SAND2011-3368C

Beryllium liner z-pinch implosions for inertial confinement fusion and dynamic materials studies at the Z pulsed-power facility*

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Lisbon, Portugal
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Outline

- Introduction to Sandia facilities
  - The refurbished Z accelerator (Z)
  - The Z Beamlet Laser (ZBL)
  - The two-frame, 6.151-keV monochromatic backlighting system for radiography
- Motivation for beryllium liner z-pinch implosions
  - Inertial confinement fusion (ICF) & magneto-Rayleigh-Taylor (MRT) studies
  - Dynamic materials (DM) and equation-of-state (EOS) studies
- EOS experiments and data
  - Shock Compression
  - Isentropic Compression Experiments (ICE)
- MRT experiments and data
- Summary

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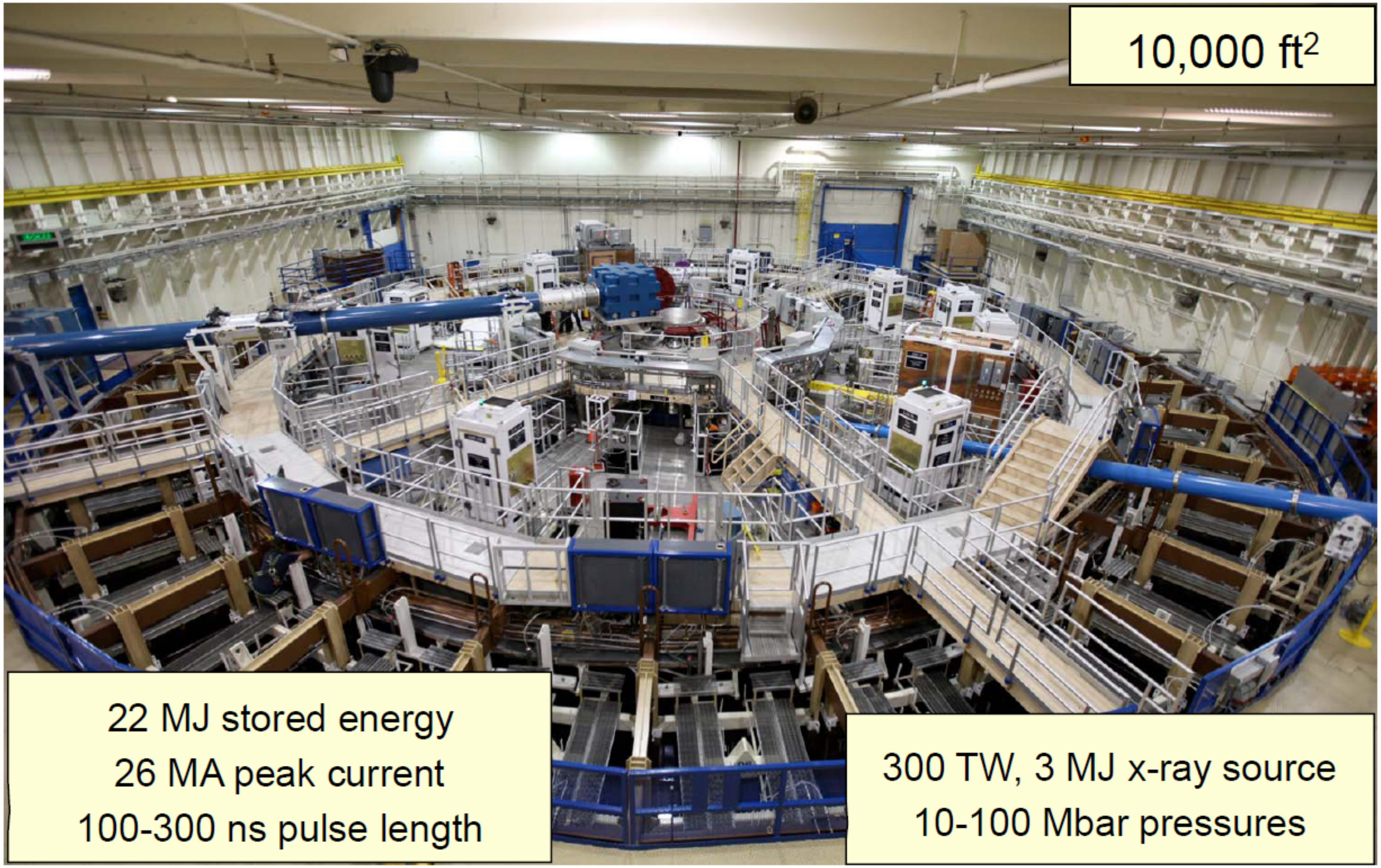
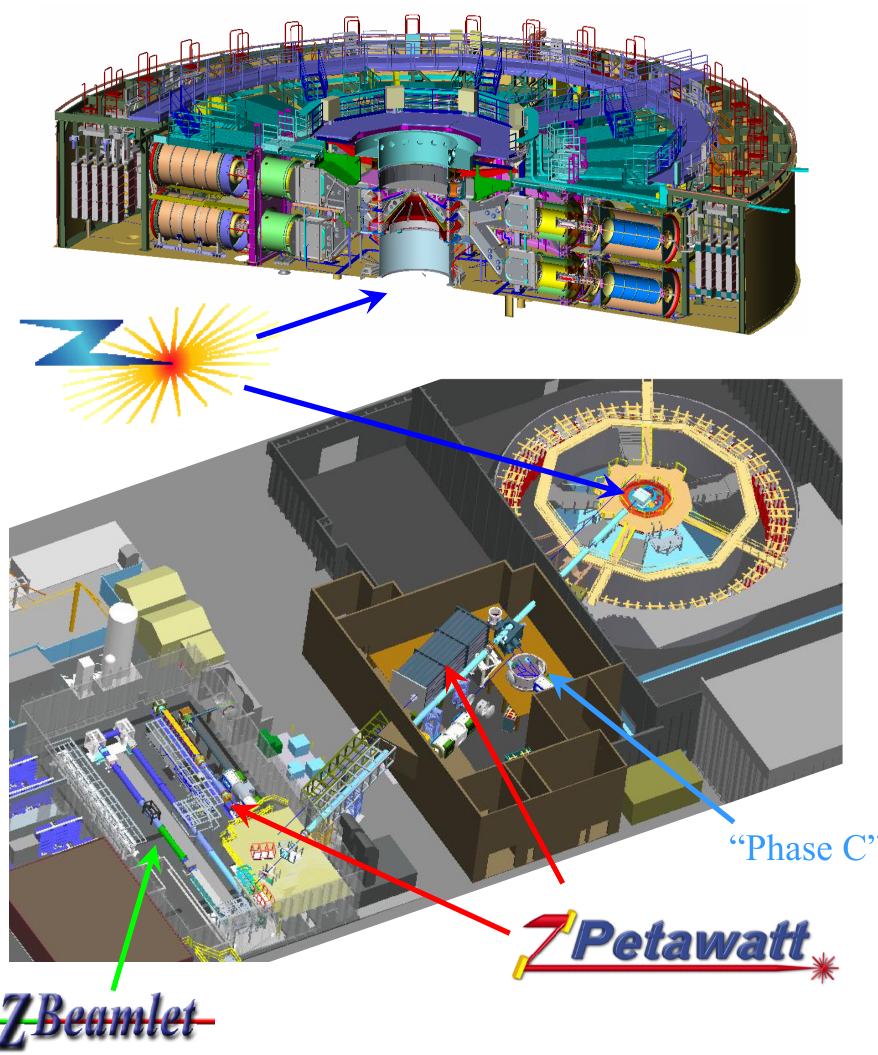
The Refurbished Z Pulsed-Power Accelerator

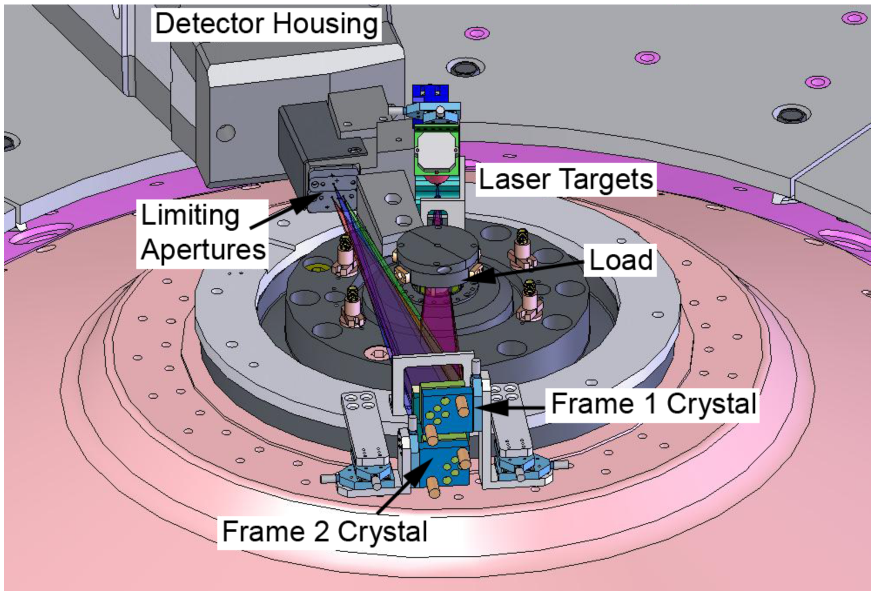


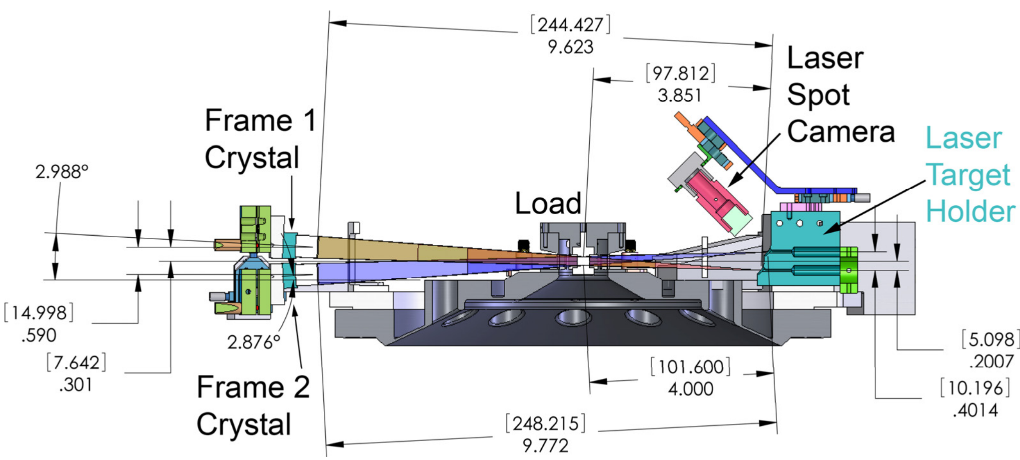
Z-Beamlet (ZBL) and Z-Petawatt (ZPW) Lasers Coupled to Z accelerator

- ZBL is a pulsed, multi-kJ, TW-class Nd:glass laser system
  - Pulse duration: 0.3–1.5 ns
  - Energy: ~1.5 kJ on target at 527 nm
- Provides radiography capabilities for Z experiments, including:
  - Monochromatic spherical crystal backlighting with 6.151-keV (Mn He$_{\alpha}$) or 1.865-keV (Si He$_{\alpha}$) photons
    - Two-frame setup, where frames are ±3° from horizontal (two color or single color)
    - Single-frame setup with 0° (radial) viewing
  - Point projection backlighting at 4.5 keV, 6.7 keV, etc…
  - Newer ZPW laser (0.5–10 ps; ~1.5 kJ) could possibly extend backlighting capabilities to 25 keV
- ZBL and ZPW can conduct HEDP experiments independent of Z in "Phase C" area



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

- **Spherically-bent quartz crystals (2243)**
- **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).**

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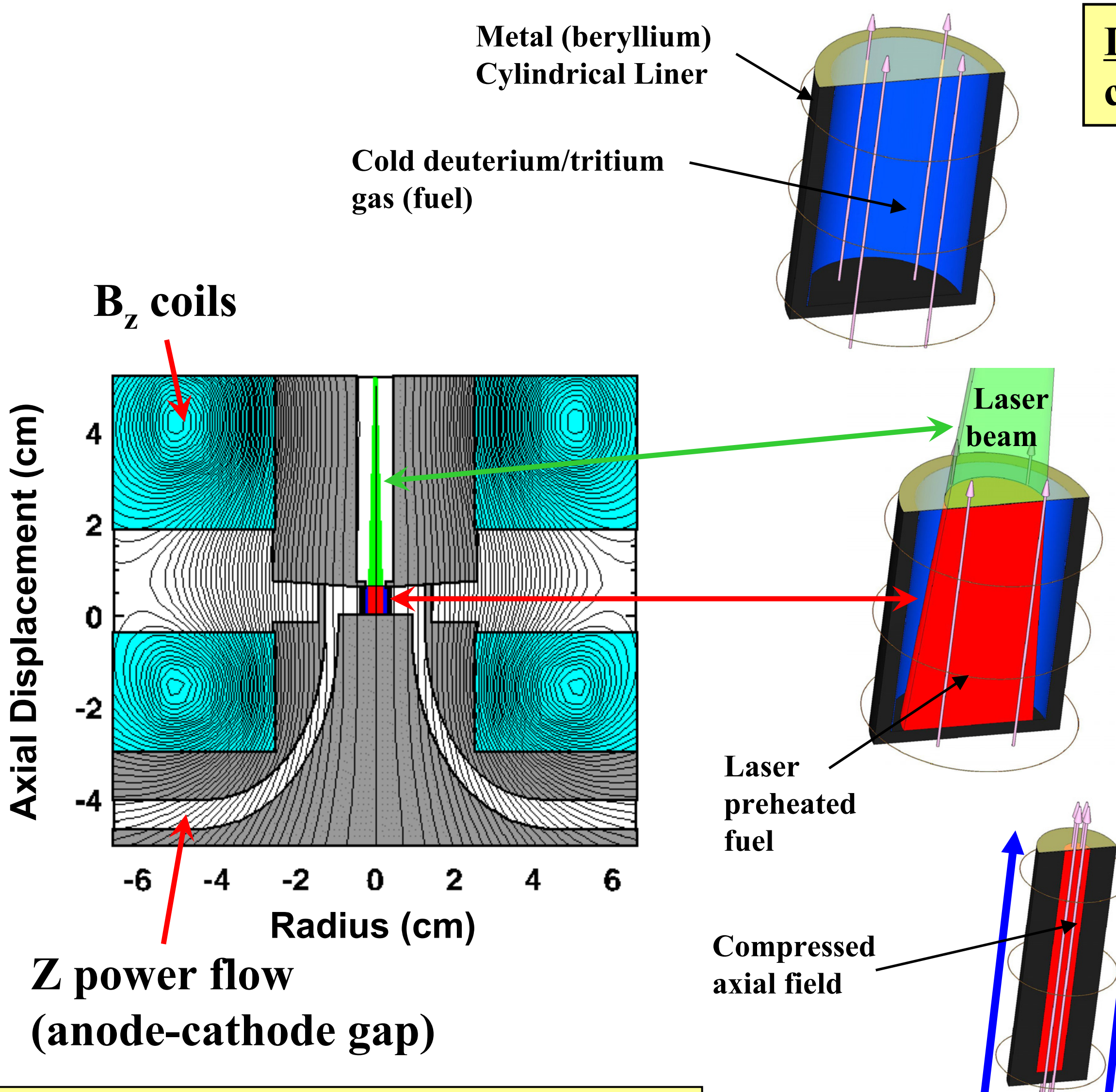
Magnetized Liner Inertial Fusion (MagLIF)* may be a promising path to high fusion yields on Z

Idea: Directly drive solid liner containing fusion fuel



1. An axial magnetic field (B_z) is applied to inhibit thermal conduction and enhance alpha particle deposition

2. Z Beamlet preheats the fuel

3. The Z accelerator efficiently drives a z-pinch implosion

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

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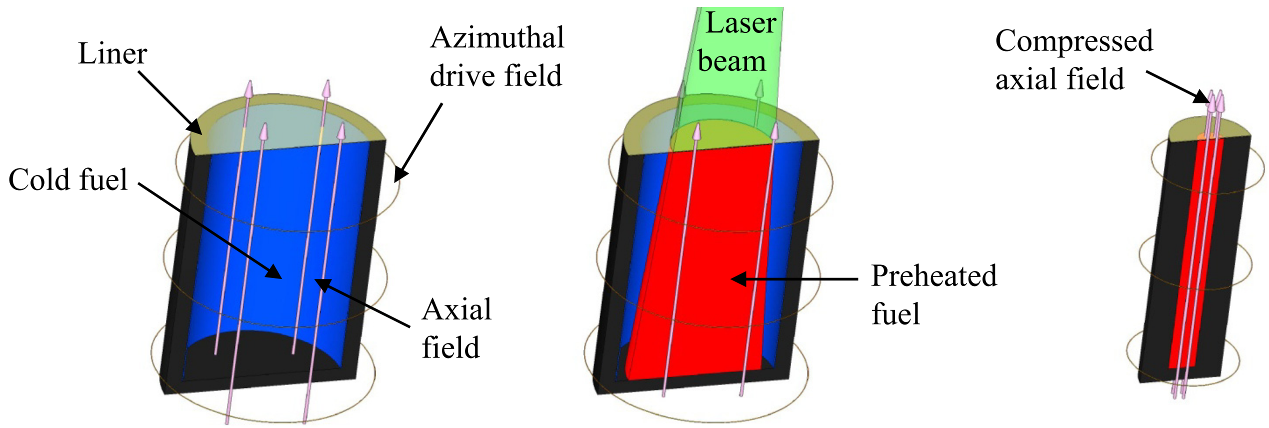

- Calculations suggest Z-Beamlet laser can do the preheat
  - Preheating fuel reduces required compression ratio to about 30 to obtain ignition temperatures on Z
  - Preheating reduces implosion velocity needed to about 5-10 cm/μs
- Axial magnetic field strength required (about 5-10 T) feasible
  - Similar coil design parameters to coils for dynamic materials tests
- Simulations suggest 100 kJ yields on Z are possible
- Success of MagLIF hinges on <u>maintaining sufficient liner integrity</u>
- The MRT experiments are designed to study liner integrity and MRT development, and to benchmark simulation codes

*S. A. Slutz *et al*., "Pulsed power driven cylindrical liner implosions with magnetized and preheated fuel" Phys. Plasmas **17**, 056303 (2010).

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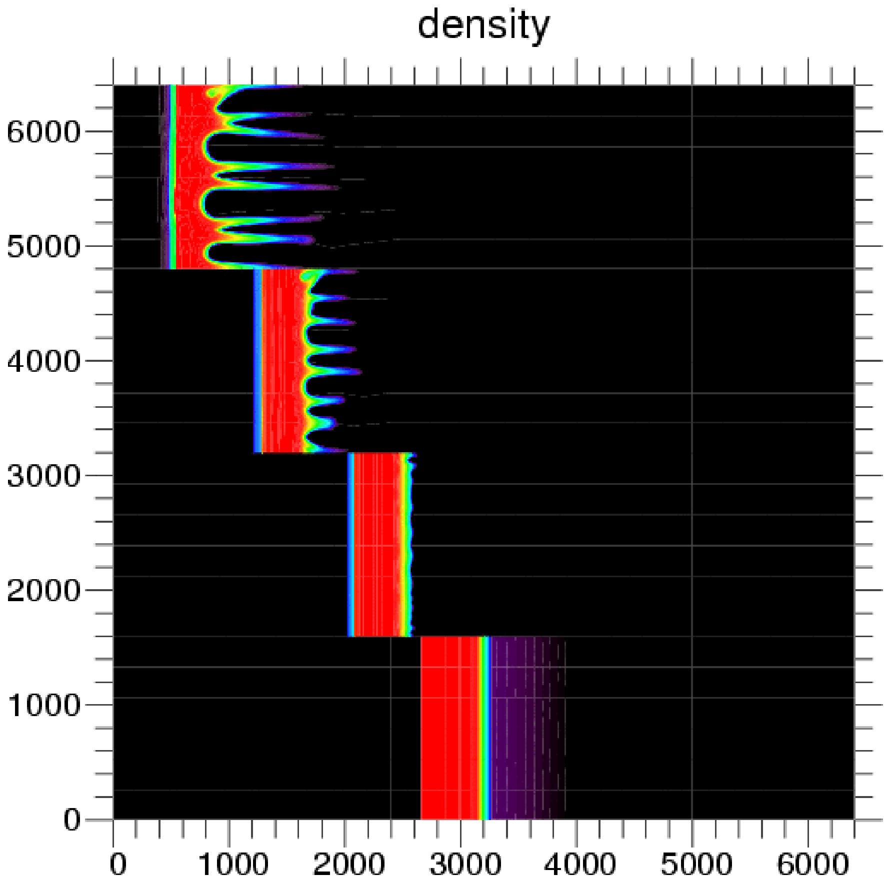
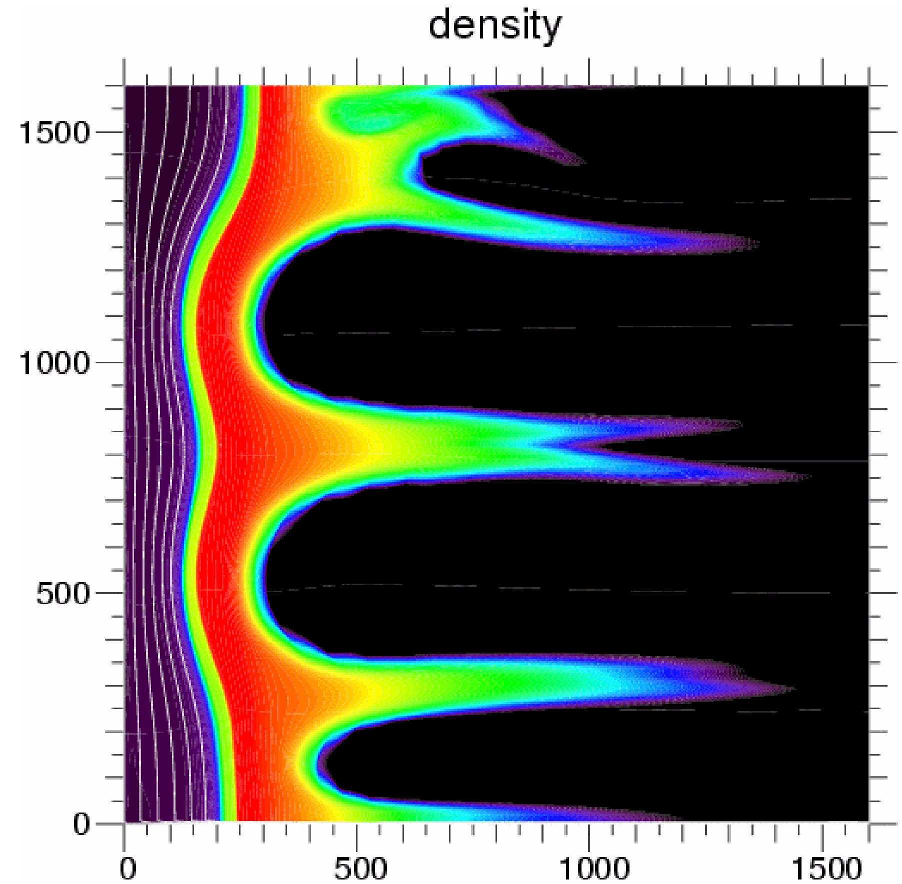
Magnetized Liner Inertial Fusion (MagLIF)* may be a promising path to high yields on Z, but liner integrity is critical





MRT predictions based on 2D LASNEX calculations

*S. A. Slutz *et al*., "Pulsed power driven cylindrical liner implosions with magnetized and preheated fuel" Phys. Plasmas **17**, 056303 (2010).

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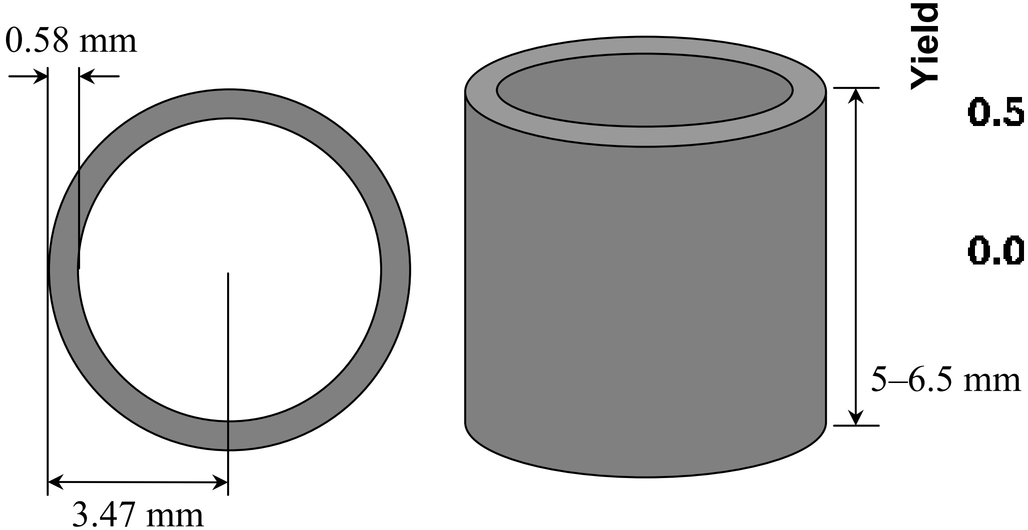
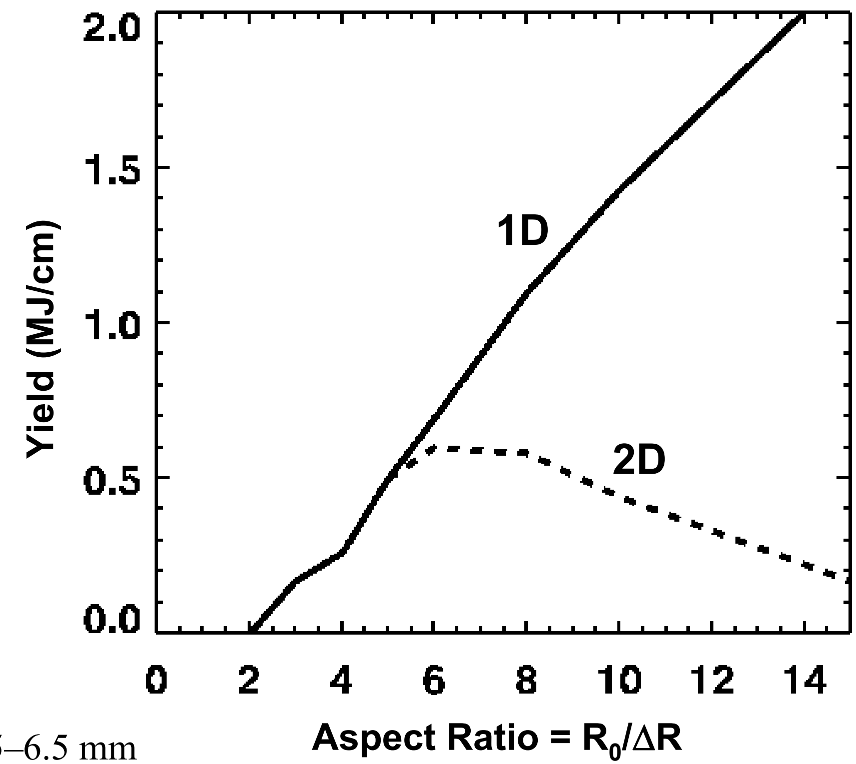
Magnetized Liner Inertial Fusion (MagLIF)* may be a promising path to high yields on Z, but liner integrity is critical

2-D MagLIF calculations to date suggest an Aspect Ratio 6 (AR=6) target will be reasonably robust to MRT instability degradation of the yield

- AR defined as initial liner outer radius divided by initial liner thickness
- AR=6:





*S. A. Slutz *et al*., "Pulsed power driven cylindrical liner implosions with magnetized and preheated fuel" Phys. Plasmas **17**, 056303 (2010).

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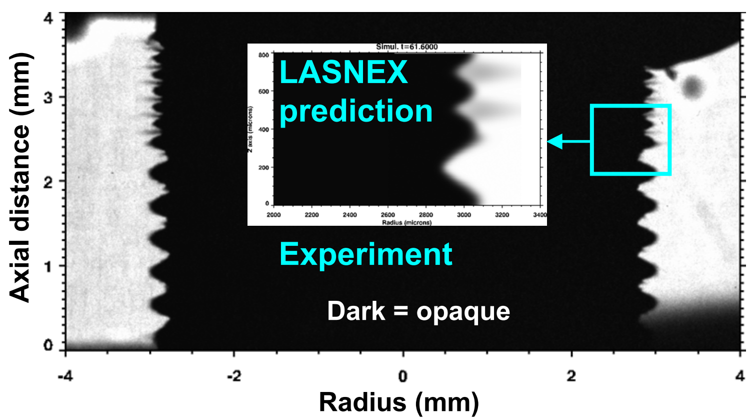
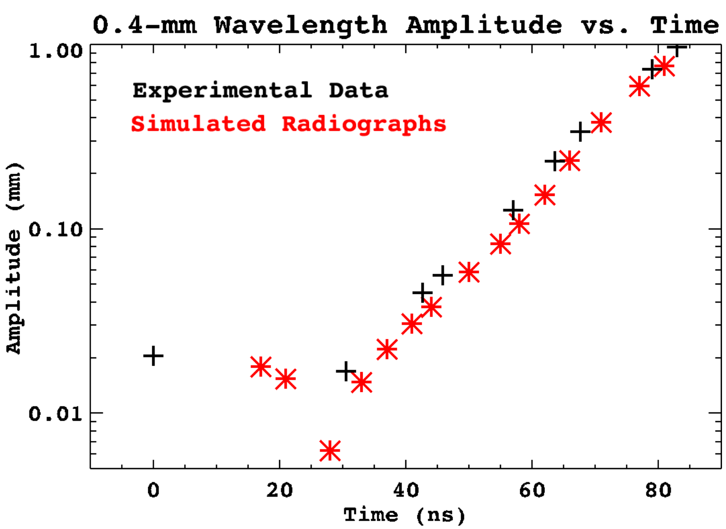
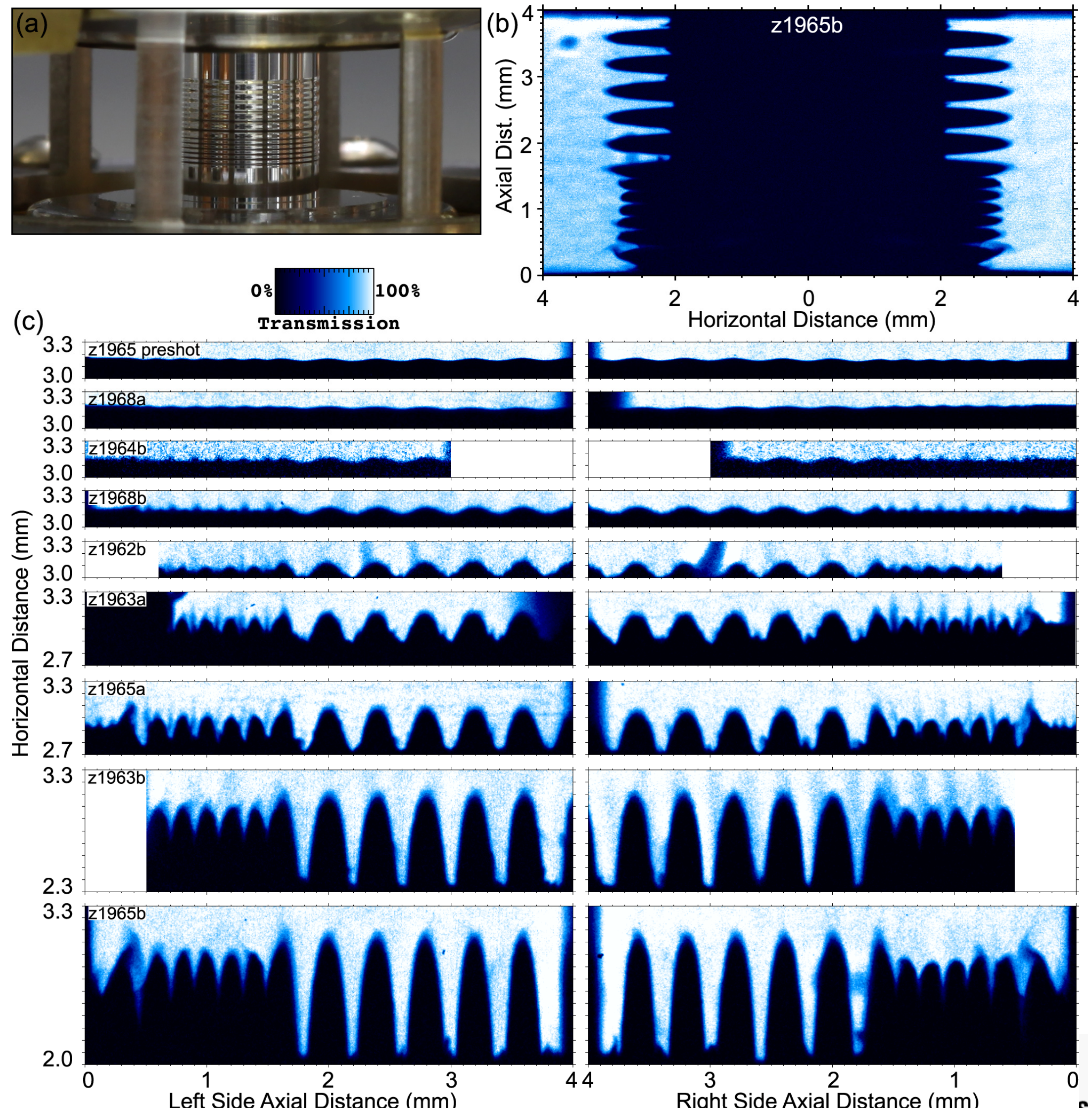
Excellent agreement between simulation and experiment for single-mode MRT growth experiments with aluminum

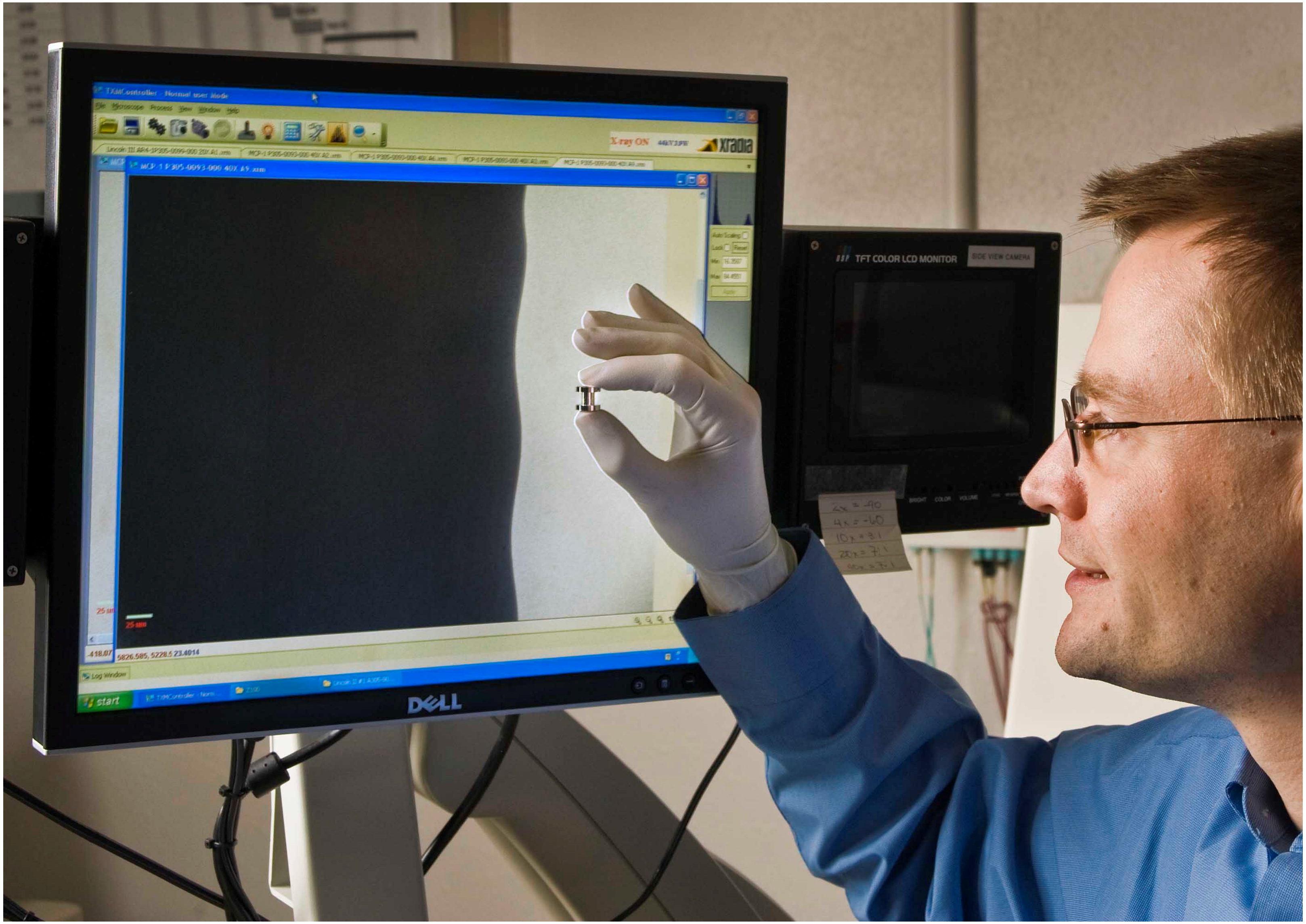
*D.B. Sinars *et al.*, Phys. Rev. Lett. (2010).
*D.B. Sinars *et al.*, Phys. Plasmas (2010).







Target Scale-Size



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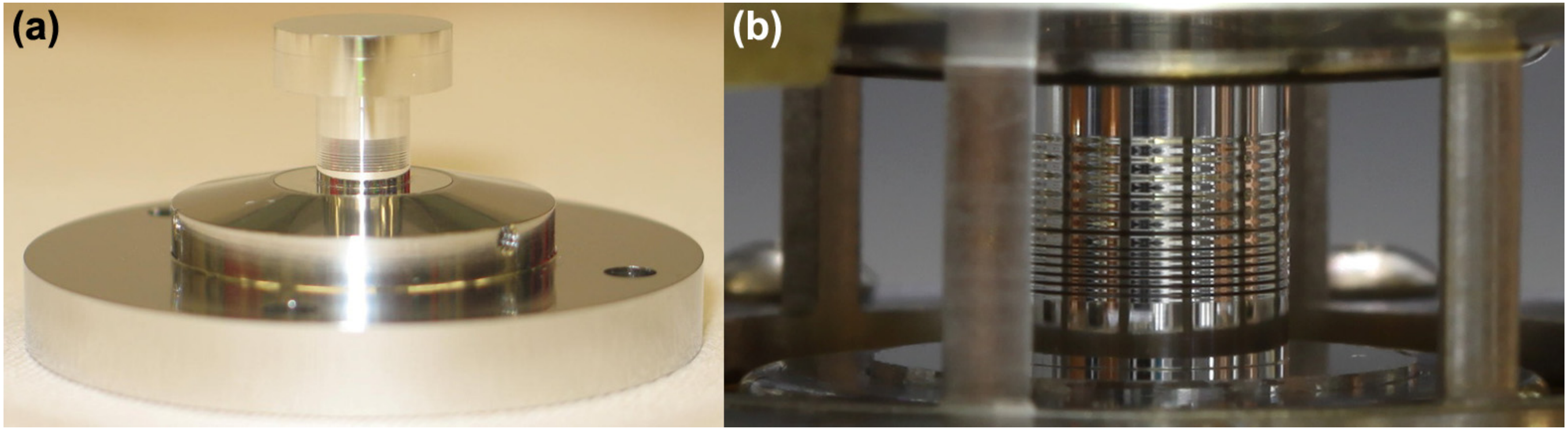
Targets



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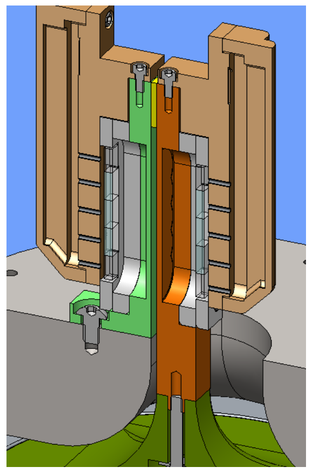
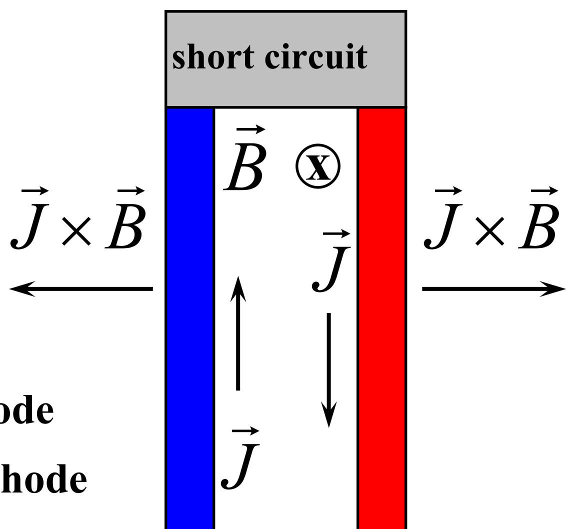
Dynamic Materials / EOS Standard Platforms for Shock Hugoniot and Isentropic Compression Experiments use Planar Geometries

Planar Stripline

- Samples and flyers on both electrodes
- Exploding system



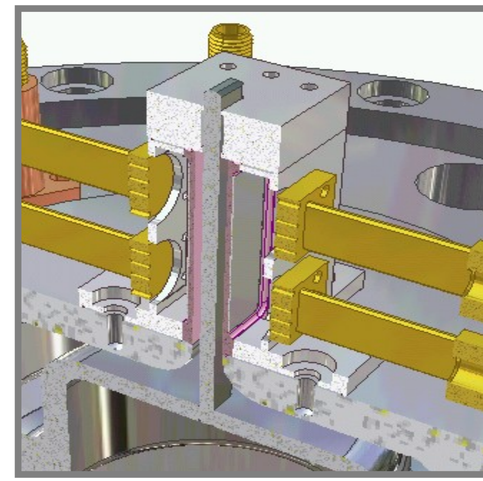


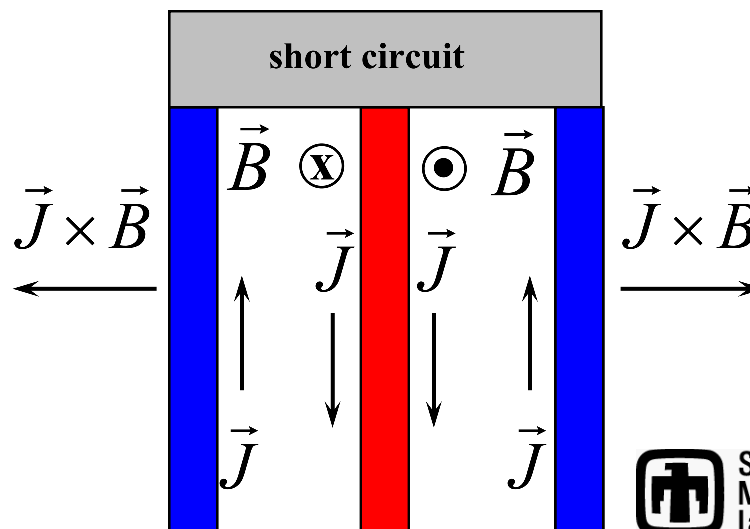
= anode

= cathode

Rectangular "coaxial"

- Samples and flyers on anodes only
- Exploding system





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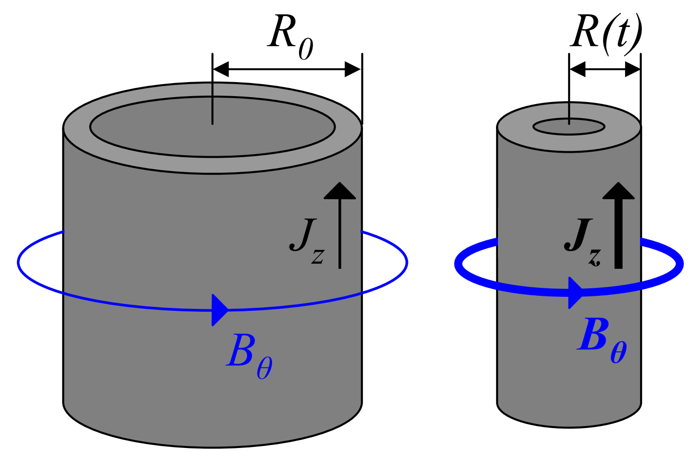
Higher Pressures Possible with Cylindrical Geometry

Magnetically-Driven Cylindrical Implosion
(Implosion Drive Pressure is Divergent!):

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

140 MBar is generated by a 300-eV radiation drive



<u>Liner = Material Sample</u>

– Measure drive pressure
– Measure sample density

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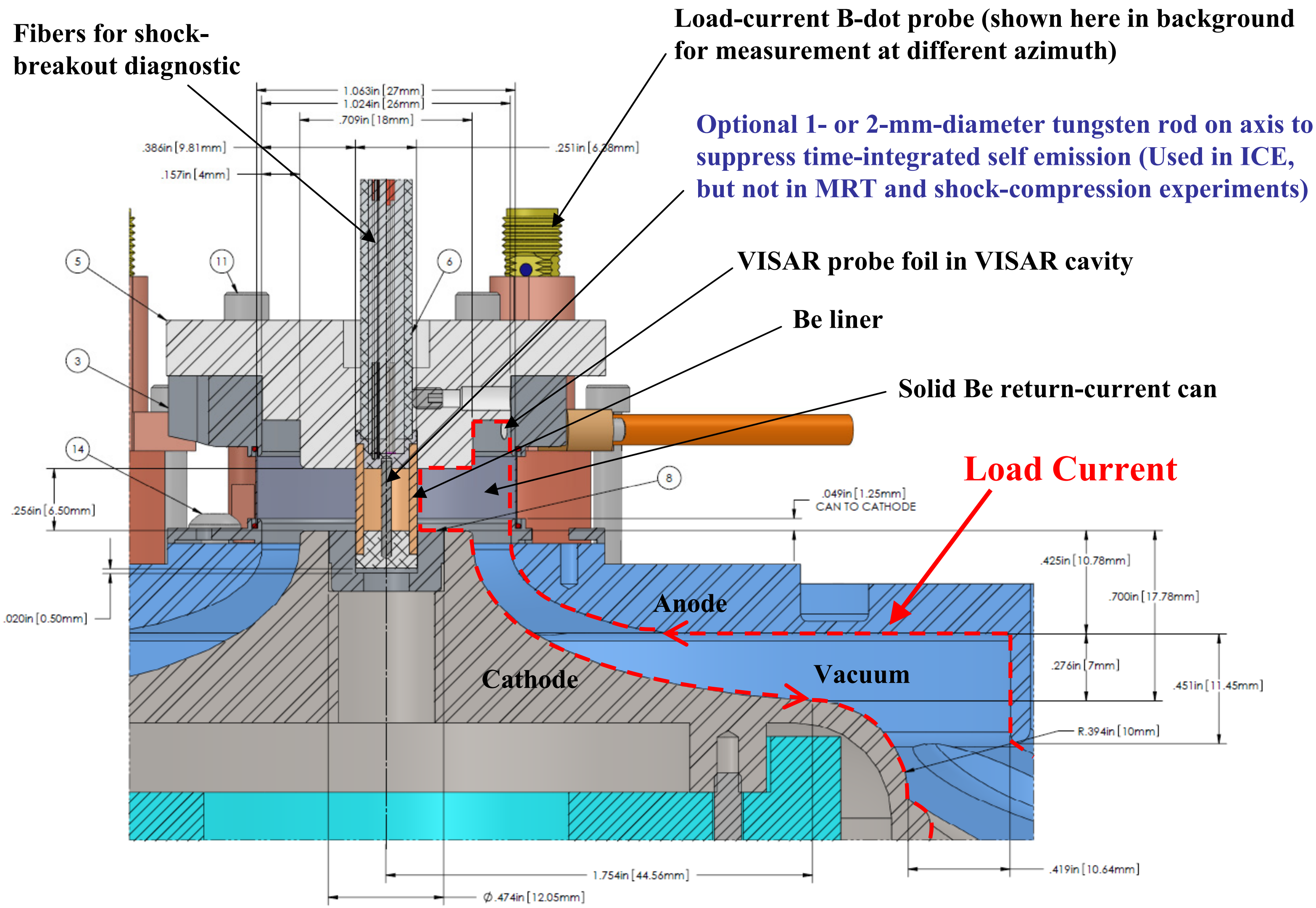
Beryllium Liner Setup for MRT, Shock-Compression, and Isentropic-Compression Experiments



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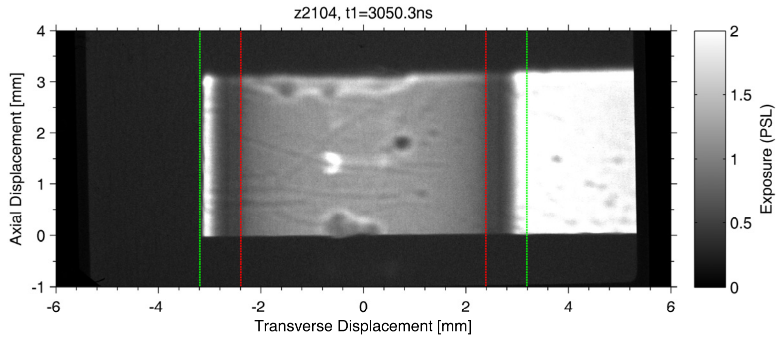
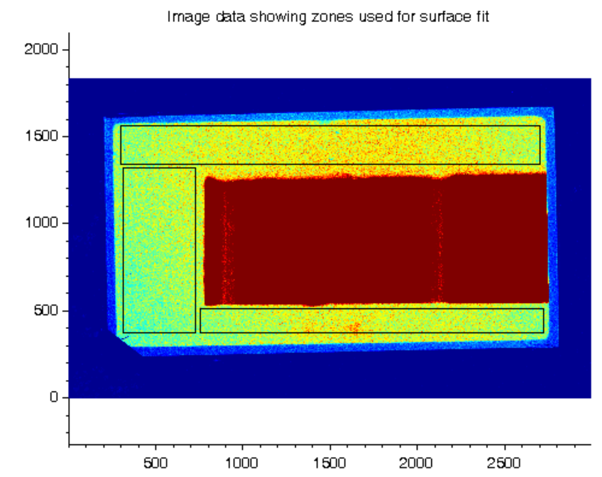
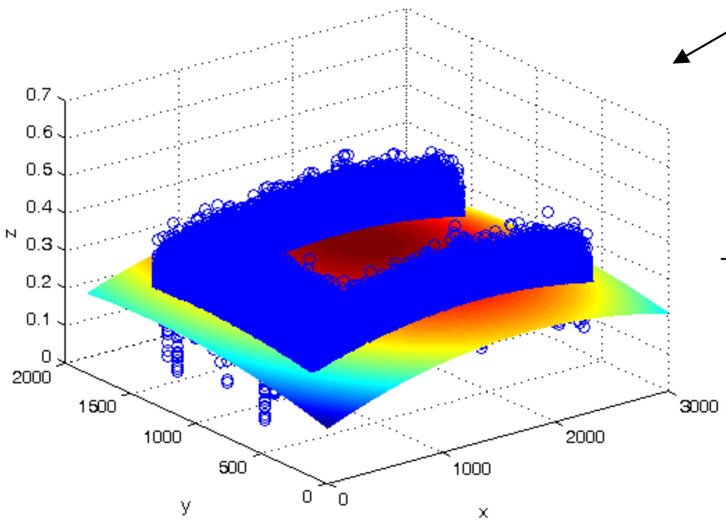
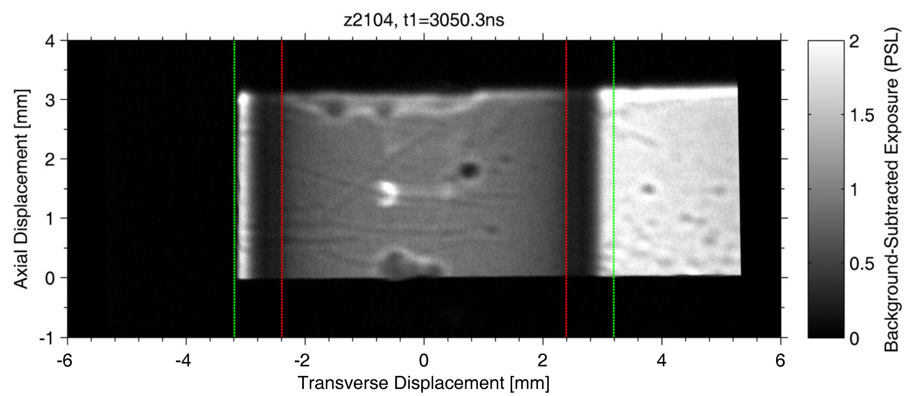
Radiograph Processing

Exposure to Background-subtracted Exposure:









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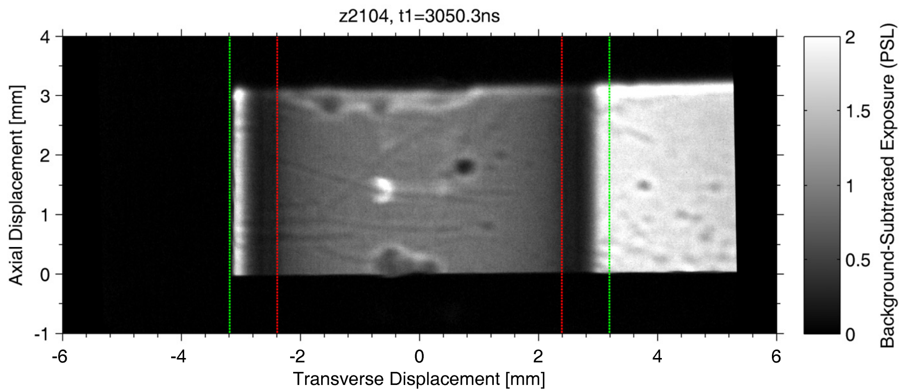
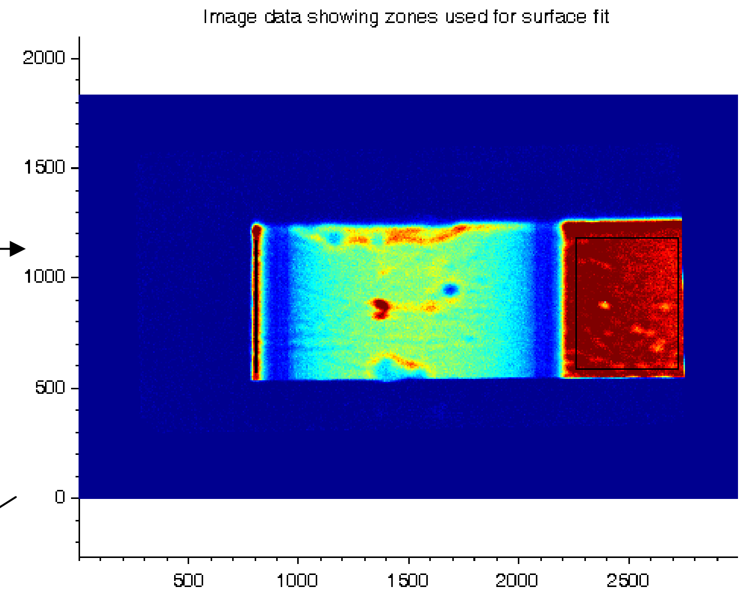
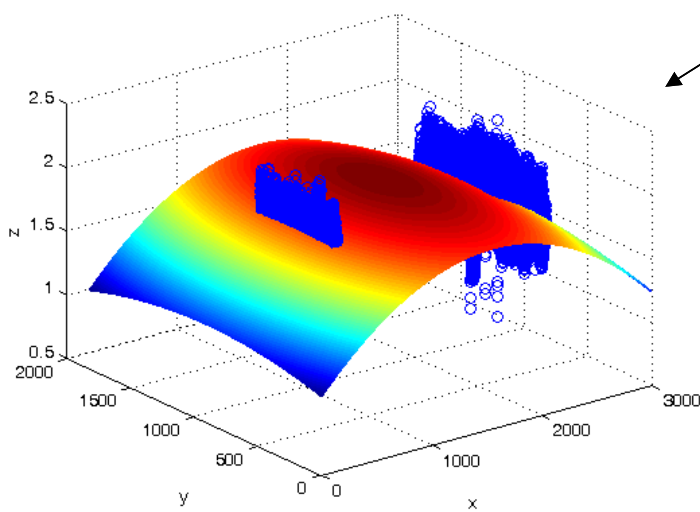
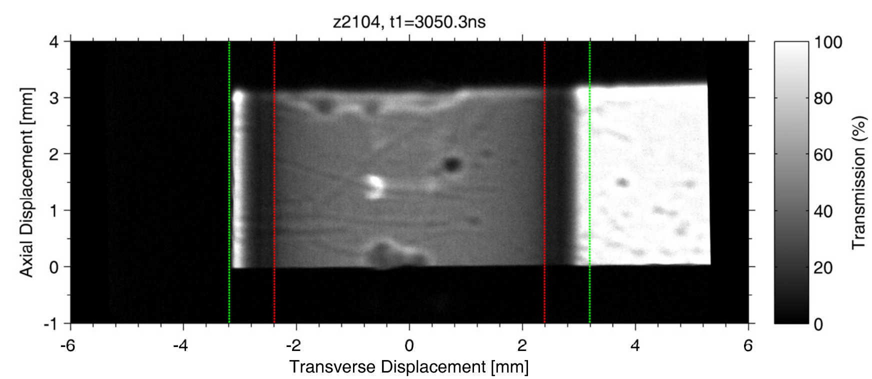
Radiograph Processing

Background-subtracted exposure to transmission:









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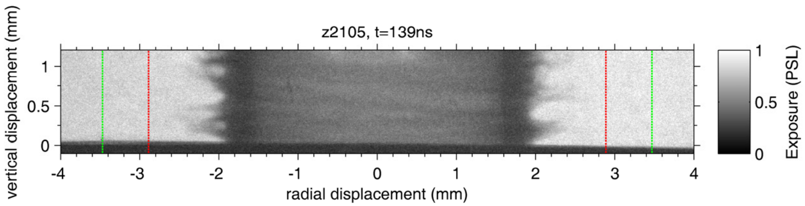
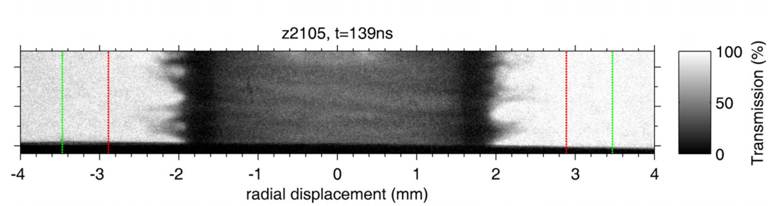
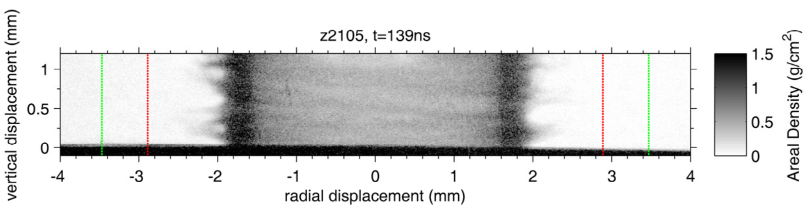
Processing of Be Liner Radiographs:



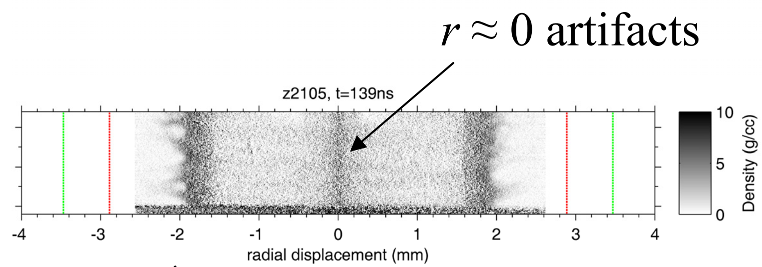
Exposure (PSL) to Transmission



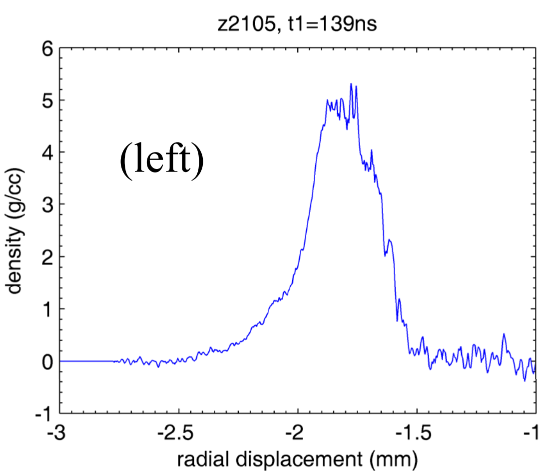
Transmission to Areal Density

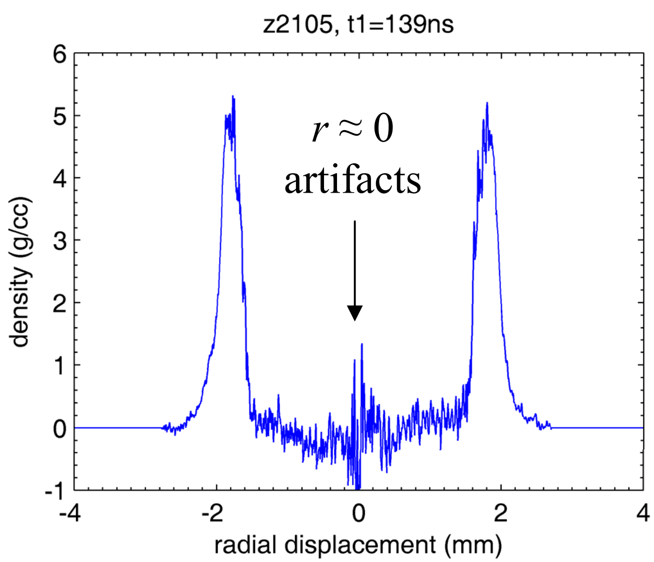


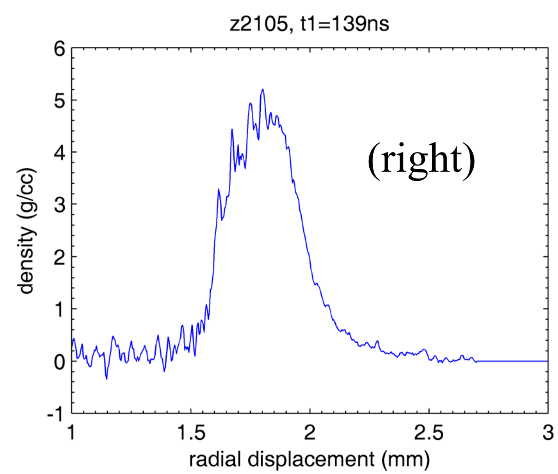
Areal Density to Volume Density Slice (Abel Inversion)



Volume Density Slice to Density Profile







Be, AR=6:

$r_{inner,0}$ = 2.89 mm

$r_{outer,0}$ = 3.47 mm

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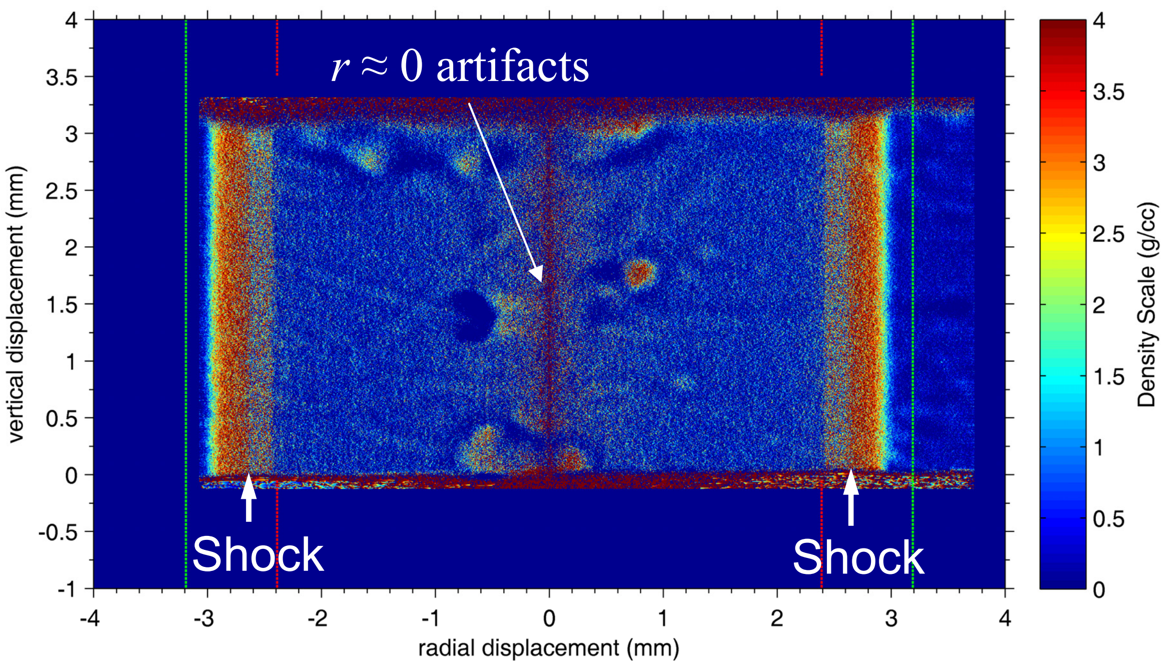
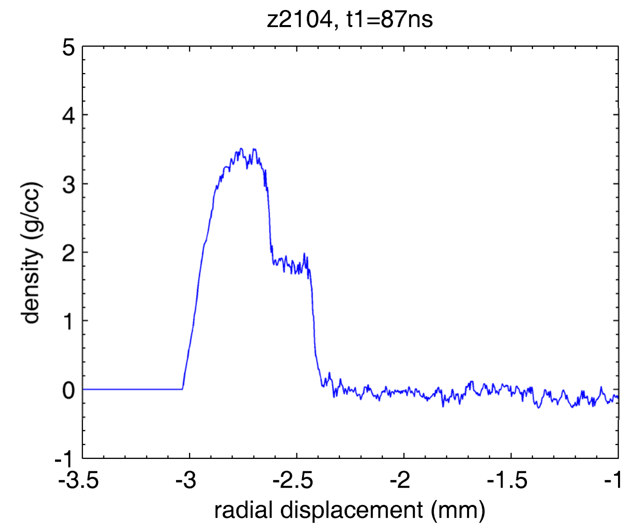
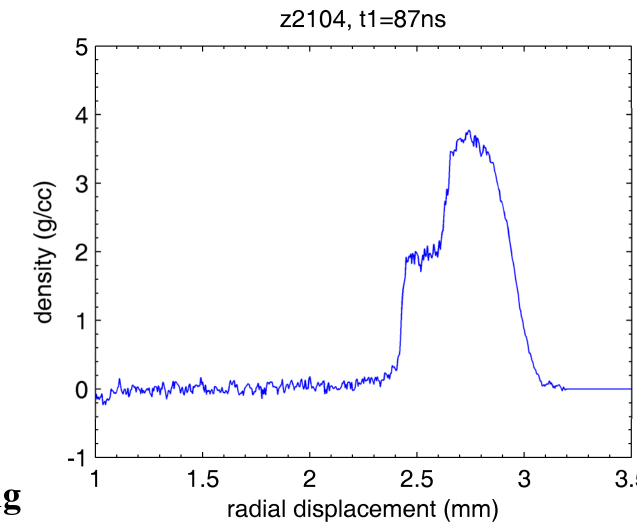
Beryllium liners also useful for ***shock equation-of-state*** experiments*,**







R. W. Lemke, *et al.
M. R. Martin, *et al.

- **Excellent agreement established between simulation and experiment density profiles**
- **Have measured shock density & velocity jump conditions (and drive pressure) for test of existing Be EOS on shock Hugoniot, with the possibility of extending the Be EOS with future experiments**

AR=4:
$r_{inner,0}$ = 2.39 mm
$r_{outer,0}$ = 3.19 mm

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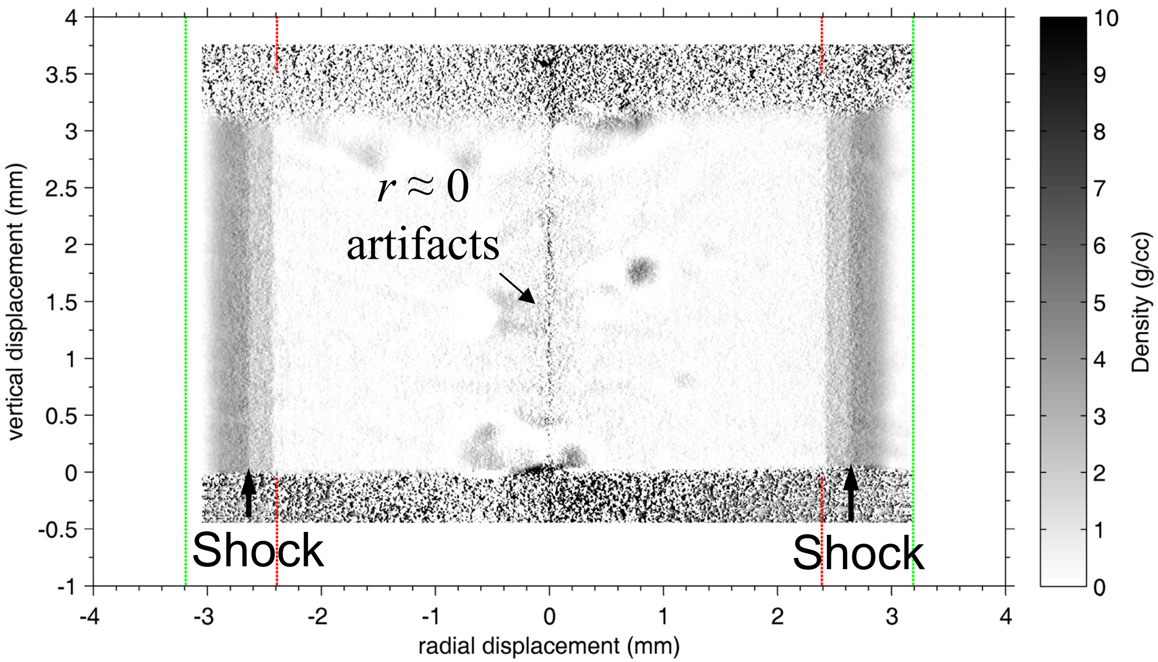

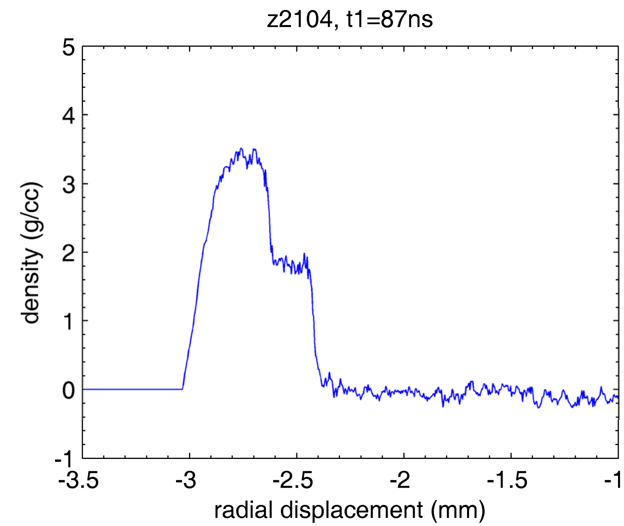

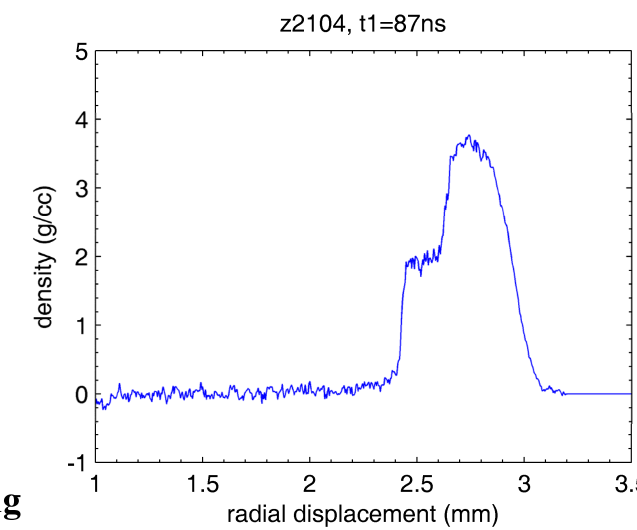

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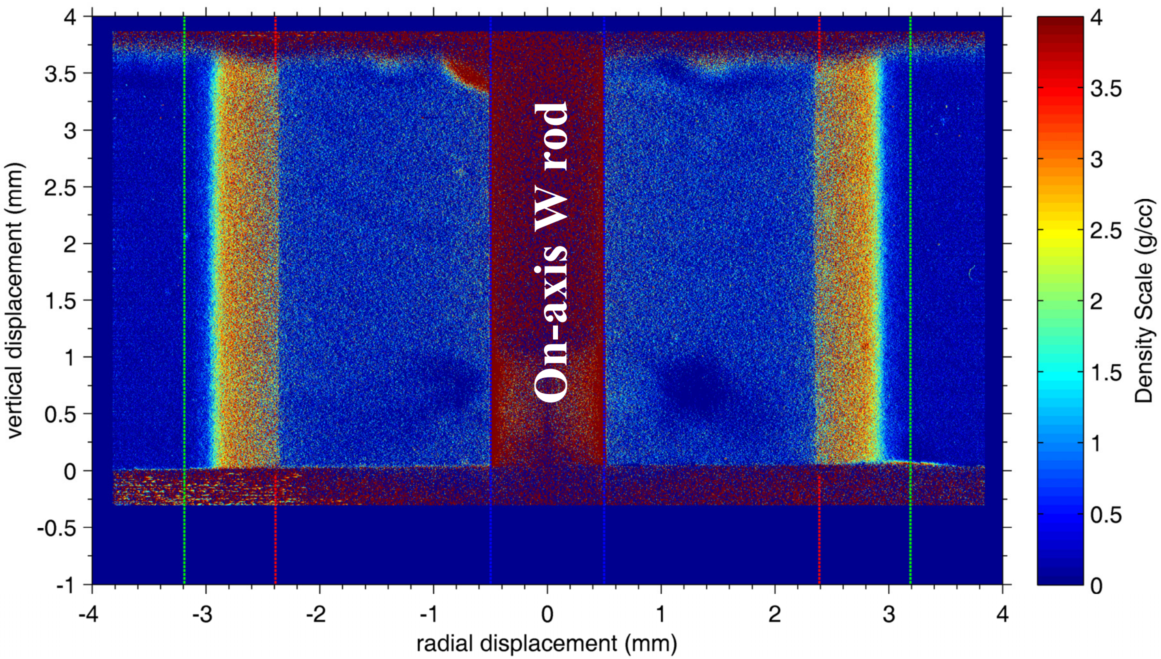
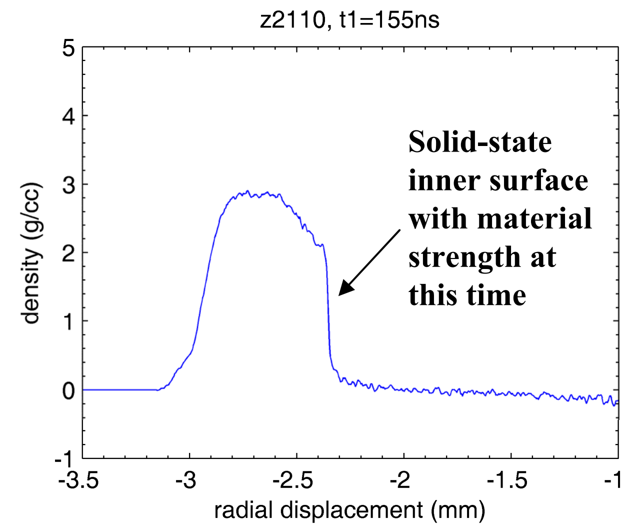
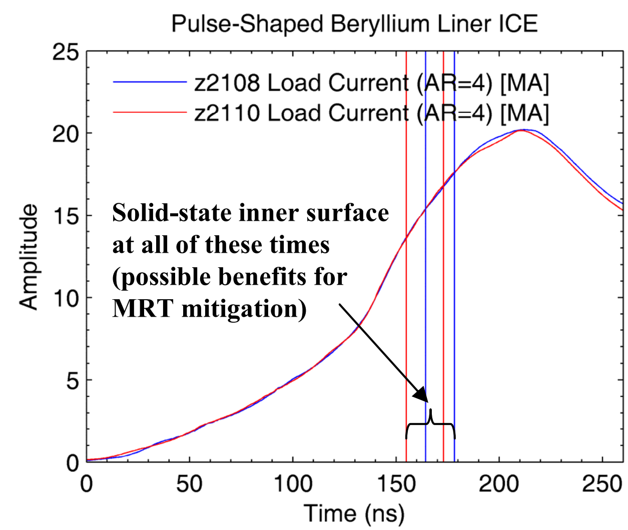
Beryllium liners also useful for ***quasi-isentropic compression equation-of-state*** experiments*,**







R. W. Lemke, *et al.
M. R. Martin, *et al.

- **Excellent agreement established between simulation and experiment density profiles**
- **Un-shocked quasi-isentropic compression experiments for test of existing Be EOS on isentrope, with the possibility of extending the Be EOS with future experiments**

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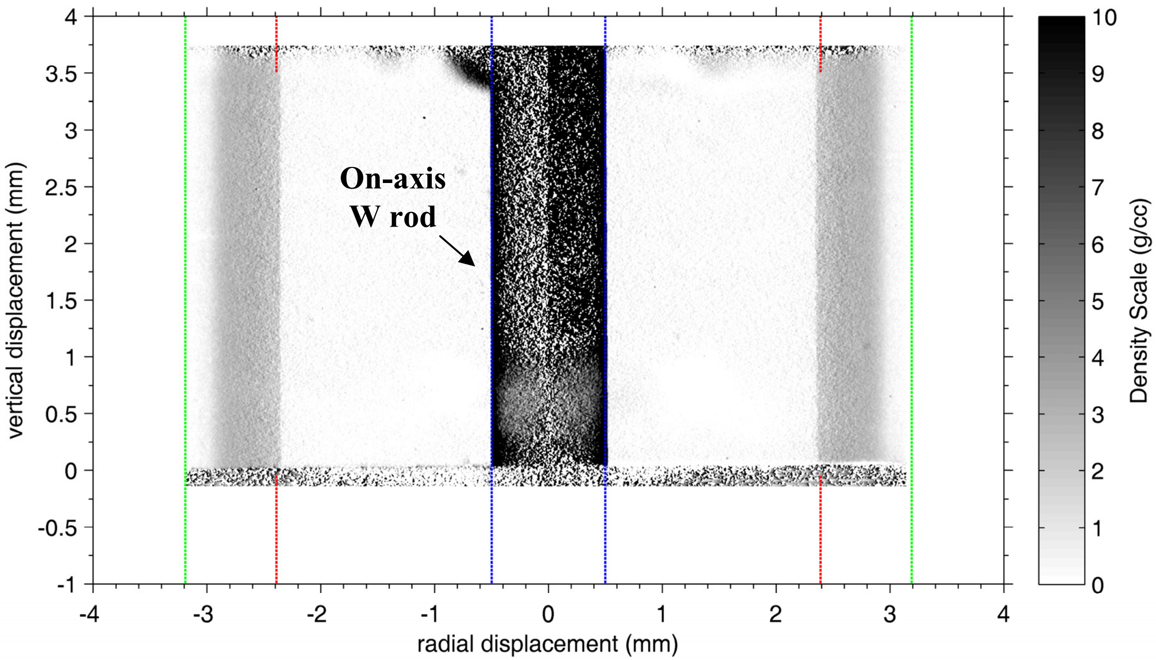
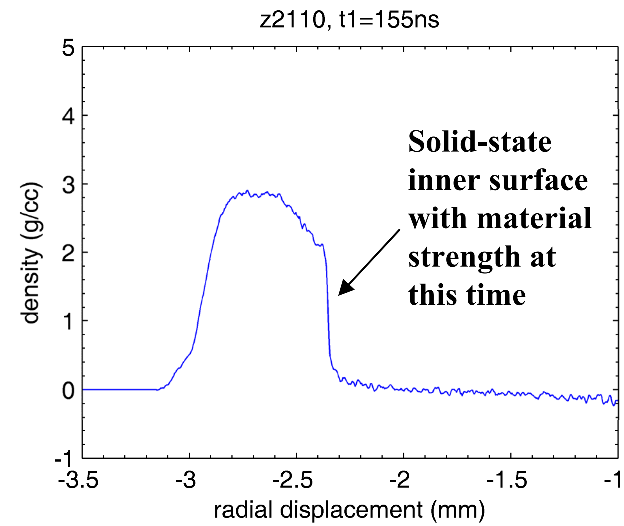
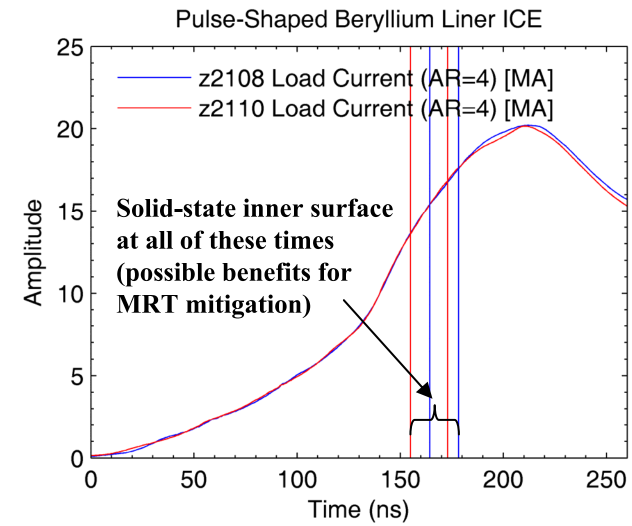
Beryllium liners also useful for ***quasi-isentropic compression equation-of-state*** experiments*,**





R. W. Lemke, *et al.
M. R. Martin, *et al.



- **Excellent agreement established between simulation and experiment density profiles**
- **Un-shocked quasi-isentropic compression experiments for test of existing Be EOS on isentrope, with the possibility of extending the Be EOS with future experiments**

AR=4:

$r_{inner,0}$ = 2.39 mm

$r_{outer,0}$ = 3.19 mm

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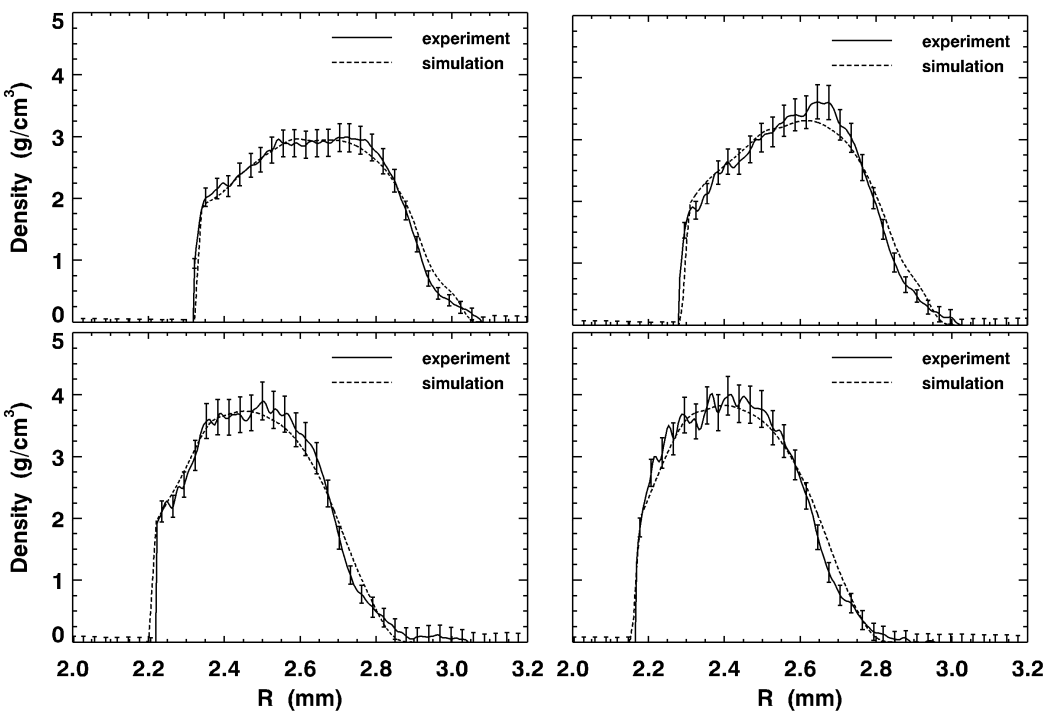
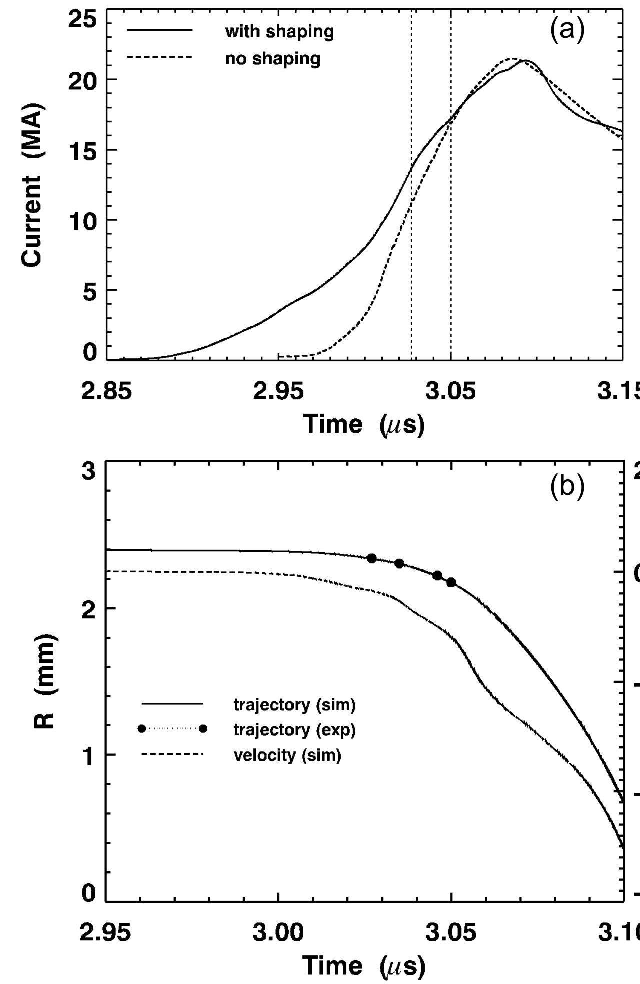
Radiography of imploding Be liners for Isentropic Compression Experiments





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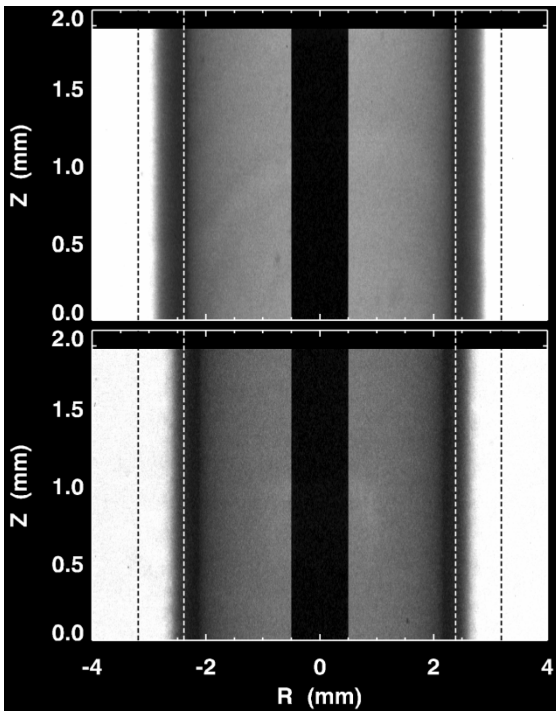
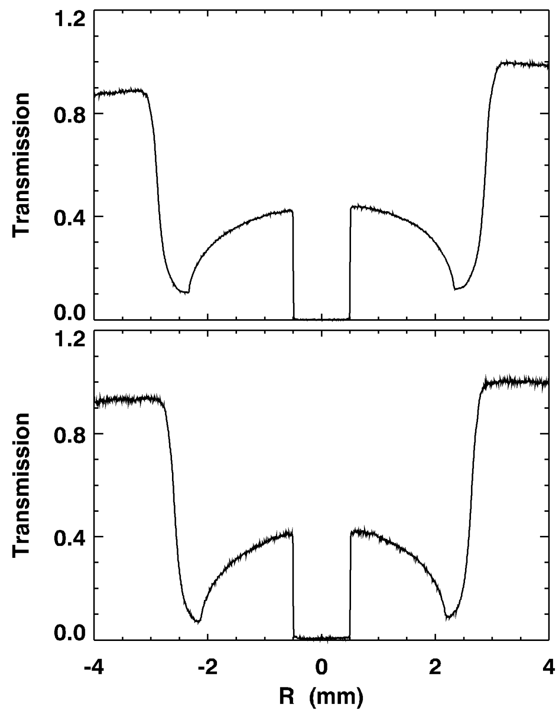
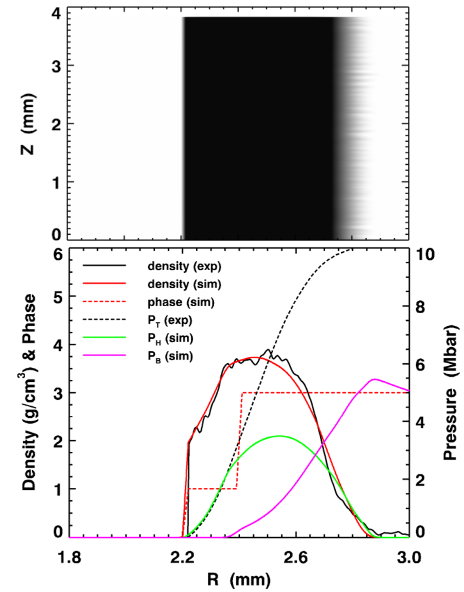
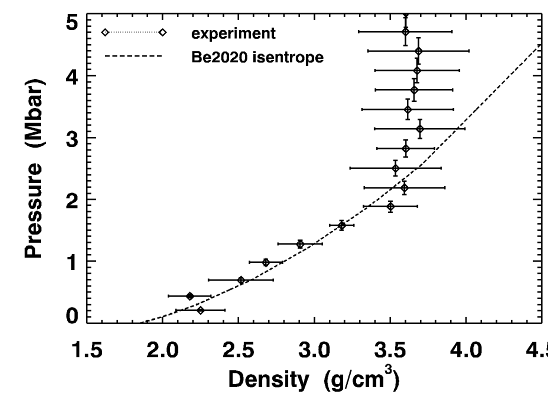
Radiography of imploding Be liners for Isentropic Compression Experiments

Isentropic Compression Liner Experiments









*R.L. Lemke, M.R. Martin *et al.*

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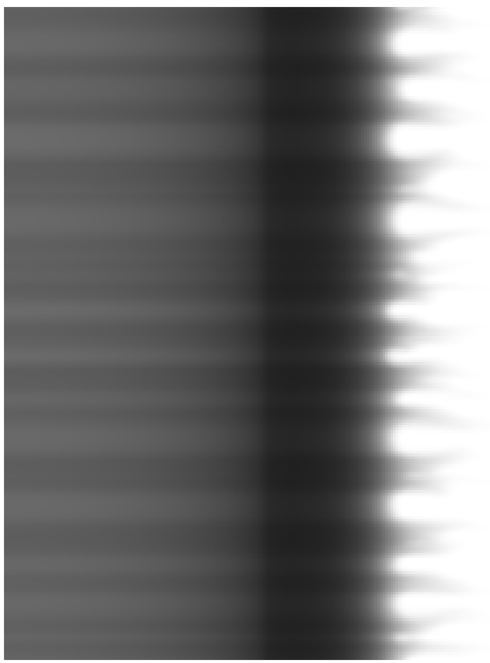
* ALEGRA simulations by R. L. Lemke and M. R. Martin

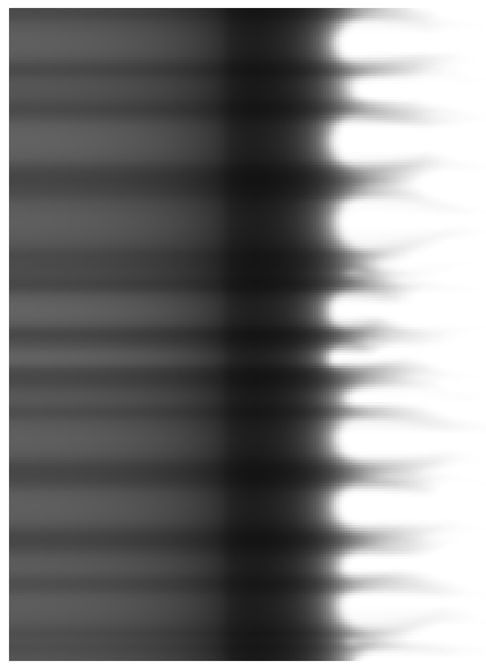
Future isentropic compression measurements to >10 Mbar might be possible on Z

Synthetic radiographs from 2D ALEGRA simulations show the impact of MRT on the intensity profiles, which might limit our ability to unfold the isentrope at very high pressures

P* ~ 4Mbar



P* ~ 8Mbar



P* ~ 12Mbar

P* -> Peak Pressure in Solid Phase

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Outline

- Introduction to Sandia facilities
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- Motivation for beryllium liner z-pinch implosions
  - Inertial confinement fusion (ICF) & magneto-Rayleigh-Taylor (MRT) studies
  - Dynamic materials (DM) and equation-of-state (EOS) studies
- EOS experiments and data
  - Shock Compression
  - Isentropic Compression
- **MRT experiments and data**
- Summary

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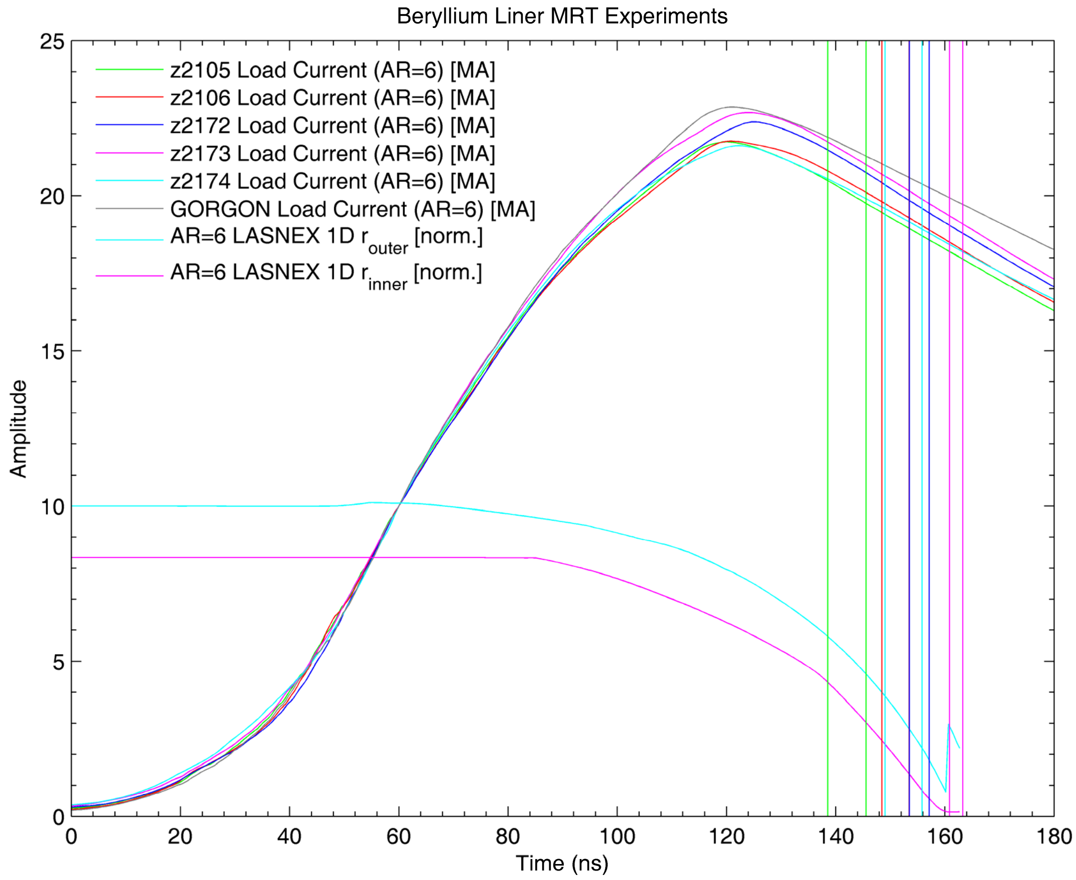
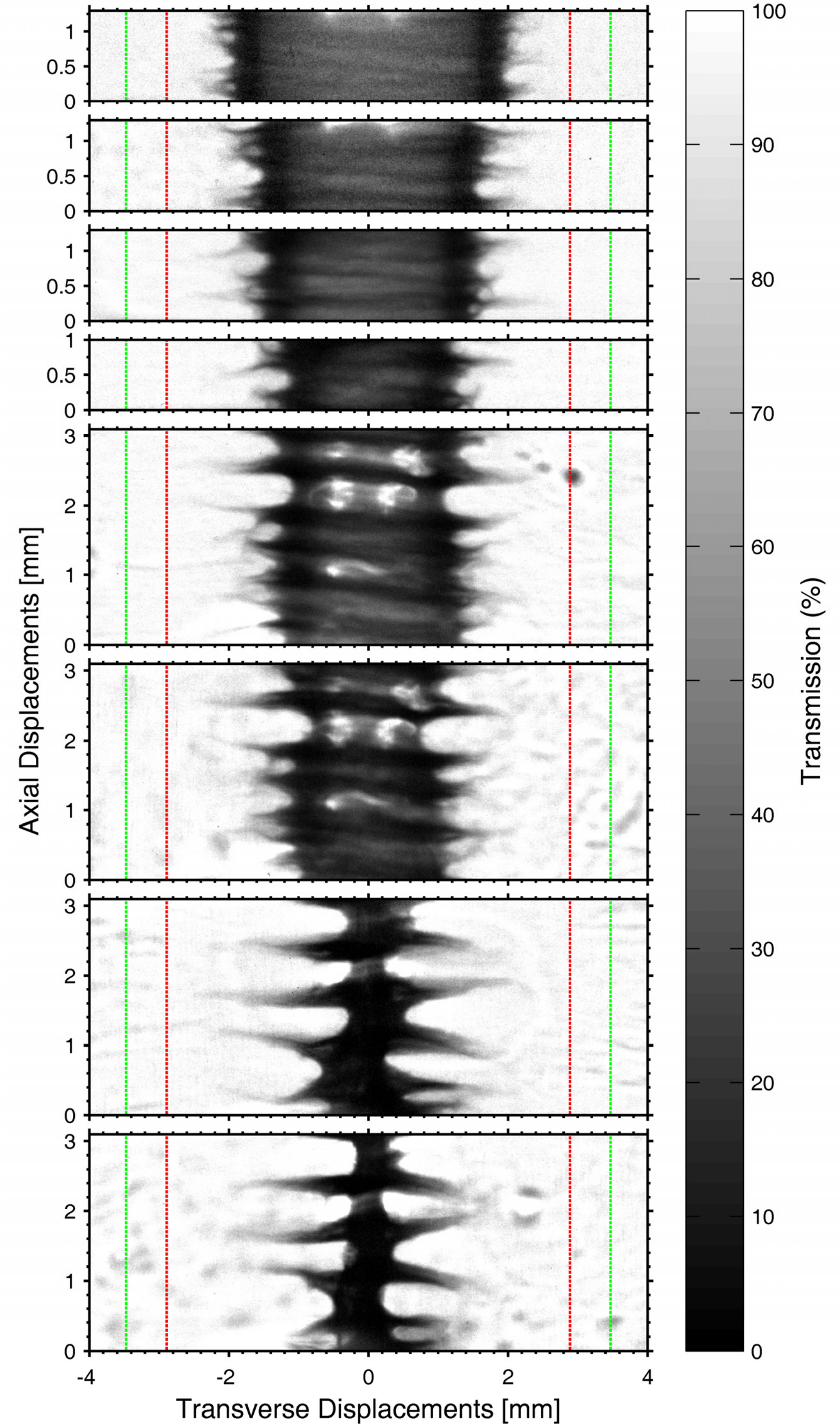
Beryllium MRT Data

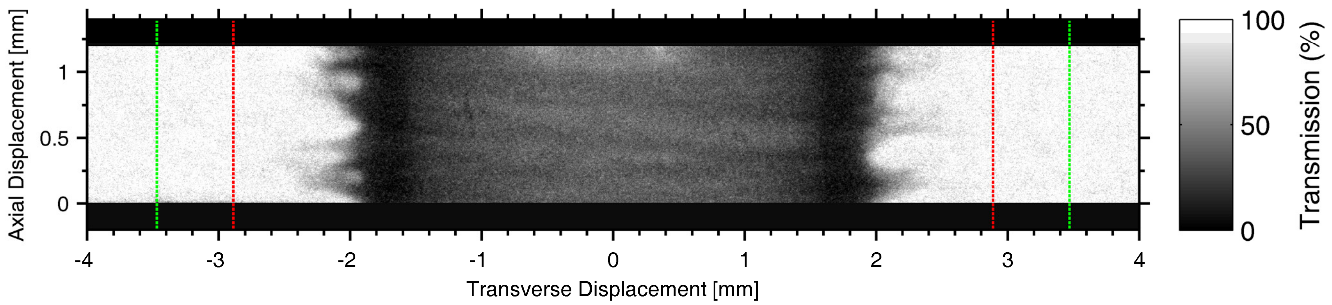


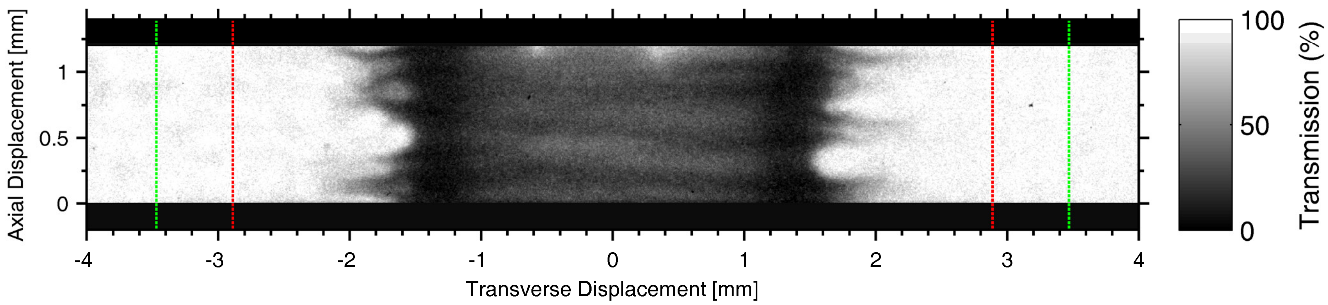


AR=6:

$r_{inner,0}$ = 2.89 mm

$r_{outer,0}$ = 3.47 mm


Axial Displacement [mm]
1
0.5
0
-4
-3
-2
-1
0
1
2
3
4
Transverse Displacement [mm]
100
50
0
Transmission (%)



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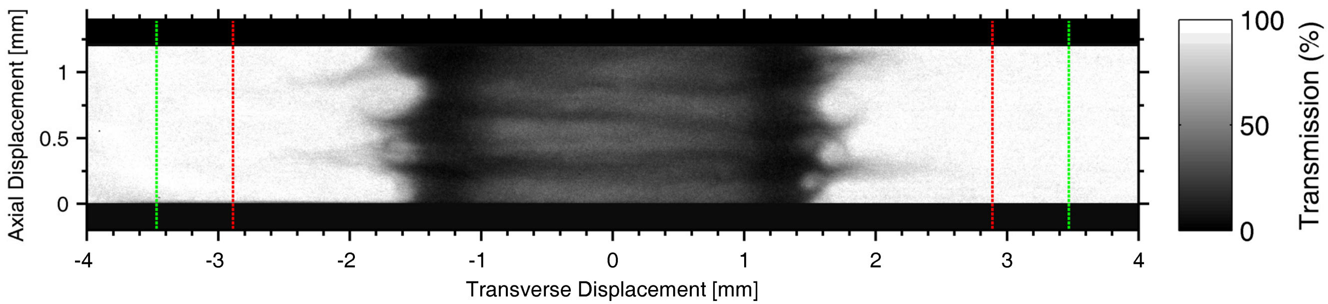

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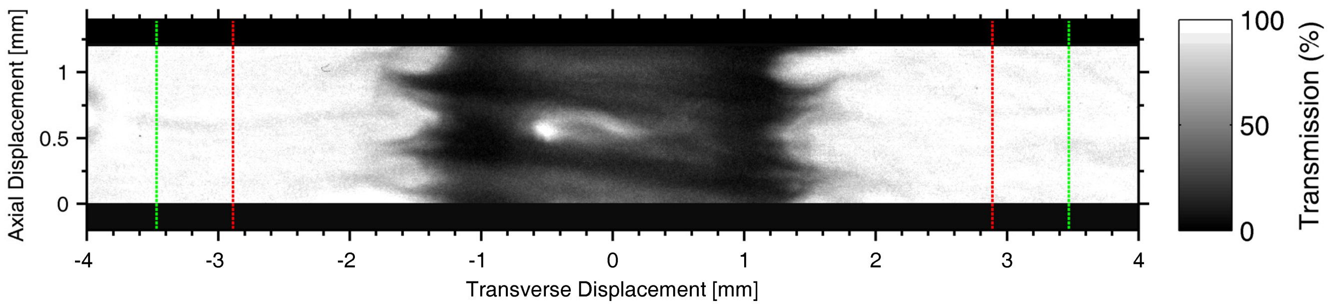
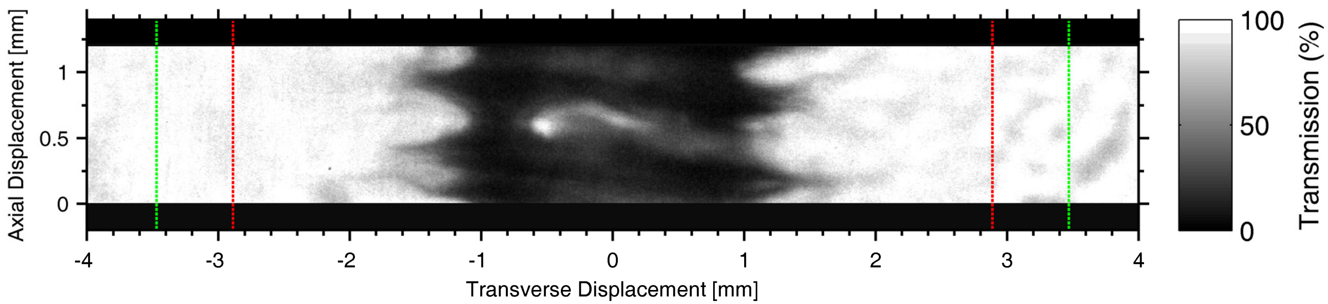


Axial Displacement [mm]
1
0.5
0
-4
-3
-2
-1
0
1
2
3
4
Transverse Displacement [mm]
100
50
0
Transmission (%)



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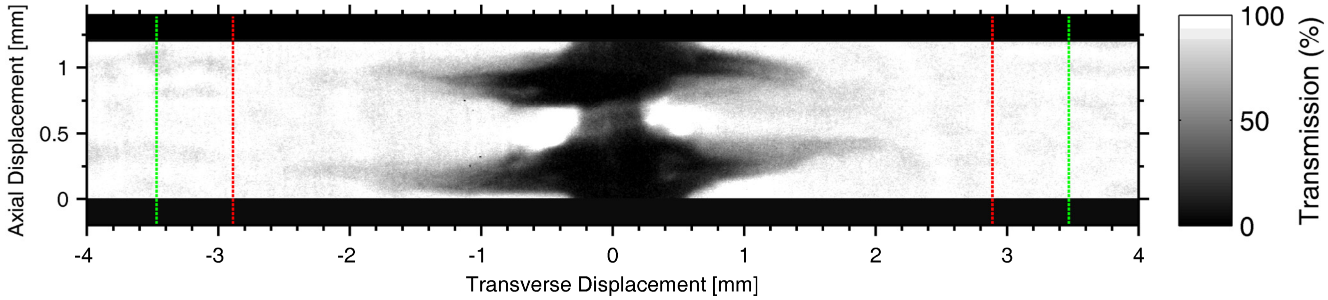
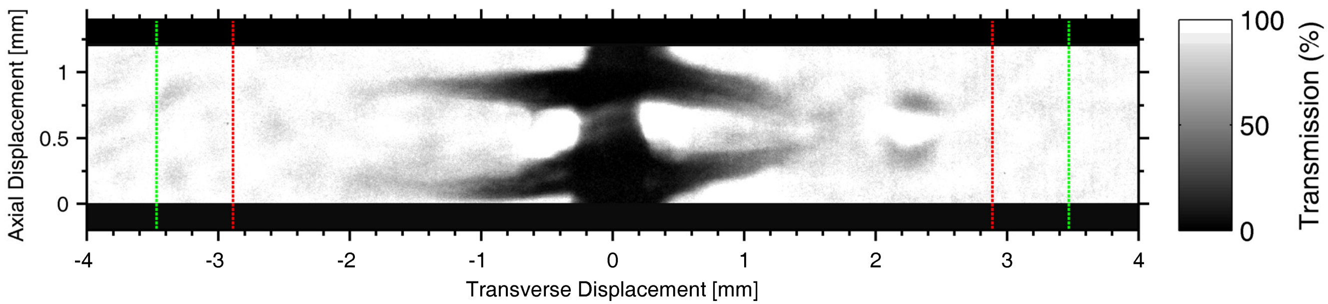
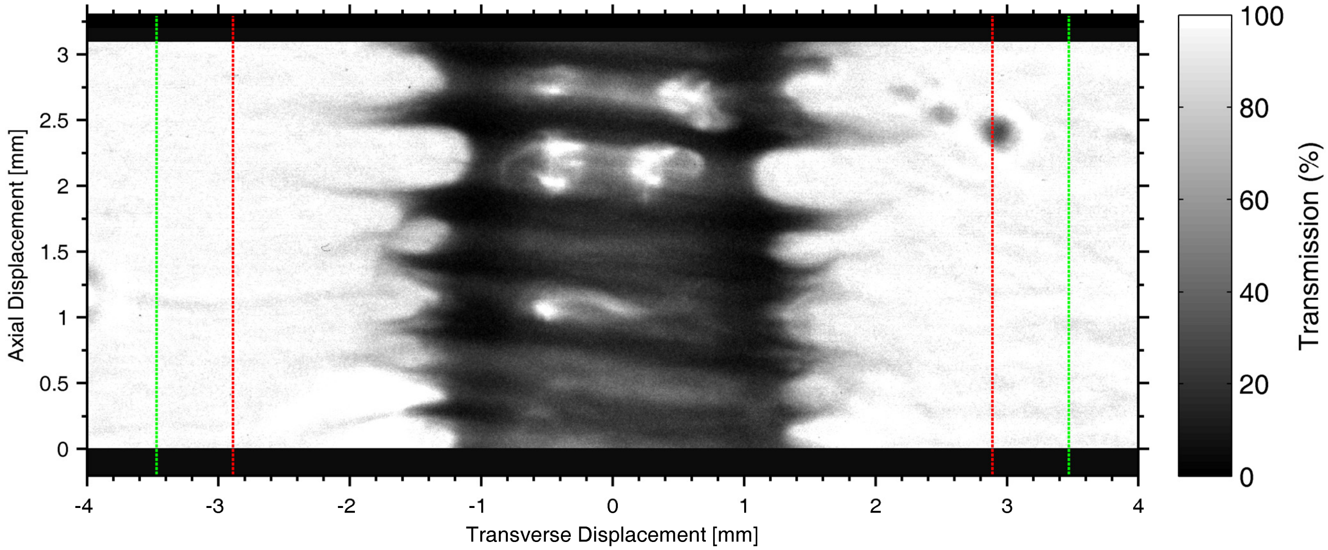

Axial Displacement [mm]
1
0.5
0
-4
-3
-2
-1
0
1
2
3
4
Transverse Displacement [mm]
100
50
0
Transmission (%)



Axial Displacement [mm]
1
0.5
0
-4
-3
-2
-1
0
1
2
3
4
Transverse Displacement [mm]
100
50
0
Transmission (%)



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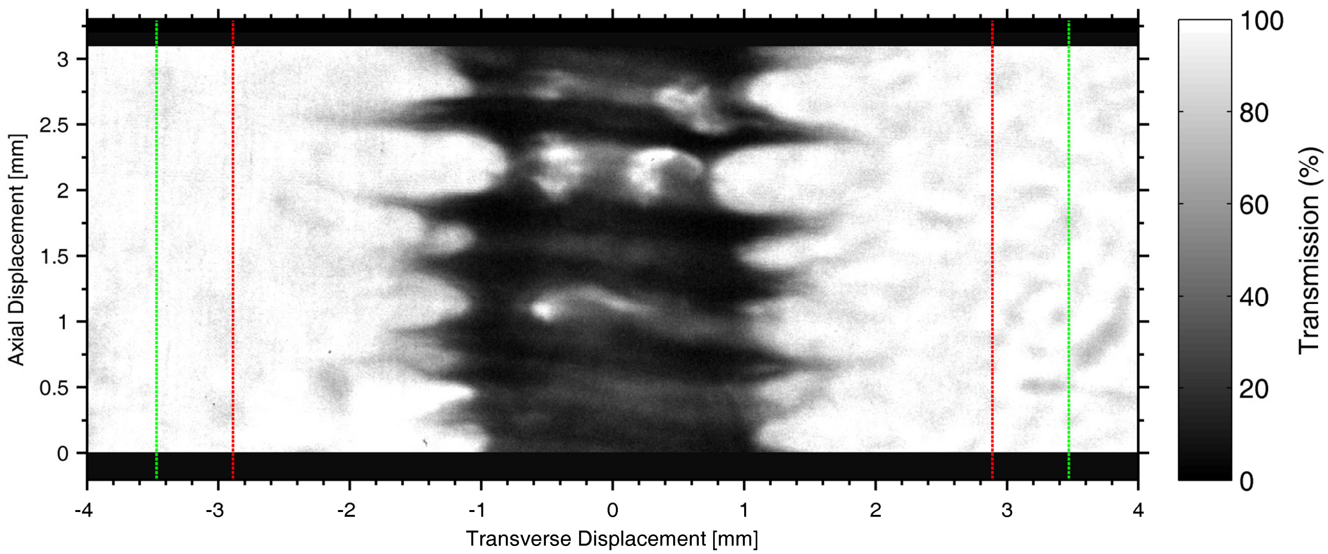

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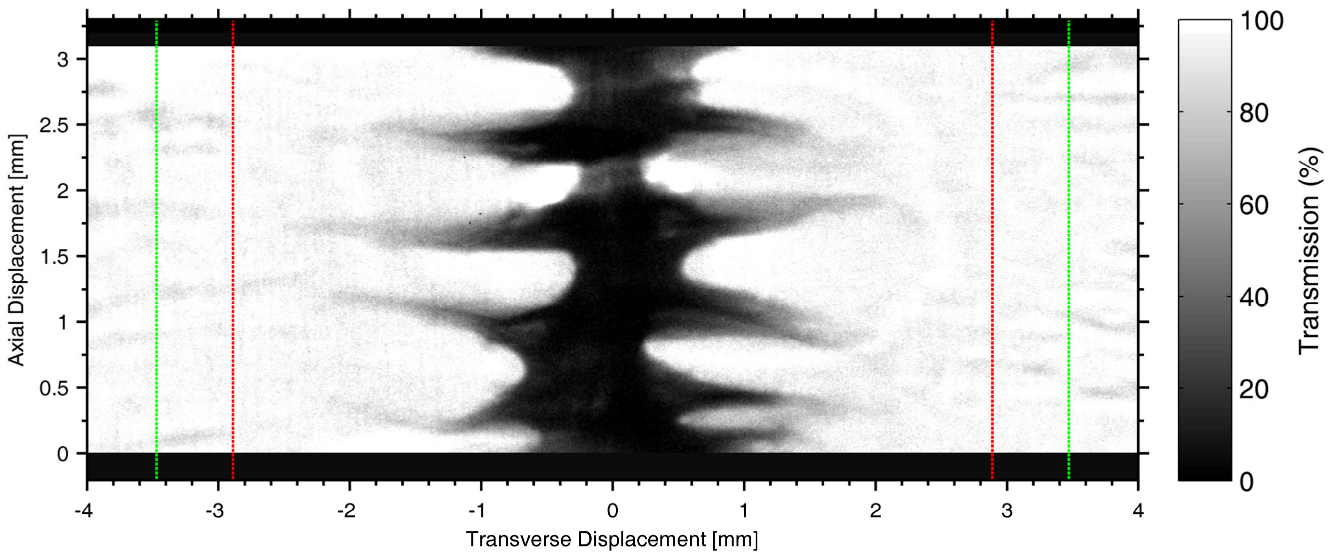

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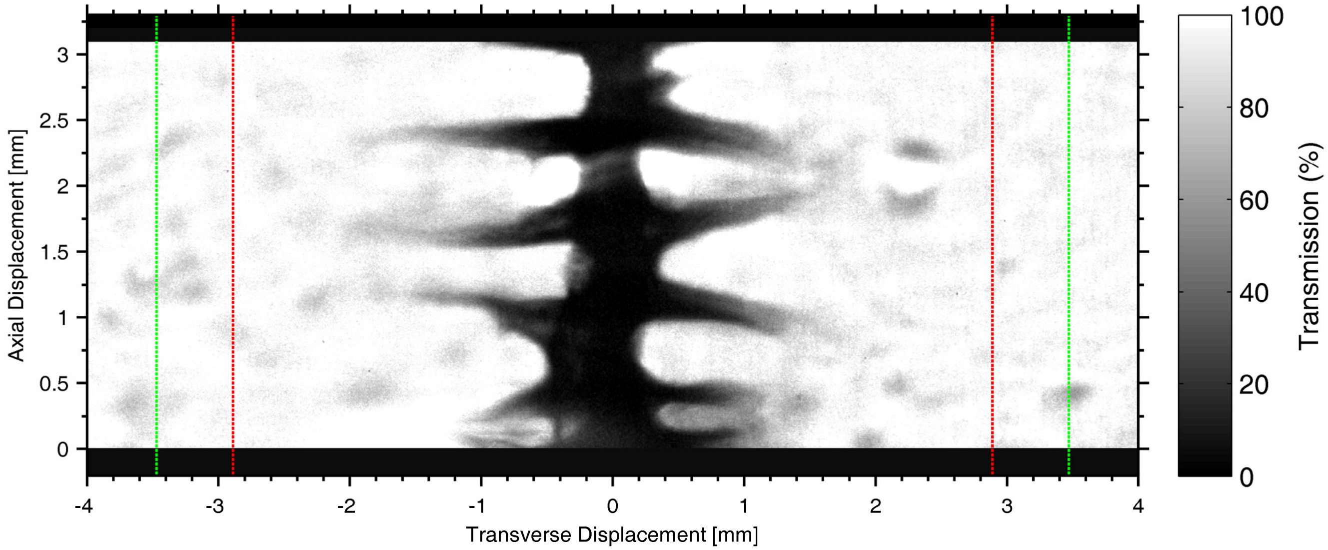

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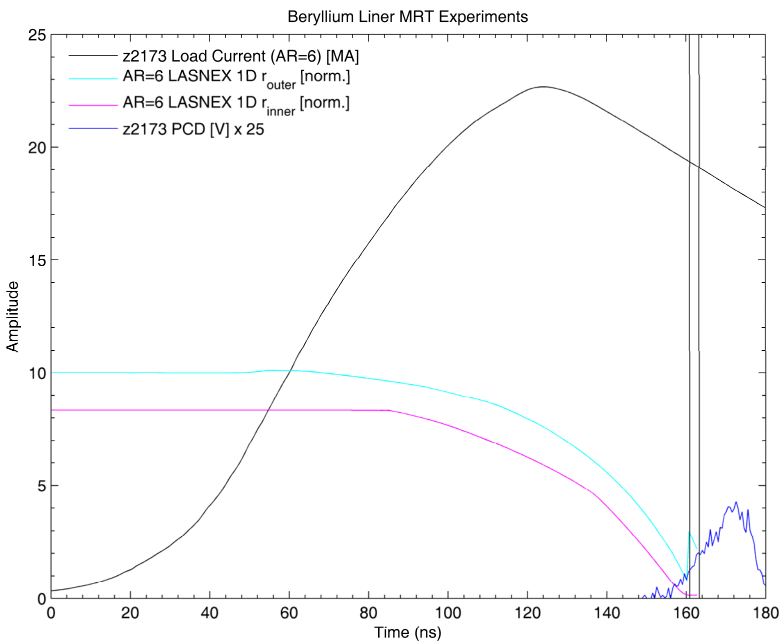
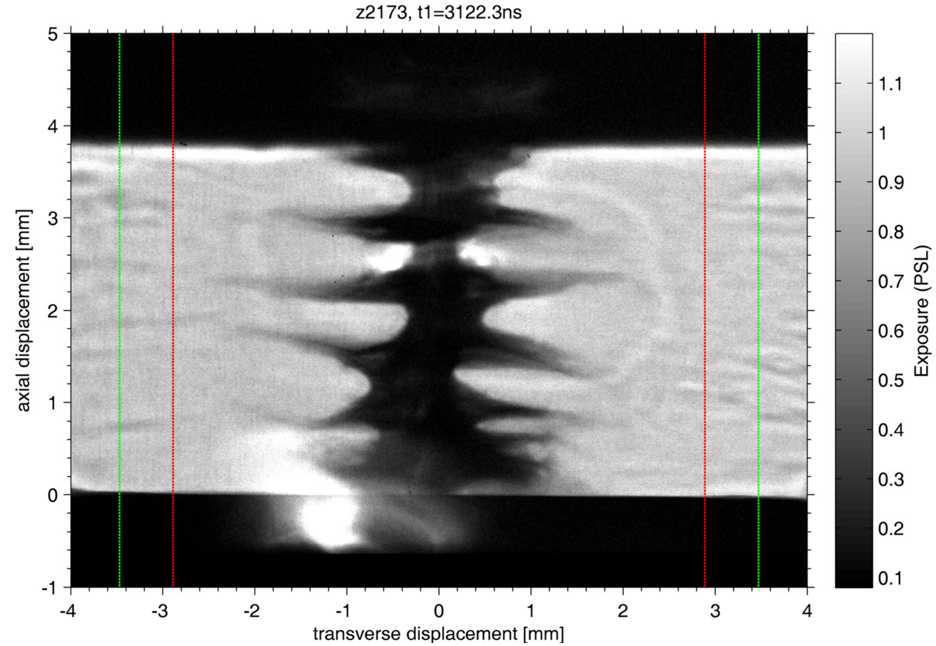
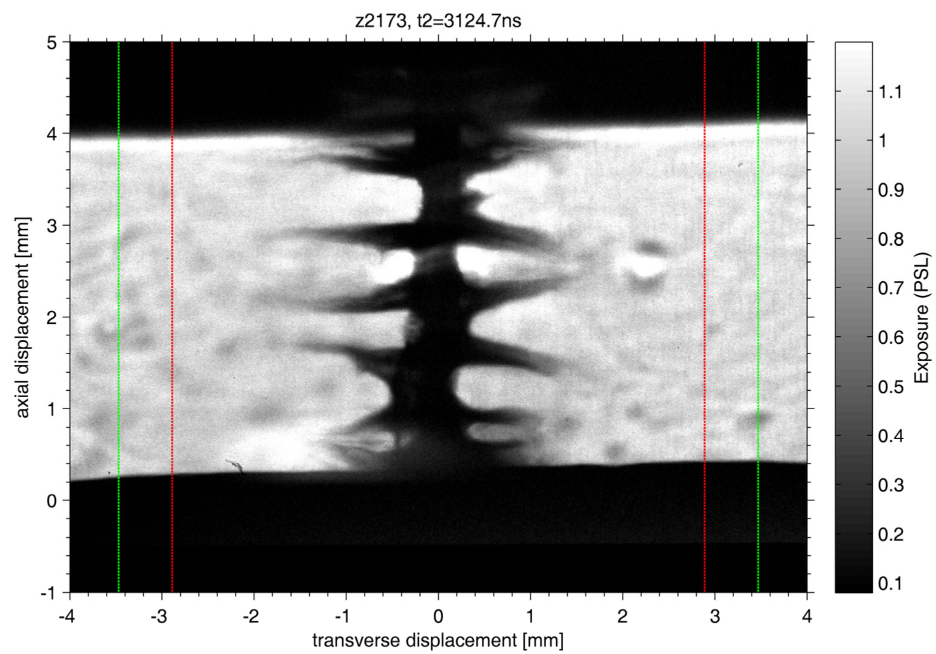
z2173 images taken during stagnation and compression:

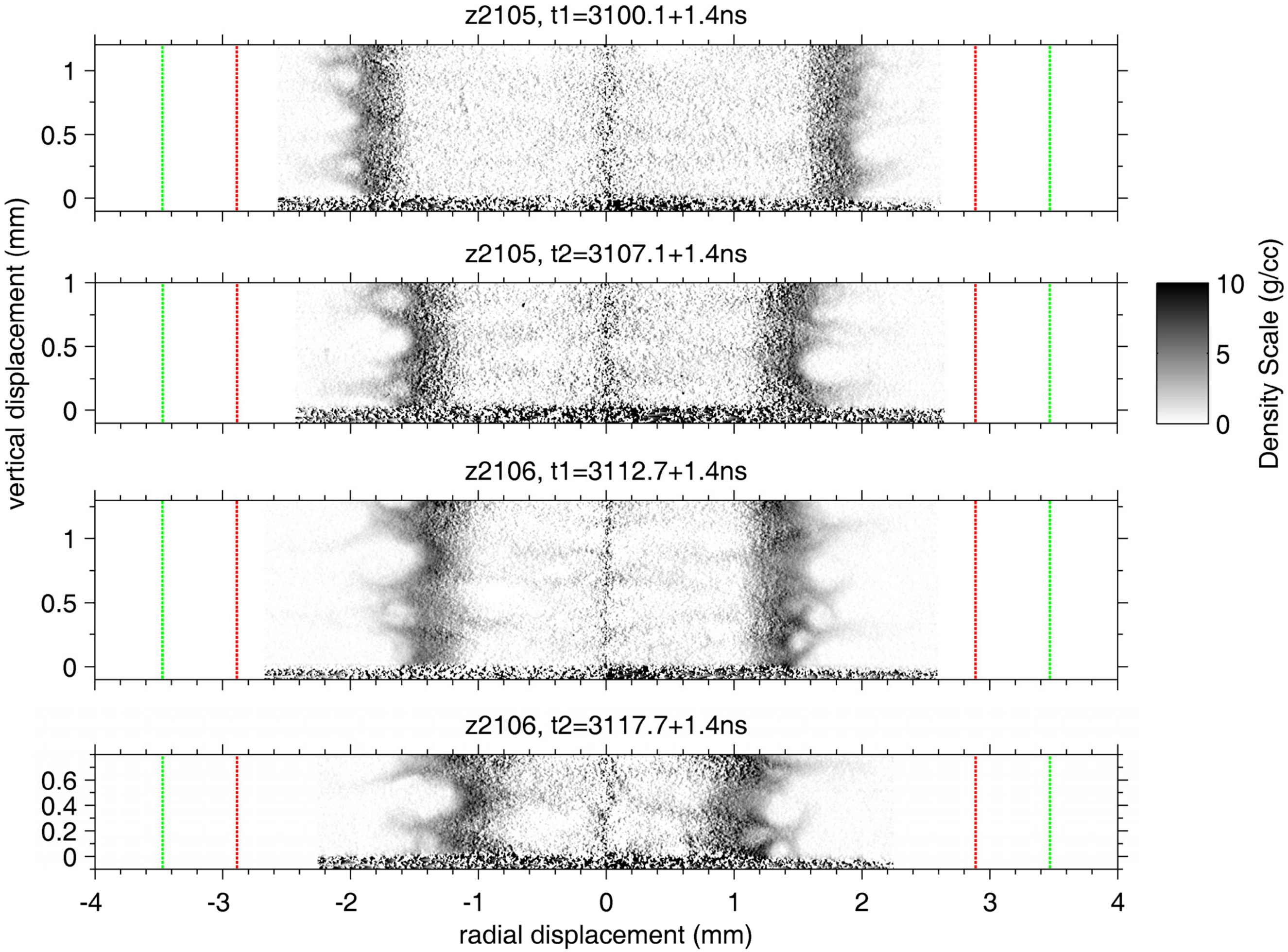






Laboratories

Abel-Inverted Data



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

Can Abel invert, but due to azimuthal asymmetries, data inversion might not be the best way to compare with simulations…

(Rq is Veeco parameter for RMS surface roughness)

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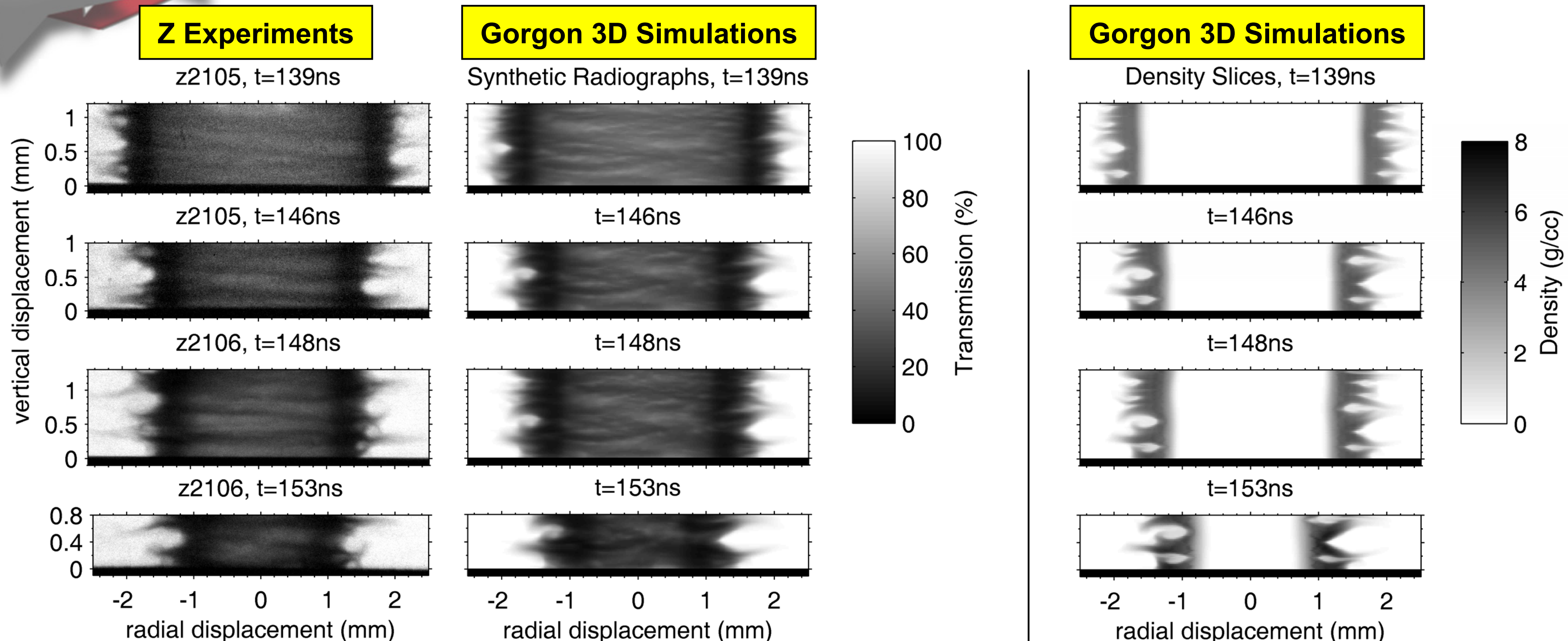
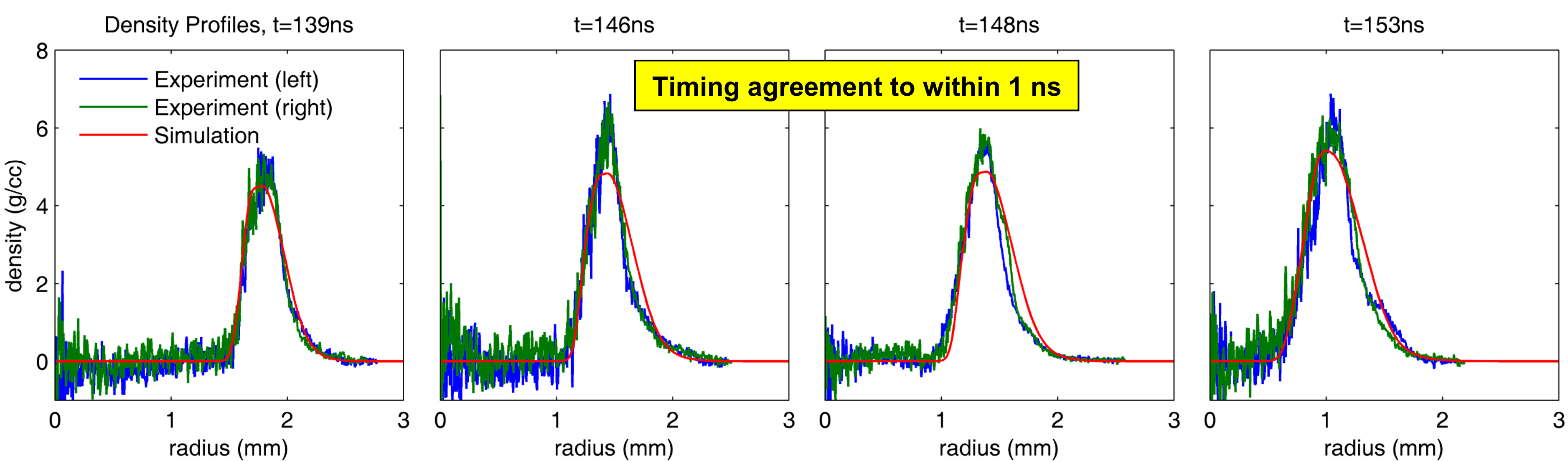
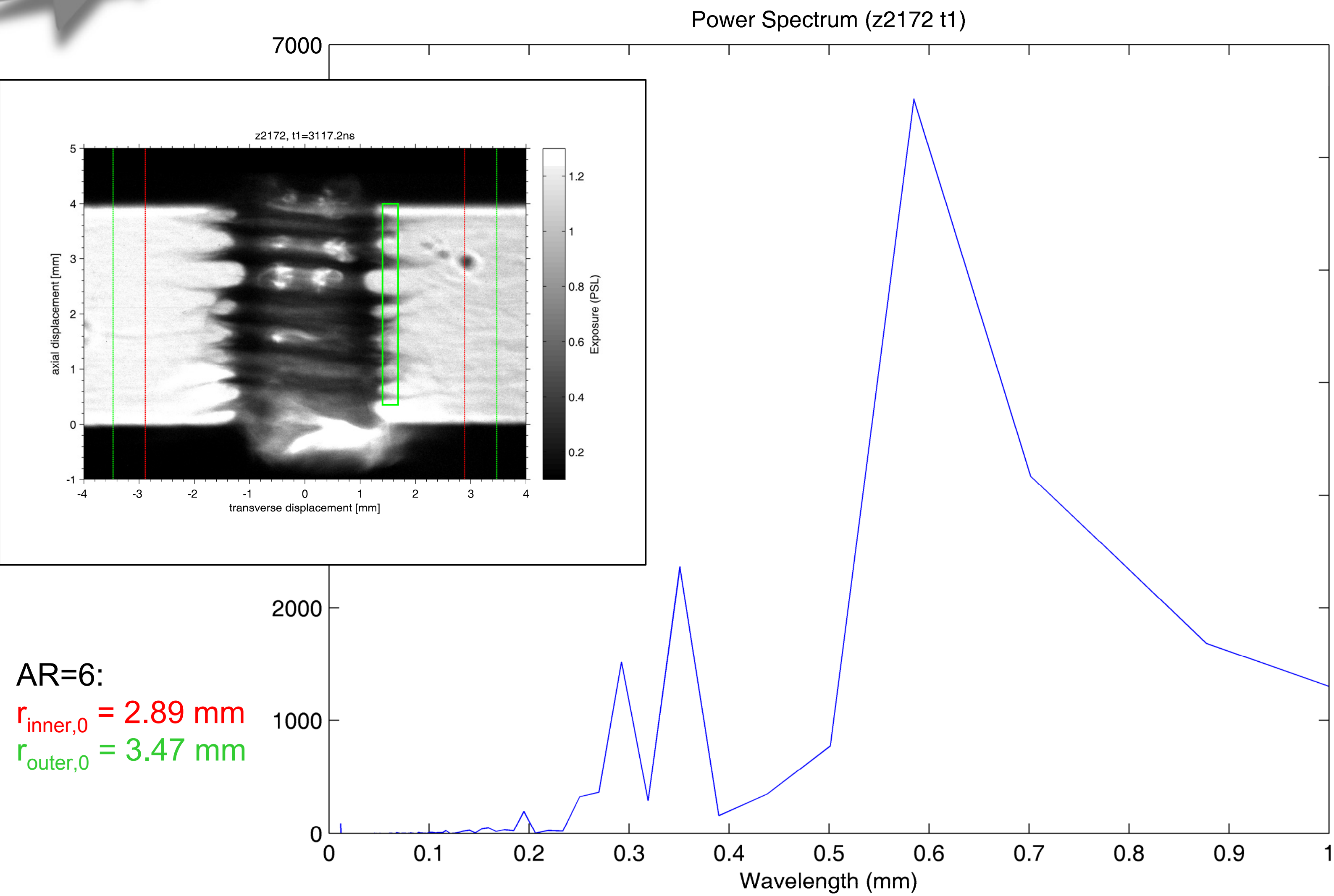
Good agreement between theory and experiment for multi-mode MRT growth experiments





≈ 7.5 ns before onset of stagnation

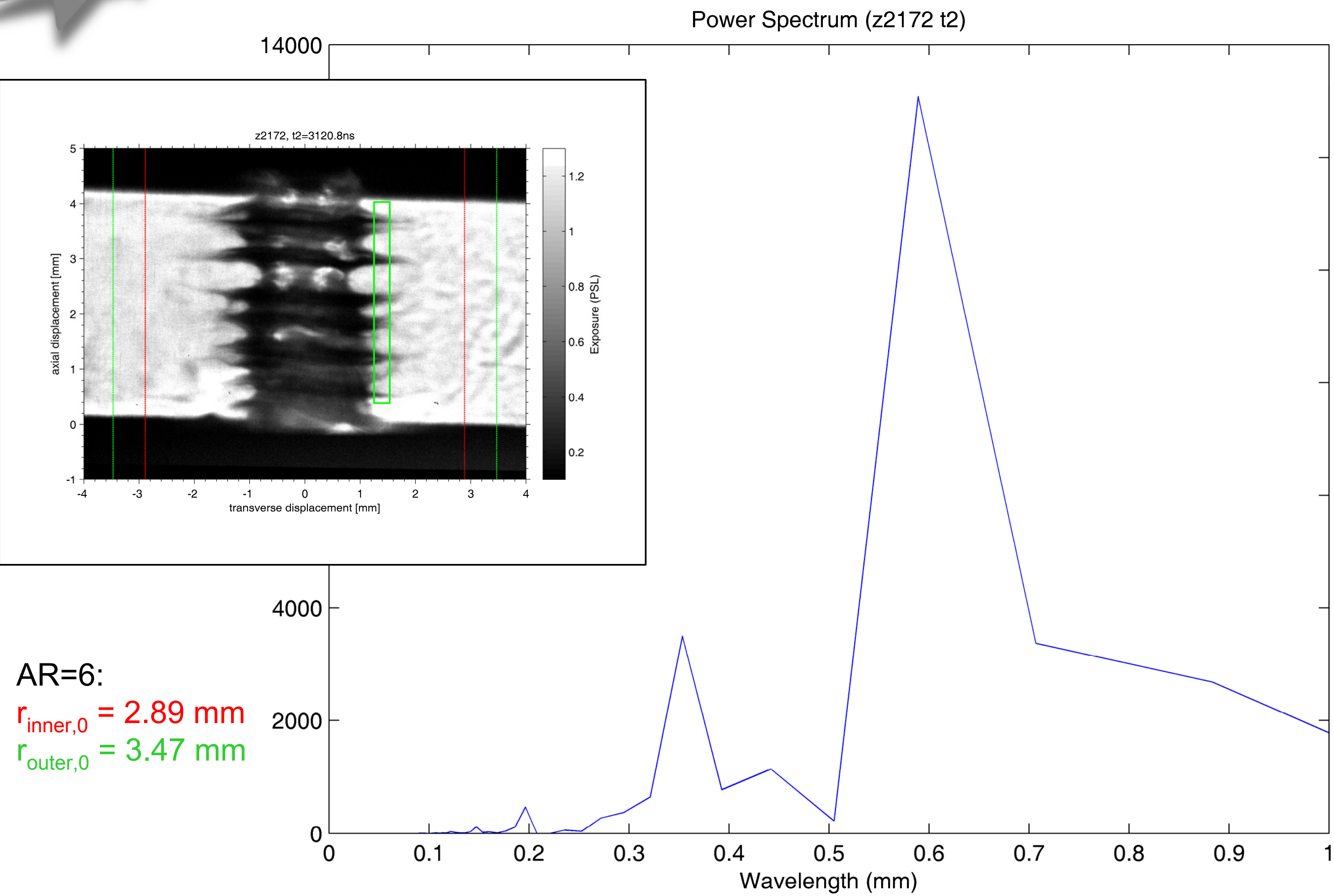


AR=6:

$r_{inner,0}$ = 2.89 mm

$r_{outer,0}$ = 3.47 mm

≈ 3.9 ns before onset of stagnation



AR=6:

$r_{inner,0}$ = 2.89 mm

$r_{outer,0}$ = 3.47 mm

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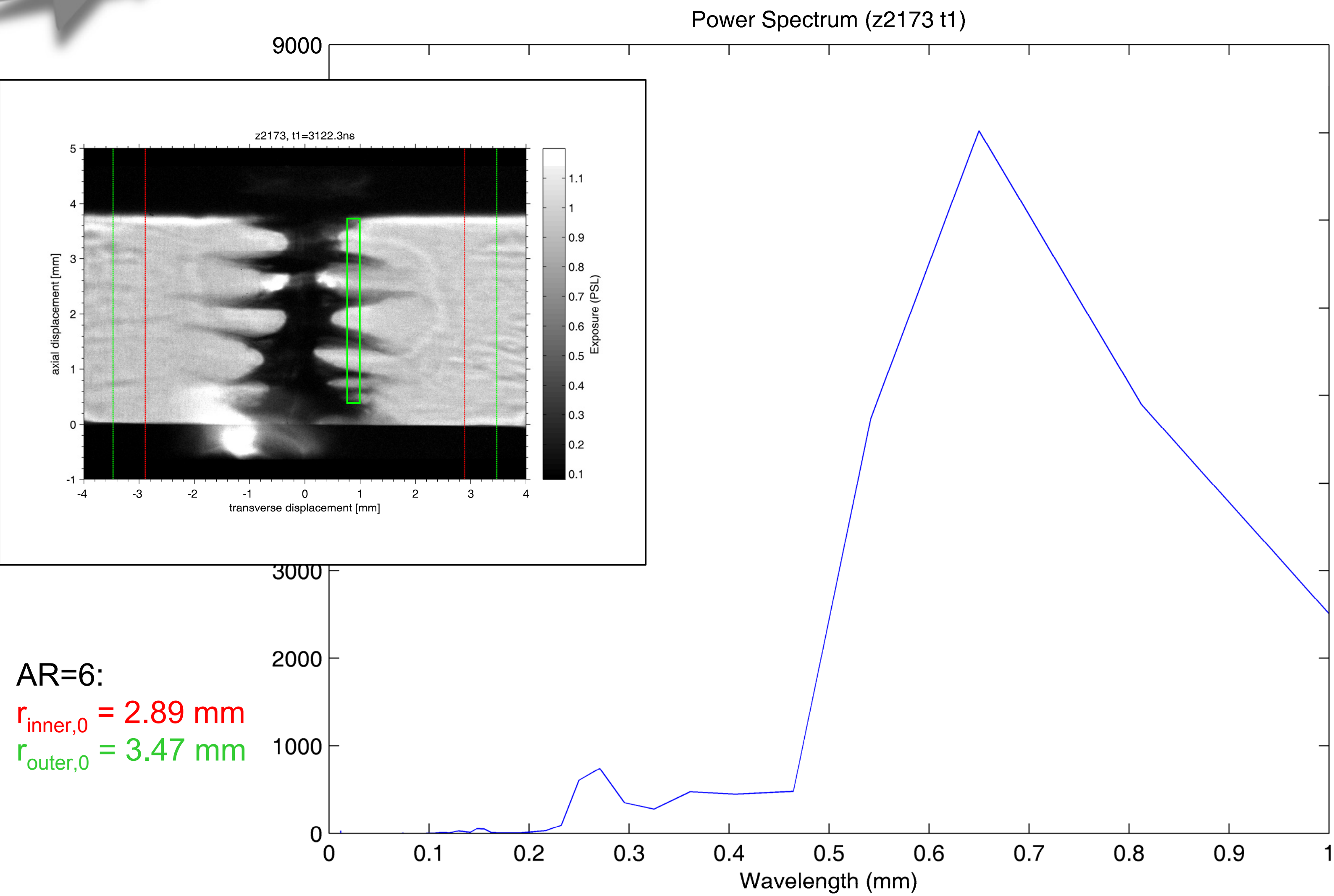
≈ 0.5 ns after onset of stagnation



AR=6:

$r_{inner,0}$ = 2.89 mm

$r_{outer,0}$ = 3.47 mm

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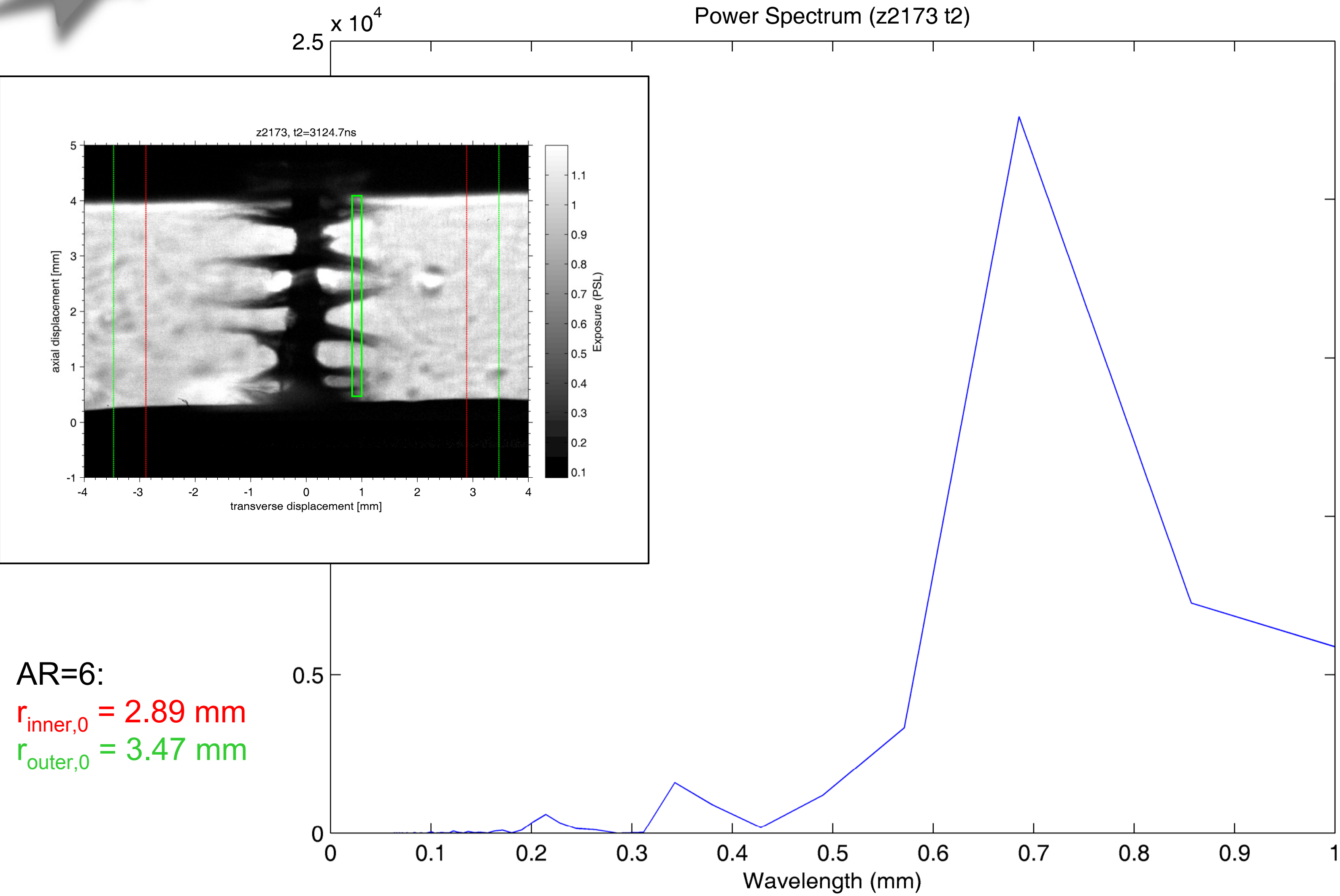
≈ 2.9 ns after onset of stagnation



AR=6:

$r_{inner,0}$ = 2.89 mm

$r_{outer,0}$ = 3.47 mm

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  - Isentropic Compression Experiments (ICE)
- MRT experiments and data
- **Summary**

Summary & Conclusions:

- We successfully measured finite transmission throughout the radiographs of imploding, initially solid, beryllium liners
- This has allowed us to:
  - Derive areal densities
  - Derive volume densities
  - Derive density profiles
    - Useful for both MRT experiments as well as shock & isentropic compression equation-of-state experiments
    - Pulse-shapes for isentropic implosions might mitigate MRT growth and might maintain a solid-state inner liner surface for longer (thus also maintaining some material strength for longer, and perhaps further reducing MRT penetration to the inner surface)
  - Validate LASNEX 2D and Gorgon 3D codes
- 3D agreement with Gorgon simulation indicates that the inner surface of the liner should remain reasonably intact despite the large MRT growth observed on the outer surface
- With the inner surface of the liner intact, efficient compression of fuel is possible, which is encouraging for the overall MagLIF concept

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Backup Slides…

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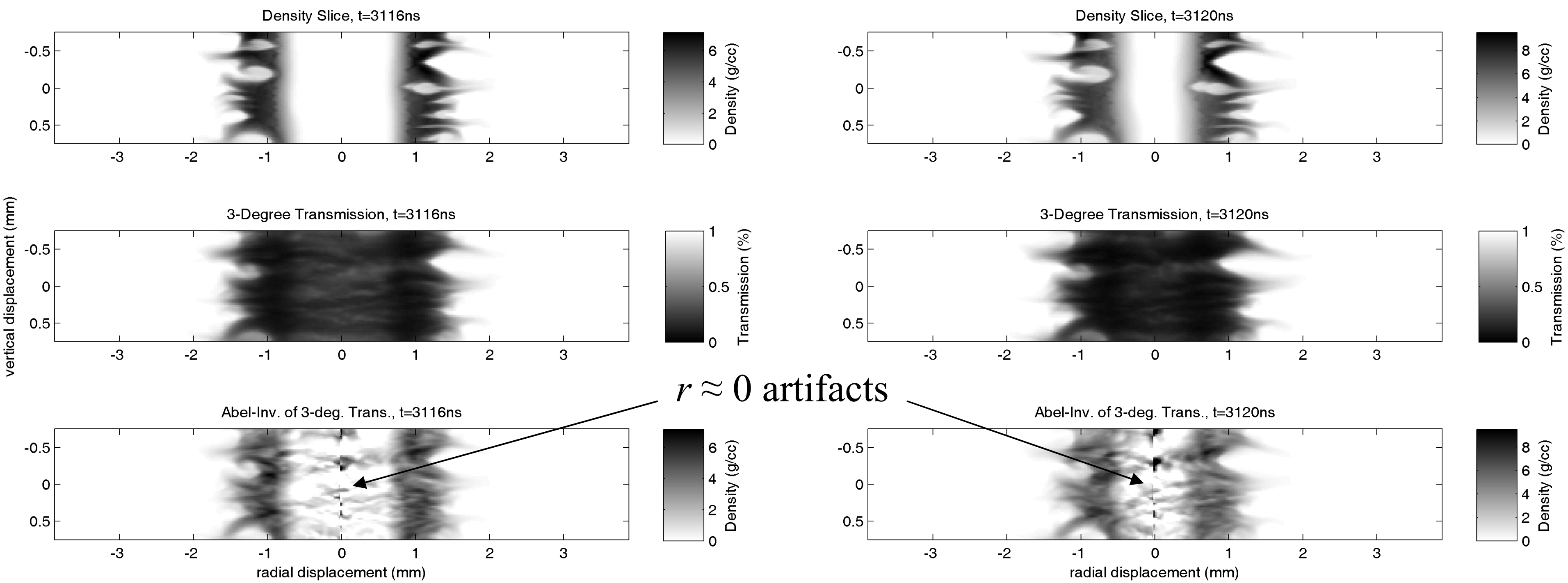
Difficulties with Abel Inversions

- Using an Abel inversion to reconstruct a volume density slice leads to a pessimistic picture of the true inner-surface quality
- This is due to azimuthal asymmetry in the 3D MRT structure on the **outer** surface
- This is illustrated here using synthetic radiographs from 3D Gorgon simulations
- Here we know the true inner-surface (the fuel-confining surface) has remained smooth at these two late times, while in the Abel unfolded image, the inner-surface appears shredded



Be, AR=6:

$r_{inner,0}$ = 2.89 mm

$r_{outer,0}$ = 3.47 mm

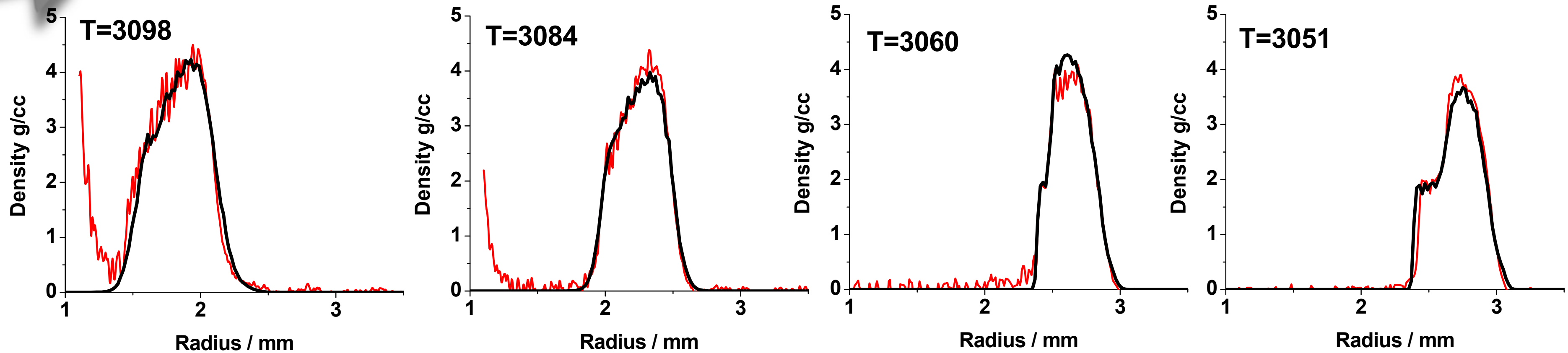
Gorgon Simulations by C. Jennings

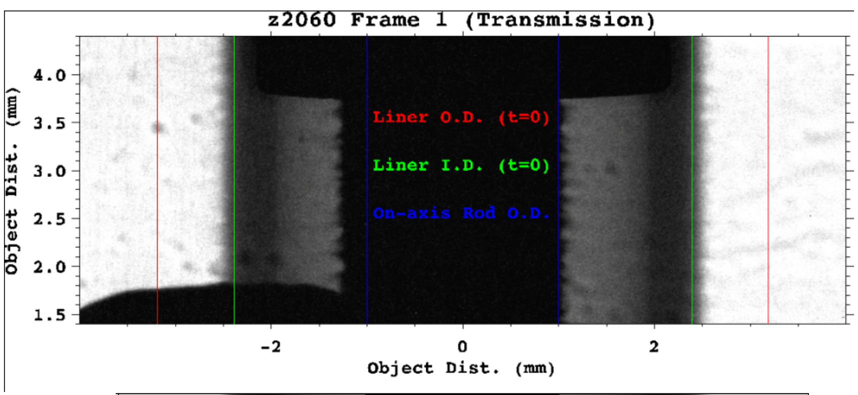
Sandia National Laboratories

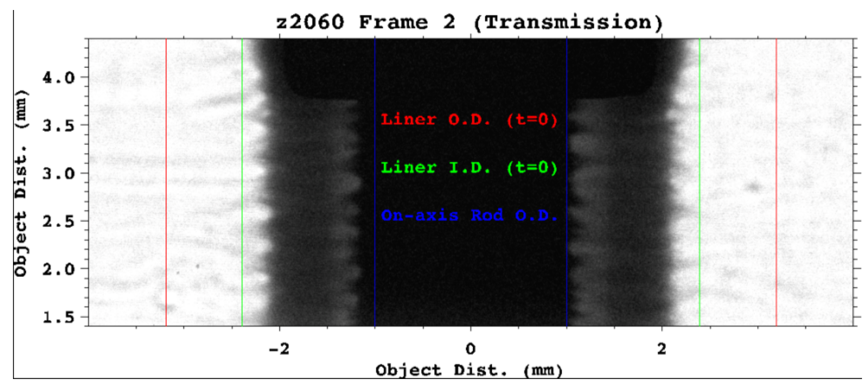
AR 4 Be Liner Implosion

Gorgon 3D Simulation
Experiment

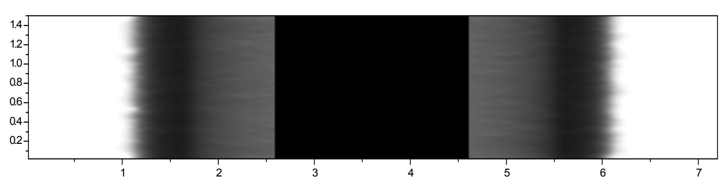
Z 2060 Z 2104

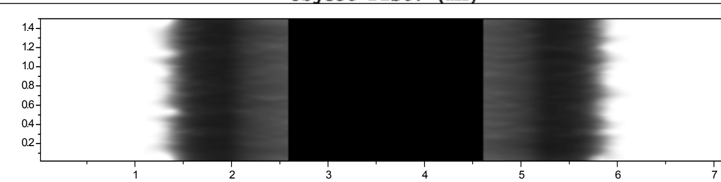




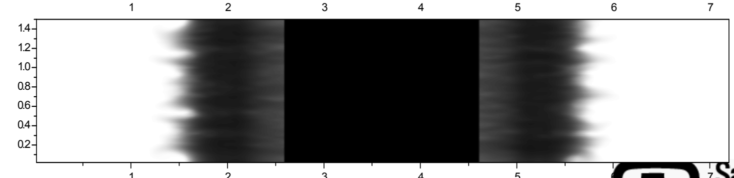


Sim.





-3ns



+2ns

Simulation initialized with random 20 micron surface roughness. Using 0.22 m^2/Kg for Be attenuation in images. Simulations are on time base for 2060

Gorgon simulations by Chris Jennings

Radiograph fell between graphical output times

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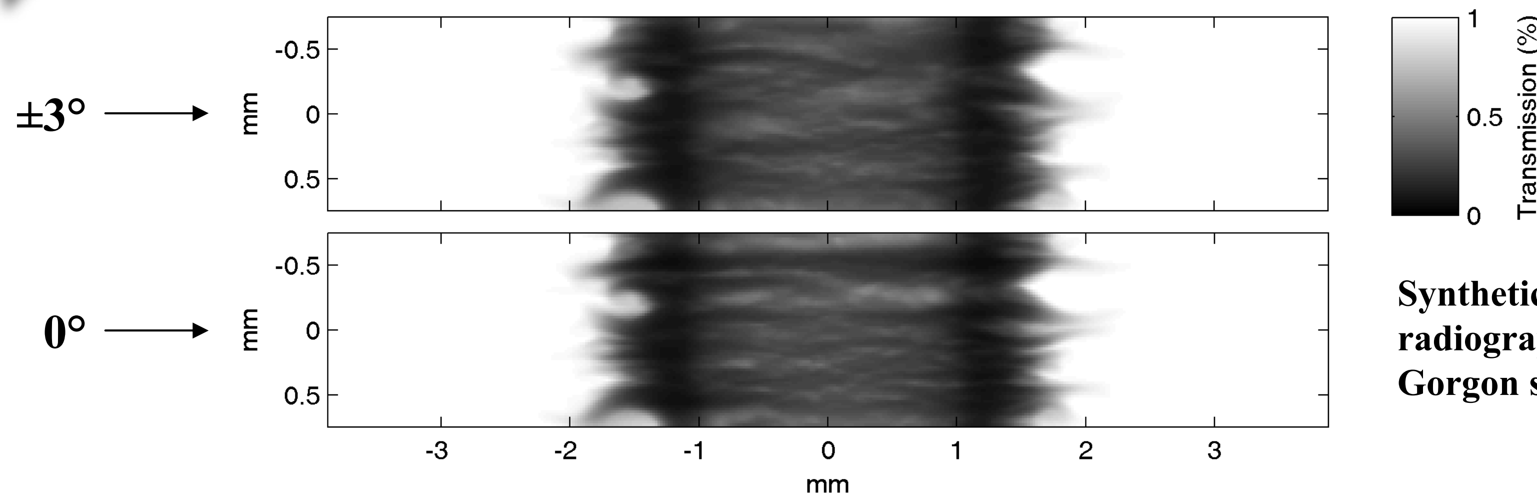
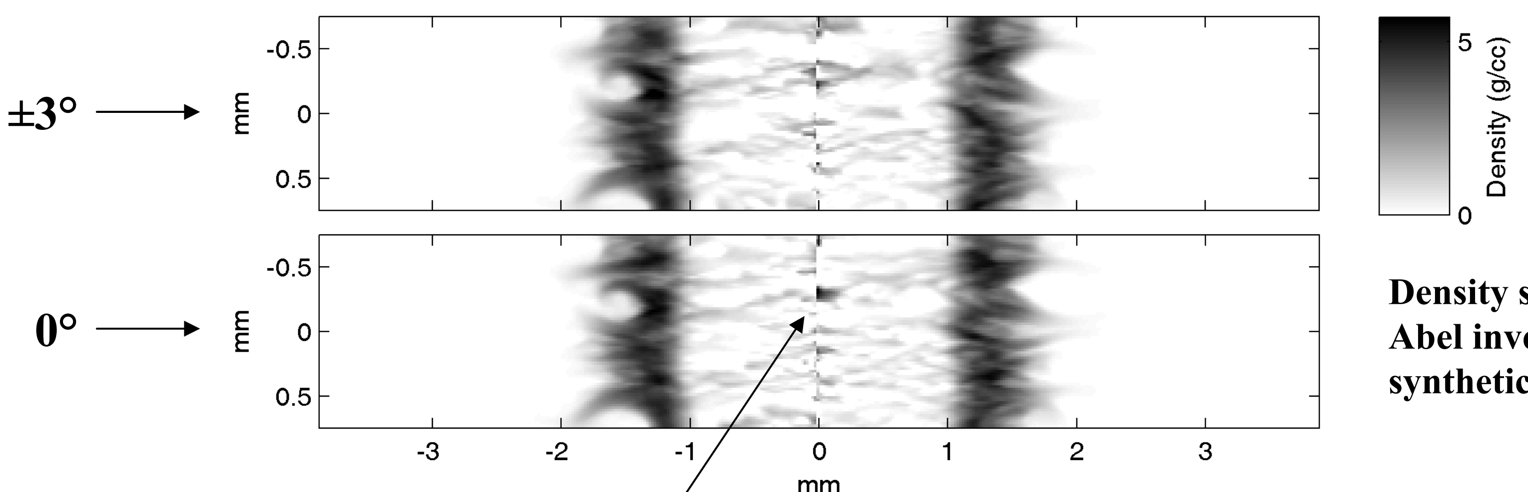
±3° Viewing angle not a problem



Synthetic radiographs from Gorgon simulations



Density slices from Abel inversions of synthetic radiographs

$r \approx 0$ artifacts

Gorgon Simulations by C. Jennings

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

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Lincoln 3 (L3) + Lincoln 4 (L4) combined overview:

L3

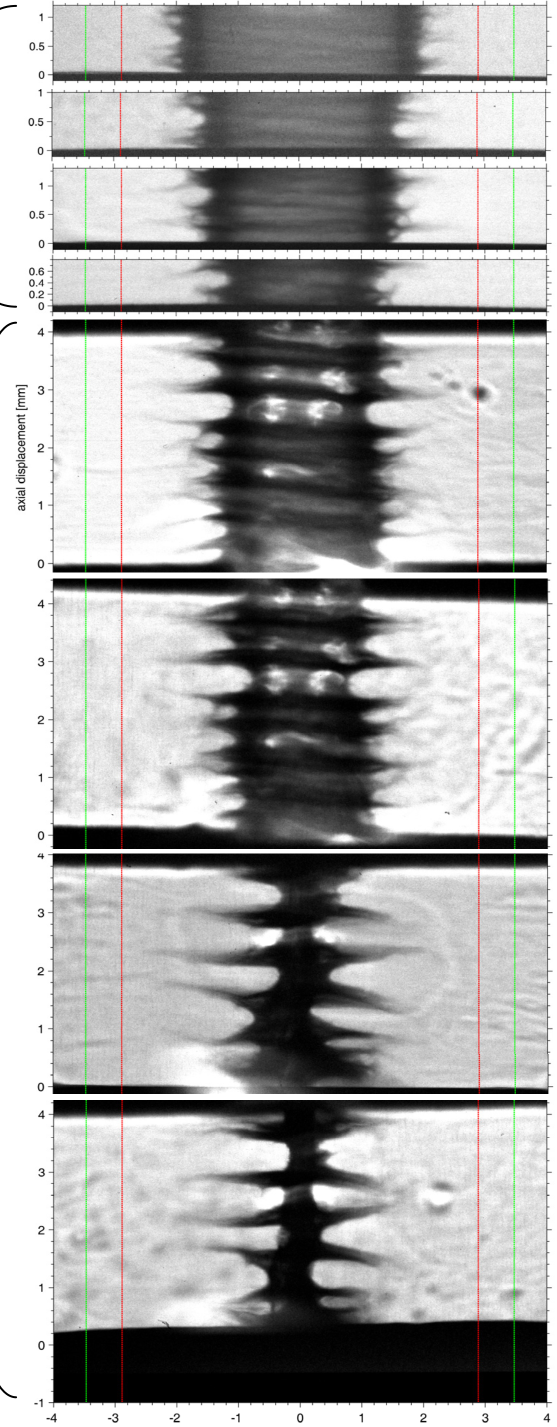
Rq > 210 nm RMS

(Rq is Veeco parameter for RMS surface roughness)

L4

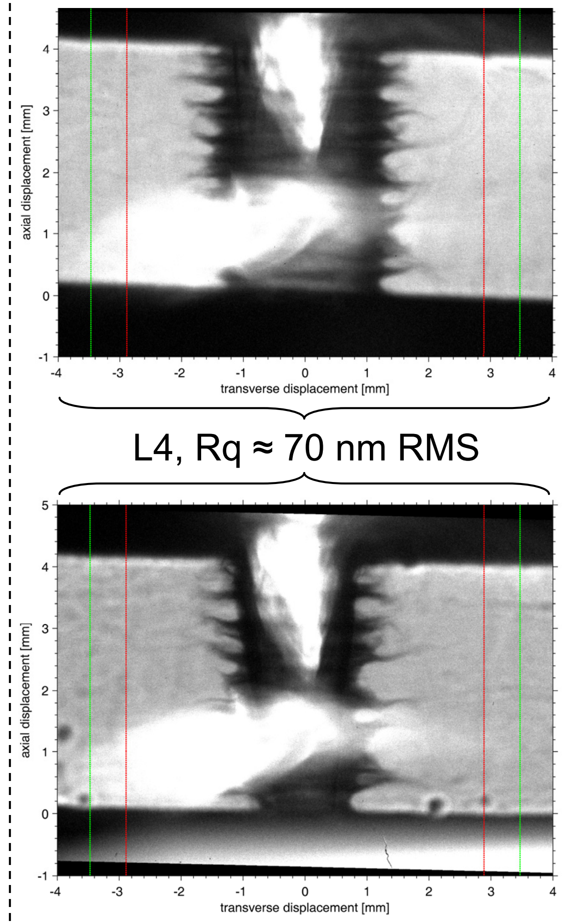
Rq ≈ 130 nm RMS

(Images taken during stagnation and compression)



vs.

vs.



L4, Rq ≈ 70 nm RMS

z2174 image times set for surface finish comparisons (note there were some anomalies with this shot)

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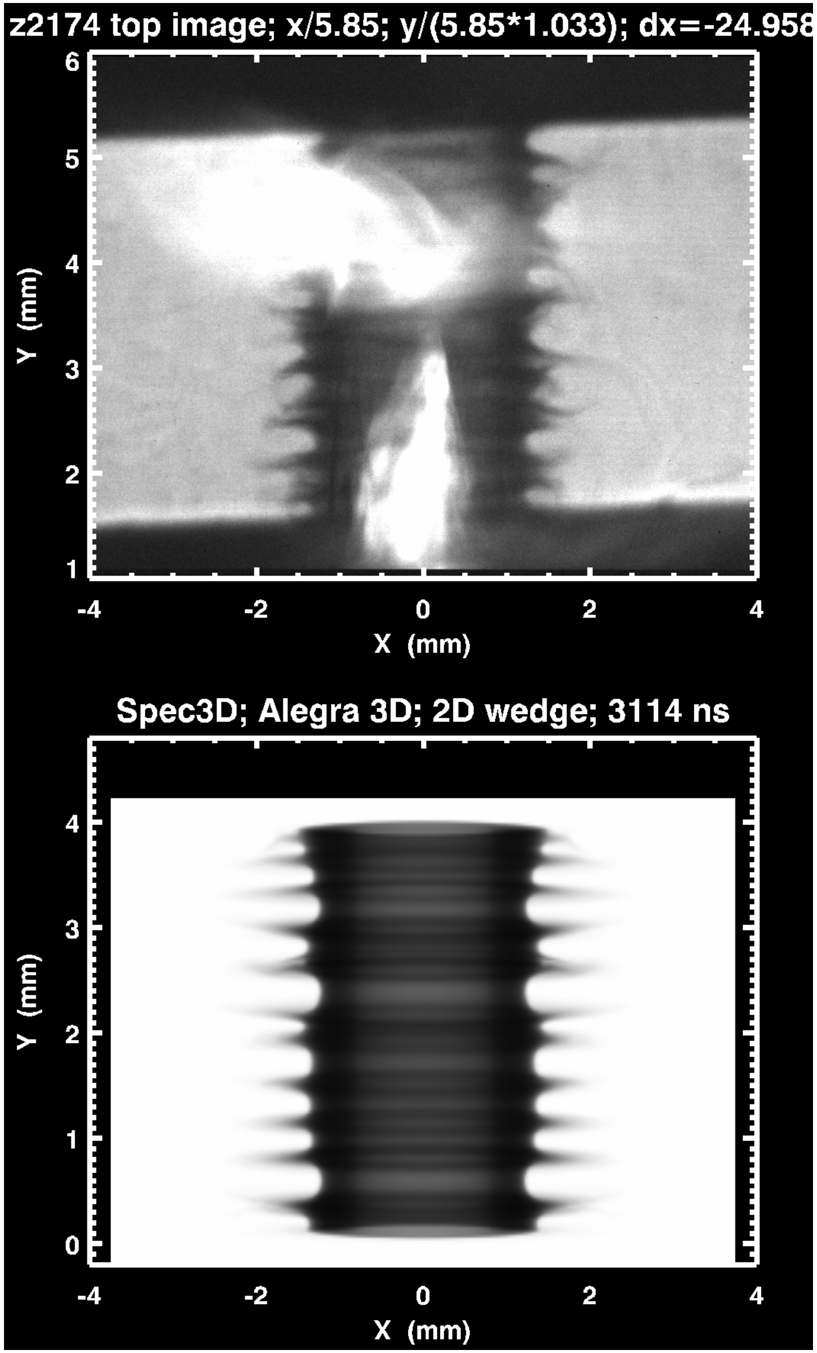
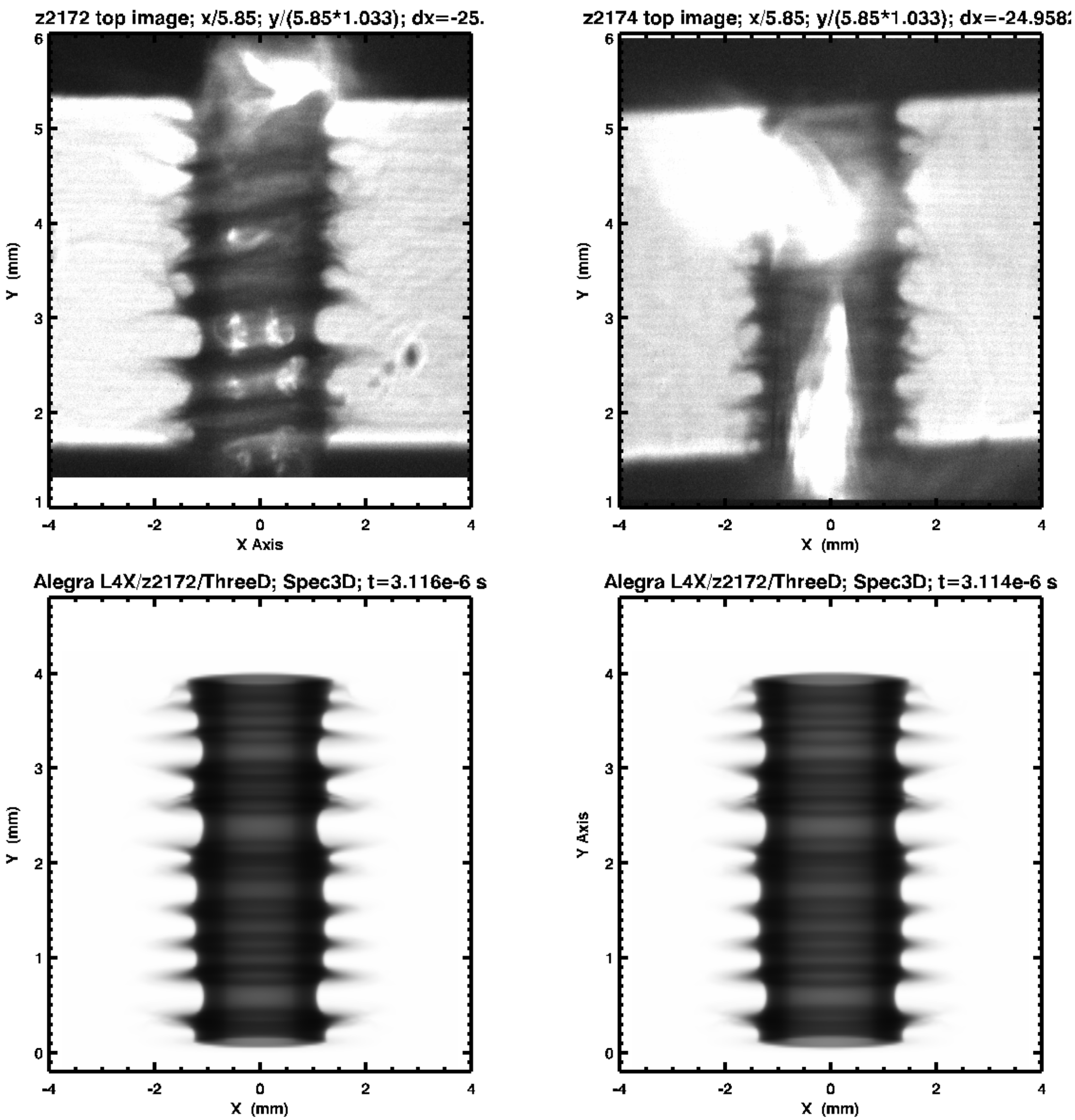
Alegra Simulation Comparisons:



Alegra Simulation Comparisons:



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