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Controlling the explosion of a high-current-density conductor through the addition of micron-scale surface defects

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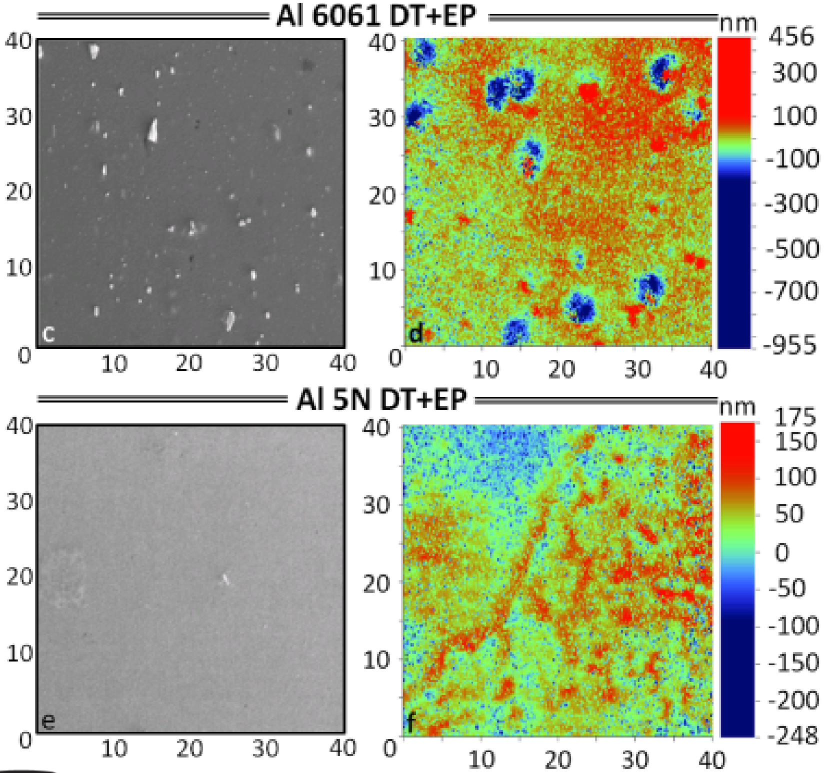
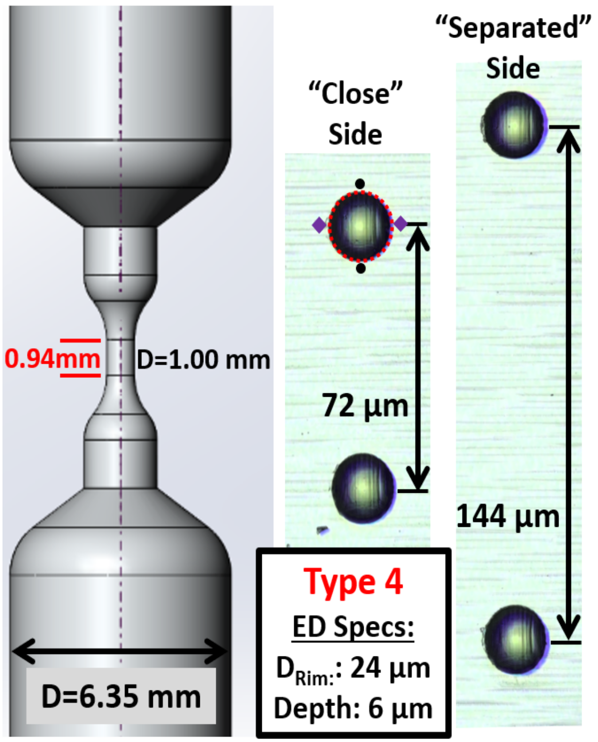
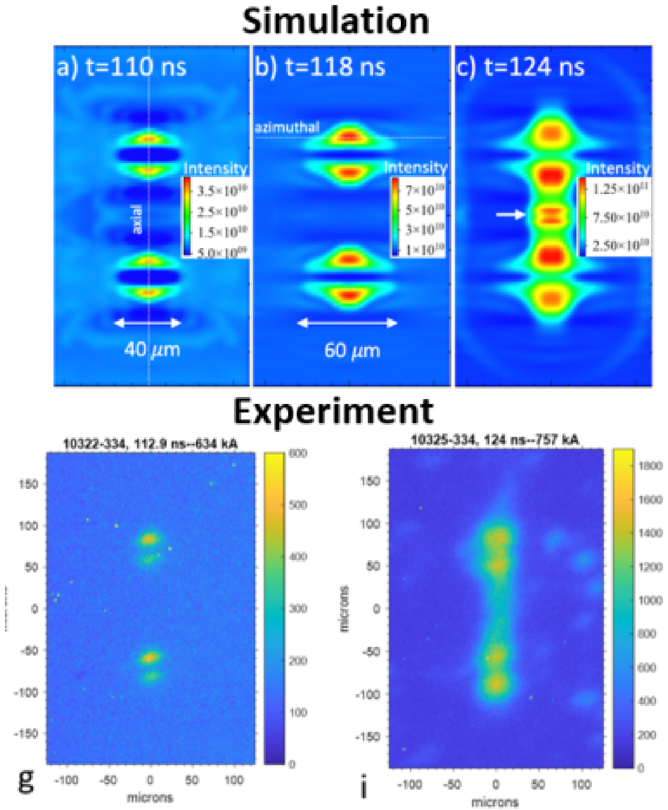
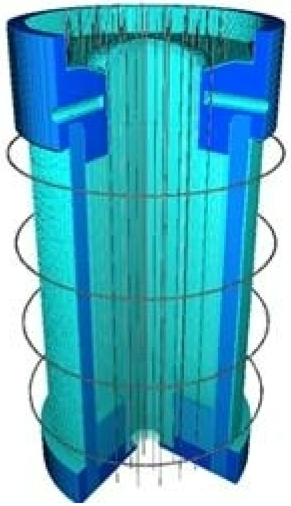






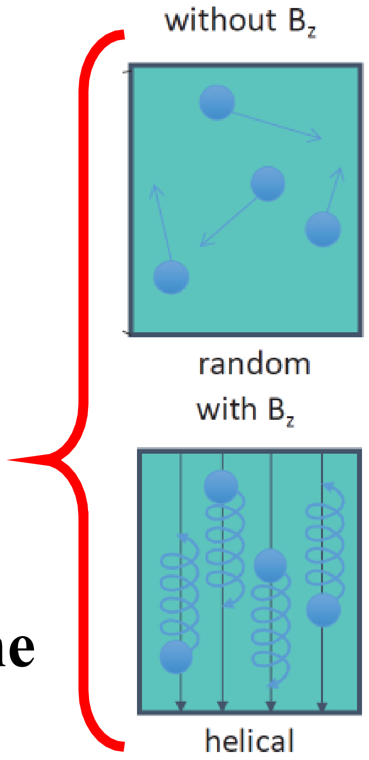
Magnetized Liner Inertial Fusion (MagLIF[1]):

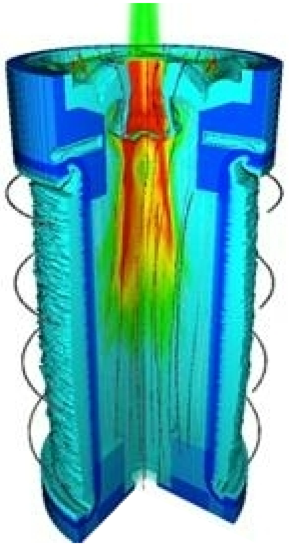
Magnetic compression of premagnetized, laser-preheated fusion fuel



- **Premagnetization[2]: 10-20 T quasi-static axial magnetic field, $B_{z,0}$, is applied to thermally insulate fuel**

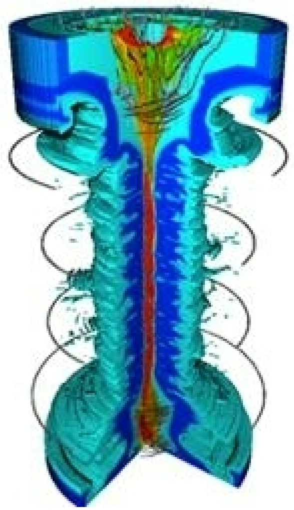
  Reduces plasma thermal conduction and thus required implosion velocity compared to unmagnetized ICF





- **Laser preheat[3]: The fuel is pre-heated using the Z-Beamlet Laser (4 kJ)**

  Reduces required compressive work required to achieve extreme temperature

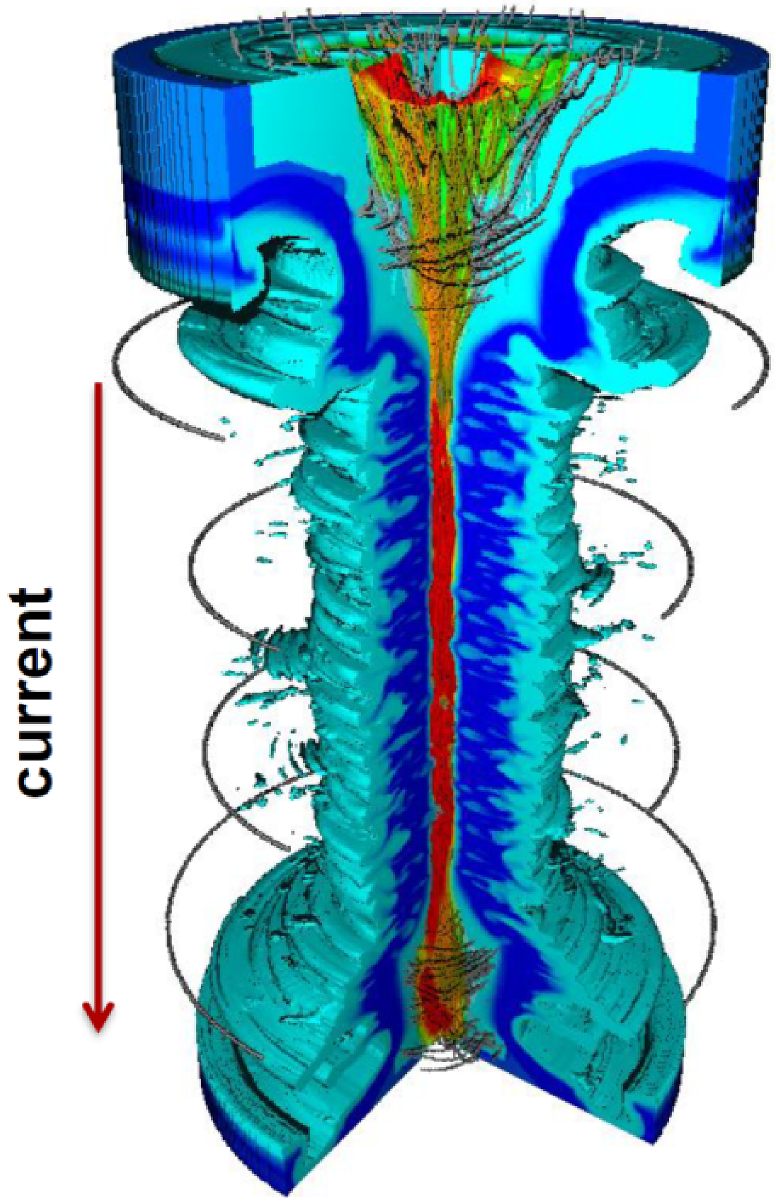


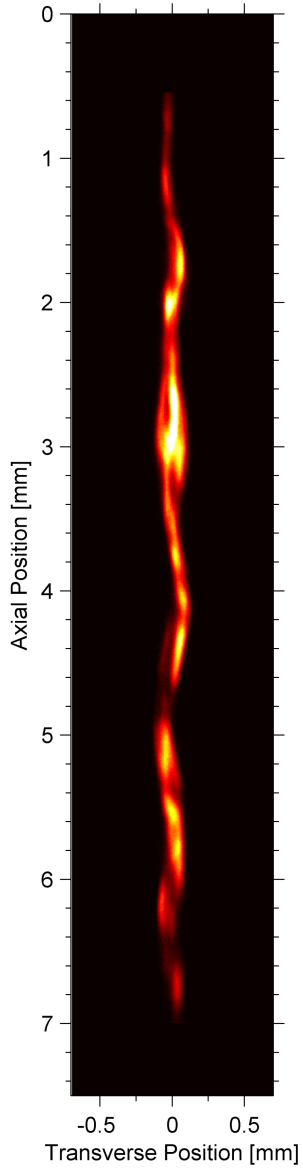
- **Compression: Z Machine drive current implodes liner, ~18 MA in 100 ns**
  - Liner compresses both fuel and field
  - Implosion symmetry must be maintained to high convergency (e.g., $CR = R_{initial}/R_{final} \sim 40$)

Deuterium-gas-filled beryllium liner (cylindrical tube)

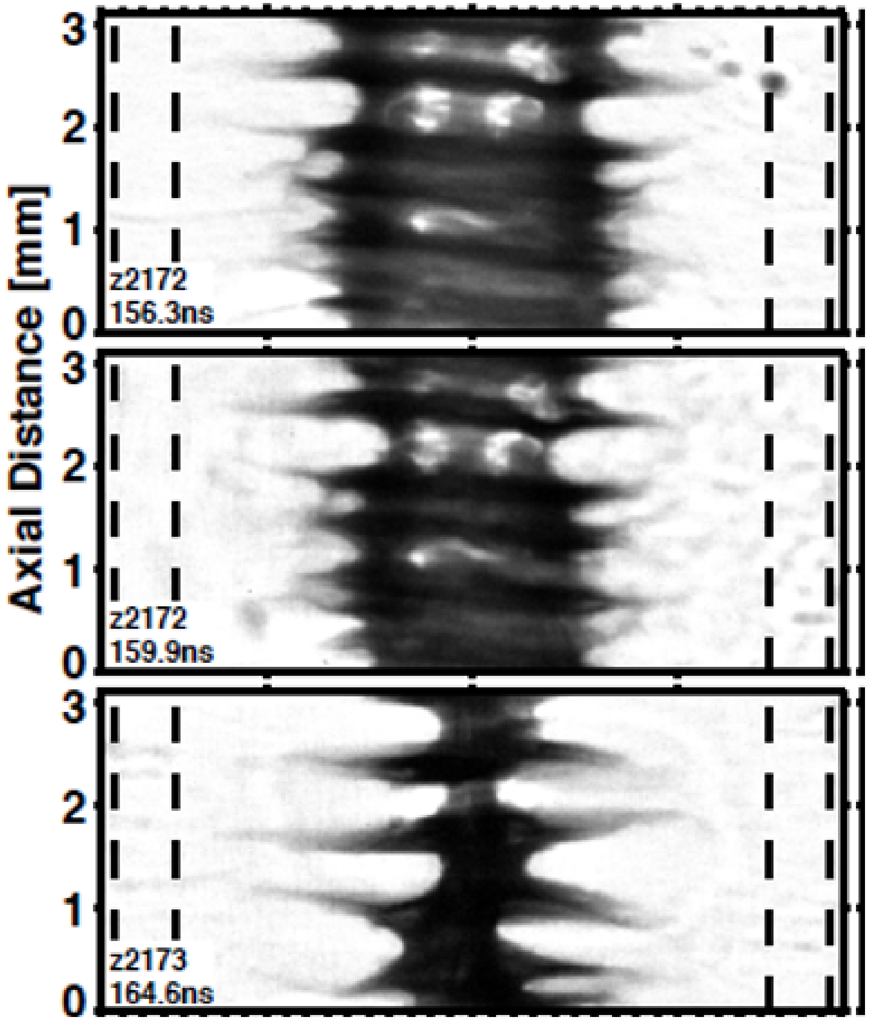
[1] S. A. Slutz et al., Phys. Plasmas **17**, 056303 (2010). [2] Rovang et al., Rev. Sci. Instrum. **85**, 124701 (2014). [3] Harvey-Thompson et al., Phys. Plasmas **26**, 032707 (2019).

Magneto-Rayleigh-Taylor Instability destroys implosion symmetry, and reduces the performance of ICF systems—What is the seed perturbation?

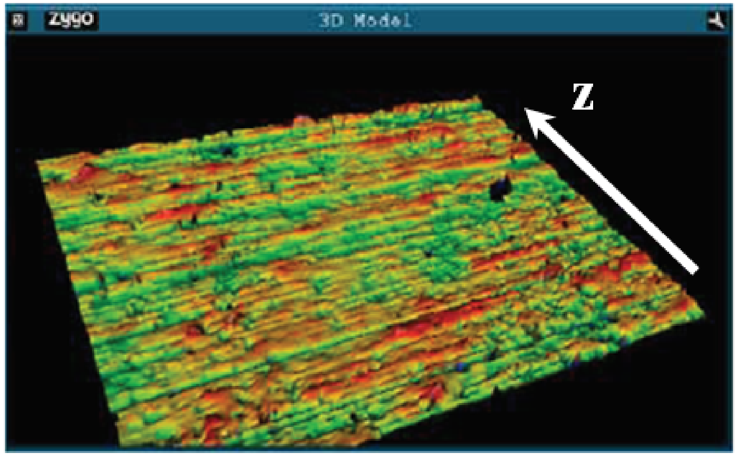




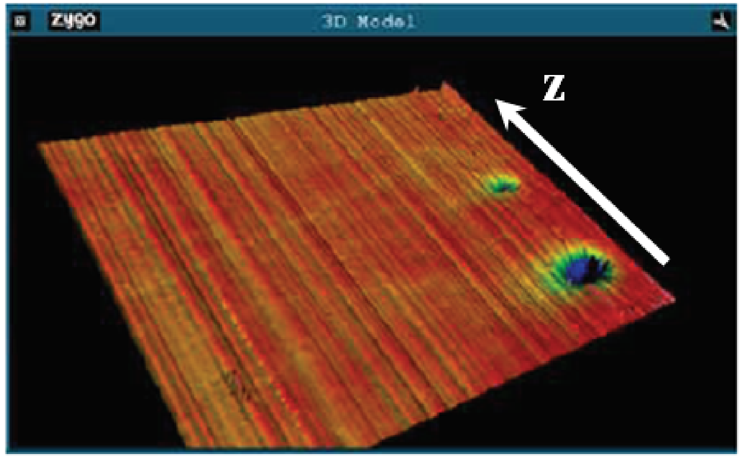
Magneto-Rayleigh-Taylor for magnetically driven systems



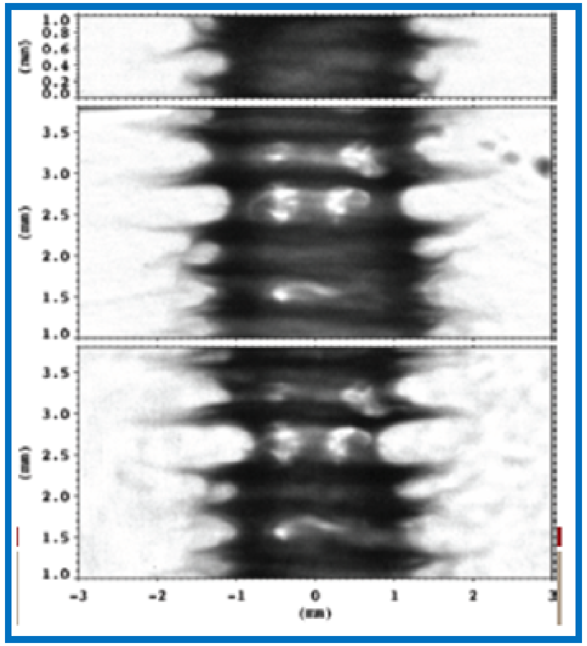
A common assumption was that the grooves which resulted from lathe machining were seeding instability growth—<u>Not True!</u>

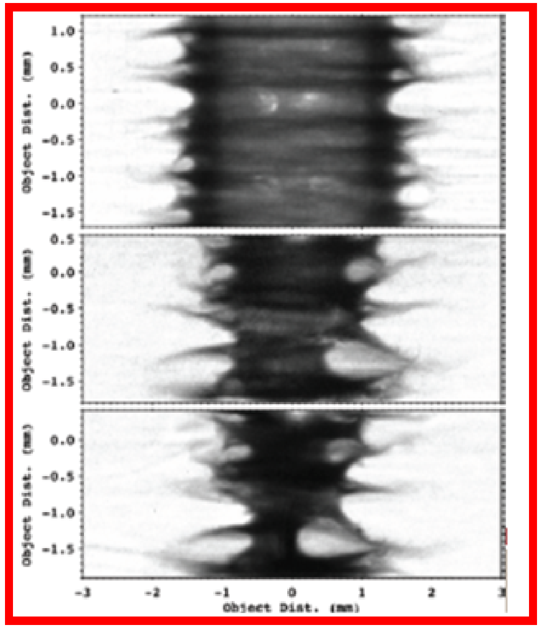


Standard process→50 nm RMS



Axially polished→50 nm RMS





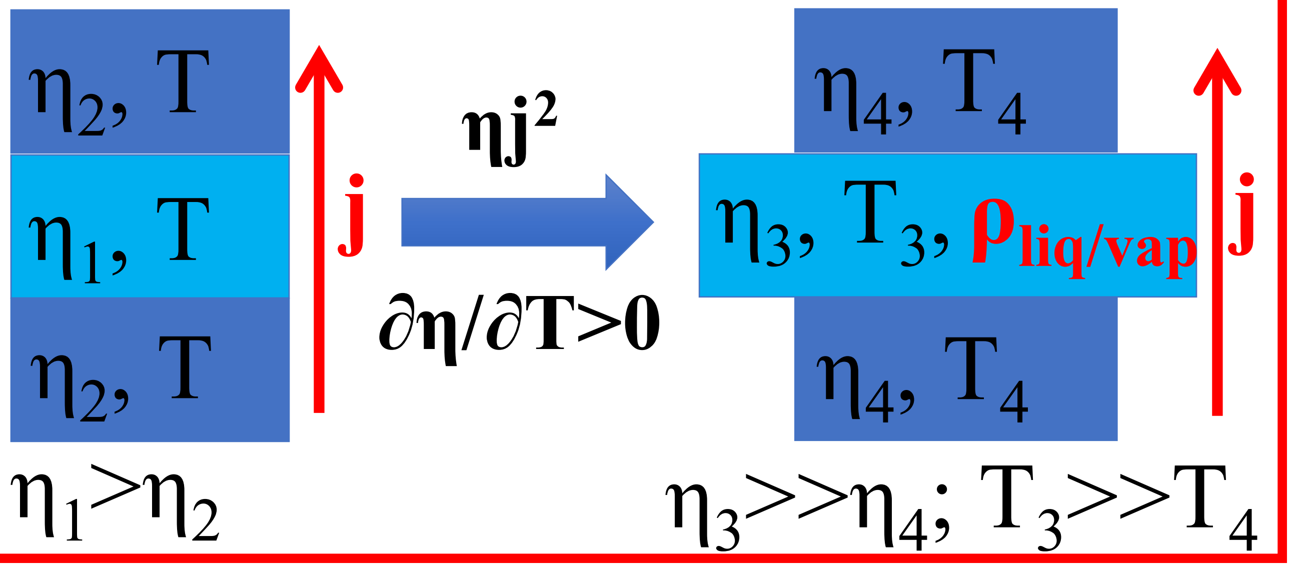
Changing the orientation of the machining grooves from azimuthal (lathe) to axial (broaching) had little impact on MRT development

What is the source of the higher than expected azimuthal symmetry of observed MRT?

<u>We need a different explanation</u>: Electrothermal instabilities are driven by Ohmic heating and arise when resistivity (η) depends on temperature (T)

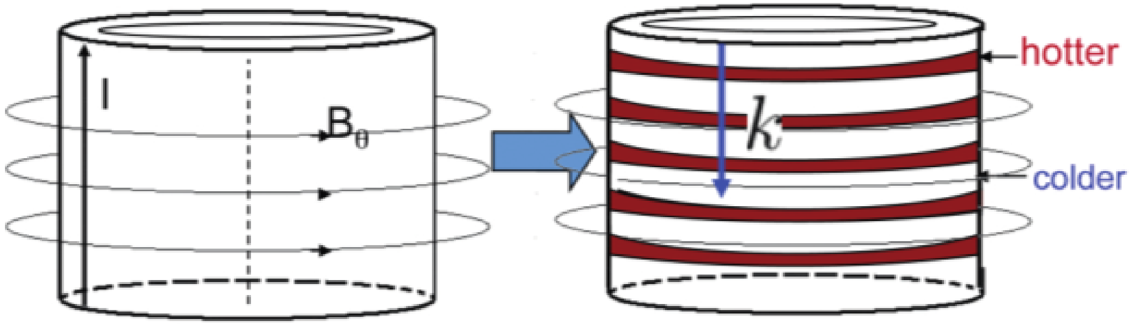
Condensed Metal

- $\partial\eta/\partial T>0$
- $\uparrow \eta_0 \leftrightarrow \uparrow \eta j^2 \leftrightarrow \uparrow T$
- Drives nonuniform phase change and expansion



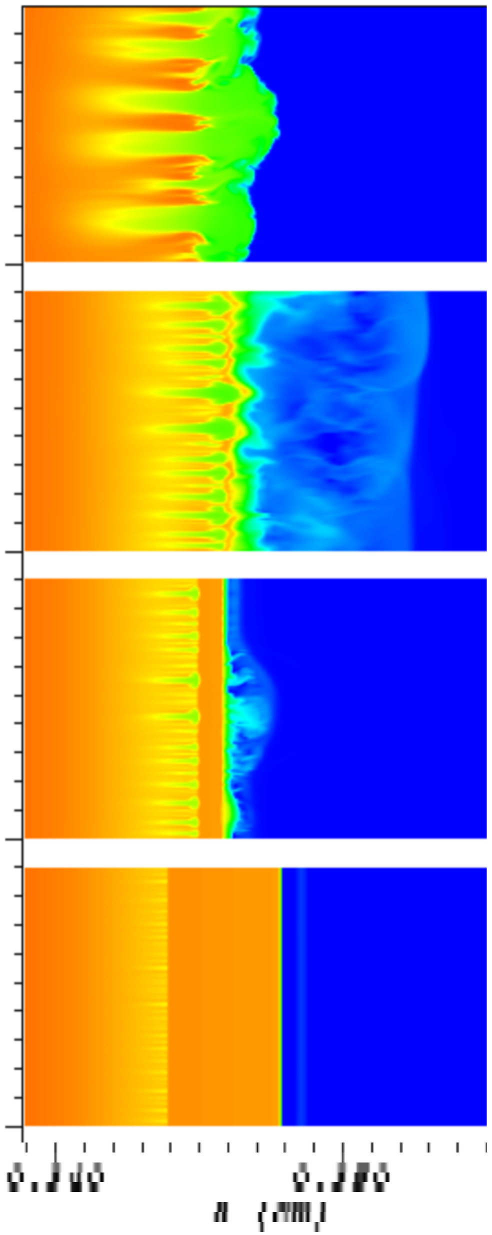
ETI "strata," which are aligned with the magnetic field, are potentially a highly effective seed for MRT!

$$\frac{d\eta(T)}{dT} > 0$$

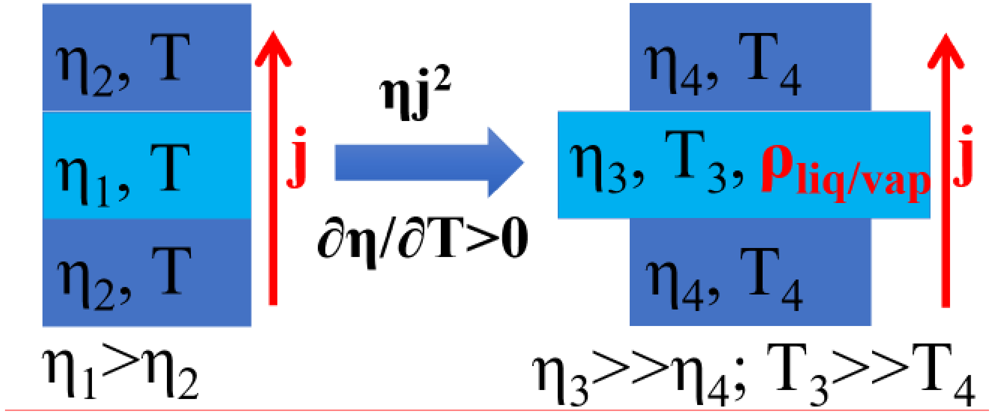


ETI grows rapidly near melt, prior to bulk implosion

If MRT is seeded by ETI, simulations suggest that the ETI-driven density perturbation can be mitigated!



Thick (>10 µm) insulating coatings mitigate effects of ETI and reduce seed for MRT growth



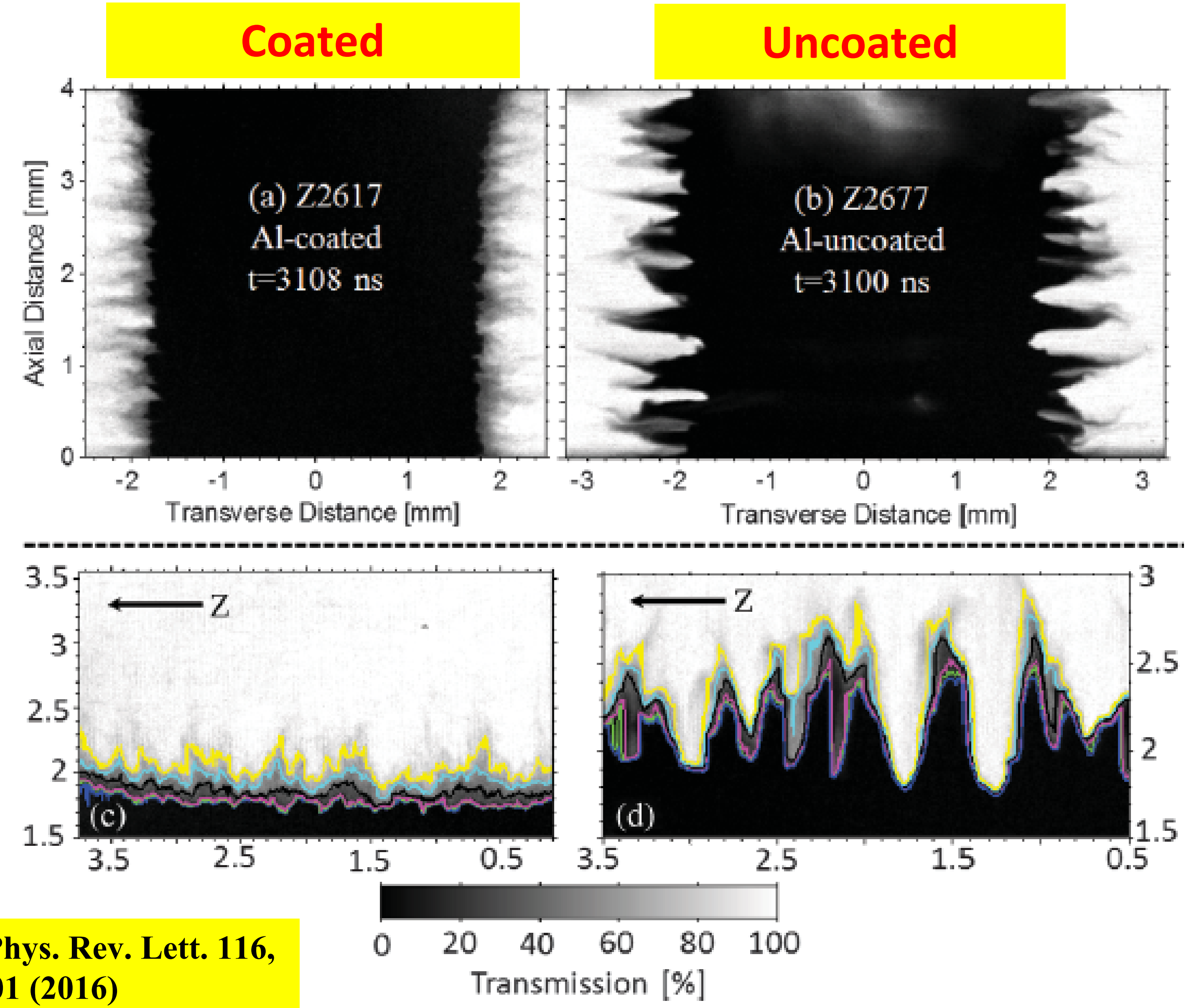
No ETI growth in the dielectric (no η,T feedback)

Nonlinear mass redistribution from ETI is significantly tamped by the coating

- Reduces seed for MRT growth

*K.J. Peterson, T.J. Awe, *et al.*, PRL **112**, 135002 (2014)

Adding a 70-micron-thick dielectric surface coating greatly enhances the stability of imploding liners!

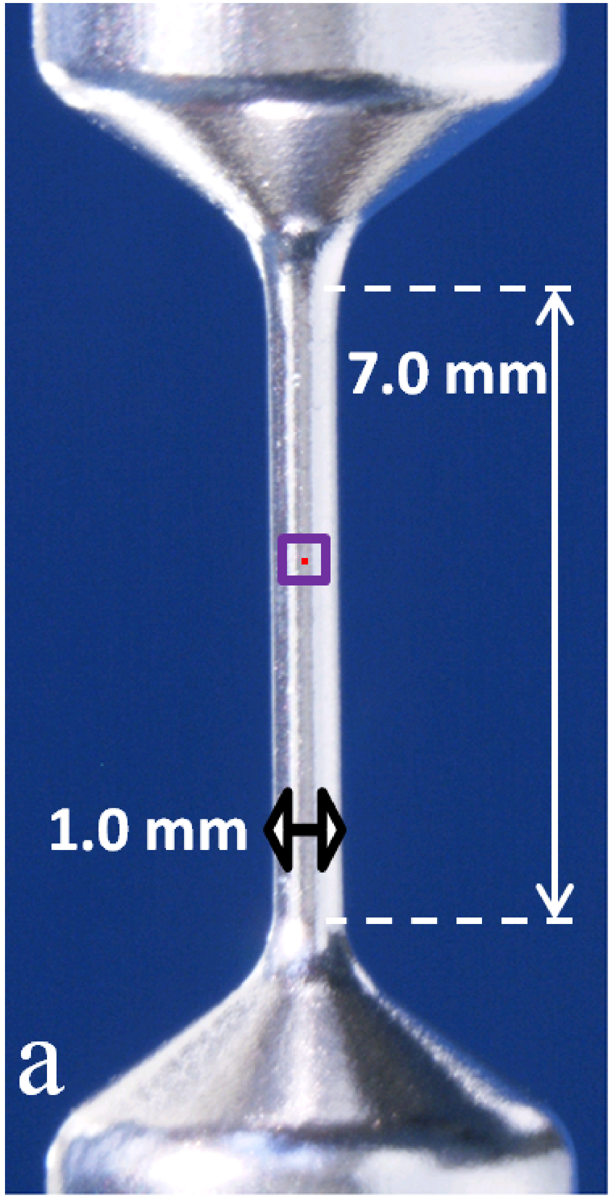


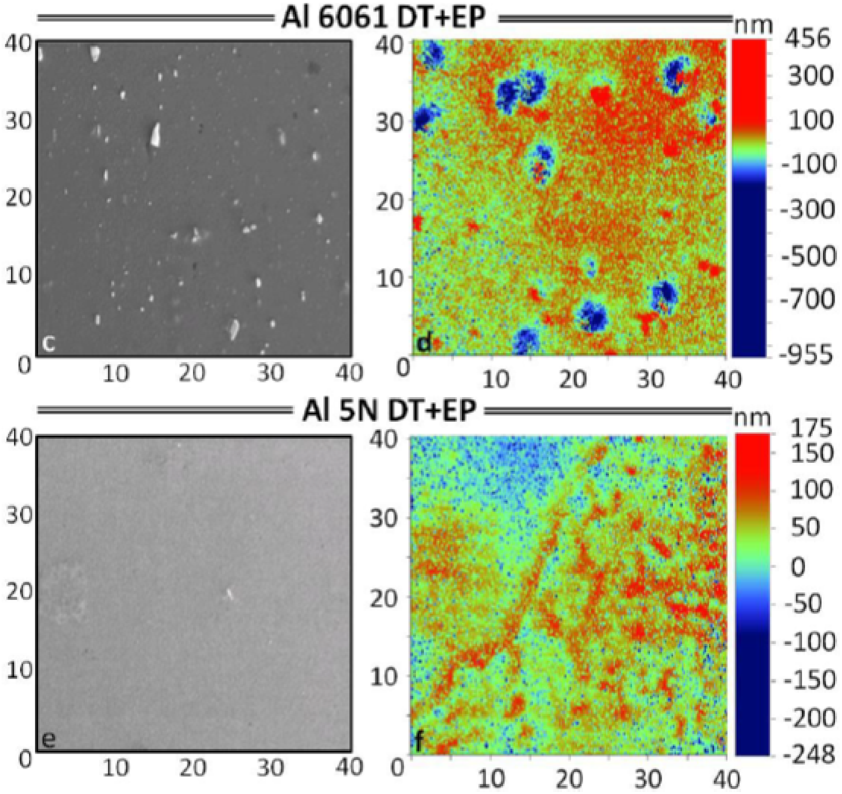
Dielectric coating carries current & implodes with liner

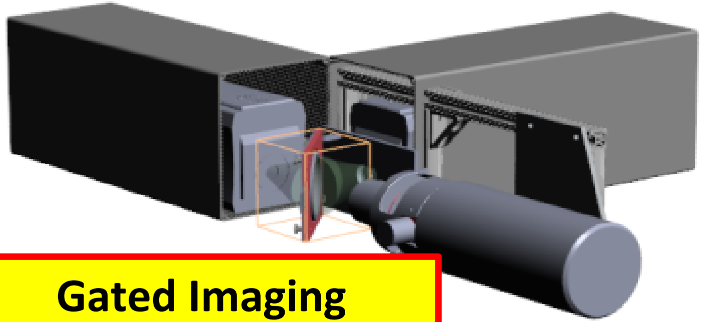
<u>**MRT amplitude reduced by 10X for coated liner**</u>

T.J. Awe *et al.*, Phys. Rev. Lett. 116, 065001 (2016)

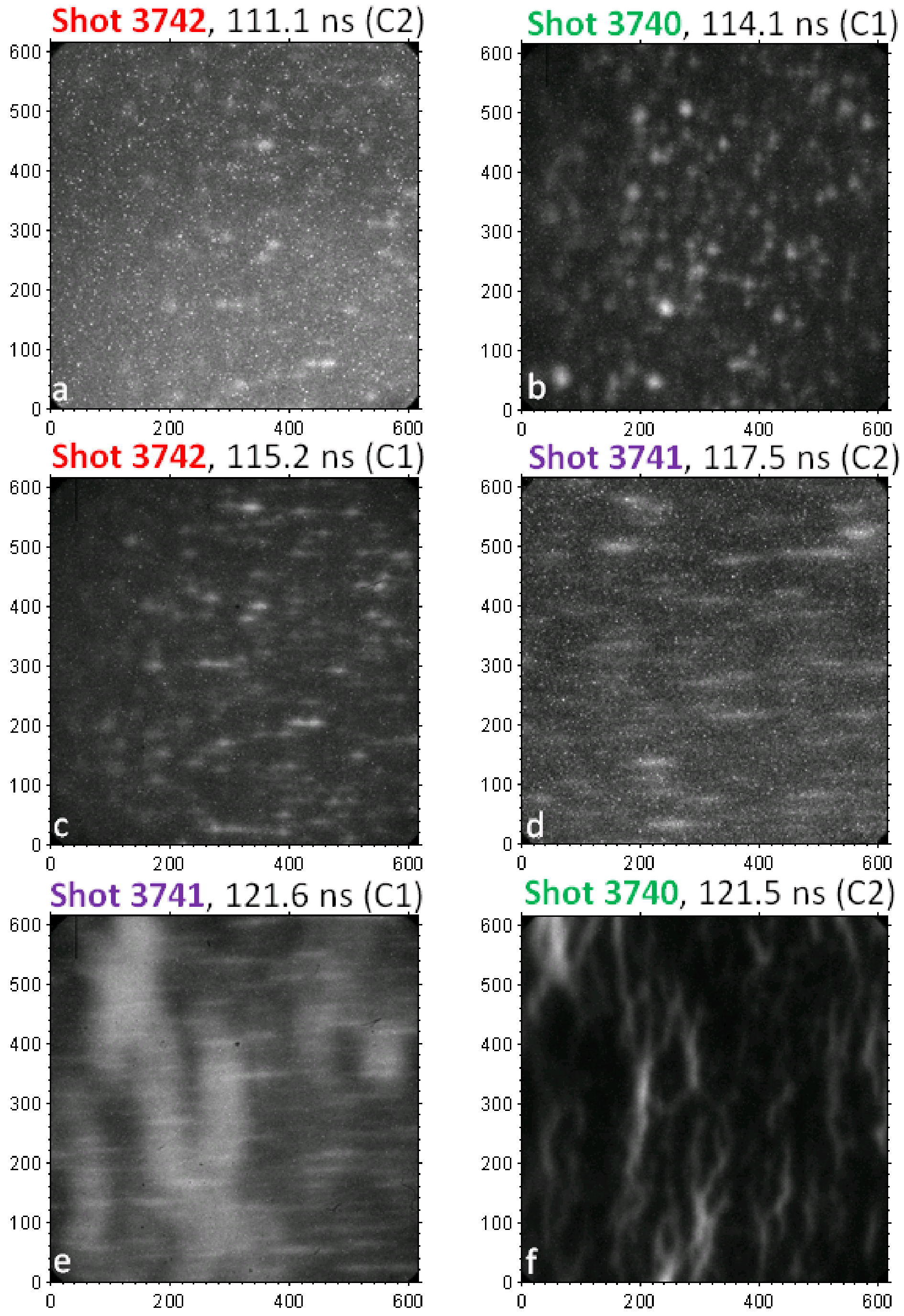
ETI and can be observed via high-resolution gated imaging in 1-MA-scale experiments





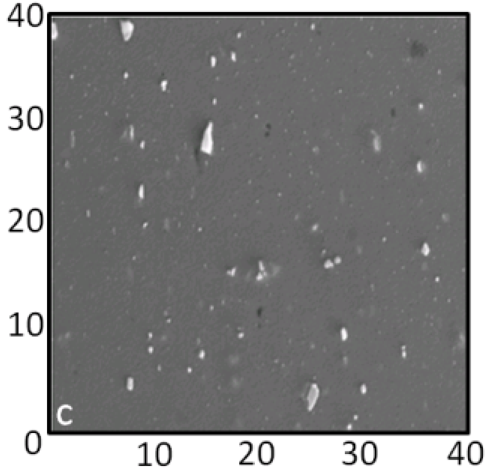


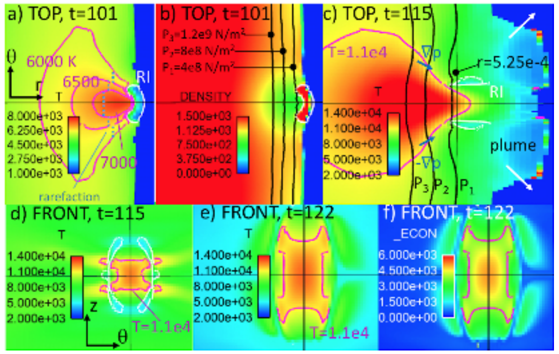
Gated Imaging
2 ns/3 µm resolution

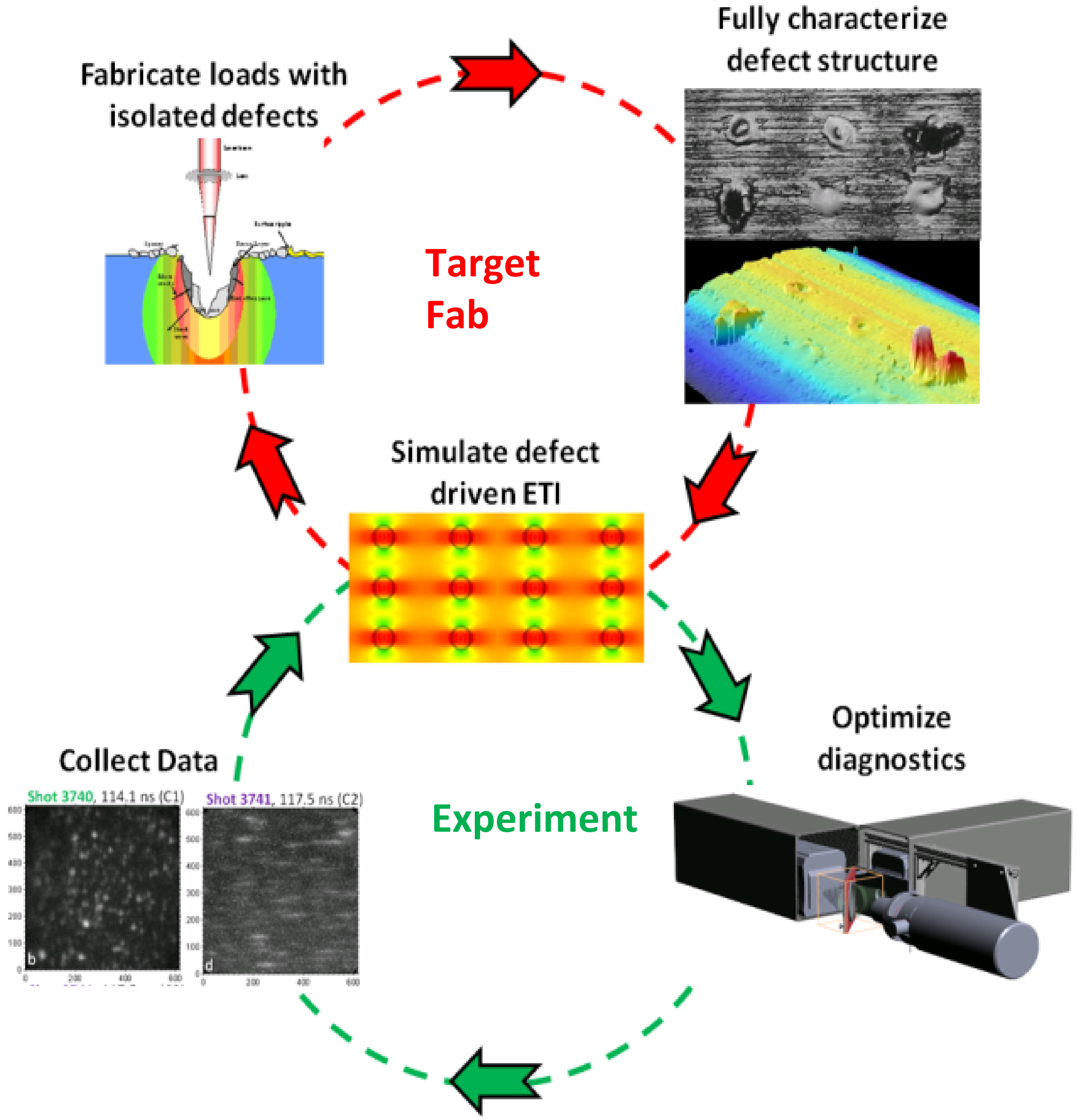


Understanding ETI requires a synergistic and iterative relationship between simulation, experiment, and target fabrication

Too Complex!!!

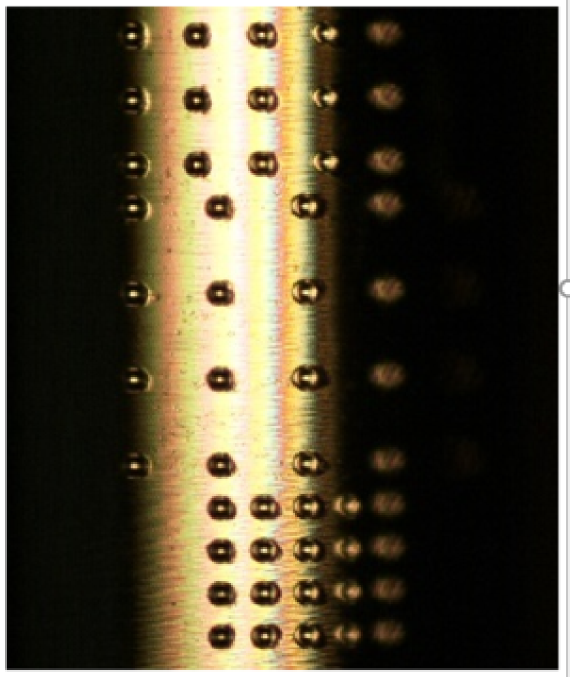




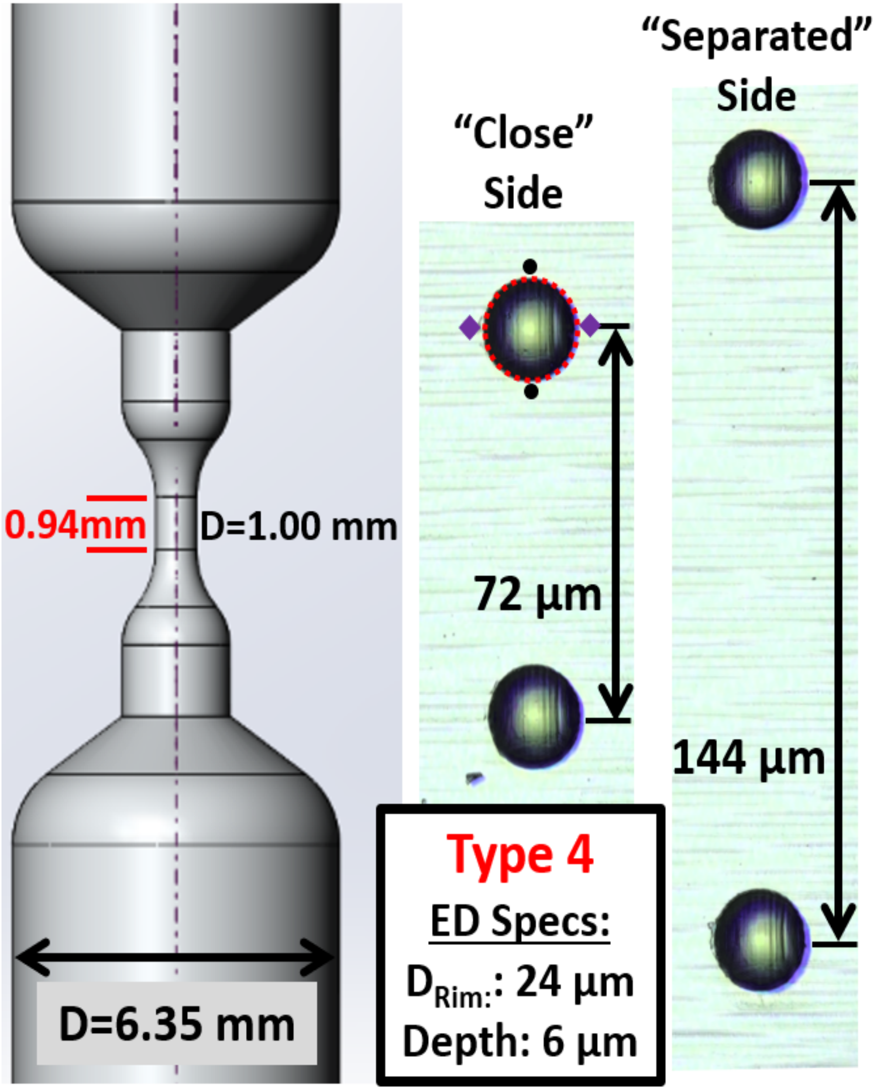


Start with "blank canvas"

- 5N Al (99.999% pure)
- Diamond turn to Ra~10 nm
- Add "engineered defects"



The "Engineered Defect" (ED) platform enables novel data on how metals explode at the micron scale for detailed comparison with simulation



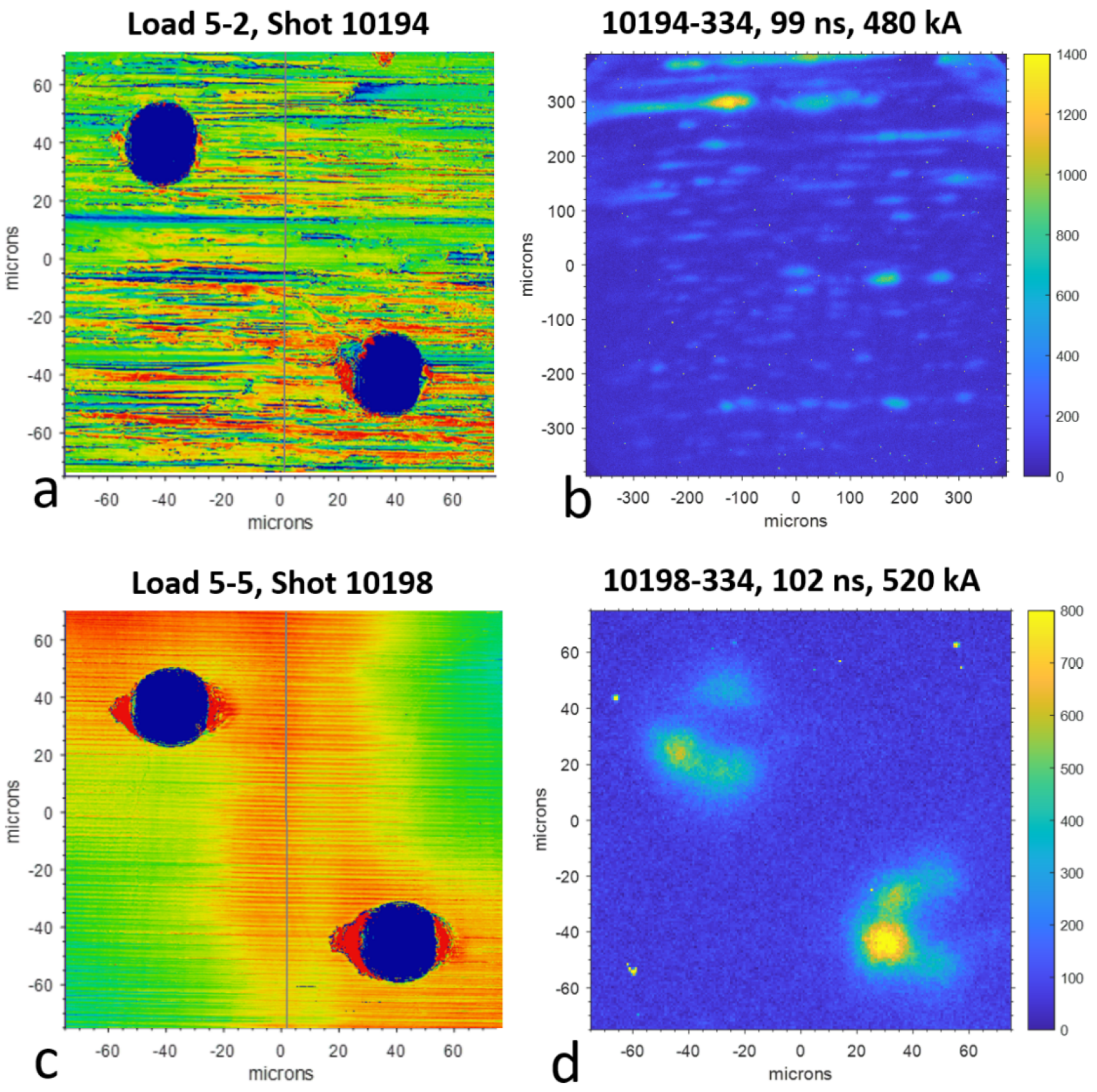
		Side at 0 degrees: "Close side"				Side at 180 degrees: "Separated side"			
Target type	Rod Diam.	# of ED	Rim Diam.	Depth	Axial C-to-C	# of ED	Rim Diam.	Depth	Axial C-to-C
2	1.00 mm	2	12 um	3 um	36 um	2	12 um	3 um	72 um
4	1.00 mm	2	24 um	6 um	72 um	2	24 um	6 um	144 um

First order question—Axially Separated ED

- Do ED heat faster than adjacent surface?
- Do isolated ED heat as predicted by 3D simulation?
- Do axially separated ED evolve to form a plasma filament?
- If so, how does this depend on ED separation?
- Do geometrically scaled defects exhibit heating uniformity?

Phys. Plasmas 28, 072104 (2021);

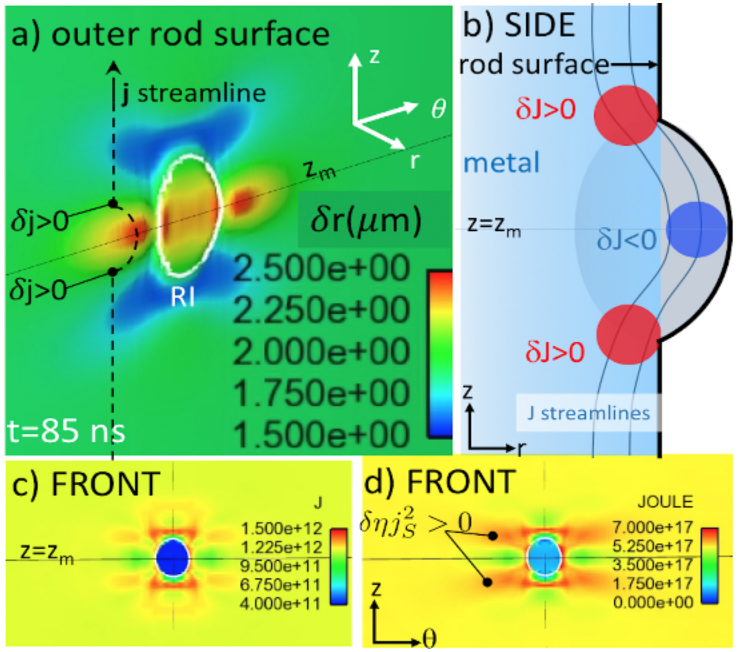
The A/λ ratio of background surface roughness must be well controlled in order for ED to provide the dominant current density amplification

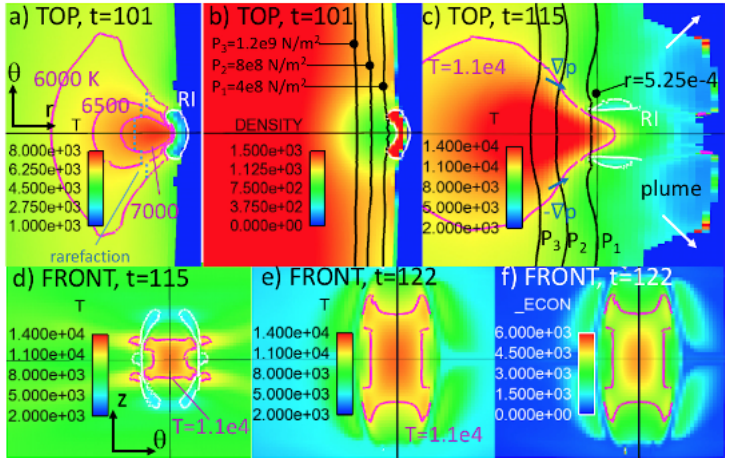


Target Serial Number	Shot Number	Rod Diam [μm]	ED Depth [μm]	D_{rim} [μm]	Adjacent Surface Ra [nm]	Emission Source
3-2	10195	801	6.0	23.5	245	Grooves
3-4	10199	803	6.0	23.5	67	Grooves
5-2	10194	800	5.5	23.5	156	Grooves
5-3	10196	801	5.5	23.0	17	ED
5-4	10197	801	5.5	23.0	41	ED
5-5	10198	802	6.5	24.0	10	ED

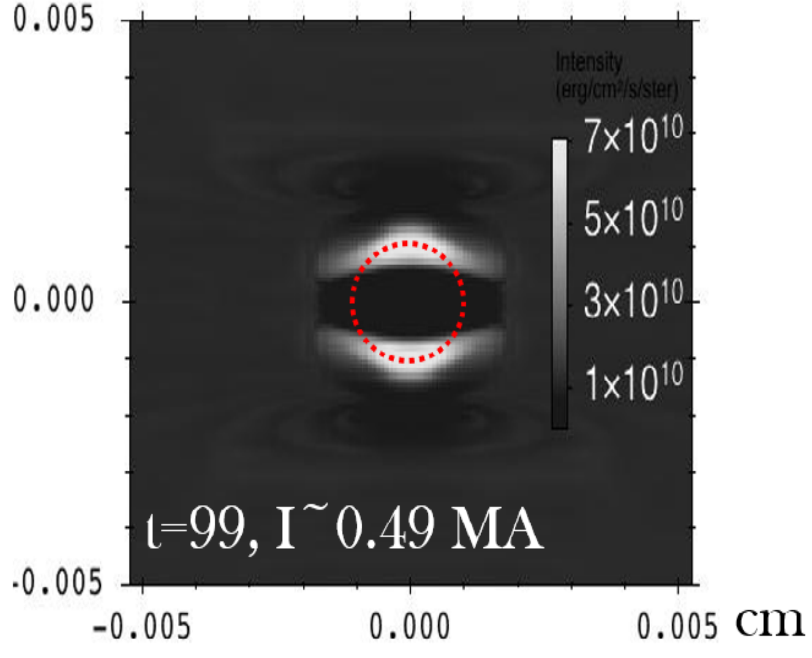
- Background roughness (curvature) amplifies **j**
  - $j_{max}/j_0 = 1 + 2\pi A/\lambda$
- ED emissions not observed for rougher targets, e.g., λ=10 μm and A= 800 nm for j_{max}/j_0= 1.5
- Rod diameter increased to 1.00 mm—allowed Ra~10 nm to be routinely achieved

Quasi-hemispherical ED drive distinctive, non-intuitive "cat eye" emission patterns, which can be compared to simulation

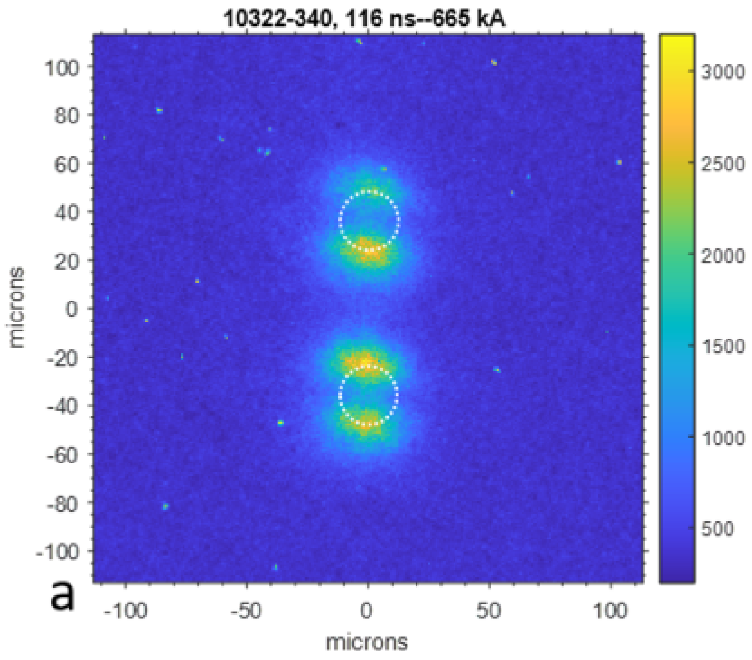




Simulated emission of single pit (SPECT3D)

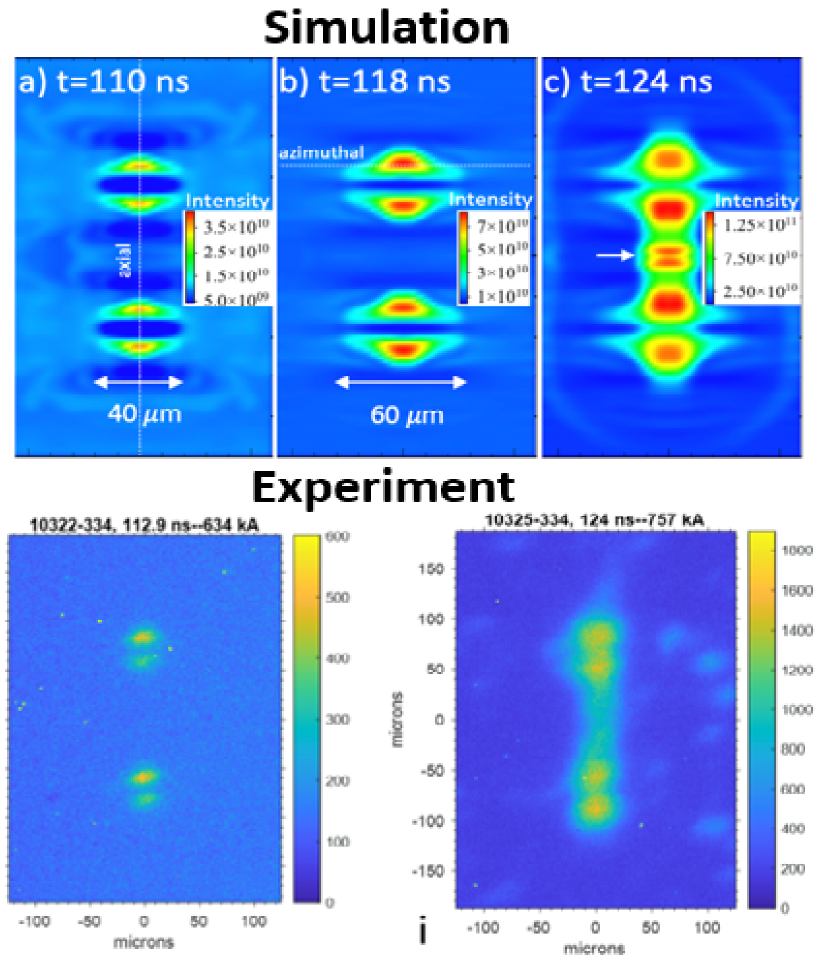


Experimental image of emission from an ED pair

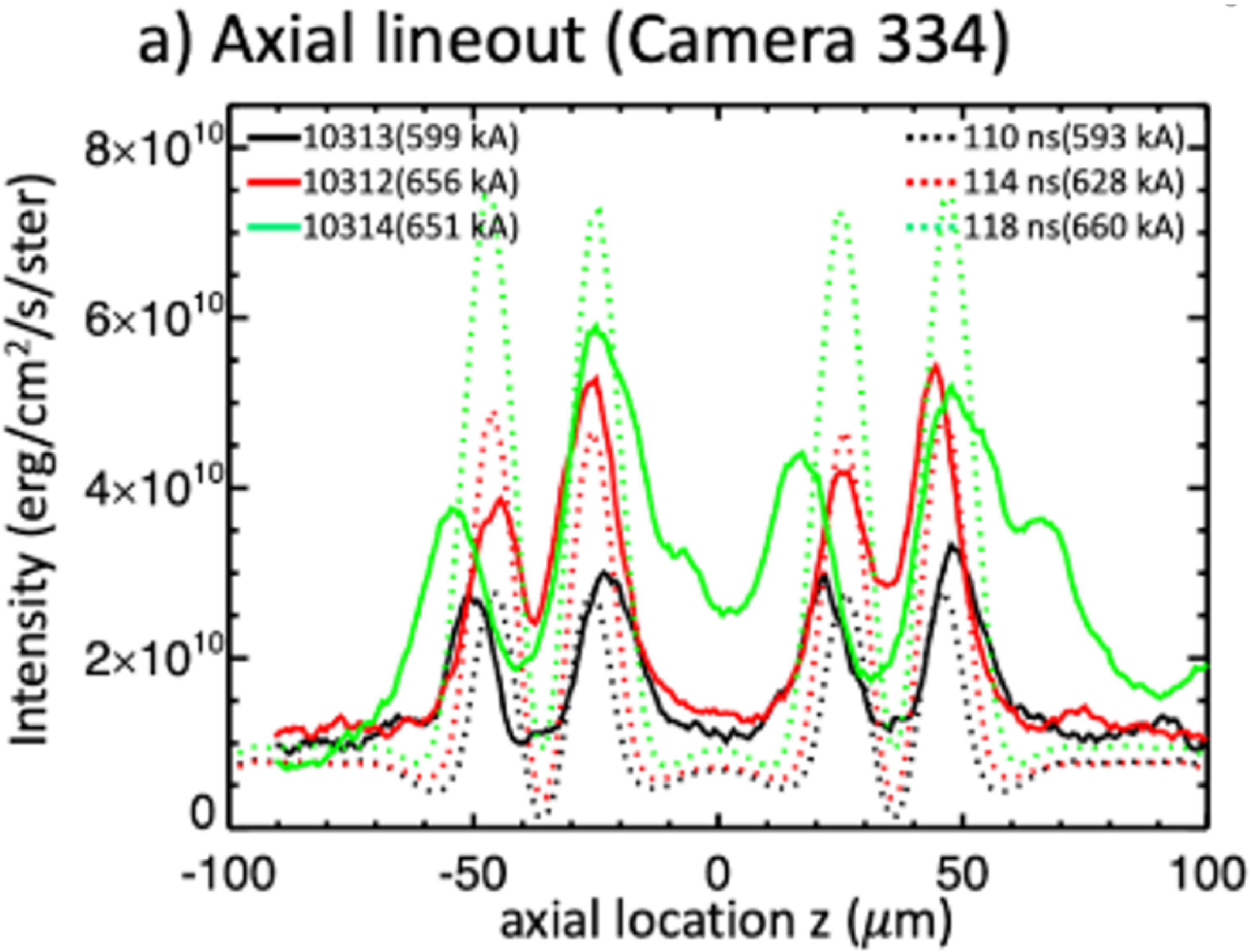


Complex 3D simulations enable synthetic images to be generated for detailed comparison with experiment

Axially separate ED form hot spots which explode & connect to form a current -carrying plasma filament—evolution is largely captured by simulation

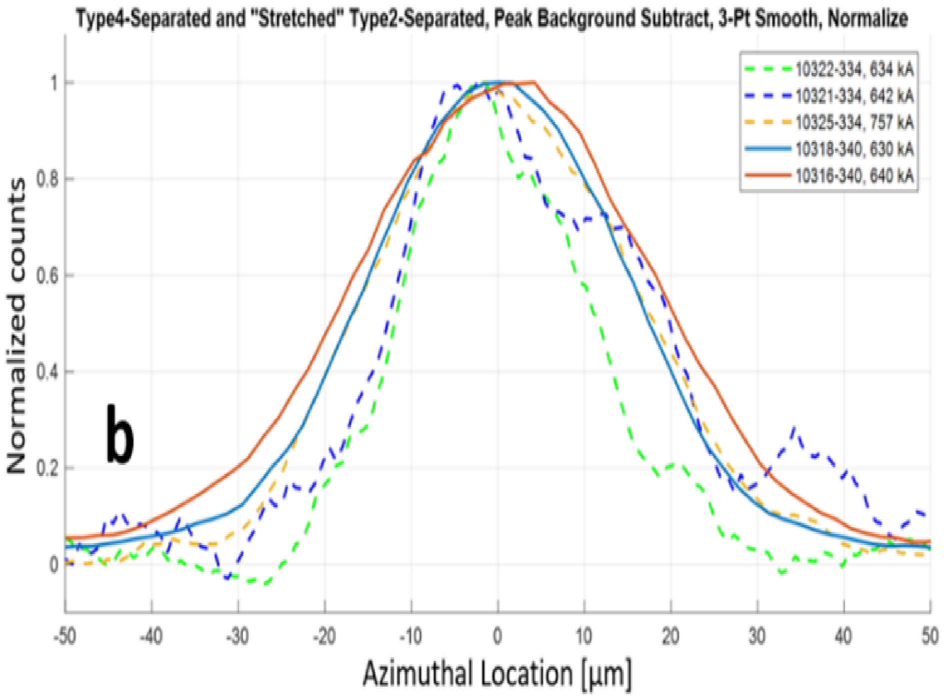


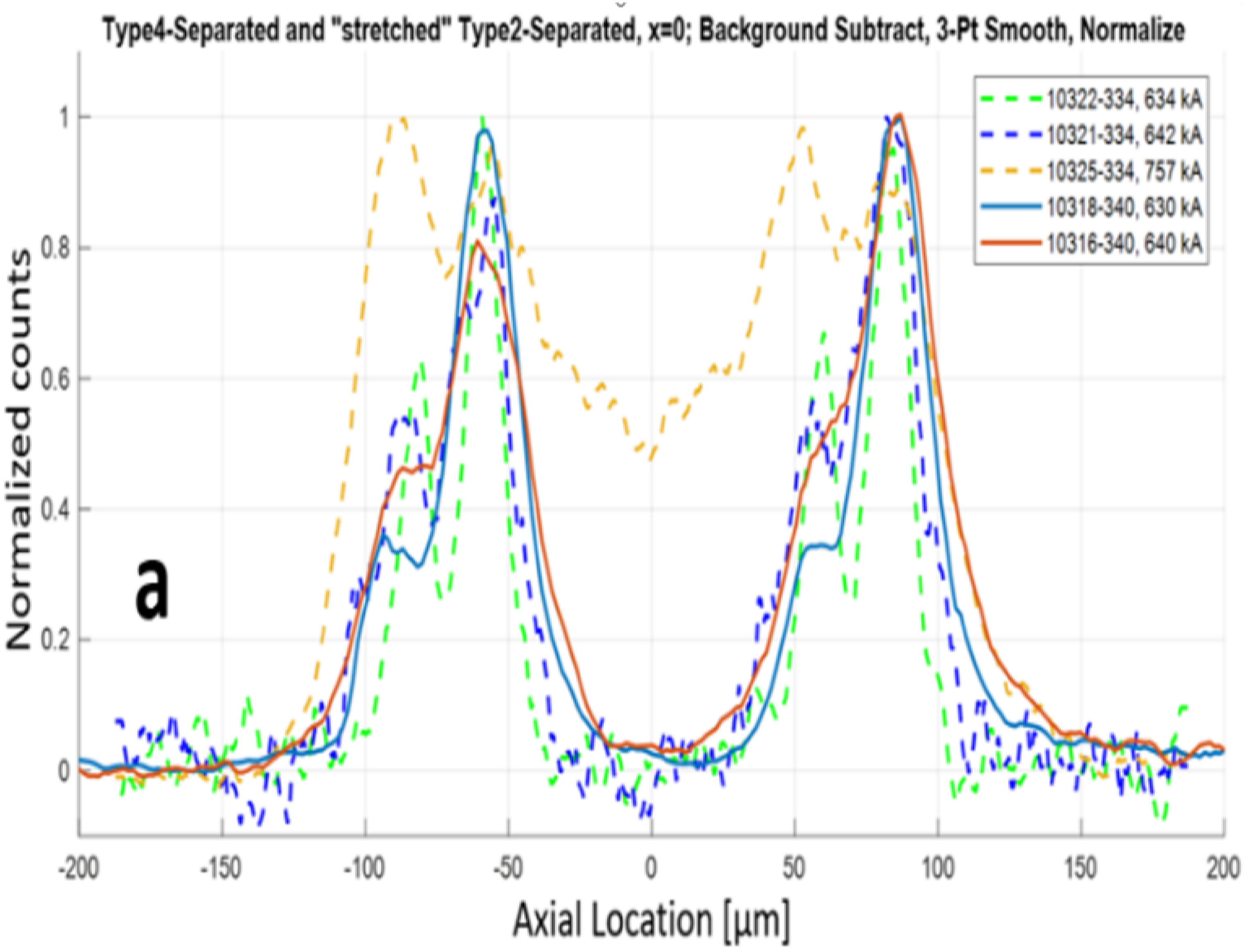
Simulation self-emission images (ALEGRA→SPECT3D) match experimental evolution, including filament formation



Type 2 and Type 4 targets have scaled defects (depth, diameter, spacing) to evaluate theory which supports heating similarity—heating is largely independent of defect size

		Side at 180 degrees: "Separated side"			
Target type	Rod Diam.	# of ED	Rim Diam.	Depth	Axial C-to-C
2	1.00 mm	2	12 um	3 um	72 um
4	1.00 mm	2	24 um	6 um	144 um





Summary

- Experiments studied 99.999% pure aluminum rods which were machined to Ra<10 nm surface finish, and then further machined to include pairs of 10-micron-scale engineered defects
- High-resolution-gated imagers captured surface emissions to provide data on local overheating—data are compared against synthetic images from hig-resolution 3D simulation
- The A/λ ratio of background surface roughness must be well controlled in order for ED to provide the dominant current density amplification
- Quasi-hemispherical ED drive distinctive, non-intuitive “cat eye” emission patterns
- Axially separate ED form hot spots which explode & connect to form a current-carrying plasma filament—evolution is largely captured by simulation
- Data from geometrically scaled defects (scaled depth, diameter, spacing) provide conditional support of theory on heating similarity