AZIMUTHAL CURRENT DENSITY DISTRIBUTION RESULTING FROM A POWER FEED VACUUM GAP IN METALLIC LINER EXPERIMENTS AT 1 MA

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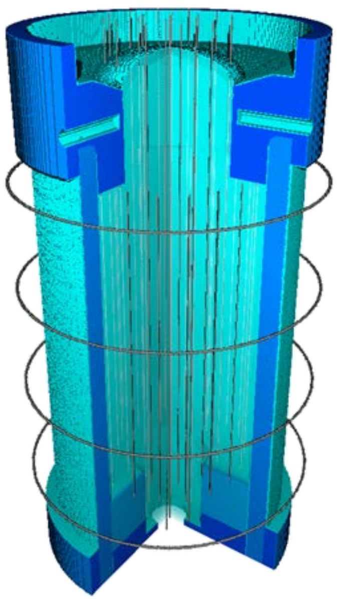
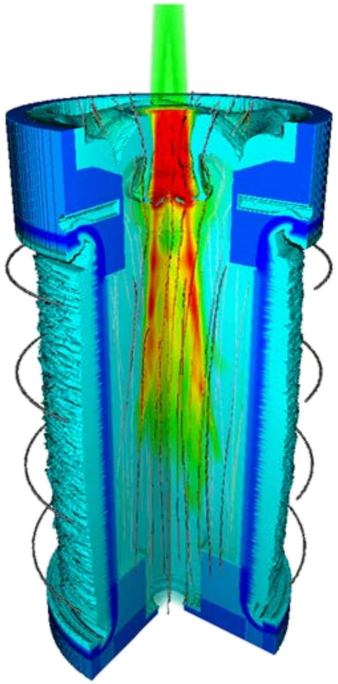
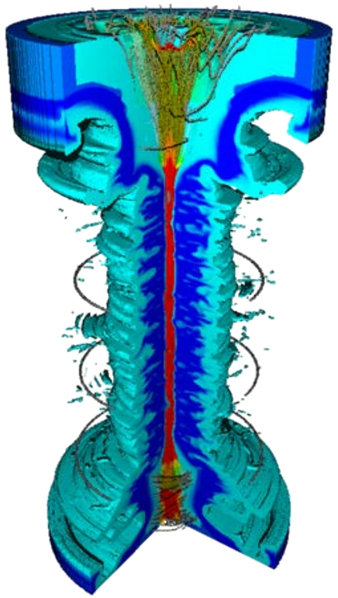
Magnetized Liner Inertial Fusion (MagLIF) is the fusion scheme presently being pursued by the z-pinch community



External Axial B-field
Liner driven by >20MA

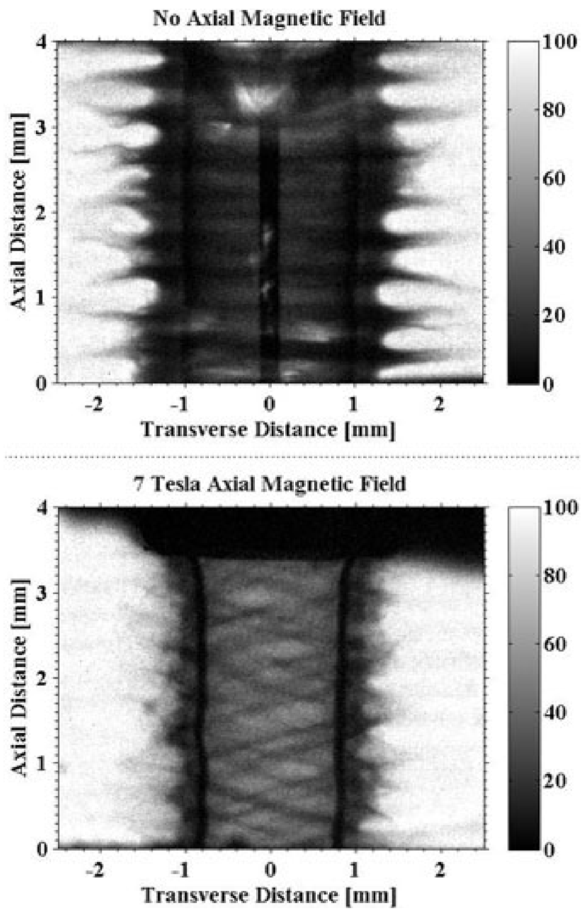


Fuel laser heated
to improve yield



Liner implosion compresses fuel, as well as axial B-field to improve confinement

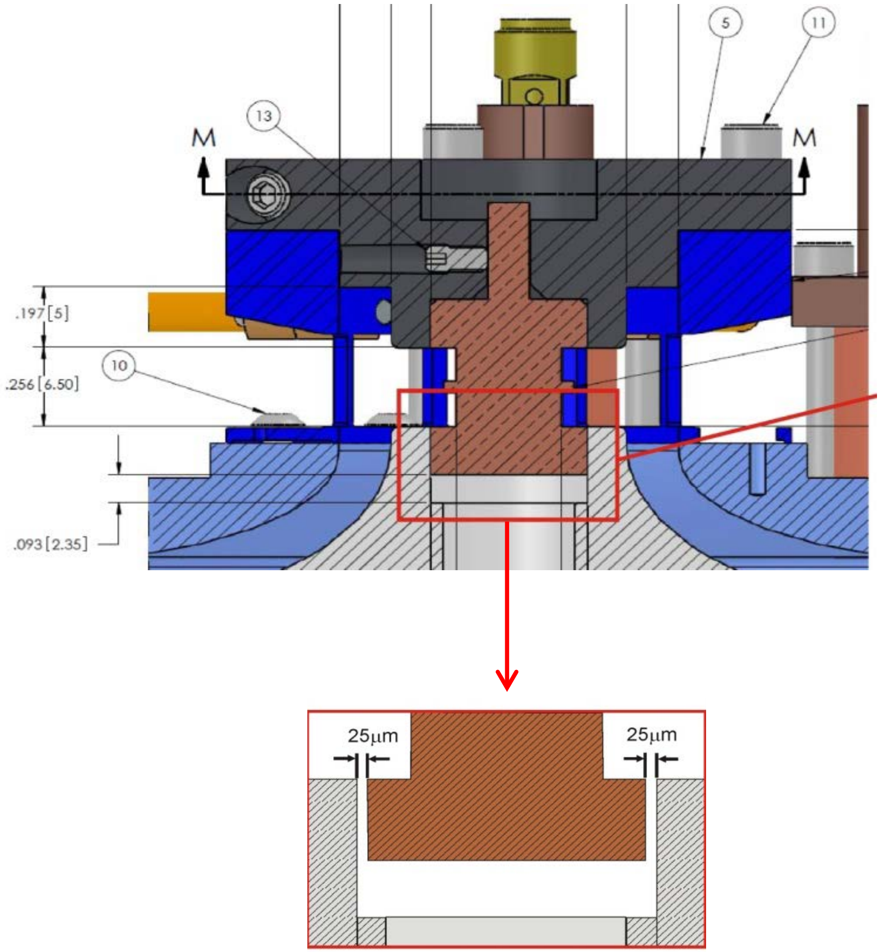
Sandia National Laboratories are carrying out integrated experiments at present

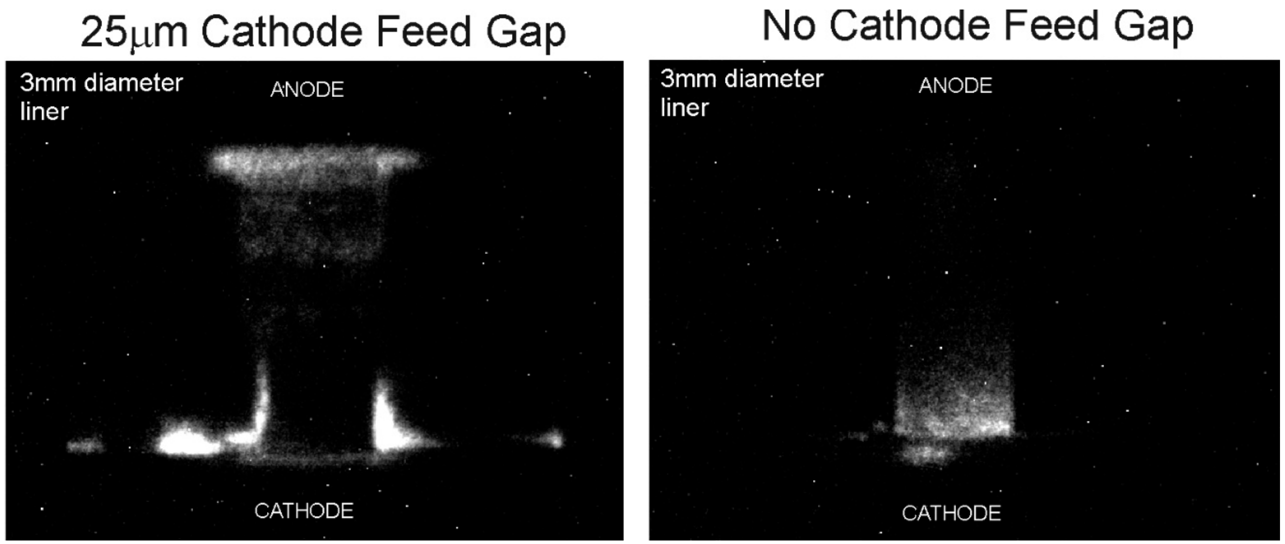


S. A. Slutz *et al, Physics of Plasmas*, **17**, p056303. (2010)

T. Awe *et al, Phys. Rev. Lett*. **111**, 235005

COBRA liners at 1MA with Cathode vacuum gap





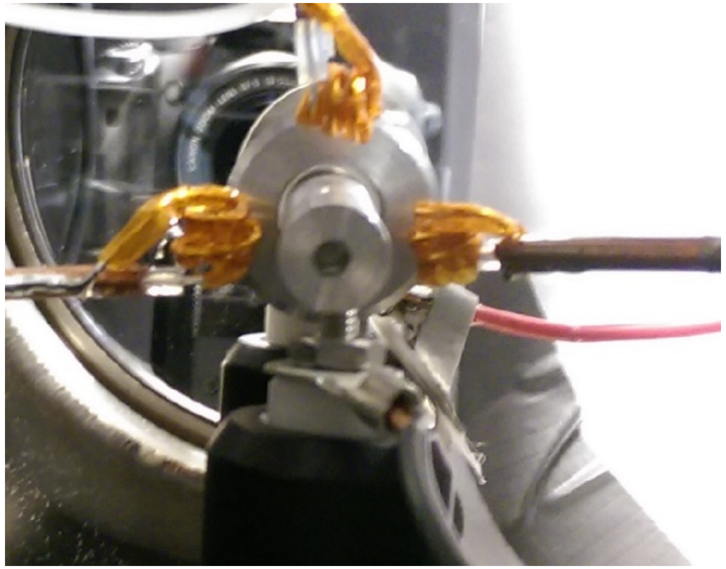
Gated optical images (10ns exposure) of Z-scale liners
(300µm thick, 6.3mm OD and 10mm tall)

- The presence of a gap at the cathode clearly has an effect on plasma formation and evolution

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

High Voltage Vacuum Gap Breakdown Experiment at UC San Diego

- Examines coaxial HV vacuum gap breakdown (15 – 30kV, 100-200 A)



- Use of bdot probes are multiple azimuthal positions allow triangulations of the effective current position

- $R = \frac{\mu I}{2\pi B}$, for each peak B-field value to estimate the corresponding distance from break down. The R value corresponds to the distance the breakdown is from the probe

S.W. Cordaro *et al, Rev. Sci. Instrumen.*, 86, 073503 (2015)

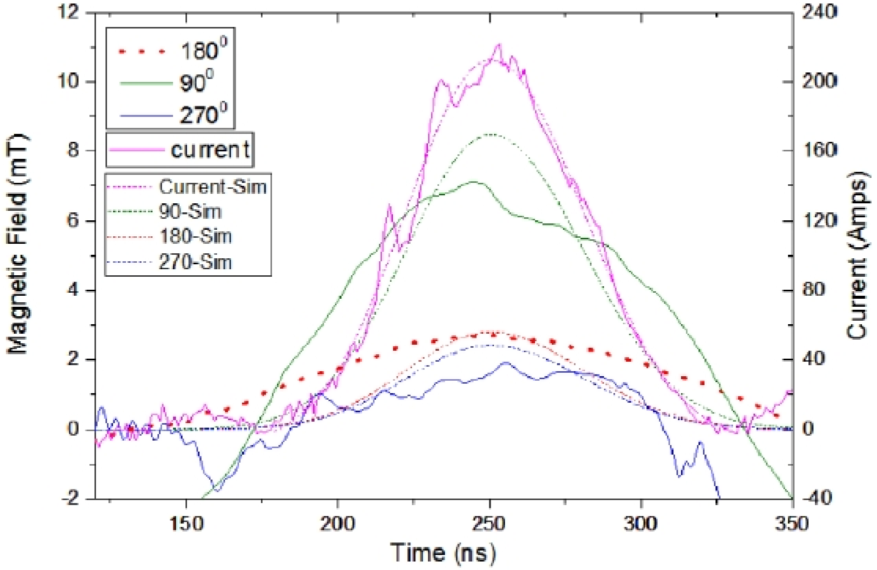
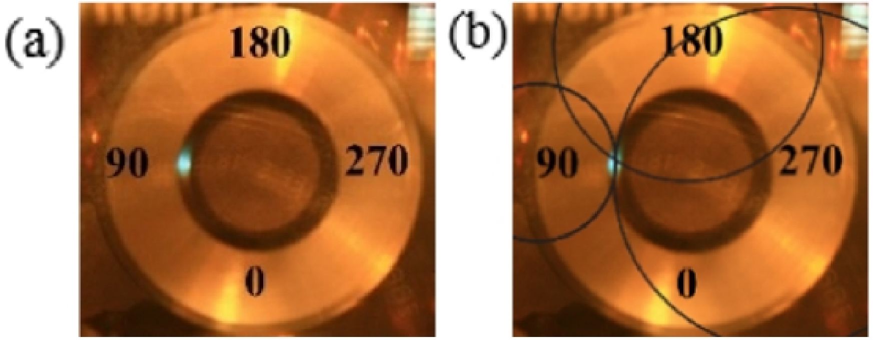
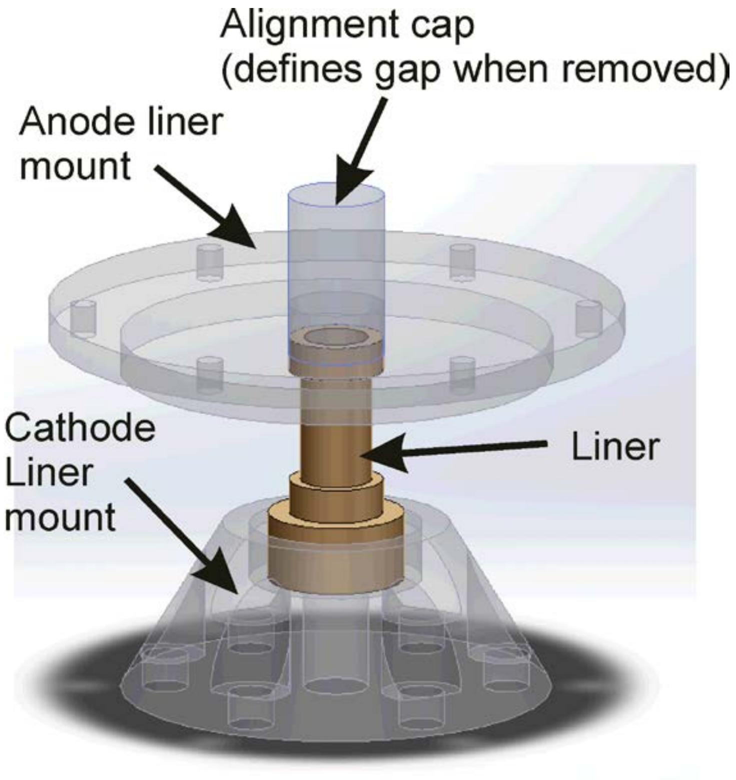


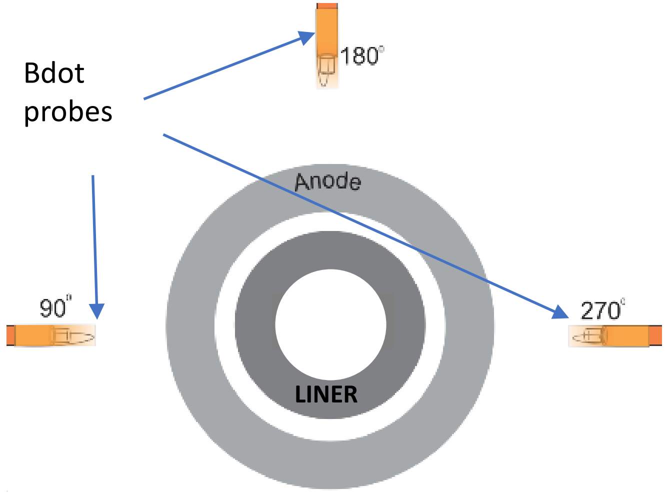
FIG. 7. Experimental vs. analytical magnetic field and current, shot no. 34.



COBRA Liner Shots with an Anode vacuum gap

- Gap alignment more accurate and reliable
- Direct imaging access to power feed gap using gated (5ns) multi-frame optical camera
- Bdot array used to enable triangulation method

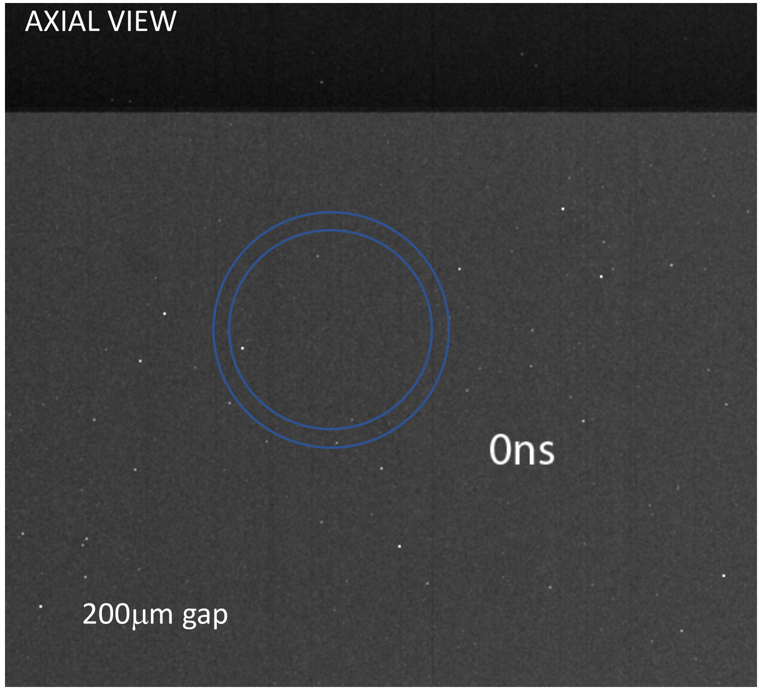


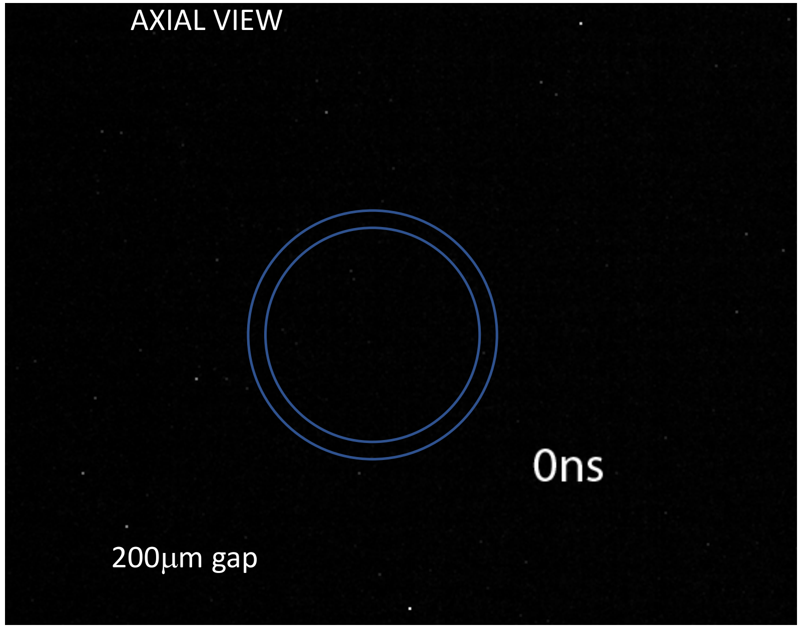


AXIAL VIEW FOR OPTICAL IMAGING

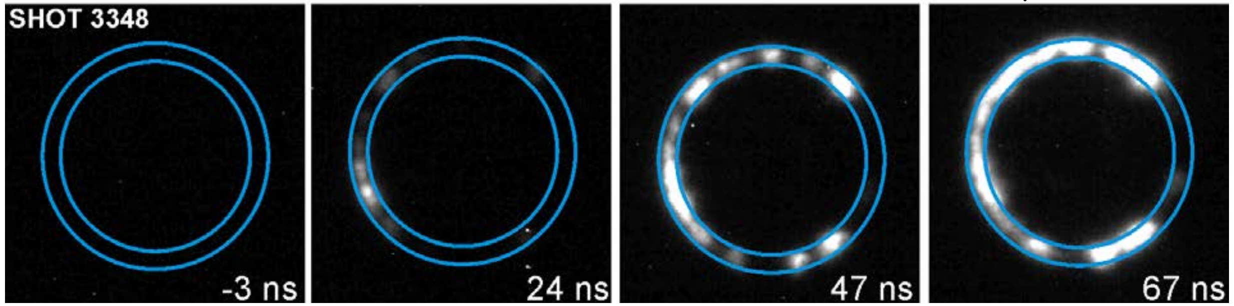
Z-scale liners, aluminum
(150μm thick, 3mm OD and 10mm tall)

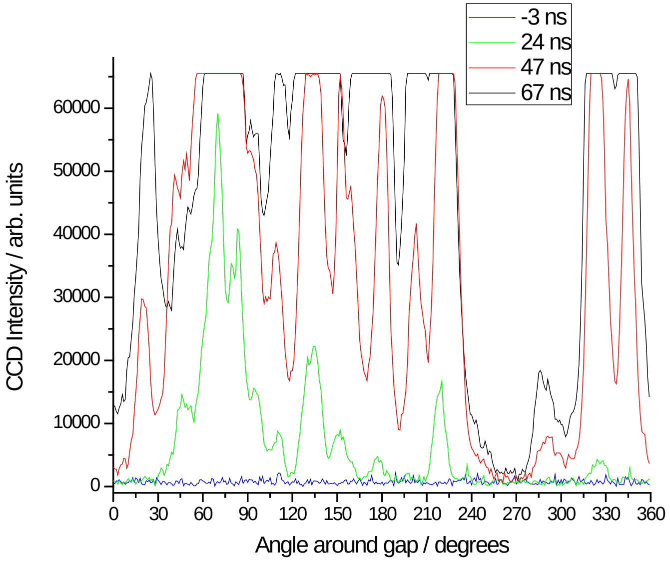
Multi-frame optical camera is ideal for following plasma evolution





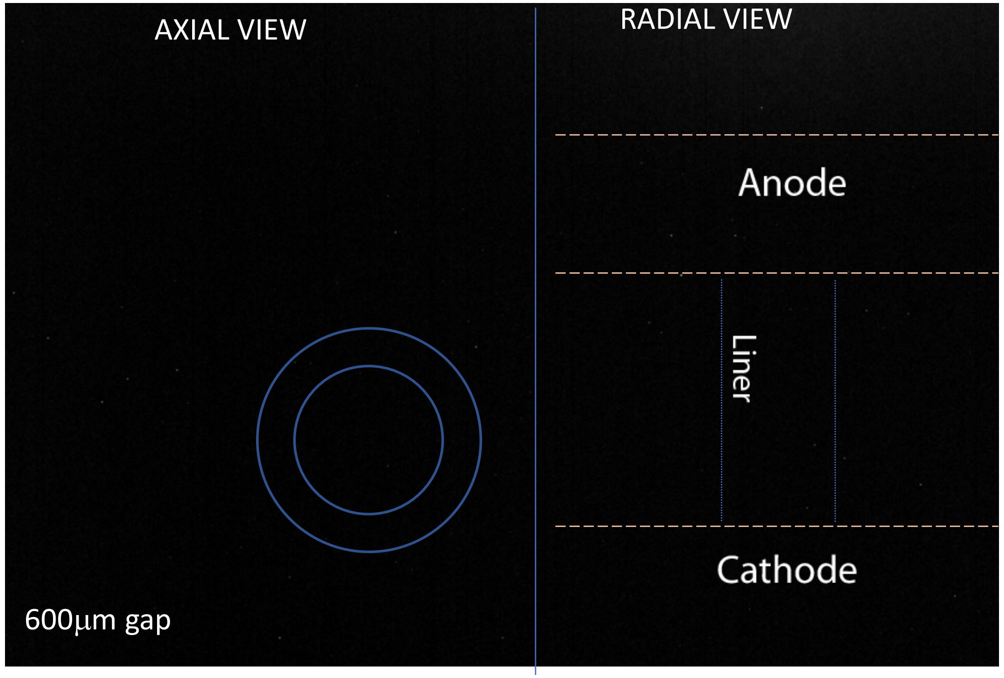
200μm gap



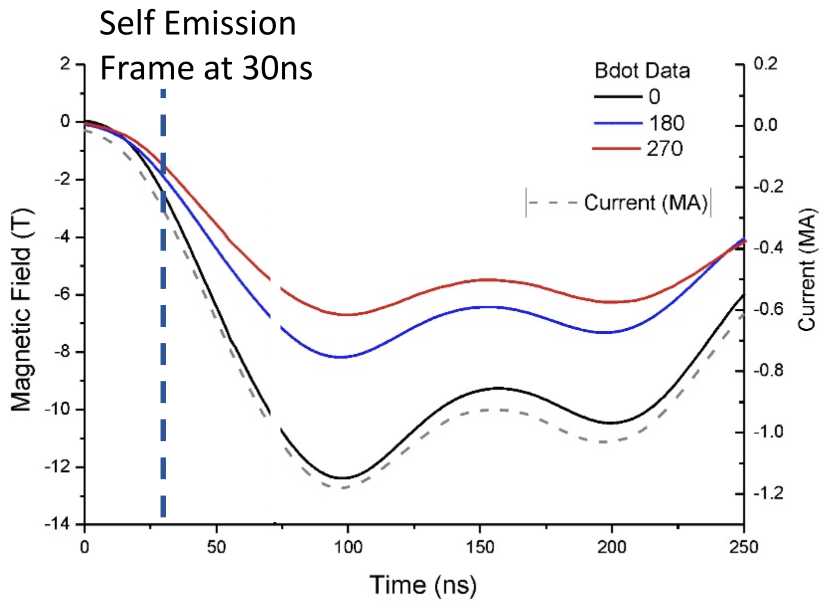


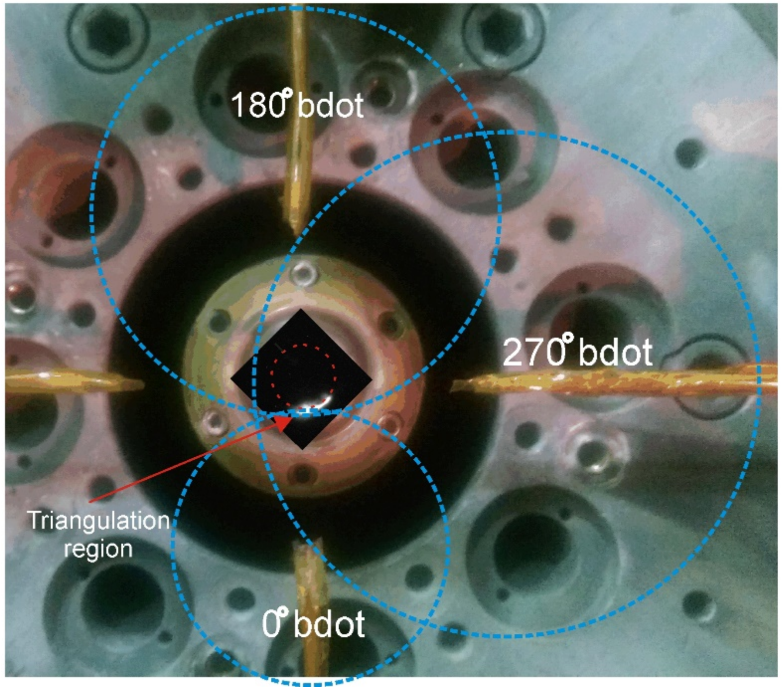
- Initial breakdowns form multiple hotspots which evolve relatively slowly
- Gap not closed uniformly in any shot

Bdot triangulation method correlated to imaging for COBRA liners



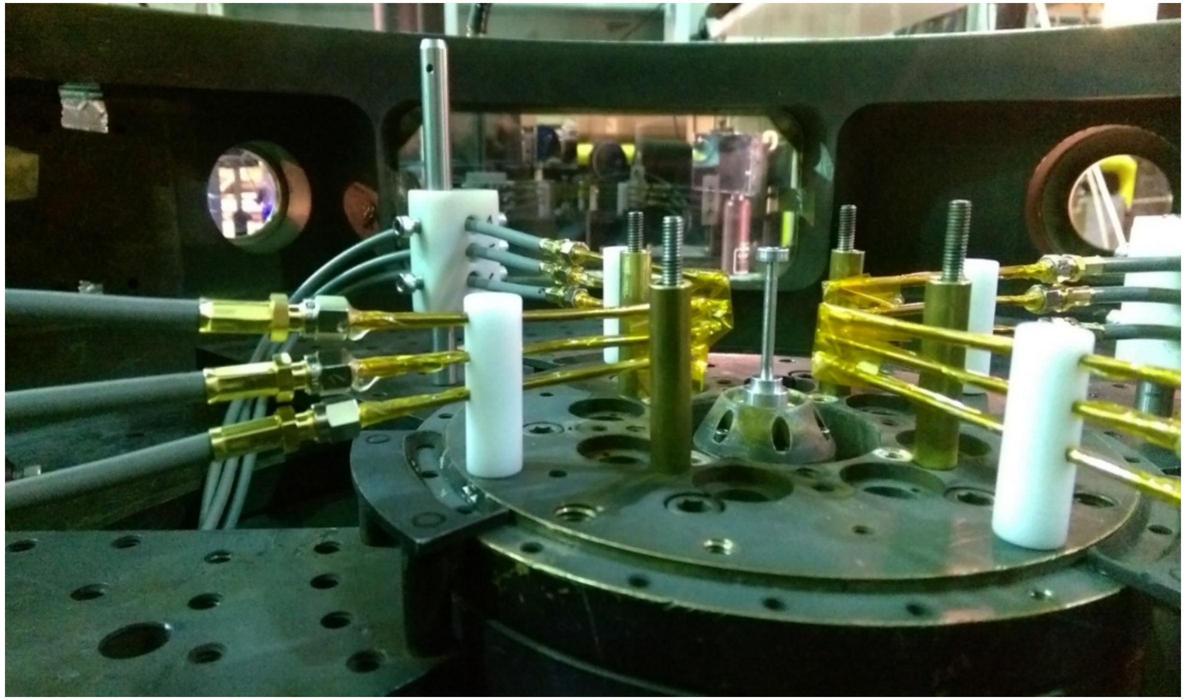
Optical emission frames (10ns exposure, 10ns interframe)

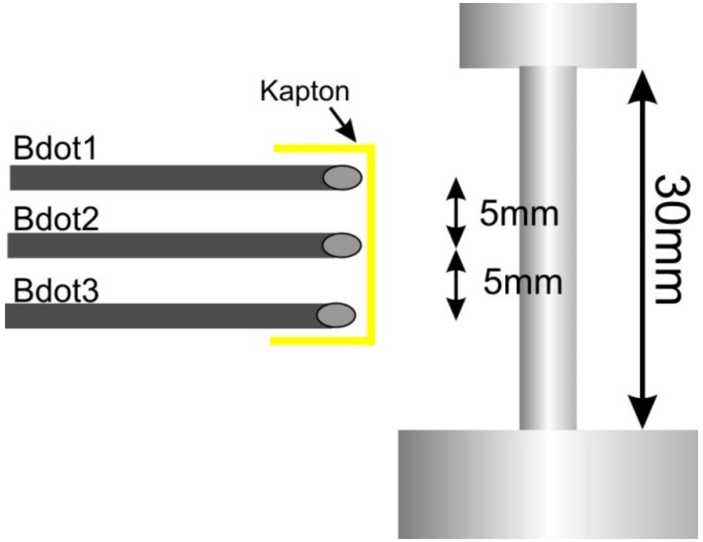




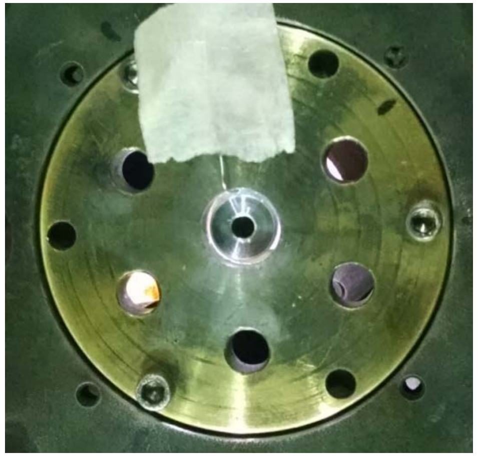
- In some shots, plasma one azimuthal position appears to dominate the profile for much of the current drive
- Effectiveness of the bdot triangulation links emission to current density
- This assumes all current at a single point

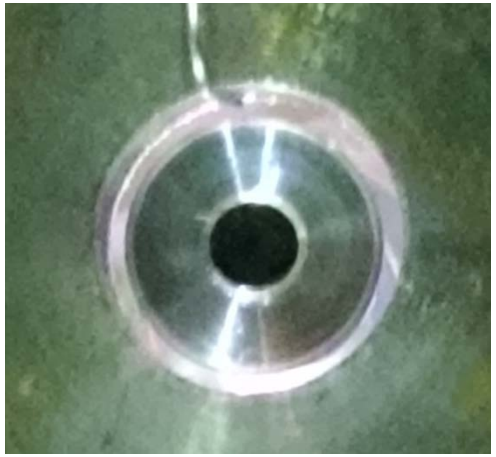
Investigations of current density as a function of axial position



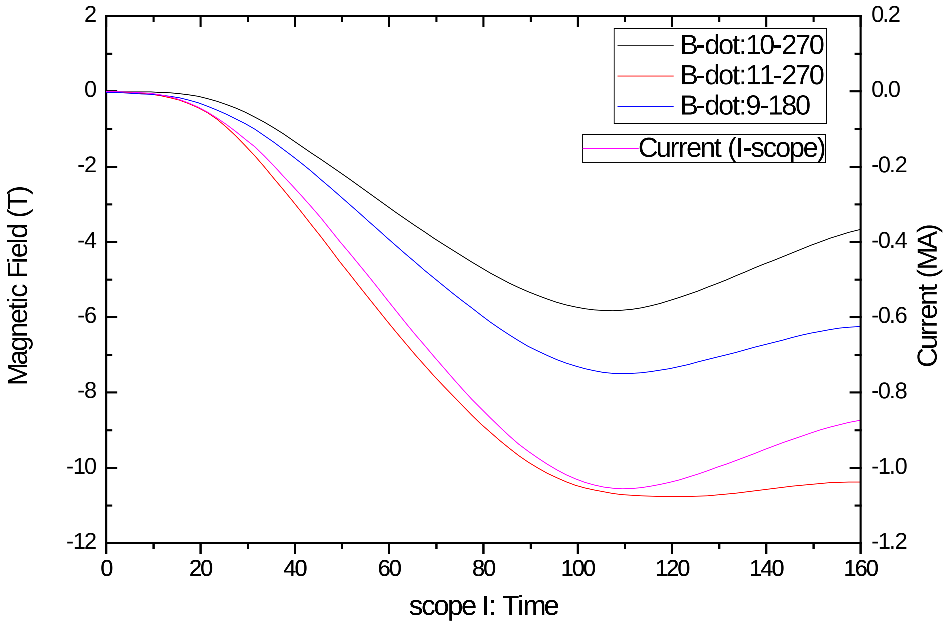


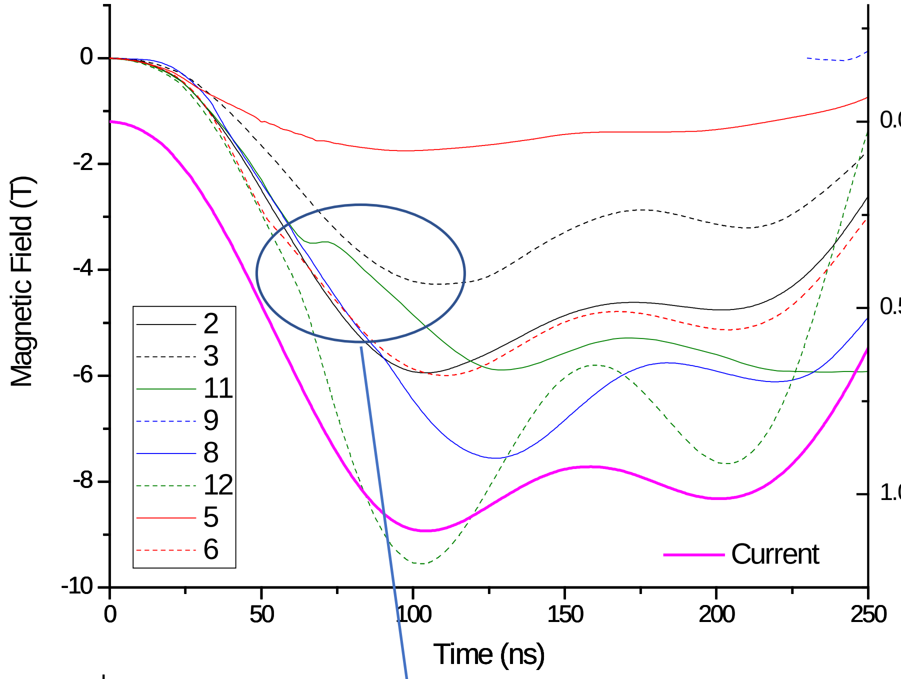
- Probes well-protected and can we used for several shot before repair required
- Pre- and post shot calibration on repaired probes identical
- Using a ‘trigger pin’ determines initial breakdown position

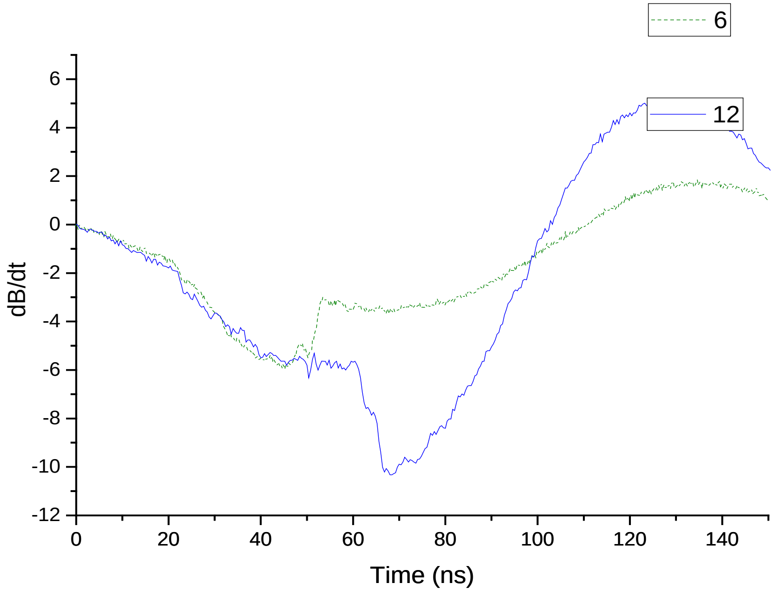


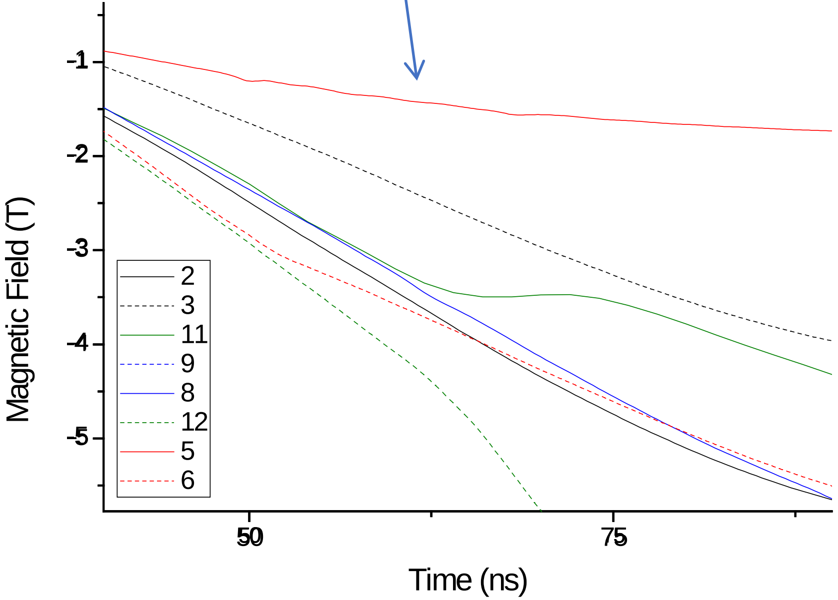


dB/dt and integrated traces show clear changes in azimuthal current distribution





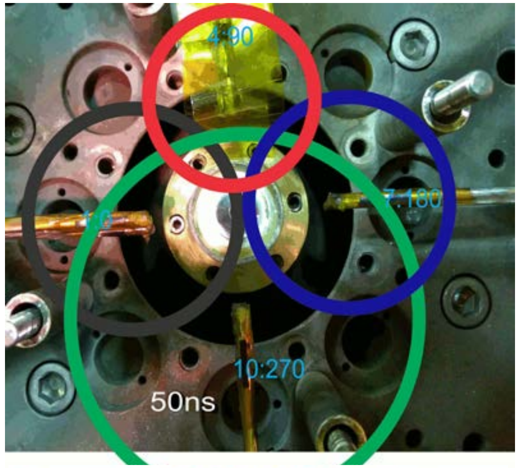


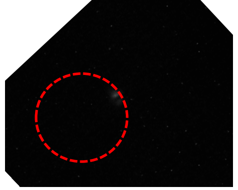


SHOT 3675

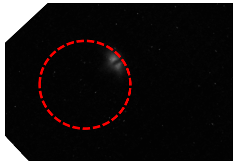
Al liner with trigger pin

Top (1,4,7,10)



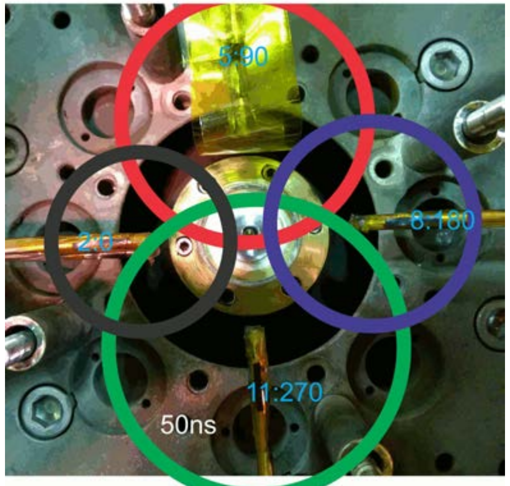


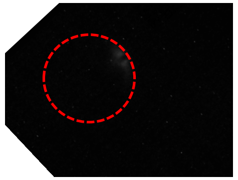
50ns



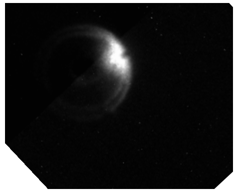
60ns

Middle (2,5,8,11)



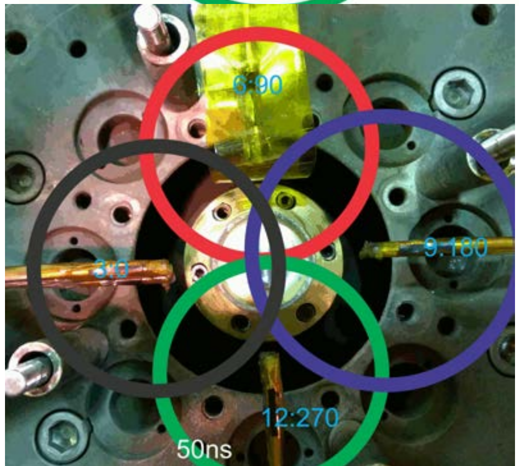


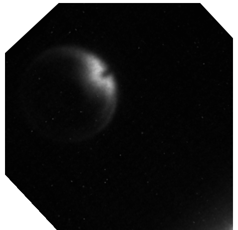
70ns



80ns

Bottom (3,6,9,12)



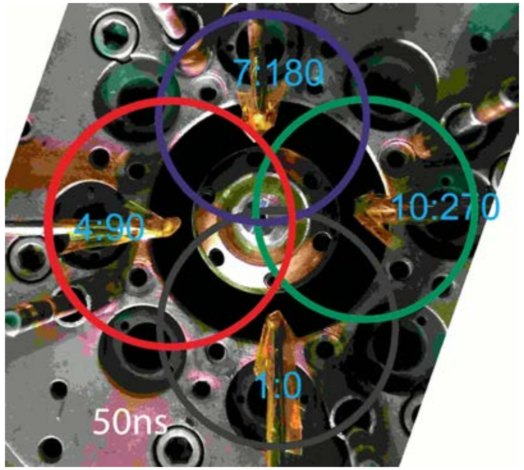


100ns

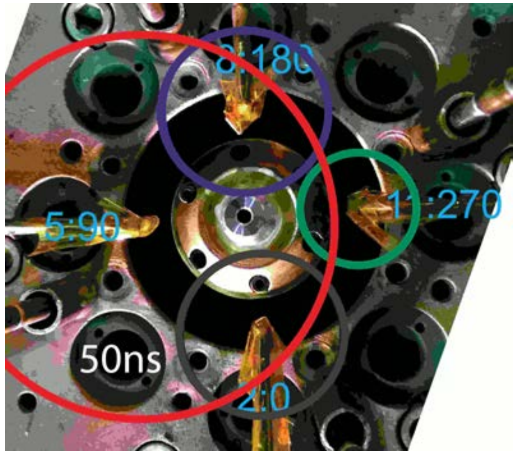
SHOT 3678

Al liner with trigger pin

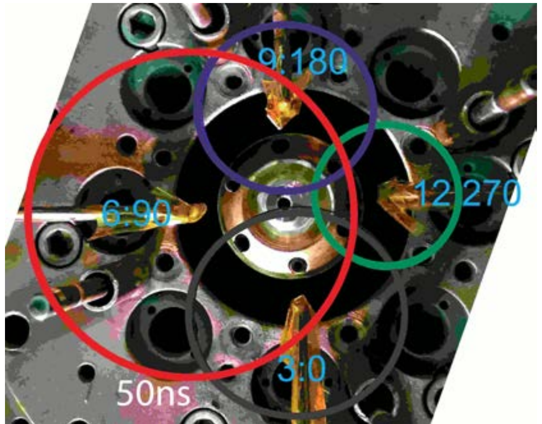
Top (1,4,7,10)

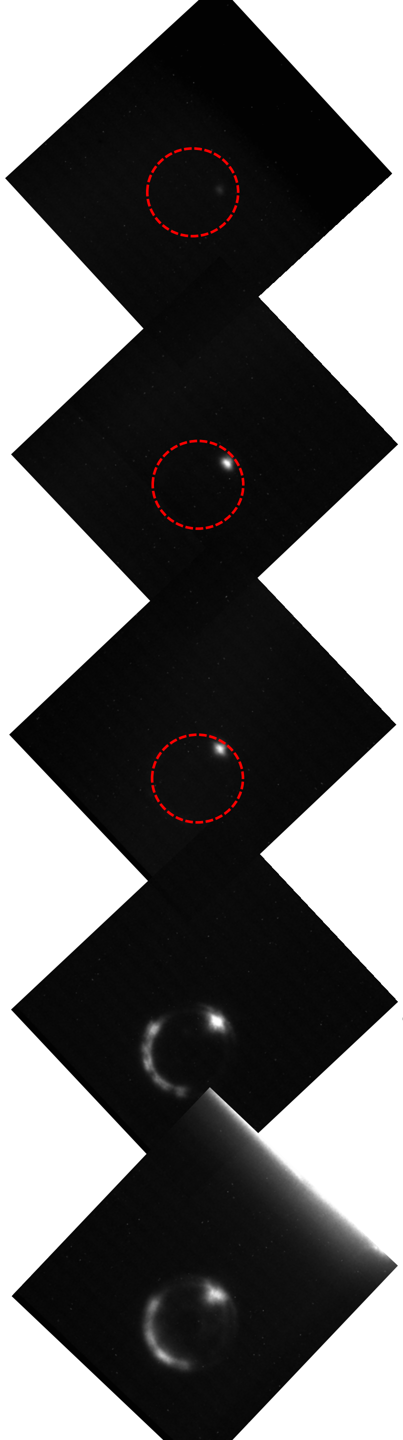


Middle (2,5,8,11)



Bottom (3,6,9,12)





50ns

60ns

70ns

80ns

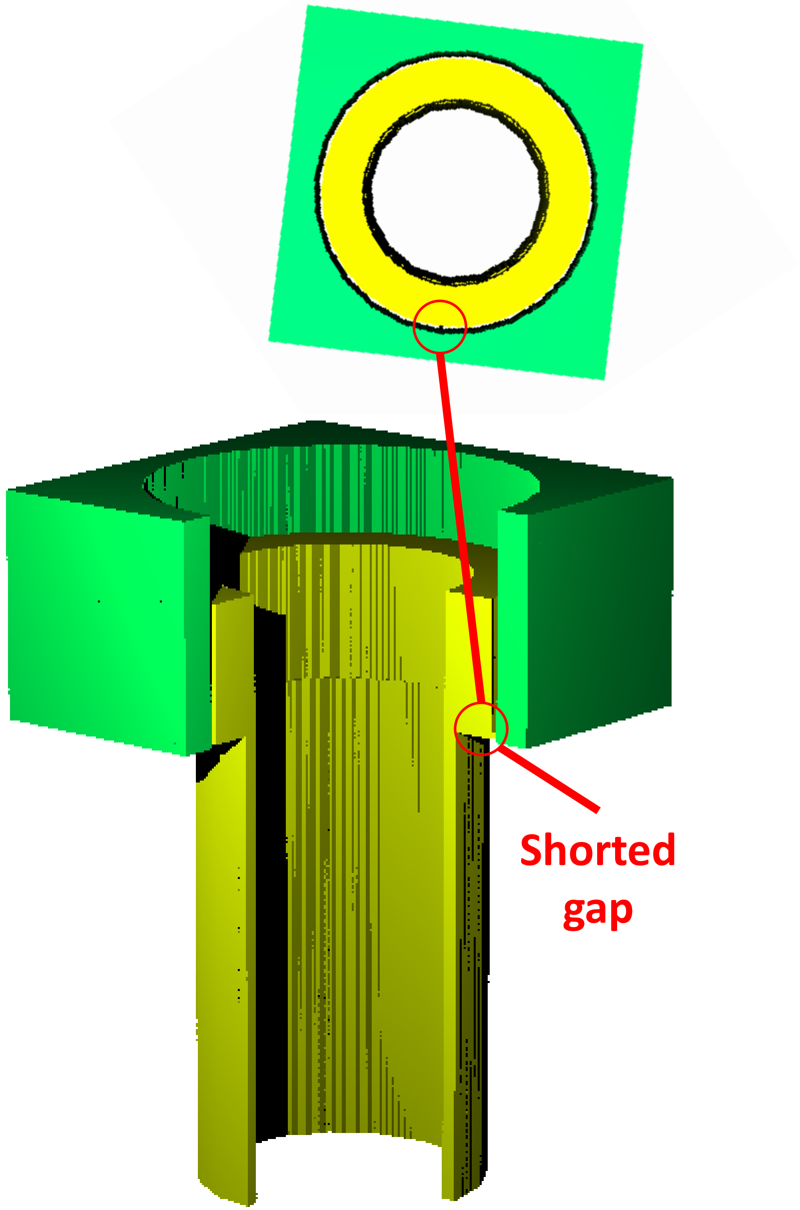
100ns

MHD modeling of how electrode contact asymmetries may influence liner implosions is very challenging

Electron emission breakdown processes not captured here, but we can try to study how an intentionally shorted gap affects later time current distribution.

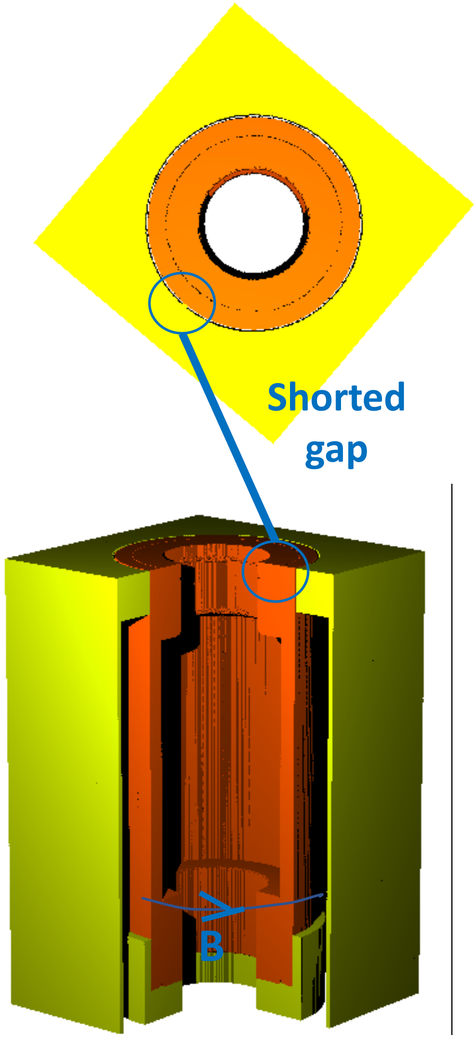
<u>Computationally challenging:</u>

- Inherently 3D with large target sizes (cm's) combined with small electrode gaps (microns).
- To be tractable we typically focus calculations the load and only adjacent electrodes – so must then impose field boundaries.
- Drive current is typically supplied through a magnetic field boundary that assumes something about current distribution (e.g. cylindrical symmetry)
- A close in boundary that allows self consistent evolution of asymmetric current distribution without dictating the solution is non-trivial, and extending modelled volume to sizes where this is less of a concern is computationally prohibitive.



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

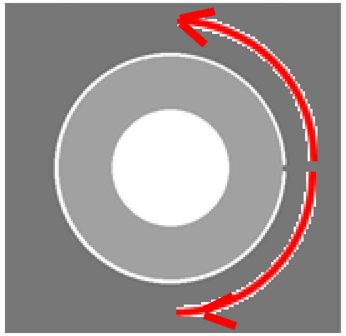
Gap shorted at top of target to allow distance for asymmetries to develop

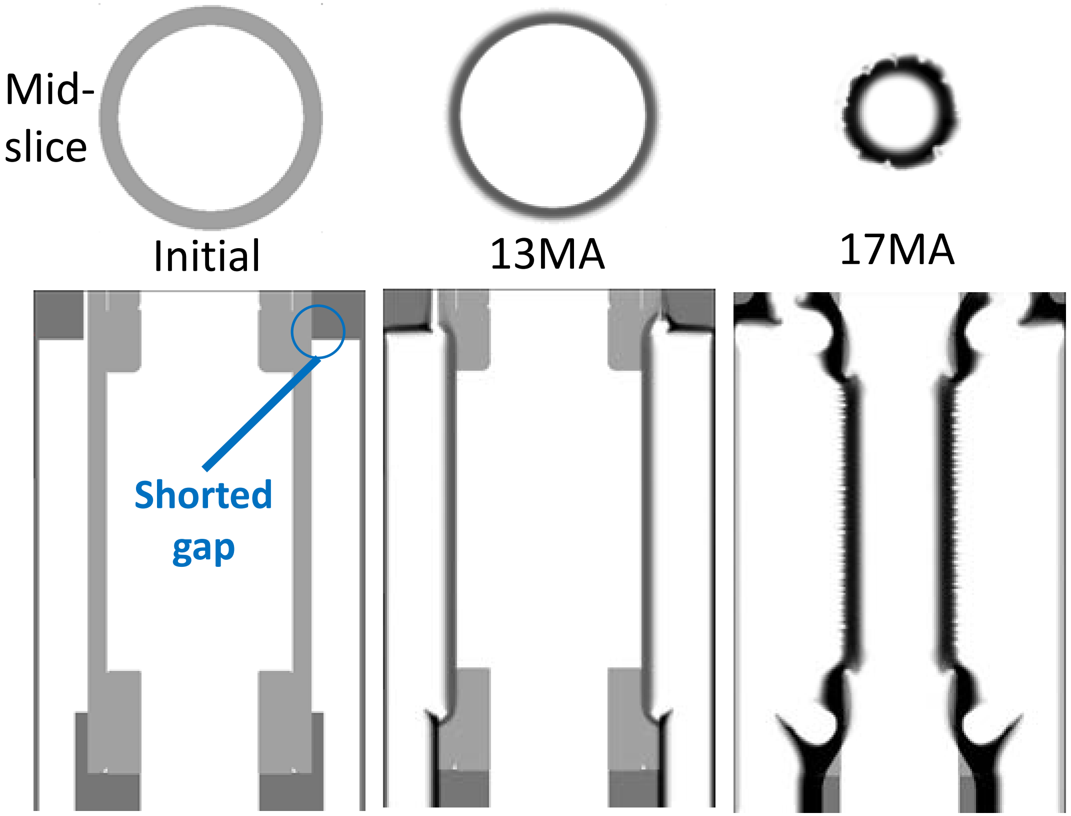


Close in return can to reduces computational volume

Azimuthally current / B-field set on bottom boundary

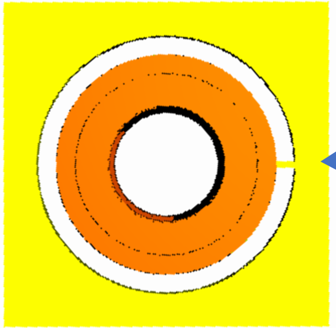
- Current rapidly azimuthally redistributed from contact point.
- Ablates electrodes, closing small gap
- Leads to symmetric field and implosion.
- How much of this is driven by symmetric bottom boundary?





Density Distributions

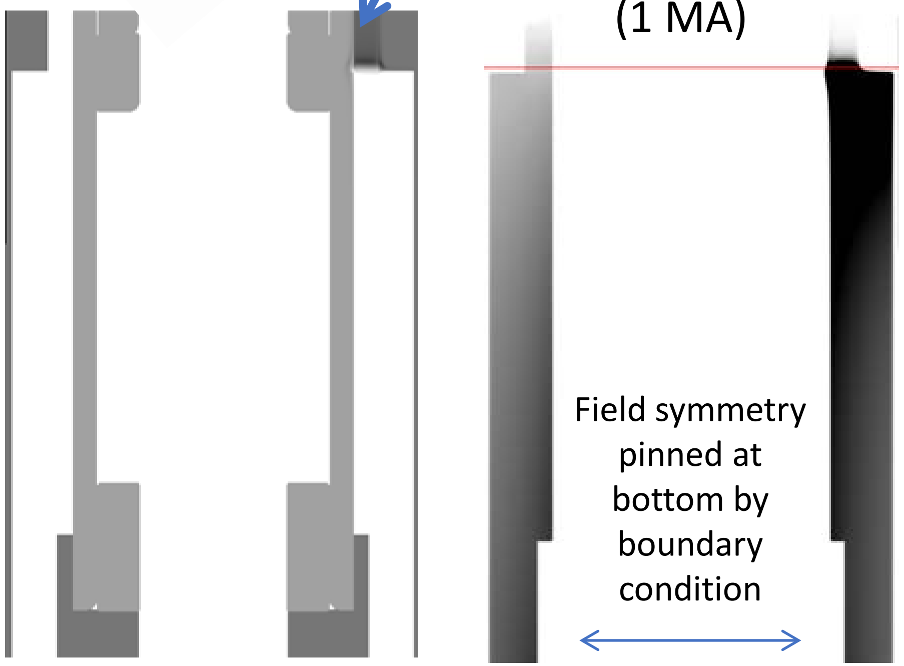
Potential Issues more apparent of we grossly exaggerate the gap



Expanding to a shorted 500 micron gap

Density

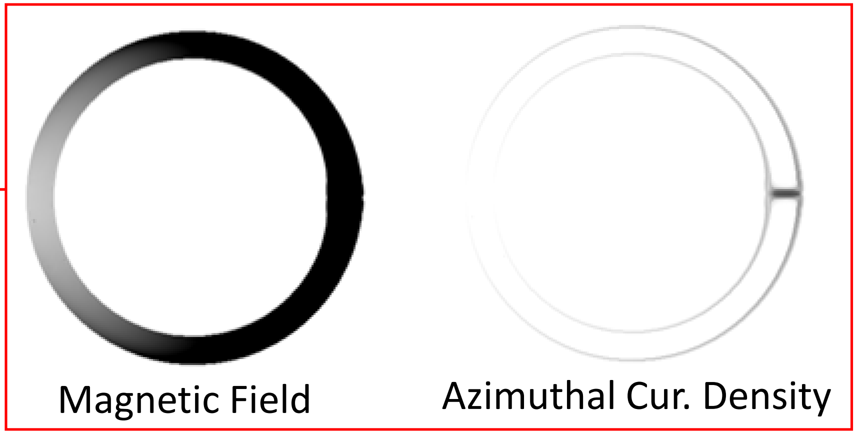
Magnetic Field (1 MA)



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



Can be addressed:

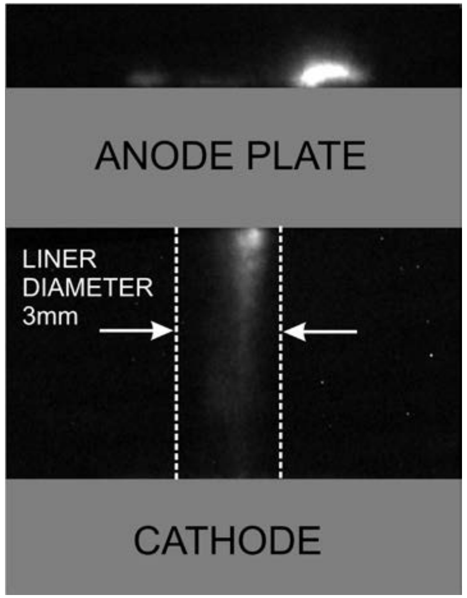
- Model much larger volume encompassing more electrode hardware (computationally intensive)
- Link computational boundary to spatially distributed transmission line network that can support and evolve large current asymmetries (more development required)

What are the driving mechanisms?

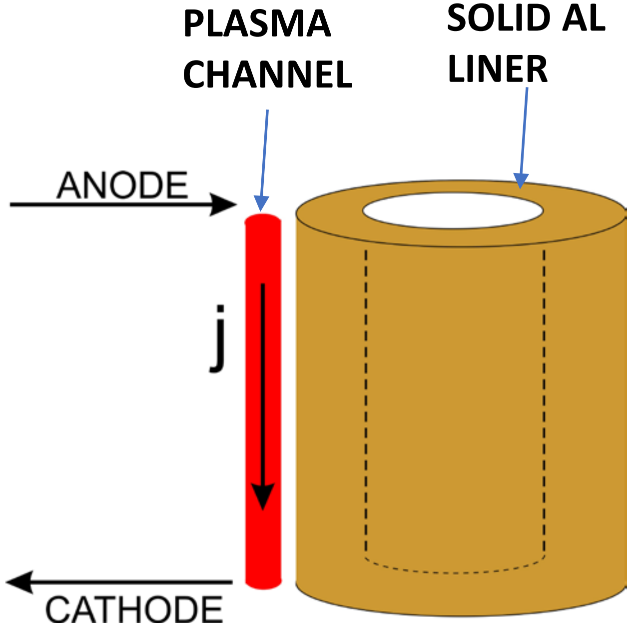
What causes:

1) the relatively slow evolution of the current profile, and

2) the development or absence of additional flashover regions?



EXPERIMENTAL IMAGE



SIMPLIFIED SKETCH

<u>Plasma channel parameters</u>

n_e upper limit ~ 10^{18} cm^{-3}

T_e upper limit ~ few eV (e.g. 10 eV) ~ T_i

Z upper limit ~ 8

radius ~ 0.5mm

Assume that current flows primarily in the plasma channel once this is formed from an initial breakdown of the vacuum gap

What are the driving mechanisms?

- Two mechanisms that might be acting in a z-pinch geometry for the plasma parameters observed

- The electron drift velocity in the current carrying plasma may be sufficiently high to trigger the Lower Hybrid Instability or the Ion Acoustic Instability

$$j=n_e e u$$

- Values of the ion sounds speed, c_s, and the ion thermal velocity, v_{ti} the cyclotron frequency, ω_{ce}, and plasma frequency, ω_{pe}, are taken from the experimental limits

For most of the current drive $u >> c_s$

$c_s > v_{ti}$

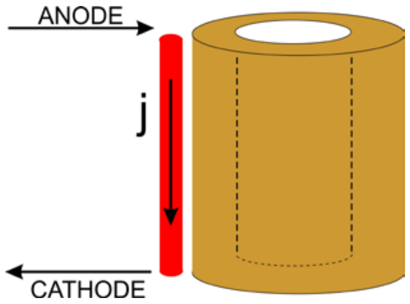
However, $\omega_{LH} << \omega_{ce}$ so LH cannot lead to resistivity increase
And $\omega_{pe} >> \omega_{ce}$ leading to stronger IAI growth over LH

Ryutov *et al, Rev. Mod. Phys*, **72**, 167 (2000)

- Values/regimes depend strongly on the actual values of the plasma – experimental uncertainty is an issue

- The result is a rapid rise in the plasma resistivity

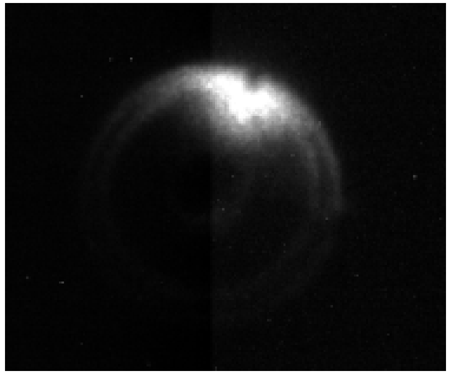
Increased resistivity can explain observed behaviour



Dramatic increase in plasma resistivity due to LH/IAT

Skin depth increases to allow Current flow in solid liner

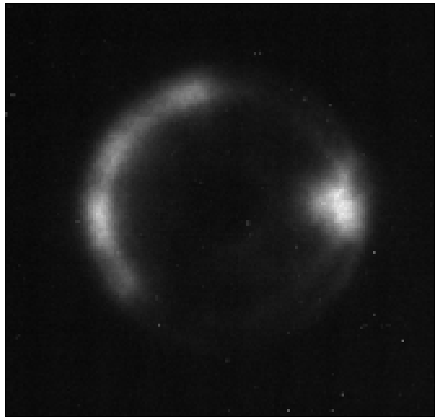
$$\delta = \sqrt{\frac{\eta}{\pi f \mu}}$$



Emission region limited to the initial position throughout the current drive

Resistive voltage at vacuum gap increases, causing more azimuthal positions to flash over and take current

$$V = \cancel{I\frac{dL}{dt}} + L\frac{dI}{dt} + \boldsymbol{IR}$$



Additional emission regions develop as current drive continues

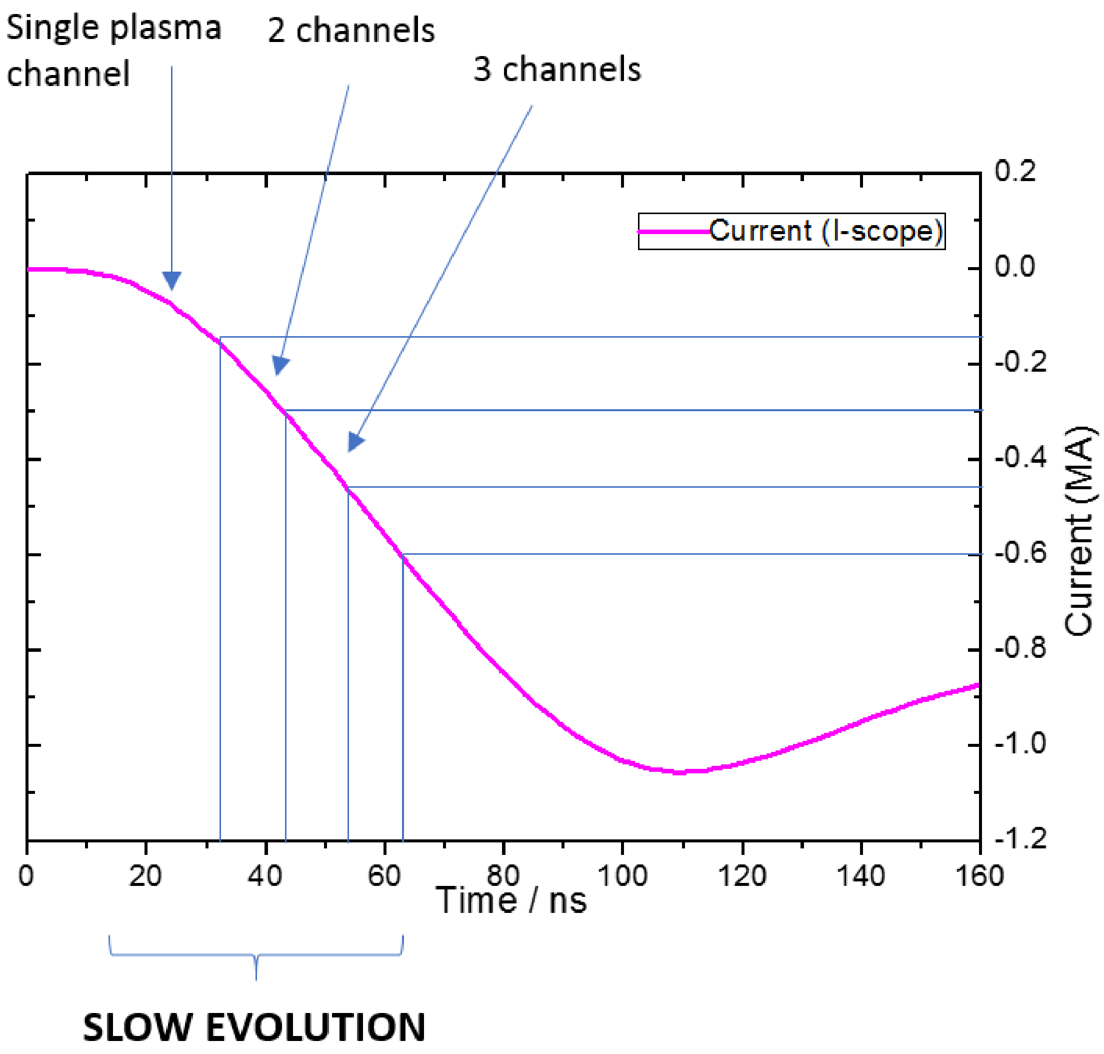
- Can explain the general behavior – sometimes multiple breakdowns as resistive voltage rises, or sometimes single position as skin depth increases
- Both these are driven by increases in initial plasma resistivity (AIT likely)

Ion Acoustic Instability may explain the observed timescale

- The rapid rise in resistivity due to IAI essentially limits the electron drift velocity in the plasma channel to values of $u_{crit} = \zeta C_s$ where $\zeta \sim 2\text{–}4$

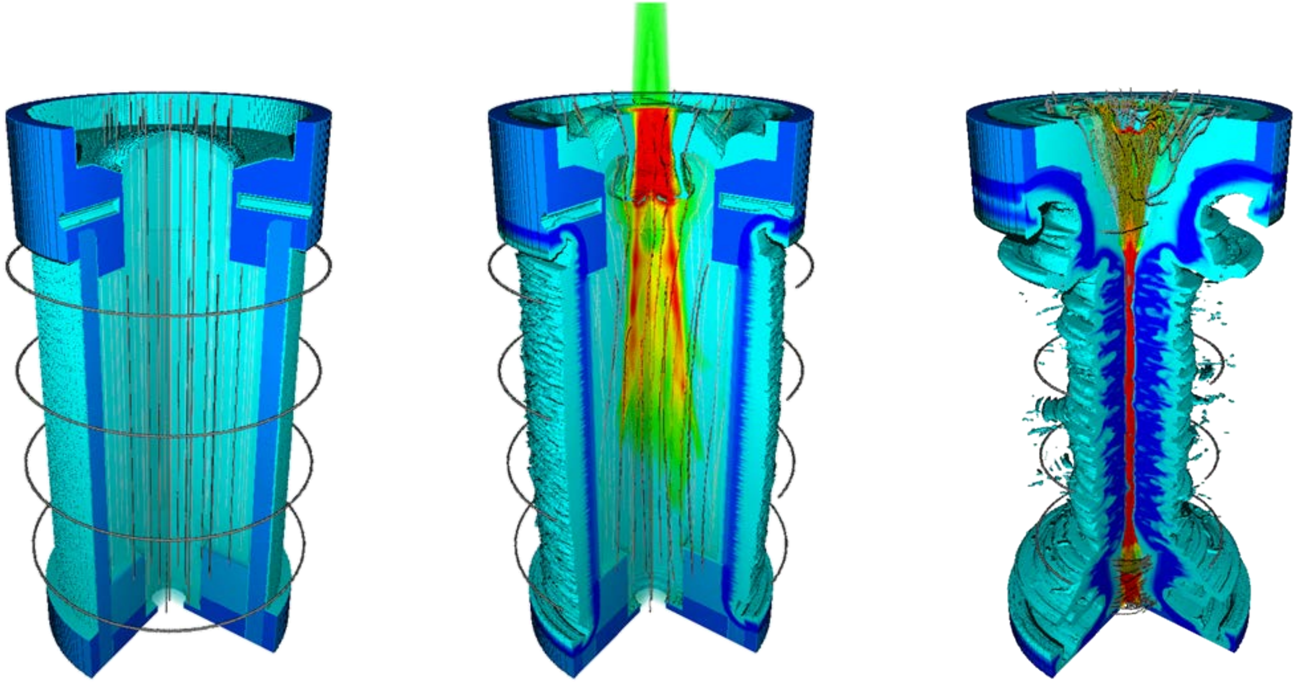
S. Lebedev *et al, AIP Proc*, **808**, 73 (2006)

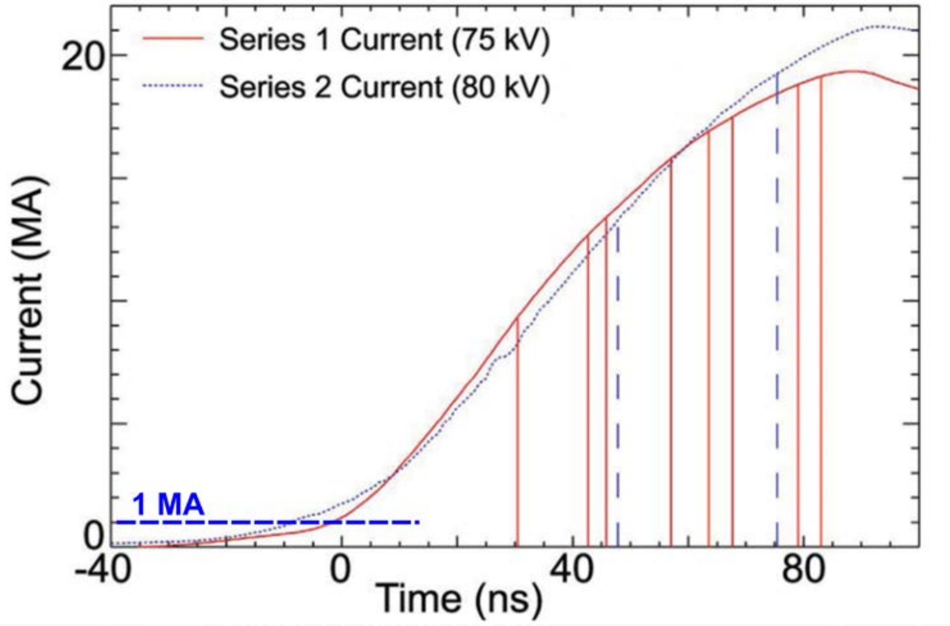
- Assume that the channel parameters don't change rapidly from the initial values
- For a fixed plasma channel, this limits the current it can carry to ~15 kA
- Matches timescale of current evolution as this is driven by the current rise-rate



Is this issue a problem for MagLIF on Z?

- Dependence on current rise-rate means conditions for forming many current carrying plasma location around the azimuth may be met early in the current drive
- Time of first gap breakdown?
- Possibly argue that we would have seen this is present results if it is an issue, but likely should be studied further.





D. B. Sinars *et al, Phys. Plasmas* **18**, 056301 (2011)

Conclusions

- The presence of a vacuum gap in the power feed close to the liner load has a strong and persistent effect of current azimuthal uniformity at 1MA
- Evolution characteristics of the current density may be consistent with increased resistivity in surface plasma caused by the Ion Acoustic Instability (timescale, plasma formation, lack of gap size dependence)
- Need more detailed, quantitative measurements of the early plasma to confirm scalings
- Possible that similar process could be at work on Z MagLIF experiments, and we are checking similar b-dot measurements and working with simulations to examine this.