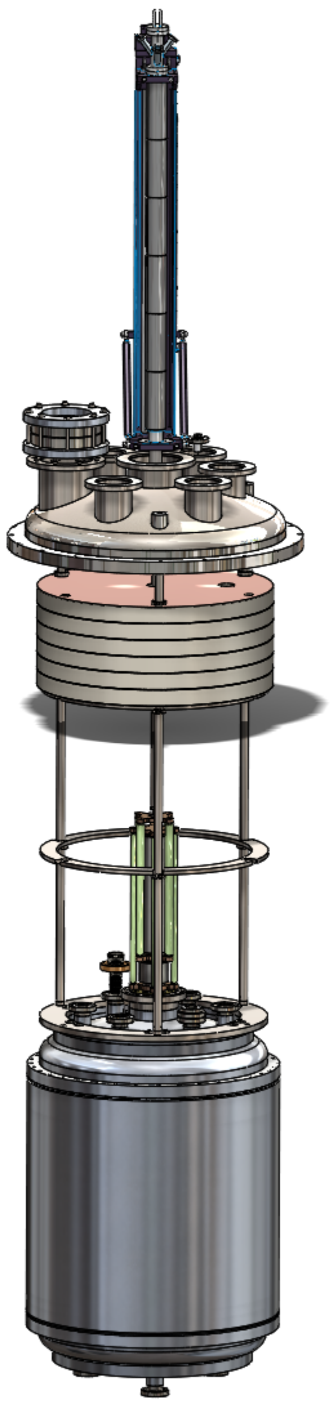
Measured Voltage
Prediction based on measured C_{ij}

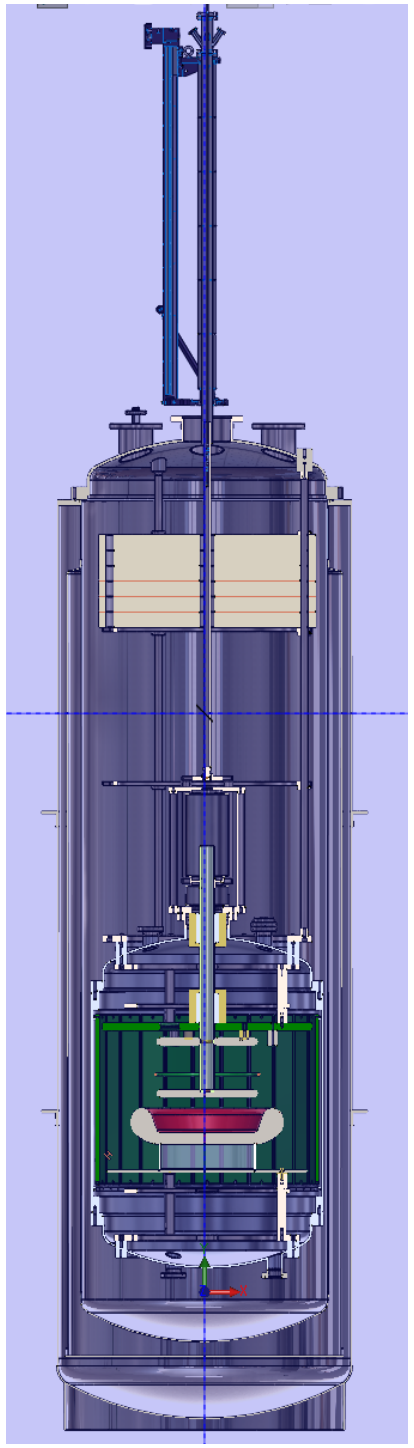
Clayton *et al* 2018 *JINST* **13** P05017

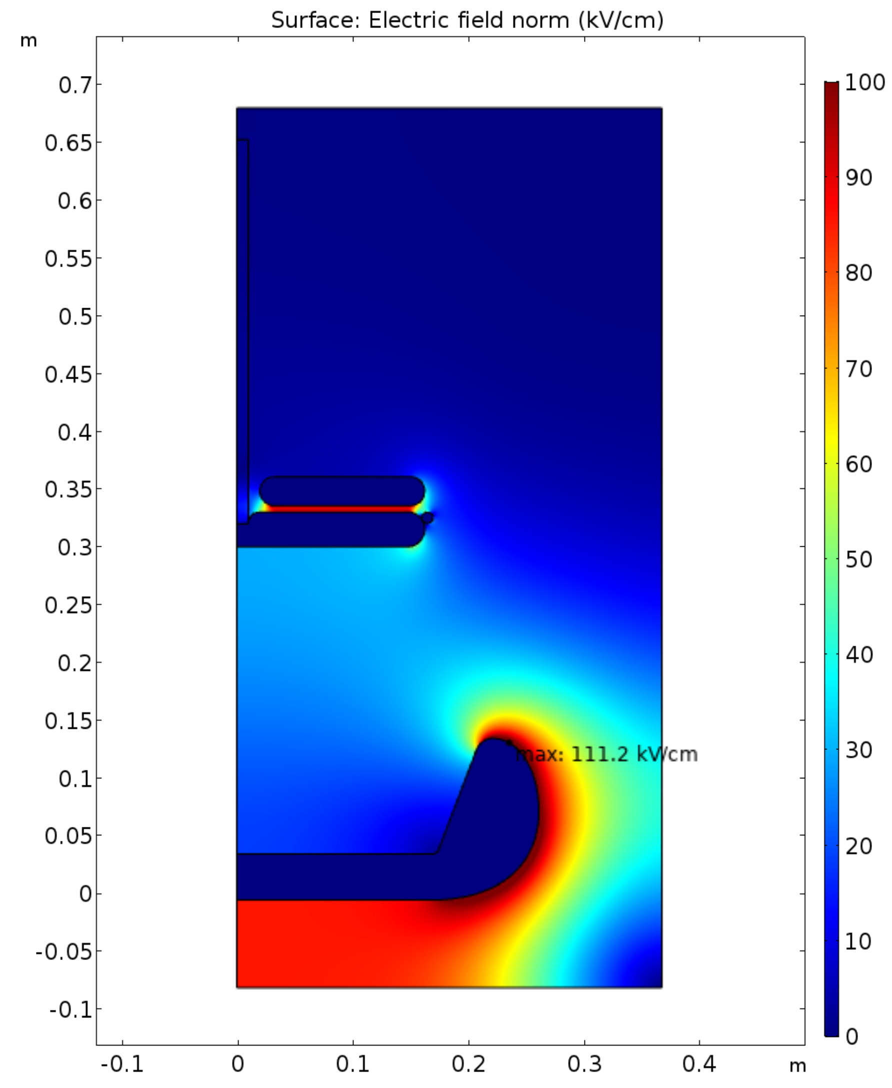
Cavallo HV multiplier development at LANL

Cryogenic prototype

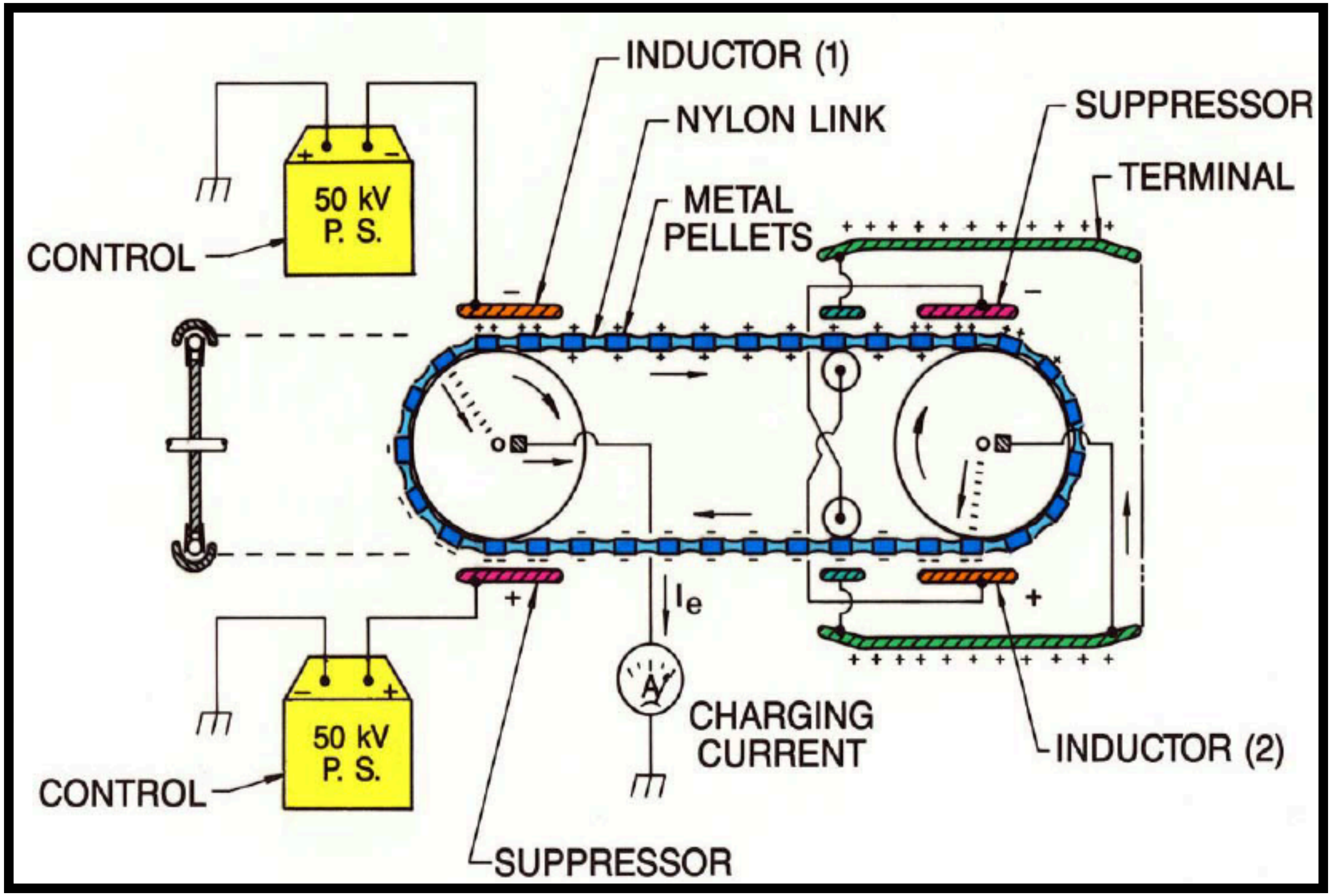








Pelletron in LHe?



Pelletron works on a similar principle to Cavallo's multiplier, but allows continuous current delivery. It is better suited for a TPC, which requires a current to be continuously flowing through a resistor chain. (See Clayton et al., JINST 13 P05017)

Thank you for your attention.