Beryllium Liner Implosions on Z: MRT & EOS Experiments*

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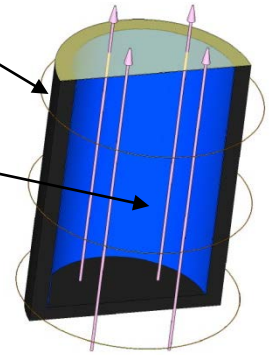
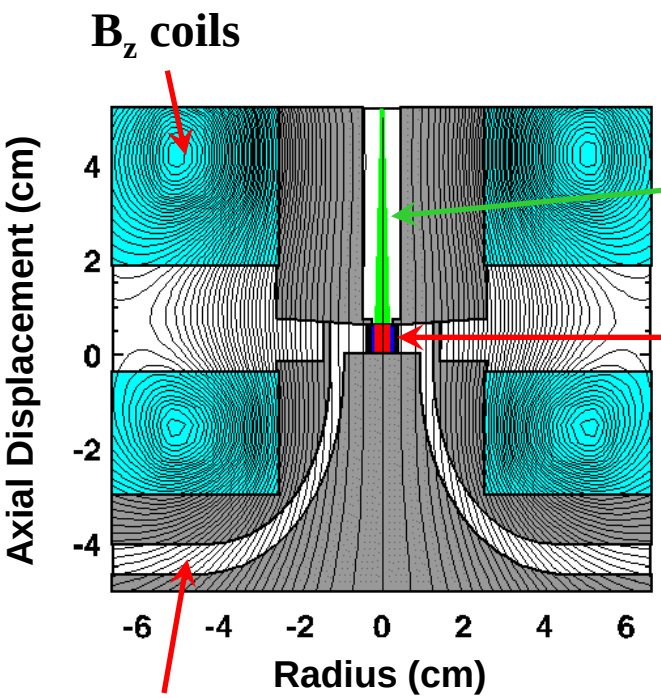
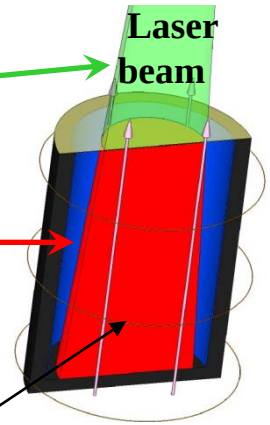
Magnetized Liner Inertial Fusion (MagLIF)* may be a promising path to high fusion yields on Z

Idea: **Directly drive solid liner containing fusion fuel**

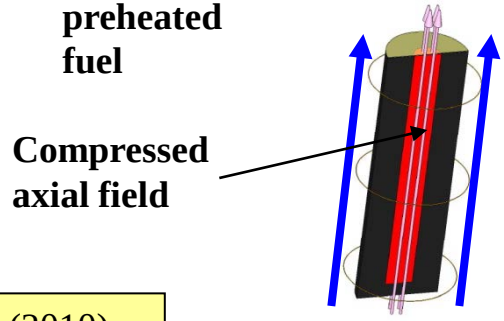


1. An axial magnetic field (B_z) is applied to inhibit thermal conduction and enhance alpha particle deposition





2. Z Beamlet preheats the fuel

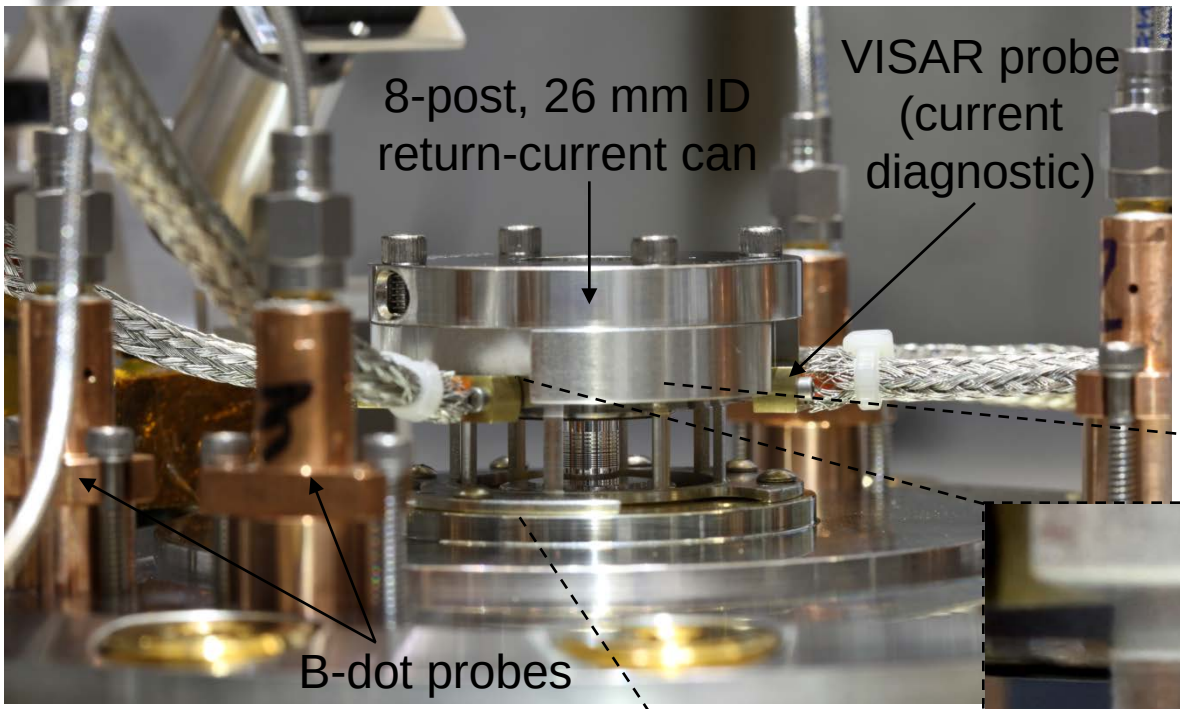


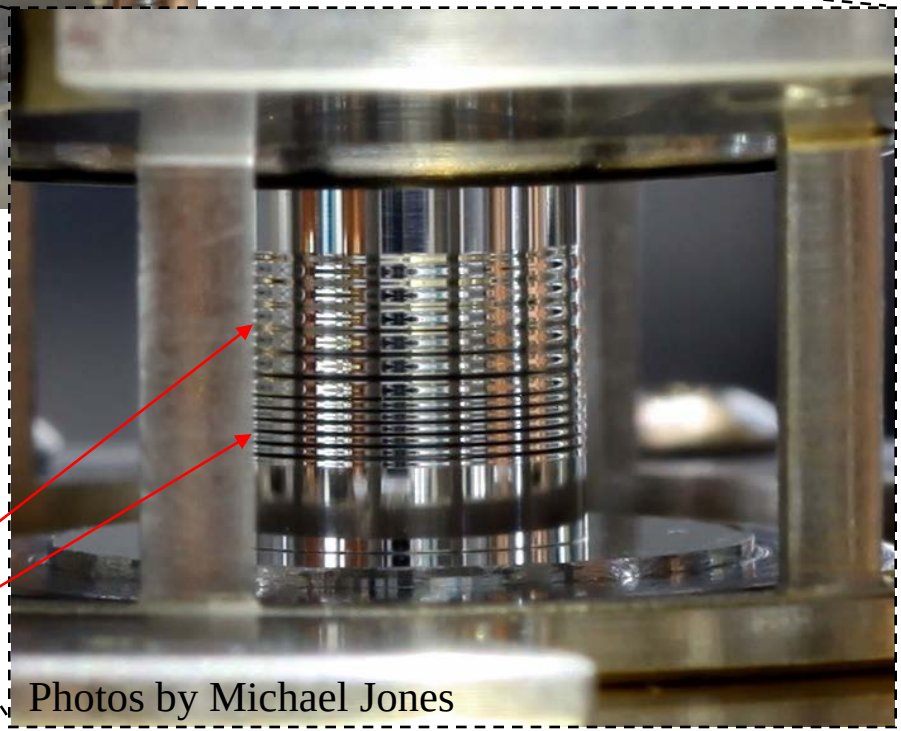
3. The Z accelerator efficiently drives a z-pinch implosion

Liner Integrity Critical

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

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



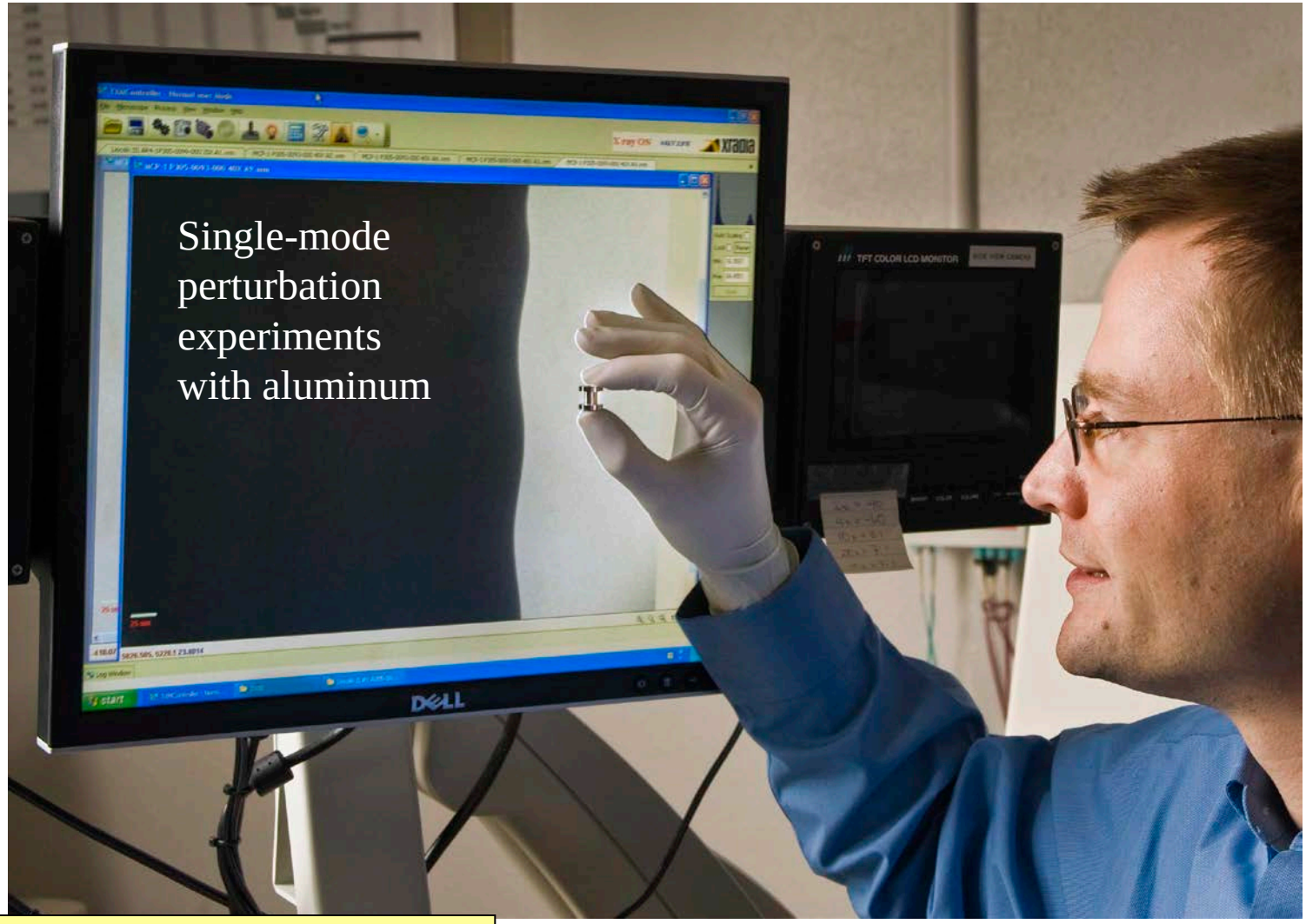


- Solid cylindrical liner (Al 1100 alloy)
- 6.5 mm tall, 6.34 mm diameter, AR=10
- 10 nm surface finish (diamond-turned)
- 12 sinusoidal perturbations:
  six 400-μm wavelength, 20-μm amplitude
  six 200-μm wavelength, 10-μm amplitude

Targets made by General Atomics

Photos by Michael Jones

Target Scale-Size



*D.B. Sinars *et al.*, Phys. Rev. Lett. (2010).
*D.B. Sinars *et al.*, Phys. Plasmas (2011).

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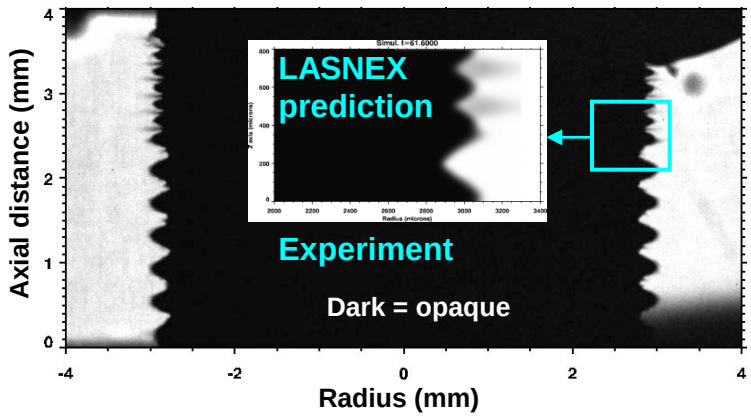
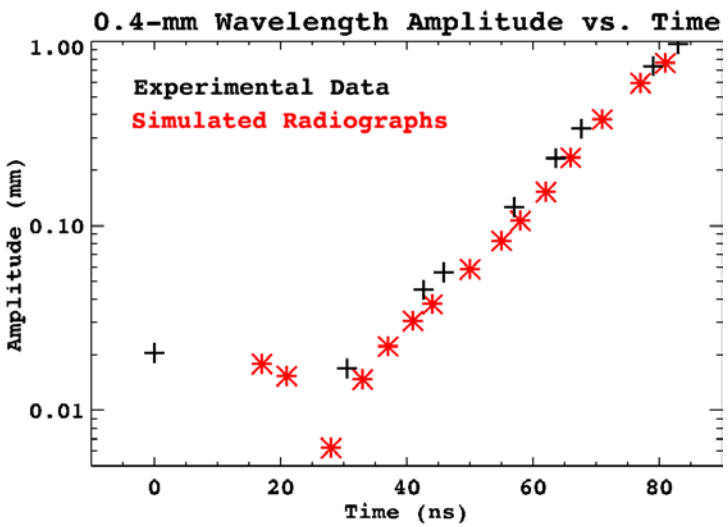
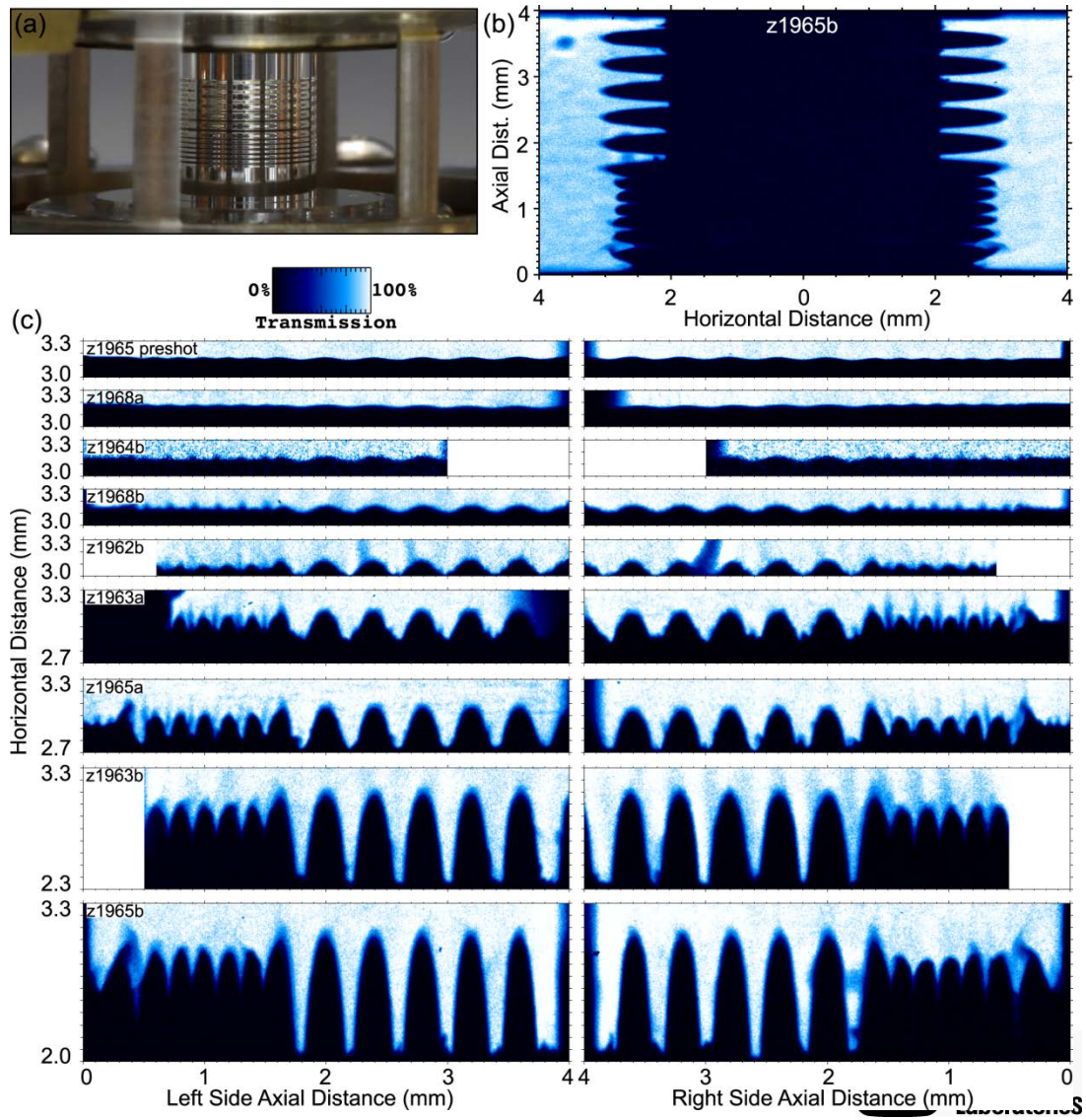
Excellent agreement between simulation and experiment for single-mode MRT growth experiments with aluminum

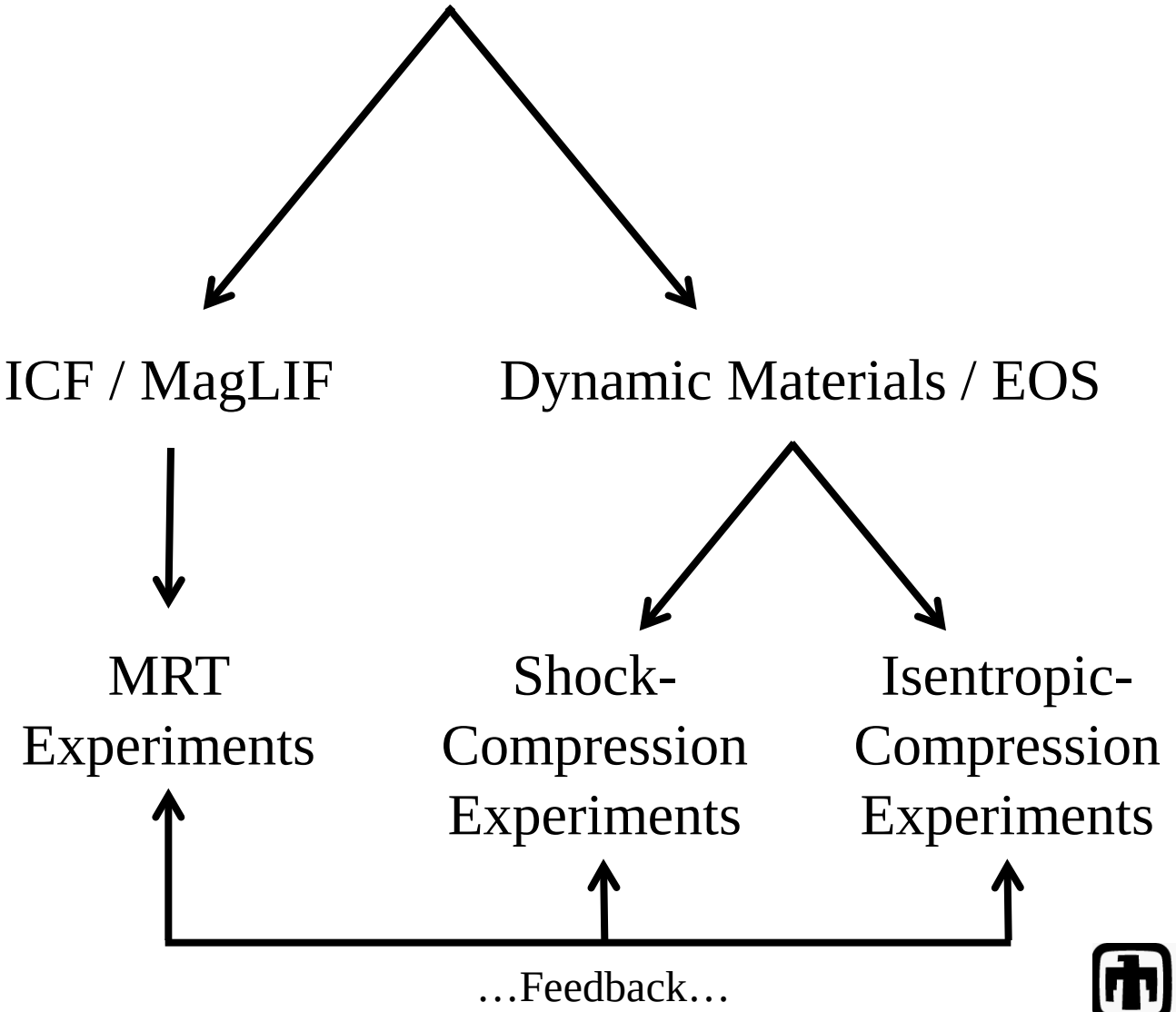
*D.B. Sinars *et al.*, Phys. Rev. Lett. (2010).
*D.B. Sinars *et al.*, Phys. Plasmas (2011).



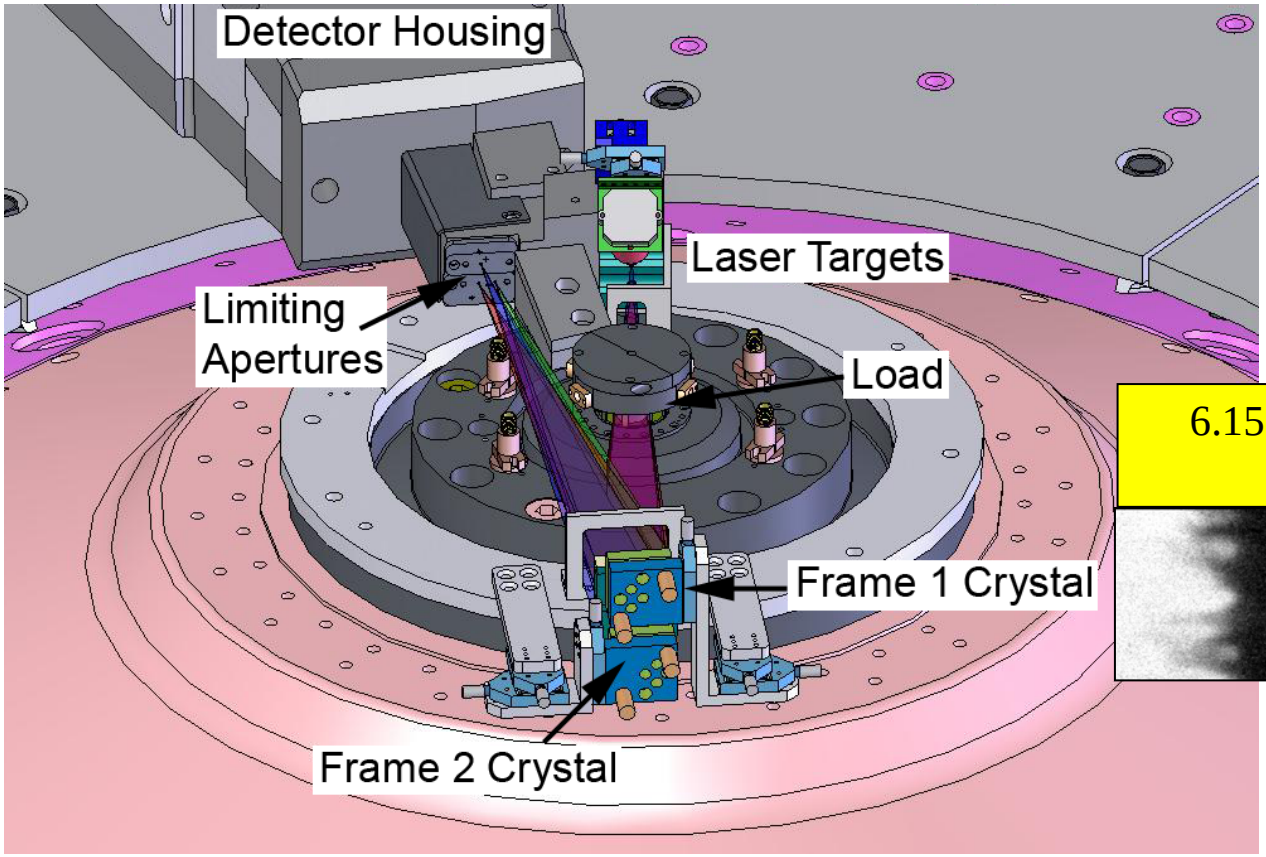




Beryllium Liners



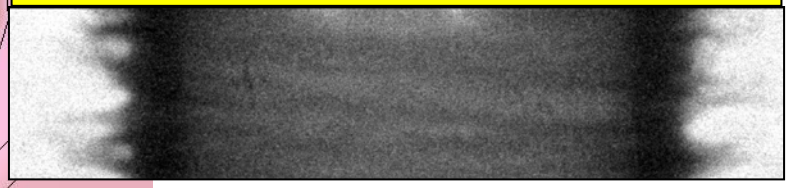
Experiments used Two-Frame 6.151 keV monochromatic crystal backlighting diagnostic



Two-frame 6.151-keV 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

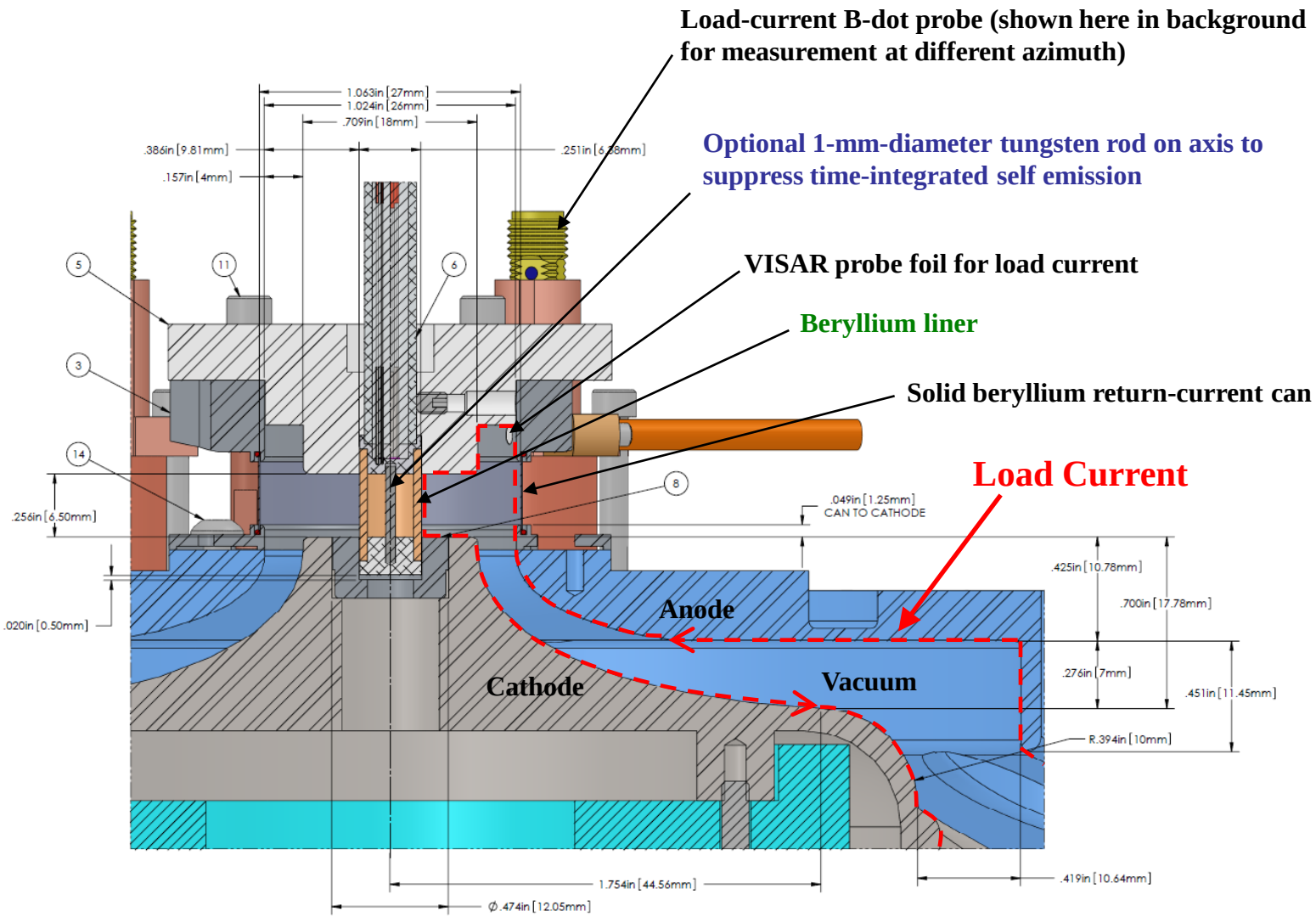
6.151-keV Radiograph of Imploding Beryllium Liner:



We can see through imploding beryllium with 6.151-keV photons (not so for aluminum and other higher-opacity materials)

- 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).**

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



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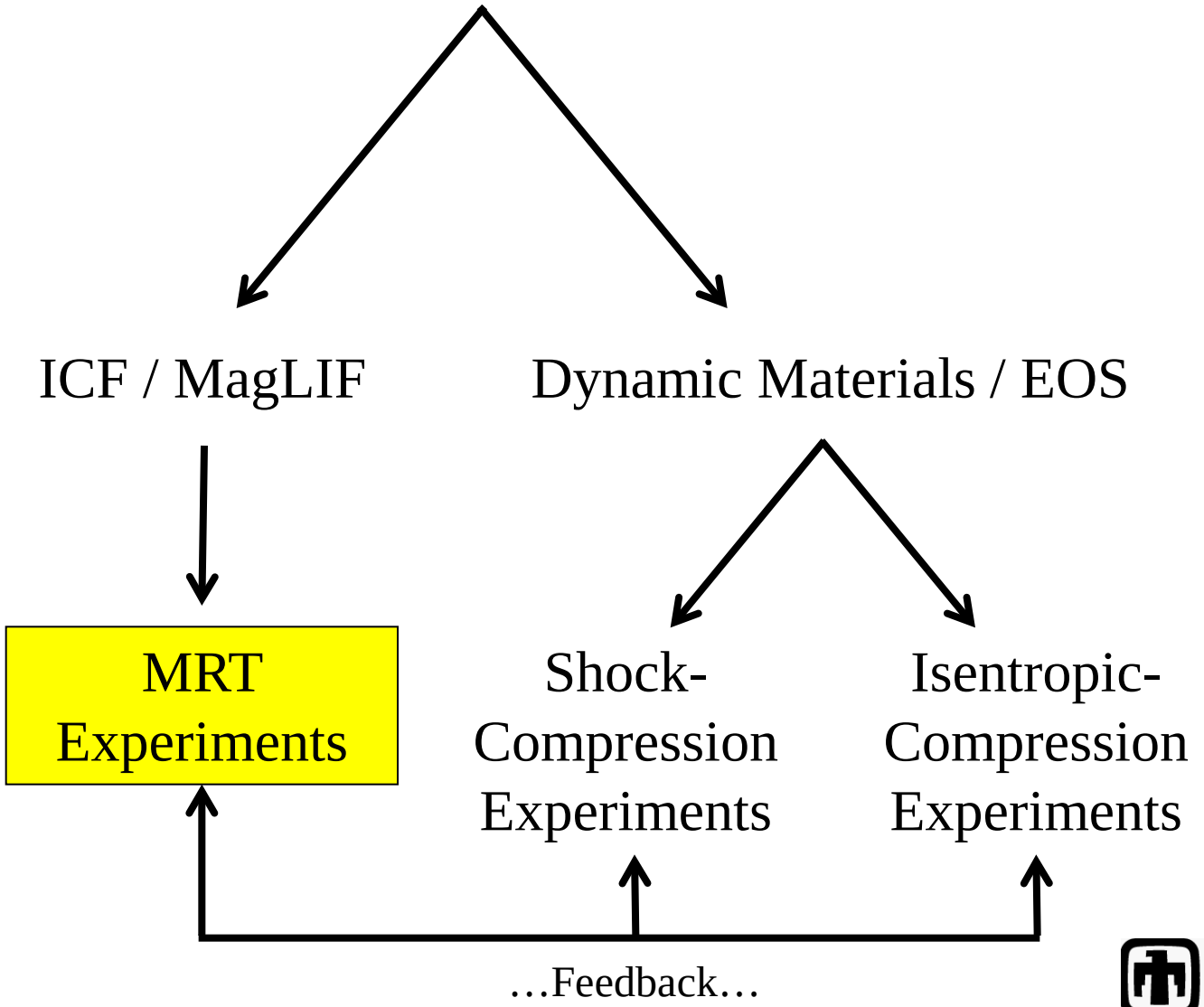
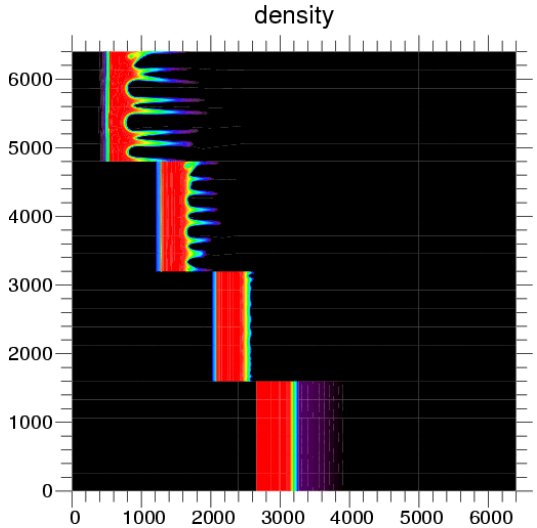
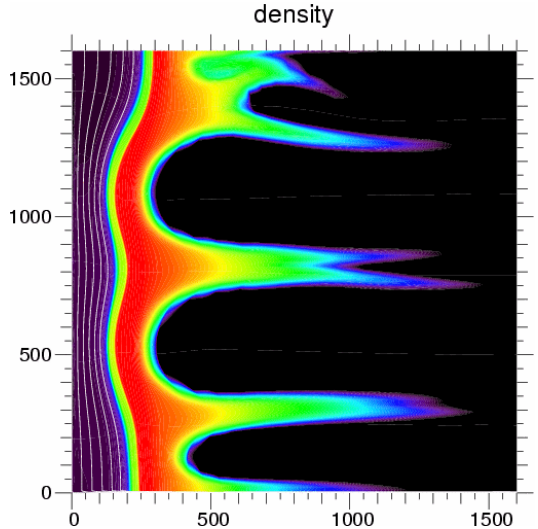
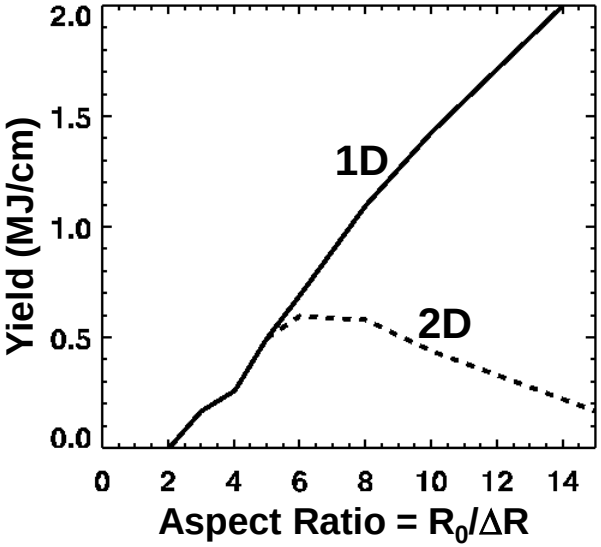
Beryllium Liners

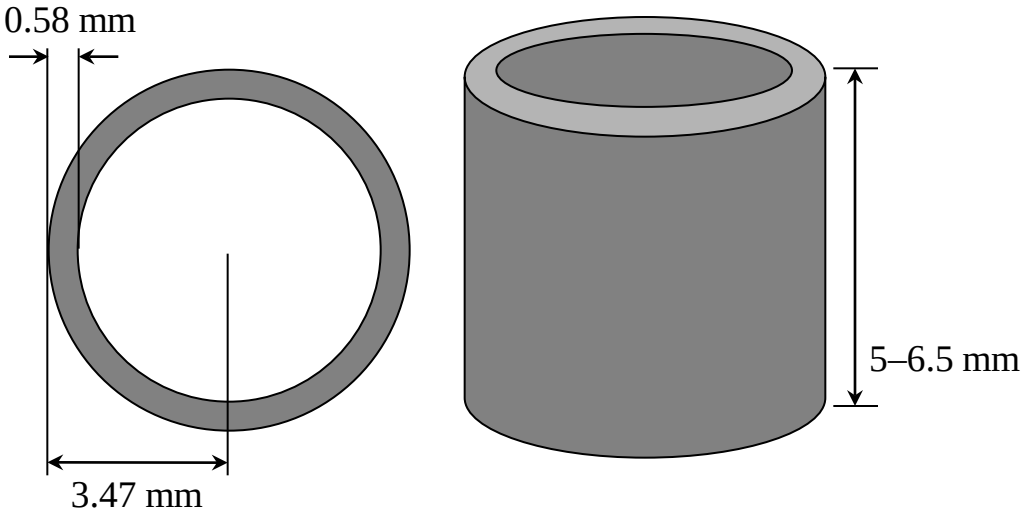


2D LASNEX Simulations of MagLIF Suggest Optimum at Aspect Ratio (AR) of 6









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

$$\mathrm{AR} \equiv \frac{r_{outer,0}}{\Delta r_0}$$

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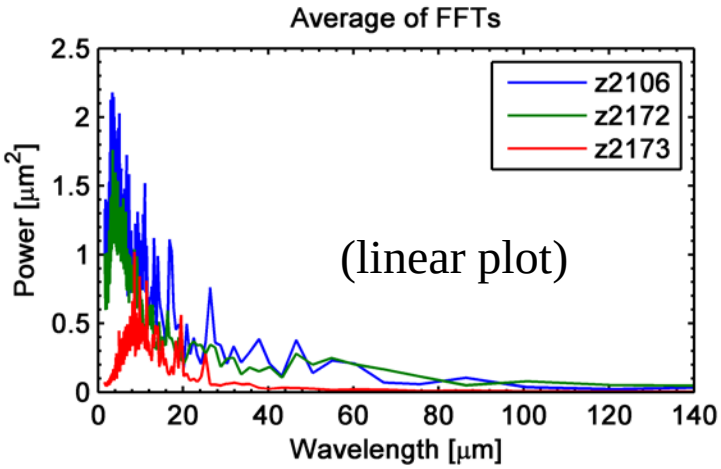
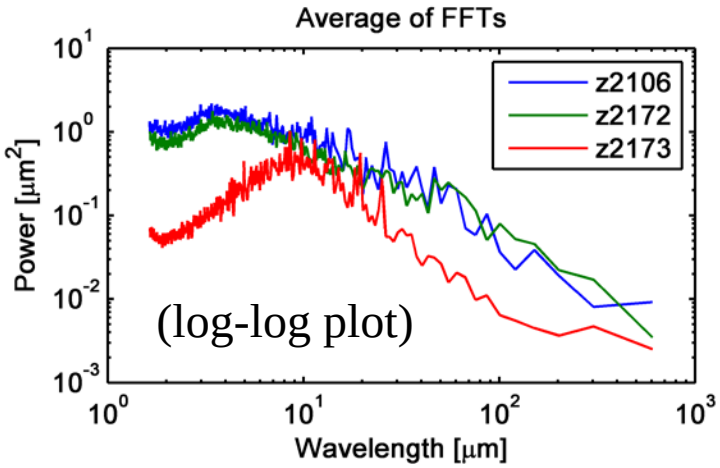
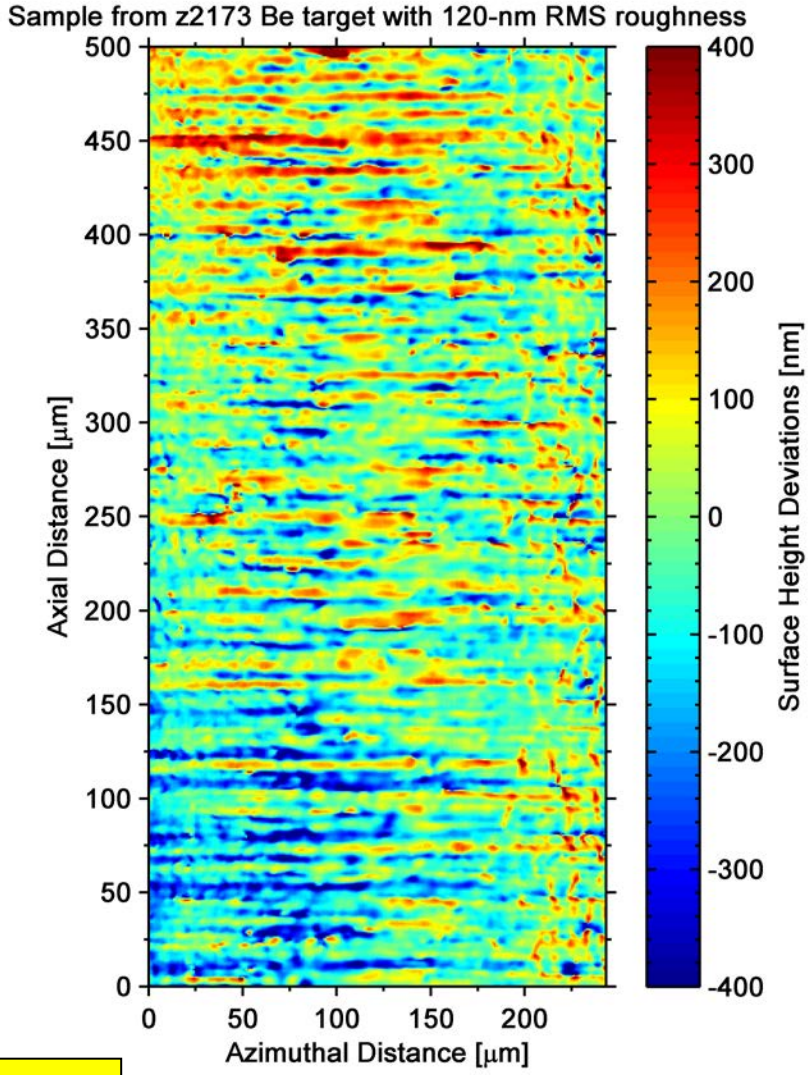
Surface Finish Characterization







~120-nm-RMS surfaces roughness

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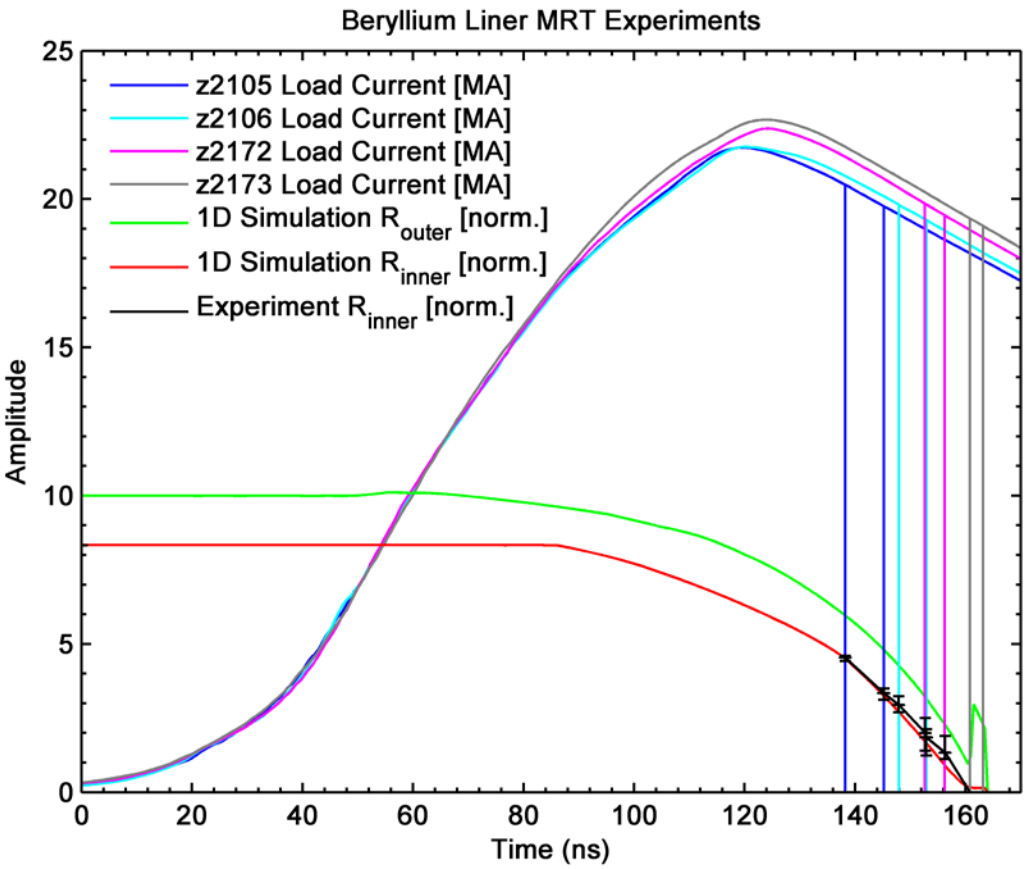
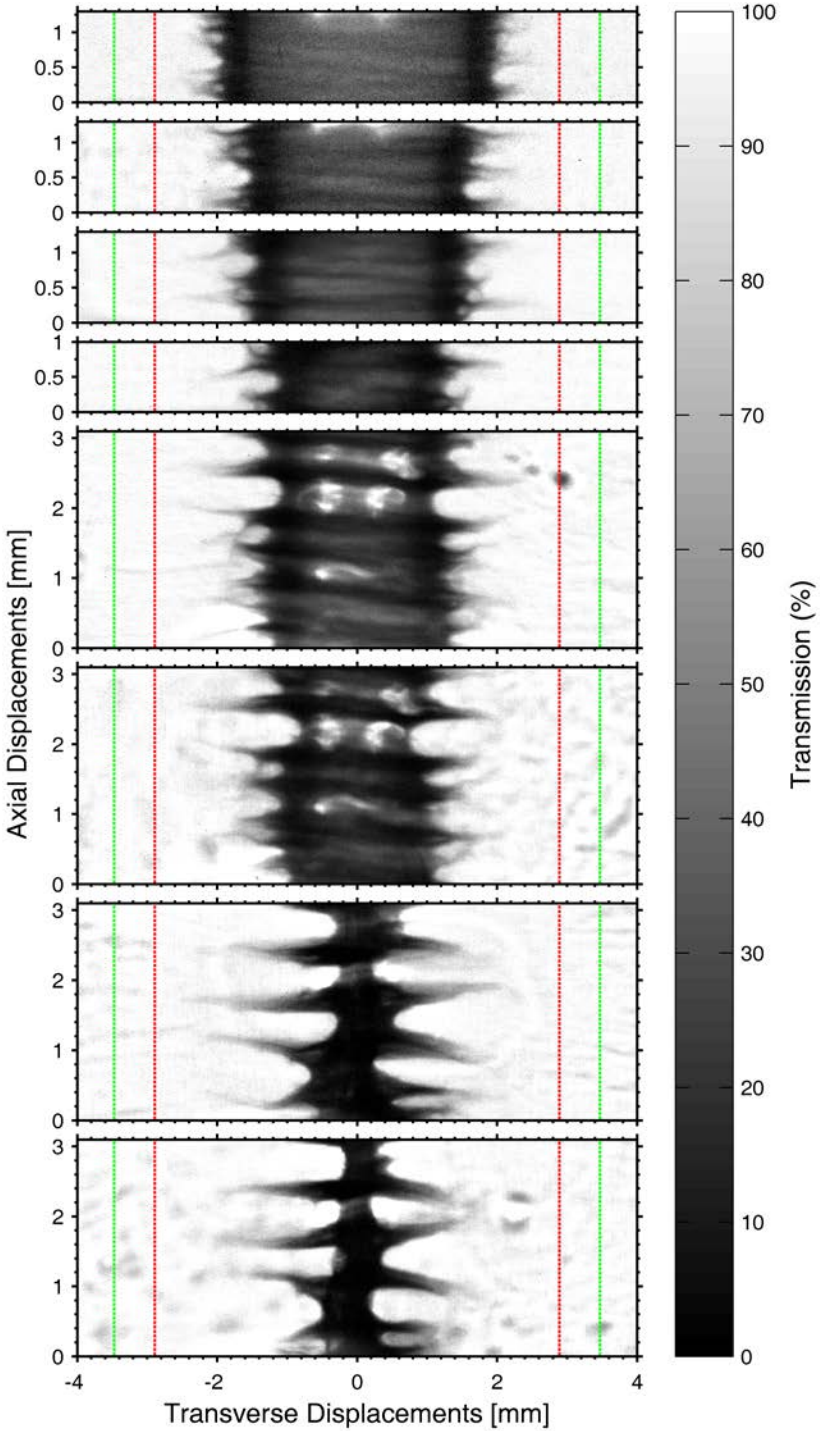
Beryllium MRT Data

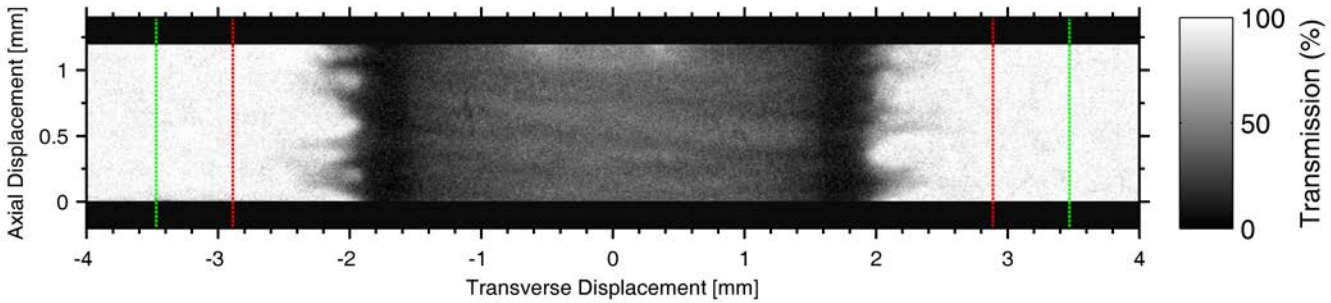




AR=6:

$r_{outer,0}$ = 3.47 mm

$r_{inner,0}$ = 2.89 mm



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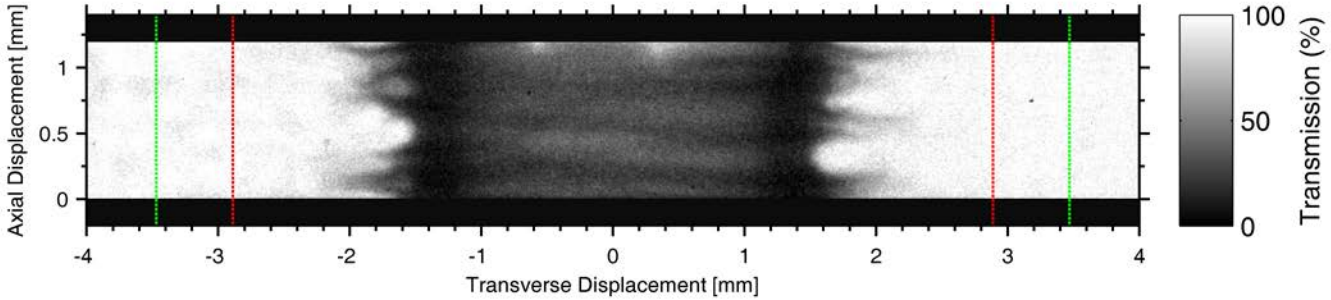

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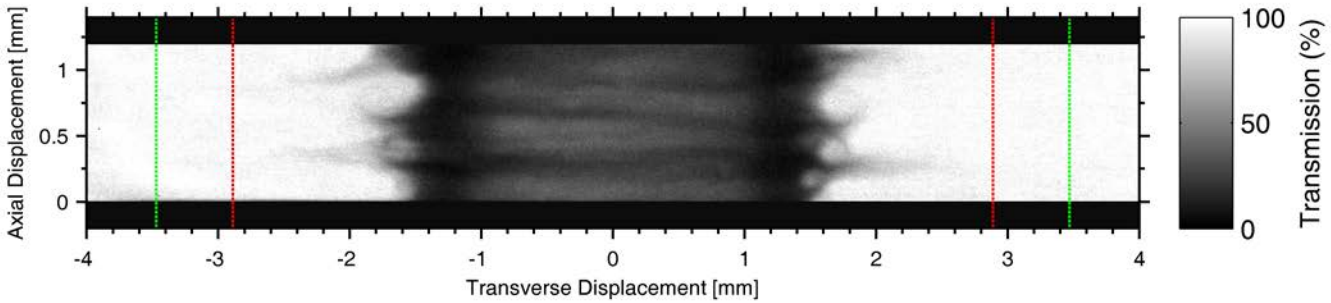

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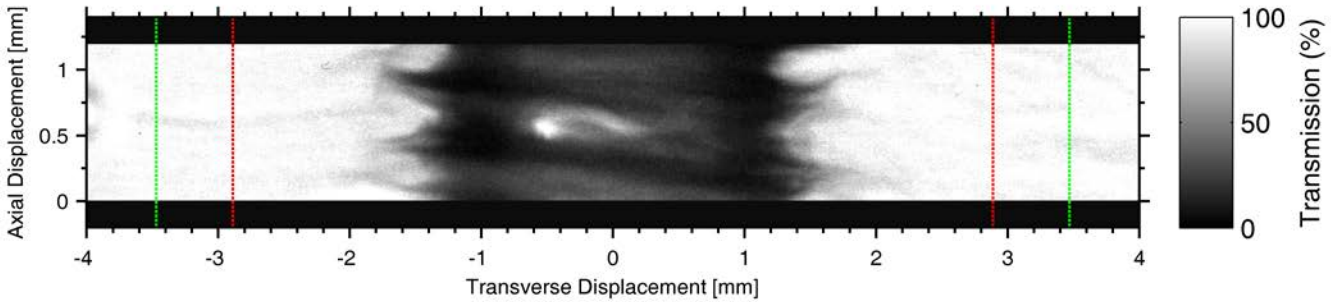

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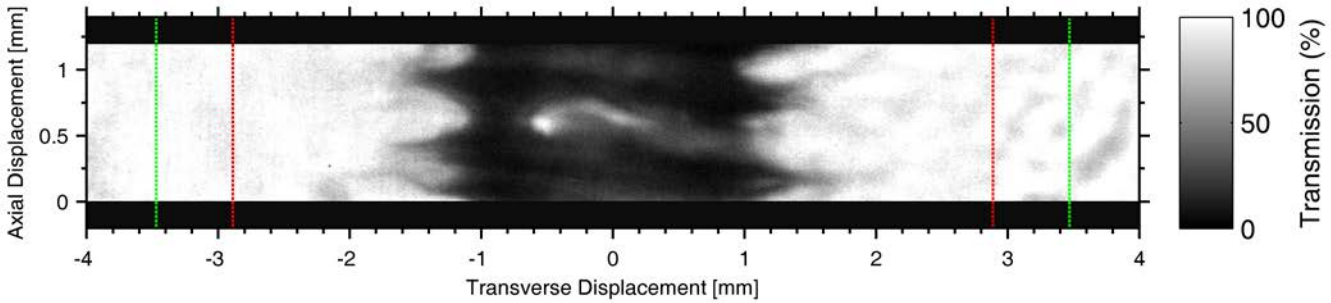

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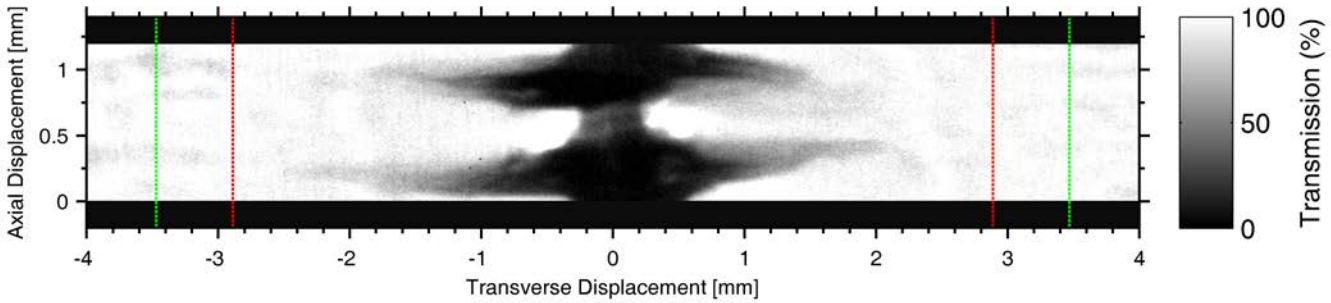

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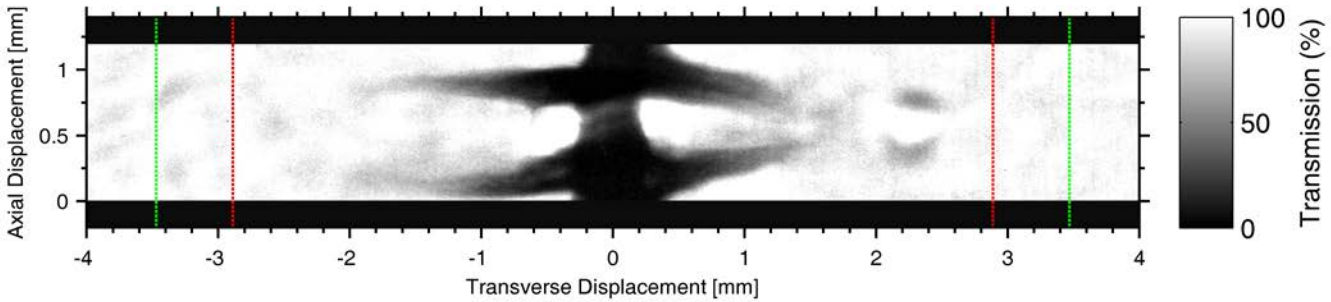

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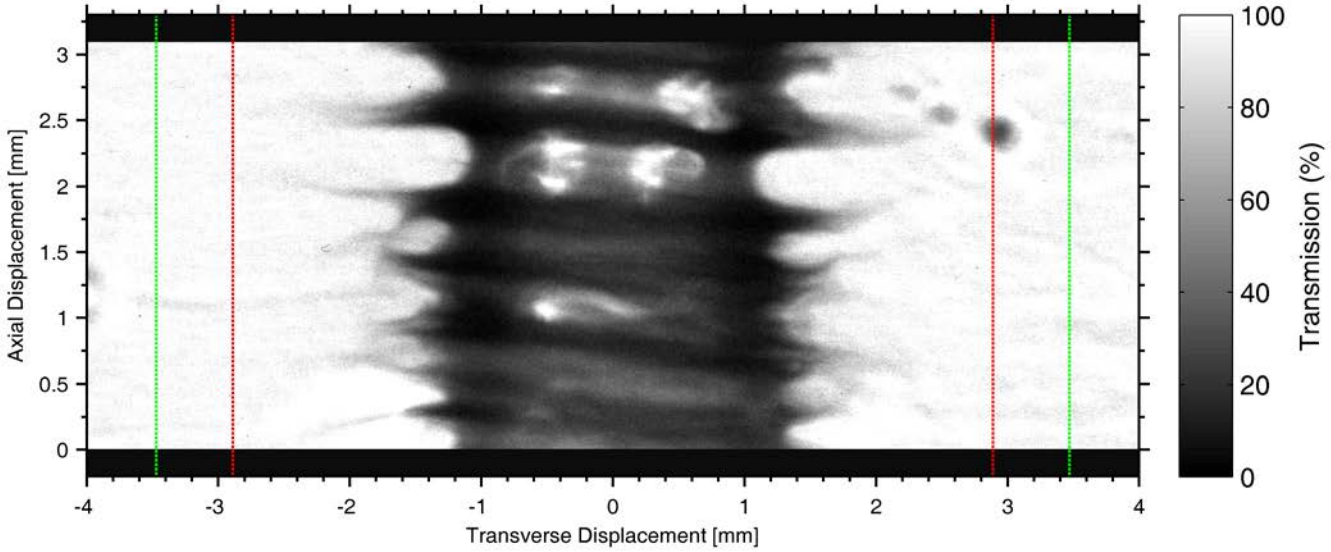

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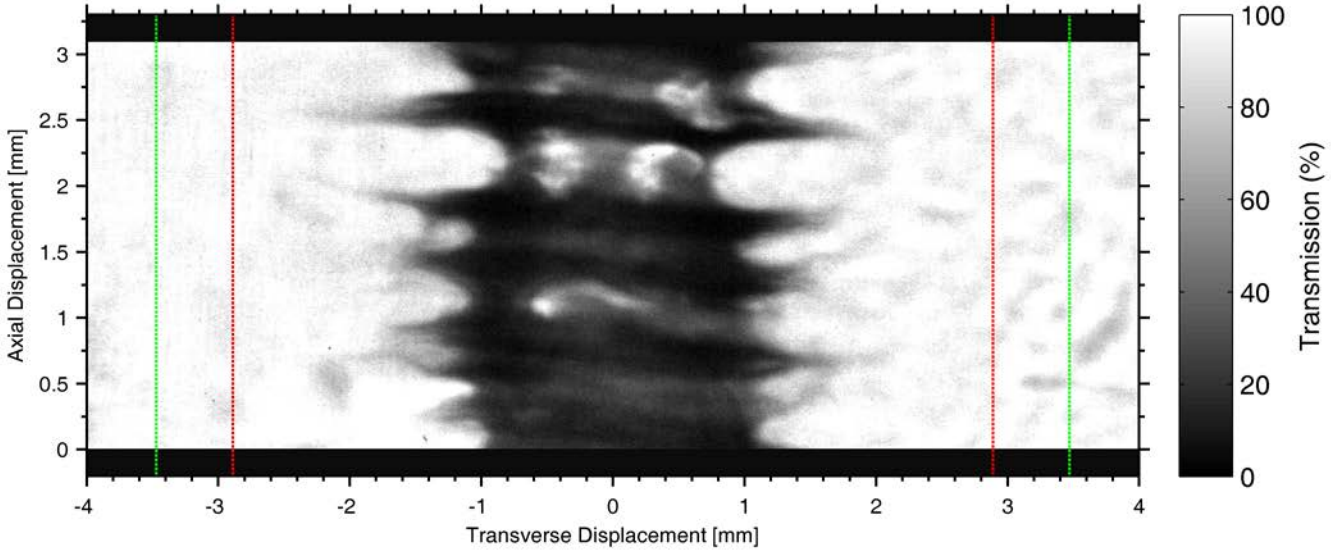

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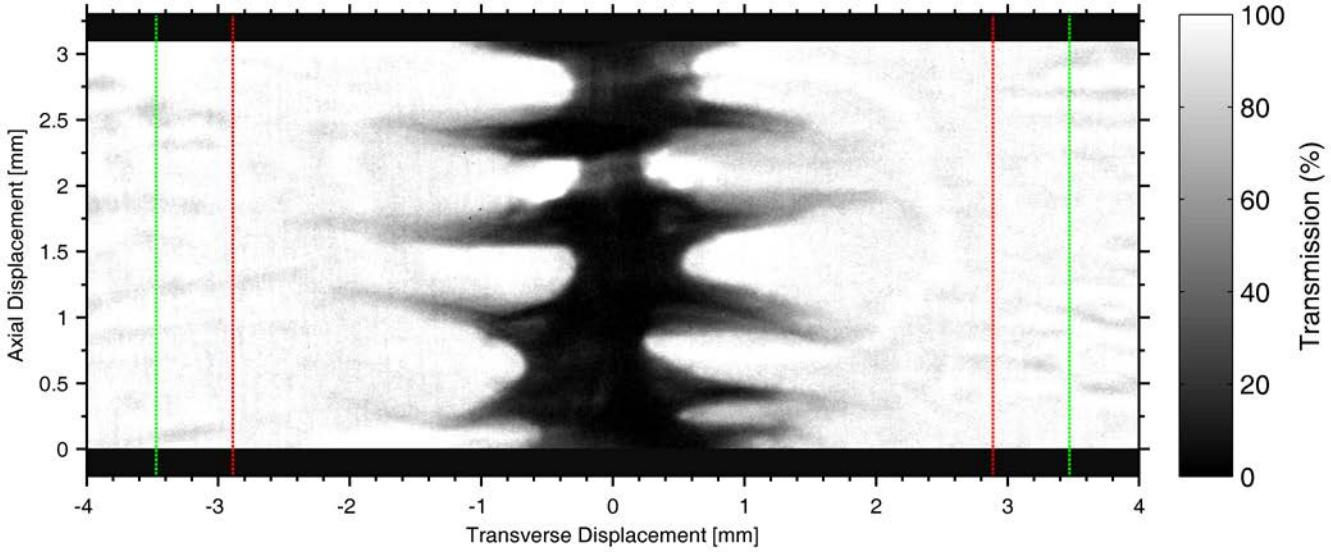

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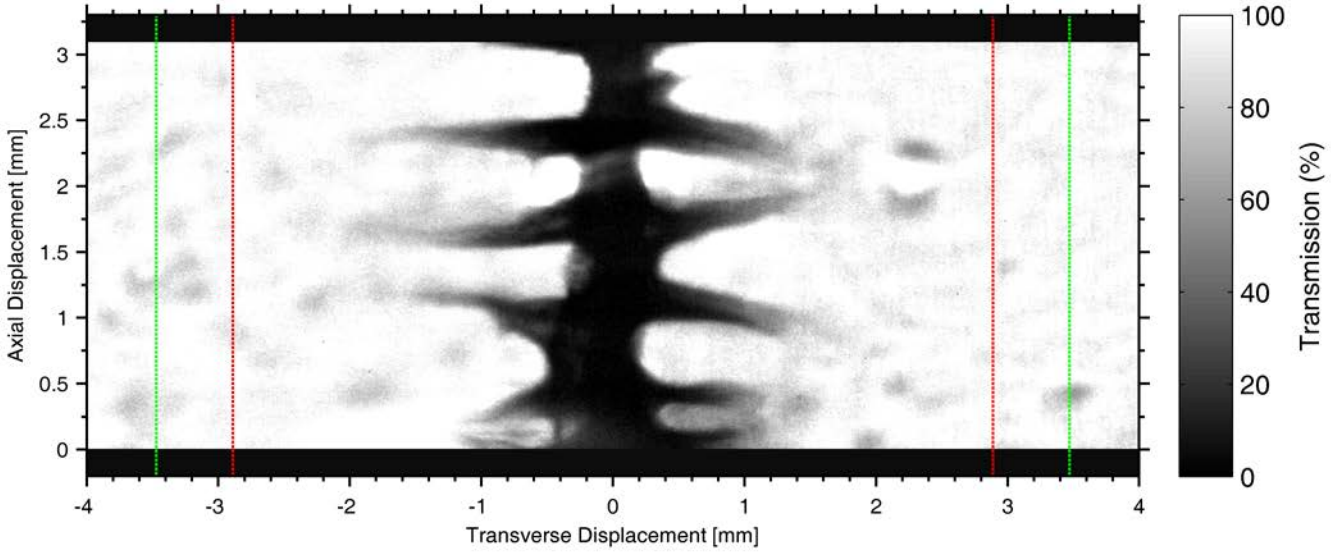

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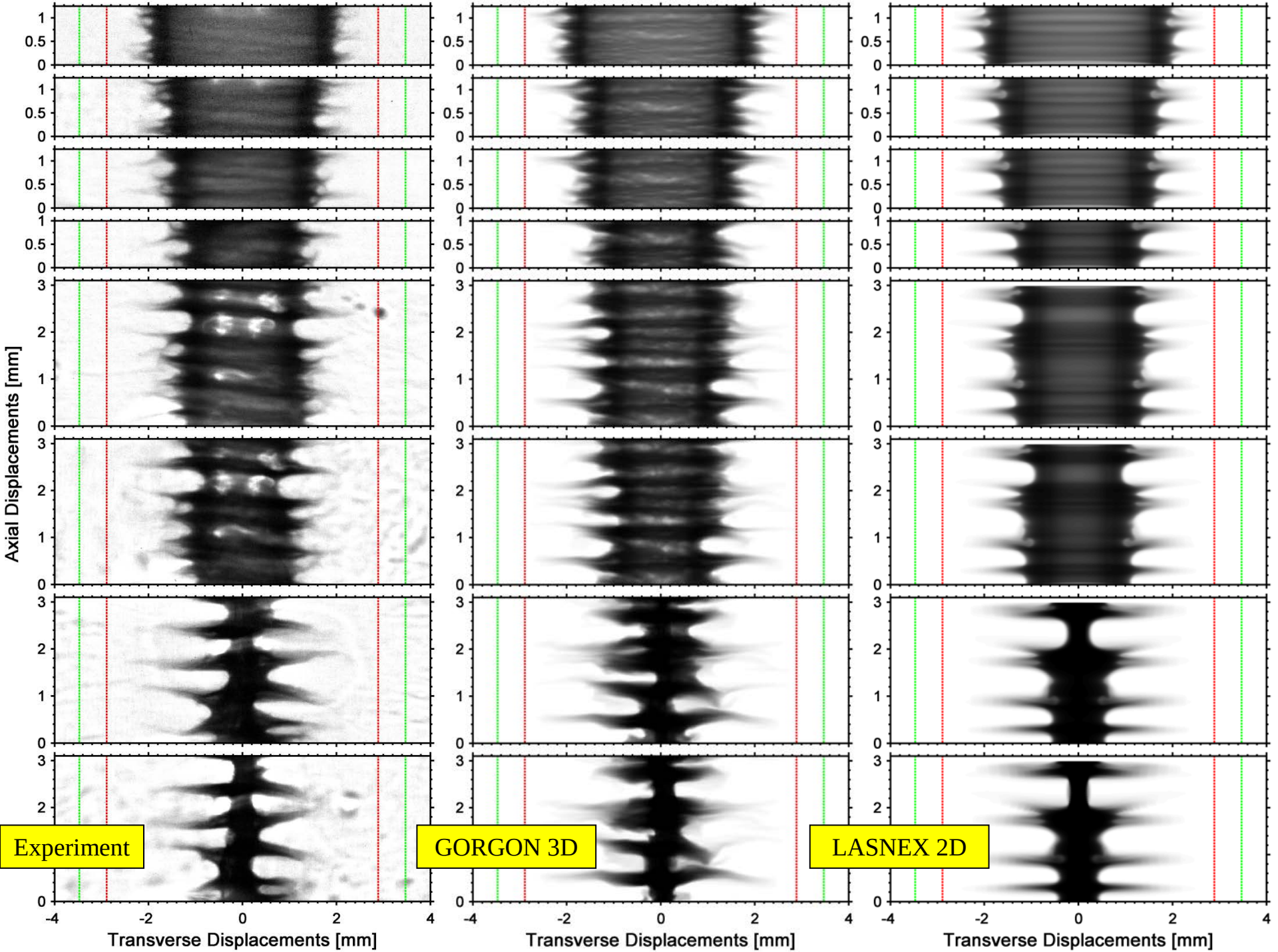
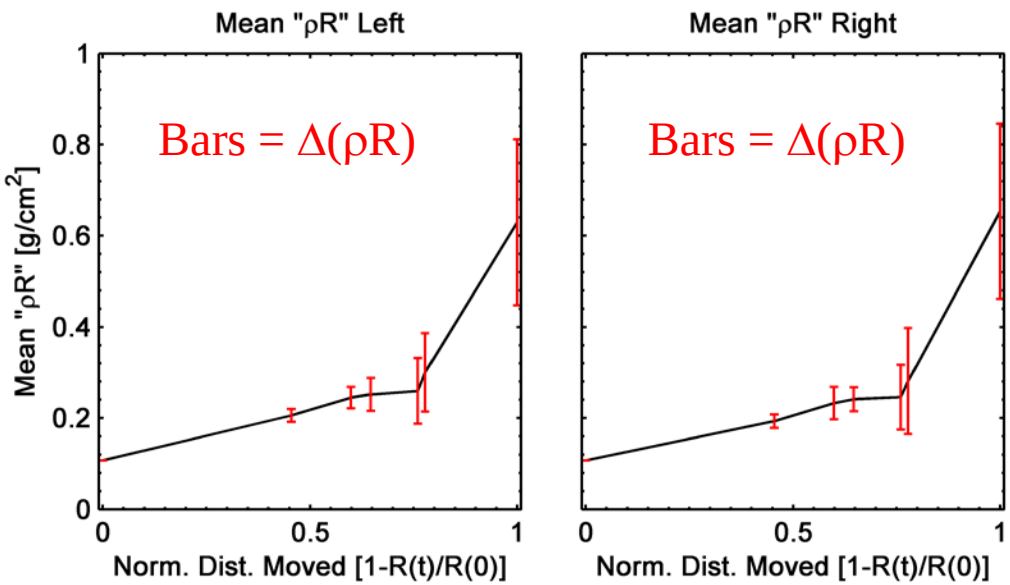

Experiment
GORGON 3D
LASNEX 2D
Axial Displacements [mm]
Transverse Displacements [mm]
Transverse Displacements [mm]
Transverse Displacements [mm]

Abel-Inverted MRT Data:

Mean ρR and Δ(ρR):



$$\text{Mean "}\rho R\text{"} \equiv \int \rho(R) \cdot dR$$

$$Q = 8.4(\Gamma\Gamma_L)^{1/2}\theta_s^{1.1}.$$

AR=6:

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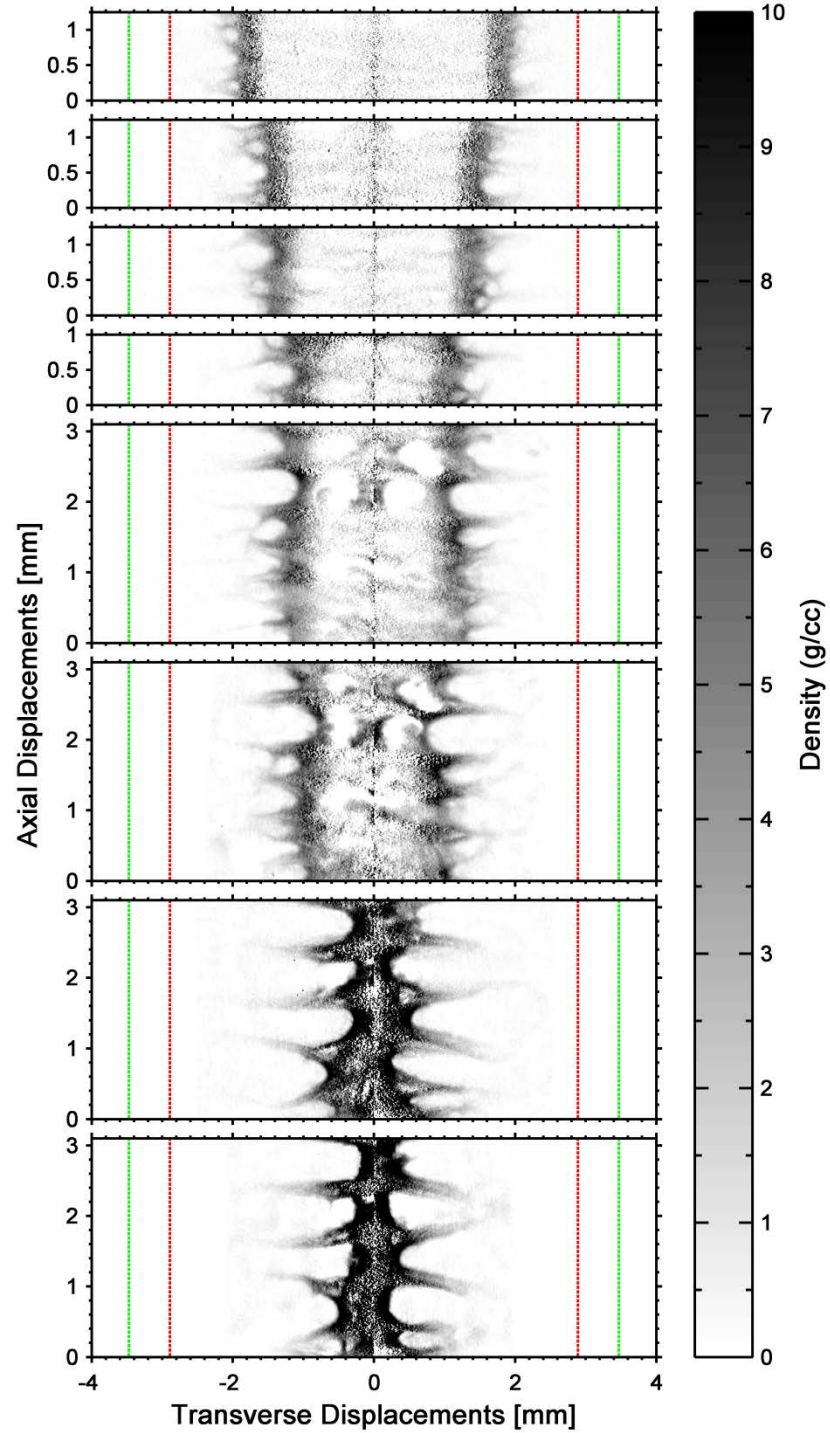
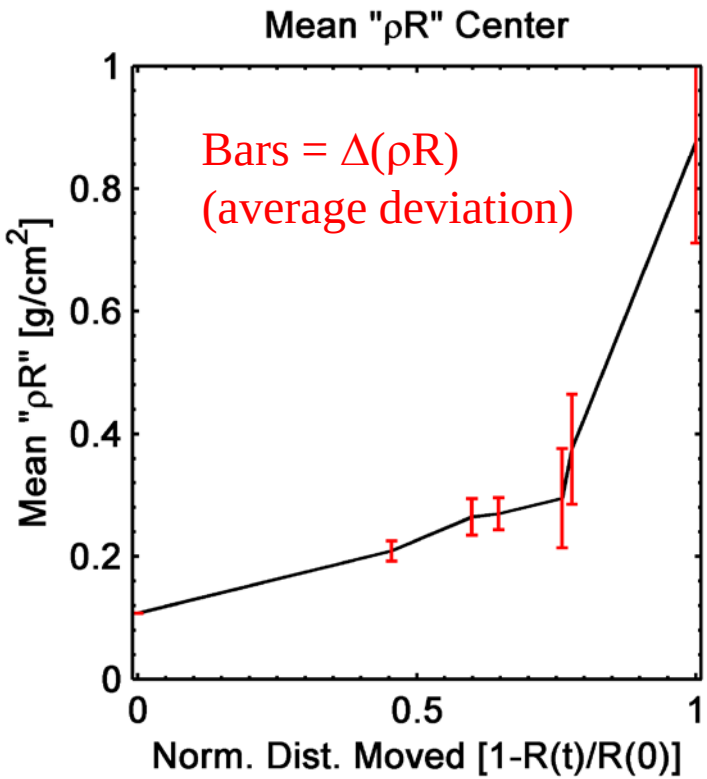
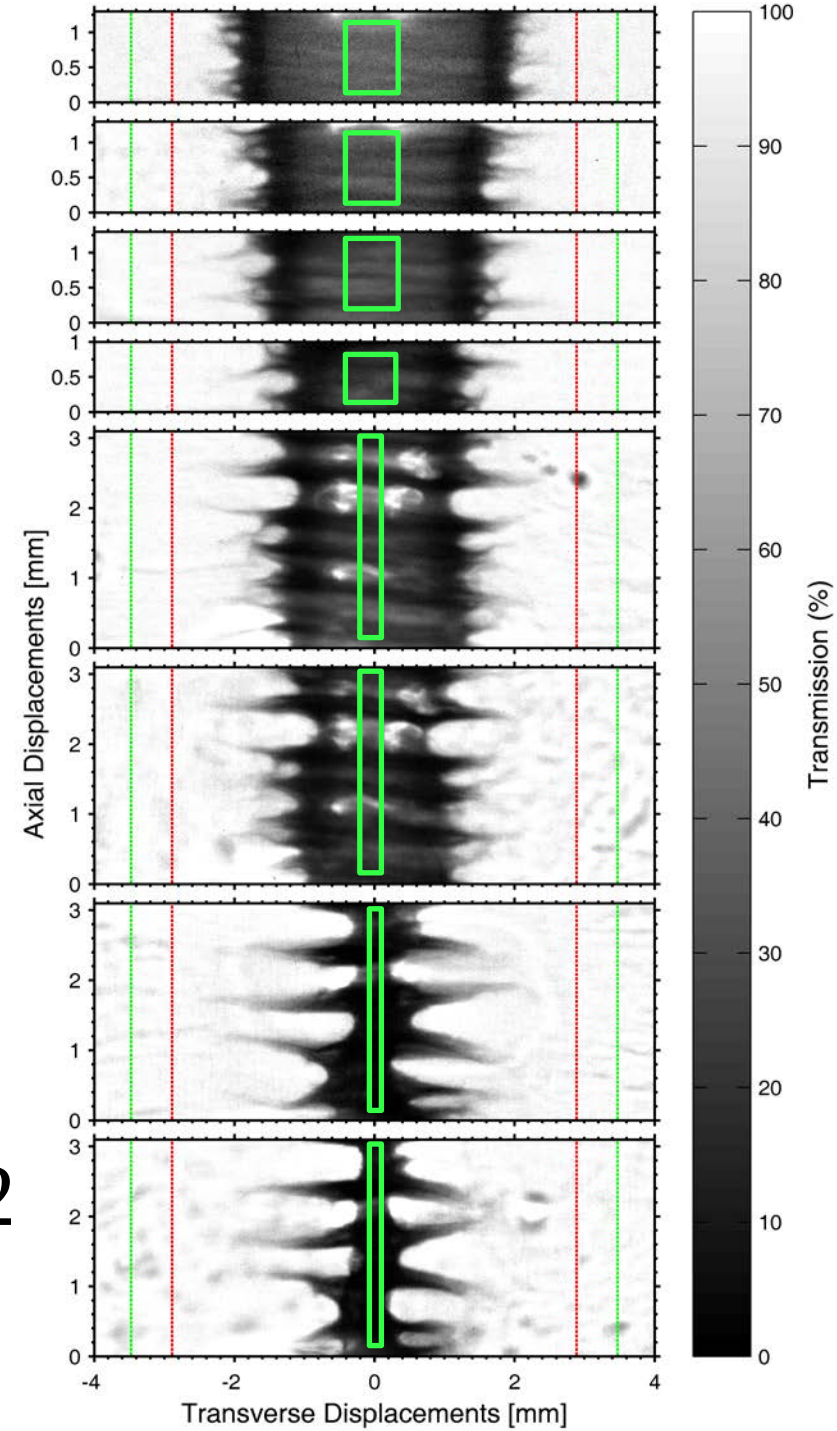


From Transmission
(Areal Density) MRT data:

Mean ρR and Δ(ρR):





$$\text{Mean "}\rho R\text{"} \equiv -[\ln(T)/\kappa_{Be}]/2$$

AR=6:

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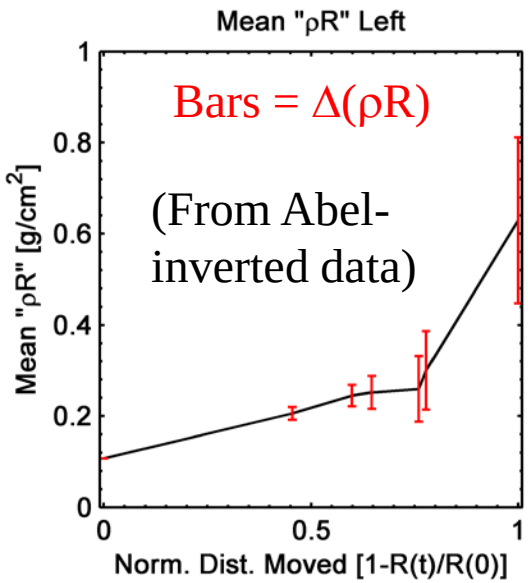
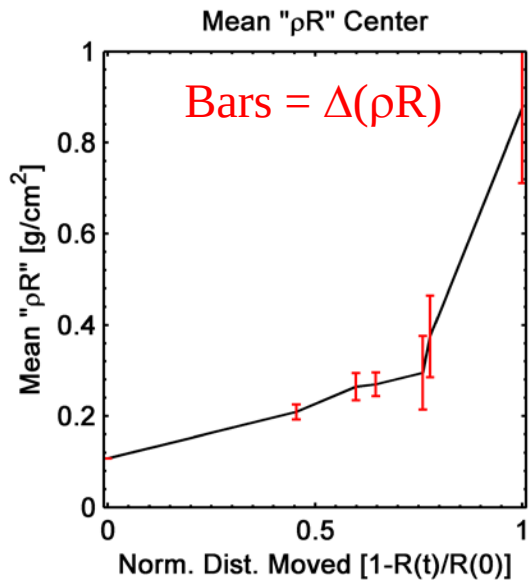
Mean ρR and Δ(ρR):

From S.A. Slutz, et al., PoP (2010):

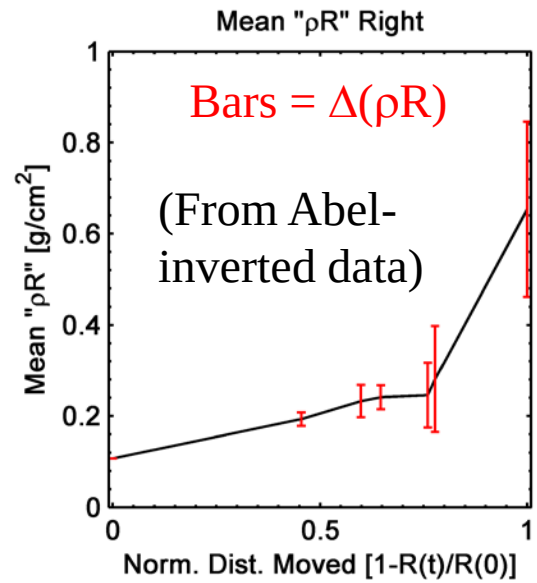
$$Q = 8.4(\Gamma\Gamma_L)^{1/2}\theta_s^{1.1}.$$



(from left half of volume density)



(from center of areal density)



(from right half of volume density)

Δ(ρR) < 30%

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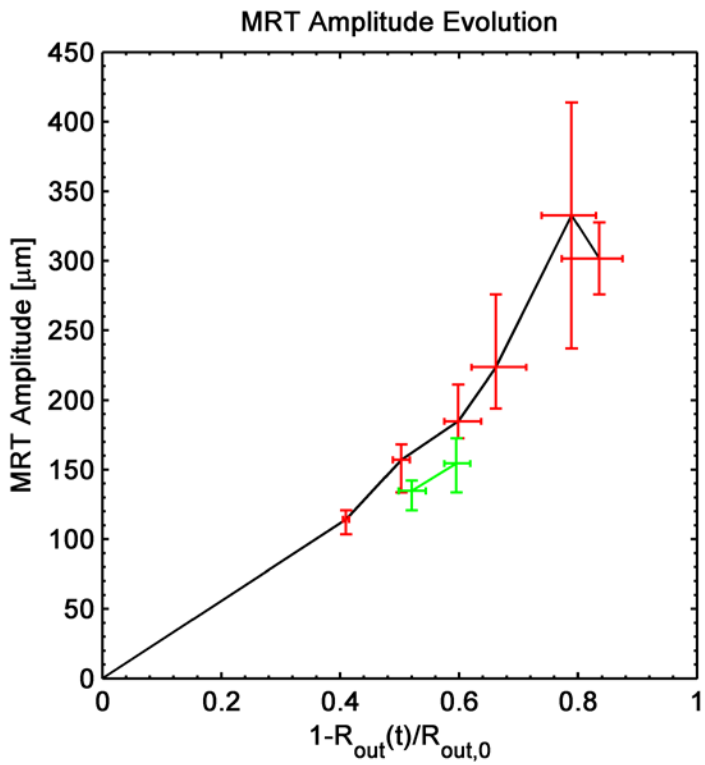
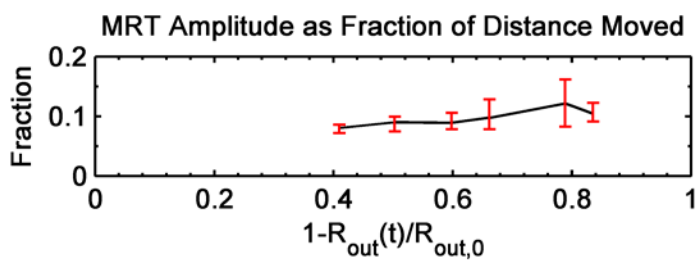
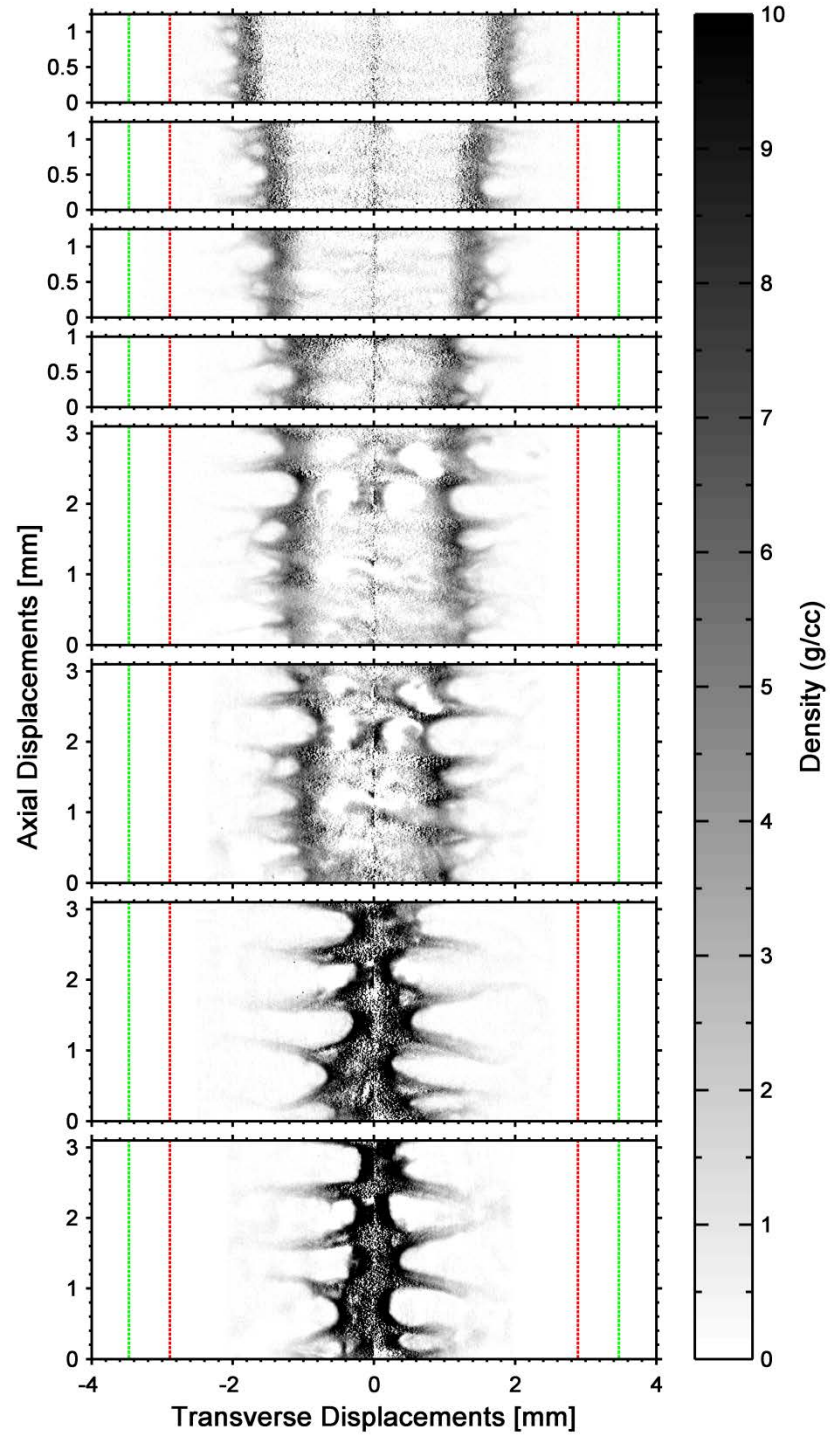
Abel-Inverted:

MRT Amplitude Growth:

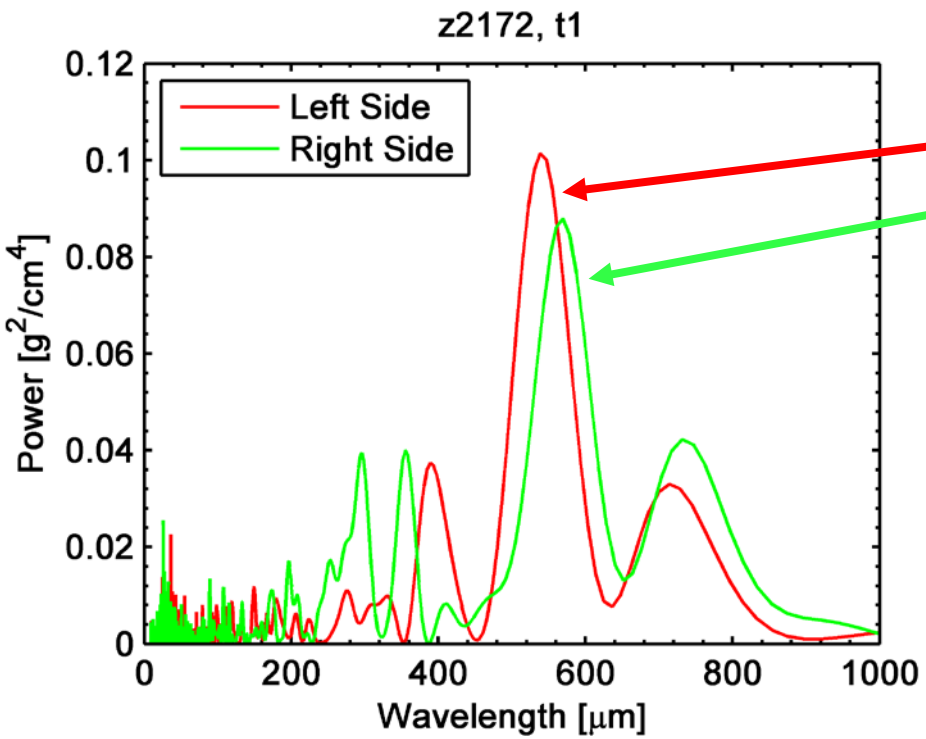


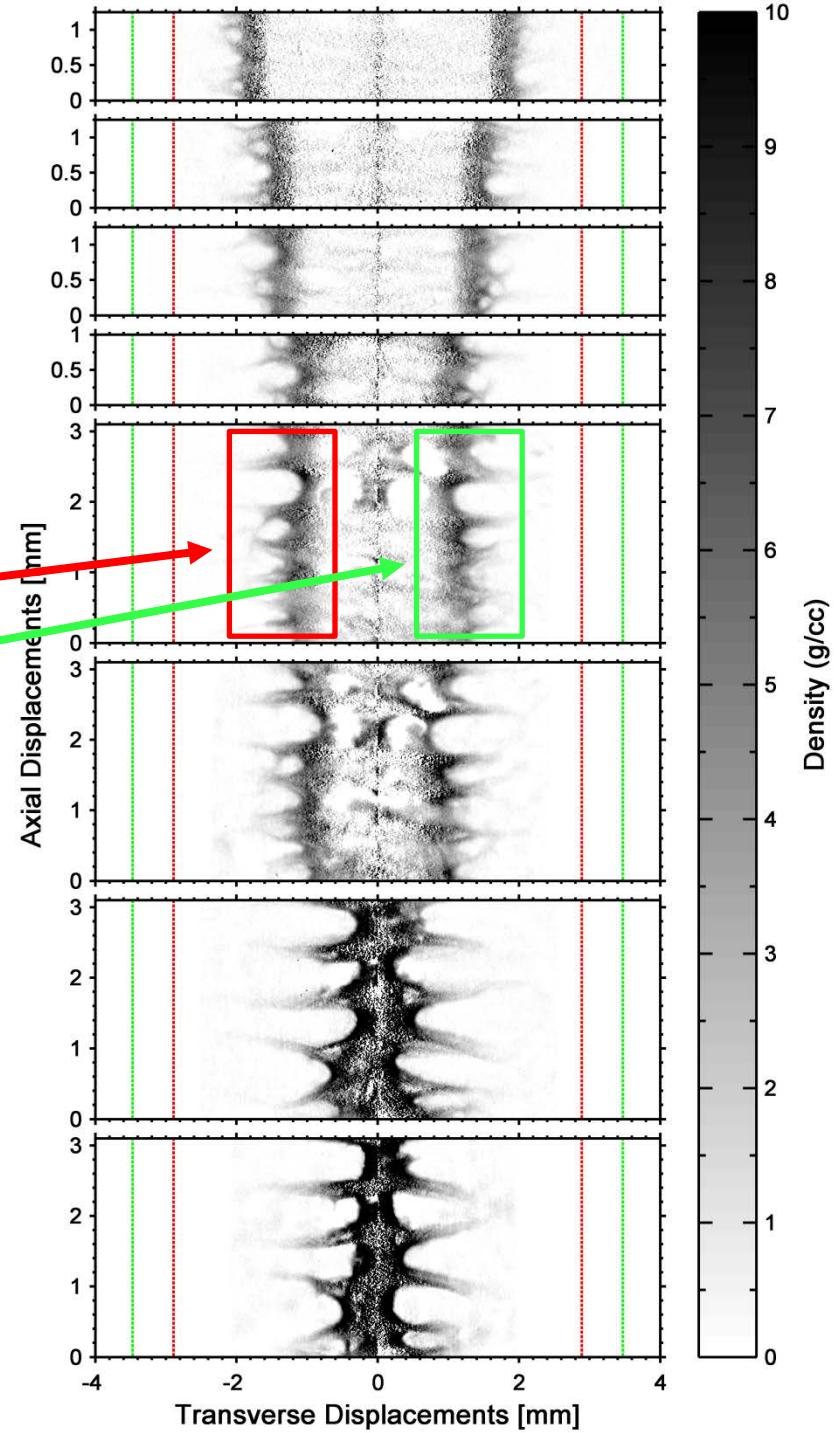




Abel-Inverted MRT Data:

Fourier Analysis:





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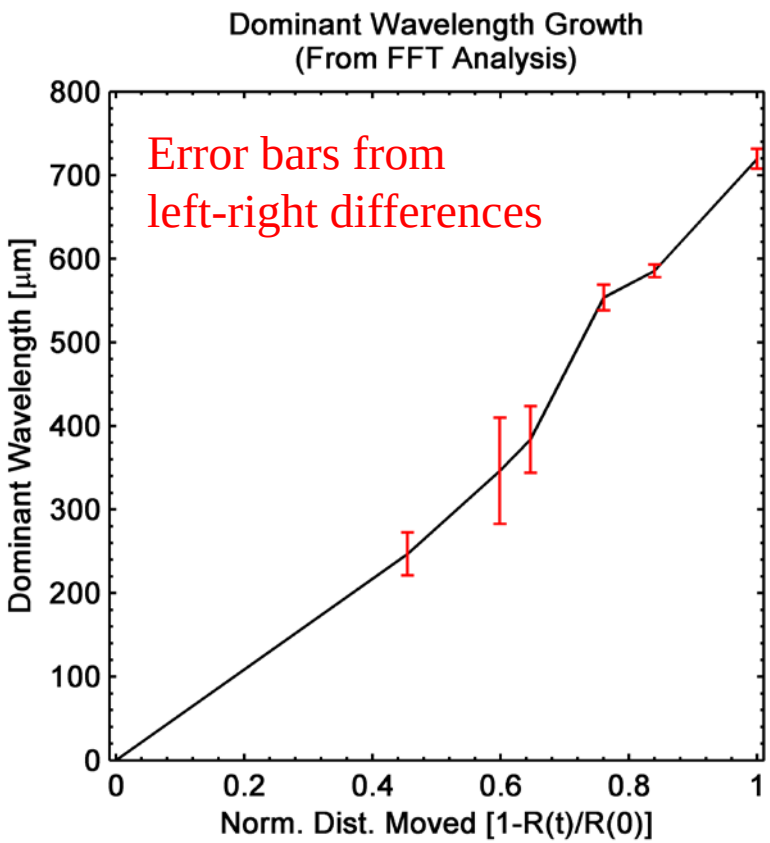
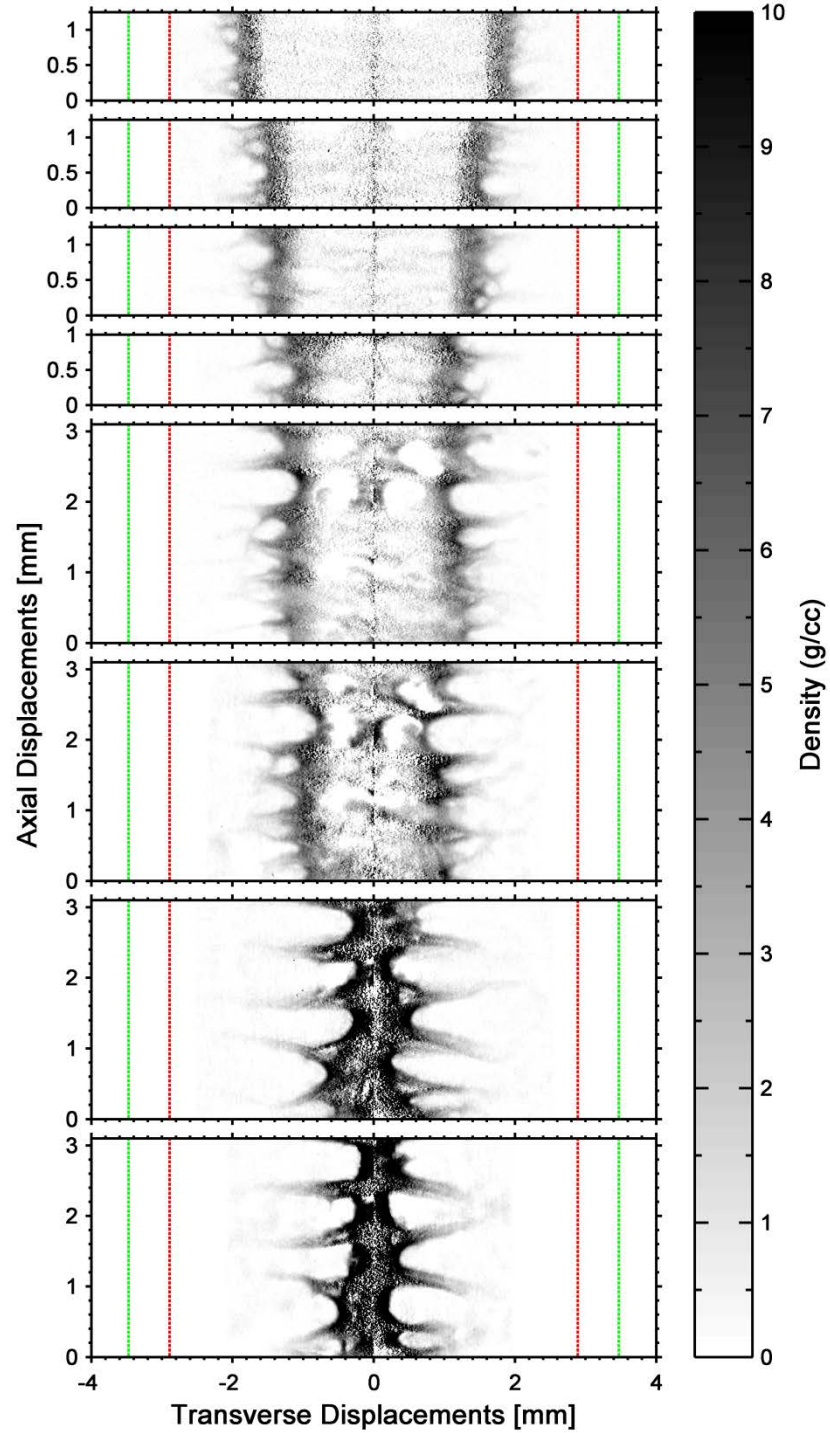
Abel-Inverted MRT Data:

Fourier Analysis:





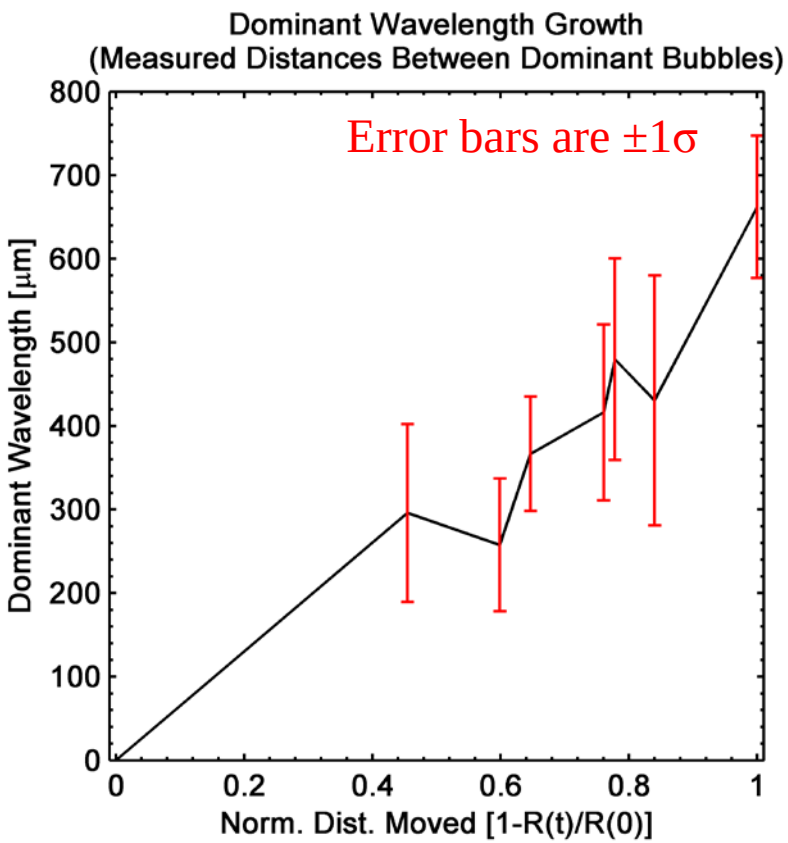
AR=6:

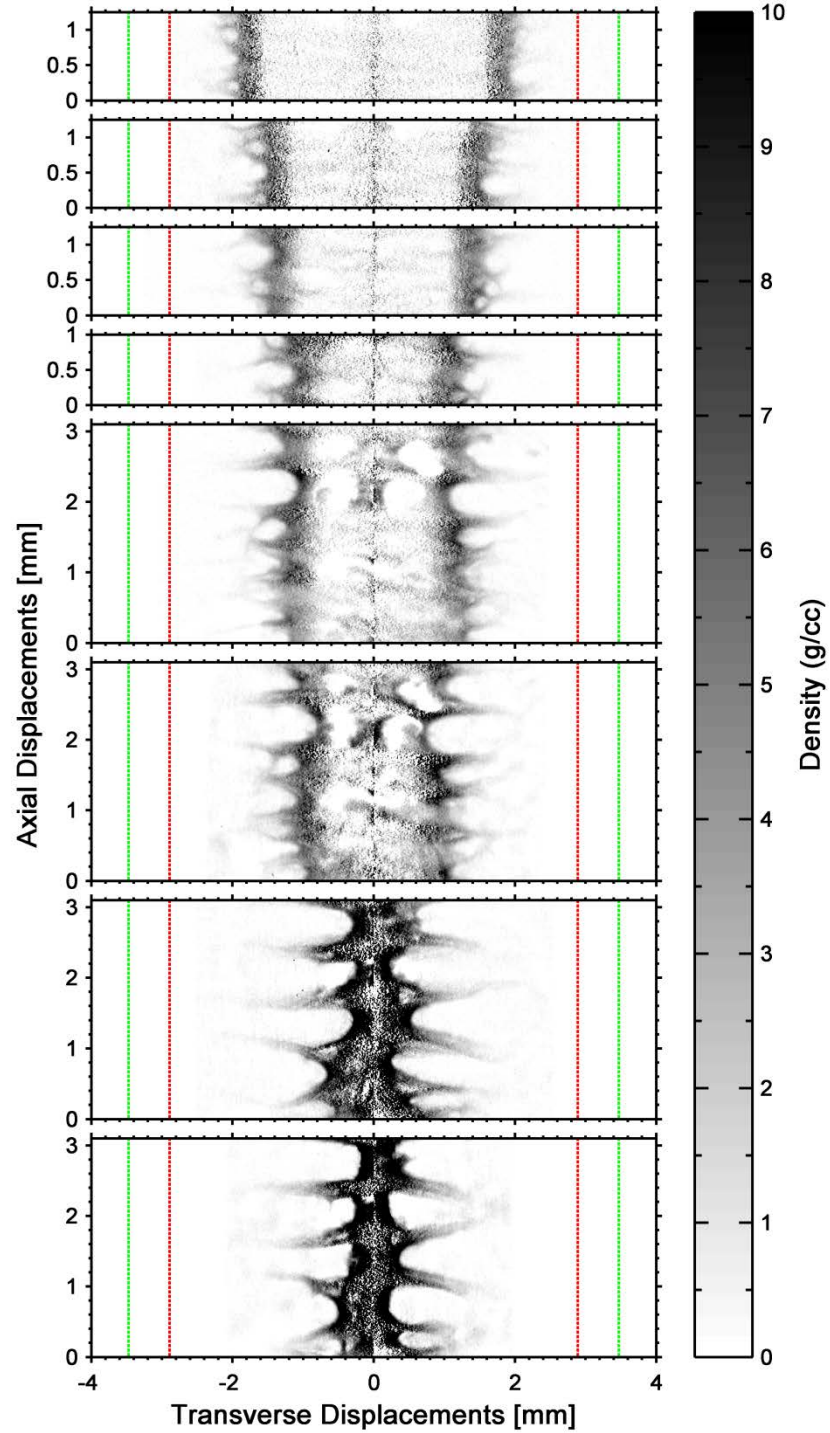
$r_{outer,0}$ = 3.47 mm

$r_{inner,0}$ = 2.89 mm

Abel-Inverted MRT Data:

Dominant Wavelength Growth:





AR=6:

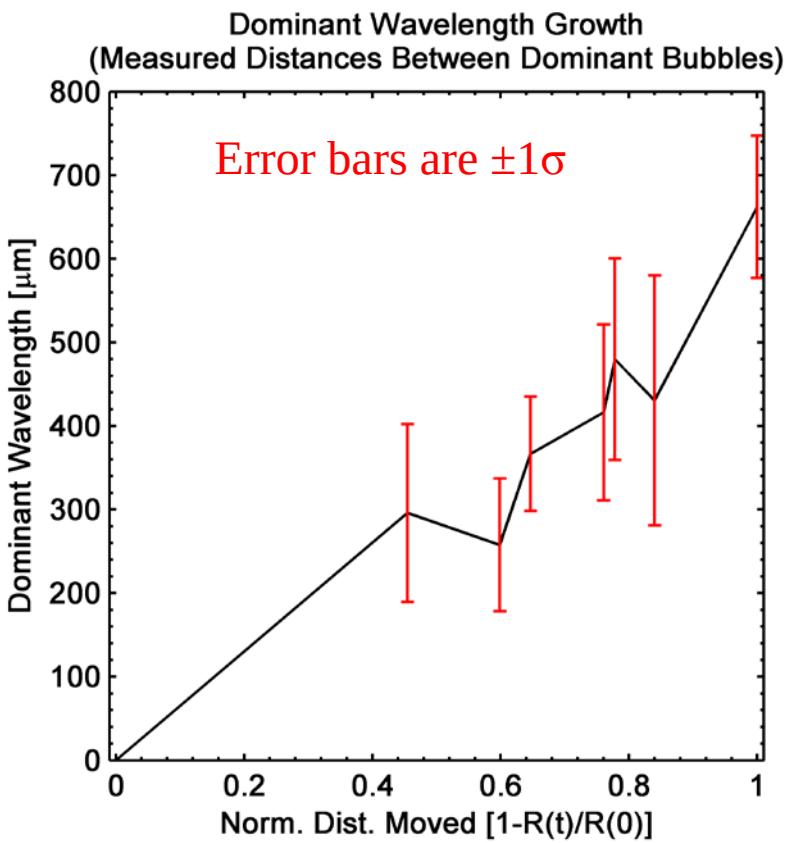
$r_{outer,0}$ = 3.47 mm

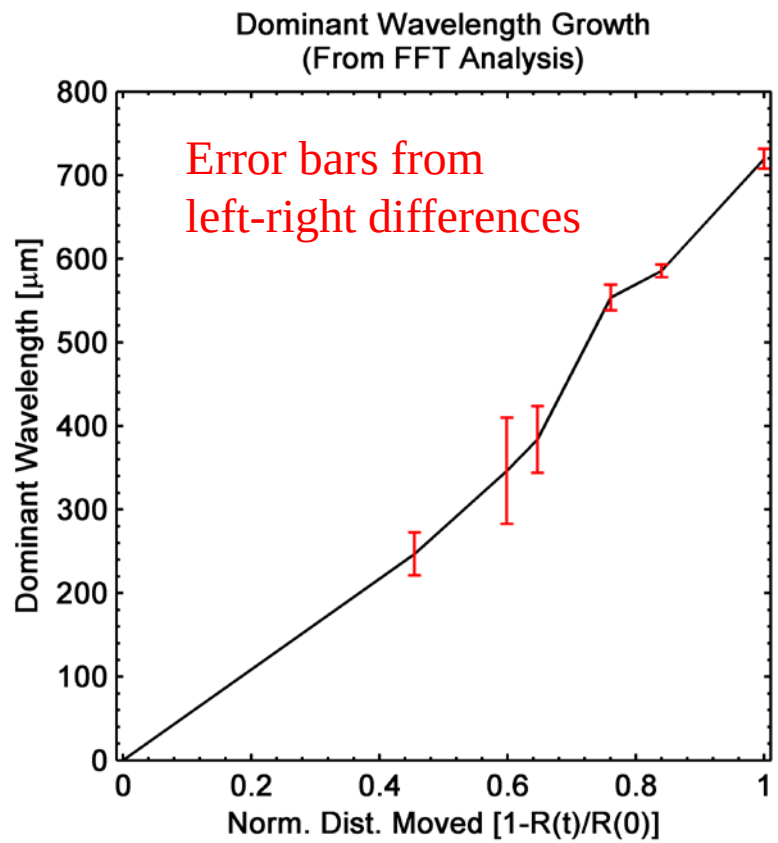
$r_{inner,0}$ = 2.89 mm

$$\lambda_{AR=6}(t) \approx \lambda_{\max}\left(1-\frac{R_{in}(t)}{R_{in,0}}\right)$$

where $\lambda_{\max} = 675 \pm 100\ \mu\text{m}$

Dominant Wavelength Growth:





AR=6:

$r_{outer,0}$ = 3.47 mm

$r_{inner,0}$ = 2.89 mm

Sandia National Laboratories

Beryllium Liners

ICF / MagLIF

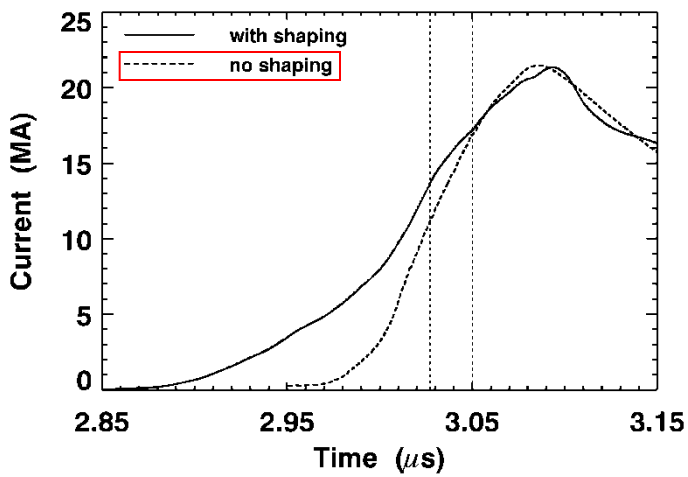
Dynamic Materials / EOS

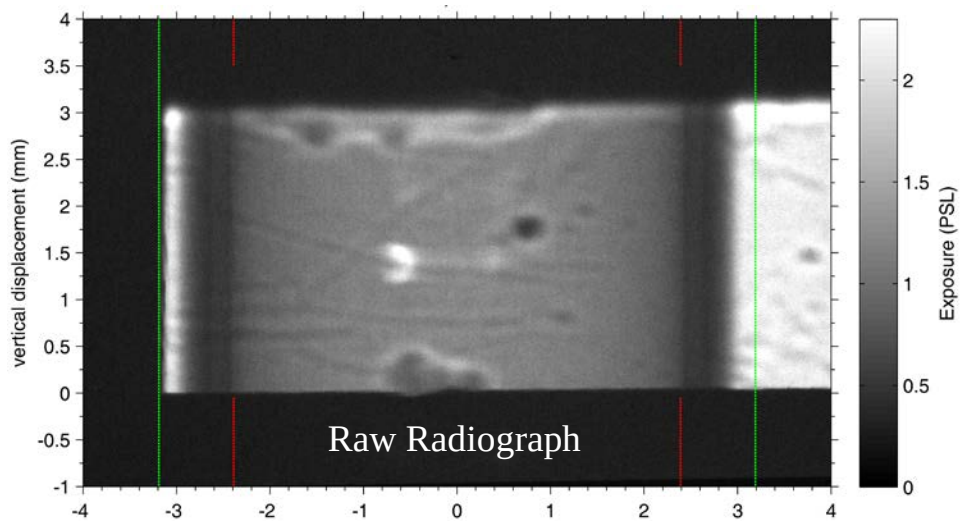
MRT Experiments

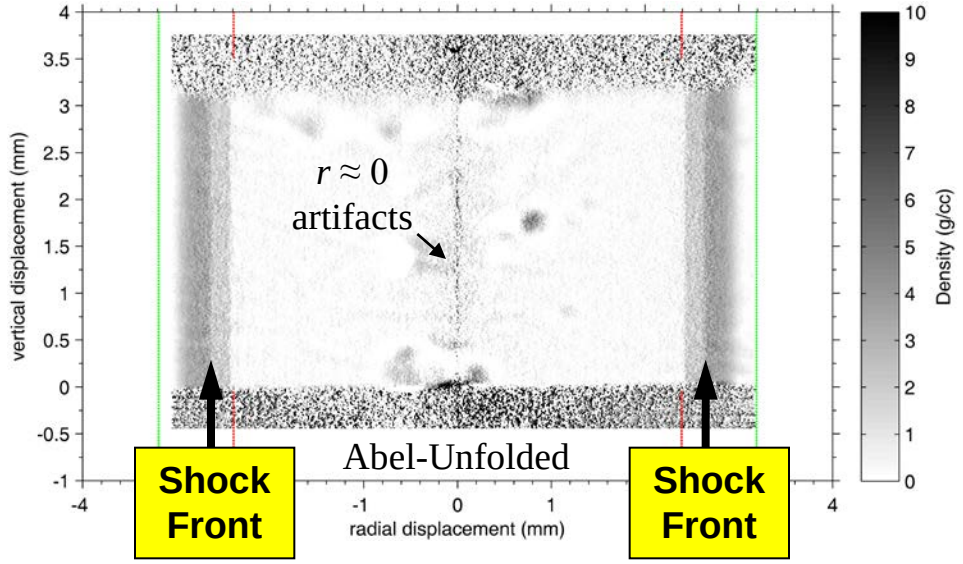
Shock-Compression Experiments

Isentropic-Compression Experiments

Beryllium Shock-Compression Experiments

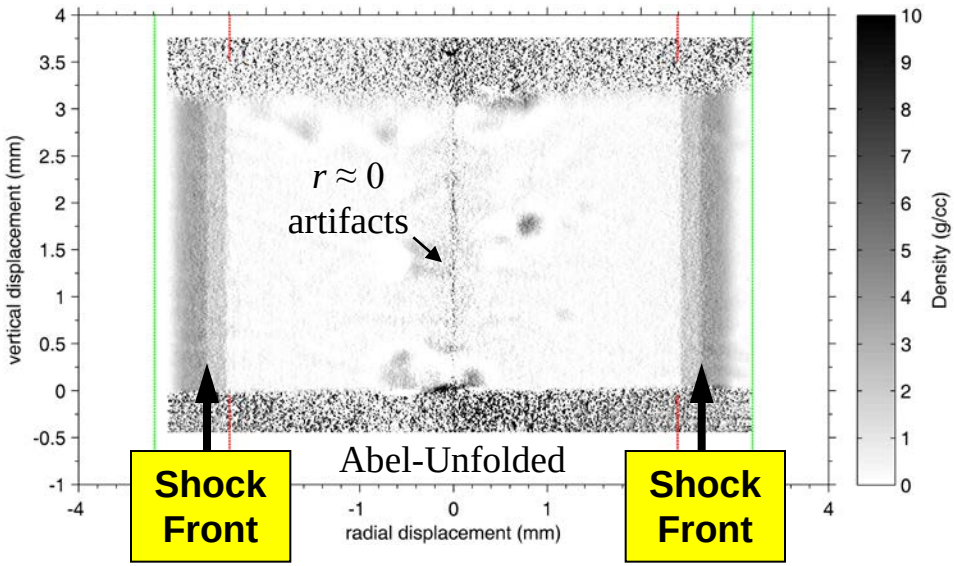


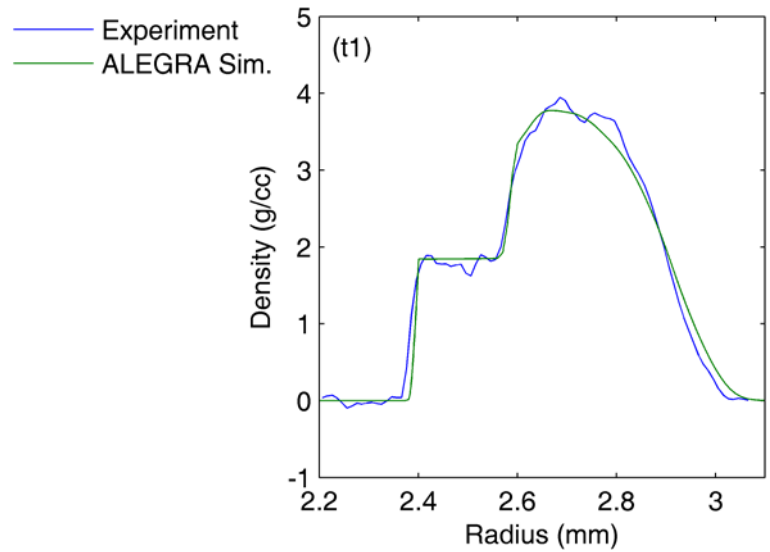


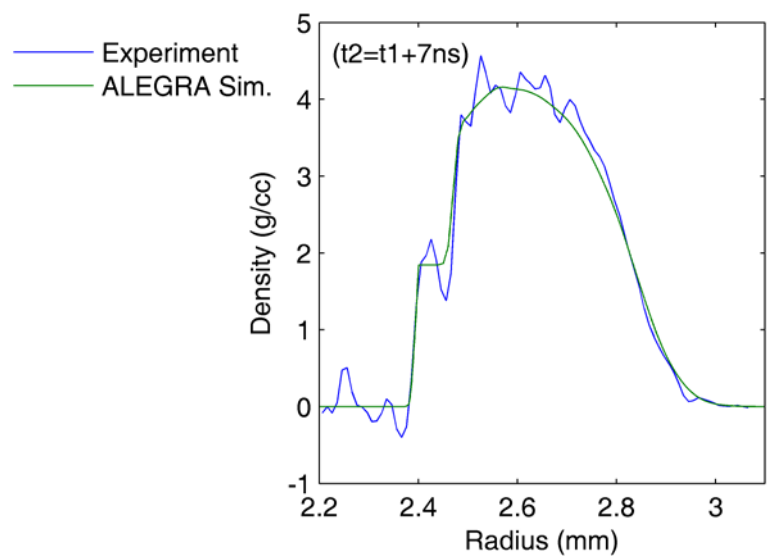


- **No pulse-shaping for shock experiments (Z accelerator in short-pulse mode)**
- **Fast rising magnetic pressure drives a shock that propagates radially inward through the beryllium liner**

Beryllium Shock-Compression Experiments







- **Excellent agreement established between experiment and simulation**
- **Measured shock velocity of about 19 km/s**
- **Measured density jump to about 2x solid density**
- **Only one shot (two images) so far**
  - **More shots needed for shock acceleration**
- **Can test existing Be EOS on shock Hugoniot**
- **Can possibly extend the Be EOS on shock Hugoniot with future experiments**

Beryllium Liners

ICF / MagLIF

Dynamic Materials / EOS

MRT Experiments

Shock-Compression Experiments

Isentropic-Compression Experiments

Sandia National Laboratories

Why is isentropic compression interesting for MagLIF?

1. Isentropic compression is more efficient hydrodynamically
   - Shock heating wastes radially-directed implosion energy
   - Isentropic compression achieves higher liner densities (higher liner rho-r)

2. Maintaining a solid metallic inner liner surface could:
   - maintain high electrical conductivity, thus result in more efficient flux compression
   - mitigate MRT disruption due to solid-state material strength

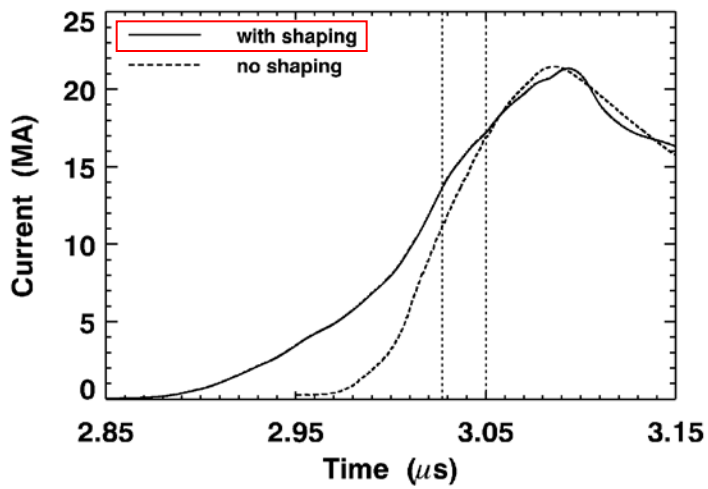
3. Possibly mitigate liner ejecta from liner's inner surface (due to shock breakout) and thus prevent liner material from prematurely mixing with the fusion fuel

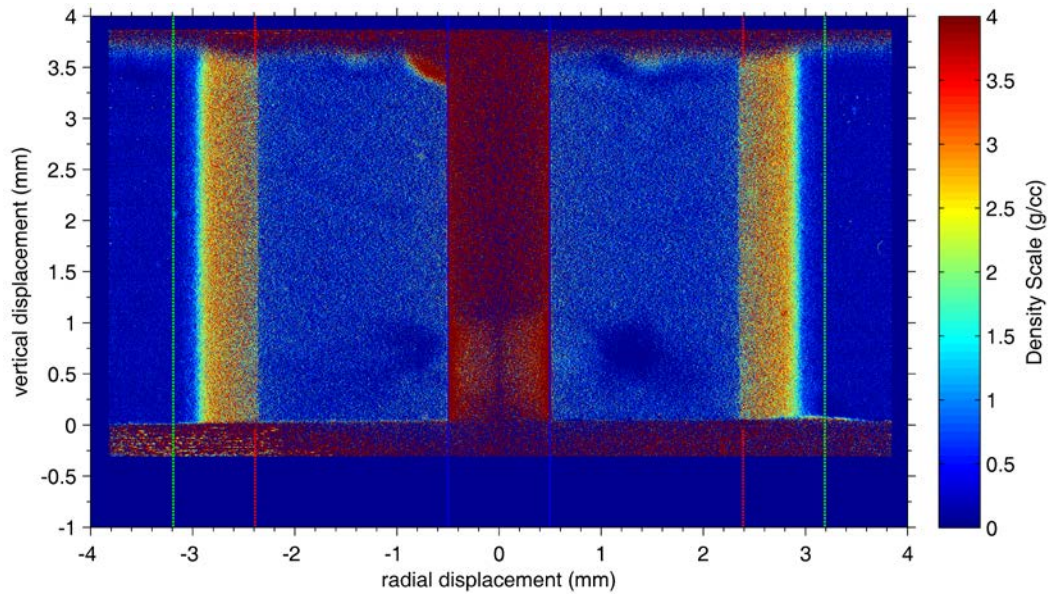
4. Longer pulse shape for isentropic compression could:
   - convert more of Z's EM energy into implosion energy
   - be favorable for next generation 60-MA drivers (longer pulse lengths)
   - be favorable for compatibility with load current multipliers (LCMs)

5. Longer isentropic compression pulse shape can still be designed to have high electrical power near stagnation, if EM power delivery at stagnation is found to be important

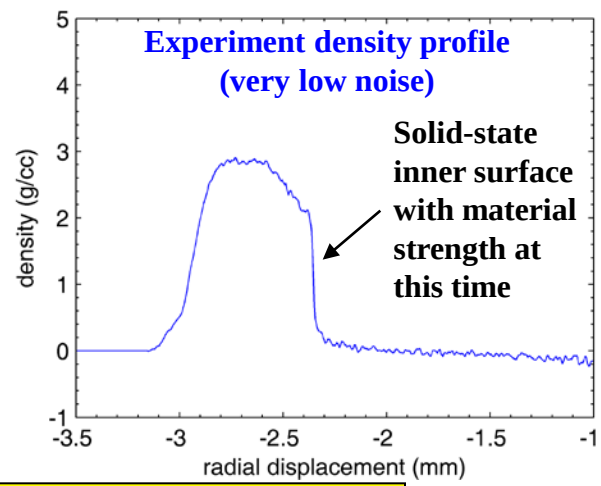
6. Etc…

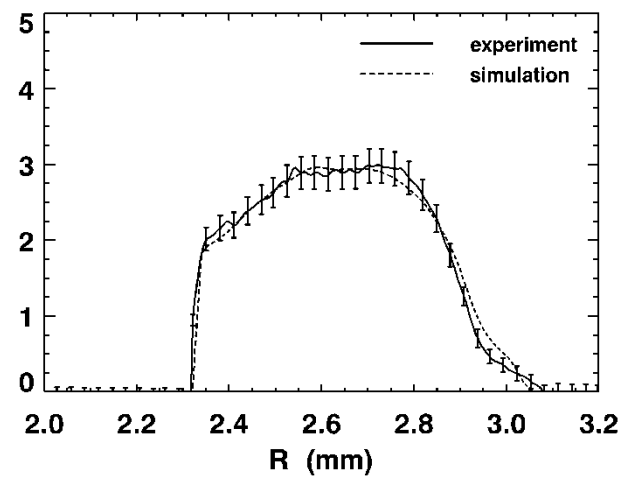
Pulse-Shaping for Be Isentropic Compression Experiments (ICE)





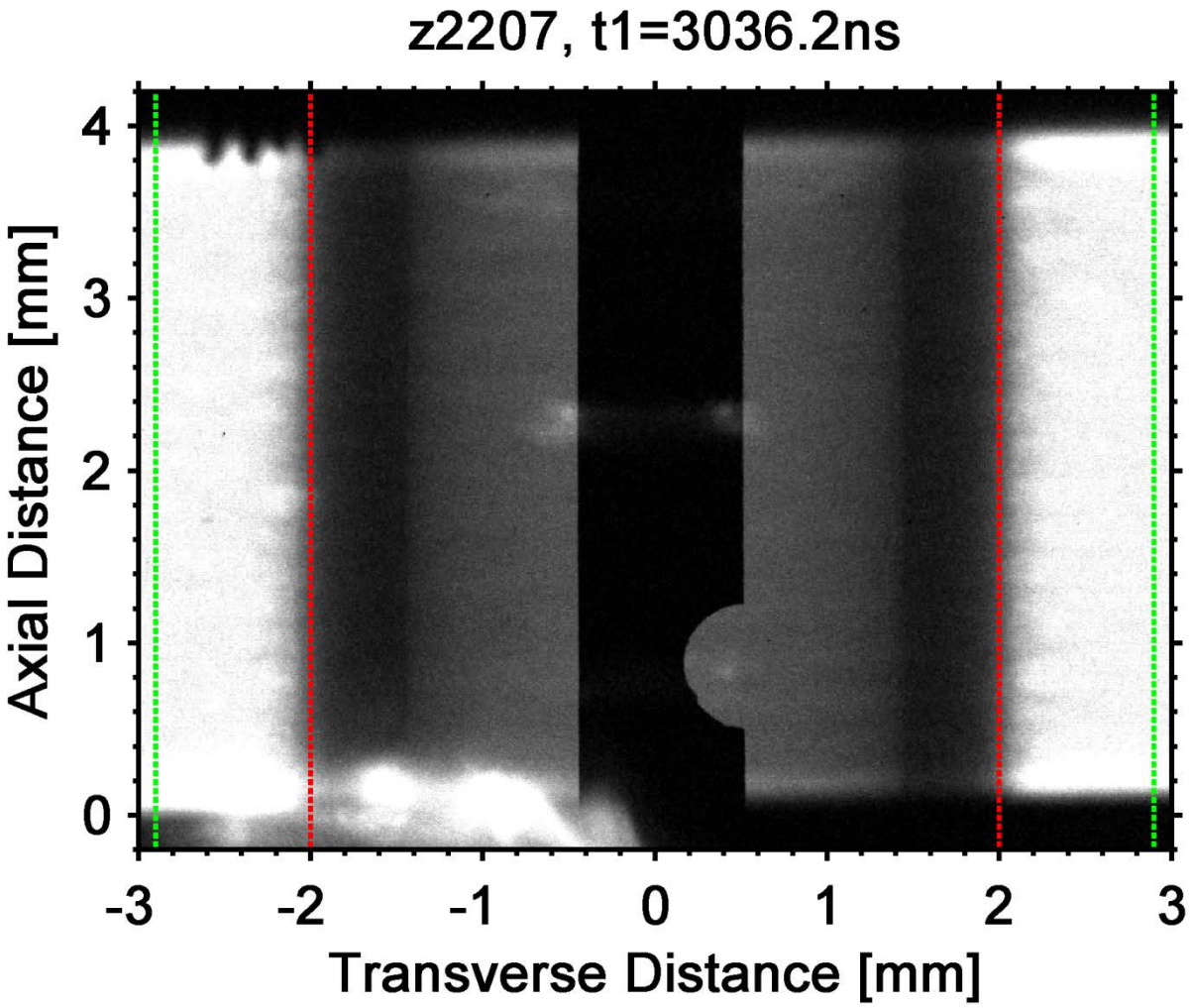
- **Z accelerator pulse-shaping used to shocklessly (quasi-isentropically) compress the beryllium liner**
- **Excellent agreement established between experiment and simulation**





*** See work by R.W. Lemke, M.R. Martin, et al.**

Most Recent Be ICE



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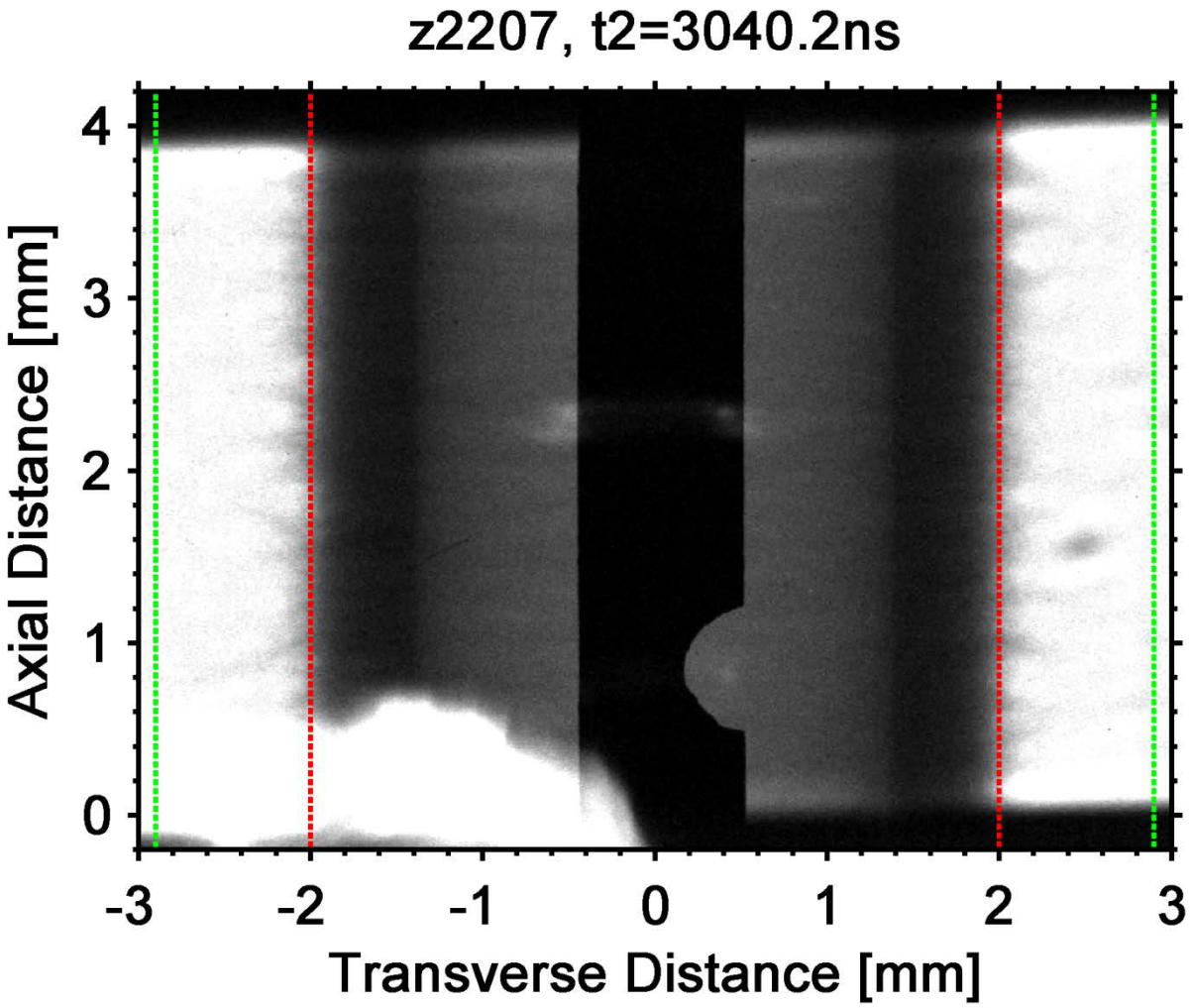
Most Recent Be ICE



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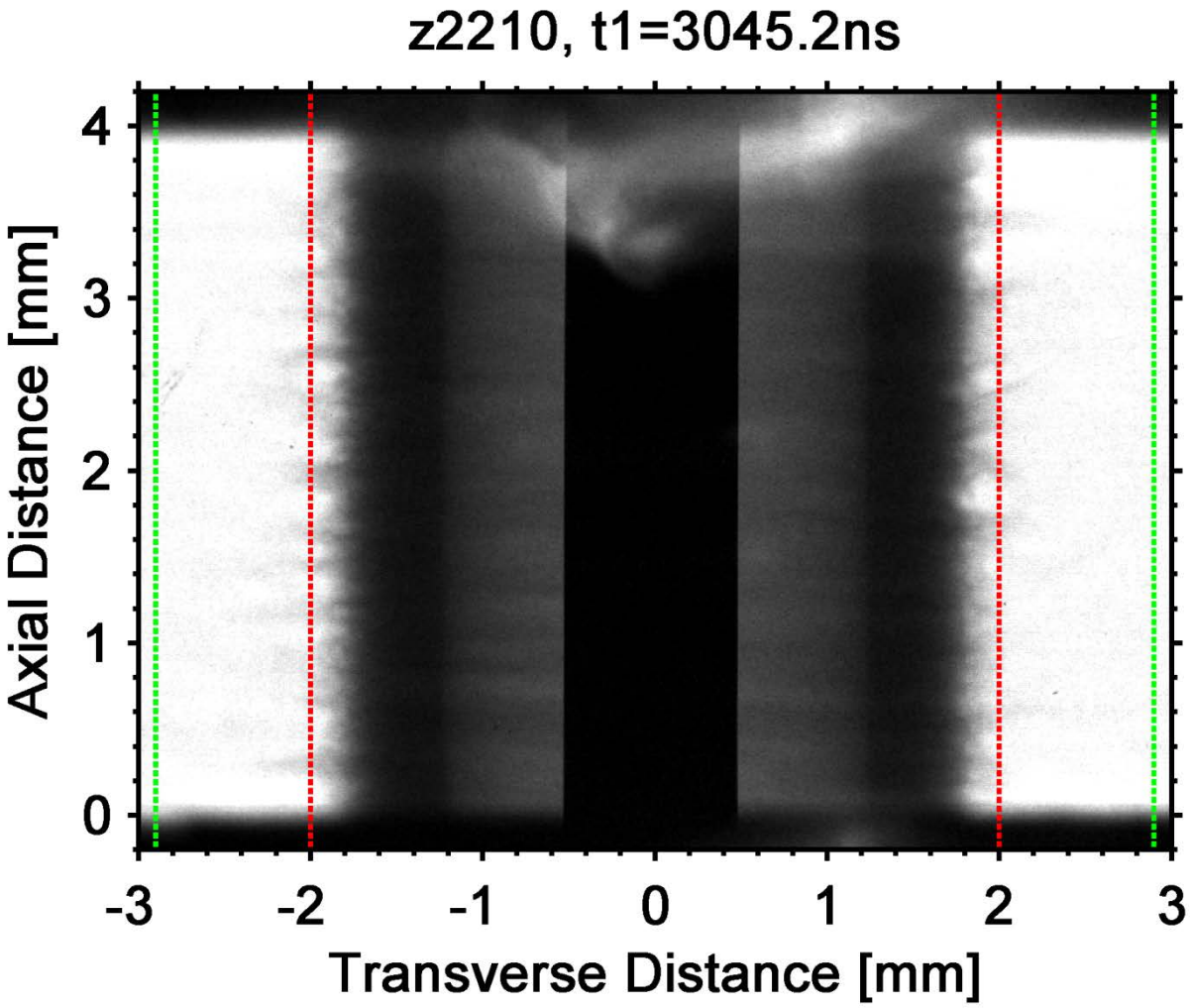
Most Recent Be ICE



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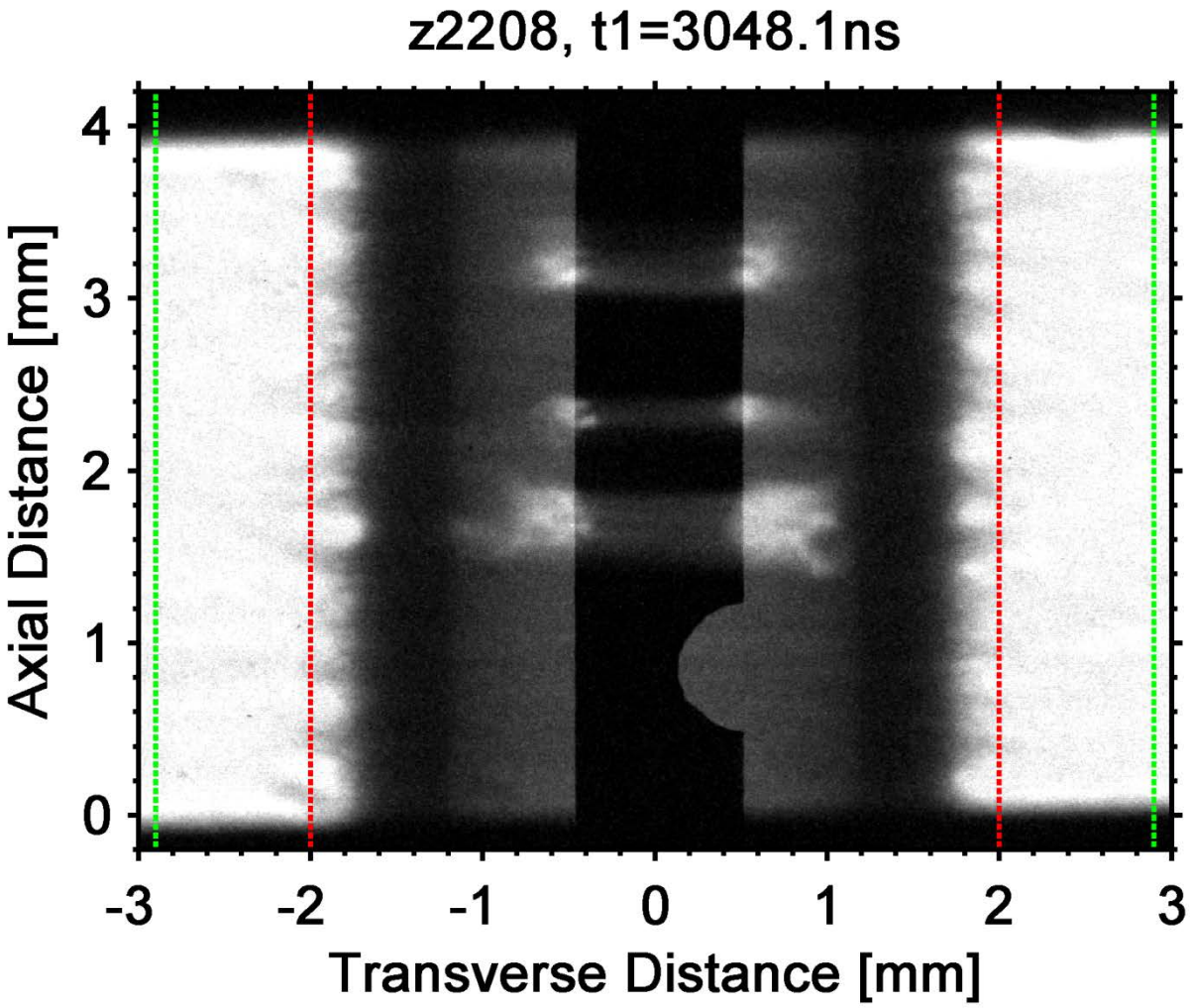
Most Recent Be ICE



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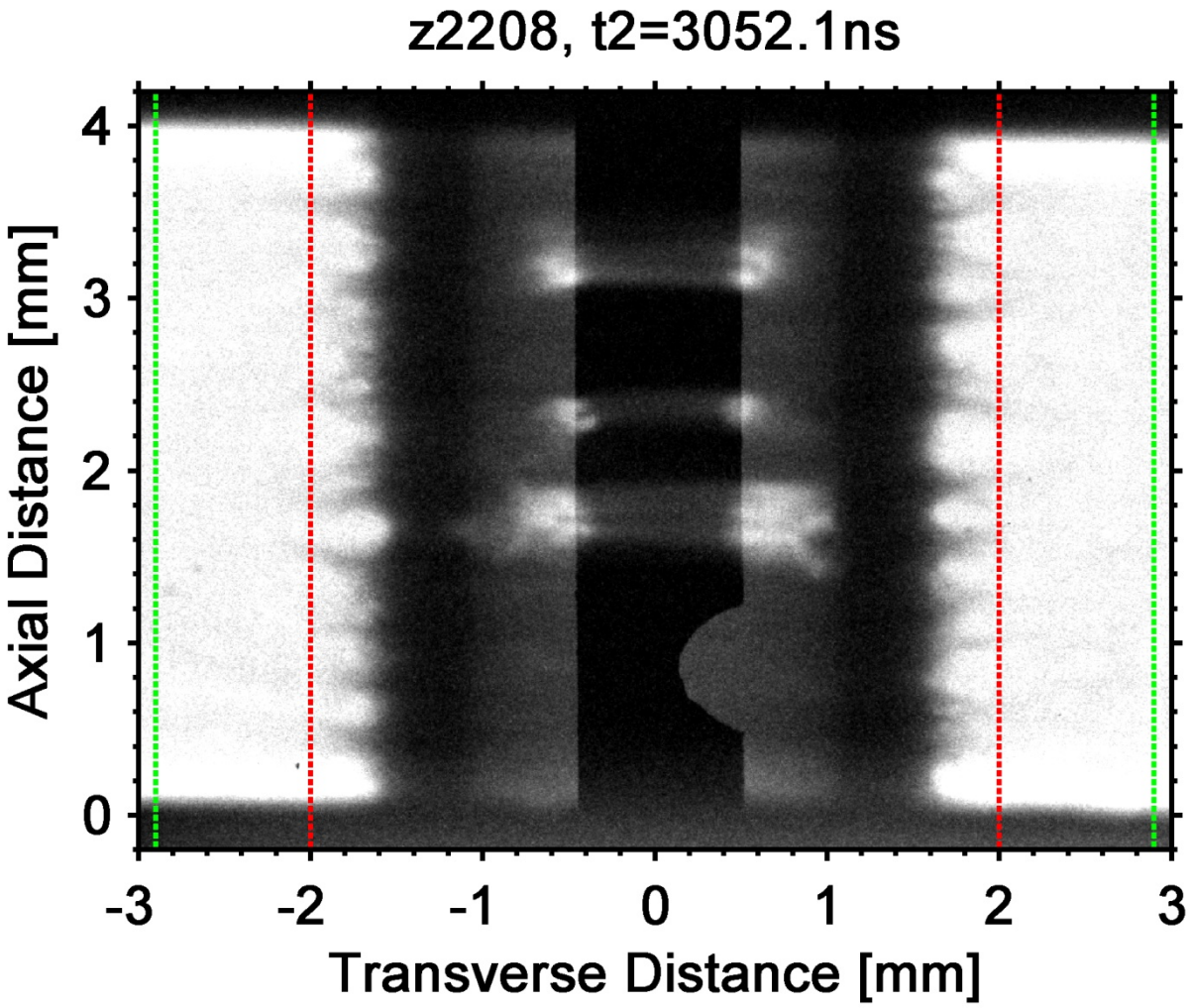
Most Recent Be ICE



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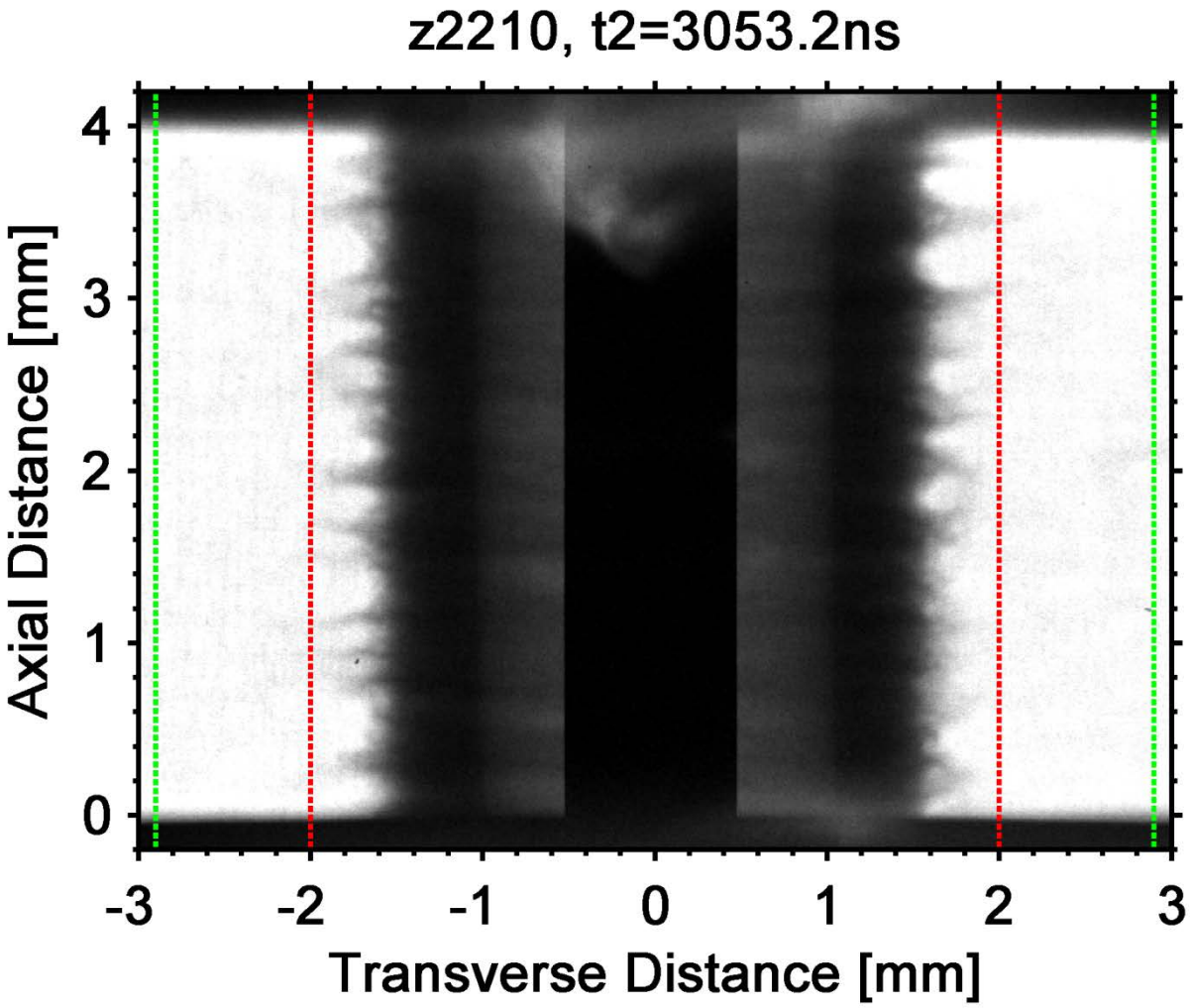
Most Recent Be ICE



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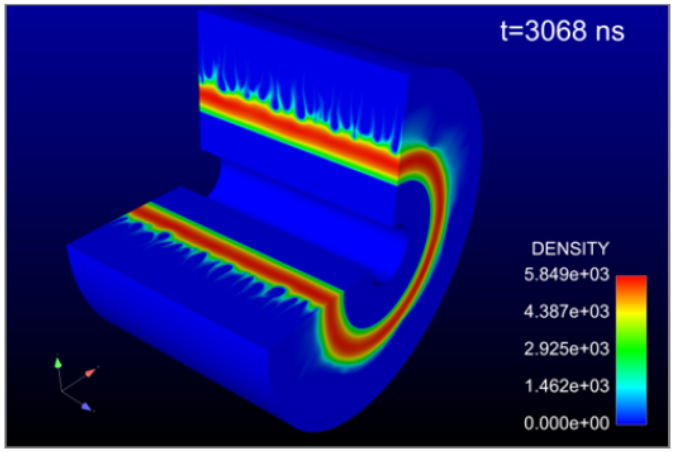
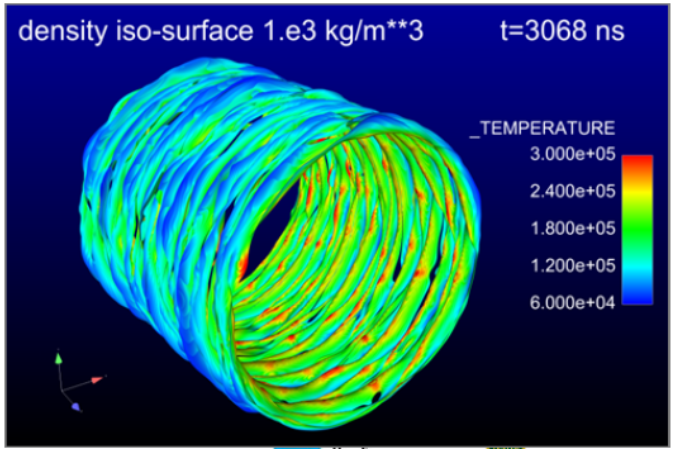
ALEGRA Simulation of Most Recent Be ICE

- 360° Rad-MHD simulation using 30,000 cores on Cielo supercomputer
- Inner surface of liner remains solid and is unperturbed by Magneto-Rayleigh-Taylor instability
- Structure of MRT instability is inherently 3D and couples into field diffusion rate





1D, 2D, & 3D ALEGRA Simulations
*** See work by R.W. Lemke and M.R. Martin**

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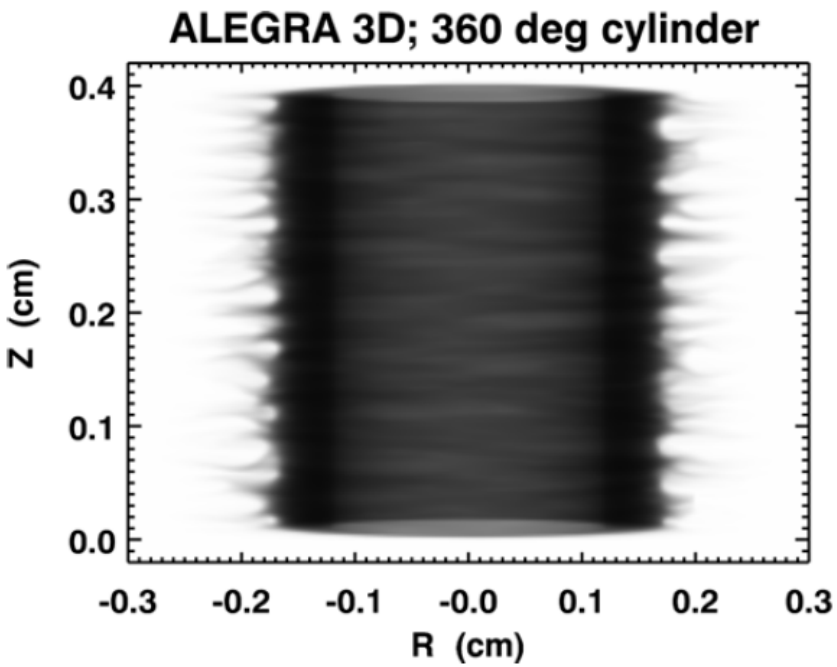
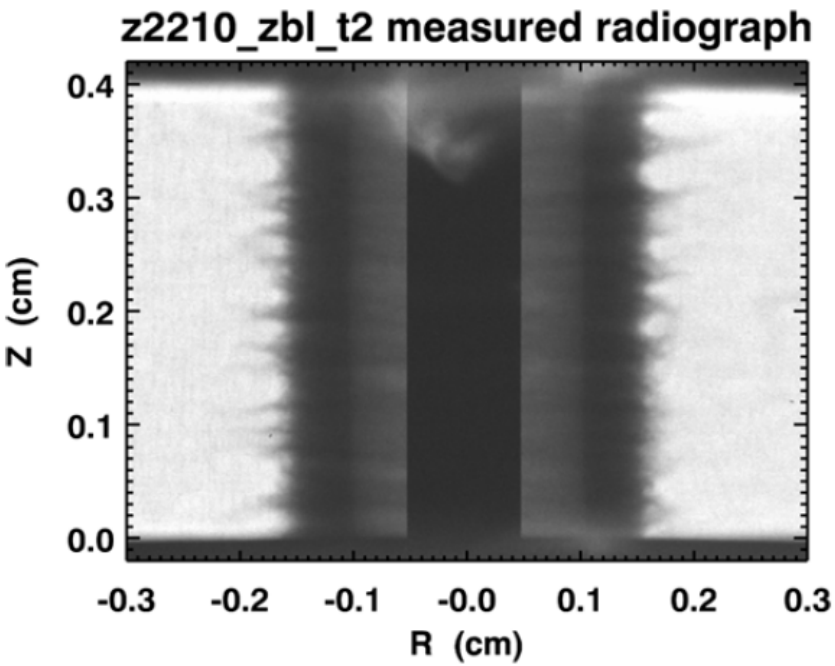
ALEGRA Simulation of Most Recent Be ICE





1D, 2D, & 3D ALEGRA Simulations
*** See work by R.W. Lemke and M.R. Martin**

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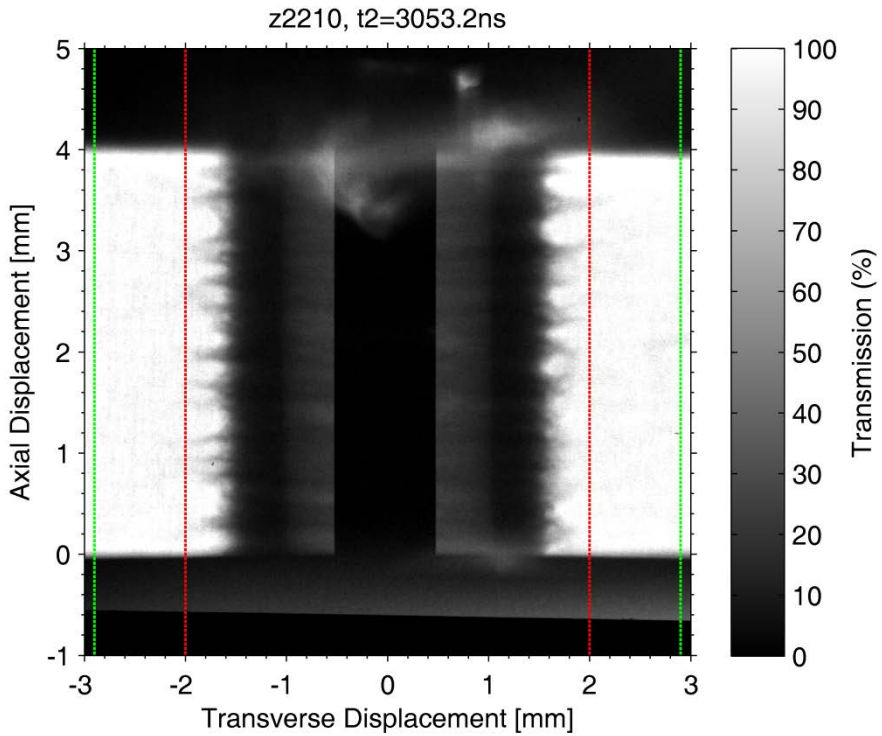
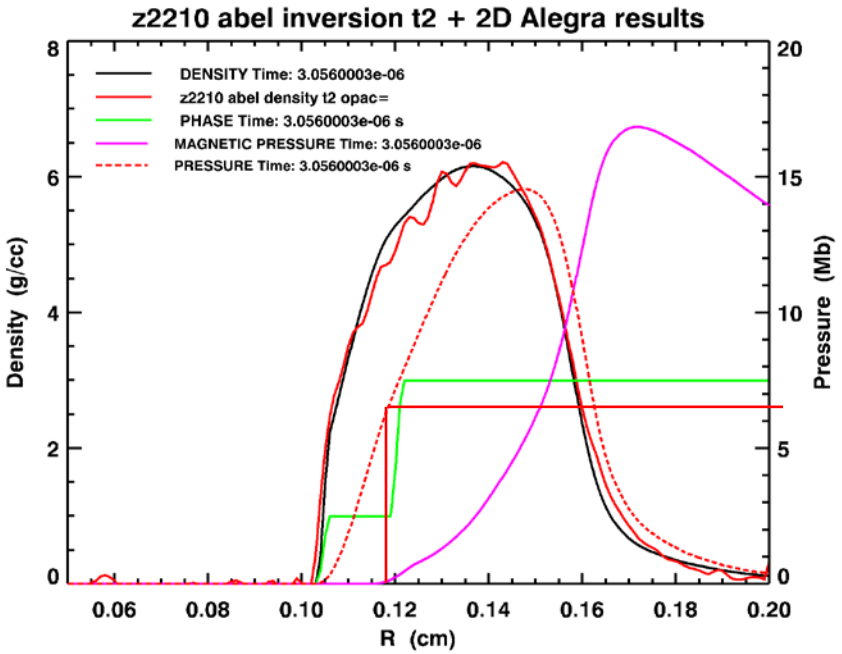
Most Recent Be ICE to >5 Mbar





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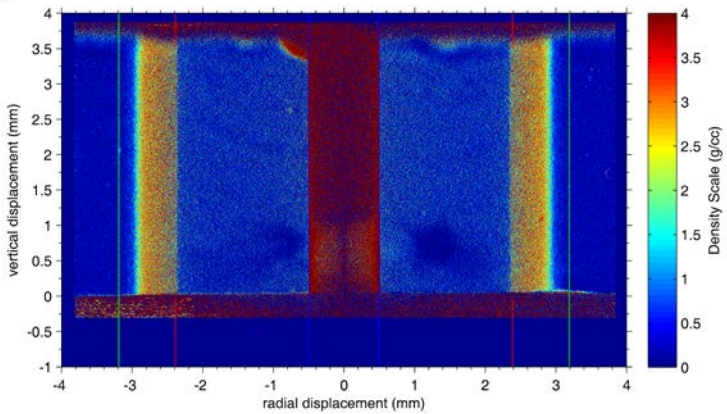
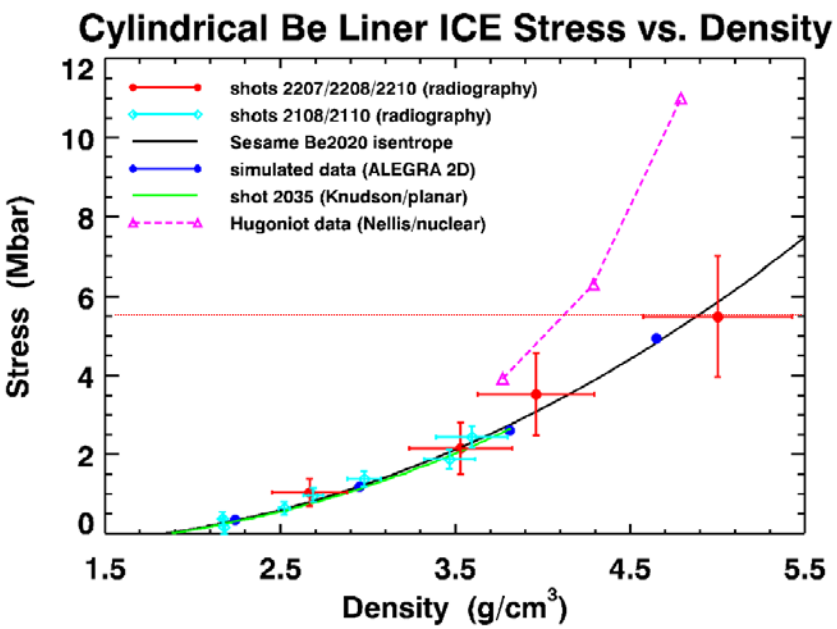
Most Recent Be ICE to >5 Mbar



Simulation <u>not</u> required for unfold of isentrope (simulation used only for experiment design, verification, assumption checking, and unfold guidance)

$$\frac{\partial(rv)}{\partial m} = \frac{1}{2\pi}\frac{D}{Dt}\left(\frac{1}{\rho}\right),$$

$$\frac{\partial P_T}{\partial m} = -\frac{1}{2\pi r}\frac{Dv}{Dt}.$$



*** M.R. Martin, R. W. Lemke, *et al.*, APS-DPP (invited; PoP to be published 2012)**

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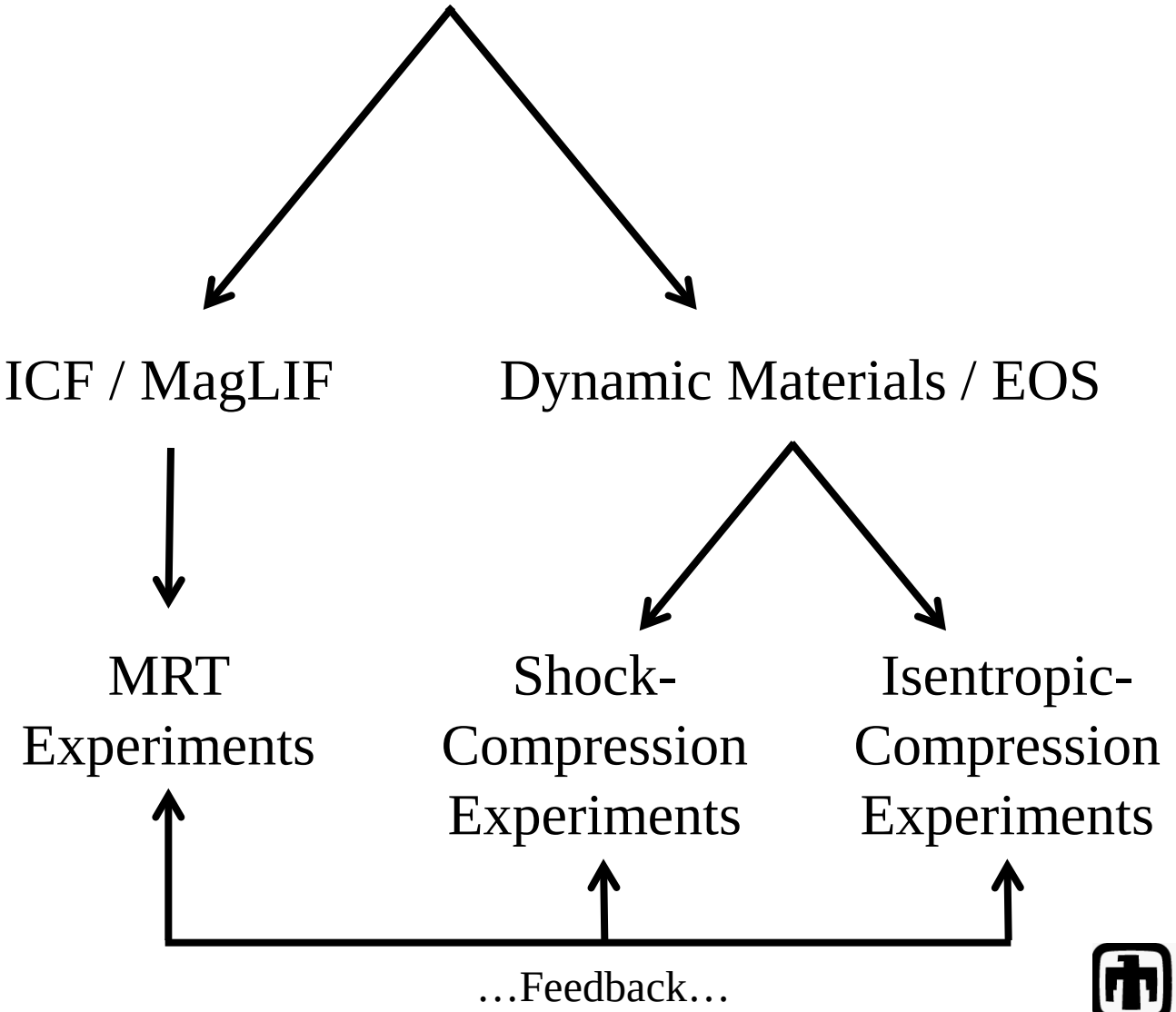
Beryllium Liners