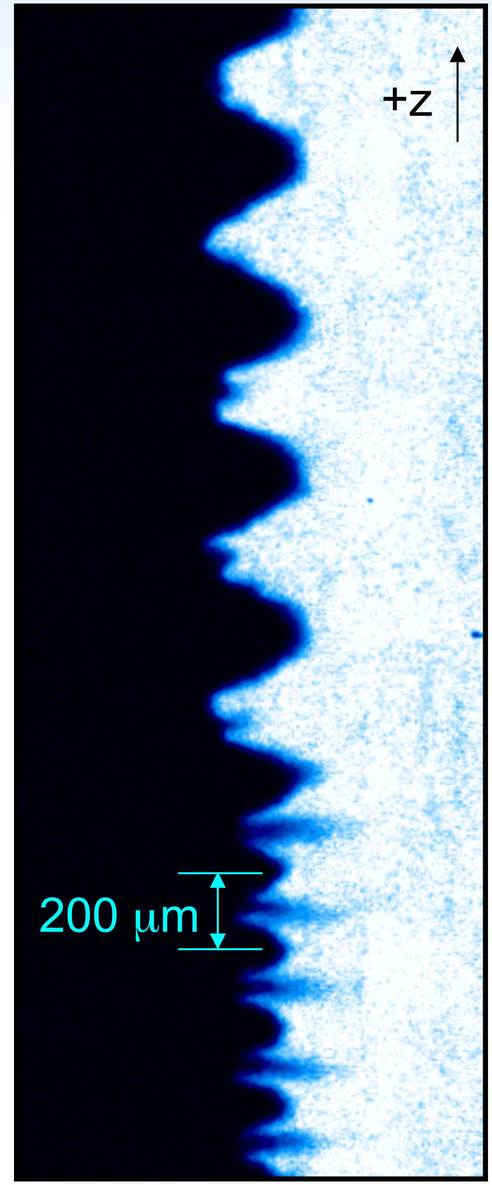
Measurements of Magneto-Rayleigh-Taylor Instability Growth in Solid Liners on the 20 MA Z Facility



Experiment Design, Planning, and Analysis

Daniel Sinars, Stephen Slutz, Mark Herrmann, Michael Cuneo, Kyle Peterson, Ryan McBride, Roger Vesey, Charlie Nakhleh

Target Fabrication

Brent Blue*, Randy Holt*, Korbie Killebrew*, Diana Schroen*, Robert Stamm*, Kurt Tomlinson

Experiment Execution

Aaron Edens, Mike Lopez, Ian Smith, Jonathon Shores, Verle Bigman, Guy Bennett, Briggs Atherton, Mark Savage, Bill Stygar, Gordon Leifeste, John Porter

with special thanks to the Z center section, Z facility, ZBL facility, VISAR, Z diagnostics, & Z hardware teams

Sandia National Laboratories, Albuquerque, NM, USA

**** General Atomics, San Diego, CA, USA***

LDRD LABORATORY DIRECTED RESEARCH & DEVELOPMENT

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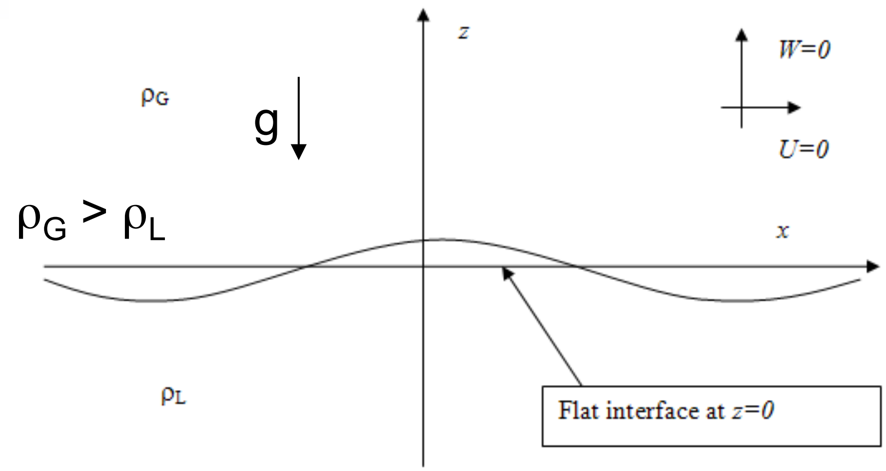
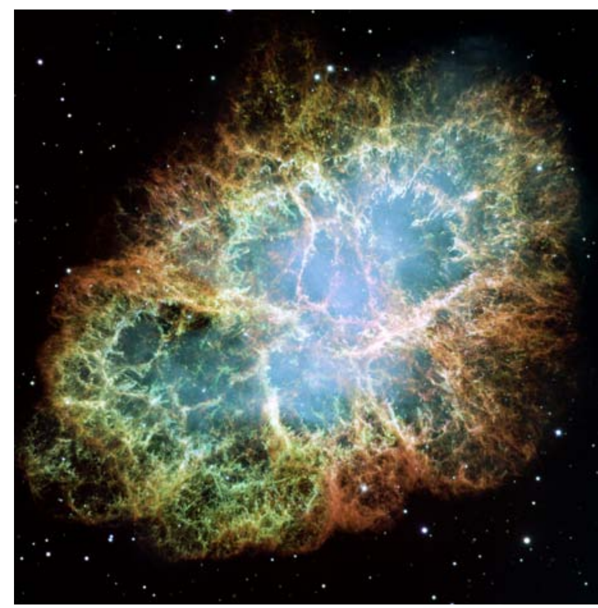
The Rayleigh-Taylor instability develops at the boundary of fluids with dissimilar densities that are under acceleration



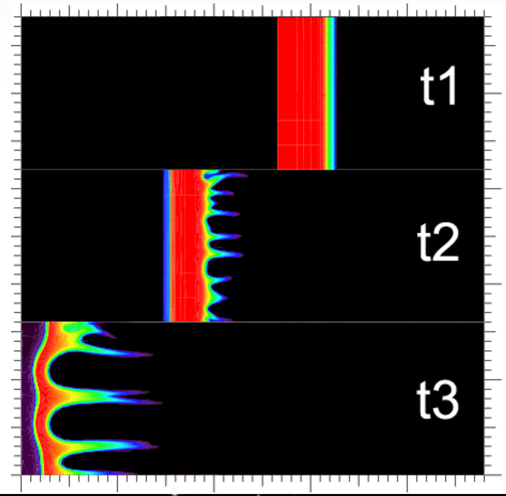
- **RT phenomena are important in astrophysics and inertial confinement fusion (mix)**
- **Numerous laser- and radiation-driven studies of RT in the literature since early 1990s (e.g., B.A. Remington et al.)**

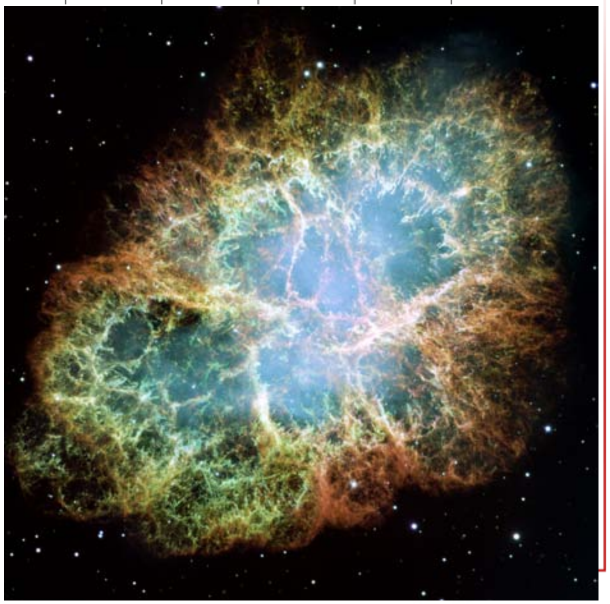


Crab Nebula

The magneto-Rayleigh-Taylor instability occurs in magnetically-driven systems and is more complex than classical RT

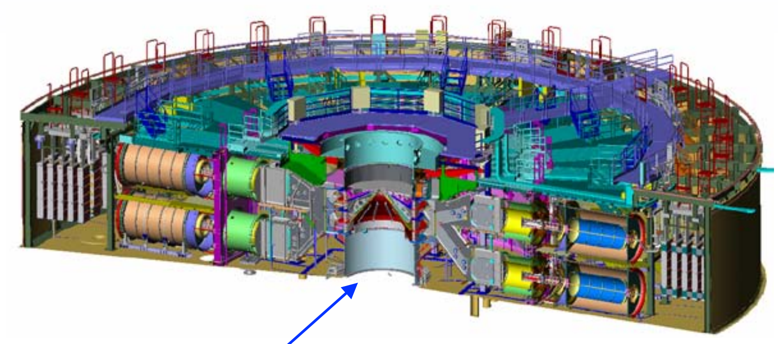
- **Magnetic field plays role analogous to the "light fluid" pushing on a "heavy" plasma**
- **In real materials with finite conductivity, the current diffuses into the plasma**
  - **Distributed magnetic pressure**
  - **Local plasma heating & ablation**
- **Some groups claim Crab Nebula structure is due to MRT rather than just RT [J.J. Hester et al., Astrophysical J. (1996)]**
- **Almost no data exists in the literature that can be used to validate our simulation tools (e.g., LASNEX, HYDRA, GORGON)**
  - **100 ns modulated wire array experiments (B. Jones et al., PRL, 2005)**
  - **6-10 μs solid liner experiments on PEGASUS (Reinovsky et al., IEEE Trans. Plasma Sci. 2002)**

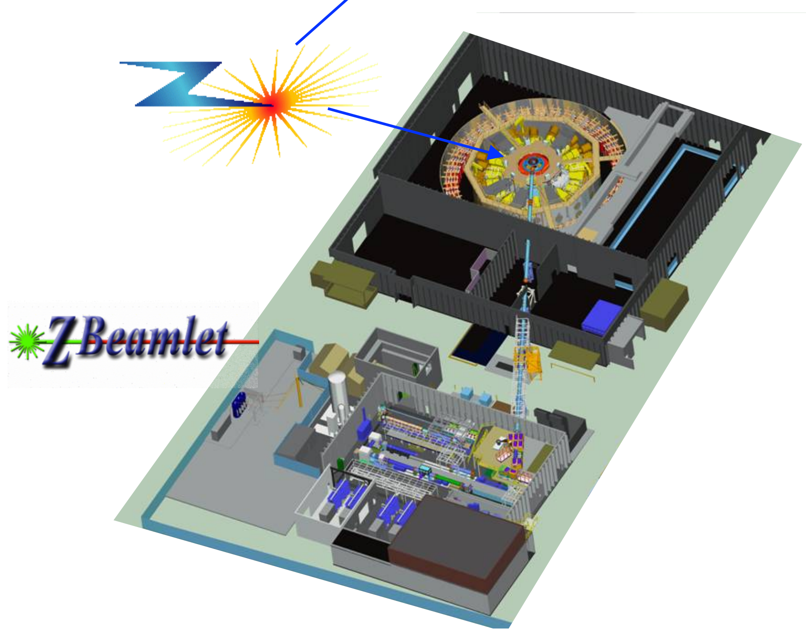


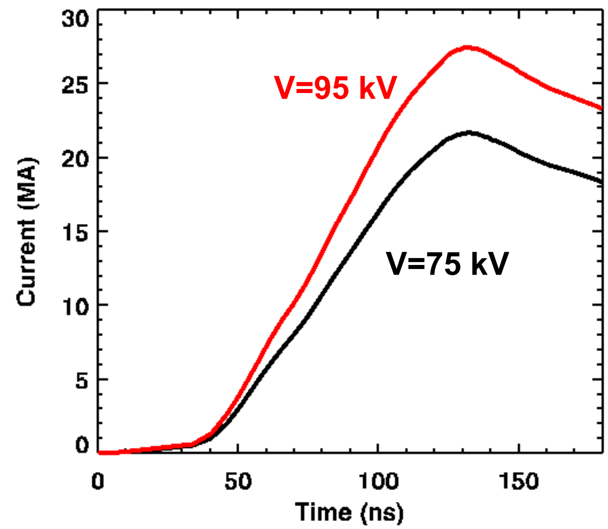


Crab Nebula

The Z facility contains the world's largest pulsed power machine and the Z-Beamlet and Z-Petawatt lasers







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

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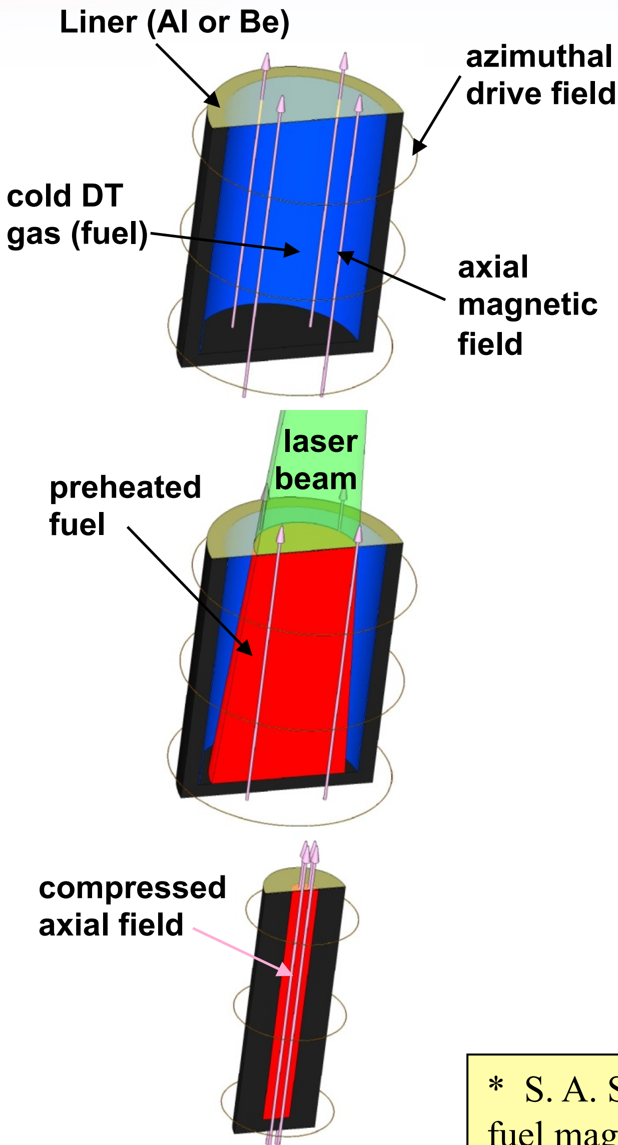
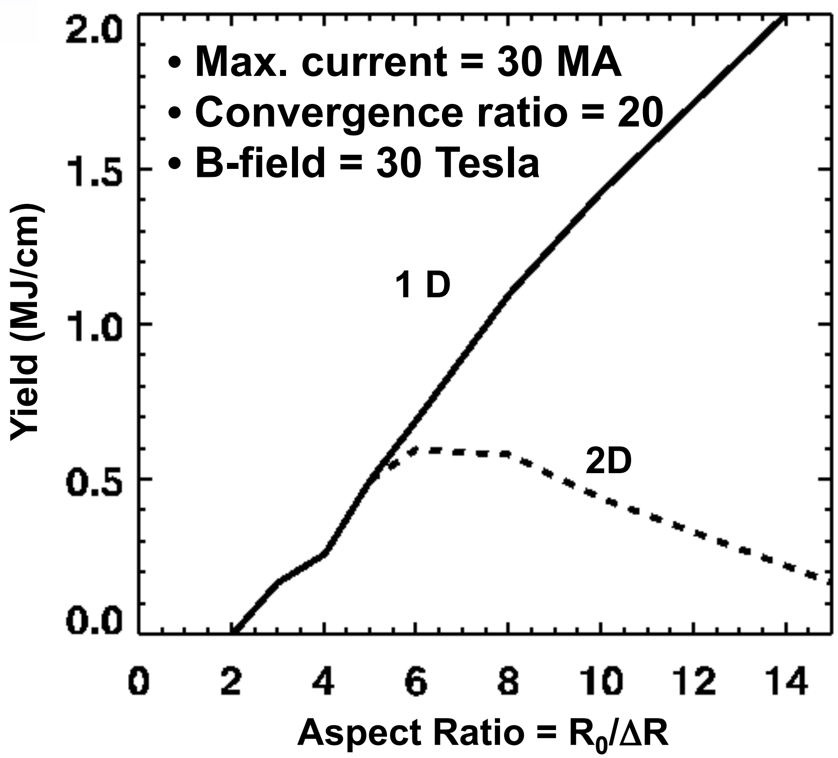
We are working toward an evaluation of a new Magnetized Liner Inertial Fusion (MagLIF)* concept

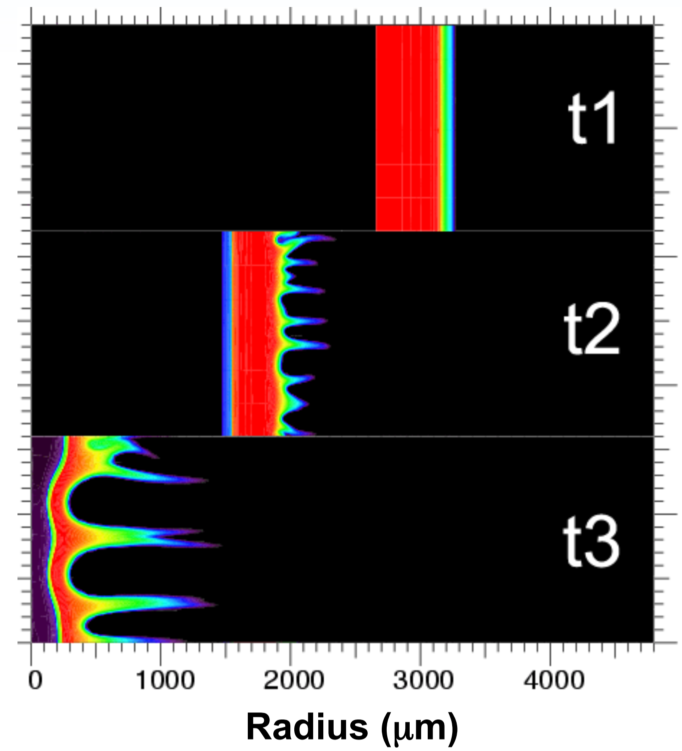


- Idea: Directly drive solid liner containing fusion fuel
- An initial ~10 T axial magnetic field is applied
  - Inhibits thermal conduction losses
  - Enhances alpha particle energy deposition
  - May help stabilize implosion at late times
- During implosion, the fuel is heated using the Z-Beamlet laser (<10 kJ needed)
  - Preheating reduces the compression needed to obtain ignition temperatures to 20-30 on Z
  - Preheating reduces the implosion velocity needed to about 10 cm/μs (slow!)
- Simulations suggest 100 kJ yields on Z possible
- The biggest concern with the concept is whether we can maintain sufficient liner integrity until stagnation
  - Slow velocity allows thick liners (aspect ratios ~6) in which the magneto-Rayleigh-Taylor instability growth on outside not predicted to break through
- How accurate are these MRT growth calculations?

* 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).

There is an optimum liner aspect ratio when the magneto-Rayleigh-Taylor instability is accounted for

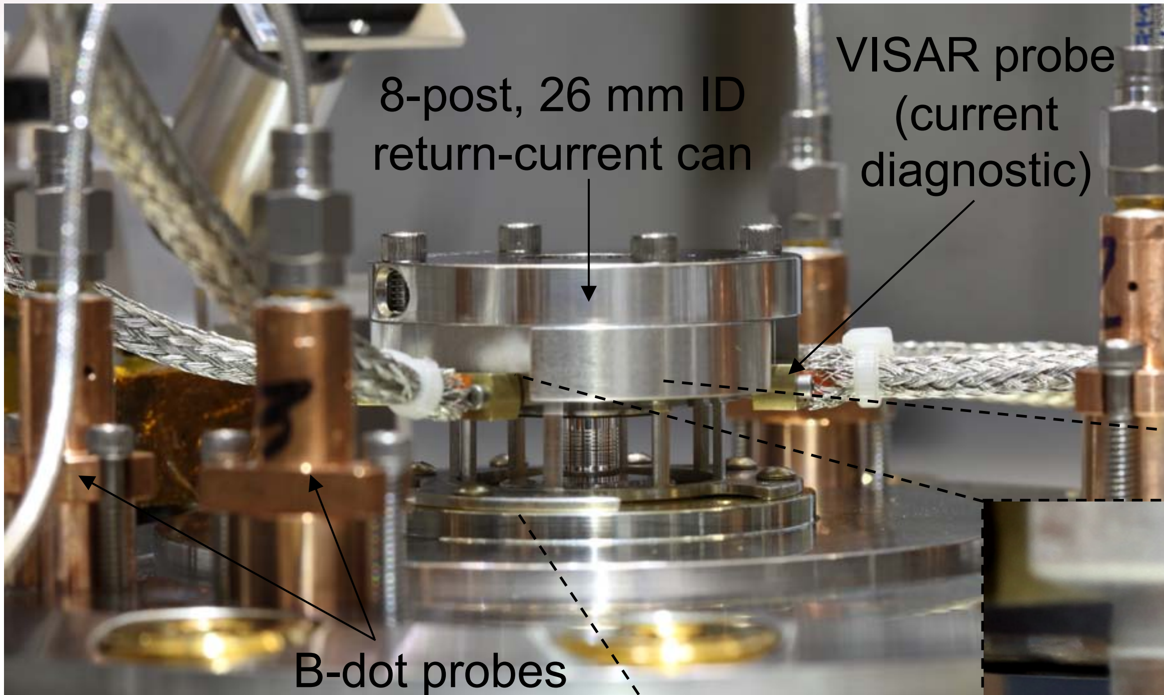


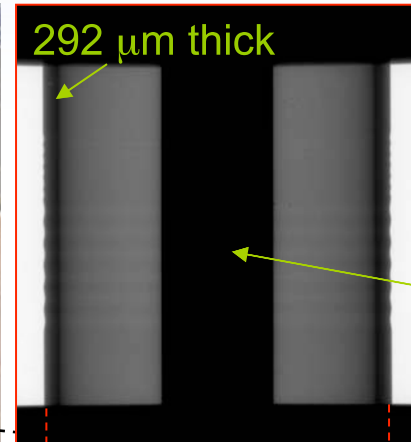


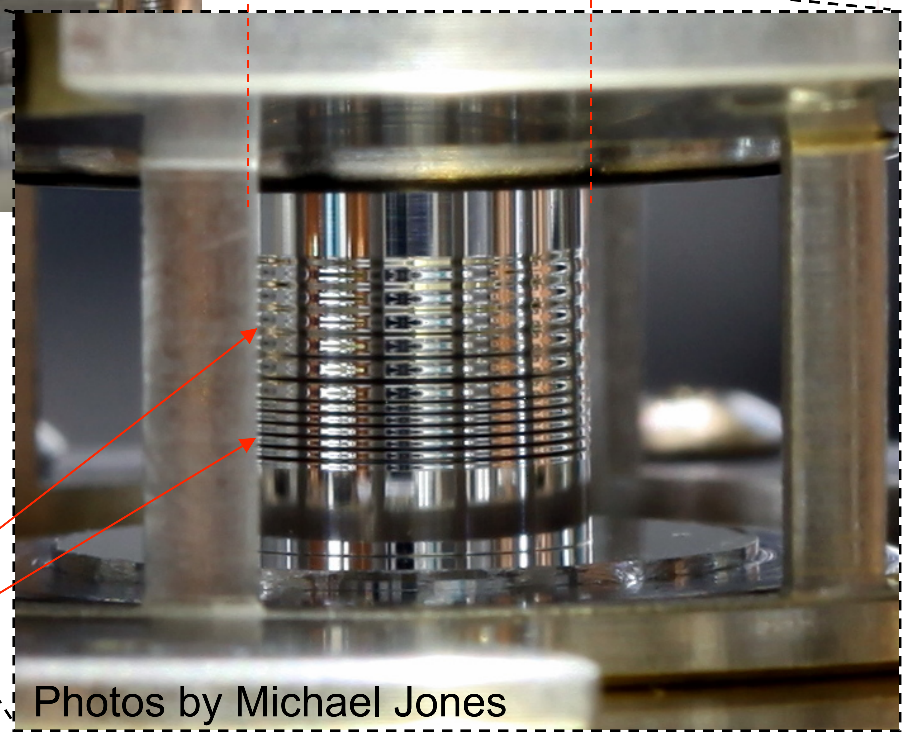
- The Magneto-Rayleigh-Taylor instability degrades the yield as the aspect ratio is increased due to decreased liner ρr
- High resolution 2D and 3D simulations are needed

- 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

Al liners with sinusoidal perturbations (λ=200, 400-μm) were fielded on five Z experiments



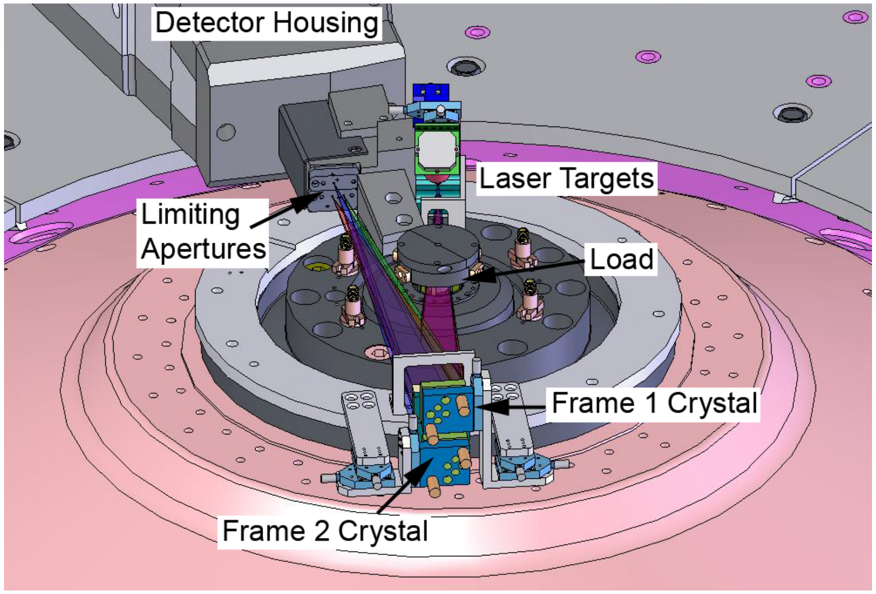




- Solid cylindrical liner (Al 1100 alloy)
- 6.5 mm tall, 6.34 mm diameter, AR=10
- 10 nm surface finish (diamond-turned)
- 12 sinusoidal perturbations:
  six 400-μm wavelength, 20-μm amplitude
  six 200-μm wavelength, 10-μm amplitude

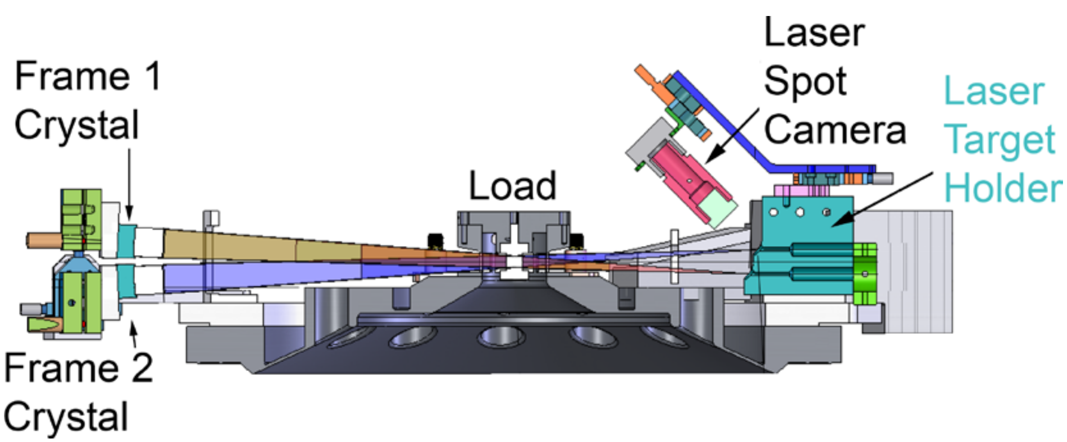
Targets made by General Atomics

Experiments used 2-frame 6.151 keV monochromatic crystal backlighting diagnostic



<u>2-frame 6.151 keV Crystal Imaging</u>

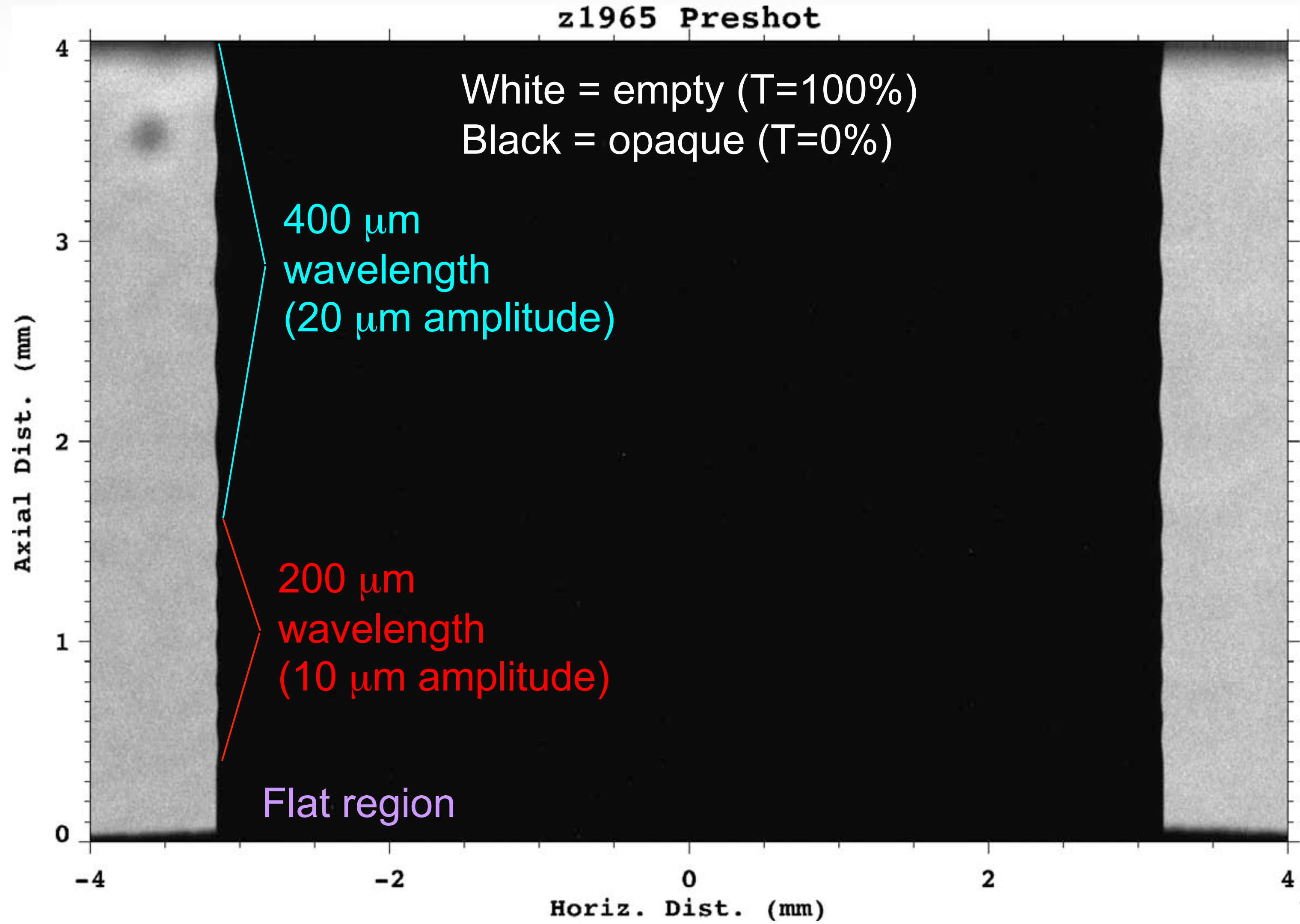
- **Monochromatic (~0.5 eV bandpass)**
- **15 micron resolution (edge-spread)**
- **Large field of view (10 mm x 4 mm)**
- **Debris mitigation**



Radiograph lines of sight ±3° from horizontal

- **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)



Note radiograph cropped slightly--horizontal field of view is 10 mm wide

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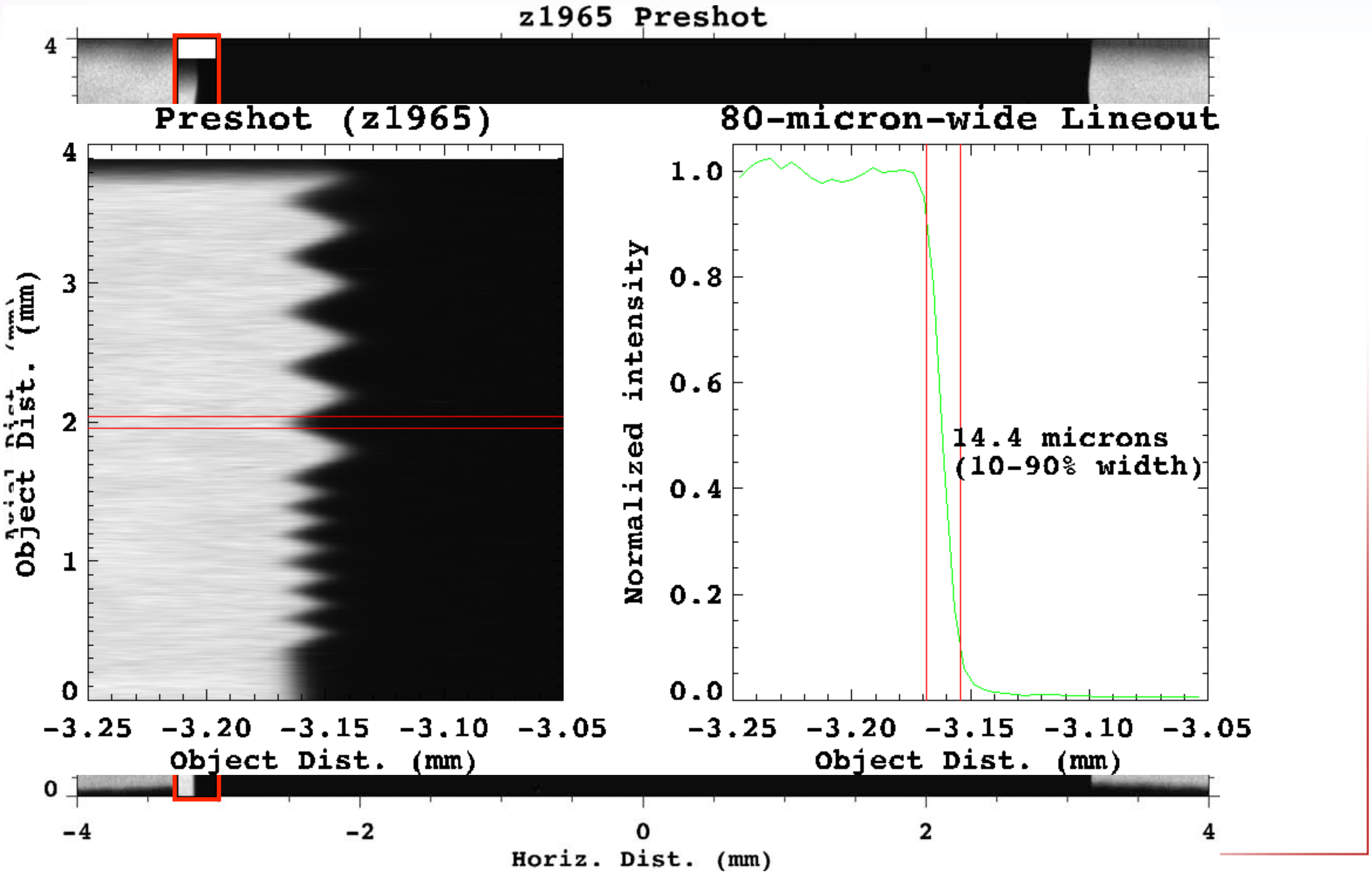
The 6.151 keV radiographs have 15 μm spatial resolution



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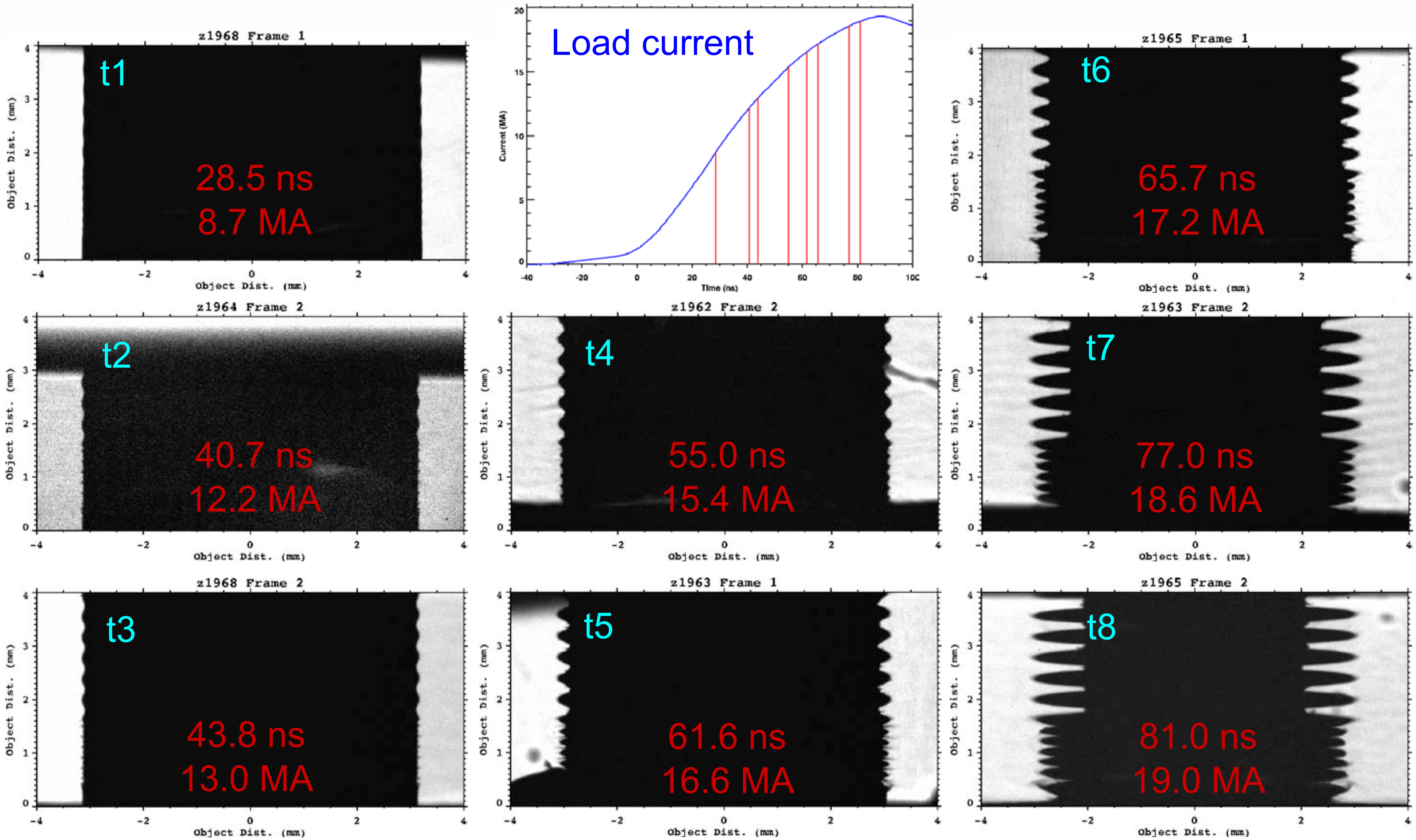
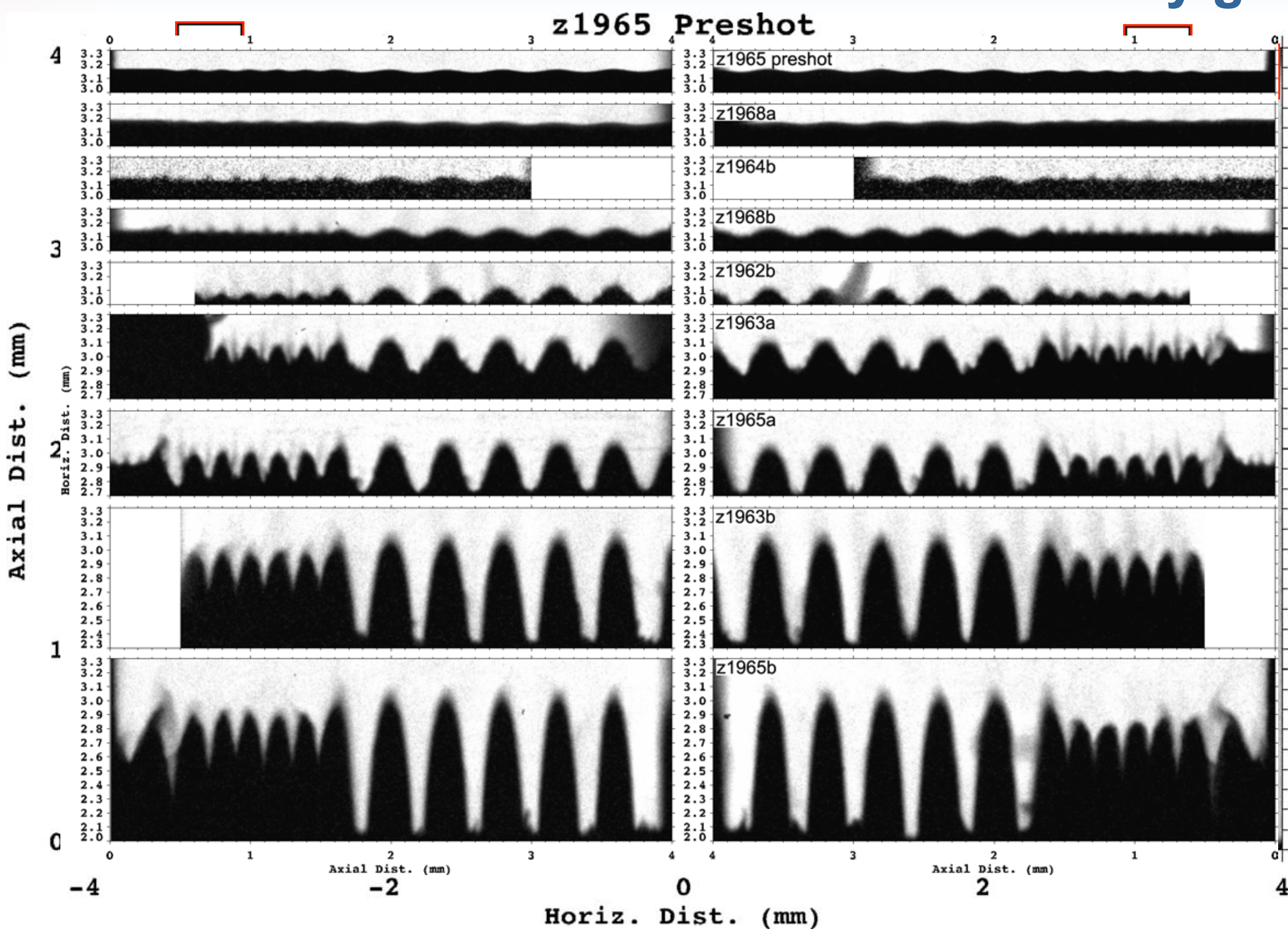
Reproducible drive currents (±1.5%) and liners enabled an 8-frame movie to be obtained over 5 shots



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



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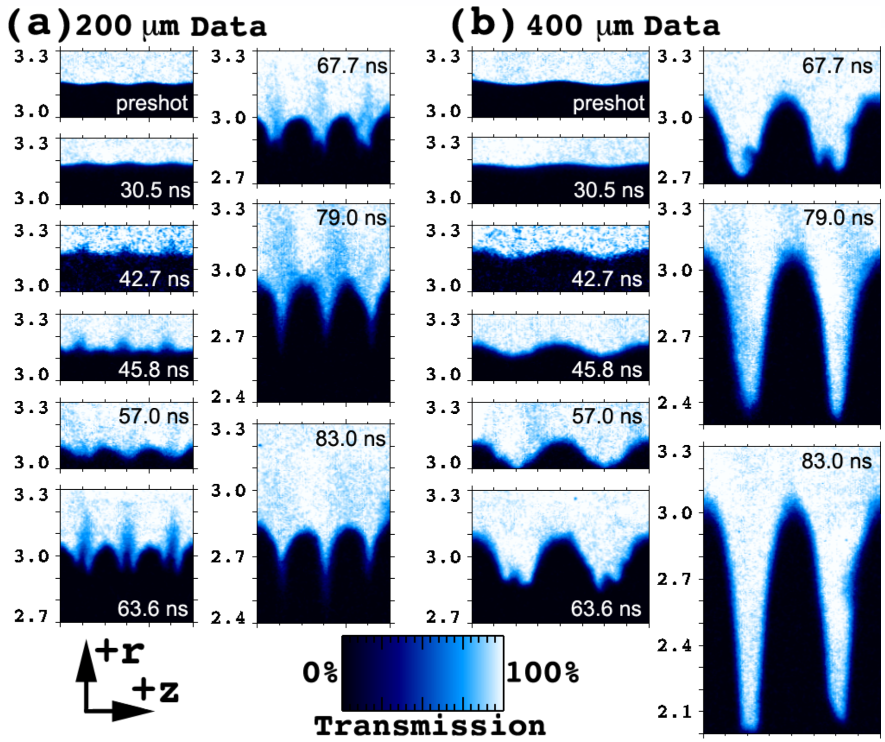
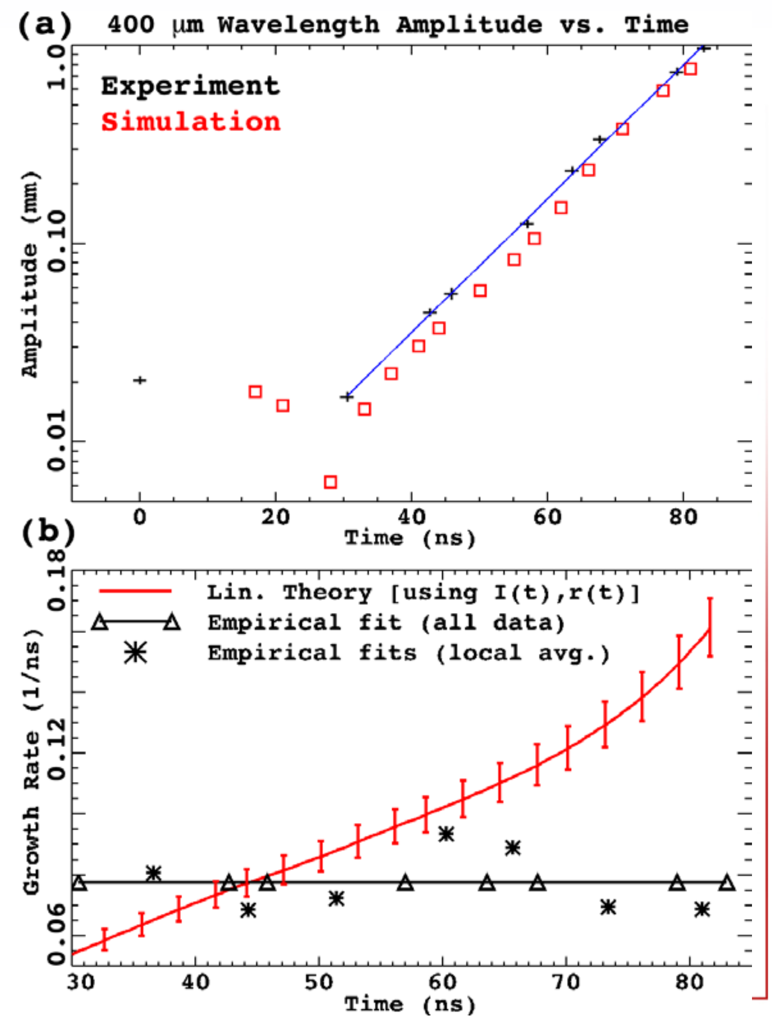
The data is being used to benchmark our modeling & simulation tools





Growth rate from linear theory

$$\Gamma^2 = kg$$

Calculate g using I(t), R(t) (red)

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

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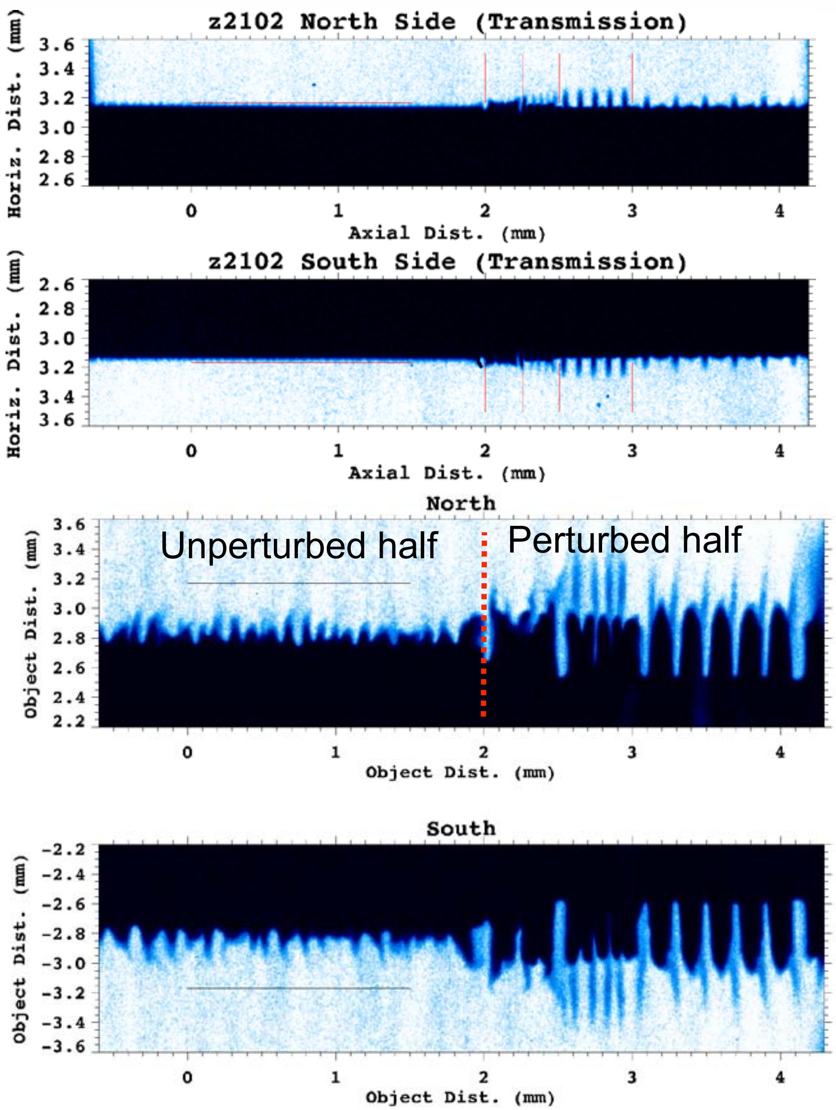
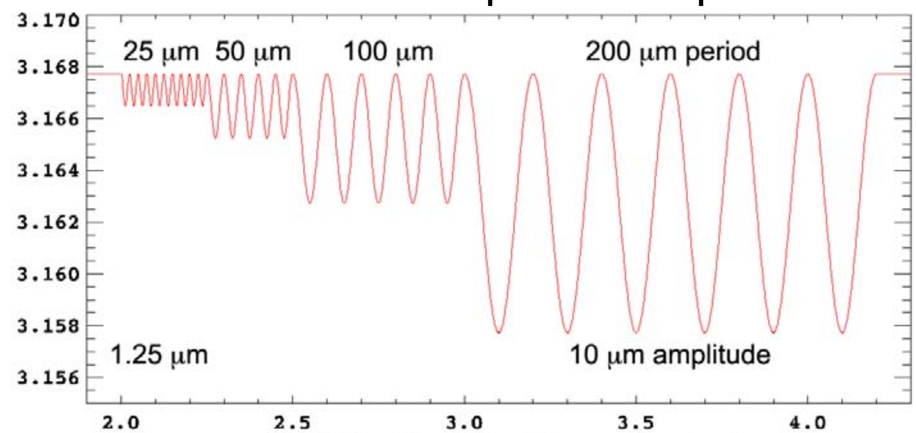
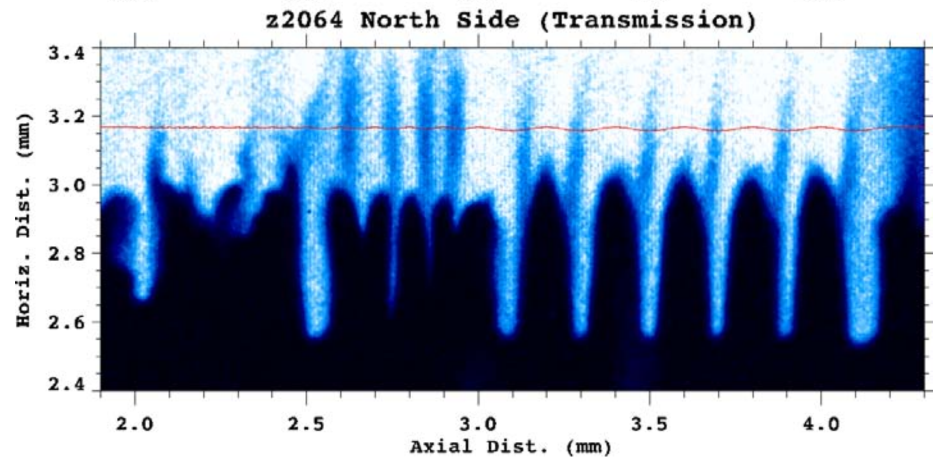
Two additional images were obtained using 1-frame, 0° backlighter of unperturbed regions and regions seeded with small (λ=25-200 μm) perturbations



Distorted aspect ratio plot





All regions have ~30 nm surface roughness with 1.25 μm axial period (due to machining)

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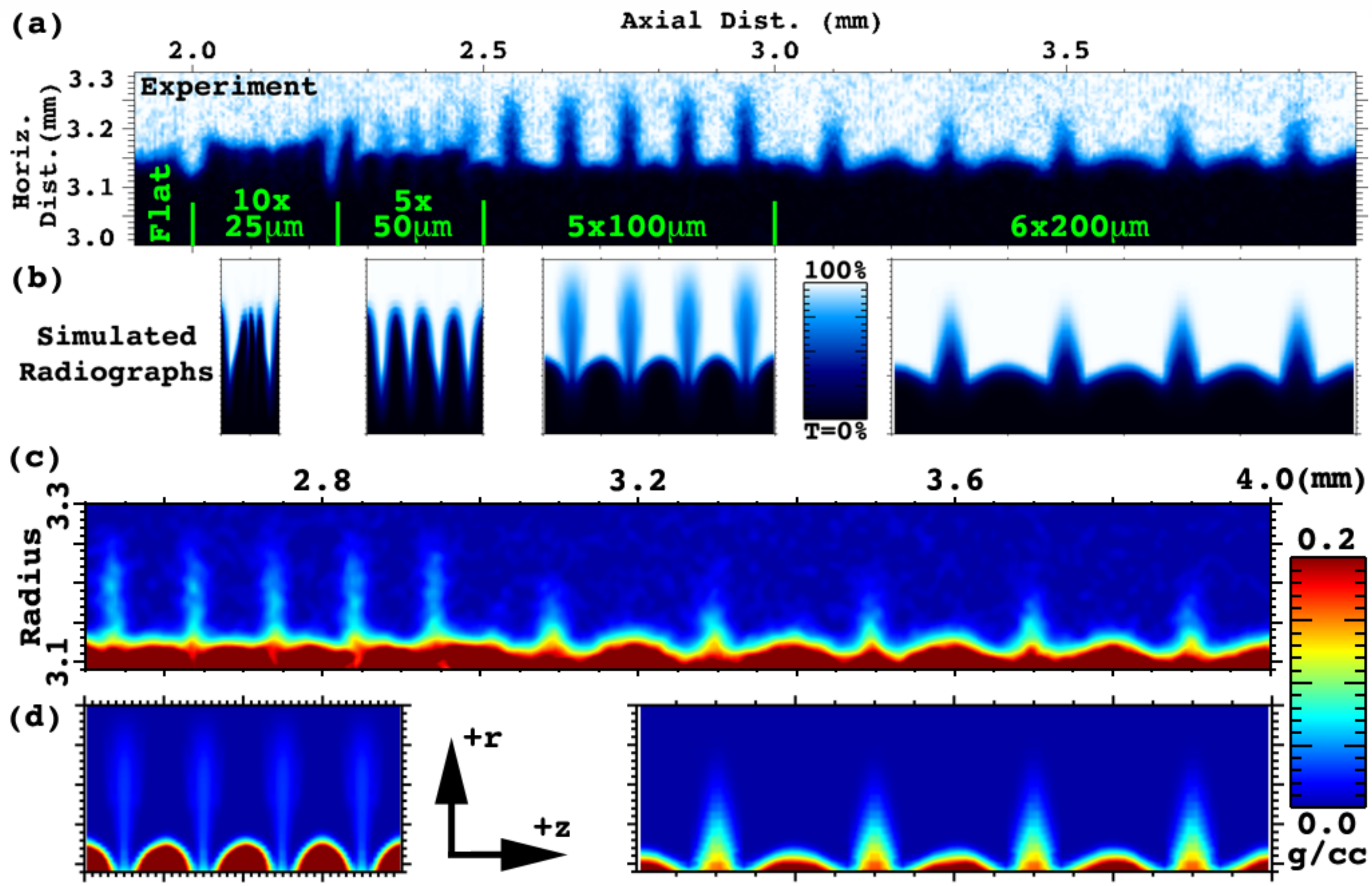
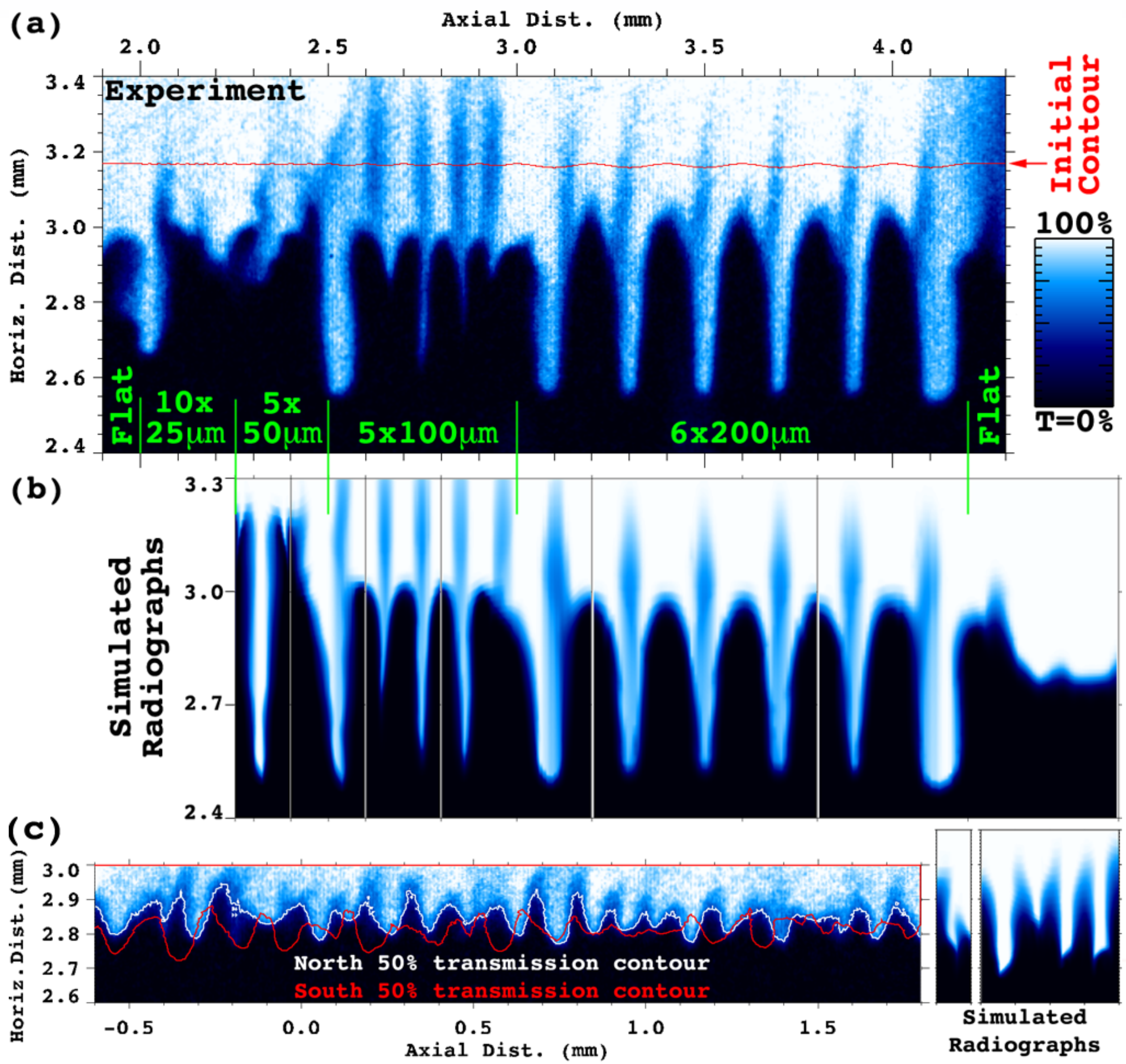
Our LASNEX simulations capture the ablation and jetting well down to ~50 μm wavelength scales



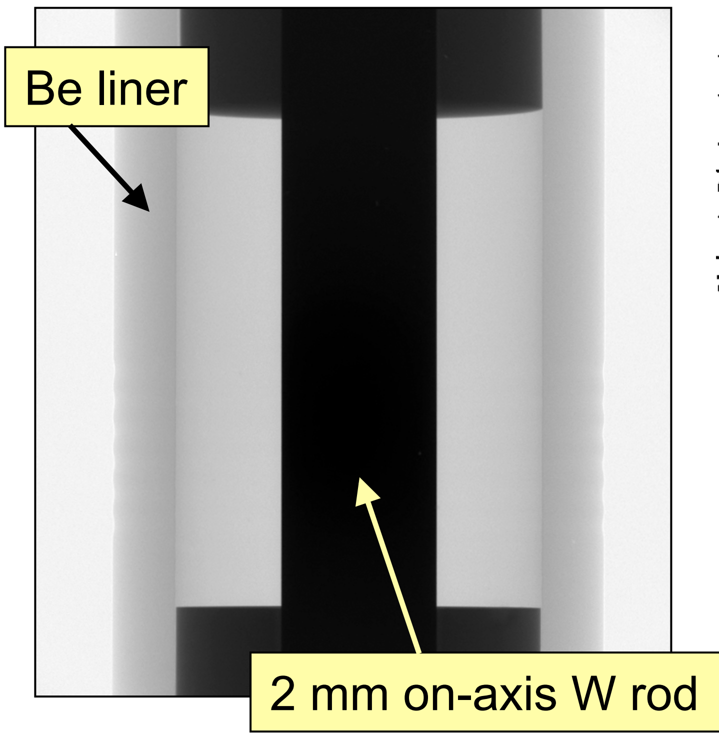
Note: We have not matched these features in HYDRA or GORGON yet

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



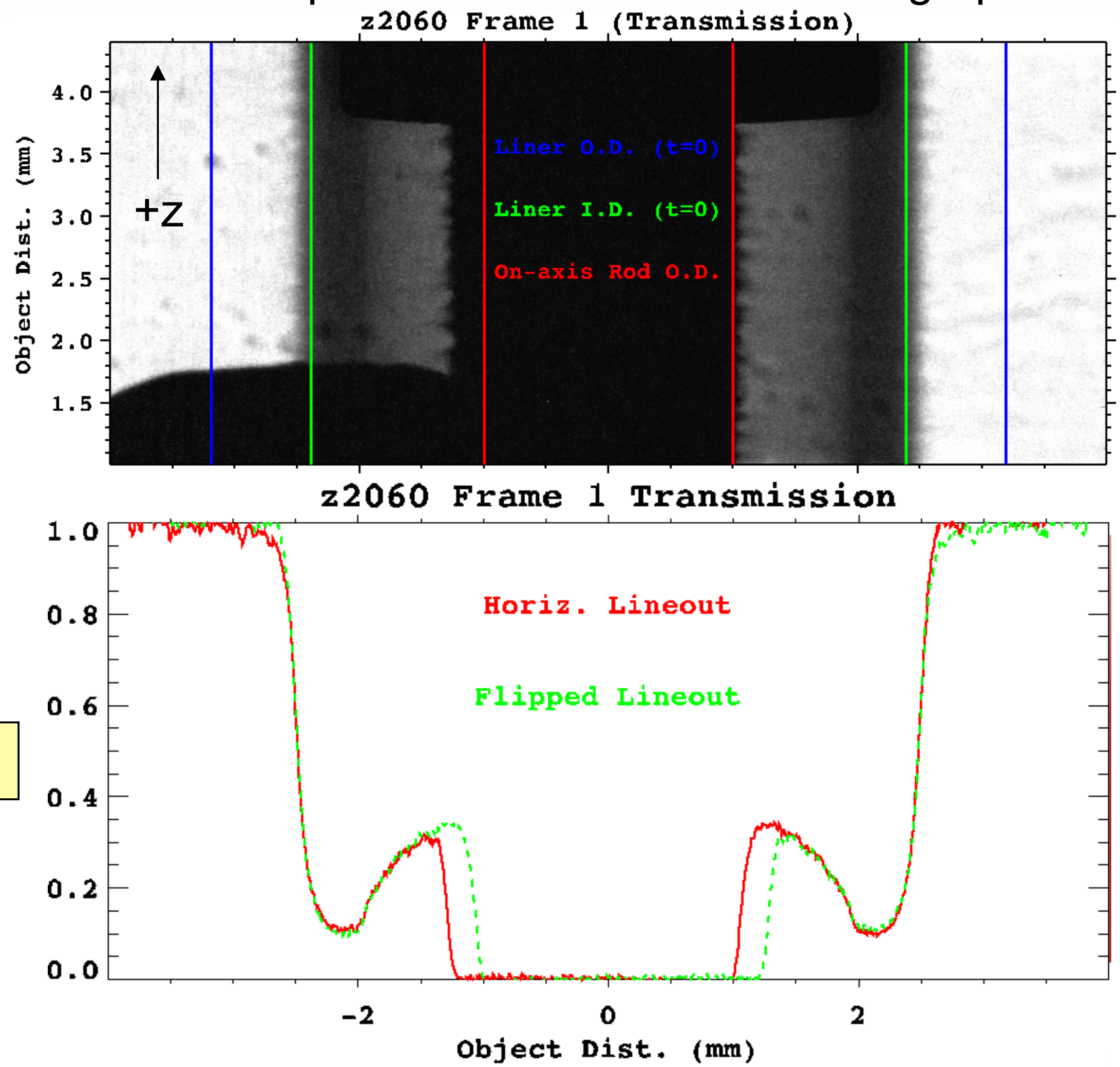
Penetrating 6.151 keV radiographs of Be liners allow us to observe both the inner and outer liner surfaces

Preshot 59 keV radiograph



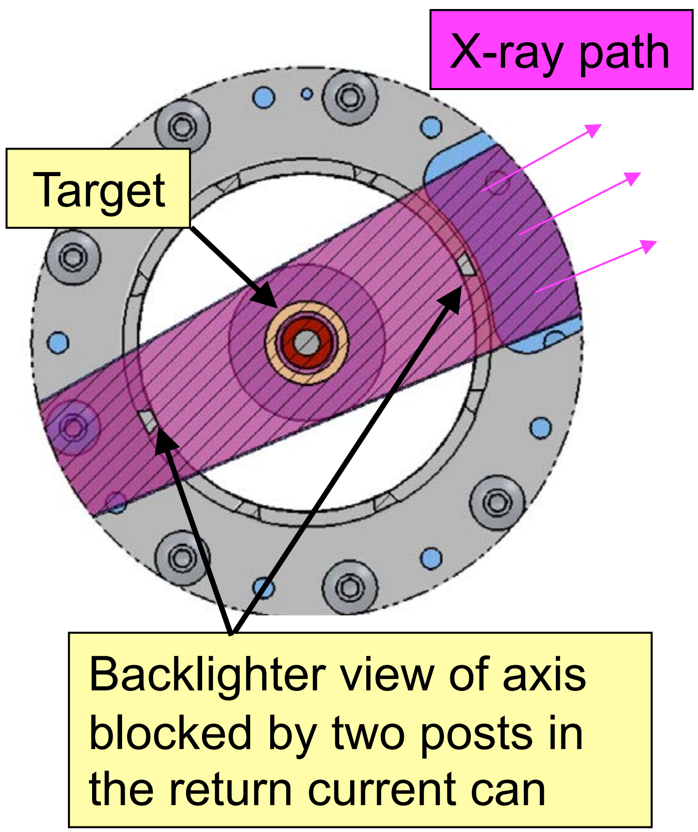
Be liner, $R_{out}/\Delta R=4$

Example downline 6.151 keV radiograph

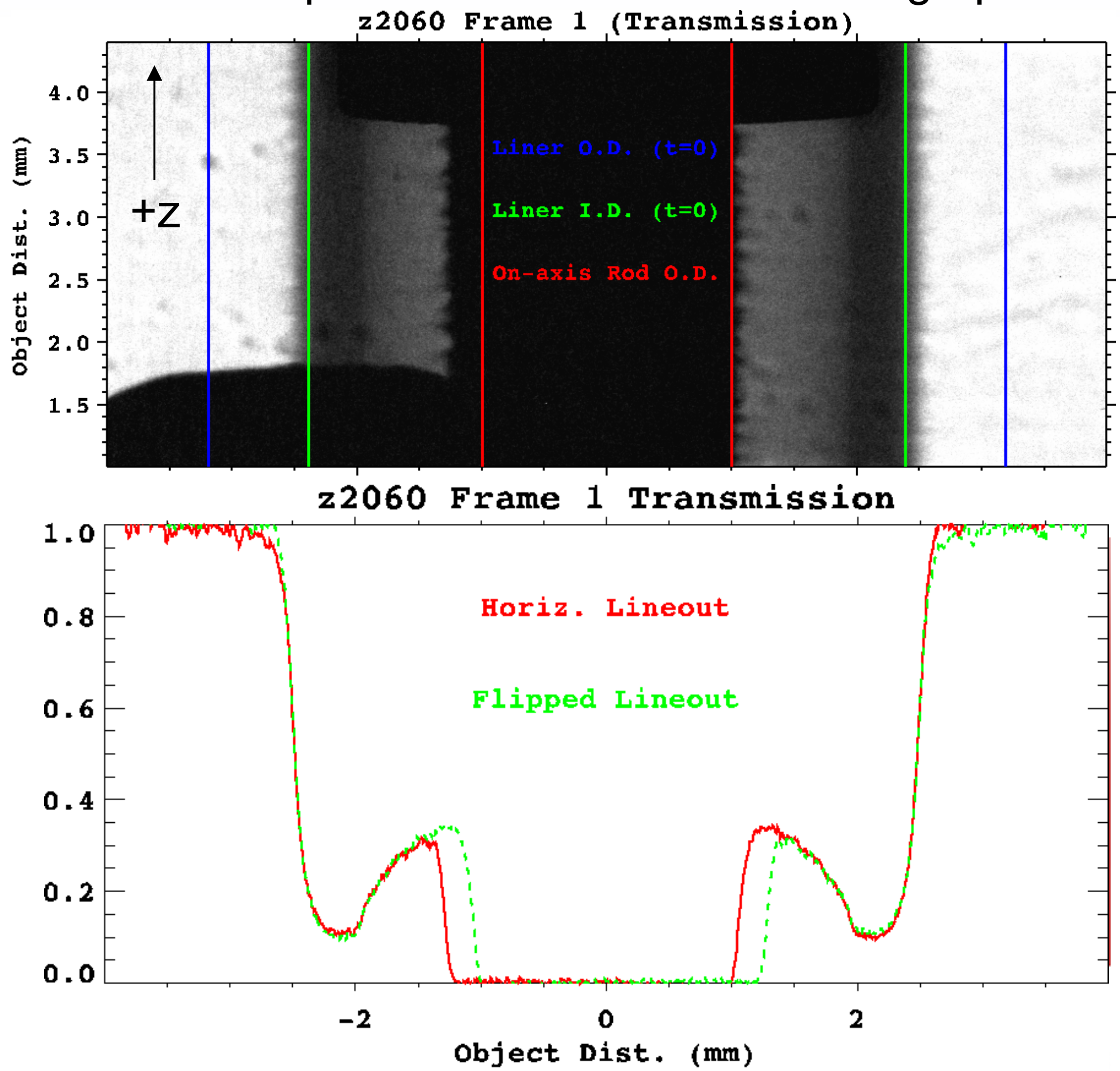


Penetrating 6.151 keV radiographs of Be liners allow us to observe both the inner and outer liner surfaces

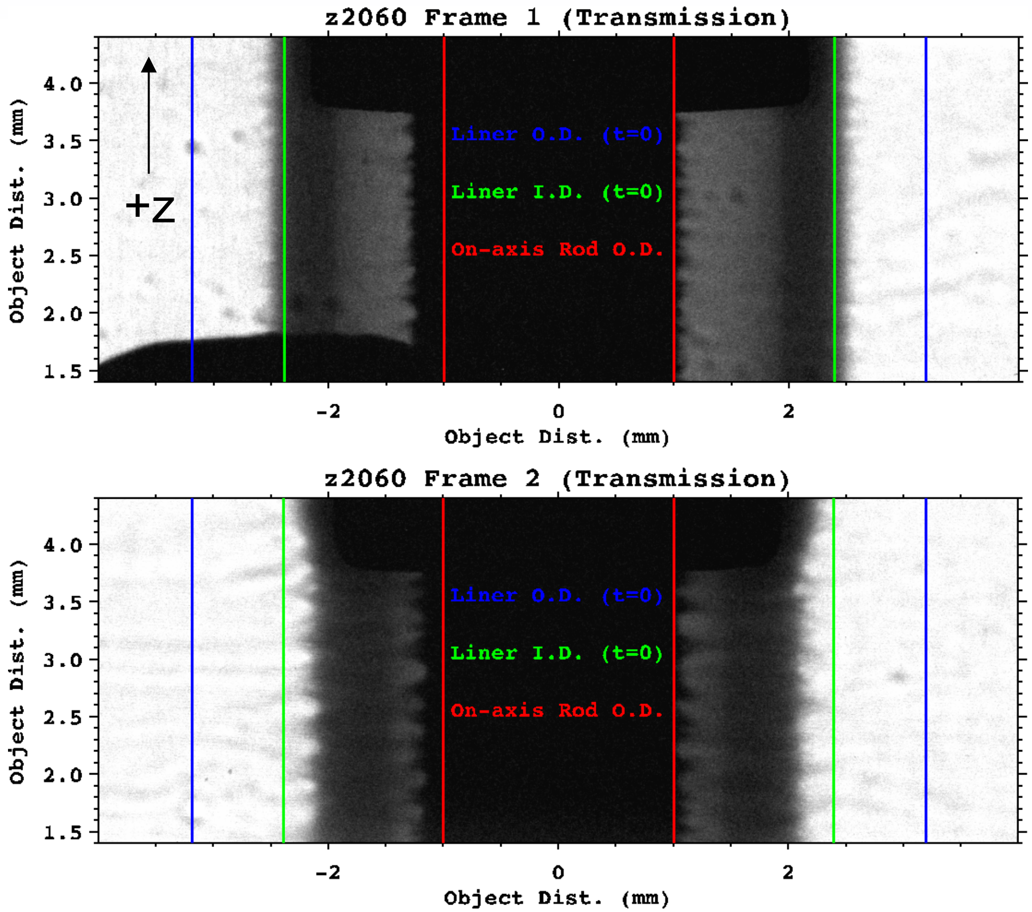
Top-down view of x-ray path through load region

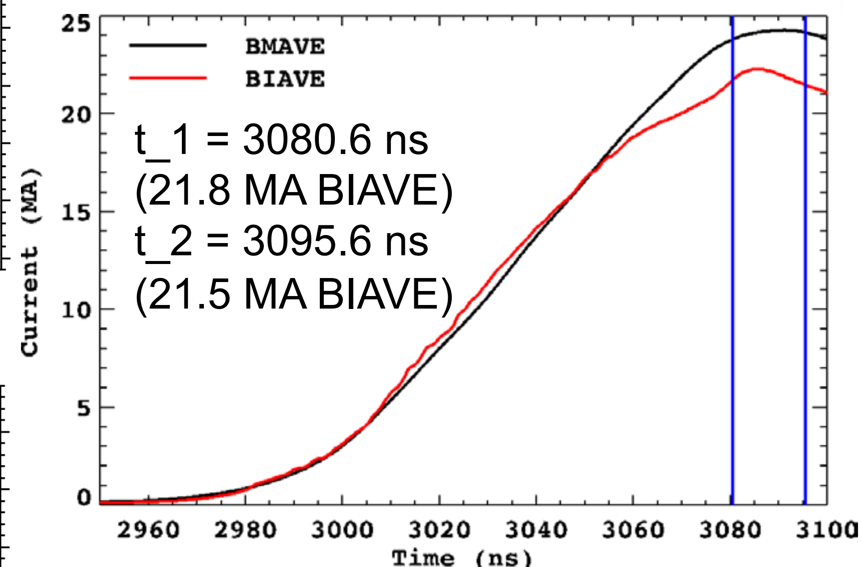


Example downline 6.151 keV radiograph

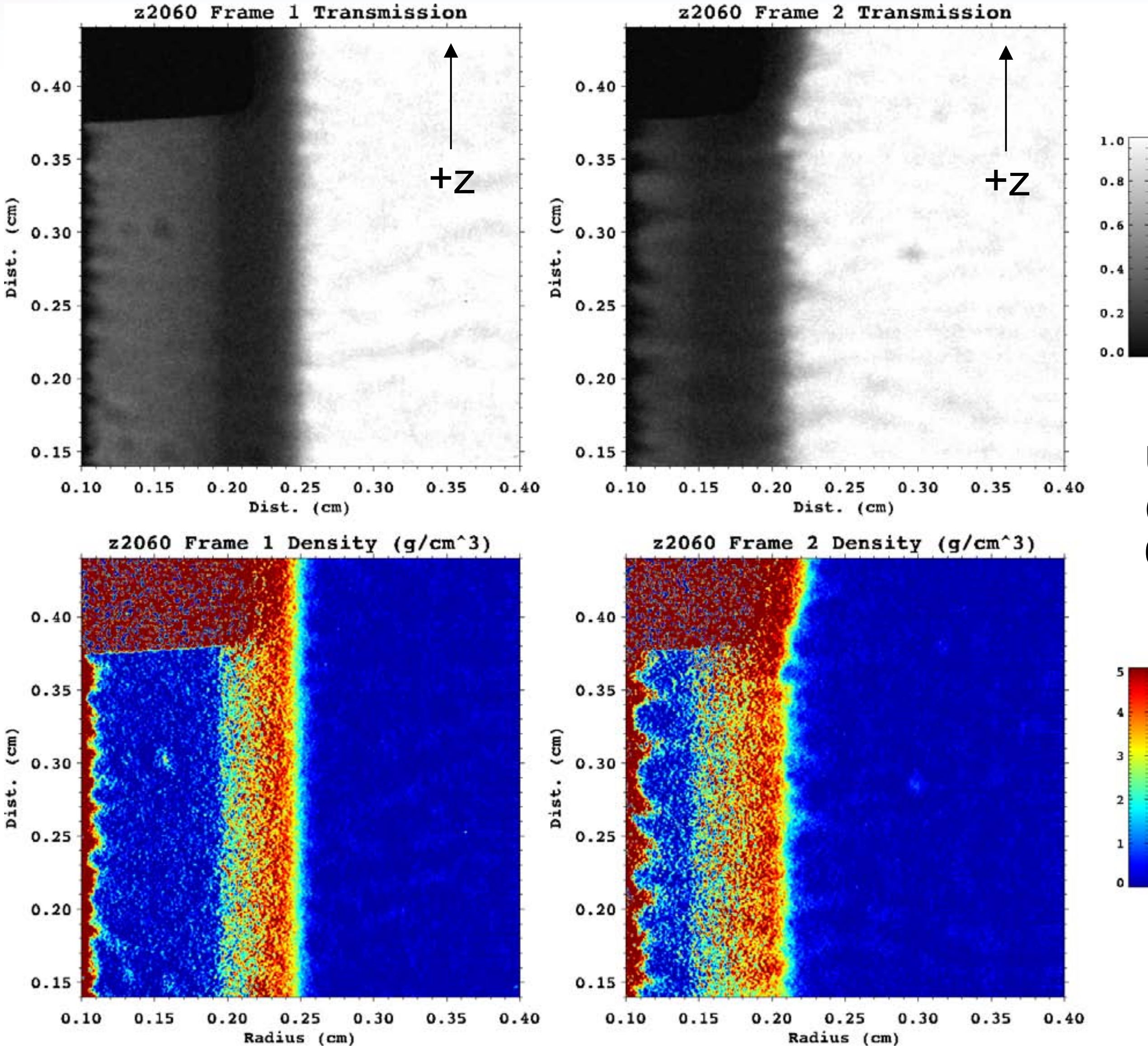


We obtained two images of a Be liner during the implosion with finite transmission everywhere





Each horizontal line through the radiographs was Abel-inverted to provide a density map



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

Note inner radius of liner appears relatively uniform

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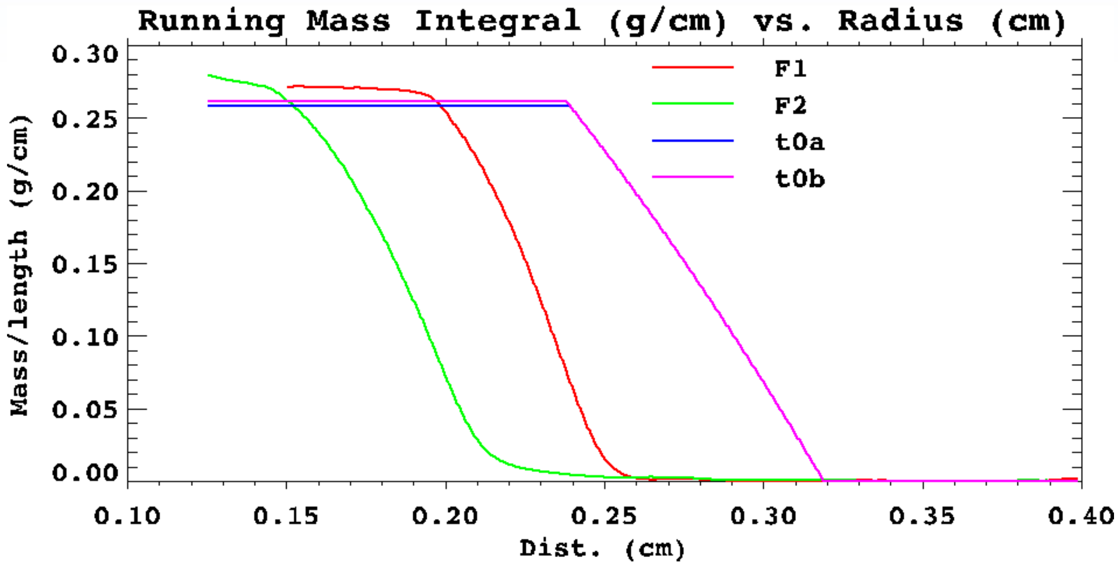
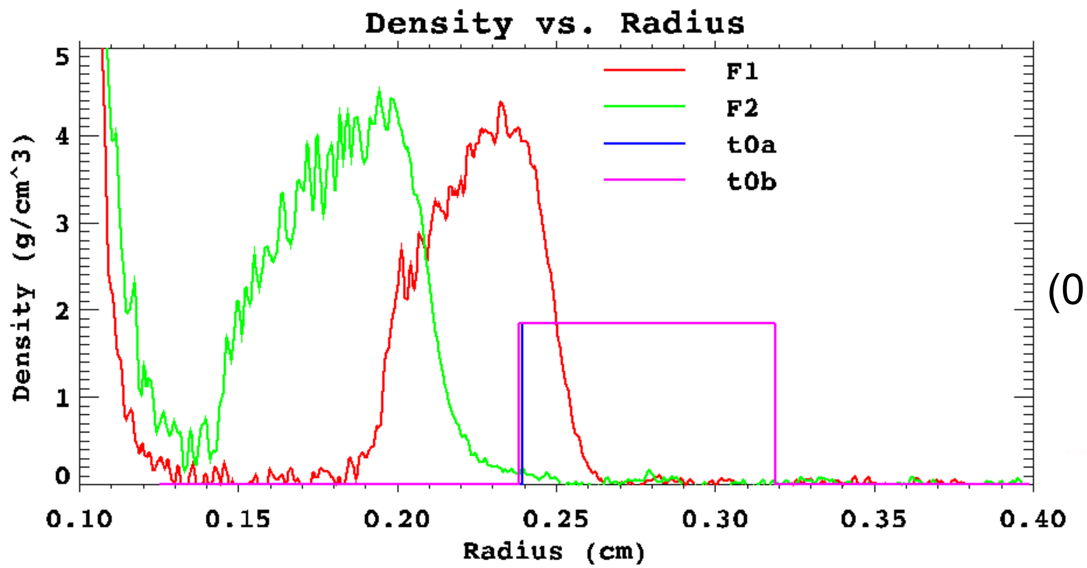
The results of the Abel inversion are consistent with the initial mass/length of the liner, show ρmax~4.1 g/cc





(0.8 mm tall lineouts)

The high-quality data we have obtained to date is serving as a useful benchmark for future calculations

- We have obtained the first high-quality radiography data of solid liner implosions driven by <1 μsecond generators
- The data show significant ablation and jetting features during the earliest stages when linear MRT theory might otherwise apply
- The data is of sufficient quality that it can be (and has already been) used to benchmark Magneto-Hydrodynamic codes (e.g., LASNEX, HYDRA, GORGON, etc.)
- Comparisons against LASNEX simulations
  - Can capture many of the large-scale details of the MRT growth
  - At smallest scales (~50 μm or less) the agreement is worse (due to perfect 2-D symmetry and/or shorting?)
  - How important is it to capture smallest-wavelength scales?
- Recent Be liner data demonstrates that it should be possible to measure the liner integrity and make comparisons between the simulated and experimental areal density.

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Our success so far in modeling the MRT instability gives us hope that MagLIF predictions are reasonable

- So far we have not collected data that grossly contradicts our MagLIF calculations
- We have started collecting data with Be liners with aspect ratios in the range of 4-13 to further test the models
- Pulsed coils for >10 T operation have been designed and will be prototyped in late 2010, early 2011
- We also plan to work on laser preheat experiments using ZBL
- We would like to work toward integrated experiments in 2012