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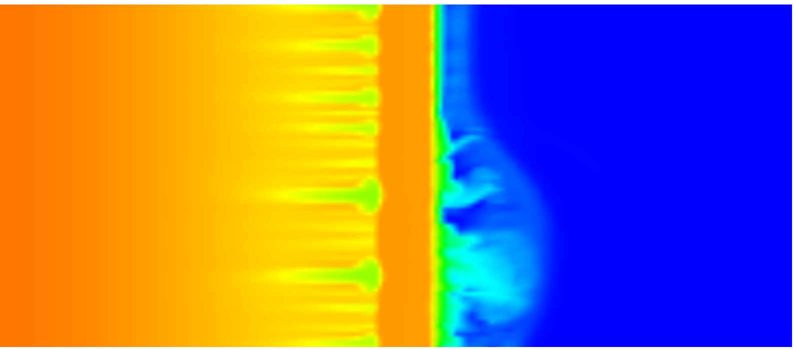

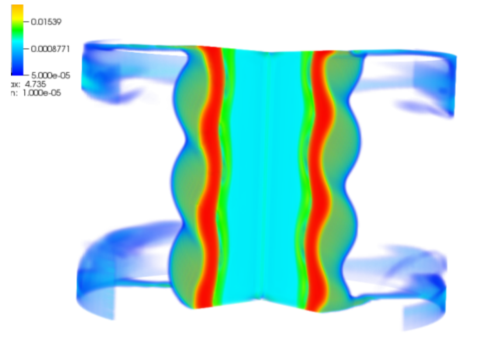


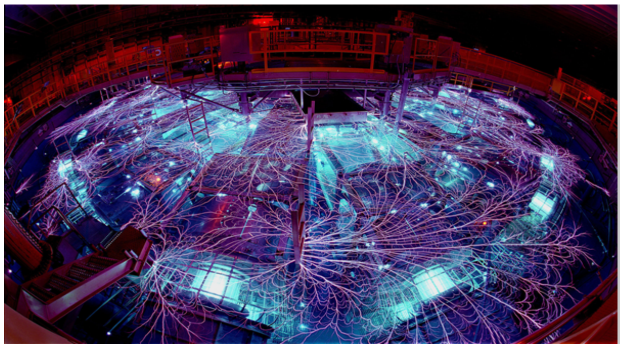

# Evaluation of instability growth, mitigation, and stabilization techniques in magnetized liner inertial fusion targets

Kyle Peterson [1], Dan Sinars [1], Edmund Yu [1], Matthew Martin[1], Ryan McBride [1], Christopher Jennings [1], Steve Slutz [1], Roger Vesey [1], Thomas Awe [1], Adam Sefkow [1], Michael Cuneo [1], Charlie Nakhleh [1], Brent Blue [2], Diana Schroen [1], Kurt Tomlinson [1], Joseph Koning [3]

*Eighth International Conference on Inertial Fusion Sciences and Applications*

*September 8-13, 2013*

*Nara, Japan*

U.S. DEPARTMENT OF ENERGY   NNSA National Nuclear Security Administration

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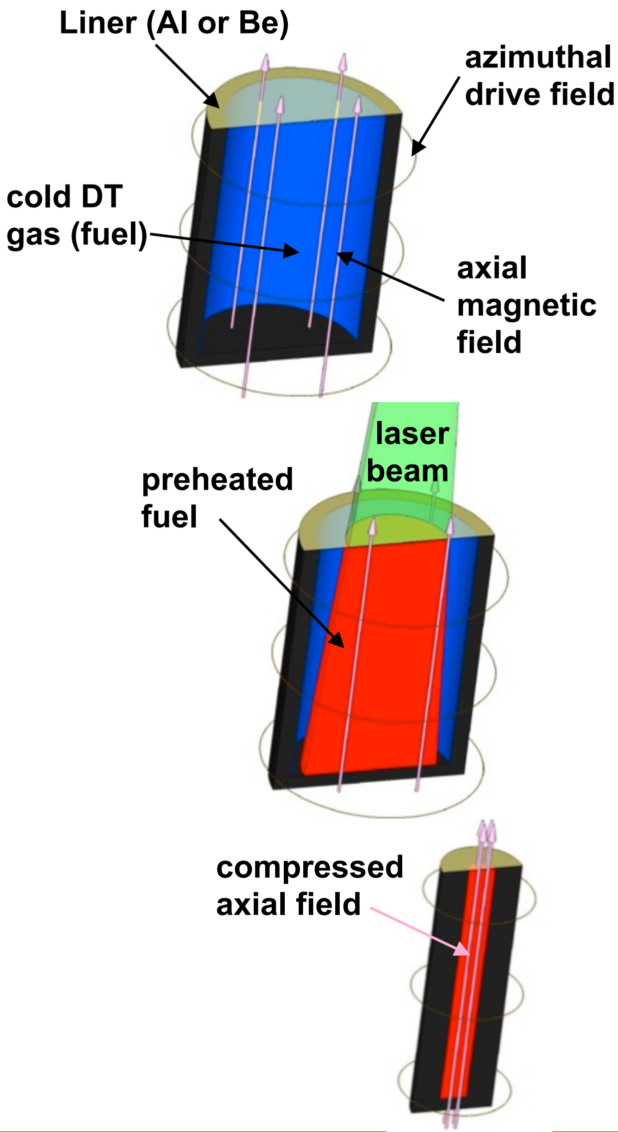
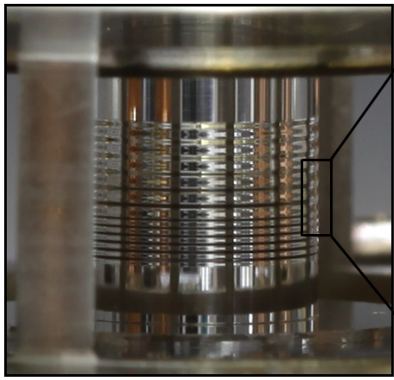
# We are working toward the evaluation of a new Magnetized Liner Inertial Fusion (MagLIF)* concept

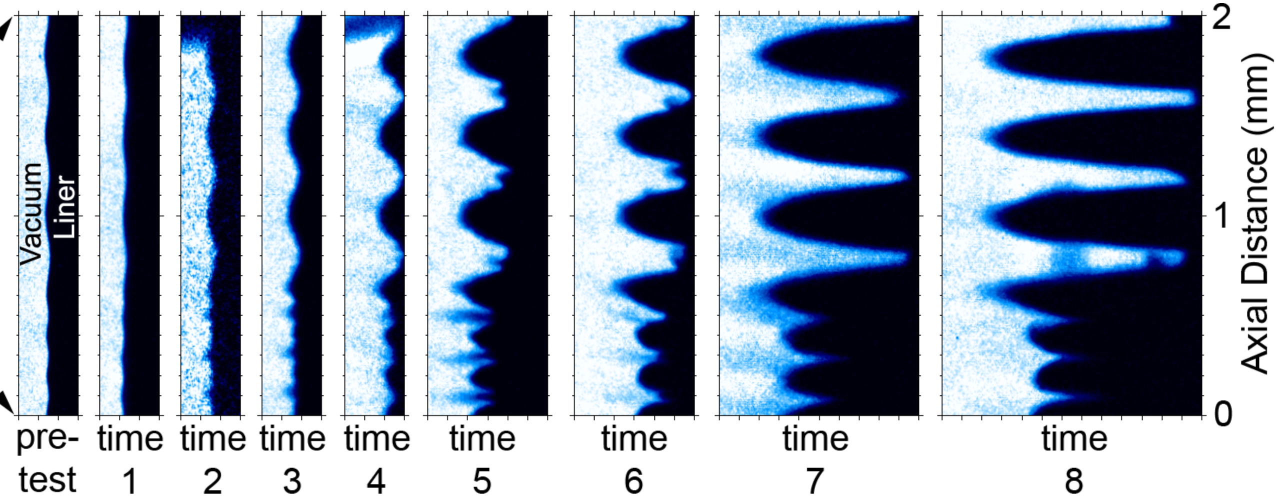


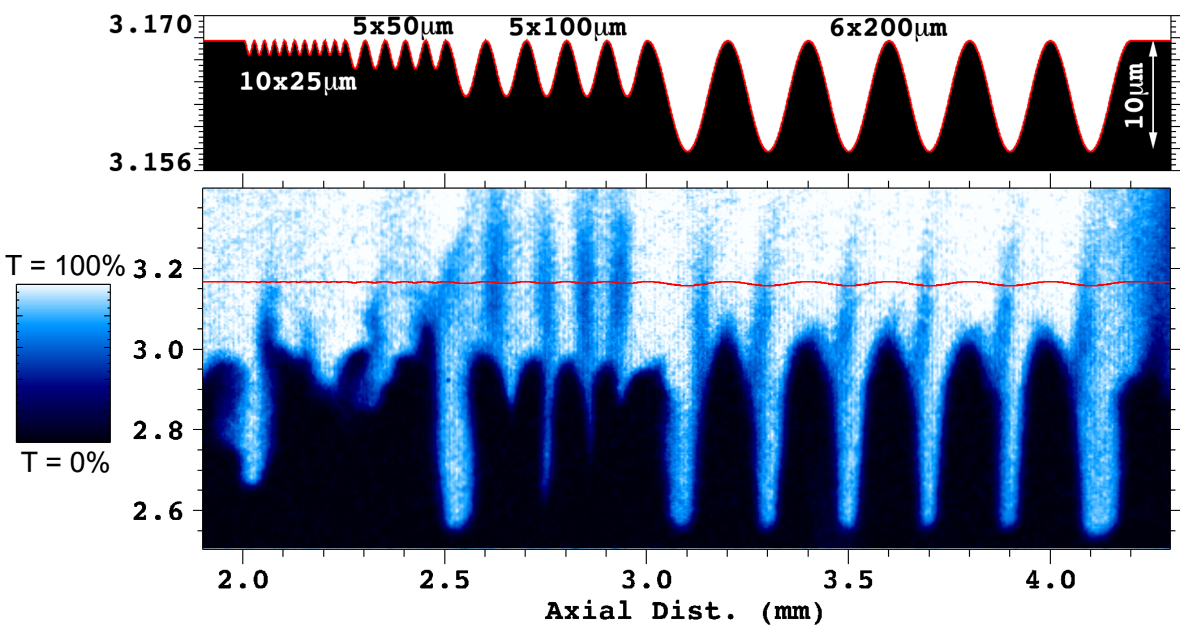

- An initial ~10 T axial magnetic field is applied
  - Inhibits thermal conduction losses
  - Enhances alpha particle energy deposition
  - May help stabilize implosion at late times
- During implosion, the fuel is heated using the Z-Beamlet laser (<10 kJ needed)
  - Preheating reduces the compression needed to obtain ignition temperatures to 20-30 on Z
  - Preheating reduces the implosion velocity needed to "only" 100 km/s (slow for ICF)
  - Stagnation pressure required is few Gbar, not a few hundred Gbar
- Scientific breakeven may be possible on Z (fusion yield = energy into fusion fuel)

# Prior experiments (Lincoln 1,2) have studied the growth of single-mode perturbations with time



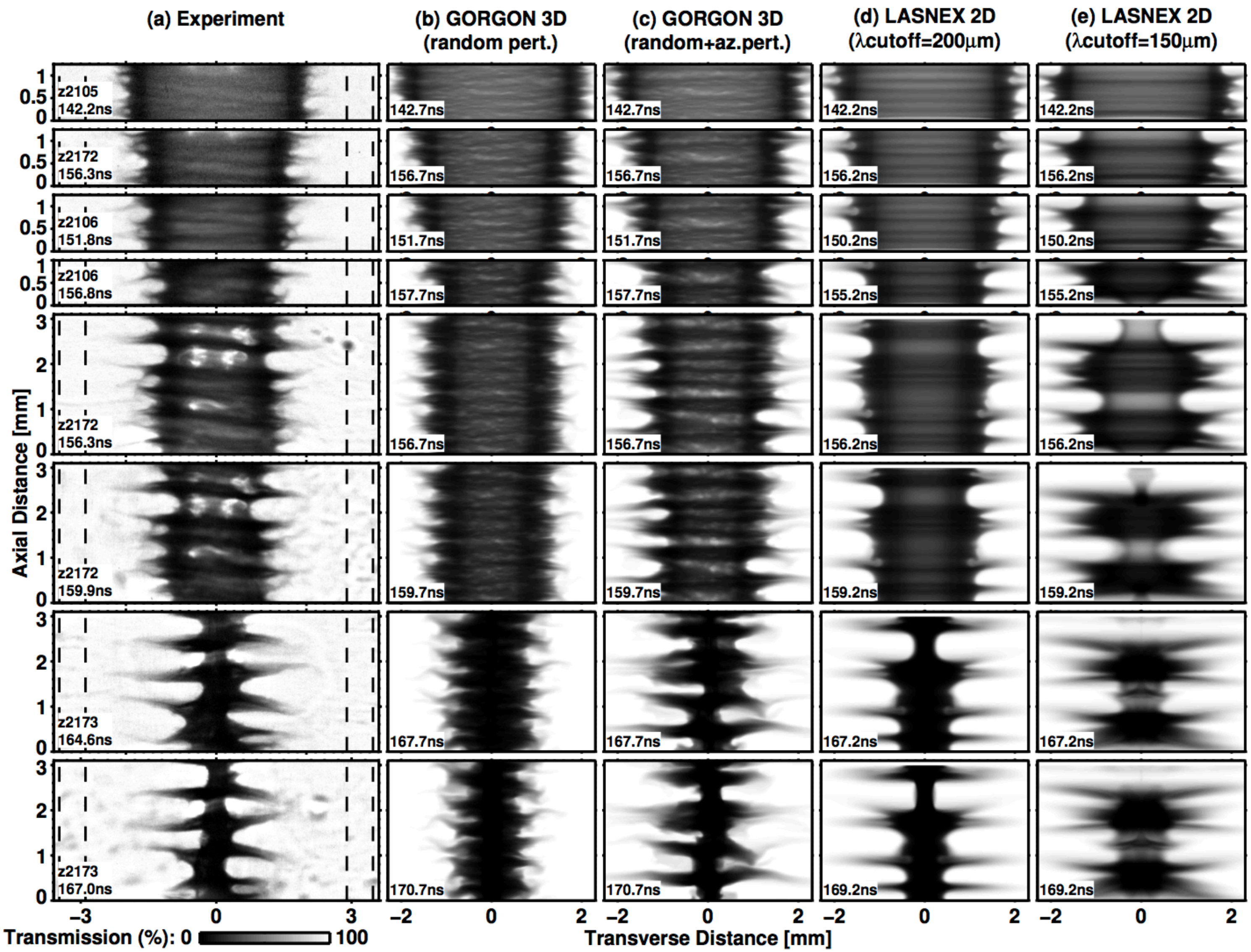
Pre-test optical photo of perturbed Al liner target




- Experiments tracked λ=400, 200, 100, 50, and 25 µm perturbations
- Tracking the details of 25-100 µm features requires a 0-degree backlighting view
- LASNEX did a good job at λ=400, 200, 100 µm, but less so at smaller wavelengths (lots of blending and end effects)

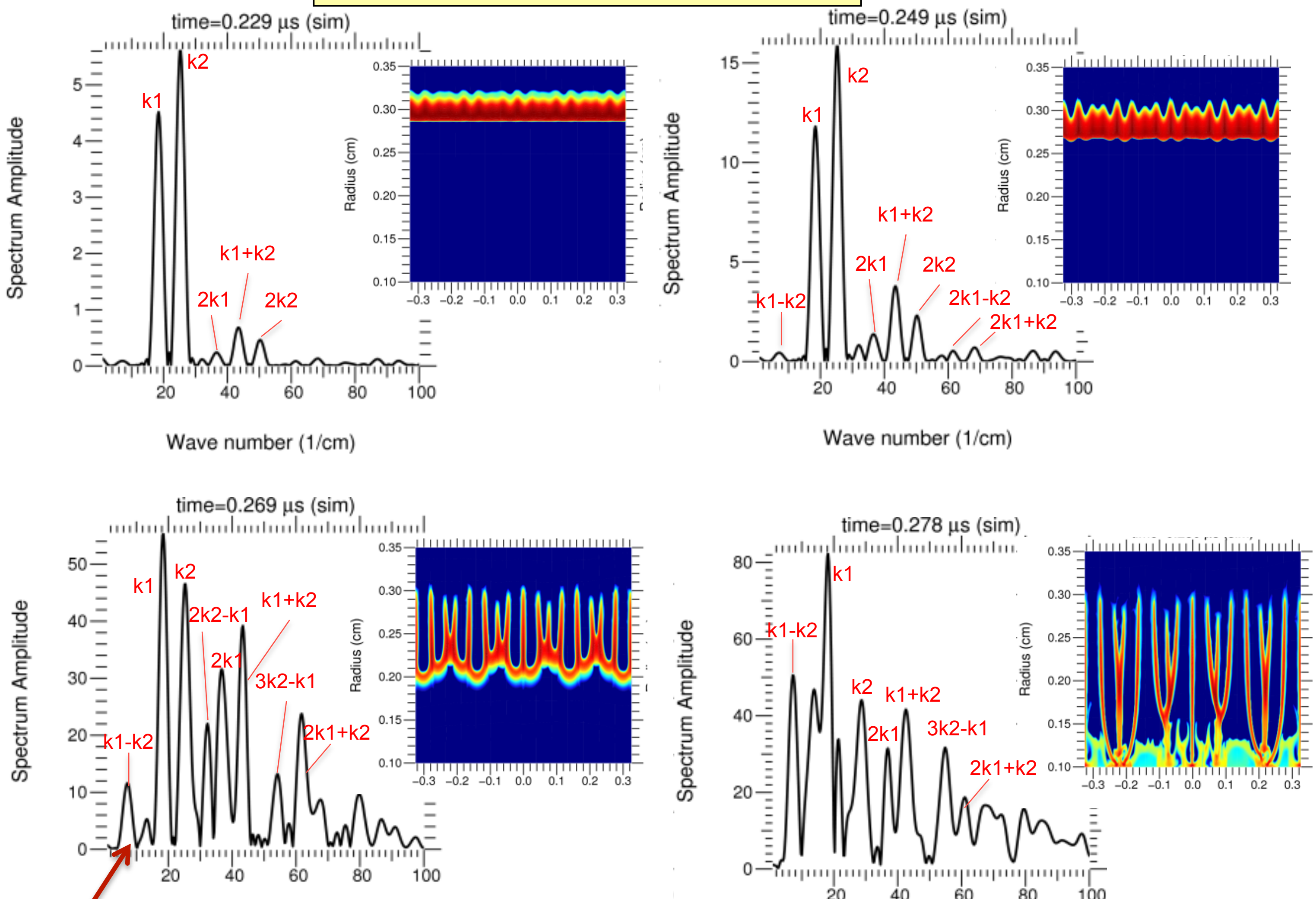
# Previous experiments have also studied multi-mode MRT growth in Beryllium liners with initially flat contours




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

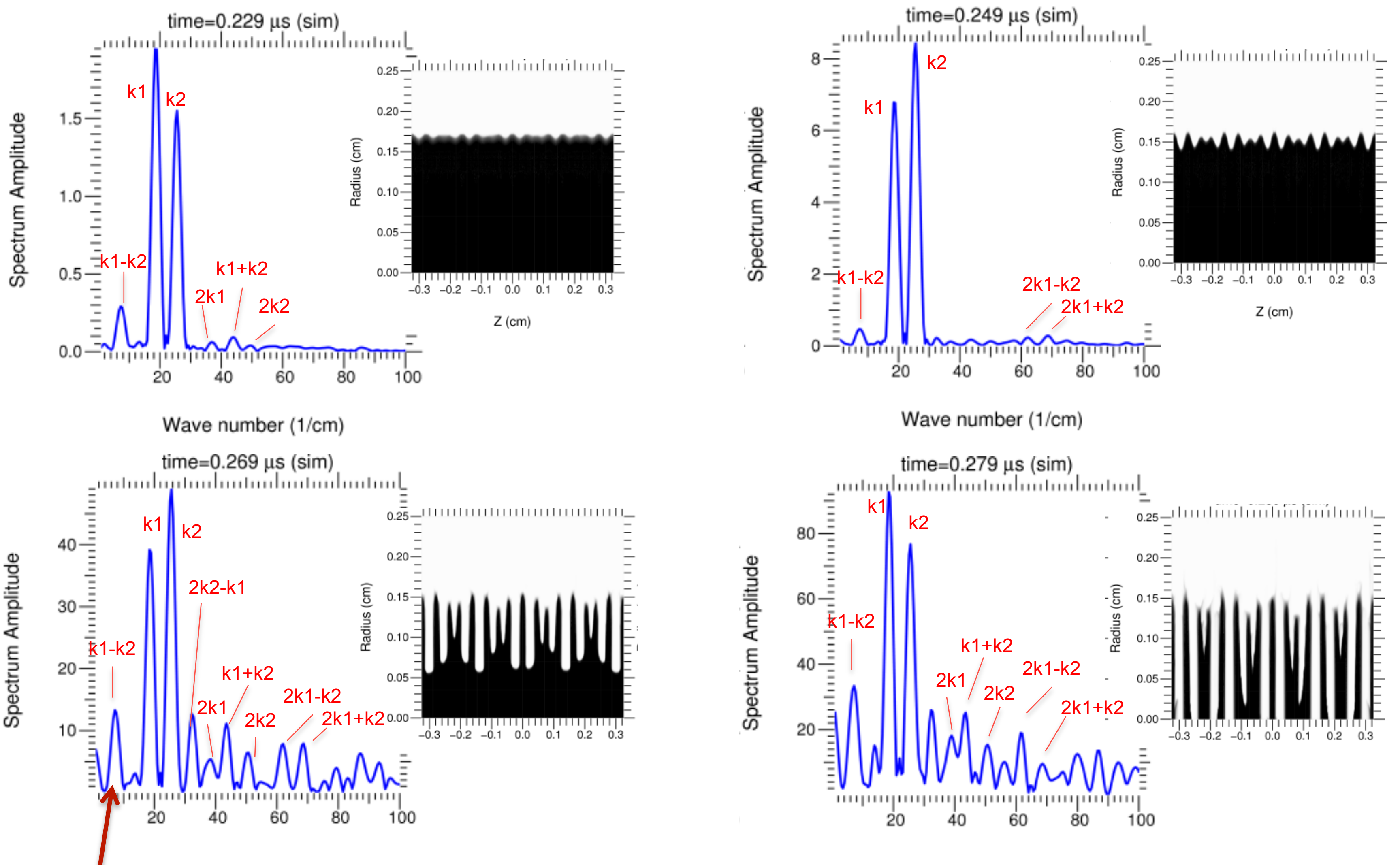
# Lincoln multi-mode experiments will test our simulation code predictions of MRT instability growth in the nonlinear regime

areal density FFT at each axial position




Inverse cascade process

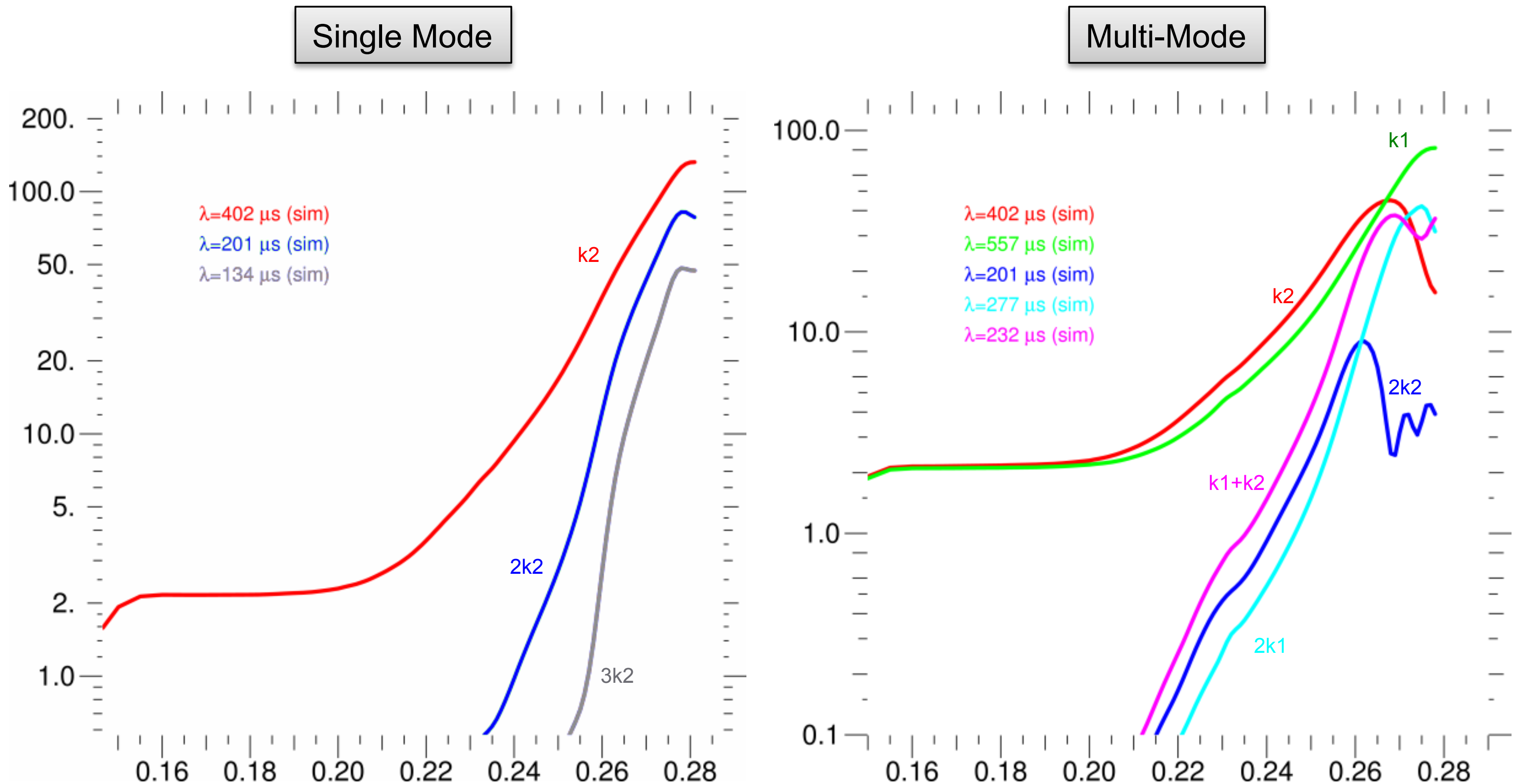
# Quantitative comparisons must account for opacity effects in the observed perturbation spectrum



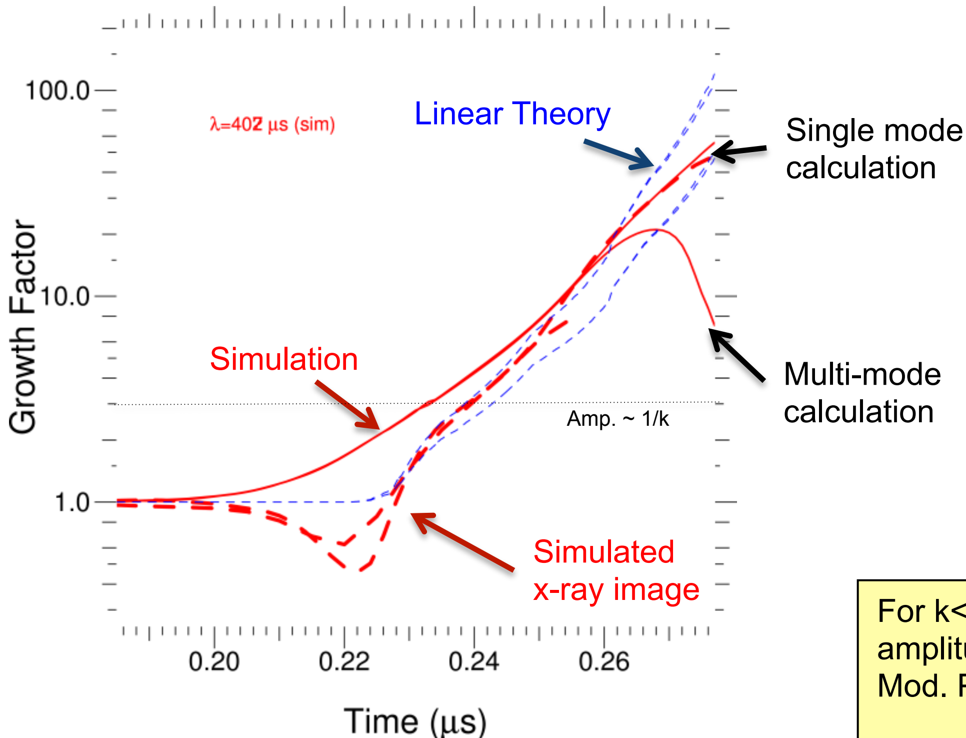

Inverse cascade process

FFT of 50% transmission contour

# Onset of nonlinear saturation occurs earlier in time at smaller amplitudes in the multi-mode case



# Both single mode and multi-mode calculations fit linear MRT theoretical growth predictions well after amplitude becomes comparable to wavelength




Growth rate from linear theory

$$\Gamma^2 = kg$$

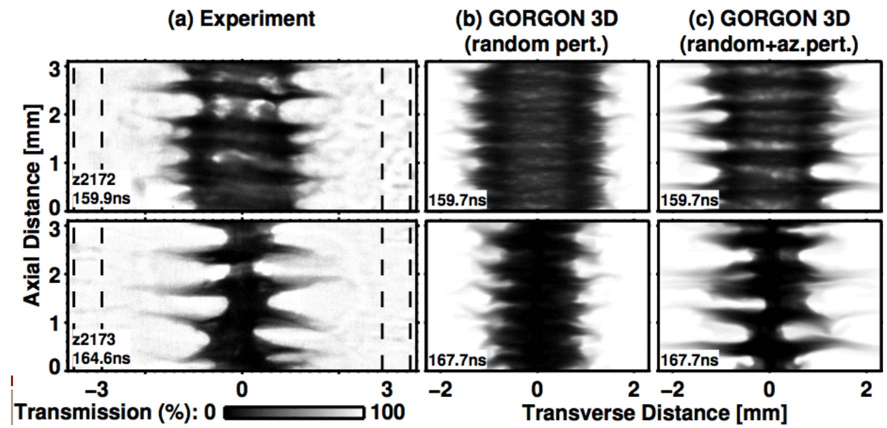
Calculate $g$ using I(t)

$$\Gamma^2 = k \frac{\mu_0}{8\pi^2} \frac{I^2}{R^2} \frac{1}{\rho(\Delta r)}$$

For k<(1/h), linear theory increasingly poor approximation as amplitude goes to ~1/k , Ryutov, Derzon, & Matzen, Rev. Mod. Phys. 72, 167 (2000).

# How sensitive is surface finish to instability growth?

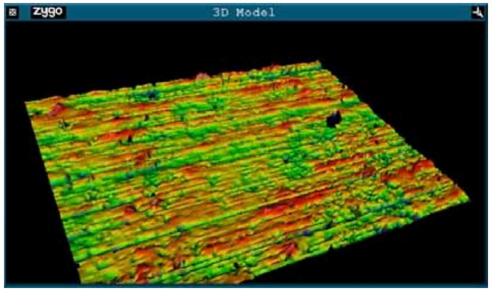
- Liners are generally diamond-turned
  - Smooth (10-50 nm RMS surface)
  - Azimuthally-correlated tool groove
  - Could seed MRT



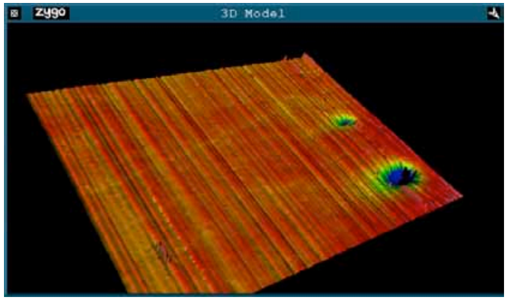

- Azimuthal correlation
  - Necessary in 3D simulations
  - Single-mode MRT growth studies

- **Axially-polished liners were developed to test effects of correlation and importance of surface roughness**

Standard Process
(50 nm RMS)



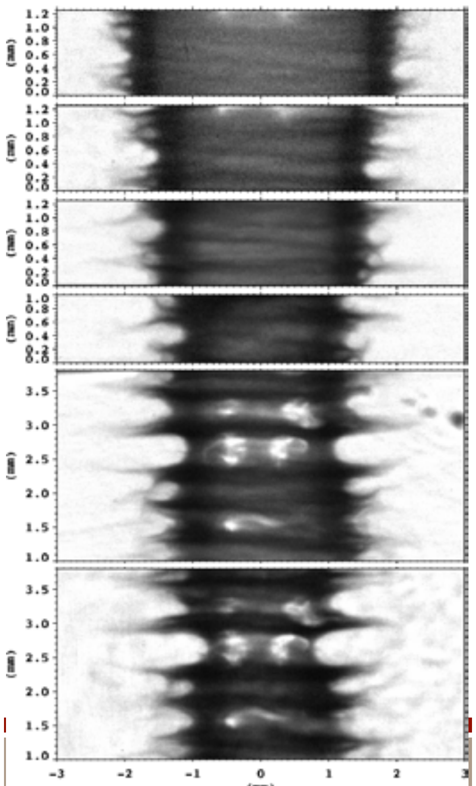

After axial polishing
(50 nm RMS)

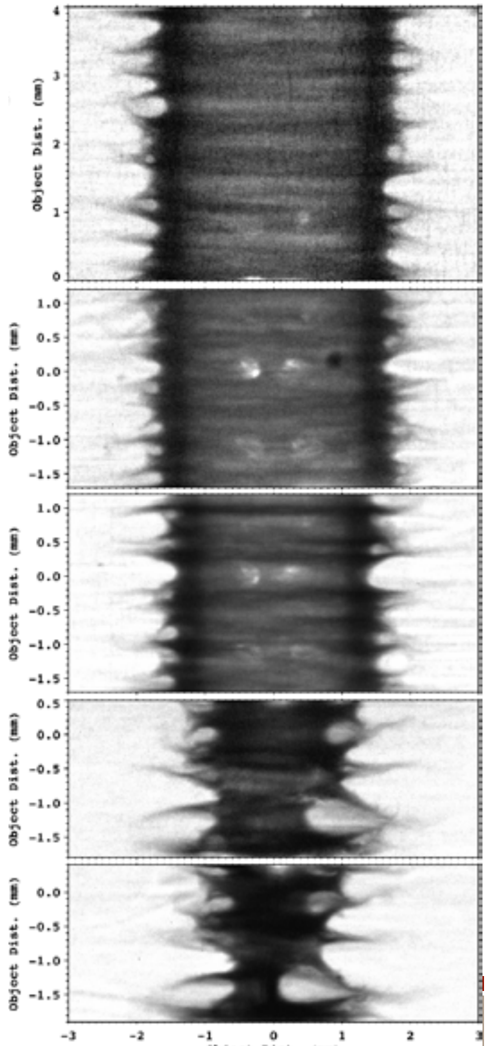


# Comparisons of data from similar points in the implosion suggest symmetry is not very sensitive to surface roughness

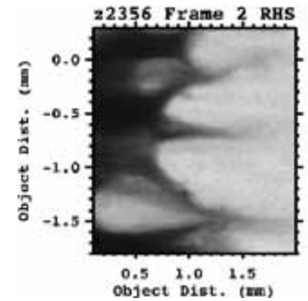
Axially-polished data →

McBride PRL data

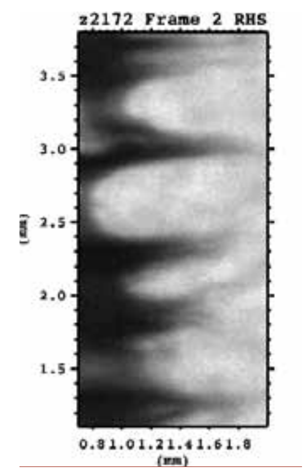



Axially-polished data




McBride PRL data




**Symmetry may generally be worse for Axially-polished liners**

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

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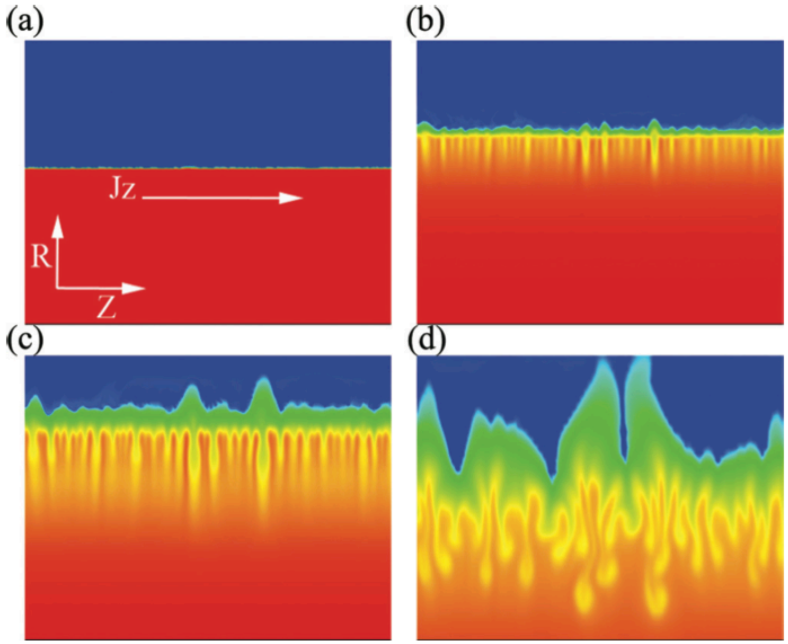
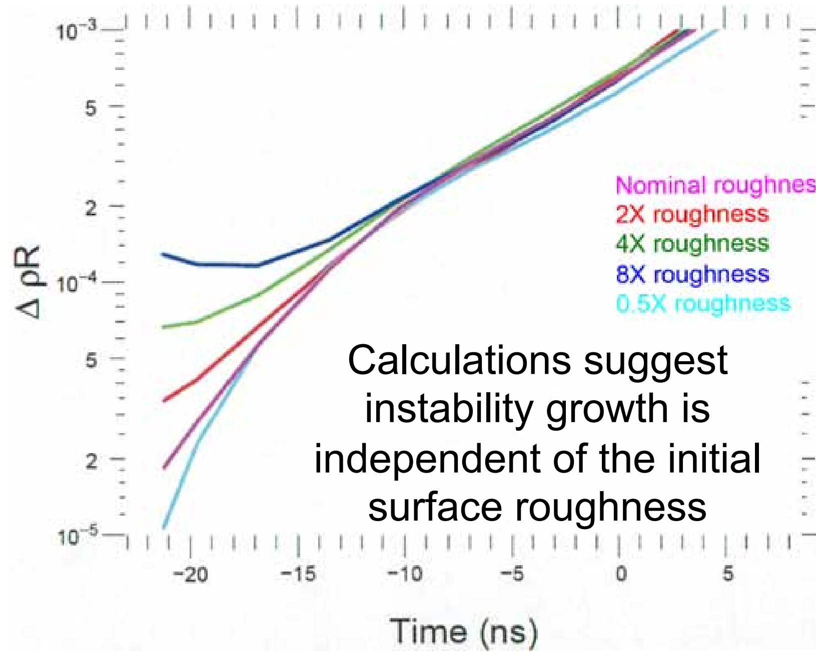


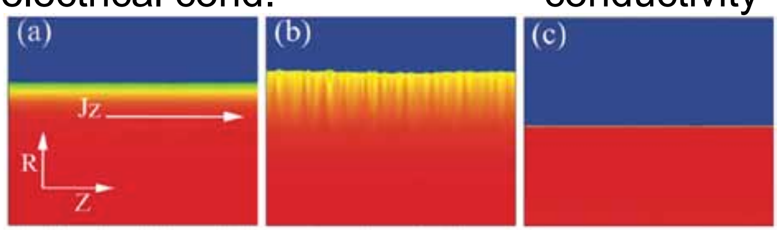




Calculations suggest instability growth is independent of the initial surface roughness

Constant electrical cond.

Nominal

10x thermal conductivity




**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)

# Comparisons between our modeling and experimental instability growth in solid Al liners are promising --- the perturbation growth is larger than expected from MRT alone

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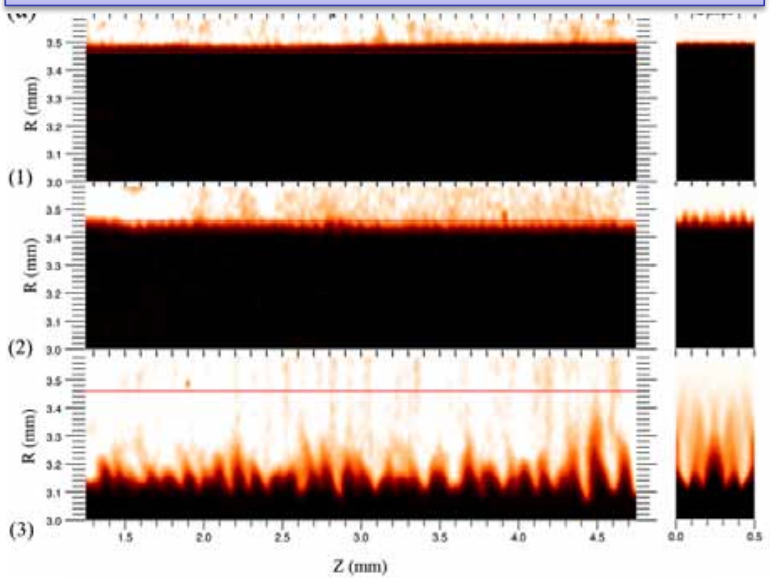
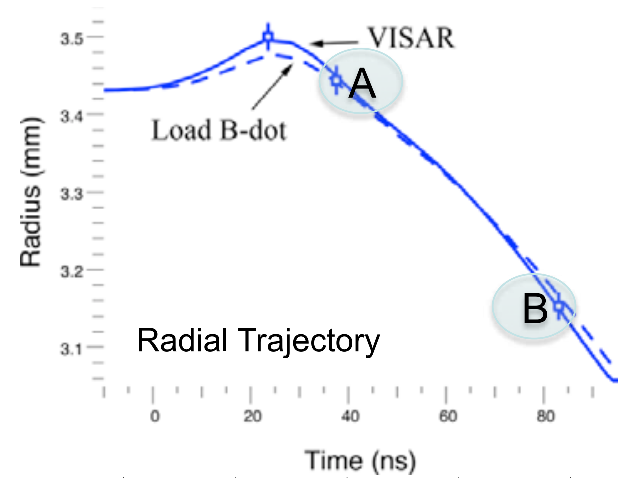
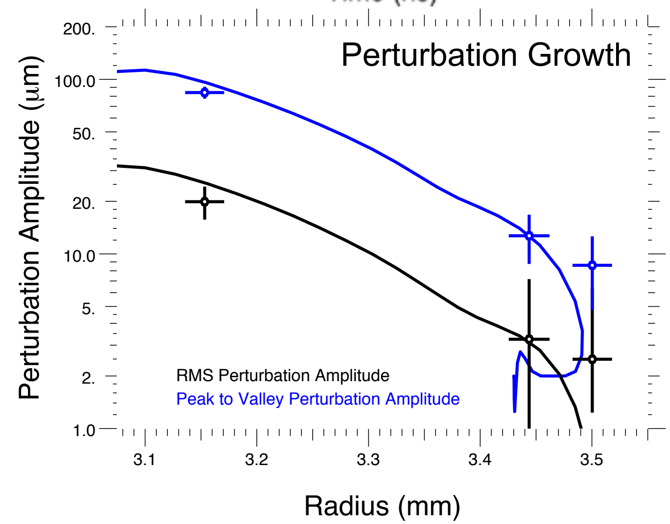
Experimental (left) & simulated (right) radiographs




Perturbation Growth Comparison

| Time | Est. MRT (λ=100 μm) | $h=0.06Agt^2$ | Observed |
|---|---|---|---|
| A | 0.36 μm | 6.2 μm | 13 ± 7 μm |
| B | 24 μm | 41 μm | 80 ± 7 μm |

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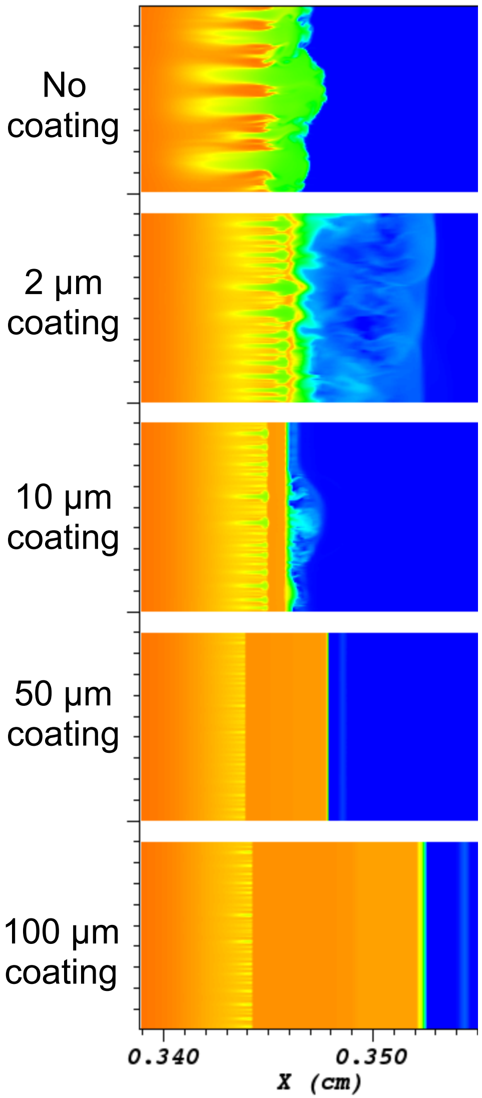
*K.J Peterson et al., Phys Plasmas 19, 092701 (2012) and Phys Plasmas 20, 056305 (2013)

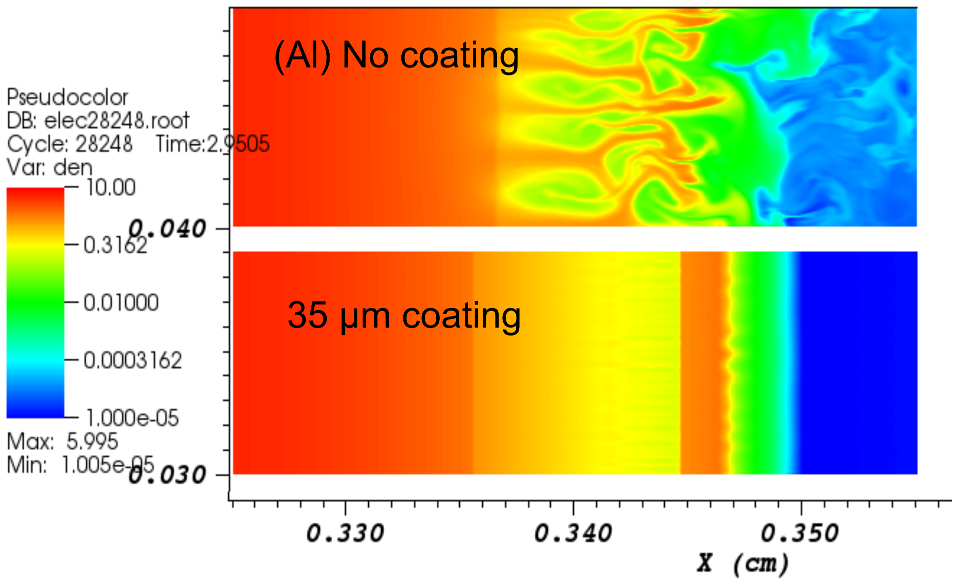
# Relatively thick insulating coatings were proposed to mitigate effects of ETI and reduce seed for MRT growth



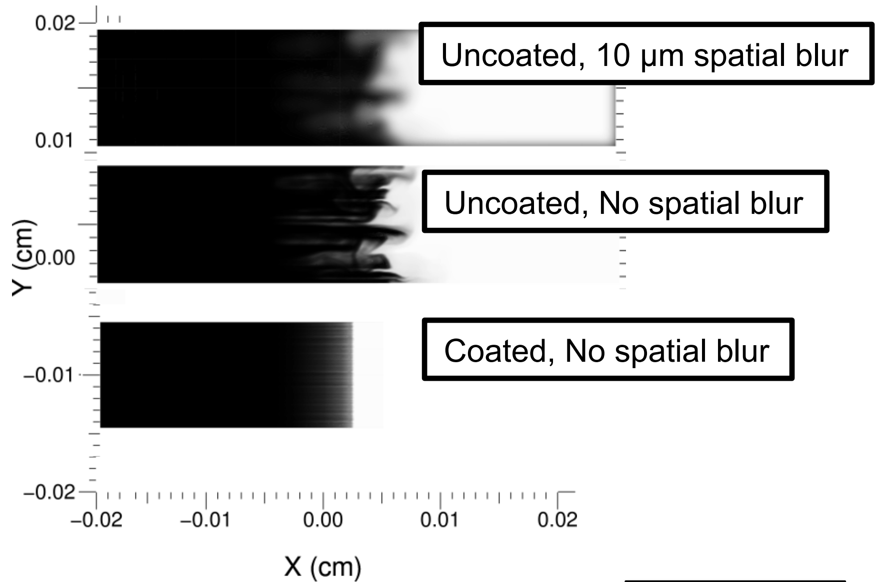

- No ETI (striation) growth in dielectric coating
  - Carries very little current
  - Theoretically ETI Stable $\frac{d\eta(T)}{dT} > 0$
- Linear ETI growth of temperature perturbations still present in metal
  - Slightly reduced by density dependence of growth rate
- Nonlinear mass redistribution from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

# Instability mitigation due to dielectric coatings was predicted to be clearly observed in radiography

HYDRA Pre-shot Simulation



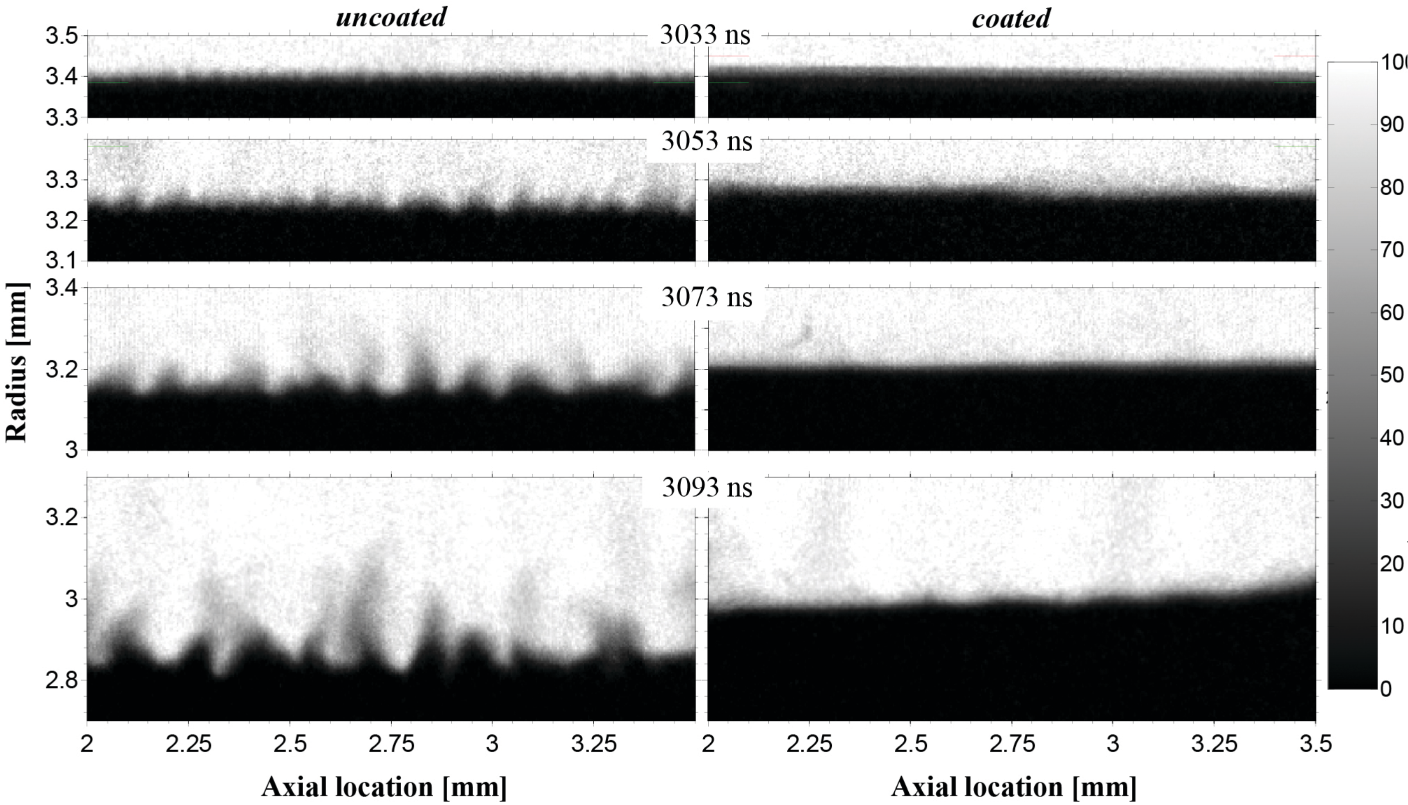

Pre-shot Simulated (Al) Radiography



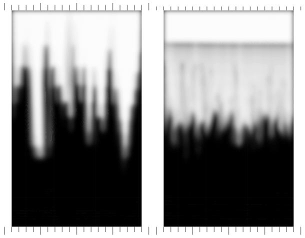

6151 eV

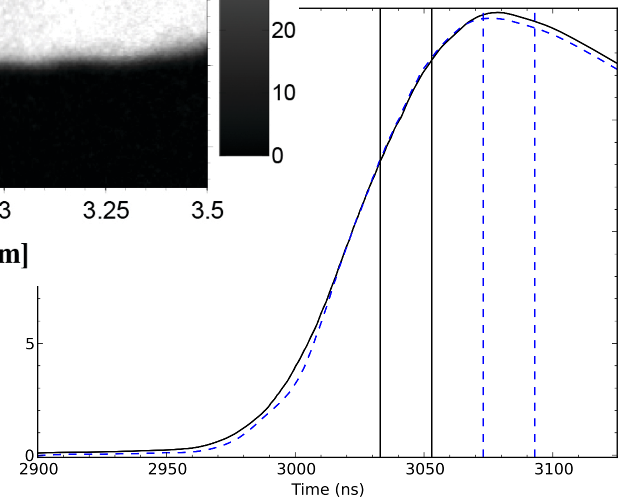
# We have recently demonstrated that thick coatings do indeed reduce the observed instability growth*

Aluminum




Simulated

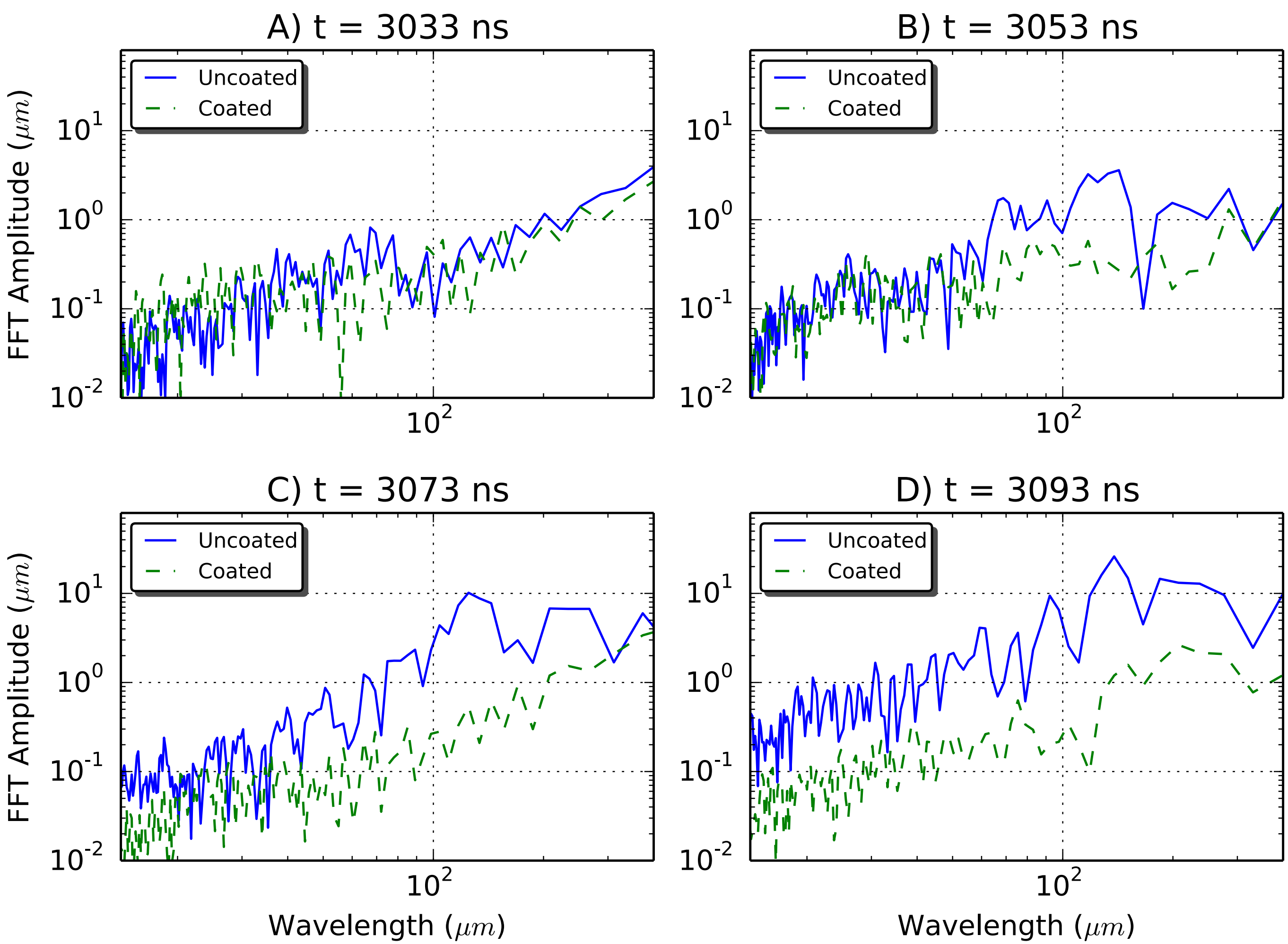






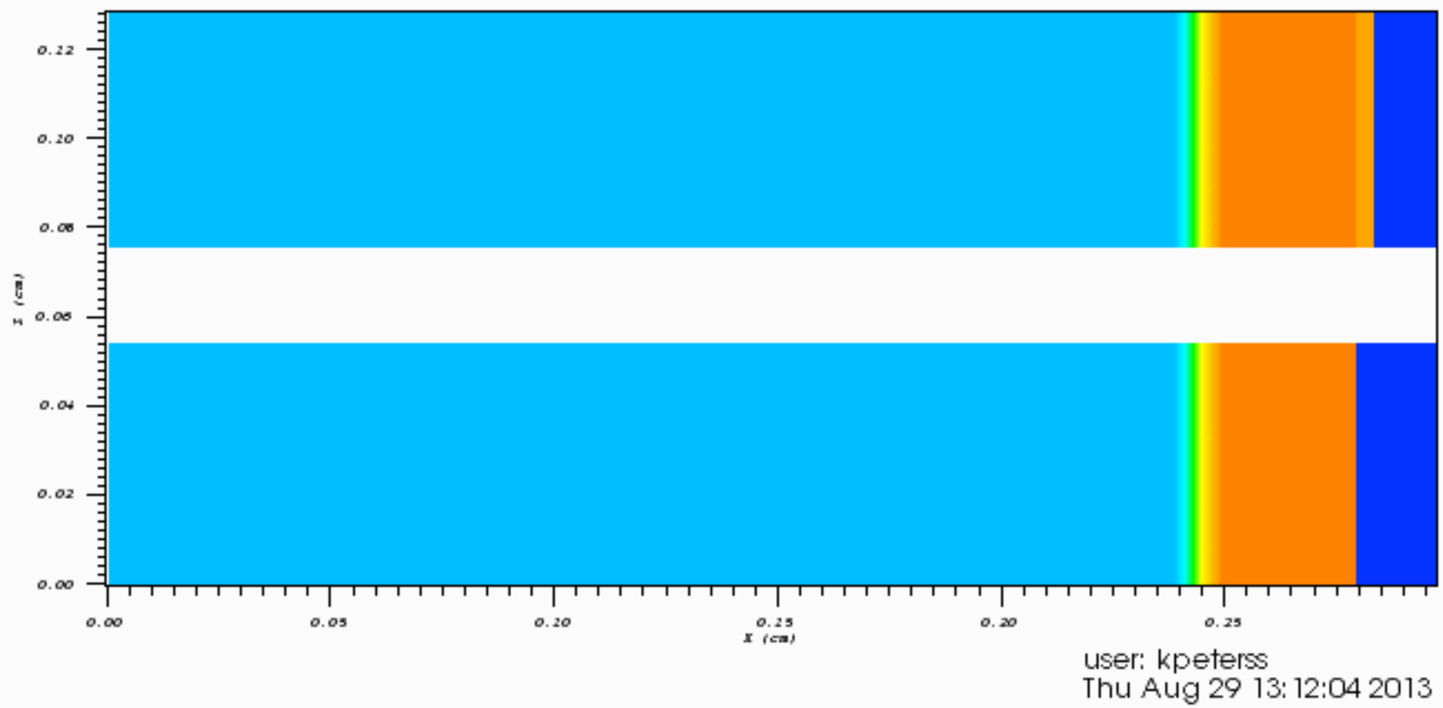

*Kyle Peterson and Tom Awe *et al.*, manuscript in preparation

# Fourier analysis shows the coated half of the rods exhibited a 10-50X reduction in instability growth



# Simulations suggest that ETI coatings will improve the stability of MagLIF liners dramatically

HYDRA MHD




40 µm coating

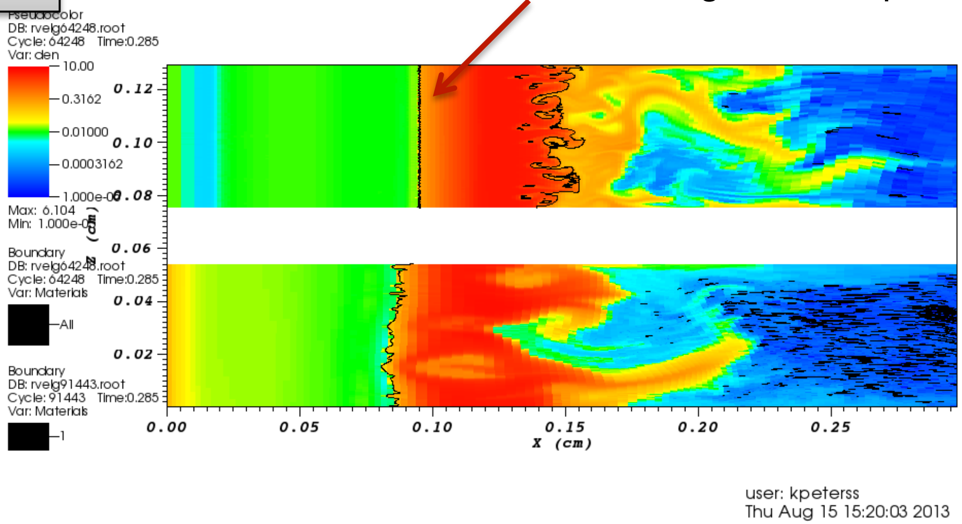
uncoated

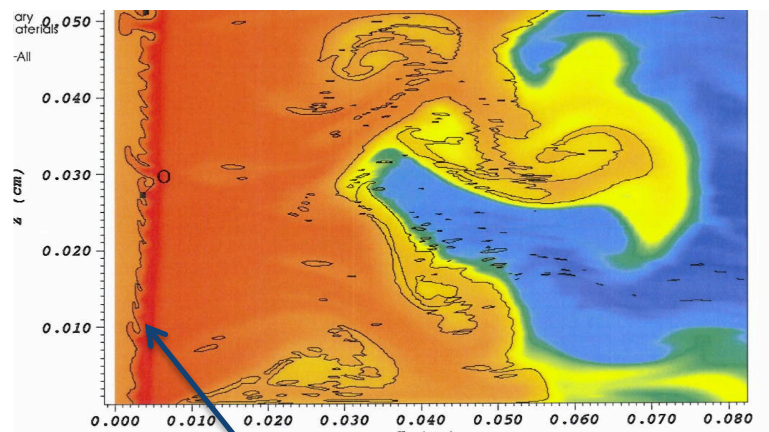
We are currently accelerating our plans to experimentally test these predictions

# In certain cases, mitigating ETI with coatings is predicted to nearly recover 1D performance

Al

ETI starting to develop on inside of liner

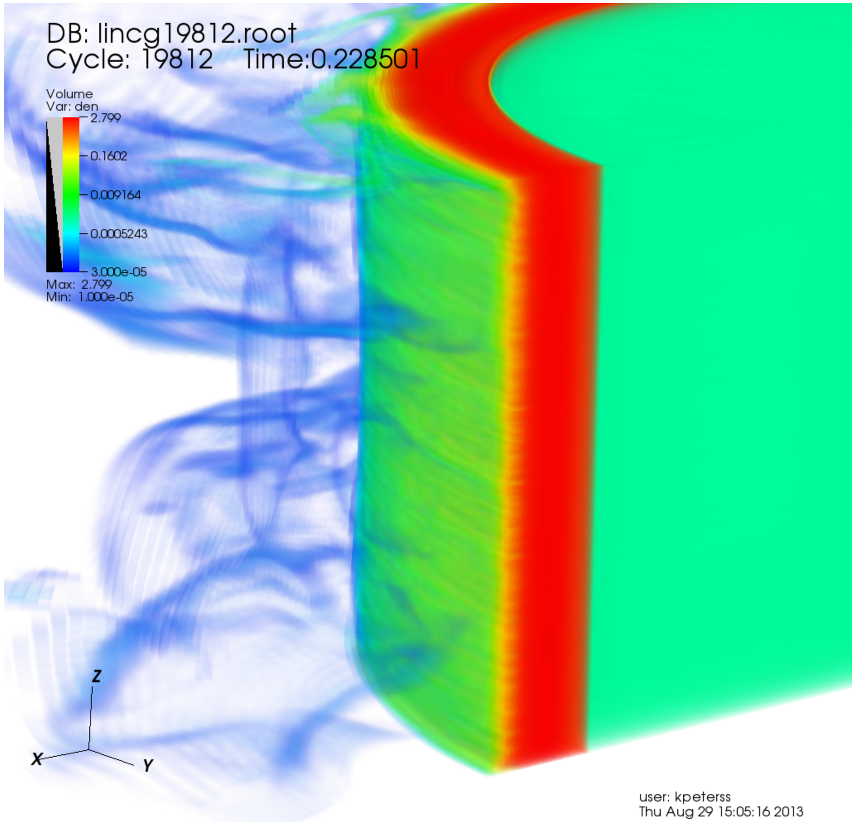



Liner/Fuel Interface near at stagnation

Only a small fraction of the current is predicted to be carried in the coating material and the implosion timing is only slightly slower than 1D.

# We are beginning to simulate ETI effects on MagLIF liners in 3D

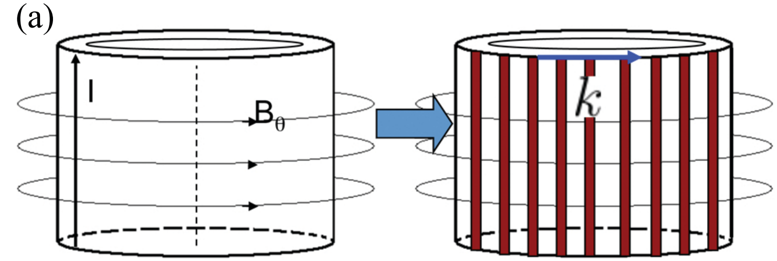



Do electrothermal instabilities explain why large initial density perturbations have been historically been required to simulate Z-pinch liners and wire arrays?

- Challenging zoning requirements
  - Large Eulerian cells (>1 µm) are not sufficient to resolve ETI
- Bz field introduces boundary condition complexities
- Link different spatial scales
  - High resolution surface ETI simulations
  - Lower resolution liner dynamics simulations

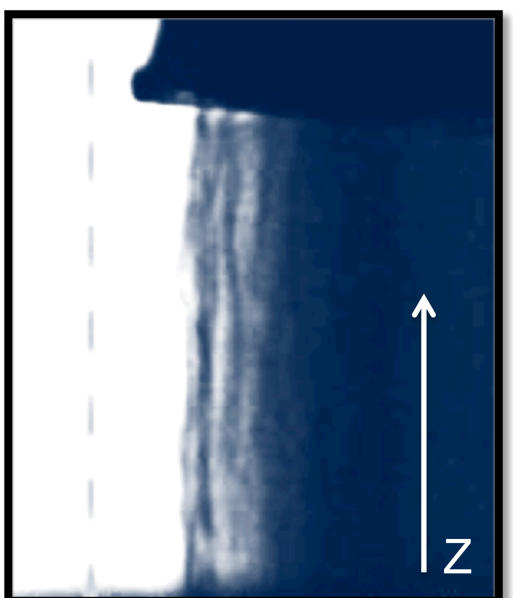
# Electrothermal filamentation may be introducing azimuthal asymmetries and limiting correlation

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

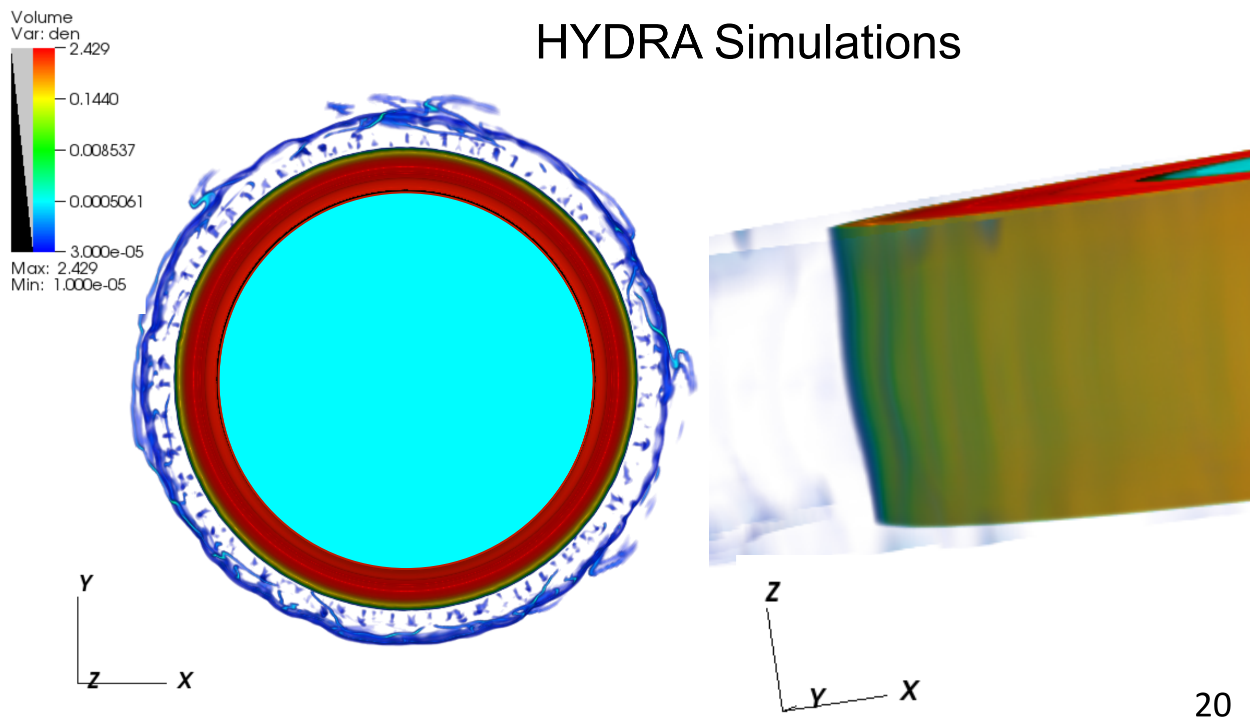



- Postulated in the past based on analytical arguments
- Relevant to Laser driven ICF concepts*
- Simulation of this physics is difficult

Evident on Z2509?




HYDRA Simulations

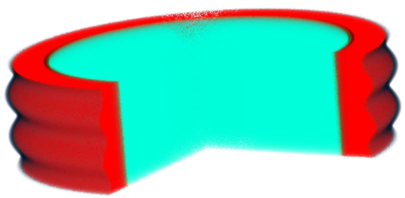




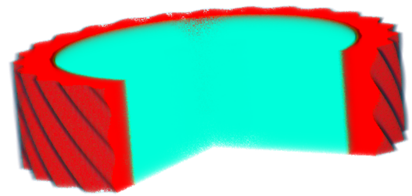

*F. H. Se´guin *et al.*, Phys. Plasmas **19,** 012701 (2012)

# Helical perturbations are also being investigated as a means to mitigate instabilities

Lincoln single-mode MRT
λ=400 µm test target

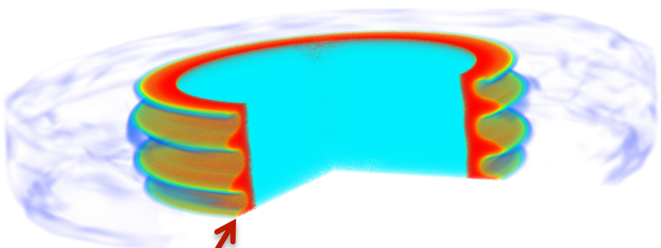


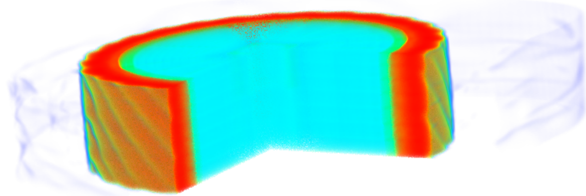
Single-mode MRT
λ=400 µm, 45° pitch target



$$\lambda_{kp} = 4\pi\Delta\cos^2\theta$$

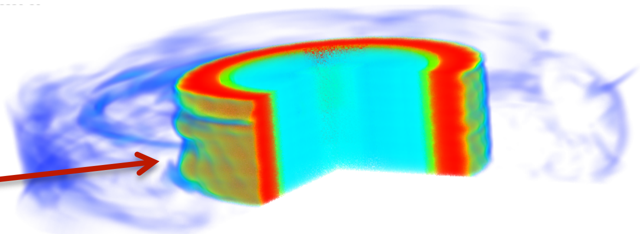
$$\lambda_{kp} = 4\pi\Delta\cos^2\theta$$

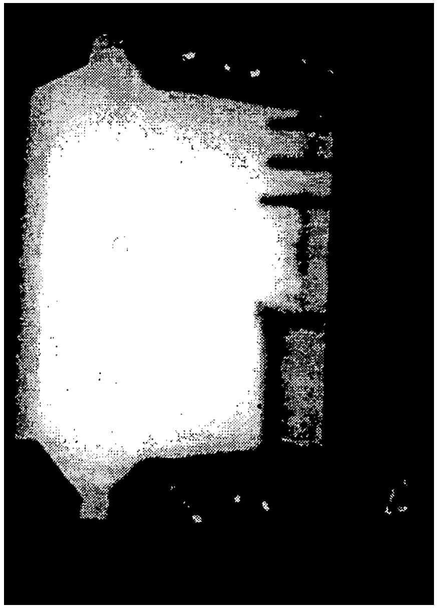




Fundamental mode grows like $\Gamma^2 = kg$

~Zero growth in Fundamental mode





Joint LANL/VNIIEF helical liner Experiment on PEGASUS*



*B. G. Anderson *et al.*, Pulsed Power Plasma Science (2001).

# Surprisingly, helical perturbation appear to be effective even with the amplitude is small compared to the skin depth

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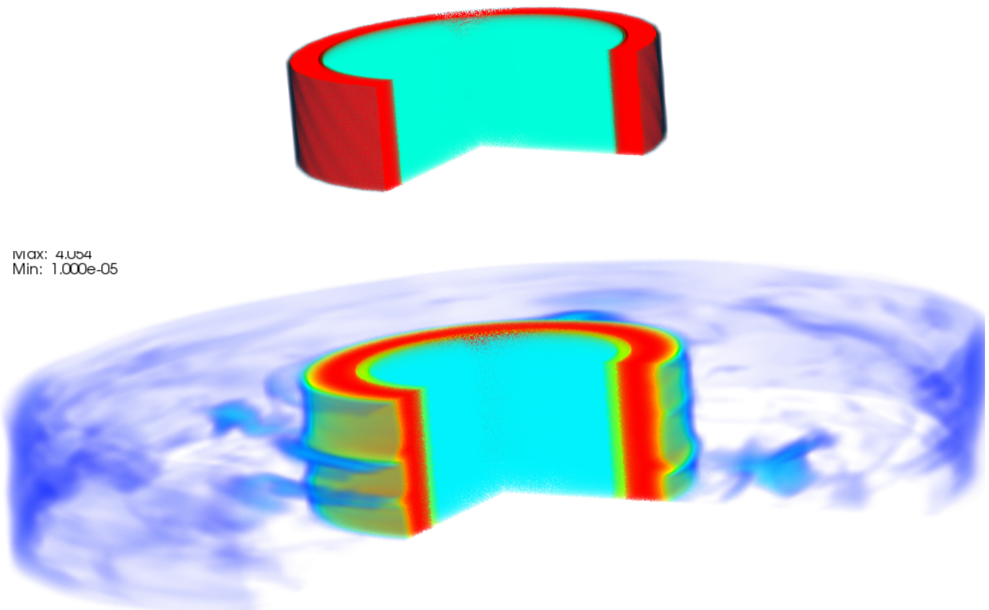
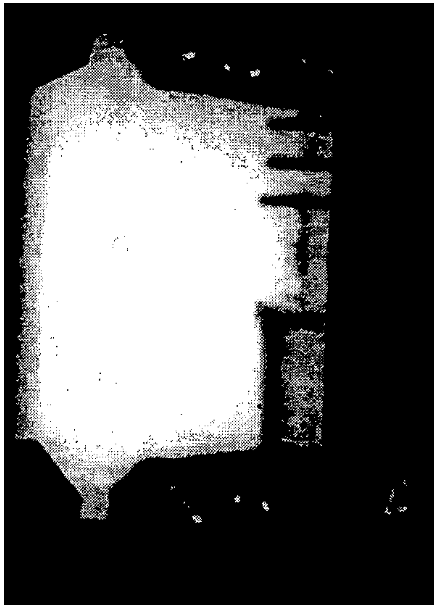
$$\lambda_{kp} = 4\pi\Delta\cos^2\theta$$

Single-mode MRT
λ=400 μm, 45° pitch target,
10 μm amplitude



Joint LANL/VNIIEF helical liner Experiment on PEGASUS*

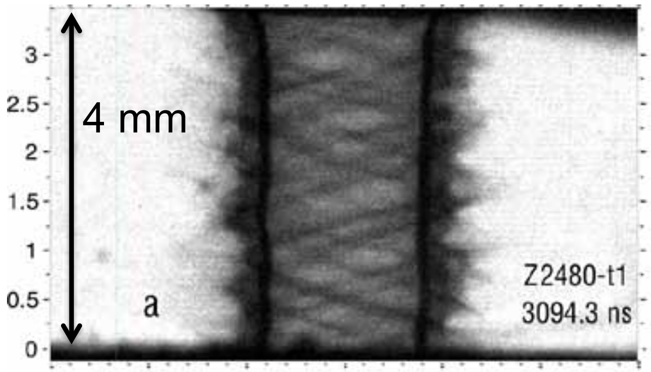


*B. G. Anderson *et al.*, Pulsed Power Plasma Science (2001).

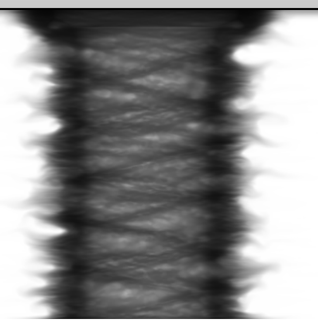
# Simulating the results obtained with the first axially-magnetized liner implosions has been difficult

Roosevelt I Experiment
with applied Bz field

CR
=2.7

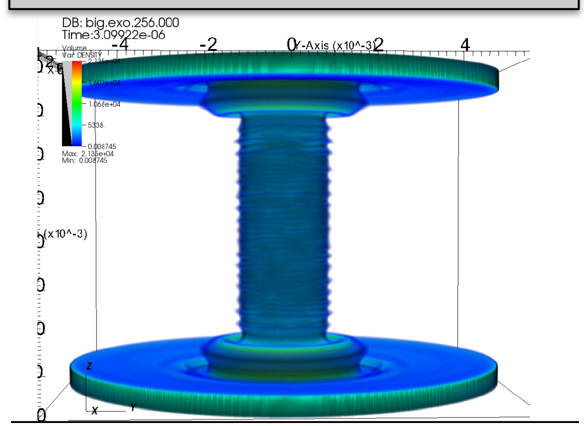



GORGON Simulation[1]
with pre-imposed helical perturbations



- Multiple simulation codes/models
  - HYDRA, GORGON, ALEGRA
- Qualitatively similar results have only been obtained using pre-imposed helical perturbation simulations
  - Unsatisfying (Doesn't constrain physics)
  - Perturbation Seed?
  - Missing physics? **ETI**?

ALEGRA Simulation[2]
with nominal surface roughness




See **O.Tu_C12**
for further discussion and theory



[1] Christopher Jennings Simulation, [2] Matthew Martin Simulation

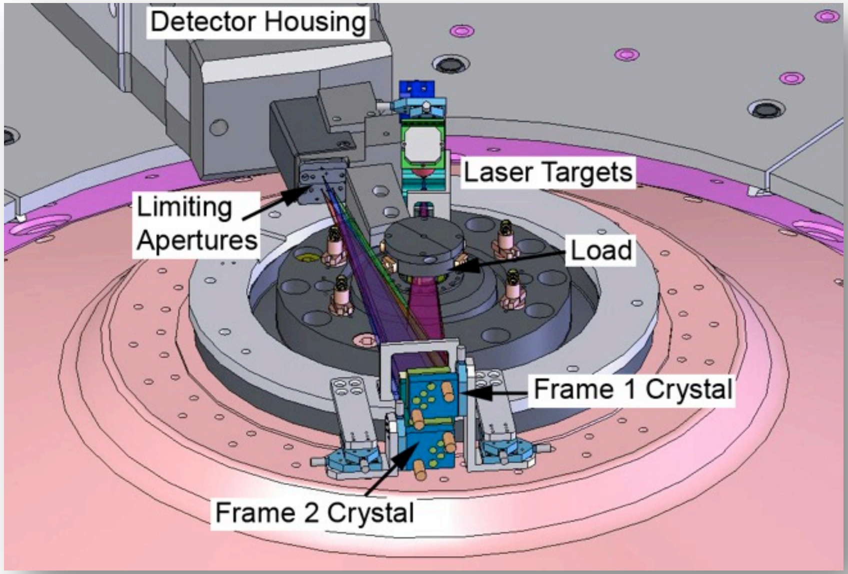
# Conclusions

- We are making significant progress in our understanding and control of instabilities in magnetized liner implosions
  - Controlled single and multimode MRT simulations and experiments
  - Influence of surface roughness and correlation on instability growth
  - Electrothermal instabilities (ETI)

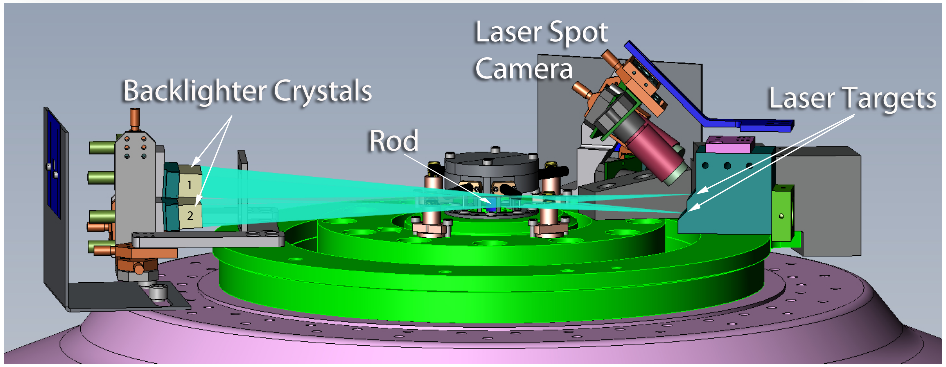
- We have demonstrated that not only can ETI can be mitigated with thick insulating coatings, but the overall instability growth is substantially reduced
  - Need to still test with high convergence imploding targets
  - Pre-shot simulations are promising

- 3D simulations are required to fully understand the nature of instability growth in MagLIF liners
  - 3D simulation capability is maturing
  - Thus far, we are unable to satisfactorily reproduce the helical structures observed in the first axially-magnetized liner implosions

# 2-frame monochromatic crystal backlighting will be used to image instability growth



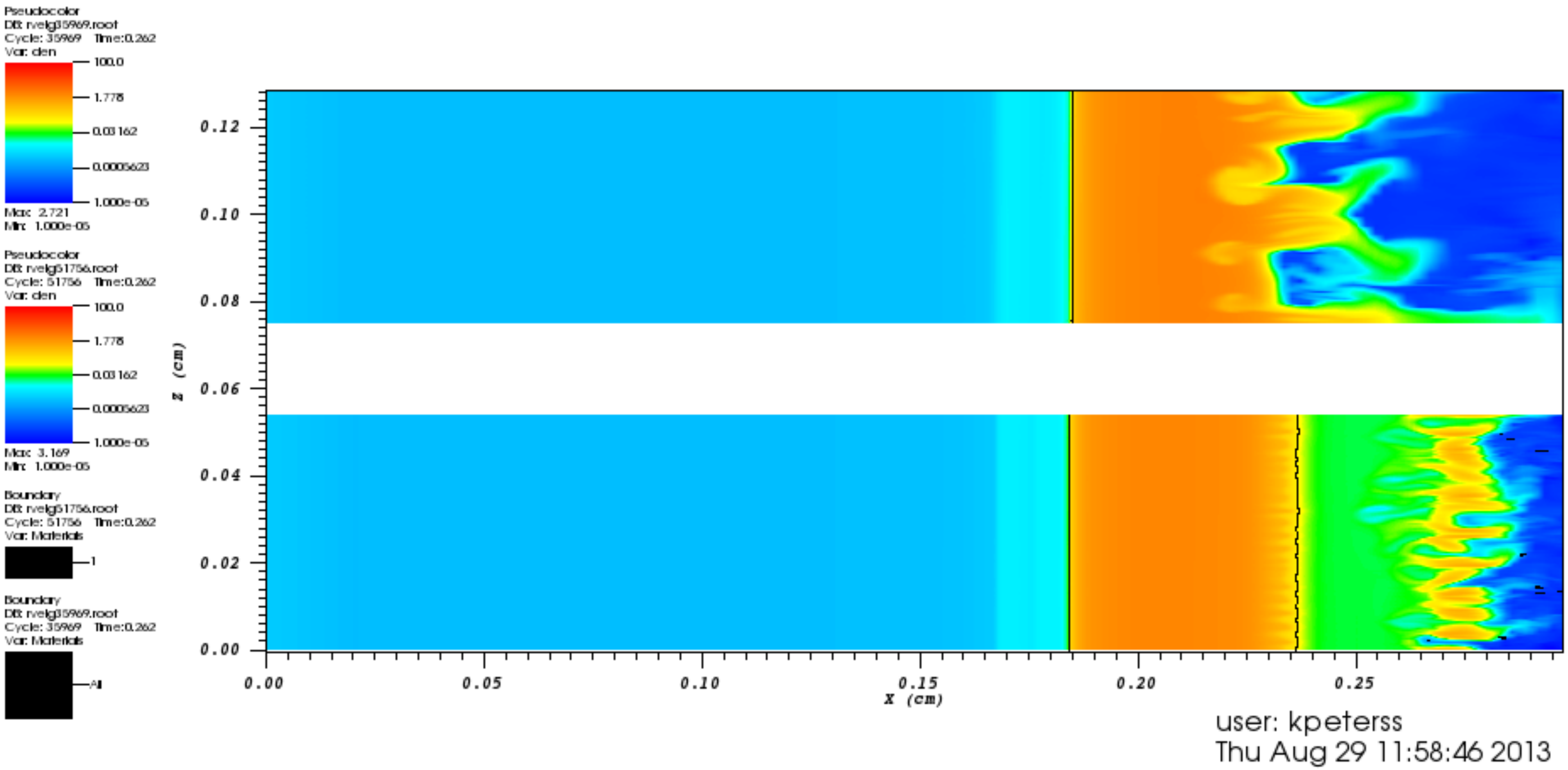

**2-frame keV Crystal Imaging**
- **Monochromatic (~0.5 eV bandpass)**
- **6.151 keV (Mn)**
- **15 micron resolution**
- **Large Field of View (4 mm x 10 mm)**
- **Debris mitigation**



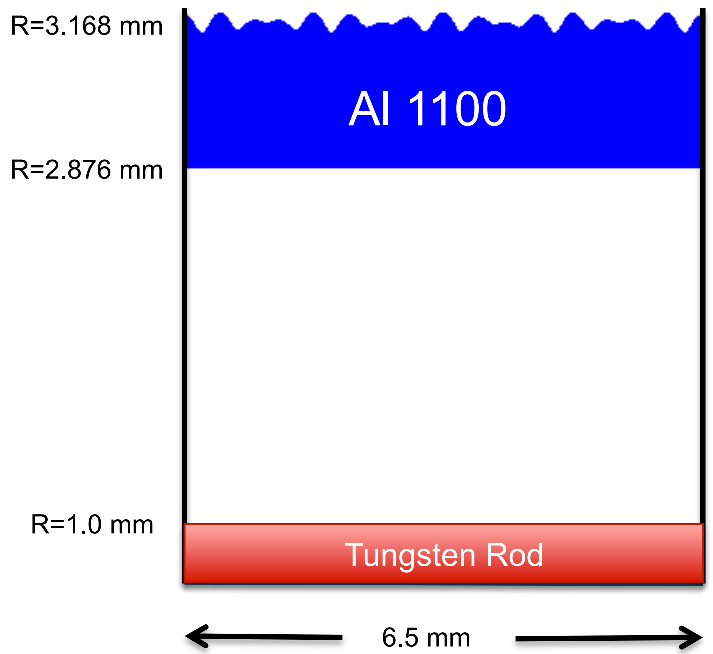

- **Original concept**
  - S. A. Pikuz *et al*., RSI (1997)
- **1.865 keV backlighter at NRL**
  - Y. Aglitskiy *et al*., RSI (1999)
- **Single-frame 1.865 keV and 6.151 keV implemented on Z facility**
  - D.B. Sinars *et al*., RSI (2004)
- **Two-frame 6.151 keV on Z facility**
  - G.R. Bennett *et al*., RSI (2008)

Radiograph lines of sight ±3° from horizontal

# ETI dielectric coatings are predicted to be equally effective in Beryllium liners

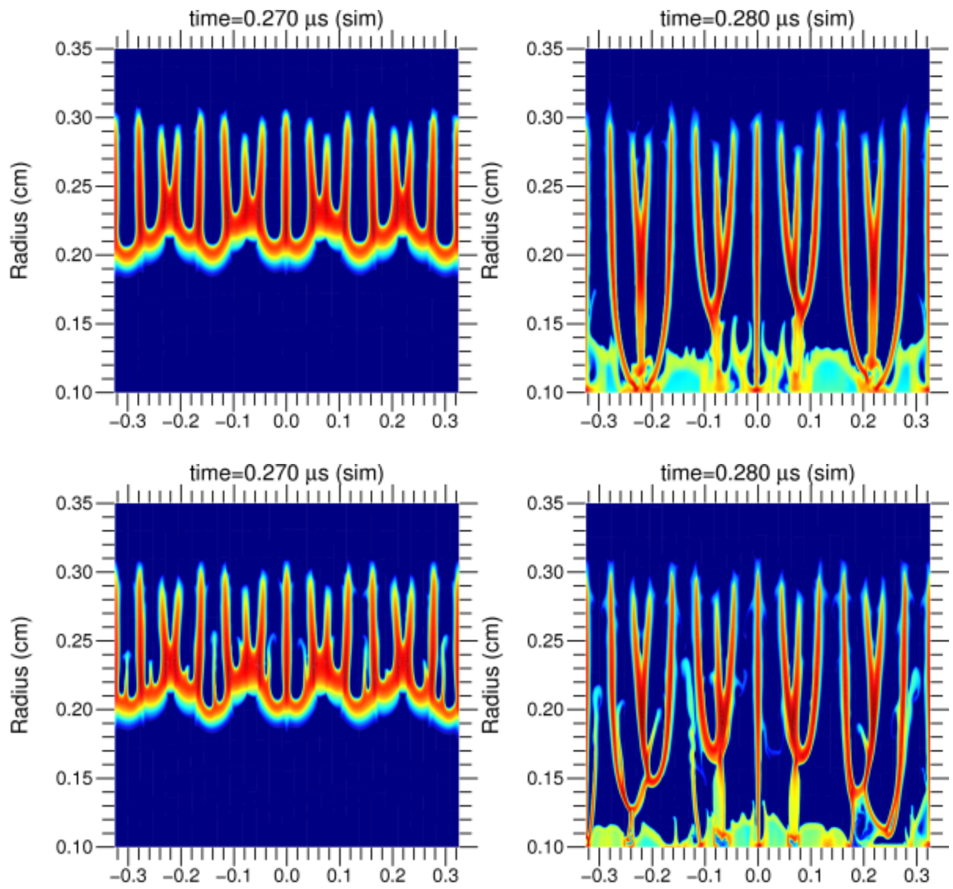


# Experiments have been designed to test our understanding of multi-mode MRT instability growth in a controlled manner




- Target parameters chosen to complement and compare to existing single mode Lincoln series experiments
- Initial wavelength (400, 550 µm) and amplitude (20 µm peak to valley) chosen to be large enough to be resolved with backlighter at t=0, dominate over electrothermal instabilities, and enter nonlinear regime quickly
- Non-integer wavenumbers chosen to remove ambiguity of mode coupling with higher mode harmonics
- Tungsten rod suppresses time integrated self emission in radiographs

# Development of well resolved long wavelengths can be affected by higher grid resolutions through nonlinear mode coupling




16 micron axial resolution
Wavelengths > 160µm resolved

8 micron axial resolution
Wavelengths > 80µm resolved

# Helical Field Configuration

Sandia National Laboratories