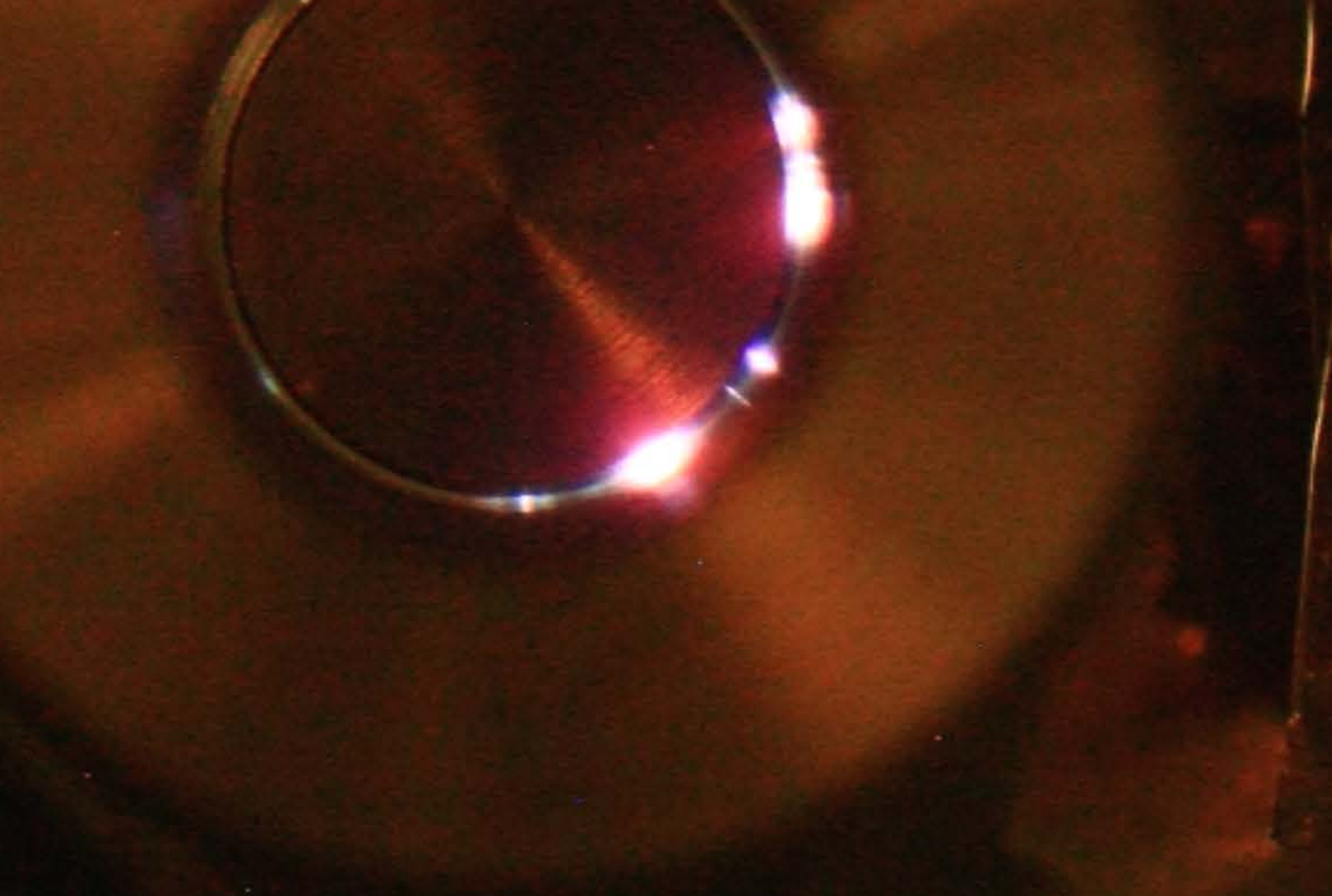
Coaxial Vacuum Gap Breakdown for Pulsed Power Liners



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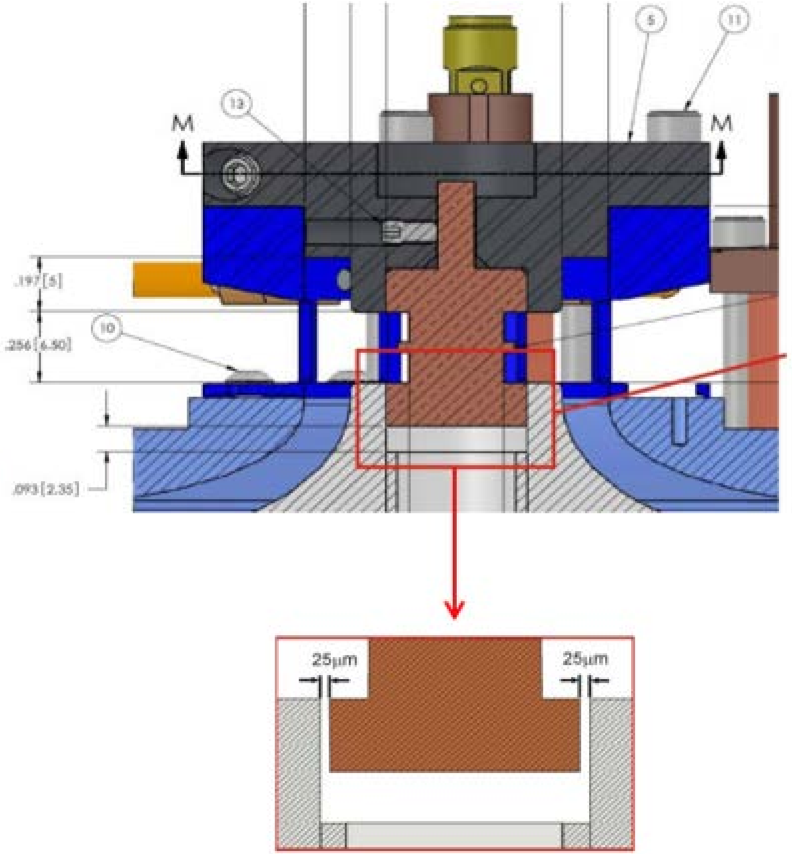
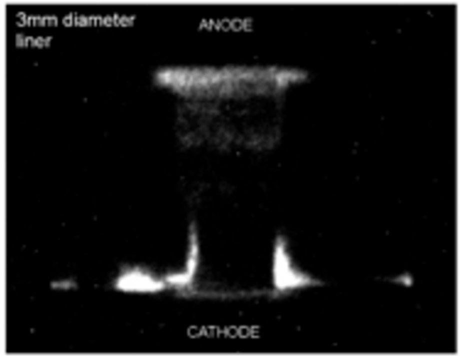
COBRA Liners at 1MA with Cathode Vacuum Gap

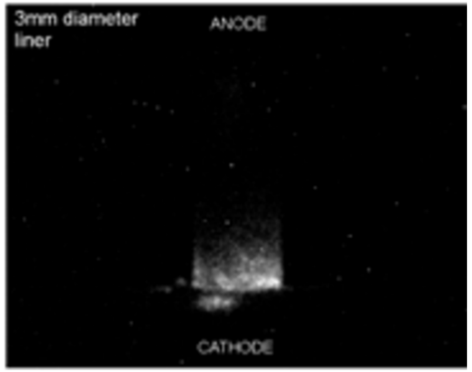


2D cross section of MagLIF experiment
Showing coaxial gap at the power feed.

25 μm Cathode Feed Gap



No cathode feed gap



Gated optical images (10ns exposure) of Z-scale liners (300μm thick, 6.3mm OD and 10mm tall)

- The presence of a gap at the cathode clearly has an effect on plasma formation and evolution
- Need to better understand mechanisms of breakdown that cause offset in coaxial gap
- Offsets could lead to early time scale instabilities
- Many pulsed power machines use coaxial gap in the power feed

S. C .Bott-Suzuki *et al*, *Phys. Plasmas*, **22**, 094501 (2015)

Coaxial Gap Breakdown Machine

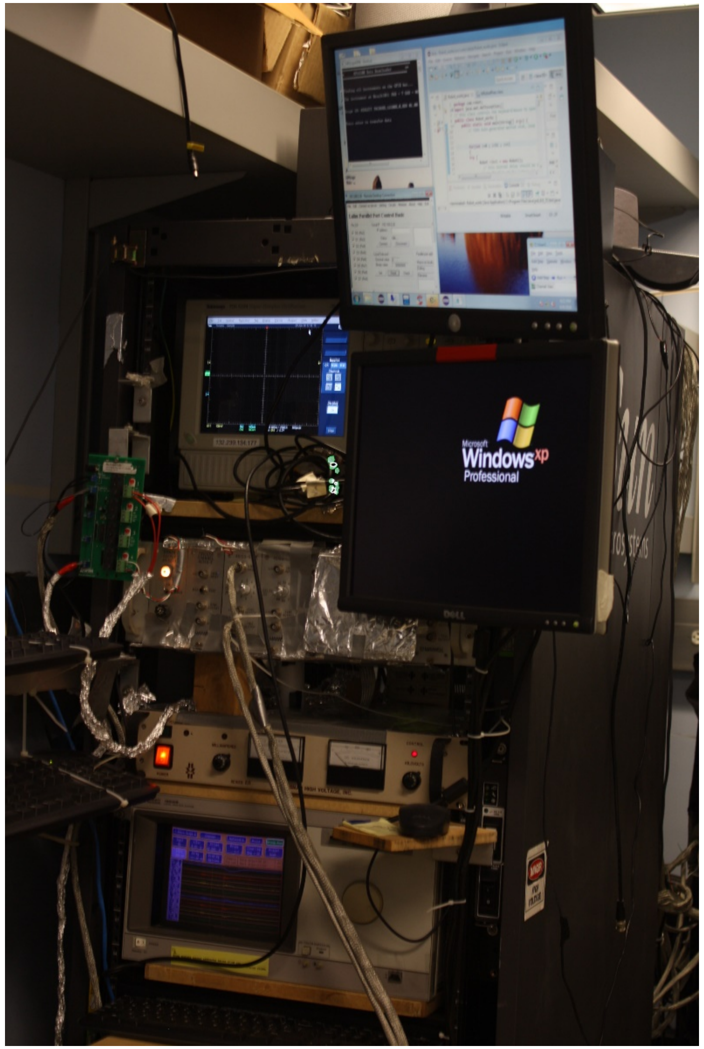


Figure 1: Master control program tower for automation

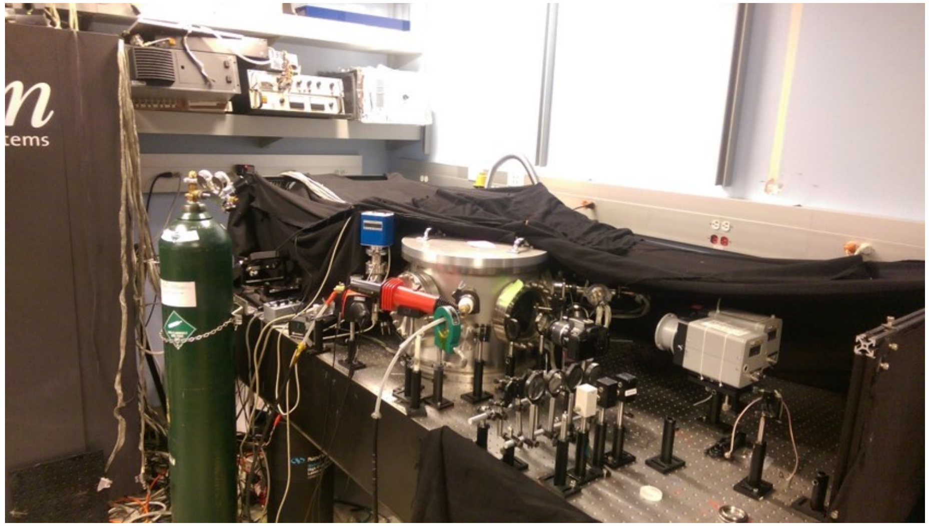


Figure 2: Coaxial gap breakdown machine

- Table top experiment
- 25kV, 240A, 150ns rise time
- Vacuum $\sim 10^{-5} Torr$
- Rep-rated machine: 0.1Hz
- 2 Voltage Probes
- Current measurements
- DSLR
- 9 magnetic field probe array

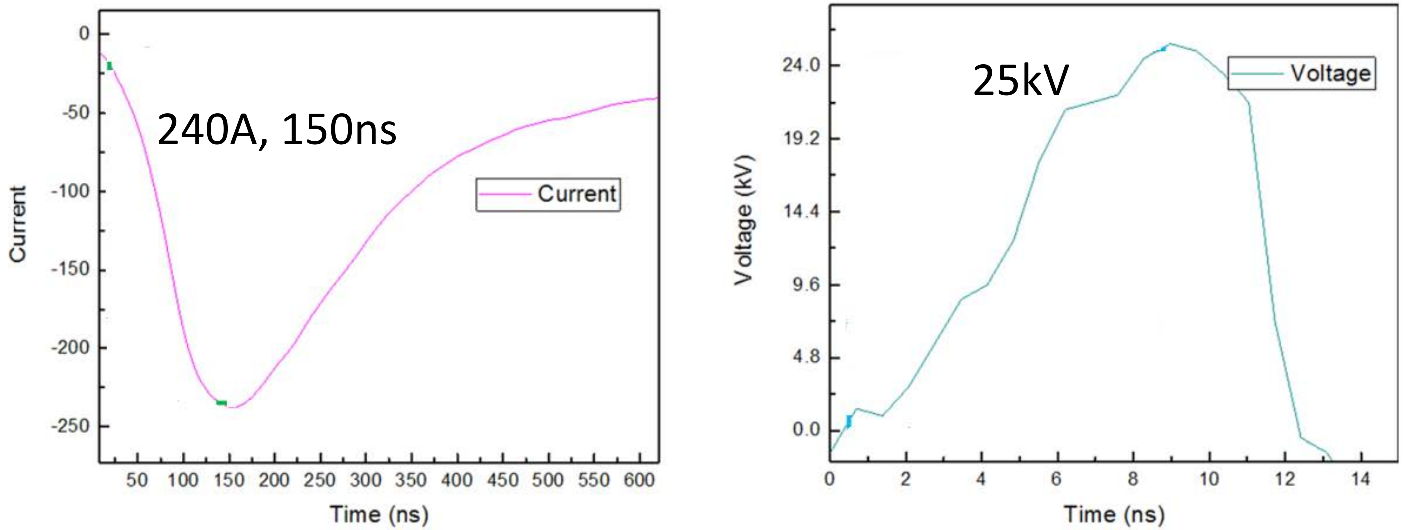


Figure : Current and voltage delivered to the load.

Electrode Geometry

- 5cm long electrodes
- $25\mu m - 1.4mm$ gap sizes
- Cathode inserted into anode (Penetration depth) PD, 1.5mm – 9.88mm
- Surface finish features ~5-10 μm

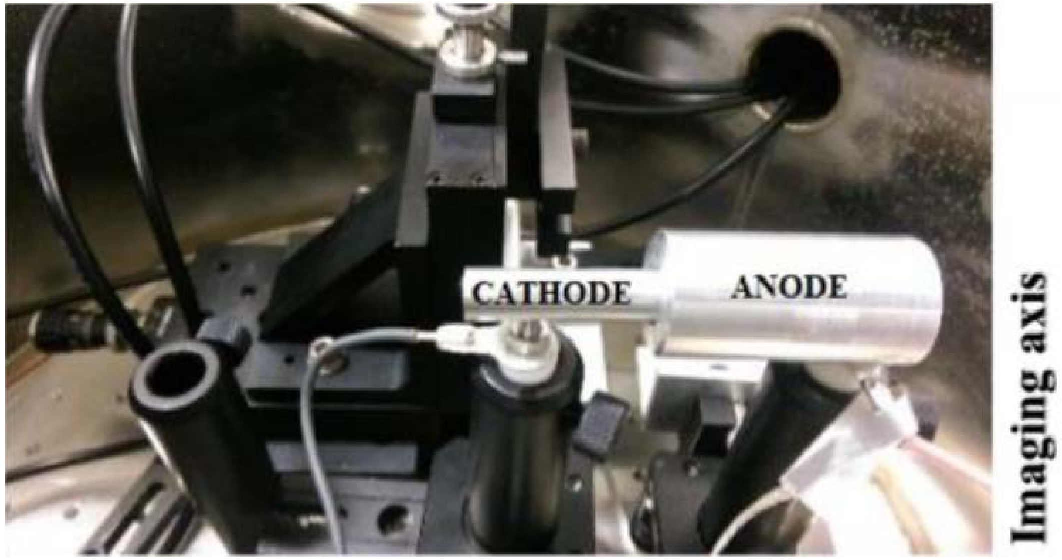


Figure 4: Aluminum coaxial electrodes – attached to 3-D electronic translational mounts

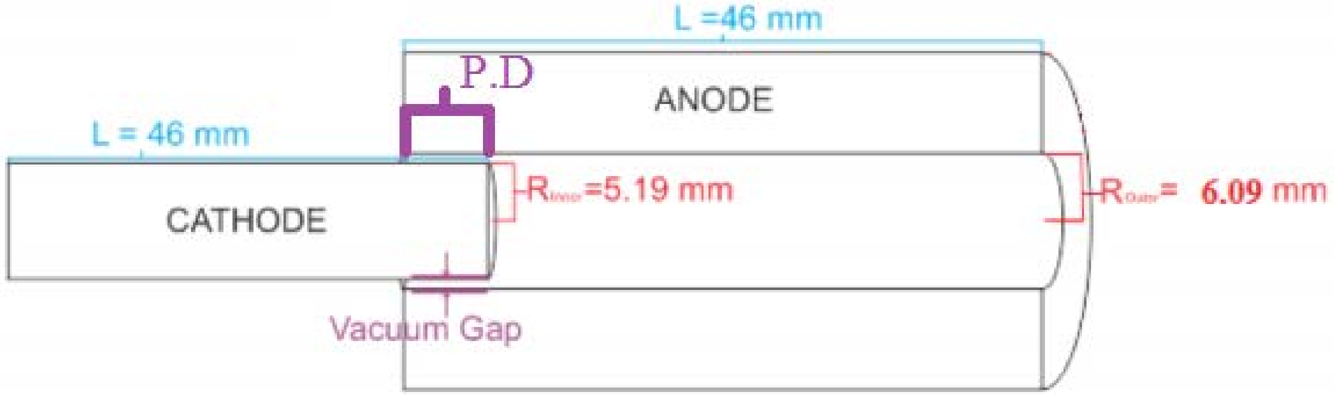


Figure: cross section of anode, with penetration depths displayed.

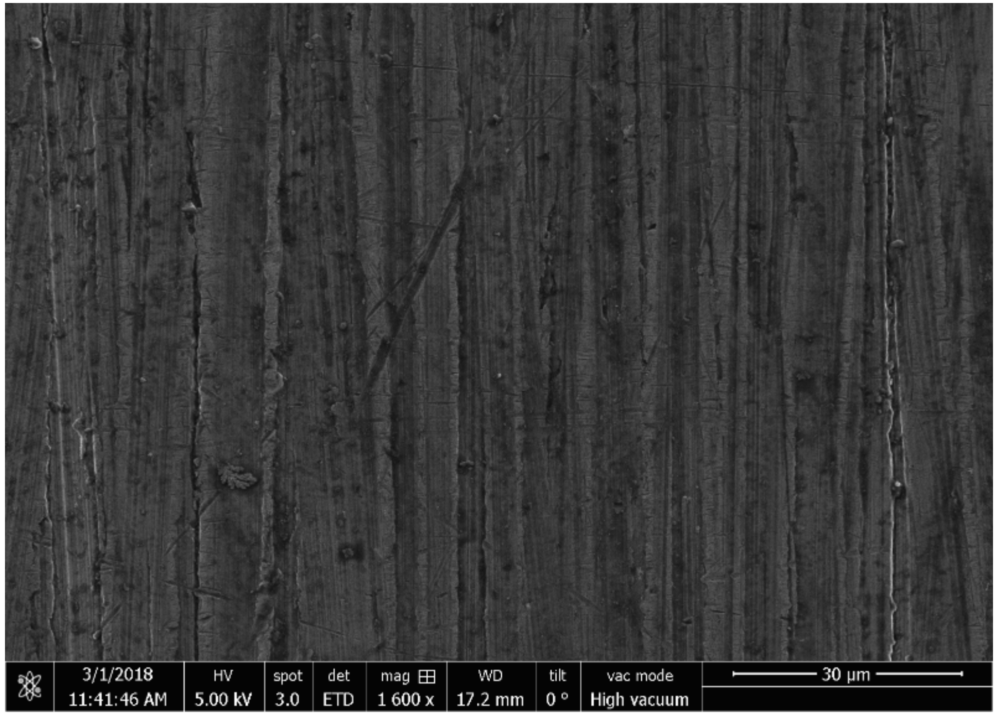
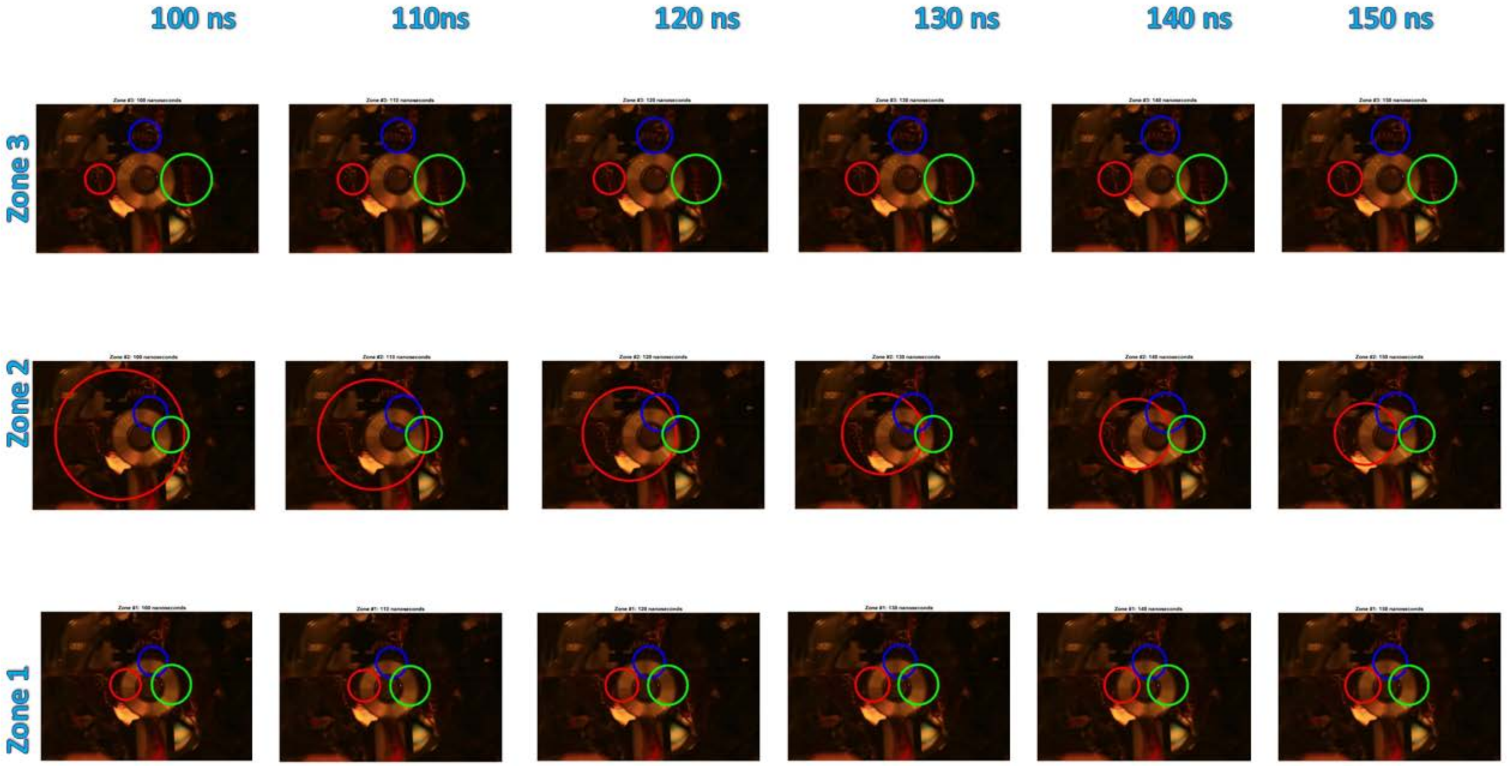


Figure 5: 330 μm gap electrode SEM images

Bdot Probe array shows Current density motion

- Relative signals of the magnetic field probes change during the current pulse
- This indicates that the current density distribution 1) is not uniform around the azimuth
  2) changes during a shot



Microprotrusions and surface evolution

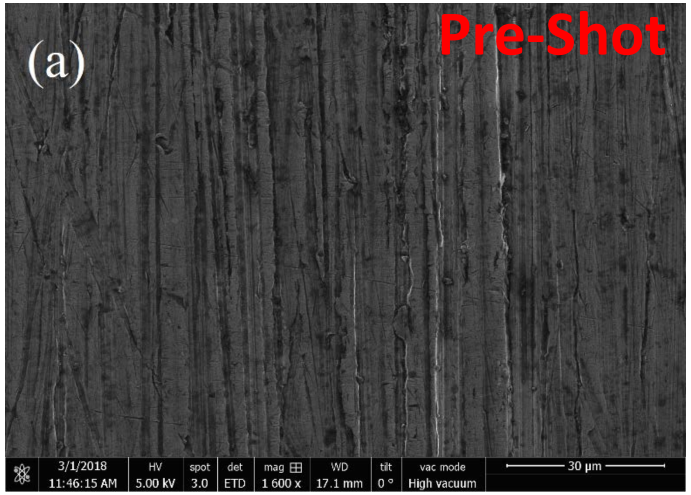


Figure: 700 um, pre-shot
X1600 magnification

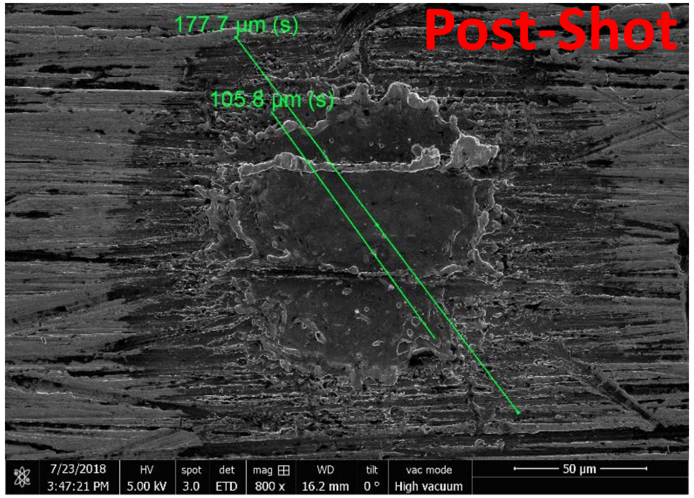


Figure: 700 um, post-shot
X800 magnification

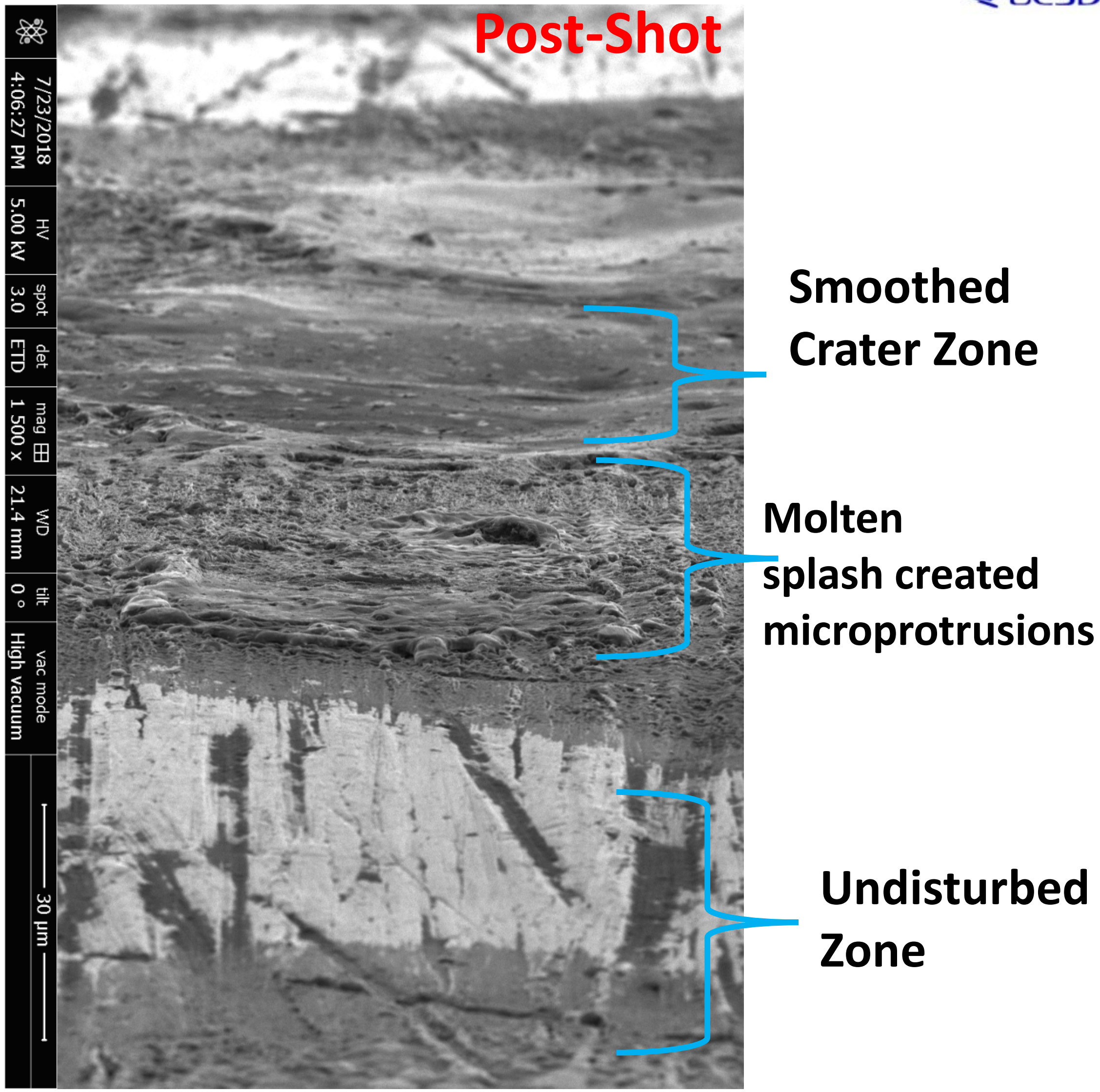


Figure: 700 um-side on, post-shot X1500 magnification

- Pre-shot ~5-10 μm Microprotrusions

- Post-shot large smooth craters, melting, splash created Microprotrusions >10 μm

Microprotrusions and surface evolution

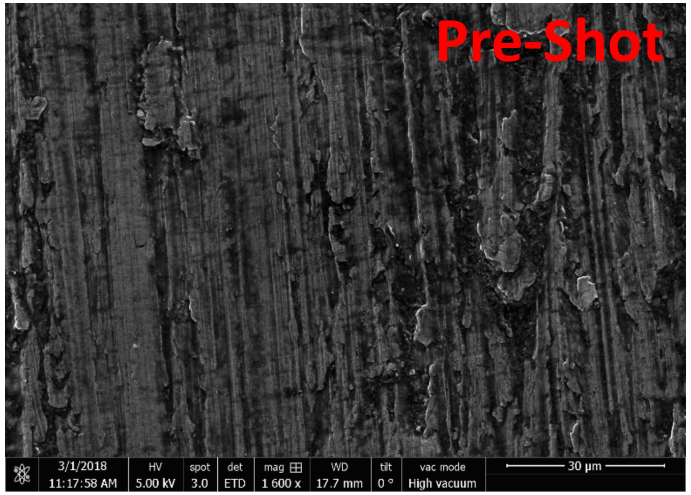


Figure: 100 um, pre-shot
X1600 magnification

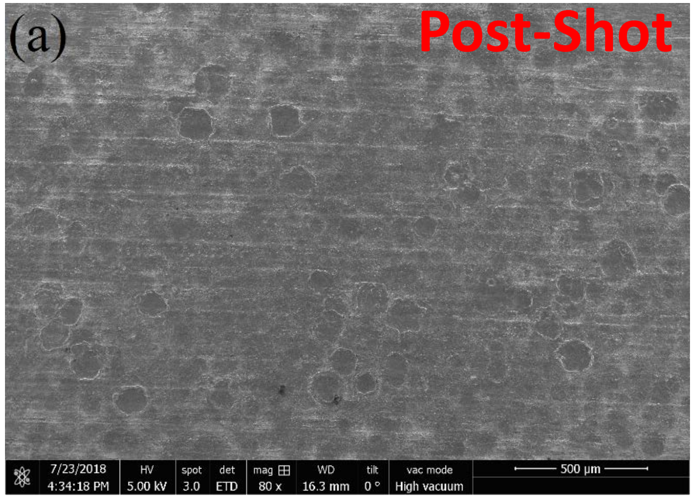


Figure: 100 um, post-shot
X80 magnification

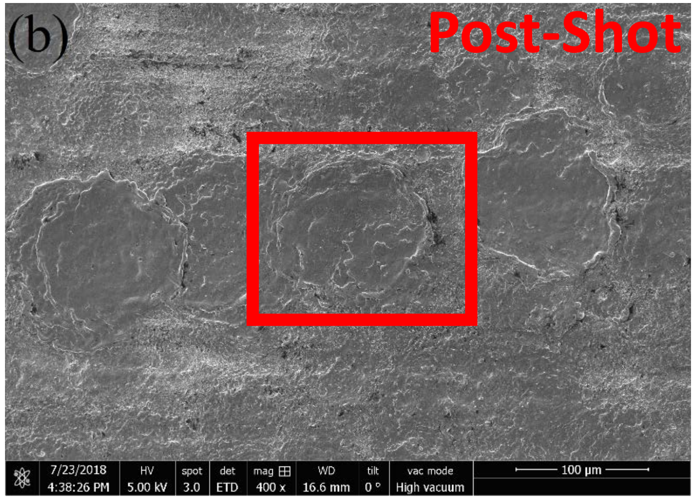


Figure: 100 um, post-shot X400 magnification

- Pre-shot ~5-10 μm Microprotrusions
- Post-shot large craters, melting, splash created Microprotrusions ~10 μm
- Large area of clustered breakdowns, yields large overlapping melt regions with nm surface roughness

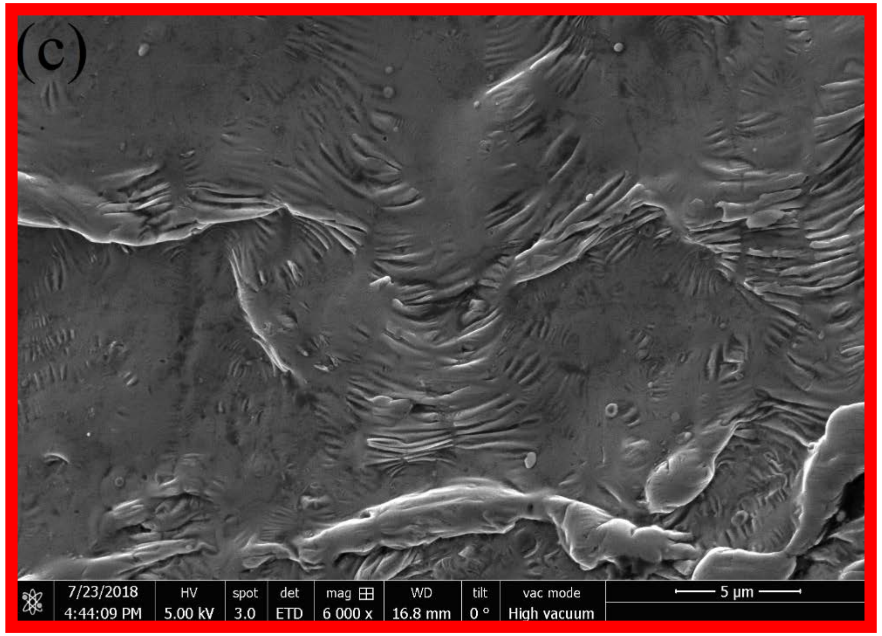


Figure: 100 um, post-shot
X1800 magnification- angle

Fowler-Nordheim (FN) Analysis

- Compare existing literature
- Understand fundamental breakdown mechanisms of a coaxial gap
- Substitution allows for current emission to be based on experimental quantities I, V, ϕ, to find β
- β is "enhancement factor" which describes chances of breakdown over and above work function

Substitute into our current density emission formula: $E_{applied} = \beta V$
$I = JA$

Results in : $I = a\phi^{-1}\beta^2 V^2 P_F \exp\left(-\frac{b\phi^{\frac{3}{2}}}{\beta V}\right)$

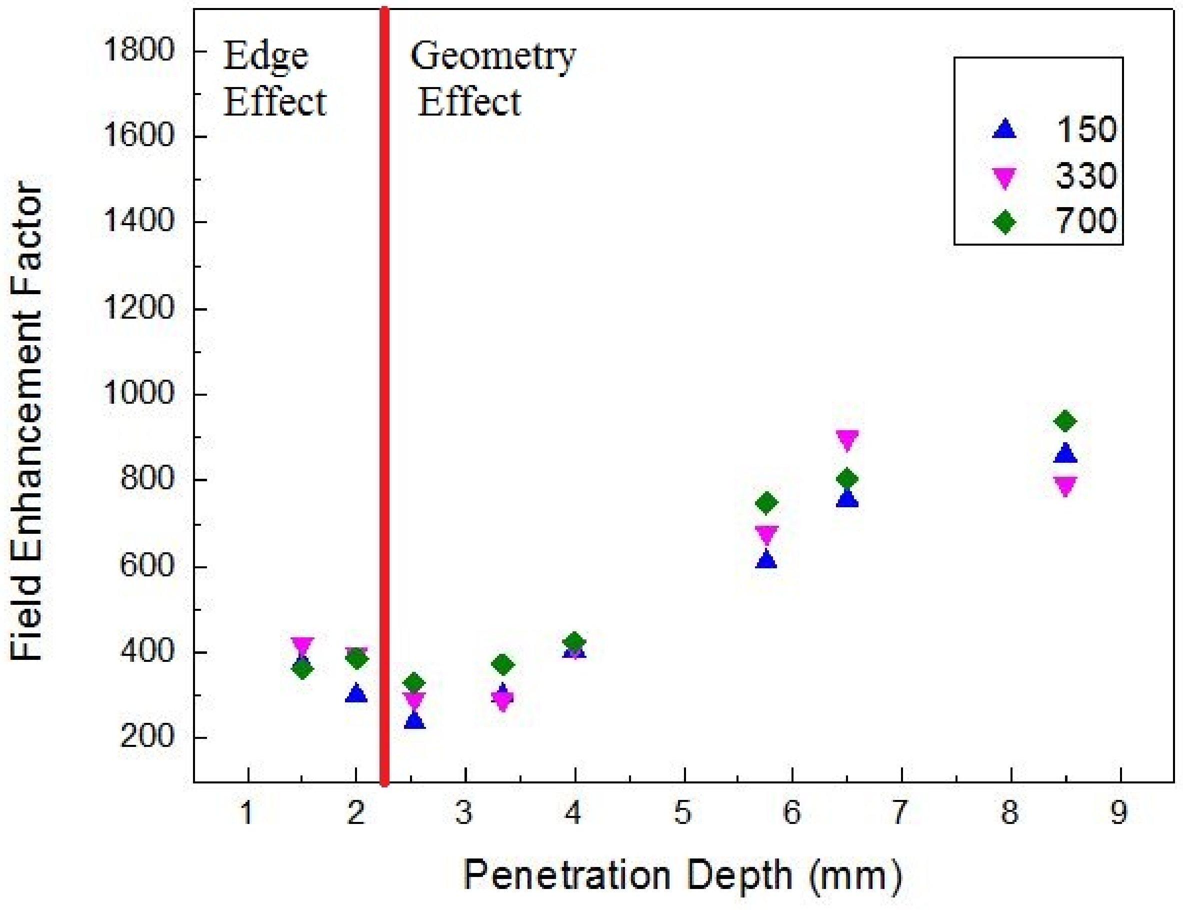
$$\rightarrow \quad \log\left(\frac{I}{V^2}\right) = -\frac{(2.9669x10^7)\phi^{\frac{3}{2}}}{\beta V} + \log\left(a\frac{\beta^2}{\phi}\right)$$

Plotting log (I/V^2) vs. 10^6/V , we can find the slope $m = -\frac{2.9669x10^3\phi^{\frac{1}{2}}}{\beta}$

R.H. Fowler and L.W. Nordheim. Proc. Roy. Soc. London 119 (1928), p. 173; 124 (1929),p. 699

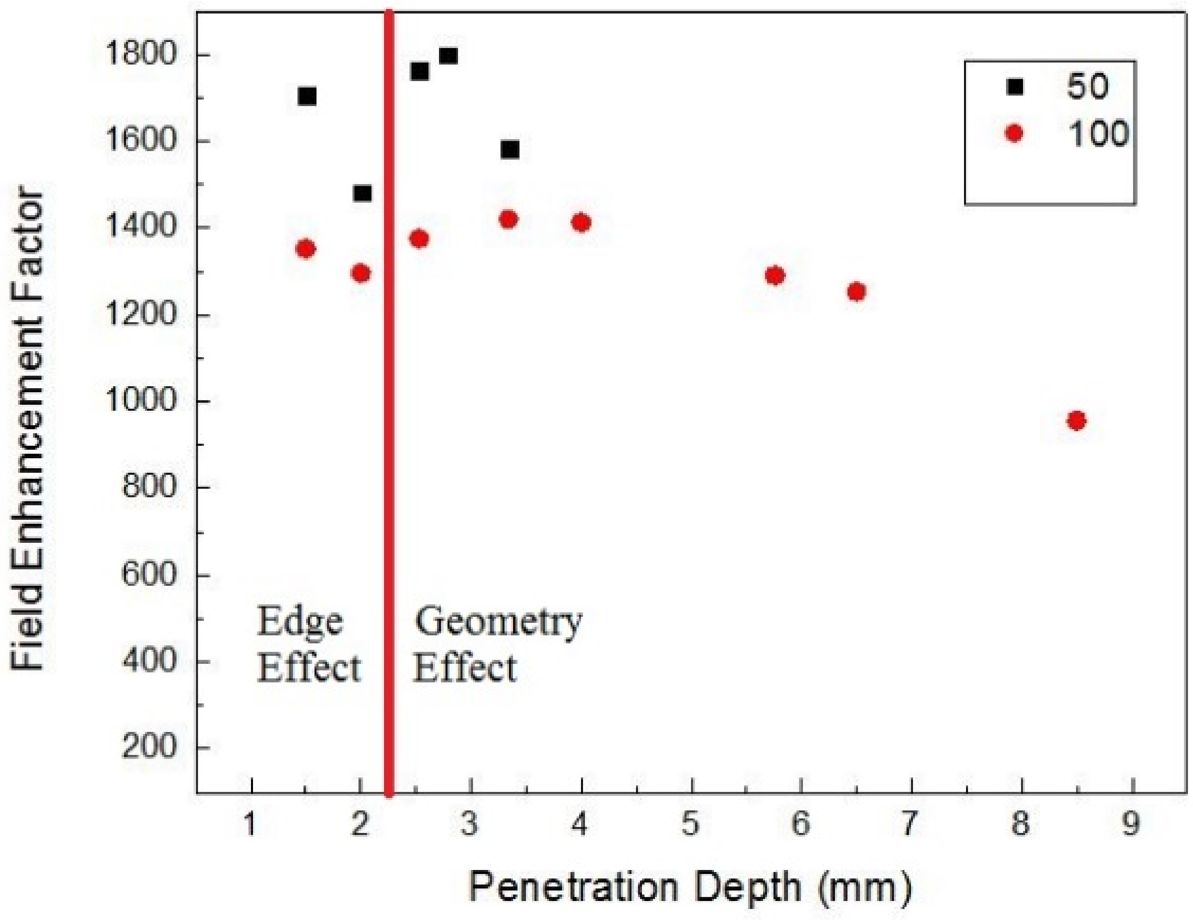
Field Enhancement Factor

$150, 330, 700\ \mu m$



- Each point represents 50 shots
- Higher β value means greater enhancement of E-field and relatively greater chance of breakdown
- At small penetration depth, edge effects dominate
- Average β increases approximately linearly with penetration depth after this
- Strongly suggest the linearly increasing area (i.e. more positions available for breakdown) dominates

Field Enhancement Factor
$50, 100, \mu m$



- Each point represents 50 shots
- Generally much higher enhancement values at lower gap sizes
- Enhancement Factor shows little trend with increasing penetration depth
- Likely that likely since pre- and post-shot surface features are comparable to gap size, this dominates over geometry effects.

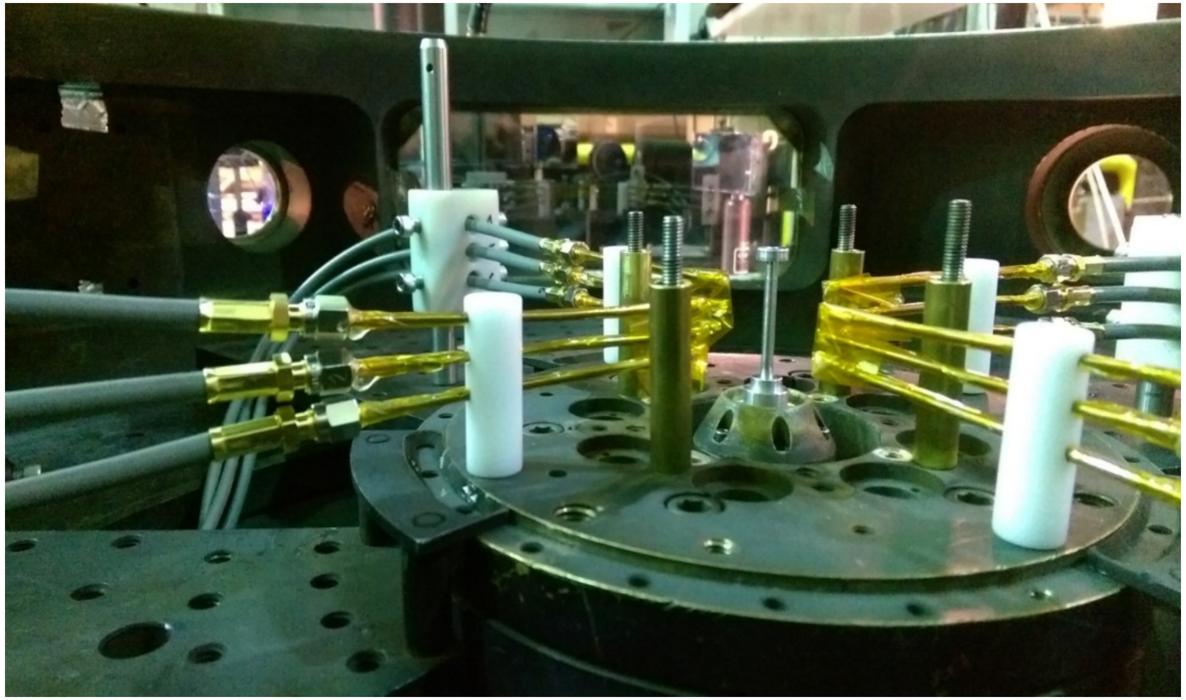
Conclusions of the UCSD Experiment

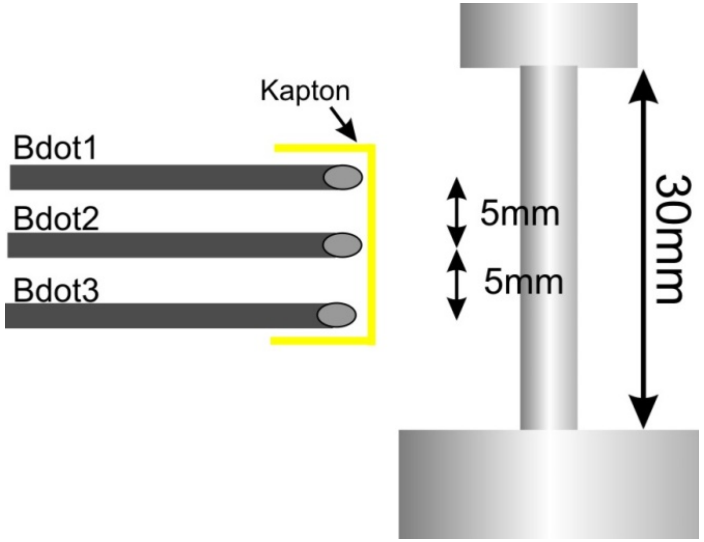
- If gap size is much larger than surface features, co-axial area overlap dominates the chances of breakdown.
- If gap size is comparable to surface features, these dominate.

- Change in enhancement factor leads to a change in current density movement
- Small gaps with large enhancement factors tend to show very non-uniform current density distributions

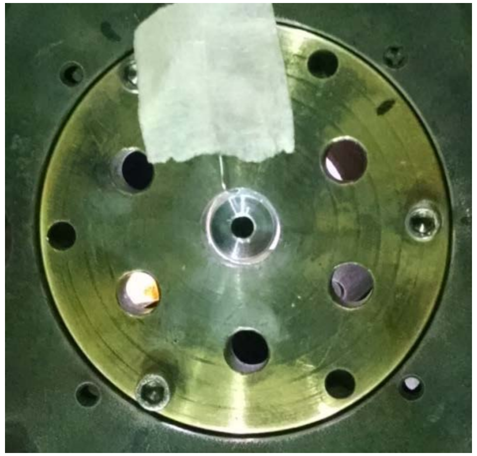
  (S. W. Cordaro and S. C. Bott-Suzuki J. Appl. Phys. 122, 213303, 2017)
- For MagLIF-type experiments with a power feed gap, we are always in the small overlap, small gap

Scaling to 1MA at COBRA



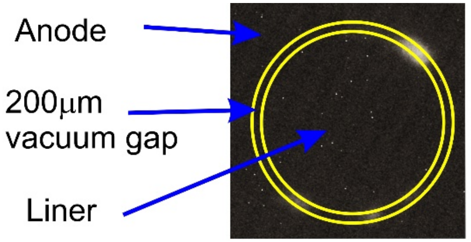


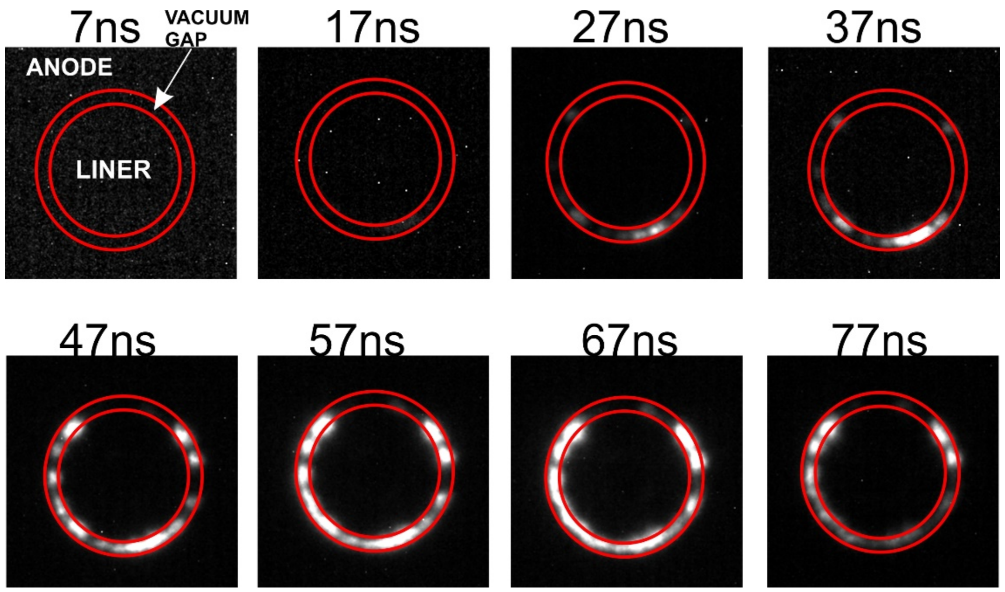
- Bdot array fielded on 30mm long liners
- Multi-frame axial gated optical imaging
- Correlation of the imaging to bdot analysis shows highly emitting region carry the majority of the current

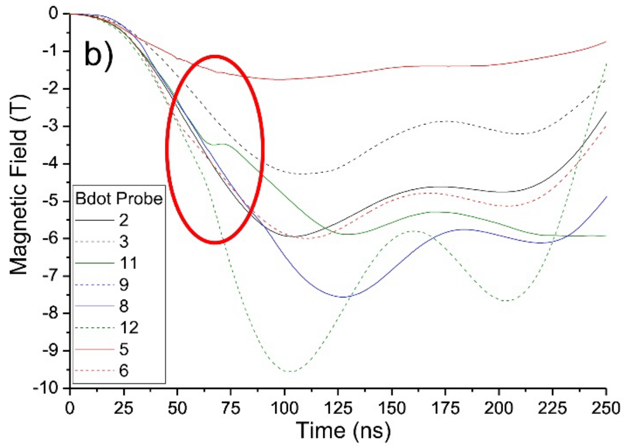


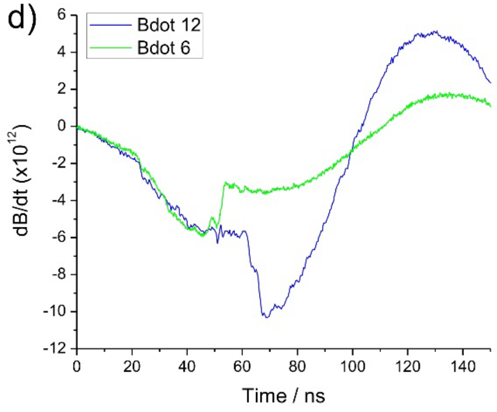
COBRA data show similar behavior to UCSD experiments

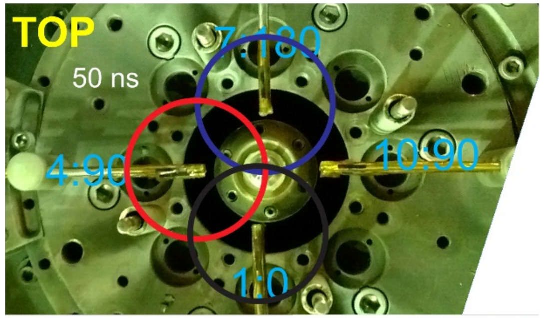
- Vacuum gap not uniformly closed in any shot
- Current density distribution moves during shot, and rarely uniform
- Shots in Sept will examine filling gaps to uniformly increase enhancement factor and examine effect on current distribution

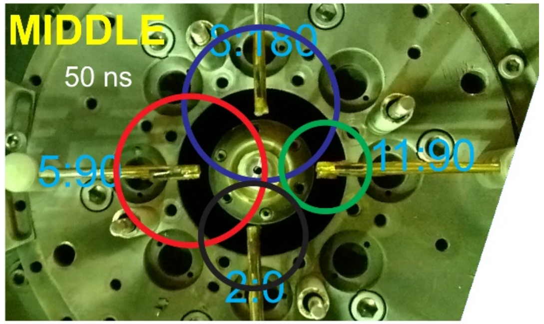


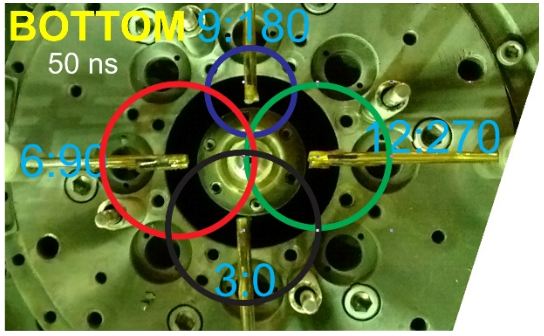








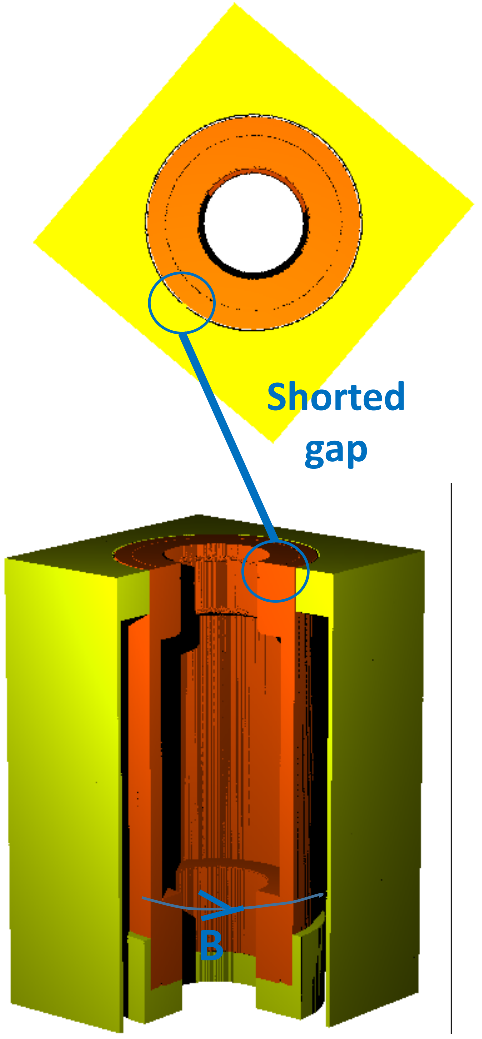




Attempt to construct Maglif scale Liner driven by Z current to study shorted gap affect on implosion symmetry

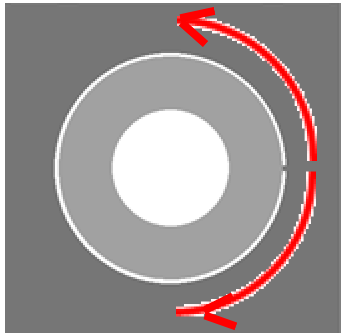
Gap shorted at top of target to allow distance for asymmetries to develop

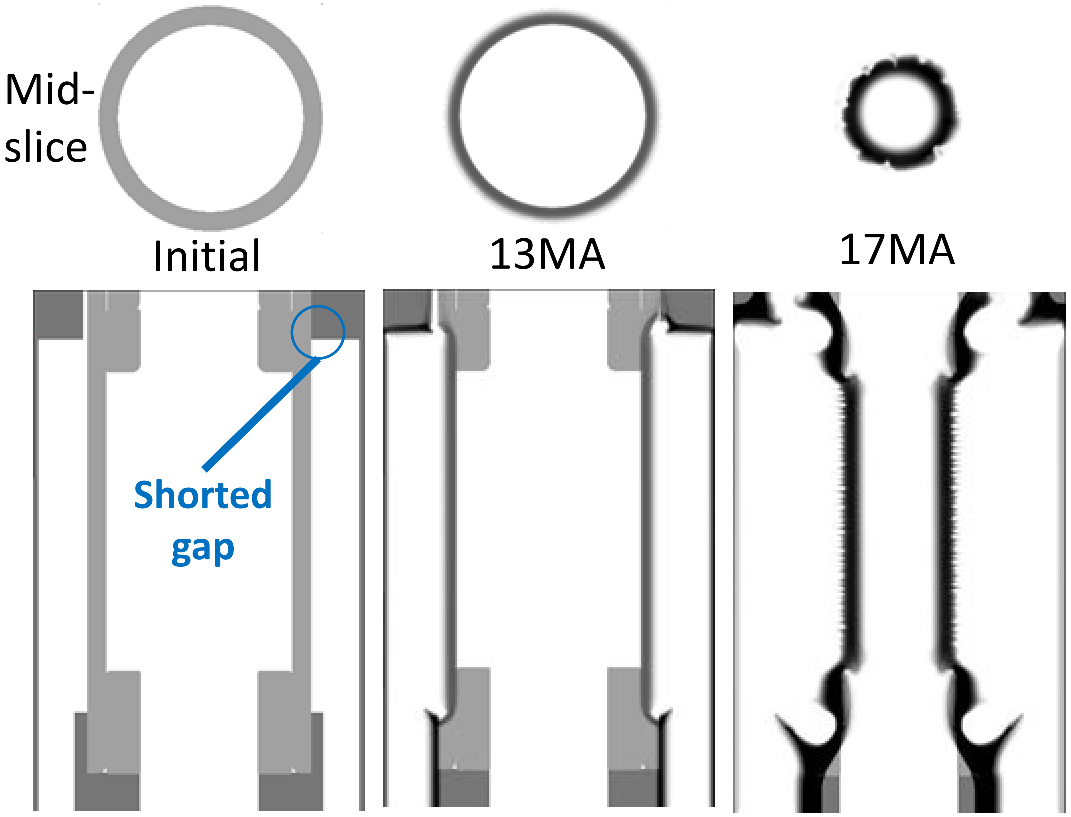
Close in return can to reduces computational volume



Azimuthally current / B-field set on bottom boundary

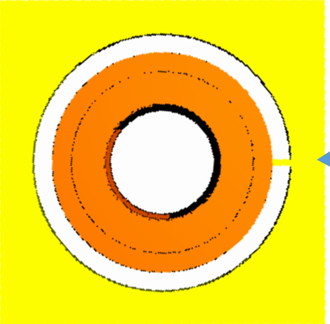
- Current rapidly azimuthally redistributed from contact point.
- Ablates electrodes, closing small gap
- Leads to symmetric field and implosion.
- How much of this is driven by symmetric bottom boundary?





Density Distributions

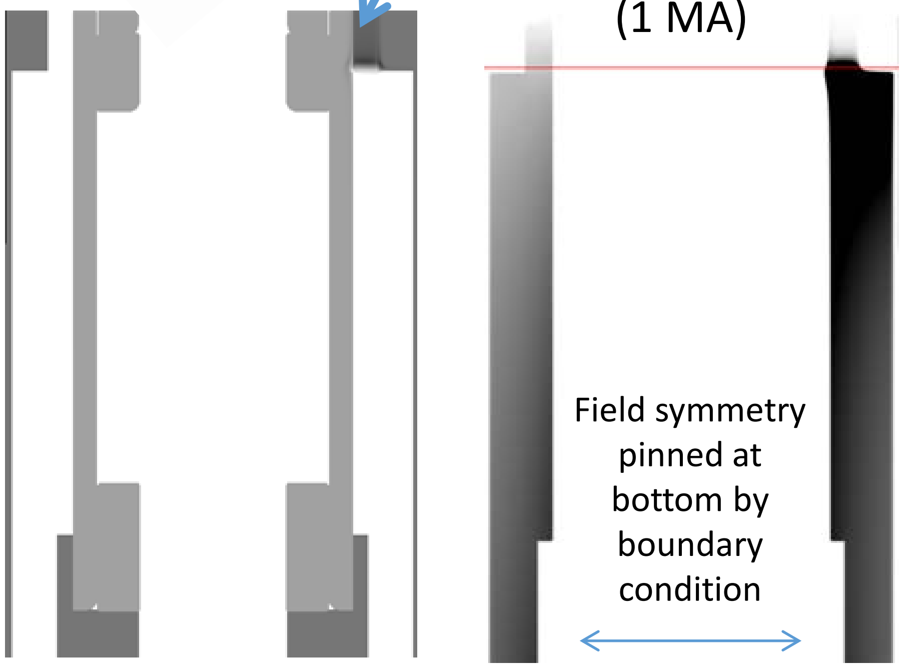
Potential Issues more apparent of we grossly exaggerate the gap



Expanding to a shorted 500 micron gap

Density

Magnetic Field (1 MA)

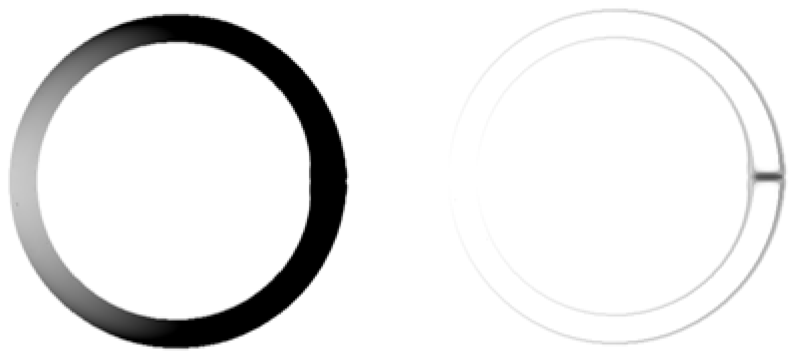


Field symmetry pinned at bottom by boundary condition

This field distribution indicates boundary condition may be playing a role in symmetrizing current in calculations

- Very large gaps can break feedback between current density ablating electrode plasma to short gaps and further symmetrizing current delivery

Current/field redistributing azimuthally at top of target



Magnetic Field

Azimuthal Cur. Density

Can be addressed:

- Model much larger volume encompassing more electrode hardware (computationally intensive)
- Link computational boundary to spatially distributed transmission line network that can support and evolve large current asymmetries (more development required)

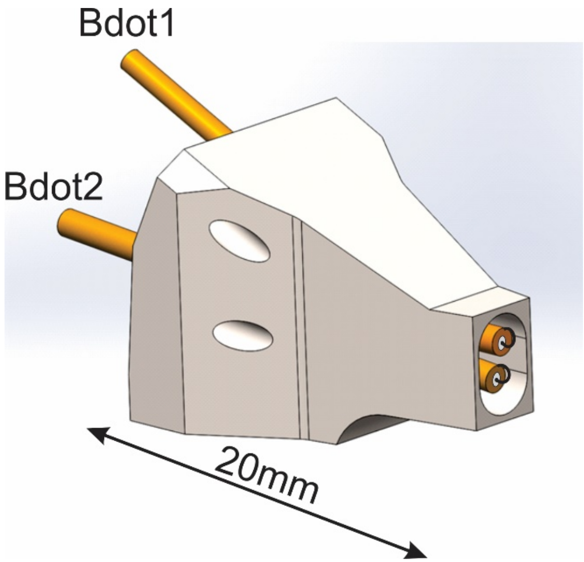
Will these effect occur on Z for MagLIF?

- Likely if effect was large, we would see effects in shots already.

  Voltages and current at early times may be large enough to close gap

- May be relevant to reloading RTL for IFE

- Currently developing similar probe system for MagLIF shots at Sandia, to assess possible impact of current non-uniformities on target convergence.



3D printed, 2-Bdot probe mount design. Shots at 26MA expected July 2019