Implosion Instability, Initiation, Growth and Mitigation

SAND2016-0295C

6th Fundamental Science with Pulsed Power Workshop

July 21, 2015

T.J. Awe, for the MagLIF and UNR-Megagauss Teams

Sandia National Laboratories

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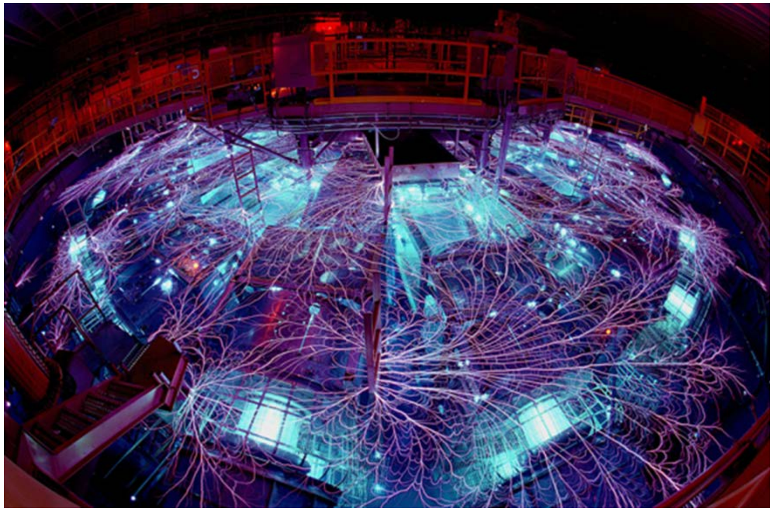
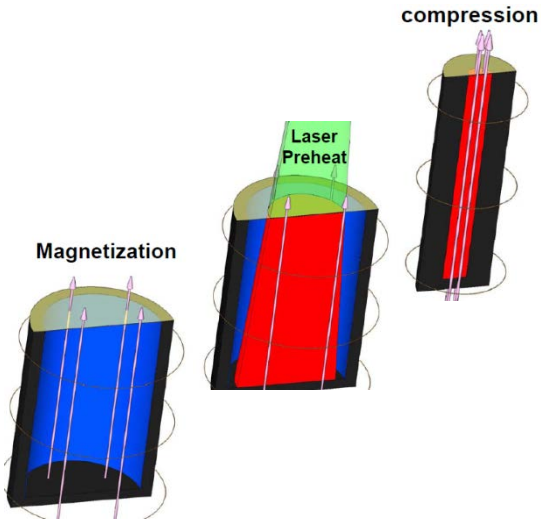
Pulsed Power Sciences — Harnessing Extreme Environments





U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

SAND Number:2013-9498 C

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T.J. Awe, K.P. Shelton, D.C. Rovang, A.B Sefkow, J.M Villalva, M.E. Cuneo, M.R. Gomez, D.B. Sinars, M. Geissel, E.C. Harding, P.F. Knapp, D.C. Lamppa, A.J. Lopez, P.F. Schmit, S.E. Slutz, D.E. Bliss, G.A. Chandler, K.D. Hahn, E.A. Hamilton, S.B. Hansen, A.J. Harvey-Thompson, M.H. Hess, C.A. Jennings, B.M. Jones, M.C. Jones, M.R. Martin, R.D. McBride, K.J. Peterson, J.L. Porter, G.K. Robertson, G.A. Rochau, C.L. Ruiz, I.C. Smith, C.S. Speas, W.A. Stygar, R.A. Vesey, E.P. Yu

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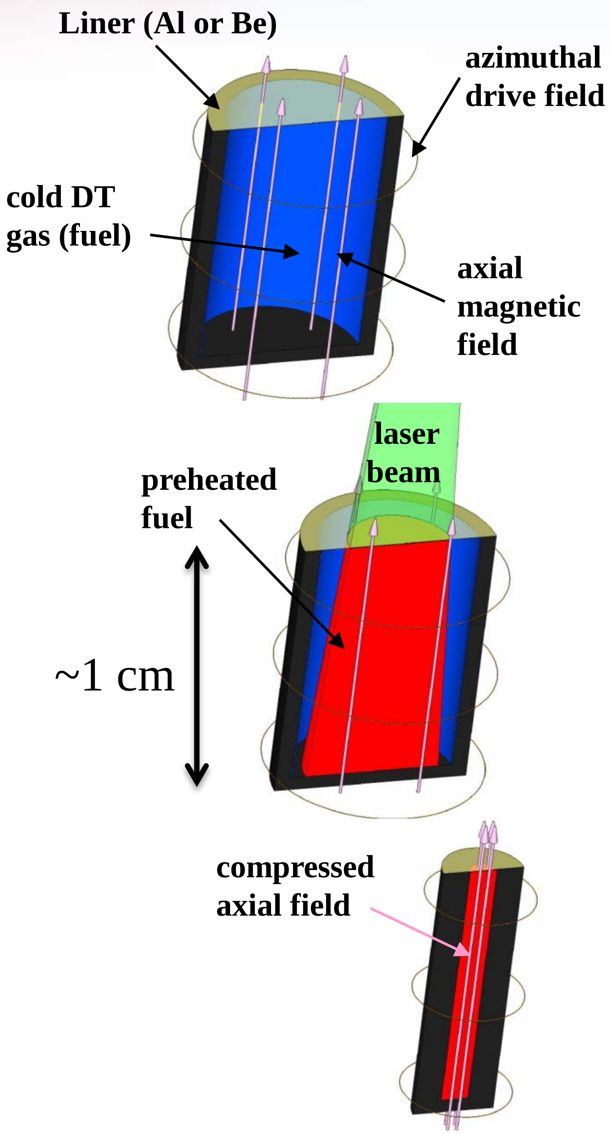
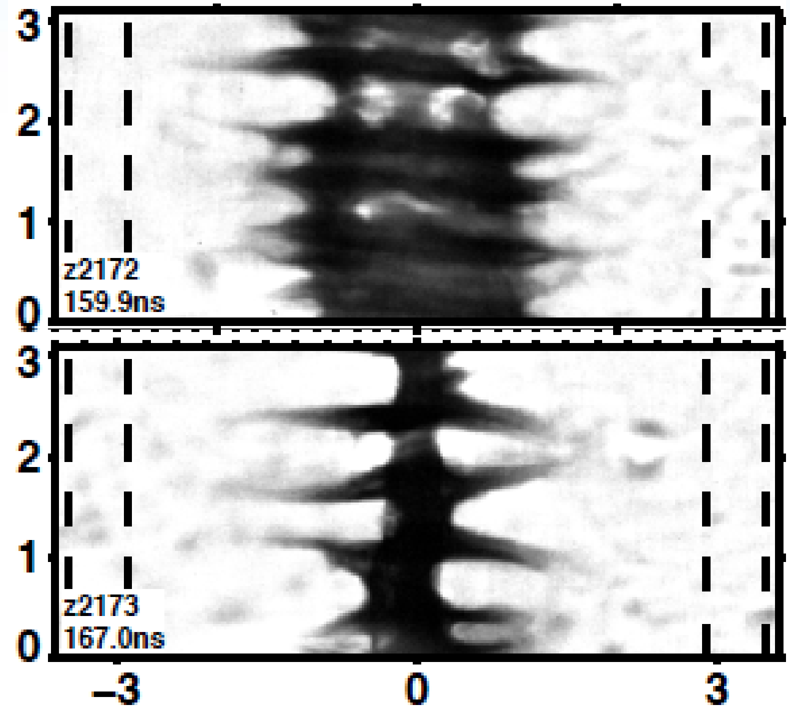
UPDATE, UNR, order

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

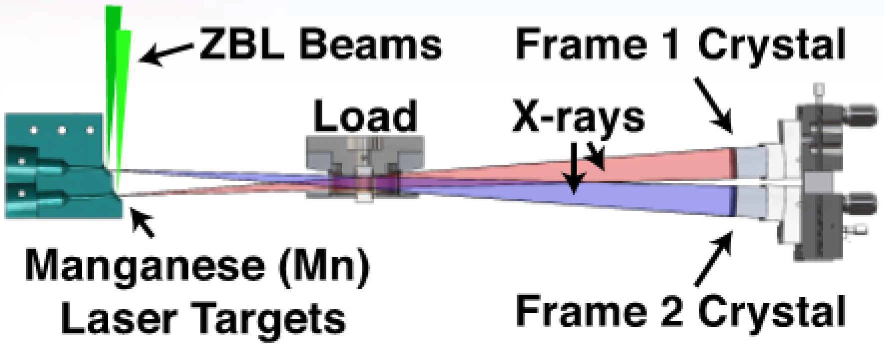




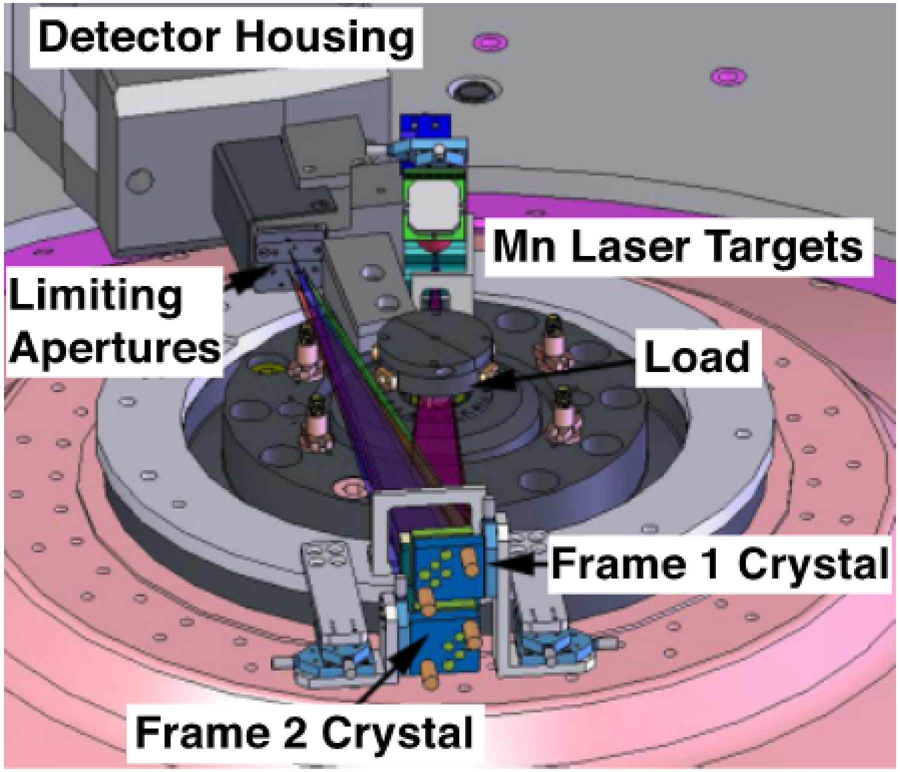
"The magneto-Rayleigh-Taylor MRT instability poses the greatest threat to this (MagLIF) approach to fusion."

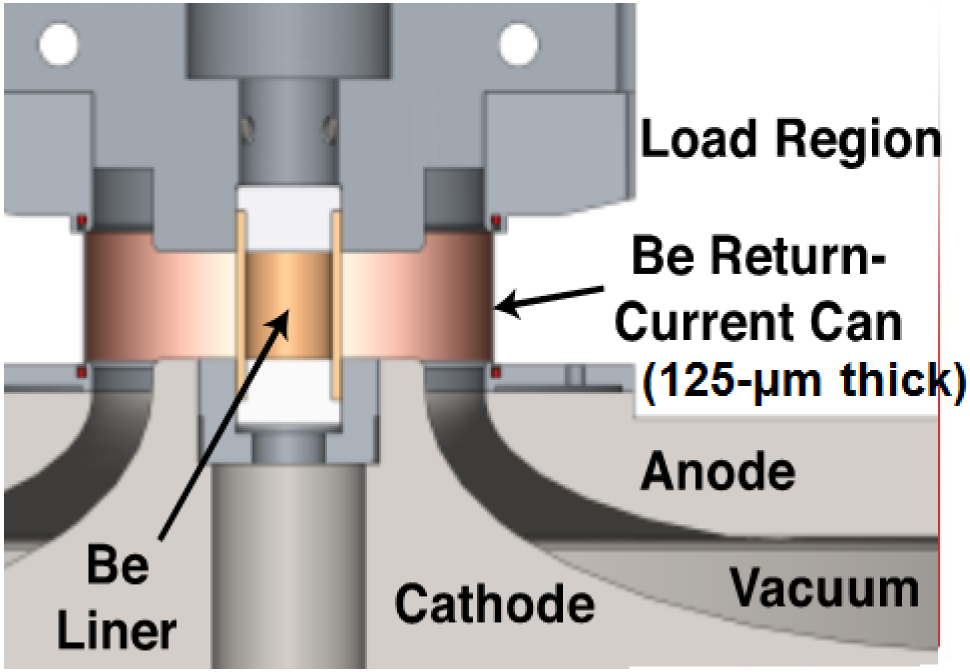
S.A. Slutz *et al.*, Phys. Plasmas **17**, 056303 (2010);

Presentation focuses on liner dynamics; primary diagnostic is two-frame monochromatic (6151±0.5 eV) radiography*



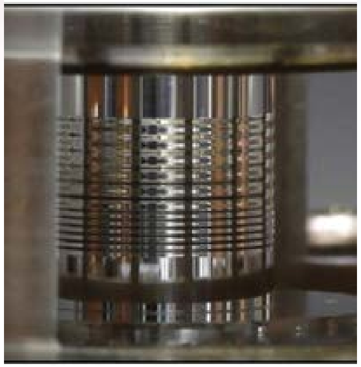
- Spherically-bent quartz crystals (22<u>4</u>3)
- 15 micron resolution (edge-spread)
- We can see through imploding beryllium (not so for aluminum and other higher-opacity materials).

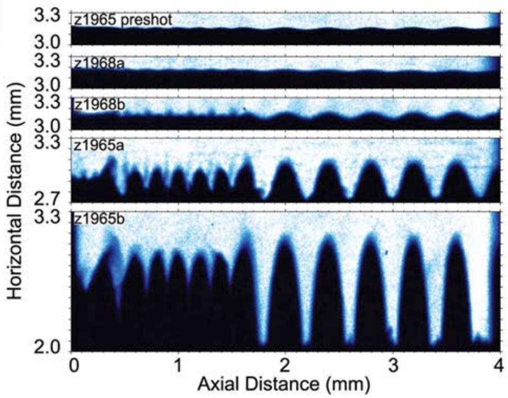




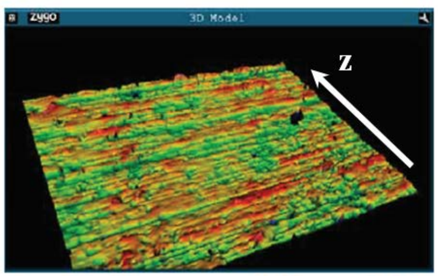
* G. R. Bennett *et al.*, RSI (2008).

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

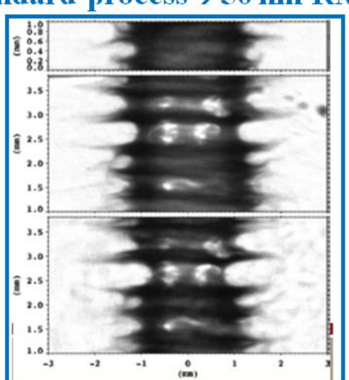


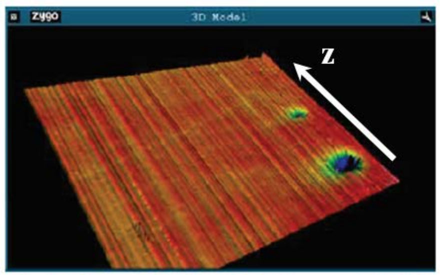


D.B. Sinars *et al*., Phys. Rev. Lett. 105, 185001 (2010)
D.B. Sinars, Invited Presentation, 2010 APS-DPP

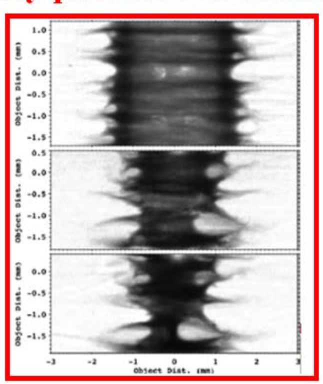


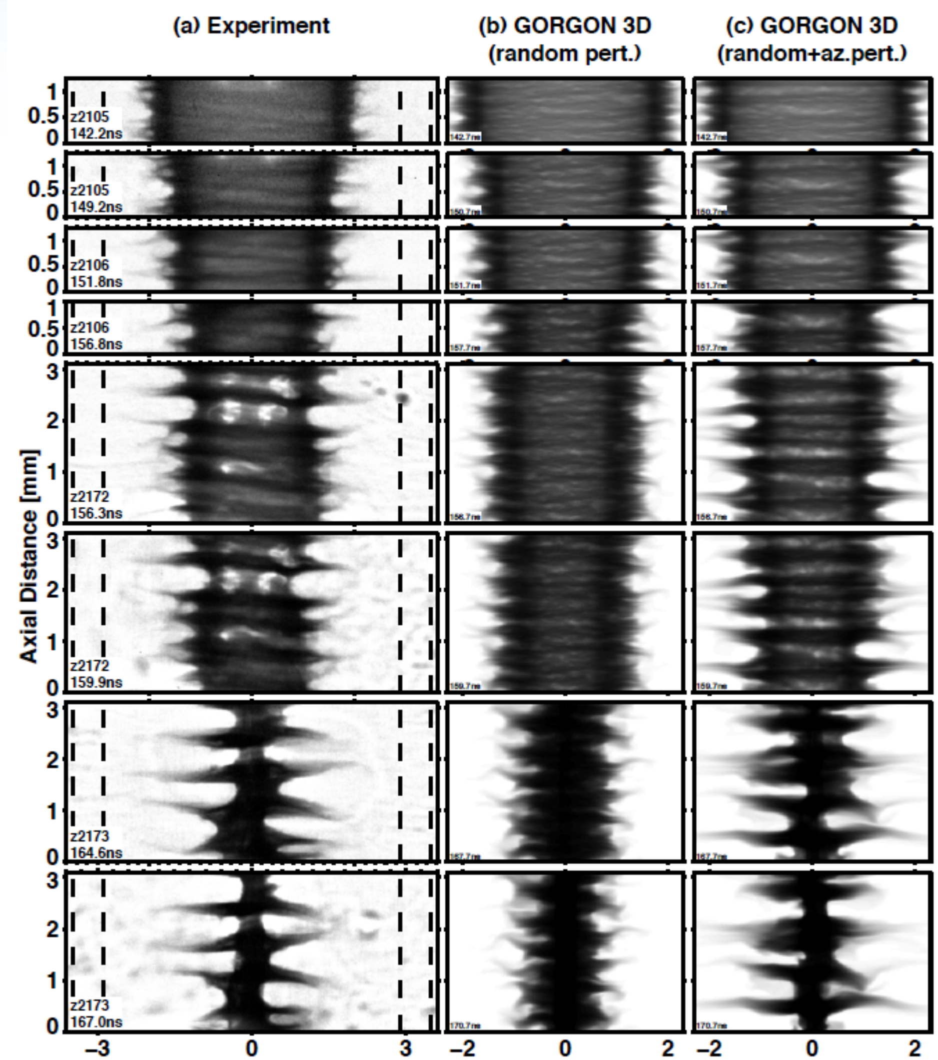
Standard process→50 nm RMS





Axially polished→50 nm RMS

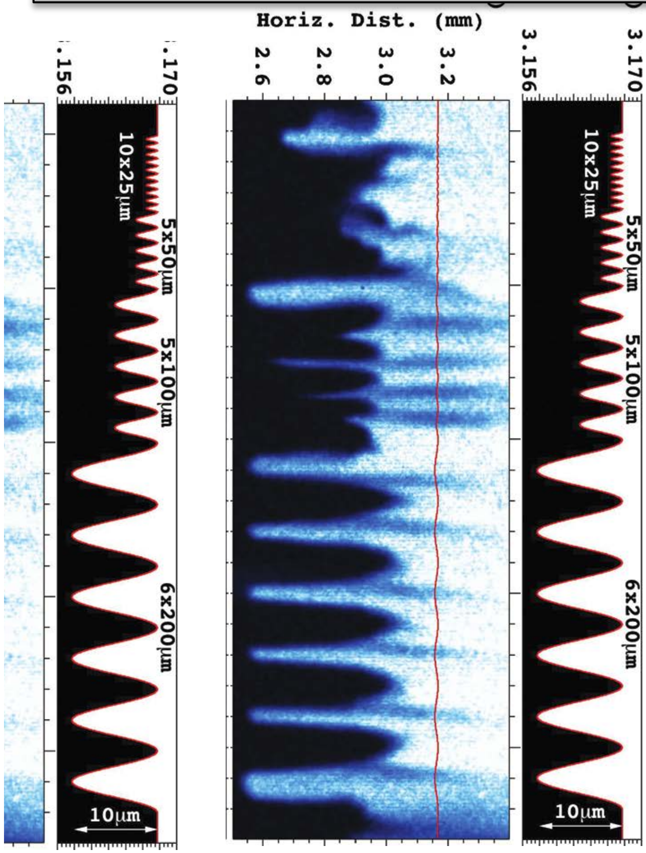




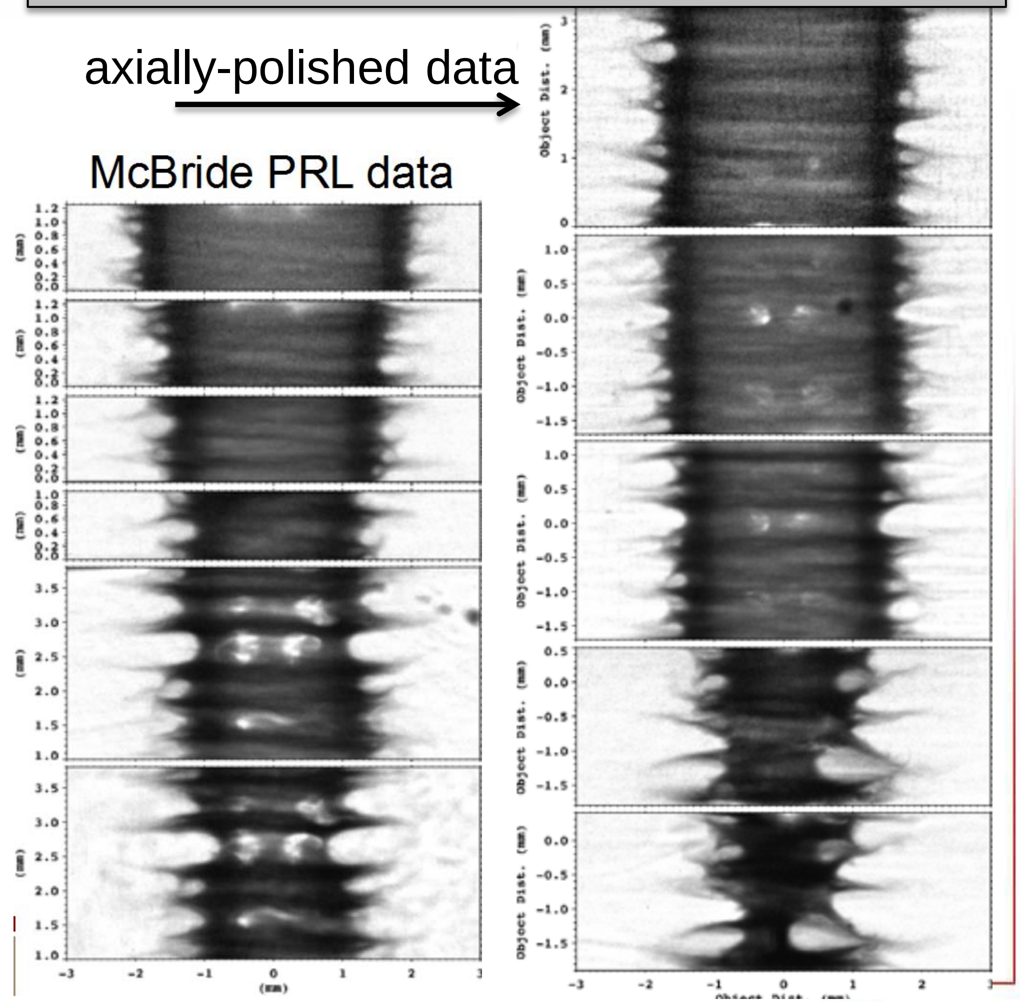
R.D. McBride *et al*., PRL 109, 135004 (2012)
R.D. McBride, Invited Presentation, 2012 APS-DPP

Surface roughness and small defects do not appear to be the seed for MRT instability growth as in radiative driven laser ICF targets

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

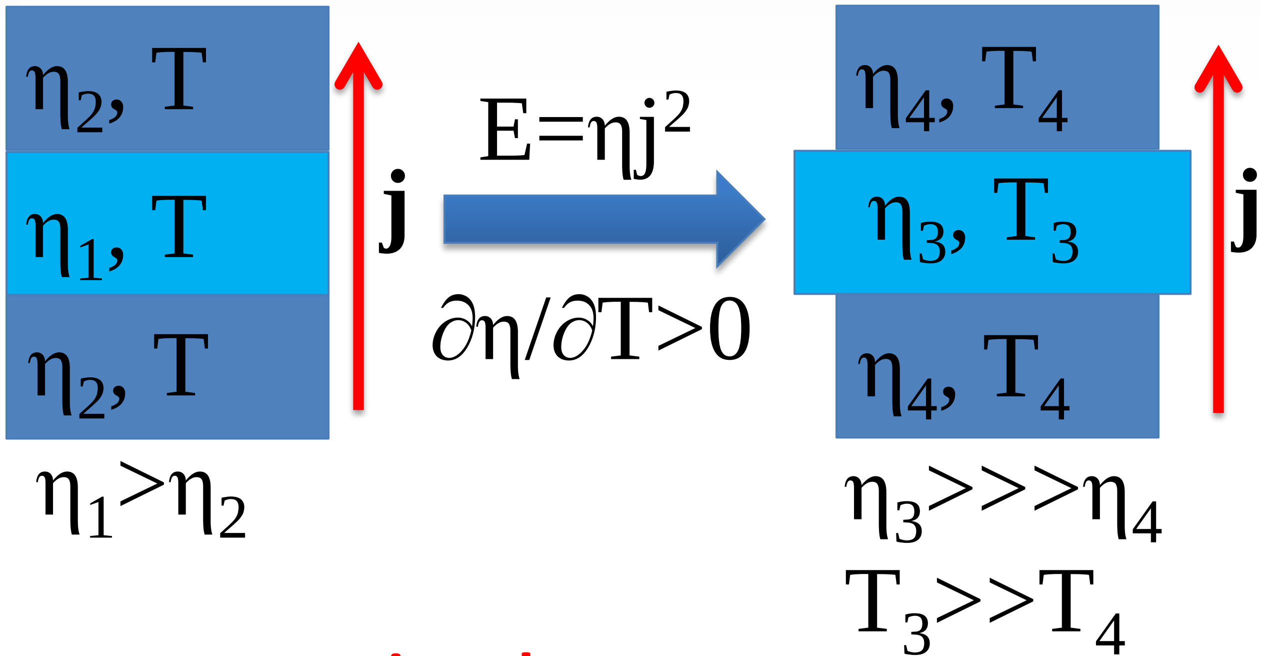


Axially polished liner experiments suggest symmetry is not sensitive to surface characteristics



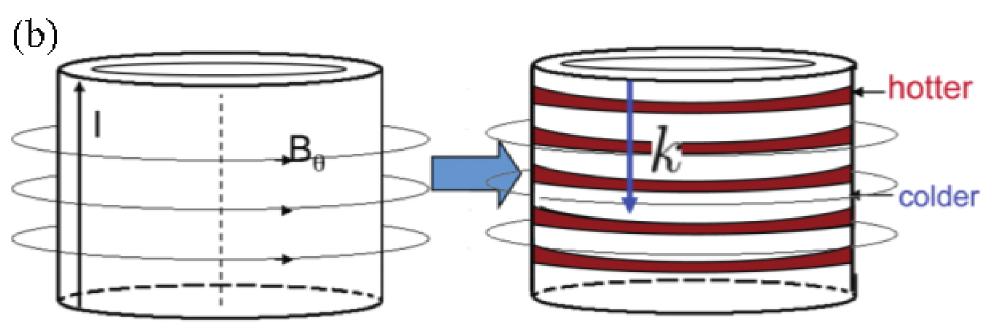
*R.D. McBride et al., Phys. Rev. Lett. 109, 135004 (2012).

Electrothermal instabilities occur when material conductivity is dependent on temperature



ETI can generate striated density perturbation on the liner surface very early in the experiment

→provides seed for MRT



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Electrothermal instabilities occur when material conductivity is dependent on temperature

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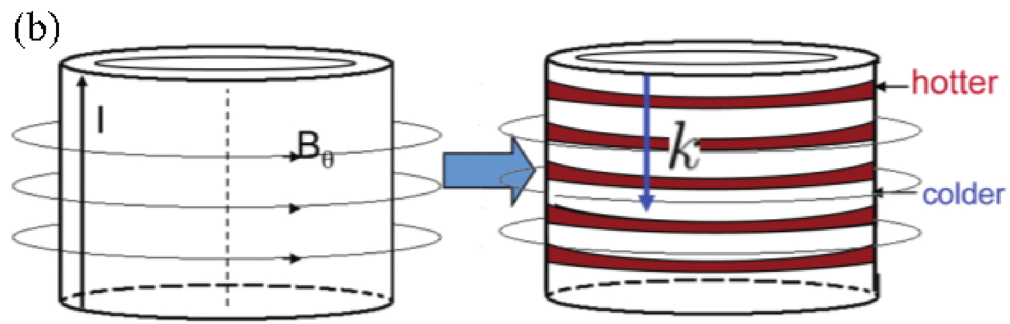
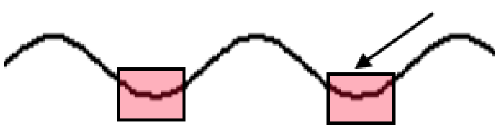
Theory

Striations

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



$$\delta T > 0$$



Consider a small temperature perturbation due to localized variations in ohmic heating

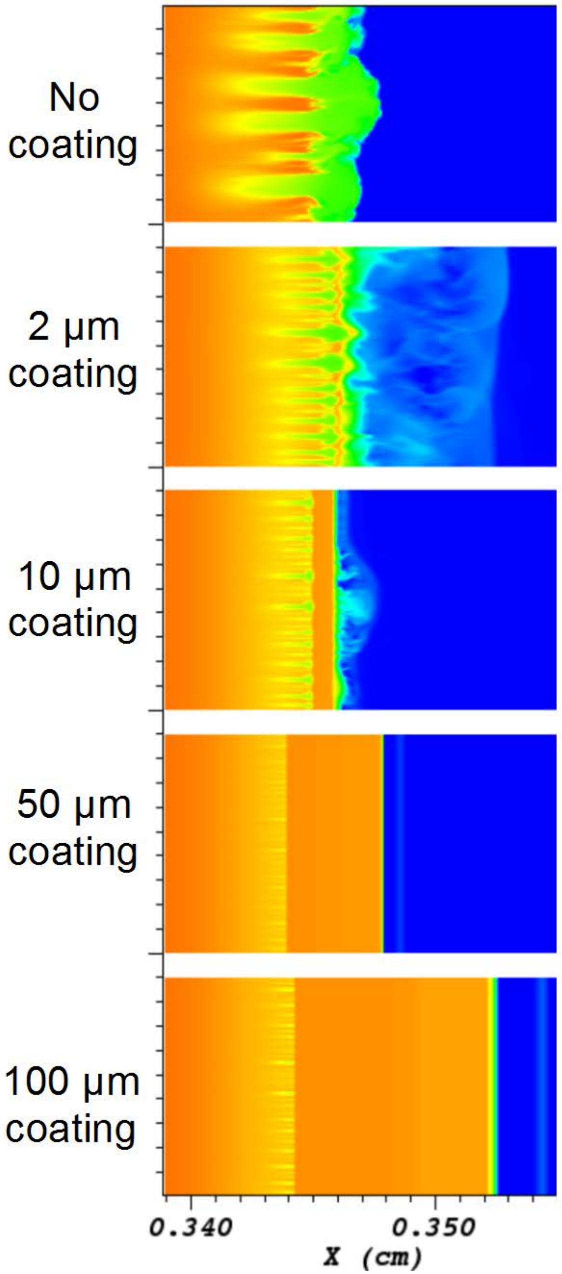
- surface contaminants (variations in η)
- surface roughness ($B_\theta \sim I/r$, in cylinders)

Then, η increases which consequently further enhances the localized ohmic heating (ηj^2),

which leads to increased δT

Temperature perturbations give rise to pressure variations which eventually redistribute mass

Relatively thick insulating coatings mitigate effects of ETI and reduce seed for MRT growth



- No ETI (striation) growth in dielectric coating
  - Carries very little current
  - Theoretically ETI Stable

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

- Linear ETI growth of temperature perturbations still present in metal
  - Slightly reduced by density dependence of growth rate
- Nonlinear mass redistribution from ETI is significantly tamped by the coating
  - Reduces seed for MRT growth
  - Reduces integral instability growth

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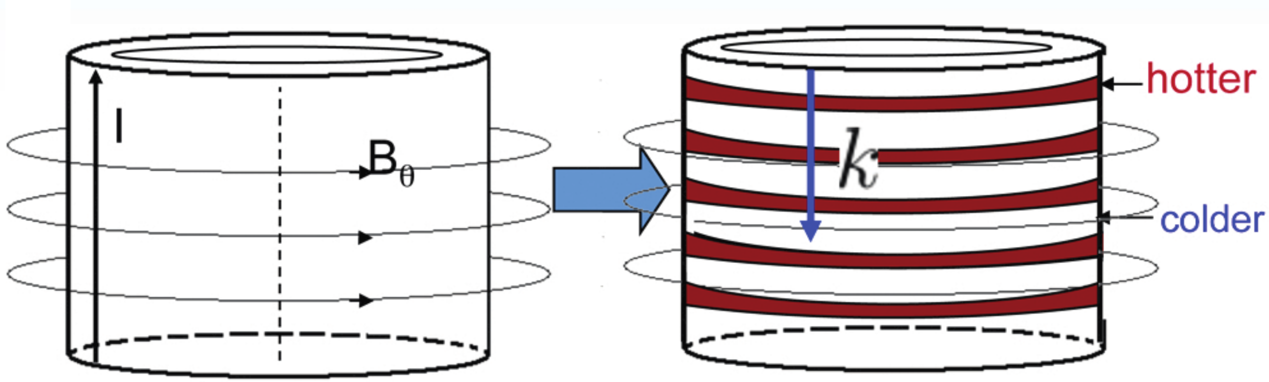
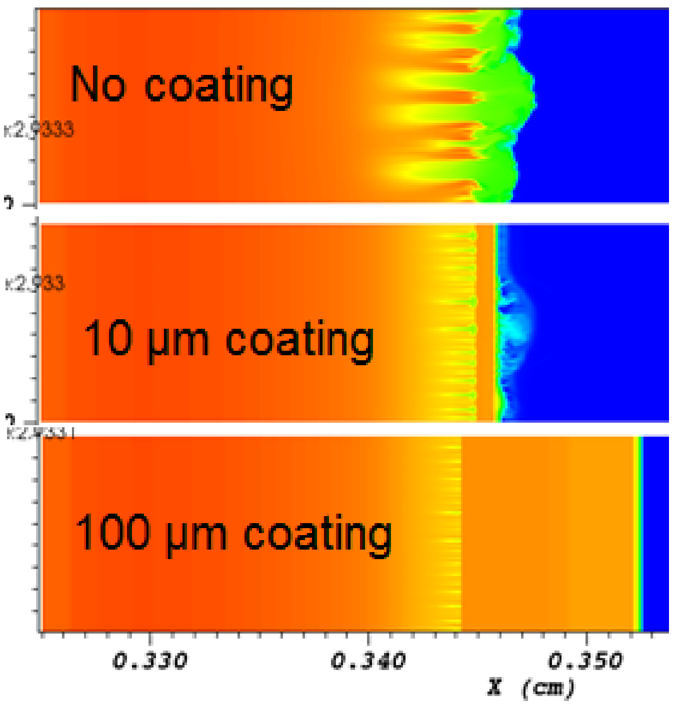
Electrothermal instabilities (ETI) may seed the Magneto-Raleigh Taylor (MRT) instability

As metal is heated:

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





Metal's initially non-uniform resistivity seeds rapid growth of electrothermal instabilities

Locations with initially higher resistivity vaporize/expand first, driving non-uniform mass redistribution at liner surface

Simulations (shown at 12 MA) predict that perturbations are mitigated by a thin dielectric coating

*K.J. Peterson et al., Phys. Plasmas, **20**, 056305 (2013)
*K.J. Peterson, Invited Presentation, 2012 APS-DPP

Electrothermal instabilities (ETI) may seed the Magneto-Raleigh Taylor (MRT) instability

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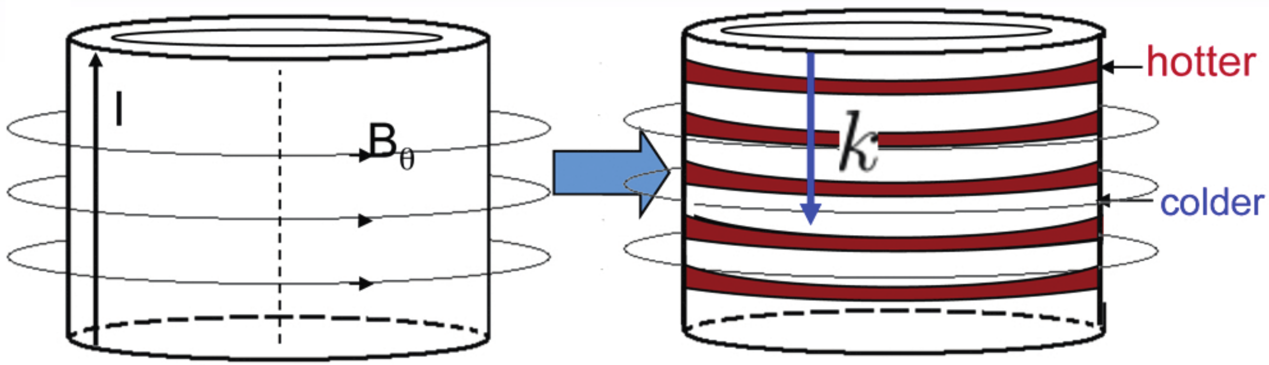
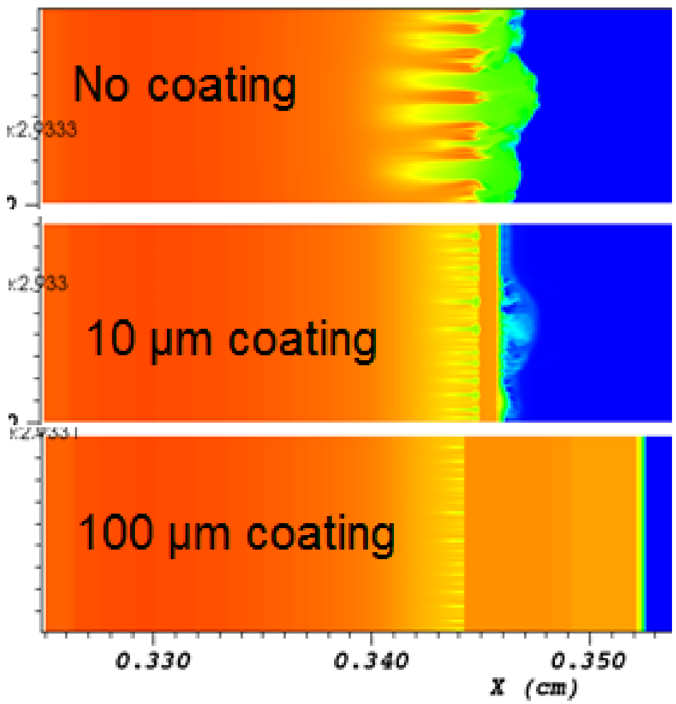
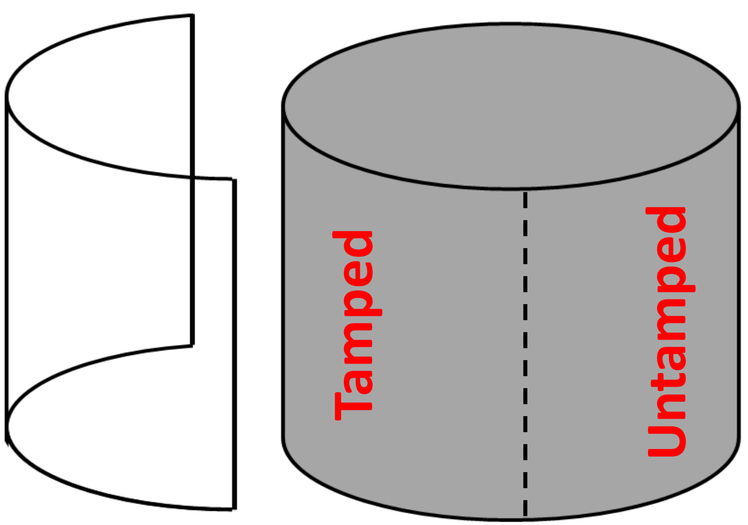
$$\frac{d\eta(T)}{dT} > 0$$





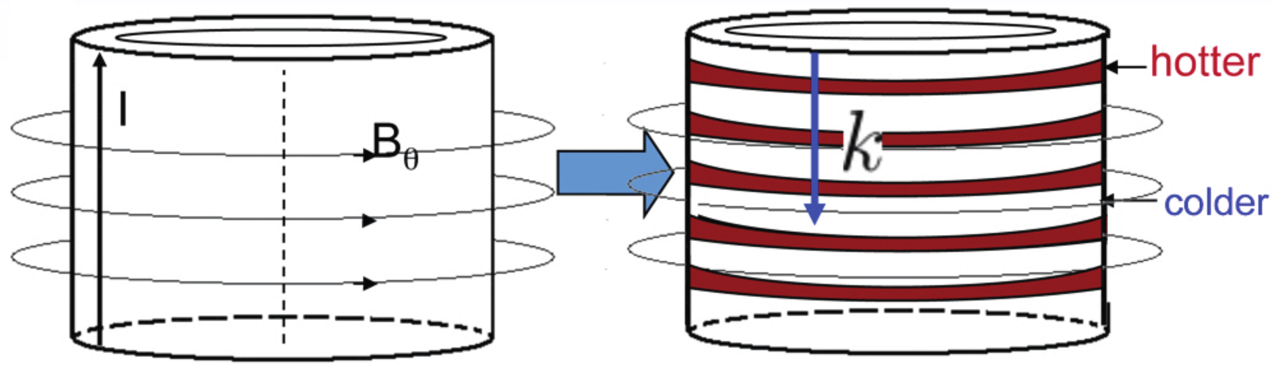
40-micron-thick dielectric tamper applied to 180° of Al rod

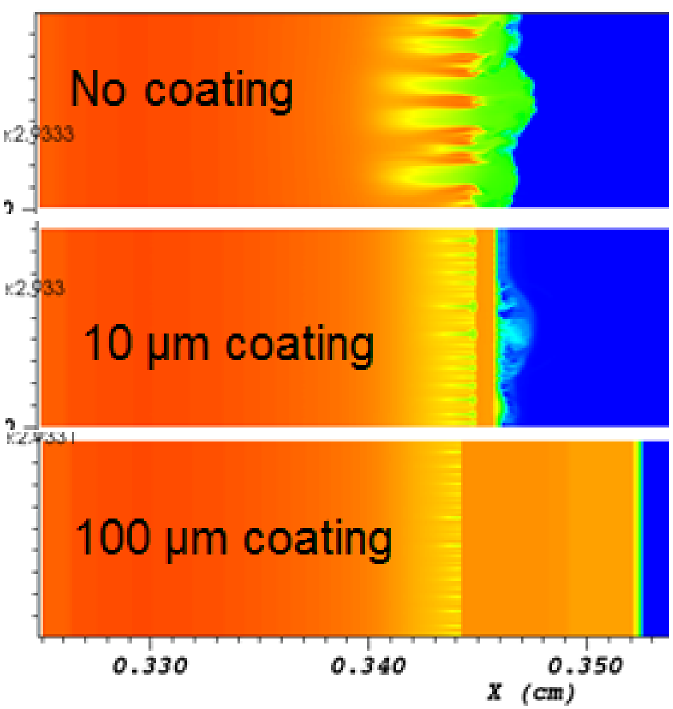


Electrothermal instabilities (ETI) may seed the Magneto-Raleigh Taylor (MRT) instability

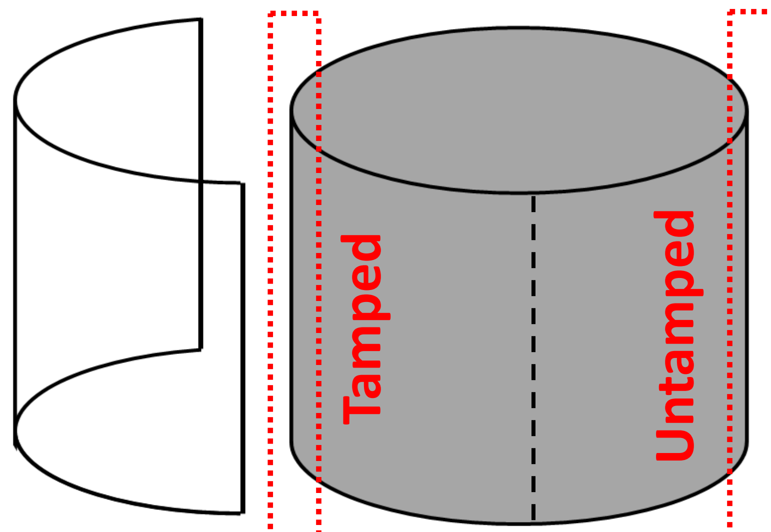
As metal is heated:

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

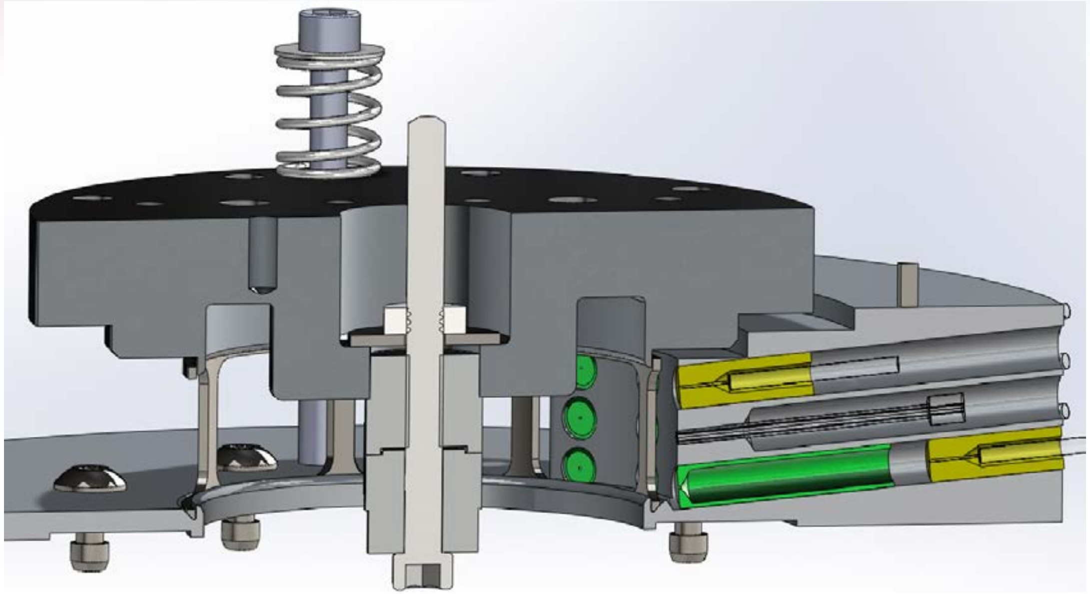


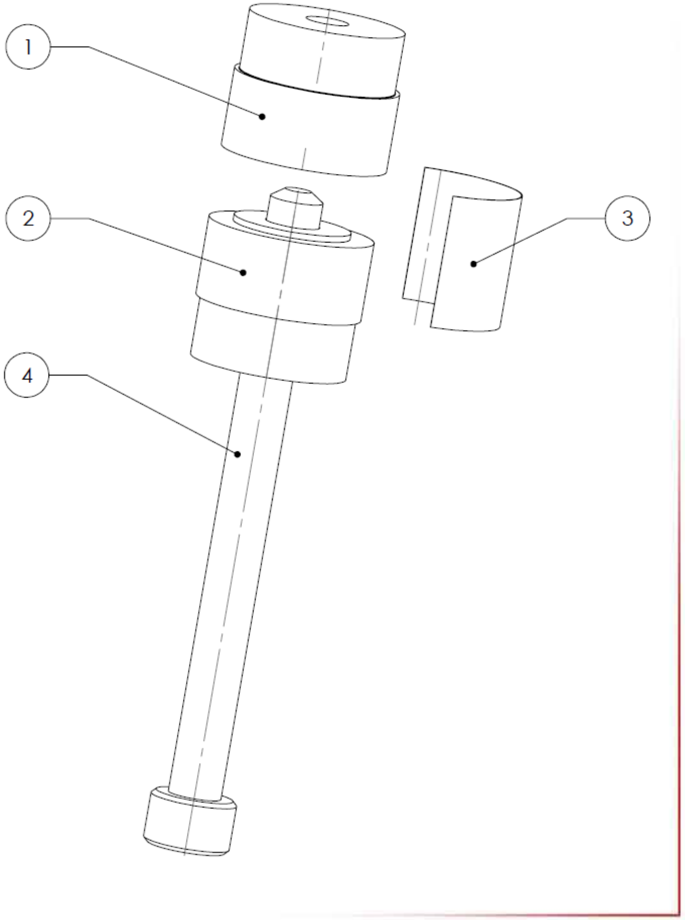


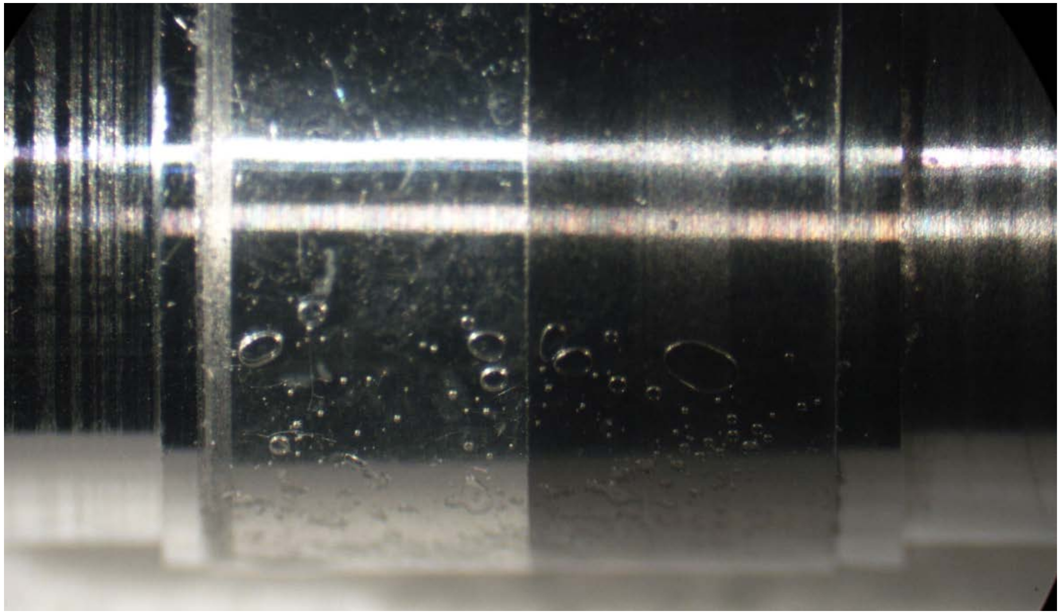
40-micron-thick dielectric tamper applied to 180° of Al rod



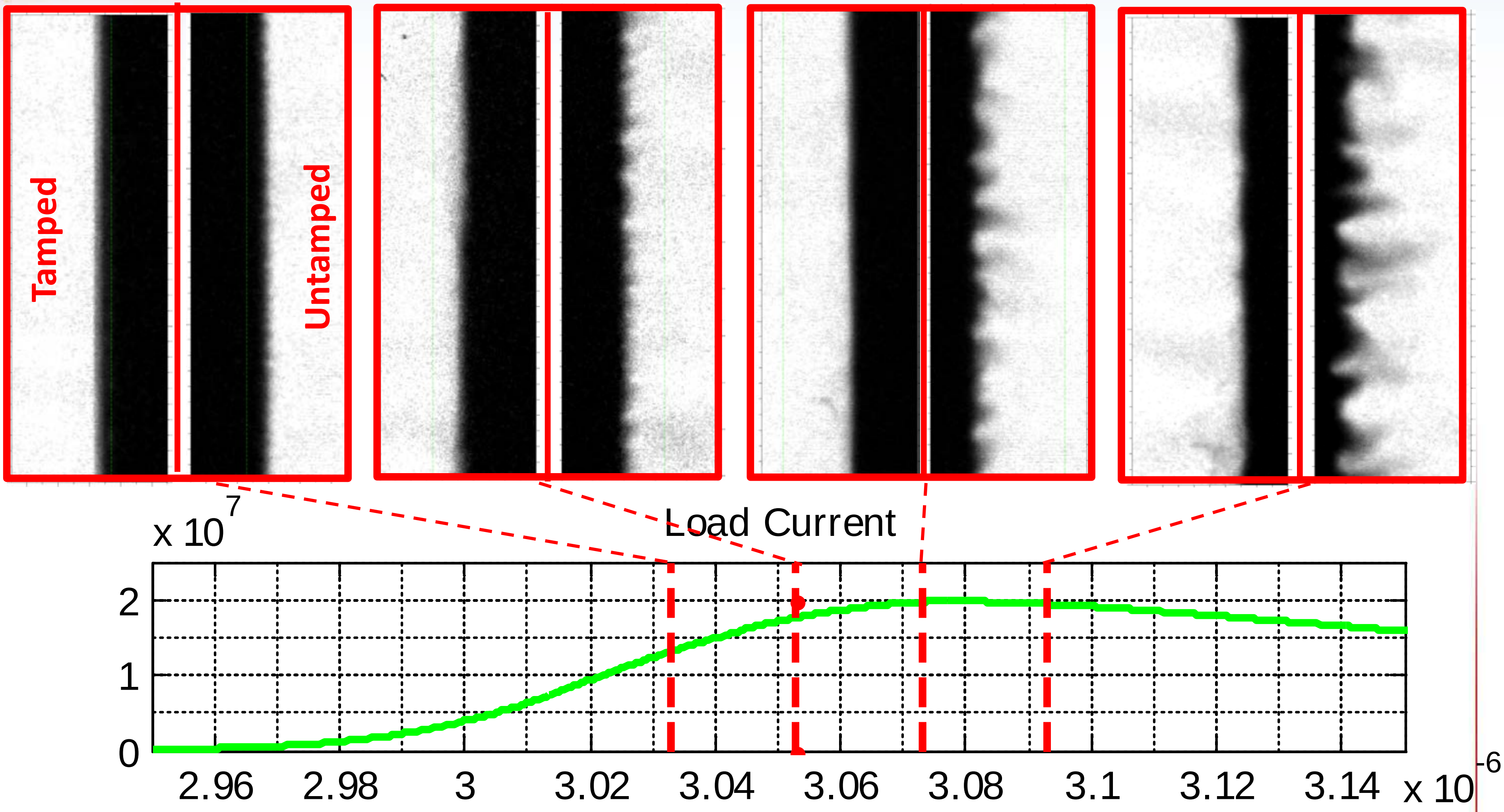
Solid rod test in April of 2013







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

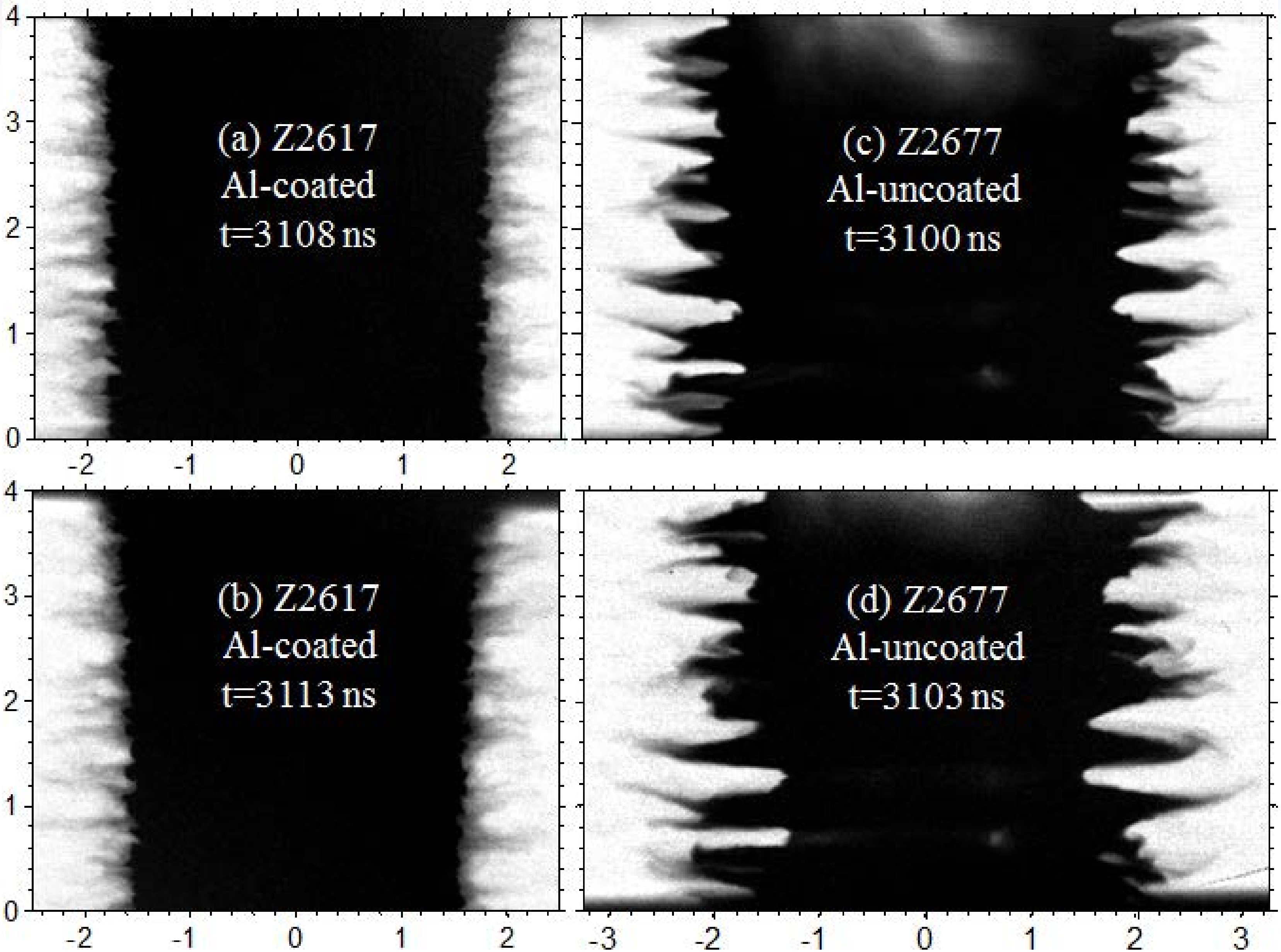


Instability amplitude reduced by a factor of 10 to as much as a factor of 50 in dominant wavelengths

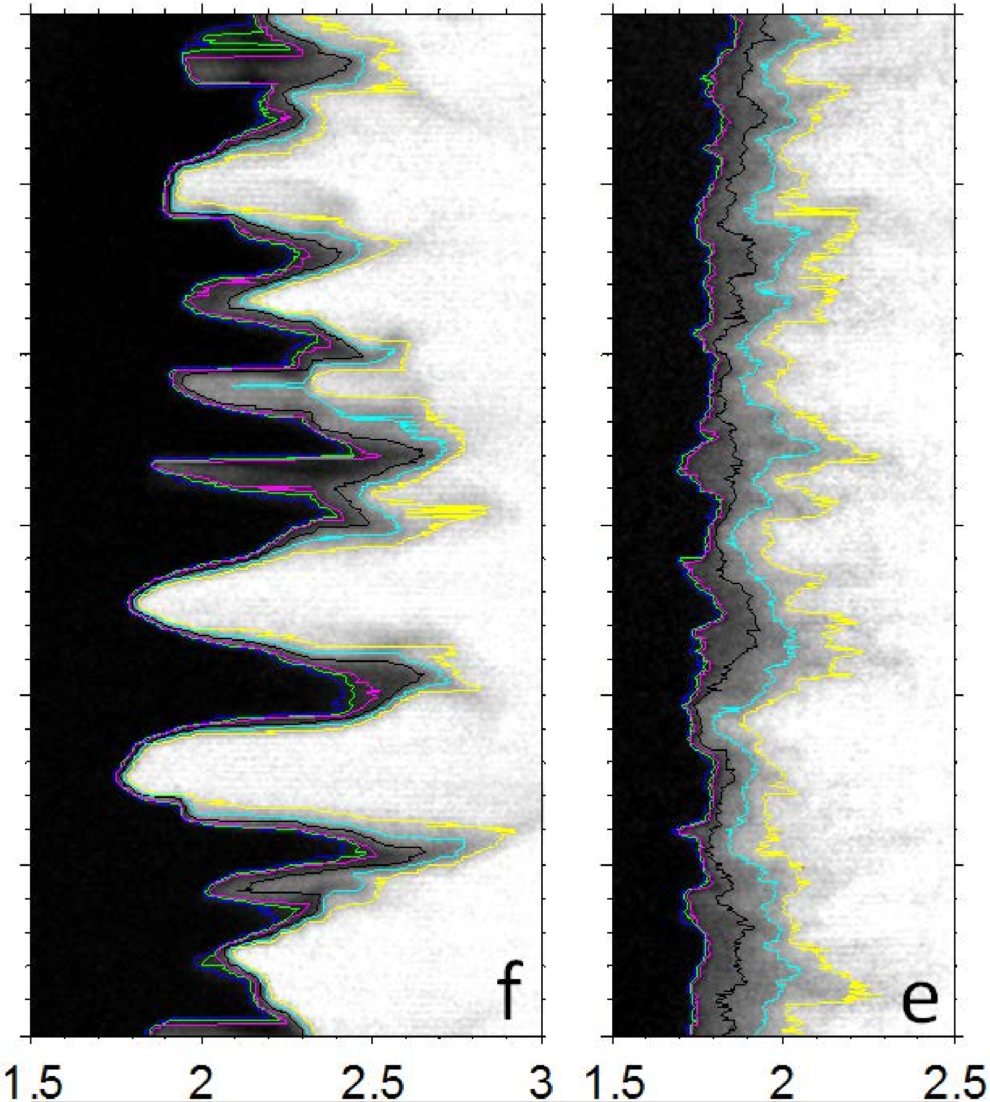
K.J. Peterson *et al*., Phys. Rev. Lett. **112**, 135002 (2014)

Imploding liner experiments with Al and Be liners provide a highly complementary dataset

Al experiments → Dielectric tamper modifies the liner's edge density gradients and greatly reduces integral MRT growth



$C_{10\%,60\%} = 0.82$ $C_{10\%,60\%} = 0.05$



(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

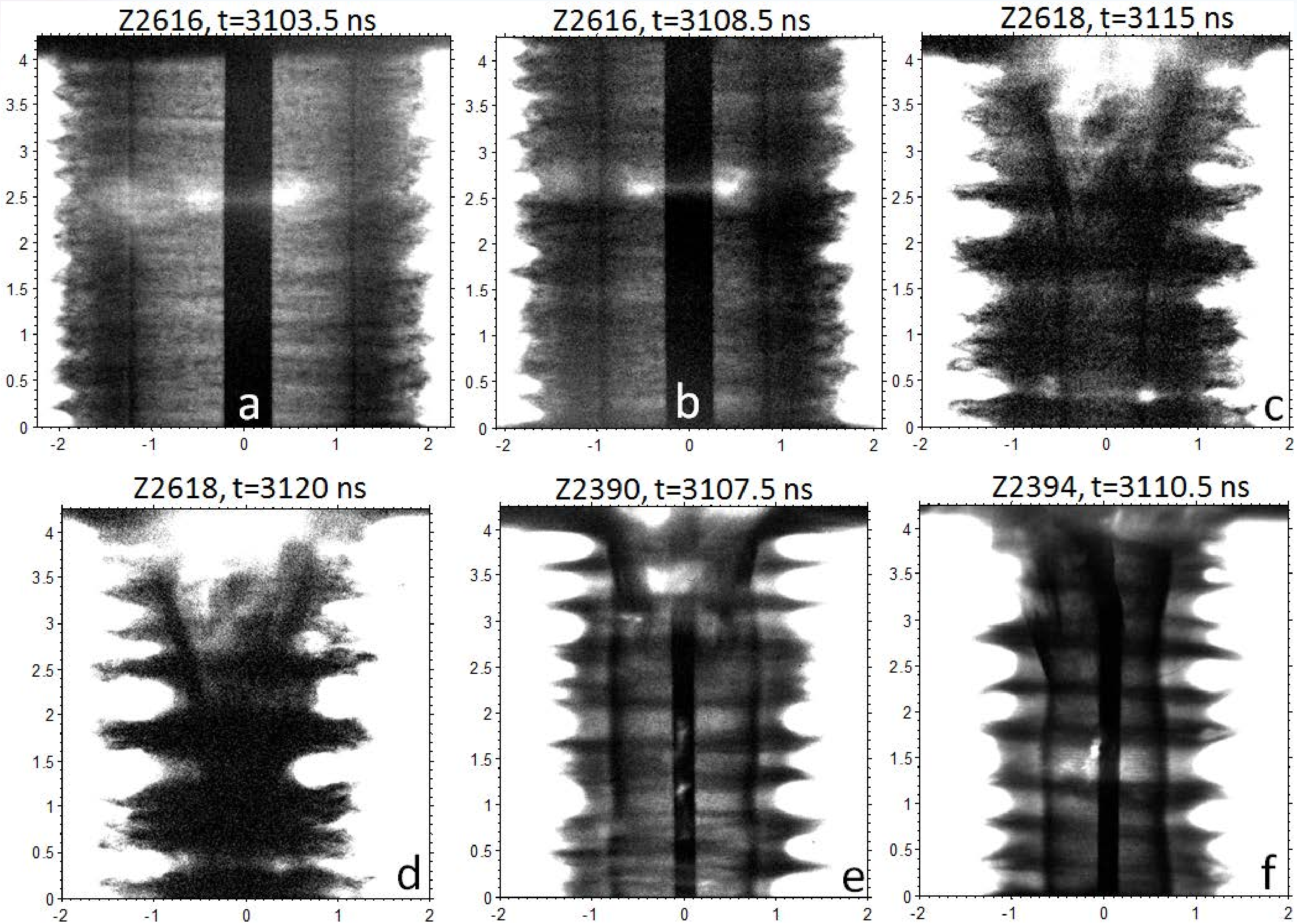
$$C_{ij} = \int_{L1}^{L2} u_i(z)u_j(z)dz \Big/ \sqrt{\int_{L1}^{L2} u_i^2(z)dz \int_{L1}^{L2} u_j^2(z)dz}$$

$C_{ij}=1$; 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

Be liners allow evaluation of inner liner surface, and classification of dominant instability orientation



Coated liners → Initially 3D structure devolves to azimuthally correlated perturbation

ETI Summary

MagLIF Helmholtz-like coil pair first fielded on Z imploding-liner experiments in February of 2013

Field strength requirements:

–10 T seed field with full diagnostic access

–30 T coils will have limited diagnostic access

Capacitor bank

2x4 mF, V_{max} = 15 kV

Use: 4 mF, 7 kV, 8.6 kA, 10 T

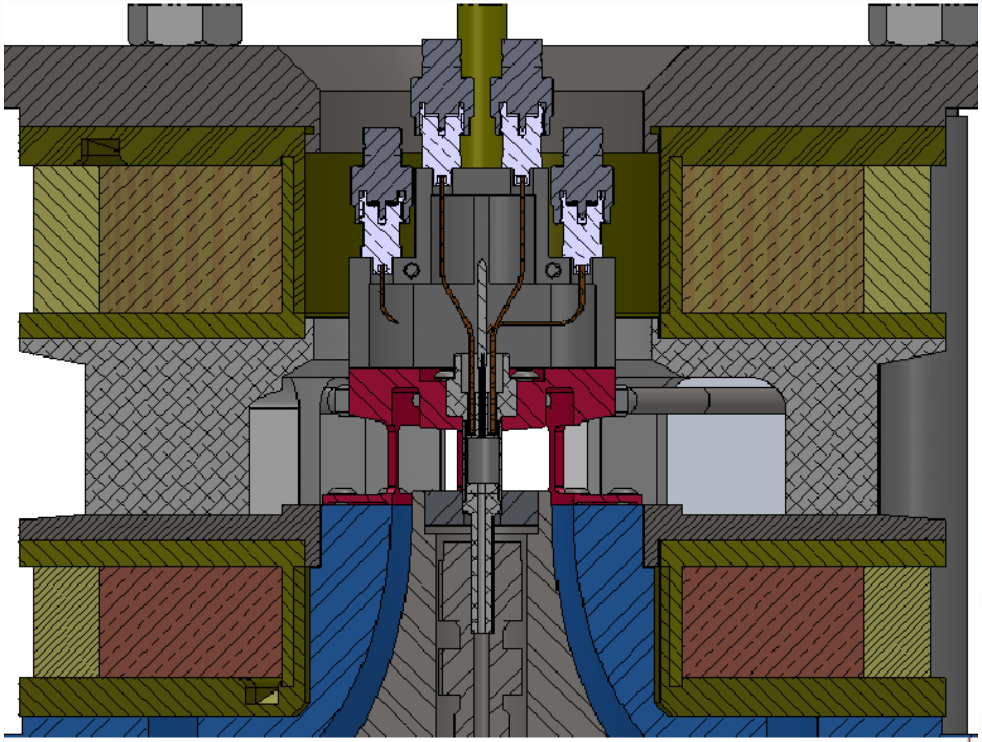
Pulse length requirement:

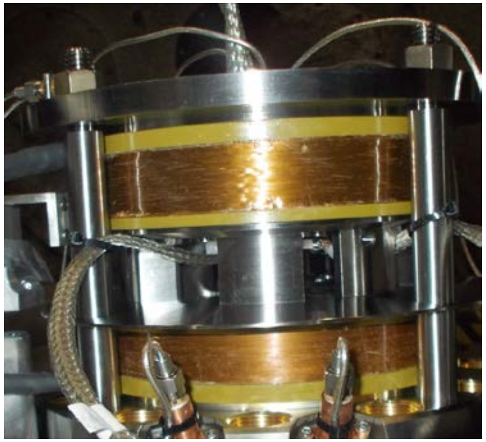
–Coil: ~1 mH

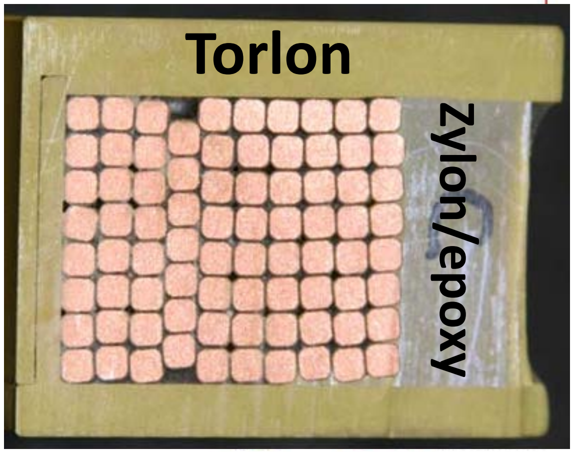
– Must not crush or buckle target or hardware

– Fully magnetize liner/fuel with uniform field

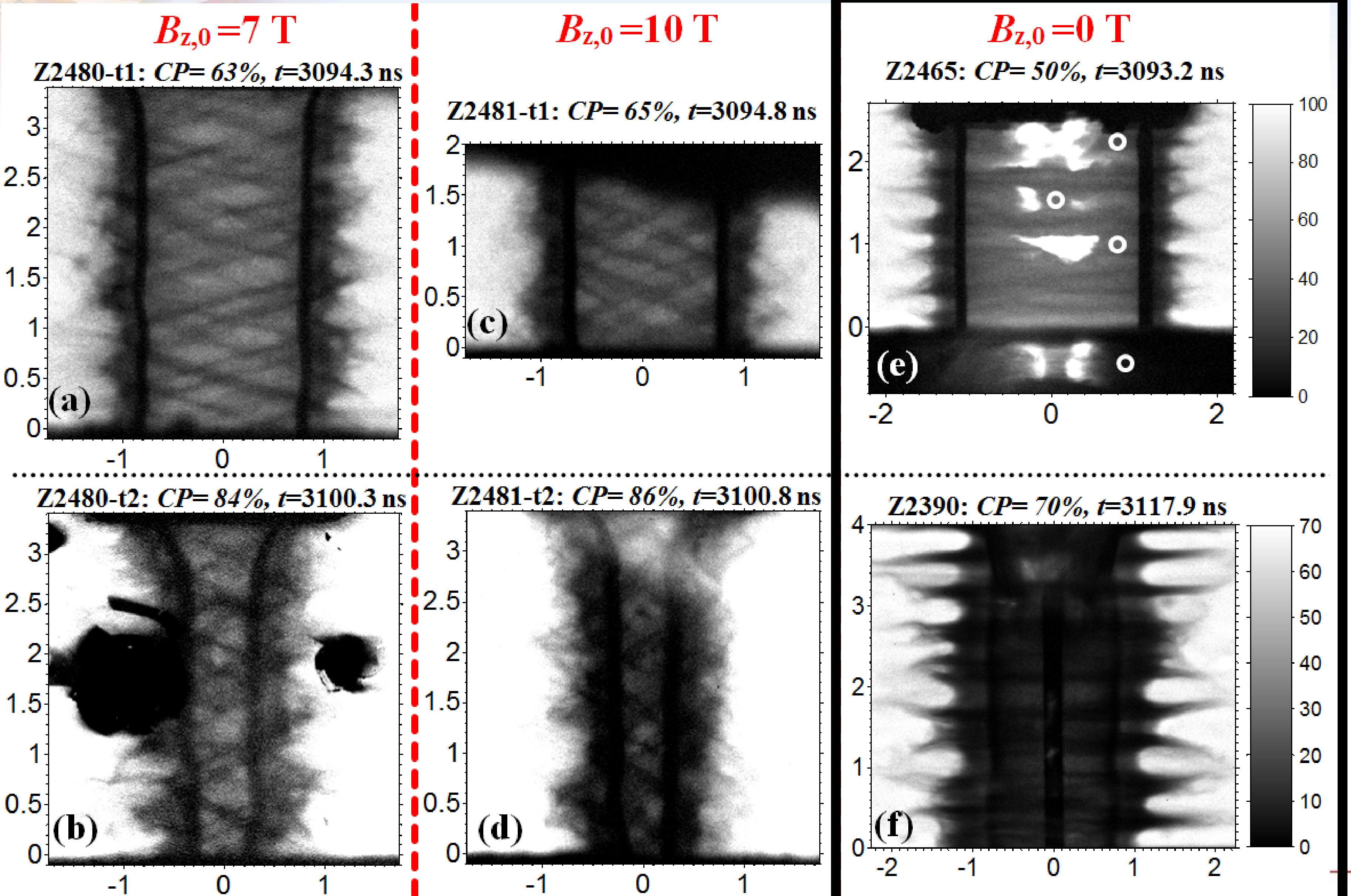
– 3.5 ms risetime used





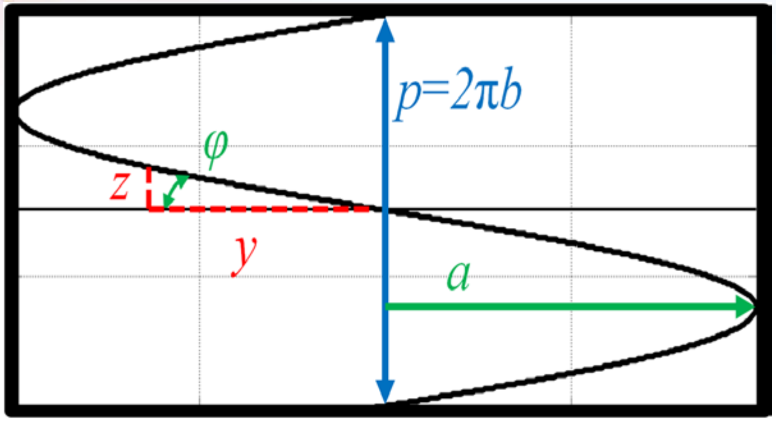


Helix-like instabilities develop on premagnetized liners



T.J. Awe *et al*. Phys. Rev. Lett. 111, 235005 (2013)
T.J. Awe *et al*. Phys. Plasmas 21, 056303 (2014)

A simple cylindrical helix model fits the data well



Cylindrical helix model

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

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

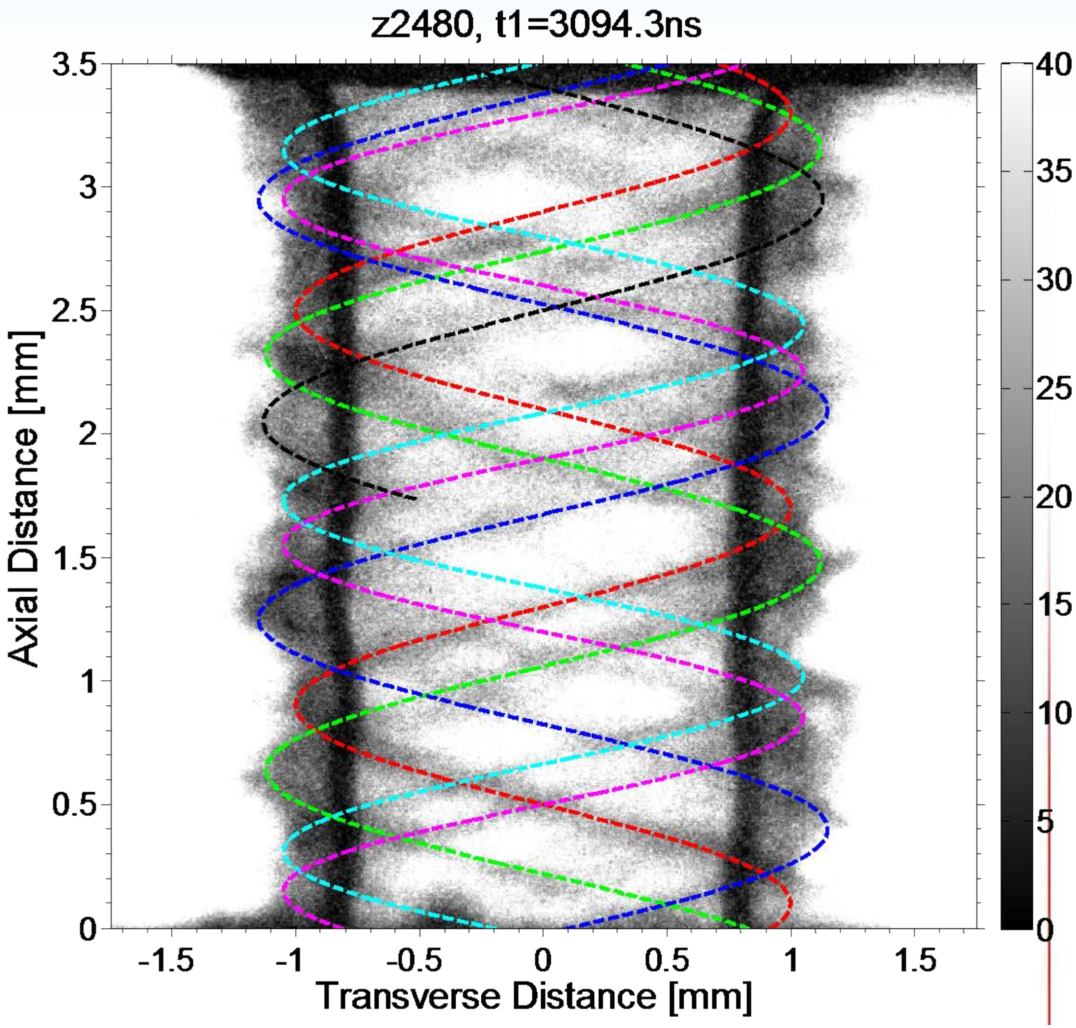
a =radius

p=pitch

"pitch angle"

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

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

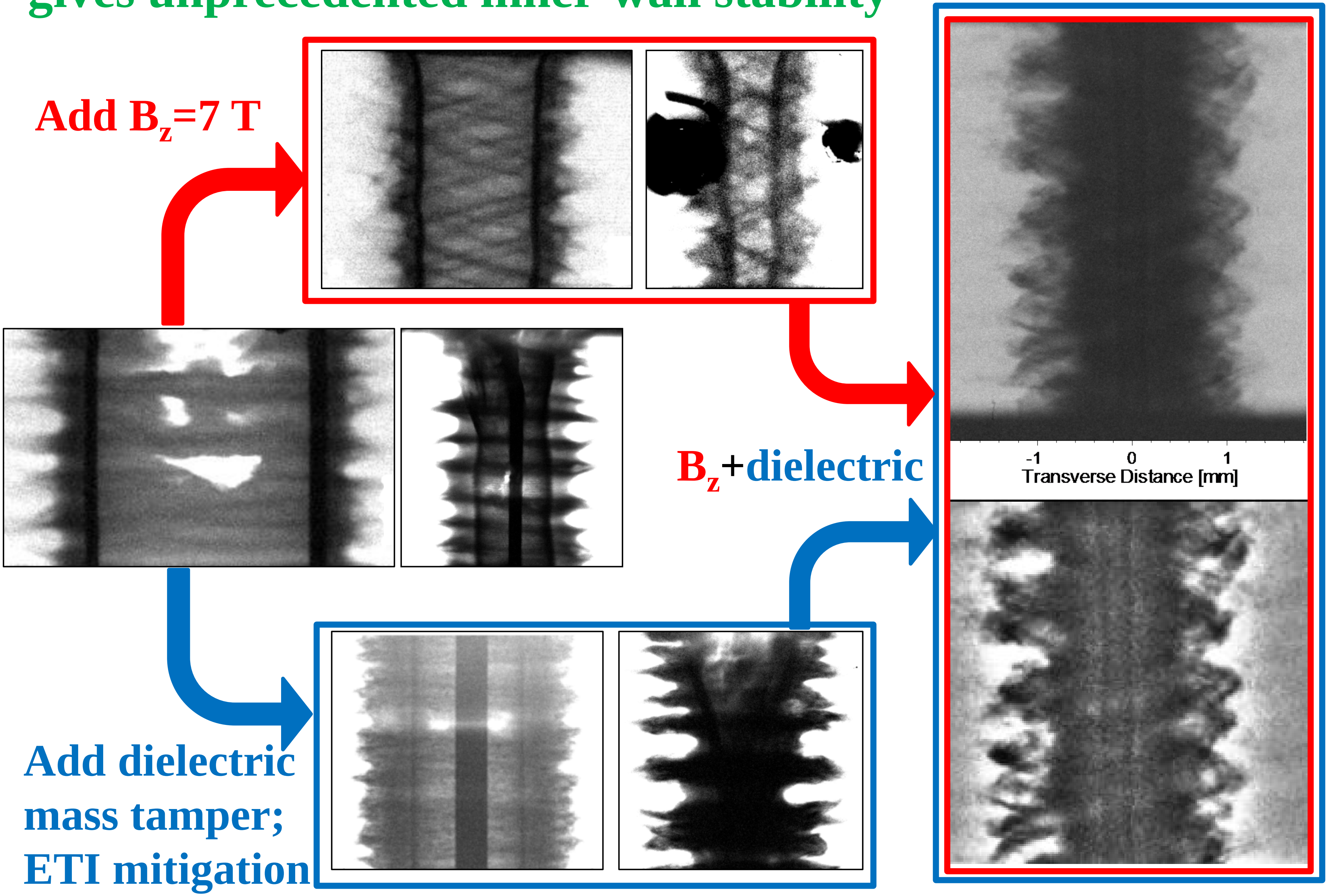


$\boldsymbol{a_{avg}=1.07}$ **mm**

$\boldsymbol{p_{avg}=1.56}$ **mm**

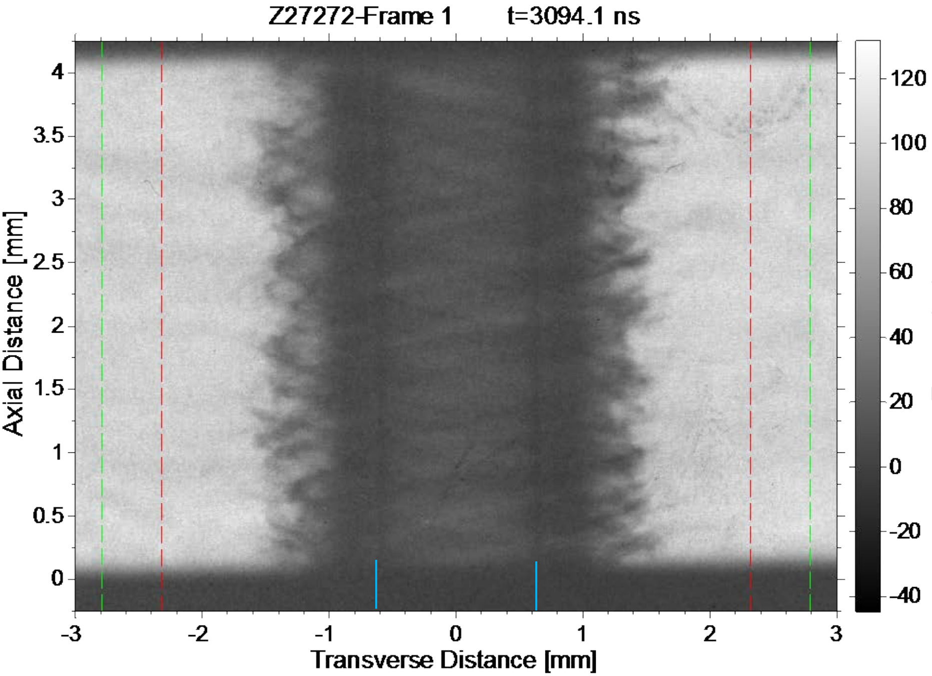
B_z with mass tamping (ETI mitigation) gives unprecedented inner-wall stability

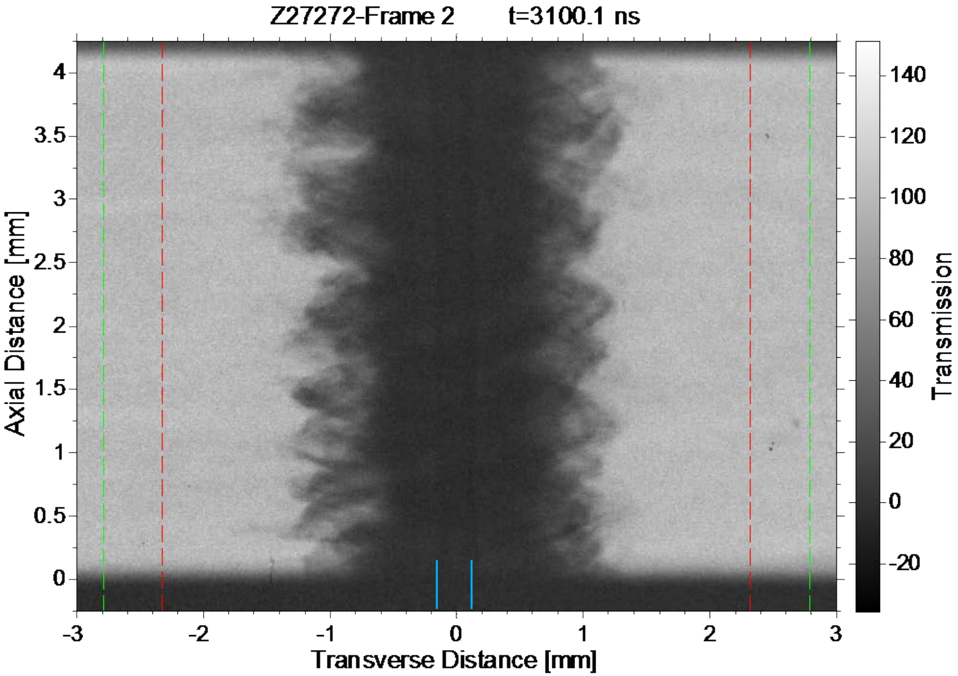
$CR = R_{in}(t=0)/R_{in}(t) = 21!$



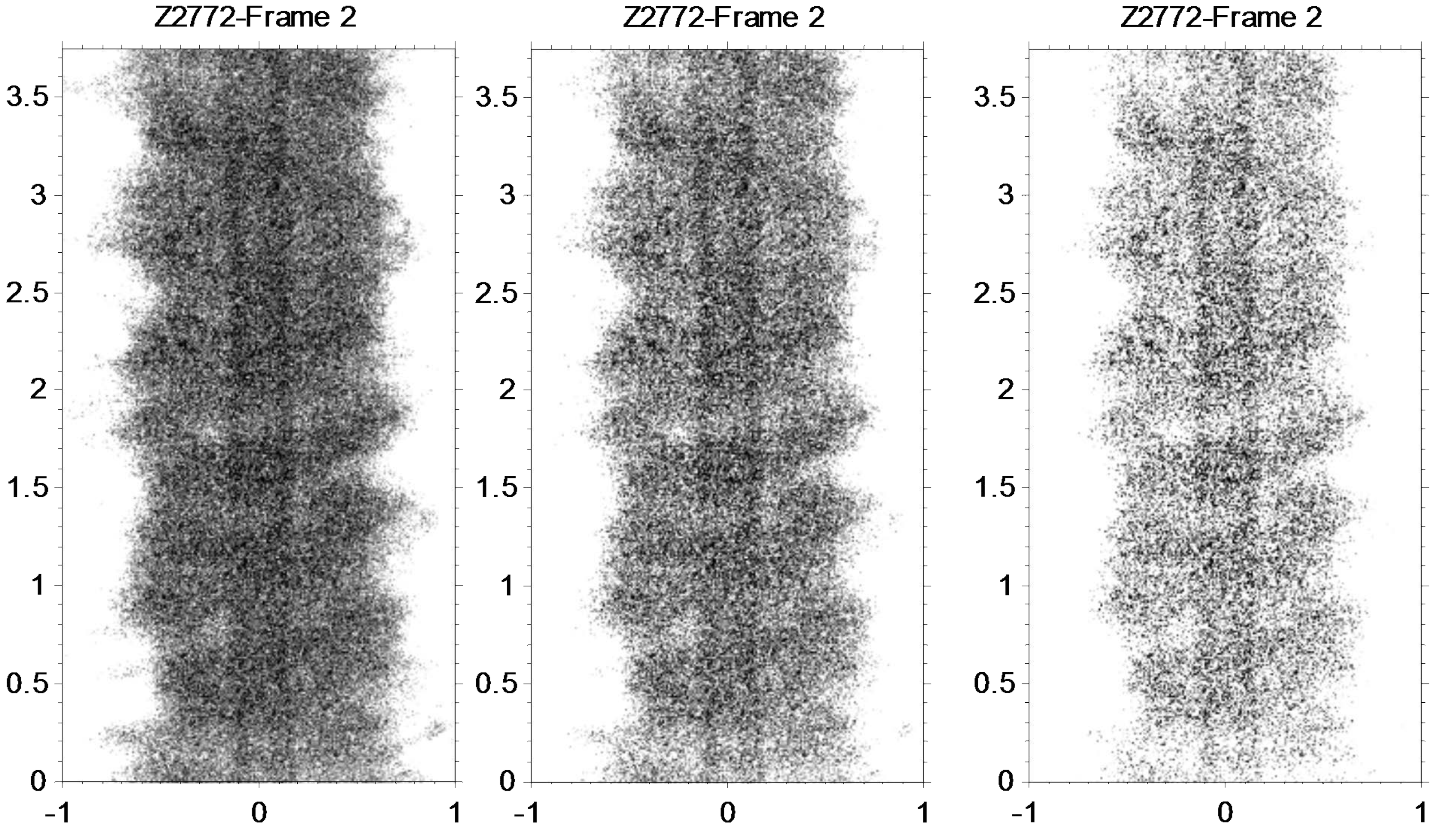
Z2772 examined ETI and MRT development on a dielectric-coated and pre-magnetized MagLIF liner

- Helical structure still present with dielectric coating added
- Radiographs demonstrate remarkable implosion uniformity
- Preliminary estimates of liner convergence ratio ($CR=R_{in}(t=0)/R_{in}(t)$) are CR=3.6 for frame 1, and CR=13 for frame 2.
  - Green and red lines indicate $R_{out}(t=0)$ and $R_{in}(t=0)$, respectively
  - CR=13 represents the highest CR radiograph of a MagLIF liner

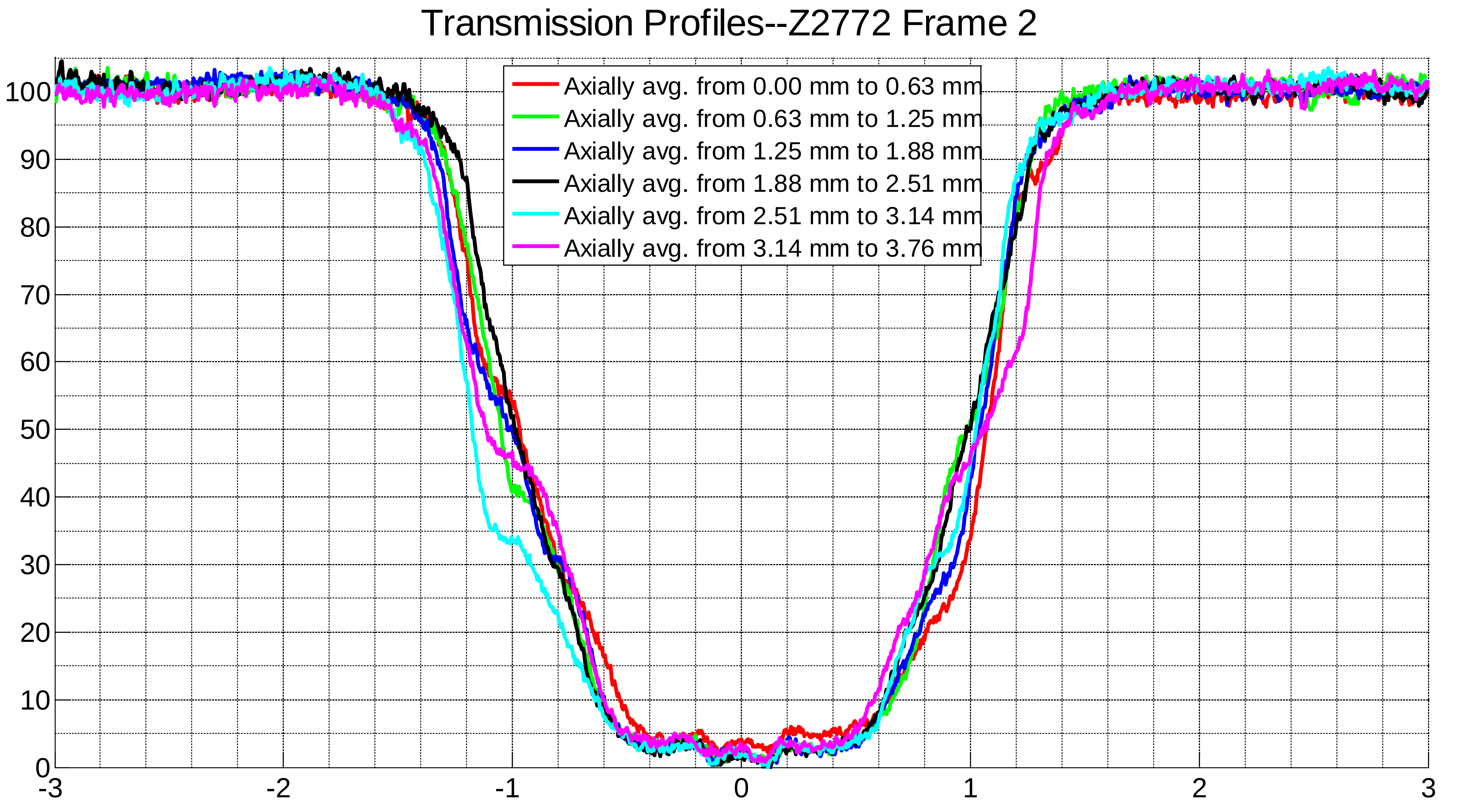




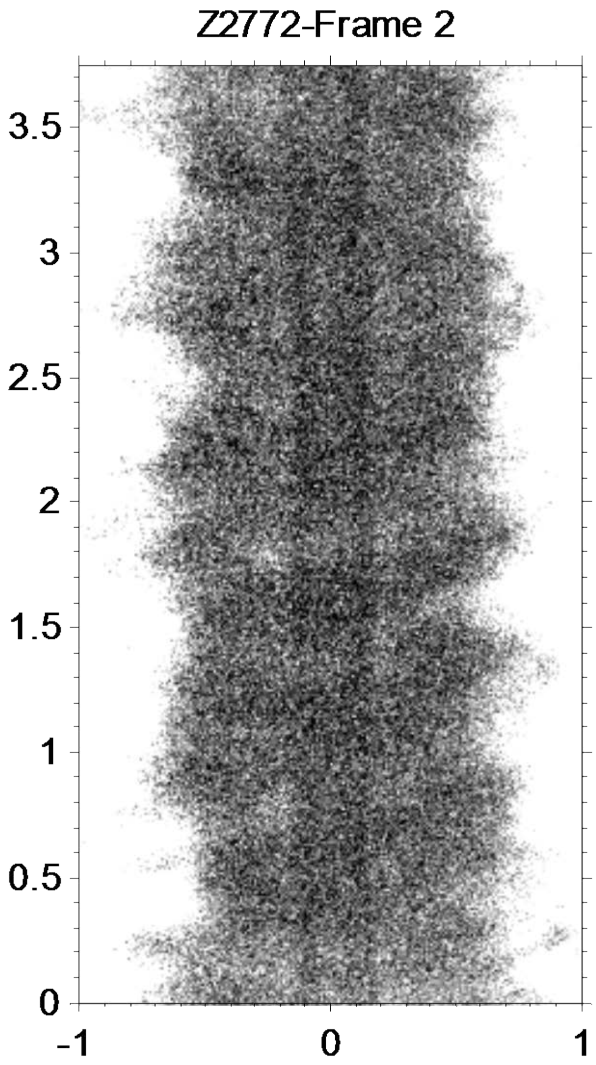
Enhanced contrast at inner liner wall

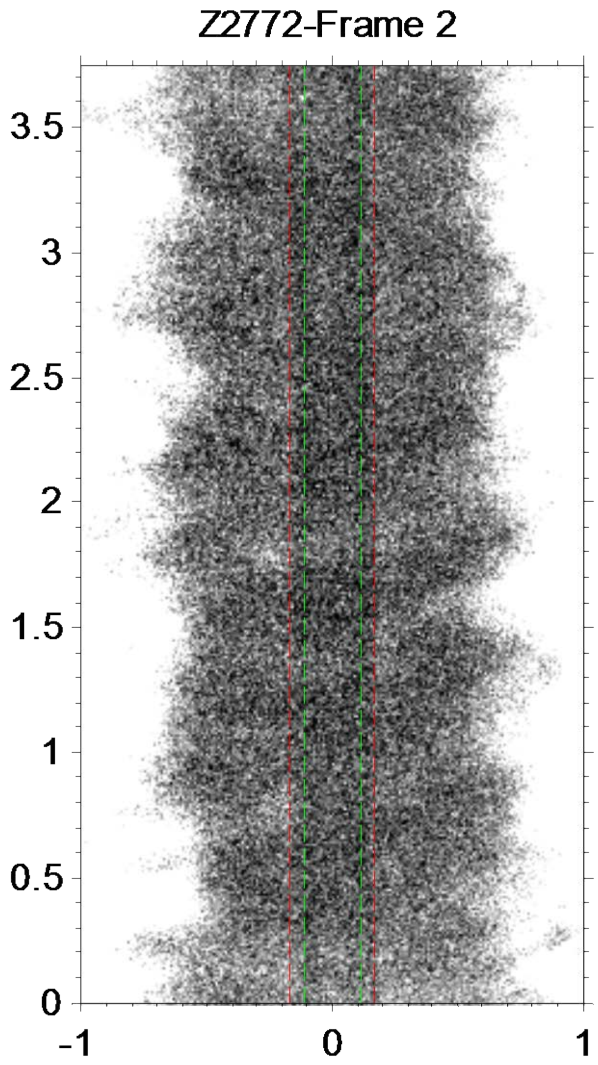


Transmission profiles. Image is binned into 6 axial bands…see next slide for reason



Enhanced contrast version; then add the average outer (CR-13.8) and inner (CR-20.6) locations of the Pt coating





Enhanced contrast version; then add the average outer (CR-13.8) and inner (CR-20.6) locations of the Pt coating

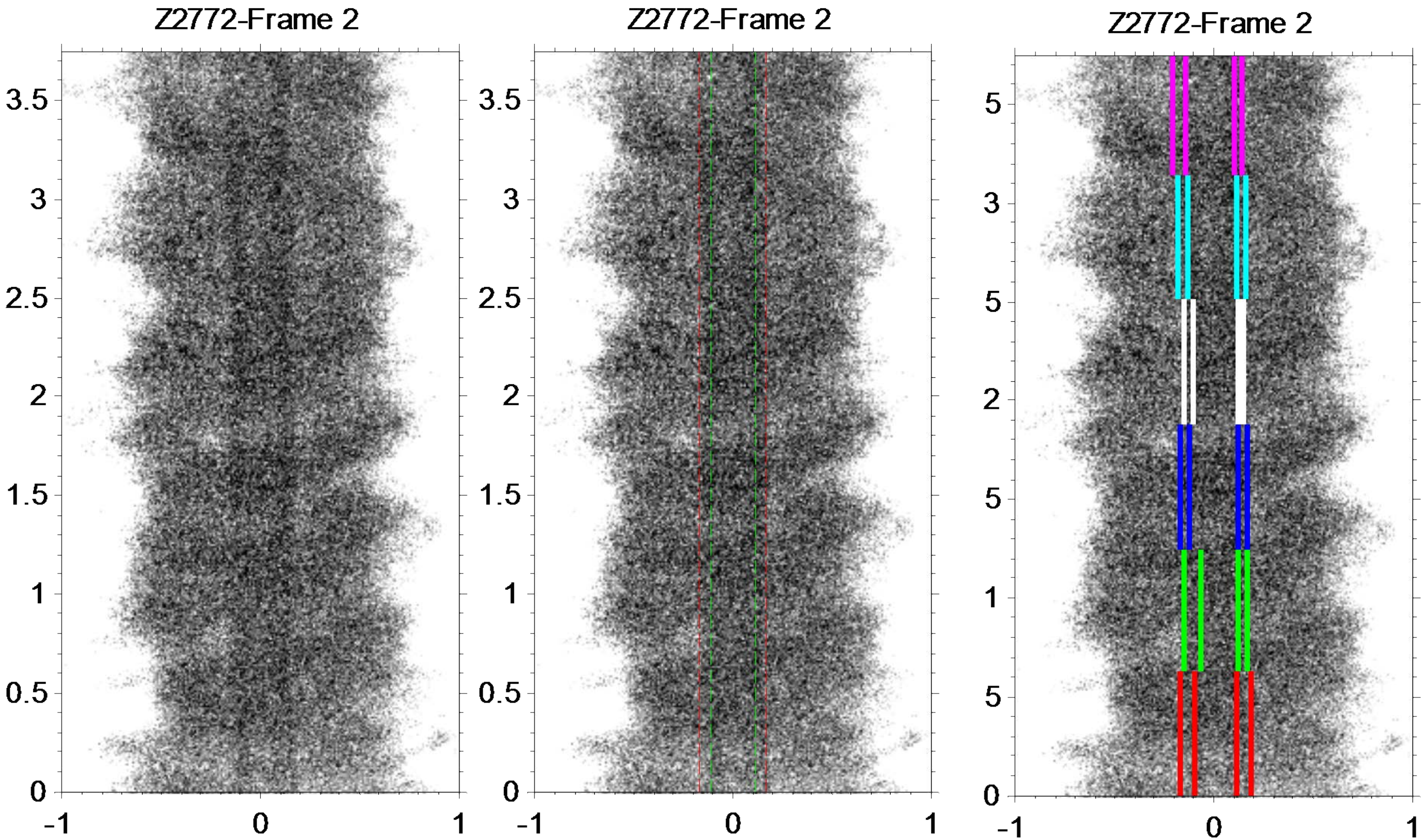
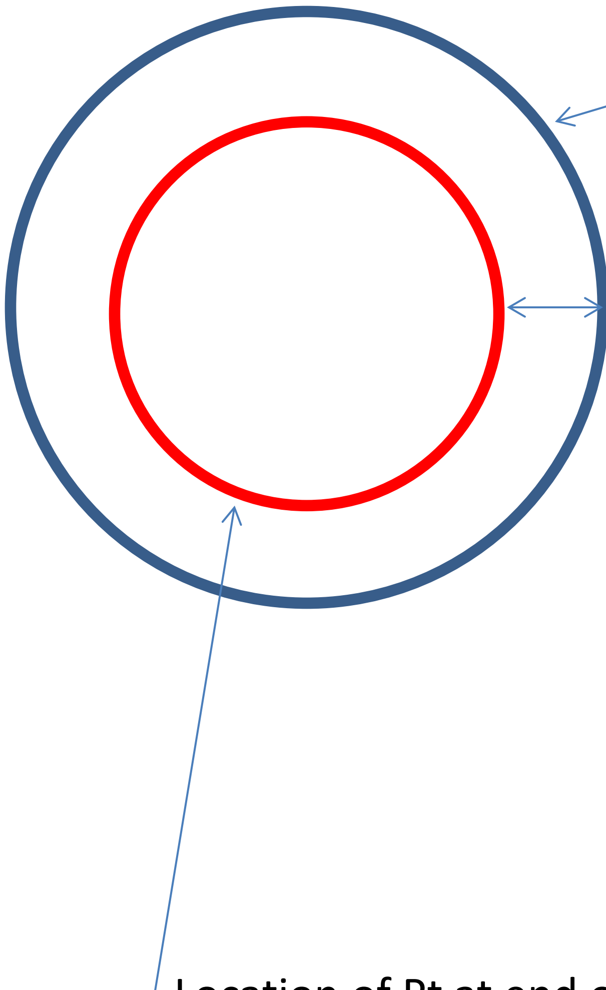


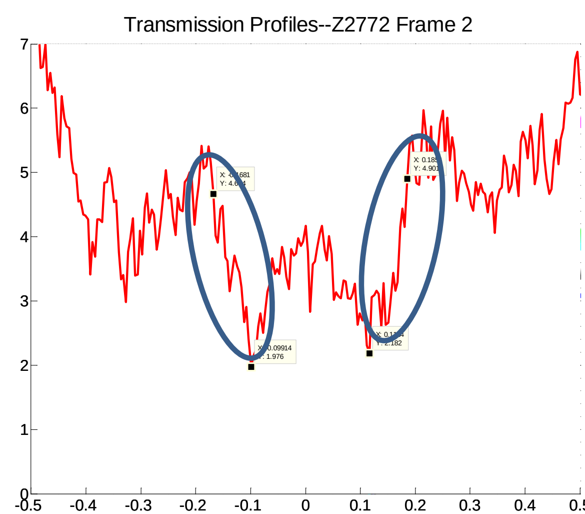
Image on far right does not average over the entire height, but just shows the values for each 630 micron high section that was averaged

Thoughts on motional blurring off the Pt coating

Location of Pt at start of 1 ns radiograph pulse



70 microns: All locations see limb darkening region of Pt for some brief amount of time (~100 ps) that it takes for Pt layer to pass by. At the outermost radius (blue) that's all the influence the Pt has on transmission. Radii inside are also influence by the non limb (cylindrical wall) regions of the Pt for some portion of the 1 ns. The innermost radius (red) is influenced by these two Pt wall for the full 1ns. That might explain the drop in transmission in the region I've circled below.

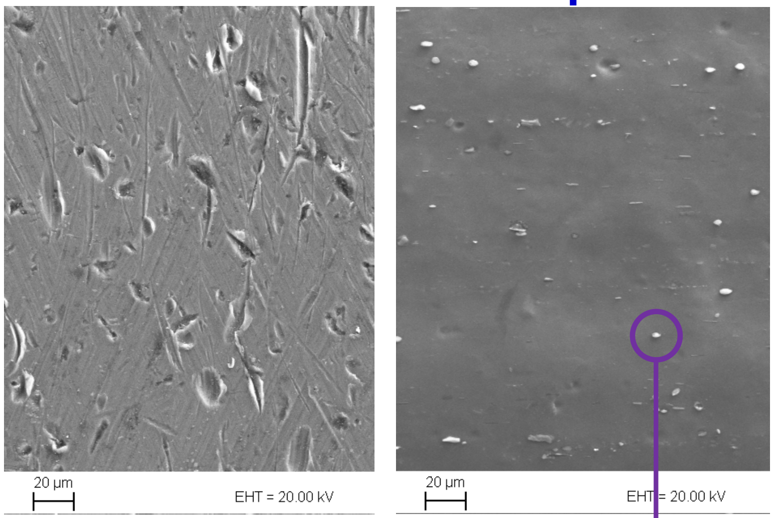


Location of Pt at end of 1 ns radiograph pulse

Mysteries of plasma formation remain

- **What are the seeds of instabilities? How do they depend on surface characteristics and material?**
- **In what way does 1D modeling represent physics of a 3D surface?**
- **E.g., Al-6061 machined surface vs. electropolished to ultra-smooth finish, but leaving Mg/Cu/Si precipitates**

Machined **Electropolished**

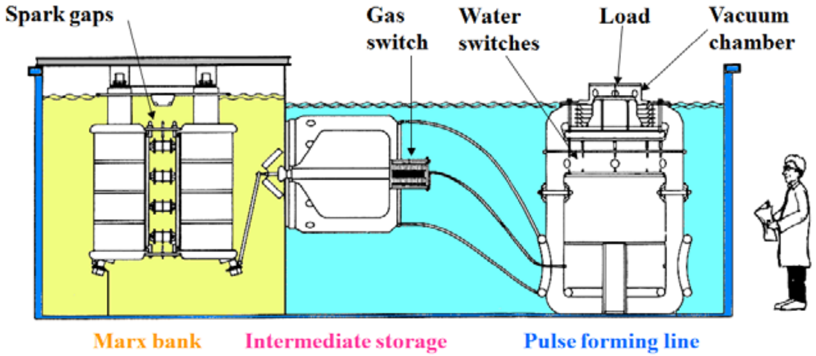


Scanning Electron Microscopy (SEM)

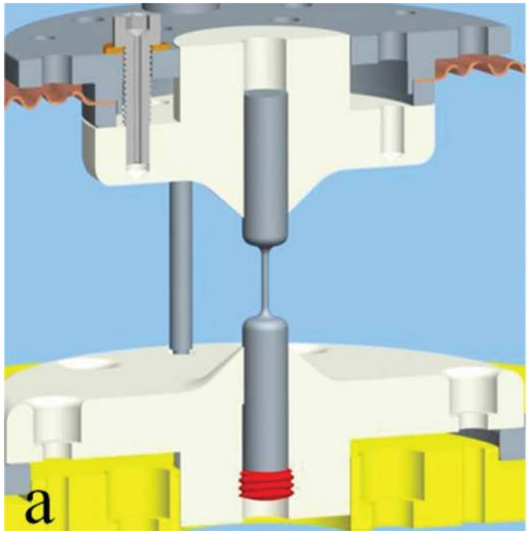
- ✓ **Deployed Questar QM-100 Long-Distance Microscope**
- ✓ **Observed fine details of plasma formation and surface dynamics**
- ✓ **Quantify early temperature variations**

The **proposed technical approach** will leverage previous work; we'll add advanced target fabrication and characterization and improved diagnostics

U of Nevada, Reno Zebra Facility
→100 ns rise time (similar to Z)
→Suite of low temperature (NIR to EUV) diagnostics suitable for ETI studies
→**Up to 5 shots per day.**



ETI occurs in condensed metal state at low energy density
A 1 MA, 100 ns facility is fully capable of reaching this state

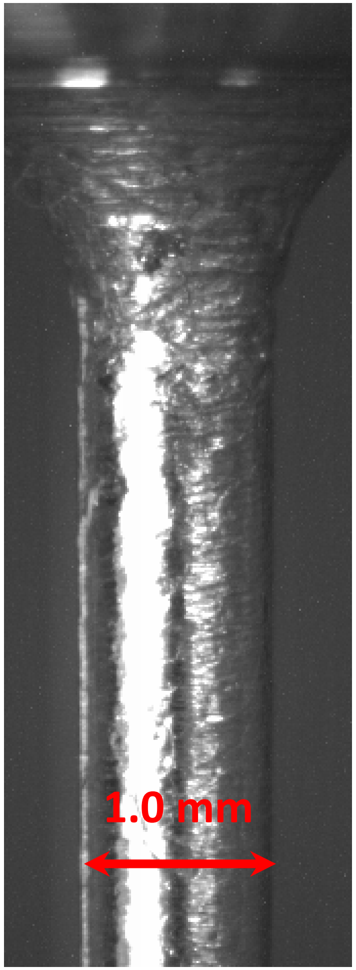


The "barbell load in knife-edge hardware" is **carefully designed to avoid non-thermal plasma formation mechanisms** common to high-voltage generators

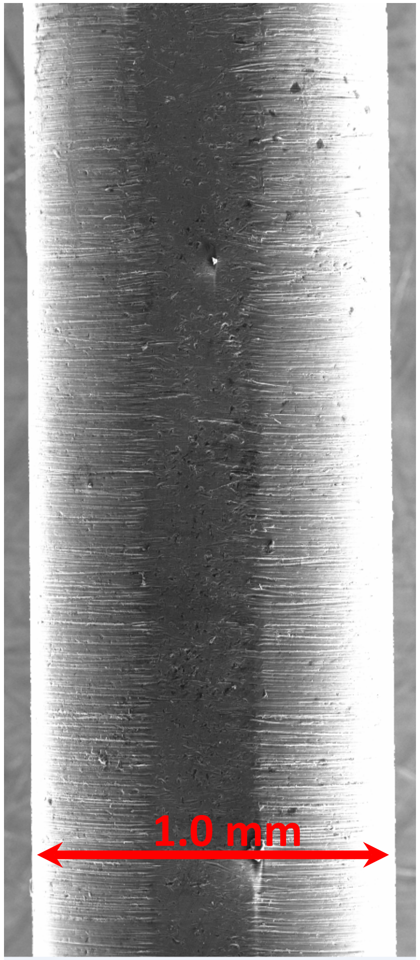
T.J. Awe, B.S. Bauer, S. Fuelling, and R.E. Siemon. Phys. Rev. Lett. **104**, 035001 (2010).
T.J. Awe, B.S. Bauer, S. Fuelling, I.R. Lindemuth, R.E. Siemon. Phys. Plasmas **17**, 102507 (2010).
T.J. Awe, B.S. Bauer, S. Fuelling, and R.E. Siemon. Phys. Plasmas 18, 056304 (2011).

Advance target fabrication techniques allow ETI to be the dominant seed for MRT

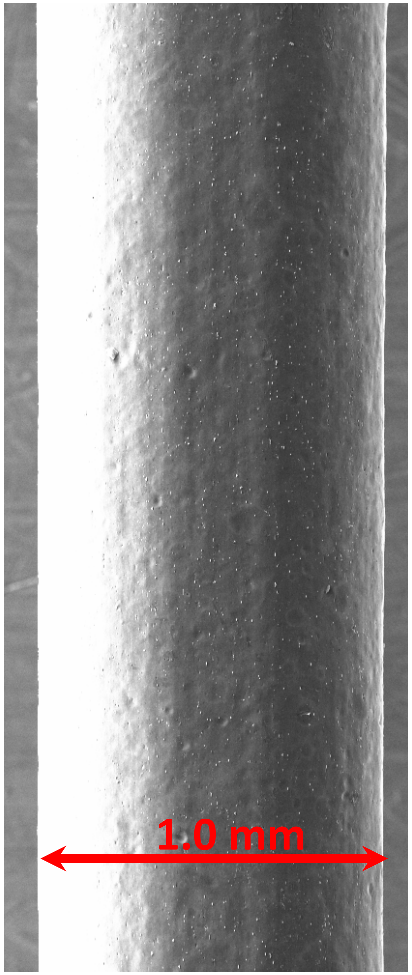
UNR machined
6061-Al load



Excel machined
6061-Al load



SNL electropolished
6061-Al load



Diamond turned
MagLIF liner

We recently initiated a collaboration with center 1800 (B. Jared) to generate diamond turned barbells

We've "designed" a high resolution (2 ns, 10 μm) gated NIR/visible imager to capture low temperature vapor/plasma emissions

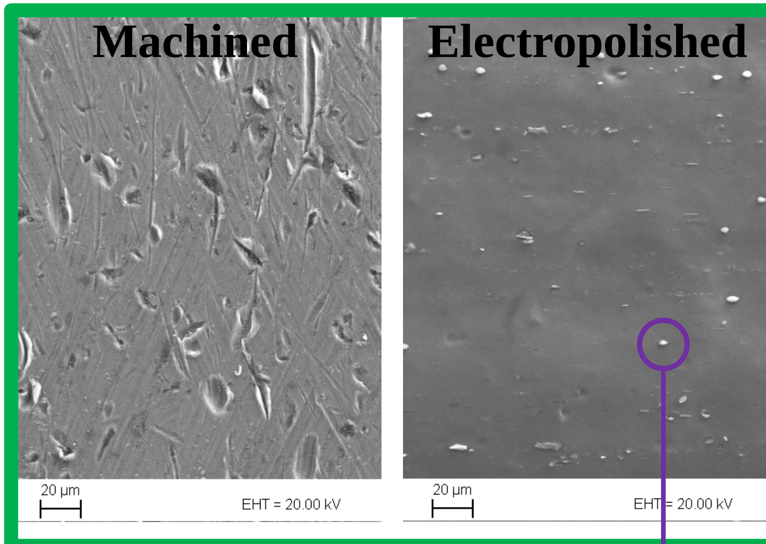
Questar QM100 long distance microscope

Andor iStar 334T intensified CCD camera

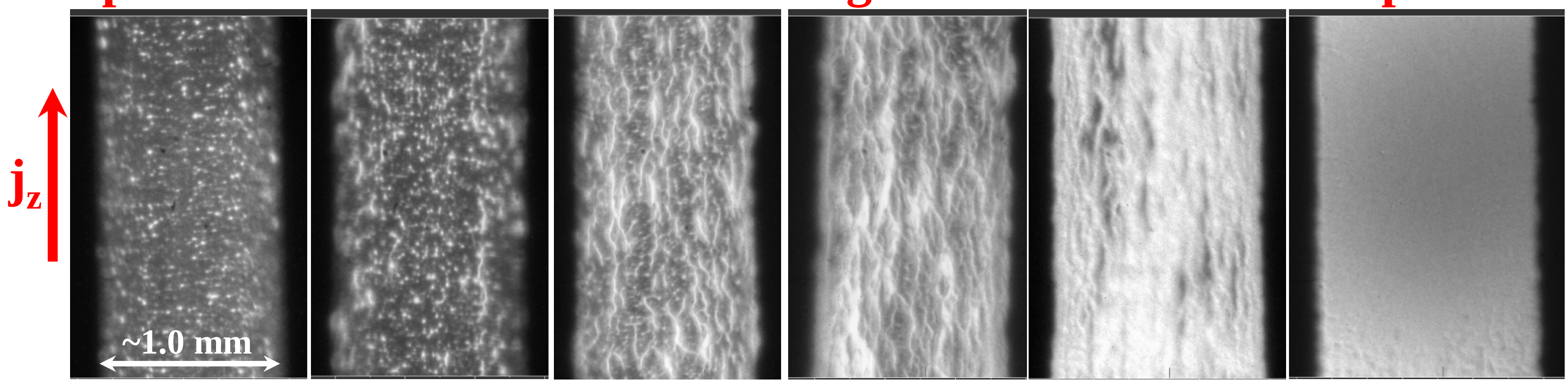
14" working distance on Zebra…performance improves if we can bring instrument closer to the load

LDRD-funded research studies the impact of resistive/electrothermal instabilities on intensely Ohmically heated conductors

- **D_0=1.0 mm 6061-Al rods pulsed to B_Θ ~ 3 MG in 100 ns by 1 MA driver**
  - **Current flows in surface skin layer**
  - **Ohmic heating drives plasma formation**
- **Machined surfaces electropolished to ultra-smooth finish**
  - **Machining artifacts removed**
  - **Mg/Cu/Si precipitates remain**

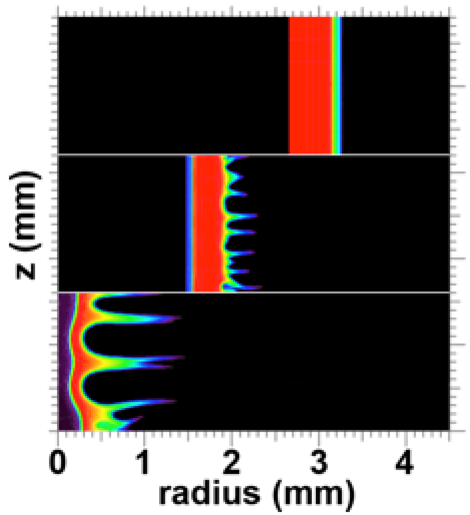


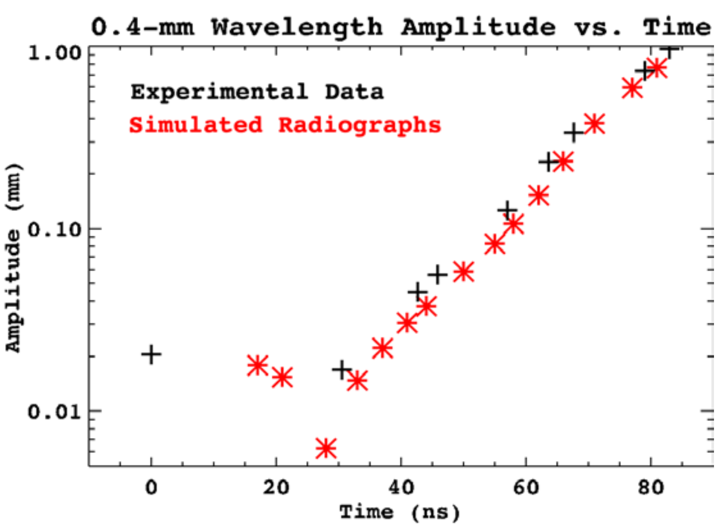
High resolution (10 µm, 2ns) imaging of visible self-emission shows complex/non-uniform structure during surface's transition to plasma

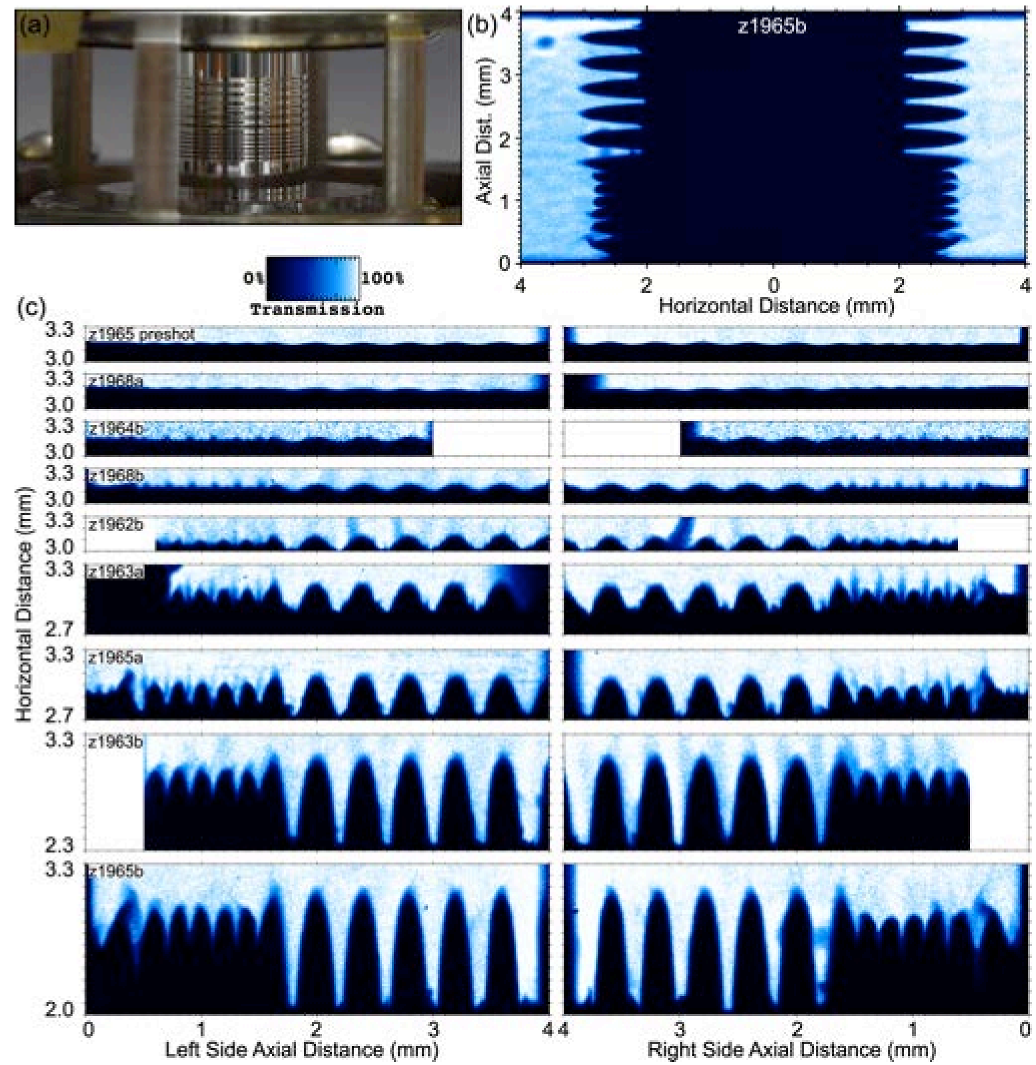


Increasing surface magnetic field (B_Θ)

We observe excellent agreement between theory and experiment for single-mode MRT growth experiments

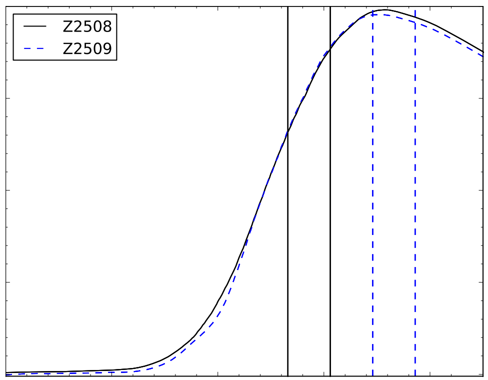


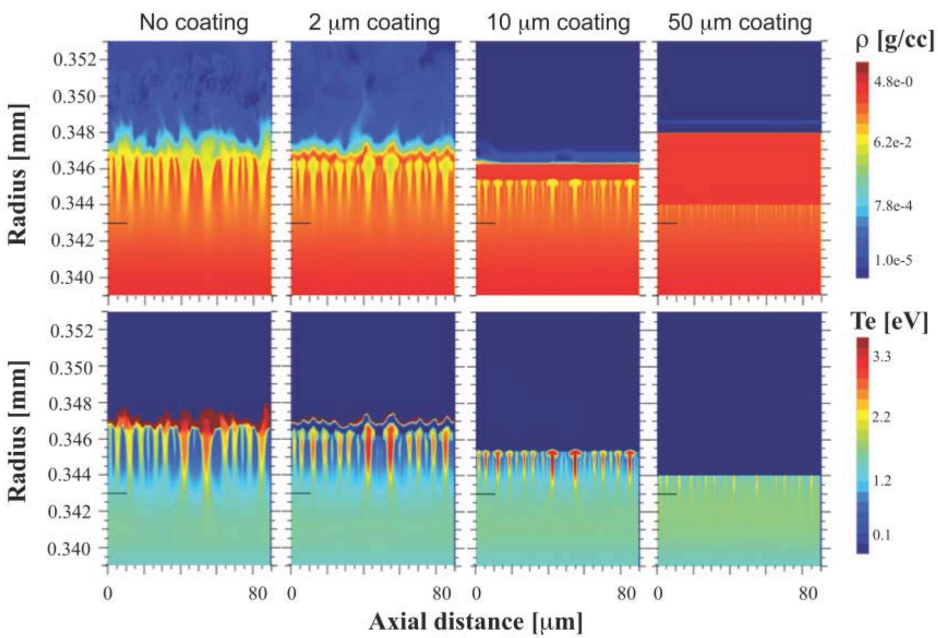


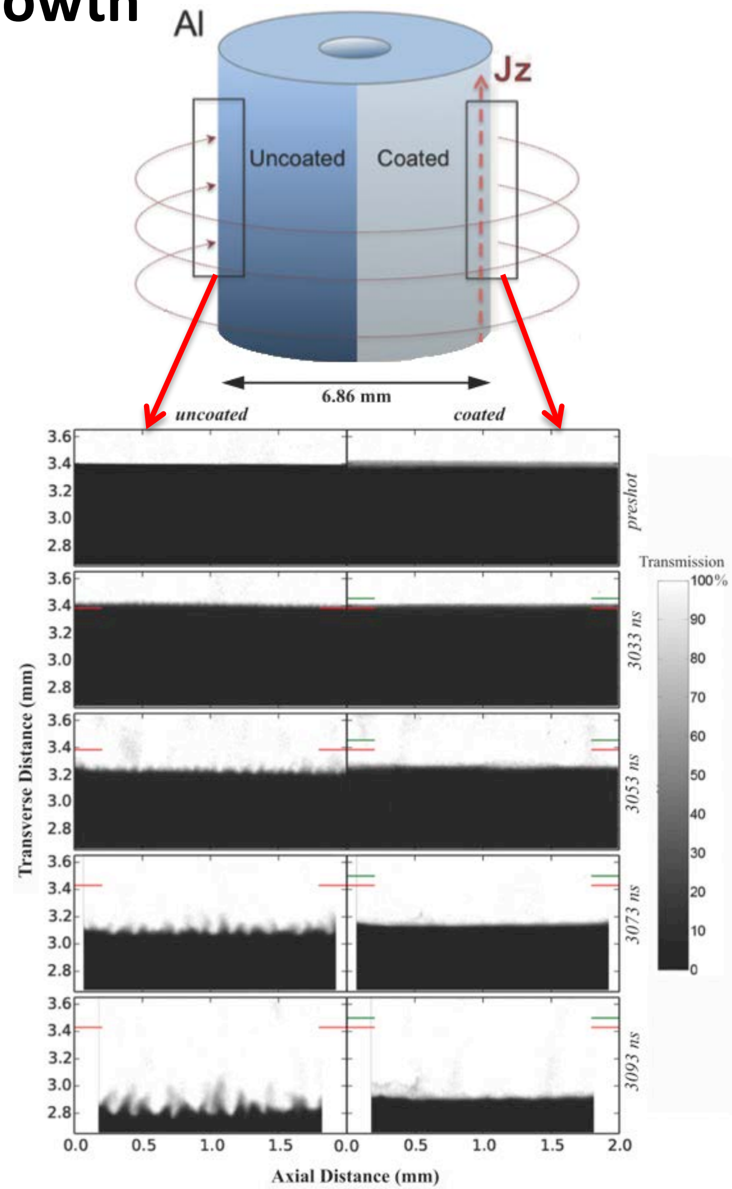


D.B. Sinars et al., Phys. Rev. Lett. (2010); D.B. Sinars et al., Phys. Plasmas (2011).

We have **confirmed experimentally that thick dielectric coatings reduce instability growth**



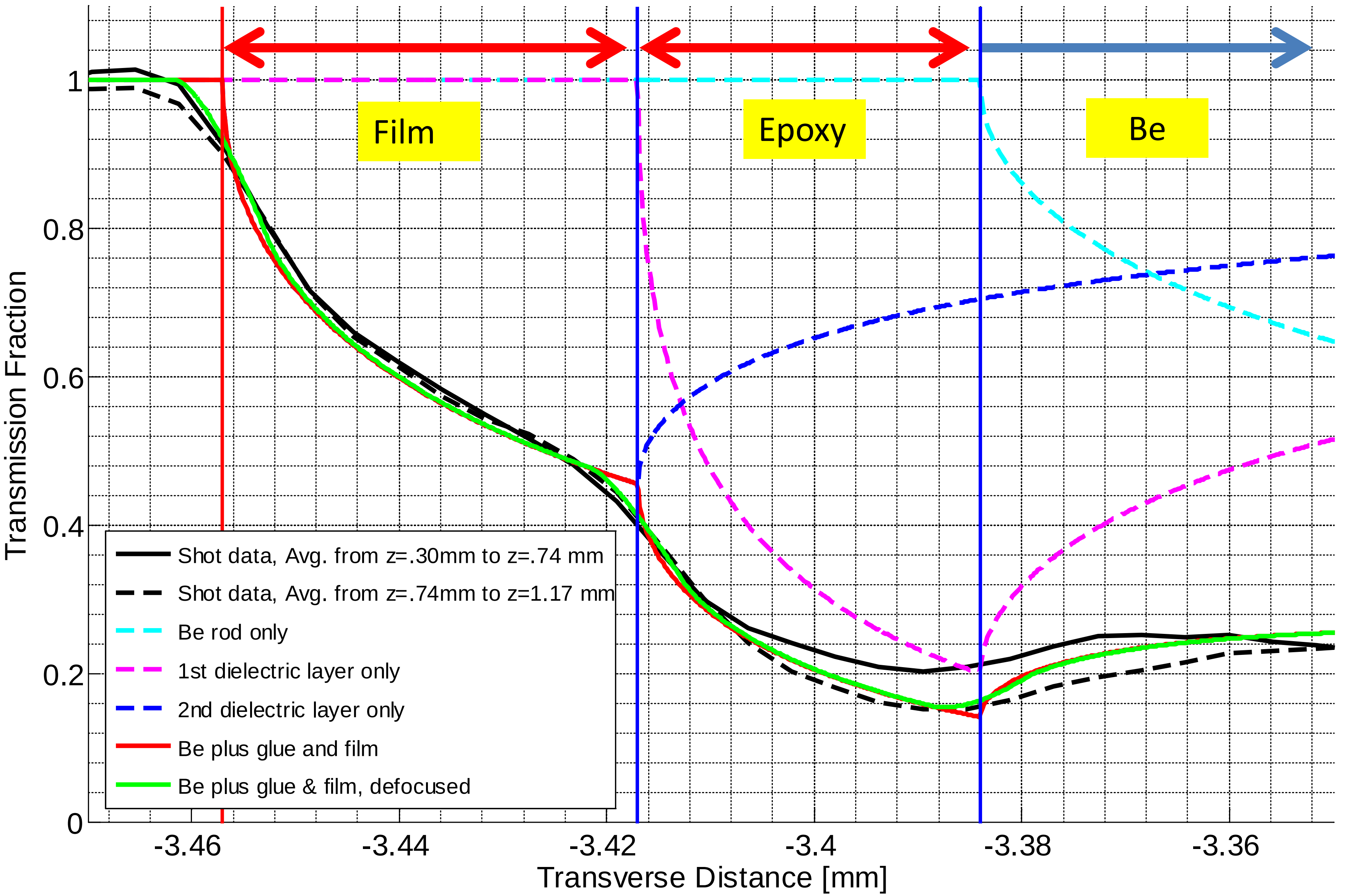




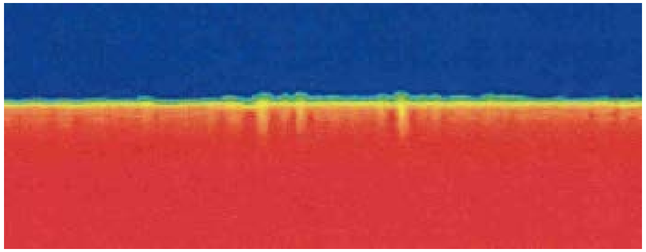
K.J. Peterson *et al.*, Physical Review Letters 112, 135002 (2014)

Transmission calculation: $R_{out,Be}$=3.384 mm (κ=2.44 cm^2/g), 33 microns of glue (κ=17), , and 40 microns of film (κ=7.5)

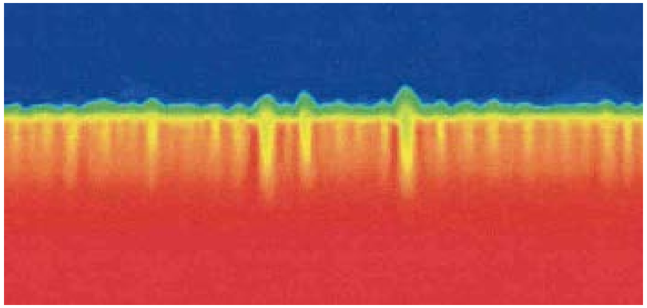
w/ 20 micron smooth for radiograph defocusing



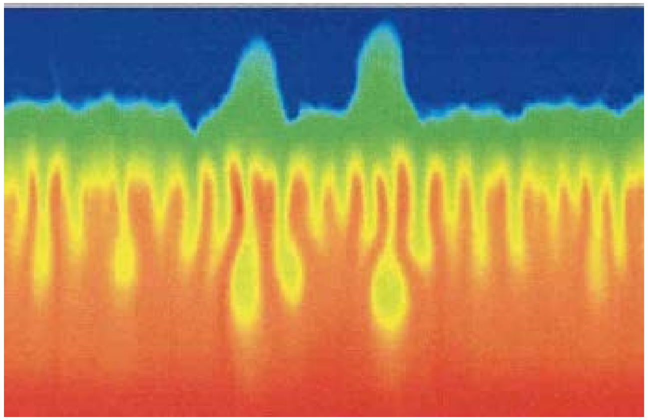
2D simulations show electro-thermal instabilities develop after melt and seed later MRT growth



Due to non-uniformities in the metal's room temperature resistivity, as the metal surface melts, electrothermal instabilities grow rapidly
Locations with initially higher resistivity vaporize/expand first→perturbation forms



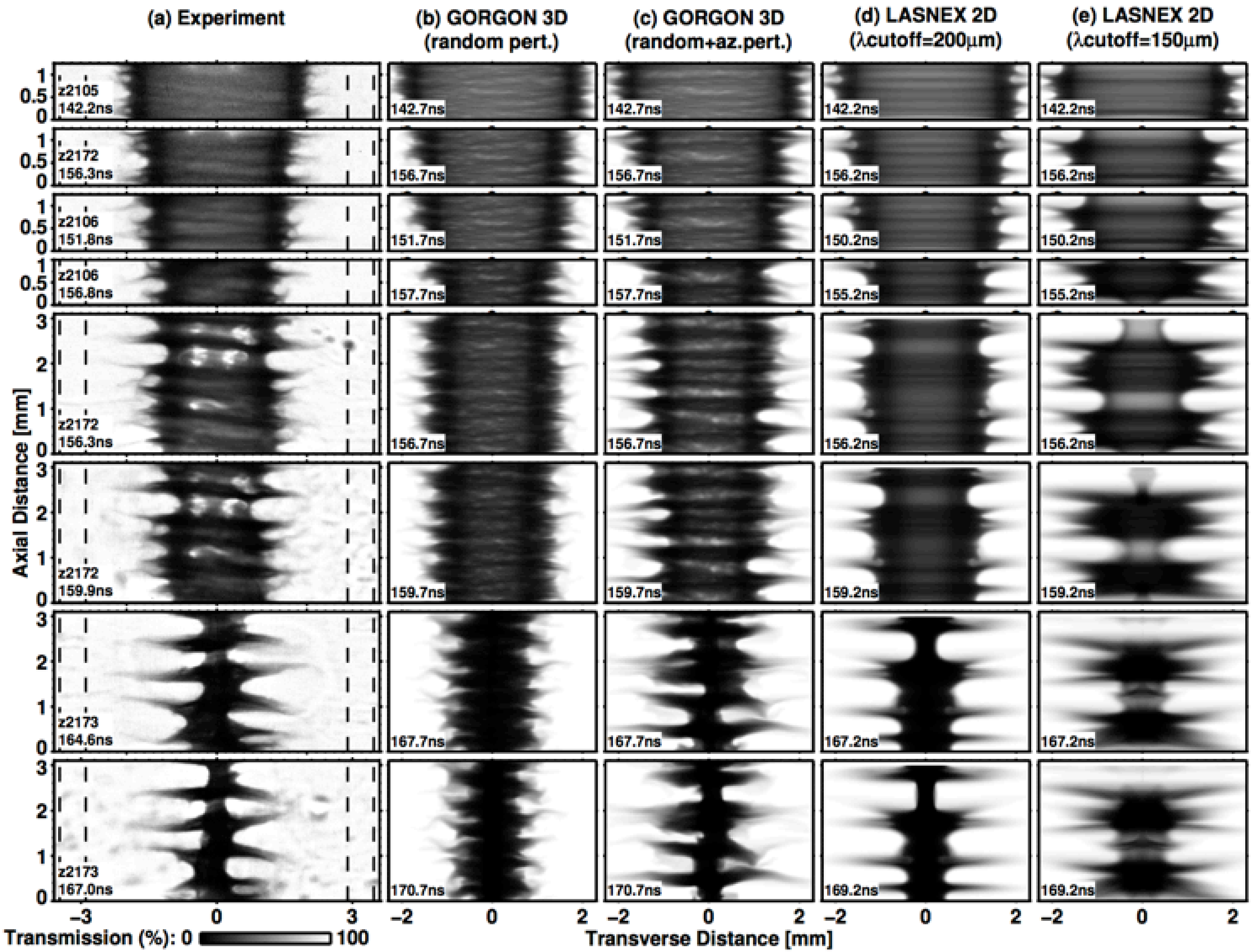
The Magneto-Raleigh Taylor (MRT) instability grows from the ETI seed, and begins to dominate



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

K.J. Peterson *et al.*, Phys. Plasmas **19**, 092701 (2012).
K.J. Peterson *et al.*, Phys. Plasmas **20**, 056305 (2013).
K.J. Peterson *et al.*, Phys. Rev. Lett. **112**, 135002 (2014)

Previous experiments have also studied multi-mode MRT growth in Beryllium liners with initially flat contours



R.D. McBride et al., Phys. Rev. Lett. 109, 135004 (2012).

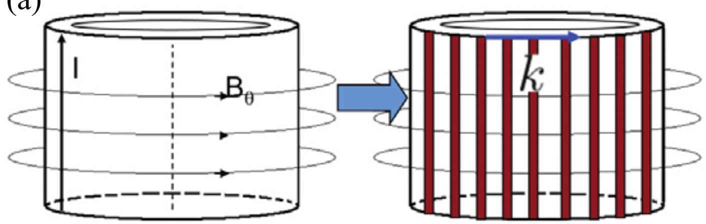
Electrothermal instabilities occur when material conductivity is dependent on temperature

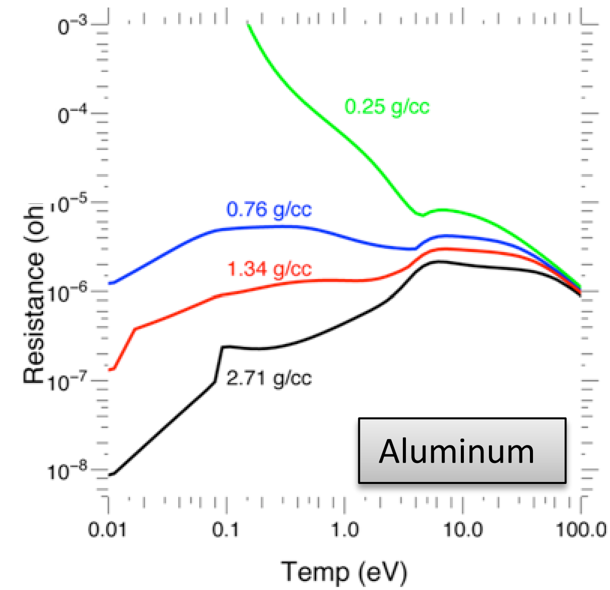
Theory

Filamentations

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

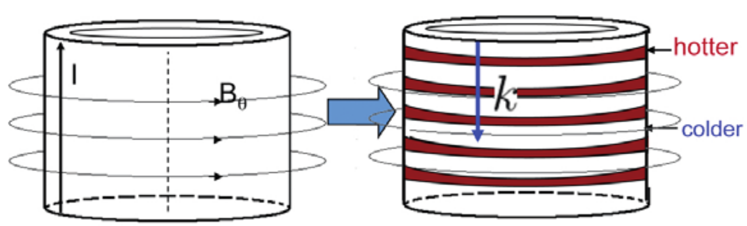
(a)





Striations

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

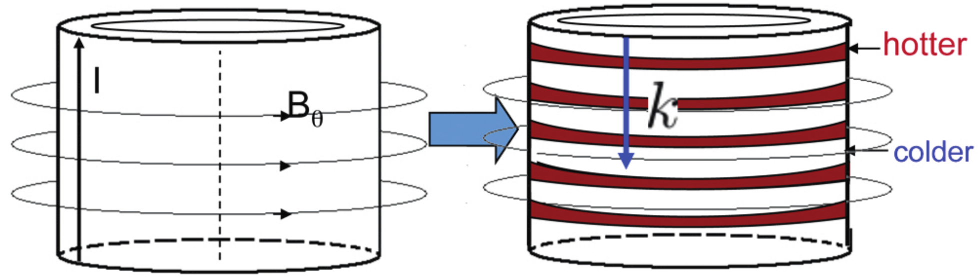


Electrothermal instabilities occur when material conductivity is dependent on temperature

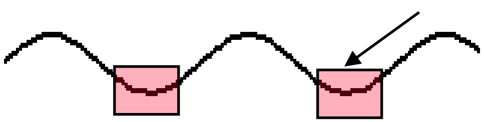
Theory

[Striations]

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



$$\delta T > 0$$



Consider a small temperature perturbation due to localized variations in ohmic heating

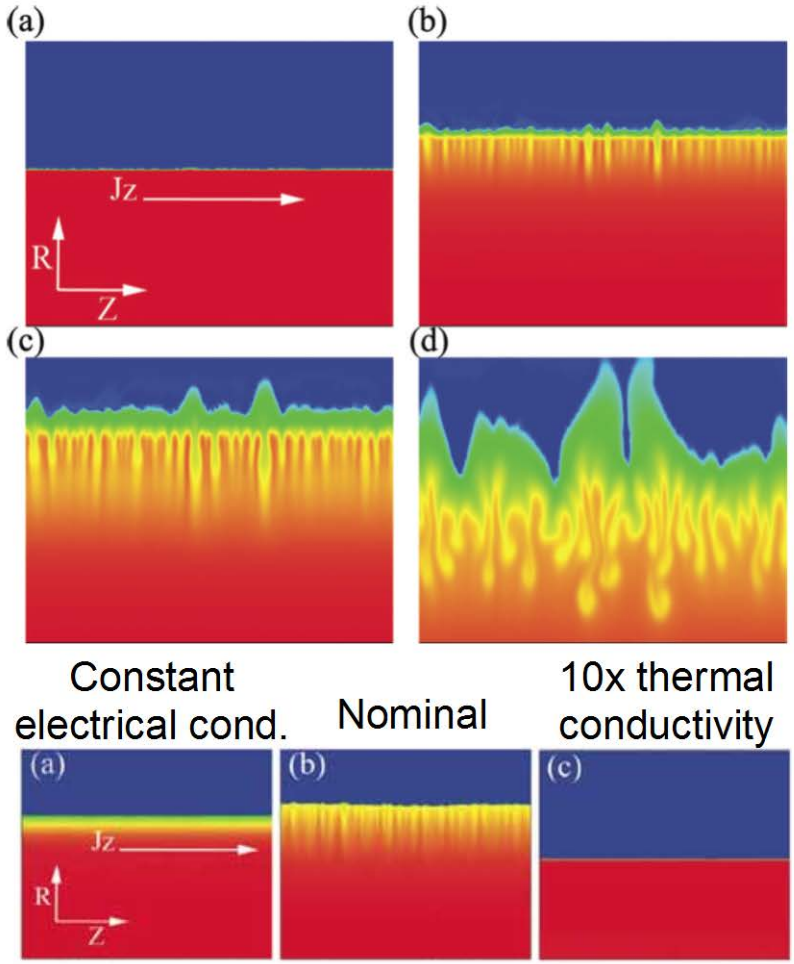
- surface contaminants (variations in η)
- surface roughness (B_θ ~ I/r, in cylinders)

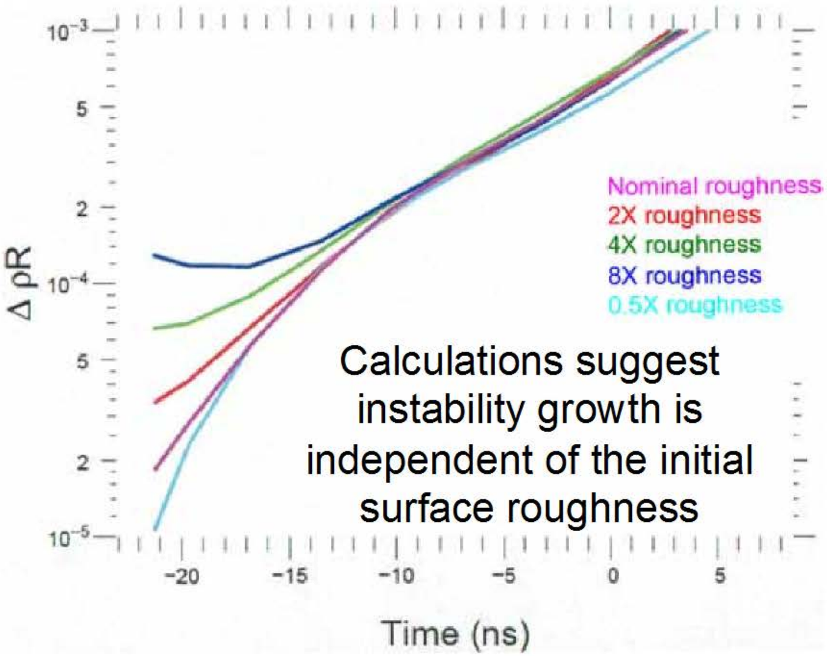
Then, η increases which consequently further enhances the localized ohmic heating (η j^2),

which leads to increased δT

Temperature perturbations give rise to pressure variations which eventually redistribute mass

The electro-thermal instability (ETI) is another important mechanism that could seed MRT growth

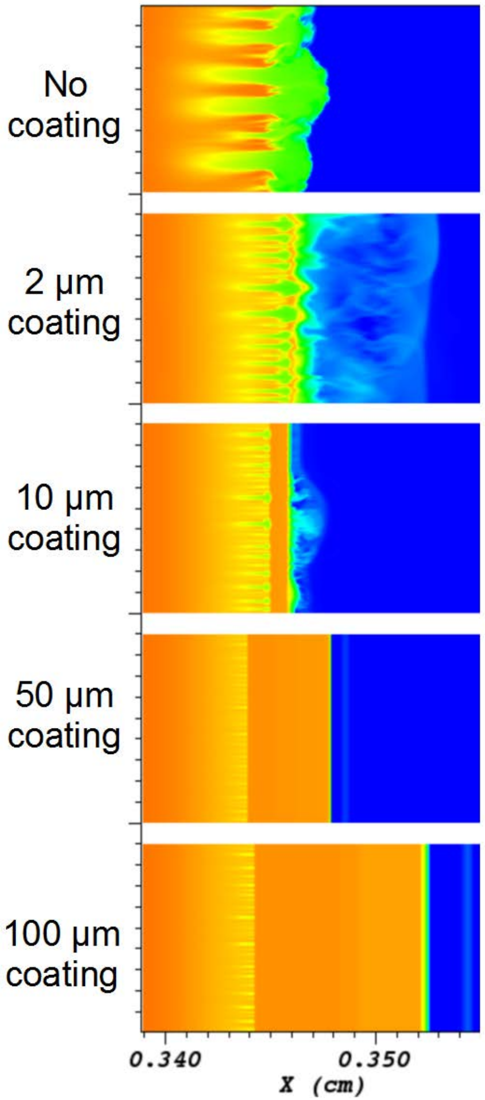




Temperature perturbations give rise to pressure variations which eventually redistribute mass

K.J Peterson et al., Phys Plasmas 19, 092701 (2012) and Phys Plasmas 20, 056305 (2013)

Relatively thick insulating coatings were proposed to mitigate effects of ETI and reduce seed for MRT growth



- No ETI (striation) growth in dielectric coating
  - Carries very little current
  - Theoretically ETI Stable $\frac{d\eta(T)}{dT} > 0$
- Linear ETI growth of temperature perturbations still present in metal
  - Slightly reduced by density dependence of growth rate
- Nonlinear mass redistribution from ETI is significantly tamped by the coating
  - Reduces seed for MRT growth
  - Reduces integral instability growth