Electric field development for cryogenic nEDM experiments

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UNIVERSITY OF SUSSEX

Science & Technology Facilities Council

Contents

- Motivation for use of LHe as a medium
- ‘Medium’ scale E field measurements with insulator present; technique and results
- Simulations to optimise electrode geometry
- ‘Large’ scale E field measurements; technique and preliminary results

Motivation for cryogenic nEDM

Superfluid LHe at 0.5K is a super thermal source for UCN which can potentially give higher N by having it in-situ with an nEDM experiment.

Dielectric strength of LHe is poorly understood, however, fields in excess of 100kV/cm at 4.2 K were reported separately by Long et al. and A.J. Davidson.

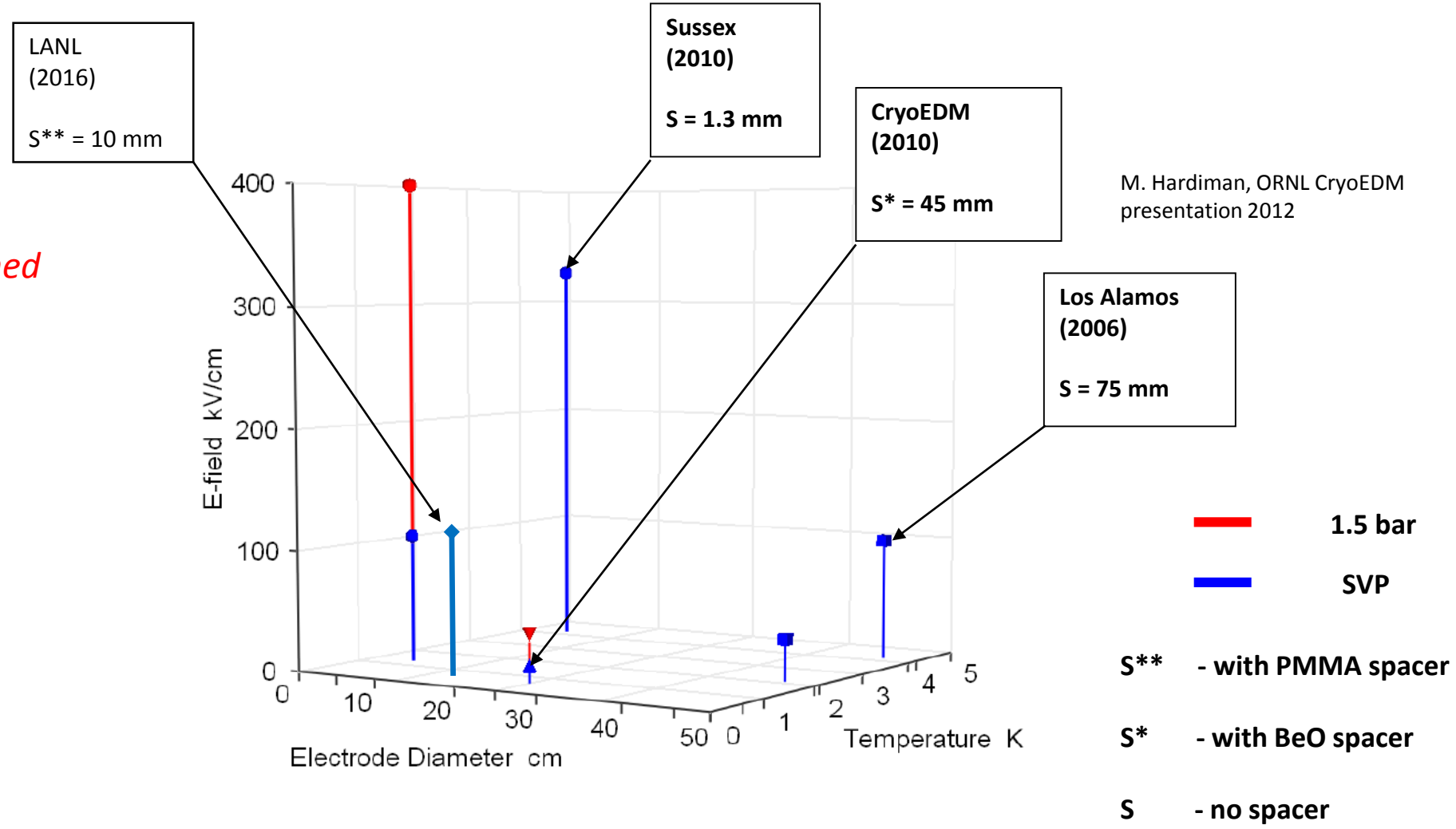
$$\sigma_{d_n} = \frac{\hbar}{2\alpha T_s E \sqrt{N}}$$

Room temperature: ~11 kV/cm

J. C. Long et al., High voltage test apparatus for a neutron EDM experiment and lower limit on the dielectric strength of liquid helium at large volumes, 2006, physics/0603231
A. J. Davidson, PhD thesis, University of Sussex, 2011

What is the maximum E-field in a cryogenic EDM Ramsey Cell at 0.5 K?

- *Diamond is E field obtained*
- *Inverted is predicted*
- *Everything is measured breakdown E field!*



Rationale

- All measurements presented are in LN2, behaviour of the fluid is similar to that of LHe
- Insulators used are analogues for materials with good Fermi potential for UCN; alumina = BeO, borosilicate glass = quartz (similar structure)
- Planned measurements in LHe will be at 4.2 K SVP as pressurising volume will recover E field.

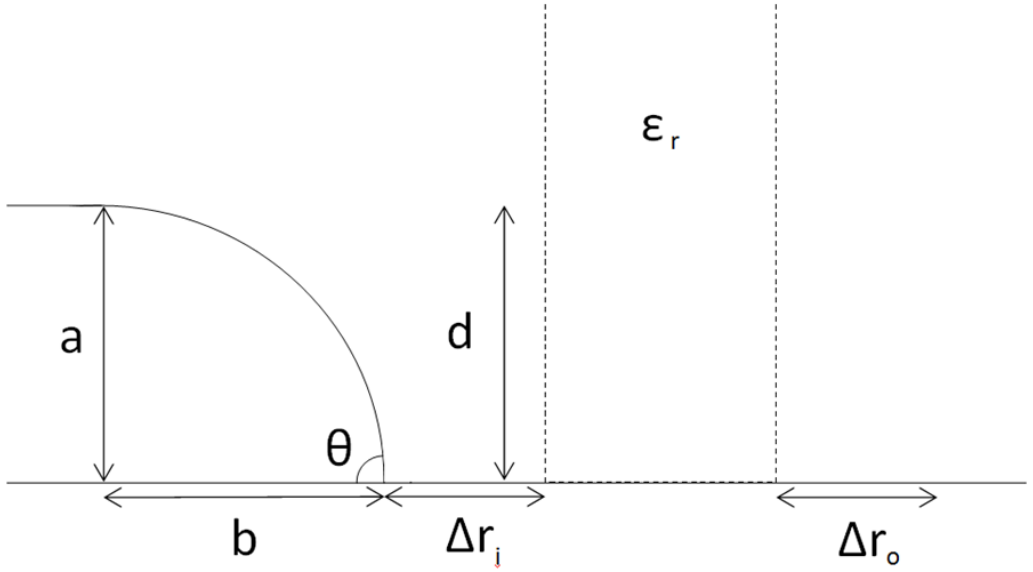
Experimental results for breakdown ‘medium’ scale tests

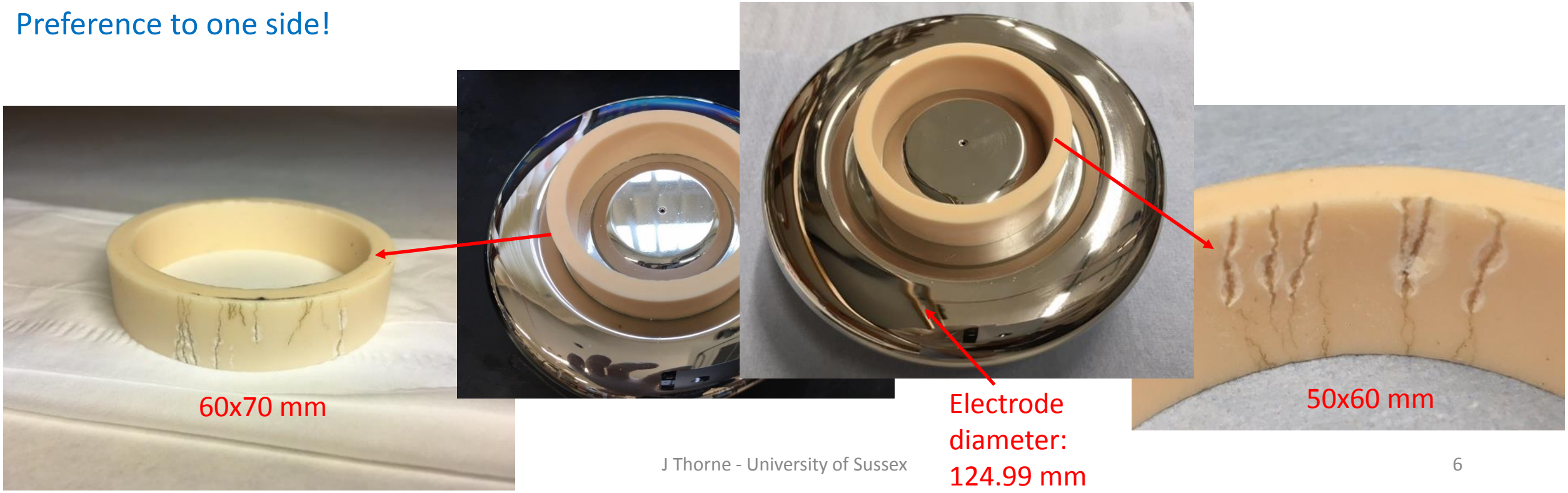
Breakdown runs in LN2; one tight to groove on outside, other tight to groove on inside at 4.94 mm separation.

Alumina relative permittivity: 9.3-11.5 (BeO: 6.76)

Tracking observed on both!

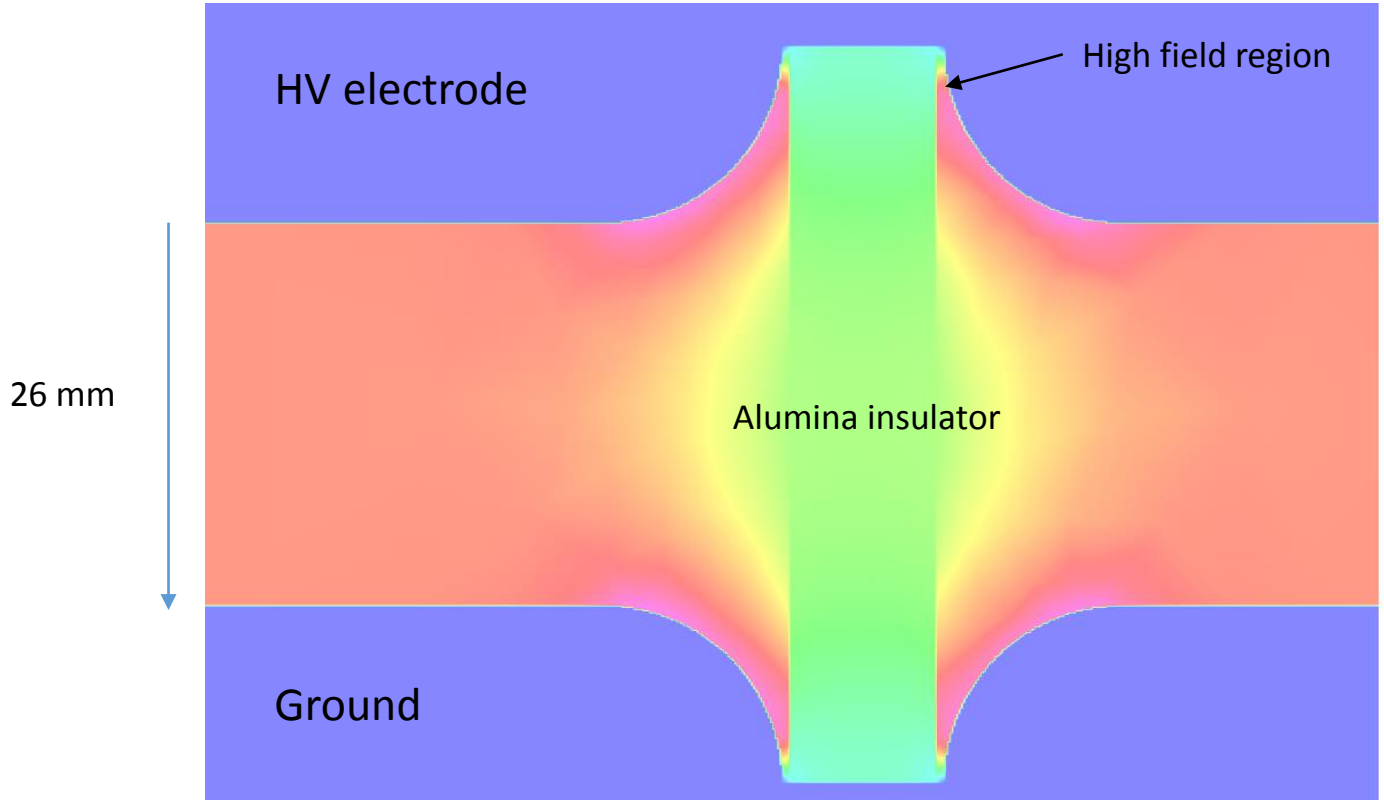
Preference to one side!

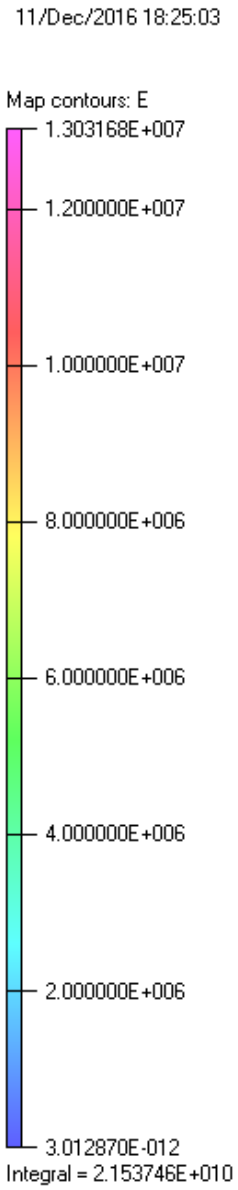




Proposed Mechanism

- Experimental thinking; the groove and presence of the insulator creates high field region at the cathode triple junction, “weak spot” of system, breakdown originates at the region by creating local heating forming gas bubble in which the breakdown can propagate to the anode.
- Tracks are the result of vaporisation of electrode material in the cathode triple junction, in this case stainless steel, via the cavitation process that forms the bubble.



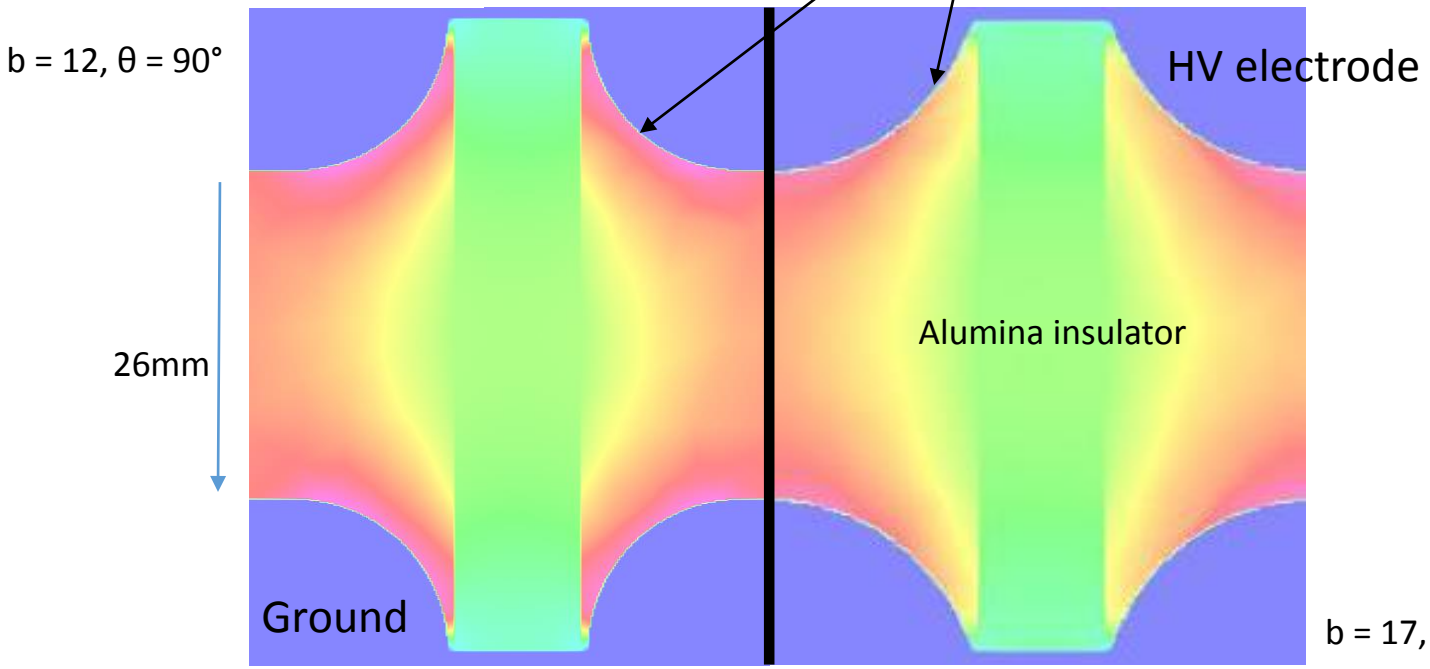


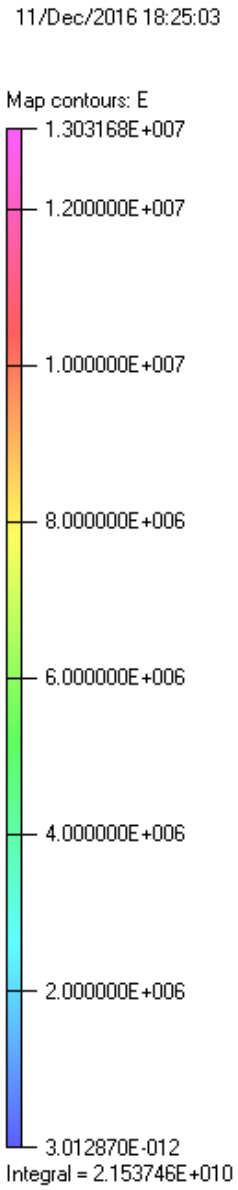
Optimised groove geometry

Simulations showed:

- Increasing b and decreasing θ lowers the high field near insulator wall.
- Lower ε_r decreases field near insulator wall.
- Increasing d will lead to trapping of UCN.
- Increasing Δr also decreases the highest field value – how to centre it?

E field has ~6% drop on groove, value less than field between electrodes!





Experimental results using glass insulators on ‘medium’ scale

Borosilicate glass insulator 60 mm x 70 mm in LN2

BG: ε_r = 4.6 (Quartz: 4.5)

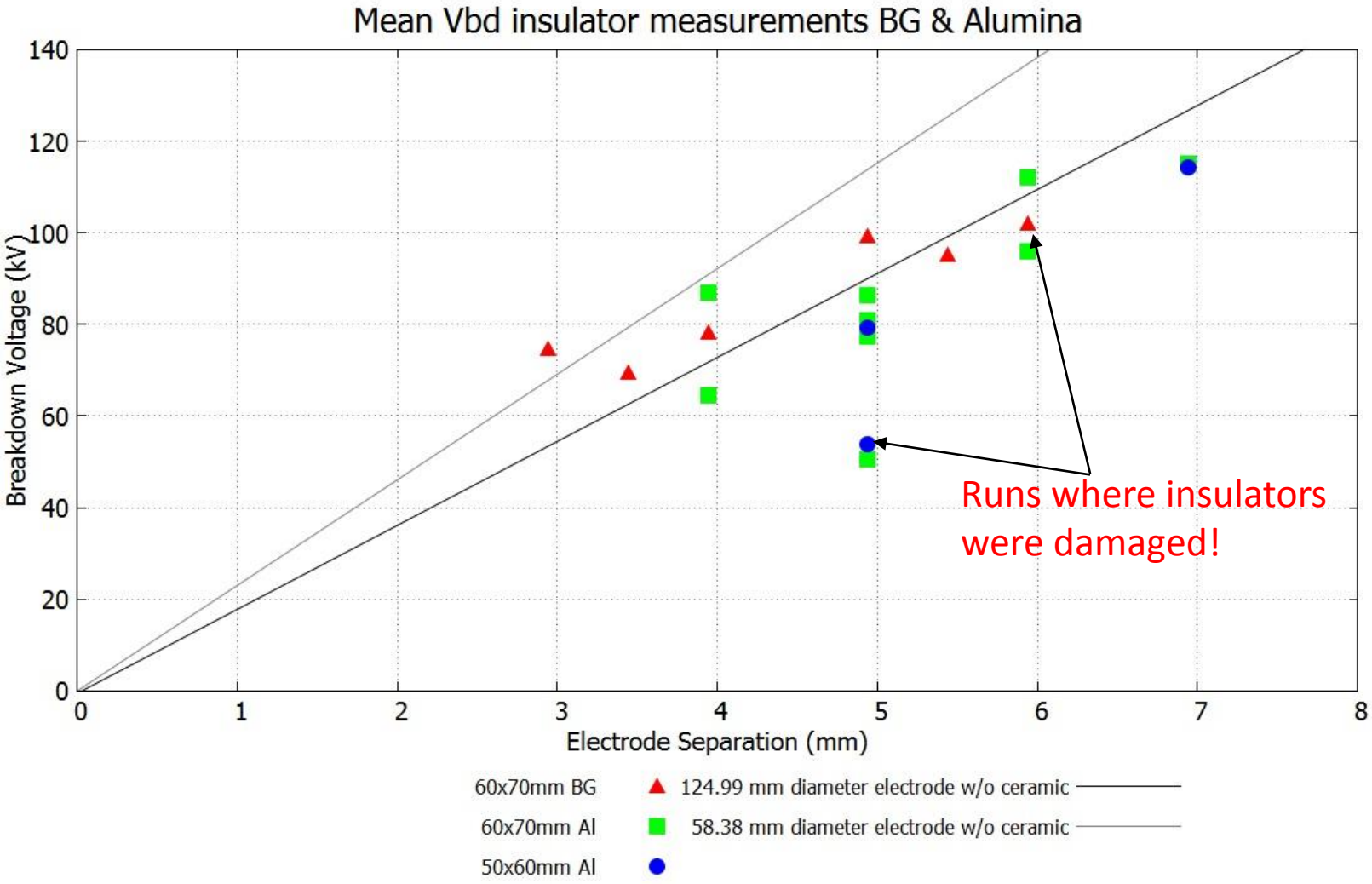
- Significant chipping from mechanical compression between electrodes.
- Polishing of electrodes and glass seemed to over come the problem of chipping, possibly relieving the local strain present.

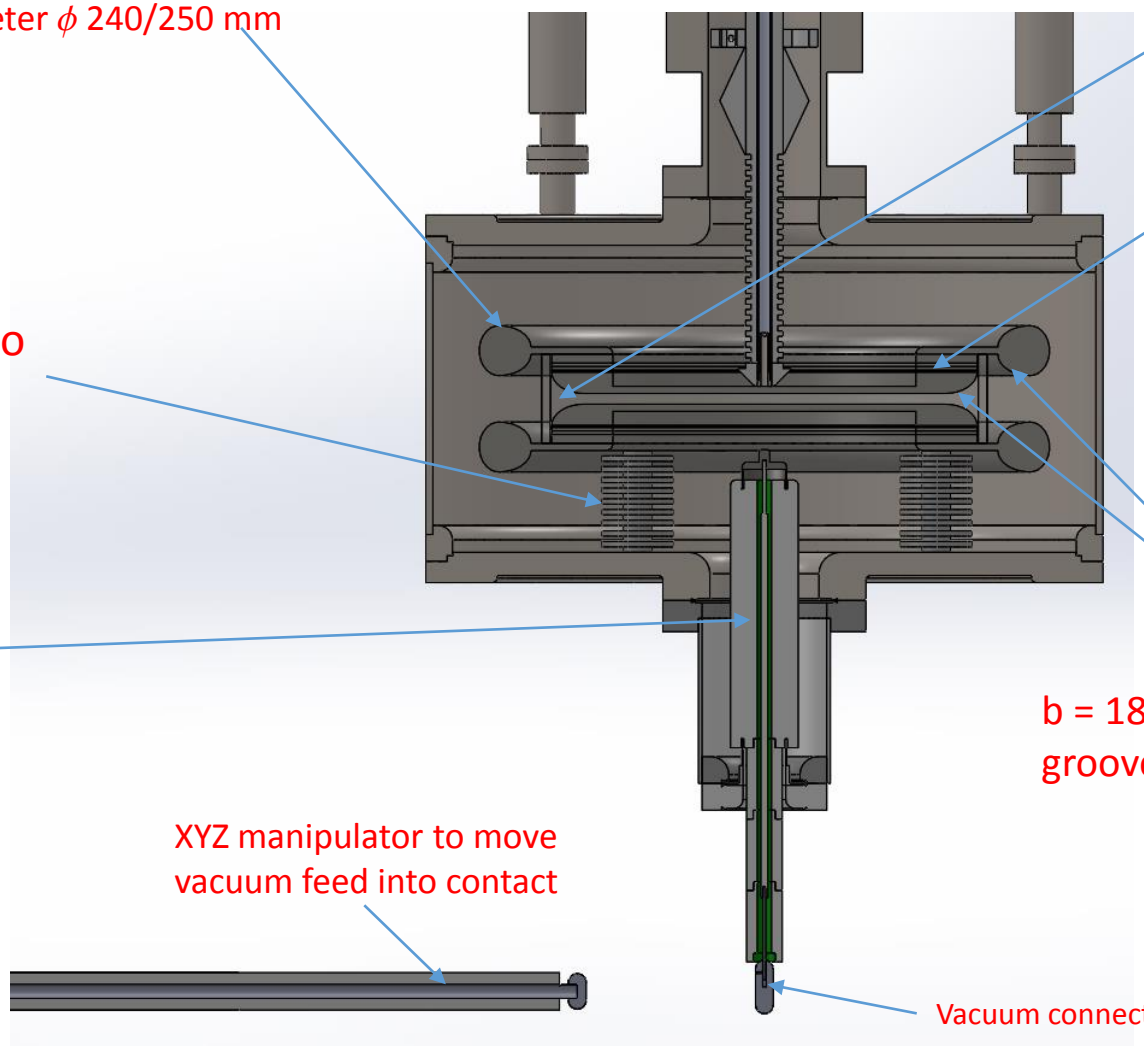
Polished surface!

Shattering tentatively attributed to cavitation stress on the triple junction surface or shock wave in fluid from breakdown could also stress the insulator.

Comparison of BG with alumina insulators

- Tracking never observed in ANY of the glass runs!
- Area effect seems to be present!
- Higher relative permittivity insulator reduces V_{bd}
- Insulator damage lowered V_{bd}

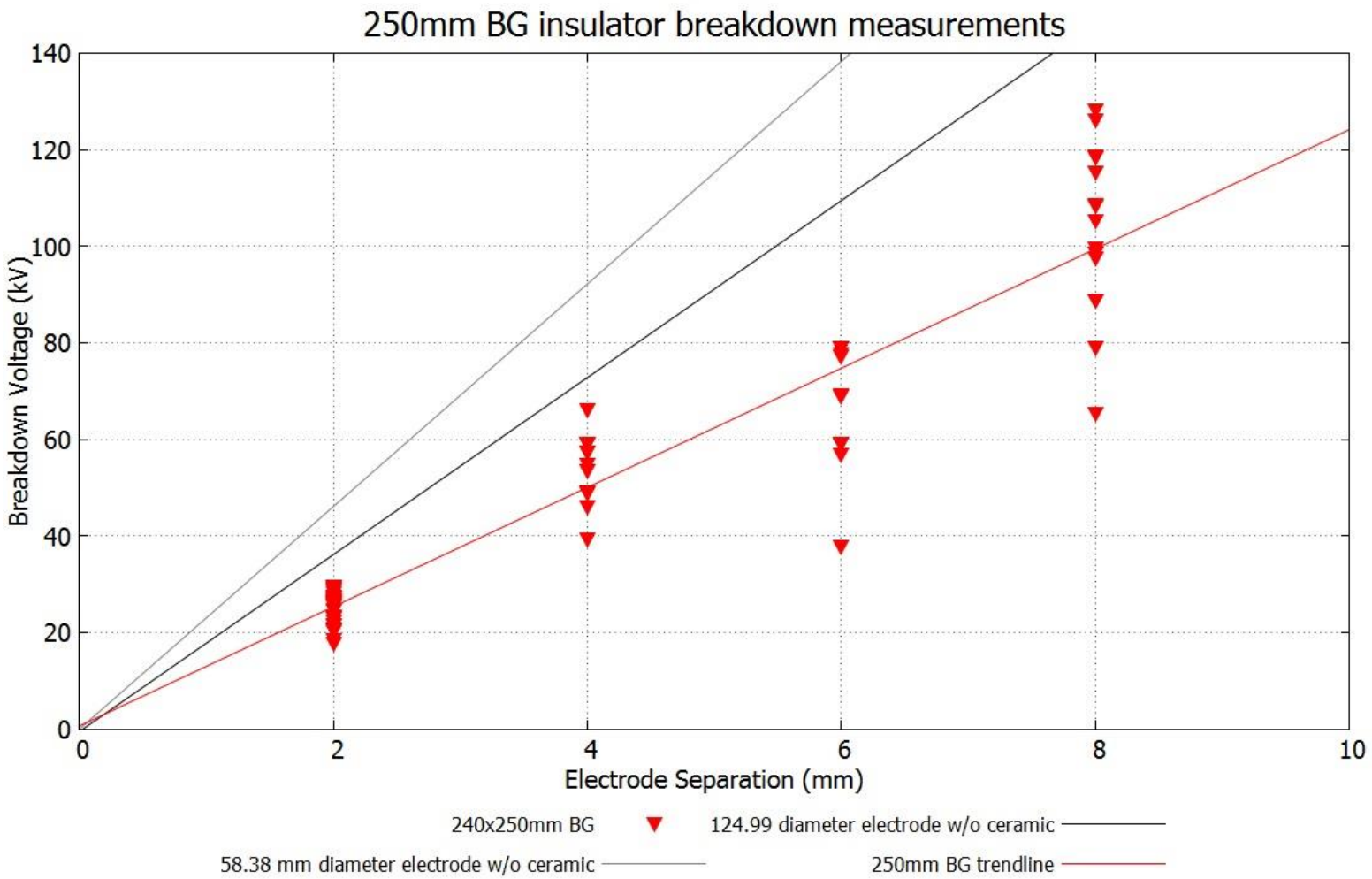




Experiment	Electrode internal geometry (mm)	Separation (mm)
PSI	ϕ 470	120
CryoEDM	ϕ 250	45

Preliminary ‘large’ scale measurements in LN2

- Surface area effect, ~54% reduced mean V_{bd} from 58.38mm trend line.
- Linear extrapolation to 26mm for 250mm: V_{bd} = 321.7 kV in LN2.
- Measurements were only done with +130 kV on the top electrode!

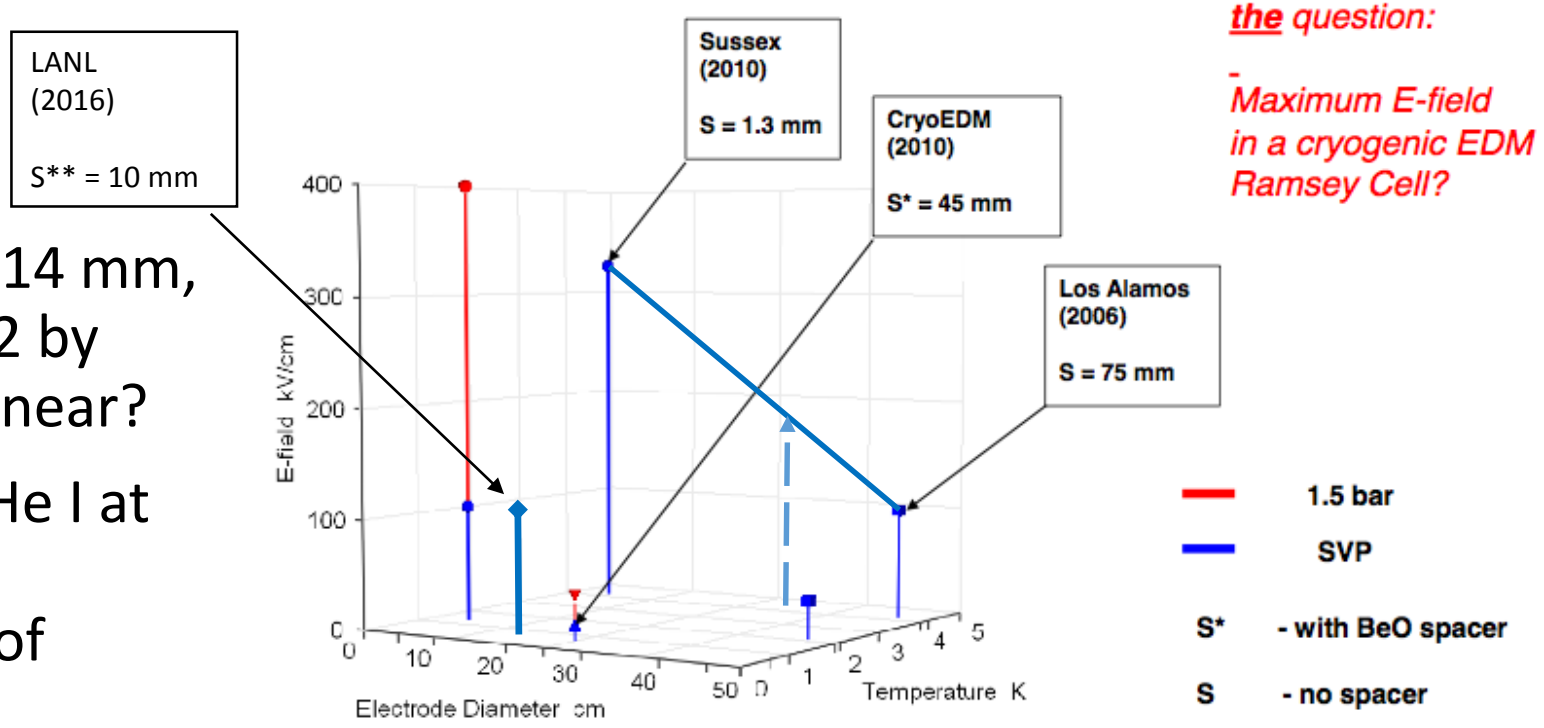


Conclusions and outlook

- Experimental results and simulations give us a possible mechanism for explaining breakdowns in a cryogenic liquid with an insulator present.
- Insulator reduces V_{bd} by about $\sim$12% for alumina, BG seems to recover this back to the trend line
- Surface area effect does reduces V_{bd} by $\sim$54% from 1cm -> 24cm ID
- However, measurements thus far have only been on small separations in LN2!
- Dielectric strength of LHe I is $\sim$60% lower then LN2, expect breakdown voltages at 26 mm on ‘large’ scale measurements at 193.02 kV using LN2 results

Conclusions and outlook

- Aim to complete breakdown measurements for separations at 14 mm, 18 mm, 22 mm, and 26 mm in LN2 by November; is V_{bd} vs. separation linear?
- By December measurements in LHe I at 4.2K SVP will be performed, same separations in LN2, with the goal of getting to 26 mm for 100 kV/cm.



the *question:*

Maximum E-field in a cryogenic EDM Ramsey Cell?

Acknowledgements

Would like to thank;

- Mike Hardiman
- Ian Wardell
- Clark Griffith

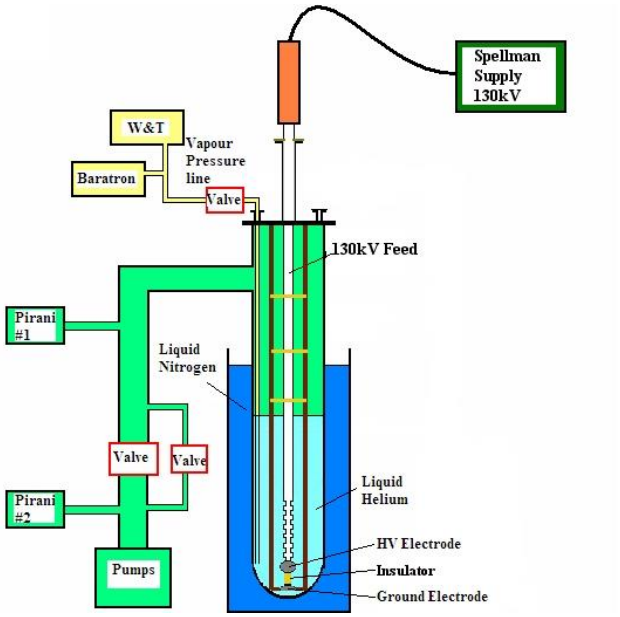
For their sizable contribution to this project.

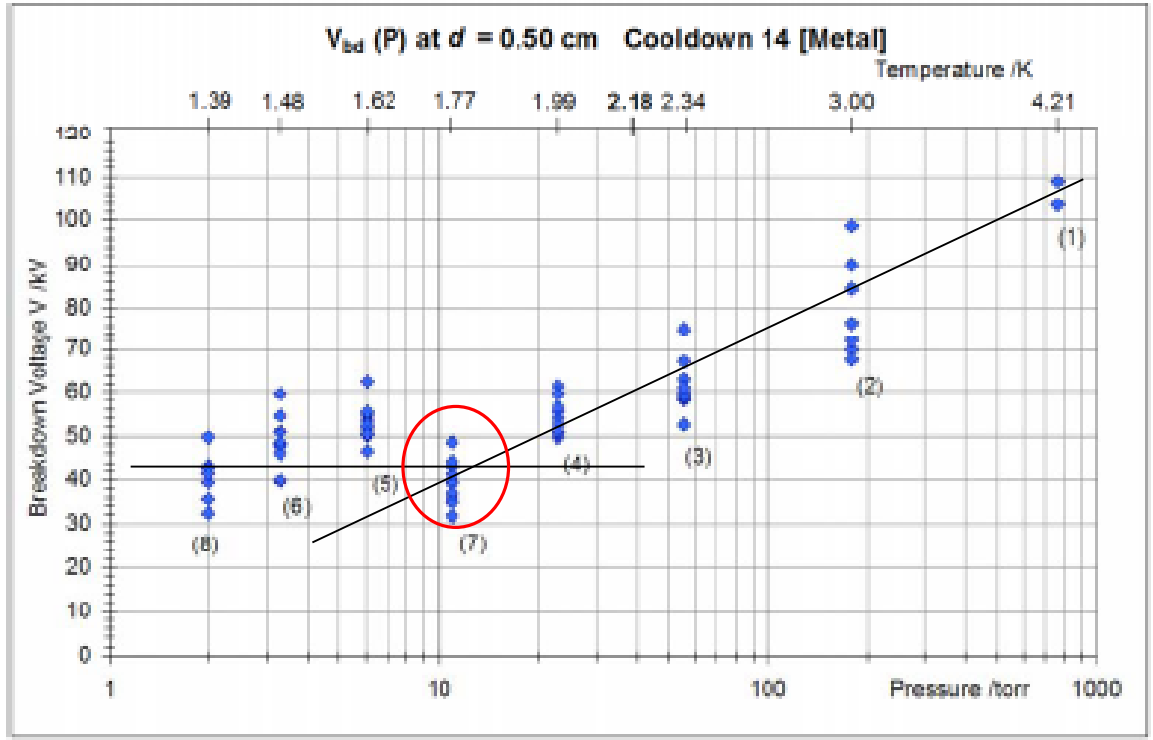
With special mention to Estelle Chanel and Dave Shiers for the help with various points on the project

Backup slides

Dielectric Strength of Liquid Helium

Temperature Dependence under SVP – James Karamath





Reduction by factor ~ 2-3

Nothing obvious at the λ-point

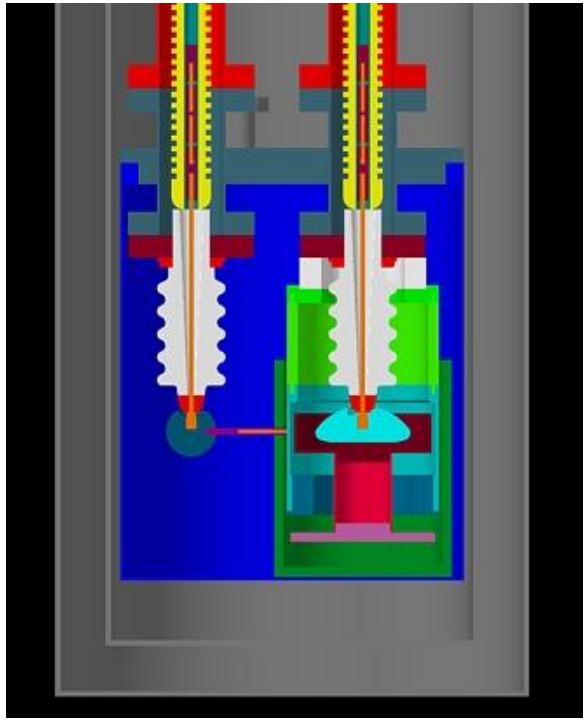
Minimum depth of He liquid gives min $P_{hydrostatic}$

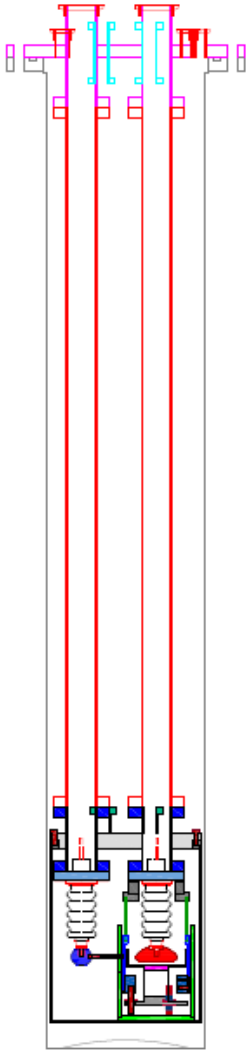
Is variation due to Temperature or Pressure ?

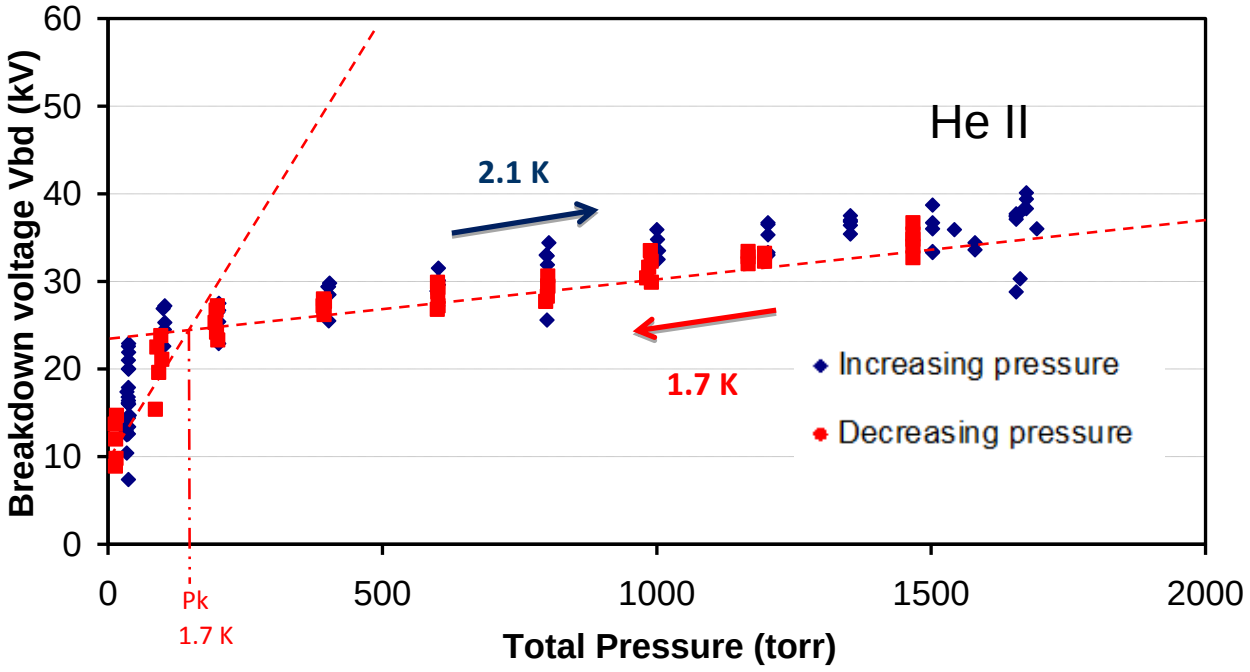
AJD apparatus for pressure dependence measurements

4.2K ≥ T ≤ 1.3K
P < 2 bar
V ≤ 50 kV using 30kV FT

Electrodes:
ϕ 53 mm overall
ϕ 32 mm plane
1.27 mm separation







Pressurising the LHe, recovers the voltage!

Two regimes

Same in superfluid to $\sim 0.6\ T_\lambda$

Breakdown sequence:

Initiation

→Neutral (seed) bubble

→Ionised bubble

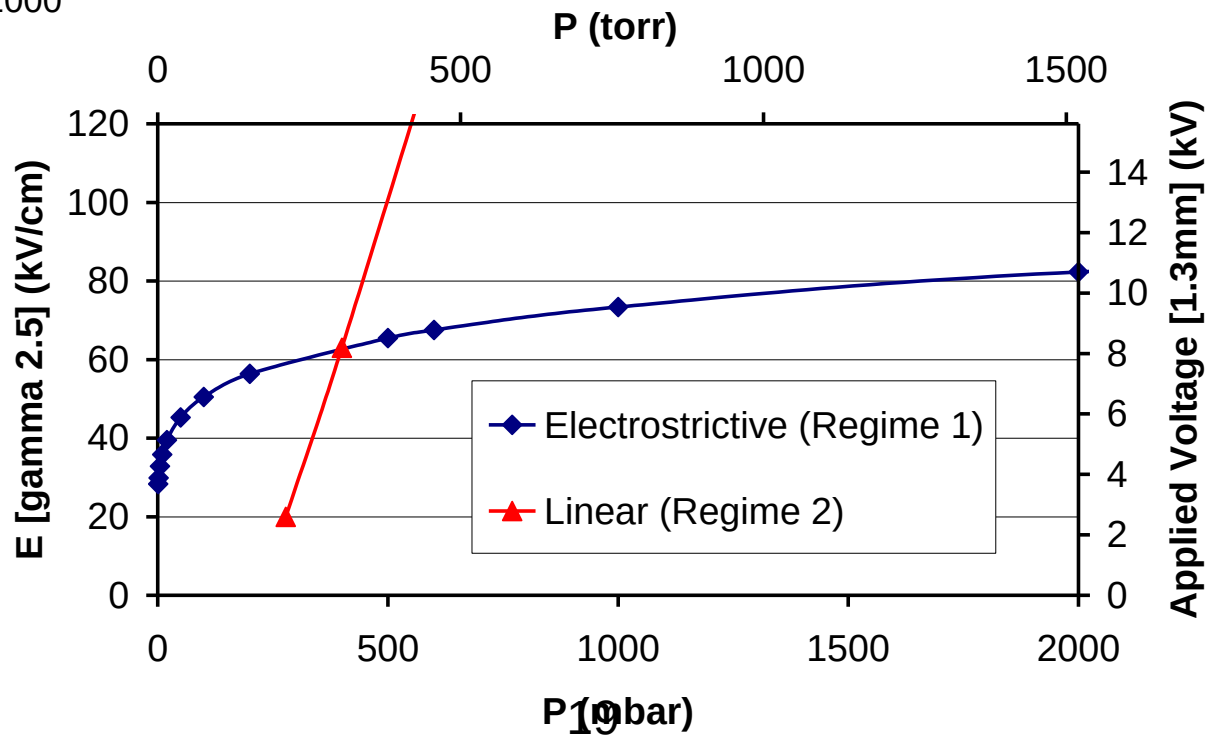
→Streamer

→Full bkdwn

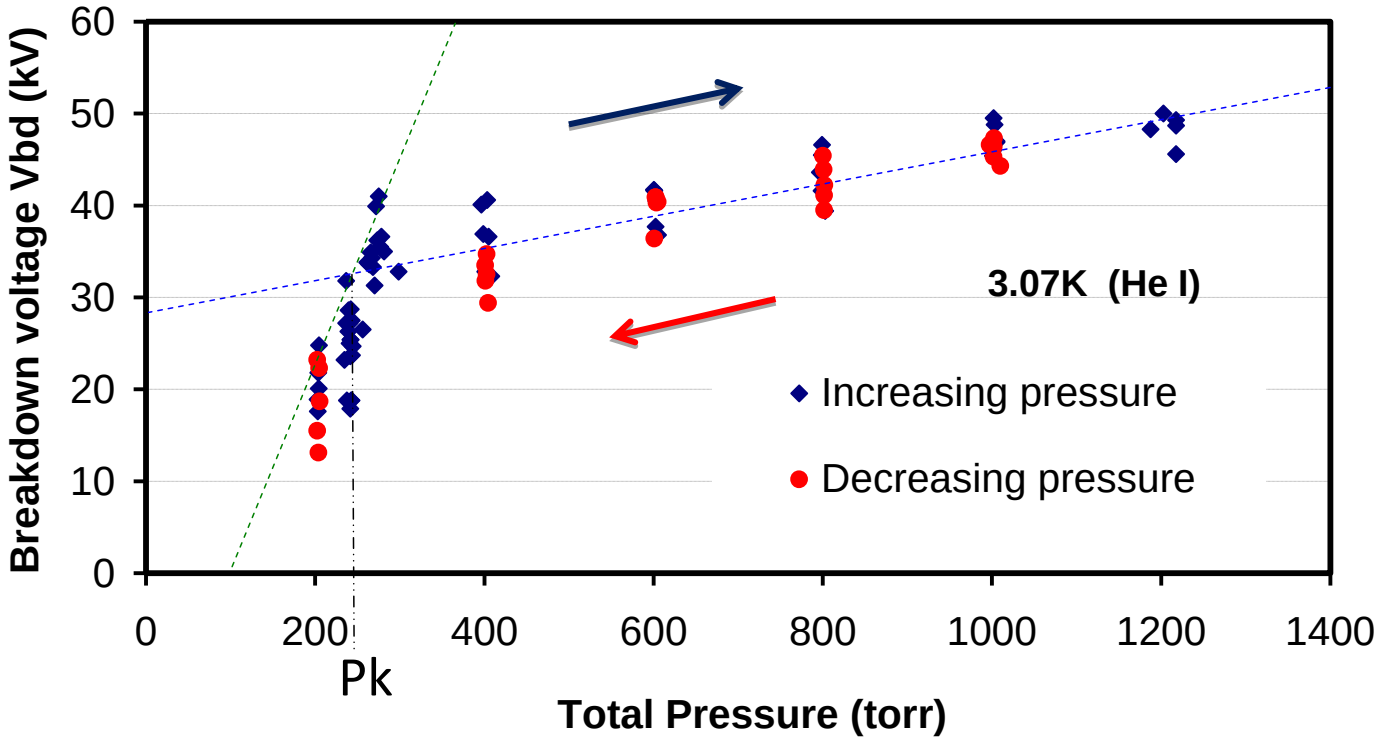
Two regimes comes from this bubble creation; dependent on its stability:

$$P_{hydro} + P_{app} + P_{electrostrictive} + \sigma C - P_{bubble} = 0$$

Garton and Krasucki
Proc Roy Soc A280 211 (1964)



General Form of V_{bd} (P) at Constant T for Liquid Helium

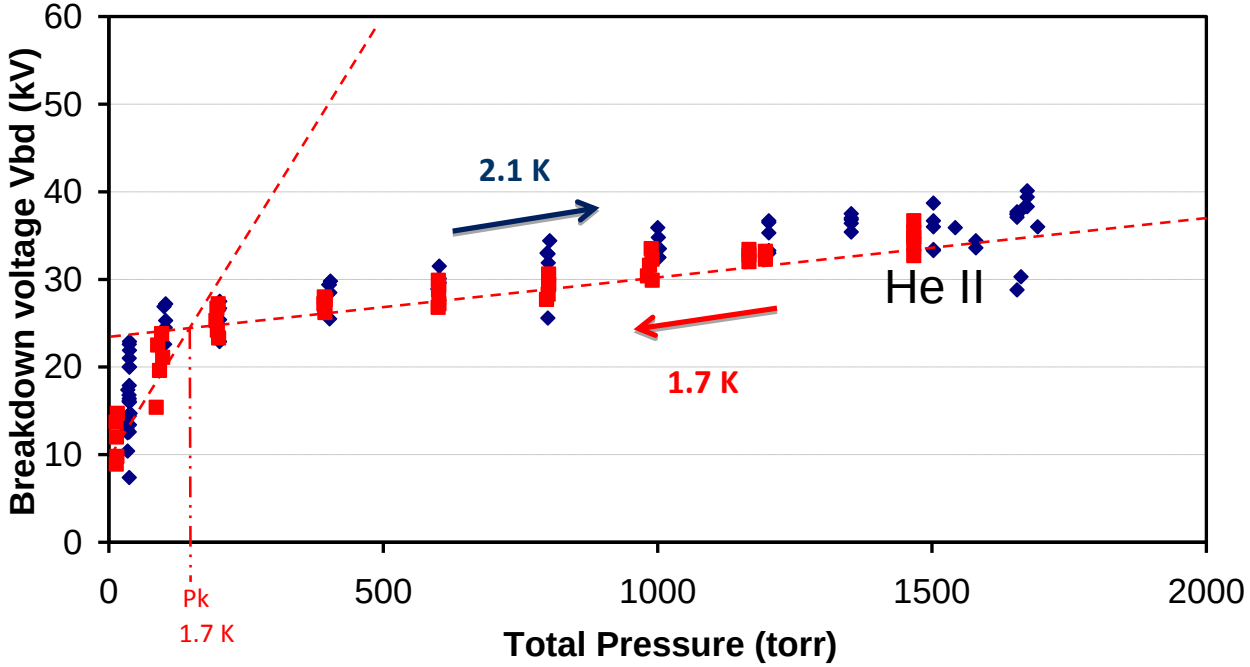


Electrode(s):
Φ 53 mm overall
Φ 32 mm plane
1.27mm separation

Two Regimes
No Hysteresis

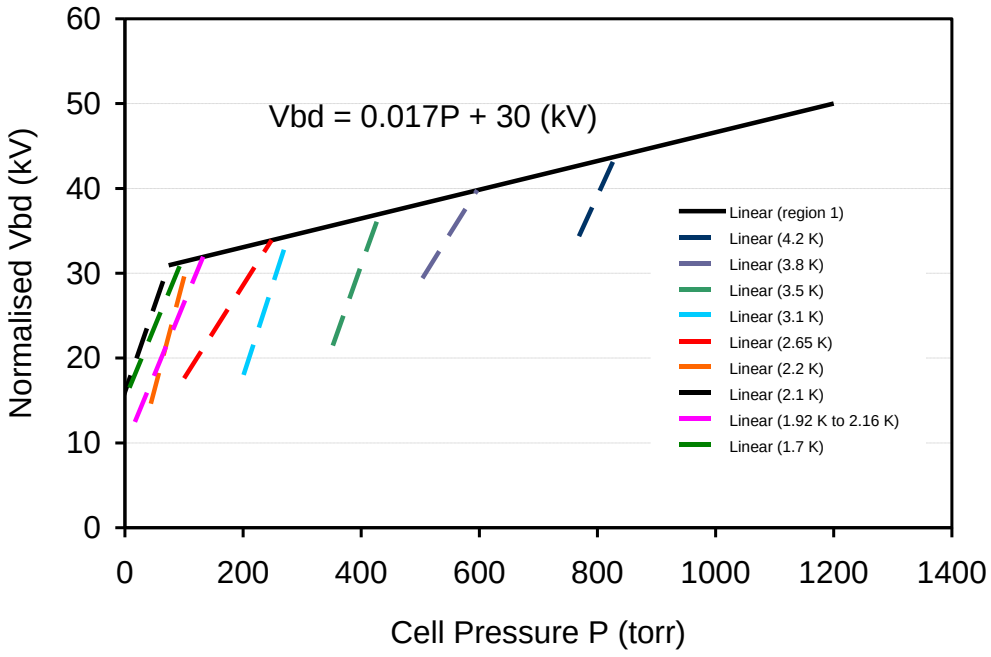
In superfluid to 1.7K

(now extended to 1.3K – Jack Roberts & Stuart Ingleby)



Electrode(s):
Φ 53 mm overall
Φ 32 mm plane
1.27mm separation

Two Regimes
No Hysteresis
Same in Superfluid to ~0.6 T_λ



All V_{bd} data normalised to 50kV at 1200 torr

Linear fits to each regime gives P_k

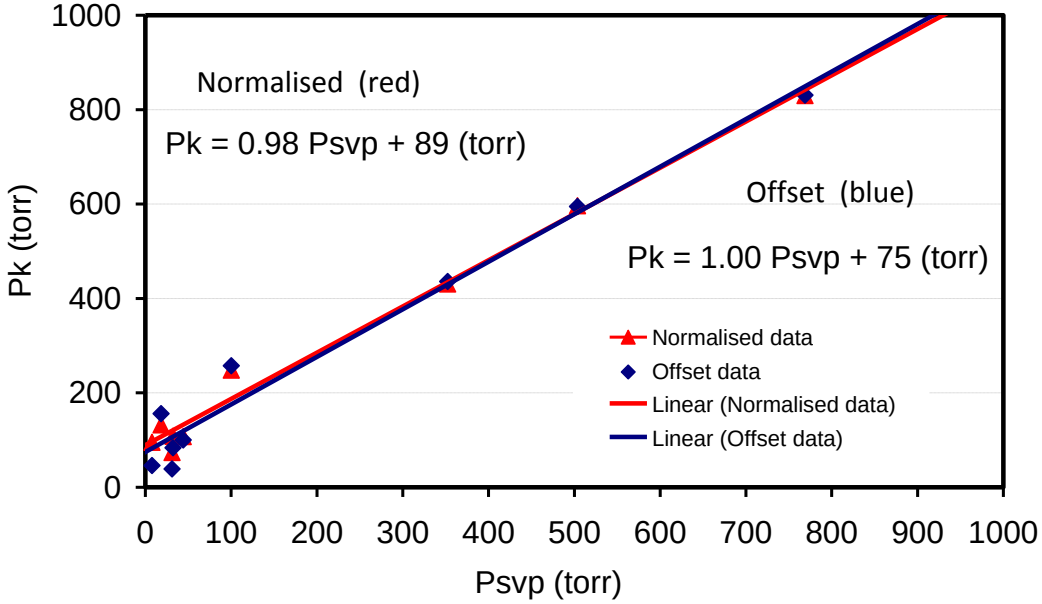
- the *"Kink Pressure"*

P_k linear with SVP & offset by 90 torr

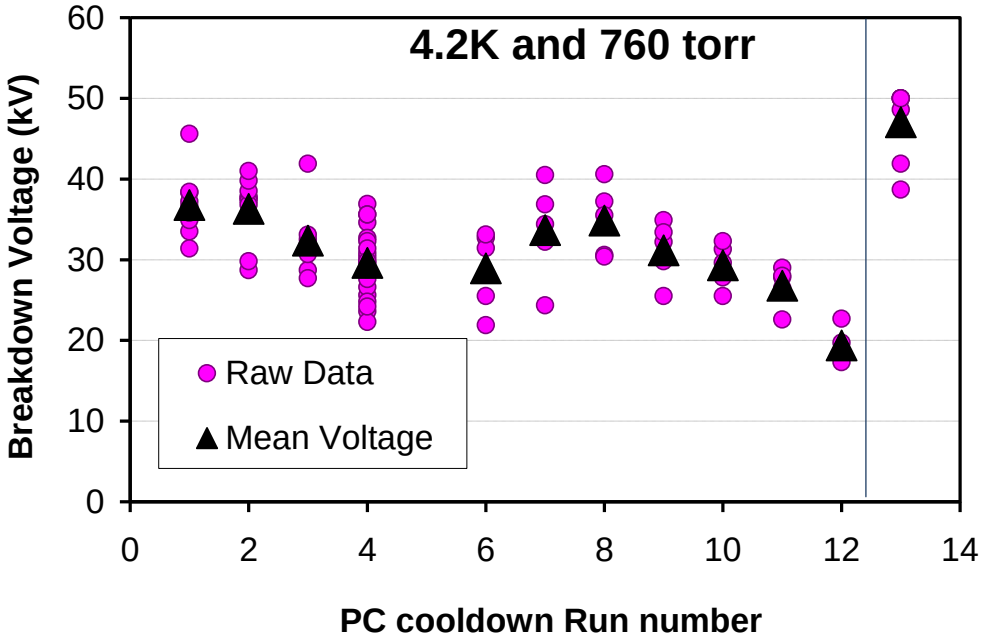
? significant number ?

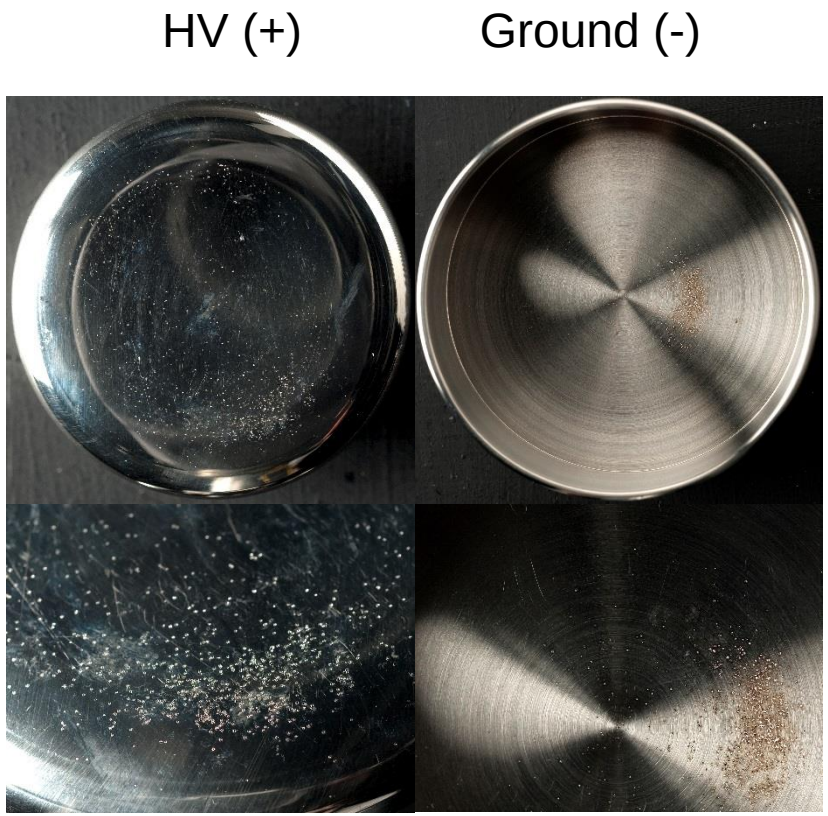
- probably not…

But why <u>two</u> regimes???



Effect of multiple breakdowns





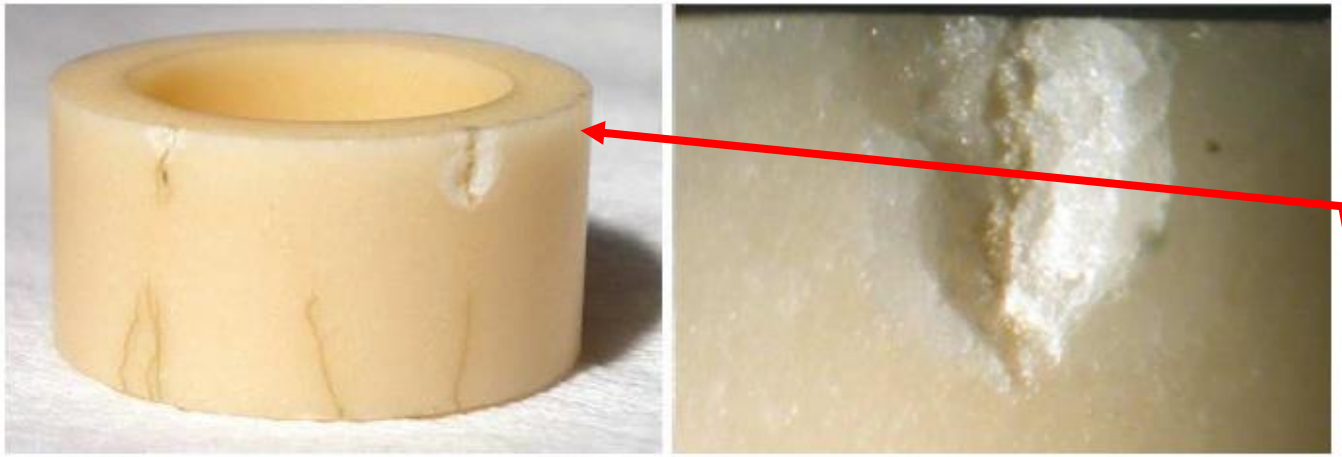
After ~1600 breakdowns

V_{bd} at 4.2K and 760 torr is reduced

Recovers after cleaning and repolishing

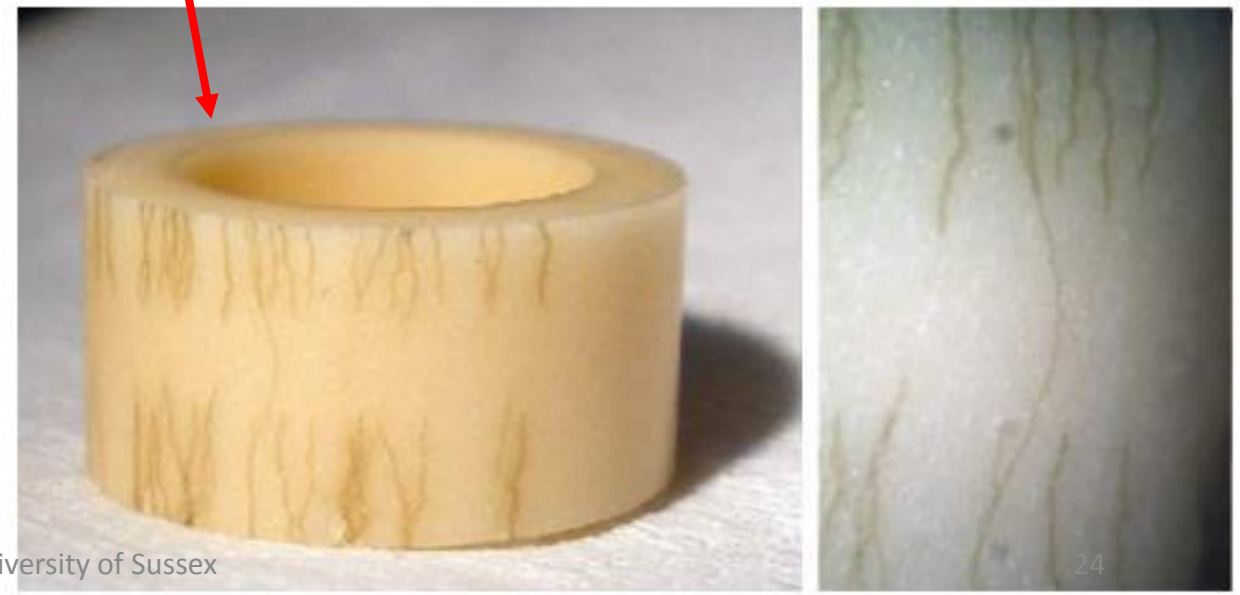
Justification to normalise

Experimental results



3/30 breakdowns through liquid volume in LHe I

10 mm x 15 mm x 7.5 mm alumina spacers; 2.96 mm electrode separation



Tracks appear to be mostly discontinuous

→ propagated to the anode from cathode

Damage at CJT - initiation point??

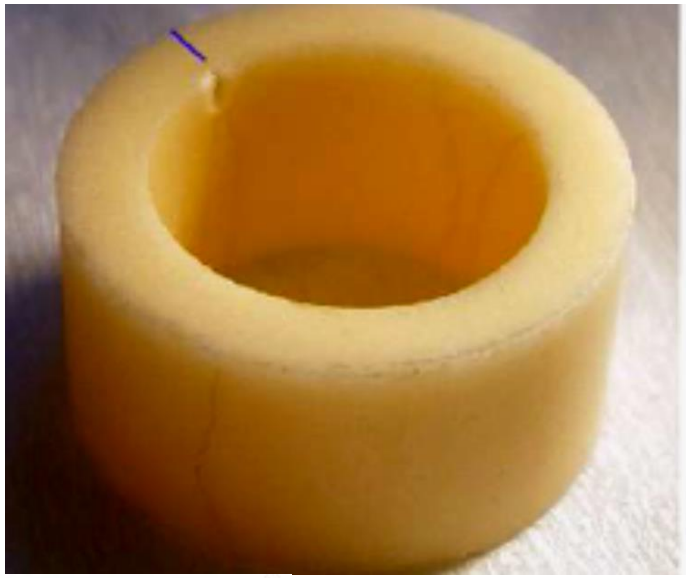
Experimental results

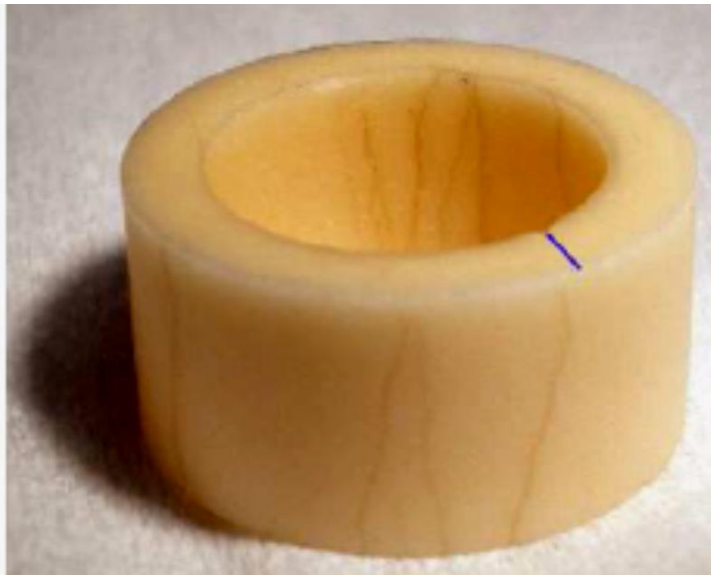
6/26 breakdowns through liquid volume in LHe II

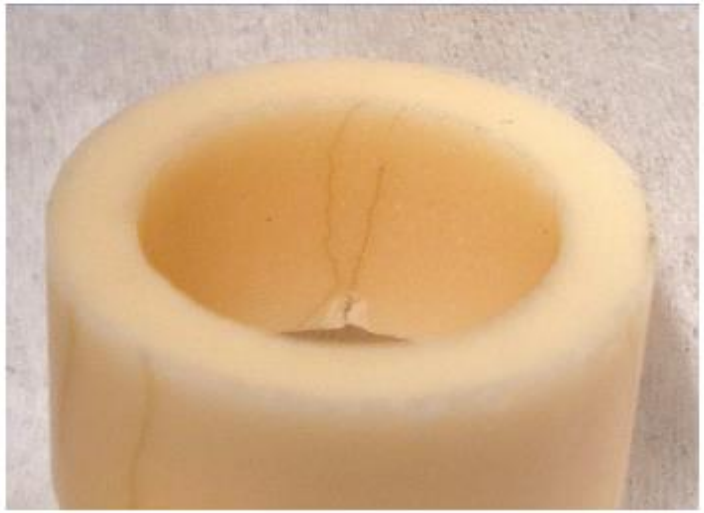
10 mm x 15 mm x 7.5 mm alumina spacers; 2.96 mm electrode separation

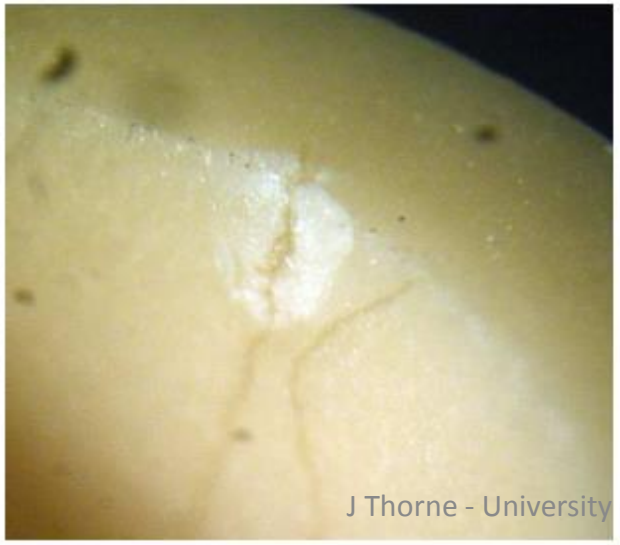
Tracks continuous on the inside and outside.

→ initiation from CTJ?







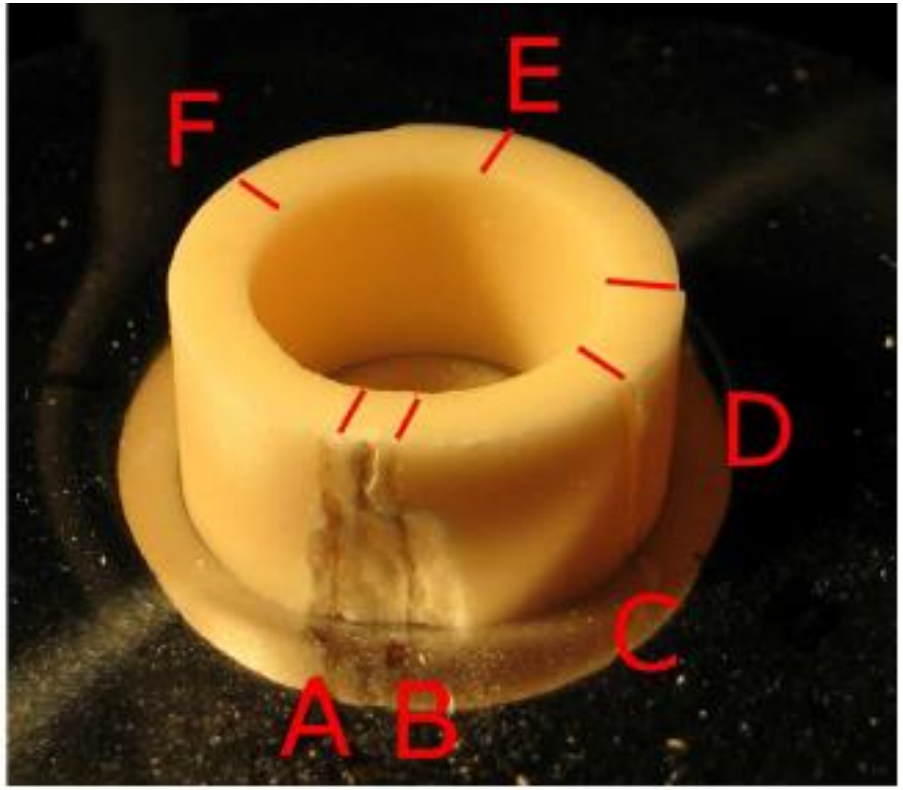


Pressure increase was also observed consistently 1-2s after breakdown – possibly due to Kapitza resistence?

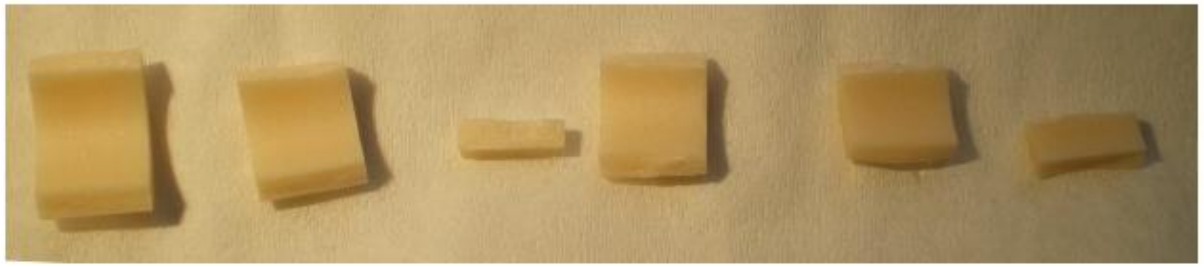
Experimental results

~18/20 breakdowns through liquid volume in LN2

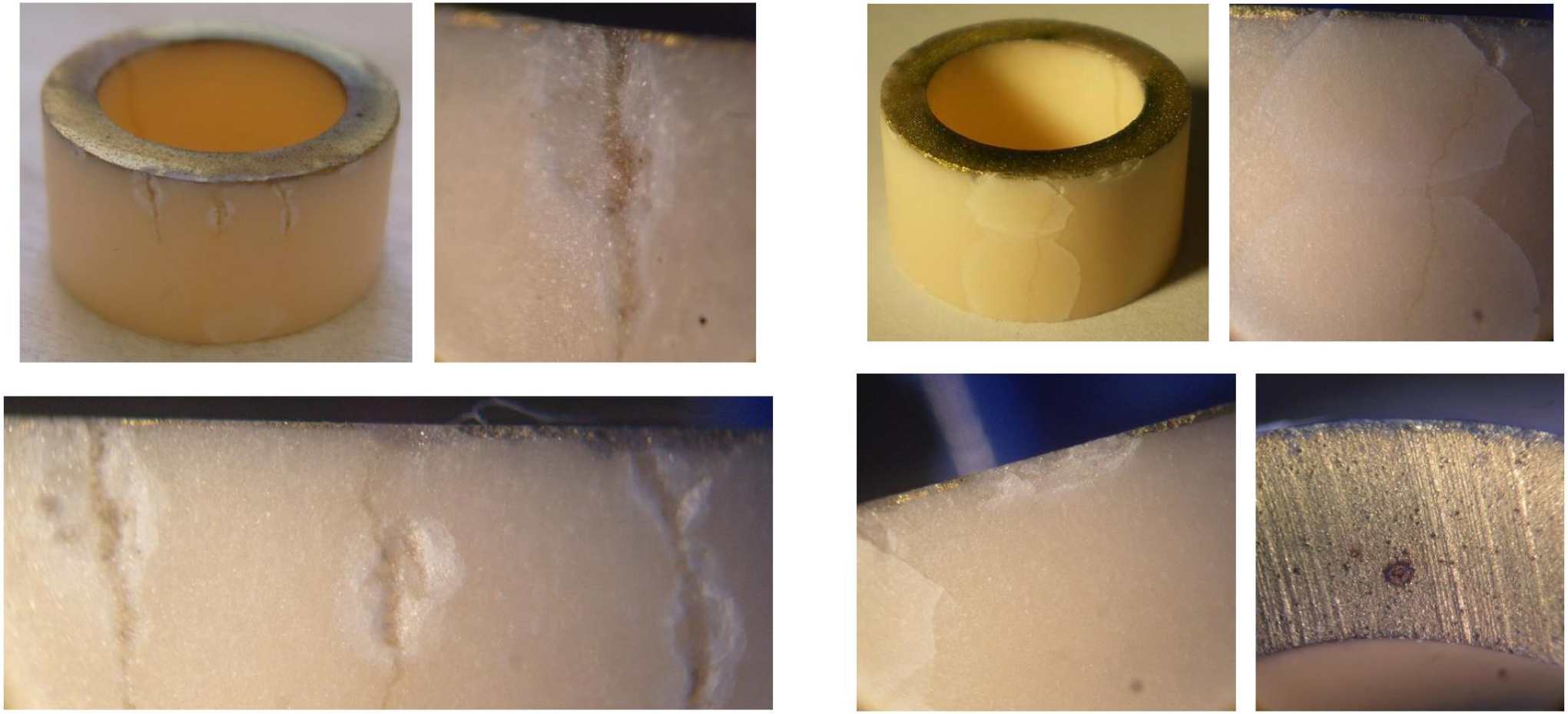
10 mm x 15 mm x 7.5 mm alumina spacers; 2.96 mm electrode separation



Catastrophic failure of insulators, breakdown through solid



Evidence of tracking at the CTJ



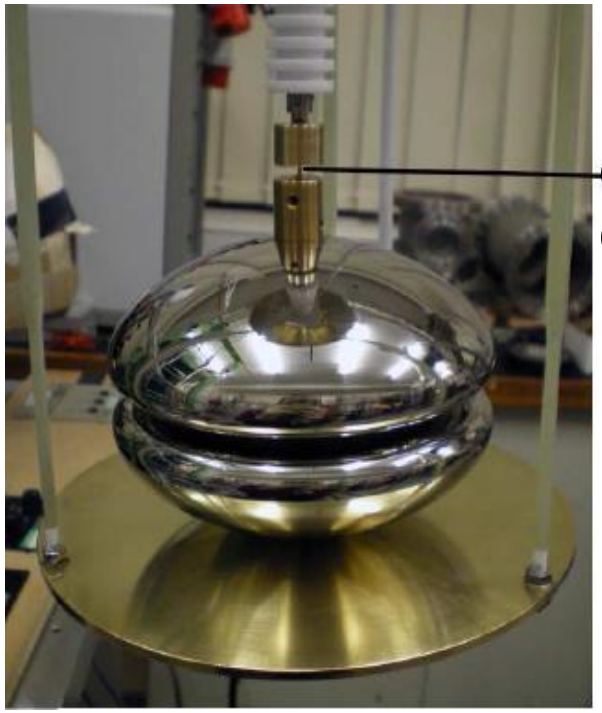
Experimental results for breakdown 'medium' scale tests

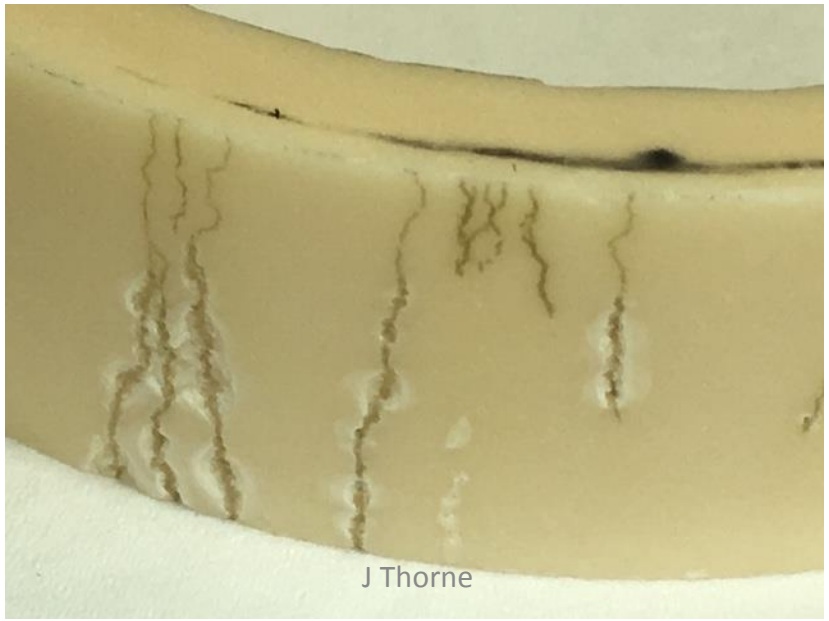
60 mm x 70 mm x 16 mm alumina spacers; 4.94 mm electrode separation, electrode diameter: ϕ124.99 mm

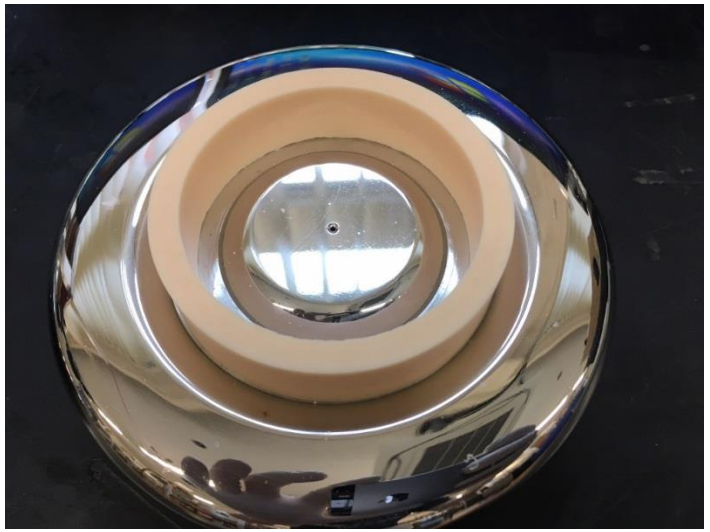
Breakdown ~1/15 through LN2 volume

Tracking observed on outside; combination of discontinuous and continuous, as well as chipping

Preference to one side!







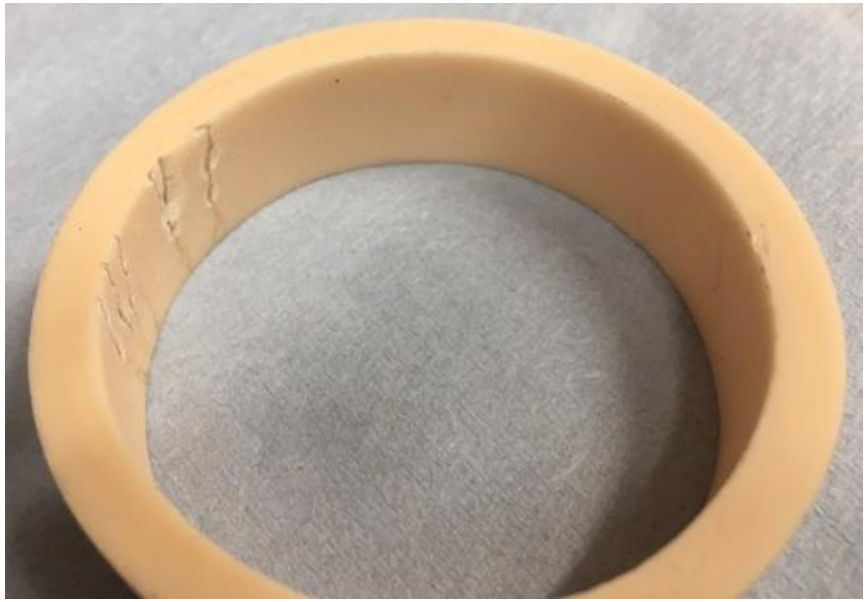
Experimental results for breakdown ‘medium’ scale tests

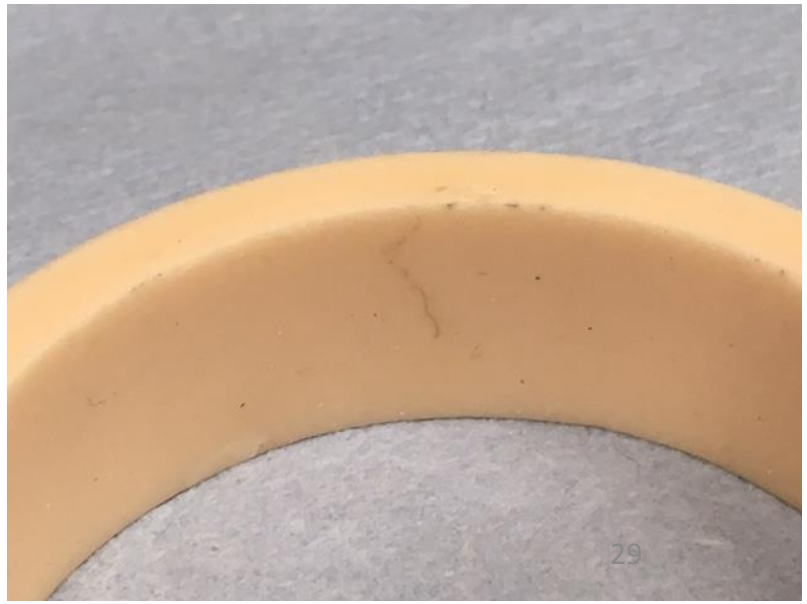
50 mm x 60 mm x 16 mm alumina spacers; 4.94 mm electrode separation

Breakdowns ~7/13 through volume

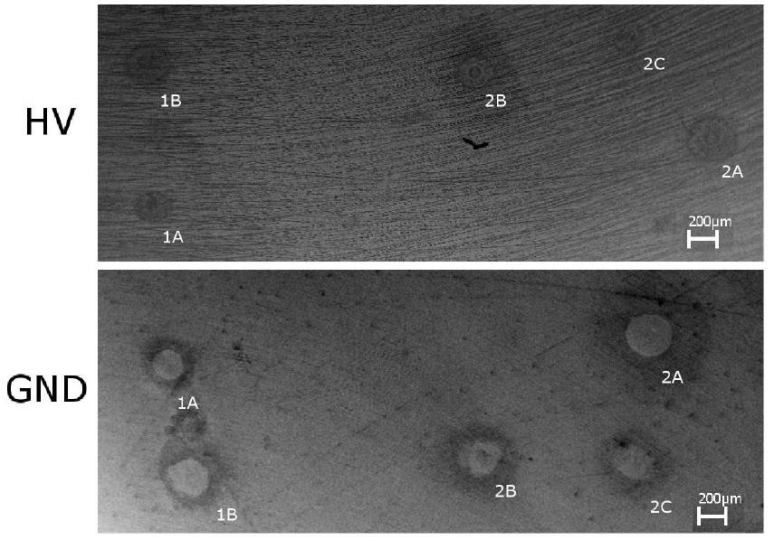
Continuous and discontinuous tracking on inside, significant chipping as well

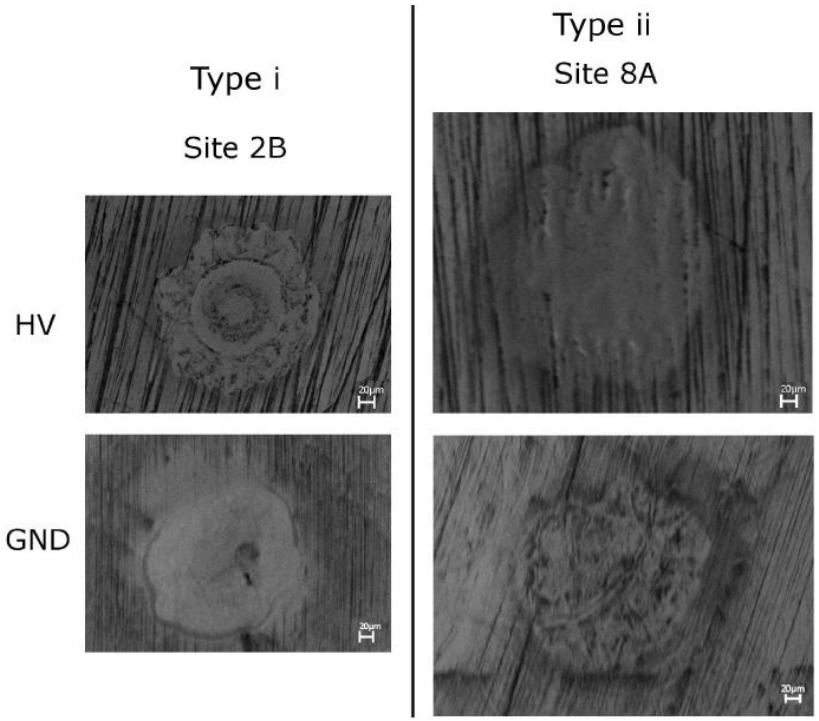
Again preference to one side!





Breakdown Damage on Electrode Surfaces *– JRK, AJD, DKH, LM*





Stainless and Titanium 50 - 100kV

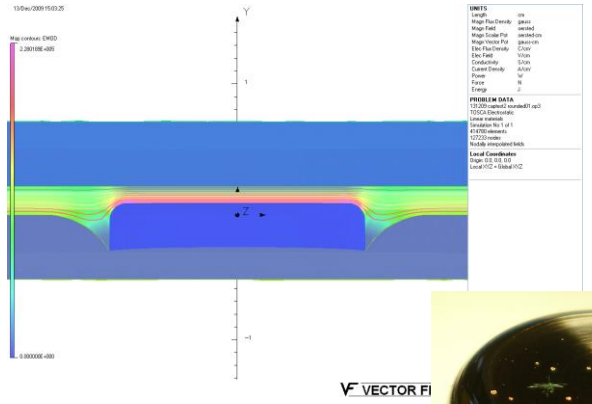
A new site for every Breakdown

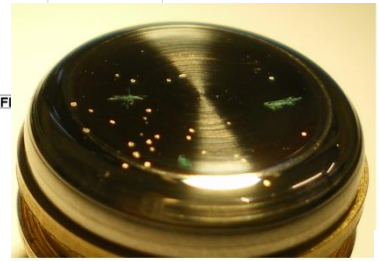
Breakdown goes ~ straight across

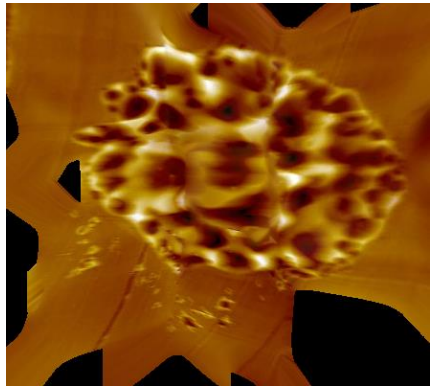
~100 -200 µm diameter

Differences between anode and cathode

AFM to get depth profiles - Lydia Munday

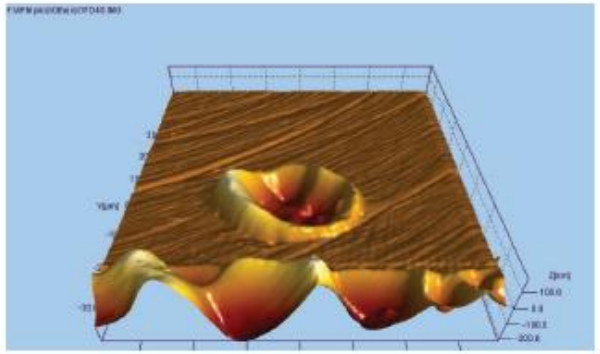




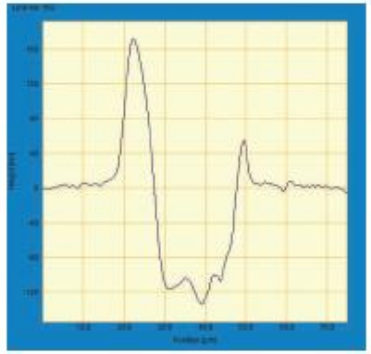


Oscillation during (single) discharge

Diameter ~ 200μm
In He I @ ~ 50kV



(a) 3D image of top part of damaged area shown in figure 8.16



(b) Line profile of crater

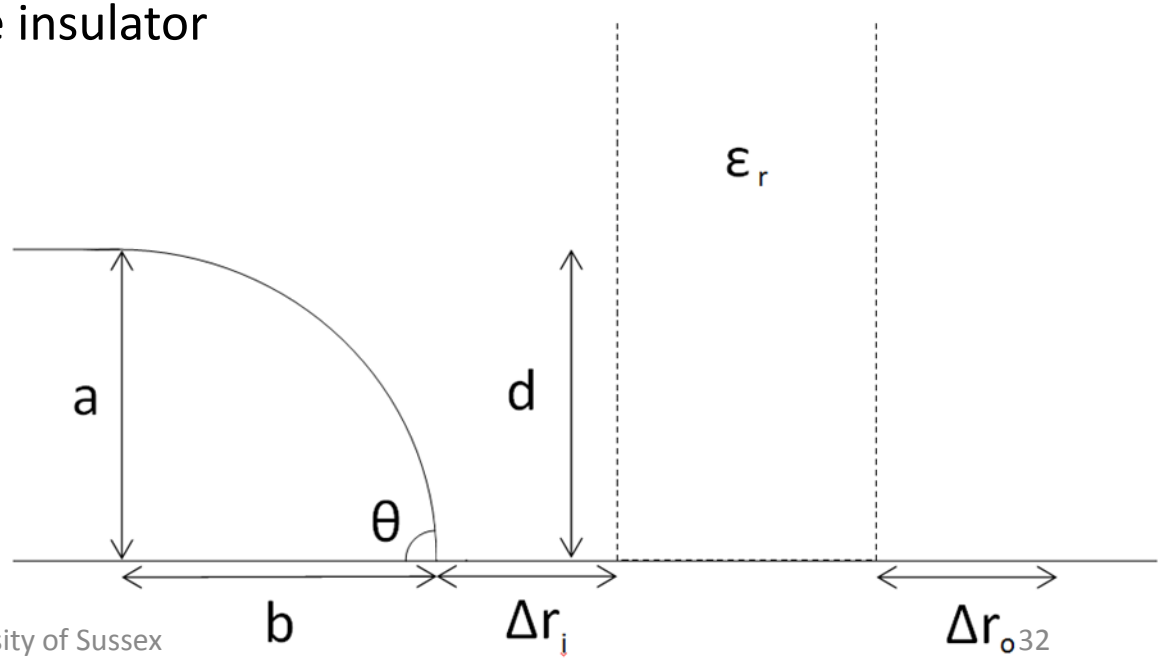
Width : Depth ~ 500 -1000:1 (~100 nm depth)
! <u>significant</u> (60%) loss of material !

Simulations to optimise the groove geometry

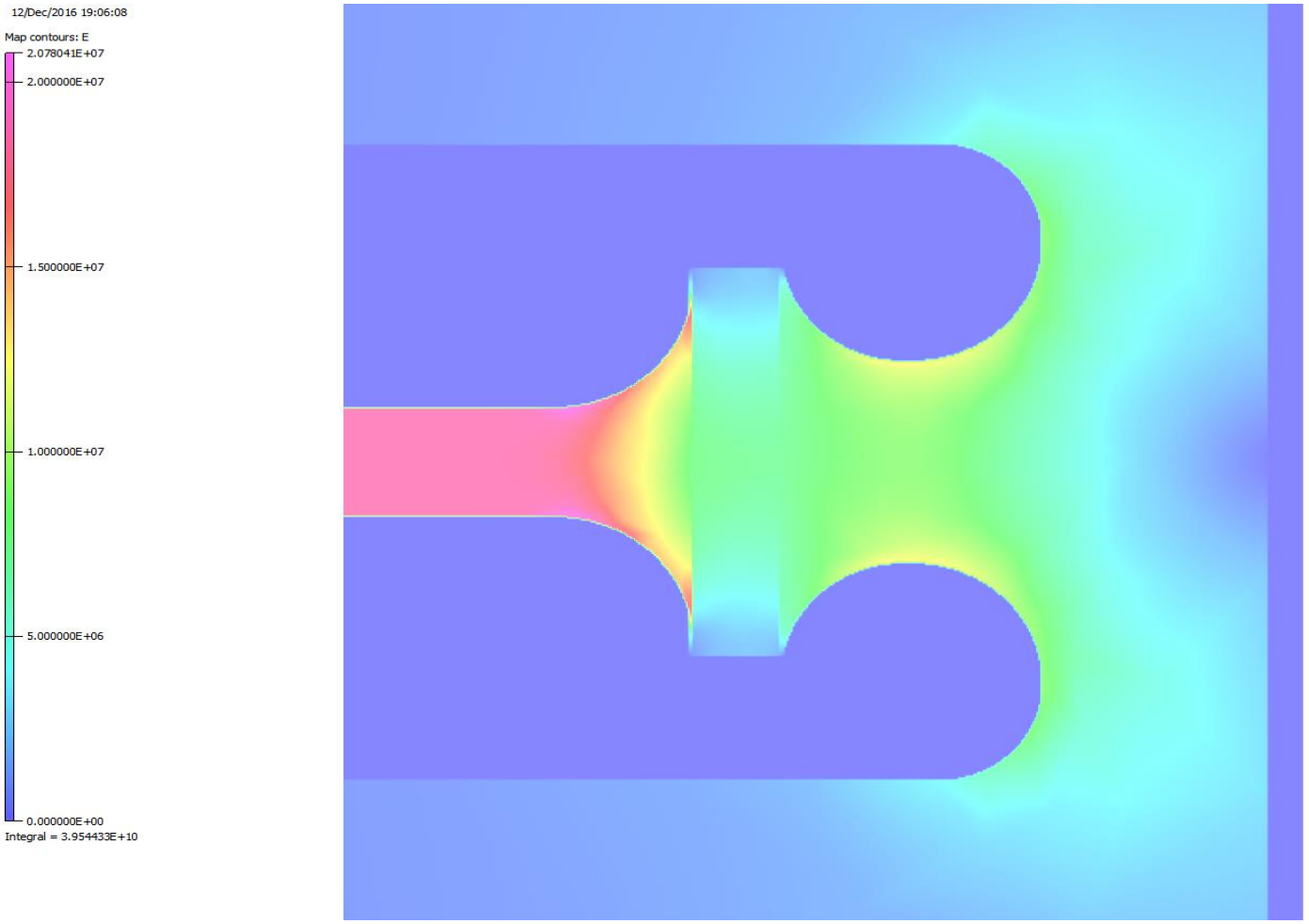
Determined the parameter space for the groove;

- a, b - major & minor radius of an eclipse
- θ - angle from base for an eclipse
- d - depth of groove
- Δr - radial separation for inside and outside of the insulator
- ε_r – relative permittivity of the insulator

Ran these parameters individually in Opera, varying each one to find an optimal geometry that decreases the E field on the groove



Electrode separation; 14mm with borosilicate glass insulator, radial separation 0.5mm



UNITS

Length	mm
Elec Flux Density	C/m²
Electric Field	V/m
Electric Pot	volt
Power	W
Force	N
Energy	J

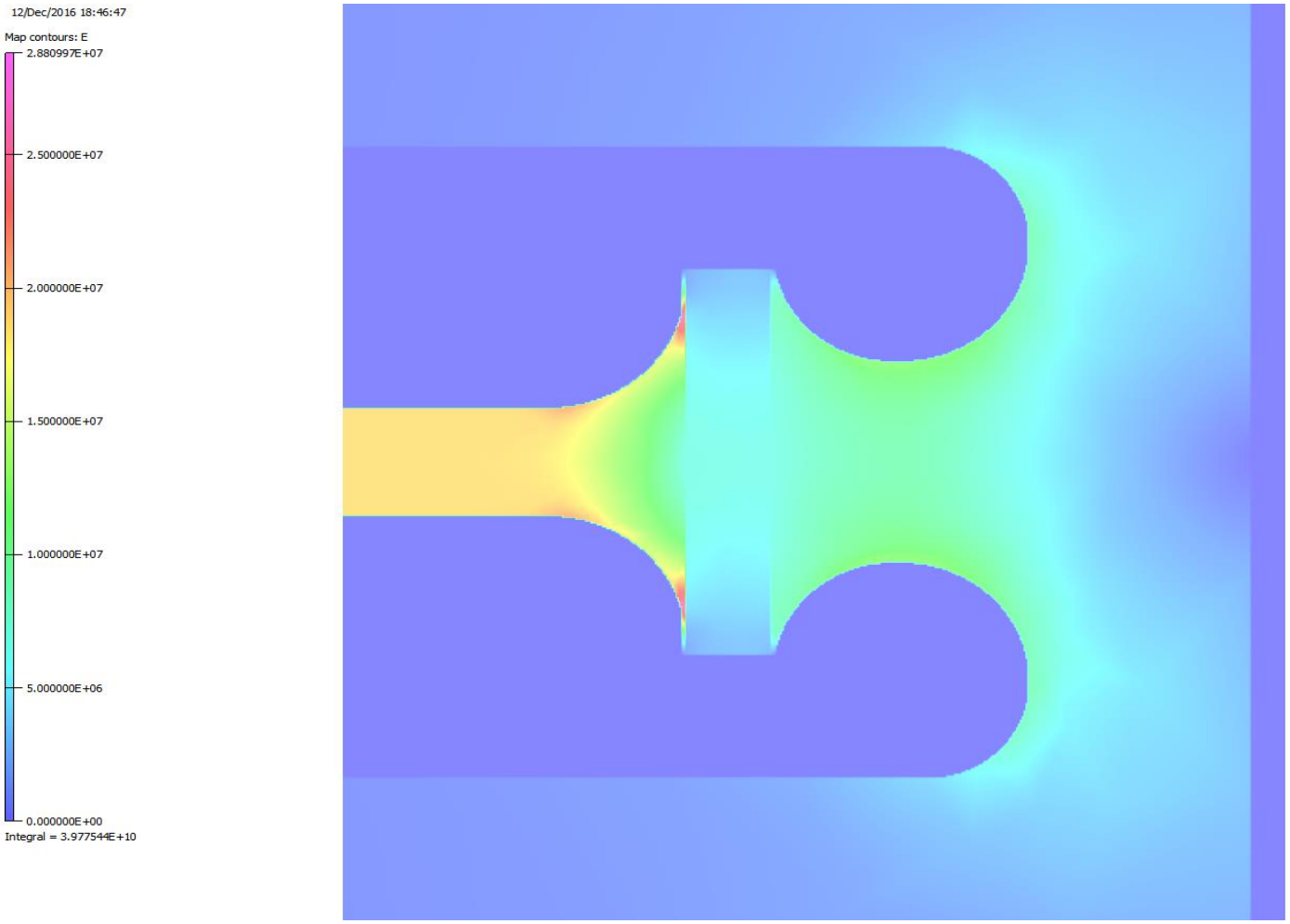
MODEL DATA
Stepper plate 6mm - BG - R16.op3
Electrostatic (TOSCA)
Linear materials
Simulation No 1 of 1
360785 elements
253423 nodes
Nodally interpolated fields
Activated in global coordinates

Field Point Local Coordinates
Local = Global

FIELD EVALUATIONS
Cartesian CARTESIAN (nodal) 500x500 Cartesian
x=0.0 y=60.0 to -60.0 z=80.0 to 190.0

opera simulation software

Electrode separation; 14mm with alumina insulator, radial separation 0.5mm



UNITS

Length	mm
Elec Flux Density	C/m²
Electric Field	V/m
Electric Pot	volt
Power	W
Force	N
Energy	J

MODEL DATA
Stepper plate 6mm - Alu - R16.op3
Electrostatic (TOSCA)
Linear materials
Simulation No 1 of 1
360785 elements
253423 nodes
Nodally interpolated fields
Activated in global coordinates

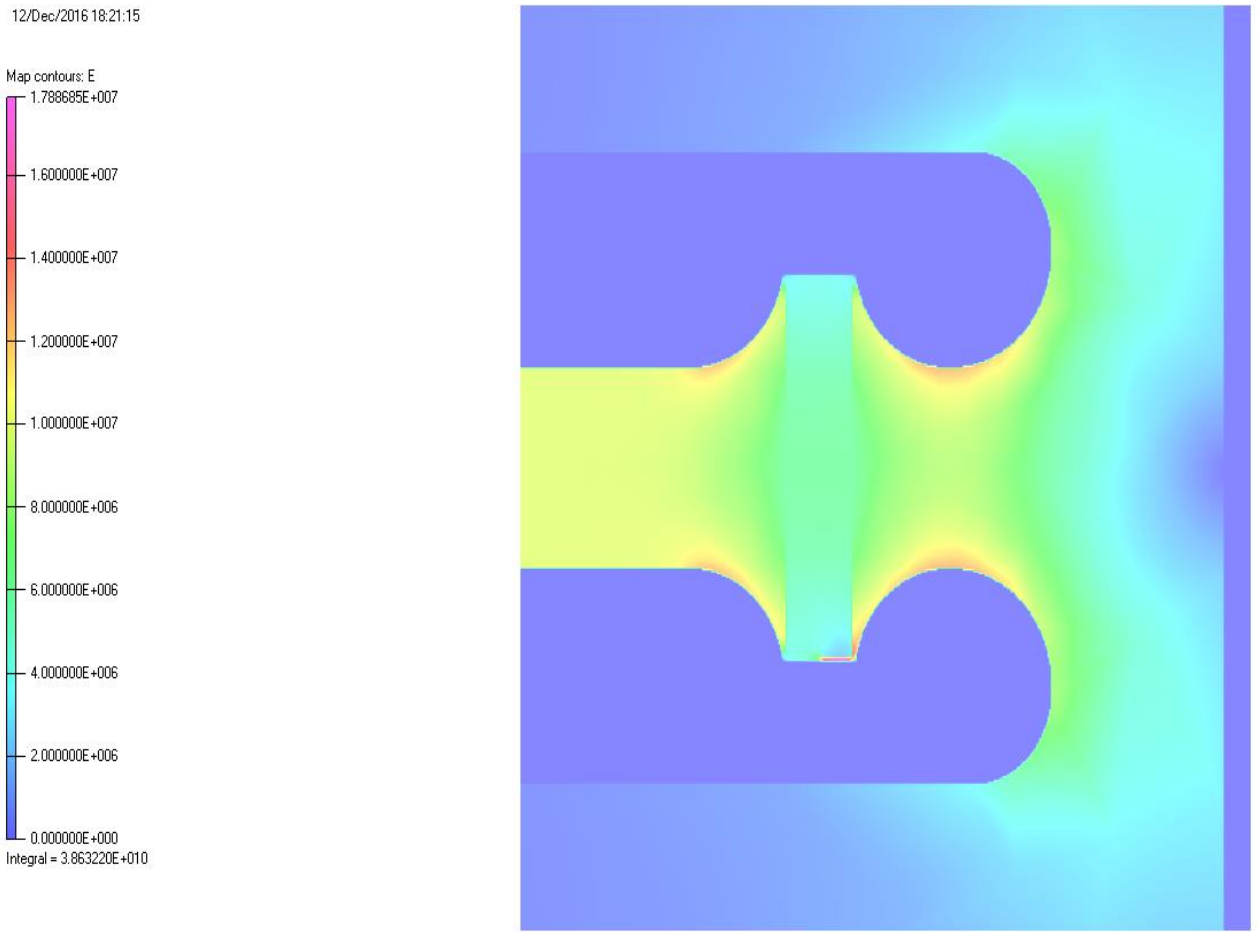
Field Point Local Coordinates
Local = Global

FIELD EVALUATIONS

Cartesian	CARTESIAN (nodal)	500x500	Cartesian
	x=0.0	y=60.0 to -60.0	z=80.0 to 190.0

opera simulation software

R14 + R15, with cut for the CTJ at the bottom of the insulator.



UNITS

Length	mm
Elec Flux Density	C/m²
Electric Field	V/m
Electric Pot	volt
Power	W
Force	N
Energy	J

MODEL DATA

Electrode setup R14 CTJ.op3
Electrostatic (TOSCA)
Linear materials
Simulation No 1 of 1
607714 elements
384358 nodes
Nodally interpolated fields
Activated in global coordinates

Field Point Local Coordinates

Local = Global

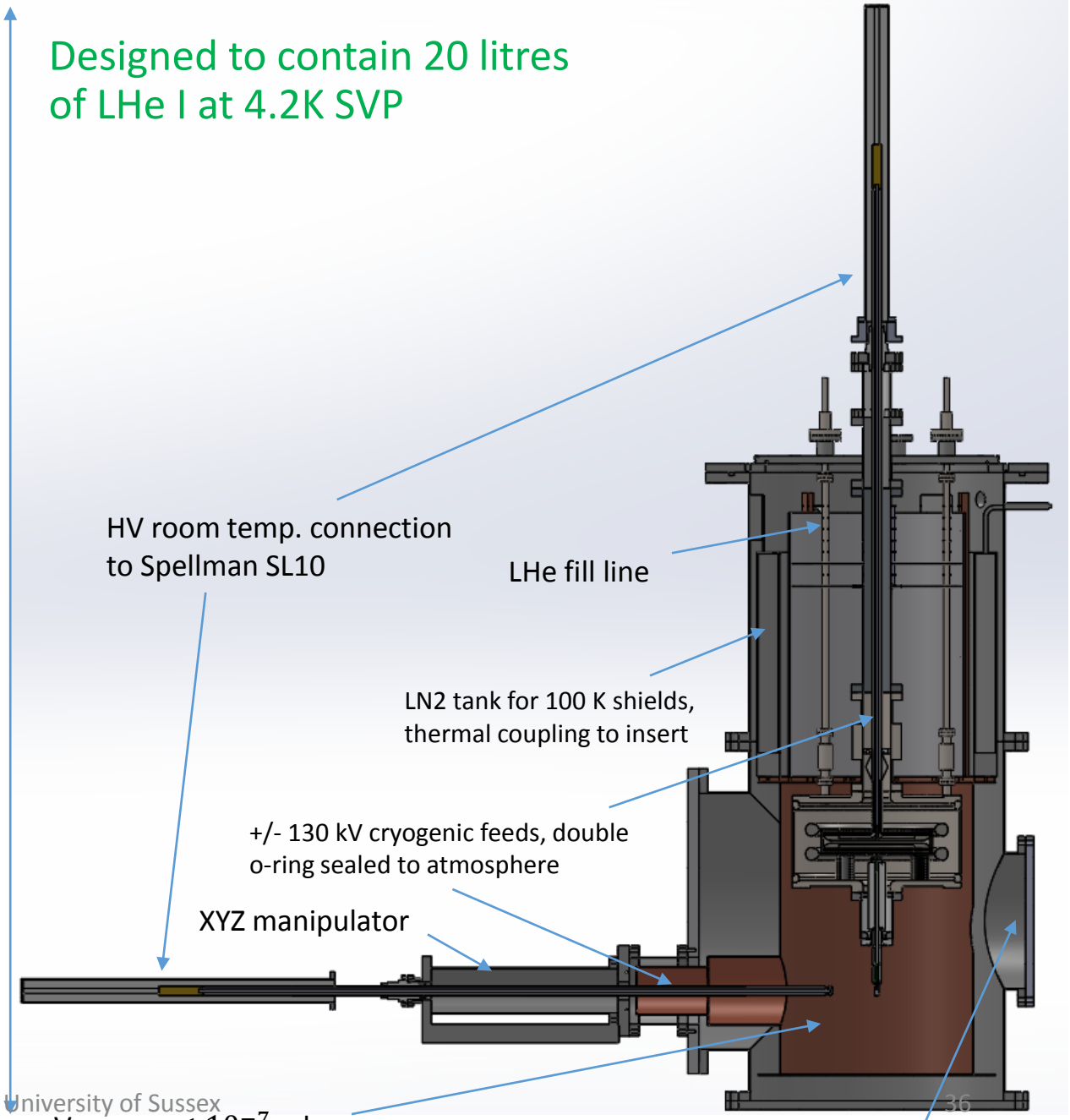
FIELD EVALUATIONS

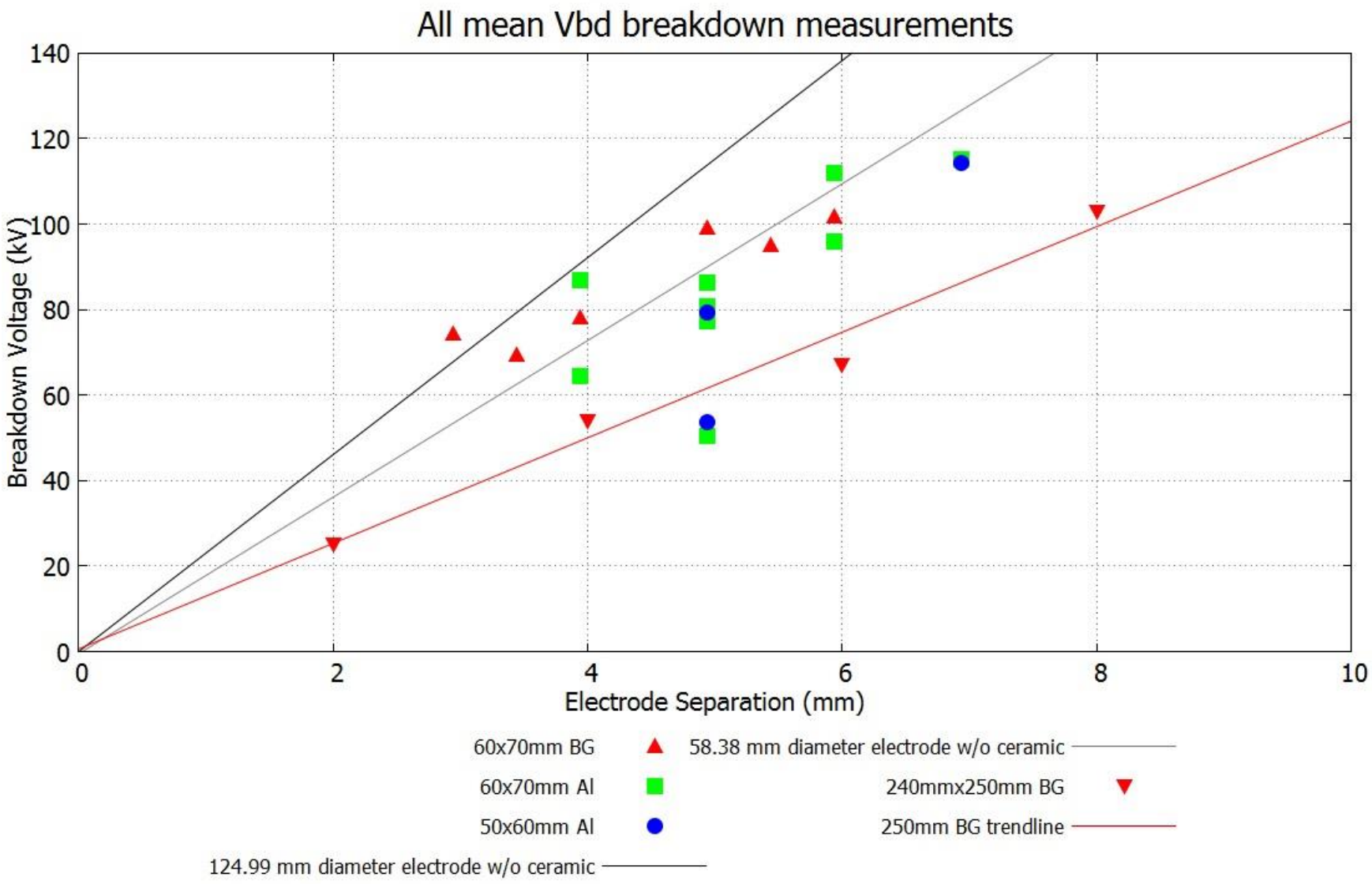
Cartesian	CARTESIAN (nodal)	500x500	Cartesian
	x=0.0	y=60.0 to -60.0	z=80.0 to 190.0
Line	LINE (nodal)	101	Cartesian
	x=0.0	y=-24.75	z=125.0 to 130.0

opera simulation software

~2.5 m

Designed to contain 20 litres of LHe I at 4.2K SVP




All mean Vbd breakdown measurements
Breakdown Voltage (kV)
Electrode Separation (mm)
0
20
40
60
80
100
120
140
0
2
4
6
8
10
60x70mm BG
60x70mm Al
50x60mm Al
124.99 mm diameter electrode w/o ceramic
58.38 mm diameter electrode w/o ceramic
240mmx250mm BG
250mm BG trendline