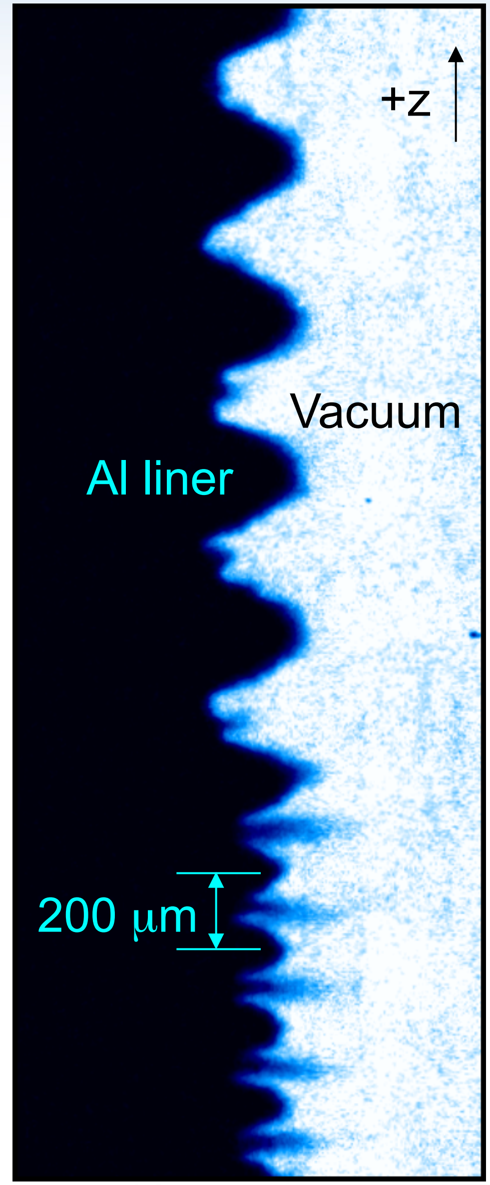
Measurements of Magneto-Rayleigh-Taylor instability growth in initially solid liners on the *Z* facility



Experiment Design, Planning, and Analysis

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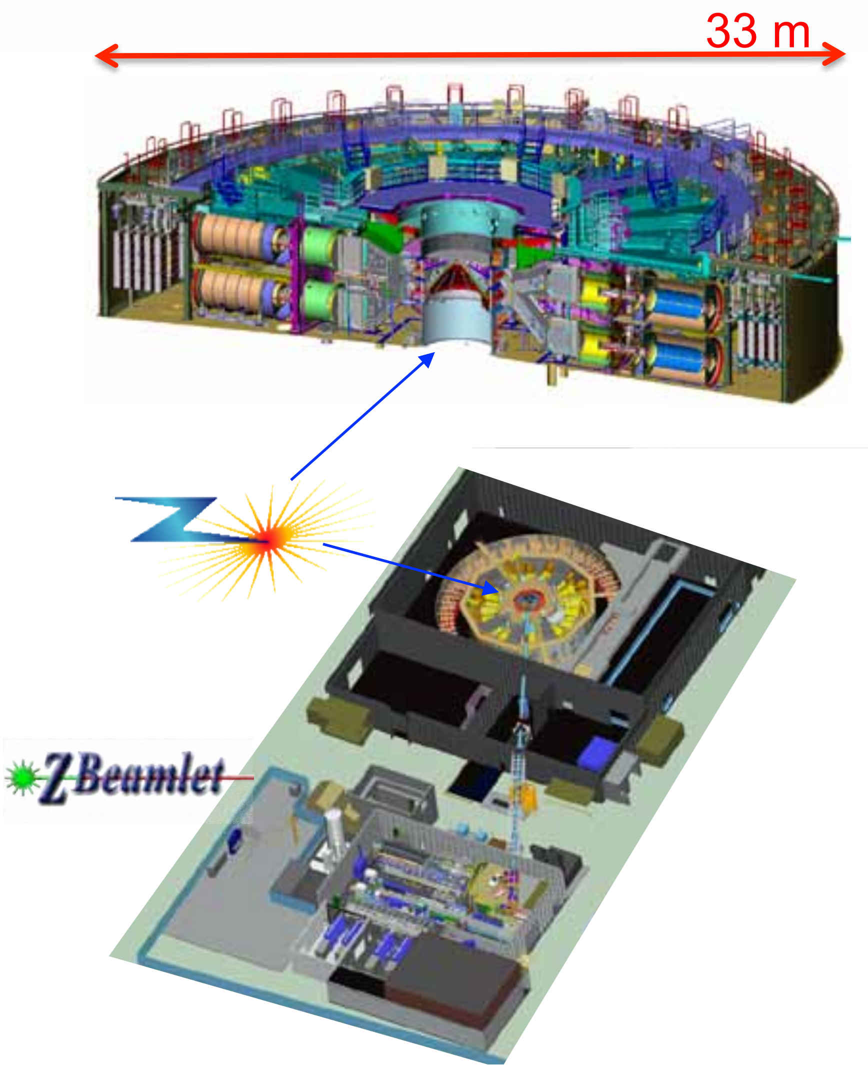
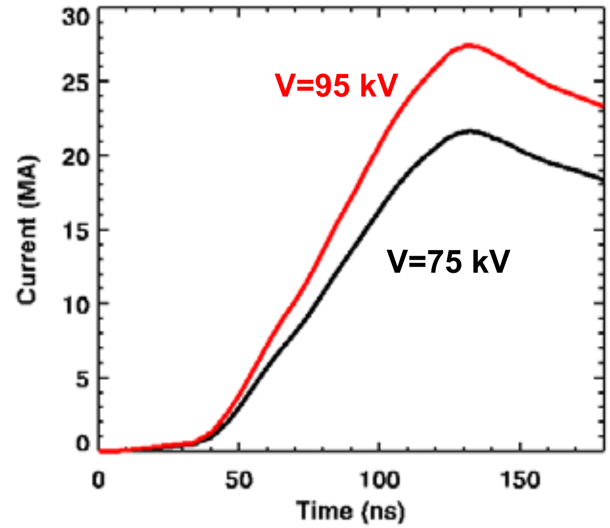
Magnetically-driven implosions on Z can be used to create extreme conditions in the laboratory





Magnetically-Driven Cylindrical Implosion

$$P = \frac{B^2}{2\mu_o} = 140\left(\frac{I_{MA}/30}{R_{mm}}\right)^2 MBar$$

140 MBar is generated by 300 eV radiation drive (e.g., NIF capsule)

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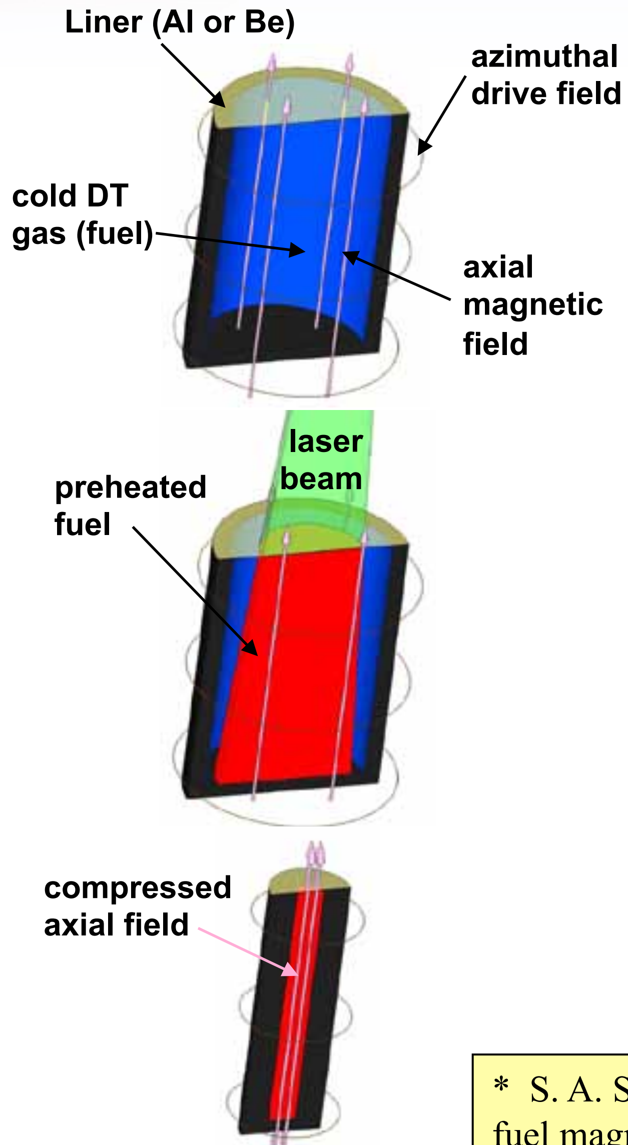
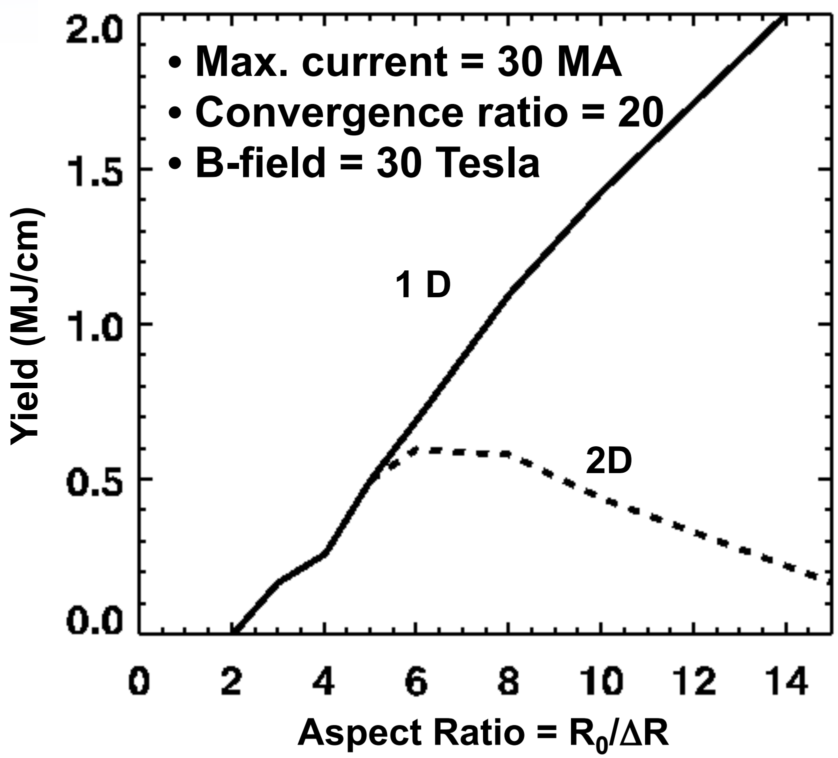
We are working toward an evaluation of a new Magnetized Liner Inertial Fusion (MagLIF)* concept



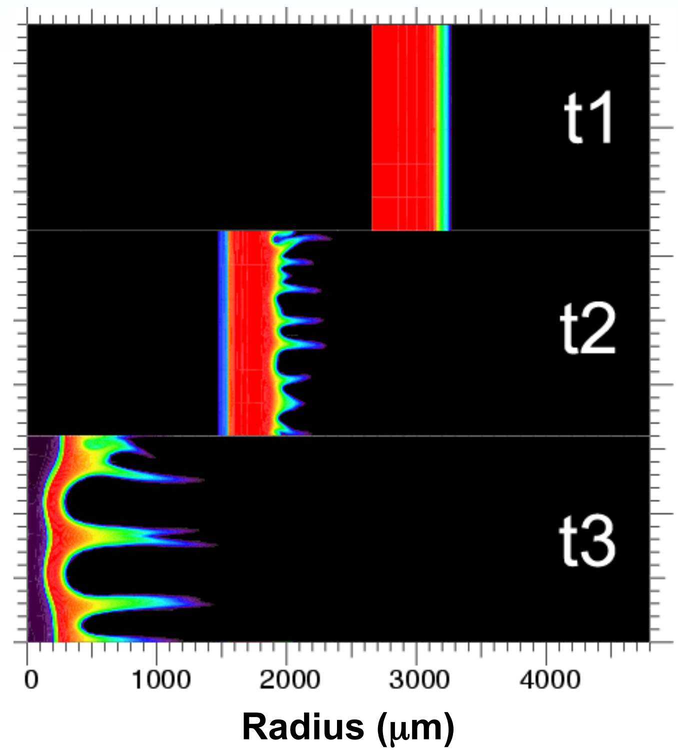
- Idea: Directly drive solid liner containing fusion fuel
- An initial ~10 T axial magnetic field is applied
  - Inhibits thermal conduction losses
  - Enhances alpha particle energy deposition
  - May help stabilize implosion at late times
- During implosion, the fuel is heated using the Z-Beamlet laser (<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)
- Simulations suggest scientific breakeven may be possible on Z (fusion yield = energy into fusion fuel); something not yet been achieved in any laboratory

* S. A. Slutz *et al*., "Pulsed-power-driven cylindrical liner implosions of laser preheated fuel magnetized with an axial field," Physics of Plasmas 17, 056303 (2010).

A major threat to the concept is the MRT instability; simulations imply a thick liner can minimize its impact



• The Magneto-Rayleigh-Taylor instability degrades the yield as the aspect ratio is increased (due to decreased liner ρr)



• Simulations of AR=6 Be liner
• Include ~60 nm surface roughness and resolve waves down to ~80 μm
• Simulations suggest wavelengths of 200-400 μm dominate near stagnation

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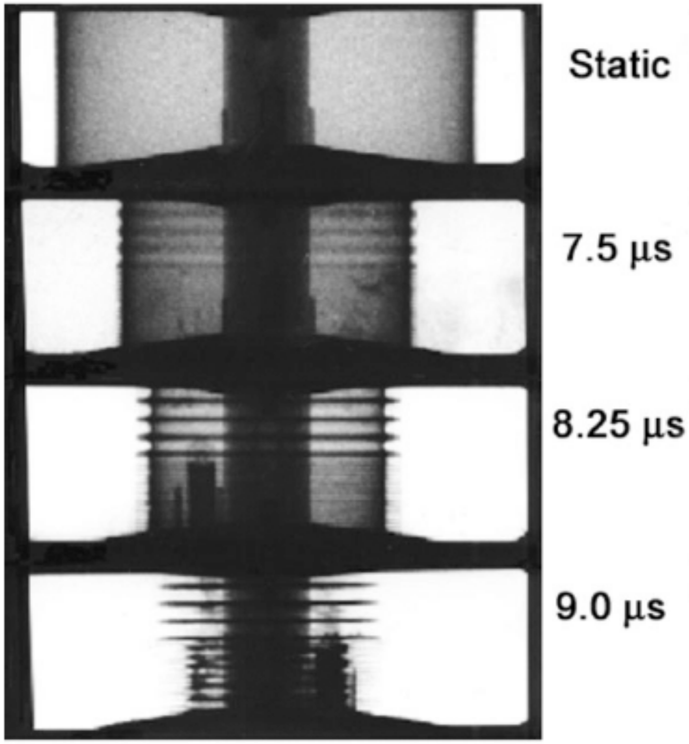
High-quality experimental data is needed for 100 ns implosions to benchmark MagLIF simulations

- **Little existing data in relevant regime**
  - **The few magneto-RT instability growth studies that have been done with solid liners have >1μs time scales (e.g., PEGASUS*)**
  - **In most ~100 ns experiments, liners reach plasma state quickly during implosions and strong shocks can develop**
  - **Some work with modulated-diameter wire arrays done (B. Jones, PRL 2005) but ablation physics dominates**
- **MRT studies complicated by diffusion of the current into the plasma liner**
  - **Distributed magnetic pressure**
  - **Local plasma heating & ablation**

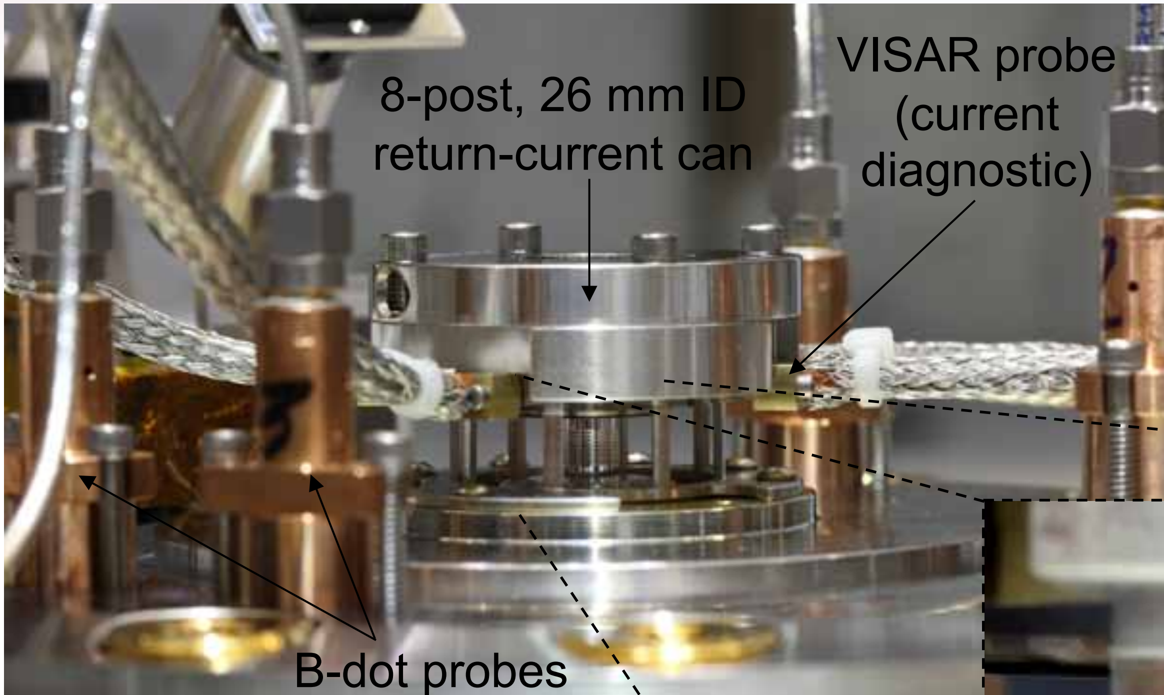


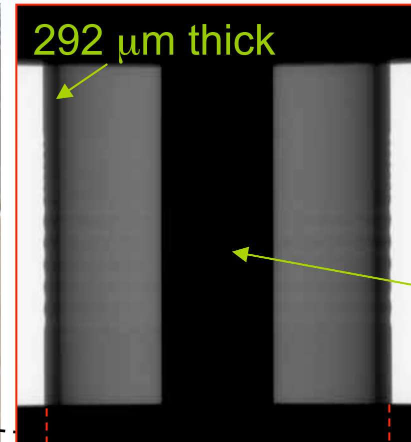
Radiographic Data

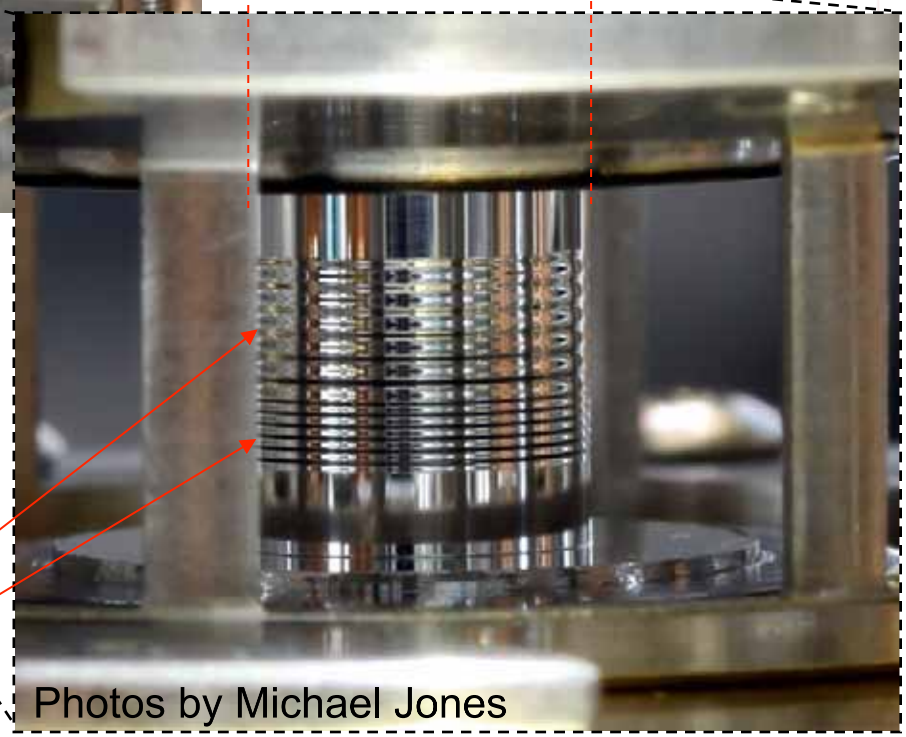
λ=2, 0.5 mm
A_0=25 μm

* R.E. Reinovsky *et al.*, IEEE Trans. Plasma Sci. (2002).
~6 MA, 7 μs rise-time current; 24 mm radius, 20 mm tall, 0.4 mm thick Al 1100.

We tested MRT growth predictions on Z using Al liners with small sinusoidal perturbations (λ=200, 400-μm)



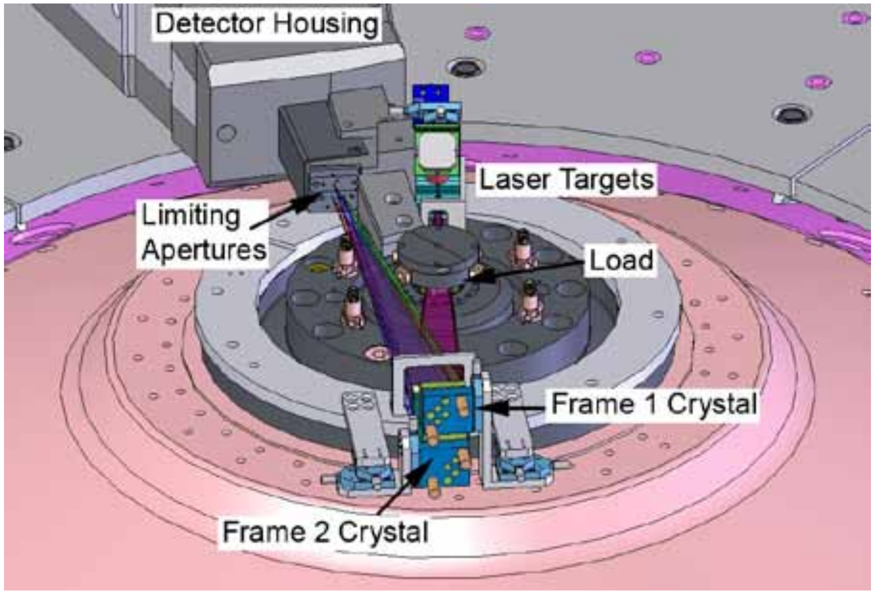


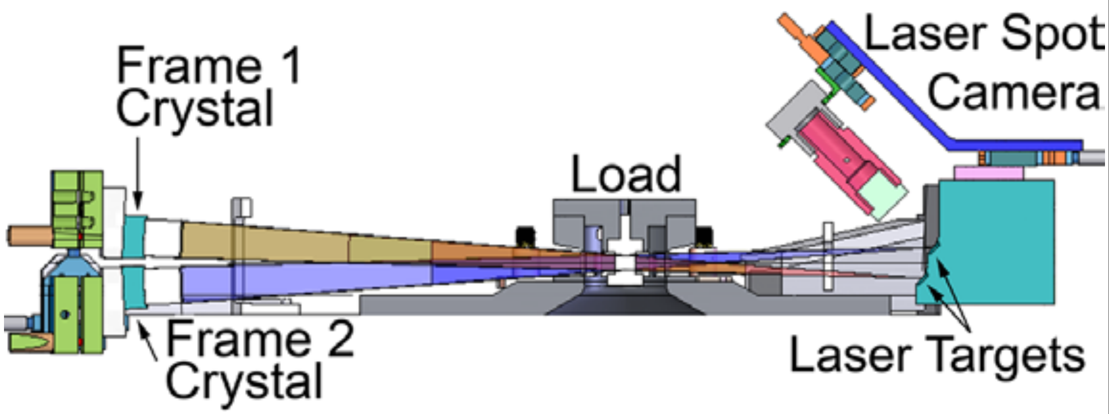


- Solid cylindrical liner (Al 1100 alloy)
- 6.5 mm tall, 6.34 mm diameter, AR=10
- 10 nm surface finish (diamond-turned)
- 12 sinusoidal perturbations:
  six 400-μm wavelength, 20-μm amplitude
  six 200-μm wavelength, 10-μm amplitude

Targets made by General Atomics

Our Z experiments used 2-frame 6.151 keV monochromatic crystal backlighting diagnostic





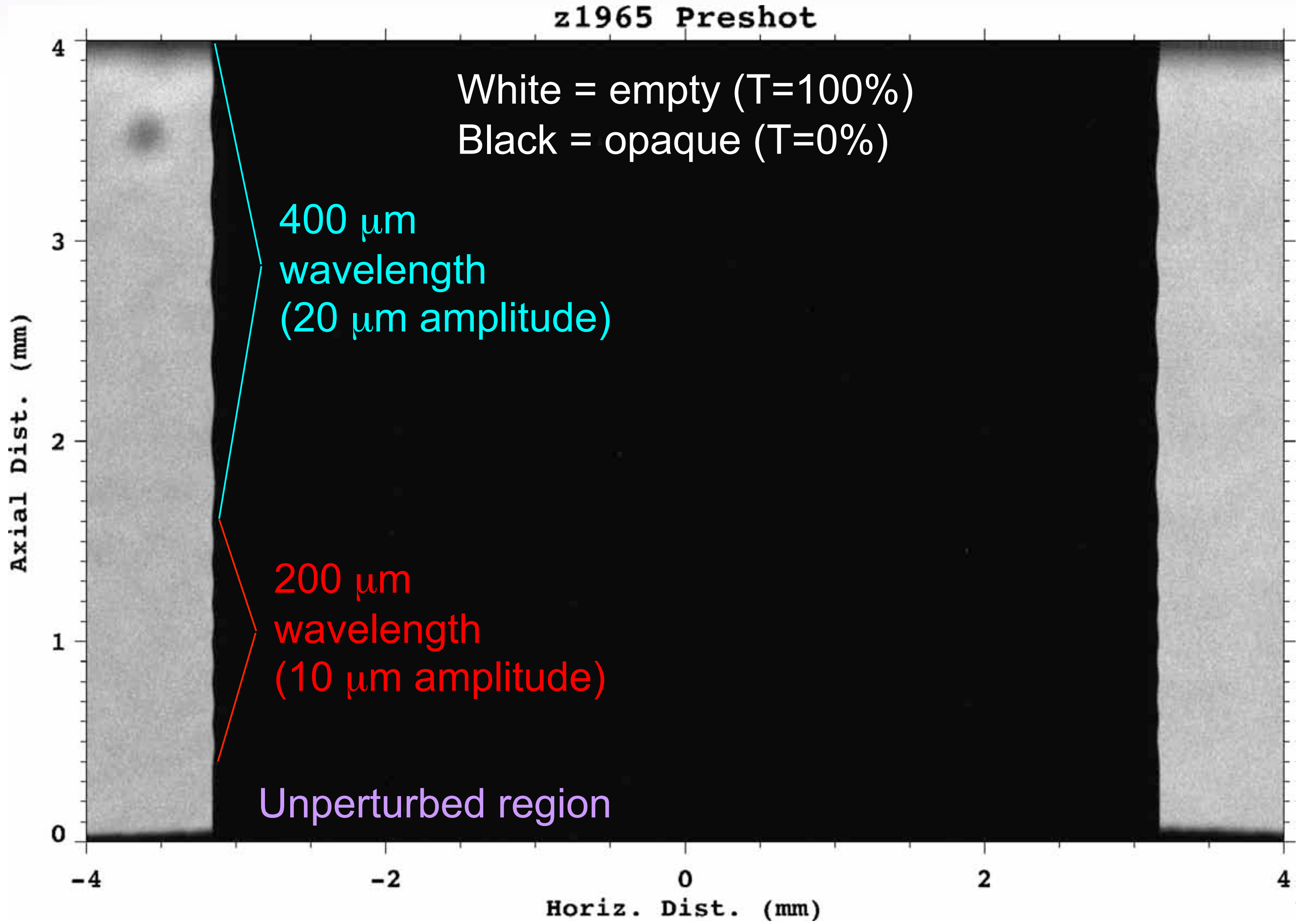
Radiograph lines of sight ±3° from horizontal

2-frame 6.151 keV Crystal Imaging

- **Monochromatic (~0.5 eV bandpass)**
- **15 micron resolution (edge-spread)**
- **Large field of view (10 mm x 4 mm); a >2 Megapixel camera**
- **Debris mitigation**

- **Original concept**
  - S.A. Pikuz *et al.,* RSI (1997).
- **1.865 keV backlighter at NRL**
  - Y. Aglitskiy *et al*., RSI (1999).
- **Explored as NIF diagnostic option**
  - J.A. Koch *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).

Example 6.151 keV radiograph (Pre-shot)



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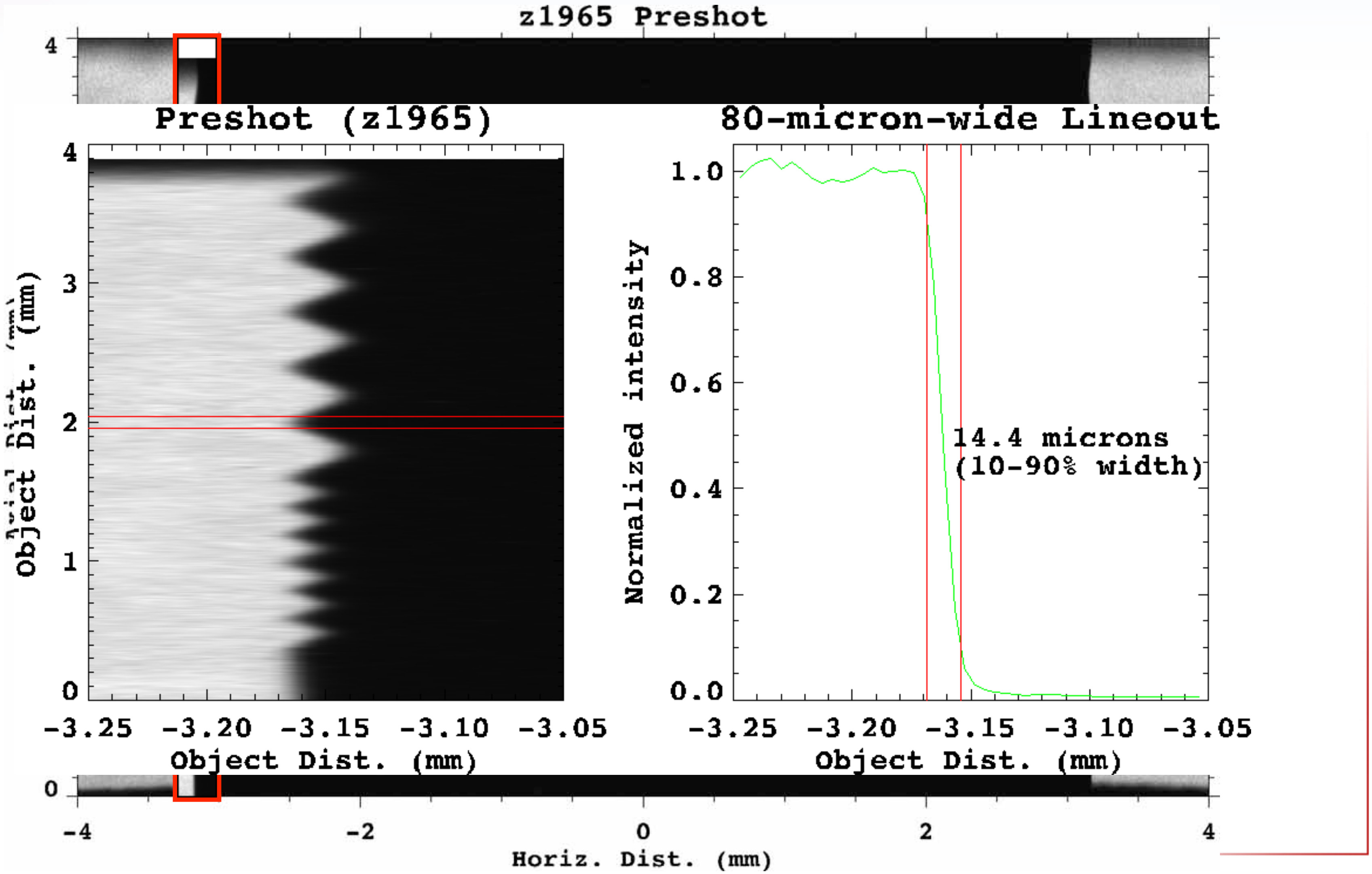
The 6.151 keV radiographs have 15 μm spatial resolution



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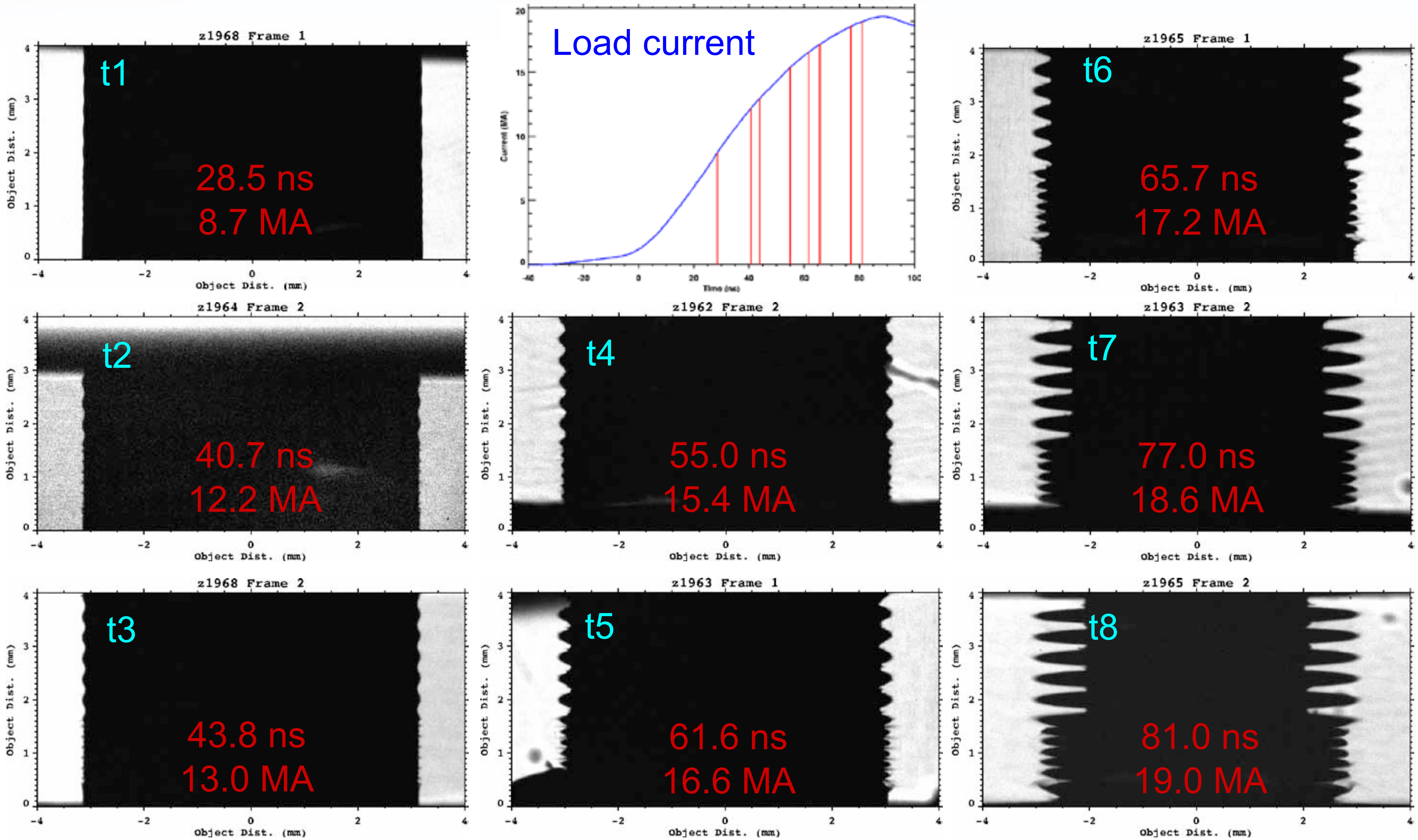
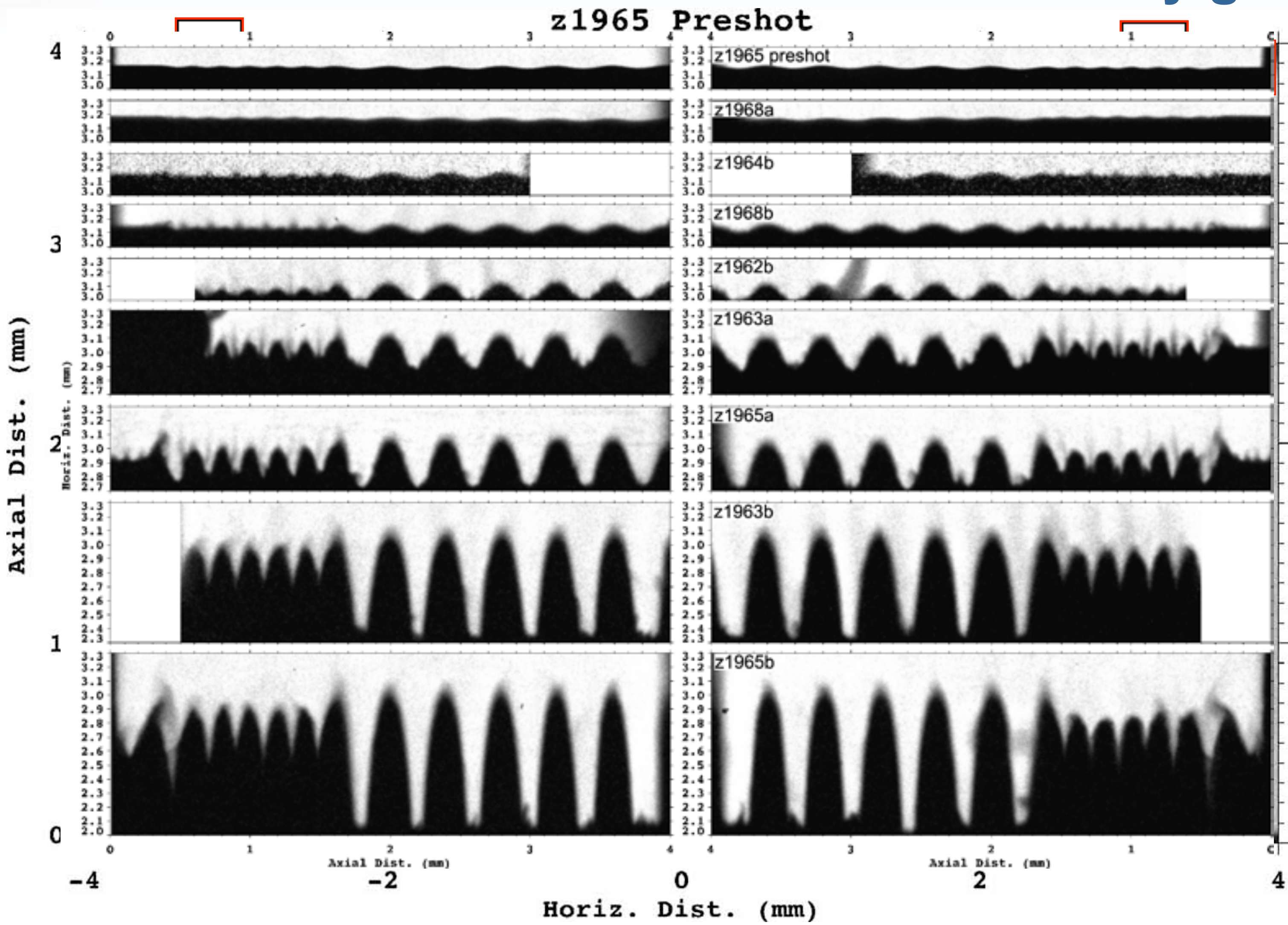
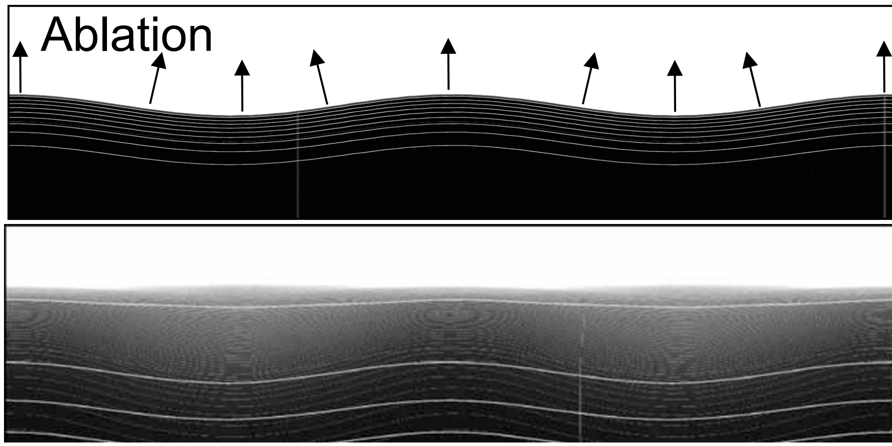
Reproducible drive currents (±1.5%) and liners enabled an 8-frame movie to be obtained over 5 shots



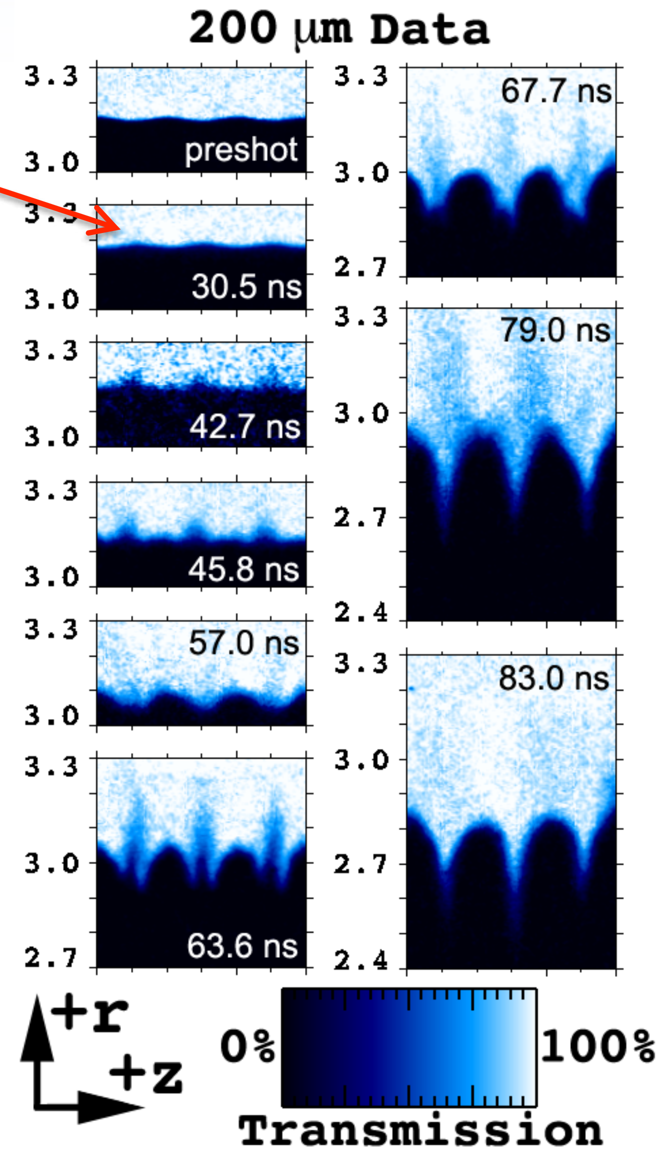
Zooming in, we see ablation, jetting, and small-scale instabilities in addition to the seeded instability growth



Zooming in, we see **ablation**, jetting, and small-scale instabilities in addition to the seeded instability growth

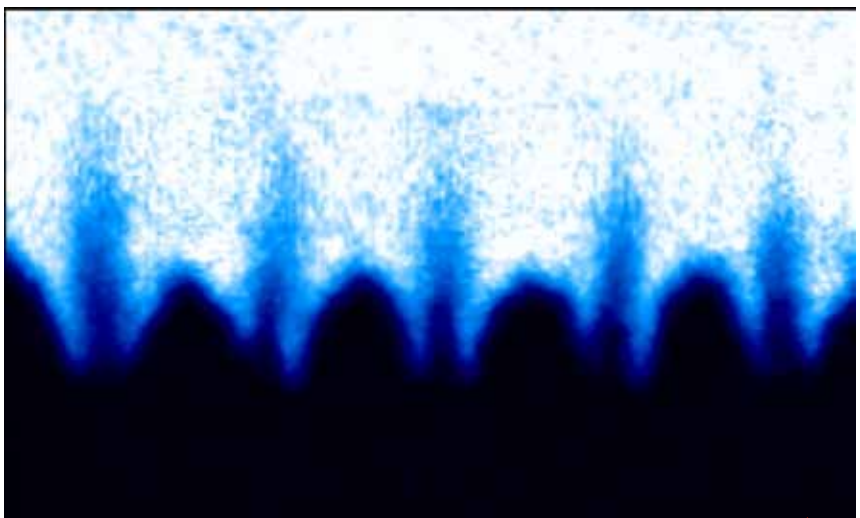


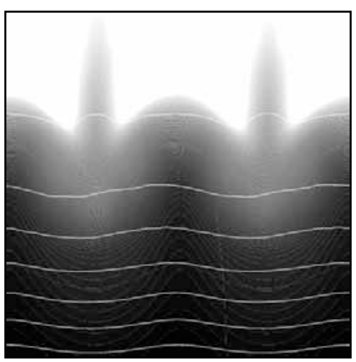
Simulated density map with rB_θ contours



The current concentrated near the liner surface at early times heats the outer layer and causes it to ablate.

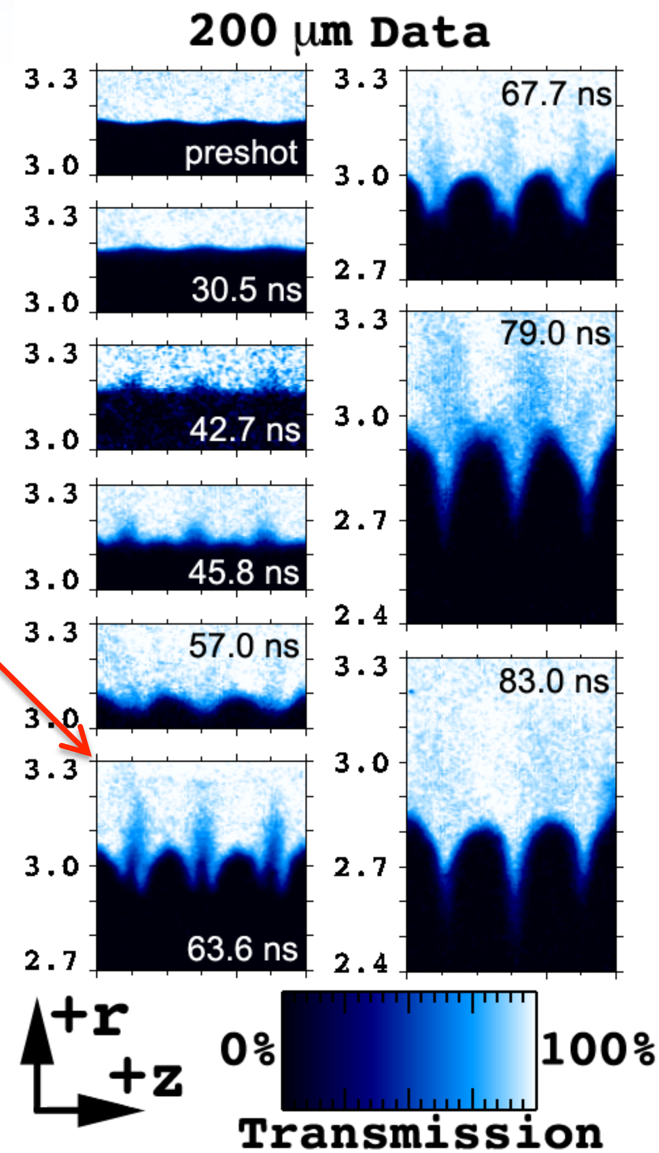
Zooming in, we see ablation, jetting, and small-scale instabilities in addition to the seeded instability growth





Simulated density map with rB_{θ} contours

Ablated material coalesces in valleys to form jets visible in the radiographs



LASNEX: T_{jets} ~30 eV; T_{valley} ~100 eV

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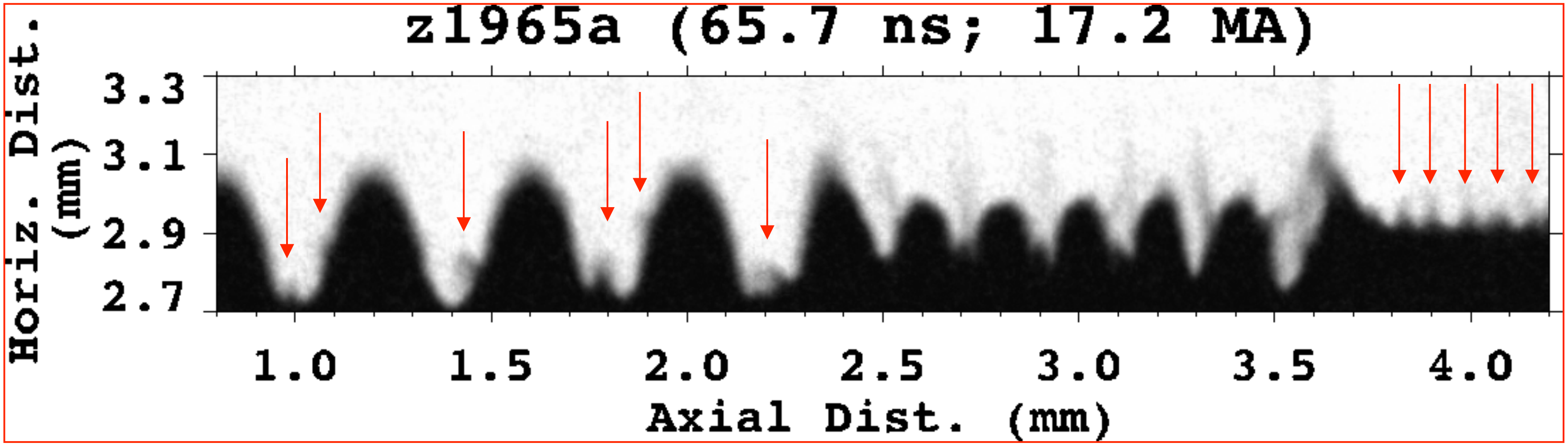
Zooming in, we see ablation, jetting, and small-scale instabilities in addition to the seeded instability growth

Small-scale instabilities appear to have similar character to instabilities growing on initially unperturbed regions



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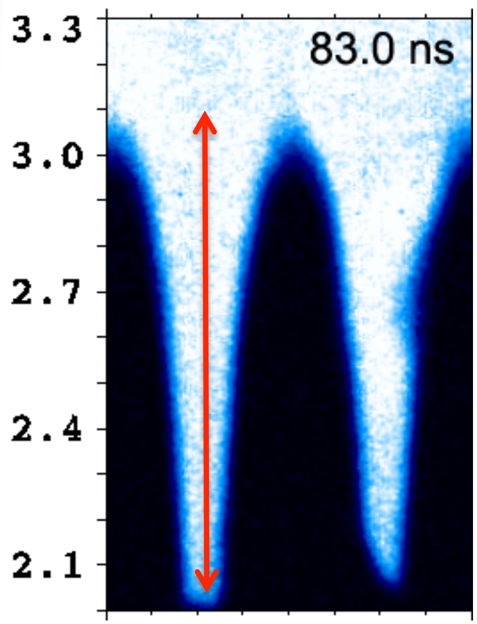
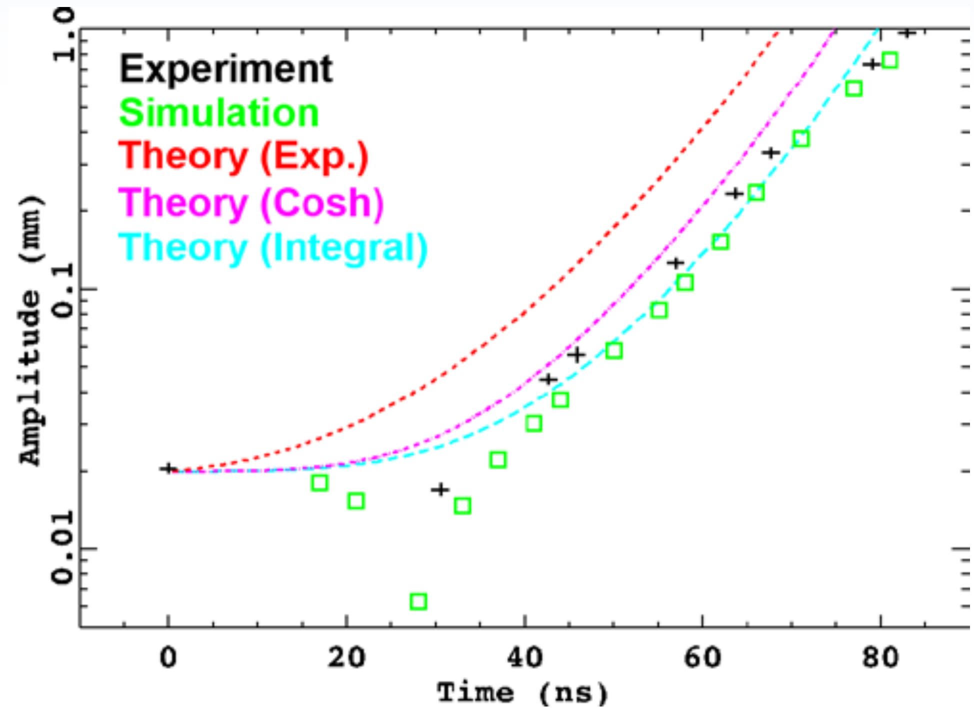
The data is being used to benchmark our modeling & simulation tools





Time-dependent dispersion relation for the perturbation amplitude*

$$\frac{\partial^2 \xi}{\partial t^2} = kg(t)\xi$$

This has two unstable roots.

Limiting case is growing exponential term,

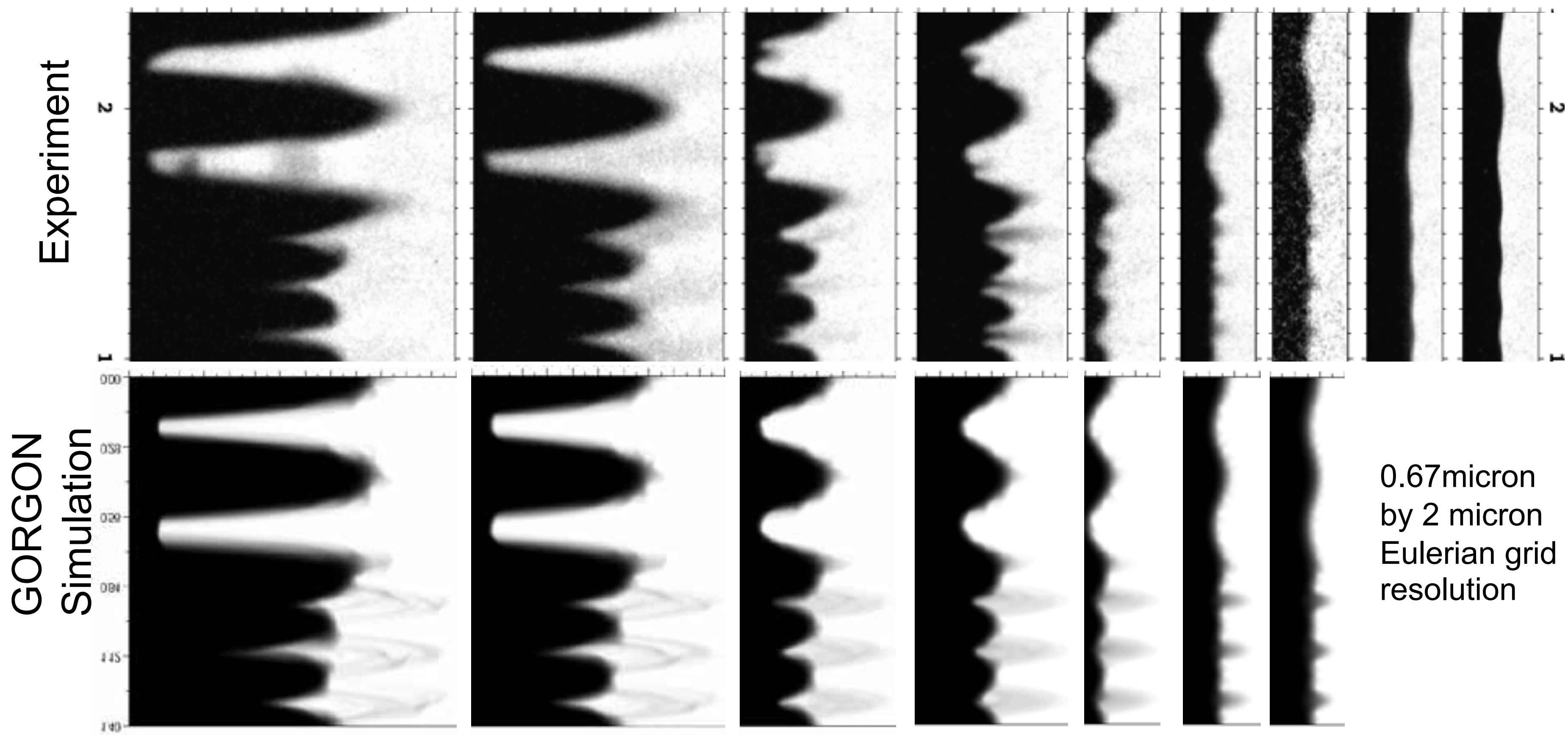
$$\xi = \xi_0 e^{\int_0^t \sqrt{kg(t')}dt'}$$ where

$$g = -\frac{\mu_0}{4\pi m_L}\frac{I^2(t)}{R(t)}$$ but at early times

the decaying solution partly cancels growth

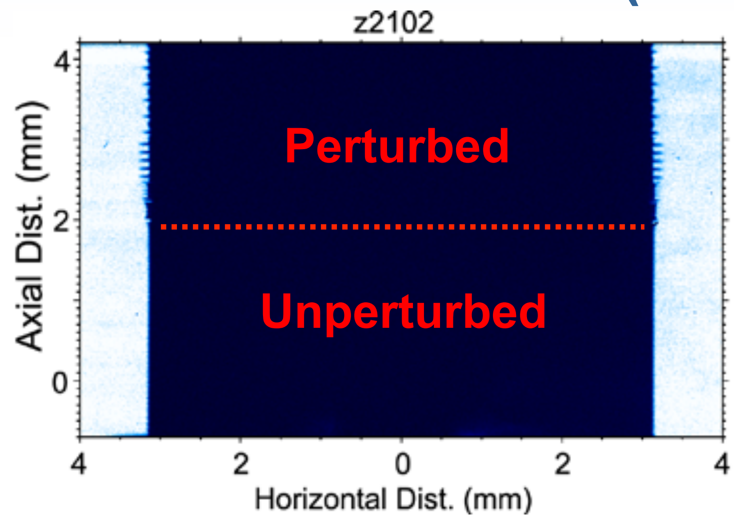
* E.G. Harris, Phys. Fluids 5, 1057 (1962).

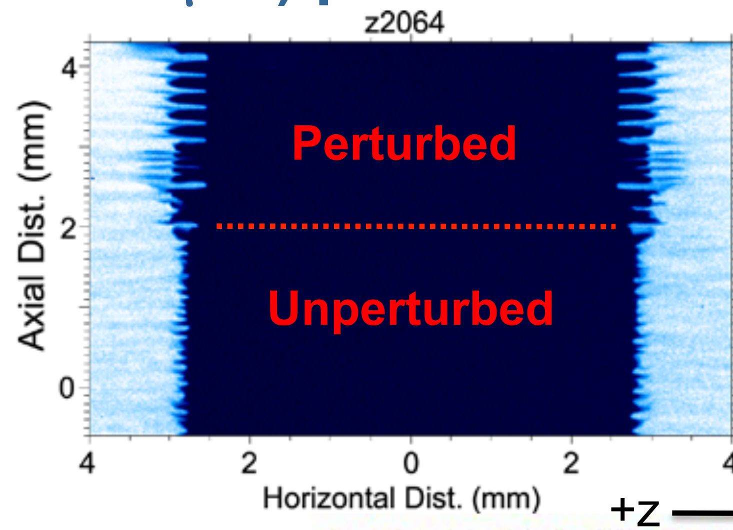
Our initial comparisons were against 2D LASNEX—we have now begun comparisons against 3D GORGON

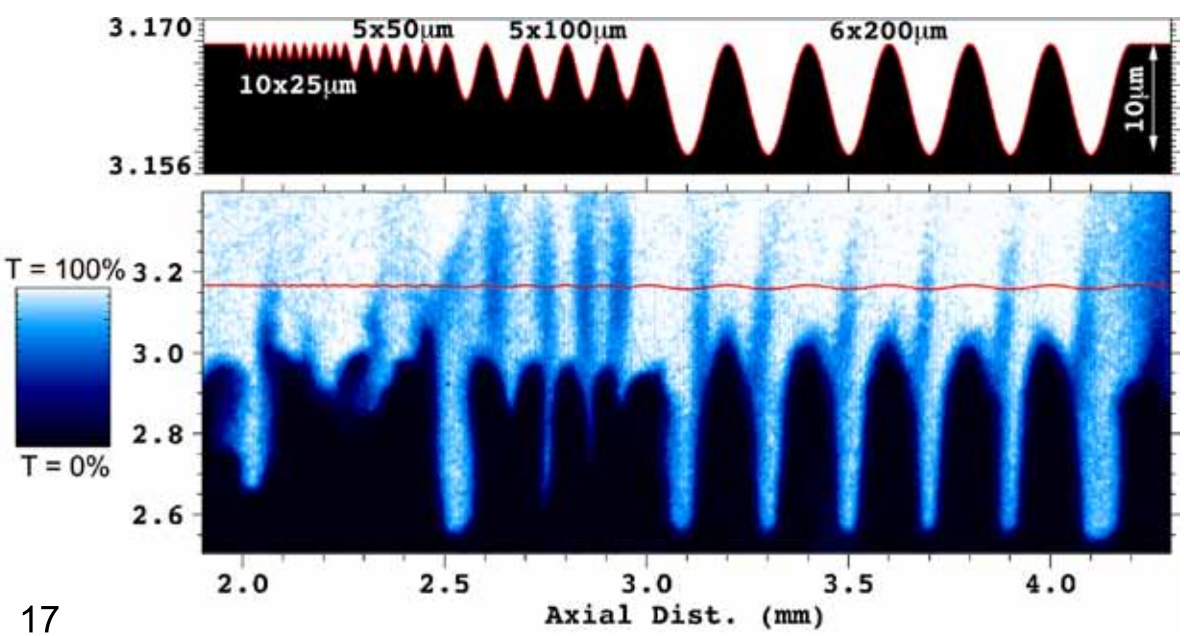


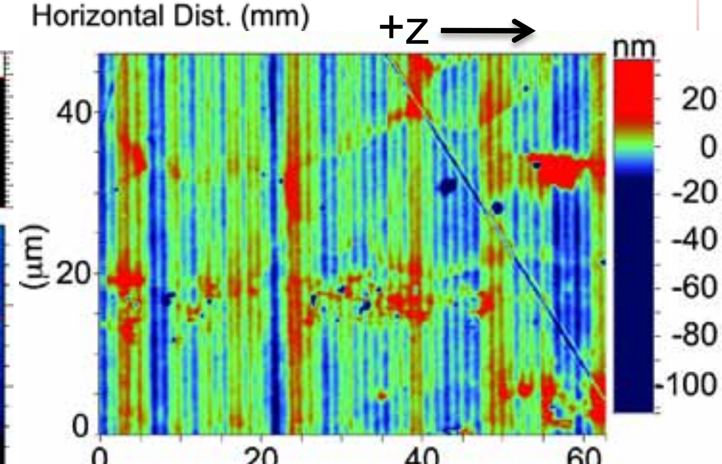
0.67micron by 2 micron Eulerian grid resolution

Two additional images were obtained using 1-frame, 0° backlighter of unperturbed regions and regions seeded with small (λ=25-200 μm) perturbations



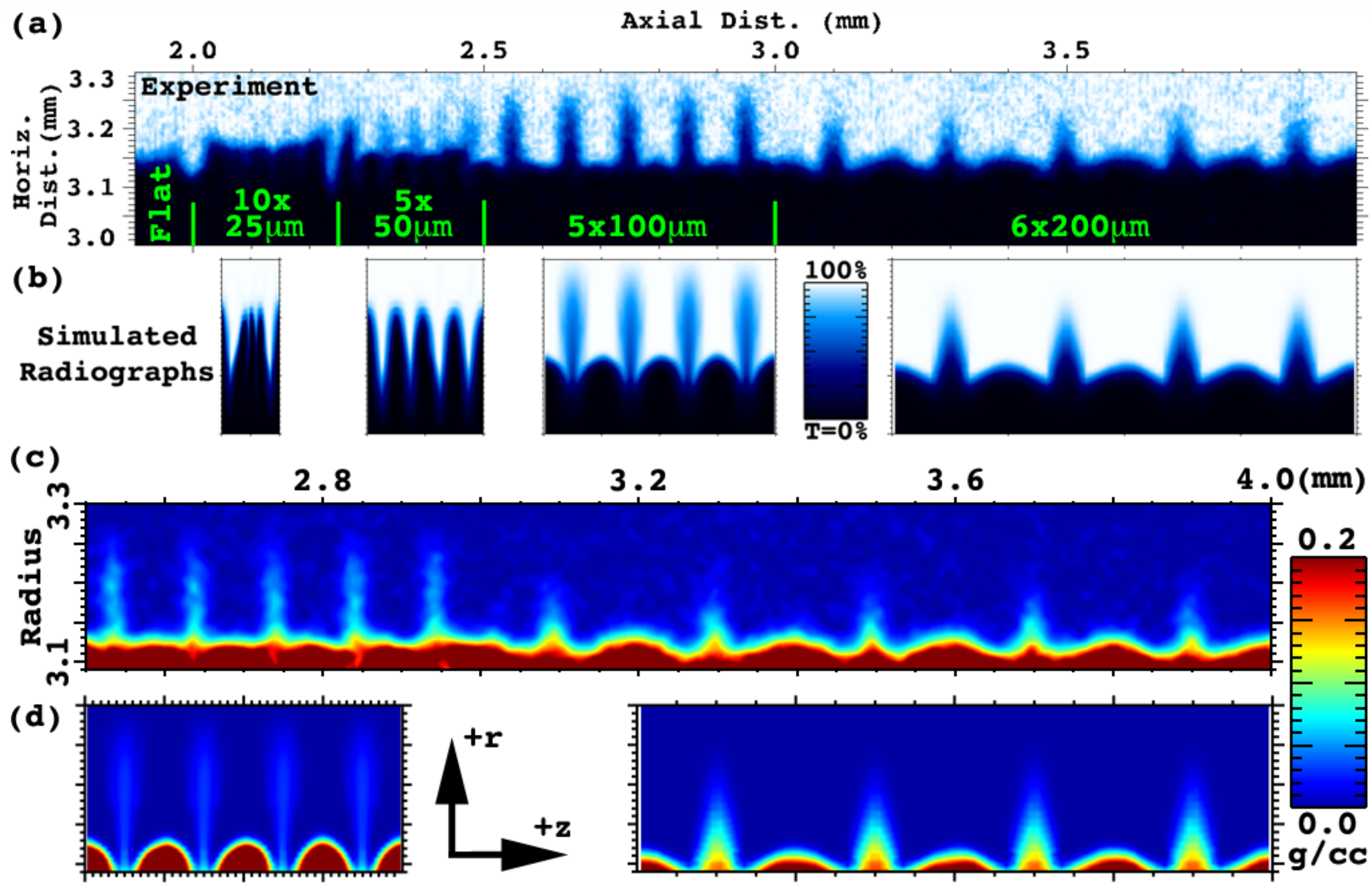




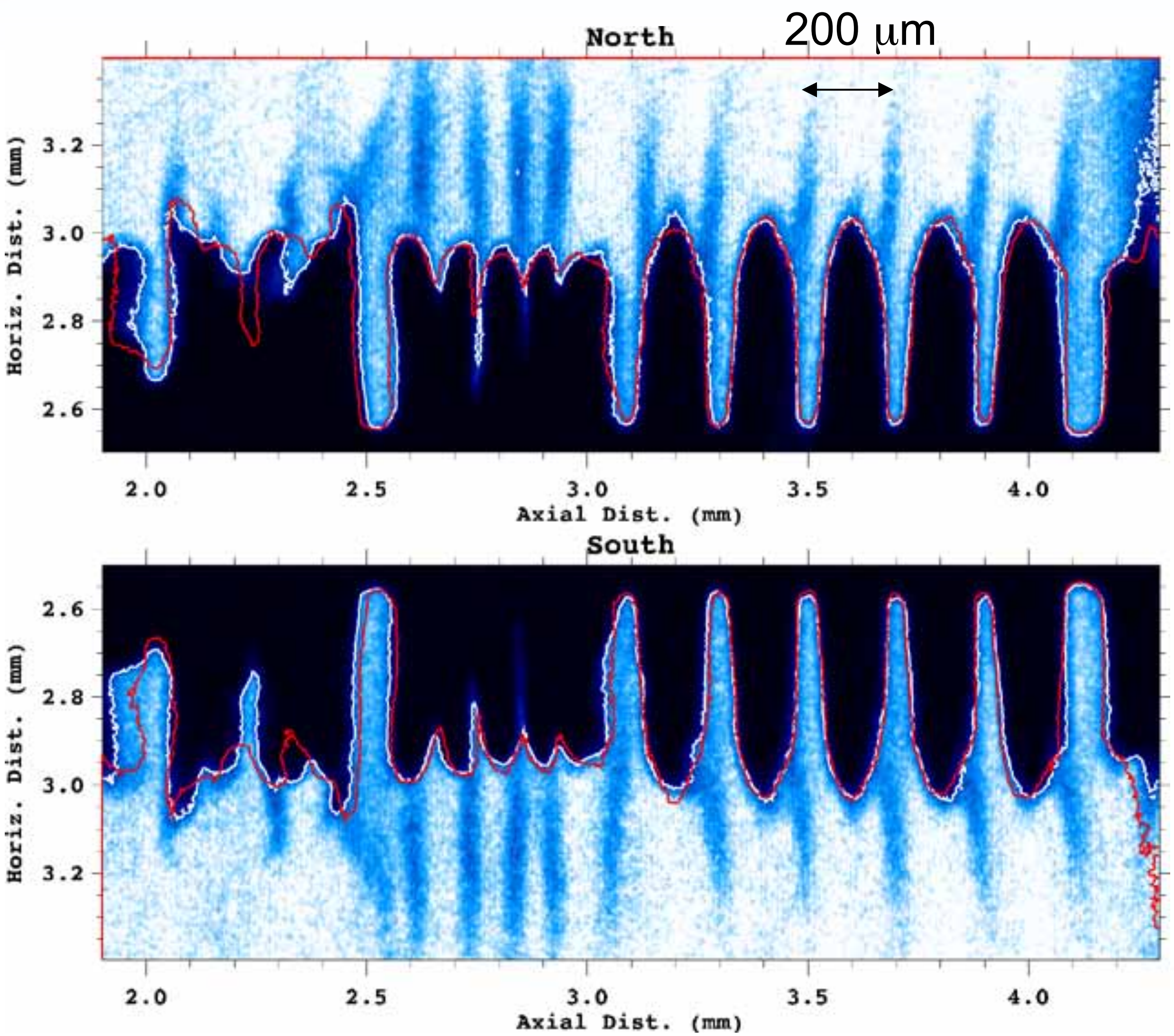


"Unperturbed" half has ~30 nm RMS surface roughness with 1.25 μm & ~8 μm axial periods

Our LASNEX simulations capture the ablation and jetting well down to ~50 μm wavelength scales



The instabilities in the perturbed regions are highly-correlated azimuthally in the late frame



50% transmission contours overlaid on images

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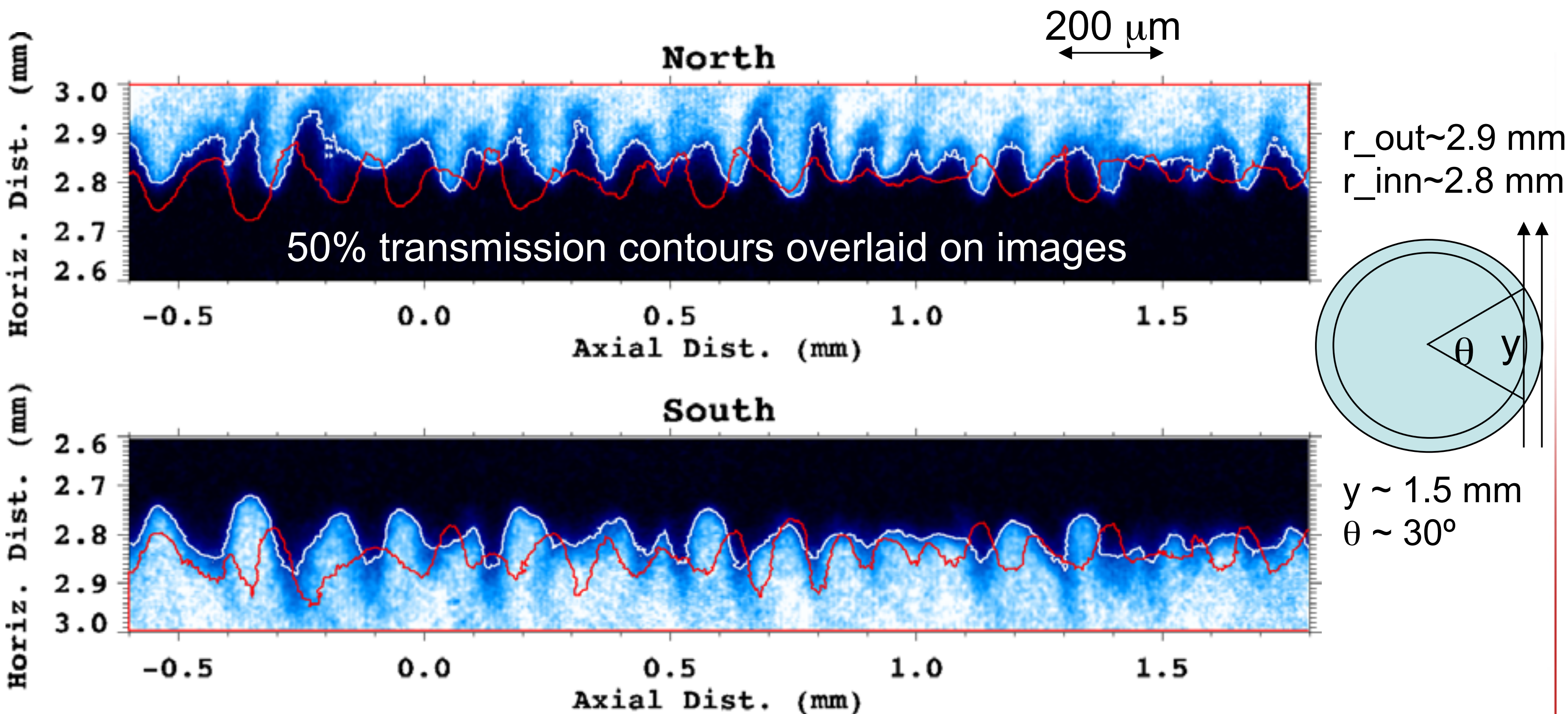
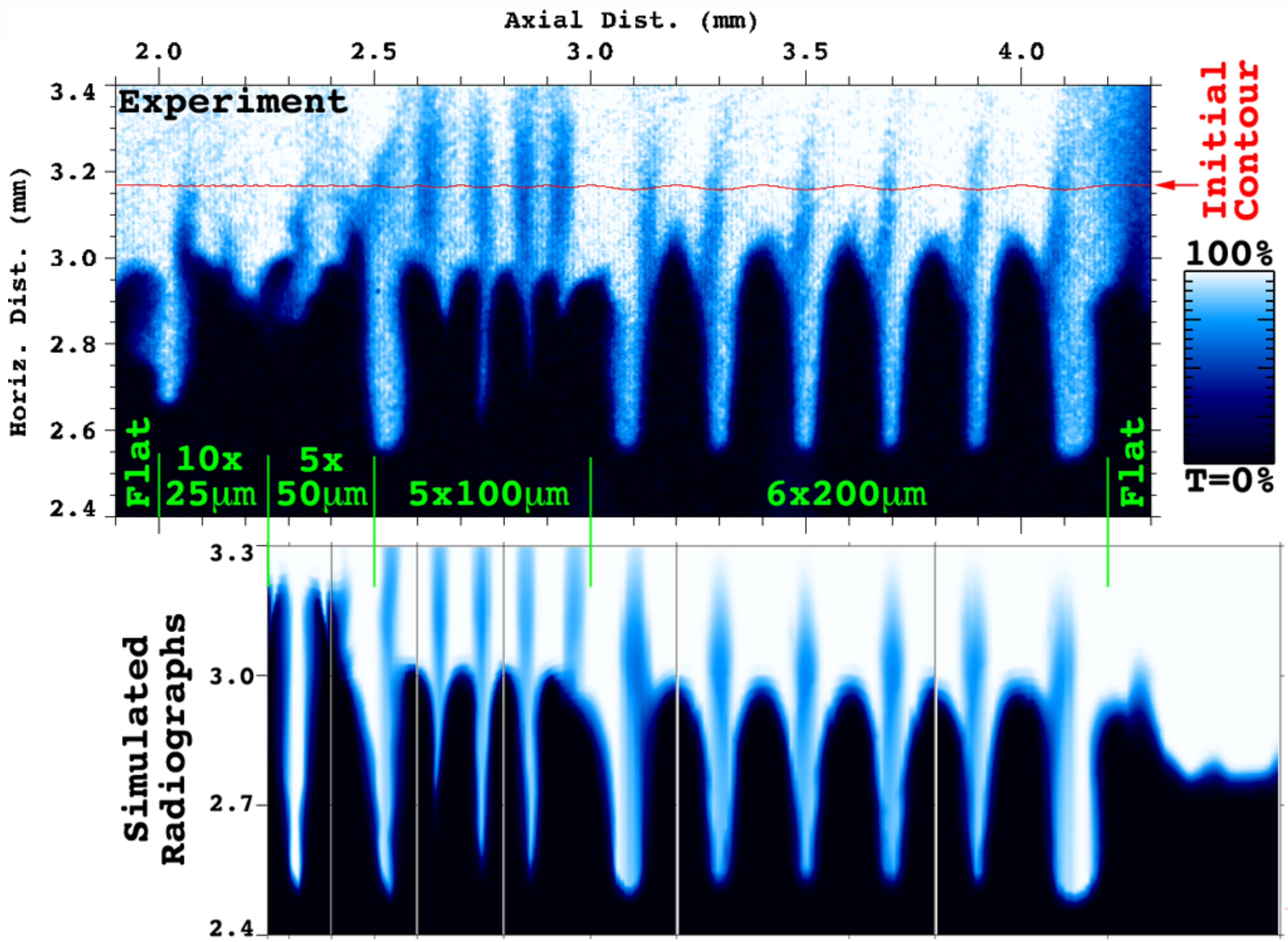
The instabilities in the flat region at that time appear to be only partially correlated along azimuthal direction



Our LASNEX simulations capture the perturbation amplitude growth down to ~50 μm wavelength scales



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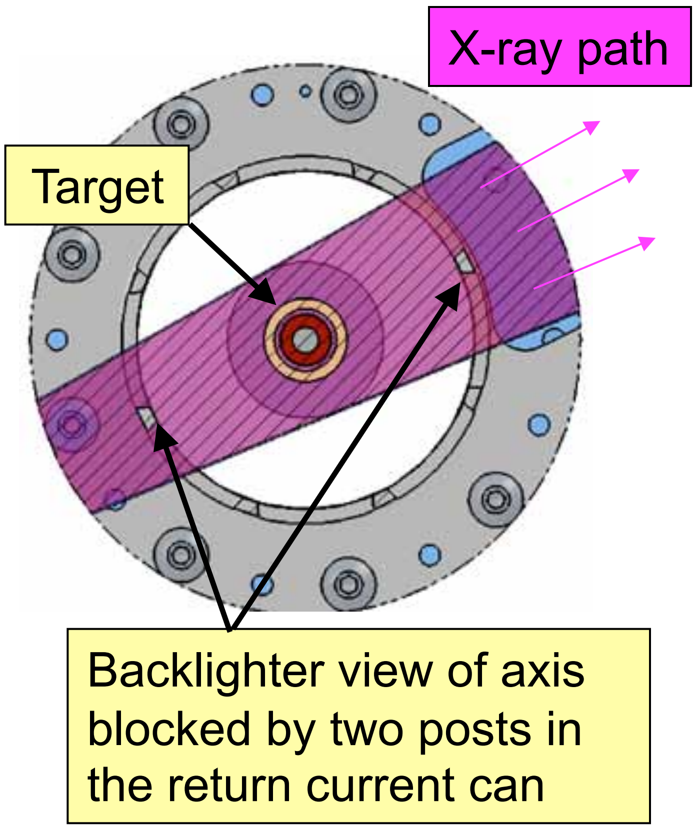
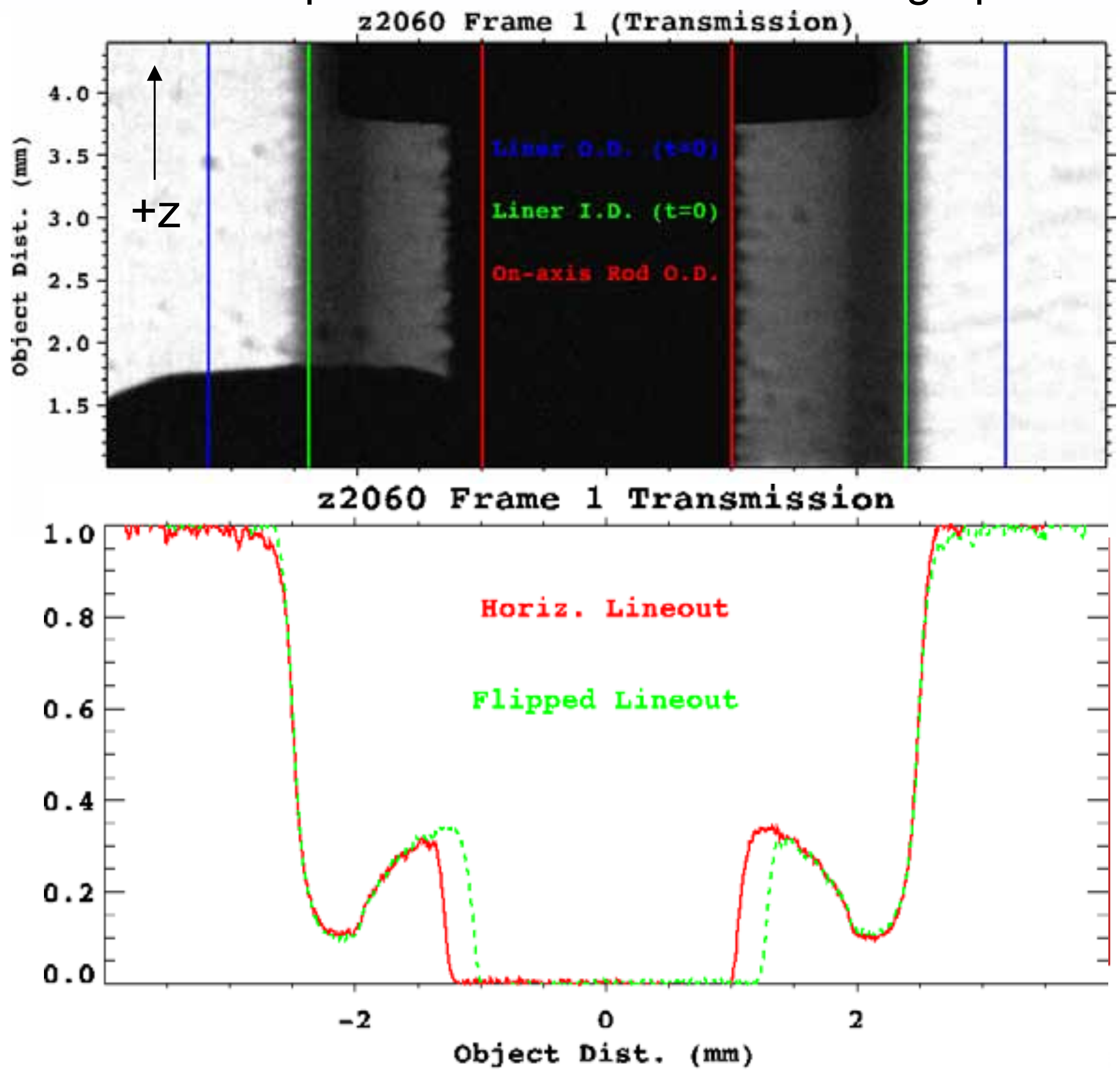
Penetrating 6.151 keV radiographs of Be liners allow us to observe both the inner and outer liner surfaces

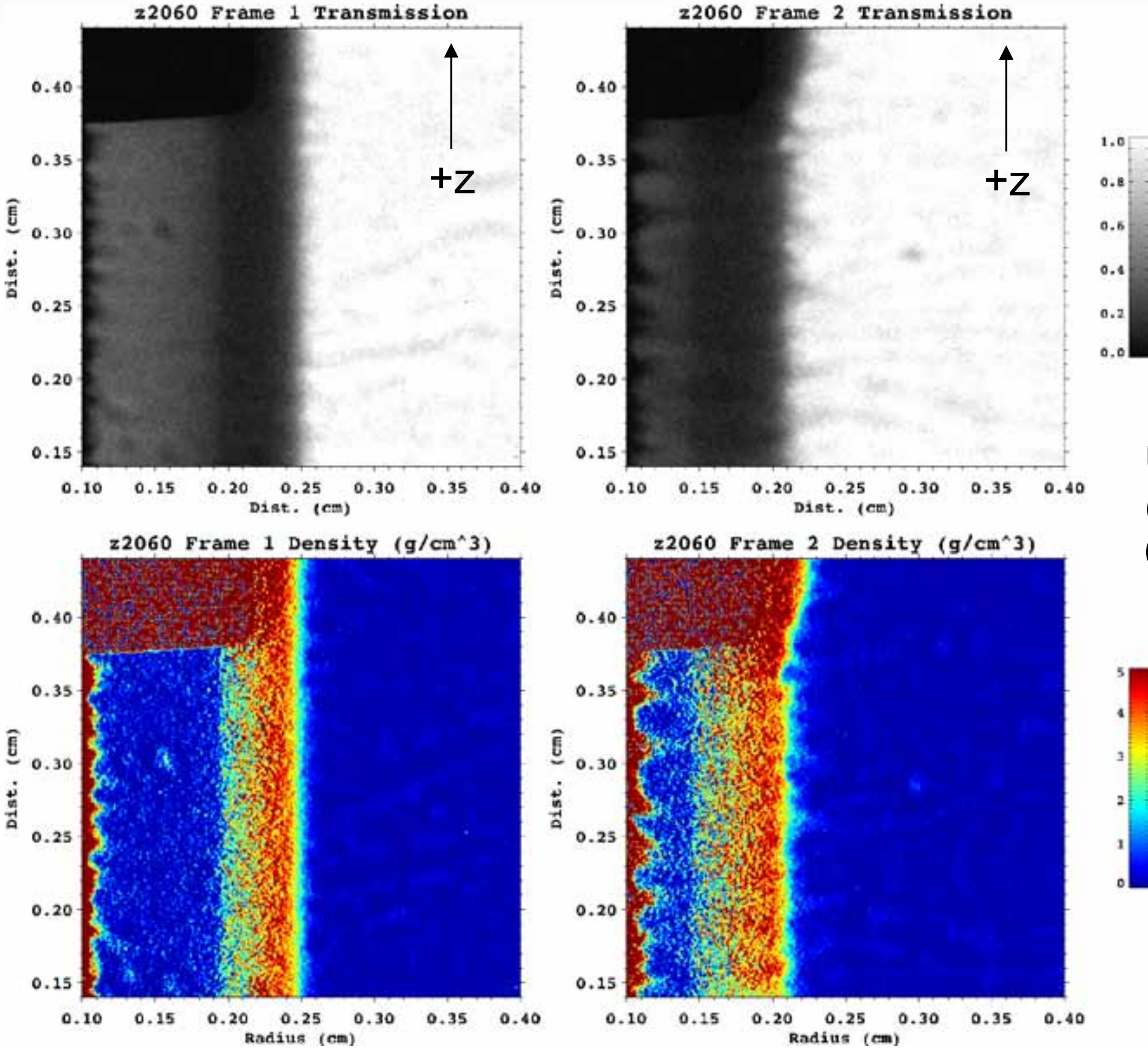
Top-down view of x-ray path through load region



Example downline 6.151 keV radiograph



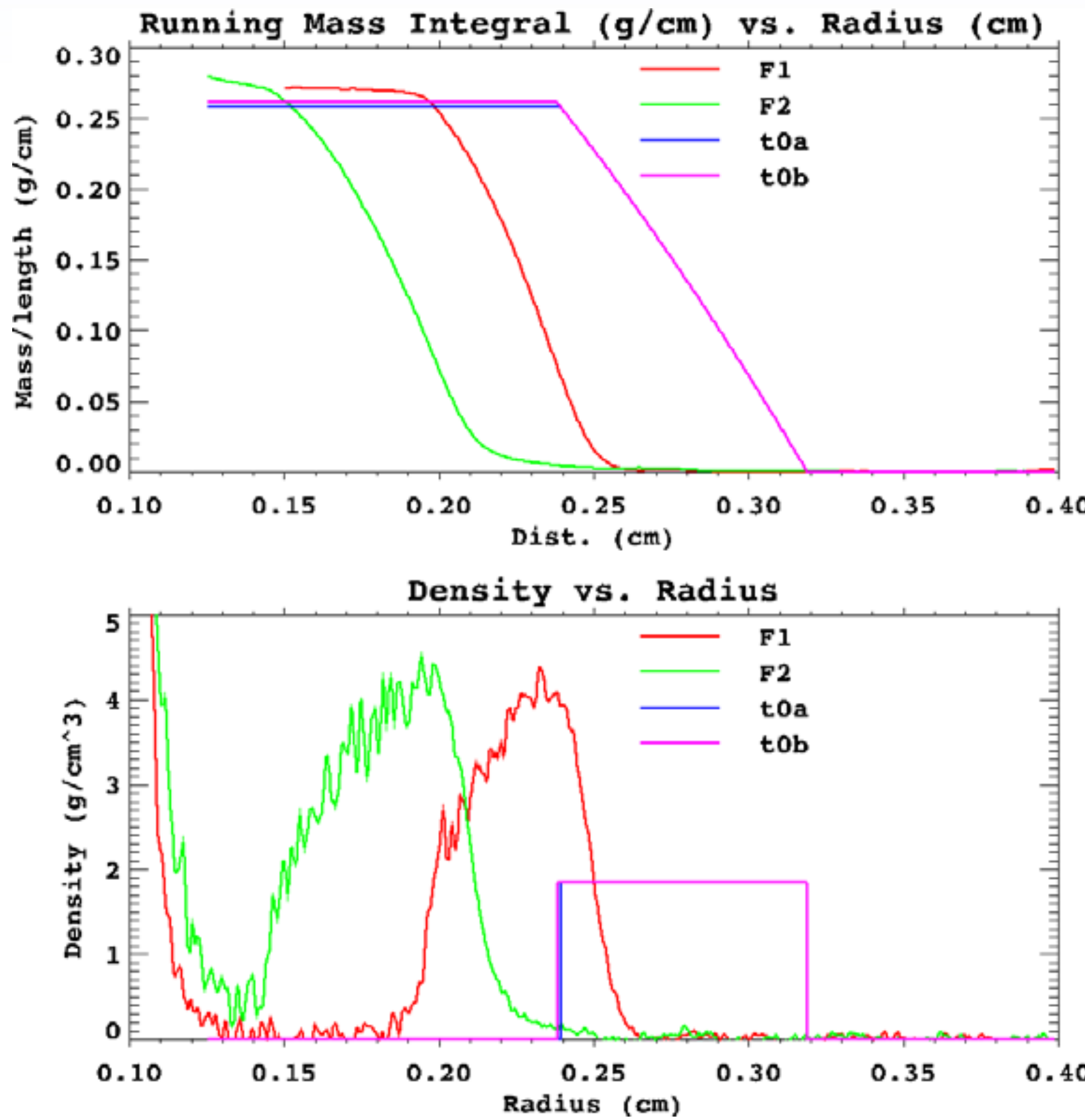
We obtained two images of a Be liner during the implosion, which were Abel-inverted to get a density map



Used κ=2.2415 cm^2/g (Cold Be opacity at 6151 eV)

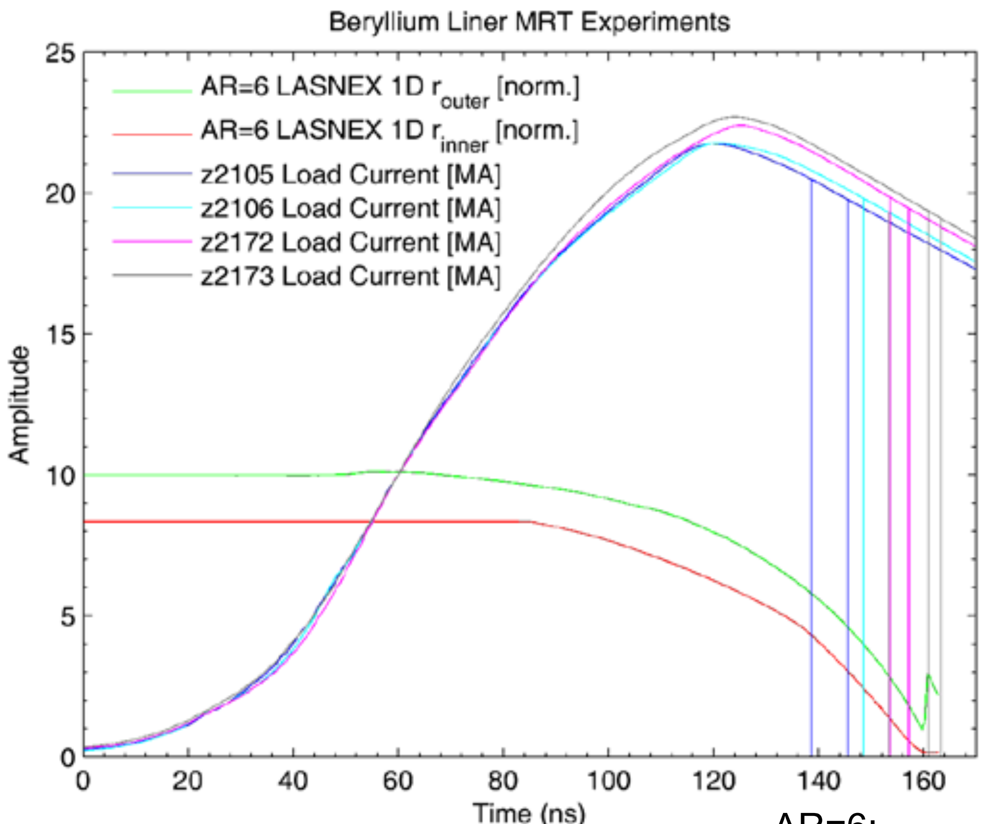
Note inner radius of liner appears relatively uniform

The results of the Abel inversion are consistent with the initial mass/length of the liner, show ρmax~4.1 g/cc

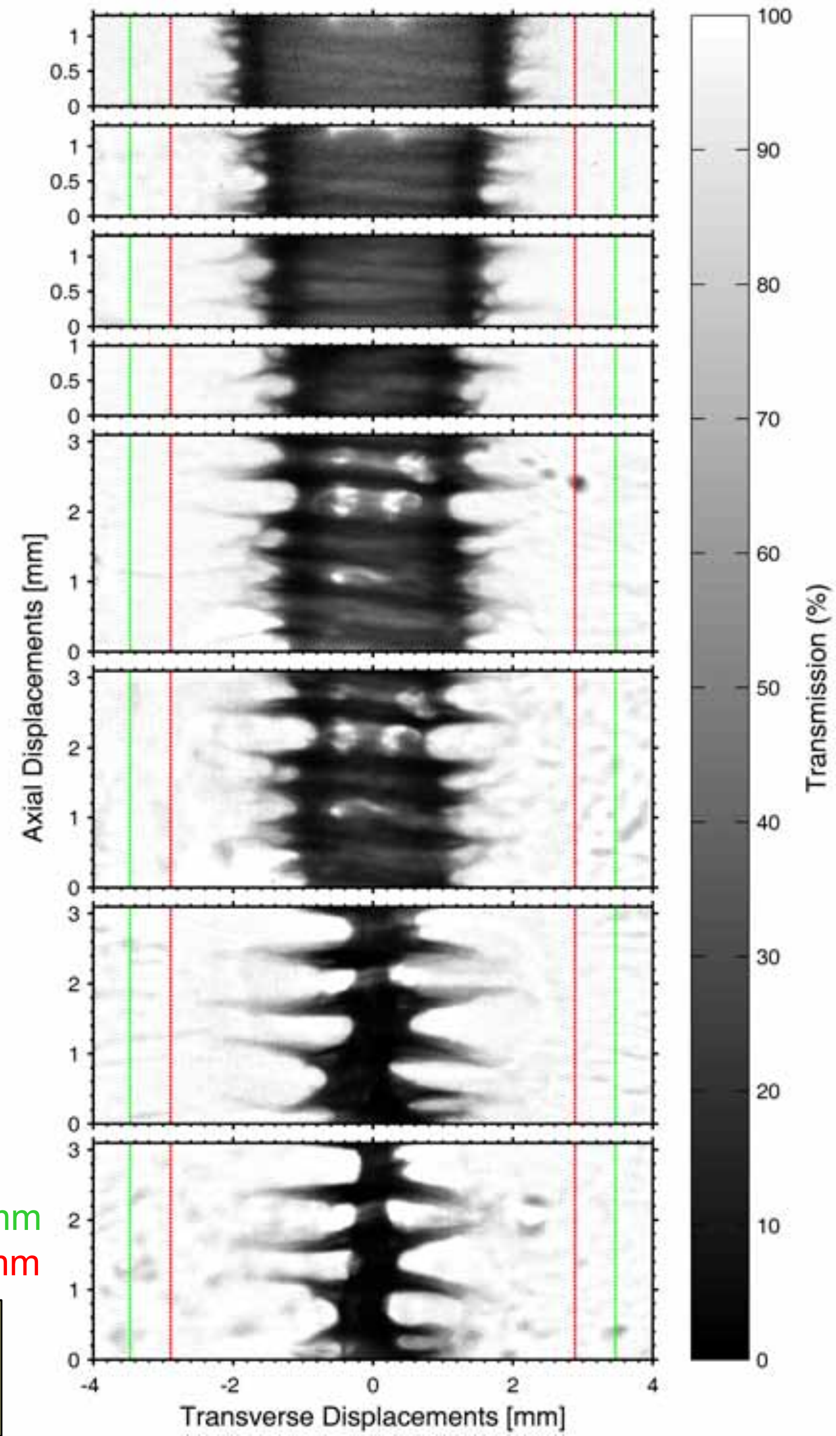


Both LASNEX & GORGON are able to match these profiles

We have collected data on multi-mode MRT growth in Be liners at high radial convergence

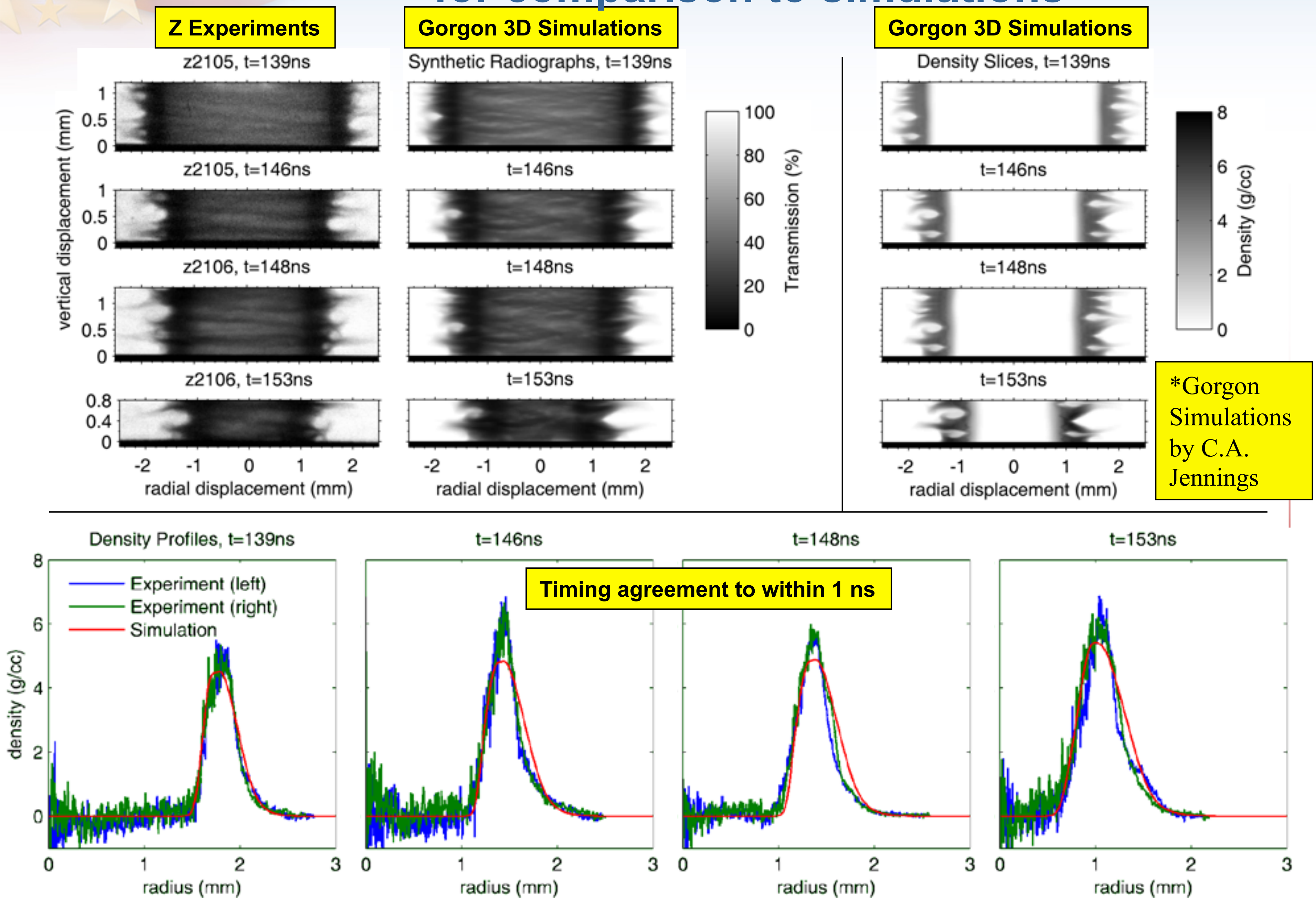


AR=6:
$r_{outer,0}$ = 3.47 mm
$r_{inner,0}$ = 2.89 mm



R.D. McBride *et al.*,
Bull. Am. Phys. Soc. **55**, CP9 80 (2010).

We are working through quantitative criteria for comparison to simulations



These results are just the beginning—many interesting scientific and practical questions remain!

- **We have performed the first controlled measurements of MRT growth in solid liner implosions driven by <1 μsecond generators**
- **The data reveal several phenomena such as ablation, jetting, and both small- and large-scale instability growth. The data are providing insight into the necessary physics that our simulation tools need to capture.**
- **A few of the many questions remaining:**
  - **Do we need to accurately model the small-scale features seen in the data (λ<50 μm), since the characteristic wavelengths near stagnation are much larger (200-400 μm)?**
  - **Can we model MRT growth on "unperturbed" liner surfaces? How best do we make quantitative comparisons to code results?**
  - **Will adding an axial magnetic field increase the liner stability near the axis (i.e., when Bz approaches Bθ)?**
  - **Can we model & measure the wavelength cascading process? Multi-mode coupling? Flux compression? Helical perturbations?**

D.B. Sinars *et al.*, Phys. Rev. Lett. (2010).
D.B. Sinars *et al.*, Phys. Plasmas (2011).
R.D. McBride *et al.*, manuscript in preparation.

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