High voltage studies and electrode development for the nEDM@SNS experiment

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LOS ALAMOS NATIONAL LABORATORY

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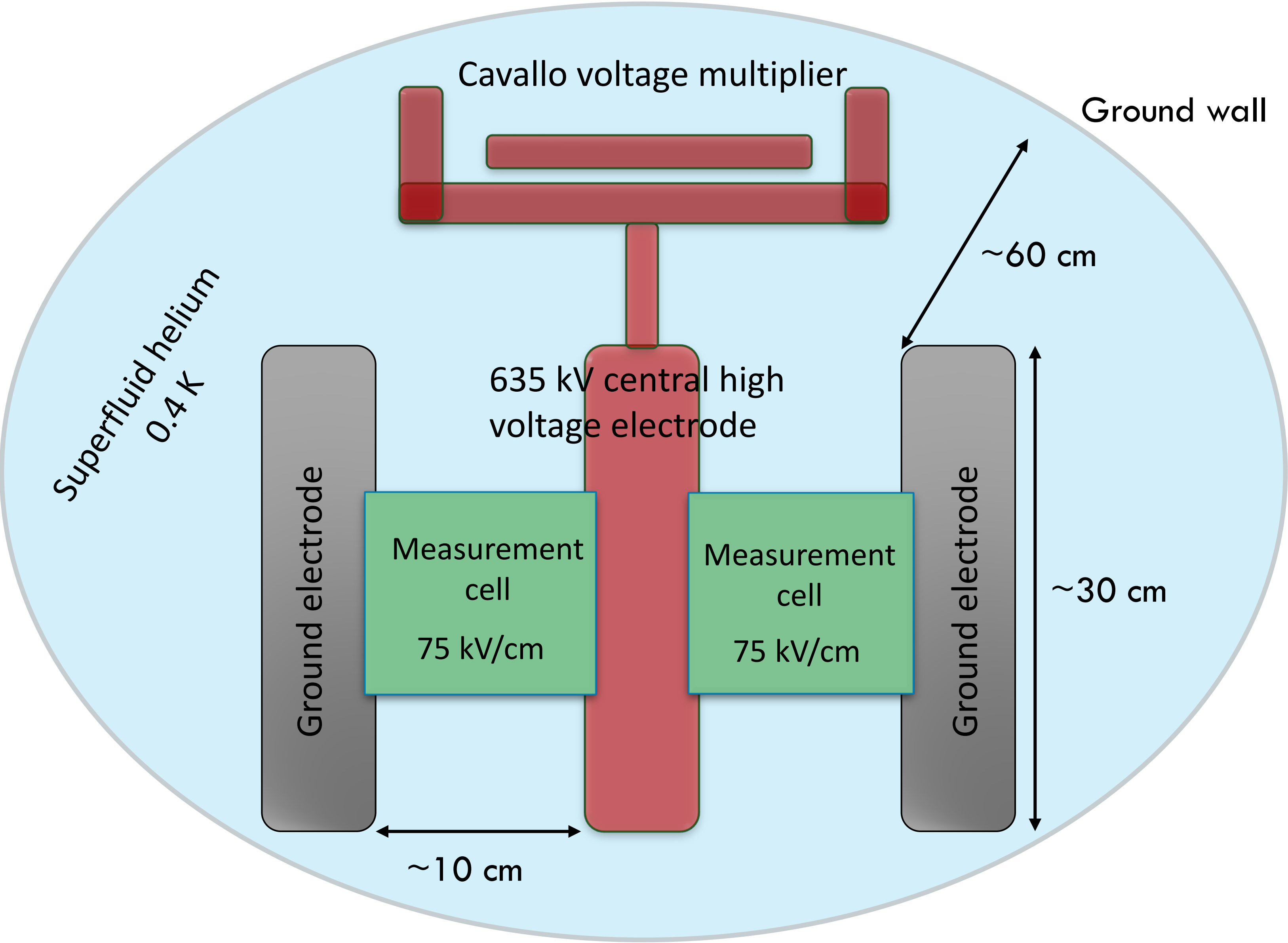
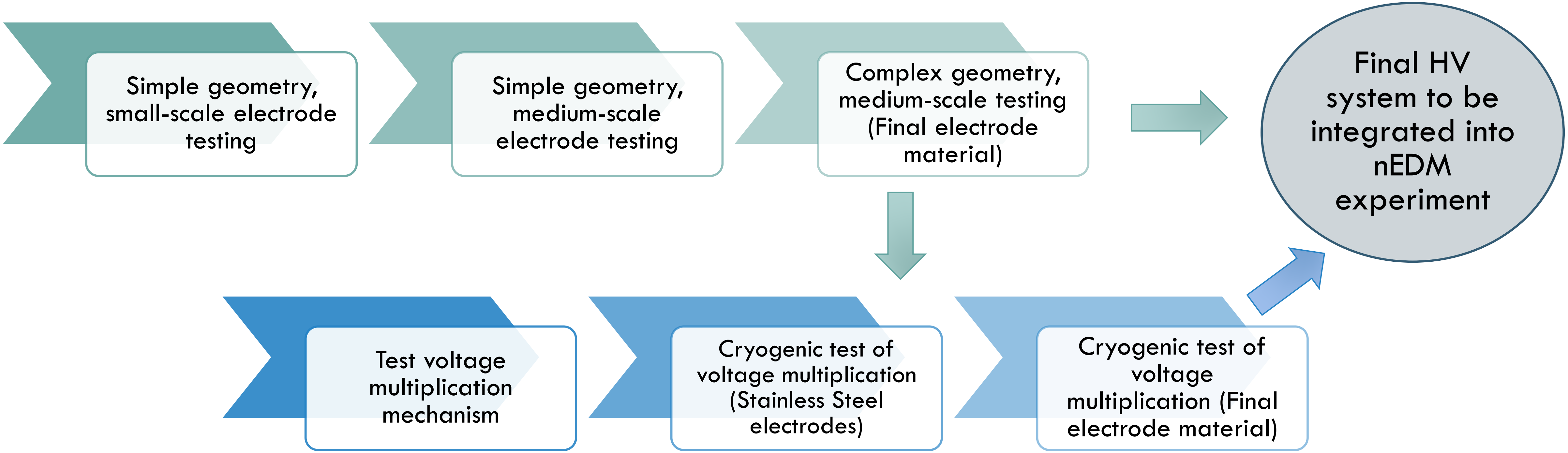
High voltage in the SNS nEDM experiment



HV system development tracks



Electrode development track

(focus of this talk)

Simple geometry, small-scale electrode testing

Simple geometry, medium-scale electrode testing

Complex geometry, medium-scale testing (Final electrode material)

Final HV system to be integrated into nEDM experiment

Test voltage multiplication mechanism

Cryogenic test of voltage multiplication (Stainless Steel electrodes)

Cryogenic test of voltage multiplication (Final electrode material)

High voltage multiplication development track

(see Cavallo talk)

Electrode development

Understanding breakdown phenomenon:

- What is the HV breakdown mechanism in liquid helium?
- What parameters affect breakdown?
  - Electrode material, surface condition, size, temperature, pressure,….
- What should the operational parameters for the HV system in the nEDM experiment be?
  - How high can/should we go? What is the breakdown probability?

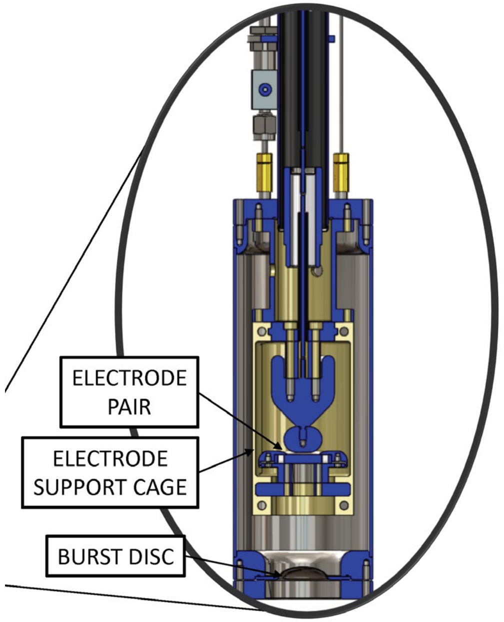
Requirements of the experiment:

- Sustain 635 kV (75 kV/cm inside measurement cells) over long time period.
- Compatible with Cavallo multiplier operation (robust, durable).
- Compatible with SQUID & dressed spin operation.
  - Constraint on resistivity of electrode material
- Low backgrounds: neutron activation
- Non-magnetic material
- Fabrication: electrodes are scalable to final size & shape. Surface properties can be well controlled.

Final electrodes

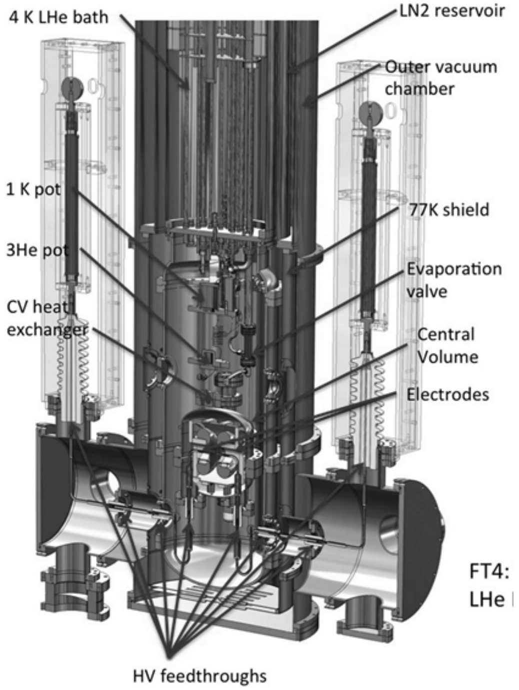
Experimental apparatuses for HV studies at LANL

Small Scale



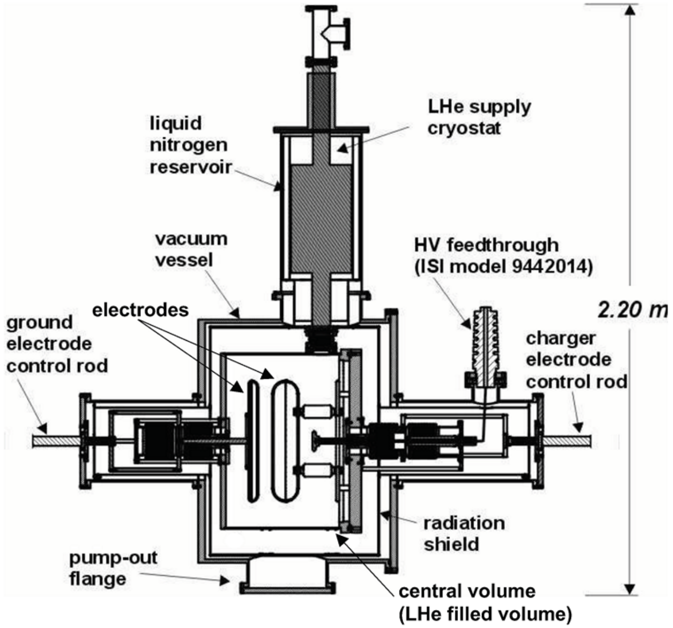
Electrode size: ~1 cm^2

Medium Scale (Non-active device)



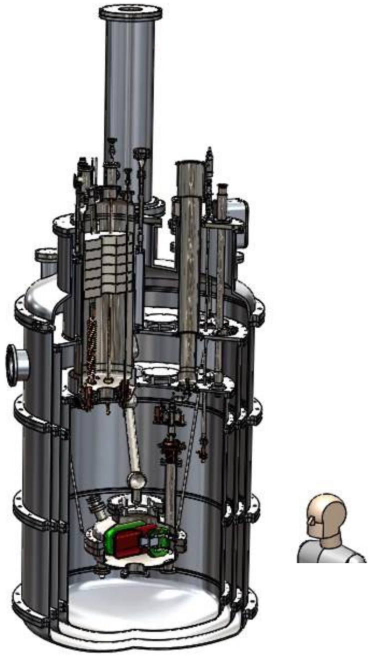
Electrode size: ~100 cm^2

Large Scale (Legacy device)



Electrode size: ~1000 cm^2

Half Scale



Electrode size: ~1000 cm^2

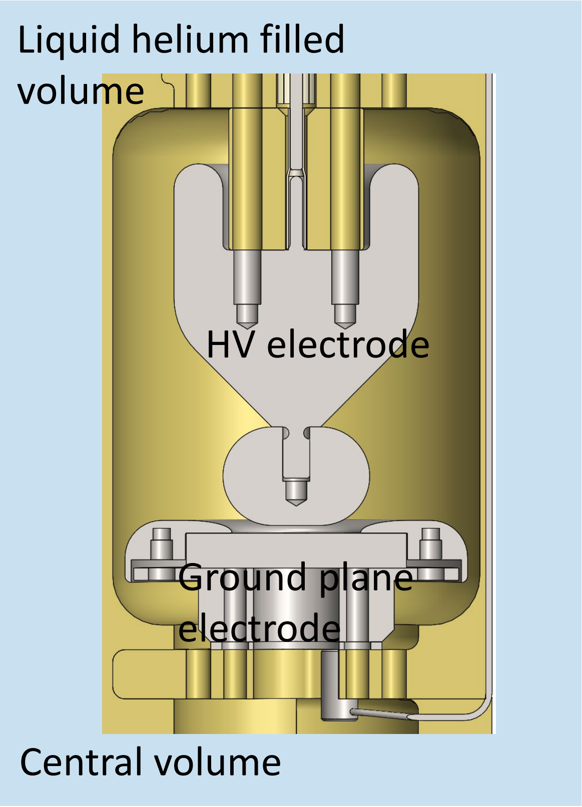
Increasing electrode area

High voltage breakdown data

Data acquisition procedure:

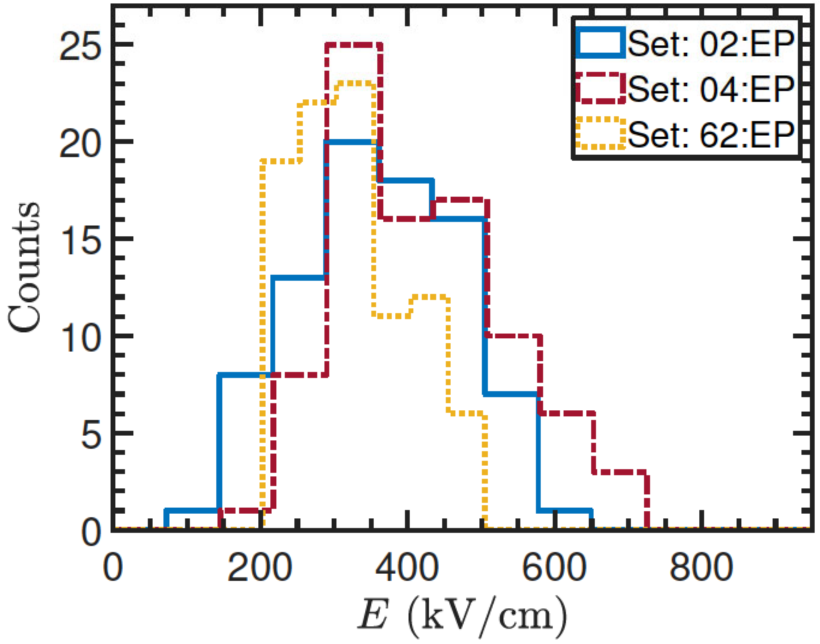
- For a set of electrodes at a fixed temperature and pressure:
  - Ramp voltage from zero until a breakdown occurs.
  - Record the breakdown voltage.
  - Repeat process to accumulate distribution.
- Change temperature, pressure, or electrodes and repeat the process.

Small-Scale High Voltage Apparatus



Sample breakdown field distributions from the Small-Scale HV system

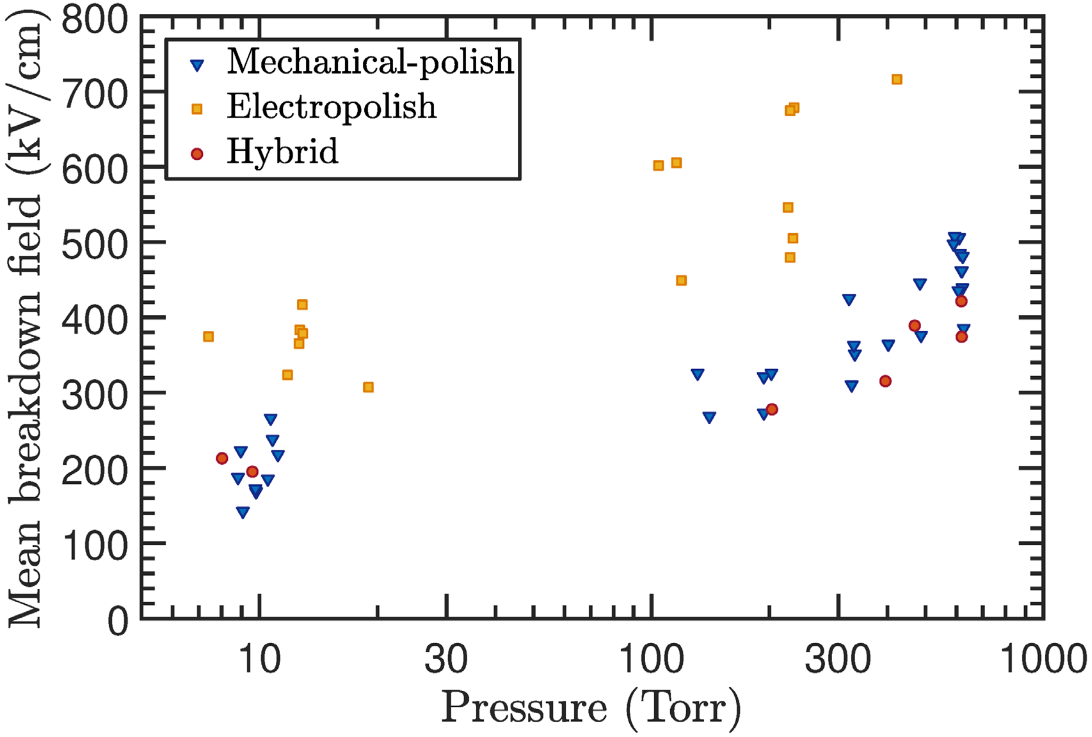
Data acquired by Wanchun Wei



(a) EP, < 20 Torr

Phan *et al.*, J. Appl. Phys. **129**, 083301 (2021), *arXiv:2011.08844*

Summary of findings



SSHV data

- Breakdown field is primarily dependent on the pressure on the liquid.
- Small temperature dependence.
- Higher breakdown fields for electro-polished electrodes vs mechanically-polished.

Additional questions:

- Explanation for pressure dependence?
- How does breakdown field scale with electrode area?
- Breakdown field for complex electrode geometry?
- Where should the operating voltage be set at?

New analysis approach

0) {Data: set of breakdown fields/voltages}

Weibull (1939, 1951)
Choulkov(2005)

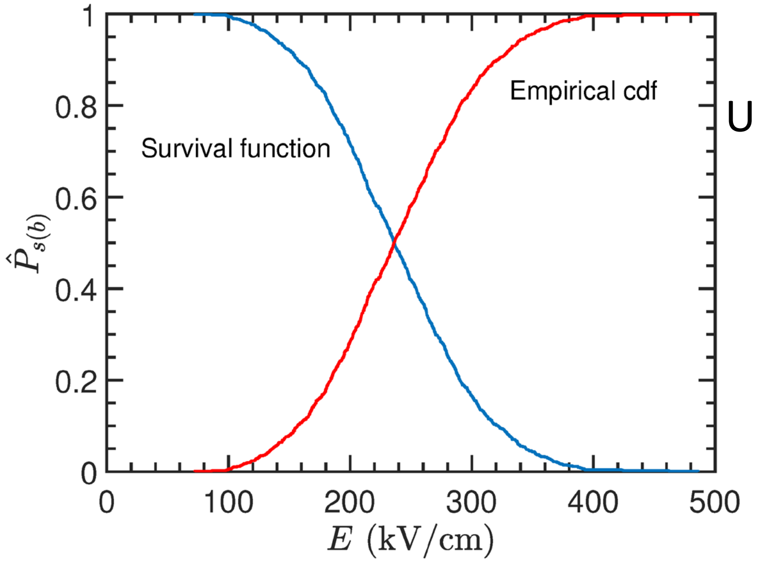
Cumulative breakdown distribution:

$$P_b(E) = 1 - e^{-SW(E)}$$

Survival function:

$$P_s(E) = e^{-SW(E)}$$

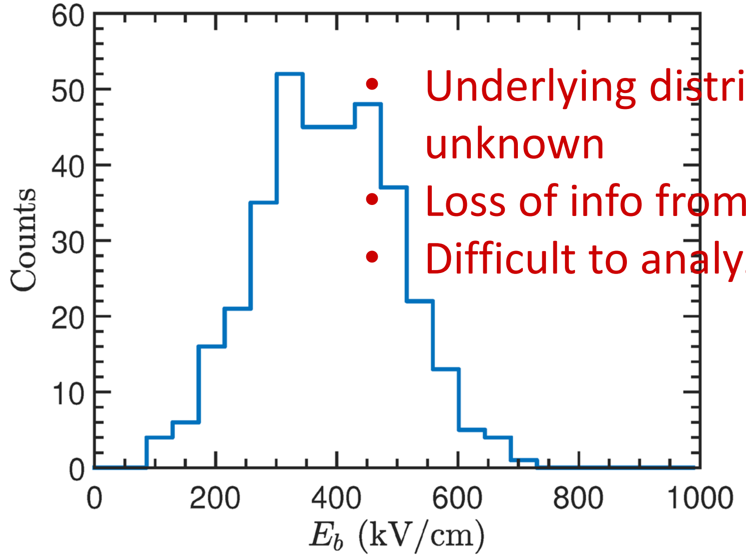
1b)



Unbinned analysis → more information

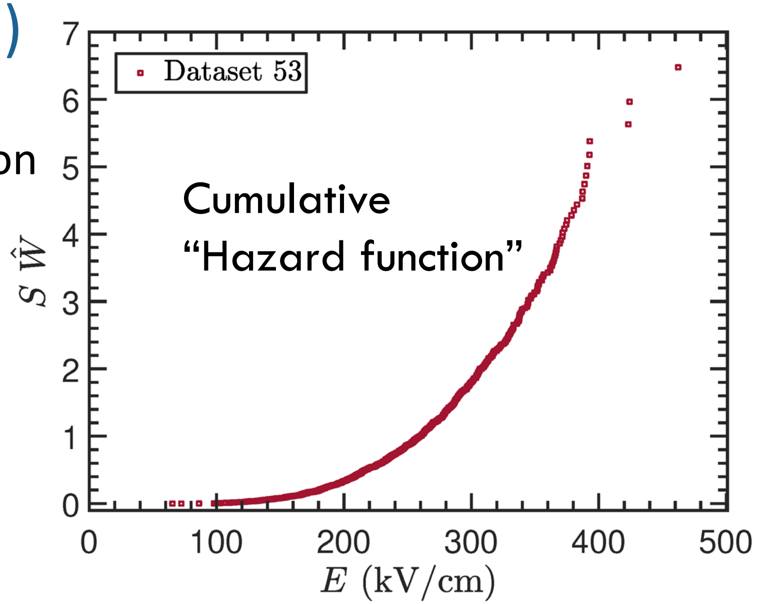
$$S\widehat{W} = -\ln(1 - \hat{P}_b)$$

1a) ✖



- Underlying distribution unknown
- Loss of info from binning
- Difficult to analyze

2)



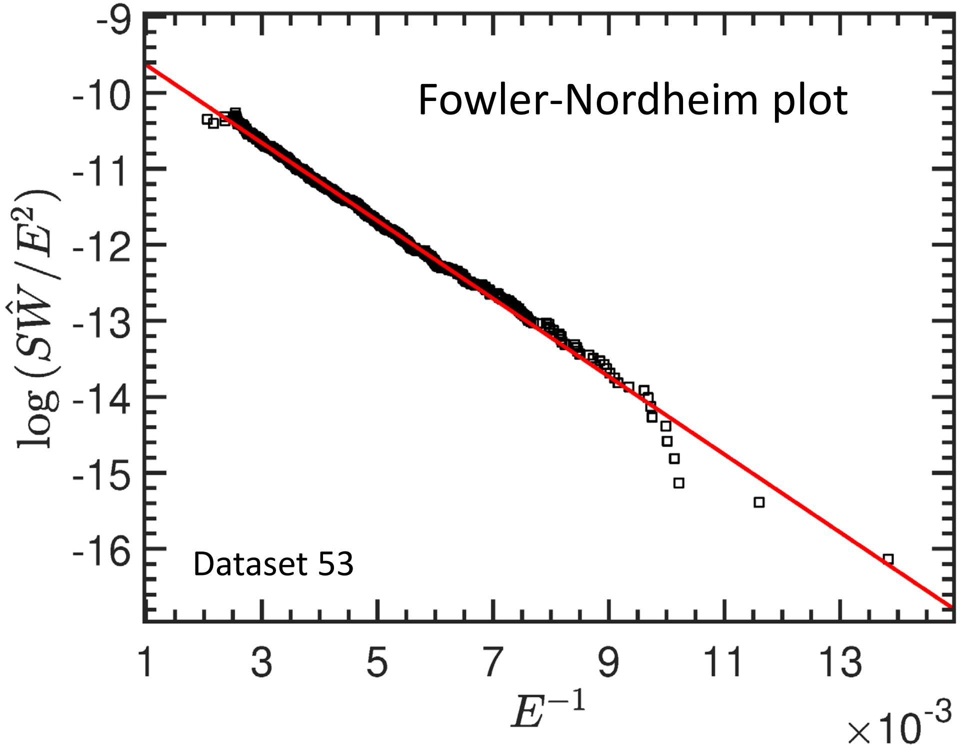
Cumulative
"Hazard function"

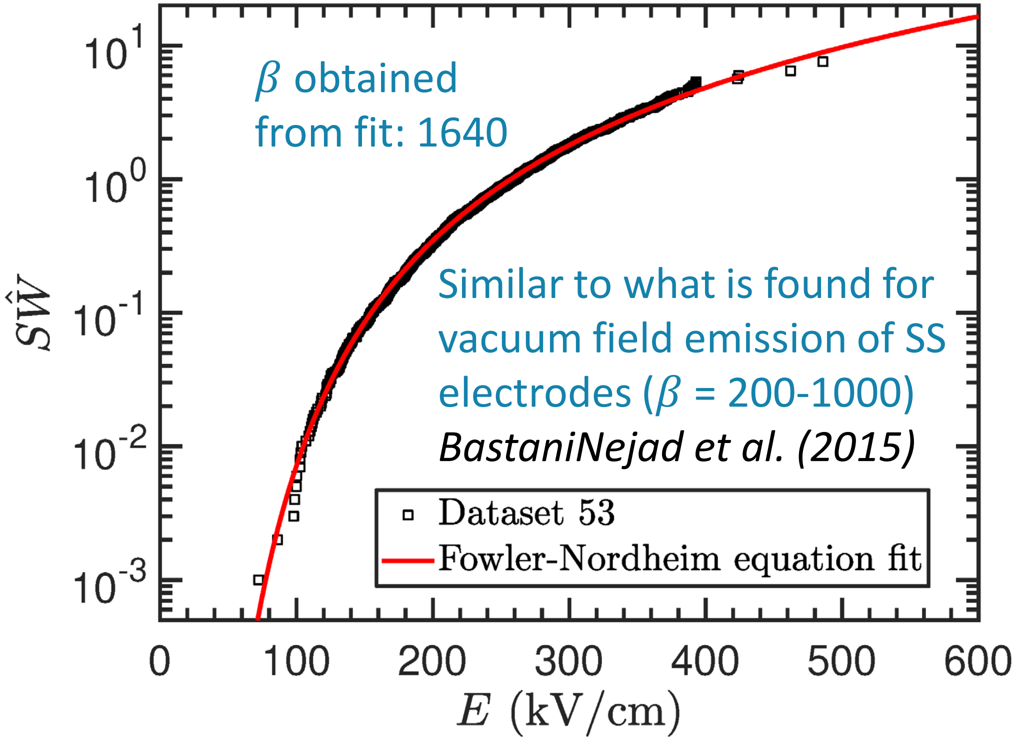
Connection to field emission

The hazard function is very evocative of Fowler-Nordheim field emission:

$$I_{FN}(E) = A_e \frac{C}{\varphi} G^{\varphi^{-\frac{1}{2}}} (\beta E)^2 \exp(\frac{-D\varphi^{3/2}}{\beta E})$$

β: field enhancement factor
φ: work function
C, D, G: constants




β obtained from fit: 1640

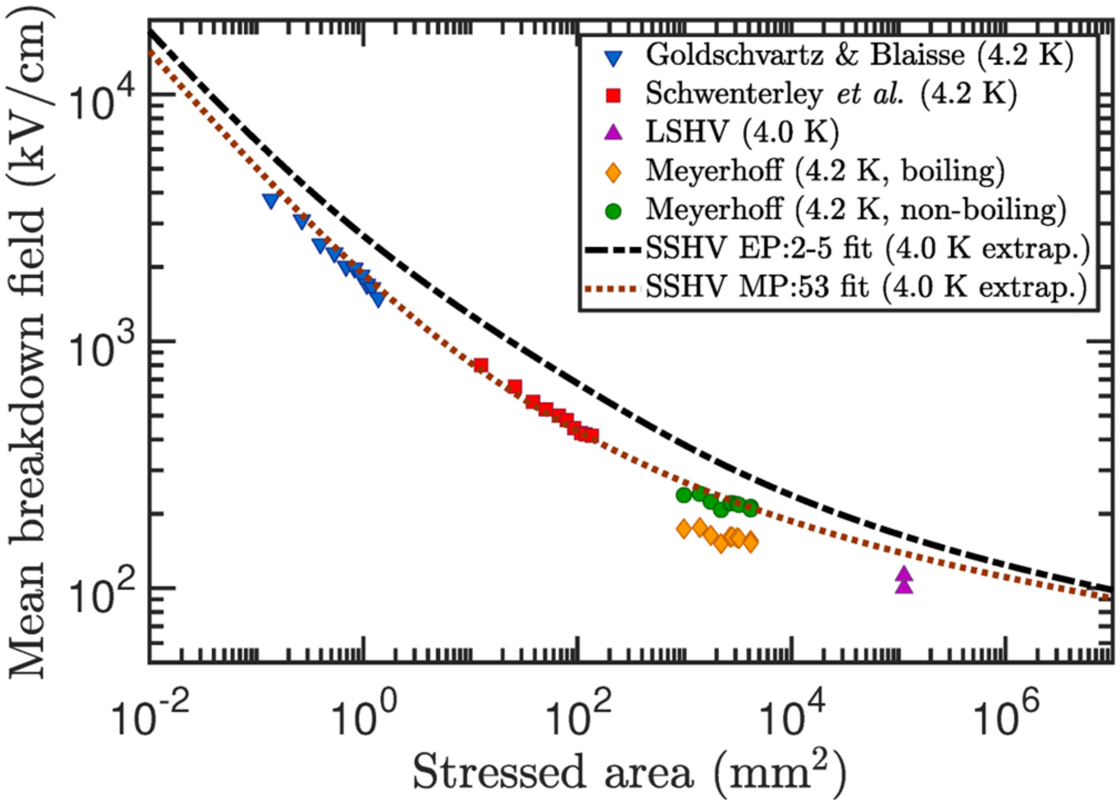
Similar to what is found for vacuum field emission of SS electrodes (β = 200-1000)
BastaniNejad et al. (2015)

Analysis approach

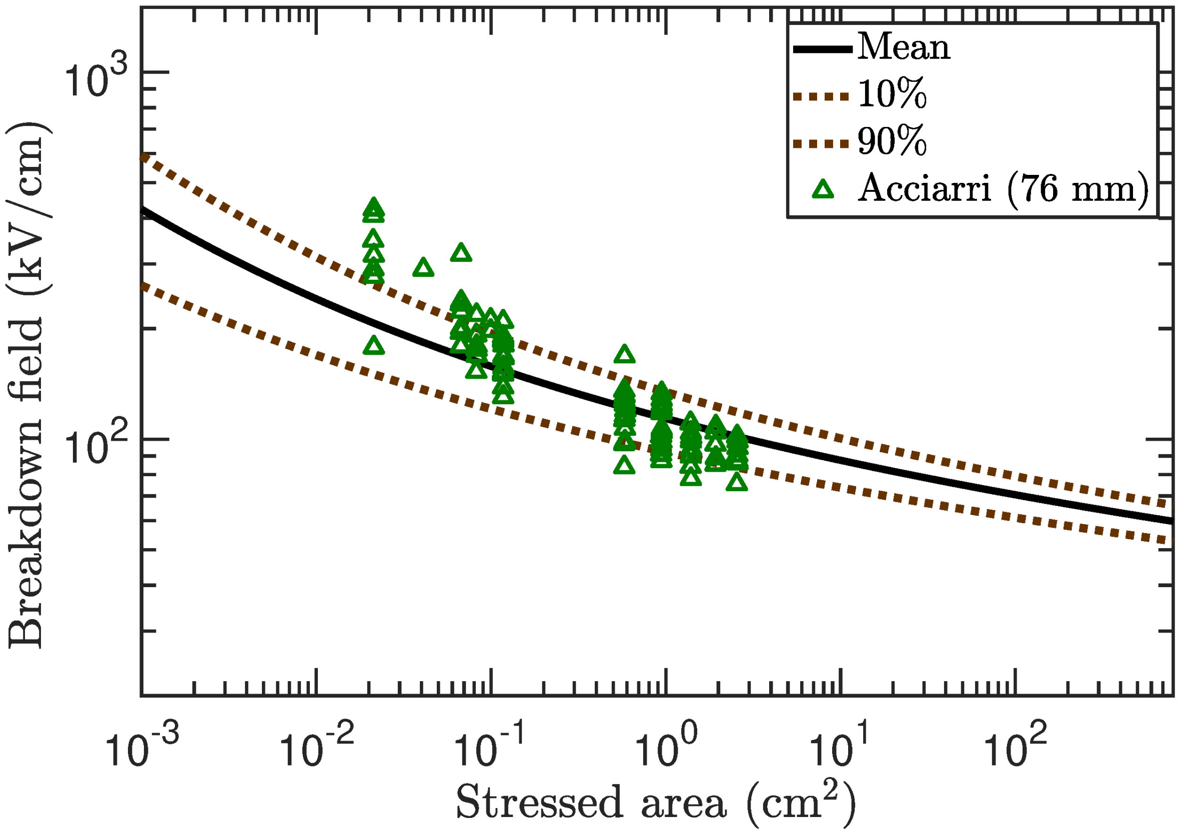
- Can predict how the breakdown field scales with the area of the electrodes.
- Can apply the same analysis method to breakdown data acquired in other noble liquids (e.g., argon, xenon).
- Can determine the probability of breakdown for an arbitrary shaped electrode.
- Can optimize electrode shape to maximize survival probability.
  - In contrast, traditional approach is to reduce the maximum surface field.
- Provides a gauge to set acceptable operational parameters to minimize risk of breakdown/failure.

Breakdown field scaling with electrode area

- Liquid helium



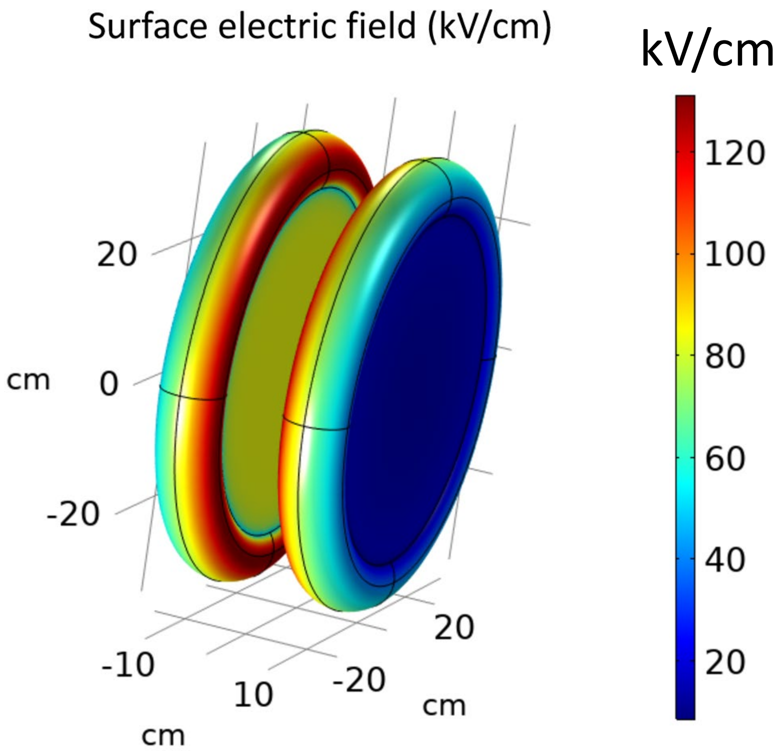
- Liquid argon



LAr data taken from Acciarri et al., JINST 9, P11001 (2014).

Breakdown probability for arbitrarily shaped electrodes

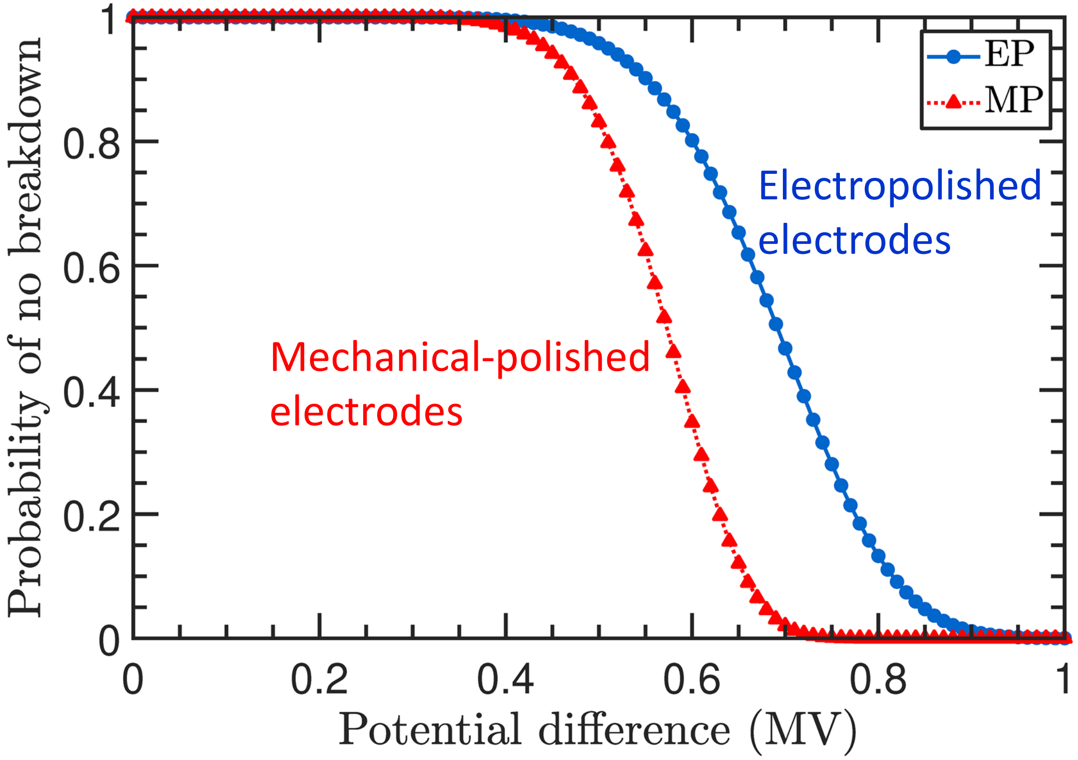
1 MV potential difference


Surface electric field (kV/cm)

Simulation input: field distribution on electrode surfaces

Cumulative hazard function {electrode type, experimental conditions (pressure, temperature, etc.)}

Experimental input: cumulative hazard function



Electropolished electrodes

Mechanical-polished electrodes

Prediction: breakdown probability vs field/voltage

Electrode material considerations

Properties to consider

- **Electrical**
  - Resistivity (Most stringent constraint)
  - Work function
- **Magnetic**
- **Nuclear**
  - Neutron activation
- **Mechanical**
  - Uniformity
  - Smoothness
  - Deposition
  - Adhesion
- **Fabrication**

Two types of materials:

- Bulk conductive material
- Conductive coating on non-conductive substrate

Challenges:

- Bulk material – meeting resistivity requirements at 0.4 K
- Coating – electrical & mechanical

Electrode material: Resistivity requirements

- Minimum electrode resistivity for nEDM@SNS comes from two considerations:
  1. Eddy current heating: Heat from the dressing field less than 6 mW.
     - Bulk material: $\rho_v > 1.42 \times 10^{-4}\ \Omega \cdot m$
     - Thin film coating: $\rho_s > 0.013\ \Omega/\square$

Copper: $\rho_v = 1.72 \times 10^{-8}\ \Omega \cdot m$
Aluminum: $\rho_v = 2.83 \times 10^{-8}\ \Omega \cdot m$
Acrylic: $\rho_v \sim 10^{14}\ \Omega \cdot m$

2. Magnetic Johnson noise: Sufficiently low noise level ($\delta B < 1\ fT/\sqrt{Hz}$) that it does not interfere with the 3He precession frequency measurement using the SQUID gradiometers.
   - Less stringent than above and depends on the specific electrode and geometry of the sensors & electrodes.
     - Bulk material: $\rho_v \sim 10^{-6}\ \Omega \cdot m$
   - Utilized a new method based on F-D theorem and FEM analysis to determine magnetic noise from an arbitrary conductor geometry (Takeyasu Ito).

Conductive coatings: ZrN & NbN on polycarbonate

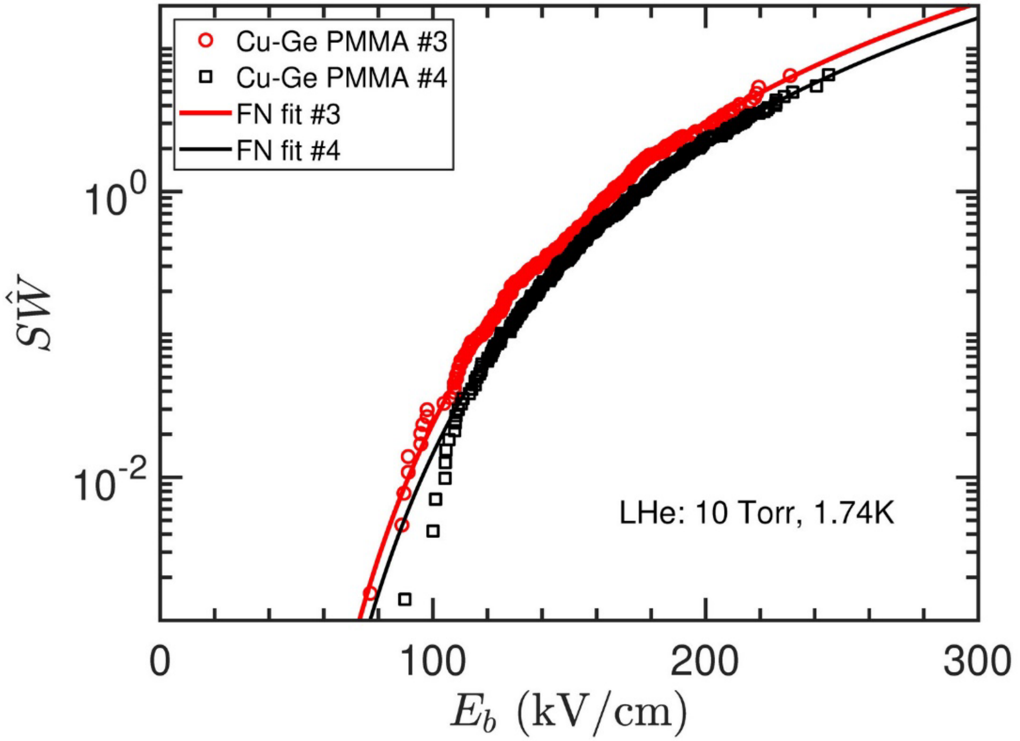
Conductive coating: Cu-Ge coated PMMA

Bulk conductive material: polycarbonate (Zelux CN-P)

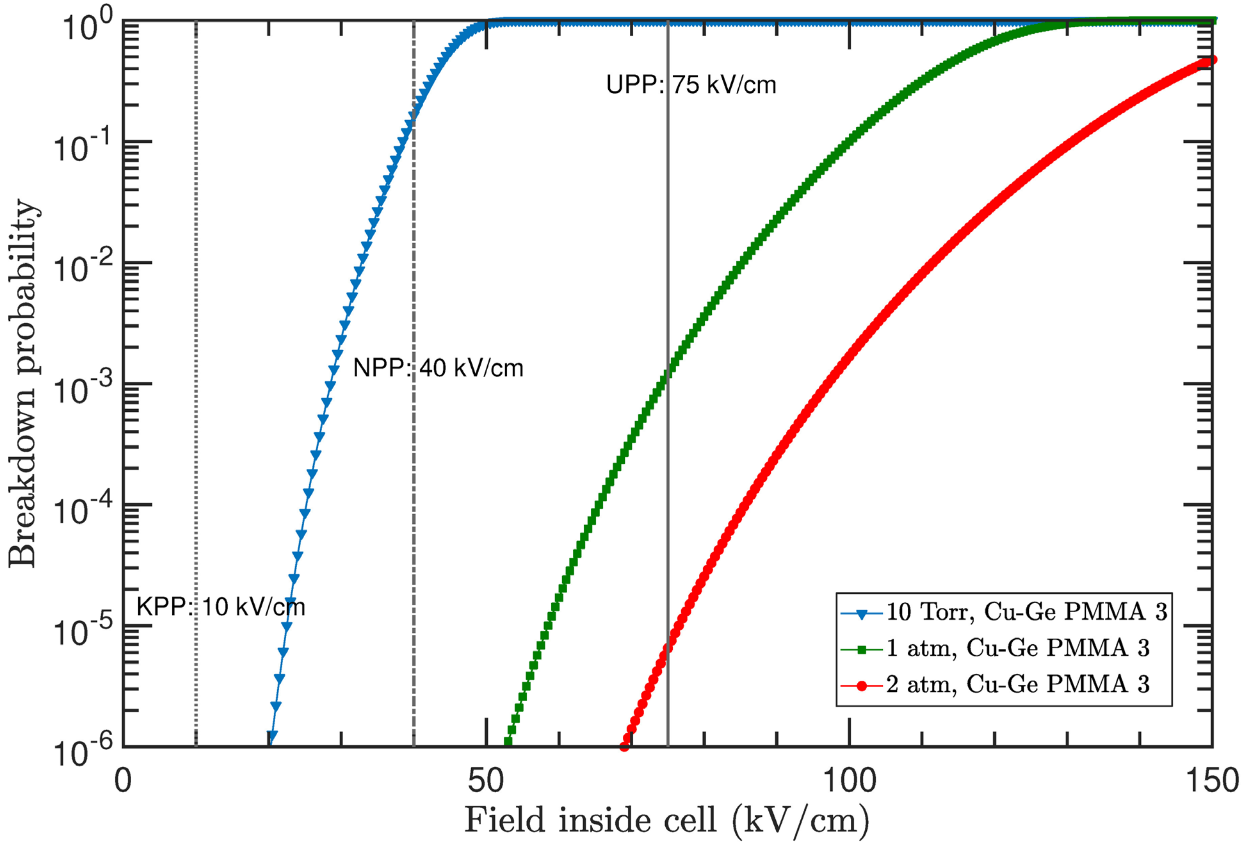
Bulk conductive material: Torlon-4435

Breakdown probability for Cu-Ge PMMA

Data for Cu-Ge coated PMMA electrodes
Acquired in Small-Scale system

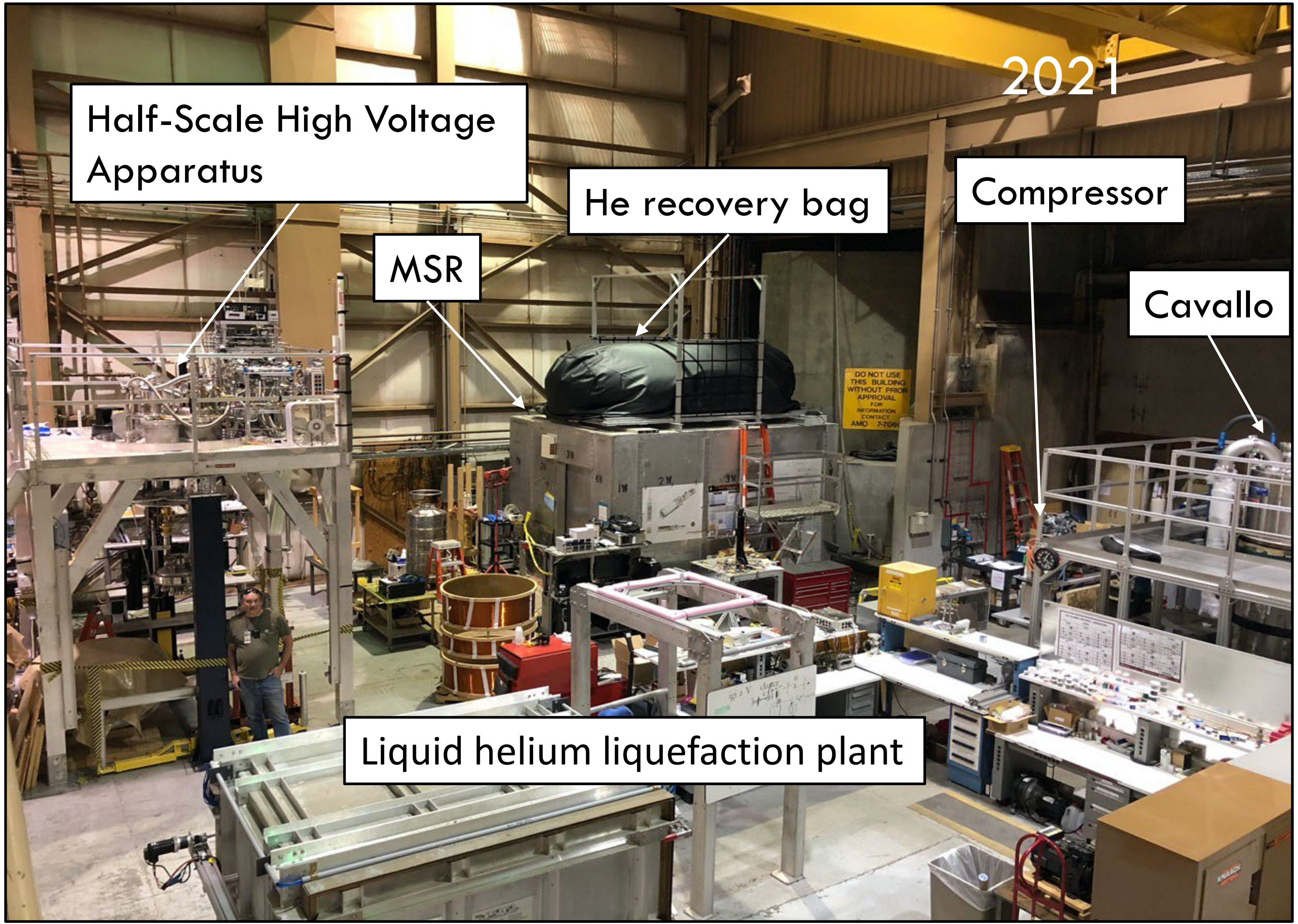


Extrapolation for Cu-Ge coated PMMA electrodes in nEDM experiment



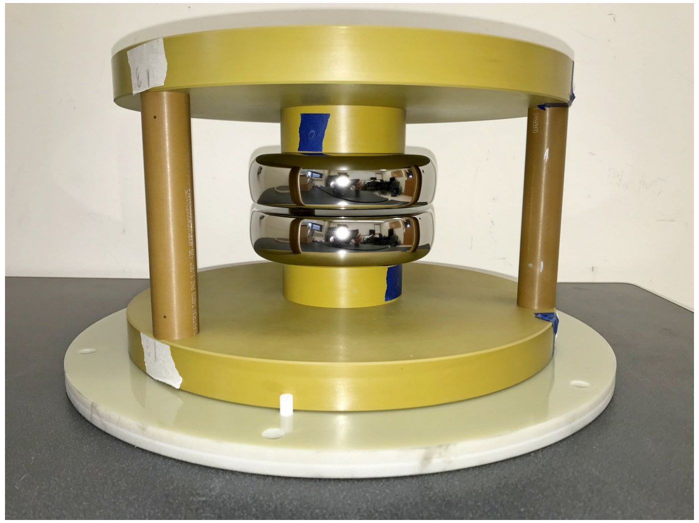
High voltage R&D supporting facilities

Liquid helium liquefaction plant

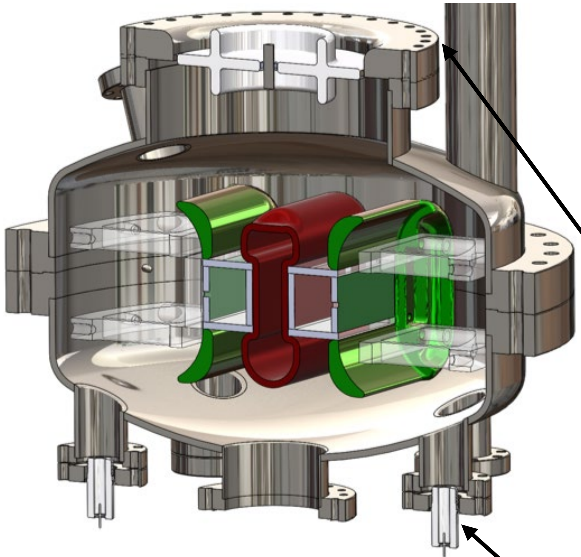


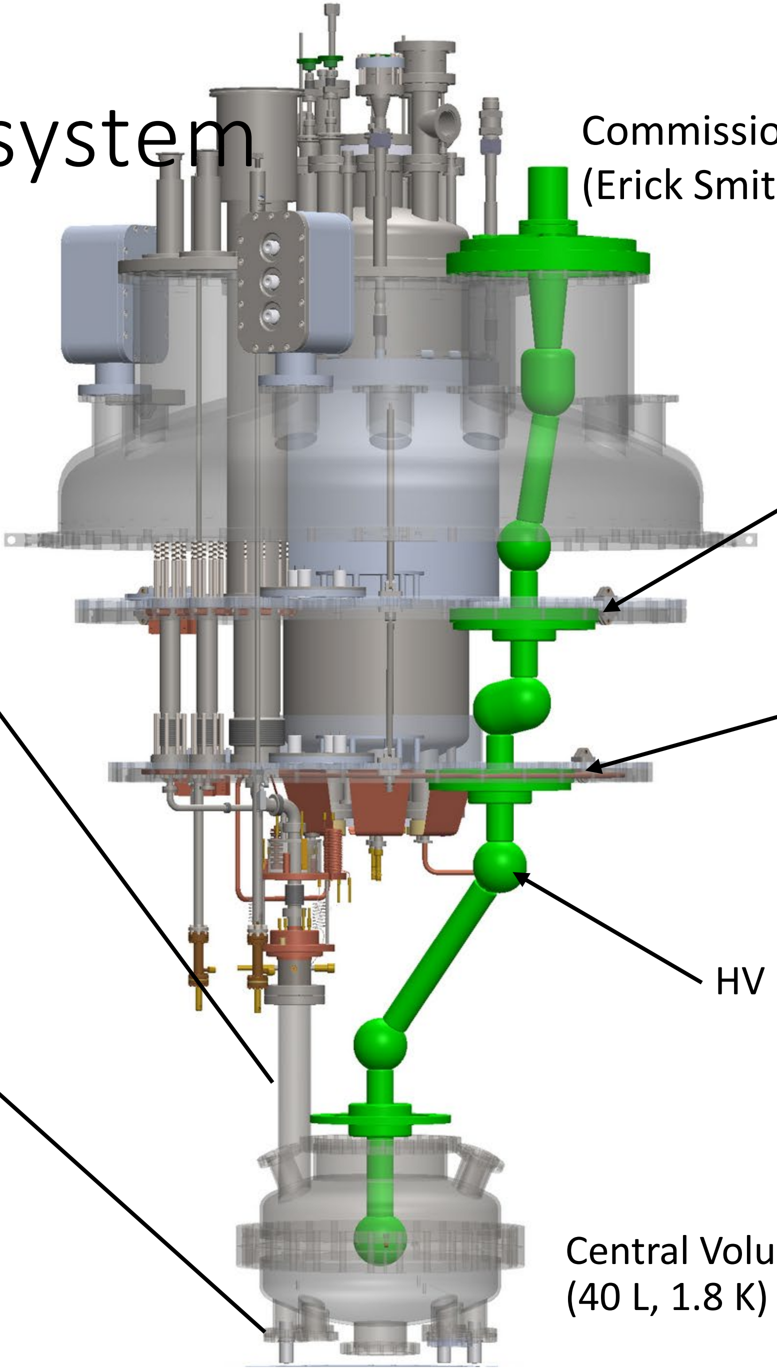
Half-Scale High Voltage (HSHV) system

HSHV Rogowski (near-uniform field) electrodes & mounting structure



1/2-scale measurement cell electrodes





Commissioning completed (Erick Smith, Grant Riley)

Half-Scale High Voltage System:

- Enables testing of larger electrodes with more complex geometries.
- Verification of predictions from Small-Scale system
- Provides additional data on time to breakdown in addition to electrode area scaling.

Summary

High voltage studies

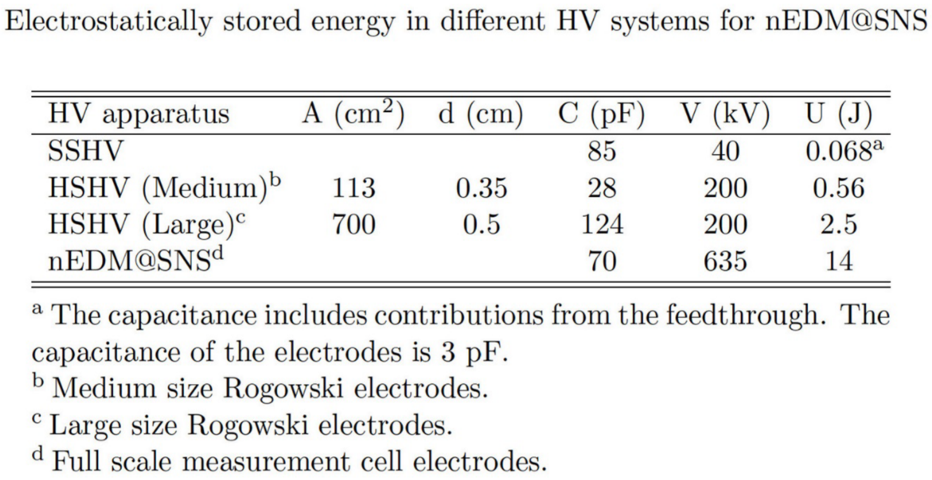
- Developed a new data-based method to predict breakdown field with electrode area scaling for any electrode geometry.
- Demonstrated a clear connection between breakdown and field emission, and the dependence of breakdown field on pressure, surface condition.
- Provided guidance for the HV R&D of SNS nEDM experiment.
- Approach is applicable to other noble liquid-based experiments.
- In preparation for testing of larger scale electrodes in Half-Scale HV system.

Electrode development

- Developed a method based on F-D theorem and FEM analysis to determine magnetic noise from a general conductor geometry.
- Several electrode materials tested (resistivity & HV performance). So far, at least one (Cu-Ge on PMMA) satisfies the requirements of the experiment.
    - Some concerns regarding fabrication and performance (durability, robustness) remain.
- Other candidate materials have also been identified. Testing/procurement in progress…

END

Stored energy in different HV systems



Electrostatically stored energy in different HV systems for nEDM@SNS

HV apparatus	A (cm^2)	d (cm)	C (pF)	V (kV)	U (J)
SSHV			85	40	0.068[a]
HSHV (Medium)[b]	113	0.35	28	200	0.56
HSHV (Large)[c]	700	0.5	124	200	2.5
nEDM@SNS[d]			70	635	14

[a] The capacitance includes contributions from the feedthrough. The capacitance of the electrodes is 3 pF.

[b] Medium size Rogowski electrodes.

[c] Large size Rogowski electrodes.

[d] Full scale measurement cell electrodes.

Static field of ~3 uT inside measurement cells

- Must be uniform to $\sim 10^{-4}$ (averaged over cell)
- Gradients: < 10 pT/cm in direction of field, < 5 pT/cm perpendicular to field

Leakage current

- < 100 pA