Electrothermal Instability Evolution on Z-Pinch Rods and Imploding Liners Pulsed with Intense Current

SAND2016-5793C

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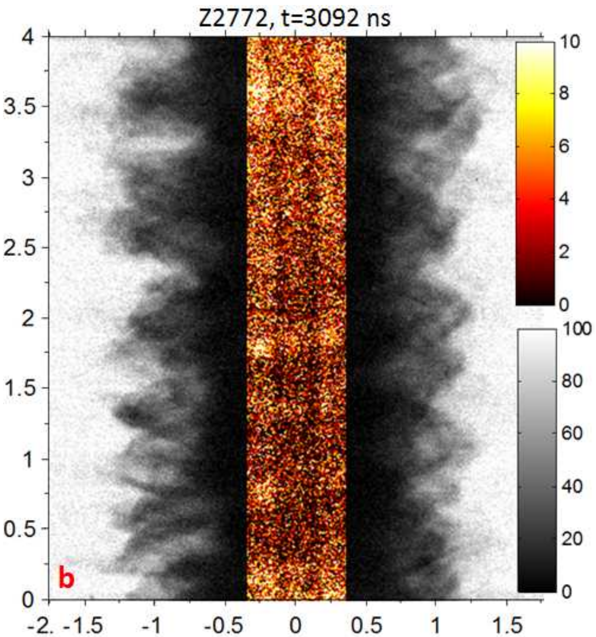
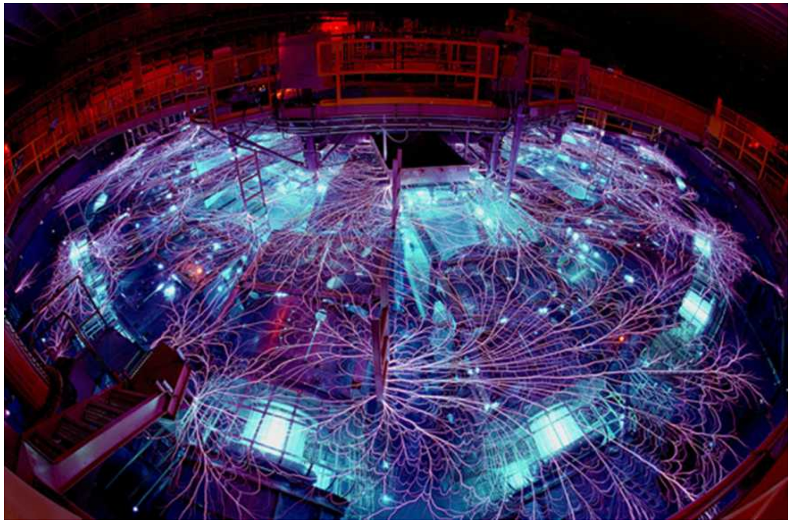
T.J. Awe—for the Sandia-MagLIF and UNR-ETI Teams





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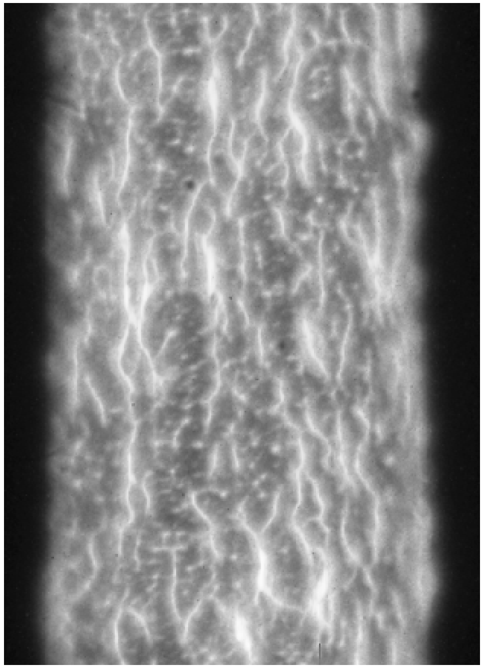

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NNSA National Nuclear Security Administration

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Many thanks to my co-authors!

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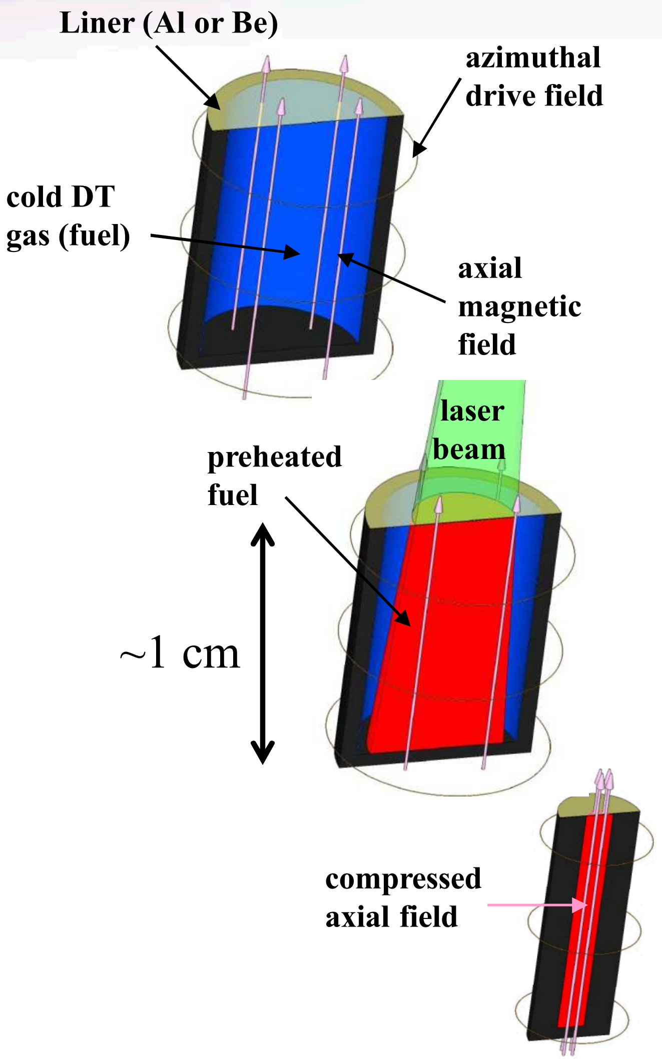
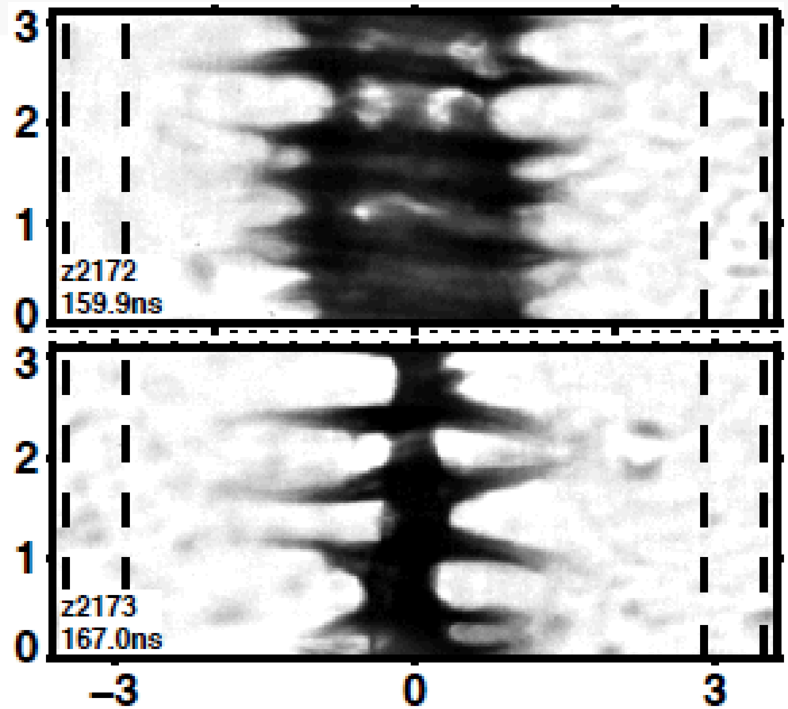
Presentation Outline

- **Why are we motivated to study the electrothermal instability (ETI)?**
  - → *Overview of recent liner dynamics research on Z*
- **What is the current state of the art in ETI research?**
  - → *Overview of recent (Late Start LDRD funded) ETI research on Zebra at U. of Nevada, Reno*
- **What is needed to greatly advance our understanding of the electrothermal instability?**
  - → *Overview of proposed research to study metals with "engineered" defects*

MagLIF: Fuel pre-heat & magnetization allow "slow" implosions to achieve significant fusion yield



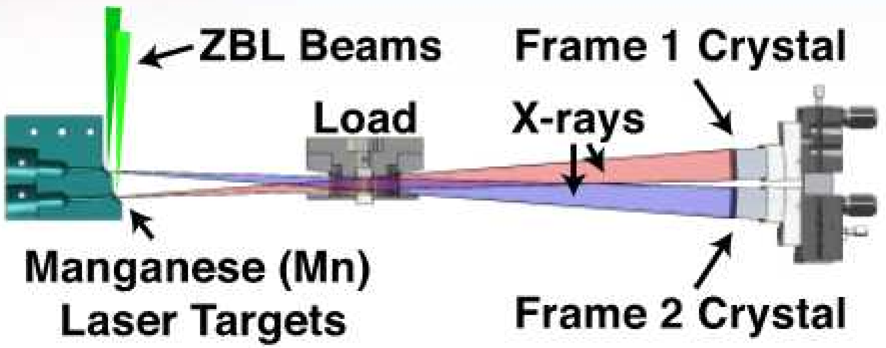


"The magneto-Rayleigh-Taylor (MRT) instability poses the greatest threat to this (MagLIF) approach to fusion."

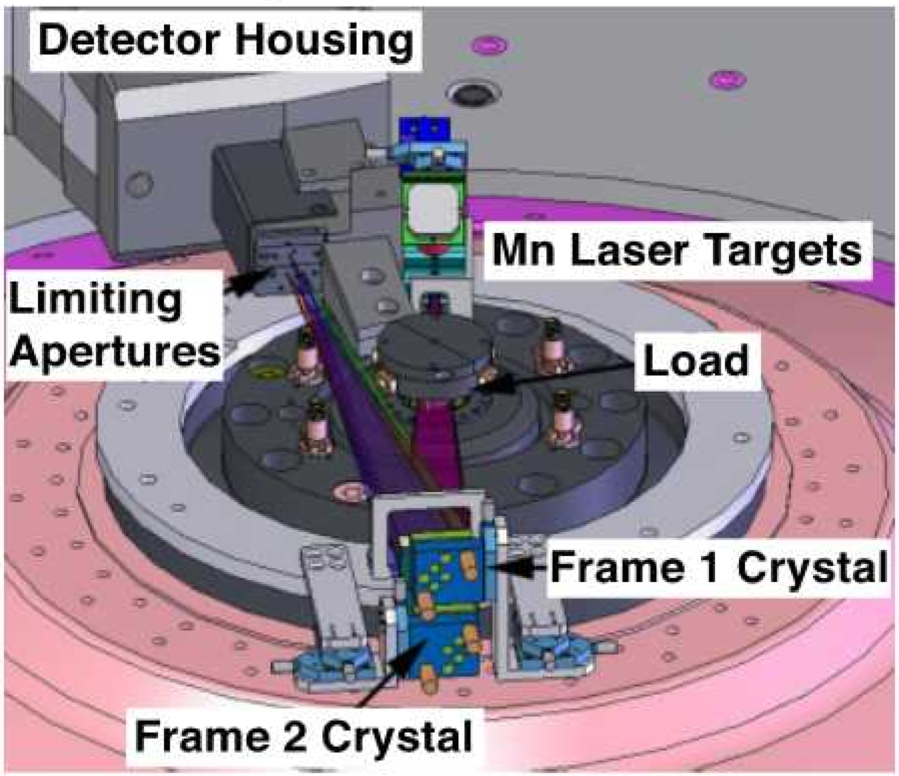
S.A. Slutz *et al.*, PoP **17**, 056303 (2010);

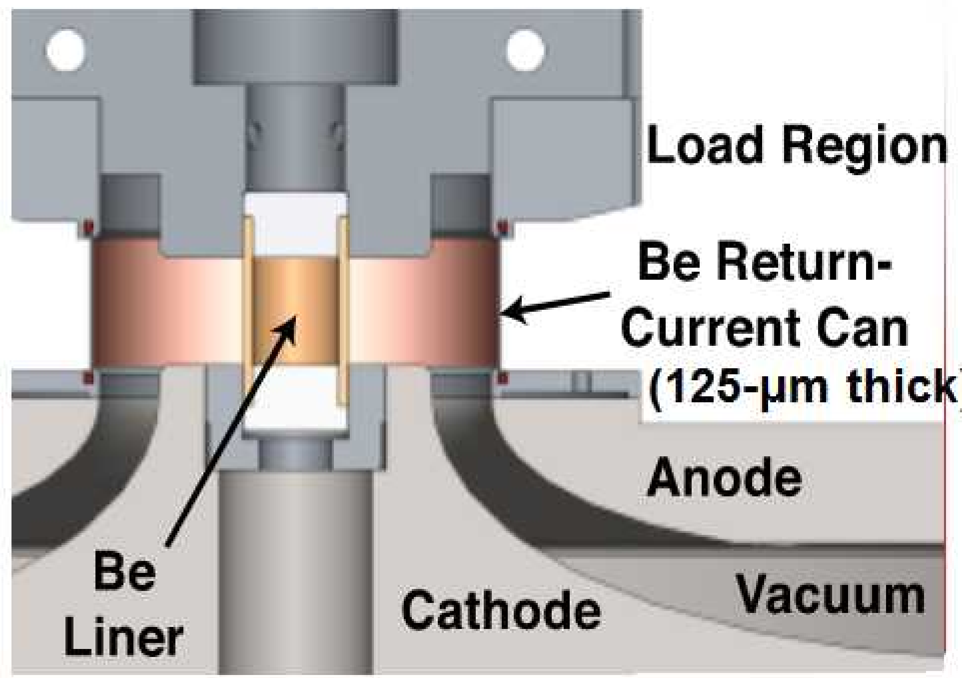
Since the 1950s, much z-pinch research has been rooted in understanding and mitigating MHD instabilities

Presentation focuses on liner dynamics; primary diagnostic on Z is two-frame monochromatic (6.151 keV) radiography*



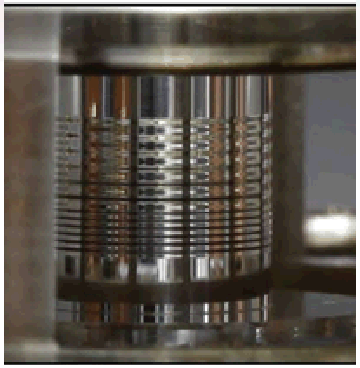
- Spherically-bent quartz crystals $(22\bar{4}3)$
- 15 micron resolution (edge-spread)
- We can see through imploding beryllium (not so for aluminum and other higher-opacity materials).

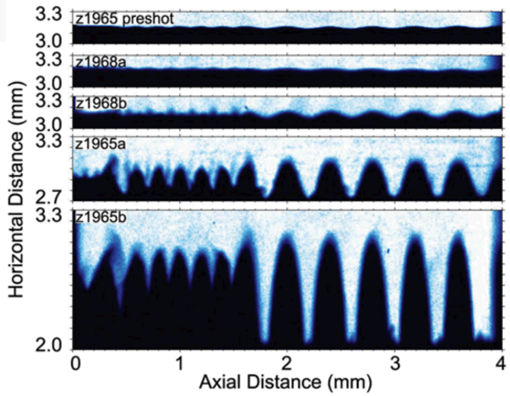




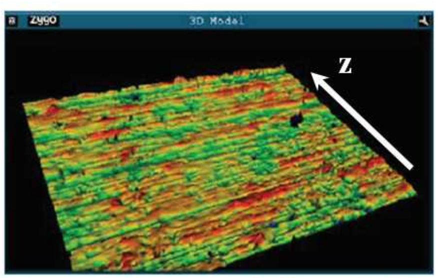
* G. R. Bennett *et al.*, RSI (2008).

Experiments have focused on developing predictive capability of instability growth of imploding liners

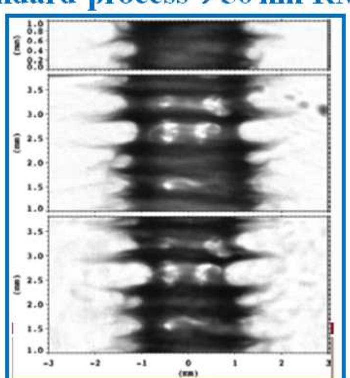


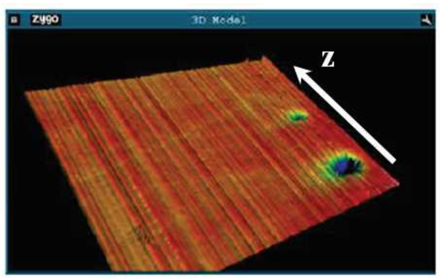


D.B. Sinars *et al.*, Phys. Rev. Lett. 105, 185001 (2010)
D.B. Sinars, Invited Presentation, 2010 APS-DPP

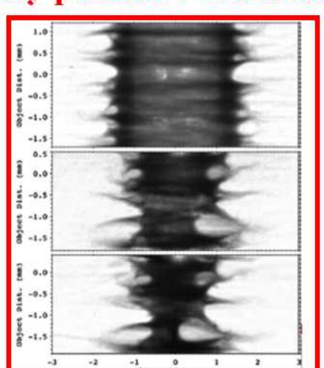


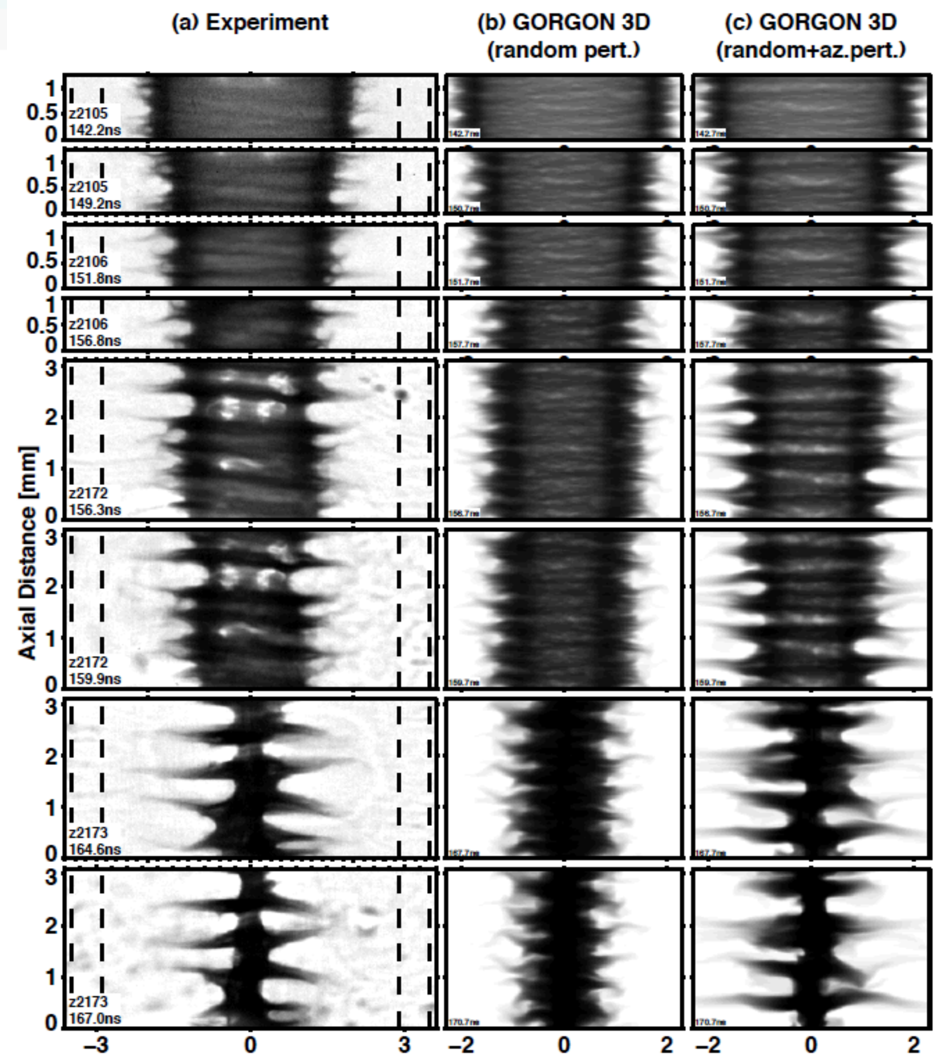
Standard process→50 nm RMS





Axially polished→50 nm RMS





R.D. McBride *et al.*, PRL 109, 135004 (2012)
R.D. McBride, Invited Presentation, 2012 APS-DPP

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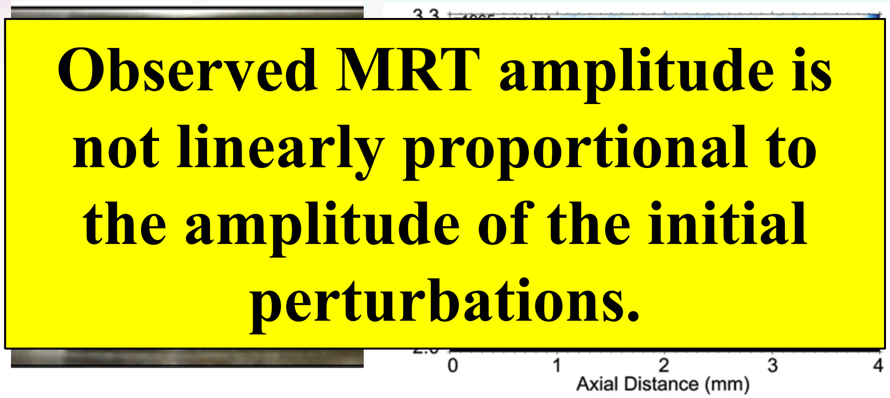

Observed MRT amplitude is not linearly proportional to the amplitude of the initial perturbations.

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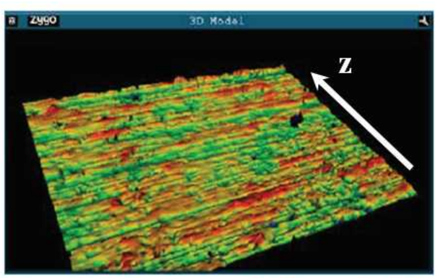

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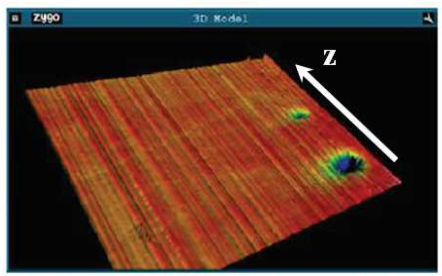

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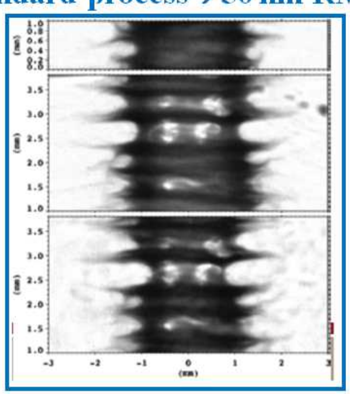

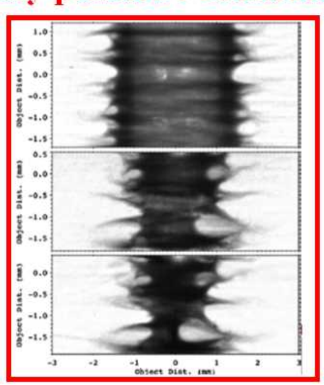

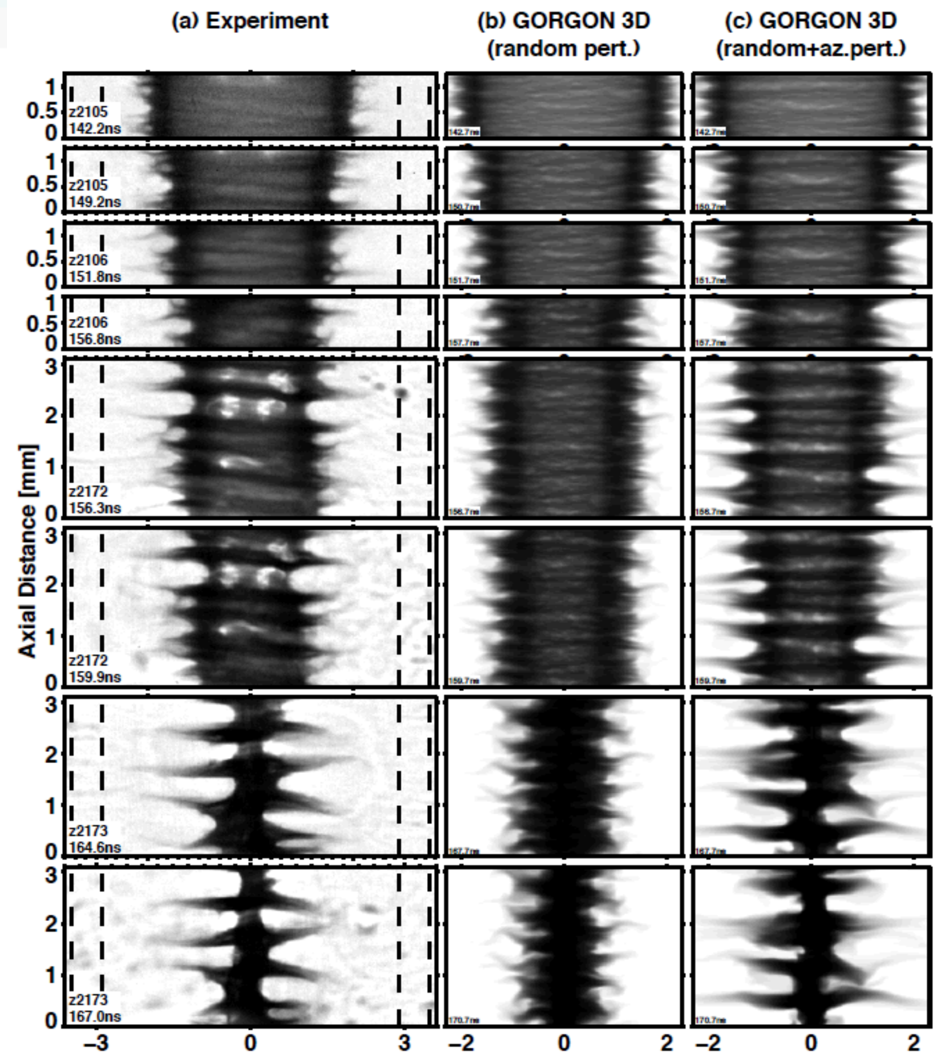

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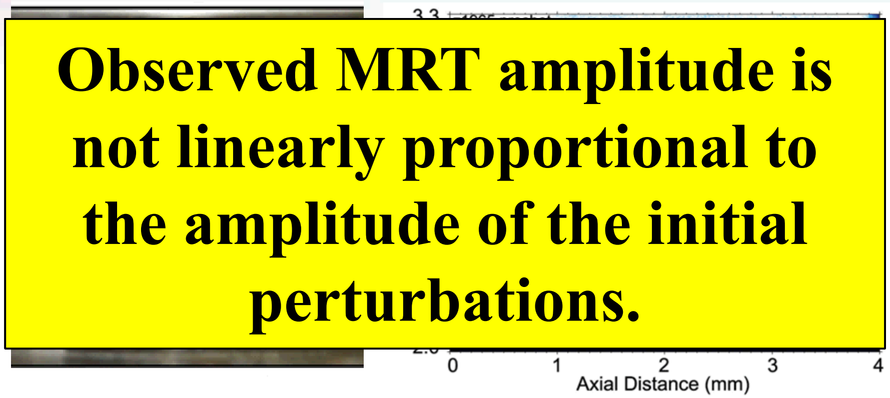

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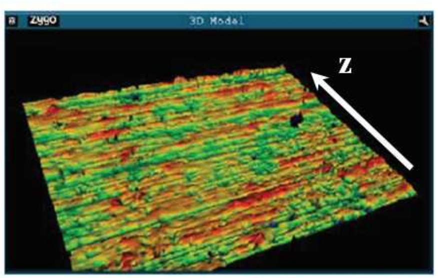

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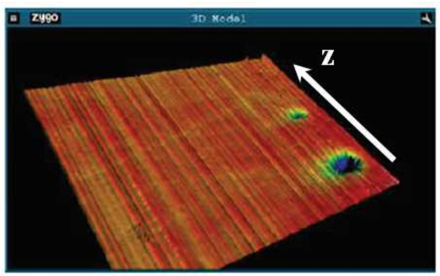

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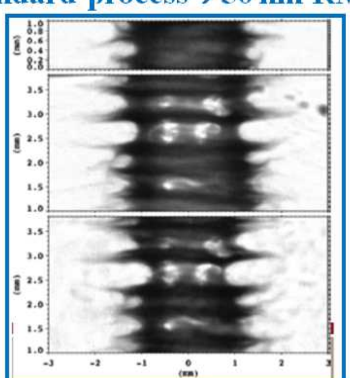

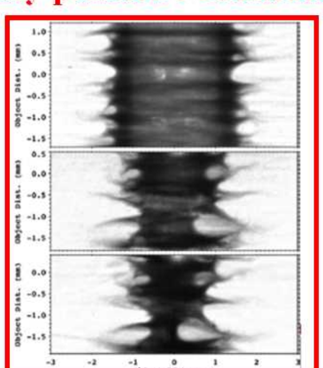

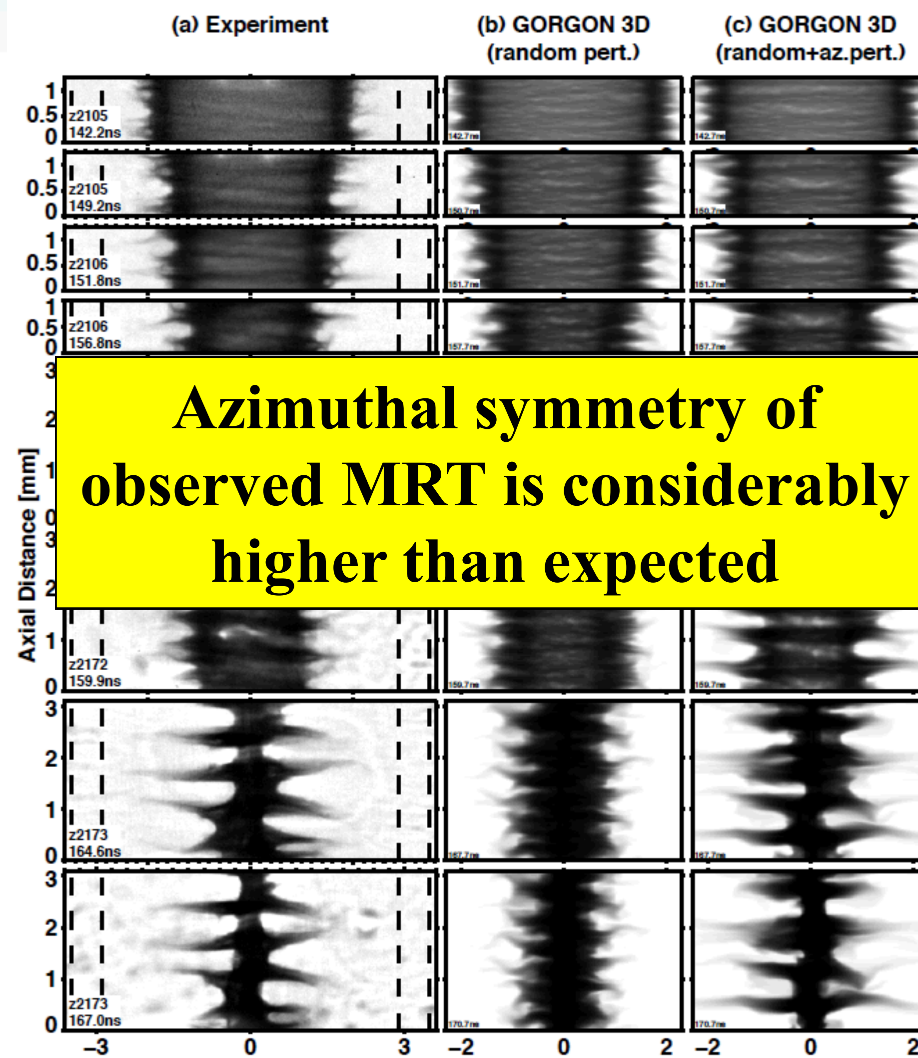

Azimuthal symmetry of observed MRT is considerably higher than expected

R.D. McBride *et al.*, PRL 109, 135004 (2012)
R.D. McBride, Invited Presentation, 2012 APS-DPP

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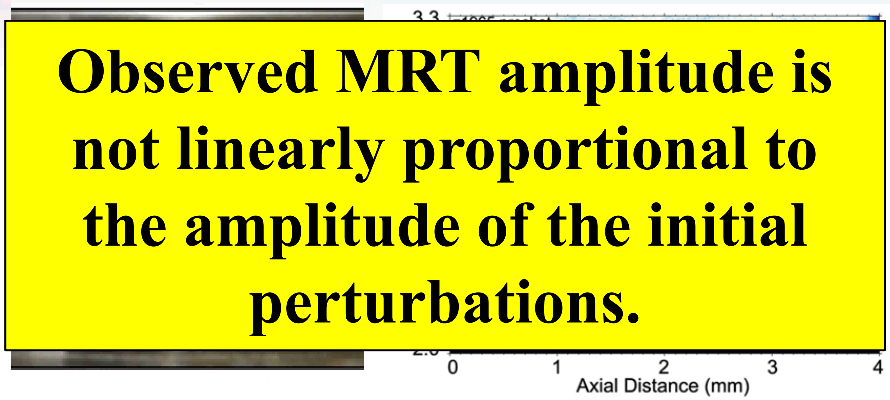

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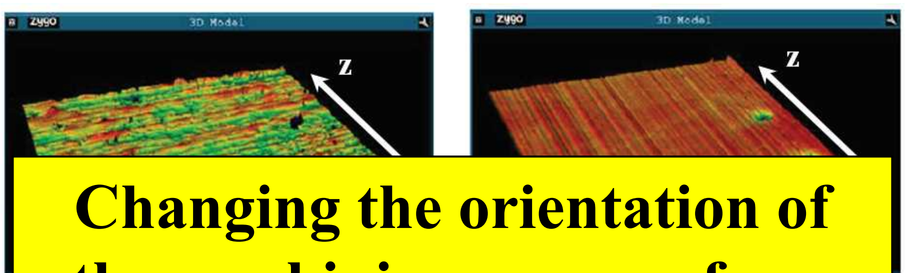
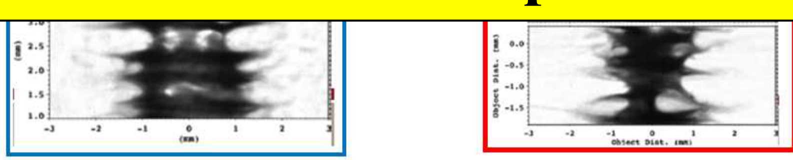
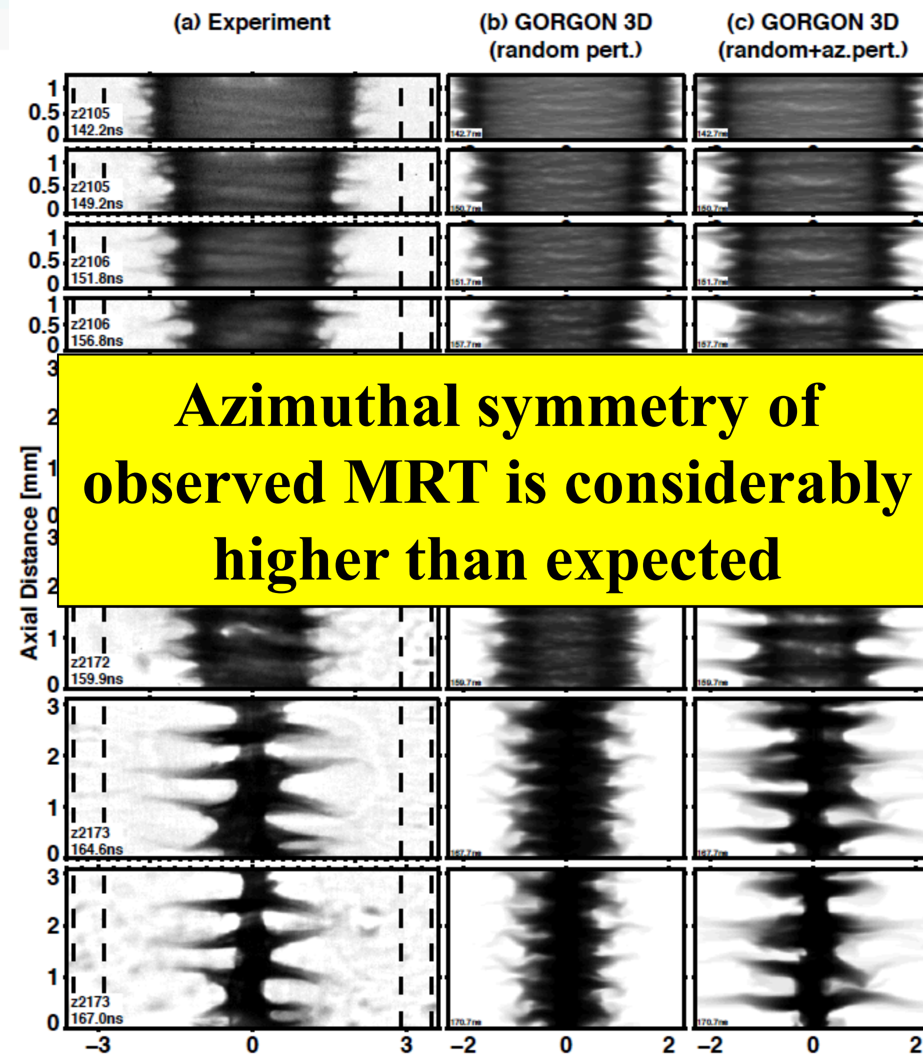


Changing the orientation of the machining grooves from azimuthal (lathe) to axial (broaching) had little impact on MRT development





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Summary of Z liner dynamics results → *Open questions remain!*

- **MRT is larger amplitude and more highly azimuthally correlated than expected →** ***Does something other than surface roughness seed MRT?***

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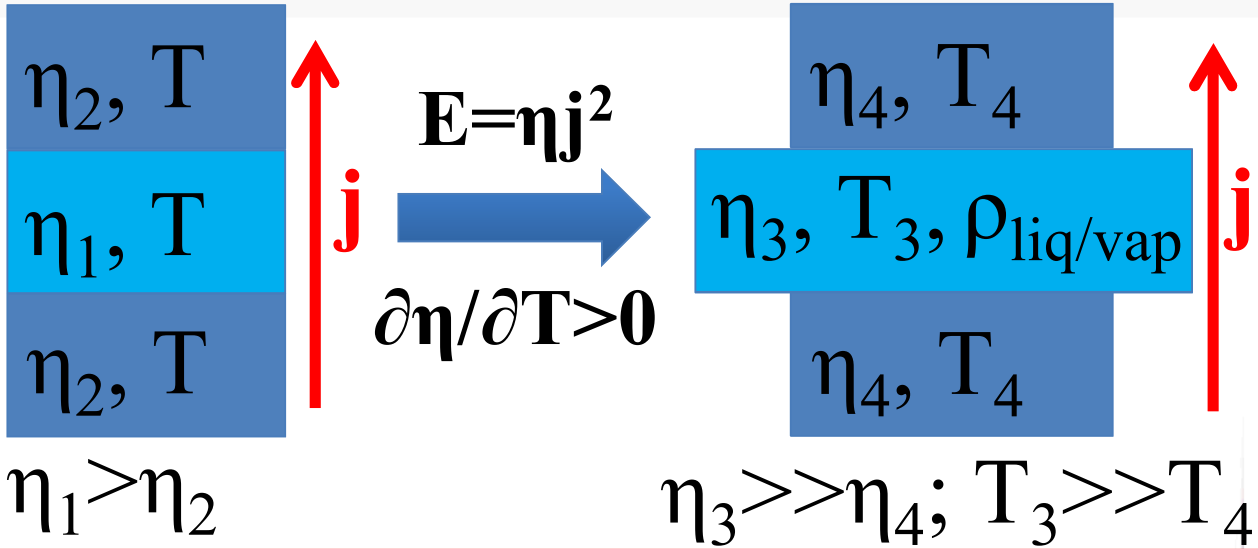
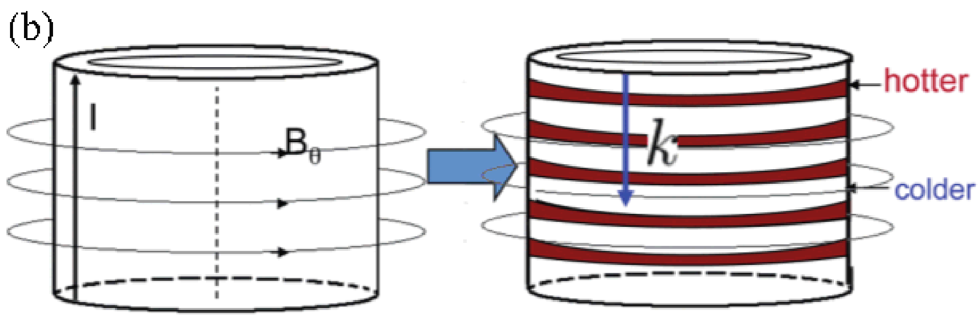
Electrothermal instabilities are driven by Joule heating and arise when resistivity (η) depends on temperature (T)

Condensed Metal

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



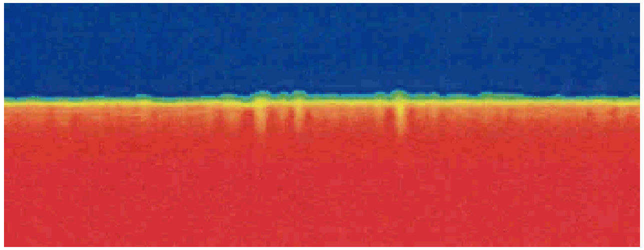
ETI strata, which are aligned with the magnetic field, are potentially a highly effective seed for MRT!



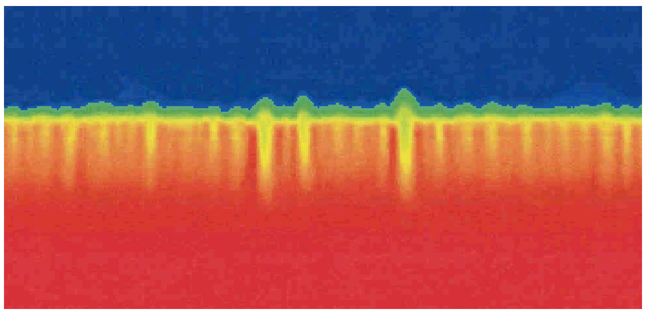
ETI grows rapidly near melt

For "thick" metals (liners or rods) which support 3D current flow, ETI physics is significantly more complex

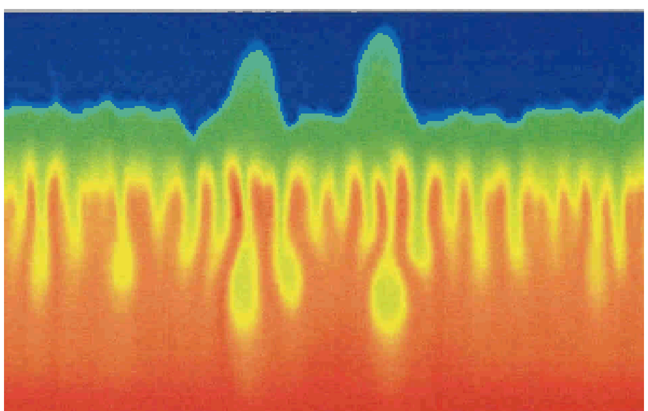
2D simulations show electro-thermal instabilities develop after melt and seed later MRT growth



Locations with initially higher Joule heating vaporize/expand first→Density perturbation forms



The Magneto-Raleigh Taylor (MRT) instability grows from the ETI seed, and begins to dominate



Non-linear MRT growth redistributes liner mass; large amplitude perturbations persist and grow

K.J. Peterson *et al.*, Phys. Plasmas 19, 092701 (2012)

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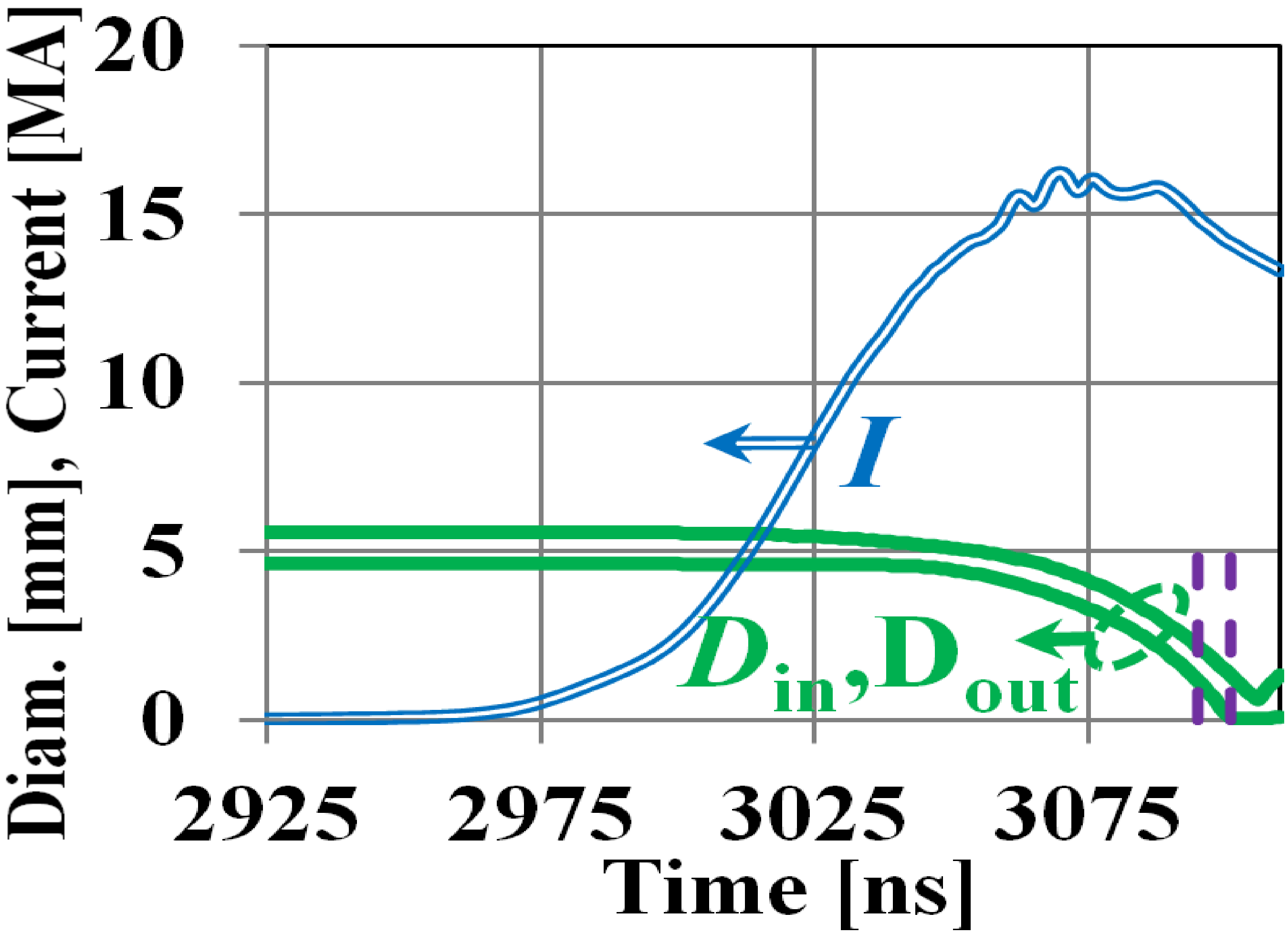
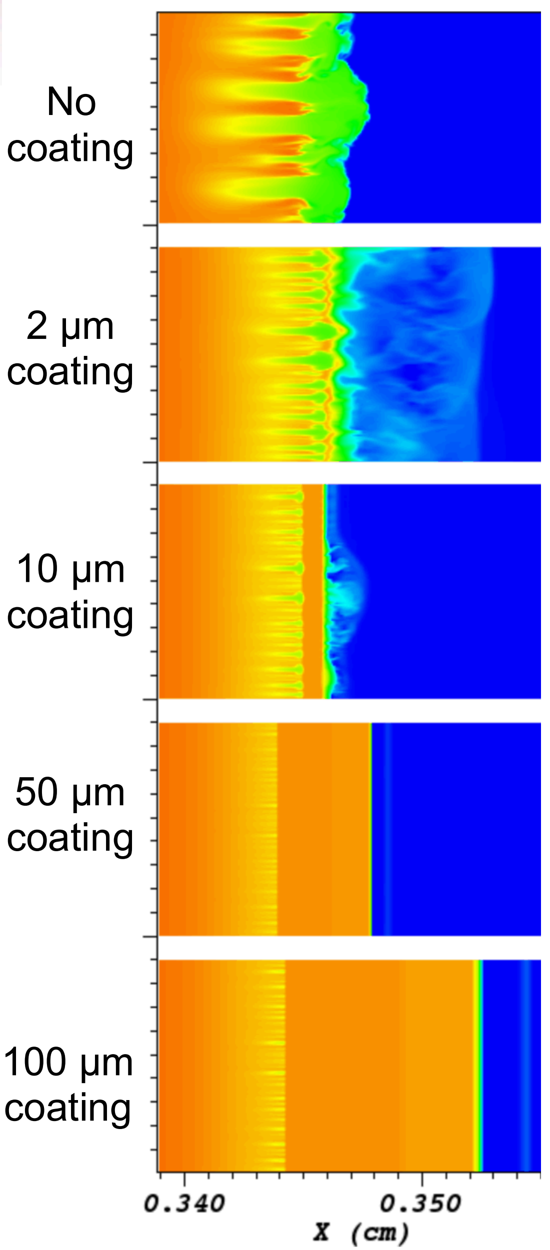
Liners on Z do not implode until the current exceeds 10 MA

Liner surfaces are nonuniformly Joule heated by >5 MA/cm lineal current density before bulk implosion begins



Joule heating driven instabilities may dominate throughout much of the experiment!

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 (striation) growth in the dielectric

Nonlinear mass redistribution from ETI is significantly tamped by the coating

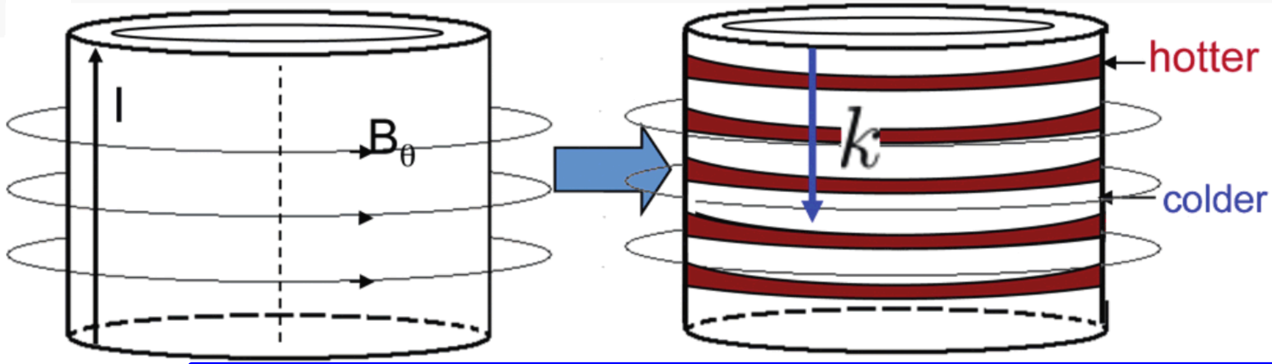
- Reduces seed for MRT growth
- Reduces integral instability growth

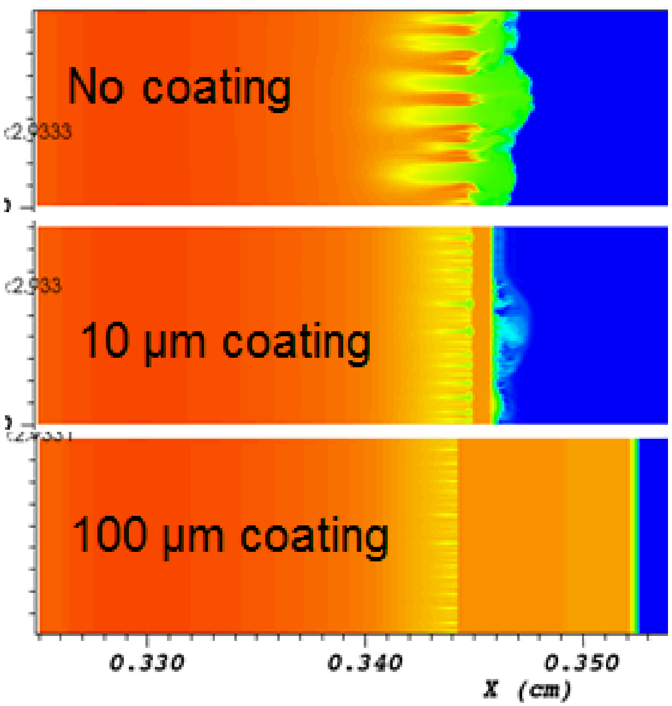
*K.J. Peterson *et al.*, PRL **112**, 135002 (2014)

Al-rod experiments enable interrogation of the Al/dielectric interface→$\kappa_{Al,\ 6.1\ keV} \sim 100\ cm^2/g$, $\kappa_{CH\ ,\ 6.1\ keV} \sim 10\ cm^2/g$

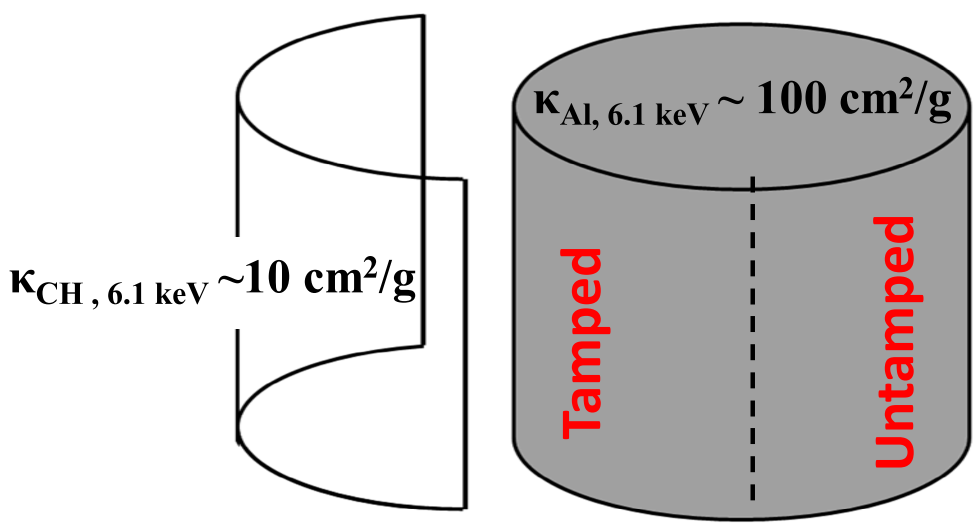
As metal is heated:

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



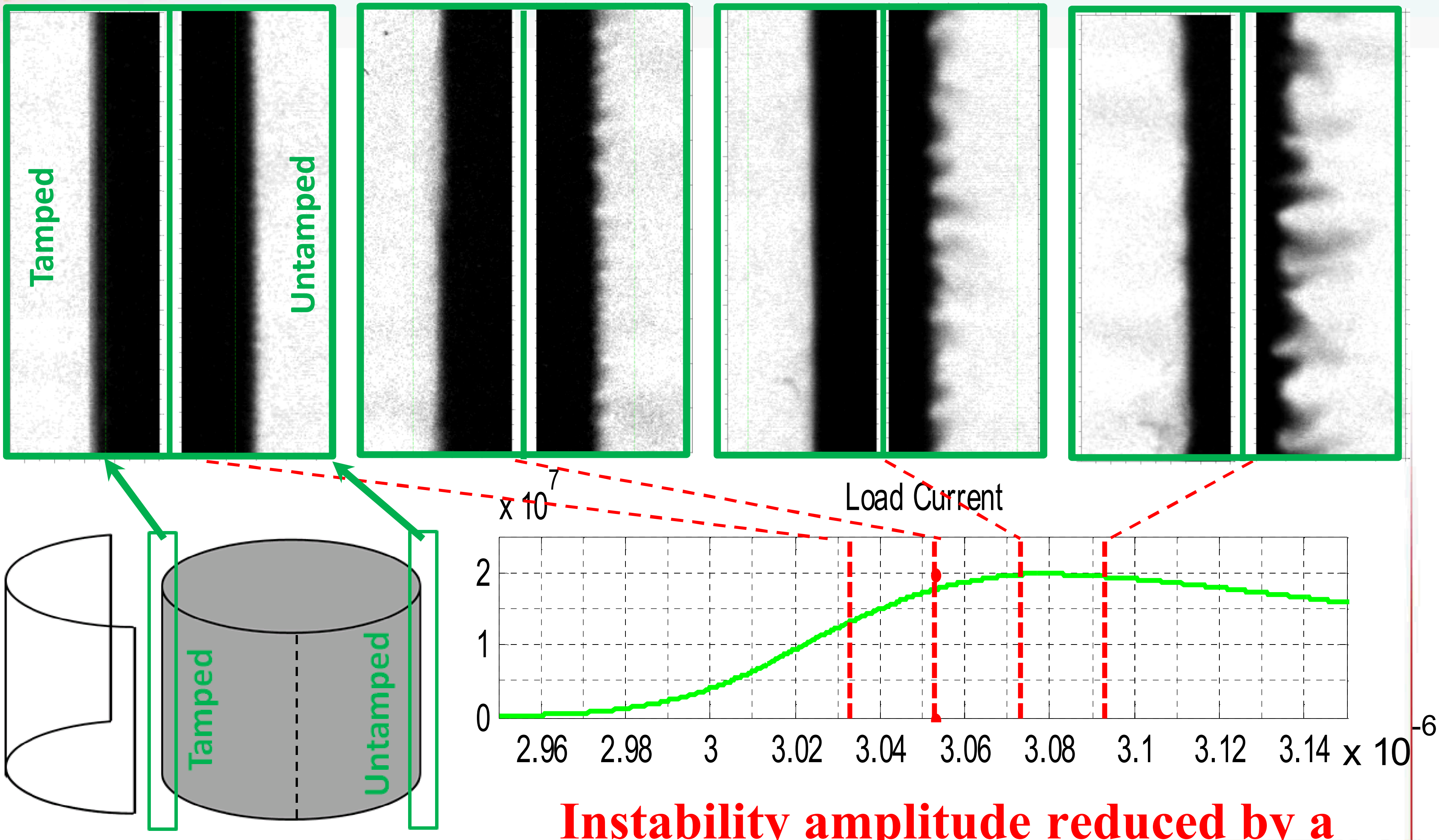


40-micron-thick dielectric tamper applied to 180° of Al rod



Directly compare coated/uncoated surface in a single experiment

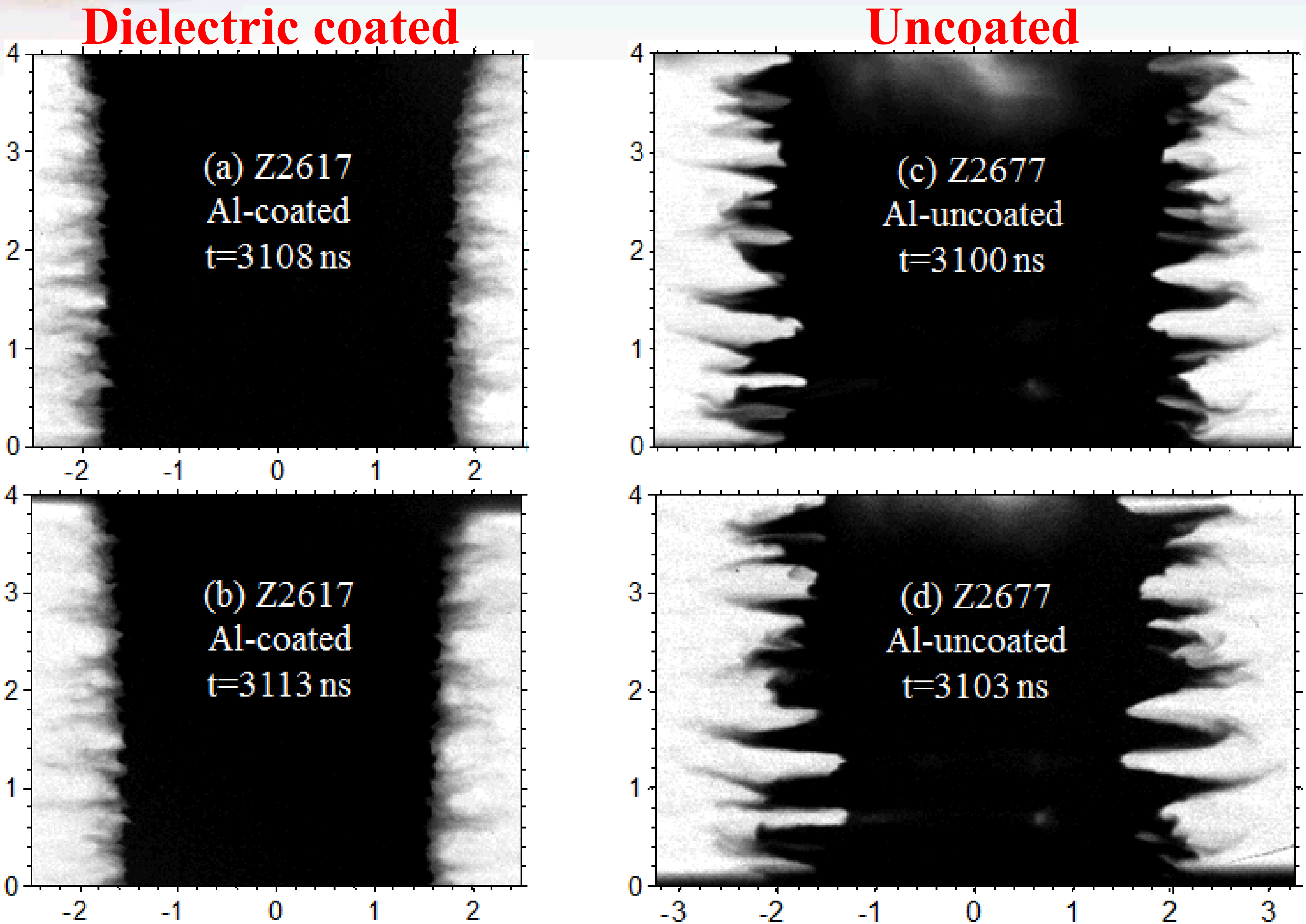
Adding a 70-micron-thick dielectric tamper dramatically alters MRT growth on a solid (R_0=3.43 mm) Al rod



Instability amplitude reduced by a factor of 10

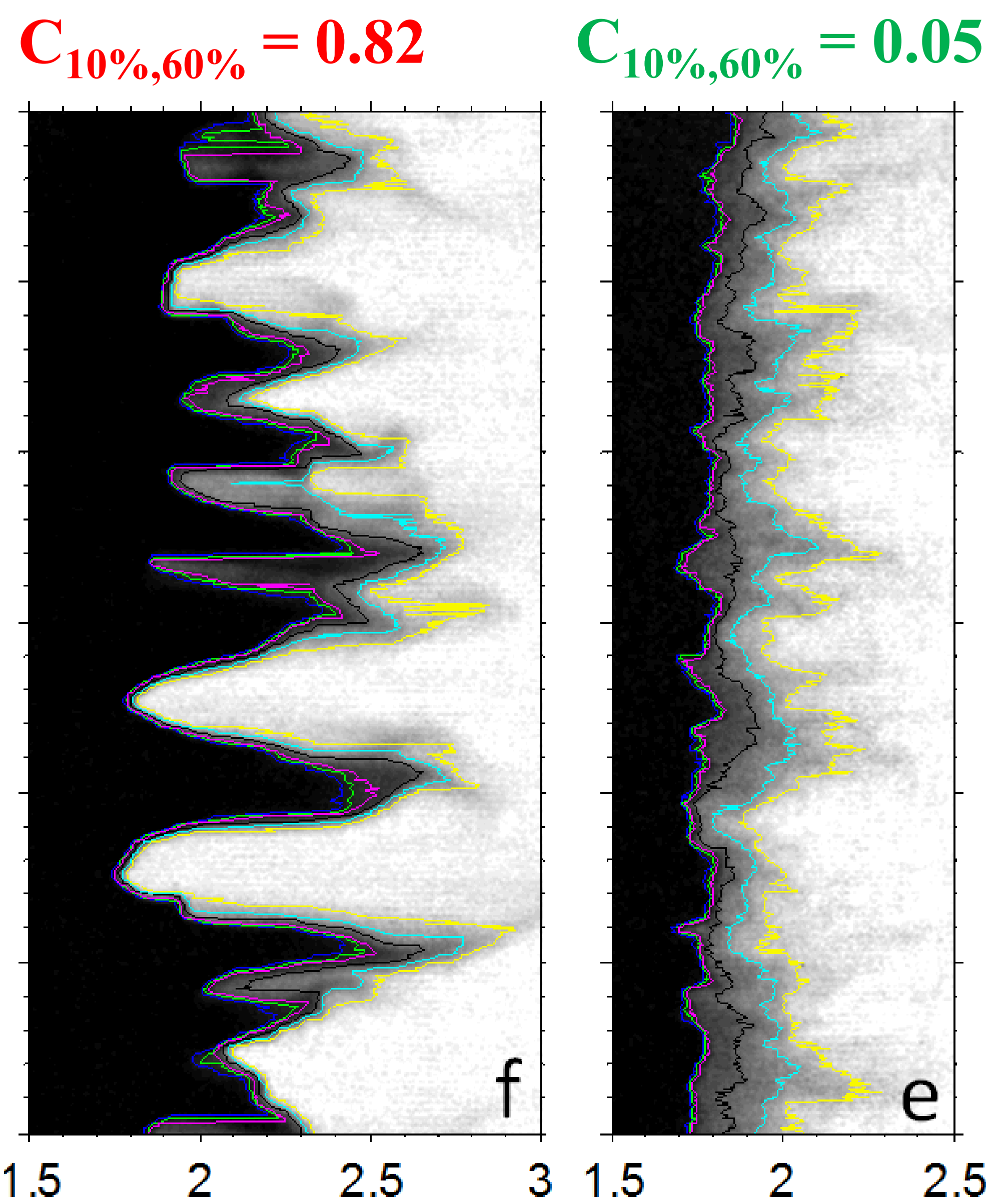
K.J. Peterson *et al.*, Phys. Rev. Lett. 112, 135002 (2014)

Rapidly accelerated aluminum liners → Tamper again greatly reduces cumulative MRT growth



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

Correlation of low/high density material may impact coupling of drive field to MRT



(Transmission %–color):
(10–blue), (15–green), (20–magenta),
(40–black), (60–cyan), and (80–yellow).

$$C_{ij} = \int_{L1}^{L2} \Delta r_i(z) \Delta r_j(z) dz \Big/ \sqrt{\int_{L1}^{L2} \Delta r_i^2(z) dz \int_{L1}^{L2} \Delta r_j^2(z) dz}$$

C_{ij}=1; perfect correlation

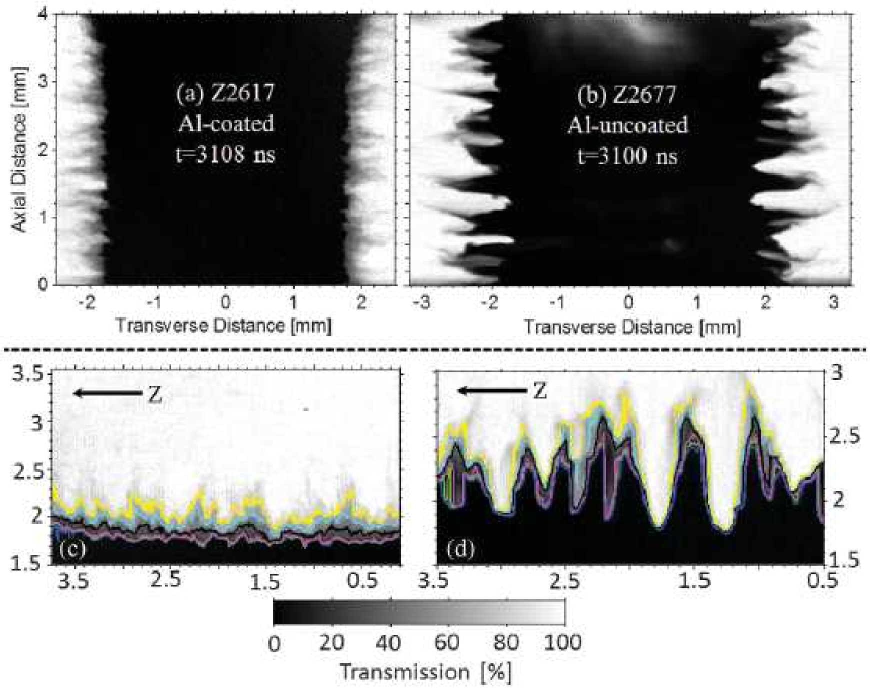
C_{ij} =0; no correlations

C_{ij} =-1; perfect anti-correlation

UNCOATED: High correlation allows unimpeded magnetic field to readily couple to instabilities

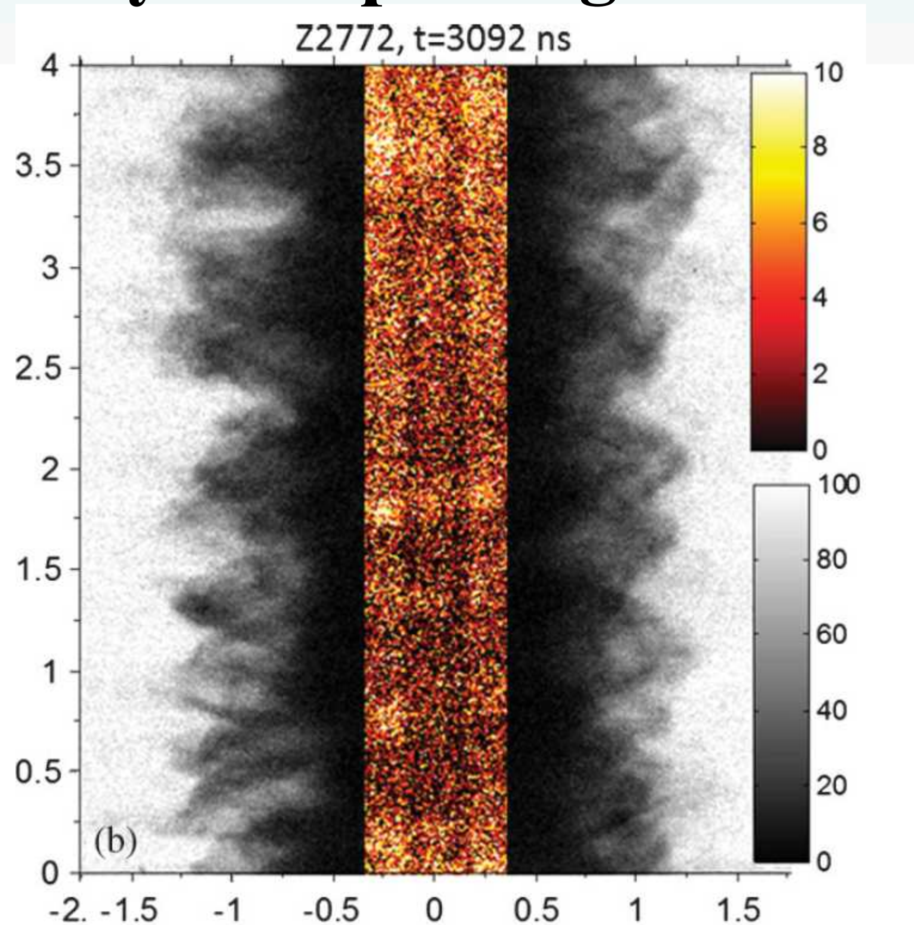
COATED: dielectric-sourced uncorrelated plasma mass surrounds metal; impairs field from driving MRT

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



Comparing coated (left) and uncoated (right) AR-9 aluminum liners:

MRT amplitude reduced by 10X for coated liner



Coated & axially premagnetized MagLIF liner: Radiograph at **CR-20** shows unprecedented uniformity

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

Summary of Z liner dynamics results→ *Open questions remain!*

- MRT is larger amplitude and more highly azimuthally correlated than expected→*Does something other than surface roughness seed MRT?*
- **Adding a dielectric tamper to solid rods and imploding liners reduces cumulative MRT amplitudes by ~10X→Does the dielectric tamper mitigate mass redistribution from ETI (ETI is NOT directly observed)?**

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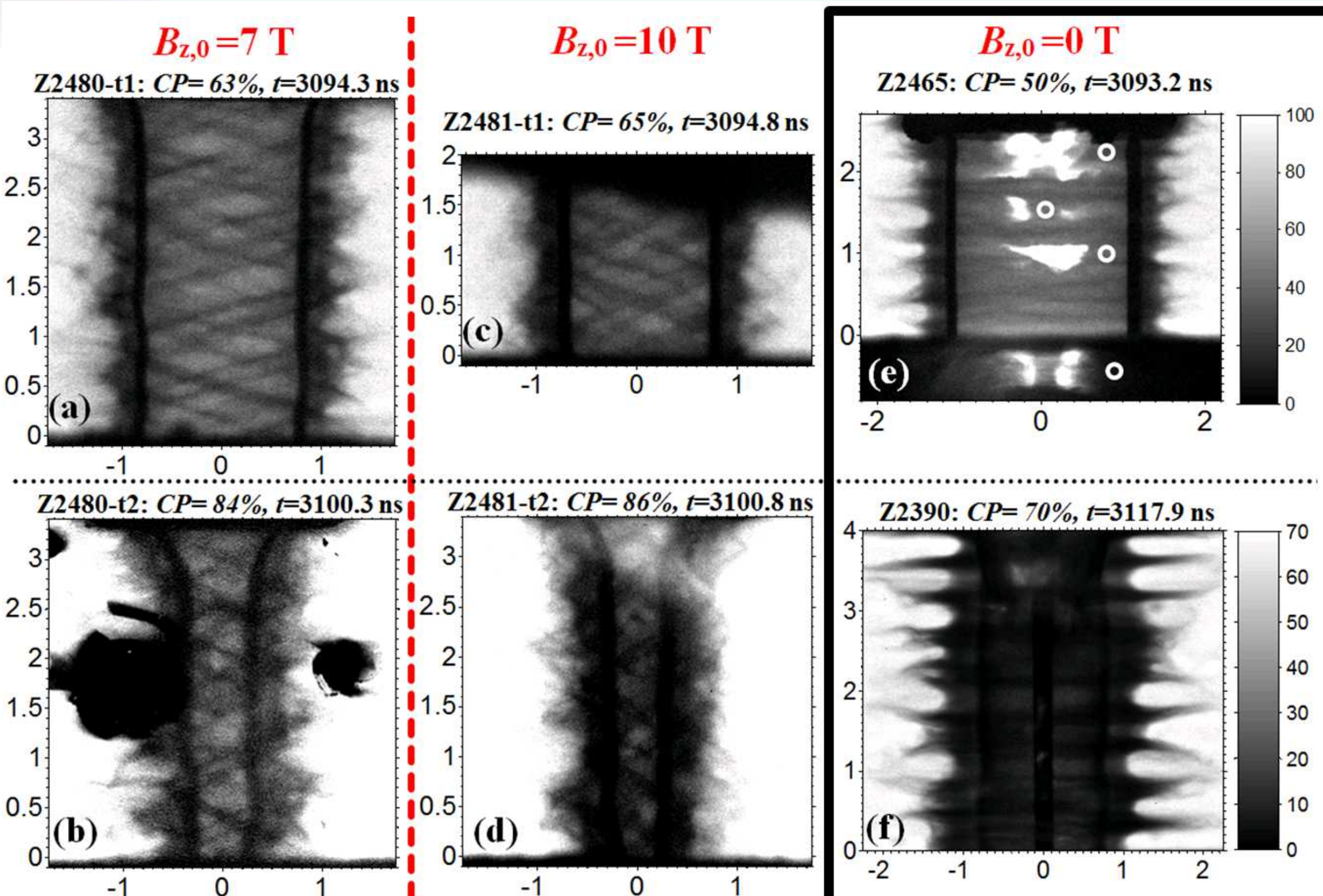
Helix-like instabilities develop on premagnetized liners

Implosion symmetry increases

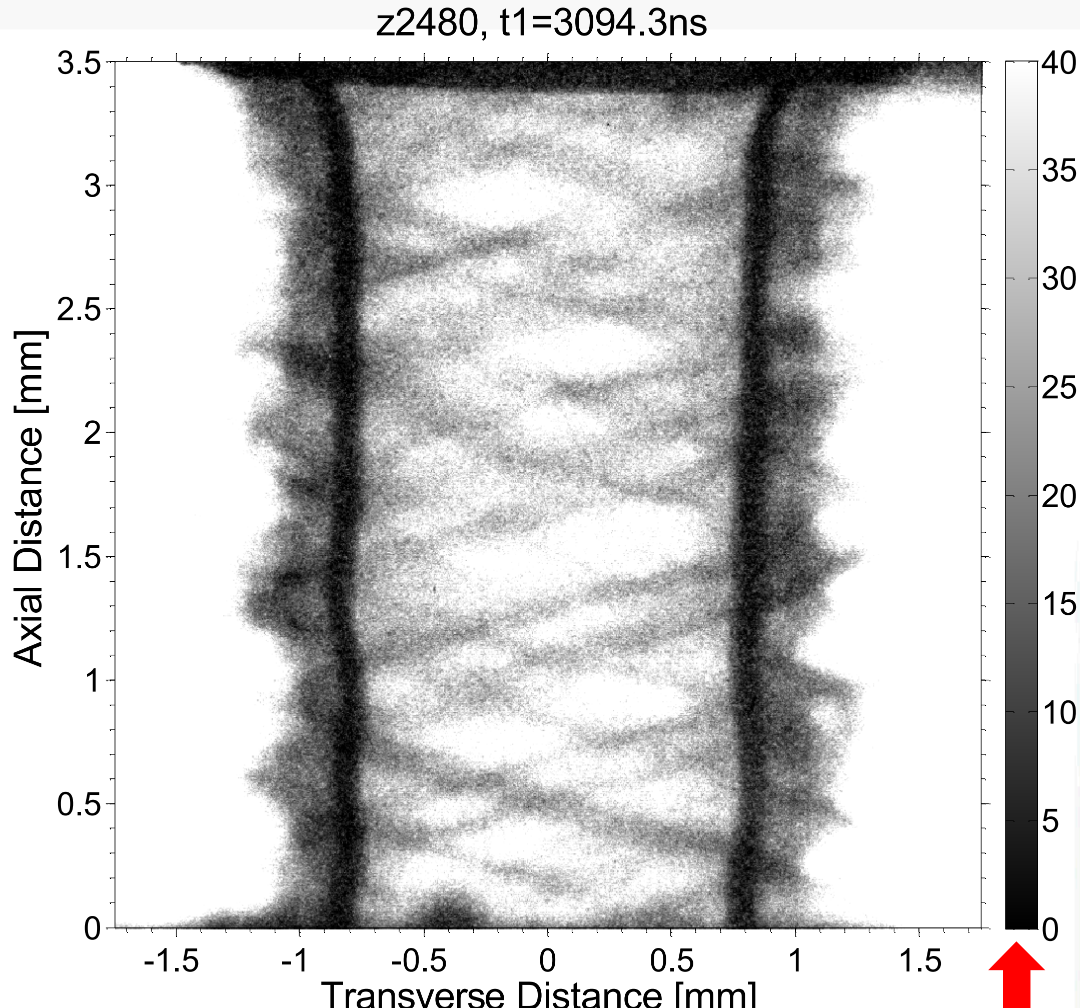


T.J. Awe *et al*. Phys. Rev. Lett. 111, 235005 (2013)

Well-connected helical structures are easily traced through multiple cycles

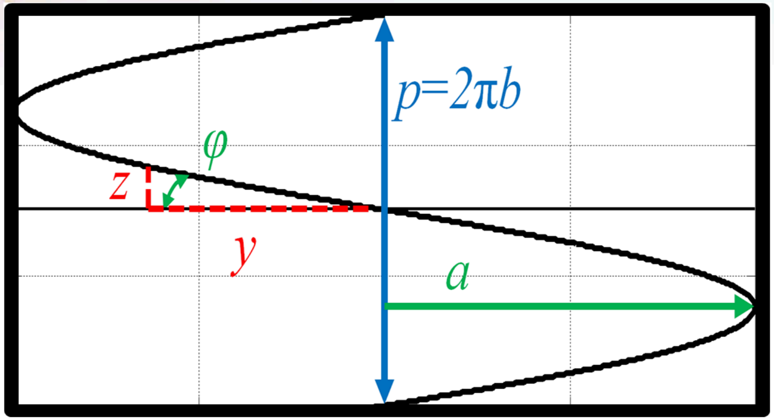
High-density structures are at large angle to the z axis

Penetrating radiography "sees" structures at "front" and "back" of liner, so structures with positive and negative slope are observe. This results in the observed cross-hatched pattern



Black=0 % Transmission
White=40% Transmission

A simple cylindrical helix model fits the data well



Cylindrical helix model

$y(\theta)=a\cdot\sin(\theta)$

$z(\theta)=p\cdot\theta/2\pi$

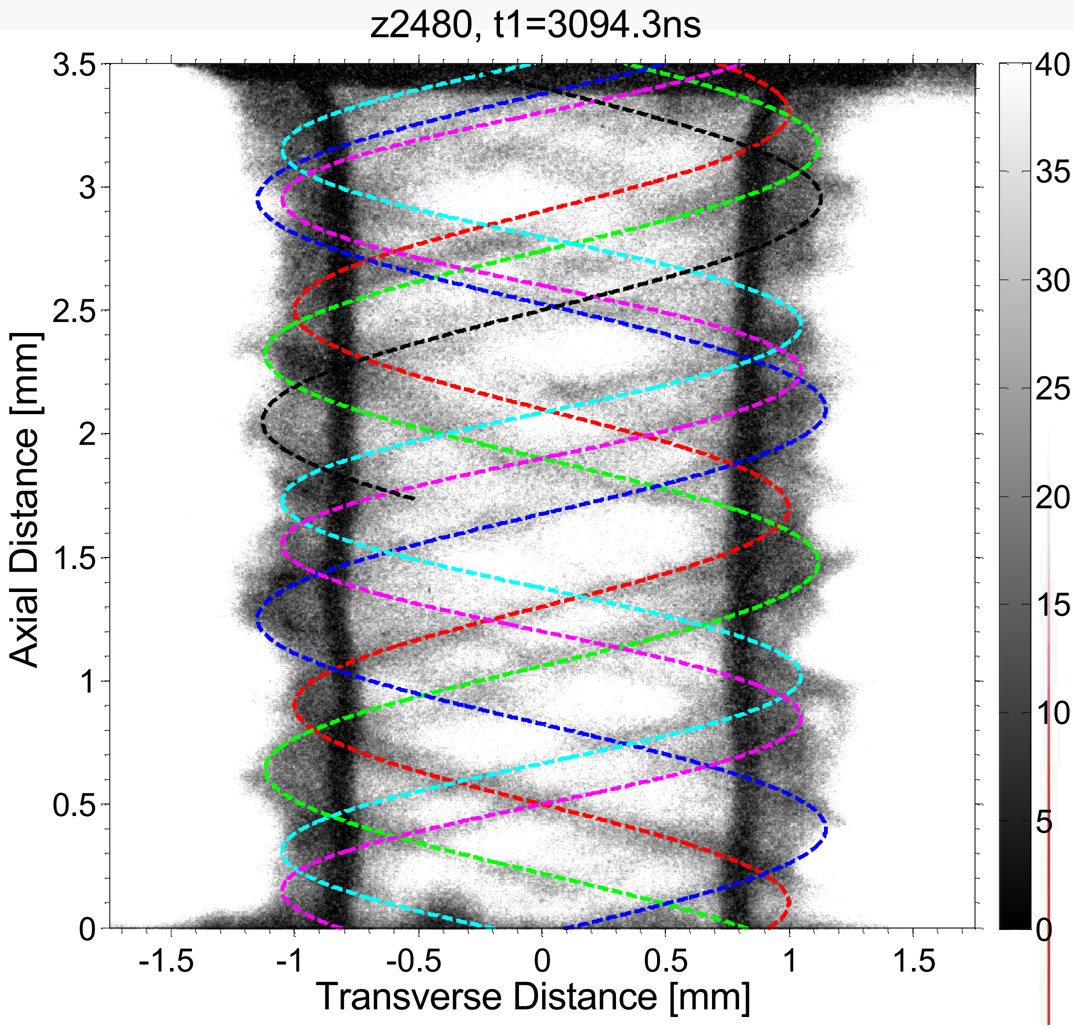
a =radius

p=pitch

“pitch angle”

$\varphi=\tan^{-1}(z/y)$

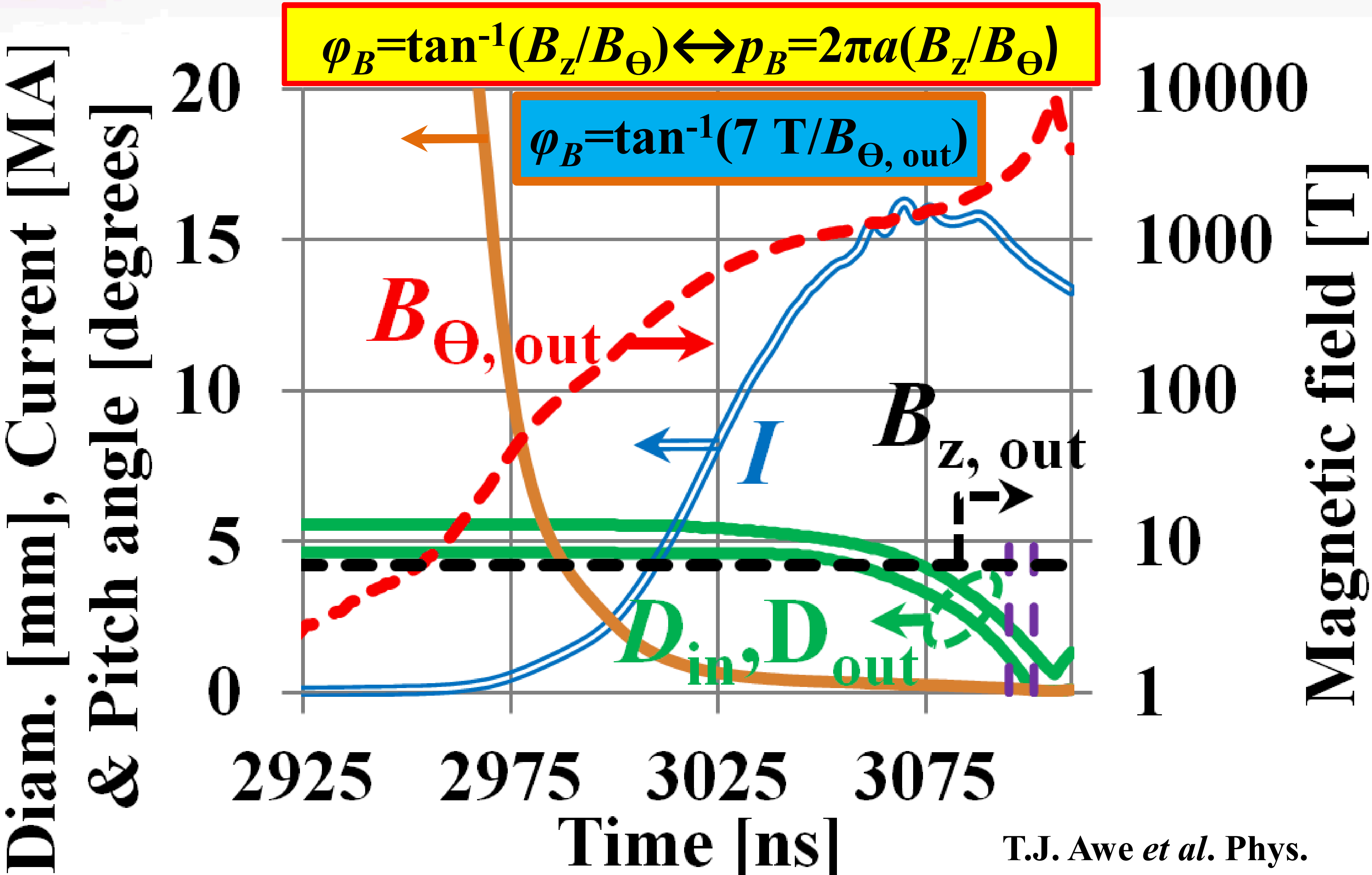
$\varphi\approx\tan^{-1}(p/2\pi a)$



$\mathbf{a_{avg}=1.07\ mm}$

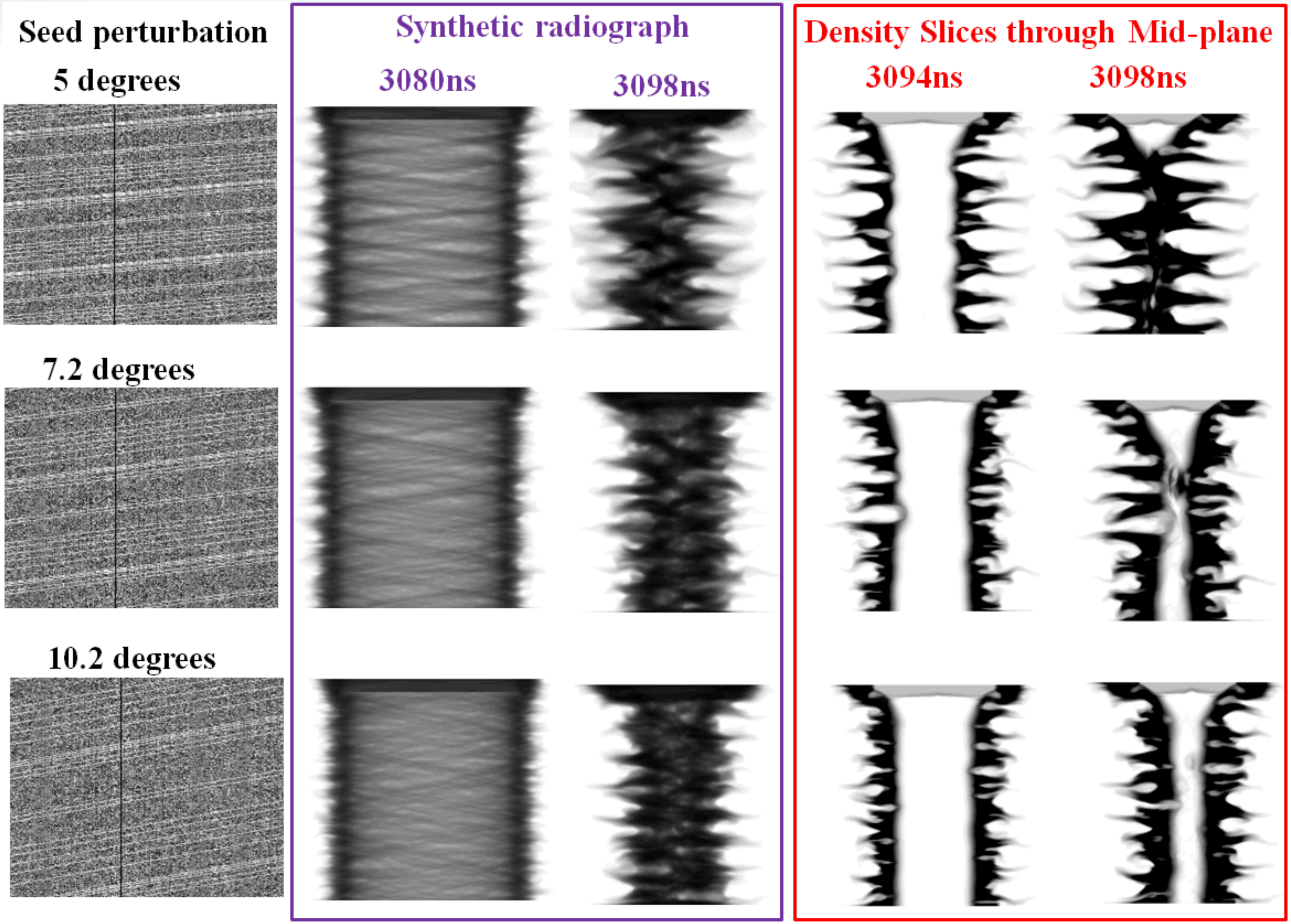
$\mathbf{p_{avg}=1.56\ mm}$

Briefly, $B_\Theta \approx B_z$ early in the experiment, but presumably $B_\Theta >> B_z$ throughout the entire implosion



T.J. Awe *et al.* Phys. Plasmas 21, 056303 (2014)

3D MHD sims show that an initial helical perturbation will grow in amplitude and pitch angle as the liner converges



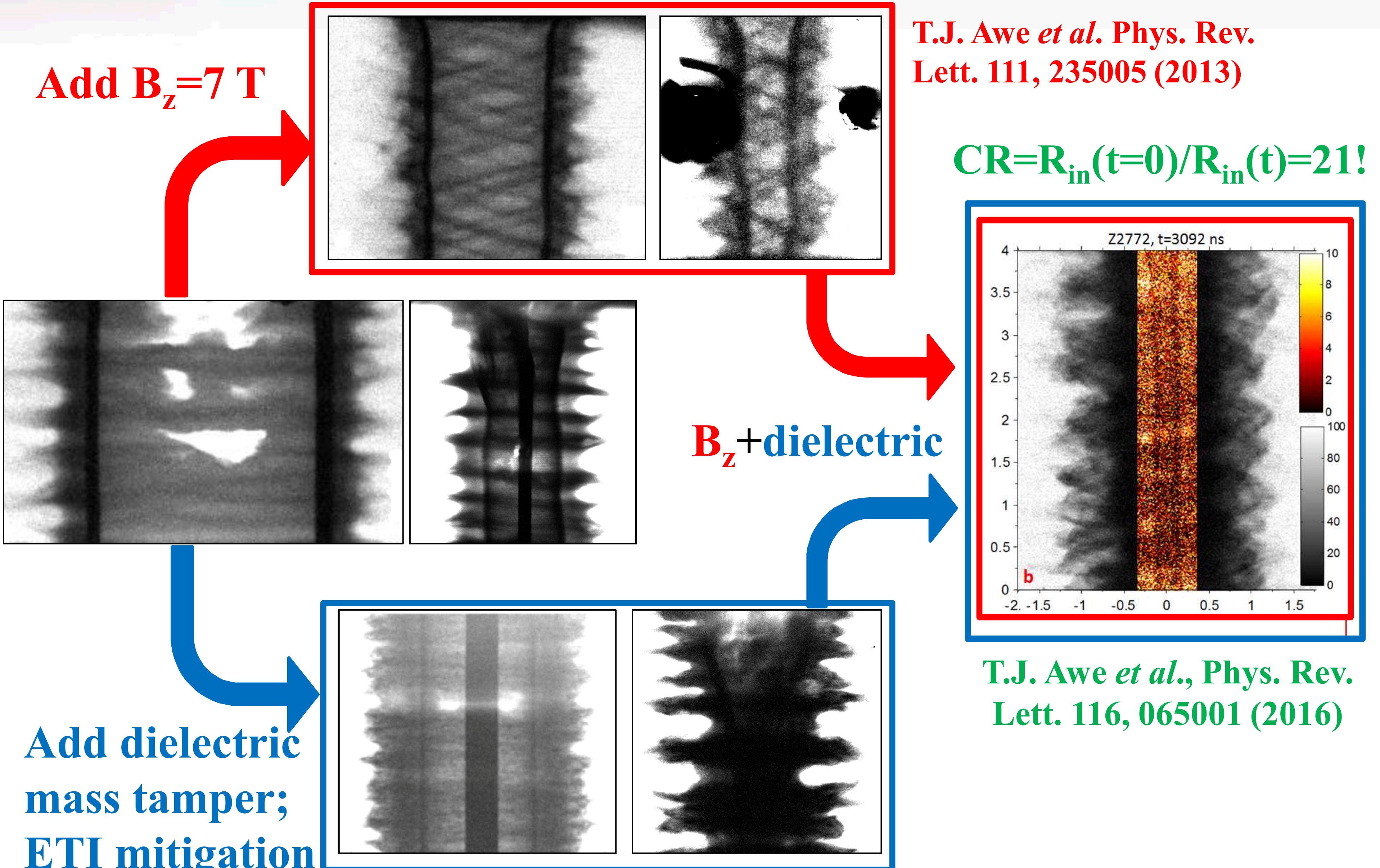
GORGON simulations by Chris Jennings

Summary of Z liner dynamics results→ *Open questions remain!*

- MRT is larger amplitude and more highly azimuthally correlated than expected→Early in the current pulse, *does something other than surface roughness provide the dominant seed for MRT?*
- Adding a dielectric tamper to solid rods and imploding liners reduces cumulative MRT amplitudes by ~10X→Does the dielectric tamper mitigate mass redistribution from ETI (ETI is **NOT** directly observed)?
- **Axially premagnetized liners develop helix-like instabilities and implode with higher symmetry than non-premagnetized liners→Are helix-like instabilities seeded when $B_z \sim B_\Theta$? If so, what physical mechanism leads to the formation of a helical perturbation?**

Sandia National Laboratories

Combining axial premagnetization with a dielectric tamper for ETI mitigation results in unprecedented liner stability



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- Premagnetized & dielectric coated liners implode with unprecedented symmetry→Can such results be explained without detailed knowledge of helical instability and ETI seeding?

Addressing the questions above requires data on the low-temperature evolution of a metal carrying skin current

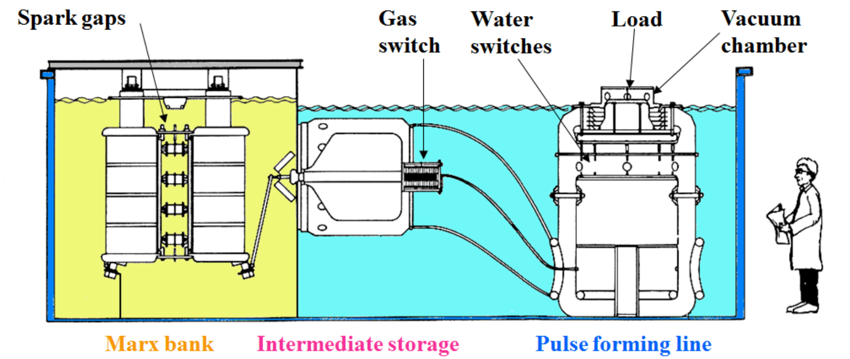
Unprecedented data on low temperature nonuniform Joule heating has given credence to ETI seeding of MRT

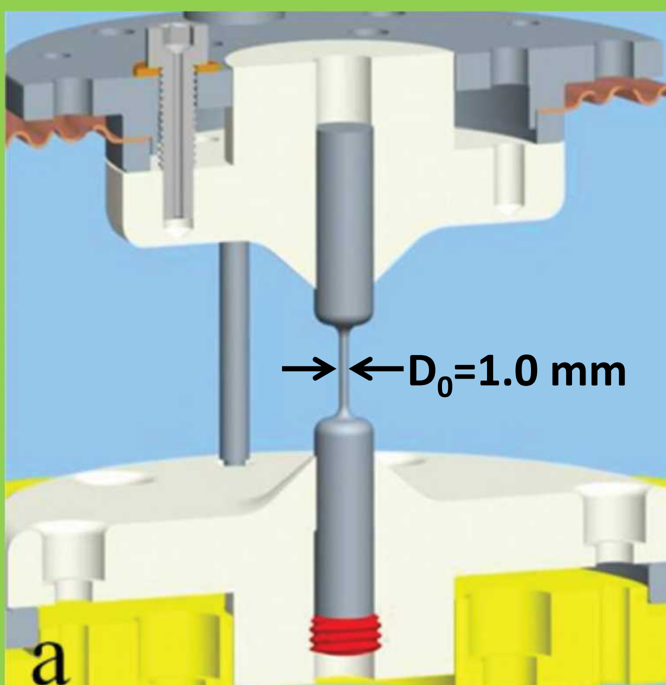
ETI stata grow in condensed metals at sub-eV temperatures

A 1 MA, 100 ns facility can access this physical regime

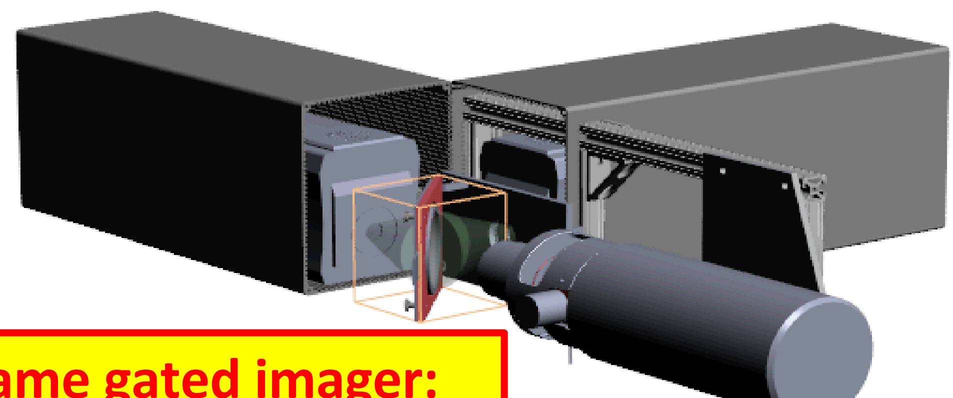
U of Nevada, Reno Zebra Facility

→100 ns rise time (similar to Z)
→Nonuniform "skin" current
→Suite of low temperature (NIR to EUV) diagnostics suitable for ETI studies



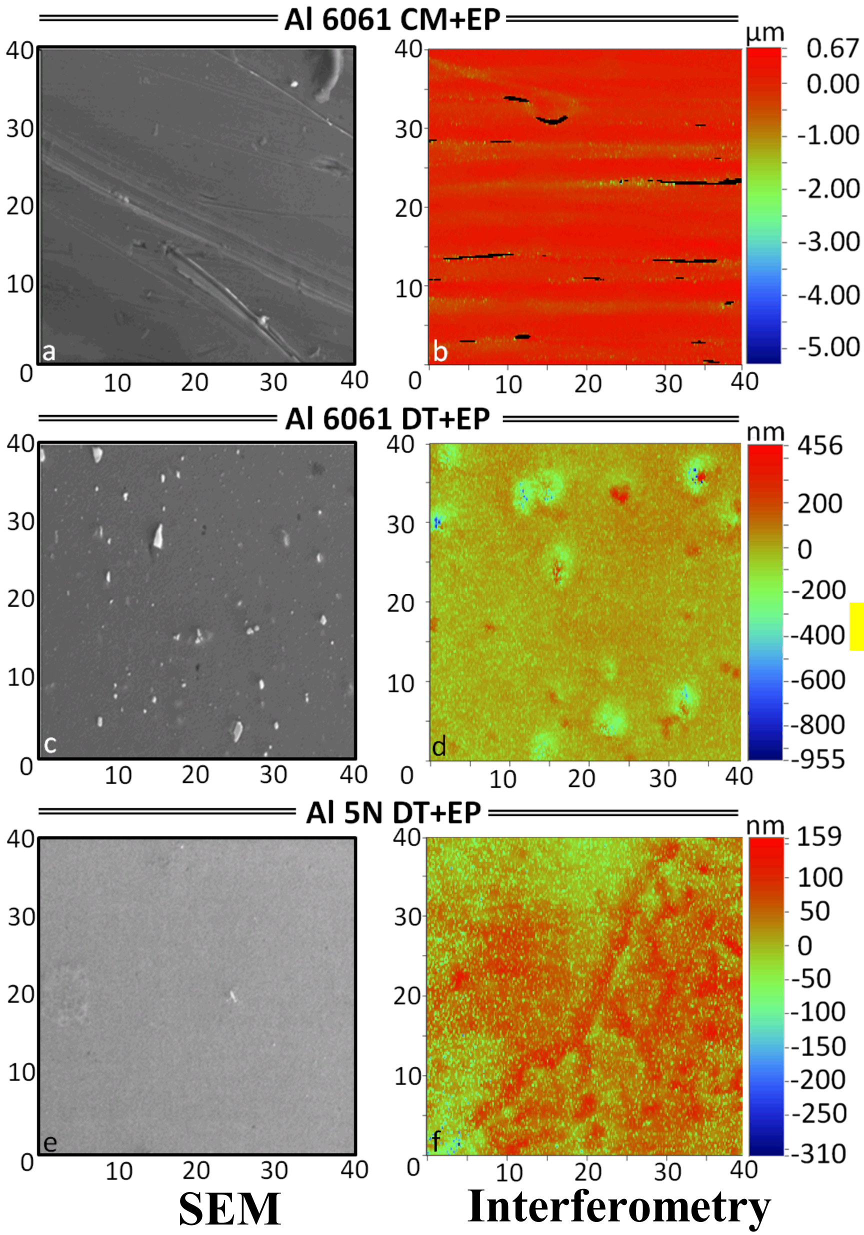


The "barbell load in knife-edge hardware" is carefully designed to avoid non-thermal plasma formation mechanisms common to high-voltage generators



2 frame gated imager:
2 ns and 3 μm resolution

Perturbations in resistivity or current density seed nonuniform Joule heating; surfaces were characterized prior to experiments



Al 6061: Machined (CM) & Electropolished (EP)

Machining grooves→λ~5 µm, few-µm amplitude

Resistive inclusions → surface and volumetric

Roughness Average, R_a=170 nm

Al 6061: Diamond Turned (DT) & EP

Machining grooves removed via electropolishing

Resistive inclusions → surface and volumetric

Surface inclusions can be quantified:

R_a=42 nm

100 defects/mm² w/ d>5 µm

1,800 defects/mm² w/ 2.5<d<5 µm

8,400 defects/mm² w/ 1<d<2.5 µm

over 200,000 defects/mm² with d<1 µm.

Al 5N (99.999% pure): DT & EP

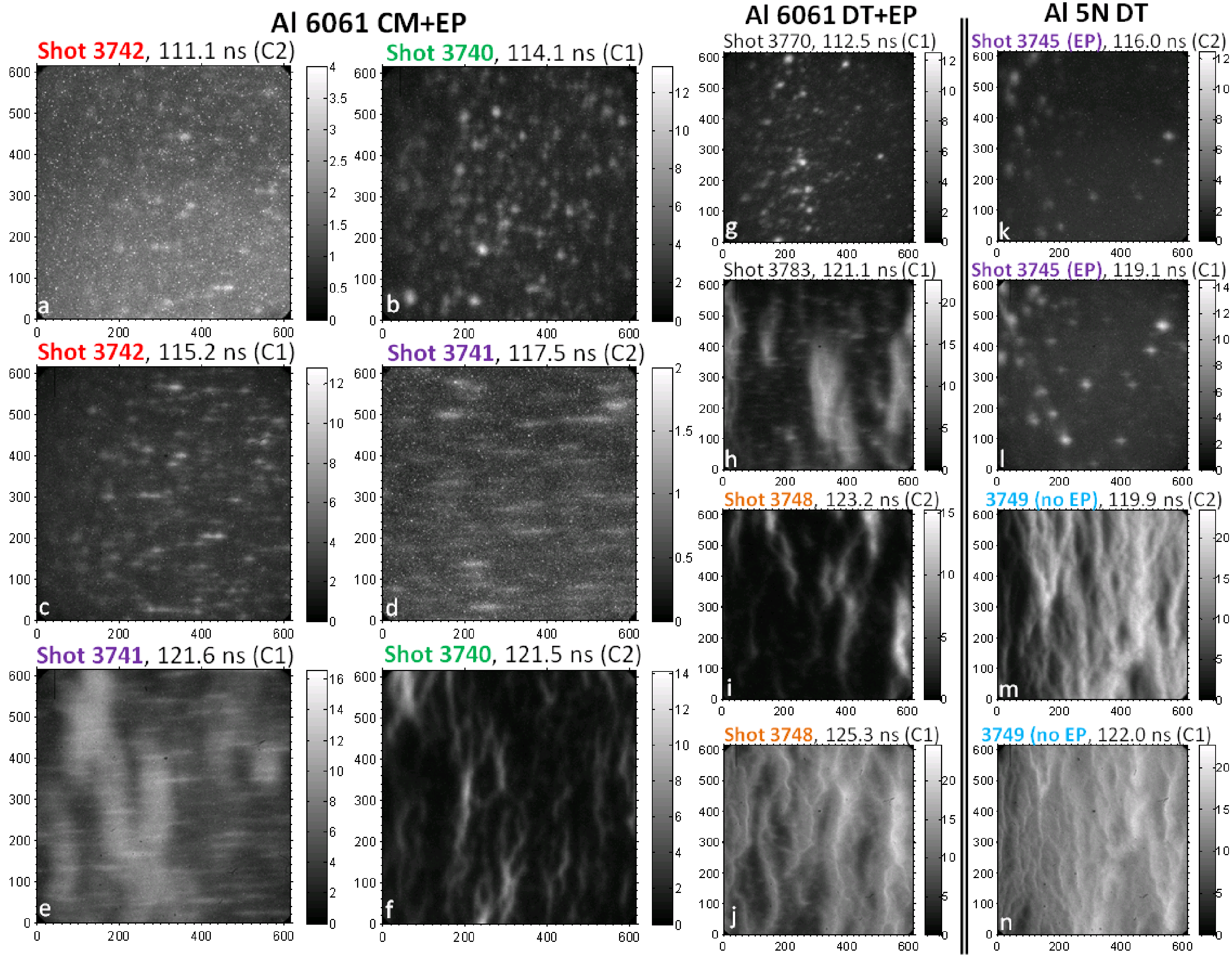
Surfaces are nearly perfect, by comparison

No resistive inclusions

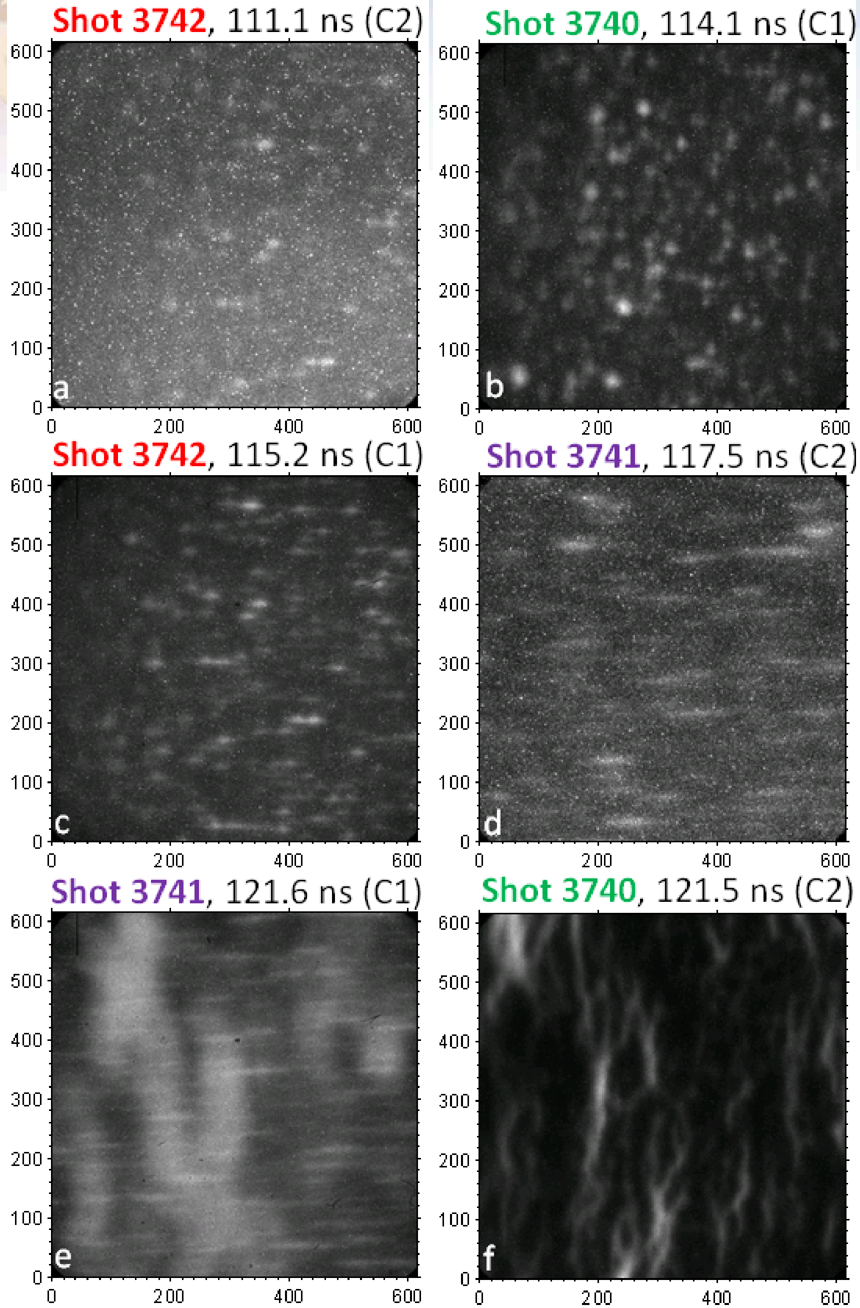
isolated surface defects do exist

R_a=29 nm

The evolution of surface emissions from Joule-heated Al rods can depend on alloy and fabrication technique

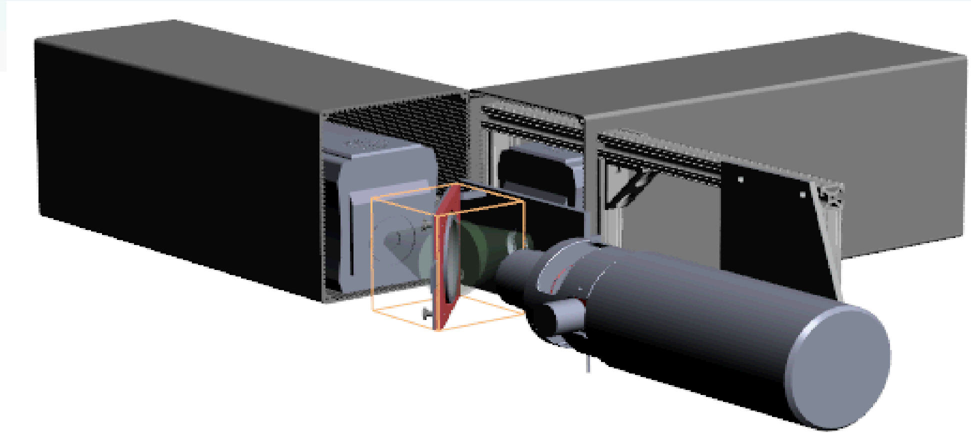


Nonuniform self-emission from Al 6061 loads evolves rapidly



Axes in [µm]

T.J. Awe, *et al.*, Submitted to Phys. Rev. Lett., May, 2016

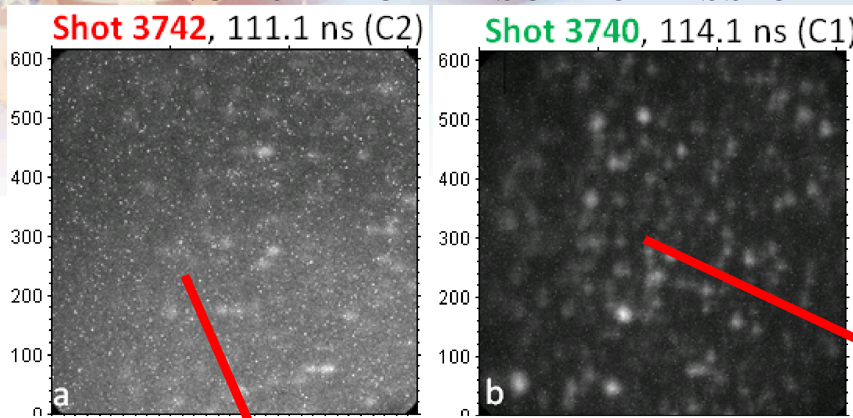


2 frame gated imager with 2 ns and 3 µm resolution captures VIS/NIR emissions from the sub-eV rod surface

Extreme diagnostic resolution enabled a variety of first ever observations!

Sandia National Laboratories

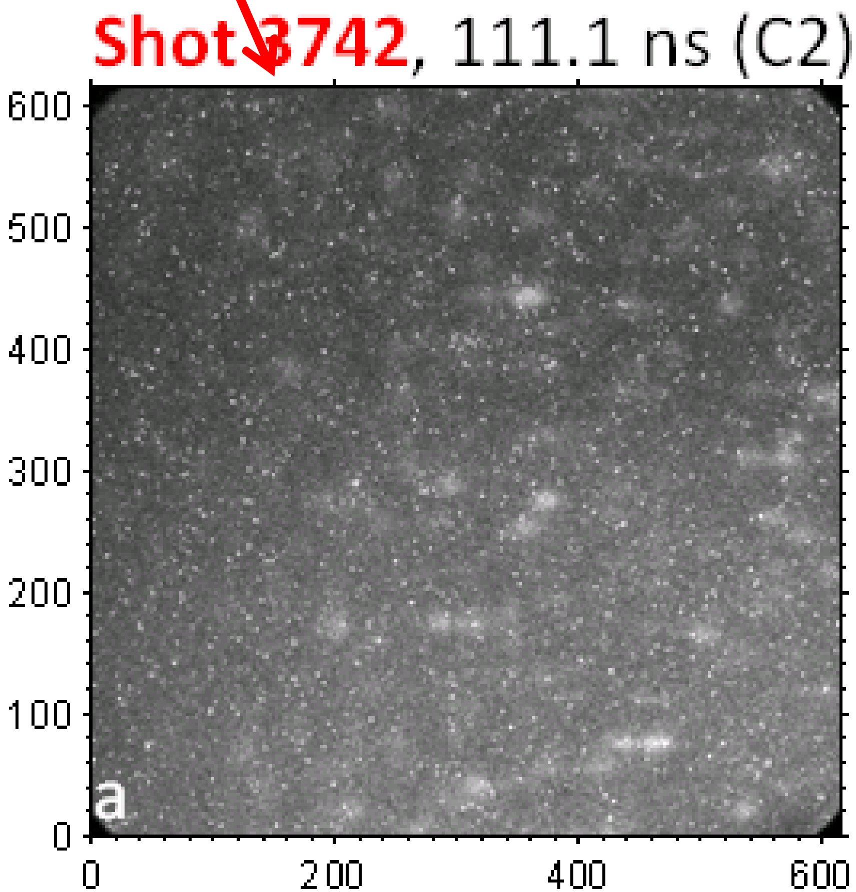
Nonuniform self-emission from Al 6061 loads evolves rapidly

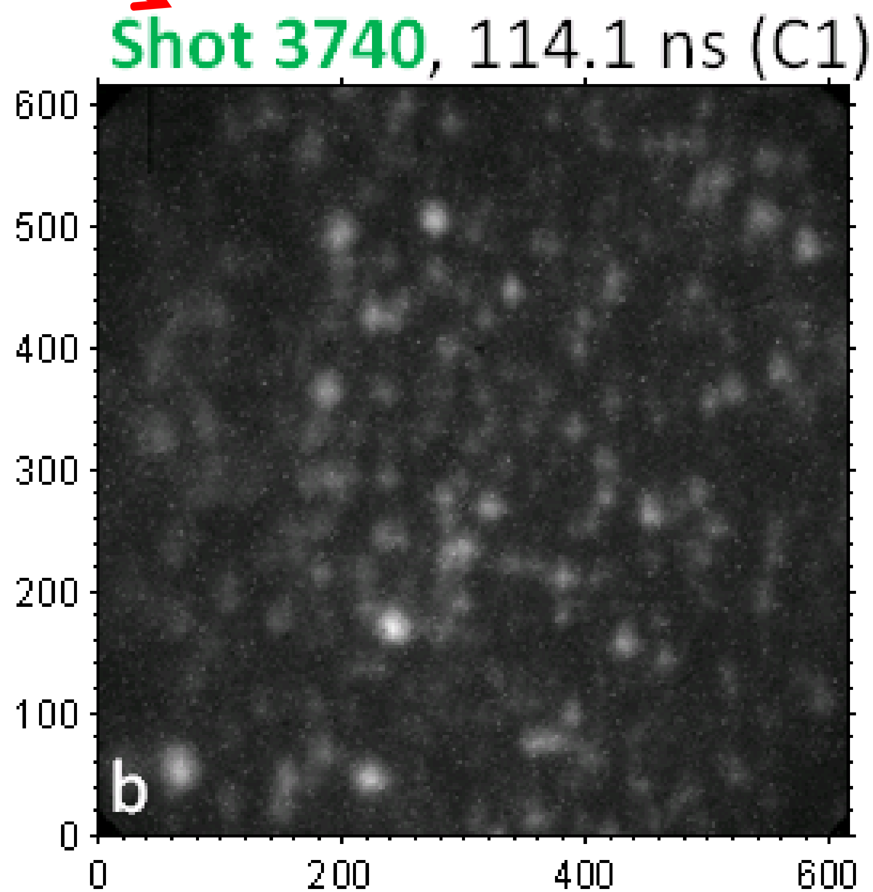


Surface Emissions evolve from…

- Discrete round Spots at ~600 kA

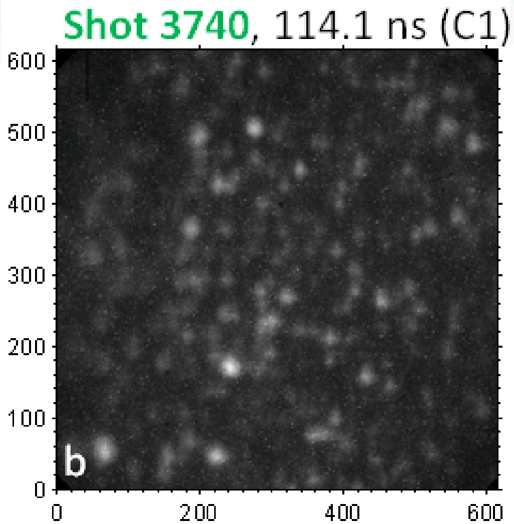
What seeds overheated spots?

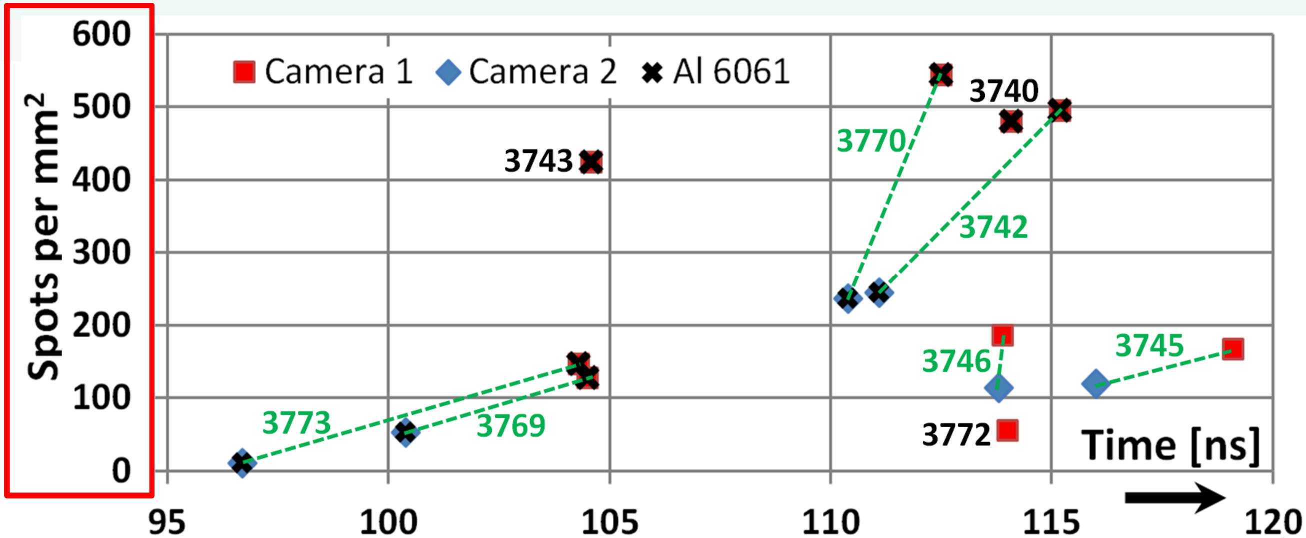


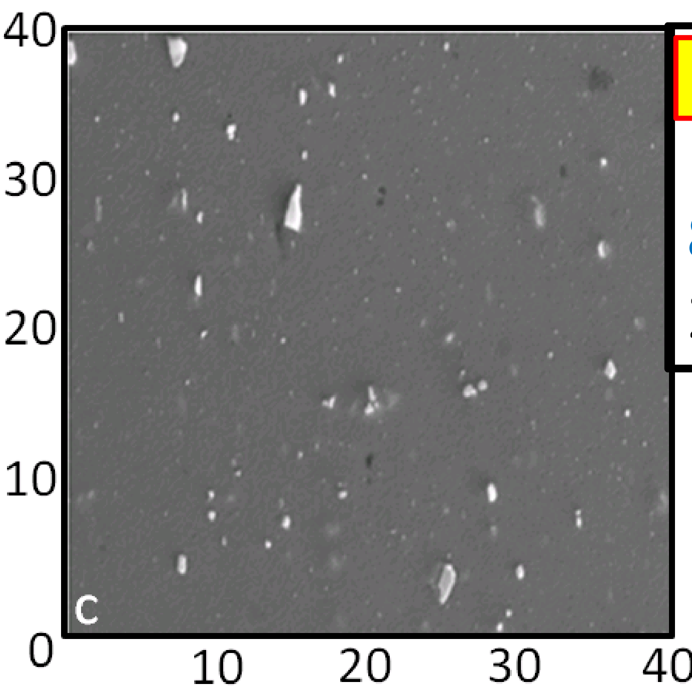


Axes in [μm]

Defects likely seed spot formation → the number of spots is comparable to the number of surface defects







100 defects/mm² w/ d>5 µm

1,800 defects/mm² w/ 2.5<d<5 µm

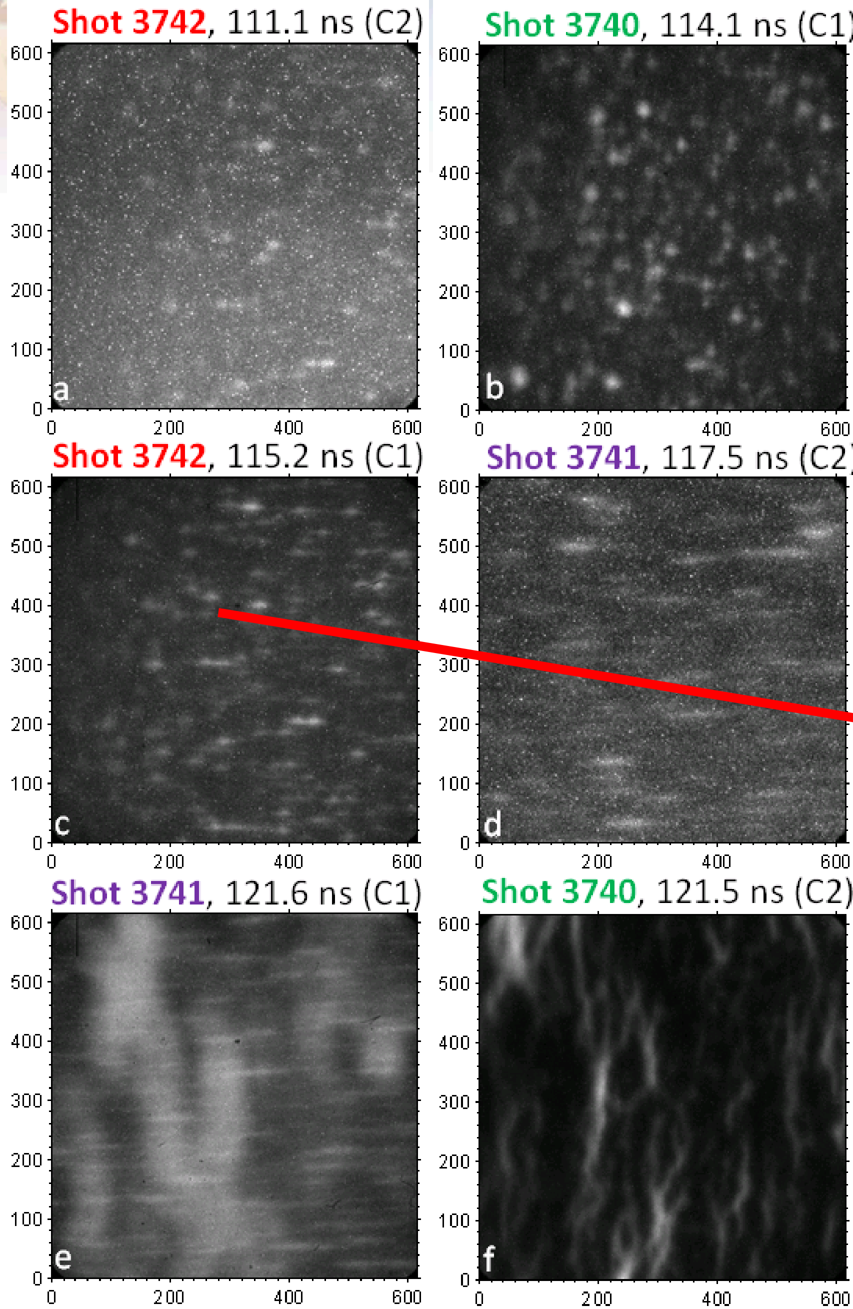
8,400 defects/mm² w/ 1<d<2.5 µm

200,000 defects/mm² with d<1 µm

Defects of scale ~5 µm may seed the observed spots

Sandia National Laboratories

Nonuniform self-emission from Al 6061 loads evolves rapidly

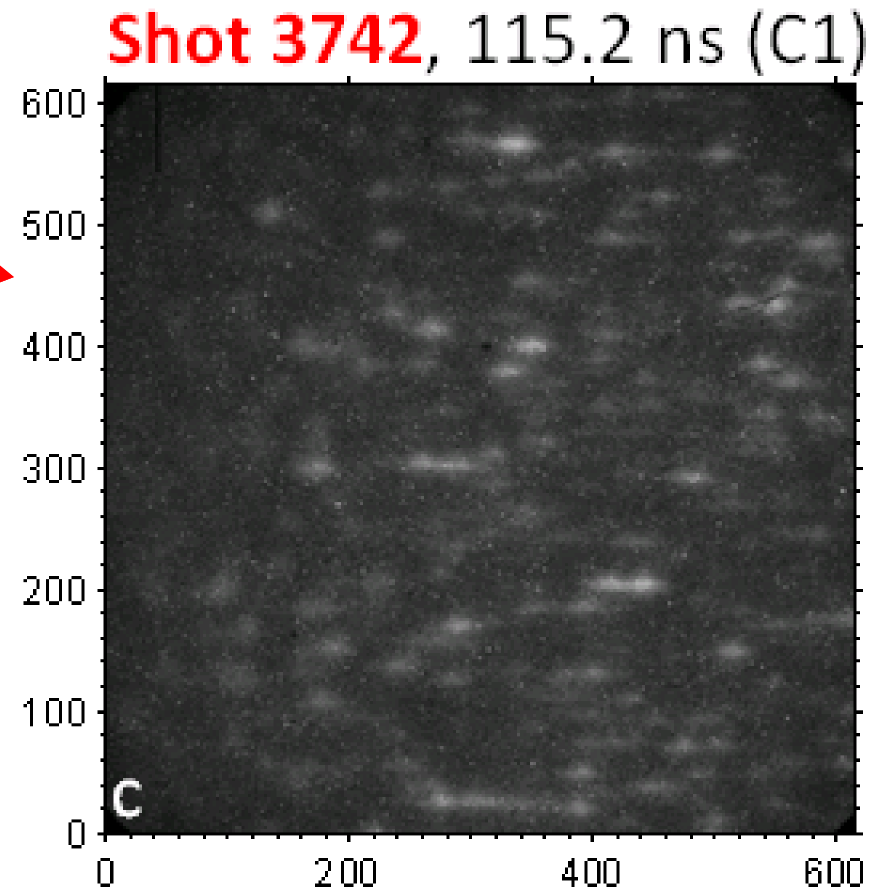


Axes in [μm]

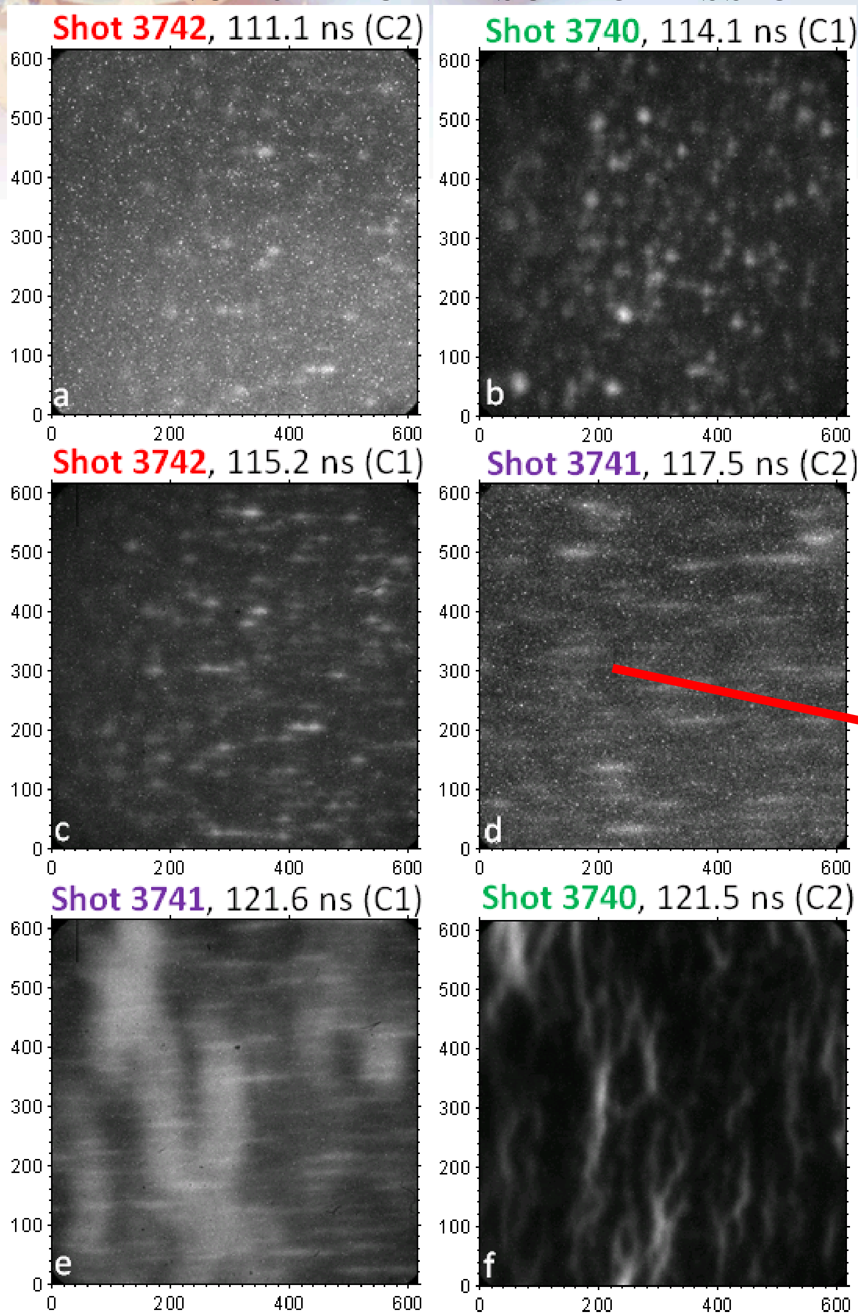
Surface Emissions evolve from discrete round spots to…

- Merging azimuthally elongated spots ($\partial\eta/\partial T>0$) at ~650 kA

What physics drives elongation?



Nonuniform self-emission from Al 6061 loads evolves rapidly

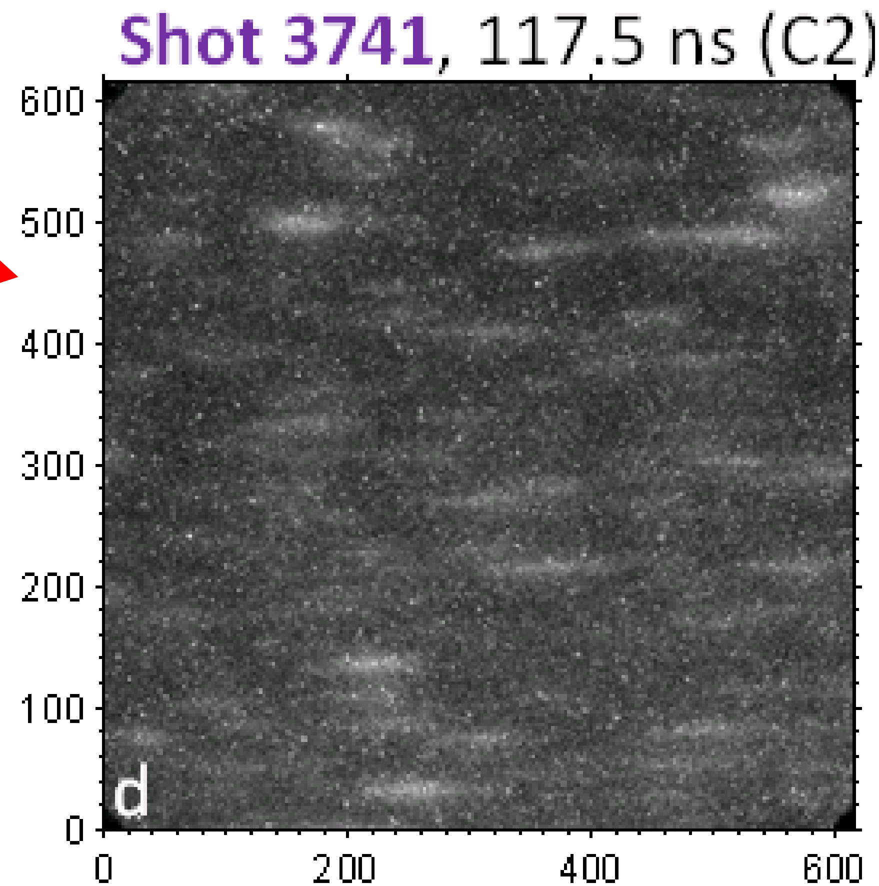


Axes in [μm]

Surface Emissions evolve from merging elongated spots to…

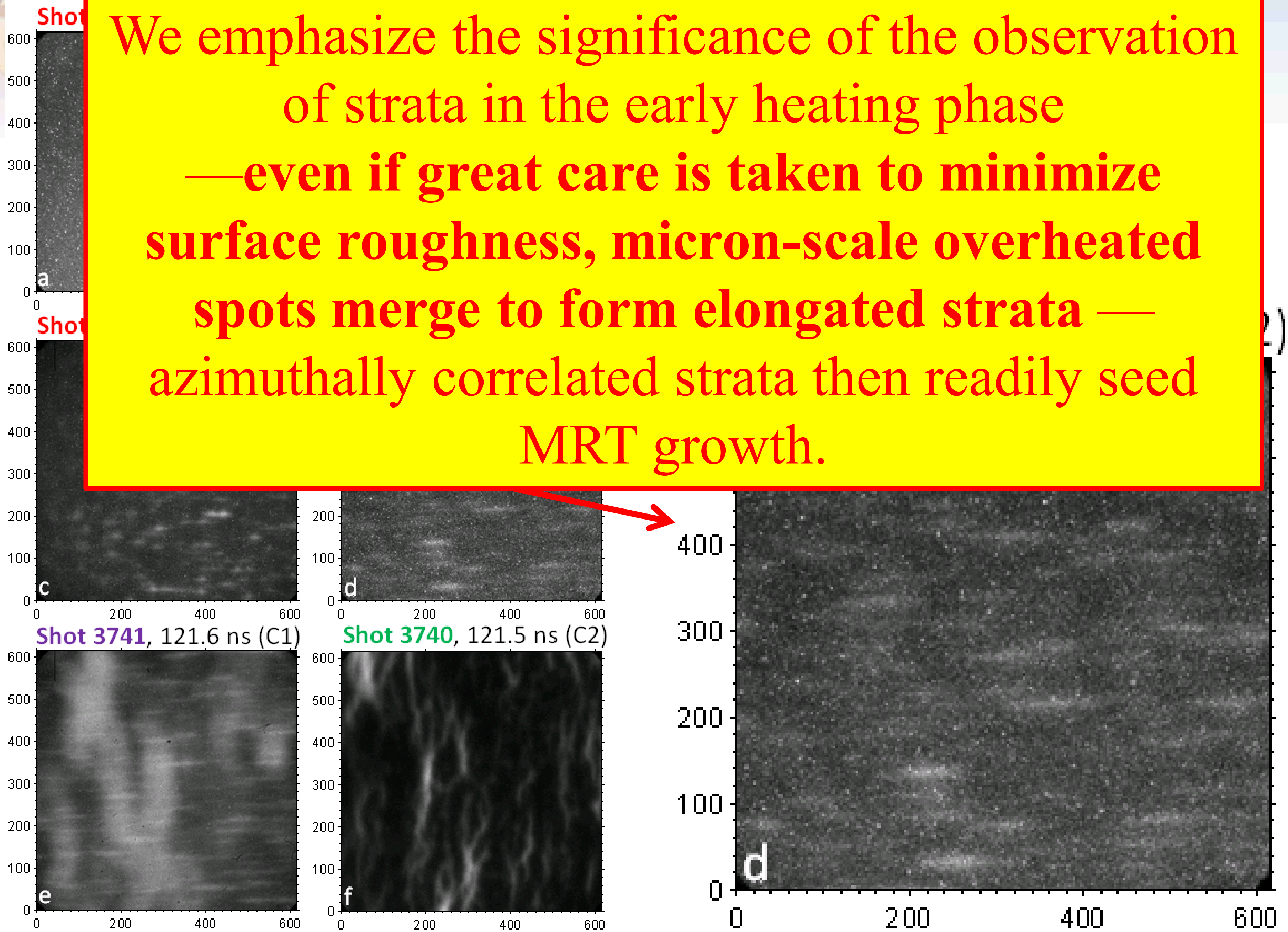
- Azimuthally elongated strata ($\partial\eta/\partial T>0$) at ~700 kA

What physics drives merging?



Nonuniform self-emission from Al 6061 loads evolves rapidly

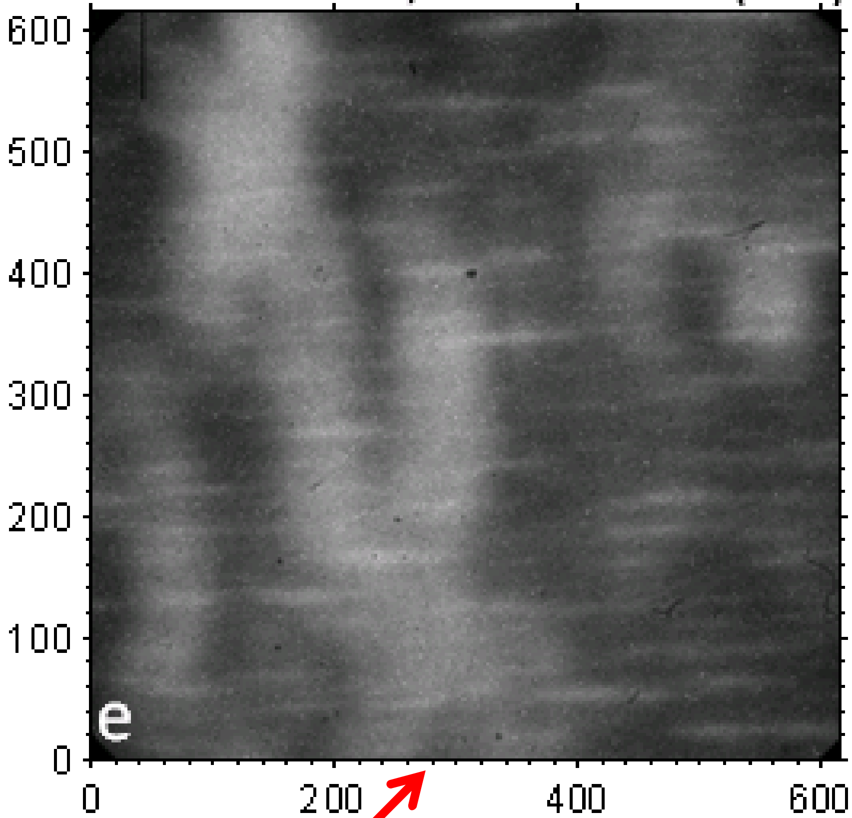
We emphasize the significance of the observation of strata in the early heating phase **—even if great care is taken to minimize surface roughness, micron-scale overheated spots merge to form elongated strata** — azimuthally correlated strata then readily seed MRT growth.



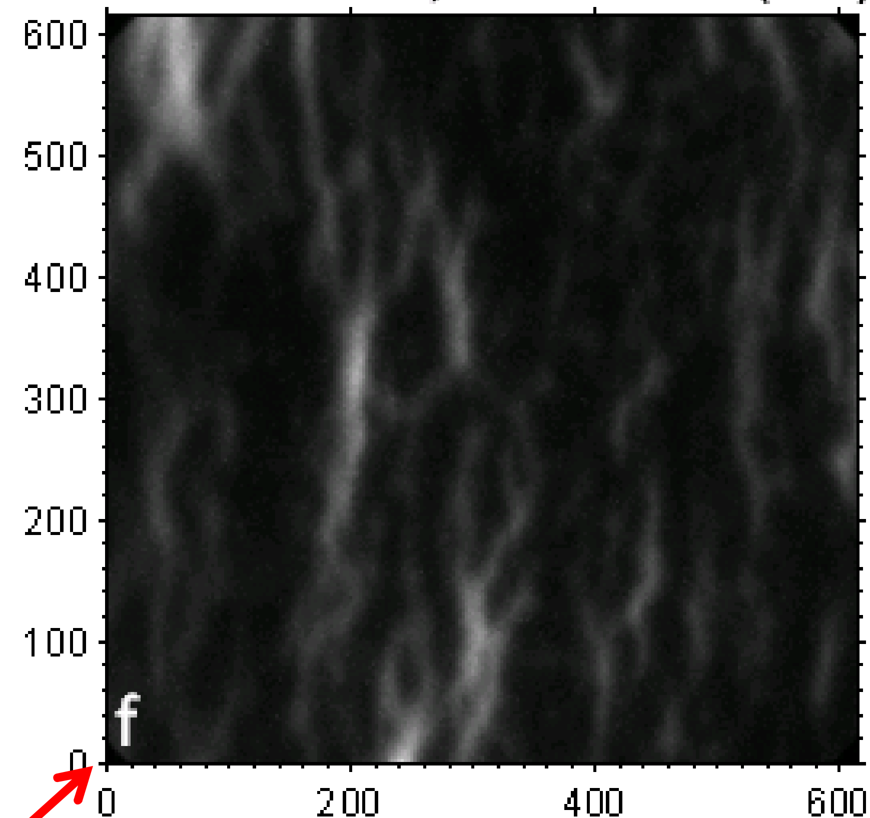
Axes in [μm]

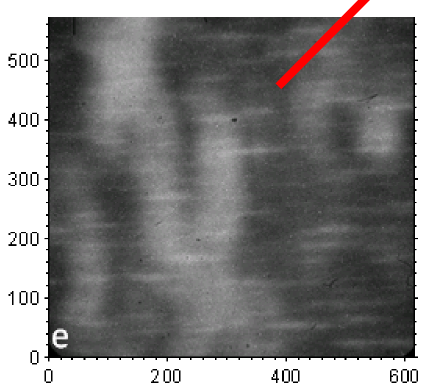
Nonuniform self-emission from Al 6061 loads evolves rapidly

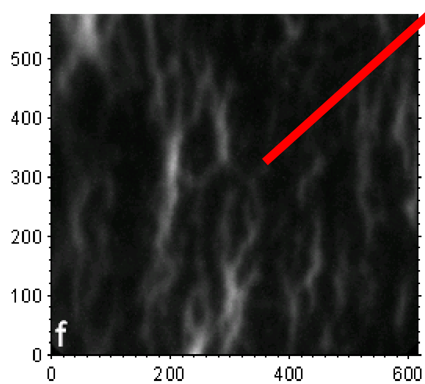
Shot 3741, 121.6 ns (C1)



Shot 3740, 121.5 ns (C2)







Axes in [μm]

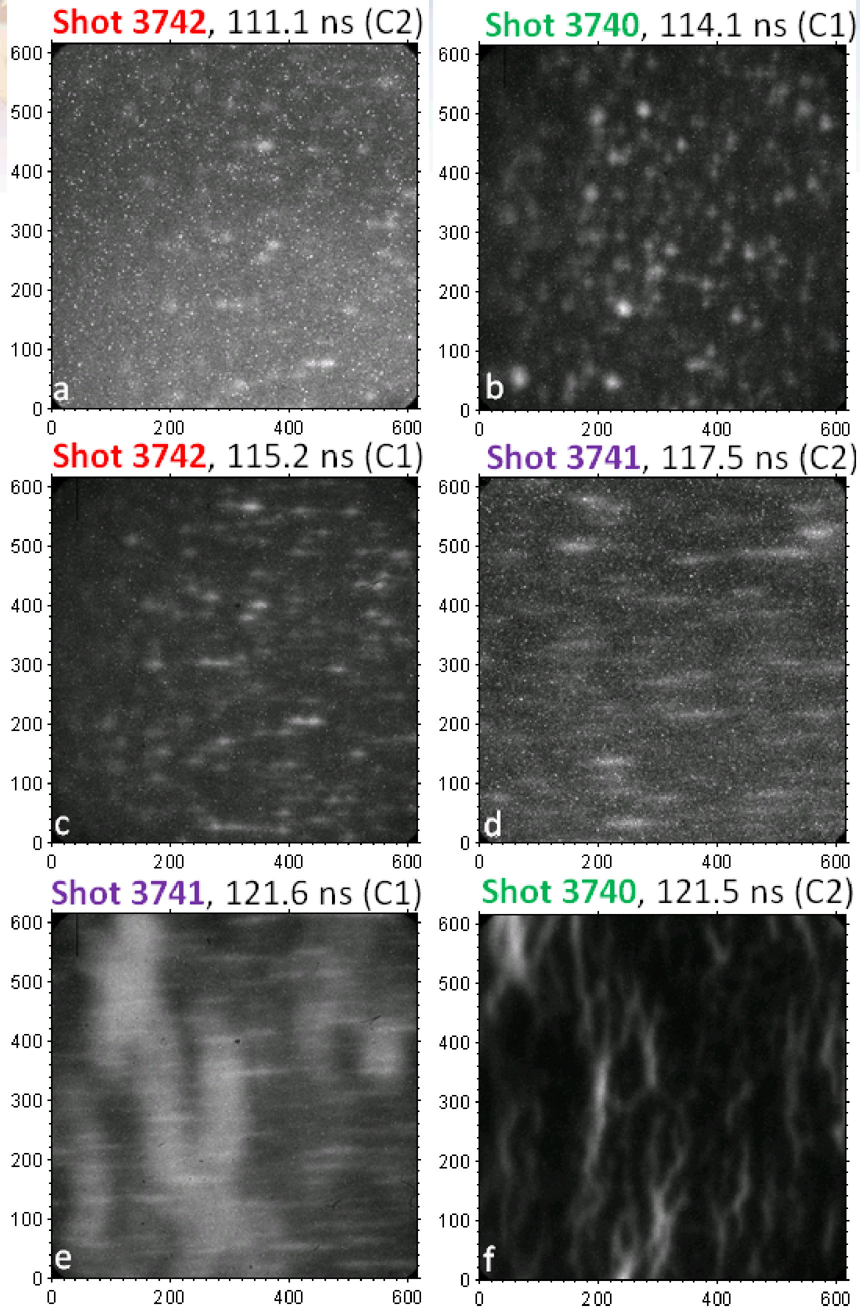
Surface Emissions evolve from strata

To…

- Vertical plasma filaments ($\partial\eta/\partial T<0$) at ~750 kA

How do filaments form and connect?

Nonuniform self-emission from Al 6061 loads evolves rapidly



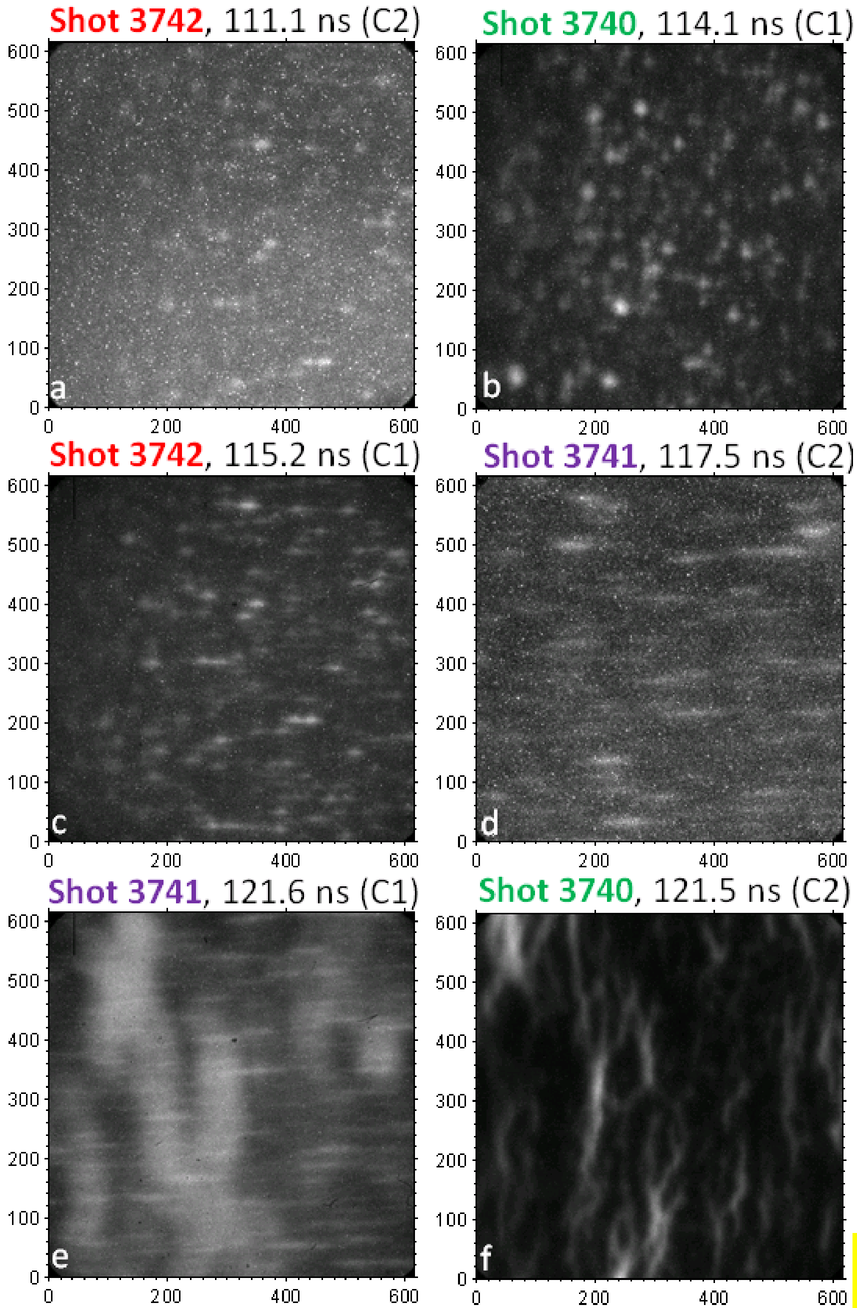
Axes in [μm]

Surface Emissions evolve from…

- Round Spots, to…
- Merging azimuthally elongated spots ($\partial\eta/\partial T>0$), to…
- Azimuthally elongated strata ($\partial\eta/\partial T>0$), to…
- Vertical plasma filaments ($\partial\eta/\partial T<0$)

Data provide a wealth of new information, yet the detailed physics is not fully understood.
This motivates future study!

Nonuniform emissions from CM and EP Al 6061 loads evolves rapidly



Axes in [μm]

Surface Emissions evolve from…

- Round Spots

To…

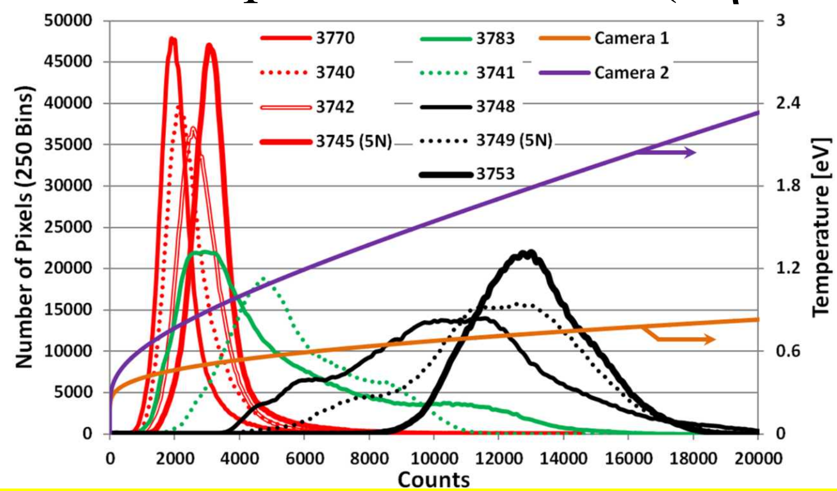
- Merging azimuthally elongated spots ($\partial\eta/\partial T>0$)

To…

- Azimuthally elongated strata ($\partial\eta/\partial T>0$)

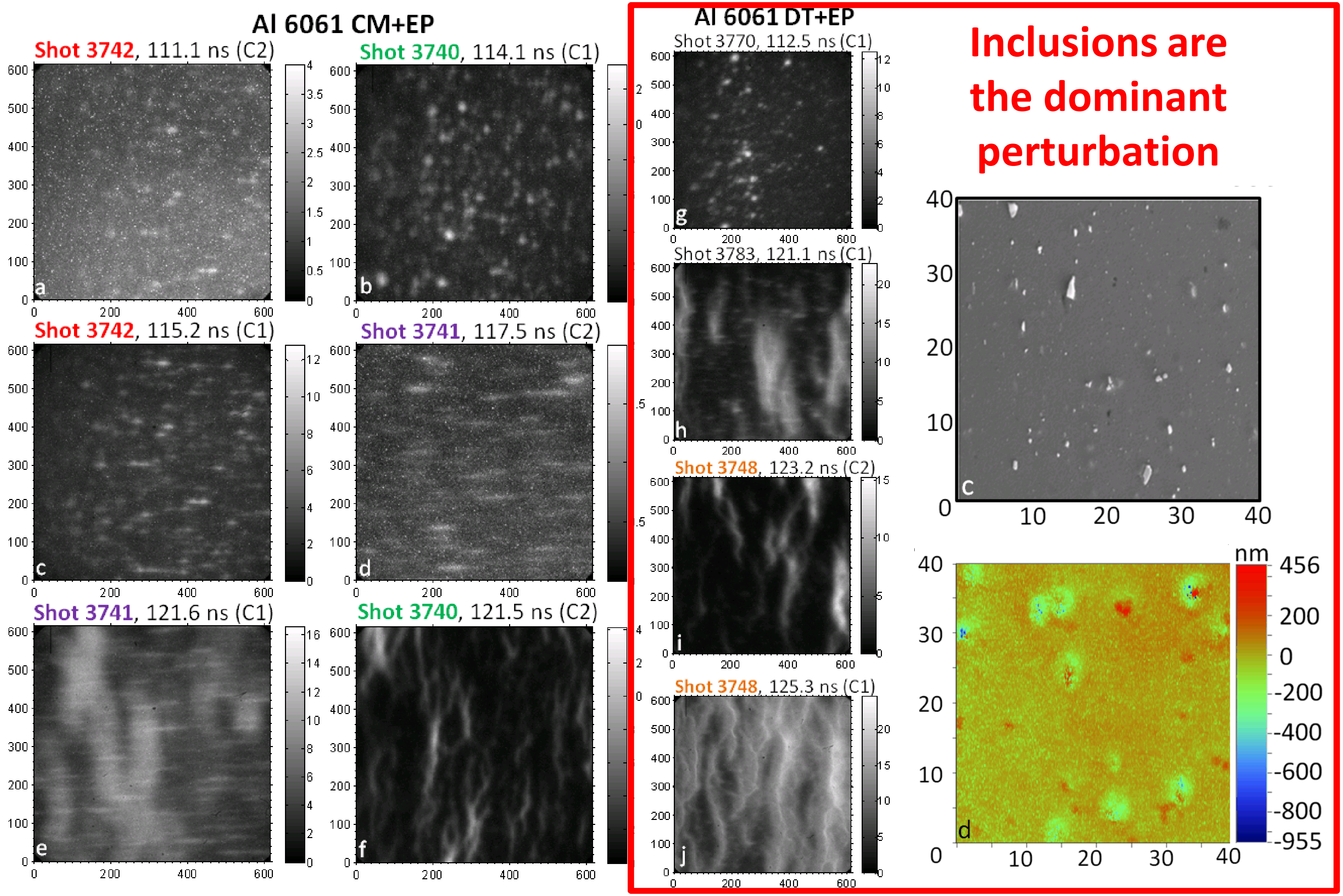
To…

- Vertical plasma filaments ($\partial\eta/\partial T<0$)



Filaments are brighter than strata→strata are brighter than spots→spots are brighter than background

Diamond turned + EP and conventionally machined + EP Al 6061 rods evolve is a similar manner…



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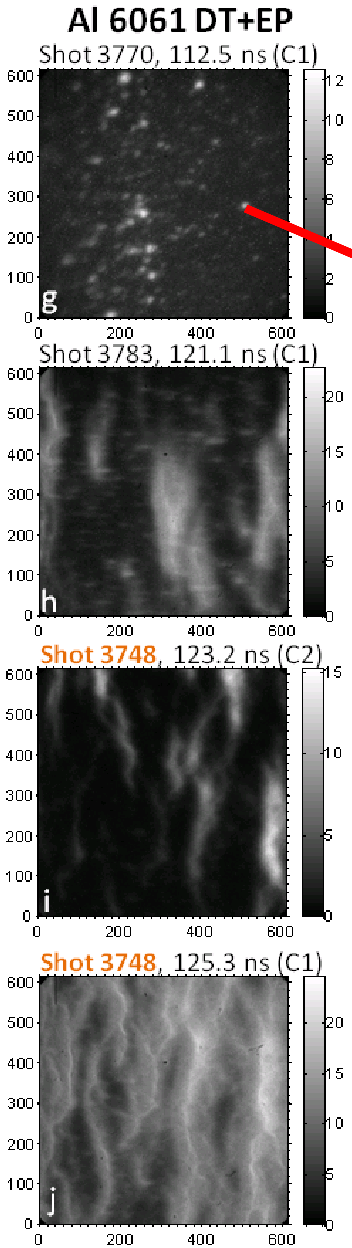
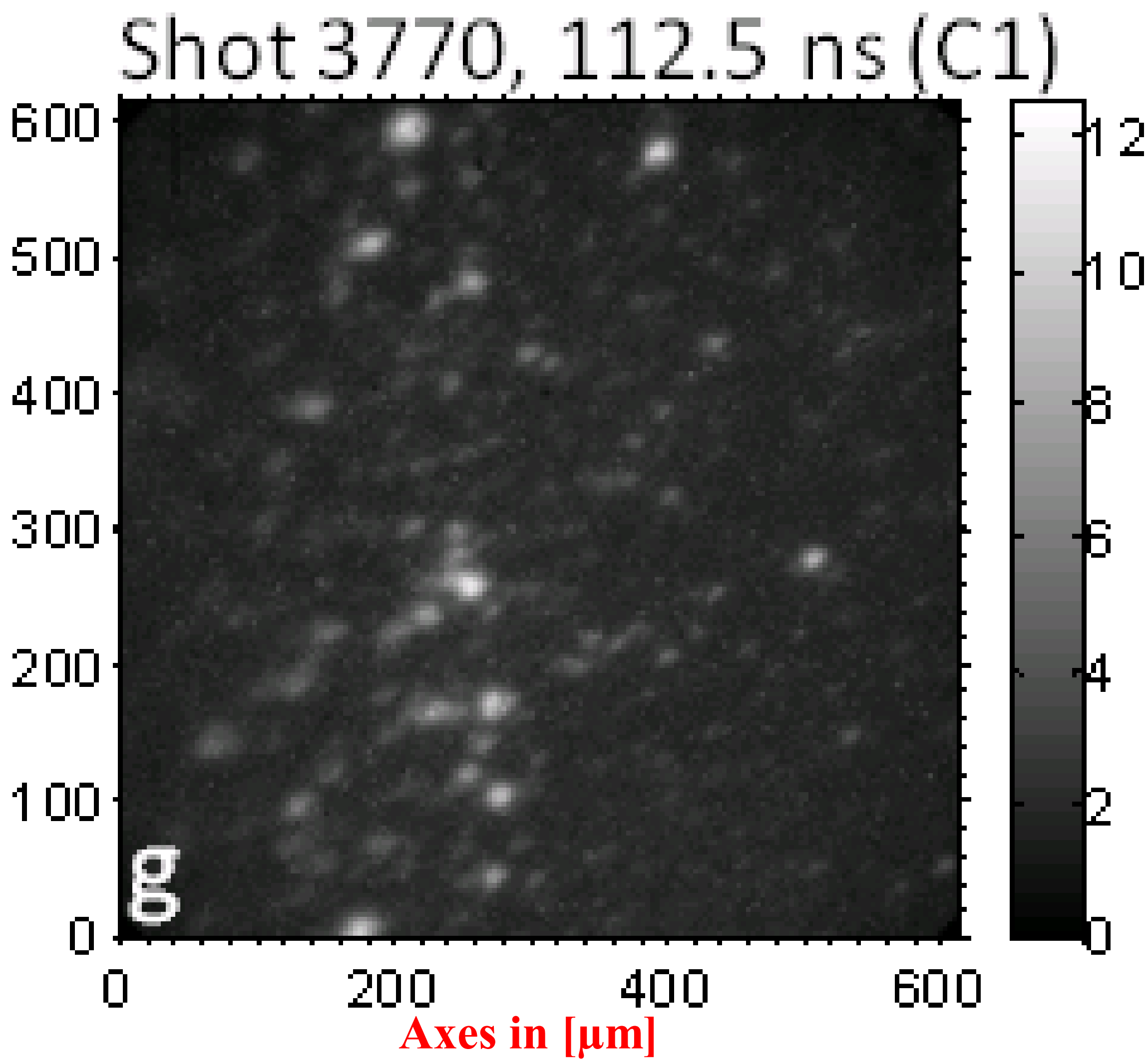
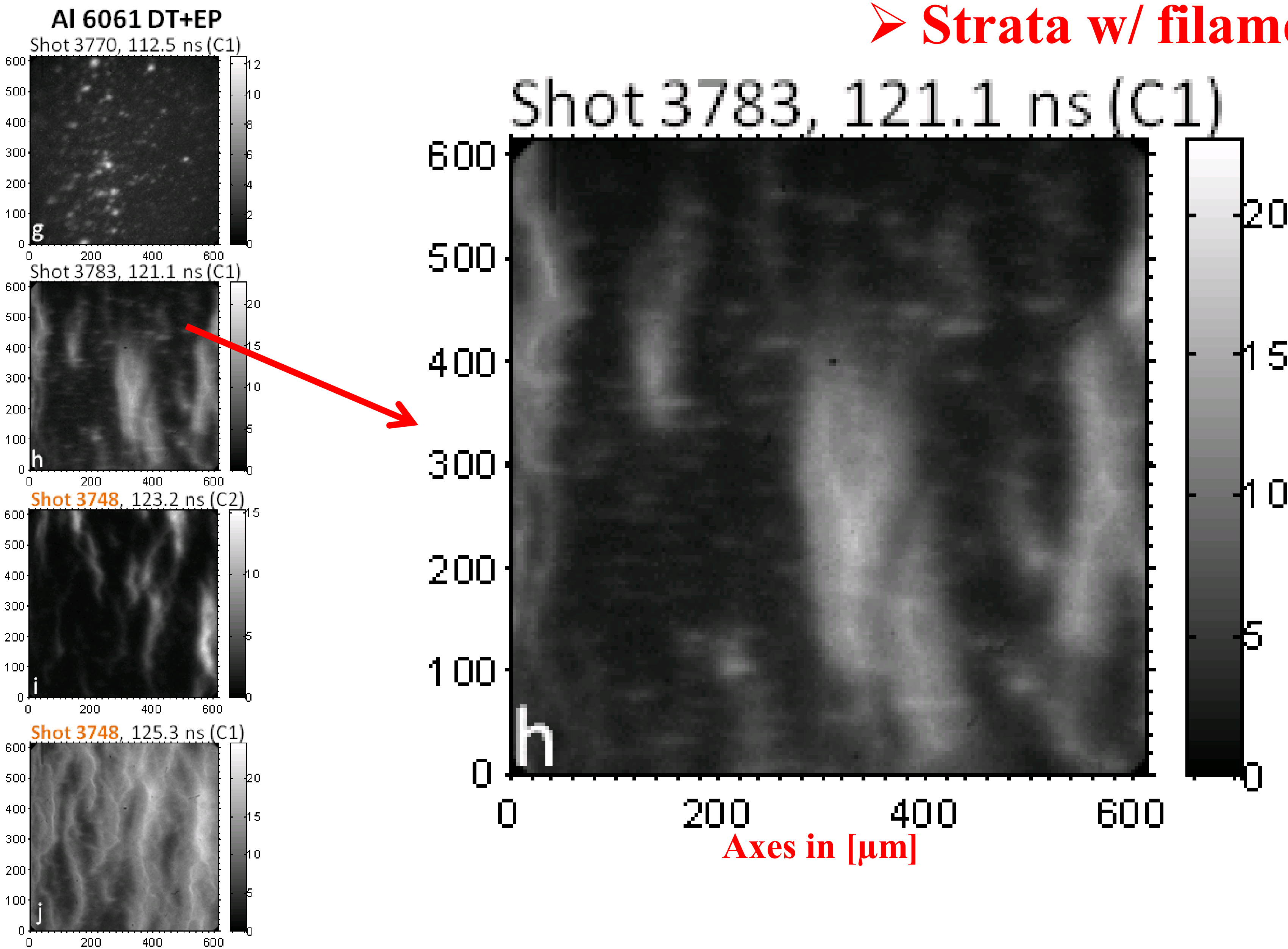


- **Round Spots**



Diamond turned + EP and conventionally machined + EP Al 6061 rods evolve is a similar manner…

- **Strata w/ filaments**



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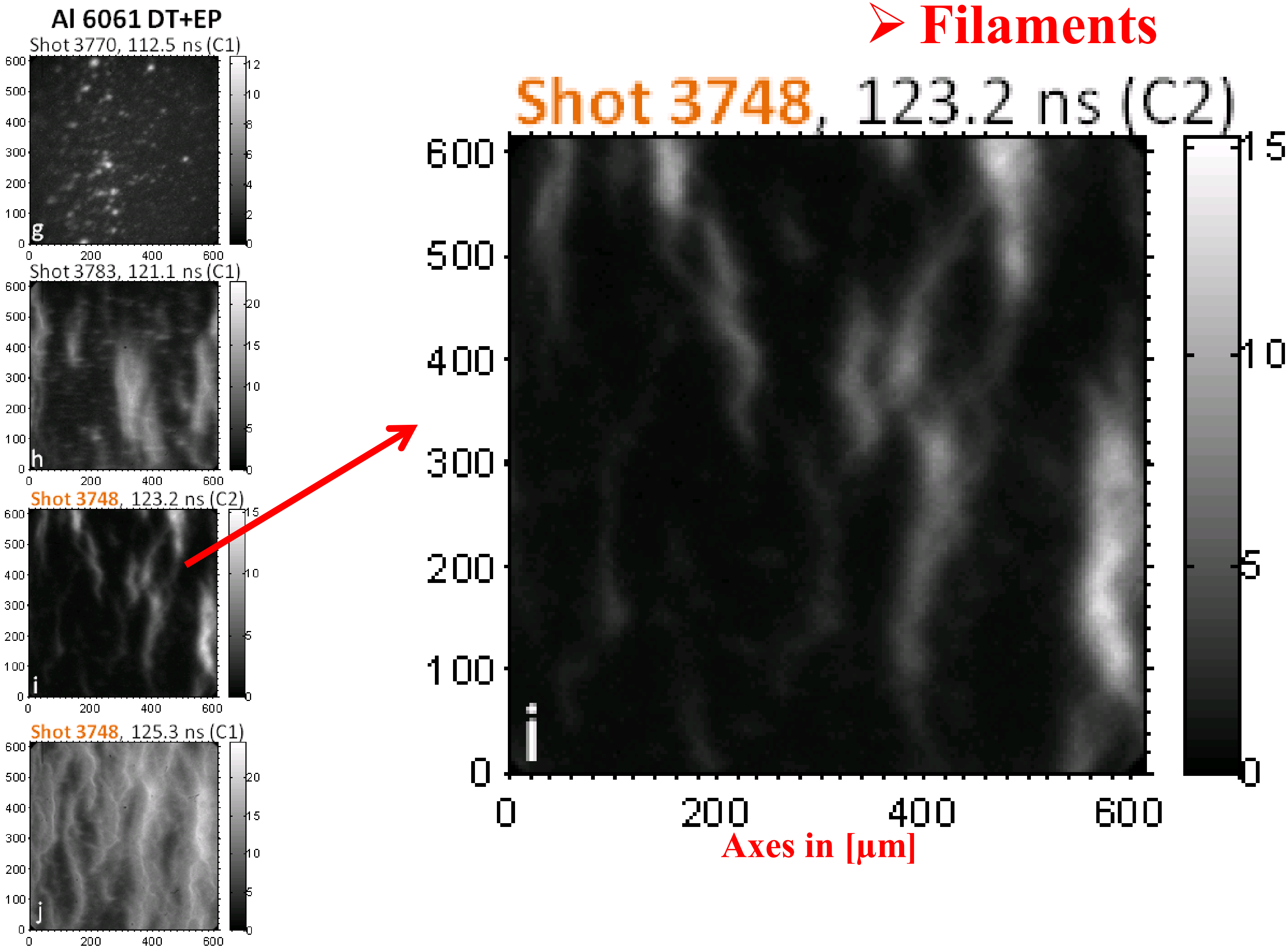
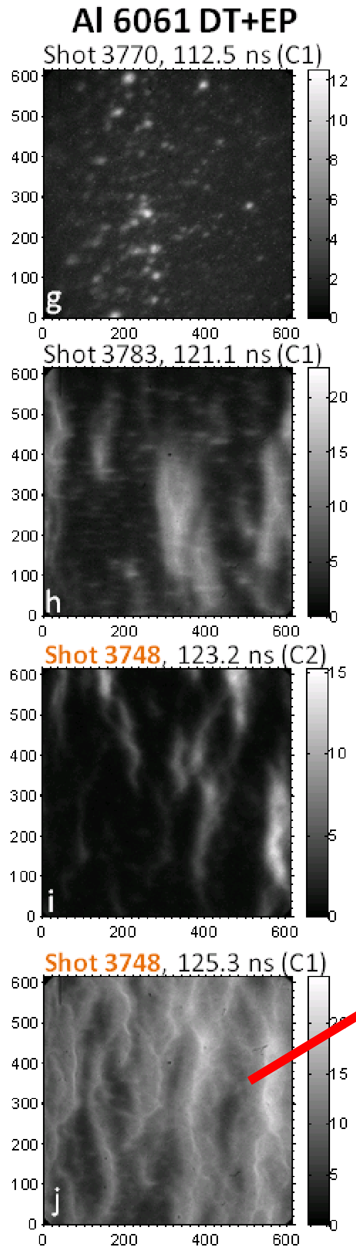
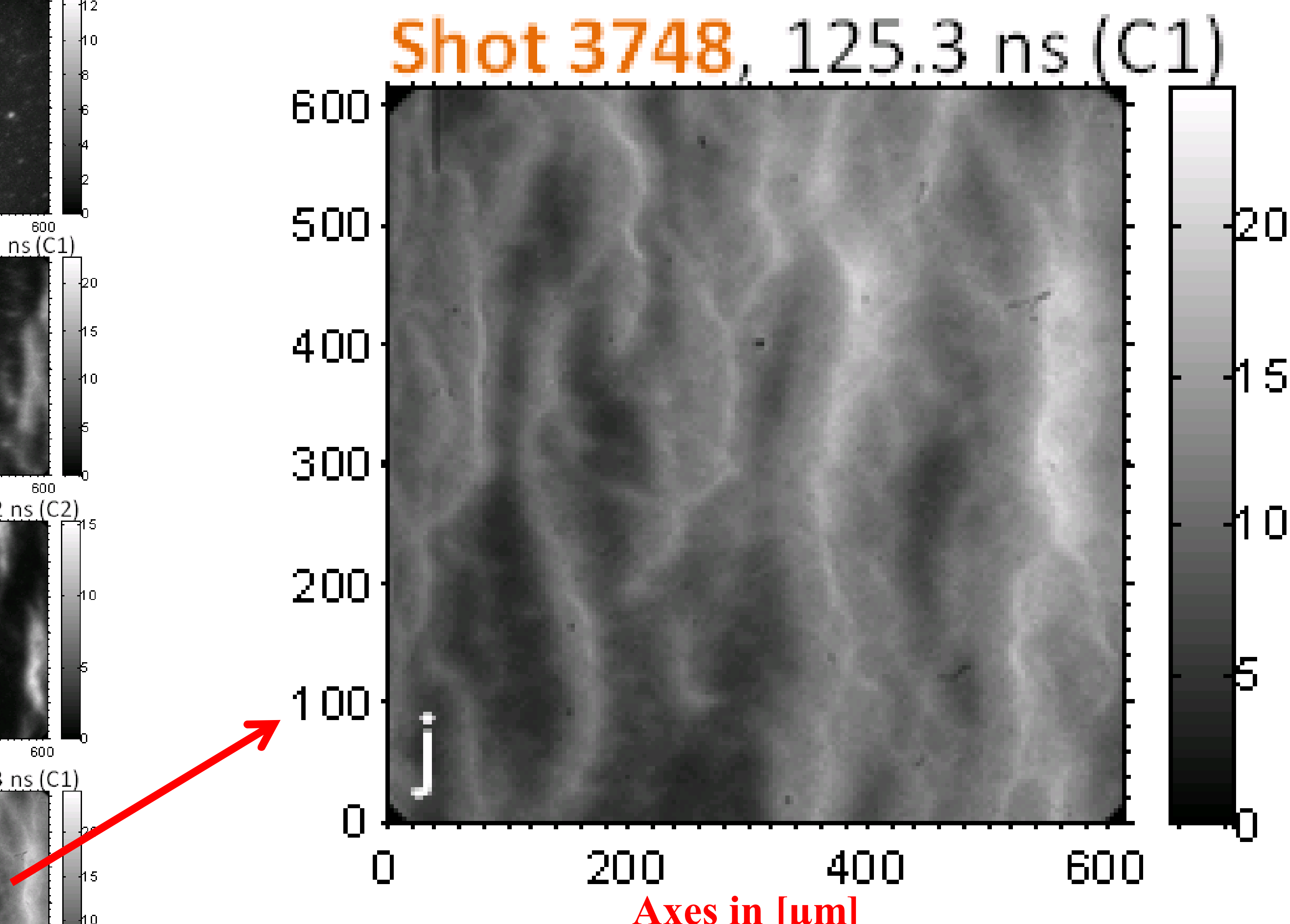


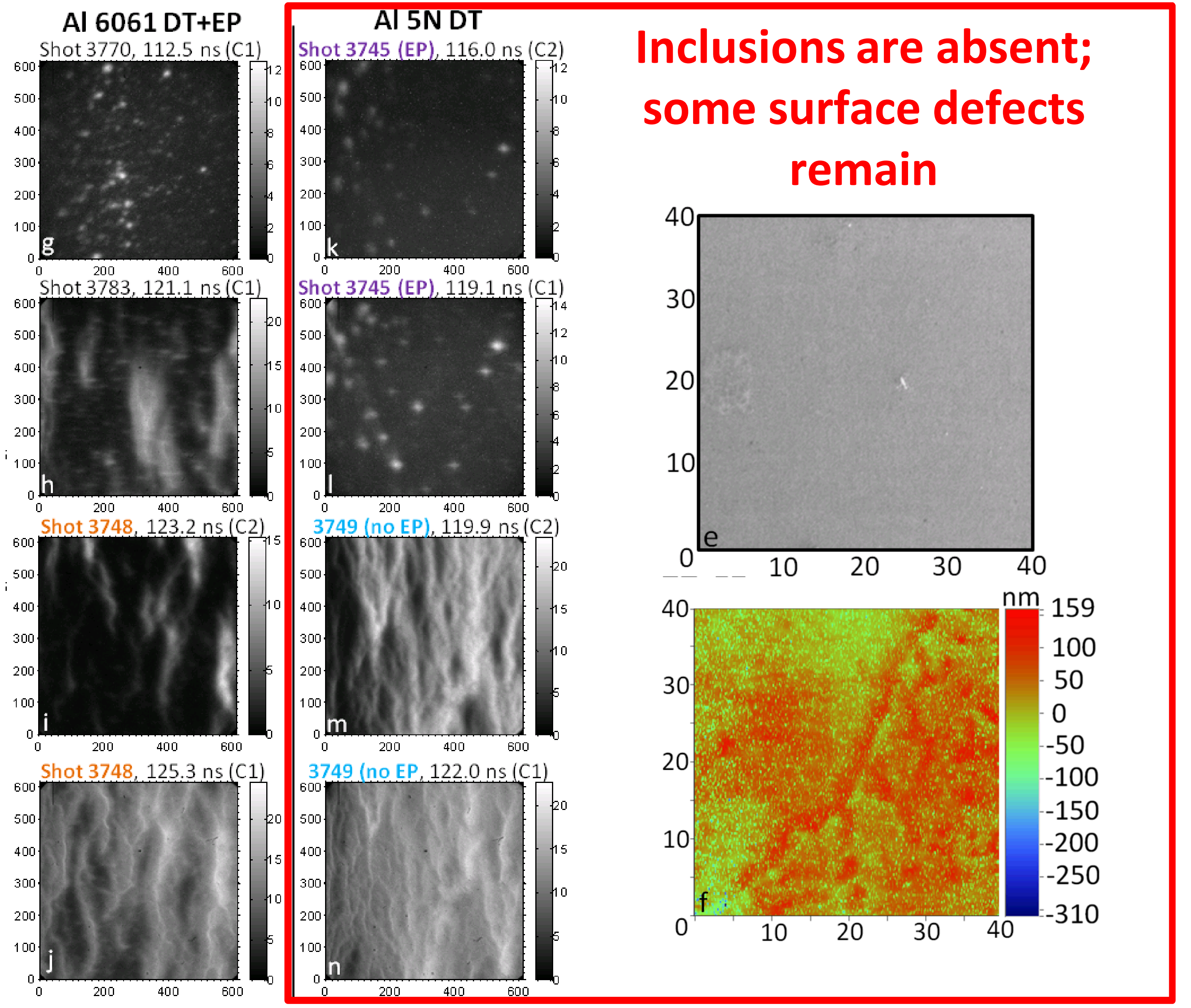
Diamond turned + EP and conventionally machined + EP Al 6061 rods evolve is a similar manner…



➢ Sharp filaments



Al 5N rods (which contain no inclusions) form fewer spots, and strata formation is not observed



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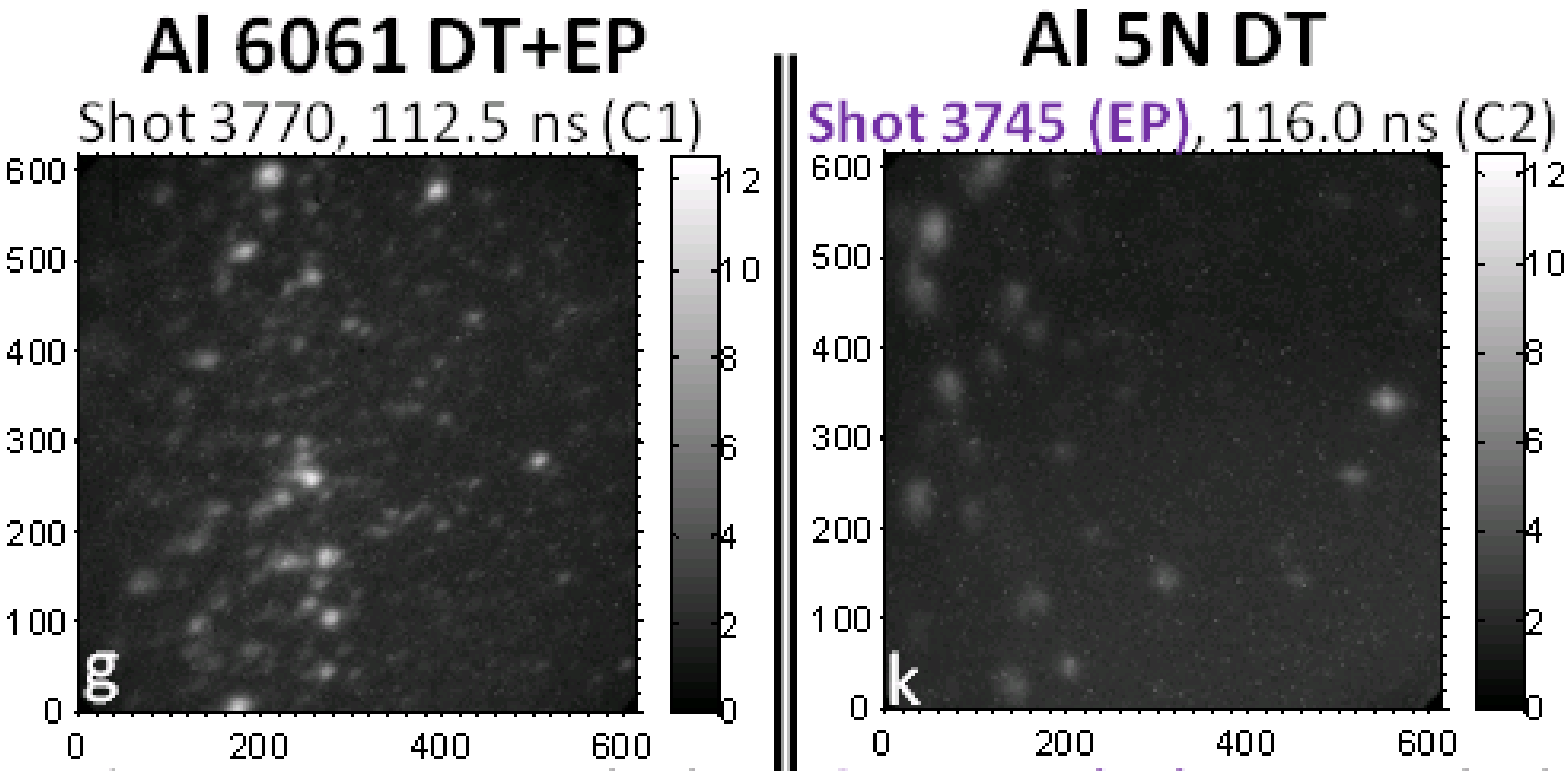
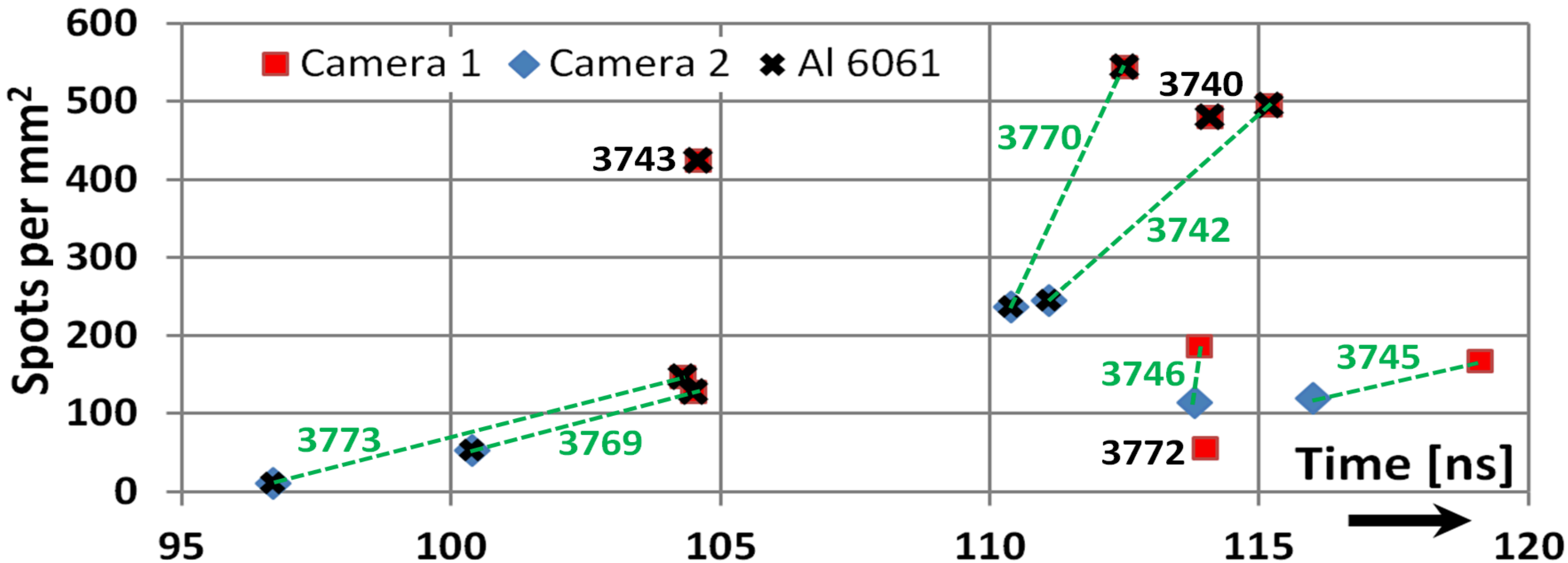
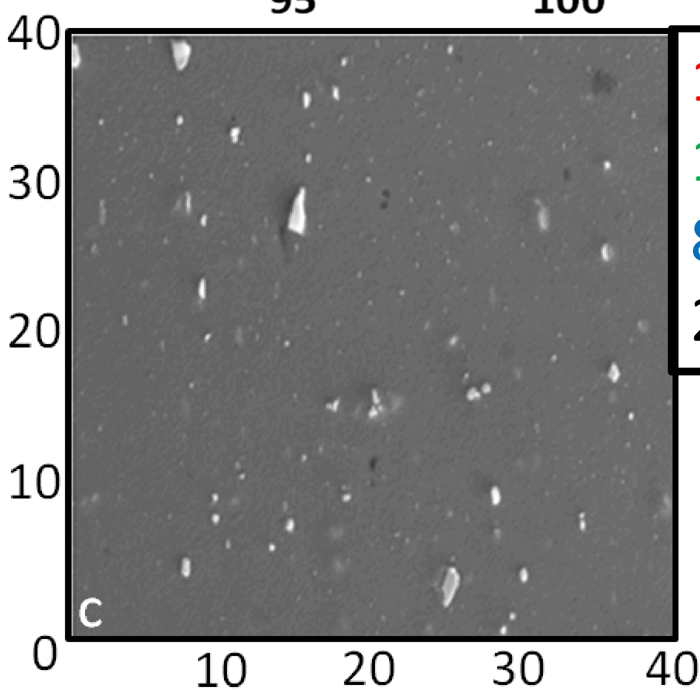


The number of spots increases with time (current), and there are 2-9 times more spots/mm^2 for Al 6061 than for Al 5N





100 defects/mm^2 w/ d>5 μm

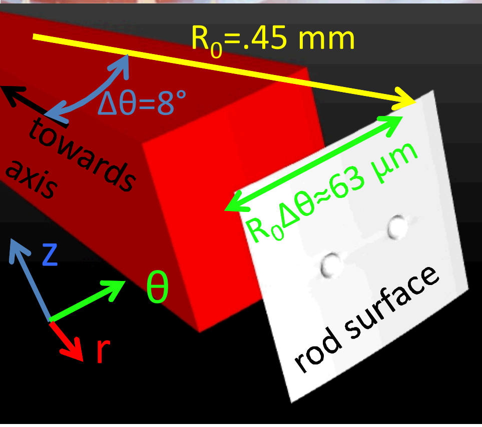
1,800 defects/mm^2 w/ 2.5<d<5 μm

8,400 defects/mm^2 w/ 1<d<2.5 μm

200,000 defects/mm^2 with d<1 μm

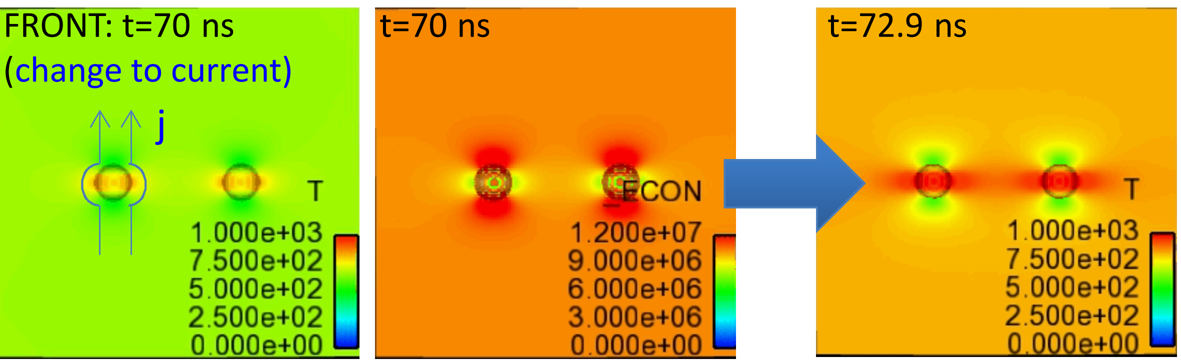
Defects of scale ~5 μm may seed the observed spots

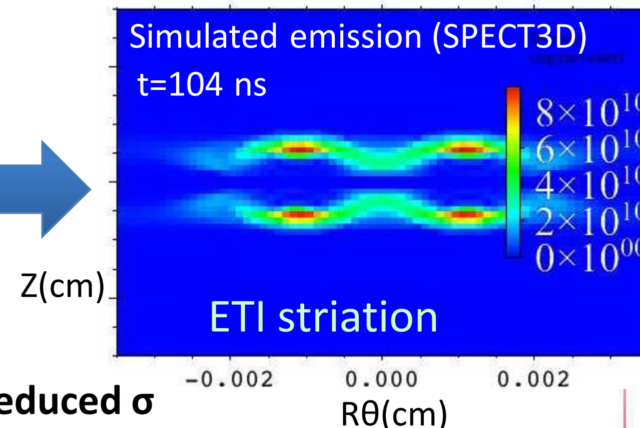
3D MHD simulations of simplified, localized perturbations (pits & ↑η inclusions) illustrate for the first time how global ETI structures form



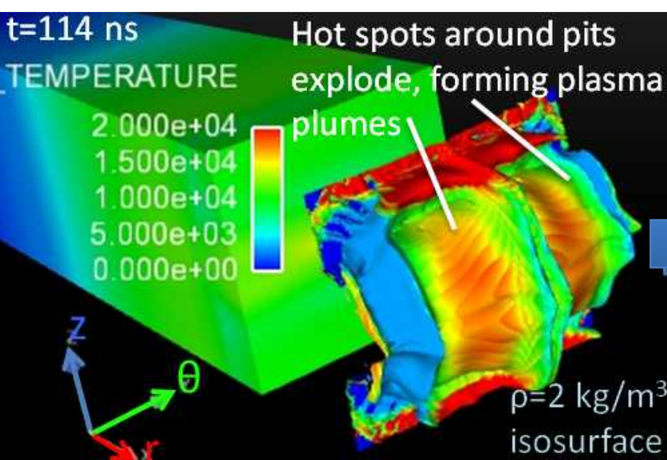
Simulations detail how current redistribution drives ETI

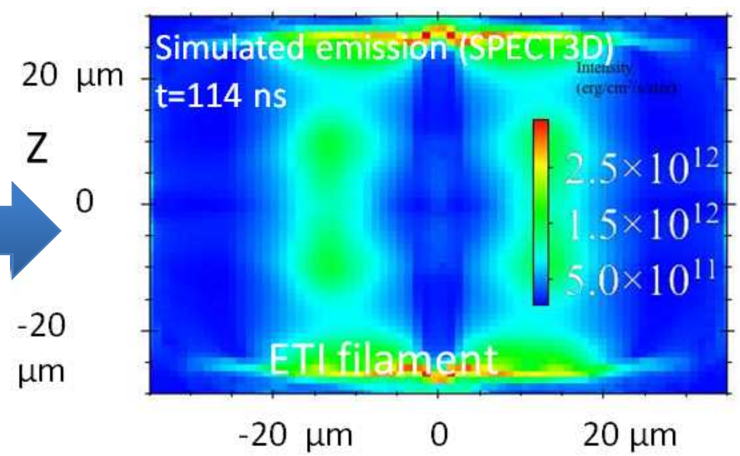
Isolated pits merge to form striations





Current bends around pit, driving enhanced J^2/σ and T at edge, and reduced σ there, effectively widening the separate perturbations until they correlate in T.



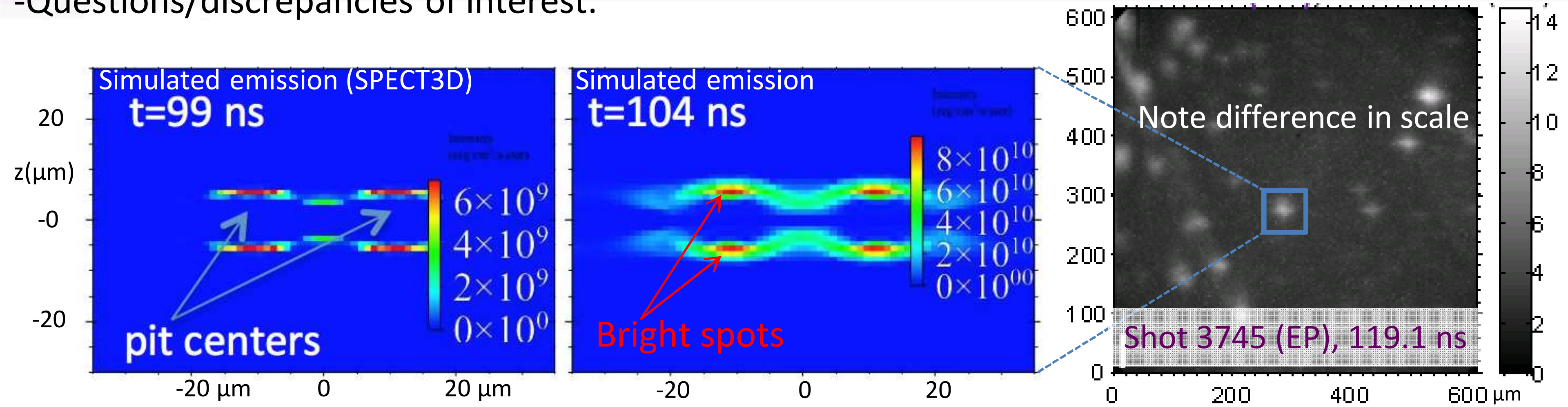


Plumes expand axially, forming ETI filaments.

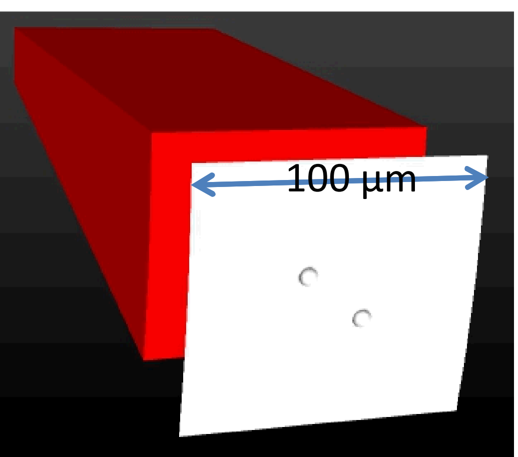
Proposed experiment will allow *quantitative* comparison with simulation

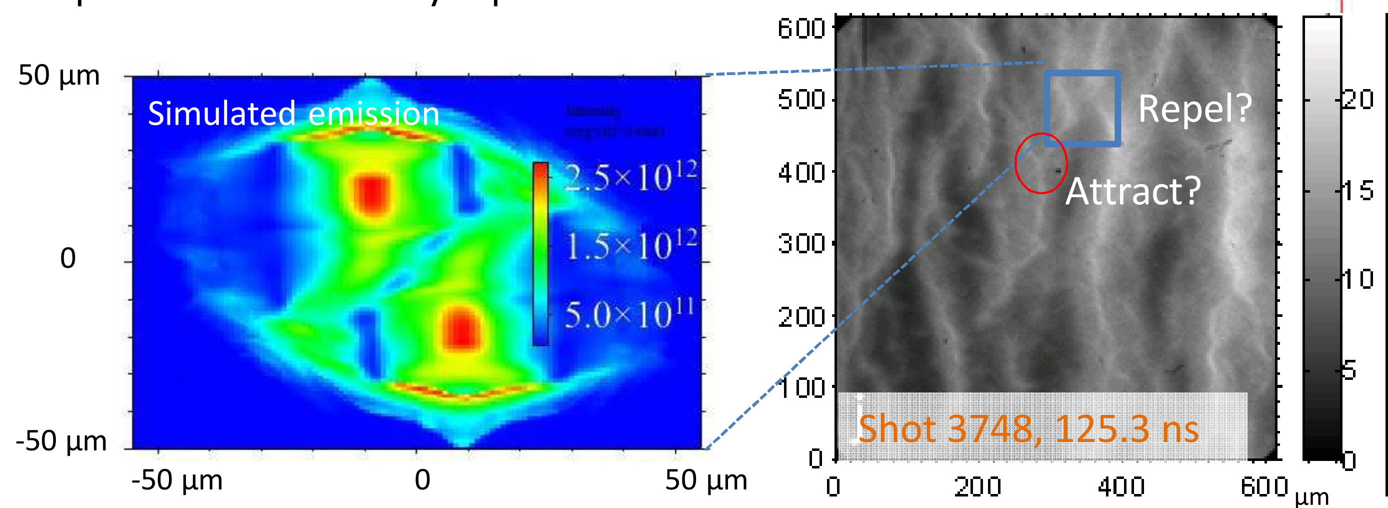
-Previous comparison with data was qualitative, due to uncertainties in impurity distribution and composition. Now consider pre-machined perturbations, larger than the imager resolution limit

-Questions/discrepancies of interest:



- In simulation, bright spots appear in pairs above/below a pit, whereas data shows individual bright spots. Is this due to time/space resolution limitations, or is hot spot evolution really different?
- In 2 adjacent pits, do simulations capture timing and qualitative features of azimuthal correlation?
- How do filaments from different pits interact? Do they repel?





Summary of experimental results

- MRT on imploding liners is larger amplitude and more azimuthally correlated than expected. Changing the orientation of machining grooves does little; early ETI growth may explain these observations
- Dielectric coatings greatly reduced cumulative MRT growth, likely through tamping ETI mass redistribution; ETI is **NOT** directly observed
- Earliest nonuniform emission is from spots. The number of spots is comparable to the number of micron scale inclusions
- Non-uniform Joule heating progresses from discrete round spots, to elongated merging spots, to azimuthally correlated strata; such observations can be explained by ETI-related current redistribution.

Future work: Study electrothermal instability (ETI) growth from z-pinches with engineered defects

Start with "blank canvas"

- Single crystal Al
- DT+EP to Ra<50 nm
- Add engineered defects

Emphasis is placed on the development of greatly advanced computational tools for the accurate modeling of ETI