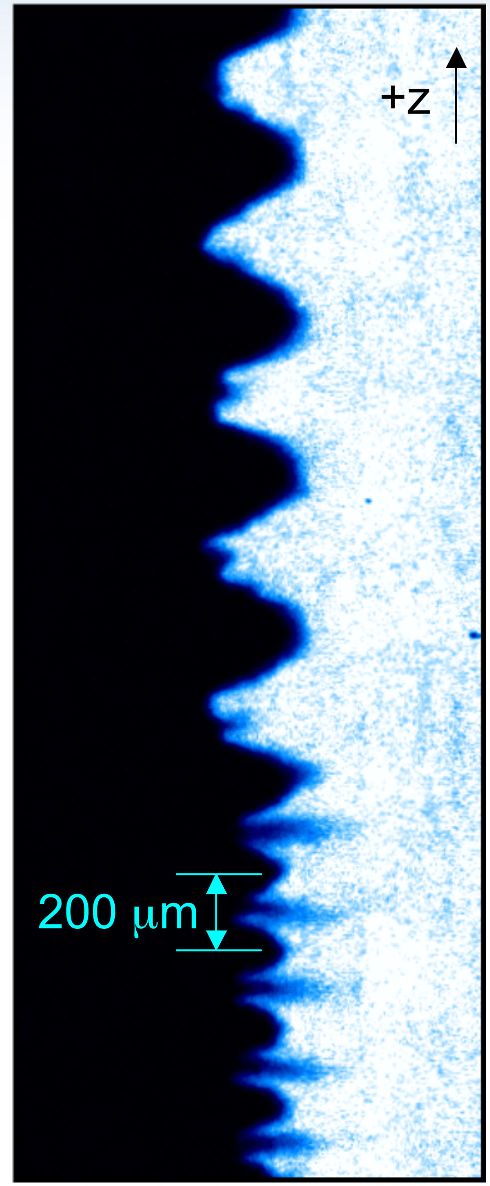
ICOPS 2010 Meeting, Norfolk, VA June 21-24, 2010
SAND 2010-6966C

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



Experiment Design, Planning, and Analysis

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

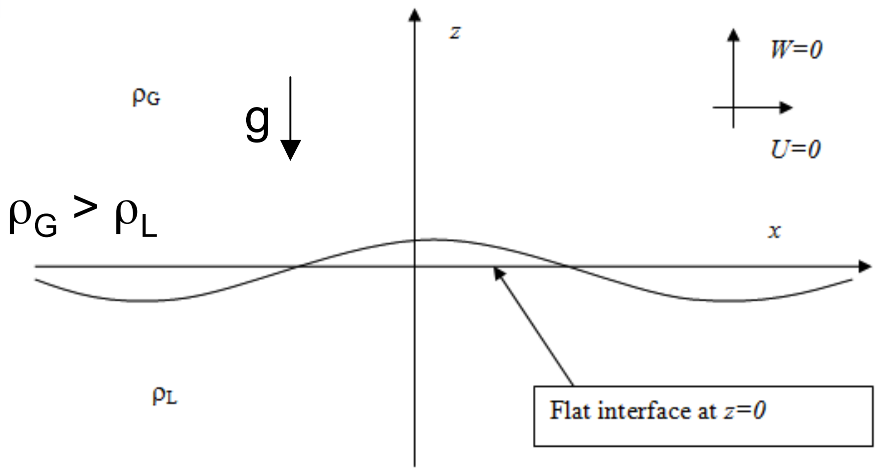
Sandia National Laboratories, Albuquerque, NM, USA

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

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Problem

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 by the labs since early 1990s (e.g., B.A. Remington et al.)**

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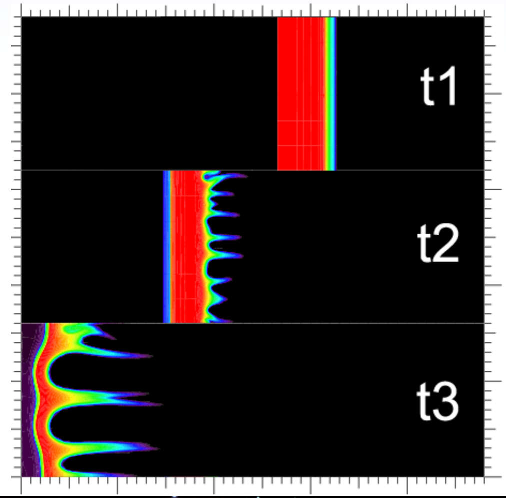
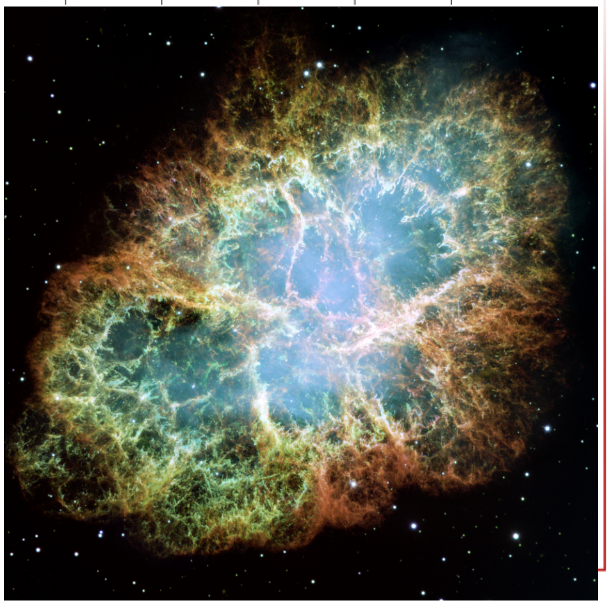
Problem

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

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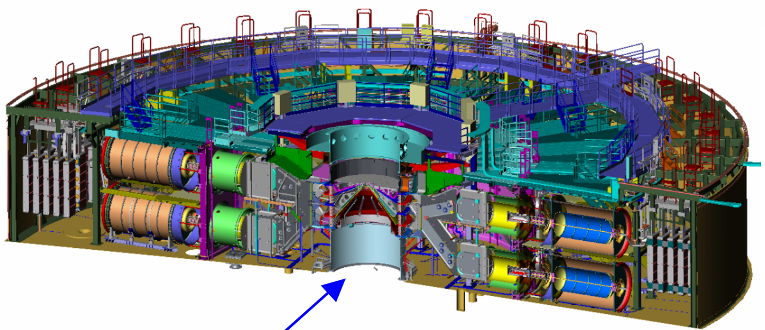
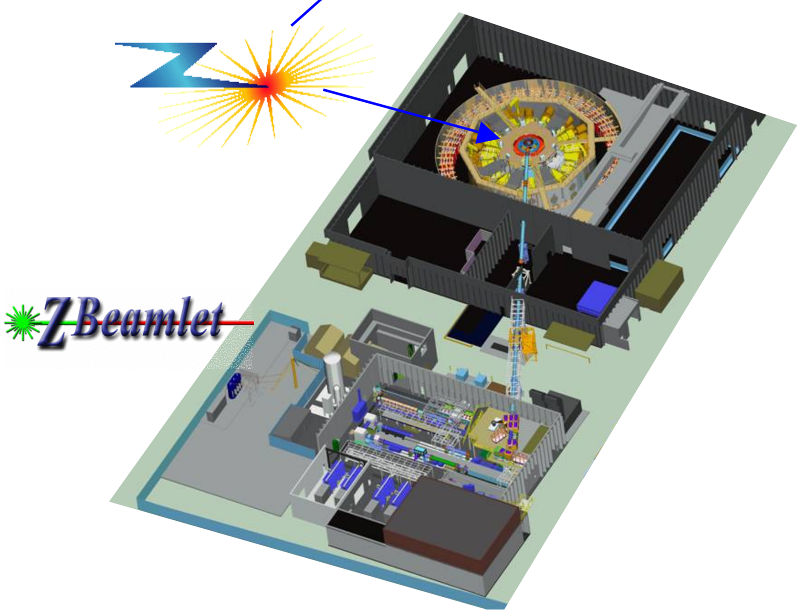
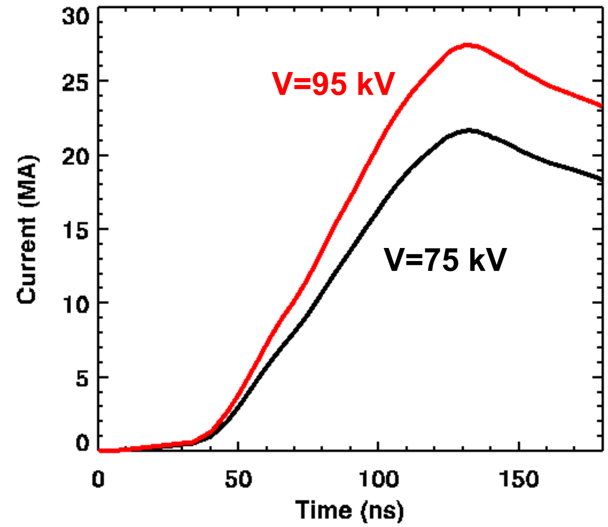
Magnetically-driven liners on Z can be used to create extreme conditions in the laboratory that are relevant to stockpile stewardship







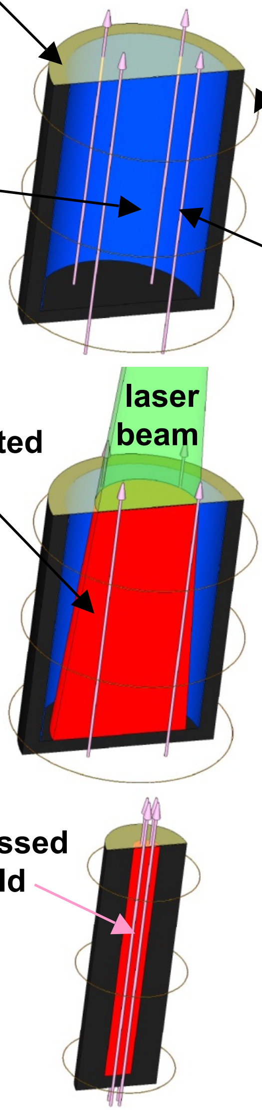
Magnetically-Driven Cylindrical Implosion

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

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

Problem

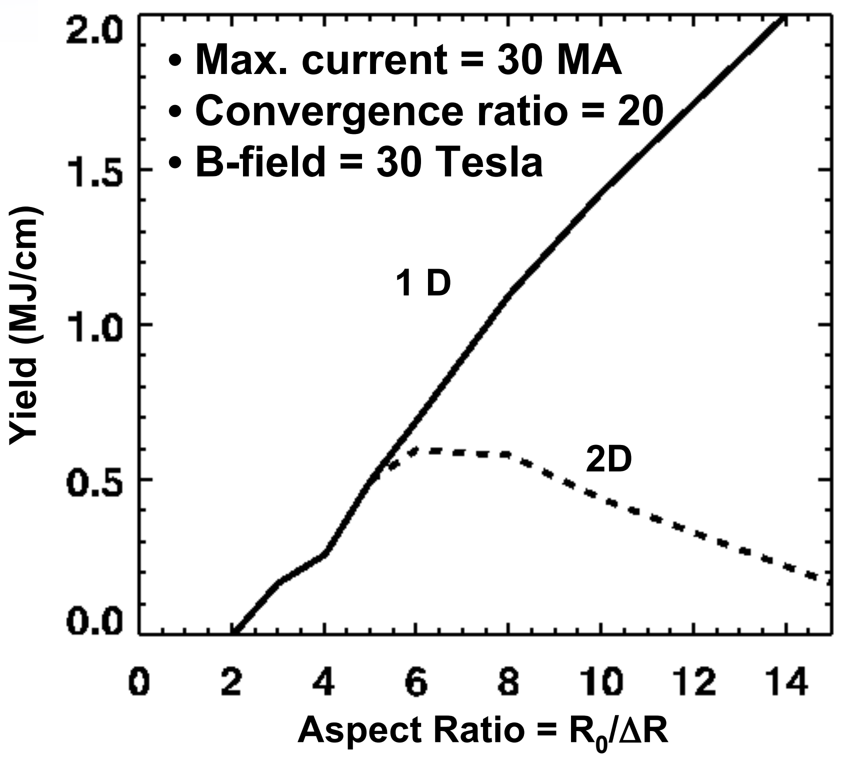
We are working toward an evaluation of a new Magnetized Liner Inertial Fusion (MagLIF)* concept

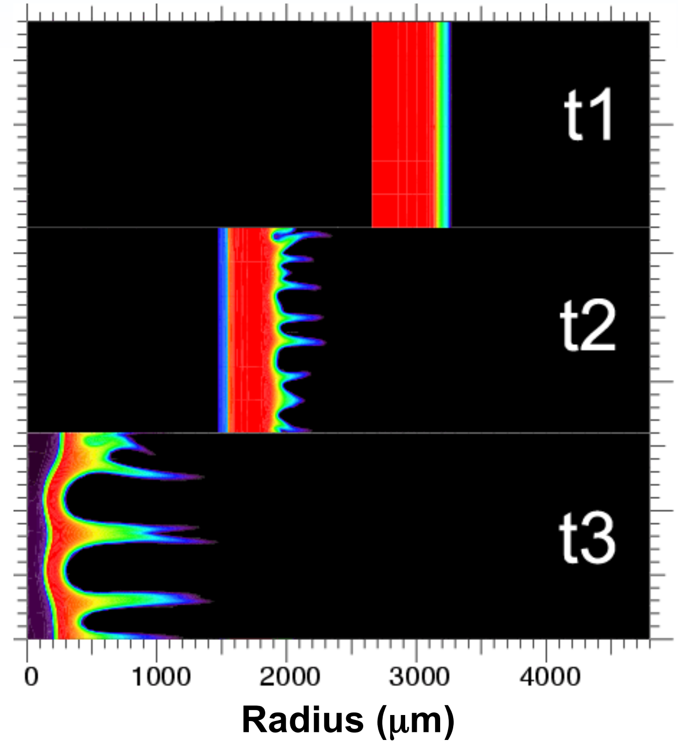


- Idea: Directly drive solid liner containing fusion fuel
- An initial ~10 T axial magnetic field is applied
  - Inhibits thermal conduction losses
  - Enhances alpha particle energy deposition
  - May help stabilize implosion at late times
- During implosion, the fuel is heated using the Z-Beamlet laser (<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 (100 km/s—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
  - The magneto-Rayleigh-Taylor instability can shred the liner during the implosion and prevent the compression of the fusion fuel

* 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).

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

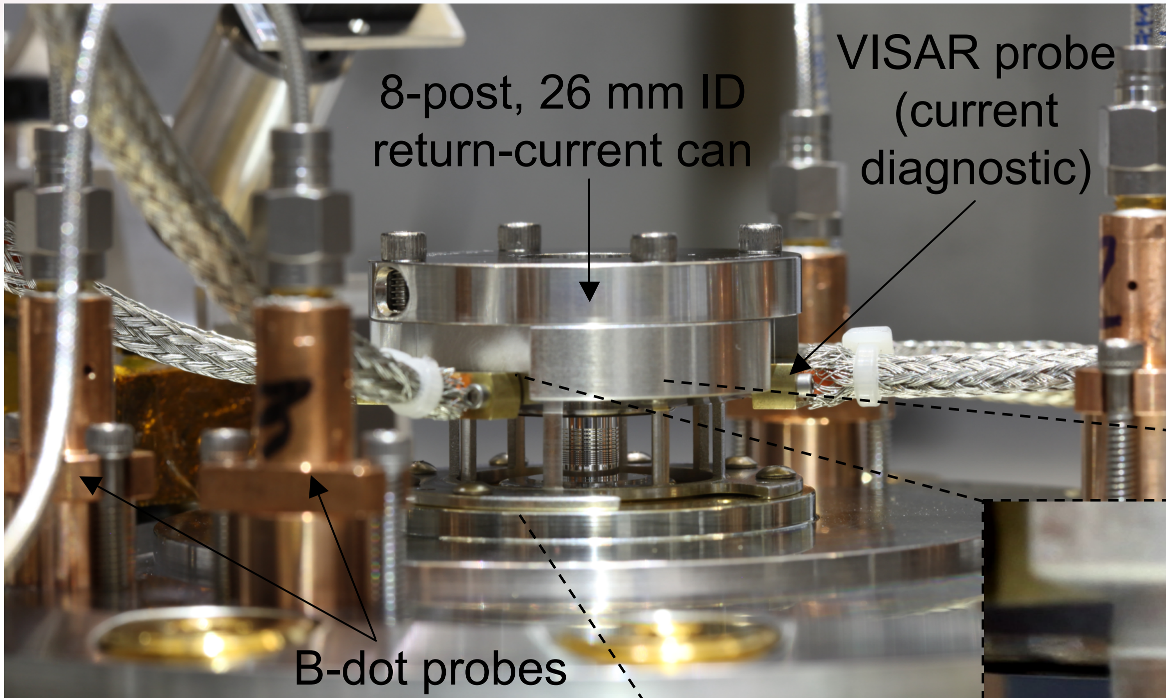


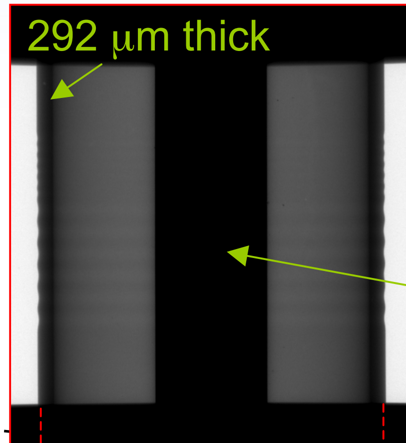


- The Magneto-Rayleigh-Taylor instability degrades the yield as the aspect ratio is increased due to decreased liner ρr
- High resolution 2D and 3D simulations are needed

- 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

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

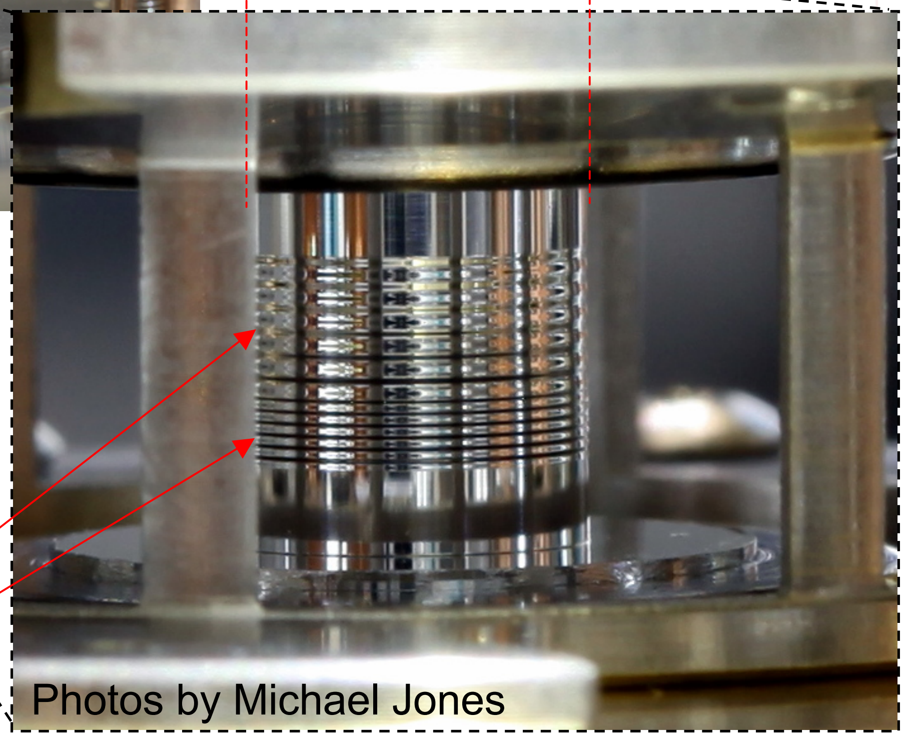




55-60 keV pre-shot radiograph (W Kα source)

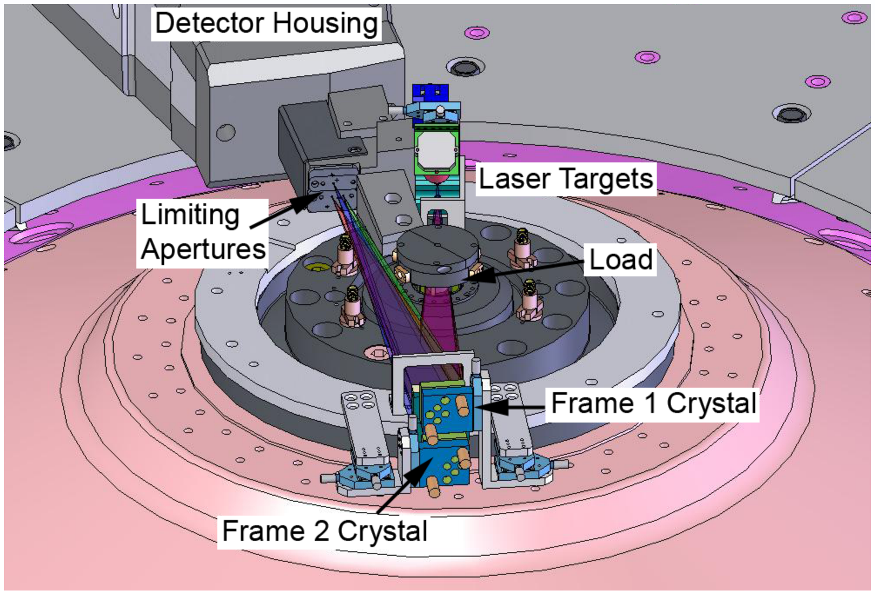
2 mm diam. W rod on axis (suppress x rays)

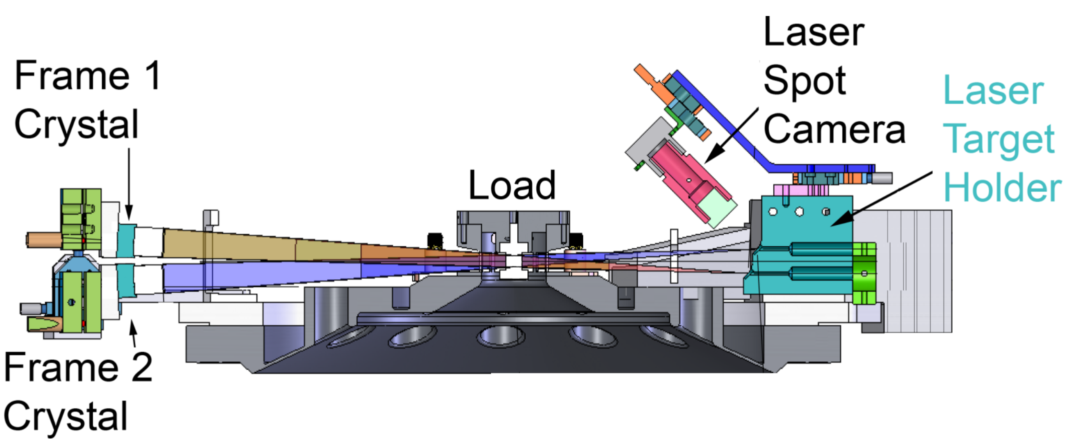
- Solid cylindrical liner (Al 1100 alloy)
- 6.5 mm tall, 6.34 mm diameter, AR=10
- 10 nm surface finish (diamond-turned)
- 12 sinusoidal perturbations:
  six 400-μm wavelength, 20-μm amplitude
  six 200-μm wavelength, 10-μm amplitude



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

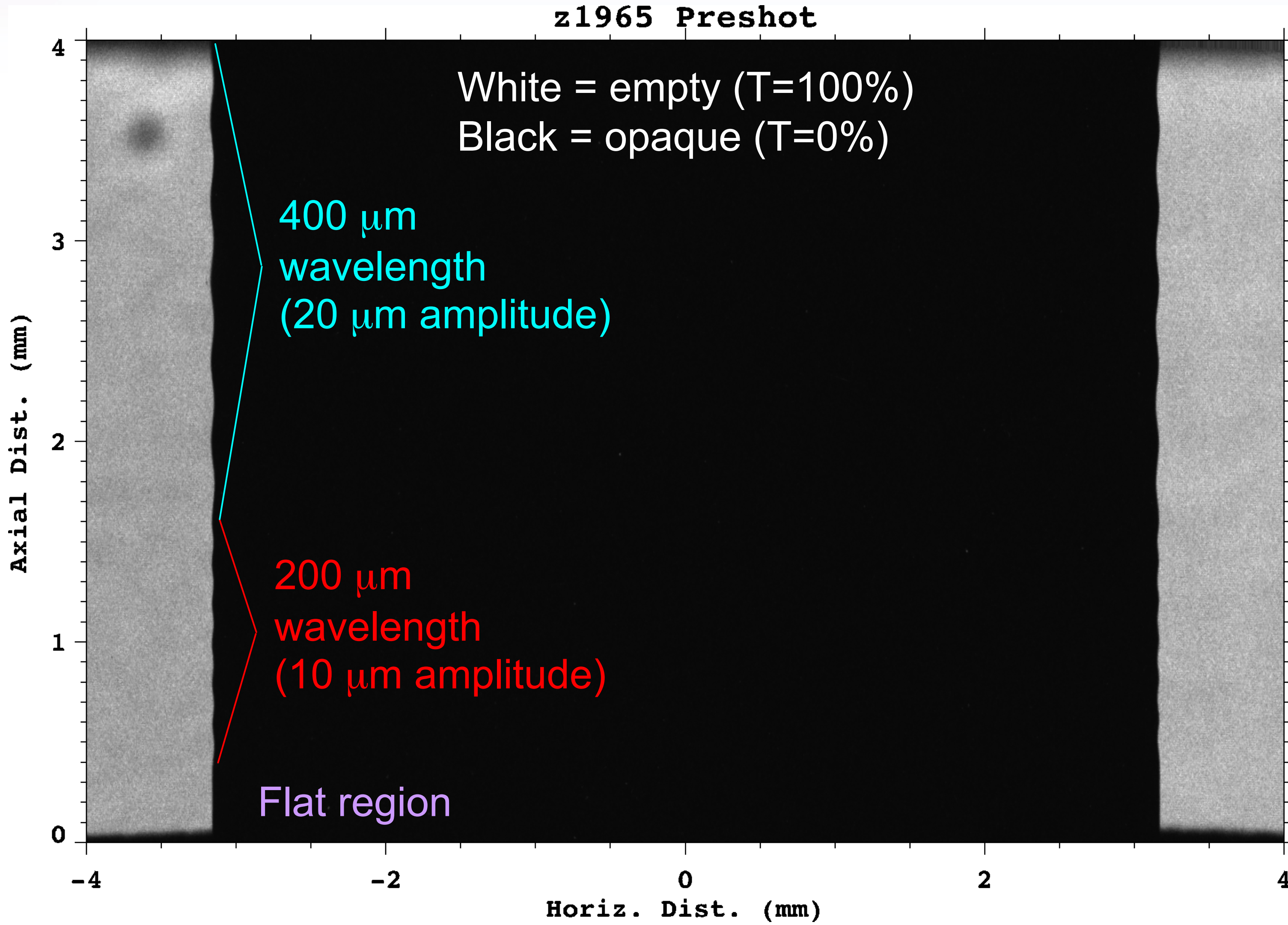
2-frame 6.151 keV Crystal Imaging

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

Approach

Example 6.151 keV radiograph (Pre-shot)



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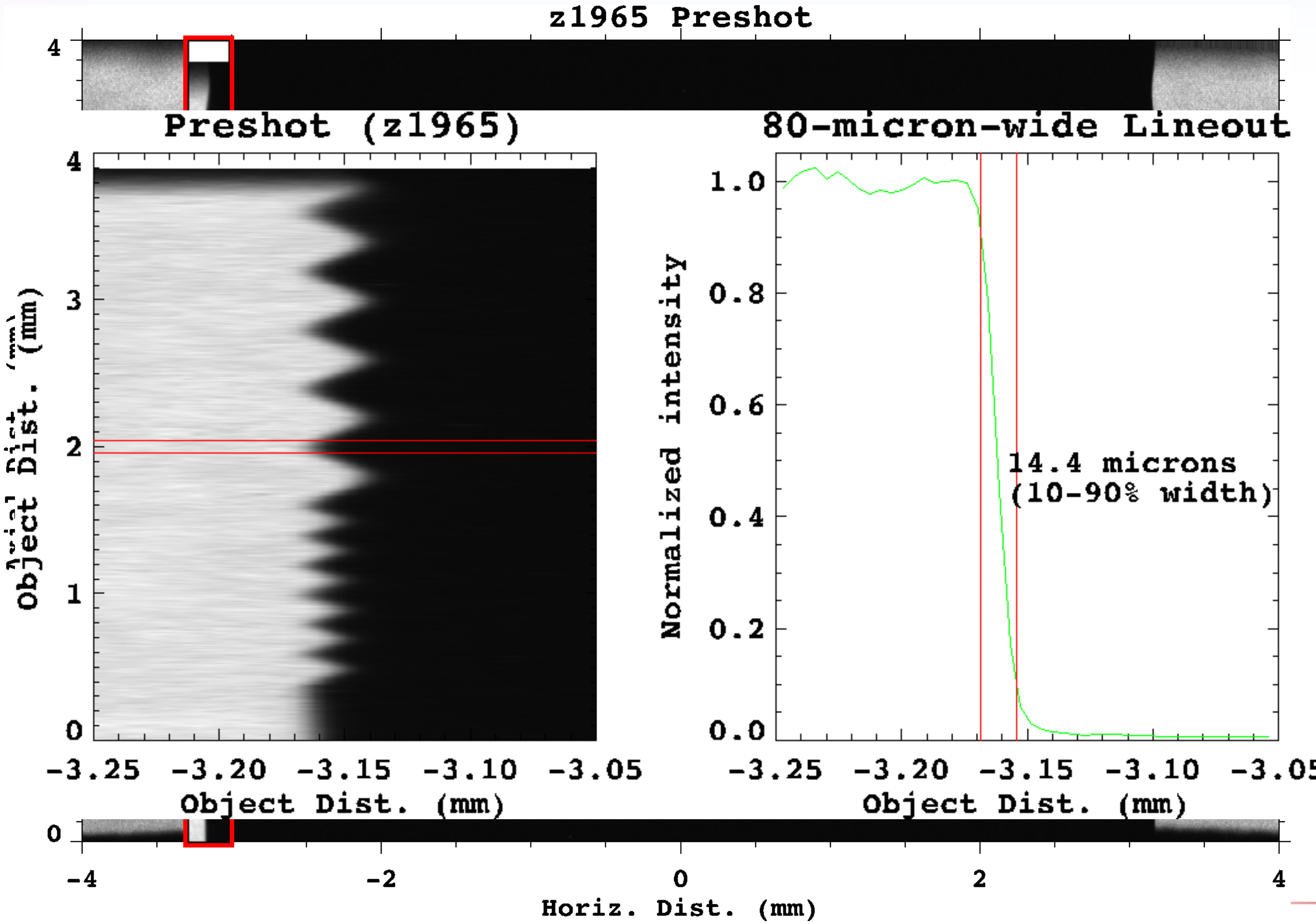
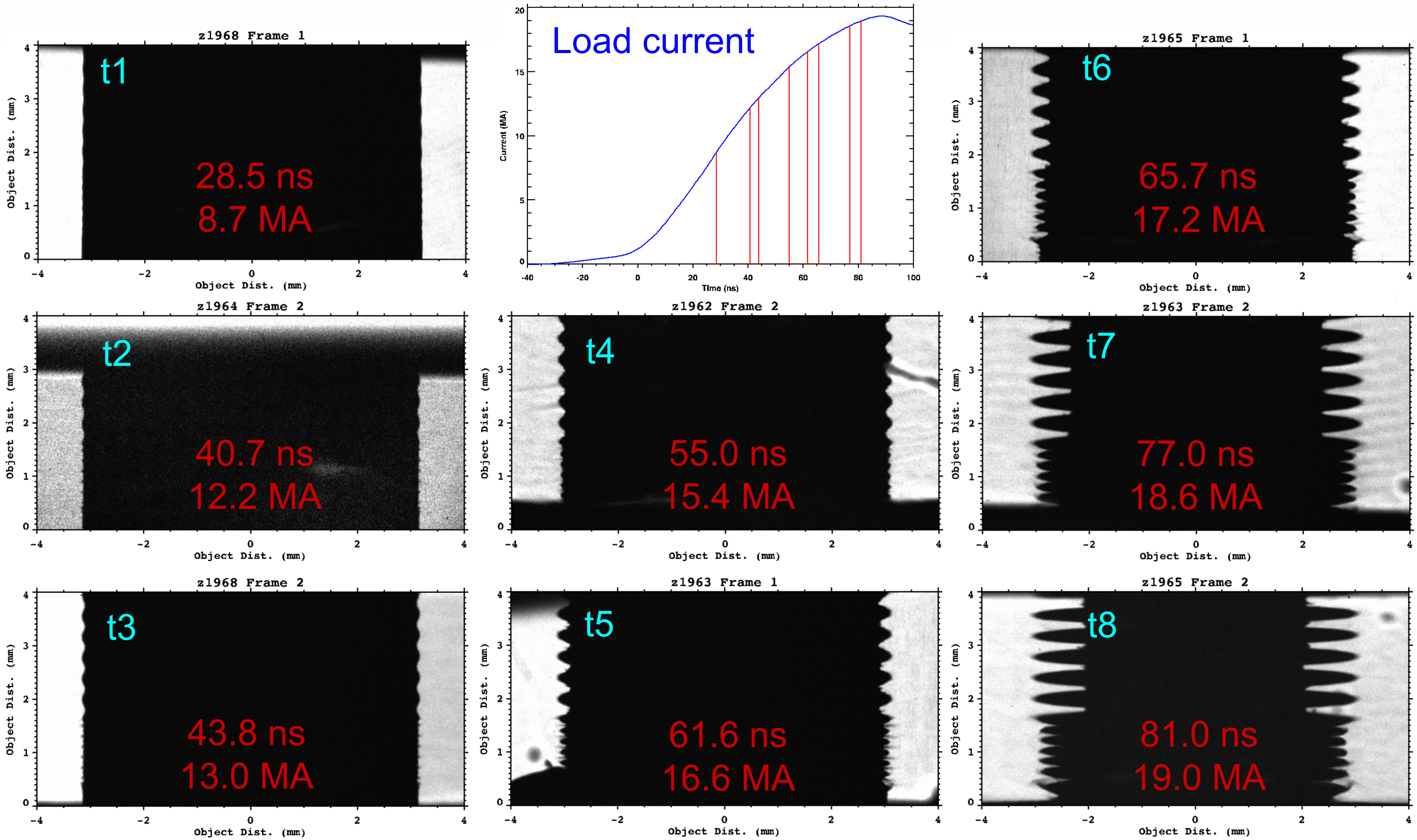
Approach

The 6.151 keV radiographs have 15 μm spatial resolution

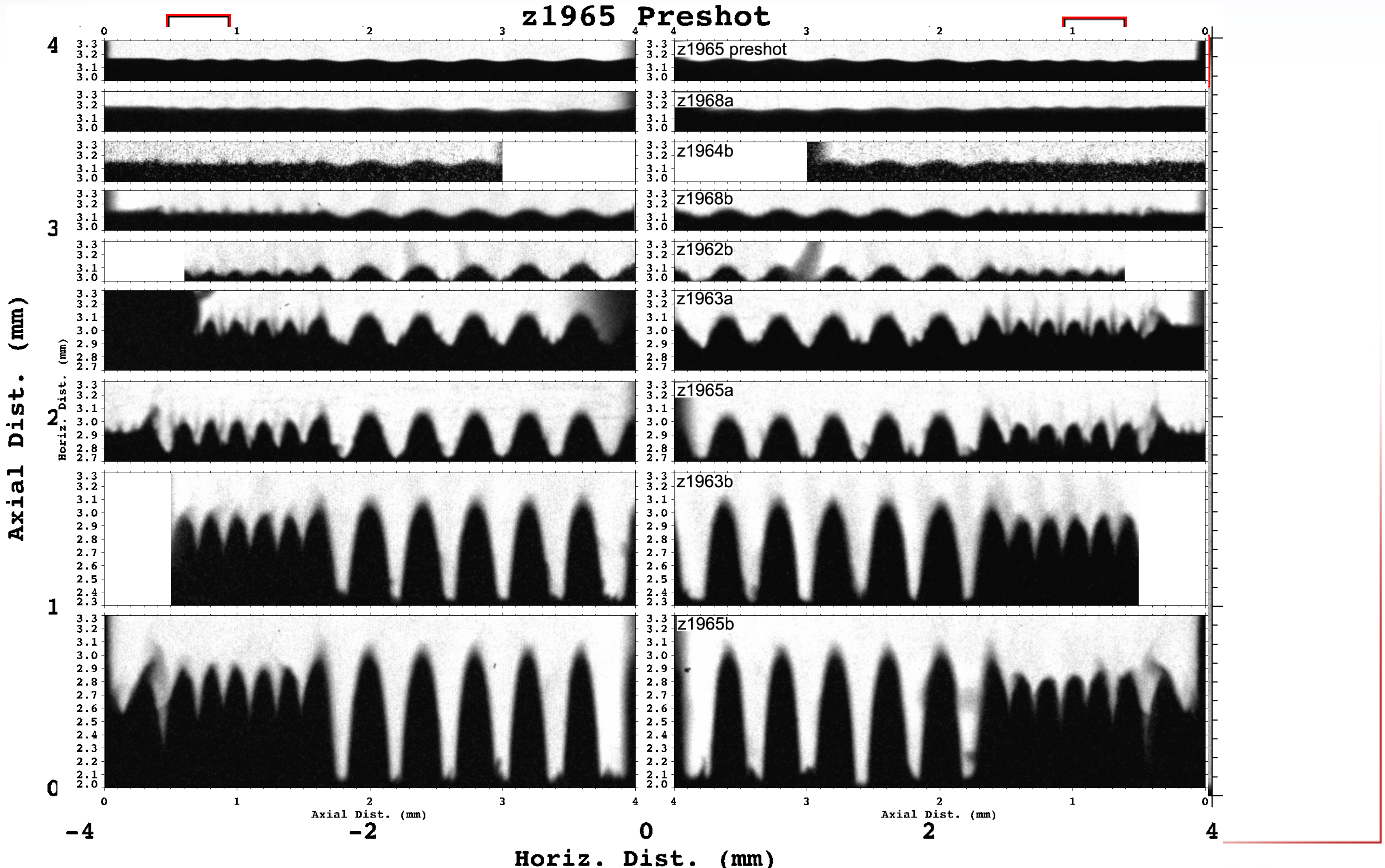


Reproducible drive currents (±1.5%) and liners enabled an 8-frame movie to be obtained over 5 shots



Results

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



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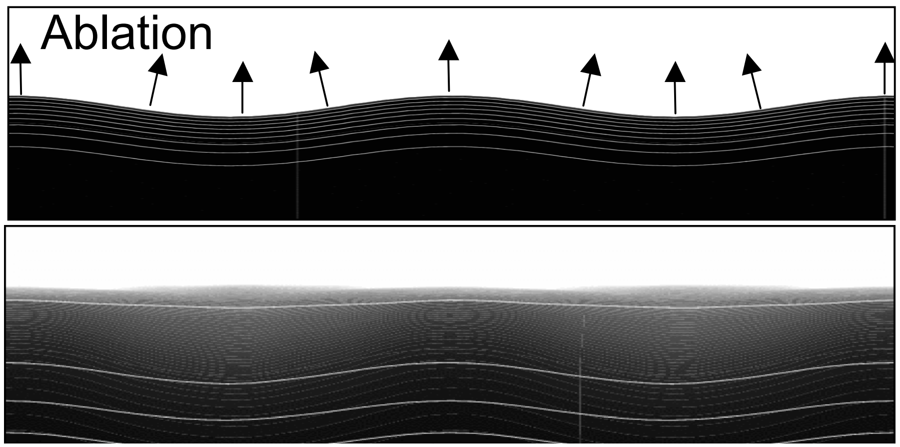
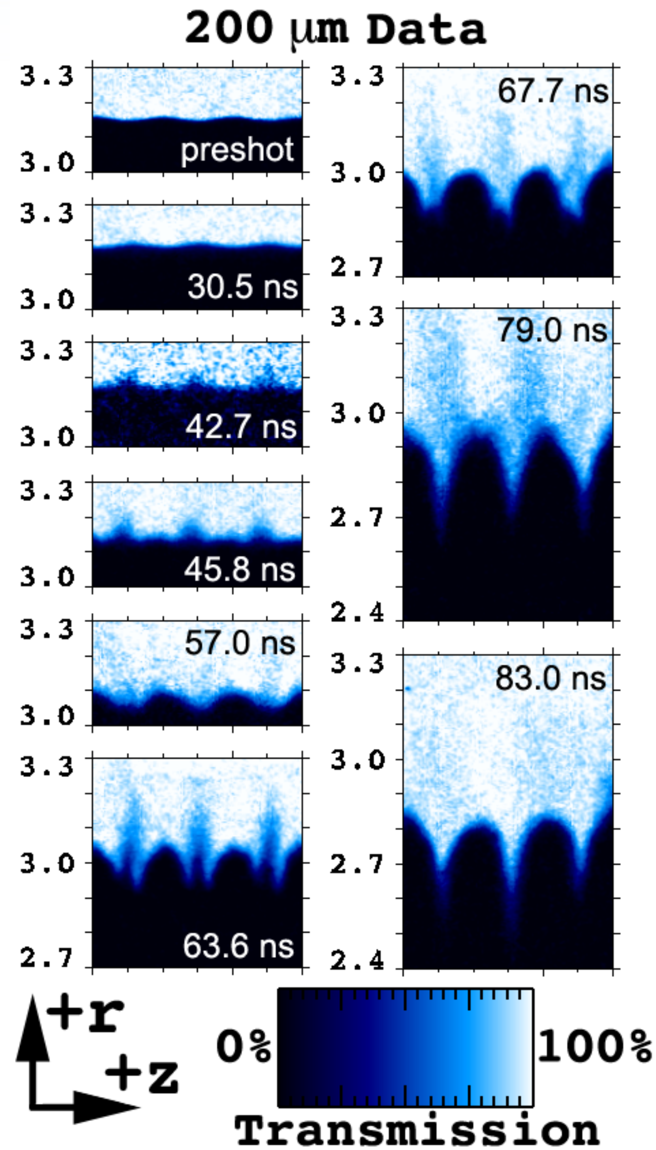


Simulated density map with rB_θ contours



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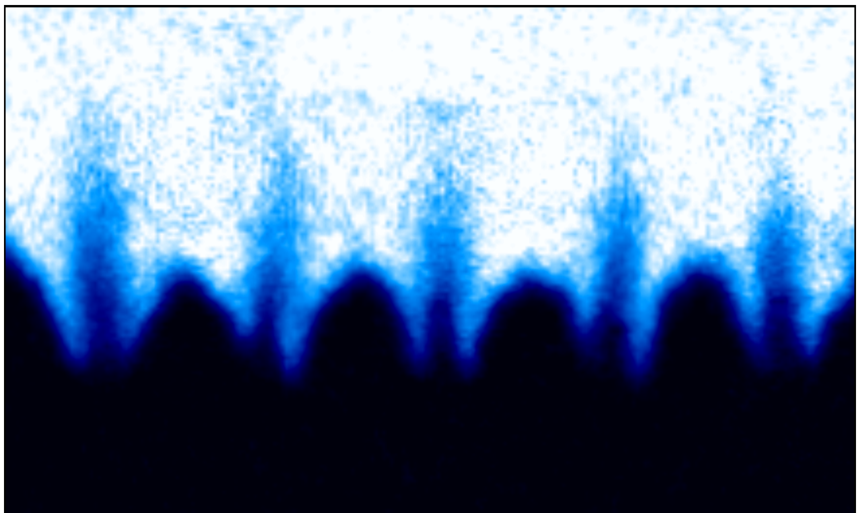
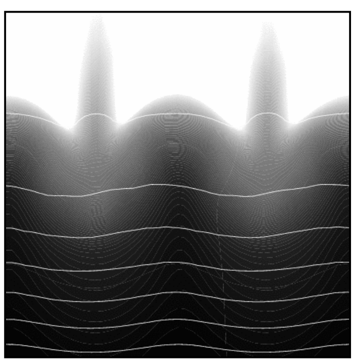
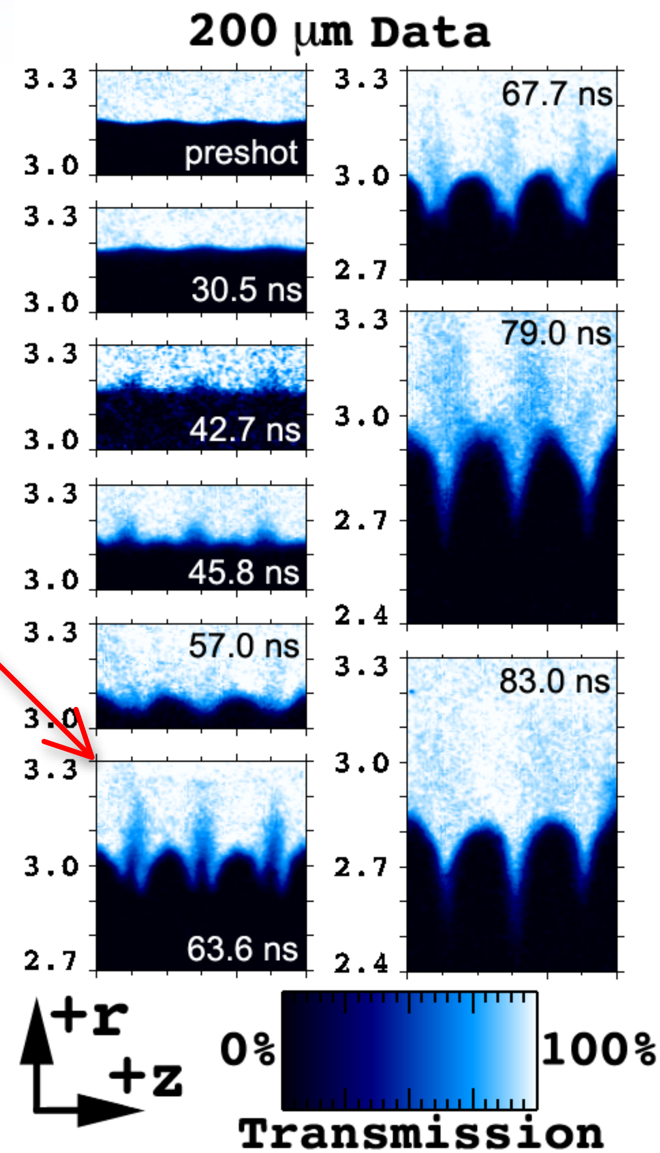




Simulated density map with rB_θ contours

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

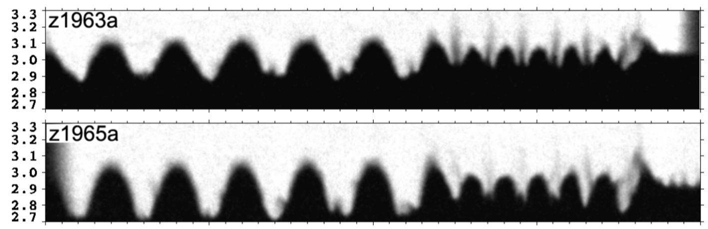


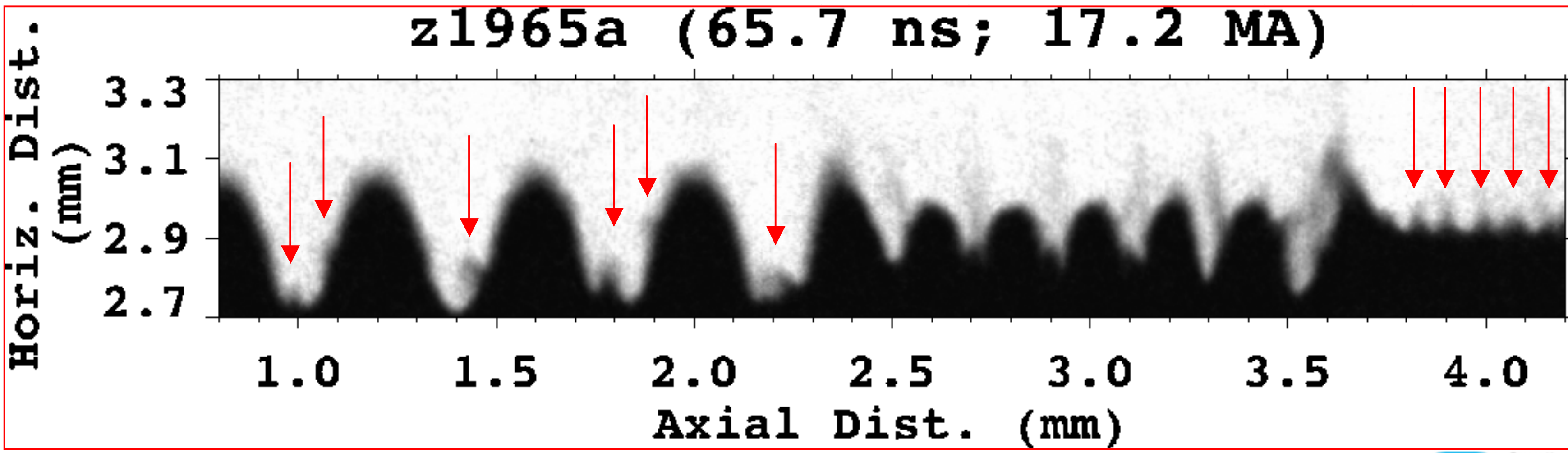
LASNEX: T_{jets} ~30 eV; T_{valley} ~100 eV

Results

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 “smooth” regions





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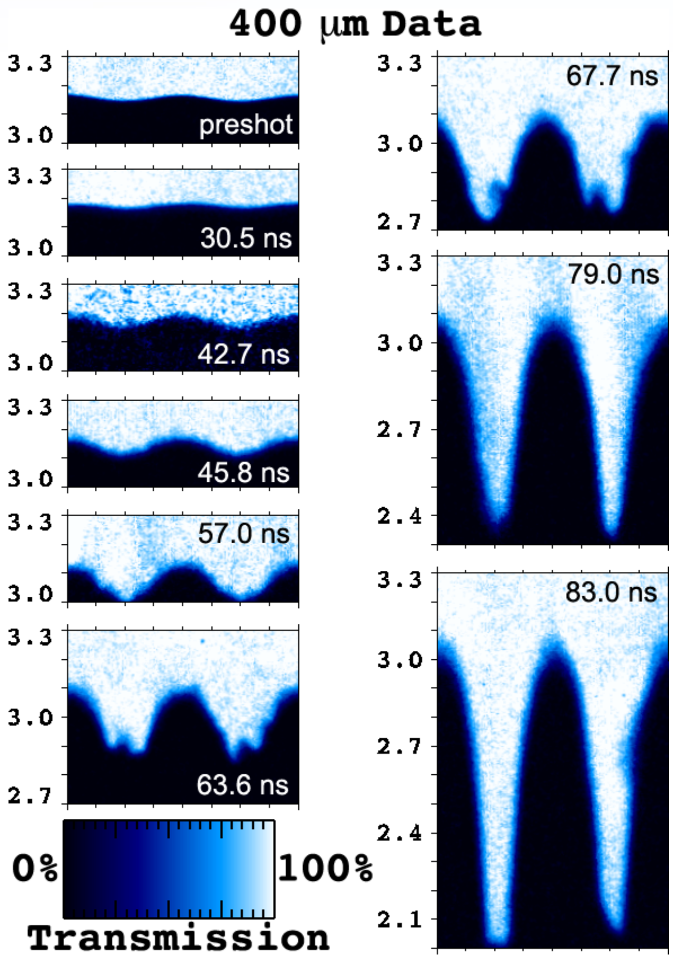
Results

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

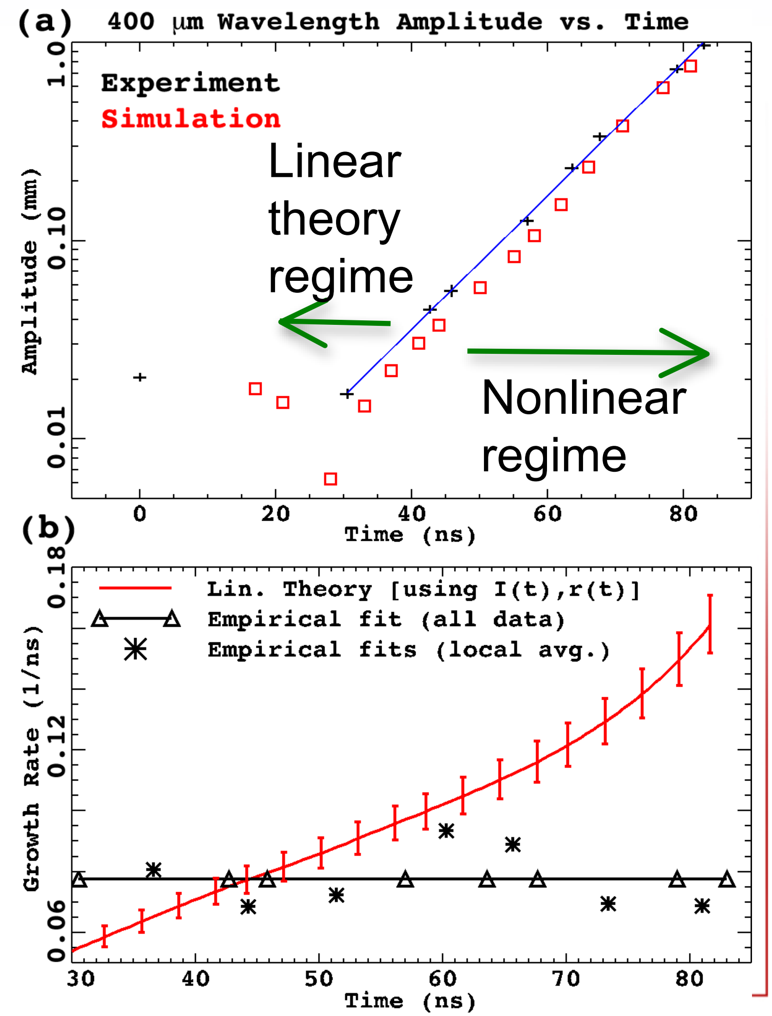


Growth rate from linear theory

$$\Gamma^2 = kg$$

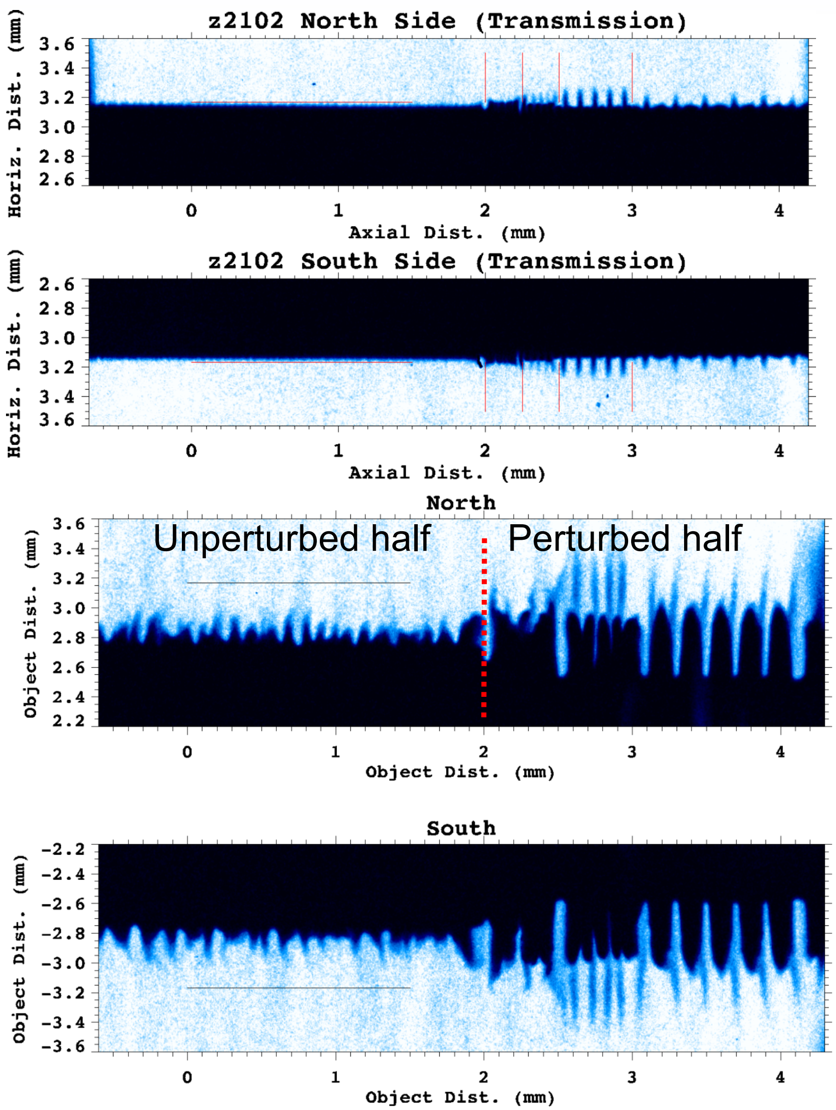
Calculate g using I(t), R(t) (red)

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

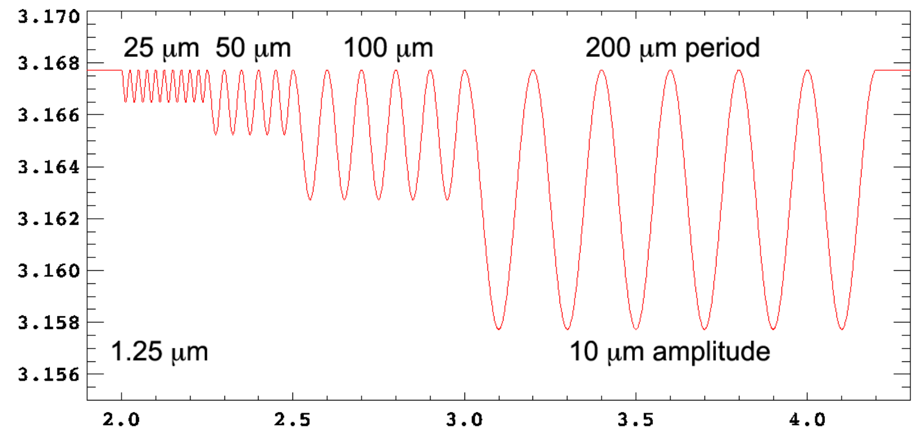


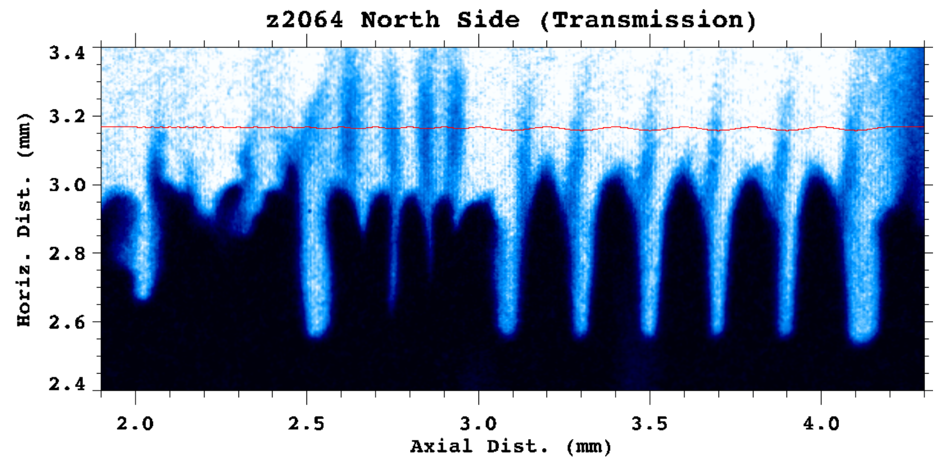
Results

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





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

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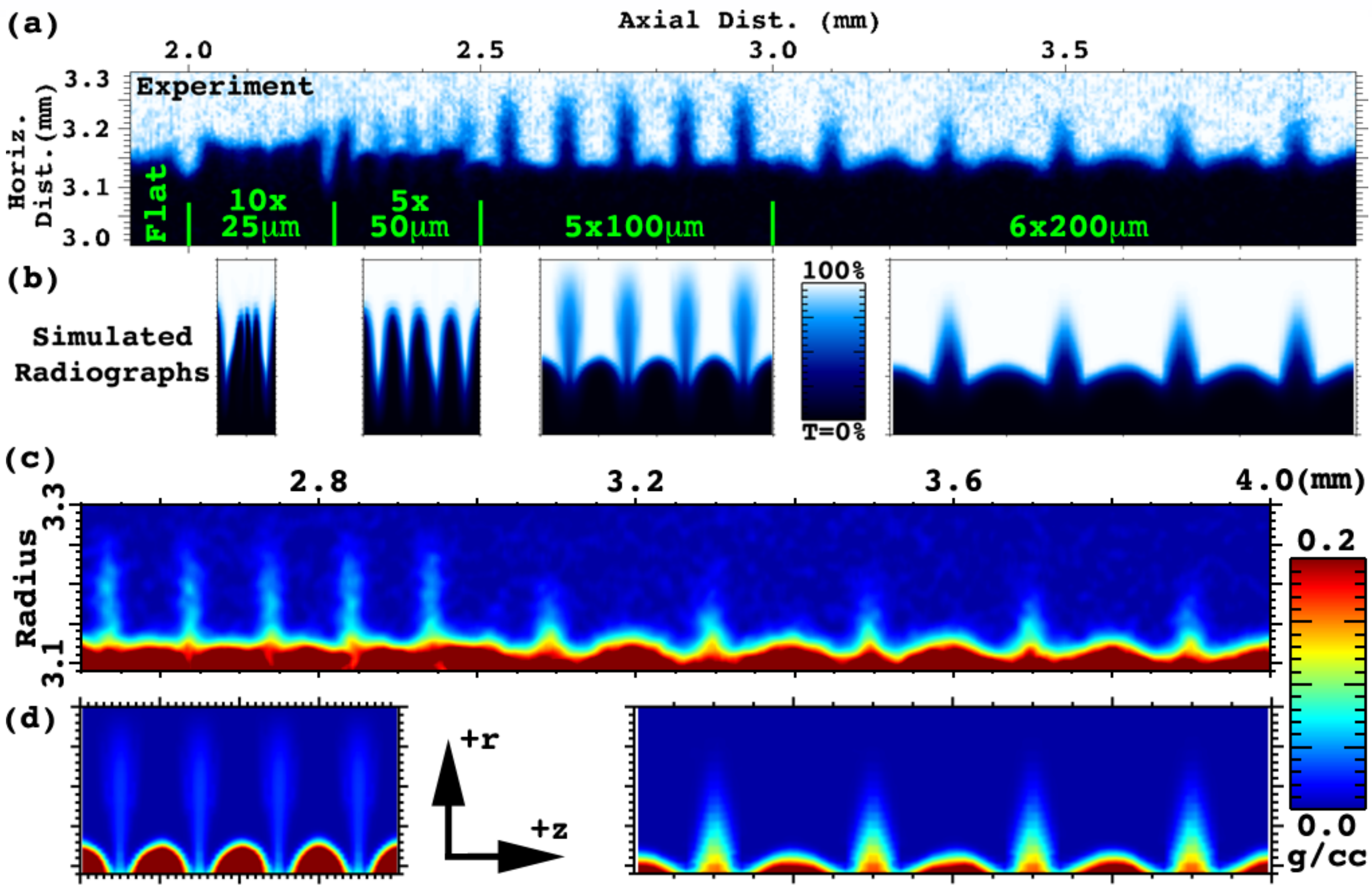
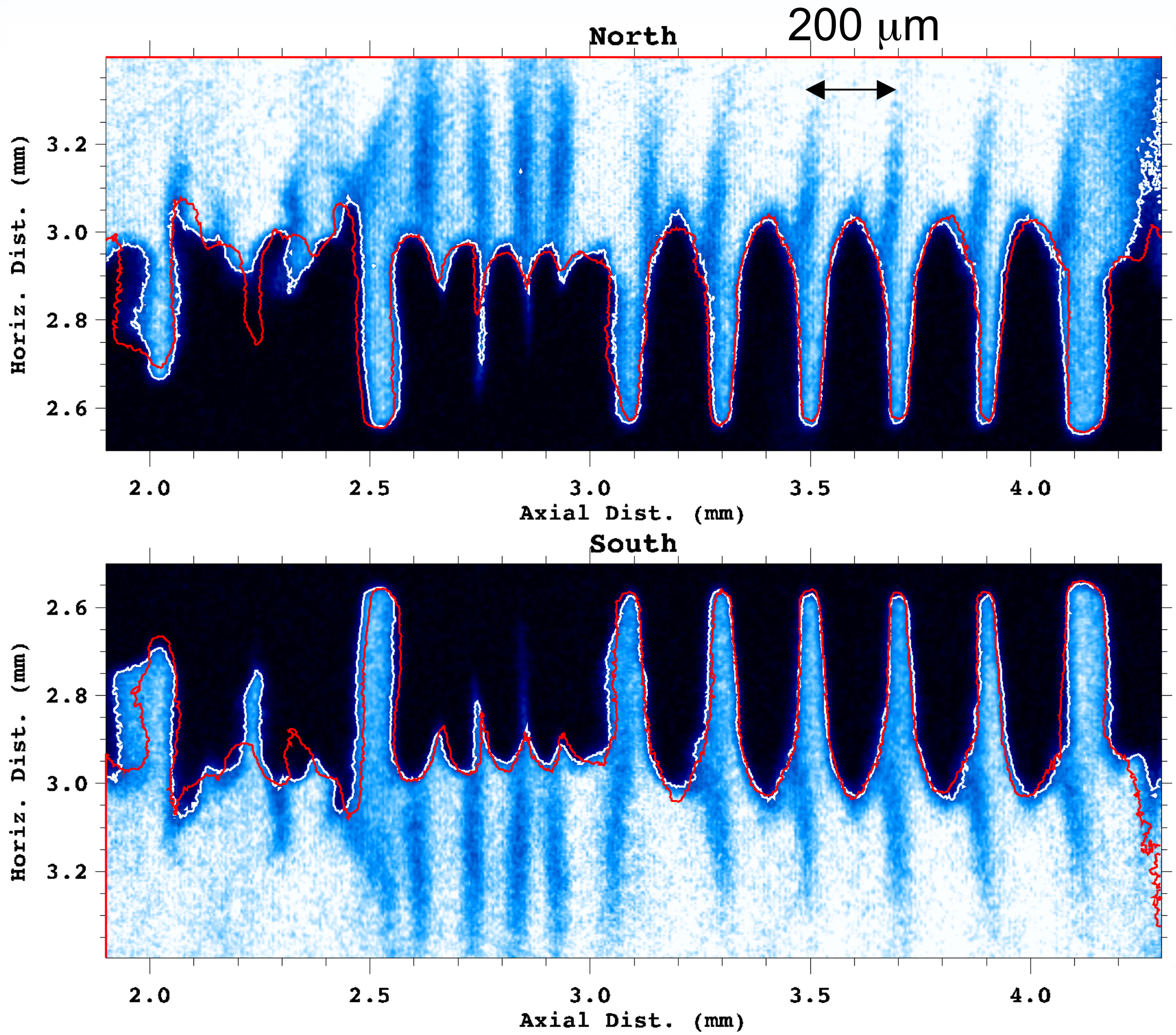
Results

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



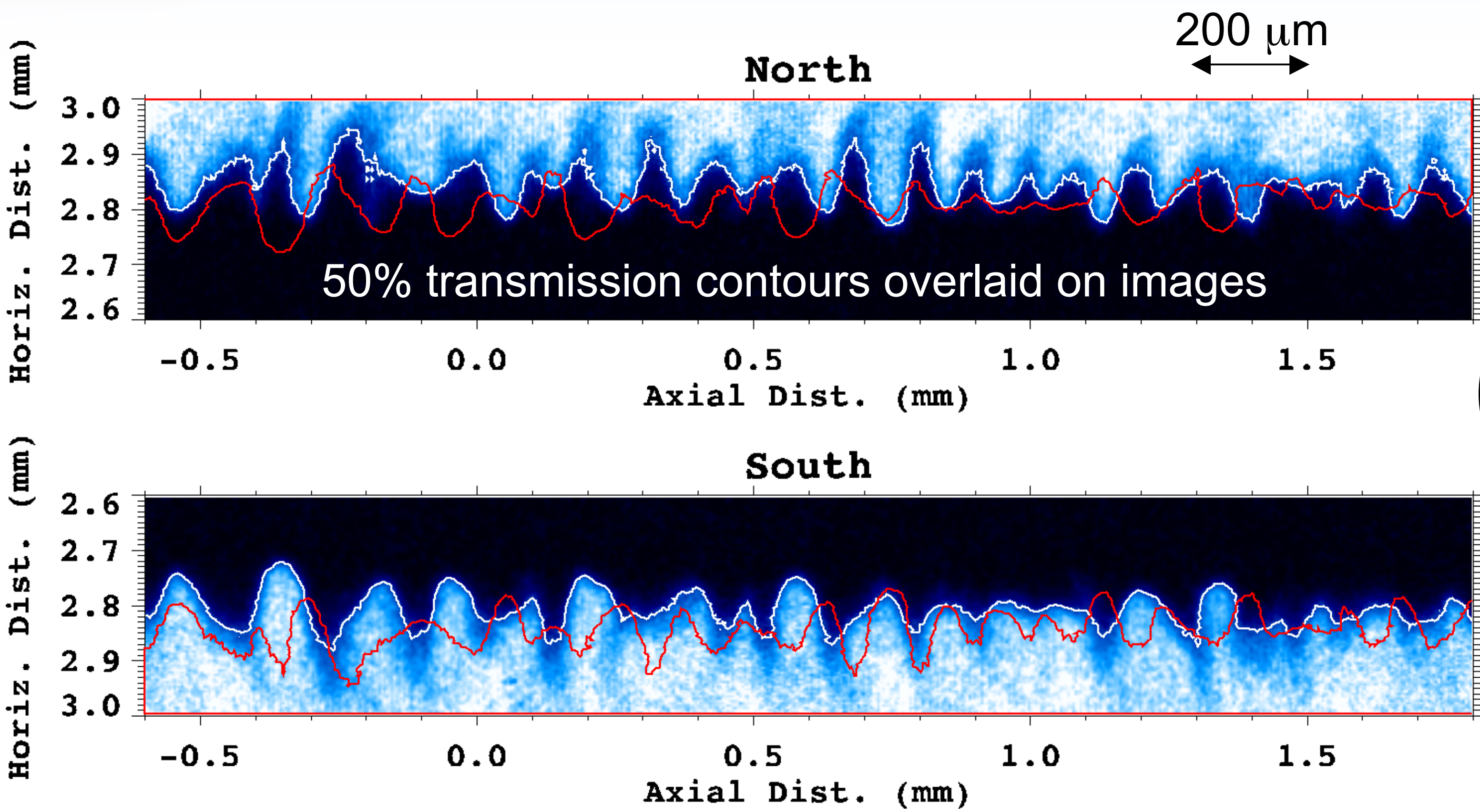
Note: We have not matched these features in HYDRA or GORGON yet

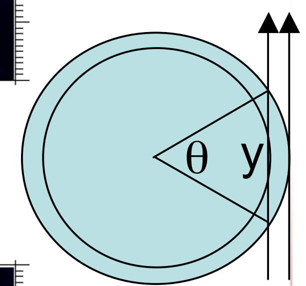
The instabilities in the perturbed regions are highly-correlated azimuthally in the late frame



50% transmission contours overlaid on images

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





r_out~2.9 mm
r_inn~2.8 mm

y ~ 1.5 mm
θ ~ 30º

But what would a radiograph of isolated (axially & azimuthally) spikes look like?

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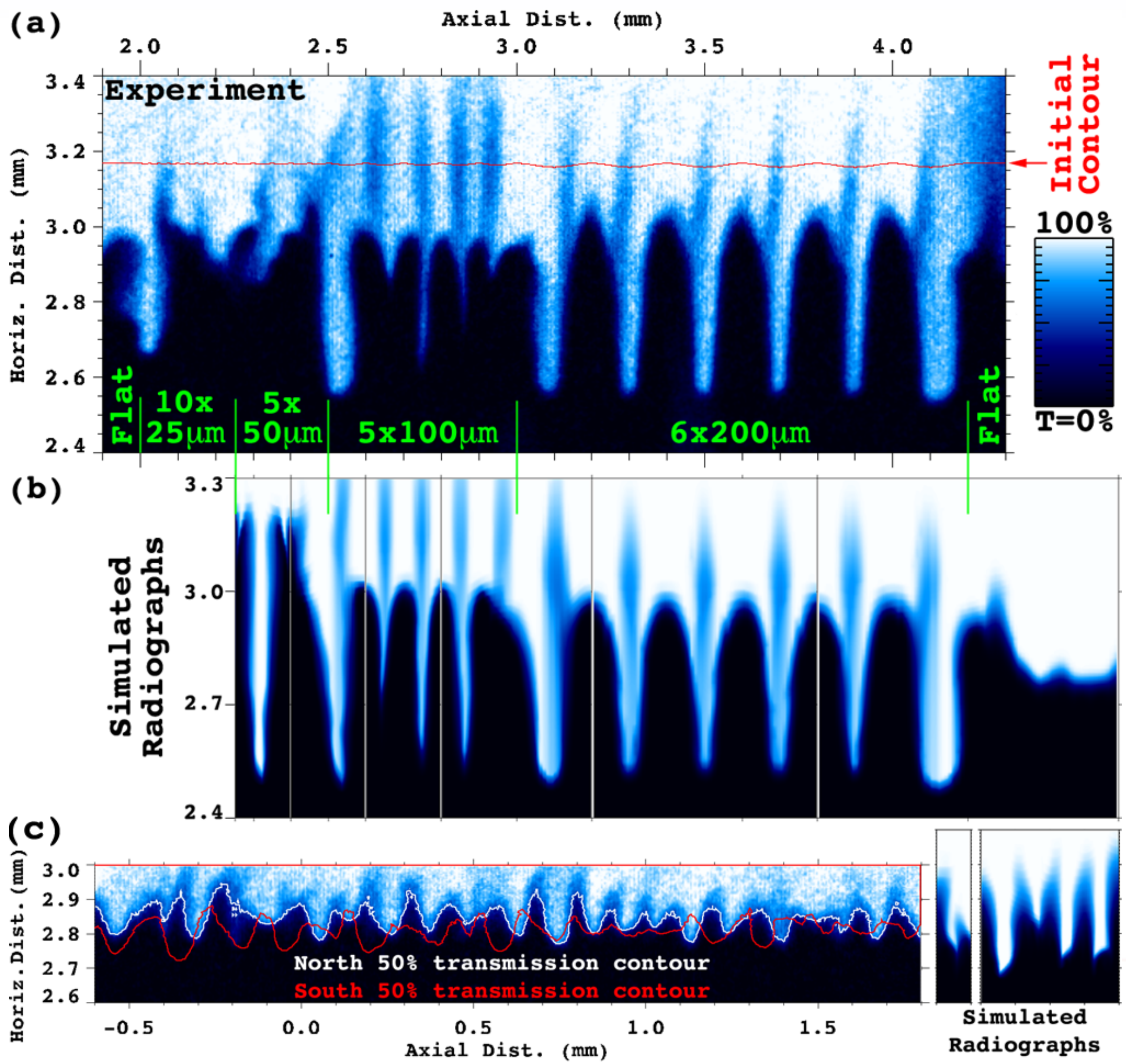
Results

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



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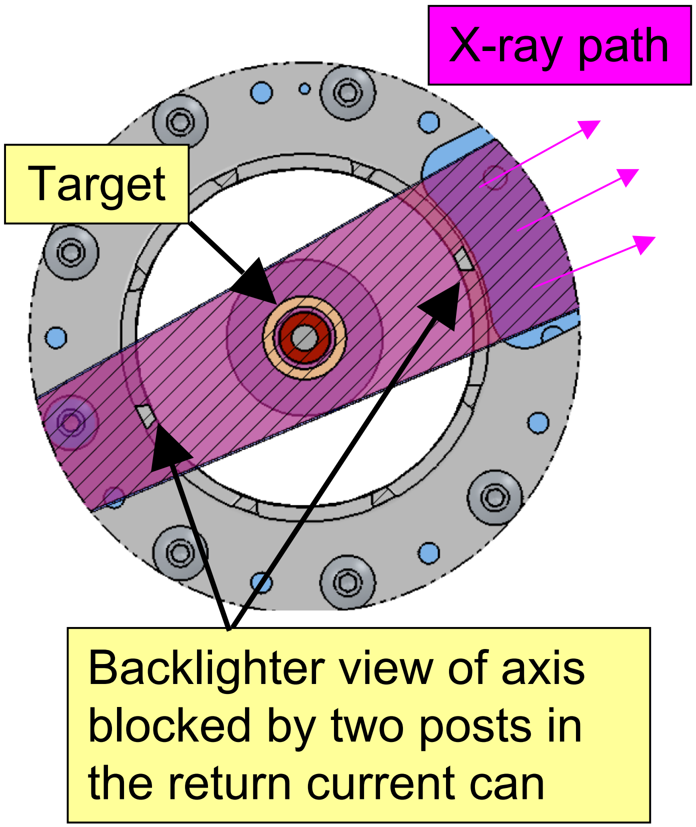
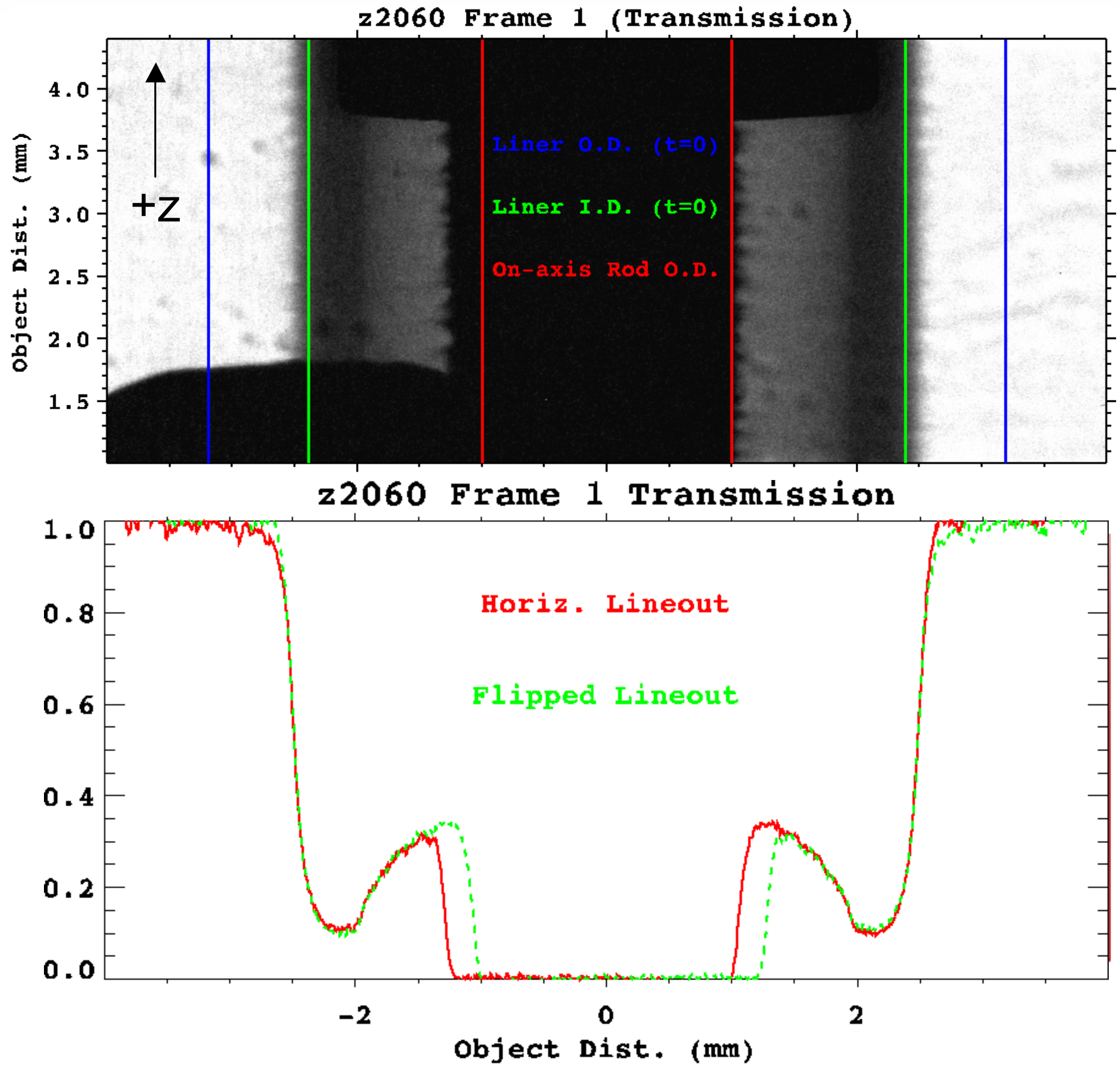
Penetrating 6.151 keV radiographs of Be liners allow us to observe both the inner and outer liner surfaces

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

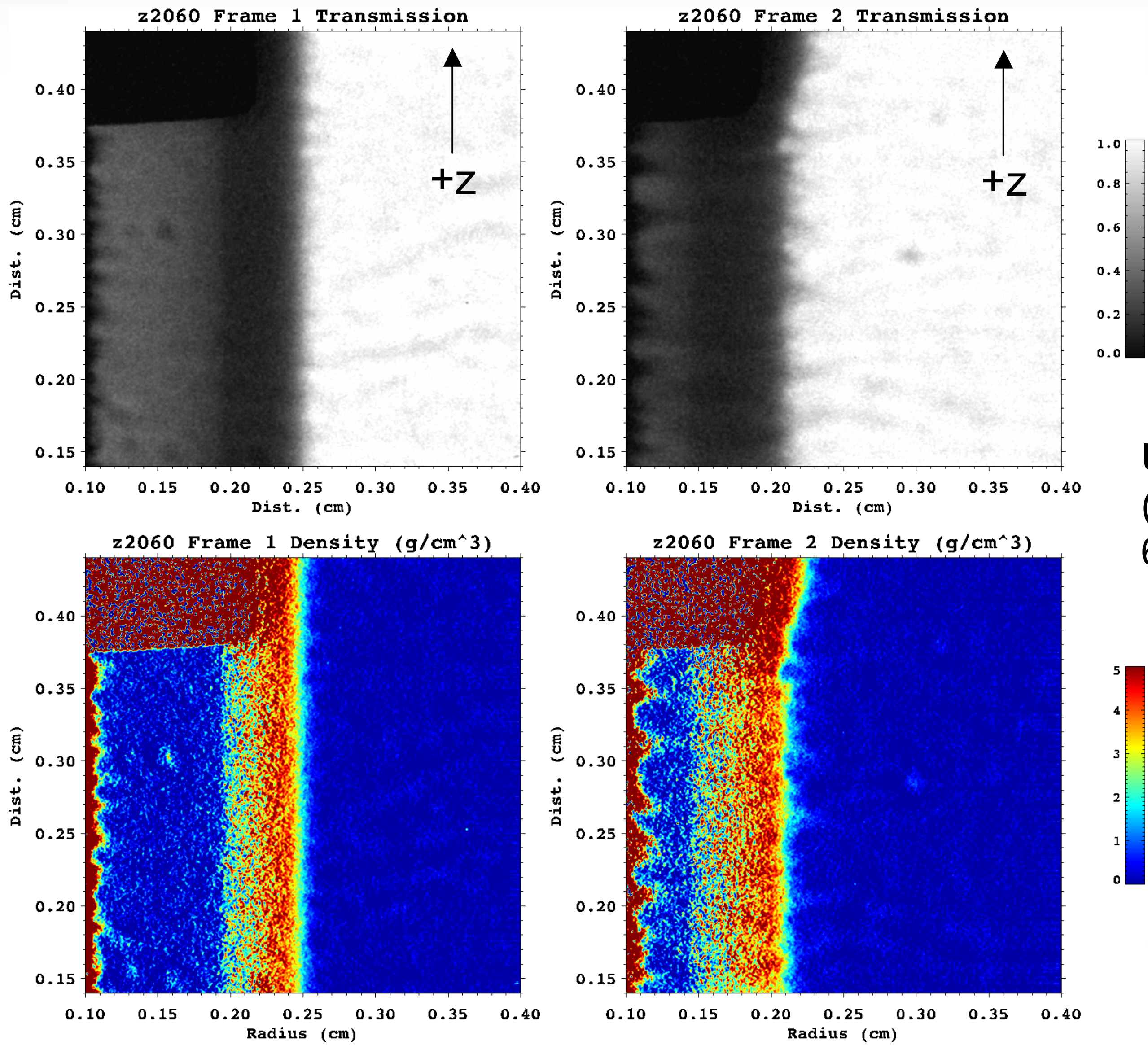


Example downline 6.151 keV radiograph



Results

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

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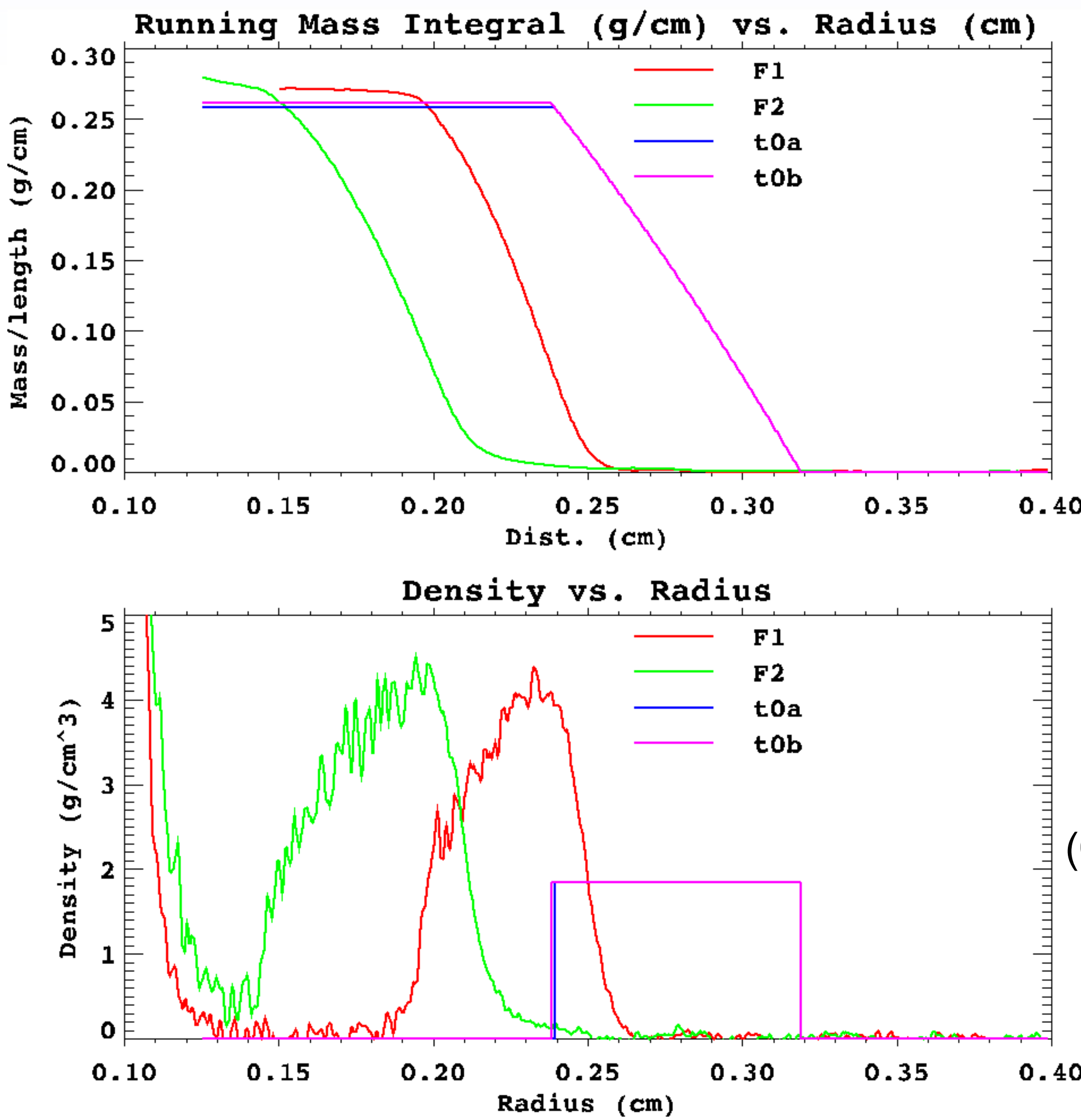
The results of the Abel inversion are consistent with the initial mass/length of the liner, show ρmax~4.1 g/cc



(0.8 mm tall lineouts)

Significance

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.)**
  - **These are some of the fundamental physics package design tools used by the stockpile stewardship program**
- **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?**

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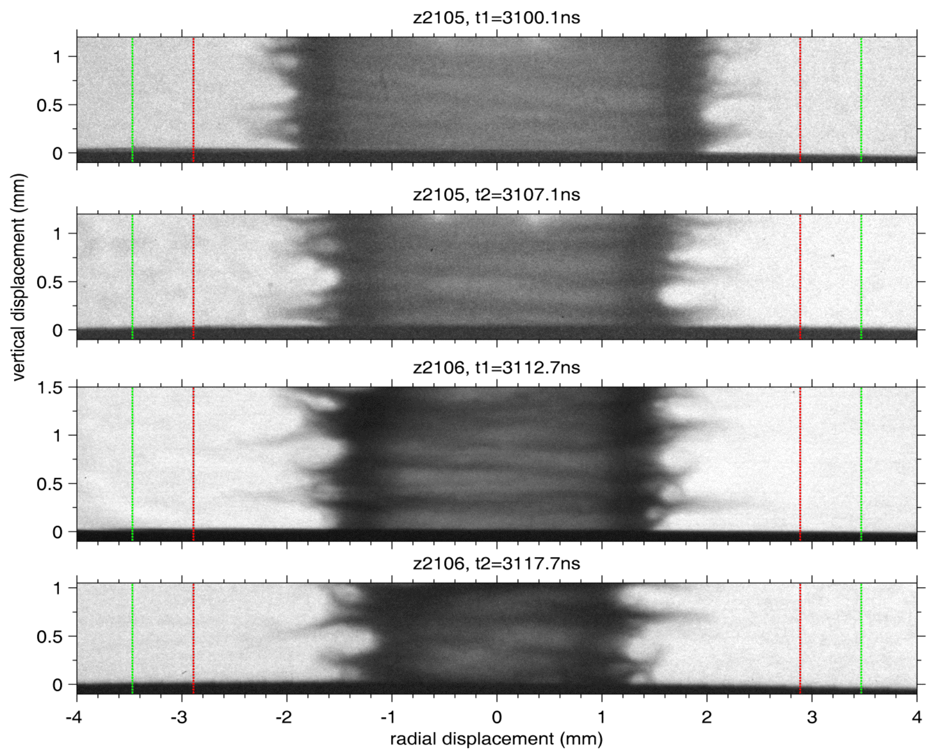
Significance

Our success so far in modeling the MRT instability gives us hope that >100 kJ yield predictions are realizable

- We have started collecting data with Be liners in which we can see changes in the areal density and integrity of the liner
- We will create axial magnetic fields of ~0.5 T using permanent magnets in 2011. 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
- This work may soon enable the Z facility to produce >100 kJ yields in a laboratory setting for stockpile stewardship science



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