Direct observation of electrothermal instability structures on intensely Ohmically heated Al with current flowing in a surface skin layer

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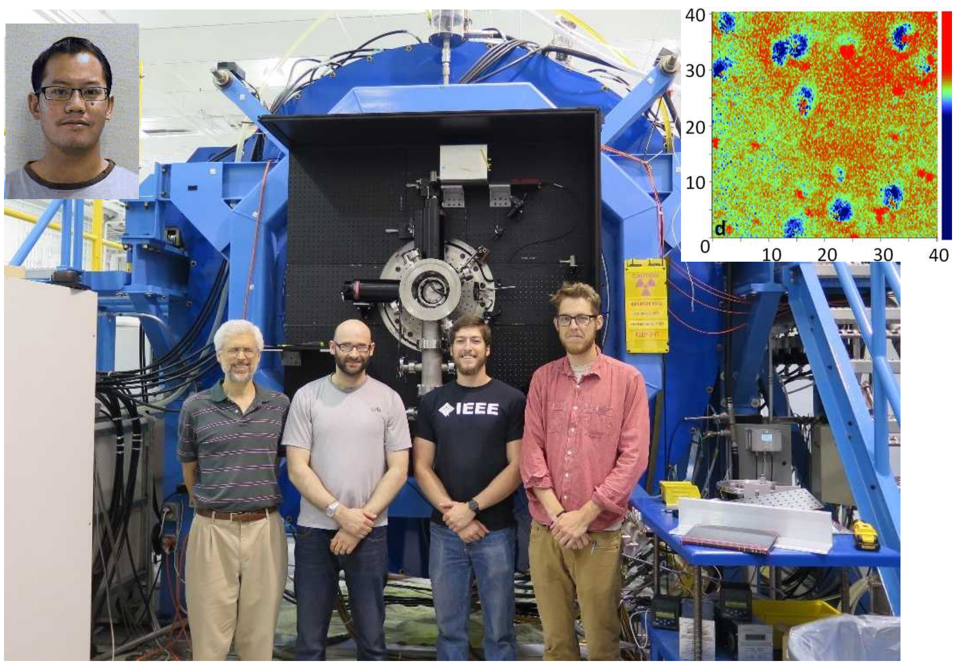

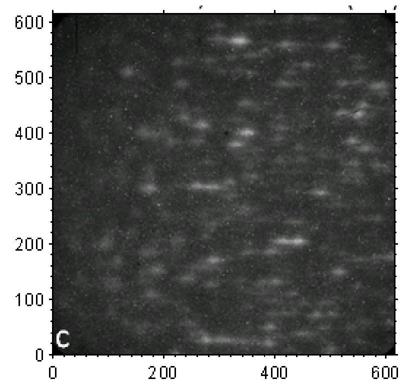

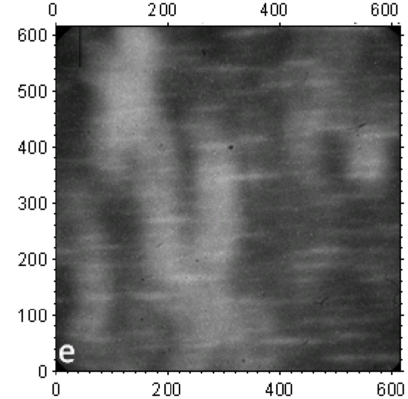

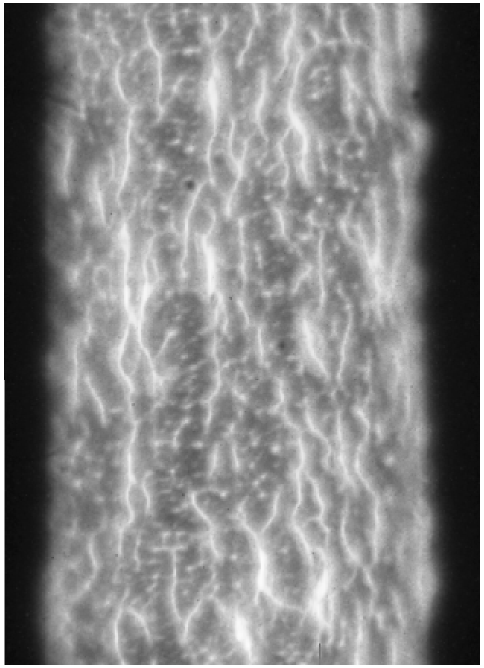

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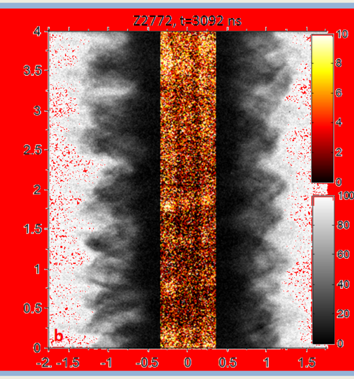
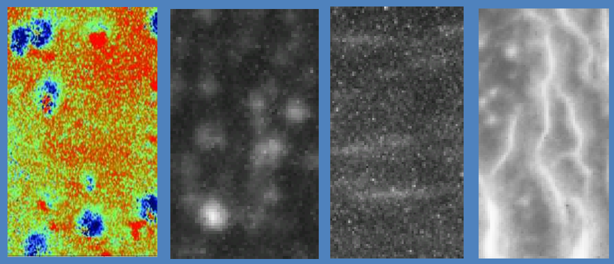
How does nonuniform Joule heating impact MRT instability growth in magnetically driven implosions?

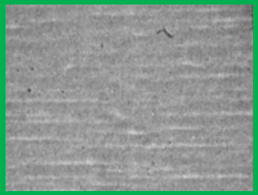
- **Why are we motivated to study nonuniform early heating of Z pinch liners and rods?**
  - → *What seeds the magneto Rayleigh-Taylor instability?*
  - → *Overview of recent electrothermal instability (ETI) research on Z*



- **What drives non-uniform Joule Heating?**
  - → *Non uniform overheating at locations of resistive inclusions*
  - → *Merging into stratified overheat structures*
  - → *Plasma filament formation*



- **ETI evolution on dielectric coated rods**
  - → *Surface tamping mitigates surface plasma formation, enabling detailed study of ETI*

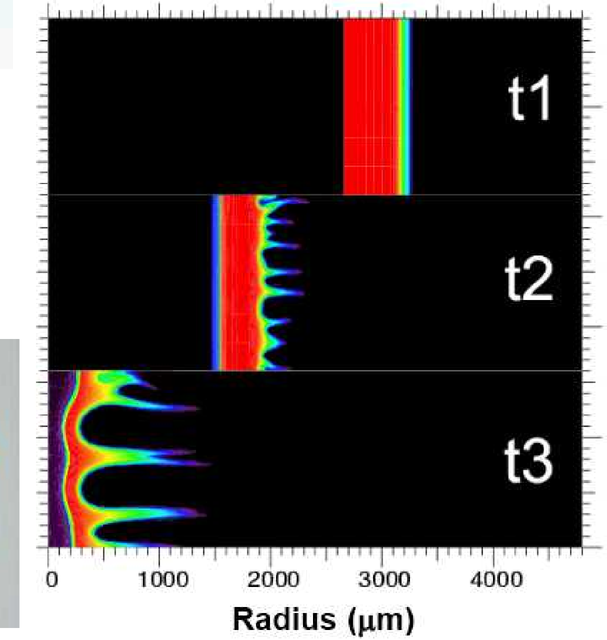


- **Connecting experiment and simulation through studies of "engineered defects"**
- **ETI evolution in the presence of strong axial magnetic field**

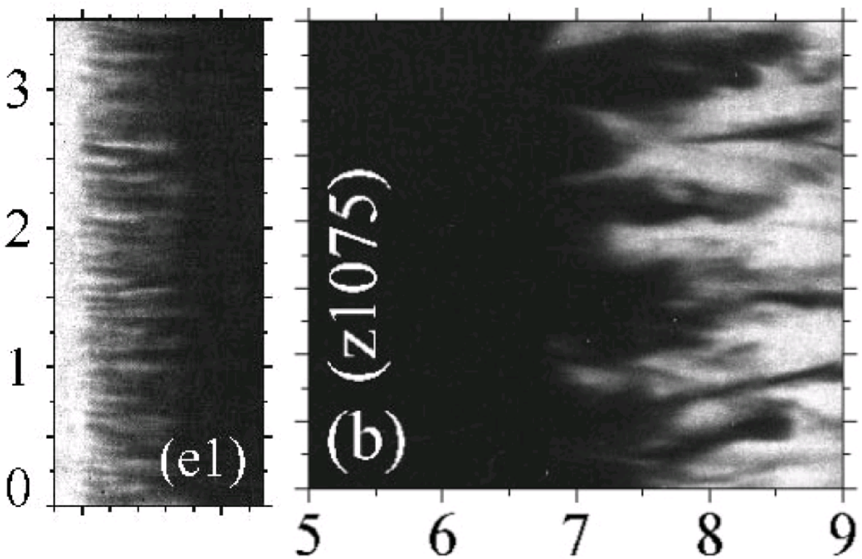
Since the 1950s, much z-pinch research has been rooted in understanding and mitigating MHD instabilities

The integrity magnetically-driven Z pinches is compromised by the magneto-Rayleigh Taylor (MRT) instability

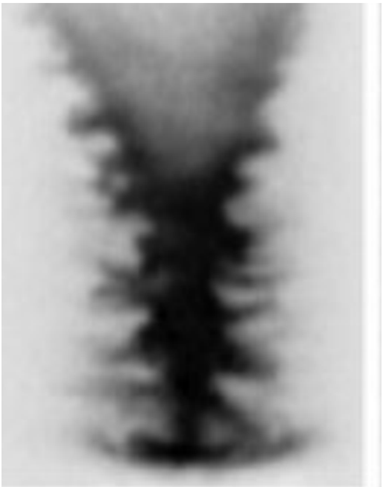
- Like the classical hydrodynamic Rayleigh-Taylor instability, when a heavy fluid (z-pinch) is accelerated by a light fluid (magnetic field), the system is unstable



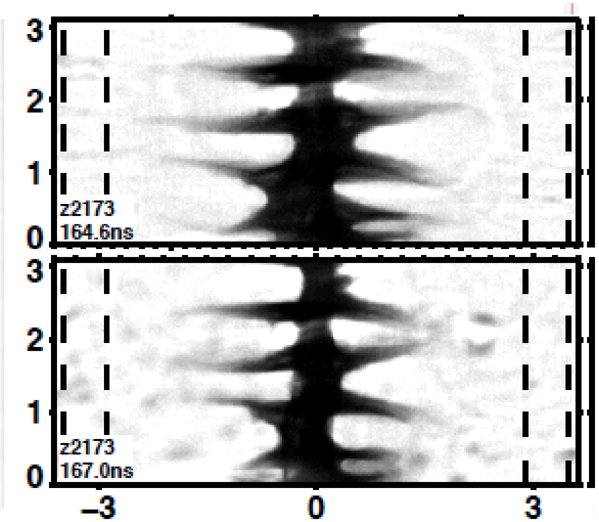
- Azimuthally correlated modes grow exponentially
- Short wavelengths saturated, while longer wavelengths persists



Wire Array, Sinars et al., 2005

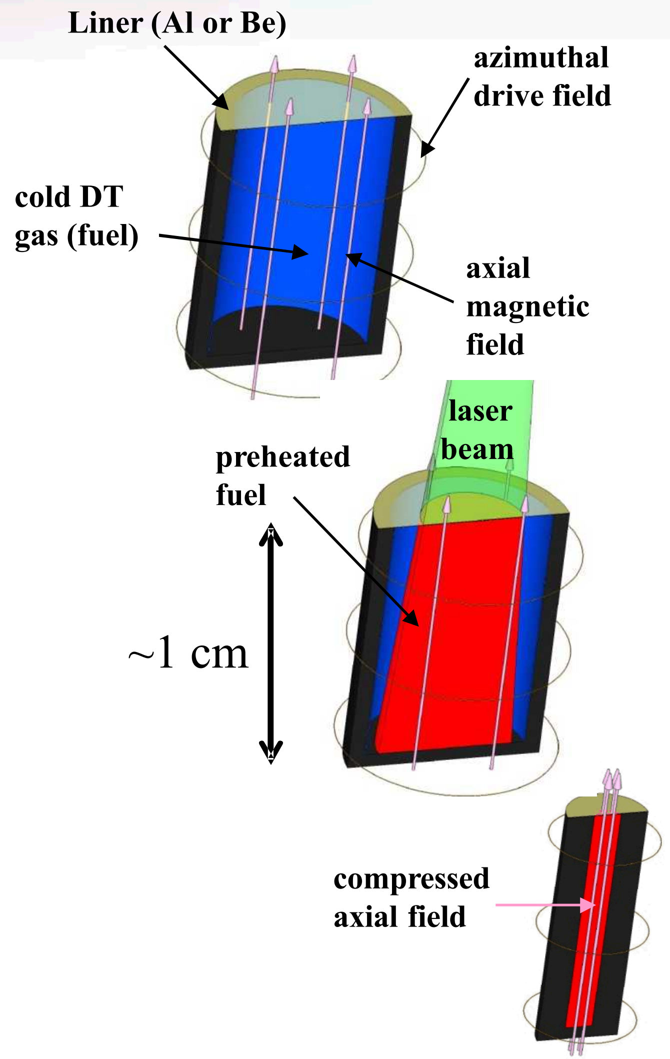


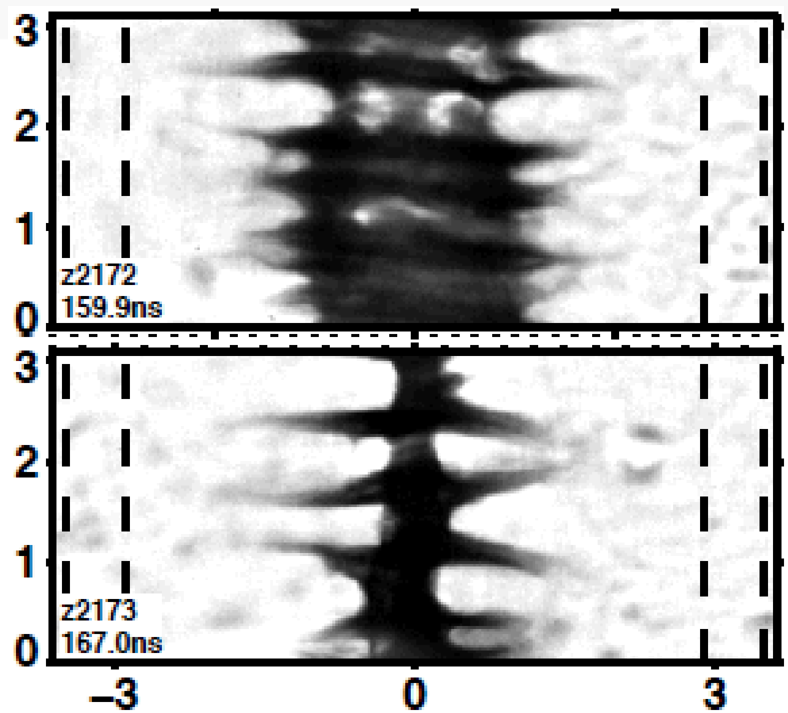
Gas Puff, B. Kuai et al., 2009



Liner, R.D. McBride *et al.*, 2012

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



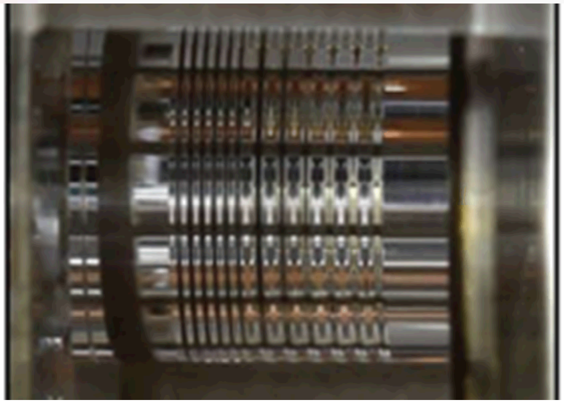


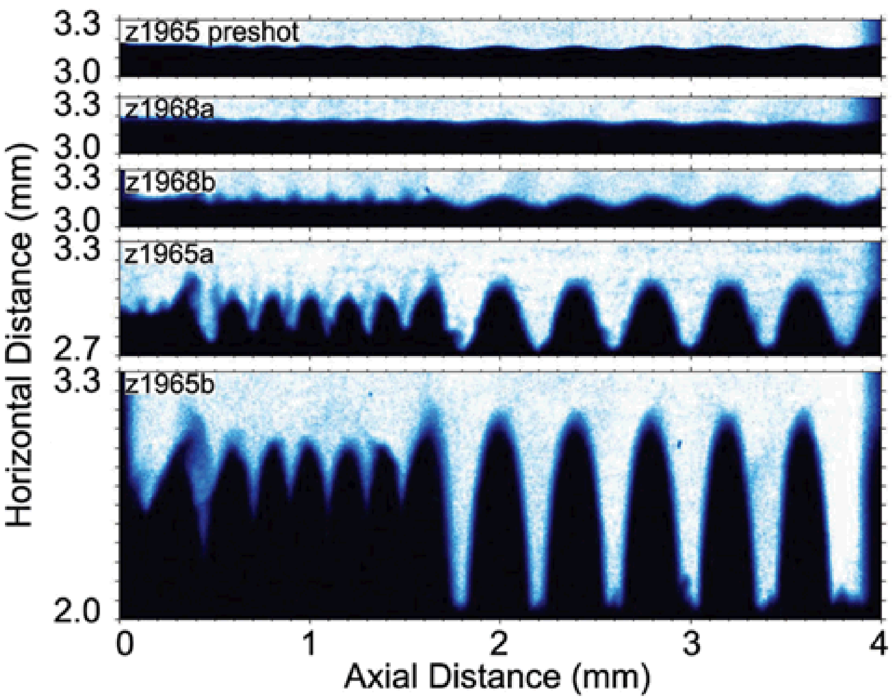
"The magneto-Rayleigh-Taylor (MRT) instability poses the greatest threat to this (MagLIF) approach to fusion."

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

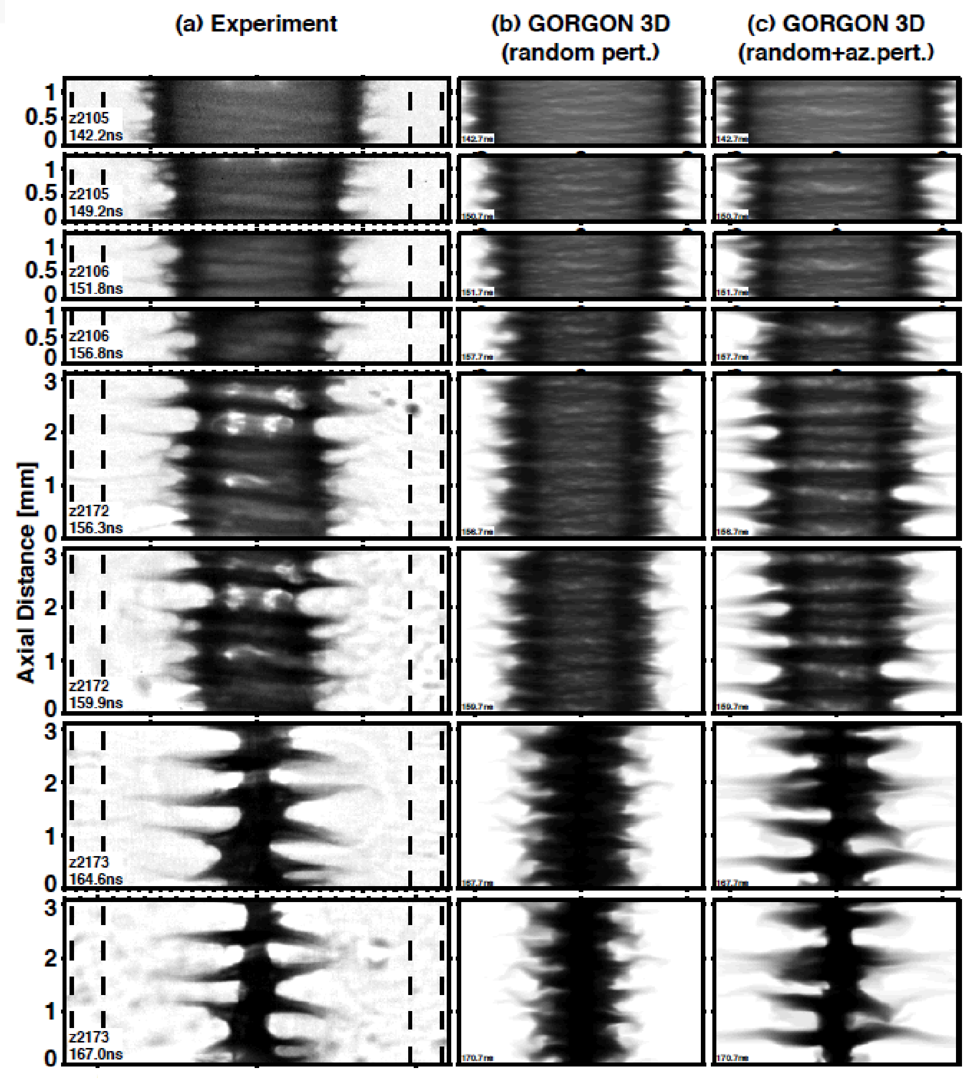
MRT seed perturbations must be understood and eliminated

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





D.B. Sinars *et al*., Phys. Rev. Lett. 105, 185001 (2010)



R.D. McBride *et al*., PRL 109, 135004 (2012)

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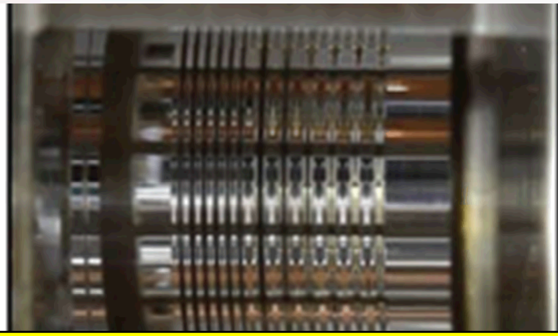
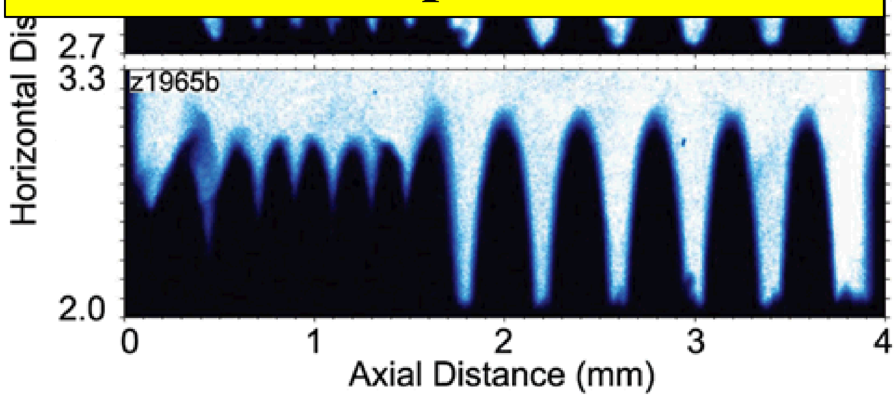
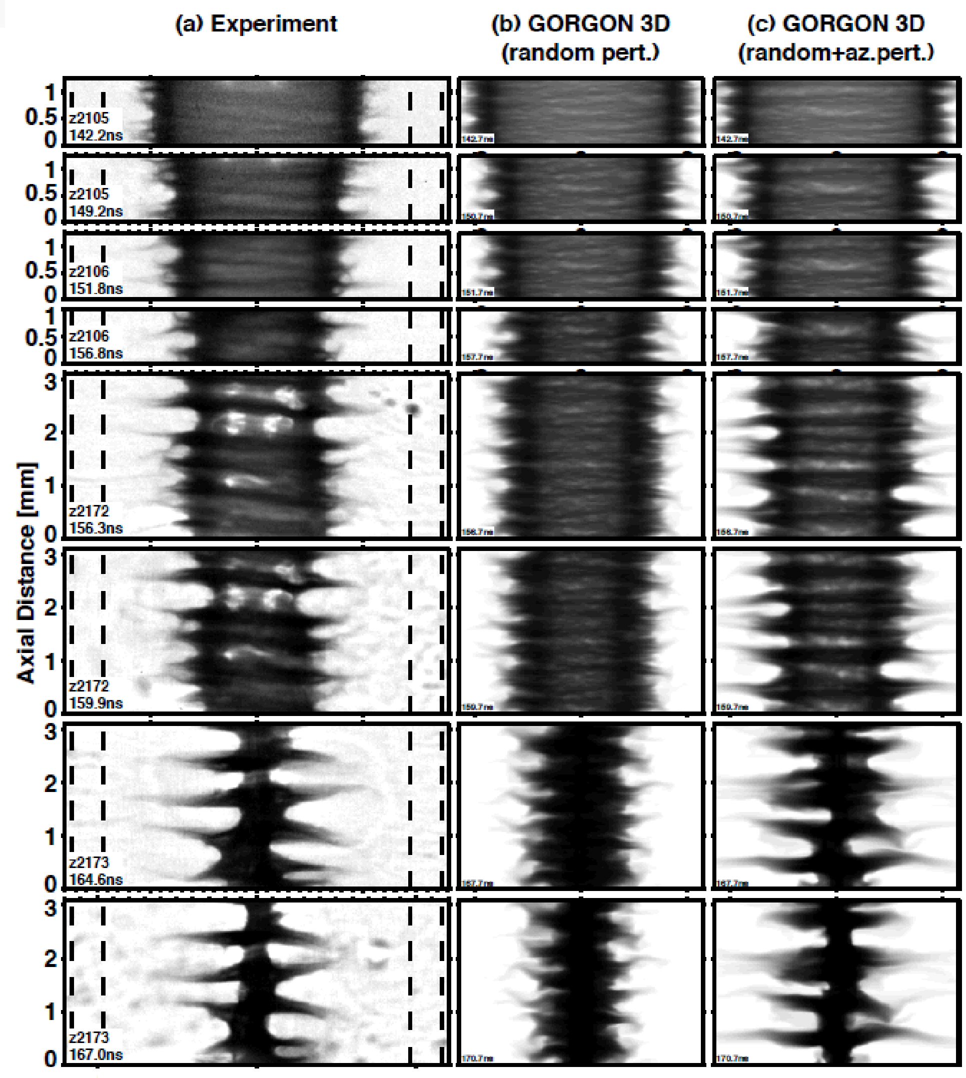


Pre-machined large amplitude perturbation: Observed MRT amplitude is not linearly proportional to the amplitude of the initial perturbations.



D.B. Sinars *et al*., Phys. Rev. Lett. 105, 185001 (2010)



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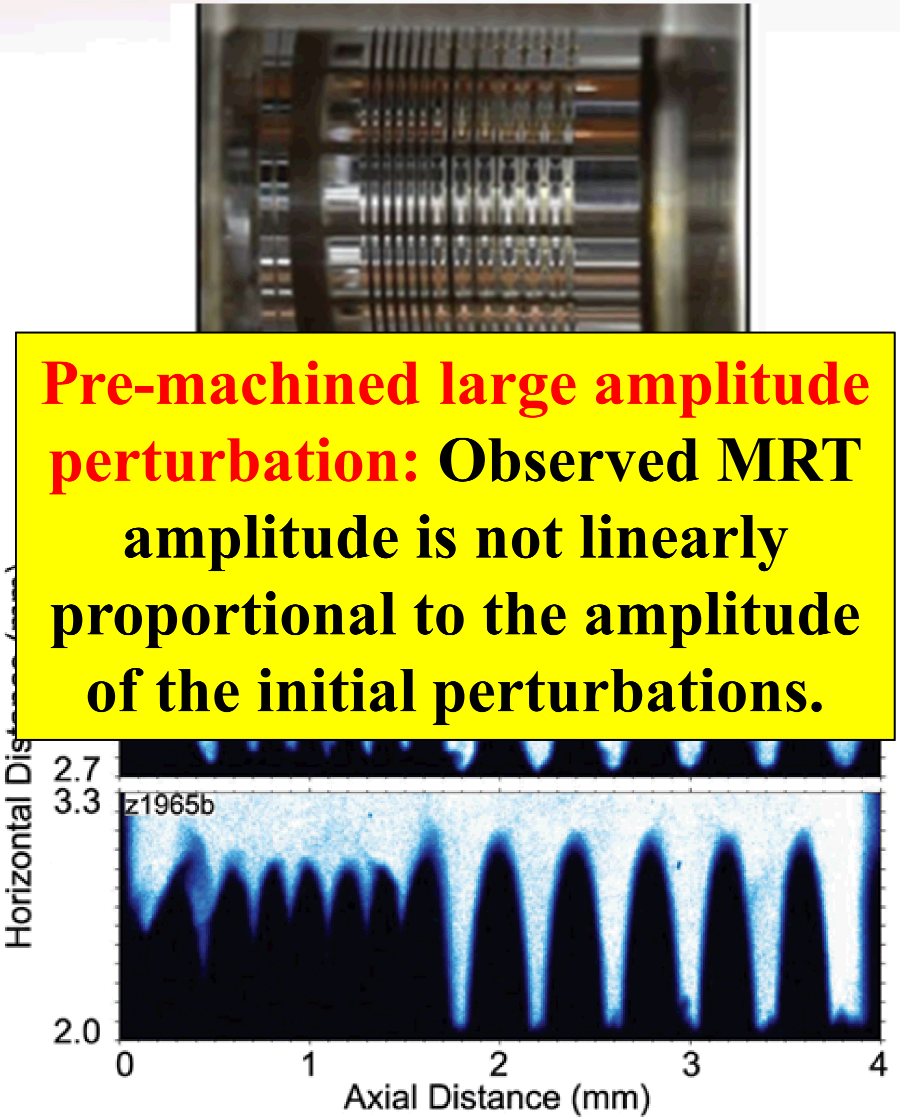

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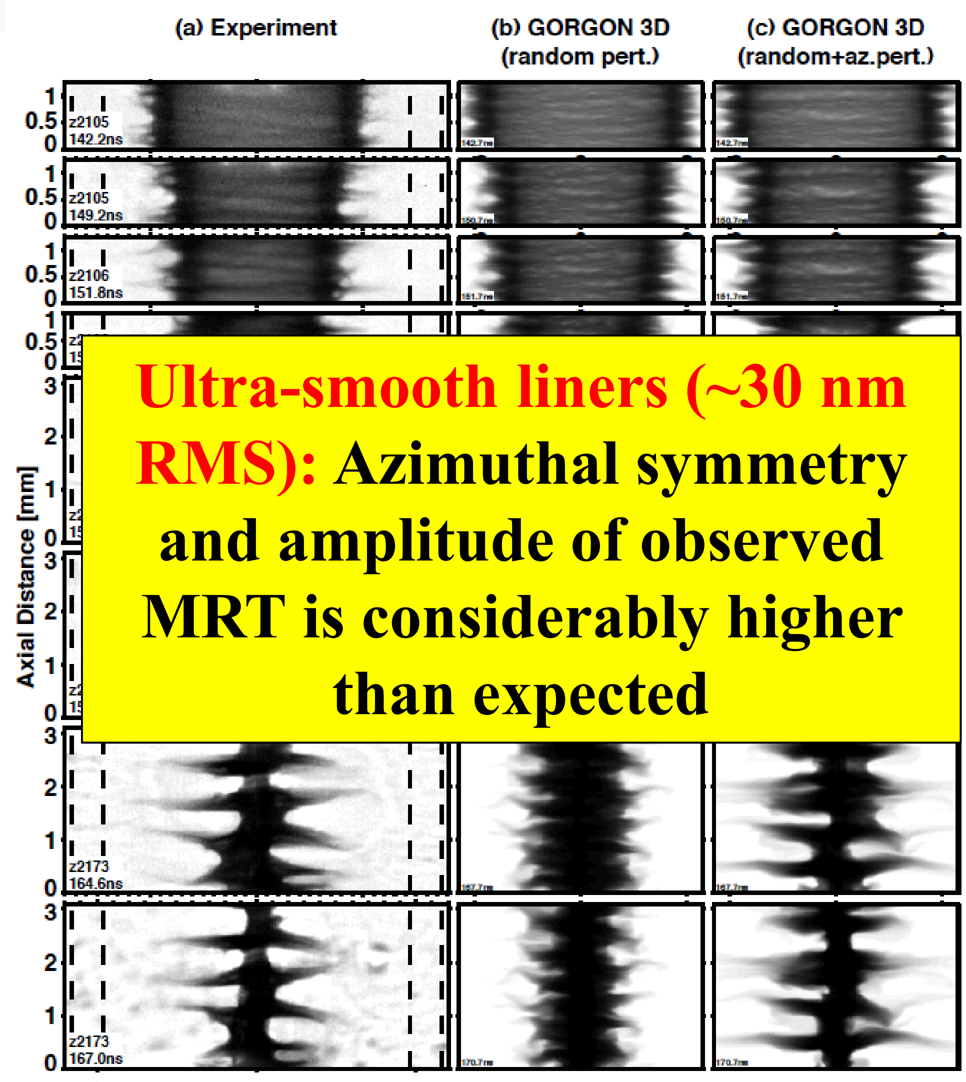

Ultra-smooth liners (~30 nm RMS): Azimuthal symmetry and amplitude of observed MRT is considerably higher than expected

R.D. McBride *et al*., PRL 109, 135004 (2012)

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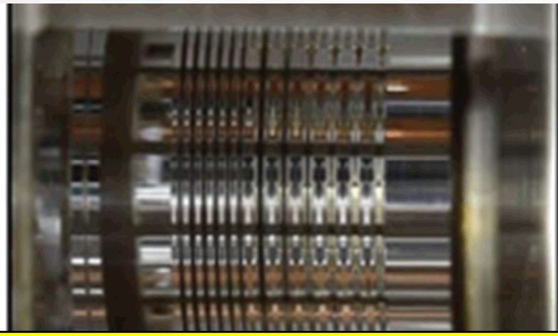

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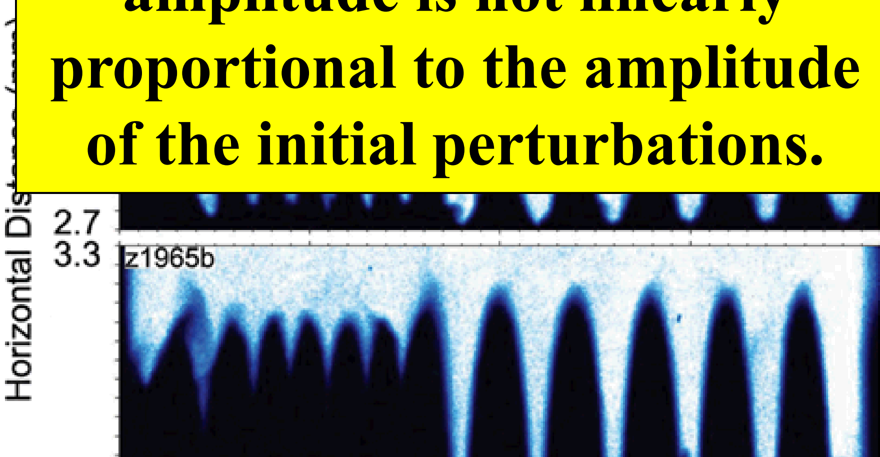
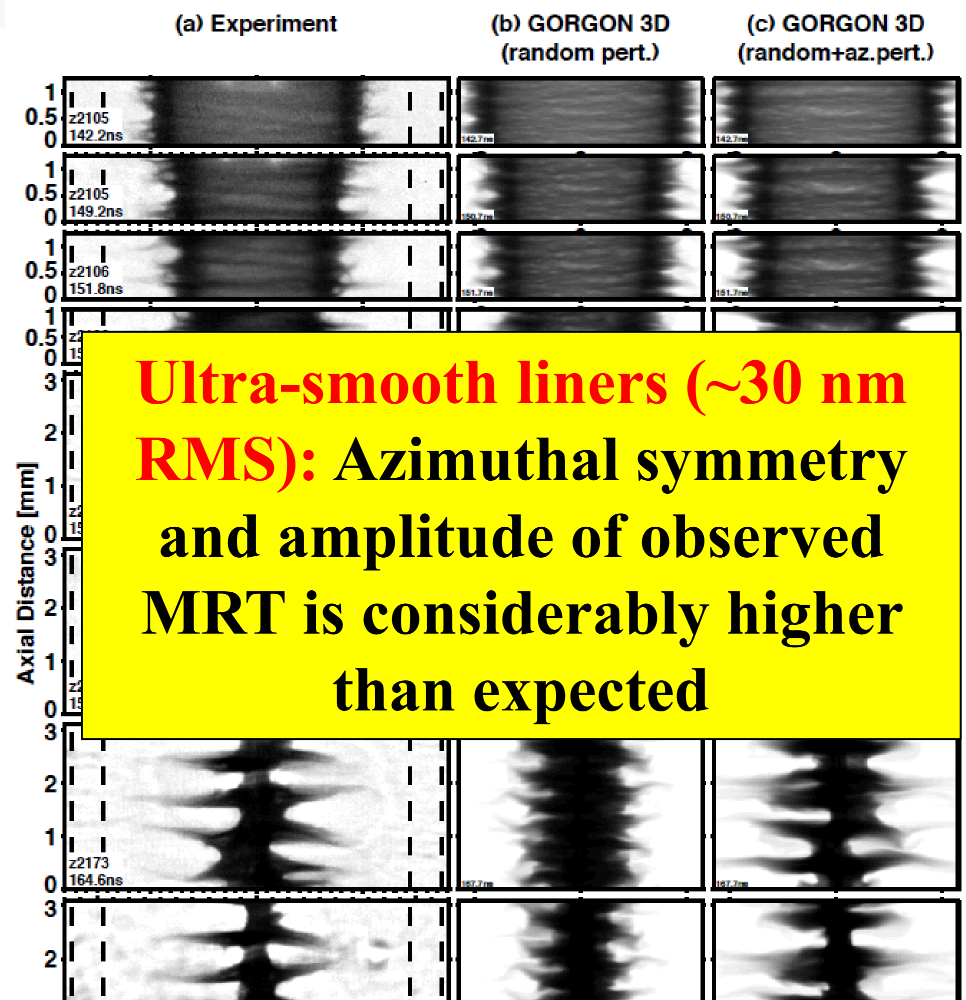




Ultra-smooth liners (~30 nm RMS): Azimuthal symmetry and amplitude of observed MRT is considerably higher than expected

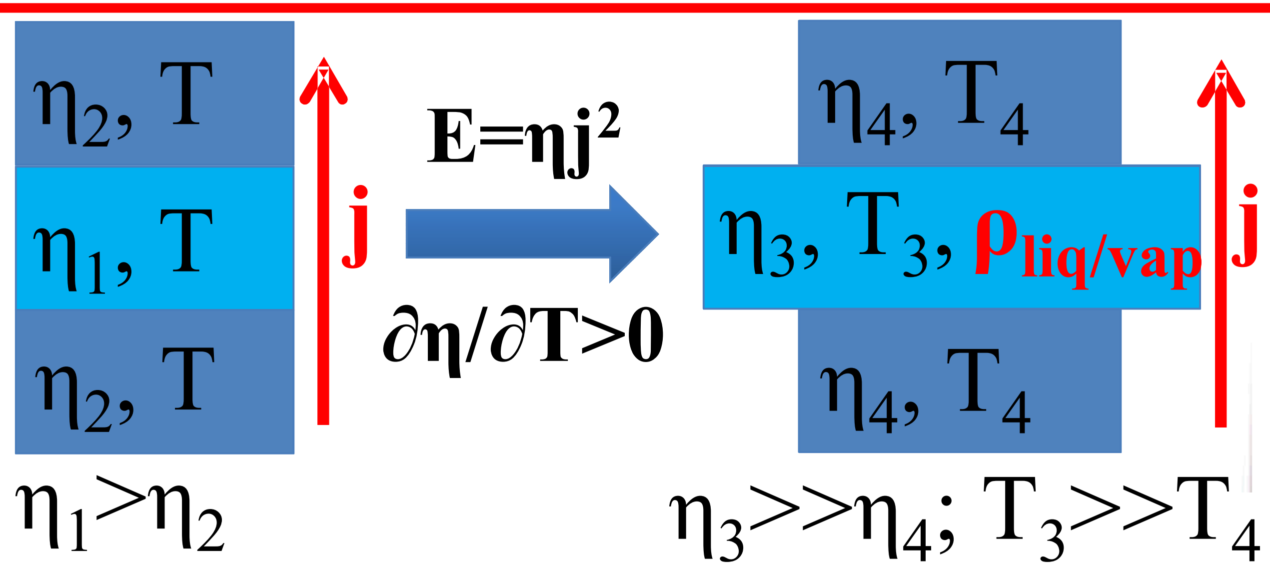
What seeds the unexpected large amplitude and azimuthally symmetric MRT?

ETI may source an azimuthally correlated perturbation

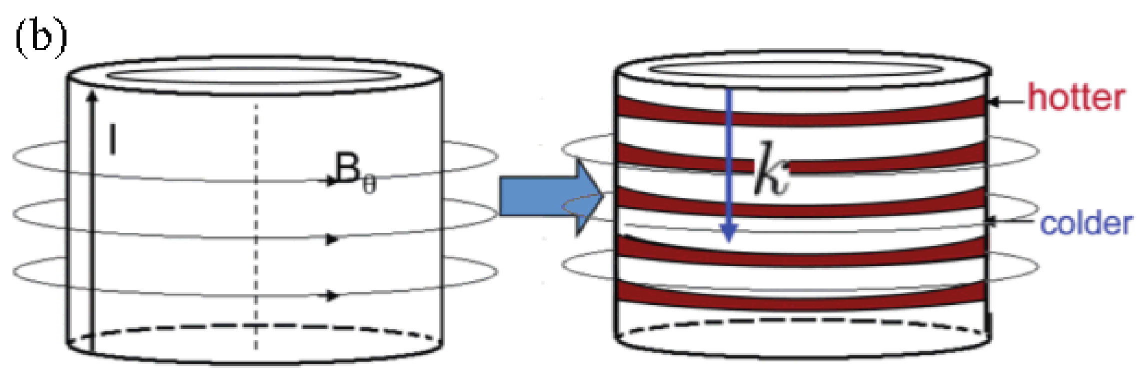
Electrothermal instabilities are driven by Joule heating and arise when resistivity (η) depends on temperature (T)

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!

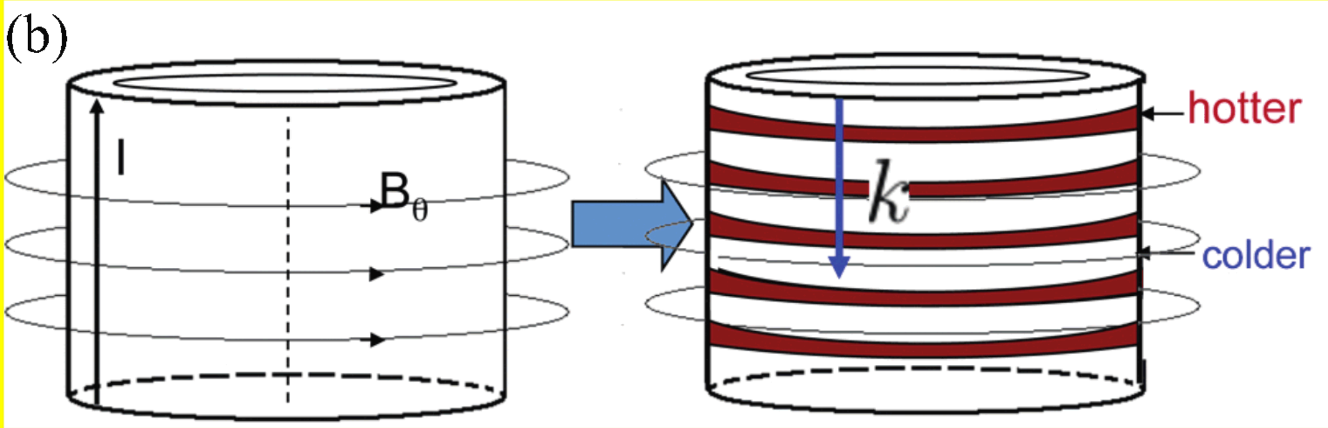


ETI grows rapidly near melt

Electrothermal instabilities occur when material conductivity is dependent on temperature

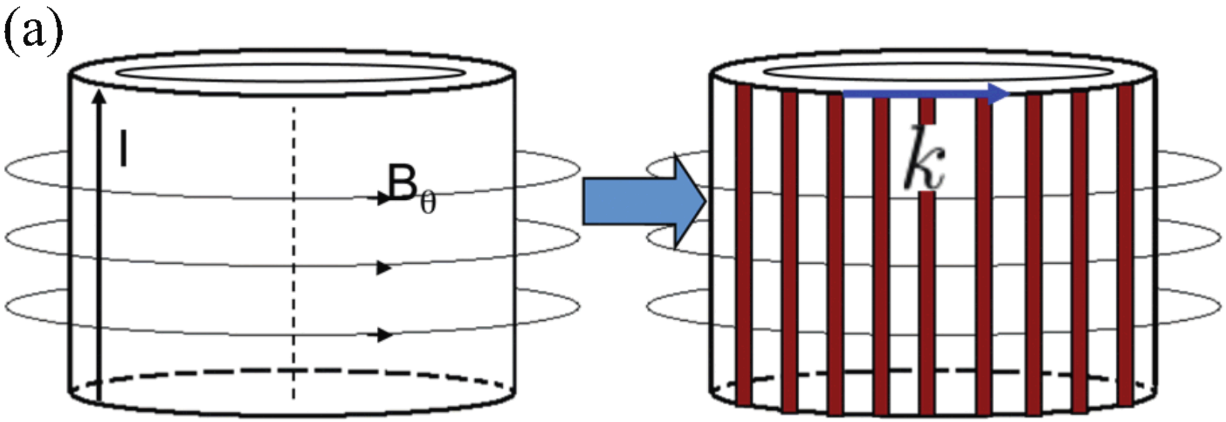
Condensed metals form striations

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

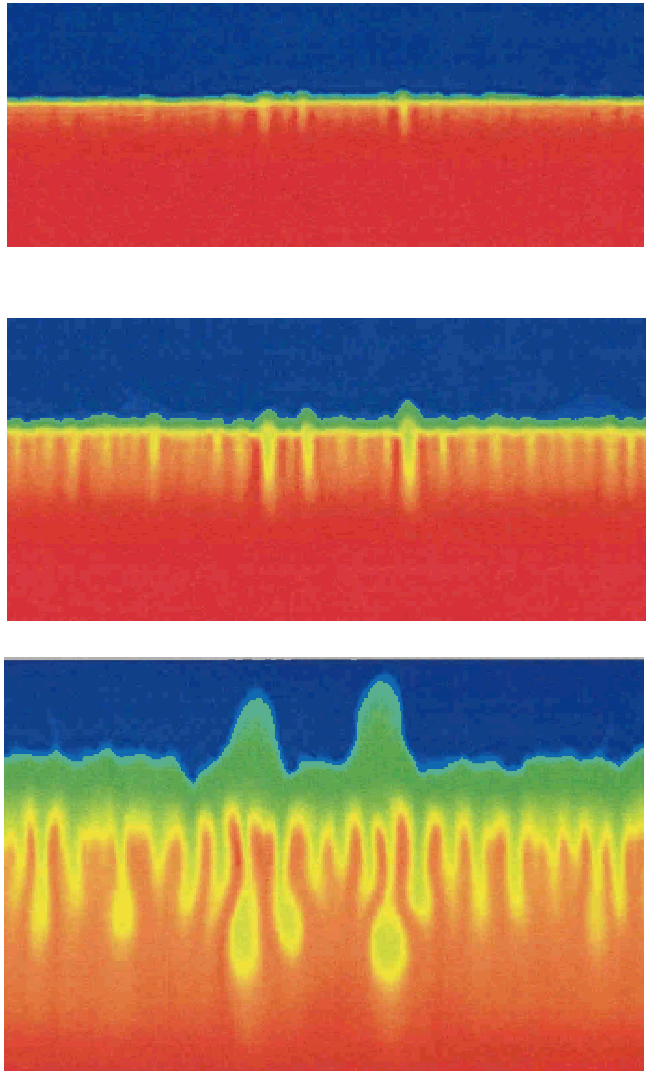


Plasmas form filaments

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



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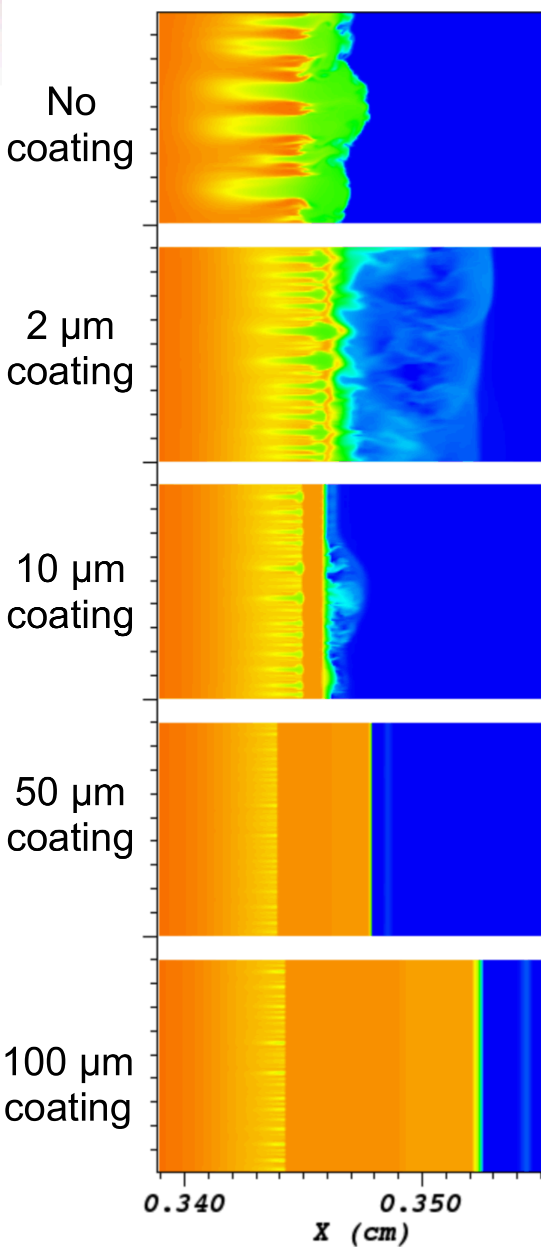
If MRT is seeded by an ETI, simulations suggest that the ETI-driven density perturbation can be mitigated!



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

No ETI (striation) growth in the dielectric

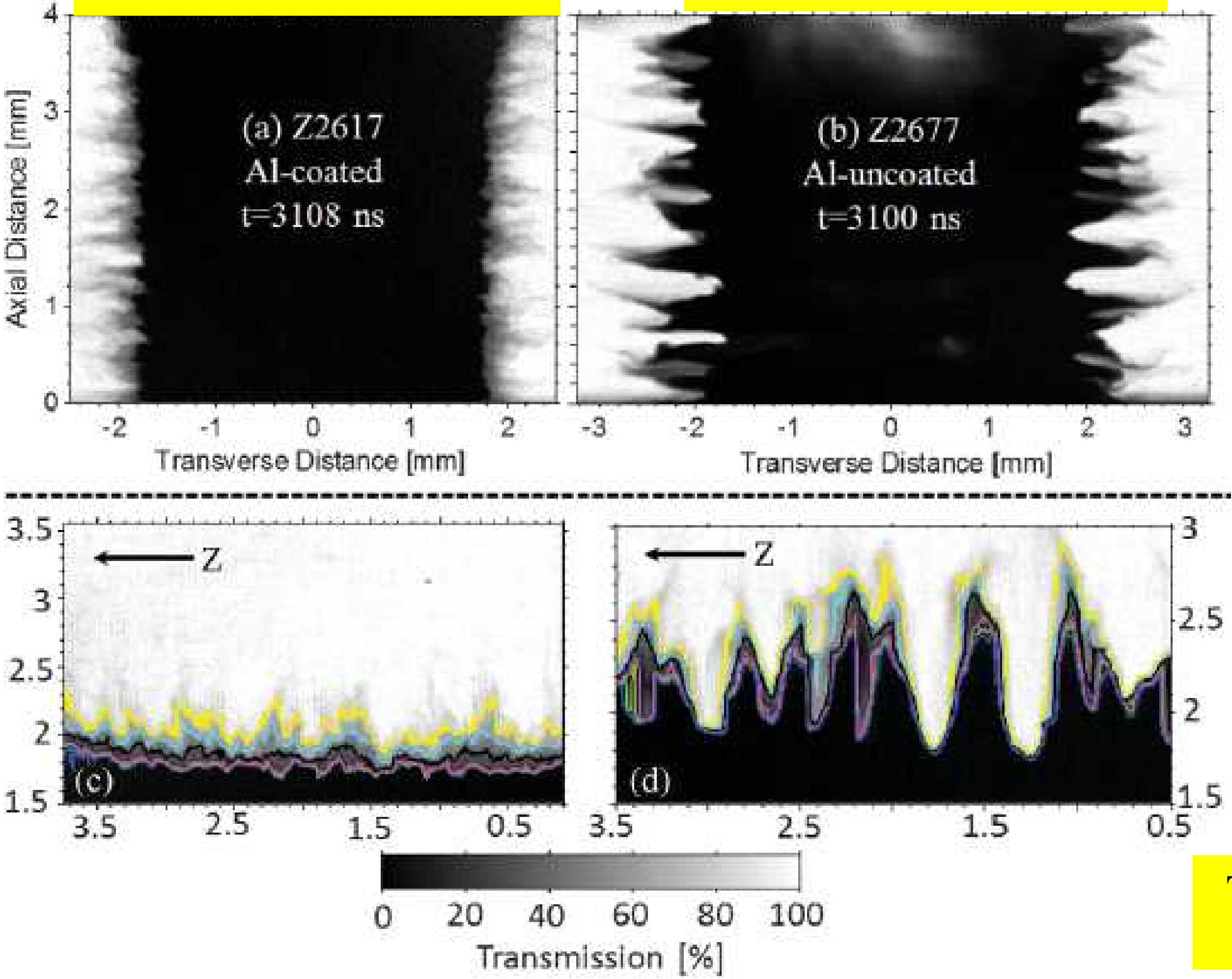
Nonlinear mass redistribution from ETI is significantly tamped by the coating

- Reduces seed for MRT growth
- Reduces integral instability growth

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

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

Coated **Uncoated**



Dielectric coating carries current & implodes with liner

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

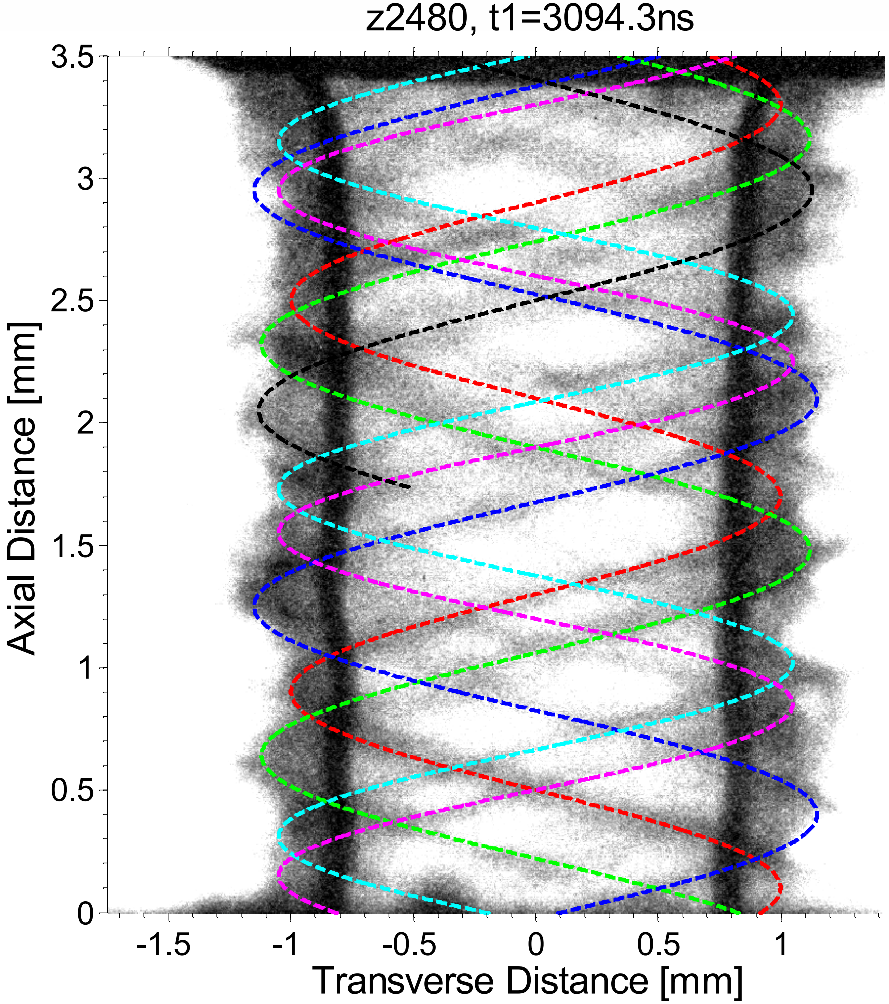
T.J. Awe *et al.*, Phys. Rev. Lett. 116, 065001 (2016)

ETI development is inferred by evaluating MRT late in the experiment.

The early nonuniform Joule heating of Z liners is not directly observed!

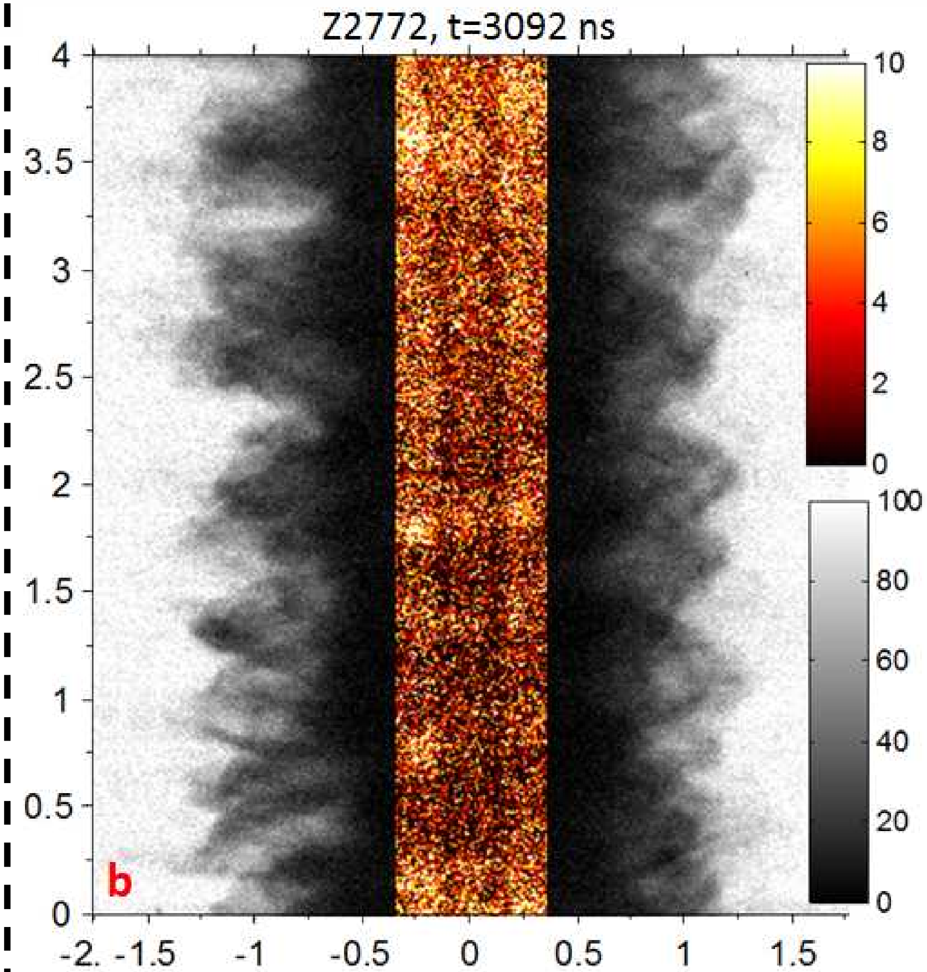
Combining axial premagnetization with a dielectric tamper for ETI mitigation results in unprecedented liner stability

$B_{z,0}$ drives helical instability



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

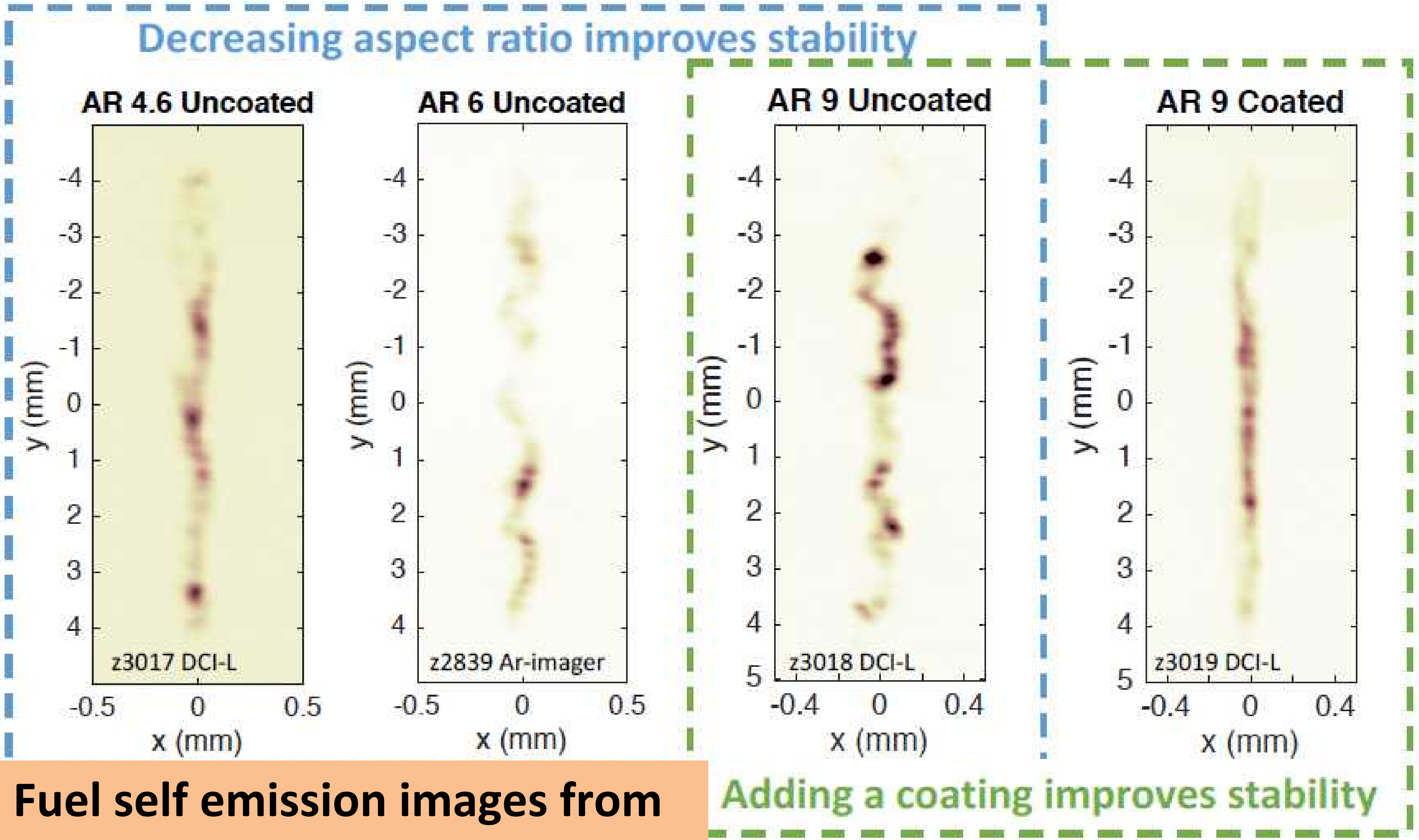
$B_{z,0}$+dielectric surface coating



$CR=R_{in}(t=0)/R_{in}(t)=21!$

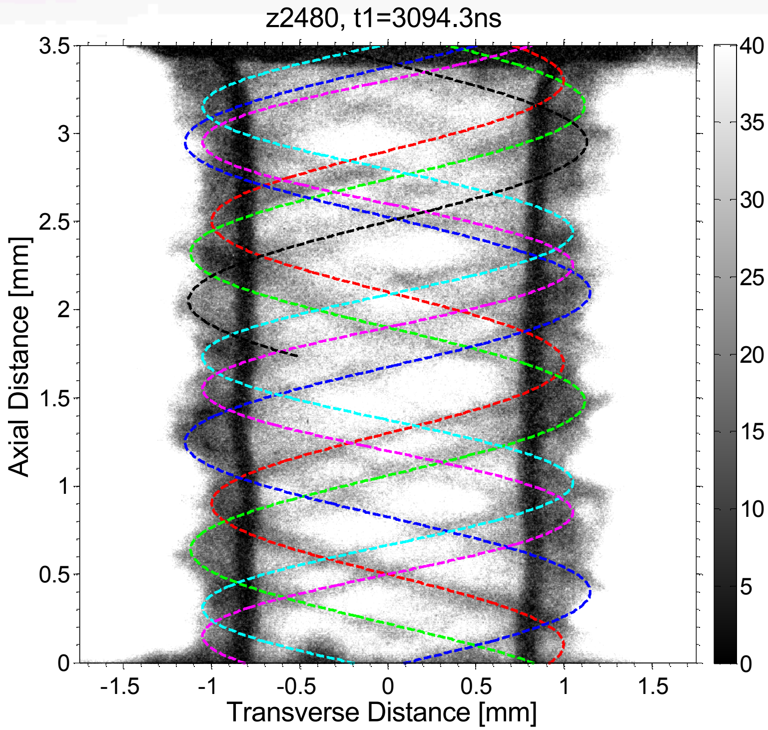
T.J. Awe *et al.*, Phys. Rev. Lett. 116, 065001 (2016)

MagLIF liners with dielectric surface tampers result in enhanced fuel uniformity upon stagnation

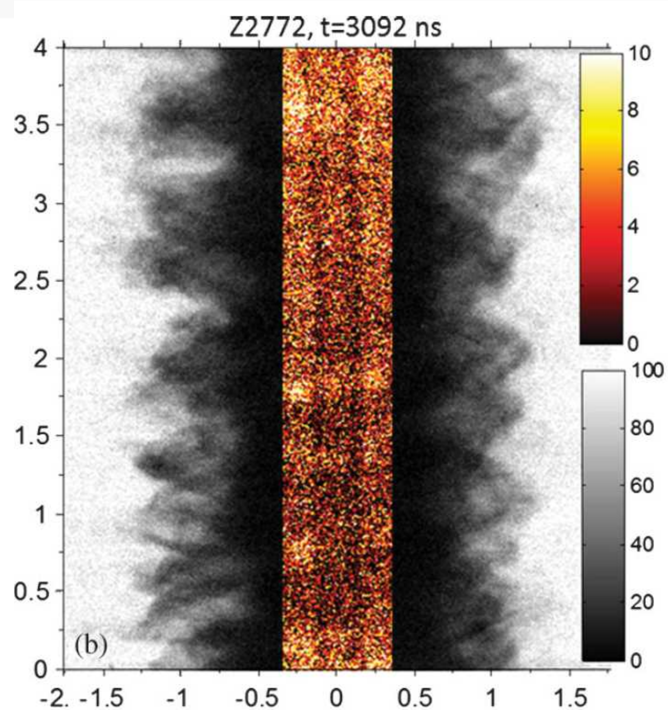


Fuel self emission images from Dave Ampleford's "MagLIF Morphology" campaign

Detailed understanding of ETI may be required to explain recent successes in increasing liner stability



What seeds the helical instability?
Why does it persist and grow?



Do dielectric tampers mitigate mass redistribution from ETI?

The early nonuniform Joule heating of Z liners is not diagnosed. ETI development is inferred by evaluating MRT late in the experiment. ETI is NOT directly observed!

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

ETI strata grow in condensed metals at sub-eV temperatures

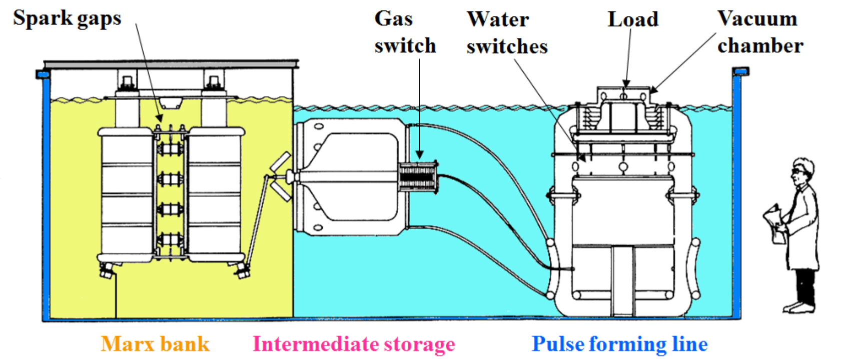
A 1 MA, 100 ns facility can access this physical regime

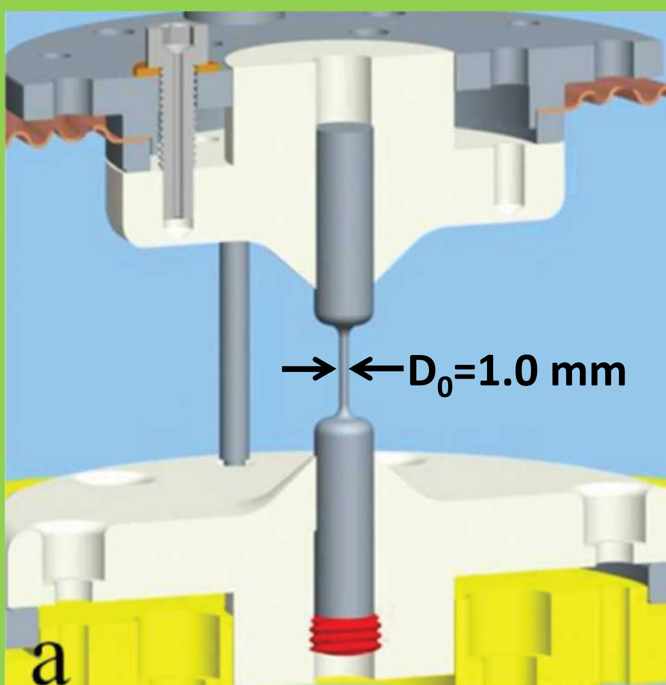
U of Nevada, Reno Zebra Facility

→100 ns rise time (similar to Z)

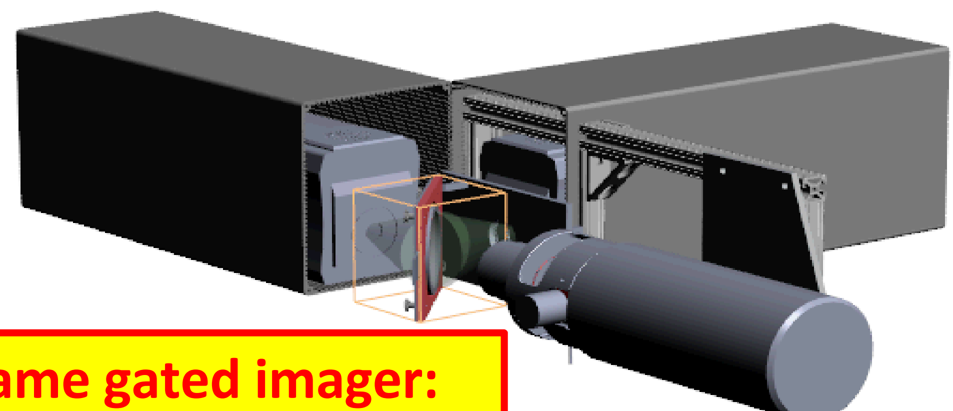
→Nonuniform "skin" current

→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

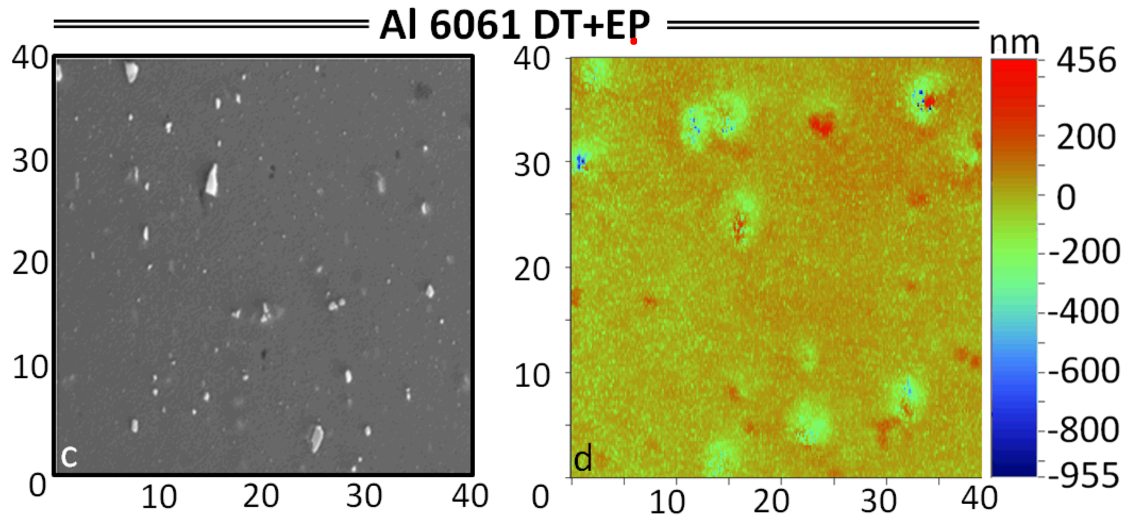


2 frame gated imager:
2 ns and 3 µm resolution

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

Al 6061: Diamond Turned (DT) & Electropolished (EP)

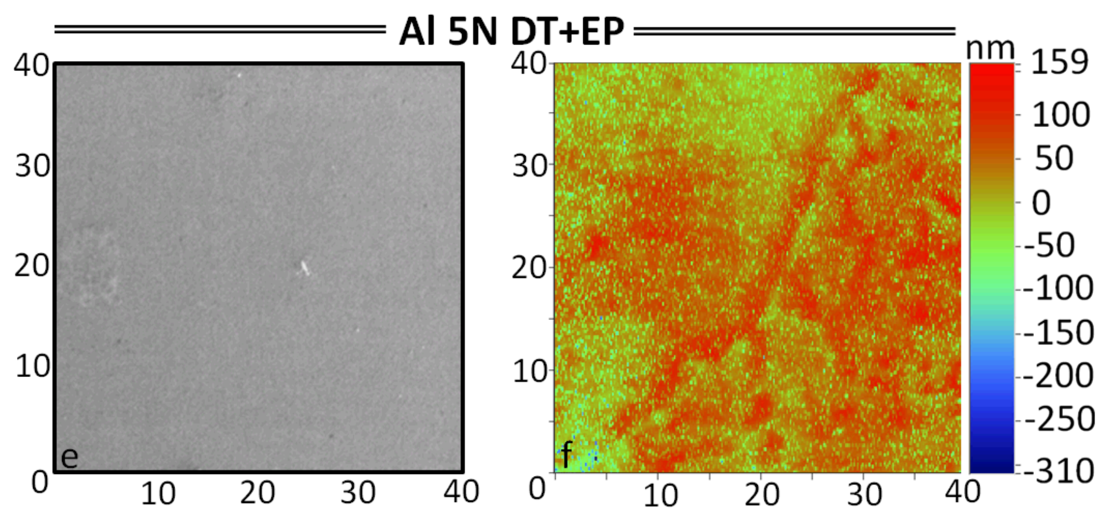
SEM



Interferometry

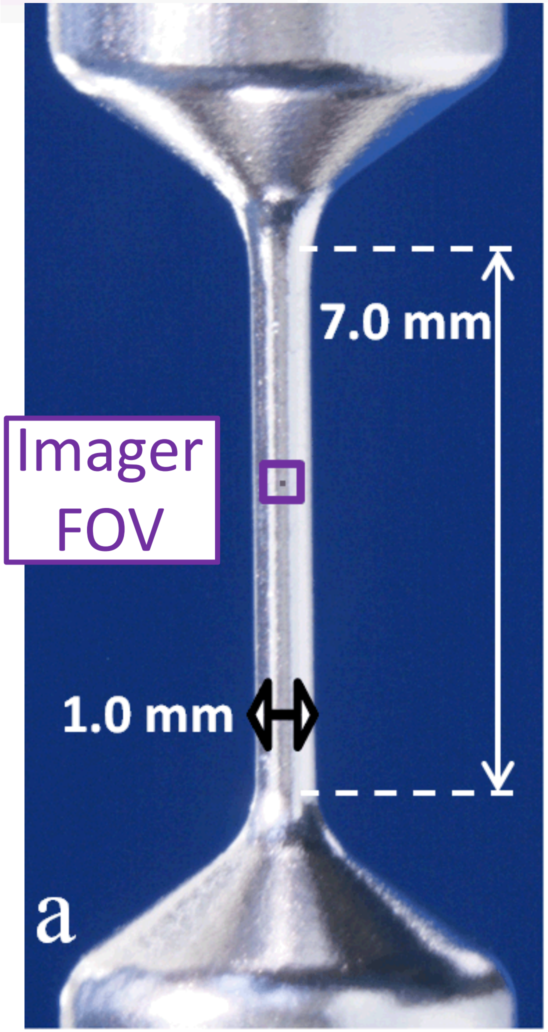
Al 5N (99.999% pure): Diamond Turned (DT) & Electropolished (EP)

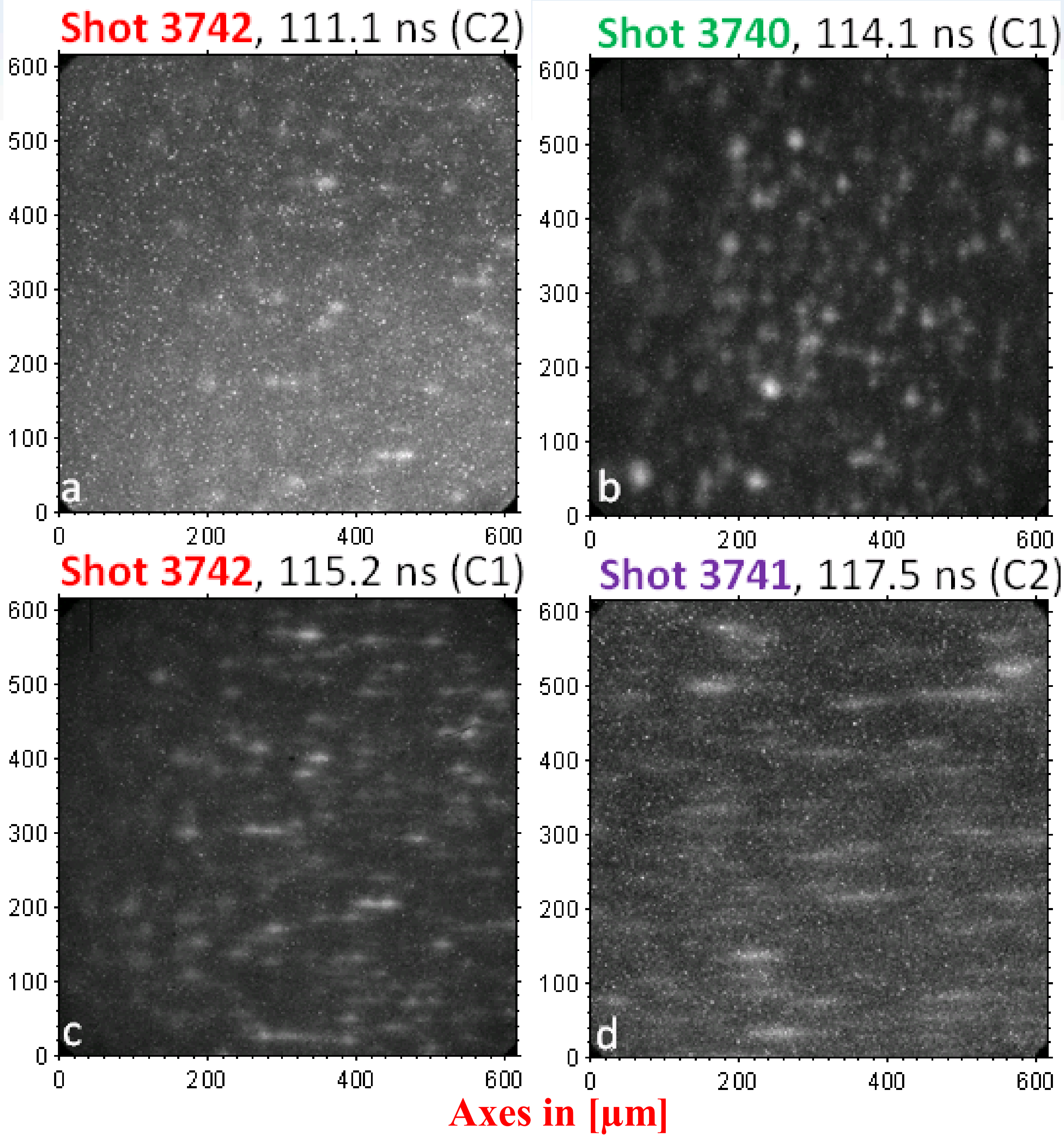
SEM



Interferometry

Extreme diagnostic resolution enables new observations





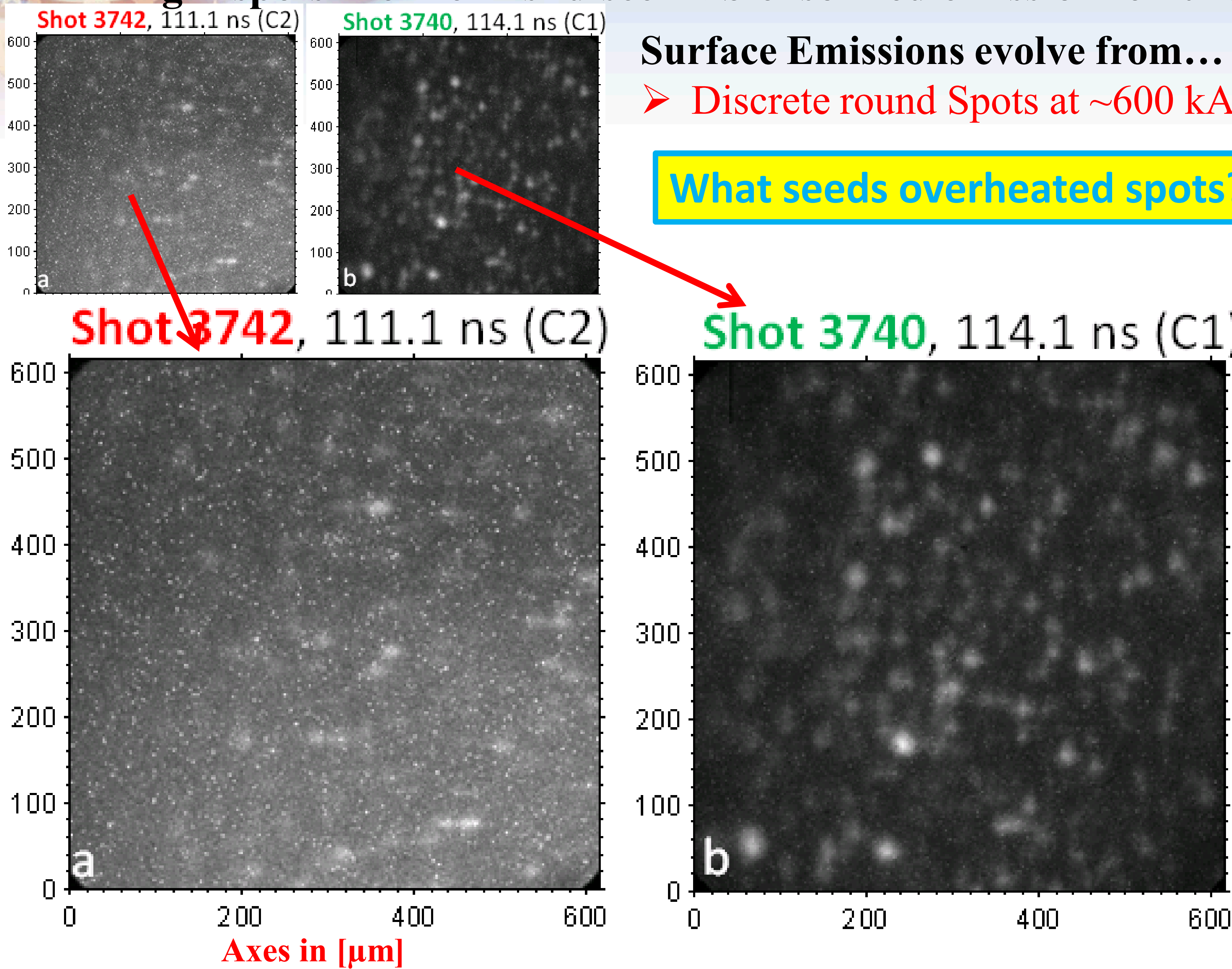
T.J. Awe *et al.*, IEEE Trans. Plasma Sci. **45**, 584 (2017)

Bright spots are the first discernable isolated emission feature

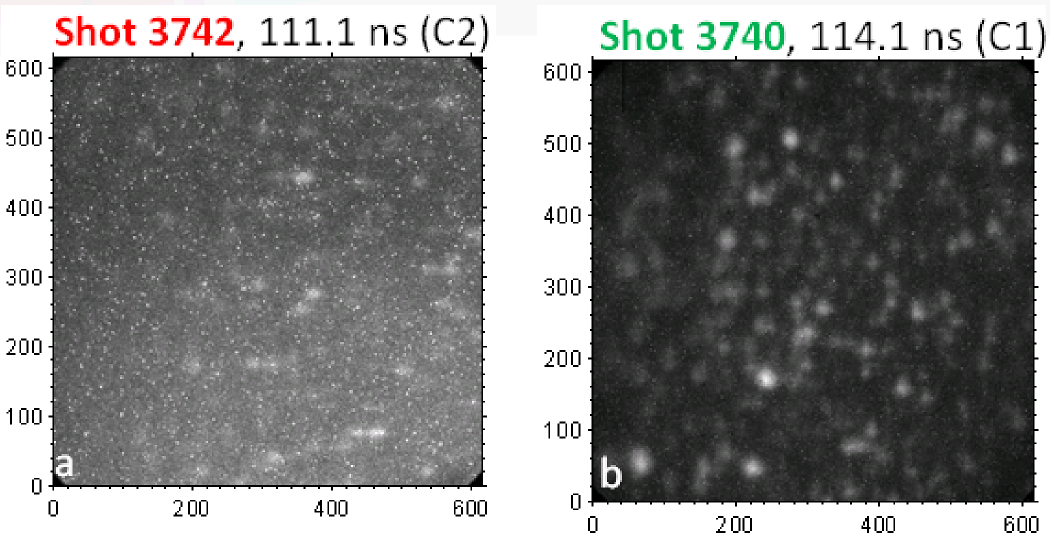
Surface Emissions evolve from…

- Discrete round Spots at ~600 kA

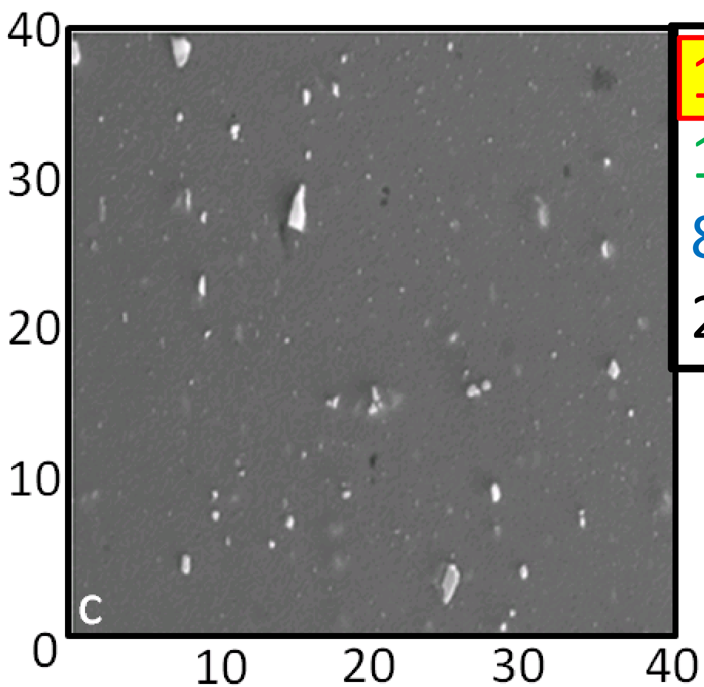
What seeds overheated spots?



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



- Images display emission from isolated overheated spots.
- Spot density is **~500 spots/mm²**



→**Axes in [μm]**

100 defects/mm² w/ d>5 μm

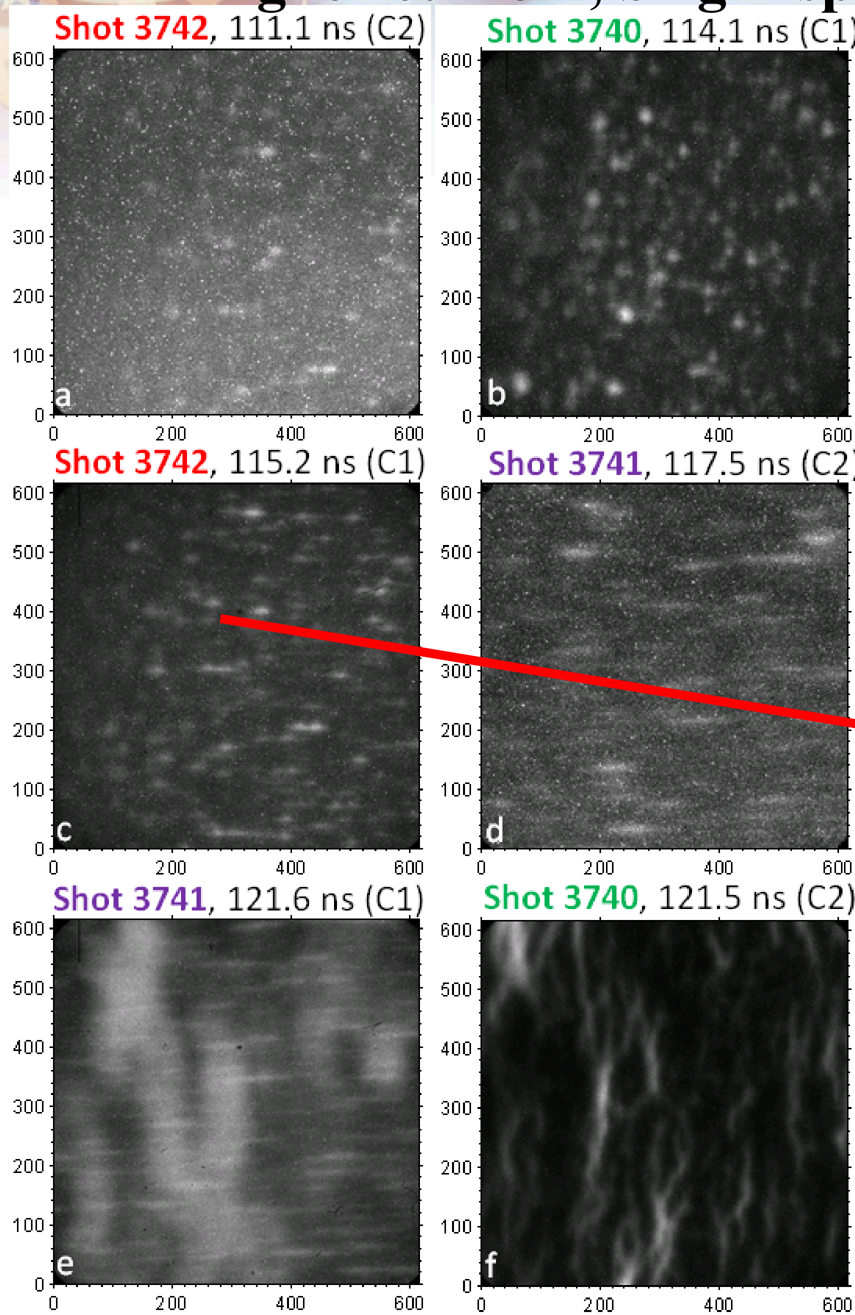
1,800 defects/mm² w/ 2.5<d<5 μm

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

At higher current, bright spots elongate azimuthally and merge

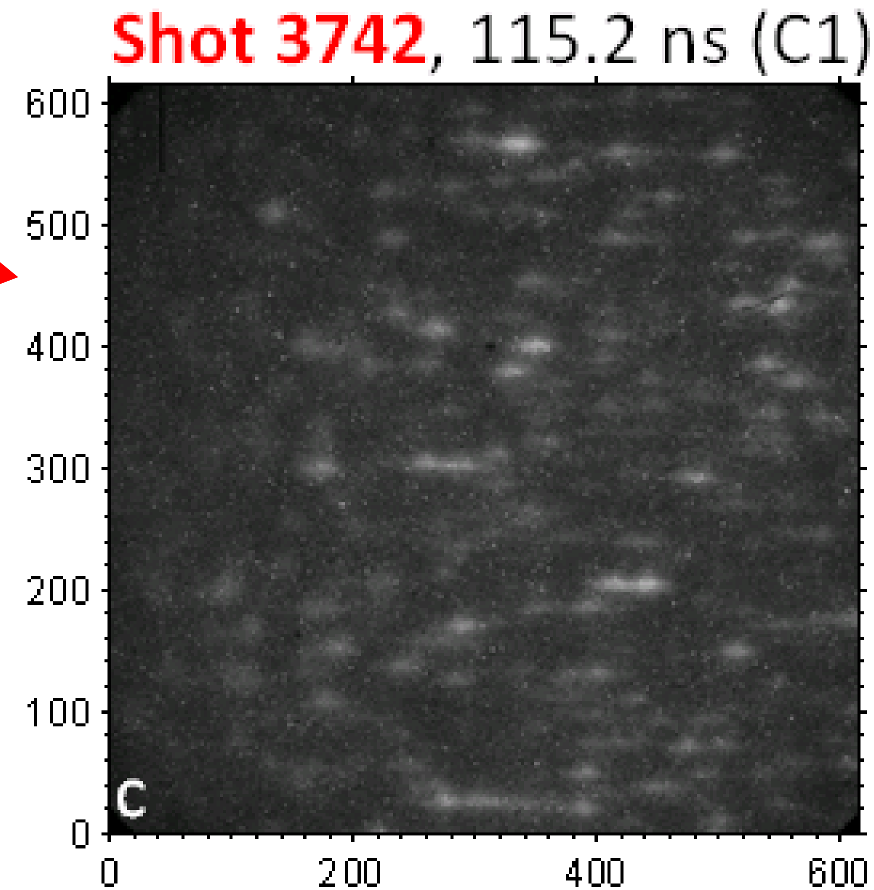


Axes in [μm]

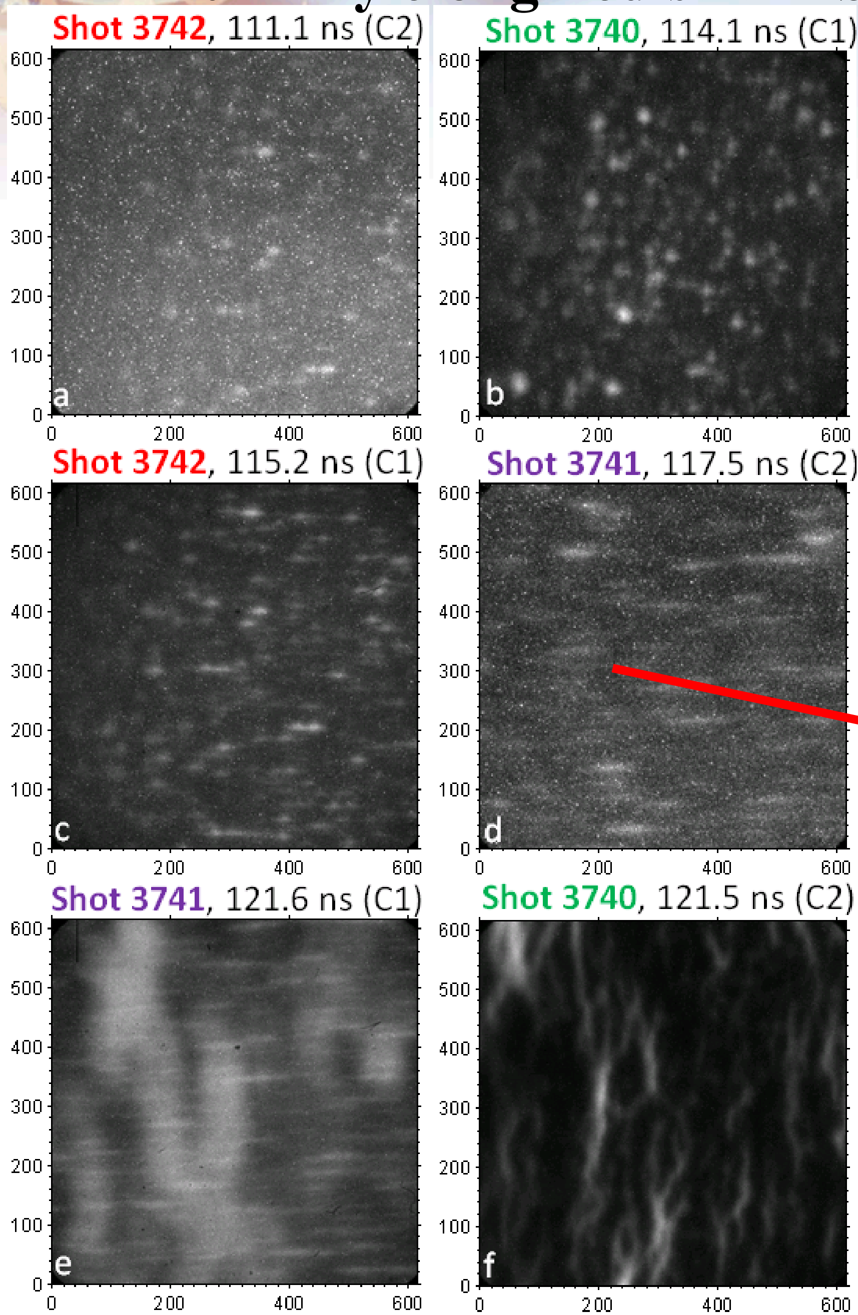
Surface Emissions evolve from discrete round spots to…

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

What physics drives elongation?



Azimuthally elongated strata become the dominant emission feature

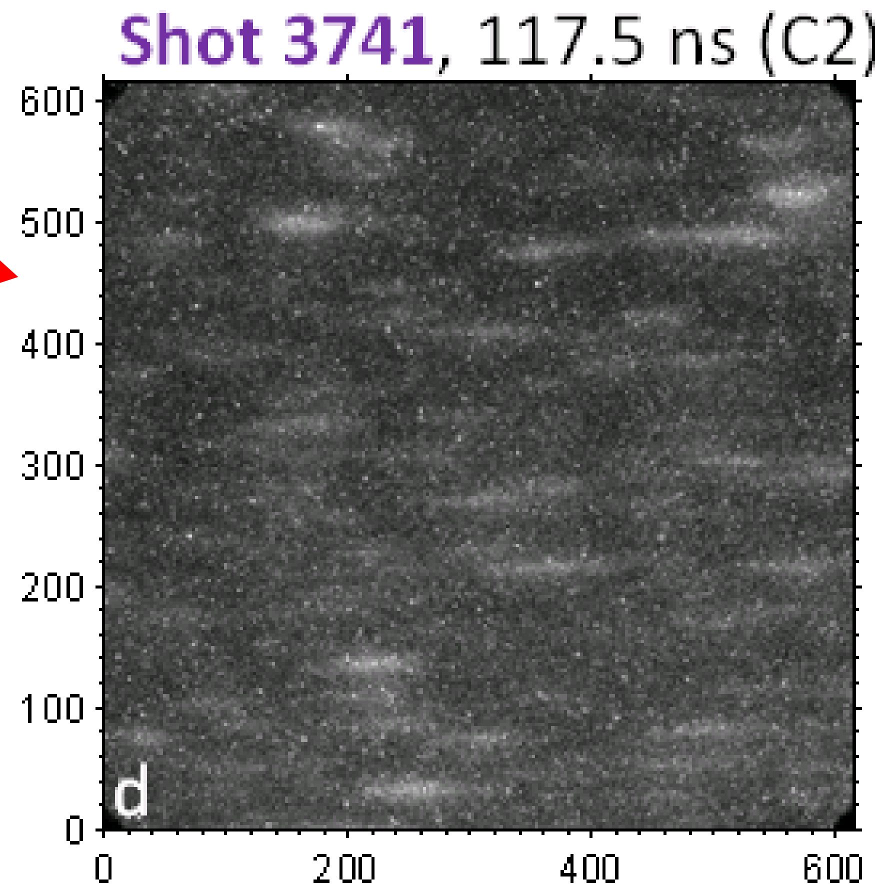


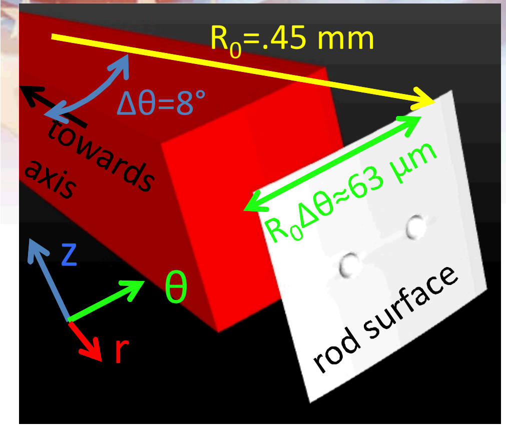
Axes in [μm]

Surface Emissions evolve from merging elongated spots to…

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

What physics drives merging?

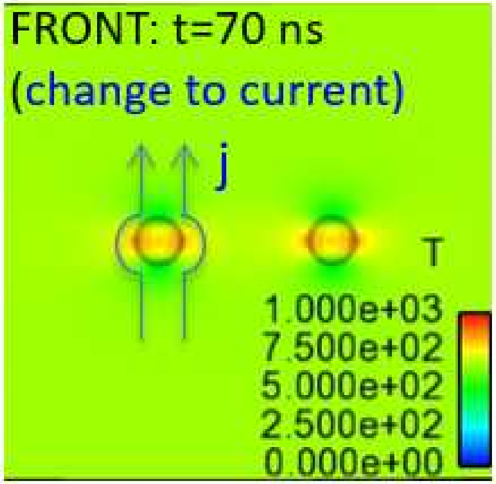


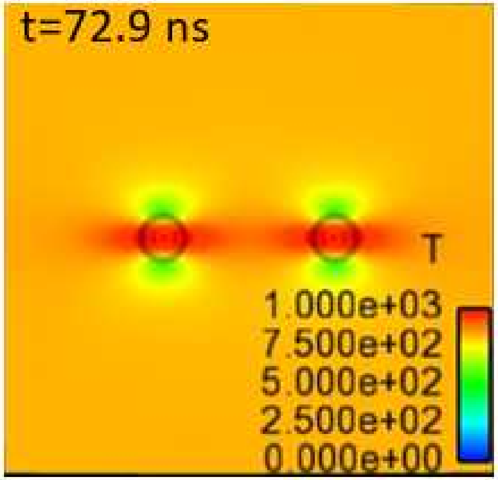


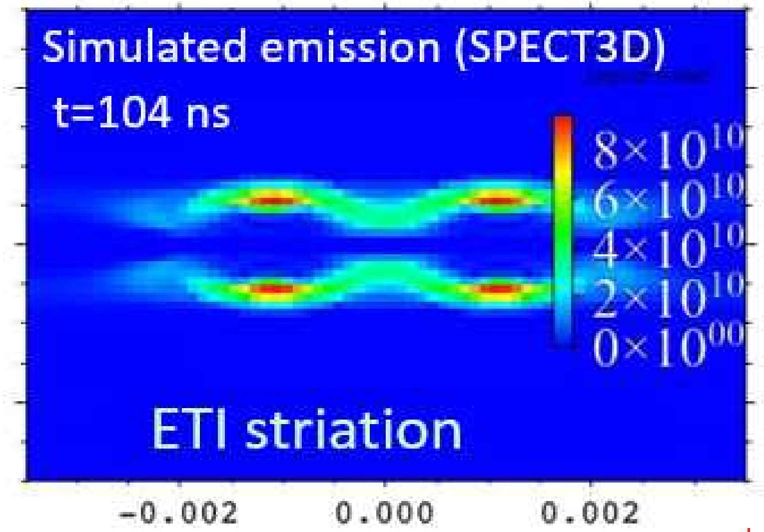
3D MHD simulations of simplified, localized perturbations (pits & ↑η inclusions) illustrate for the first time how global ETI structures form

Simulations detail how current redistribution drives ETI

Isolated pits merge to form striations

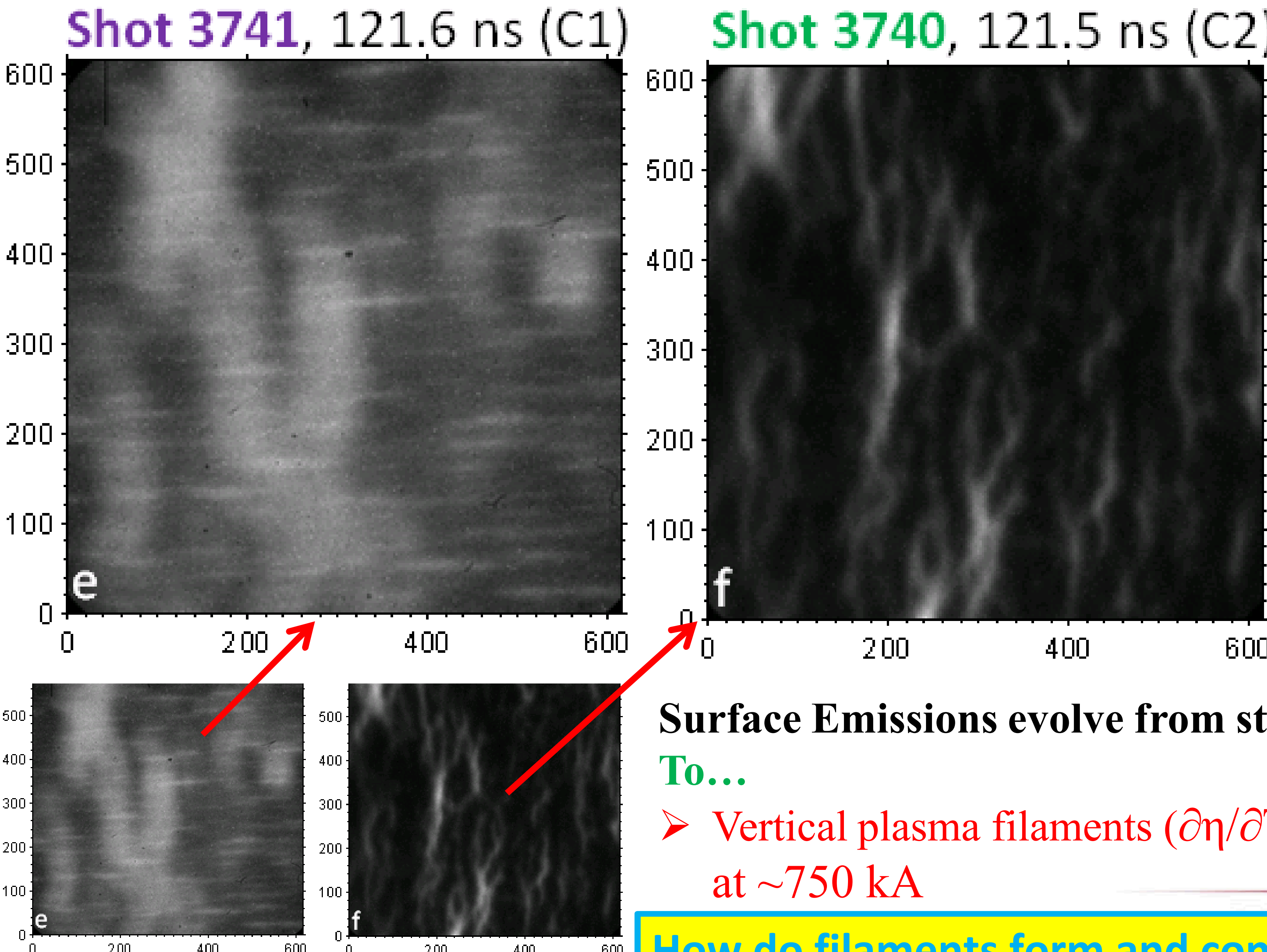






Current bends around pits or resistive inclusions, driving enhanced Joule heating and T at edge, thus locally reducing the conductivity. This effectively widens the perturbation; in this way neighboring perturbations merge.

As plasma forms, strata give way to brightly emitting plasma filaments



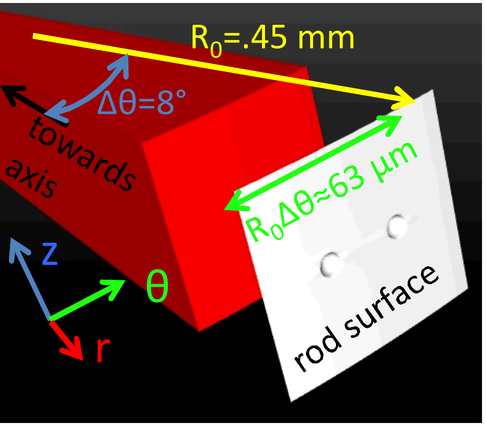
Axes in [μm]

Surface Emissions evolve from strata

To…

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

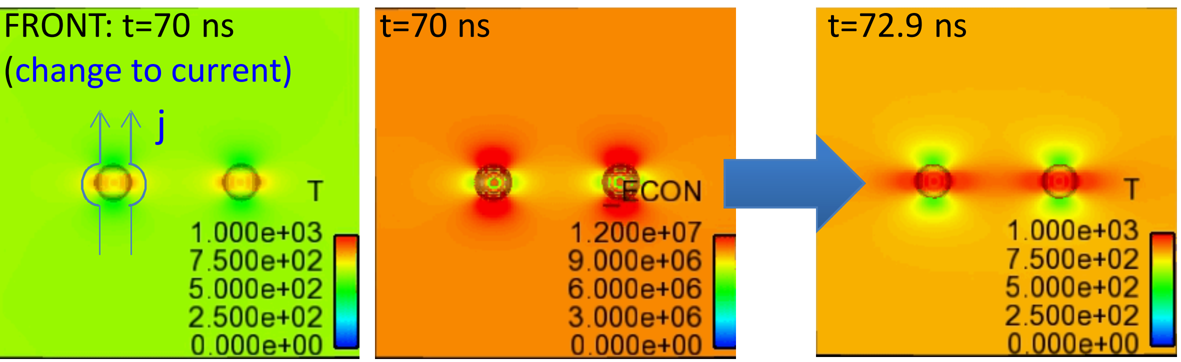
How do filaments form and connect?

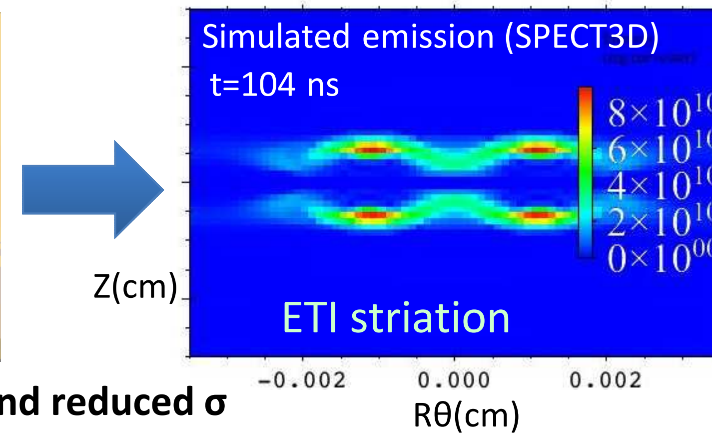


3D MHD simulations of simplified, localized perturbations (pits & ↑η inclusions) illustrate for the first time how global ETI structures form

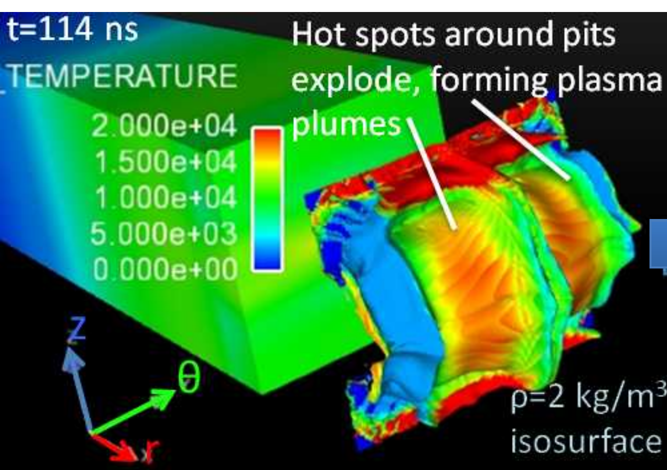
Simulations detail how current redistribution drives ETI

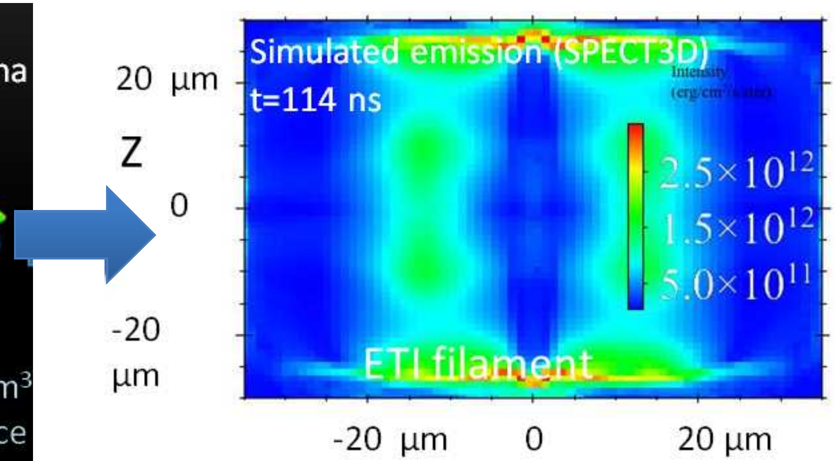
Isolated pits merge to form striations





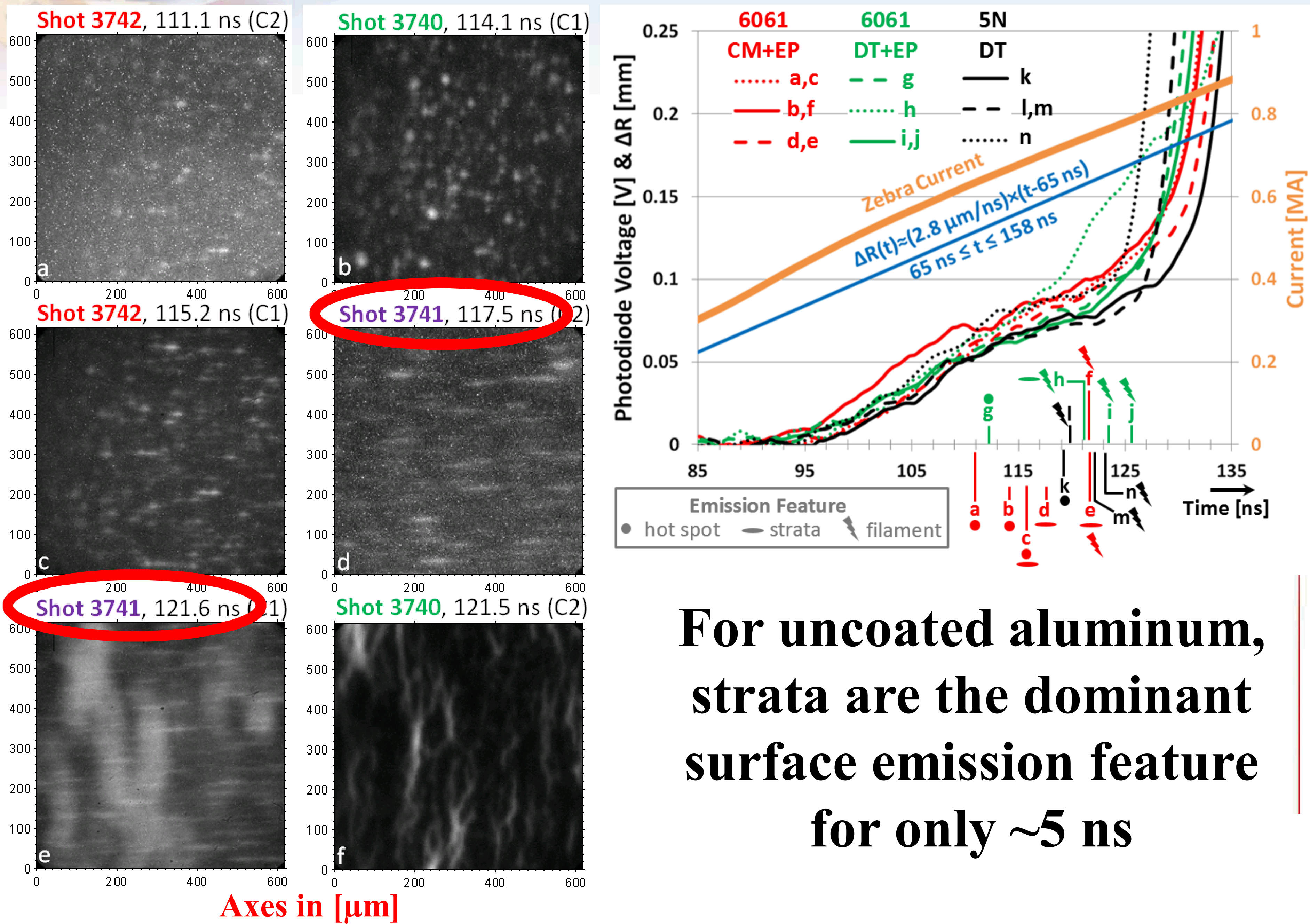
Current bends around pit, driving enhanced $J^2/σ$ and T at edge, and reduced σ there, effectively widening the separate perturbations until they correlate in T.





Plumes expand axially, forming ETI filaments.

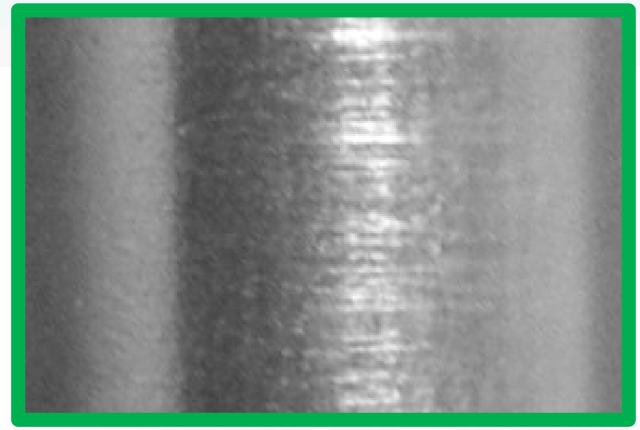
Surface Plasmas limit our ability to study ETI strata evolution



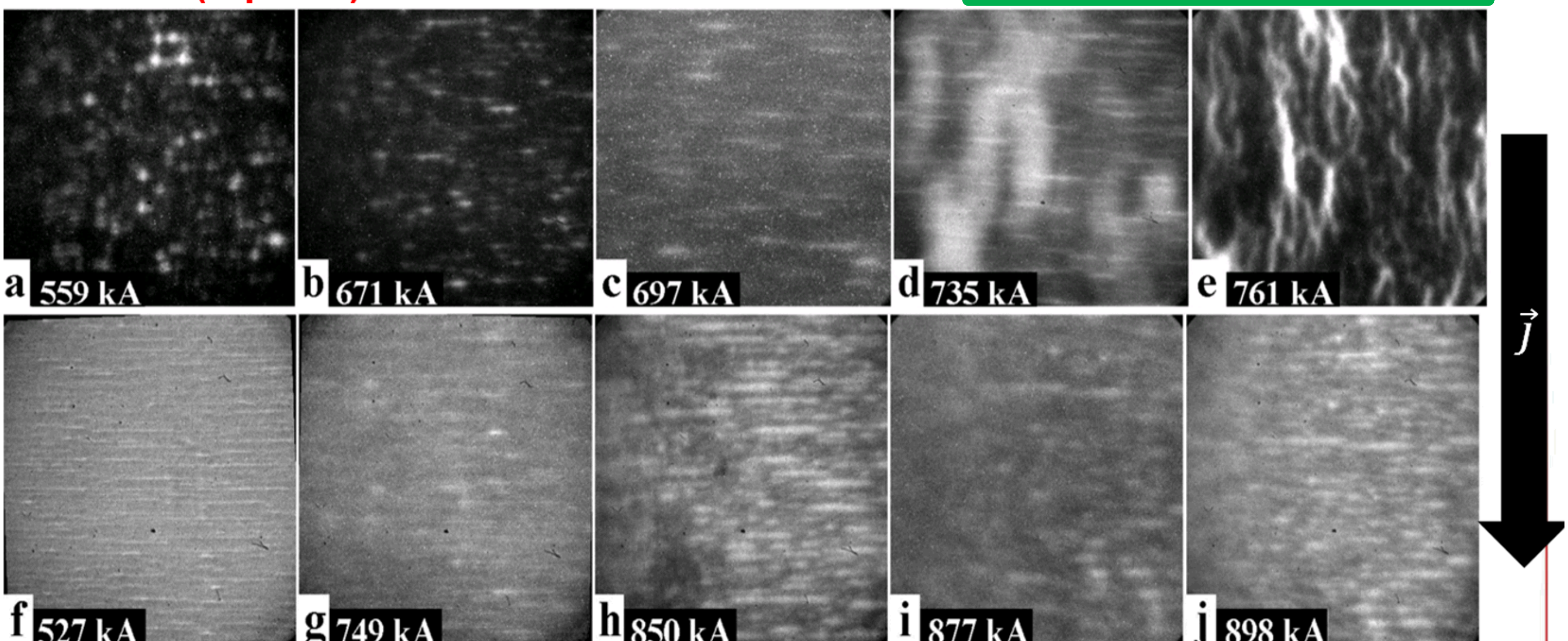
For uncoated aluminum, strata are the dominant surface emission feature for only ~5 ns

Dielectric coatings tamp expansion and mitigate surface plasma formation, enabling prolonged study of ETI strata

- Onto five rods was chemical vapor deposited with $\mathbf{70 \ \pm 5} \ \boldsymbol{\mu m}$ **of dielectric**
- 70 μm **transmits 85% visible light**
- Machining structure visible through Parylene in **optical microscope pictures**

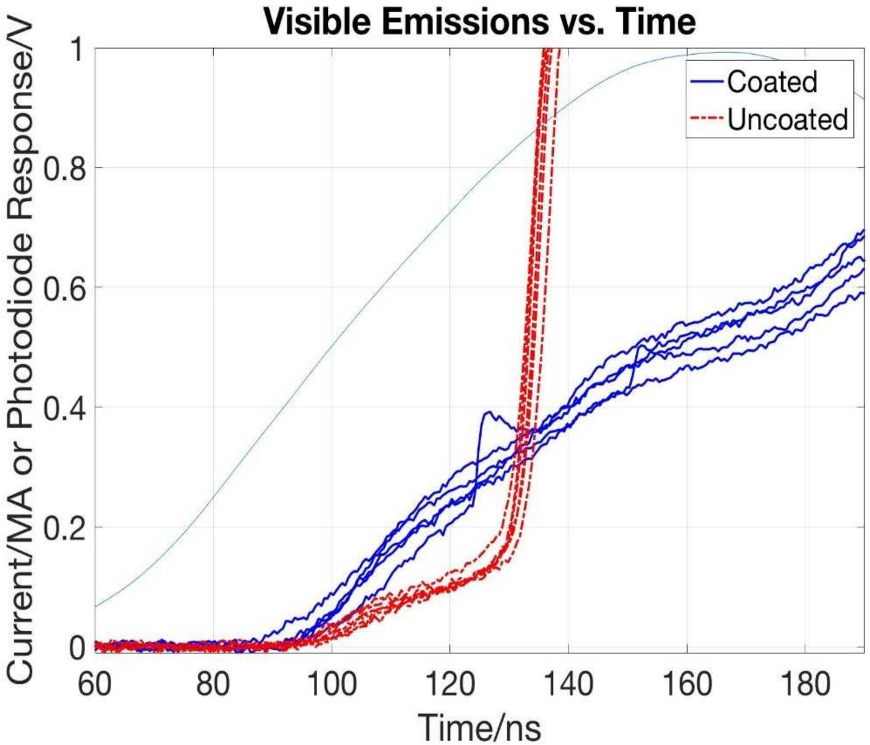


Uncoated (top row)

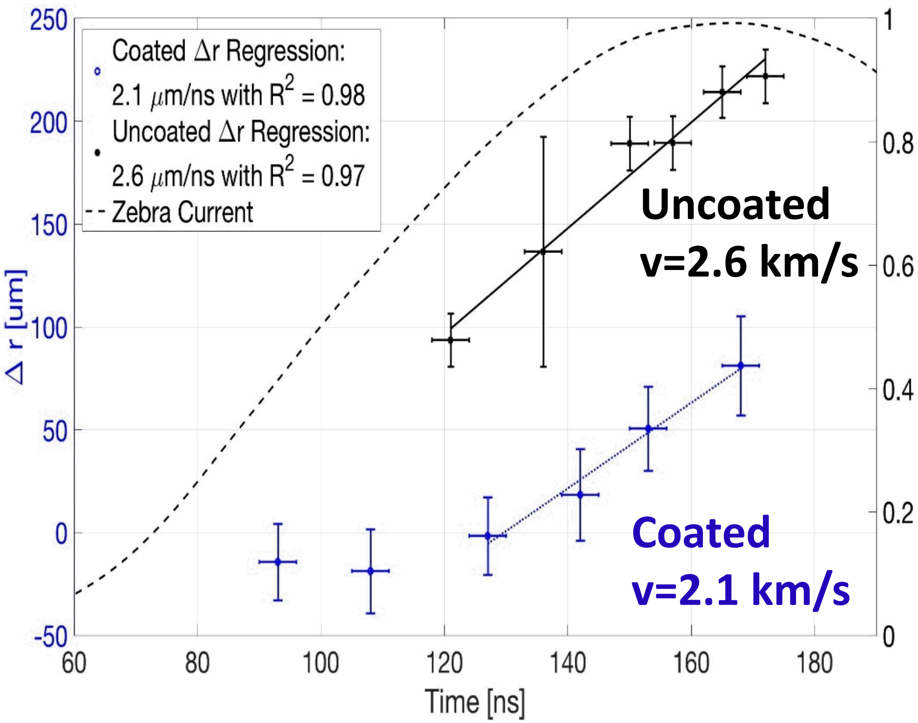


Dielectric coated (bottom row)

VIS Emissions suggest Dielectric Coated Loads do not form plasma



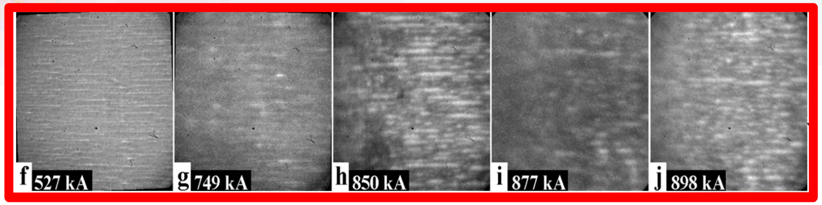
Shadowgraphy indicates tamping, and no appreciable MRT instability growth



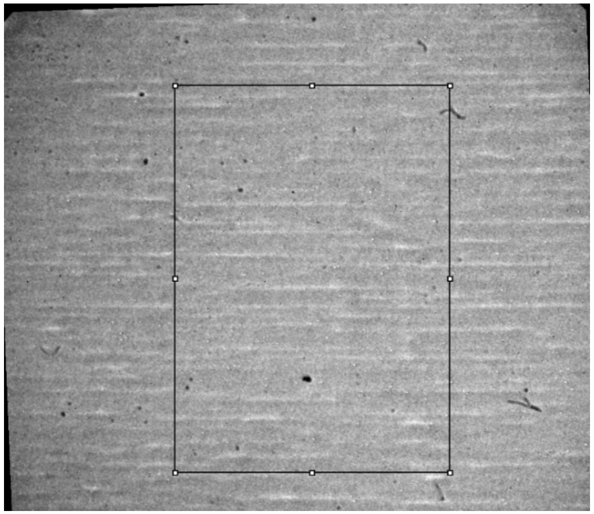
- Coated: Less pdV cooling after melt results in higher early surface temperature
- Uncoated: Sharp knee indicates surface plasma formation; rapid heating follows

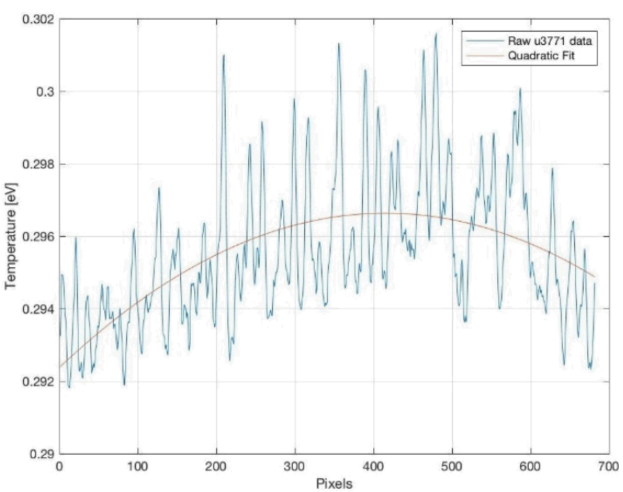
All available data (images, radiometry, expansion) indicate plasma does not form for coated rods

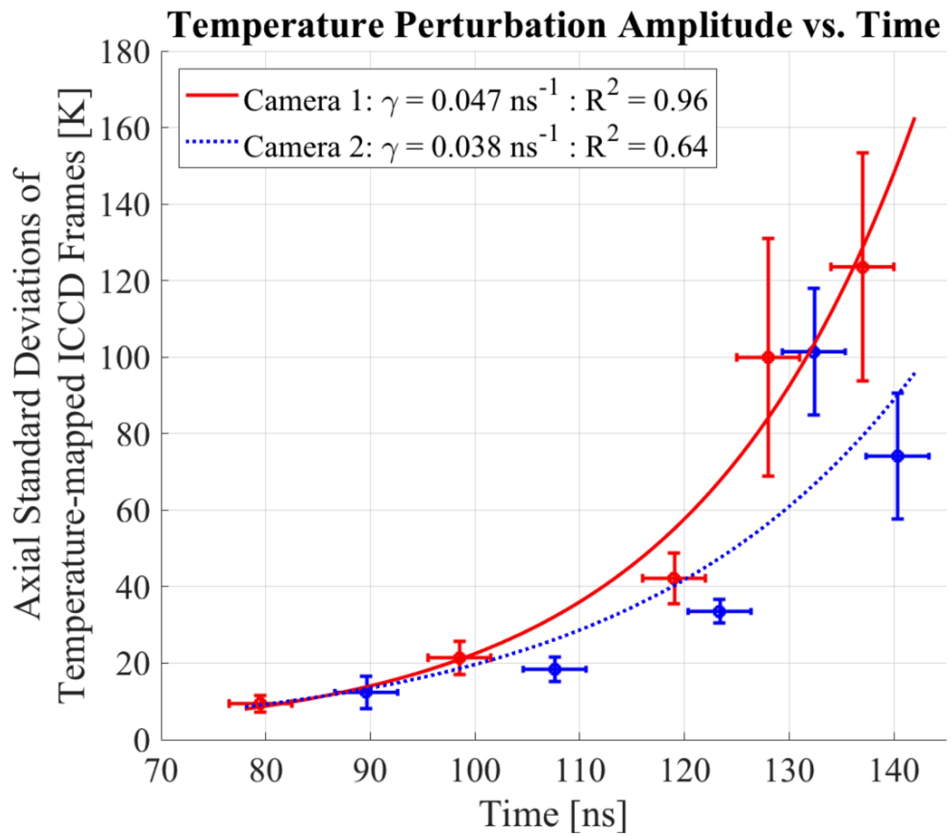
Measured strata δT grows in time and is best fit with an exponential (T.M. Hutchinson, PO8, Wed. afternoon)



The first direct observation of stratified ETI on the surface of thick metal has been made



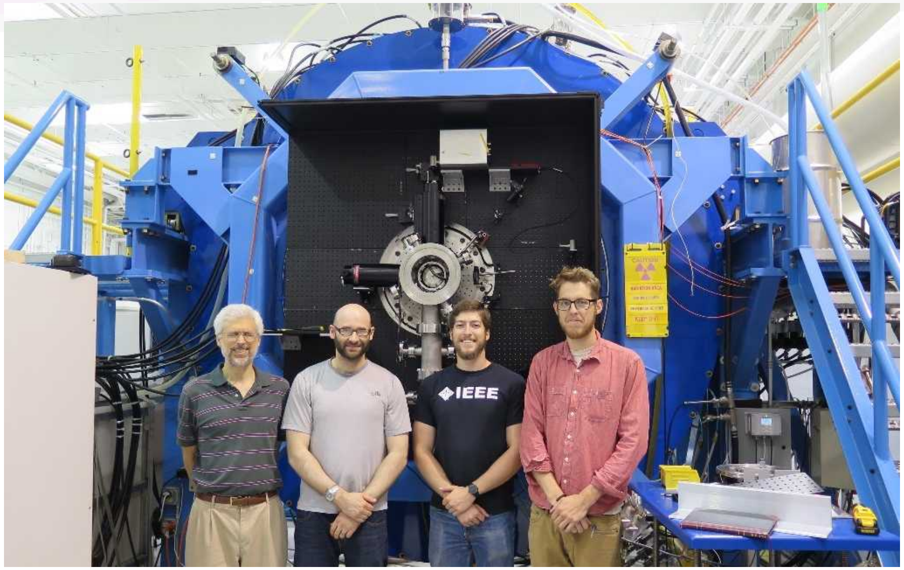


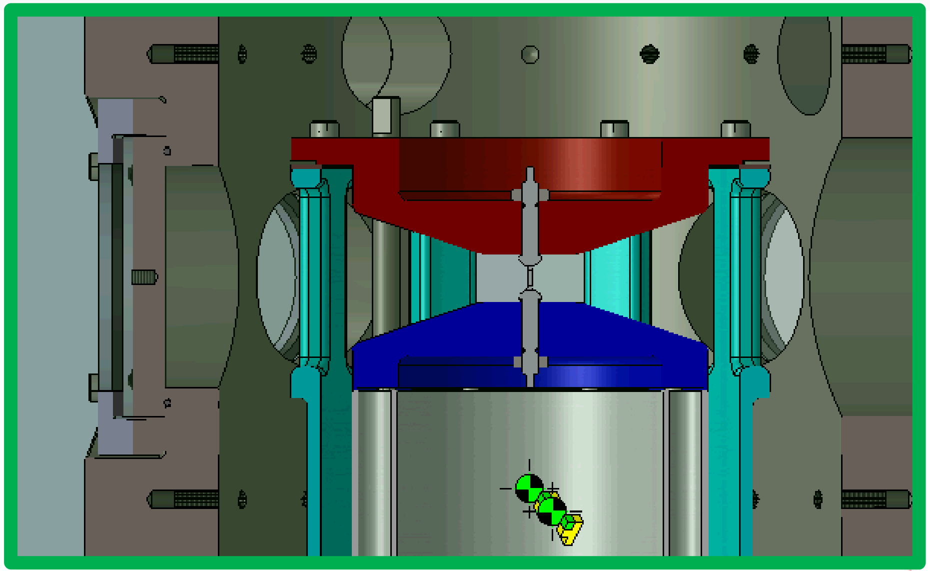


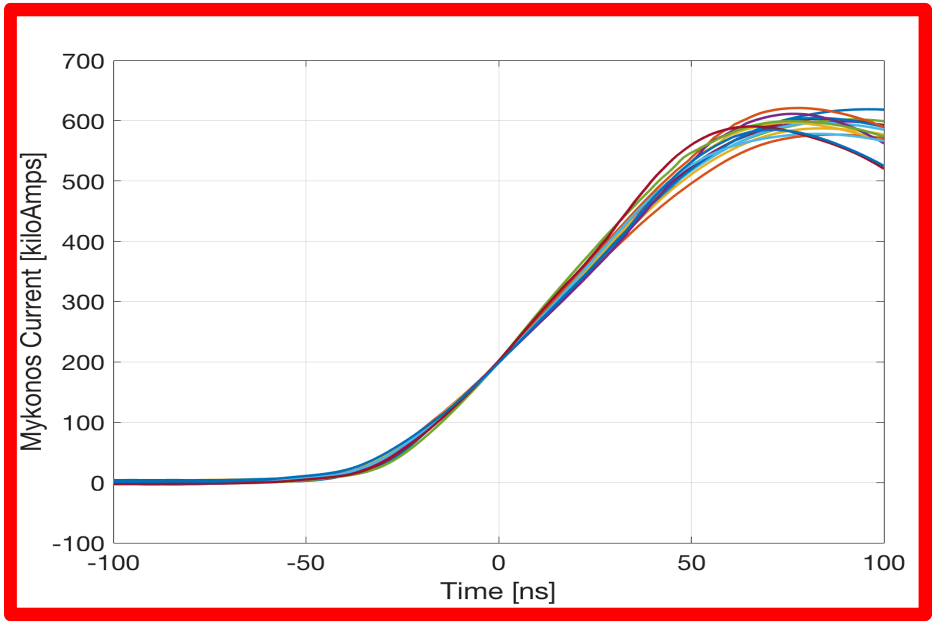
T.M. Hutchinson *et al.*, manuscript submitted to PRL

***γ compared against thin wire theory and simulation**

Experiments on Sandia's Mykonos LTD will provide new data on ETI evolution

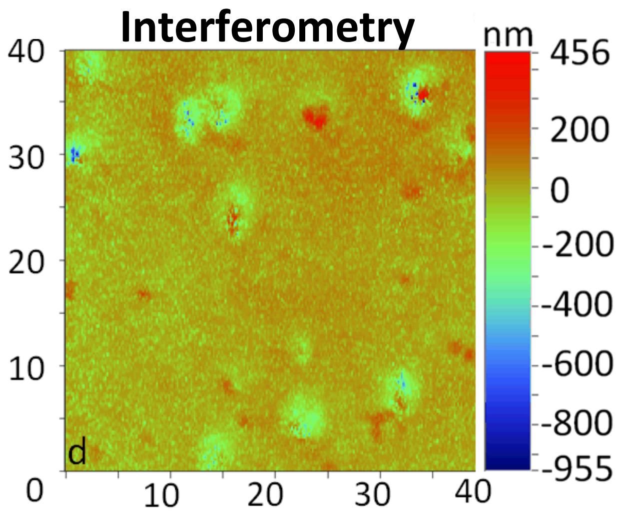


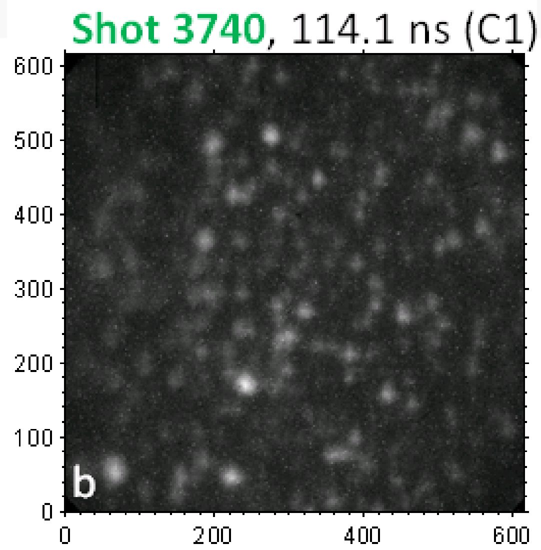


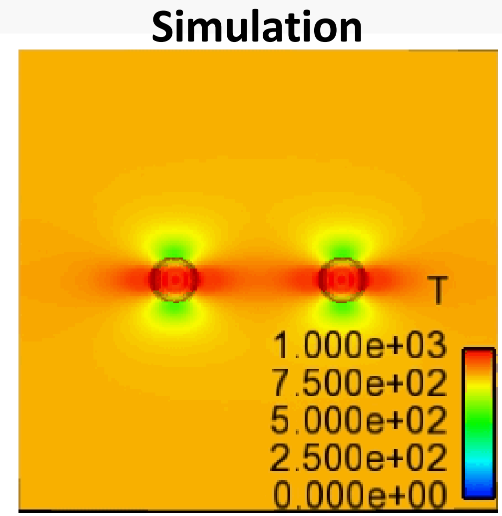


- Small radius vacuum chamber allows optics ~5" from load (versus ~13" on Zerbra)
- Reproducible ~600 kA peak current
- Add streaked visible spectroscopy (SVS) and chordal photon doppler velocimetry (PDV) diagnostics
- Pulsed-laser timing fiducial

<u>In progress</u>: Advanced targets and simulations are required to unravel the complex physics of ETI







Accurately modeling ETI is a significant challenge

Comparative dataset must be unambiguous

- **Off the shelf metals contain extremely complex resistive inhomogeneity, making <u>detailed comparison with simulation nearly impossible</u>**

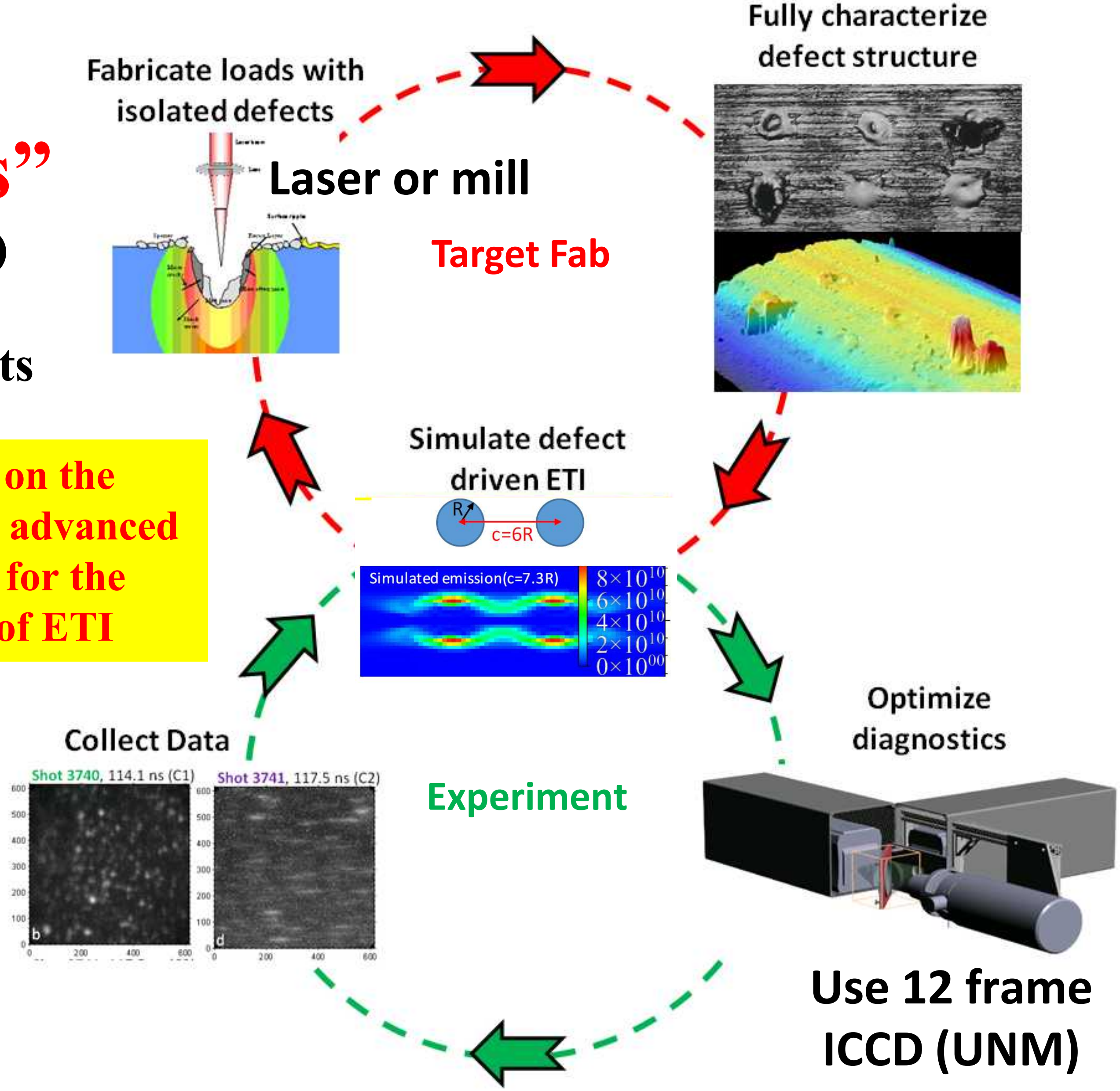
In progress: Study electrothermal instability (ETI) growth from z-pinches with "engineered defects"

Start with "blank canvas"

- 5N Al (single crystal?)
- DT+EP to Ra<50 nm
- Add engineered defects

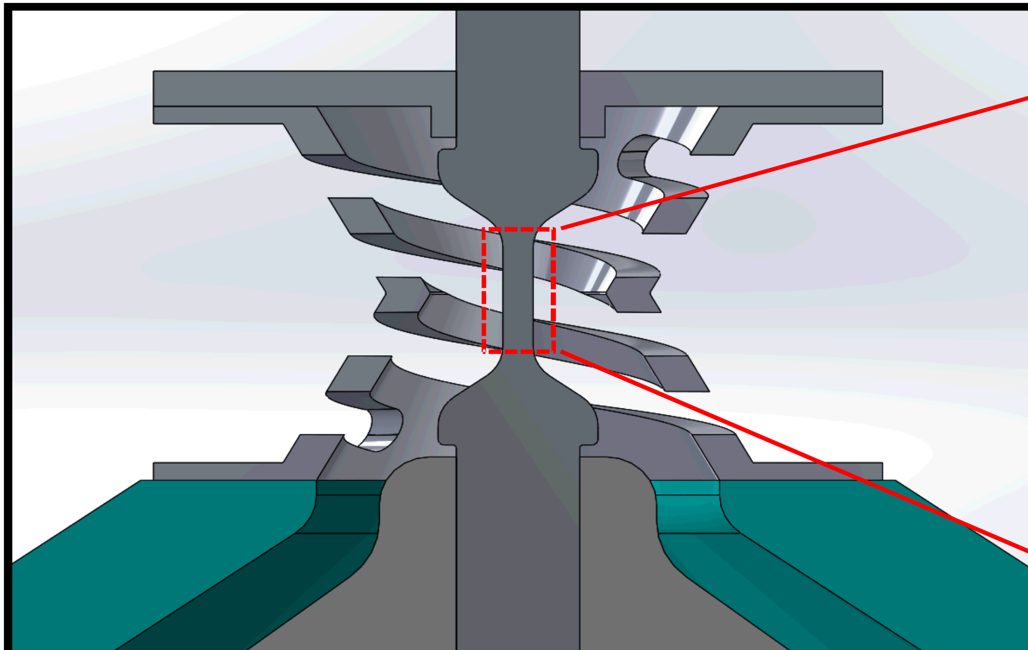
Emphasis is placed on the development of greatly advanced computational tools for the accurate modeling of ETI

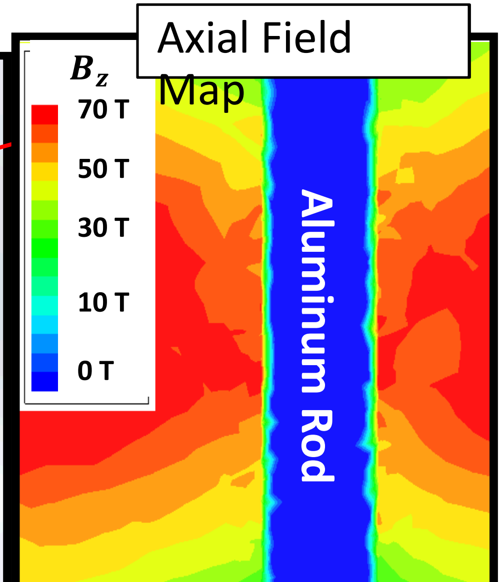
General atomics will begin fabrication of 5N rods with engineered defects early in CY18



Future work: A mixed drive field ($\vec{B} = B_\phi \hat{\phi} + B_z \hat{z}$) may fundamentally alter ETI strata and filaments

Twisted return can drives B_z (J_ϕ) at the rod surface





1mm diameter rod

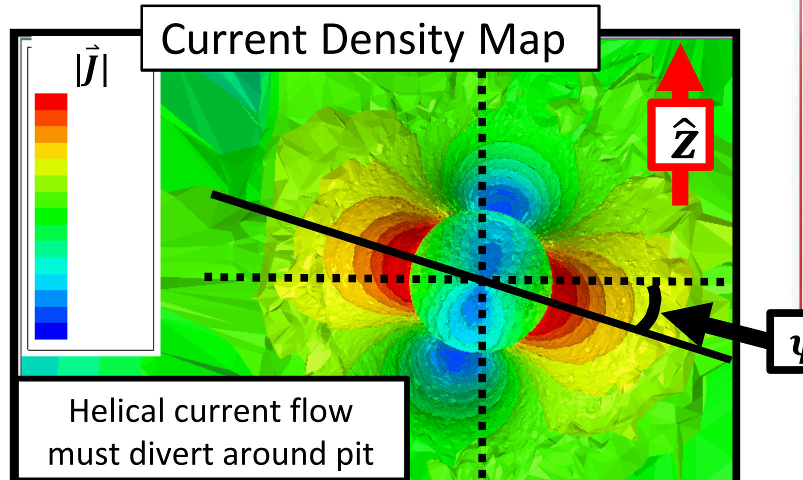
For rod surface at 600 kA:

$$B_\phi \sim 240 \text{ T}$$

$$\frac{B_z}{B_\phi} = 0.25$$

($\frac{B_z}{B_\phi}$ remains constant!)

- Additional magnetic field (current density) at the rod surface could alter ETI mode formation, orientation, and growth duration
- Current flow around a surface pit indicates that ETI modes will form and extend in a helical sense aligned with the drive magnetic field



Summary

- 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 reduce MRT amplitude, likely by tamping the ETI-driven surface perturbation; ETI is **NOT** directly observed
- Early nonuniform Joule heating has been observed with unprecedented precision
  - Emission is first observed from 10-micron-scale, sub-eV spots. Which merge to form azimuthally correlated strata
- 3D MHD simulations of simplified, localized perturbations (pits & ↑η inclusions) illustrate for the first time how global ETI structures form
- Dielectric coatings provide surface tamping and suppress plasma formation, enabling prolonged observation of strata. Image analysis indicates exponential growth of temperature perturbations.
- Future studies: ETI growth from Al z-pinches with lattices of "engineered" defects, and impacts of a mixed drive field (add B_z)

Summary

- MRT on imploding liners is larger amplitude and more azimuthally correlated than expected. Early ETI growth may explain these observations
- Dielectric coatings greatly reduce MRT amplitude, likely by tamping the ETI-driven surface perturbation; ETI is NOT directly observed
- Early nonuniform Joule heating has been observed with unprecedented precision

  →Emission is first observed from 10-micron-scale, sub-eV spots. The number nearly equals the number of micron-scale inclusions

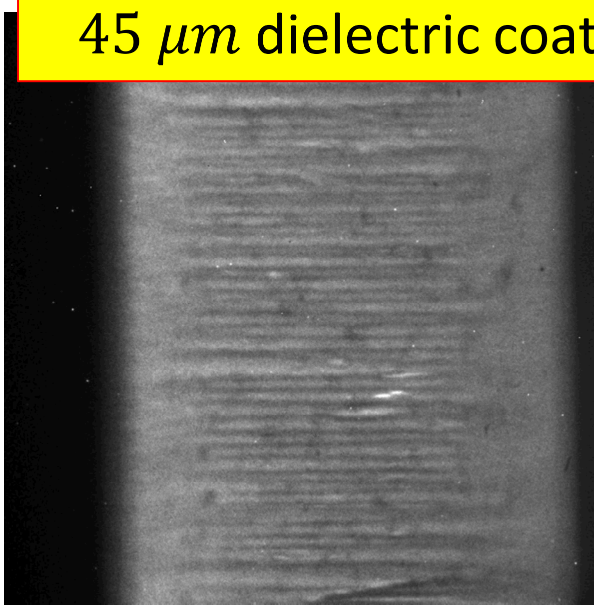
  →Discrete round spots, merge to form azimuthally correlated strata; such observations can be explained by ETI-related current redistribution
- The first direct observation of stratified ETI on the surface of thick metal has been made. Dielectric coatings inertially tamp the metal and suppress surface plasma formation, enabling prolonged observation of strata. Radiometry indicates exponential growth of temperature perturbations.

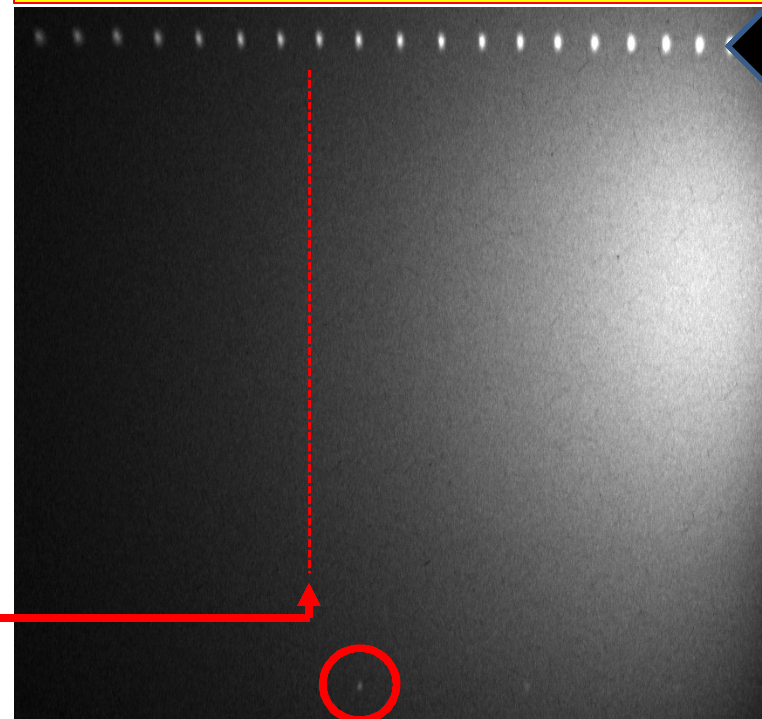
END

Experiments observed ohmic heating and ETI on Mykonos (ADD uncoated data)

Coated Load Spectrum vs. Time shows no spectral lines → no plasma

ICCD Imaging shows strata with $\lambda \approx 20\ \mu m$ under $45\ \mu m$ dielectric coatings

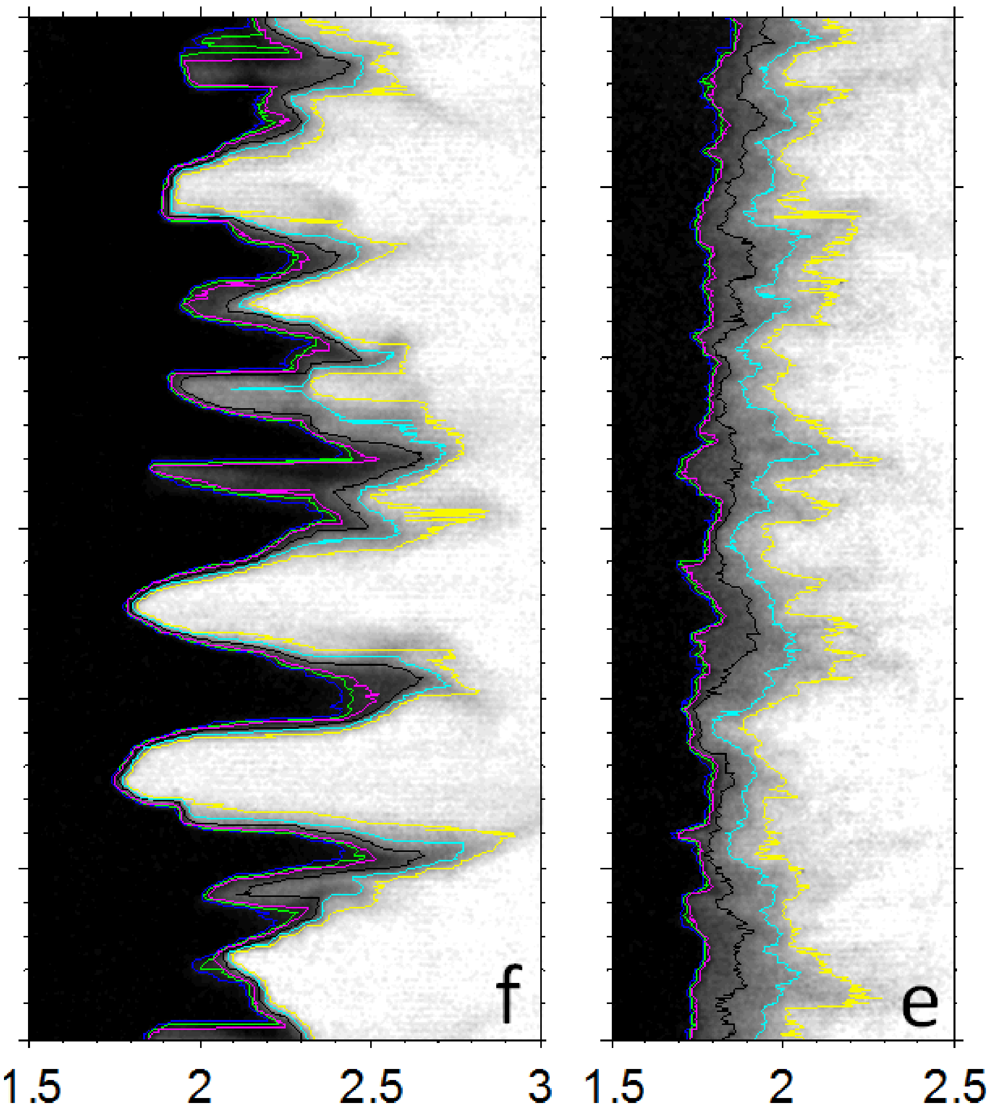




$\sim 500\ kA$

260 kA

Timing Fiducial, 550 kA



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

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

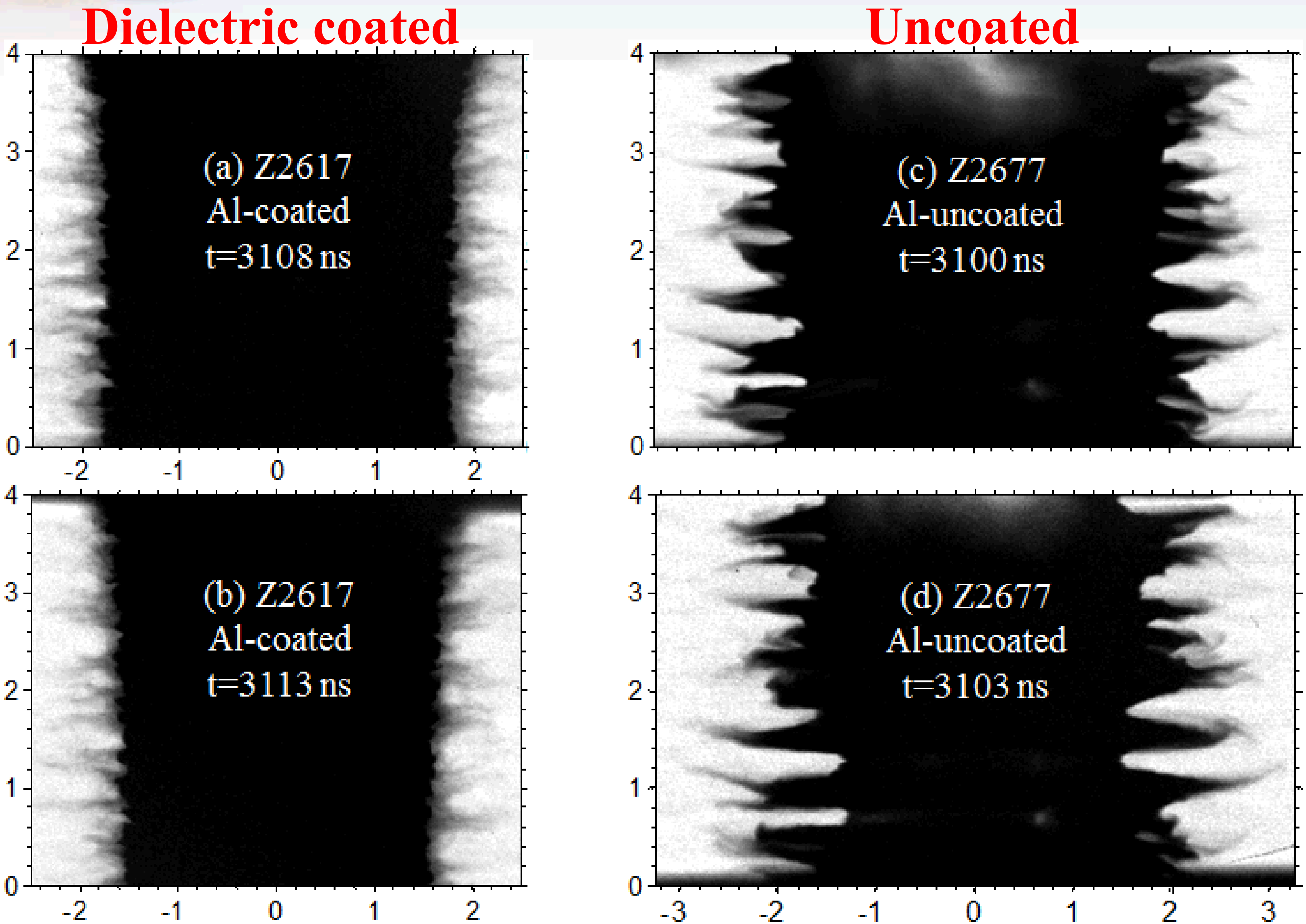
$$C_{ij} = \int_{L1}^{L2} \Delta r_i(z)\Delta r_j(z)dz \Big/ \sqrt{\int_{L1}^{L2} \Delta r_i^2(z)dz \int_{L1}^{L2} \Delta r_j^2(z)dz}$$

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

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

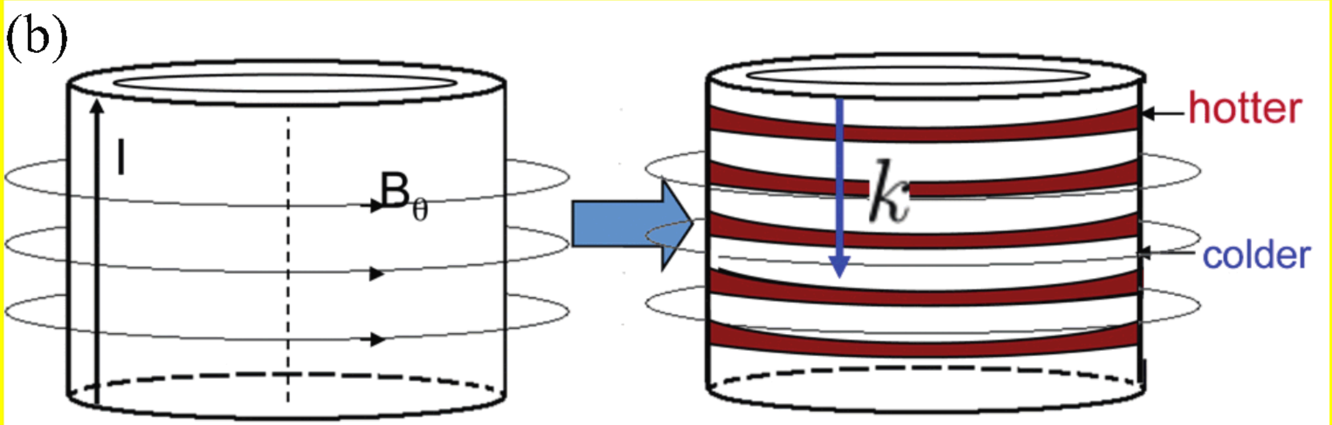


T.J. Awe *et al.*, Phys. Rev. Lett. 116, 065001 (2016)

Electrothermal instabilities occur when material conductivity is dependent on temperature

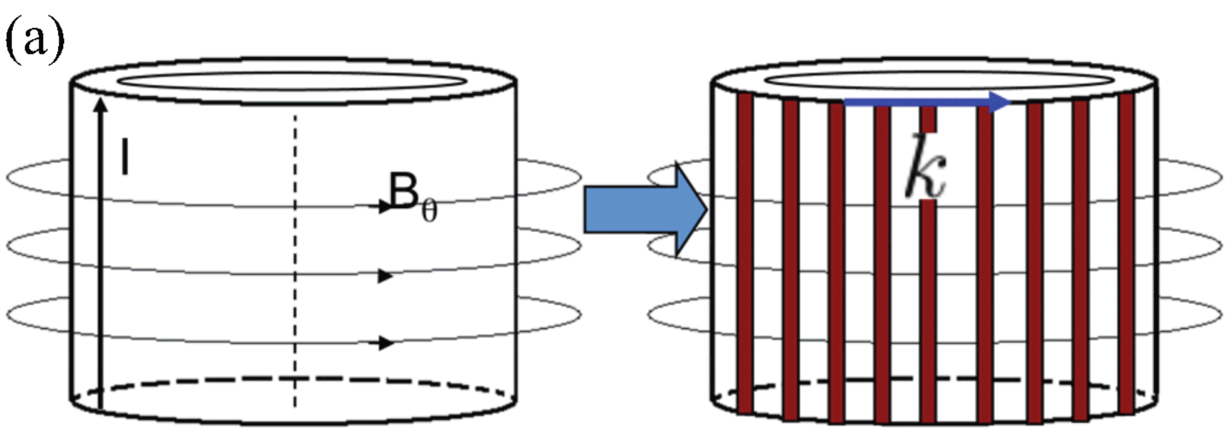
Condensed metals form striations

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

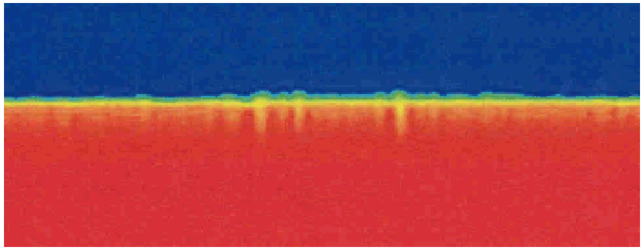


Plasmas form filaments

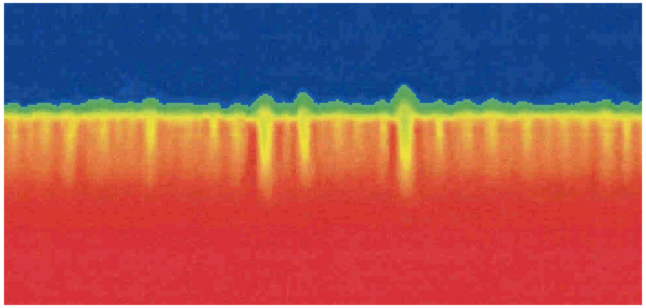
$$\frac{d\eta(T)}{dT} < 0$$



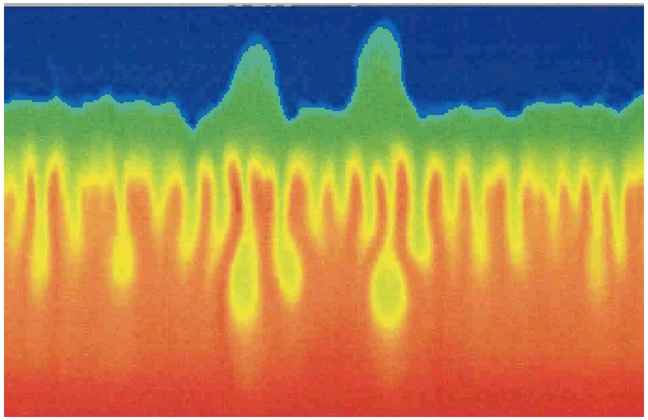
2D simulations show electro-thermal instabilities develop after melt and seed later MRT growth



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

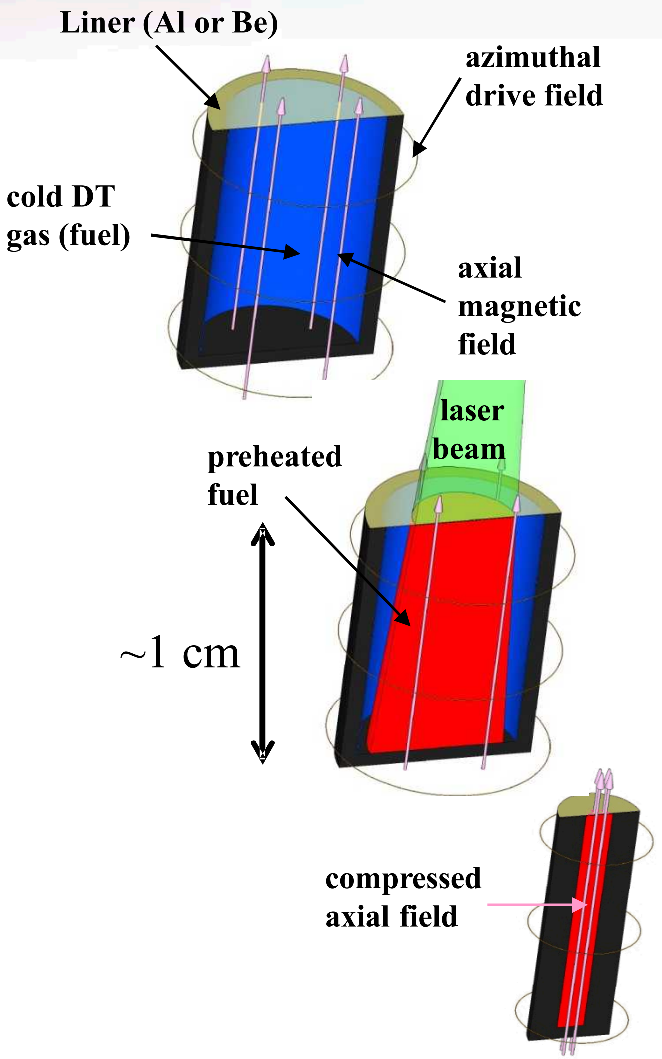


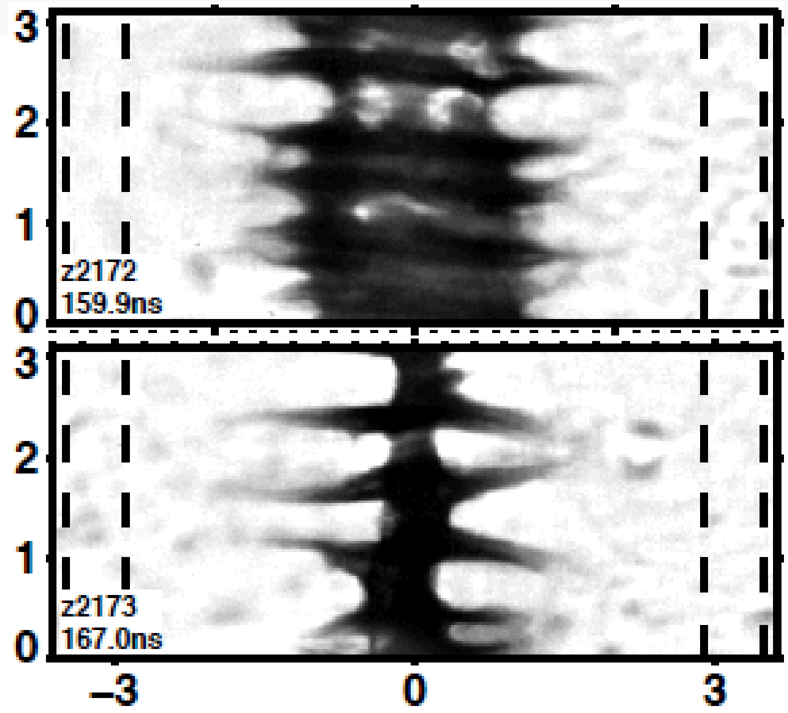
Non-linear MRT growth redistributes liner mass; large amplitude perturbations persist and grow

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

Sandia National Laboratories

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



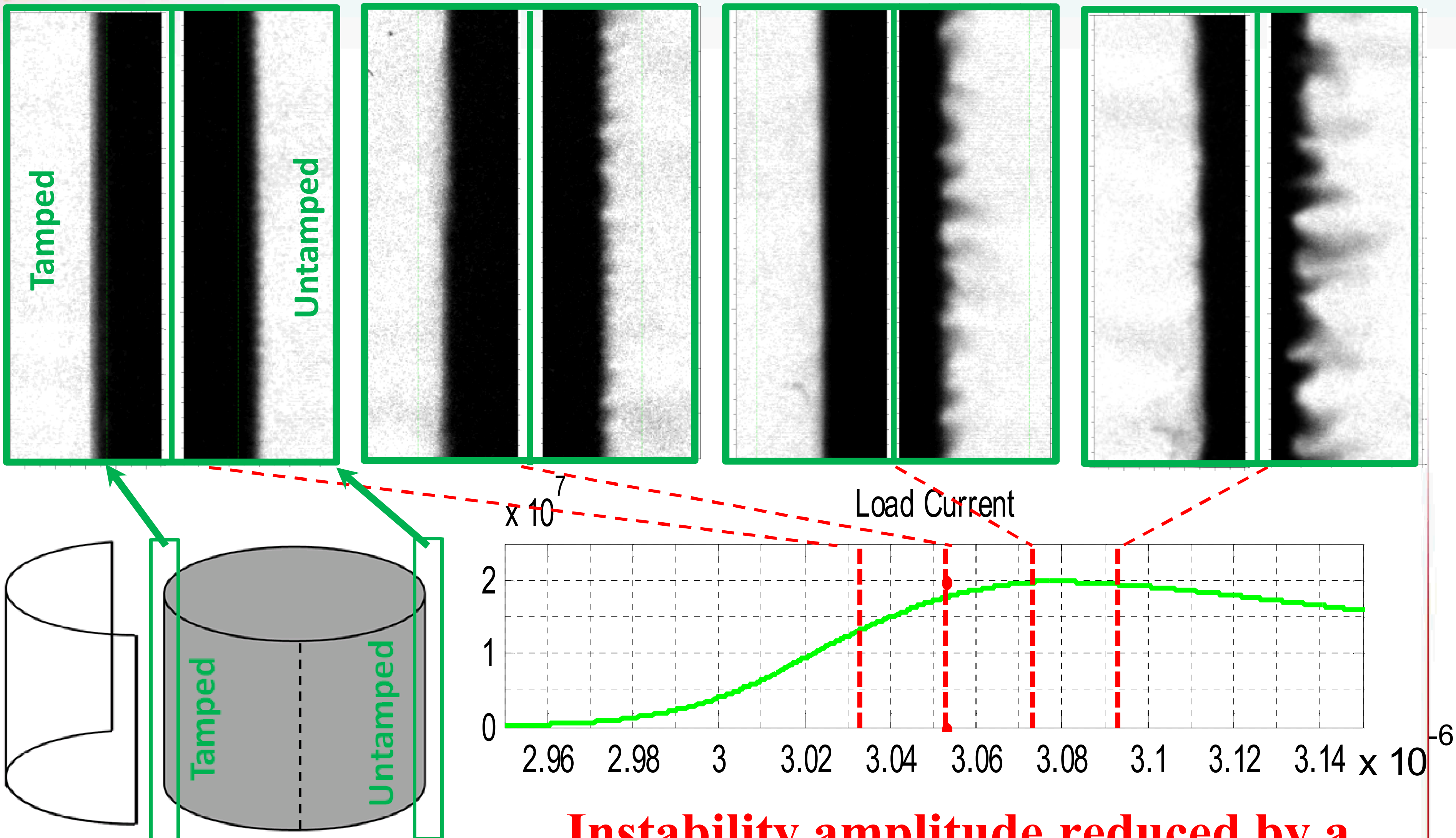


"The magneto-Rayleigh-Taylor (MRT) instability poses the greatest threat to this (MagLIF) approach to fusion."

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

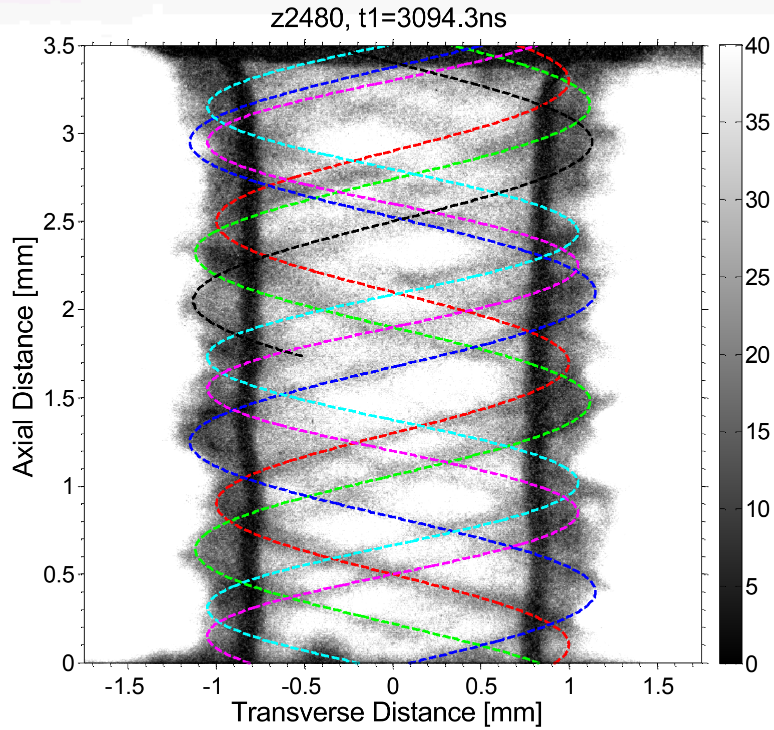
Adding a 70-micron-thick dielectric tamper dramatically alters MRT growth on a solid (R_0=3.43 mm) Al rod

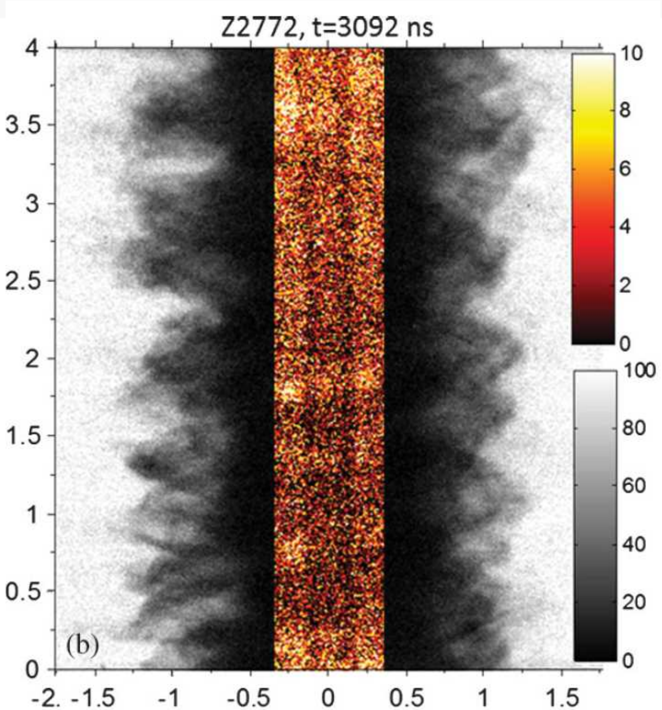


Instability amplitude reduced by a factor of 10

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

Detailed understanding of ETI may be required to explain recent successes in increasing liner stability



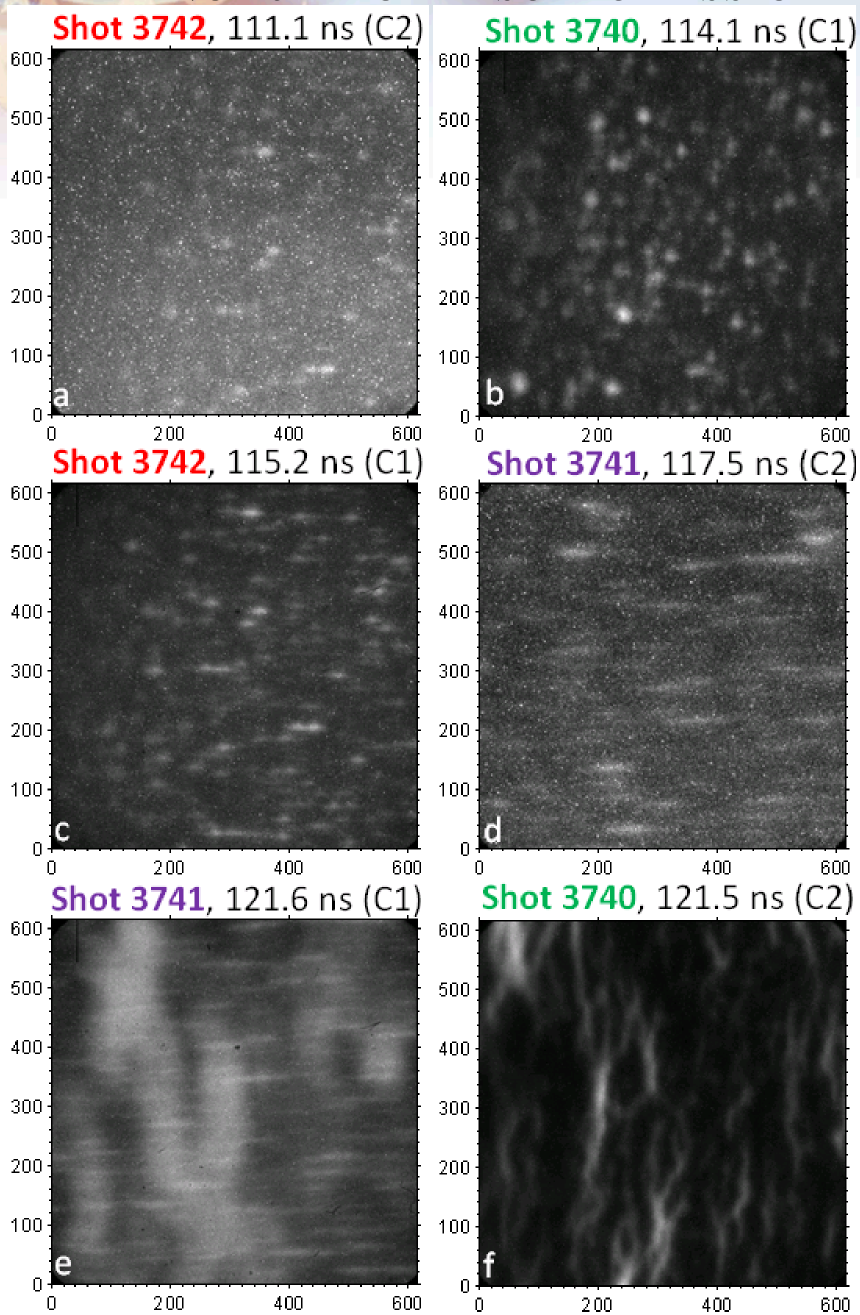


What seeds the helical instability?
Why does it persist and grow?

Do dielectric tampers mitigate mass redistribution from ETI?

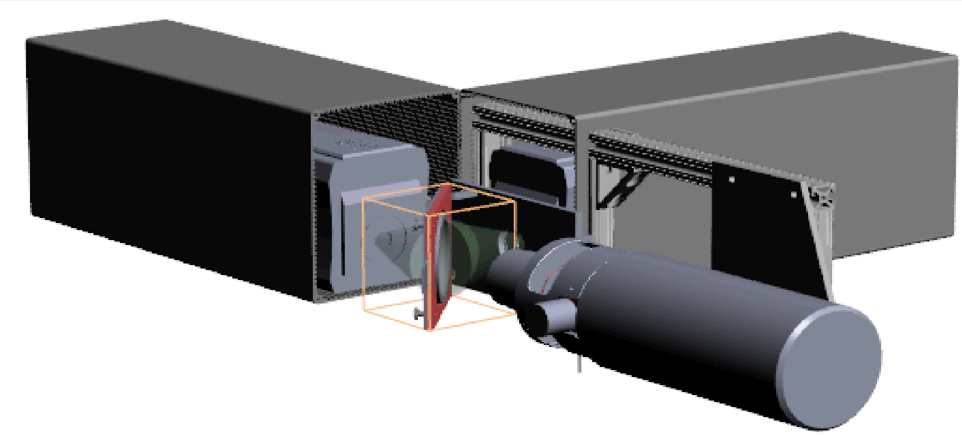
The early nonuniform Joule heating of Z liners is not diagnosed. ETI development is inferred by evaluating MRT late in the experiment. ETI is NOT directly observed!

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!

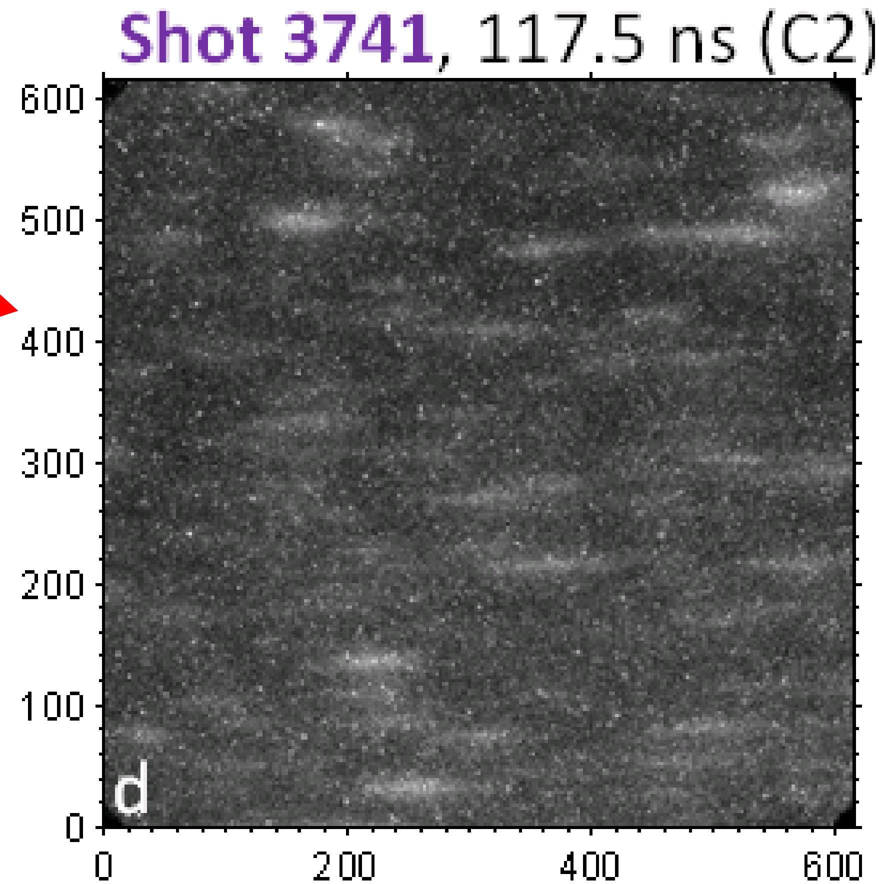
Nonuniform self-emission from Al 6061 loads evolves rapidly

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.

Surface Emissions evolve from…

To…

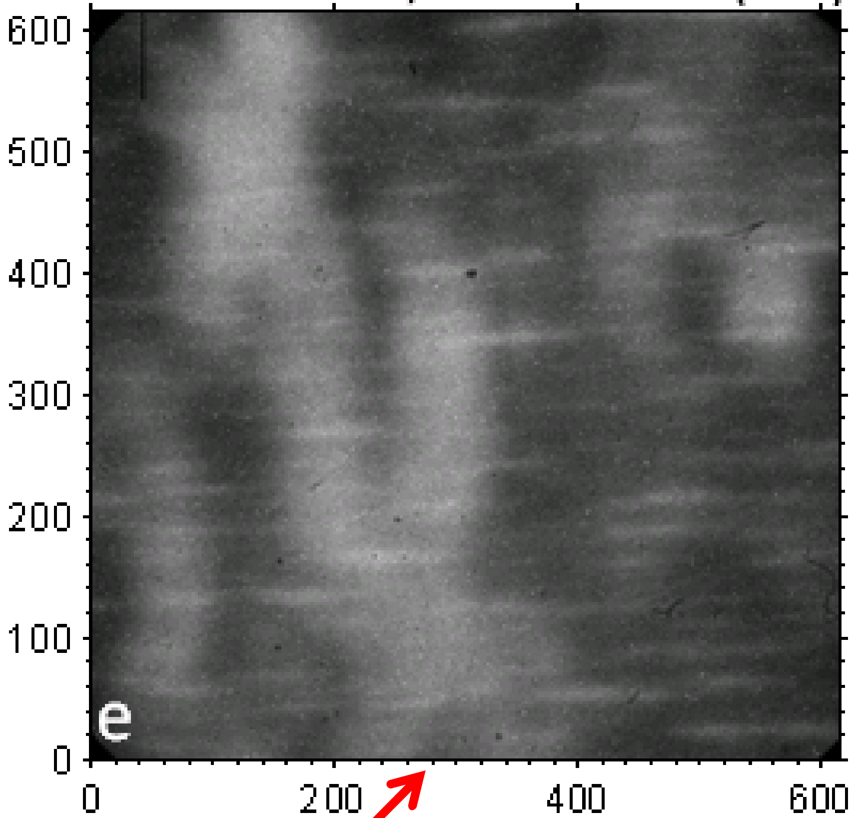
- Azimuthally elongated strata ($\partial\eta/\partial T>0$)



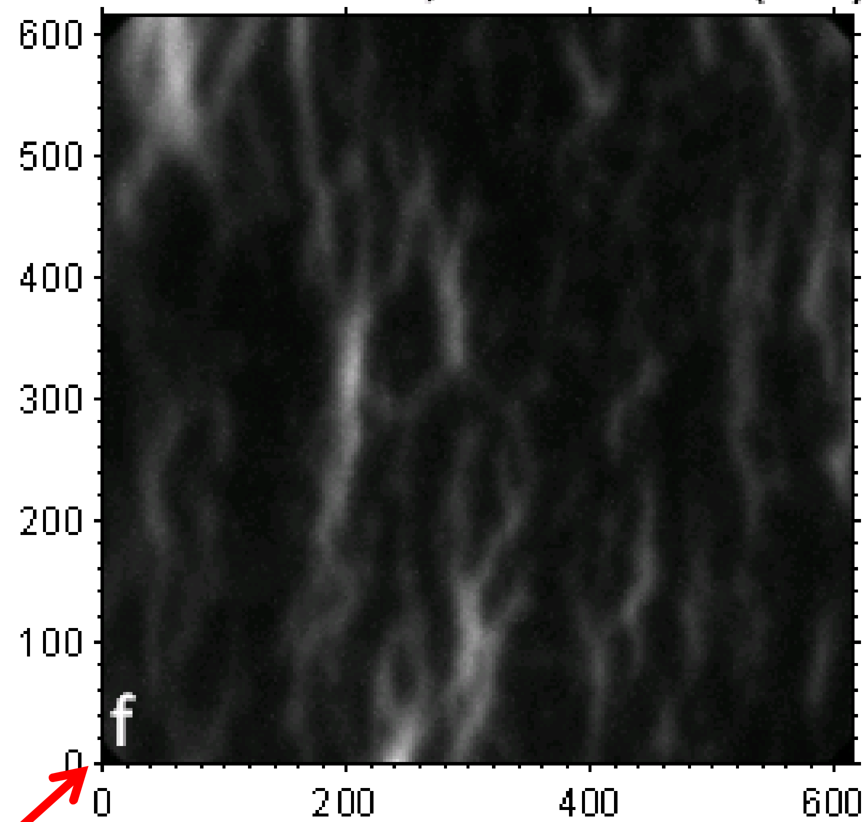
Axes in [μm]

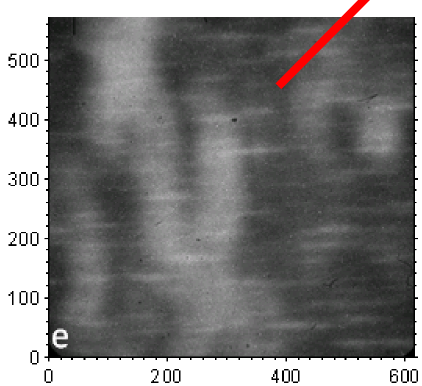
Nonuniform self-emission from Al 6061 loads evolves rapidly

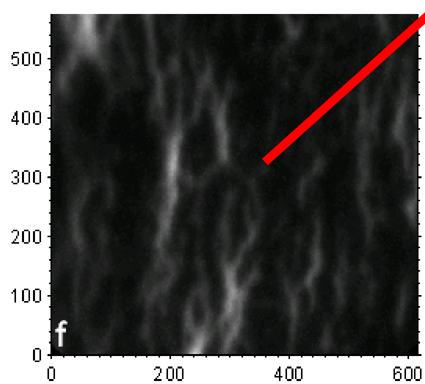
Shot 3741, 121.6 ns (C1)



Shot 3740, 121.5 ns (C2)







Axes in [μm]

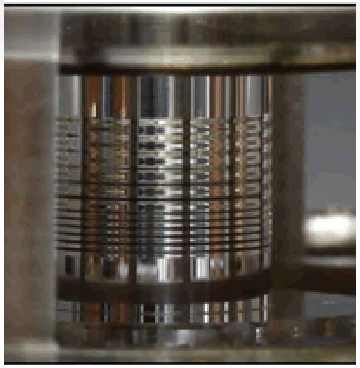
Surface Emissions evolve from strata

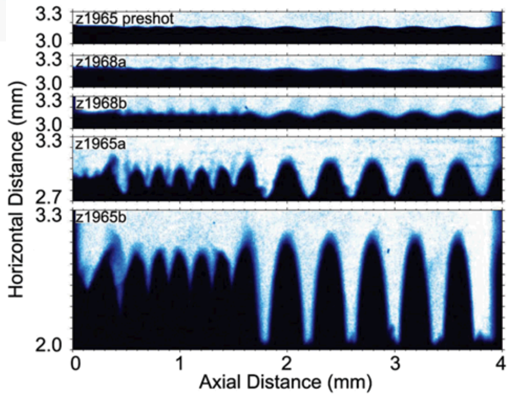
To…

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

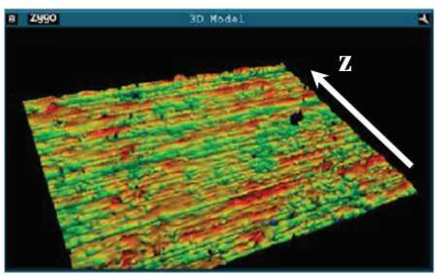
How do filaments form and connect?

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

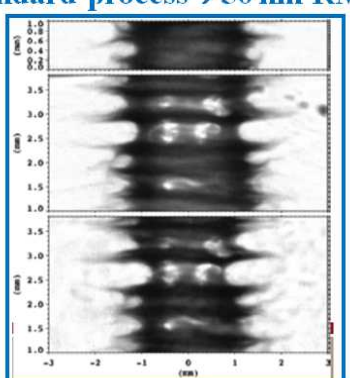


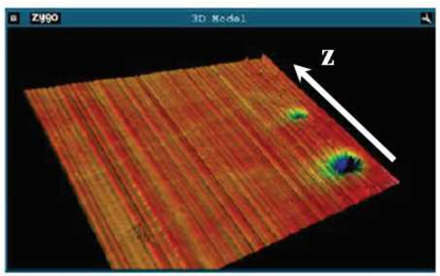


D.B. Sinars *et al*., Phys. Rev. Lett. 105, 185001 (2010)

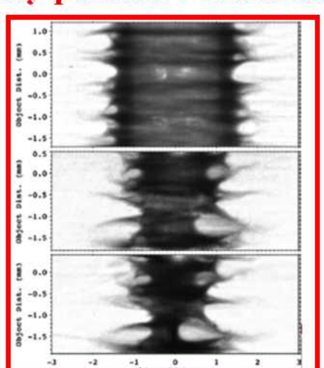


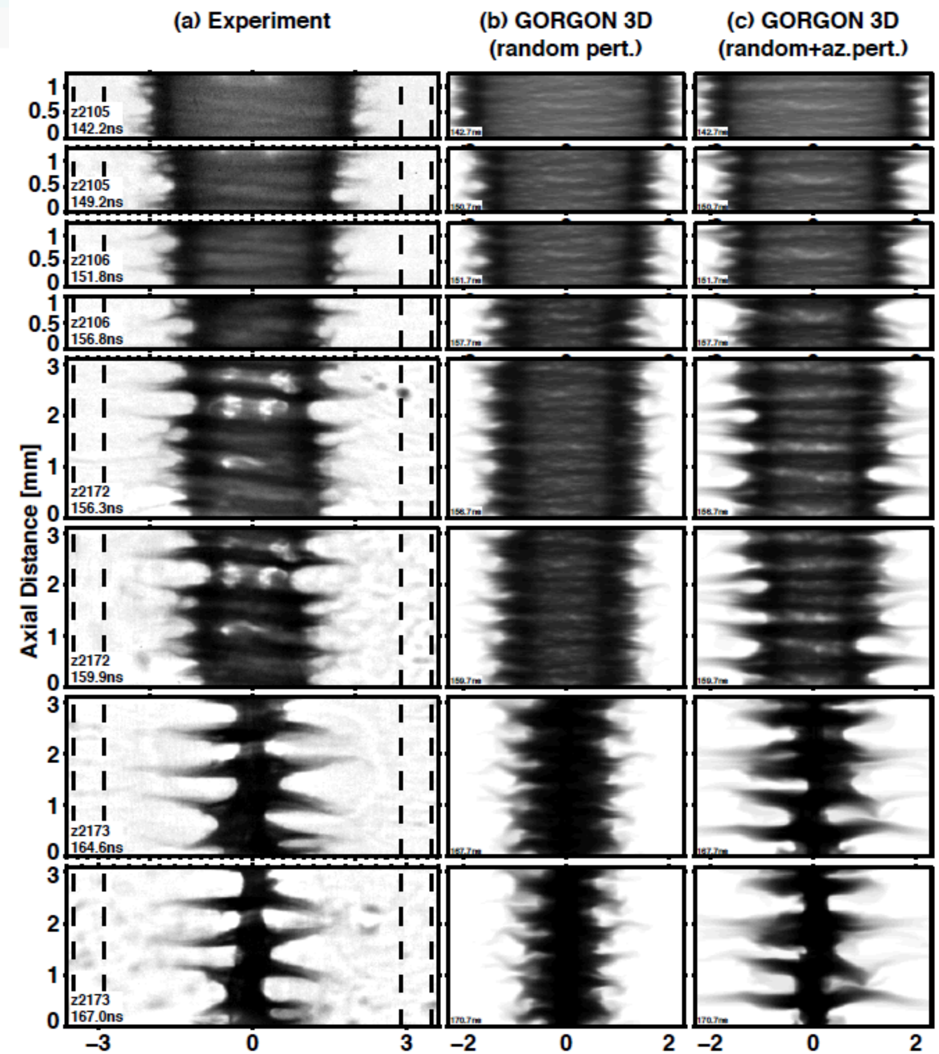
Standard process→50 nm RMS





Axially polished→50 nm RMS



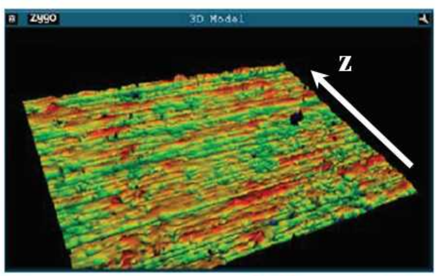


R.D. McBride *et al*., PRL 109, 135004 (2012)

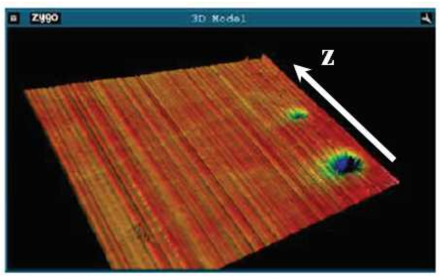
Z Experiments have focused on developing predictive capability of instability growth of imploding liners

Pre-machined large amplitude perturbation: Observed MRT amplitude is not linearly proportional to the amplitude of the initial perturbations.

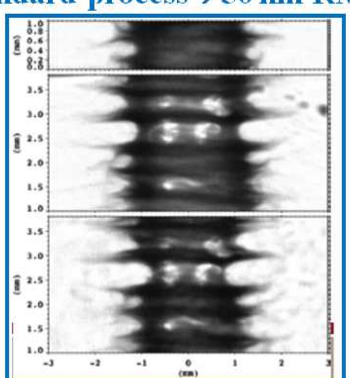
D.B. Sinars *et al.*, Phys. Rev. Lett. 105, 185001 (2010)

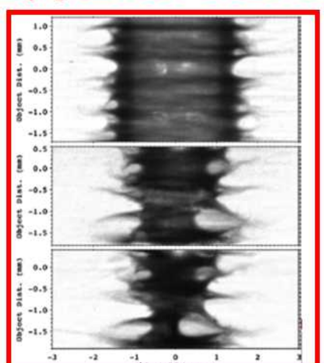


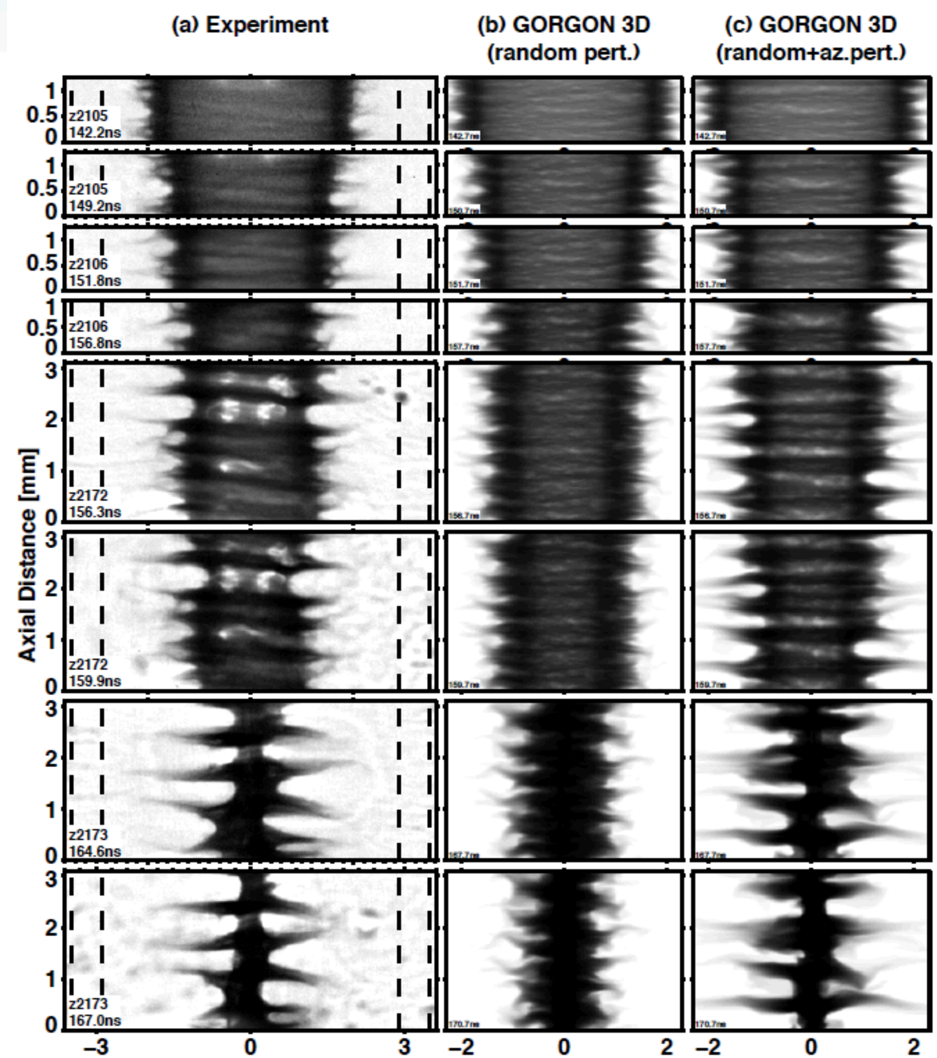
Standard process→50 nm RMS



Axially polished→50 nm RMS

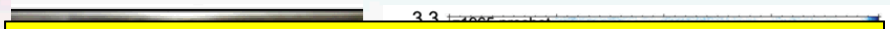






R.D. McBride *et al.*, PRL 109, 135004 (2012)

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



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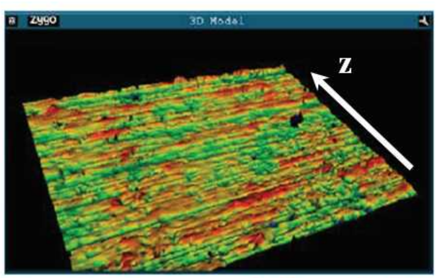

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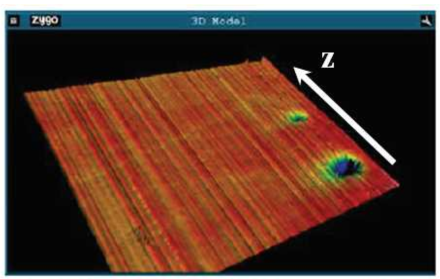

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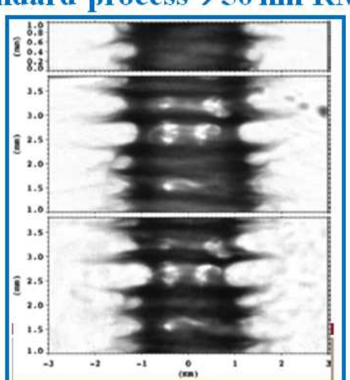

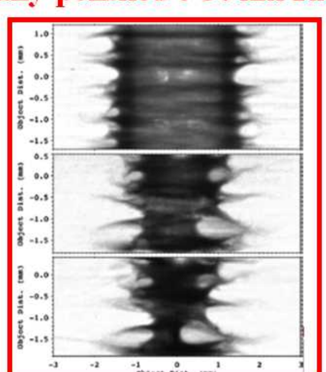

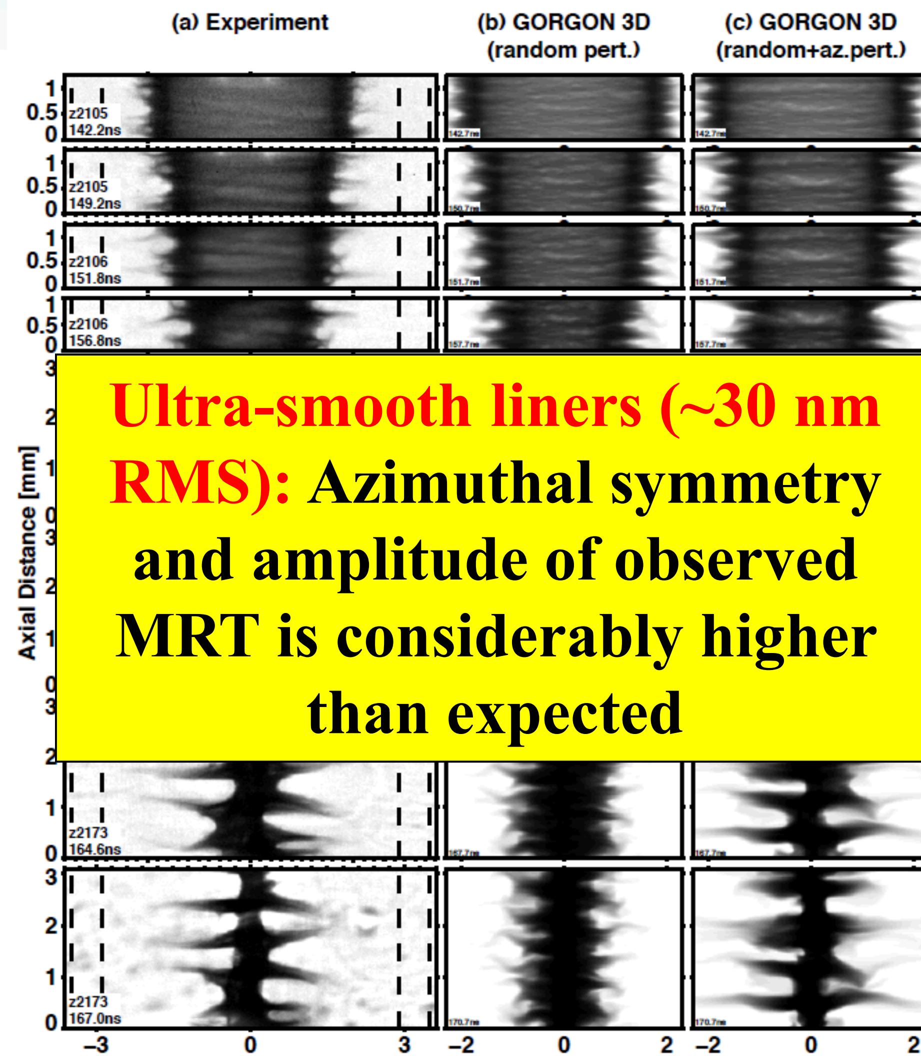

Ultra-smooth liners (~30 nm RMS): Azimuthal symmetry and amplitude of observed MRT is considerably higher than expected

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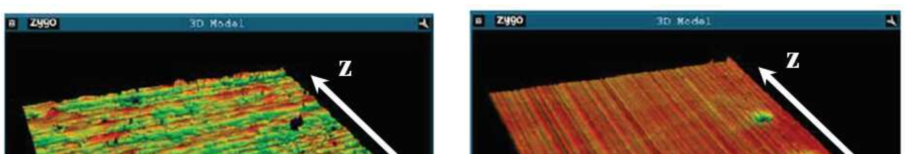
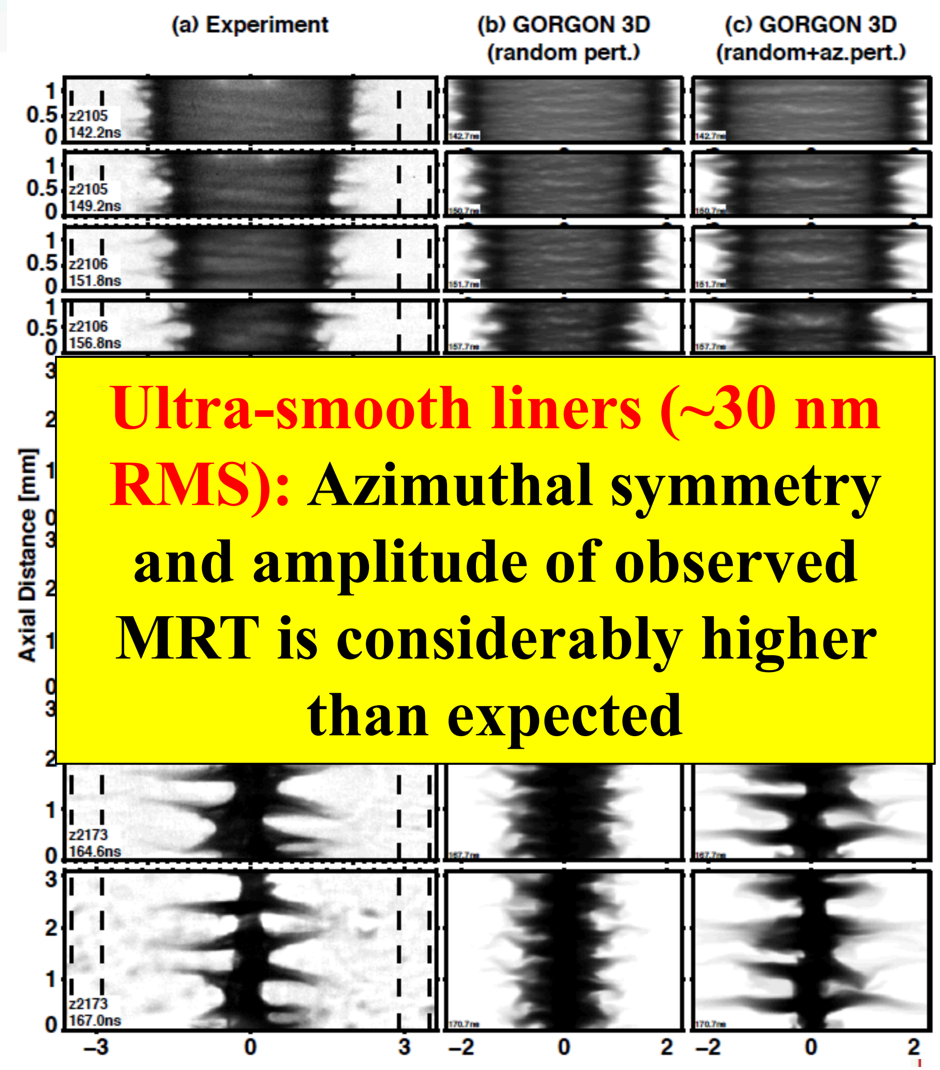


Modified Fabrication Process: Changing the orientation of the machining grooves from azimuthal (lathe) to axial (broaching) had little impact on MRT development



Ultra-smooth liners (~30 nm RMS): Azimuthal symmetry and amplitude of observed MRT is considerably higher than expected

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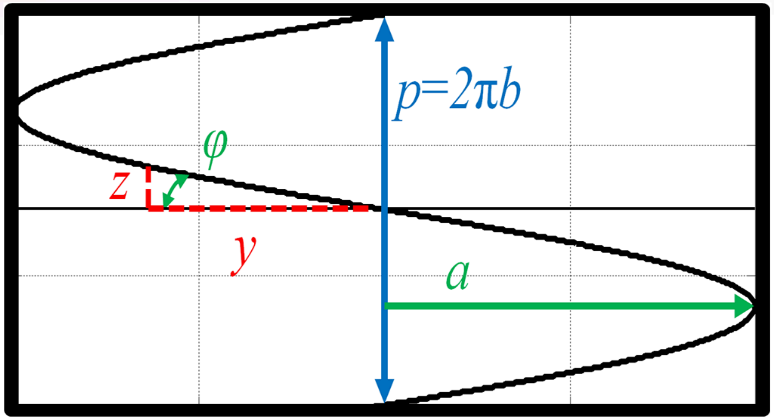
Helical instabilities develop on liners premagnetized with an axial field: *Implosion symmetry increases*



Cylindrical helix model

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

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

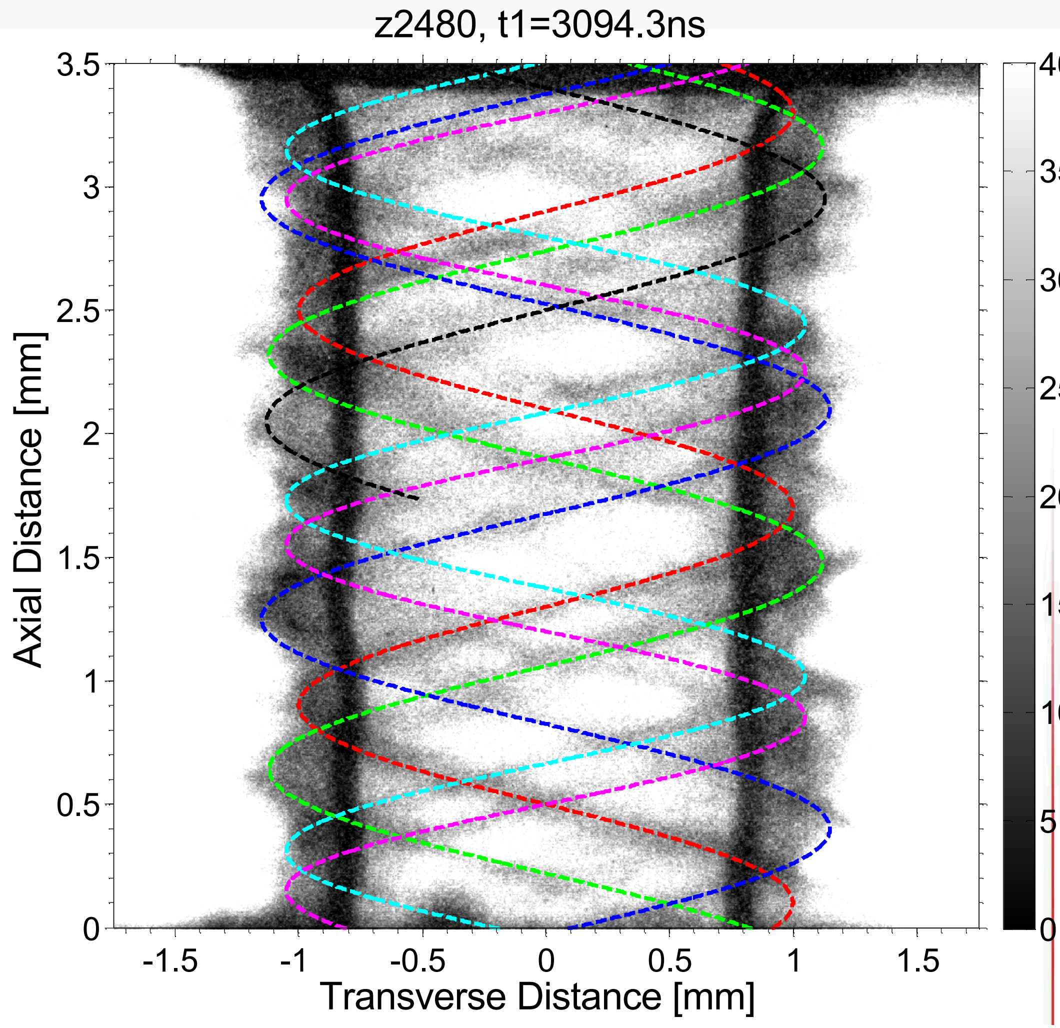
a =radius

p=pitch

"pitch angle"

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

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

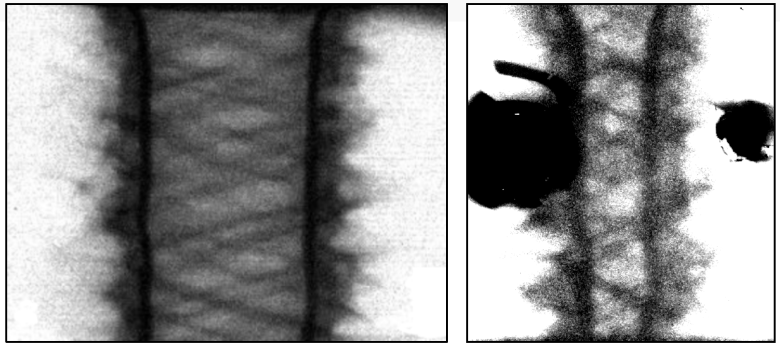


a_{avg}**=1.07 mm**

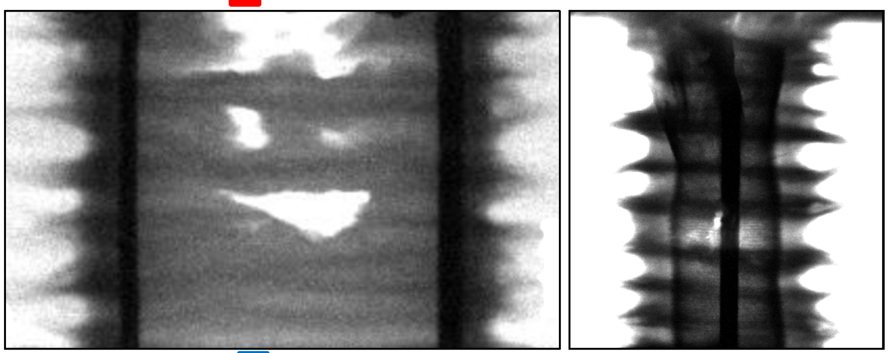
p_{avg}**=1.56 mm**

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

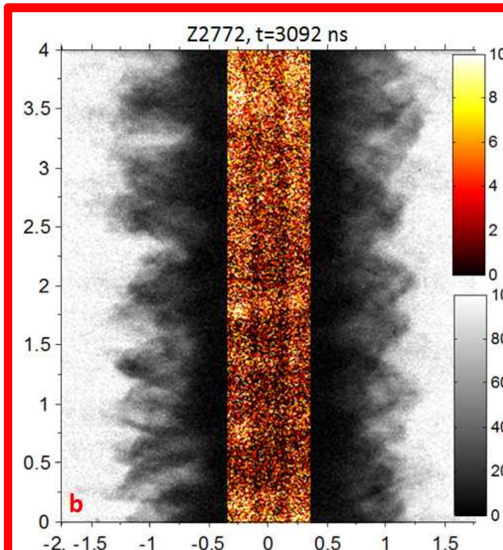
Add B_z=7 T



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

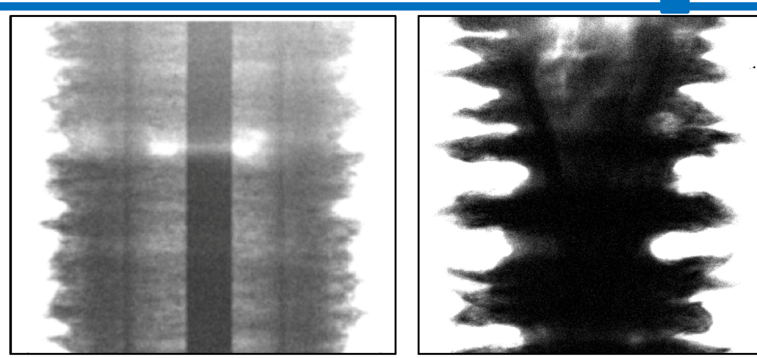


CR=$R_{in}(t=0)/R_{in}(t)$=21!



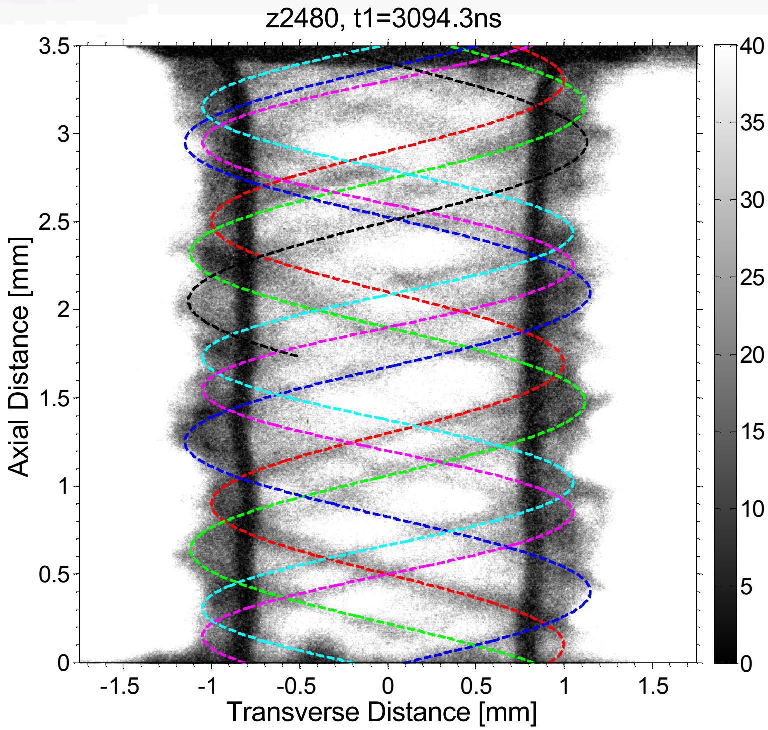
B_z+dielectric

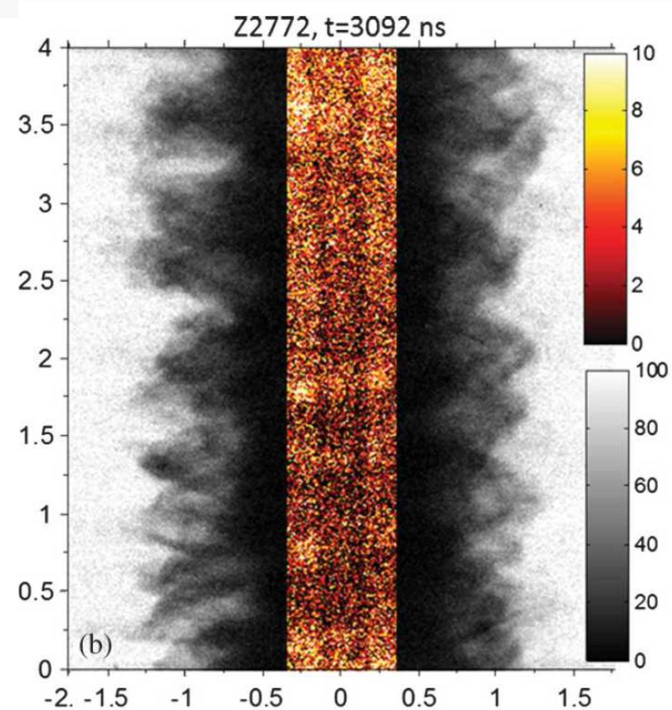
T.J. Awe *et al*., Phys. Rev. Lett. 116, 065001 (2016)



Add dielectric mass tamper; ETI mitigation

Detailed understanding of ETI may be required to explain recent successes in increasing liner stability



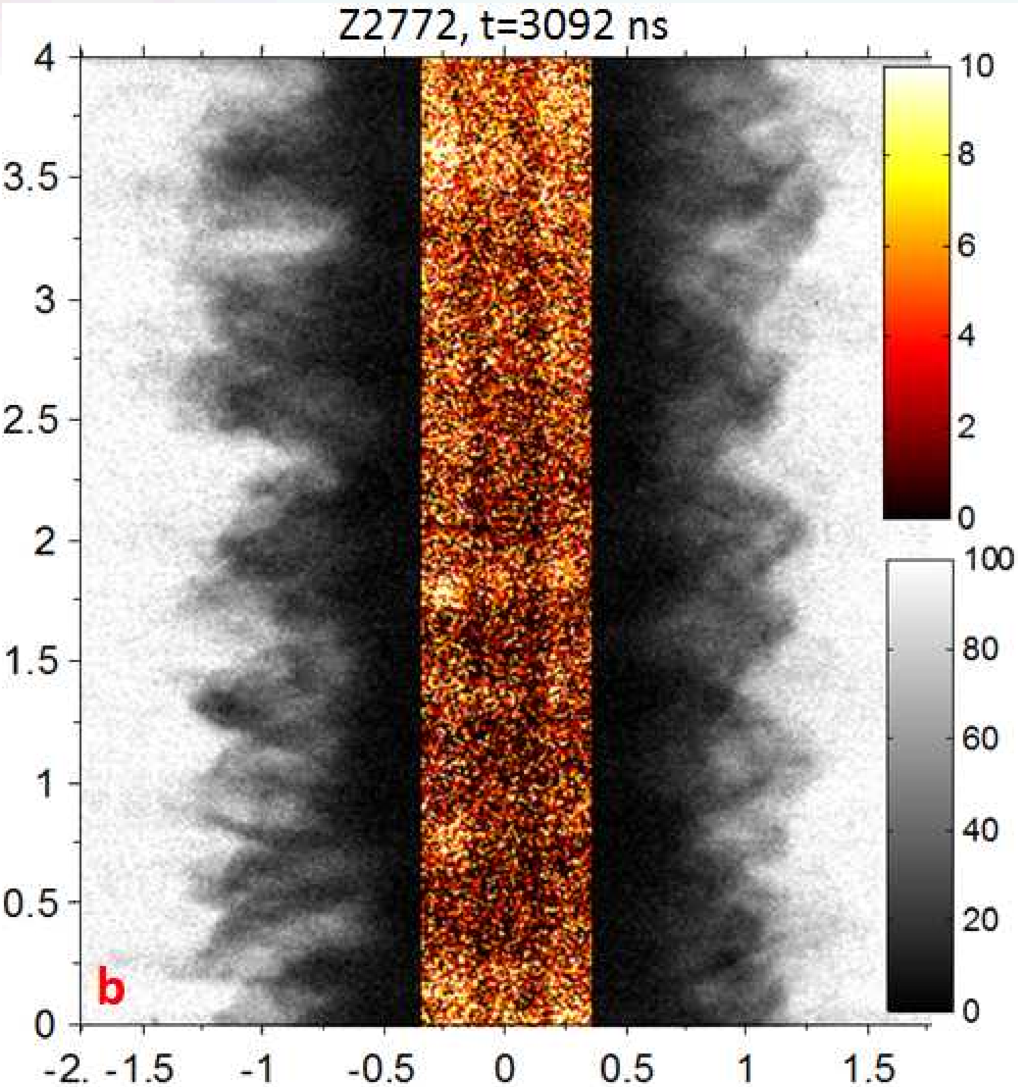


What seeds the helical instability? Why does it persist and grow?

Do dielectric tampers mitigate mass redistribution from ETI?

The early nonuniform Joule heating of Z liners is not diagnosed. ETI development is inferred by evaluating MRT late in the experiment. ETI is NOT directly observed!

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



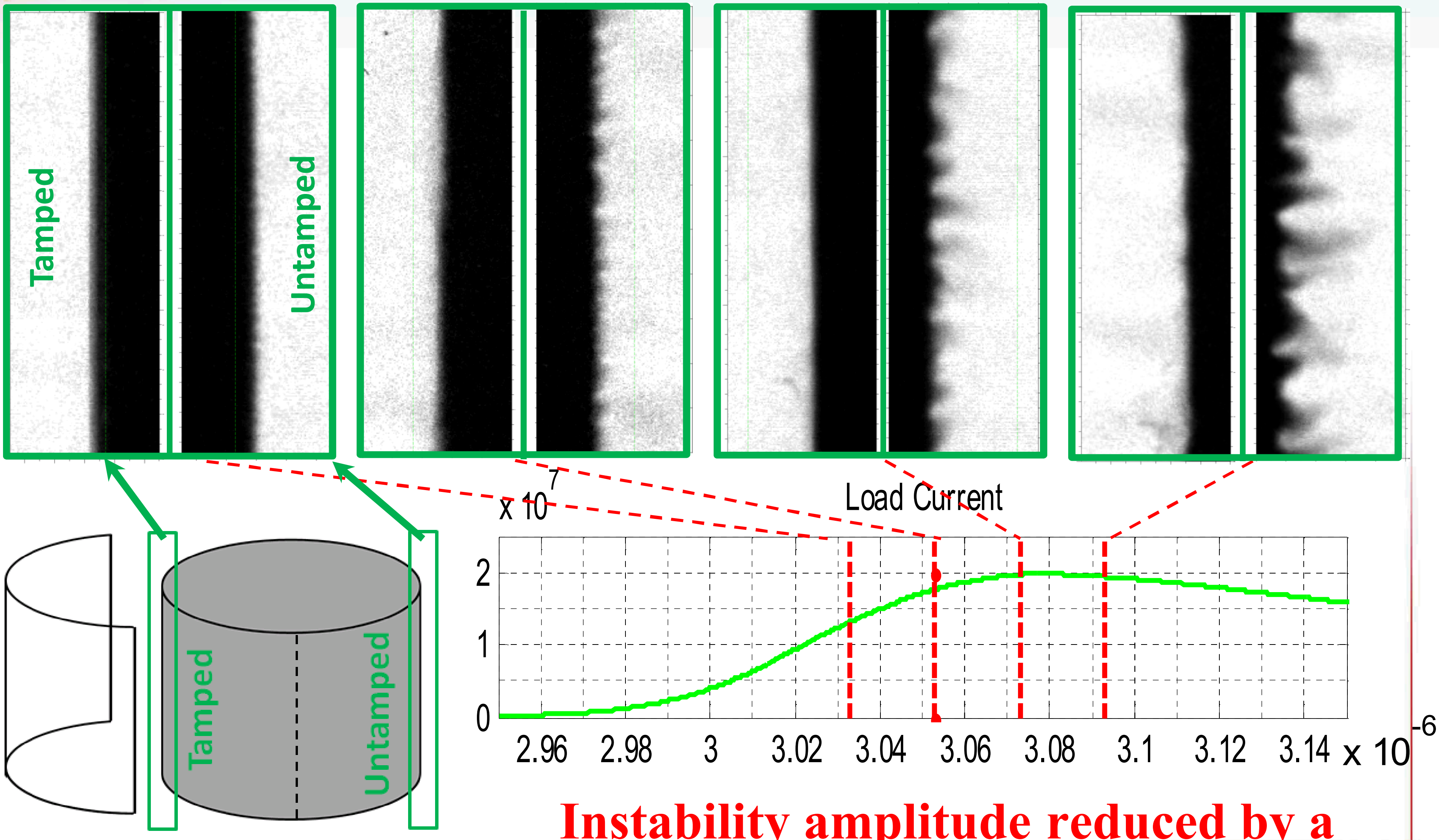
$CR = R_{in}(t=0)/R_{in}(t) = 21!$

The early nonuniform Joule heating of Z liners is not diagnosed. ETI development is inferred by evaluating MRT late in the experiment. ETI is NOT directly observed!

We seek to better understand the fundamental physics behind this astonishing result

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

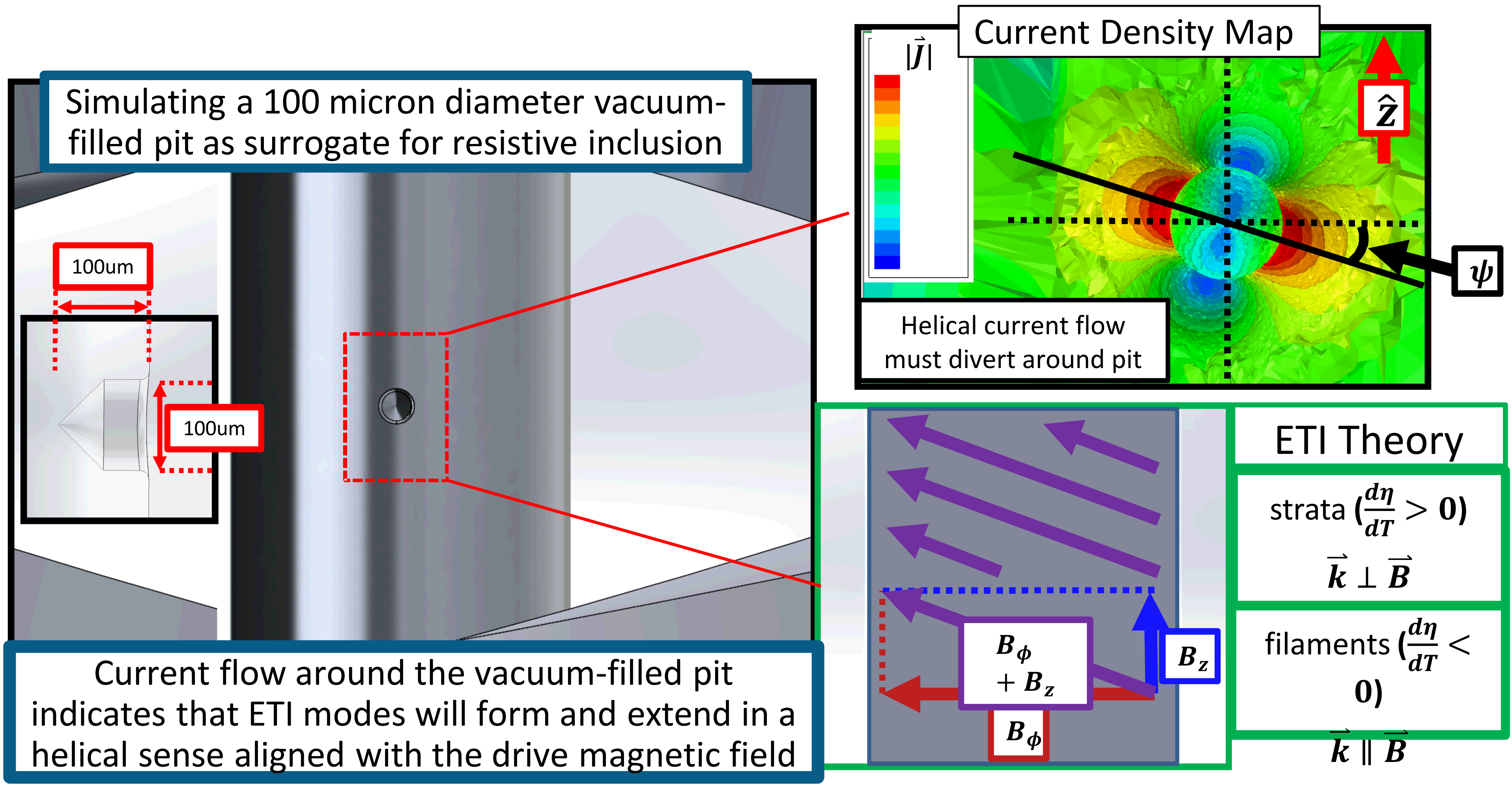
Adding a 70-micron-thick dielectric tamper dramatically alters MRT growth on a solid (R_0=3.43 mm) Al rod



Instability amplitude reduced by a factor of 10

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

Magnetic transient* simulations indicate that drive current will be helical on rod surface



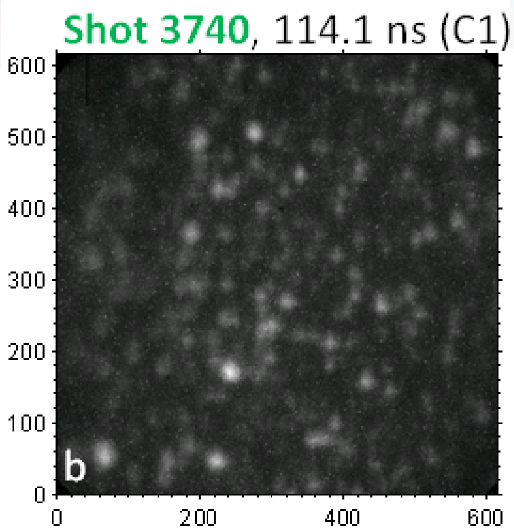
In progress: Advanced simulations are required to unravel the complex physics of ETI

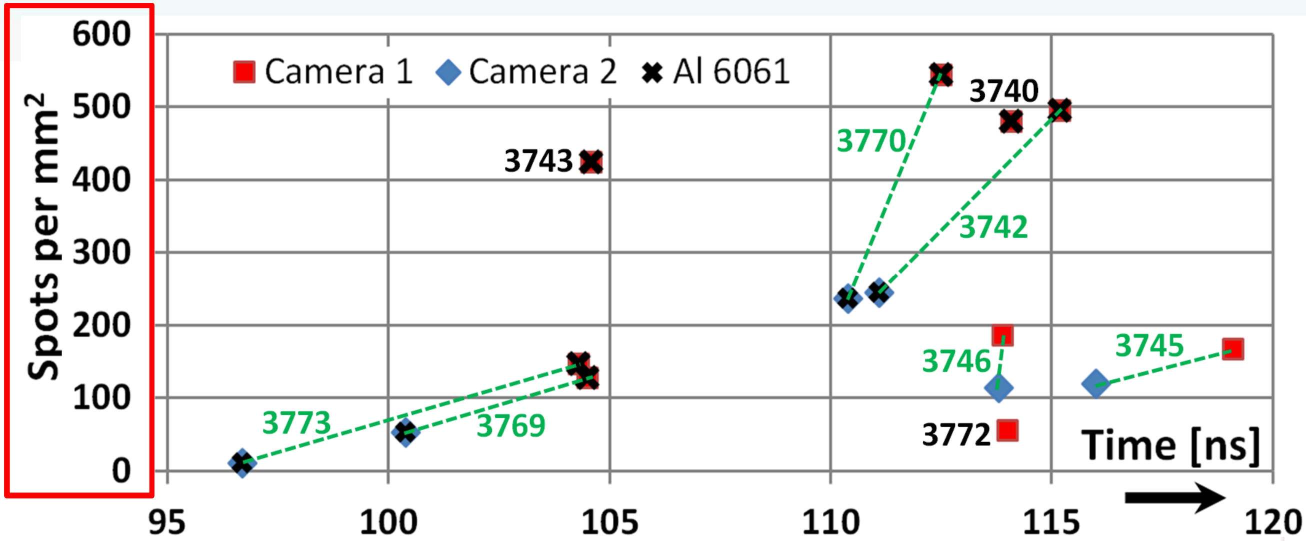
- NEW experimental data suggests that micron-scale defects can lead to the formation of global perturbations; such physics has not been simulated
- **Extremely high resolution is required** to address the redistribution of current density due to micron-scale inhomogeneity
  - Simulations show that micron scale defects drive local overheating
- **Off the shelf metals contain extremely complex resistive inhomogeneity, making detailed comparison with simulation nearly impossible**

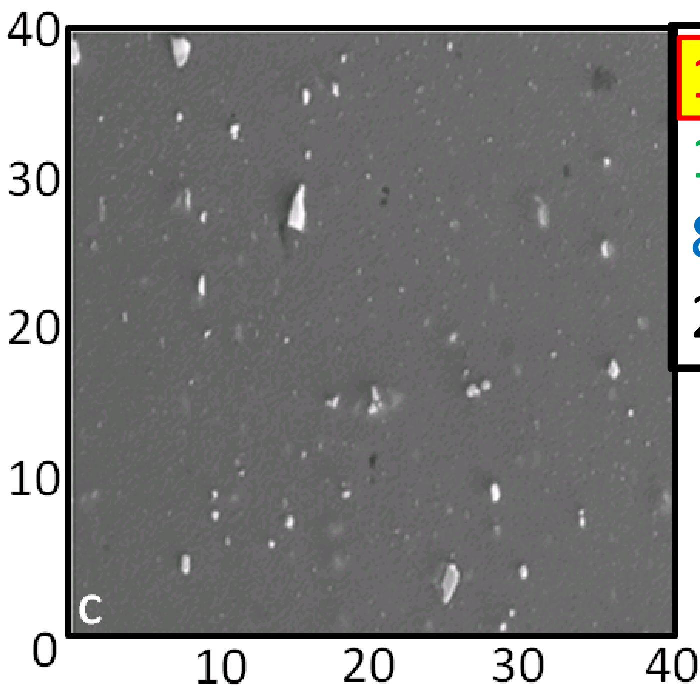
Accurately modeling ETI is a significant challenge

Comparative dataset must be unambiguous

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







→Axes in [μm]

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

Sandia National Laboratories

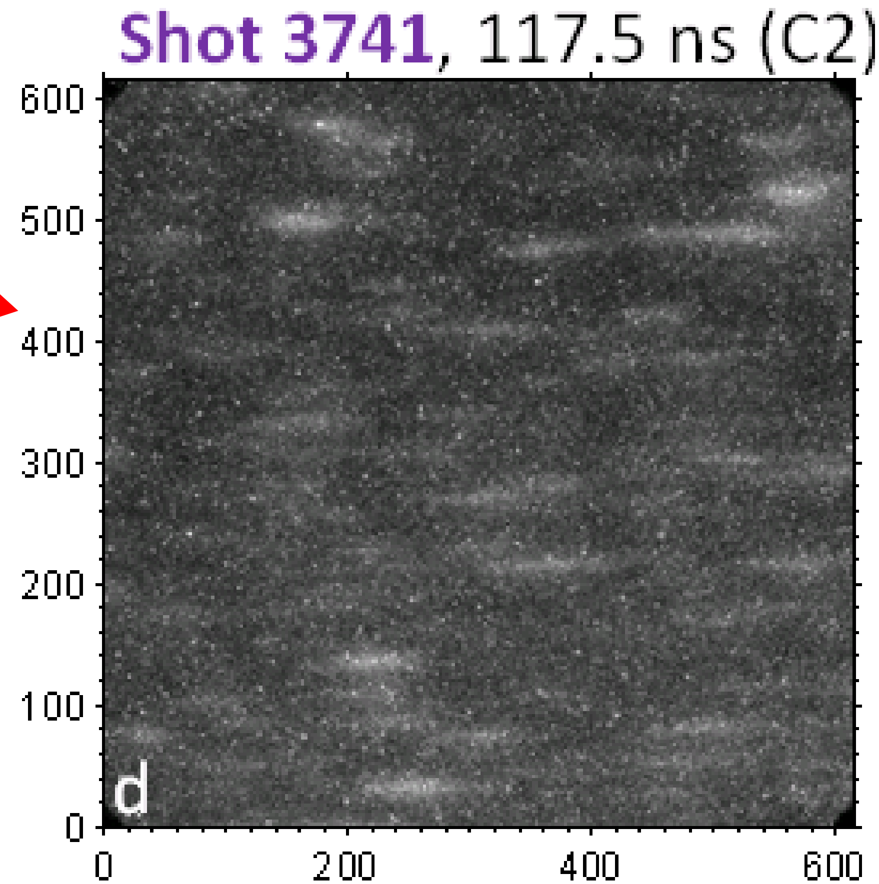
Nonuniform self-emission from Al 6061 loads evolves rapidly

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.

Surface Emissions evolve from…

To…

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



Axes in [μm]