Statistics of Breakdown in Liquid Helium

Nguyen Phan (Los Alamos National Laboratory)

N. BOUMAN, S. CLAYTON, S. CURRIE, T. ITO, J. RAMSEY, W. WEI

nEDM2017, Harrison Hot Springs, Canada

Outline

- Background
- Experimental Goals
- Experimental Setup and Procedure
- Data
  - Breakdown distributions
  - Electrode surface smoothness
  - Temperature & pressure dependence
  - Ramp rates and time distributions
  - Correlations

Background

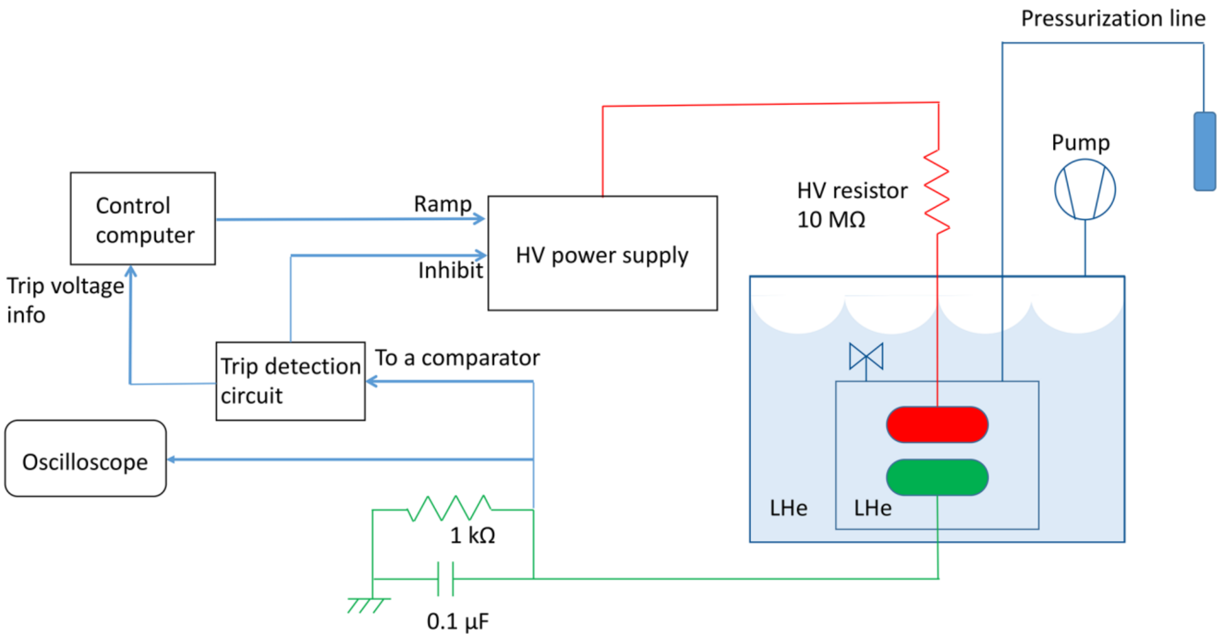
- Lack of consistency in experimental results due to differing experimental conditions and procedure.
  - As such, modelling and understanding the breakdown phenomena in liquid helium remains an outstanding problem.
  - Many parameters affecting breakdown: electrode area and spacing, liquid purity, experimental procedure, pressure and temperature, and electrode surface conditions, etc.
- Most analysis breakdown data have used Weibull and extreme value statistics to fit experimental data
  - Tend to obscure connection between types of testing (e.g. ramp voltage vs constant voltage), hides the physical phenomena

Goals

- Study breakdown voltage dependence on:
  - Temperature and pressure of liquid helium
  - Electrode surface smoothness: Mechanically-polished vs. electropolished
- Study possible correlations between i^{th} and i^{th}+1 breakdown.
- Look at waveform of current from ground electrode for clues about breakdown mechanism
- Develop interpretation/model of breakdown voltage and time distributions → prediction of behavior with scaling of electrode area.
- **Help inform design for SNS nEDM high voltage system.**
  - **SNS nEDM design goal of ~ 70 kV/cm → ~ 700 kV on electrode**

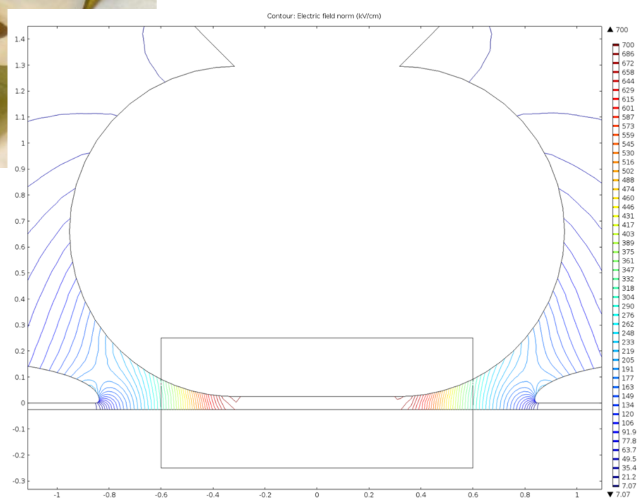
Experimental Setup

SSHV: Small-scale High Voltage Apparatus



Temperature **and** pressure control

Test Geometry and Electrode Properties



Electrode gap set to 0.5 mm.

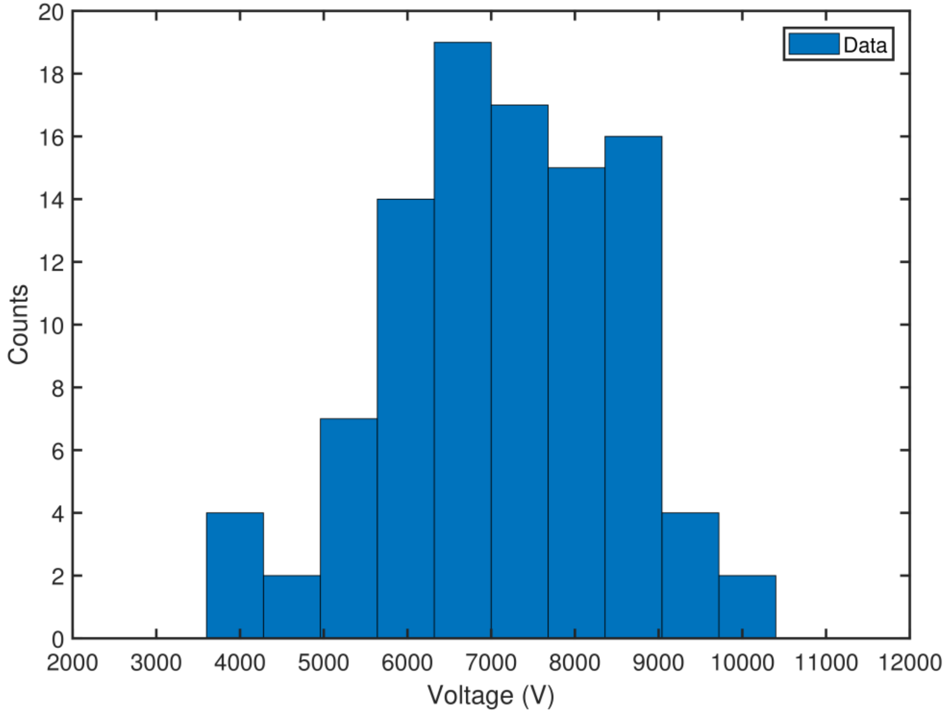
- Some uncertainty in exact gap size due partially to thermal contraction of various parts, hence, breakdown voltages instead of breakdown fields are stated.
- The stressed area ~ 0.3 cm^2
- Mechanically polished and electropolished electrodes were used
- Surface finish ~ 10 μm for mechanically polished electrodes

Experimental Procedure

- Data collected:
  - Breakdown voltage distribution for various temperatures and pressures (mechanically polished electrodes, electropolished electrodes)
  - Breakdown voltage distribution for different voltage ramp rates (mechanically polished electrodes)
  - Distribution of time to breakdown (mechanically polished electrodes)

Electrodes	T(K)	P(Torr)	Measurement
Mechanically polished SS	1.7-4.2	SVP-600	Breakdown voltage distribution with constant ramp rate, for three different ramp rates. Time to breakdown distribution
Electro-polished SS	1.7-3	SVP-200	Breakdown voltage distribution with constant ramp rate

Sample Breakdown Voltage Distribution



- Measurements of breakdown voltage for a constant DC voltage ramp.

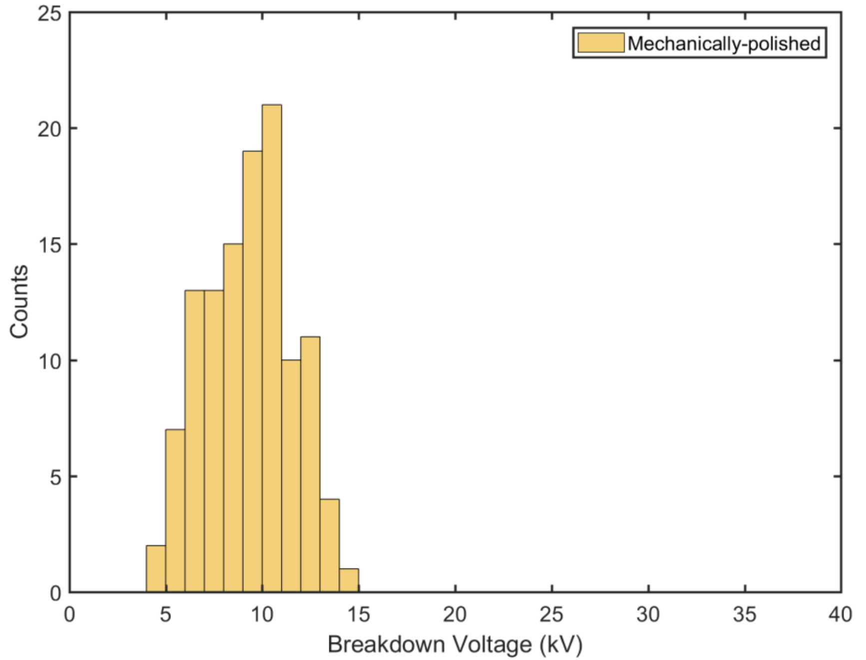
Mechanically polished electrode 1.7 K (~ 10 Torr).

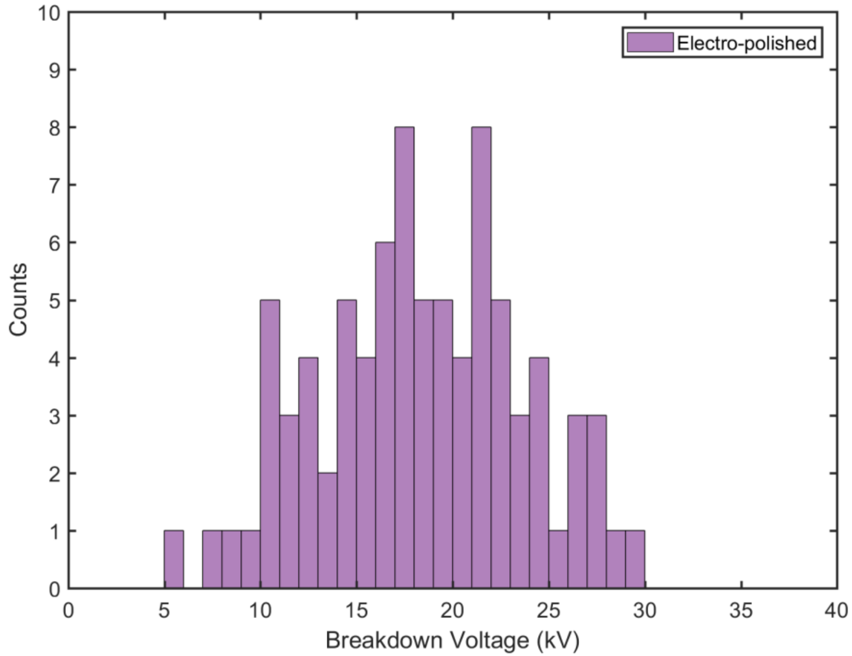
Fairly symmetric distribution.

Mean breakdown voltage is ~ 150 kV/cm!

Mechanically Polished vs. Electro-polished

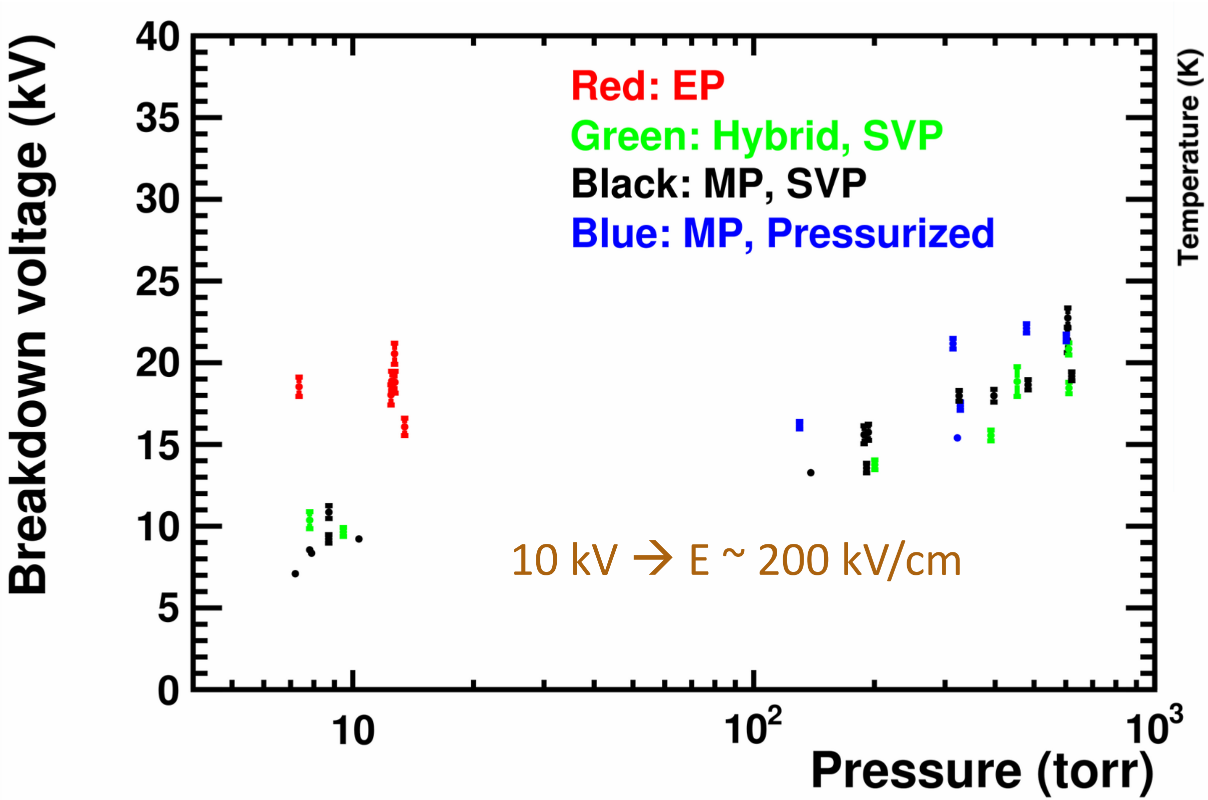
Both at ~ 1.7 K (~ 10 Torr)

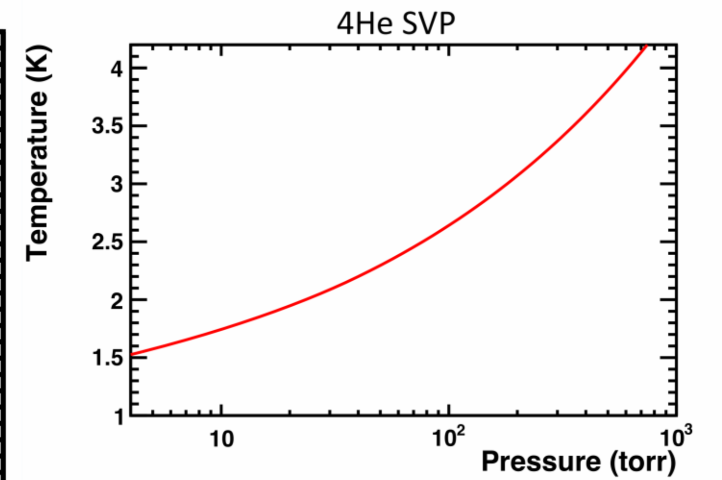




- Similar minimum/threshold breakdown voltage (~ 5 kV)
- Threshold voltage dependence on liquid properties at given temp/pressure and other characteristics of system rather than surface roughness?

Breakdown Voltage vs Pressure





Observed smooth transition across λ-point (no kink).

Breakdown voltage is a function of pressure.

Possible form for breakdown probability

- S: electrode surface area
- $\mu(E)$: probability density of breakdown initiation in a short time interval at a small element of an electrode surface with electric field, E.

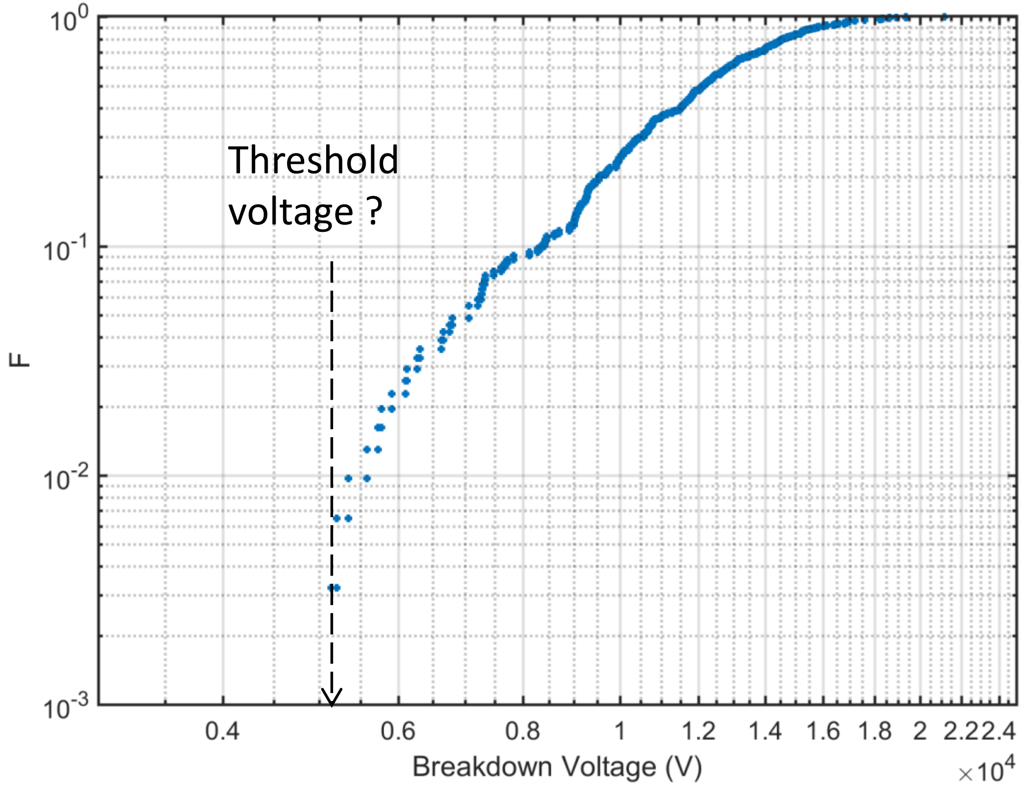
$$P_b = 1 - exp\left(-\int_0^t \left(\int_S \mu(E)dS\right)dt\right)$$

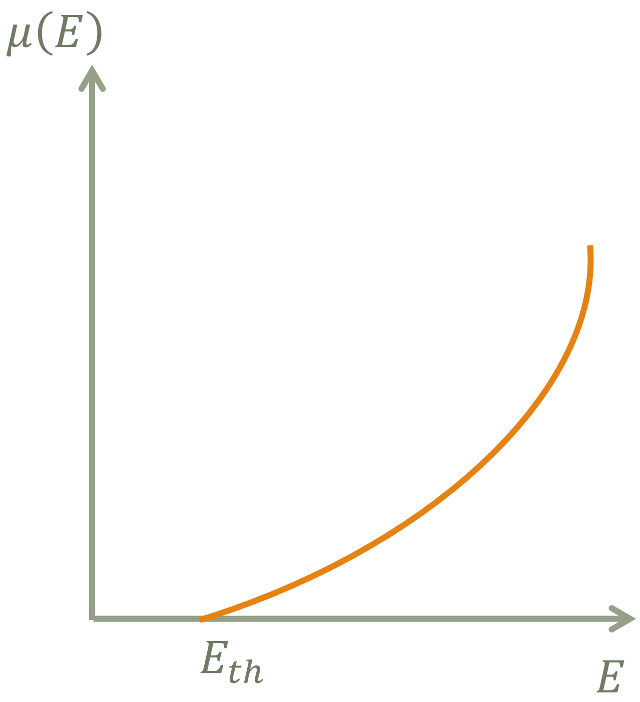
$$P_b = 1 - exp\left(-S\int_0^t \mu(E)dt\right)$$ (for flat electrodes)

A. L. Kupershtokh et al, J. Phys. D: Appl. Phys. 35 (2002).

Reconstruct $\mu(E)$ from data → determine breakdown initiation probability for different electrode geometries and voltage applications (magnitude, duration, etc.)

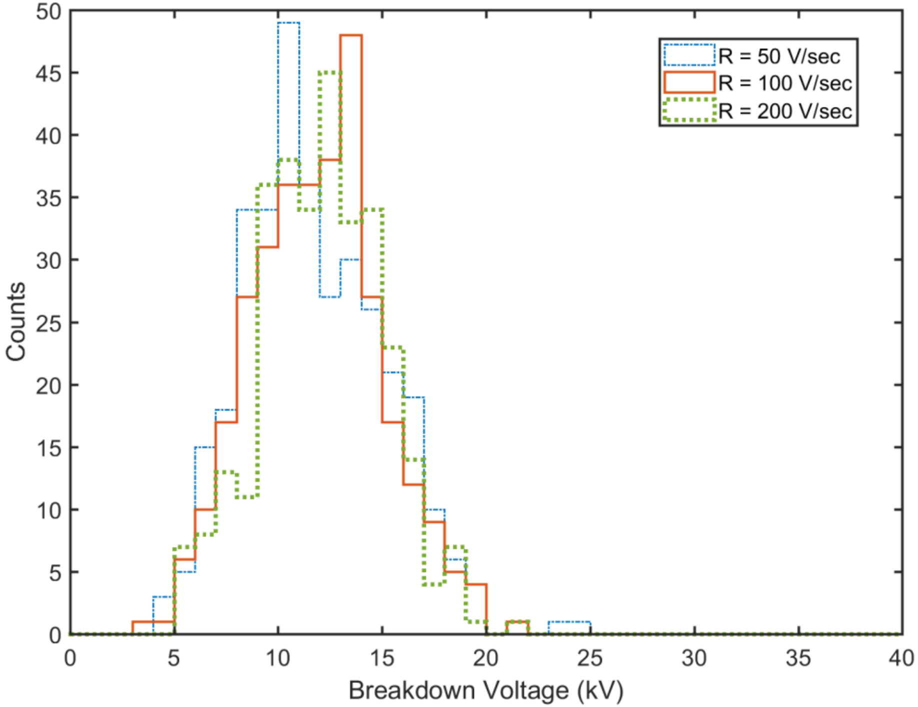
Threshold Voltage





- Practical experience: no breakdown in high voltage system below certain value.

Distribution for Different Ramp Rates



$$P_b = 1 - exp\left(-S\int_0^t \mu(E)dt\right)$$

$$= 1 - exp\left(-S\int \mu(E)\frac{dE}{k}\right)$$

k: voltage ramp rate

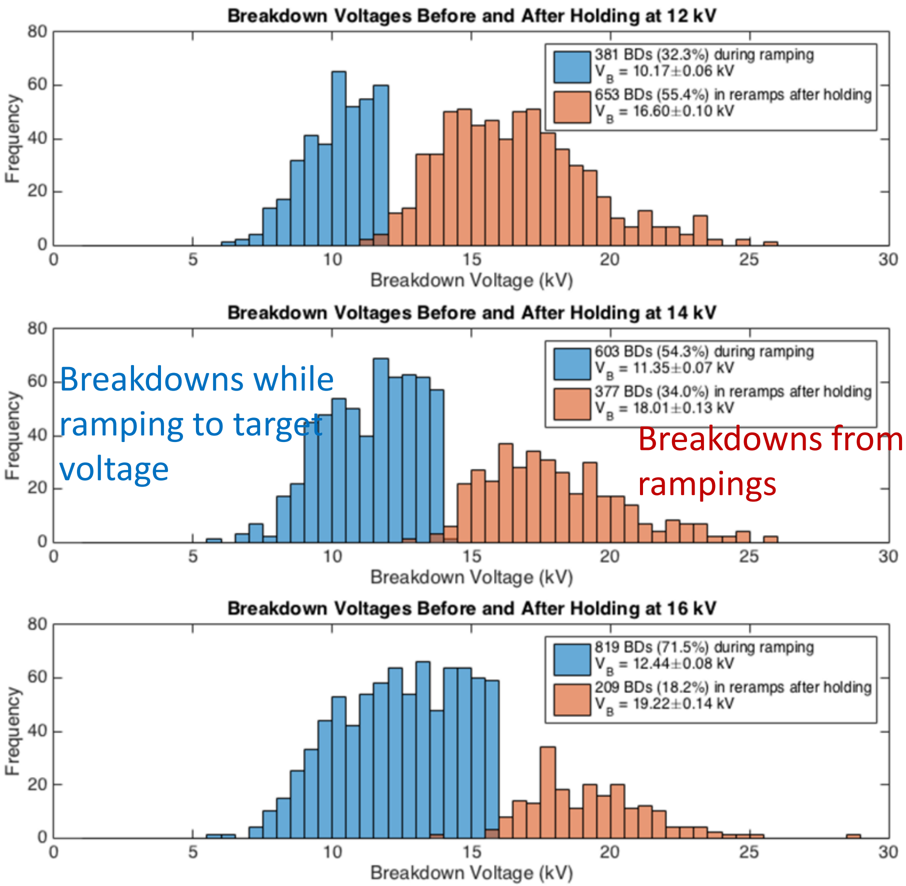
Very small difference among different ramp rates. $\mu(E)$ as breakdown prob. per unit time not consistent with data.

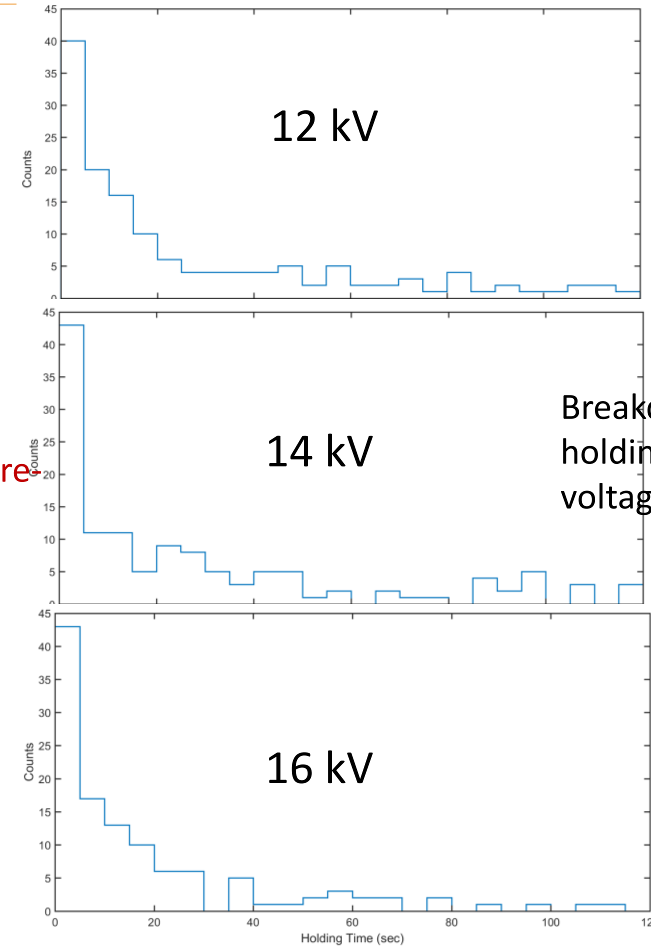
- Measurements with three different ramp rates are interleaved with each other in order to avoid the effect of "conditioning" affecting the results.

Breakdown Time Distribution

- Data taking procedure:
  - Ramp to a predetermined target voltage (e.g. 12 kV).
  - If breakdown occurs during ramp, record breakdown voltage.
  - If target voltage is reached, measure time until breakdown.
  - If breakdown is not observed after waiting for a preset amount of time (2 min) at target voltage, then ramp down voltage to zero and ramp back up until a breakdown is observed.

… continued


Breakdown Voltages Before and After Holding at 12 kV
381 BDs (32.3%) during ramping
V_B = 10.17±0.06 kV
653 BDs (55.4%) in reramps after holding
V_B = 16.60±0.10 kV
Breakdown Voltages Before and After Holding at 14 kV
603 BDs (54.3%) during ramping
V_B = 11.35±0.07 kV
377 BDs (34.0%) in reramps after holding
V_B = 18.01±0.13 kV
Breakdown Voltages Before and After Holding at 16 kV
819 BDs (71.5%) during ramping
V_B = 12.44±0.08 kV
209 BDs (18.2%) in reramps after holding
V_B = 19.22±0.14 kV
Frequency
Breakdown Voltage (kV)
Breakdowns while ramping to target voltage
Breakdowns from re-rampings

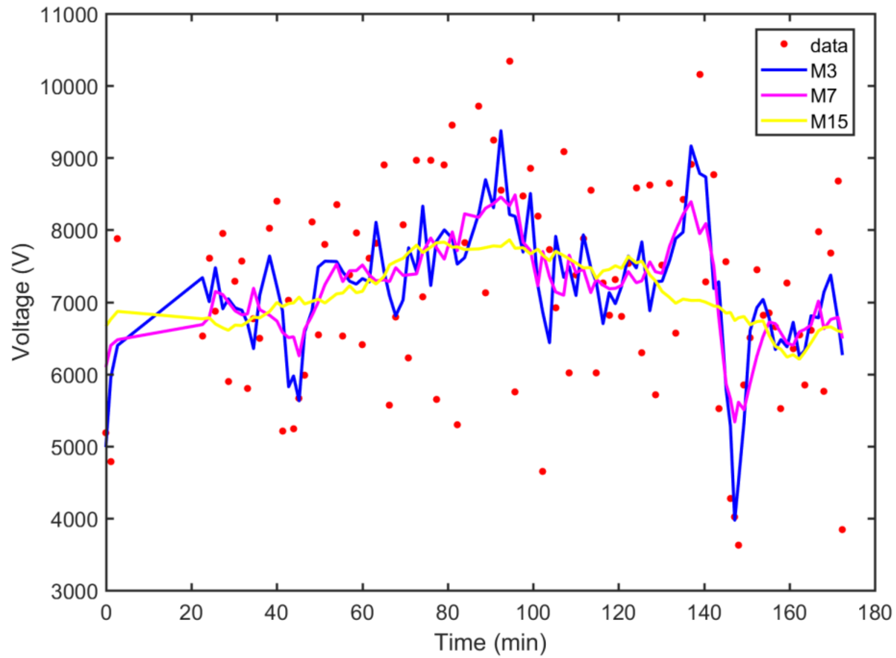

12 kV
14 kV
16 kV
Counts
Holding Time (sec)
Breakdowns while holding at target voltage

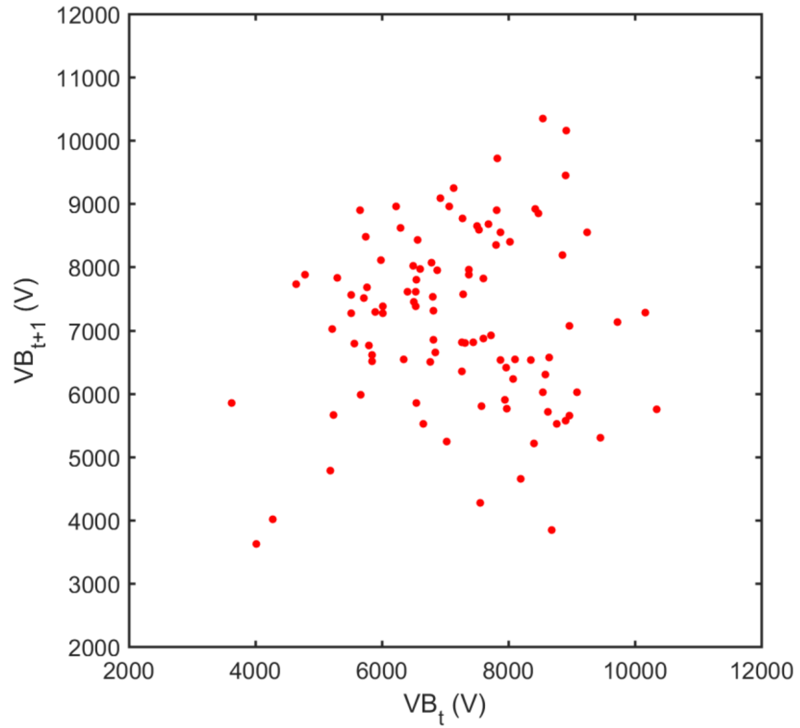
Correlation Between Breakdowns

- “Serial correlation”, "autocorrelation" or "lagged correlation”: relationship between observations of the same variable (breakdown voltage) over specific periods of time.
- We, intuitively, expect some form of correlation because each breakdown should alter the surface conditions of the electrodes, hence, affecting subsequent breakdowns.
  - Energy estimate of breakdown → crater created is O(size of surface features)

Search for First Order Correlation

- Consider one of the datasets:
  - 1.7 K (~10 Torr)
  - Mechanically polished

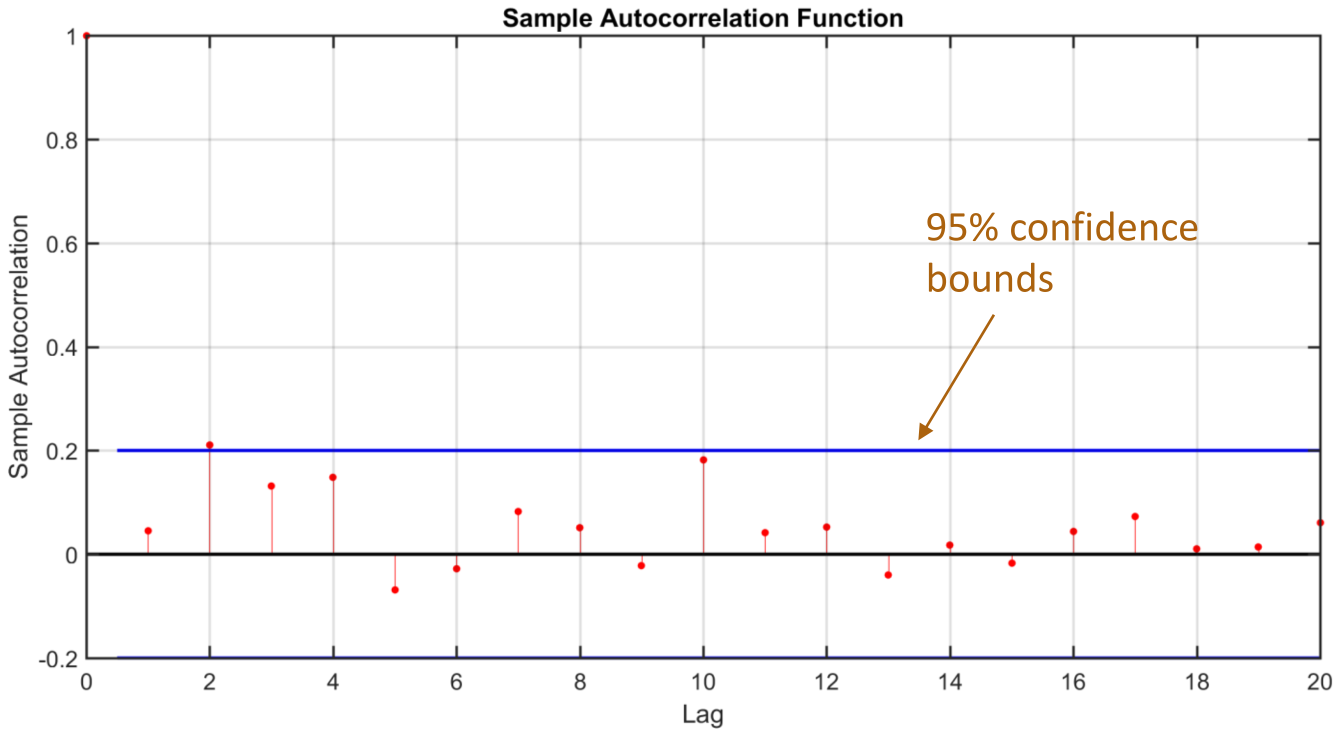




- No correlation found between variables from simple correlation coefficent

Higher Order Correlation

Correlogram



$$r_k = \frac{c_k}{c_0}, c_k = \frac{1}{T}\sum_{t=1}^{T-k}(y_t - \bar{y})(y_{t+k} - \bar{y})$$

Correlation from Test on Residuals

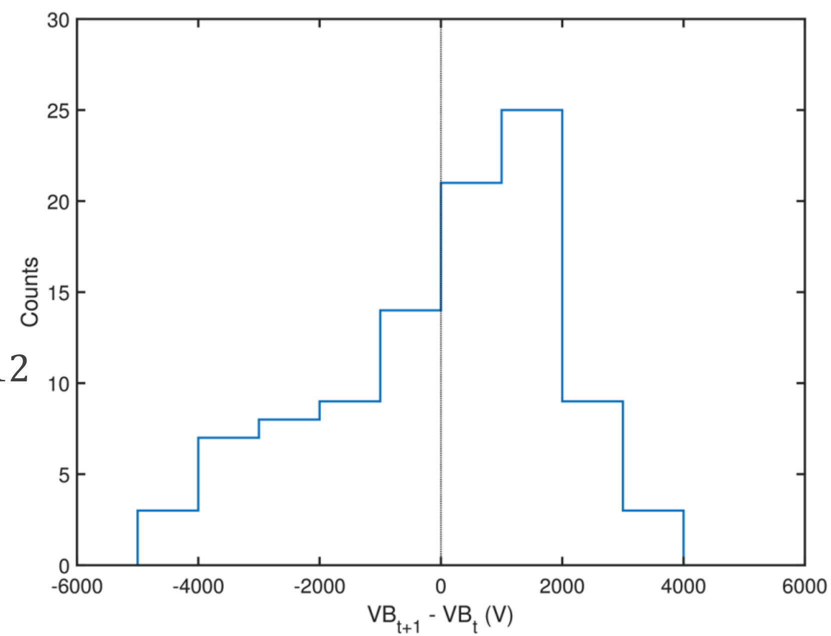
- Common tests for autocorrelation in residuals include the Durbin-Watson Test (lag k=1, linear corr test) and Ljung-Box Q-test (test on higher-order corr).
  - Weakness of these tests due to dependence on regression model (simplest model is a constant given the mean of the breakdown voltage distribution).
  - Test statistics can often lie in the borderline/gray area and uncertain whether to accept/reject test hypothesis.
  - Assumptions of test often not met by the data.

Hint of possible dependence

- Take a step back and ask whether samples are random (i.e. independent and from the same distribution).
- Use Sign-Test by computing differences $V_{t+1} - V_t$
- Under null hypothesis of randomness:
  - Positive difference distribution has mean $\mu = m/12$ and $\sigma^2 = (m+2)/12$ (m is number of differences in set).

For this dataset, number of positive differences is ~ 3σ from expected mean

Skewness: -0.5728

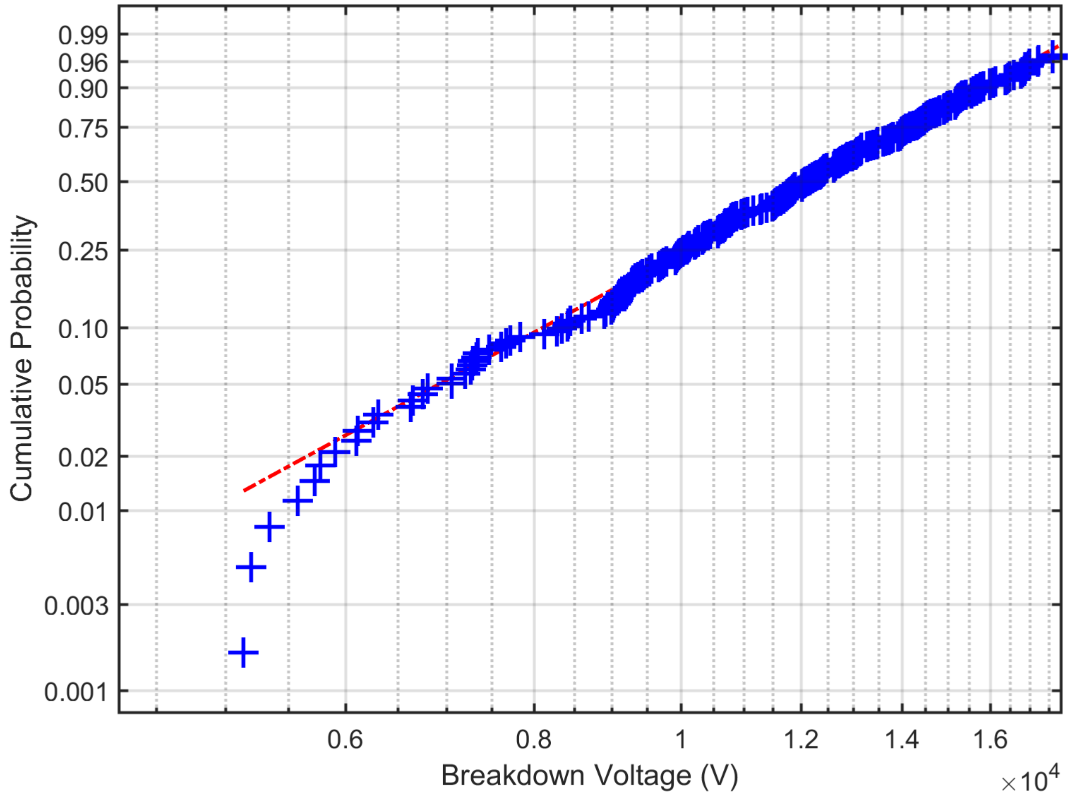


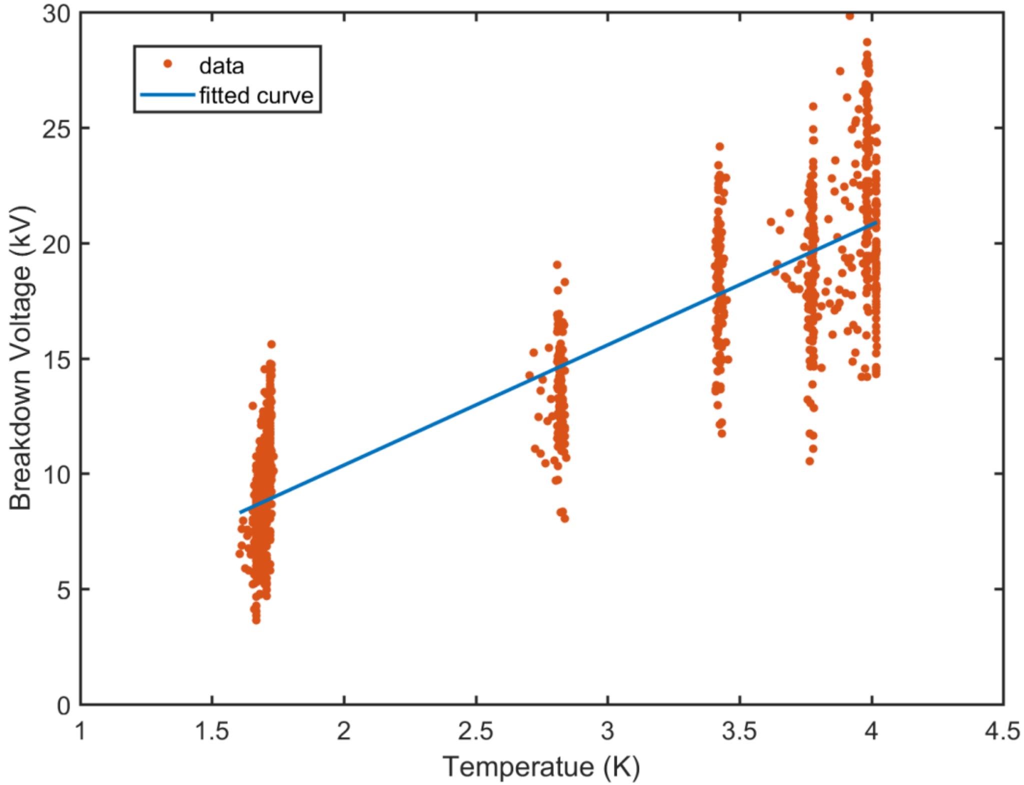
Summary

- Copious amount of data gathered for difference pressures, temperatures for two electrode surfaces in liquid helium.
- Typical breakdown field: 200 – 400 kV/cm
- Data allow separation of temperature and pressure dependence
- Surface smoothness has large impact on mean breakdown voltage.
- Very large dataset, need more time to make sense of it.

Thank you for your time!

- The Weibull plot
- Vertical axis: Weibull cumulative probability expressed as a percentage
- Horizontal axis: ordered failure voltage (in a log10 scale)
- The vertical scale is ln(-ln(1-*p*)) where *p*=(*i*-0.3)/(*n*+0.4) and *i* is the rank of the observation. The scale is chosen in order to linearize the resulting plot for Weibull data.





data
fitted curve
Breakdown Voltage (kV)
Temperatue (K)
0
5
10
15
20
25
30
1
1.5
2
2.5
3
3.5
4
4.5

Breakdown Voltage vs Temperature