Beryllium liner implosion experiments on the Z accelerator in preparation for MagLIF

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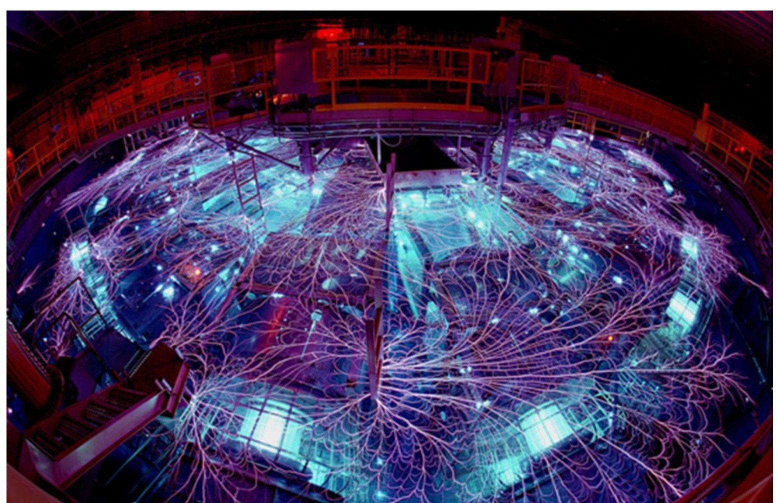

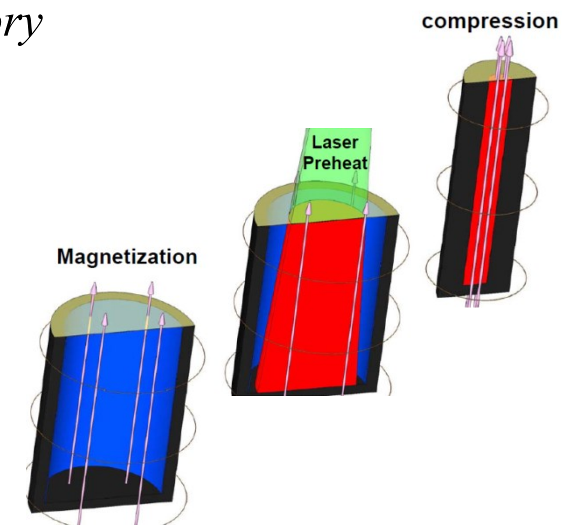

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NNSA National Nuclear Security Administration

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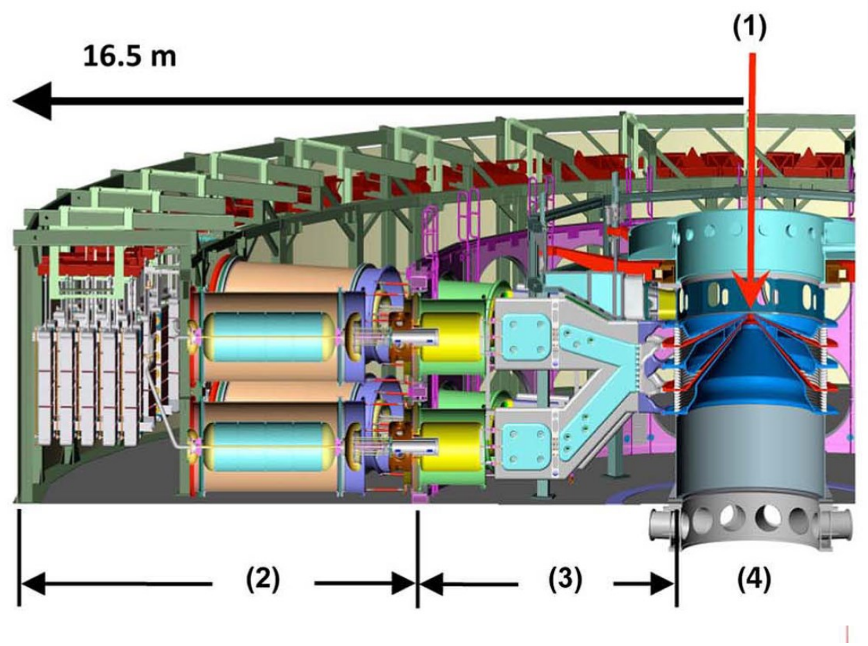
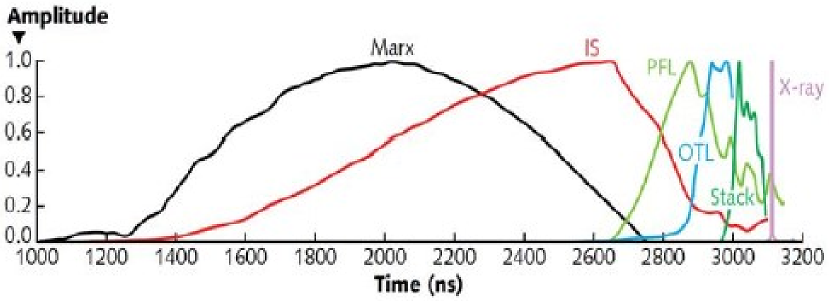
Pulsed-power generators provide an energy-rich platform for inertial confinement fusion experiments

Sandia National Lab Z Facility

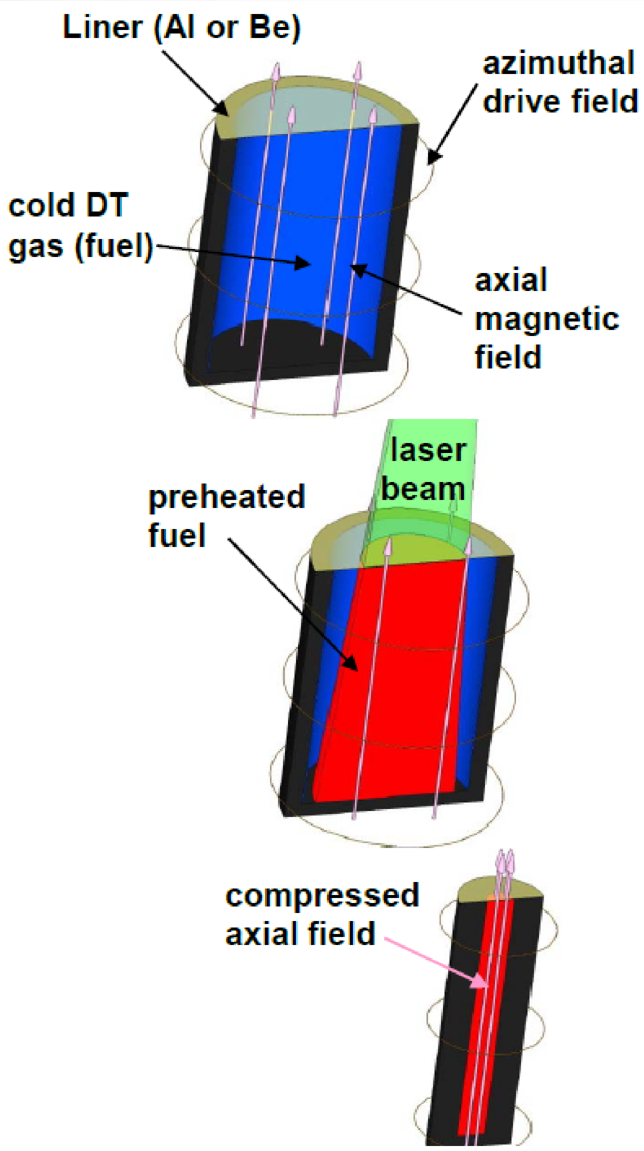


- 21 MJ stored energy at 85 kV
  500 kJ delivered to cm-scale targets
  100 kJ delivered to fusion fuel
- 26 MA into low impedance loads
- 33 m diameter footprint
- Facility refurbishment completed in 2007 at a cost of ~4$/J



High energy density achieved through multiple stages of spatial and temporal pulse compression

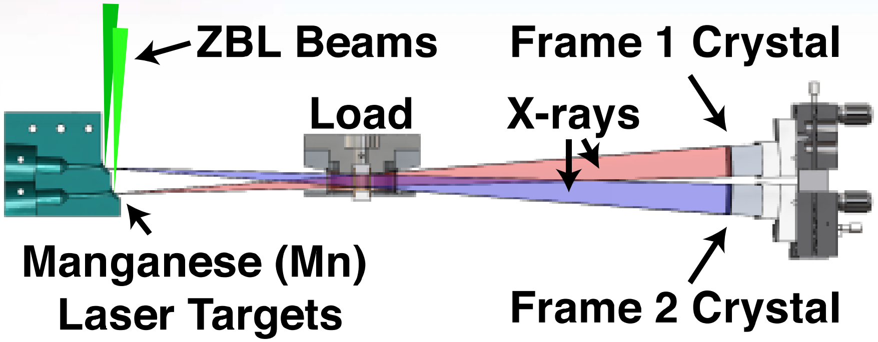
MagLIF: Fuel pre-heat & magnetization allow relatively slow implosions to achieve significant fusion yield



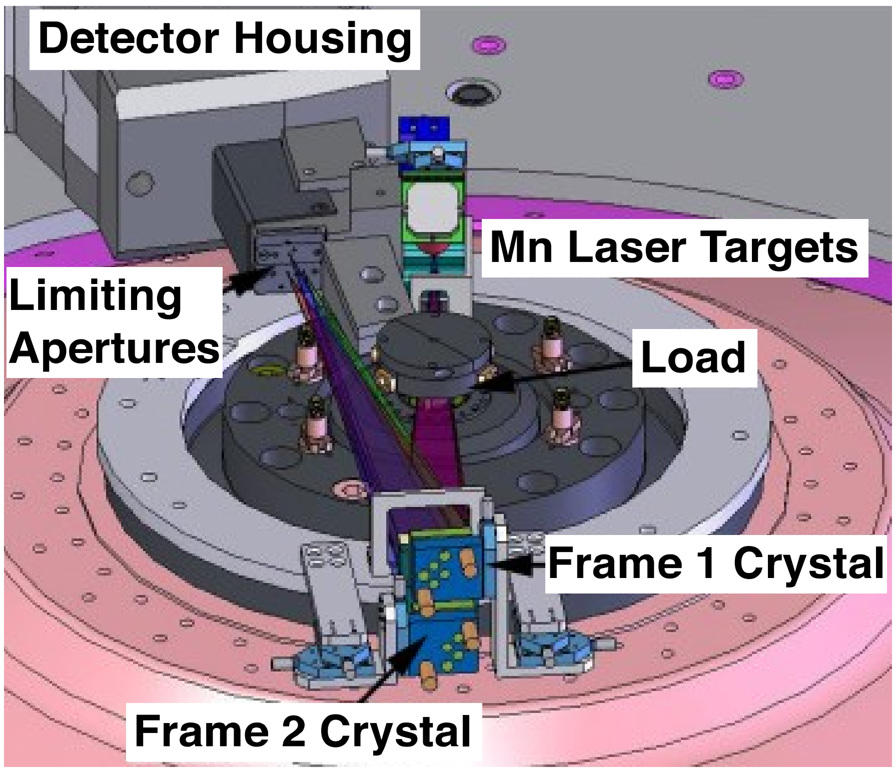
- An initial ~10 T axial magnetic field is applied
  - Inhibits thermal conduction losses
  - Enhances alpha particle energy deposition
  - May help stabilize implosion at late times
- During implosion, the fuel is heated using the Z-Beamlet laser (<10 kJ needed)
  - Preheating reduces the compression needed to obtain ignition temperatures to 20-30 on Z
  - Preheating reduces the implosion velocity needed to "only" 100 km/s (slow for ICF)
  - Stagnation pressure required is few Gbar, not a few hundred Gbar
- Scientific breakeven may be possible on Z (fusion yield = energy into fusion fuel)

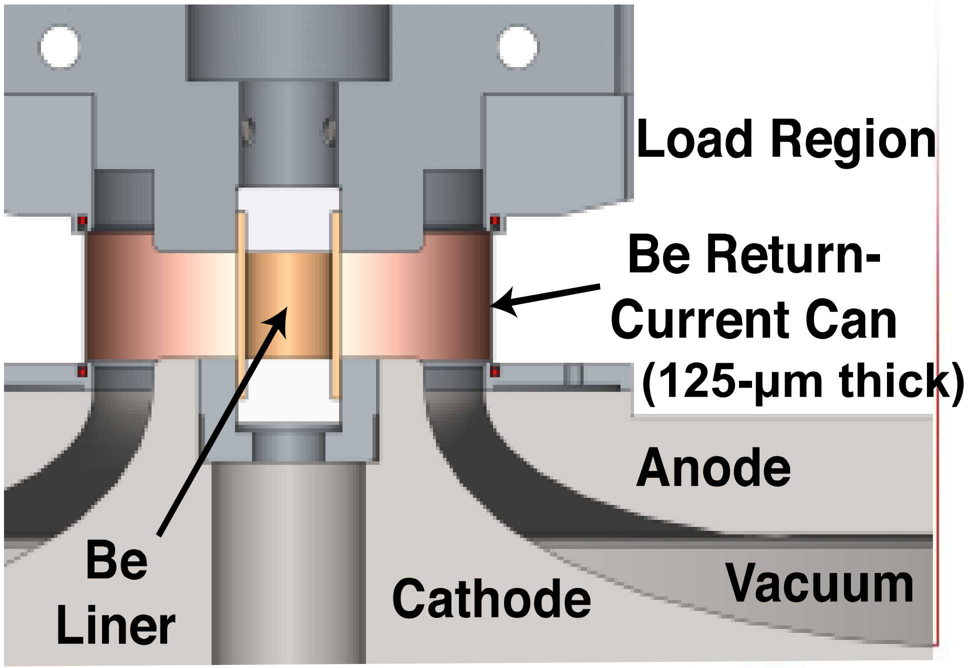
*S.A. Slutz *et al.*, Phys. Plasmas **17**, 056303 (2010); Slutz and Vesey, Phys. Rev. Lett. **108**, 025003 (2012)

Presentation focuses on liner dynamics; primary diagnostic is two-frame monochromatic (6151±0.5 eV) radiography*



- Spherically-bent quartz crystals (22<u>4</u>3)
- 15 micron resolution (edge-spread)
- We can see through imploding beryllium (not so for aluminum and other higher-opacity materials).





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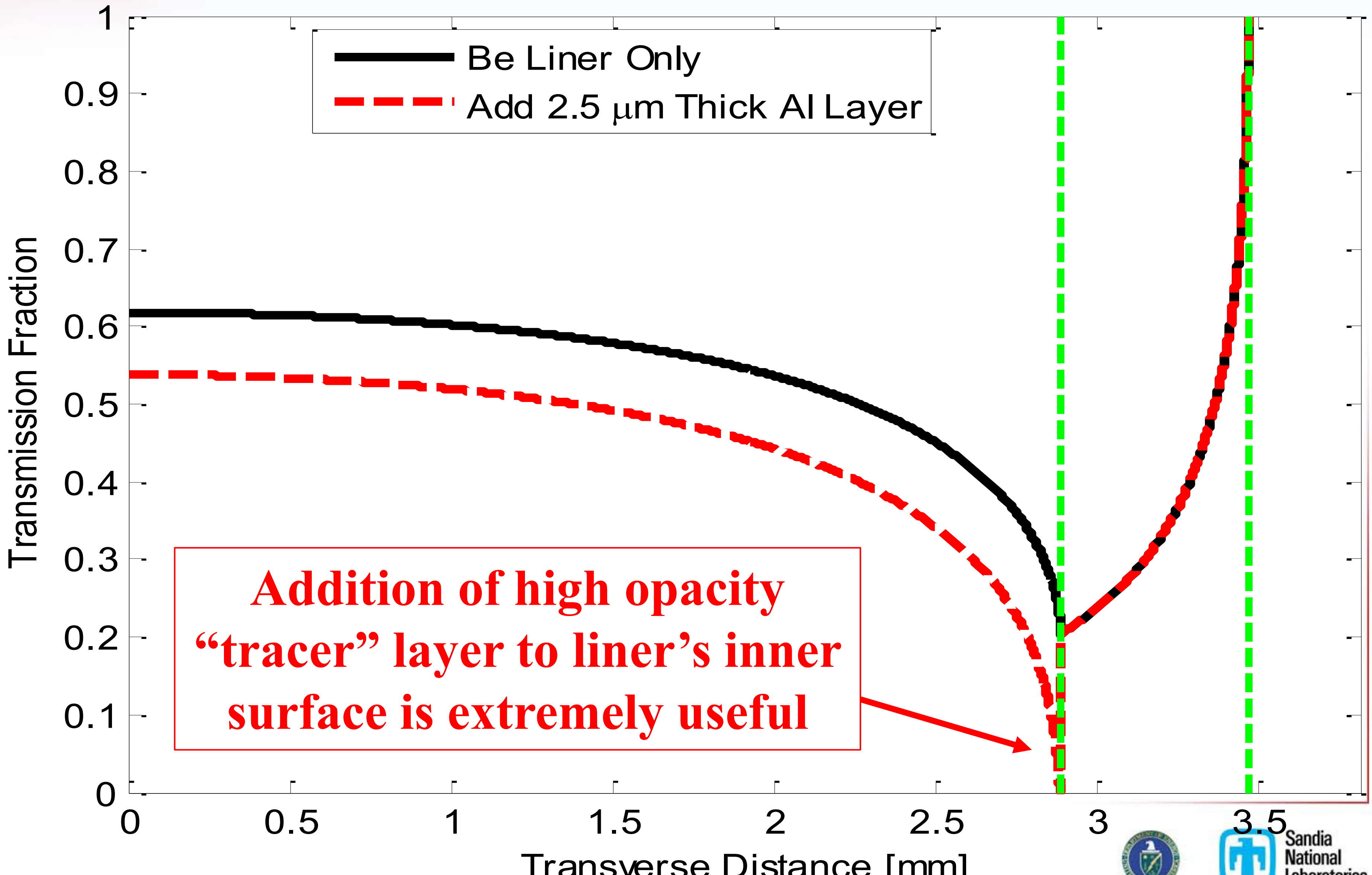
* G. R. Bennett *et al.*, RSI (2008).

The low opacity of beryllium to 6.151 keV photons allows measurement of liner's inner surface



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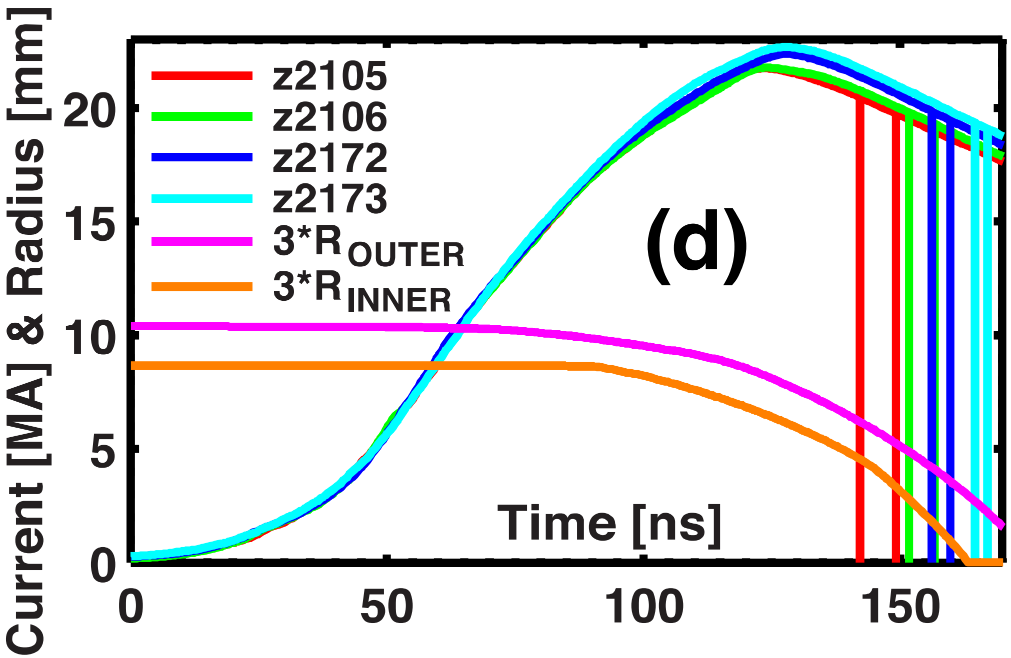
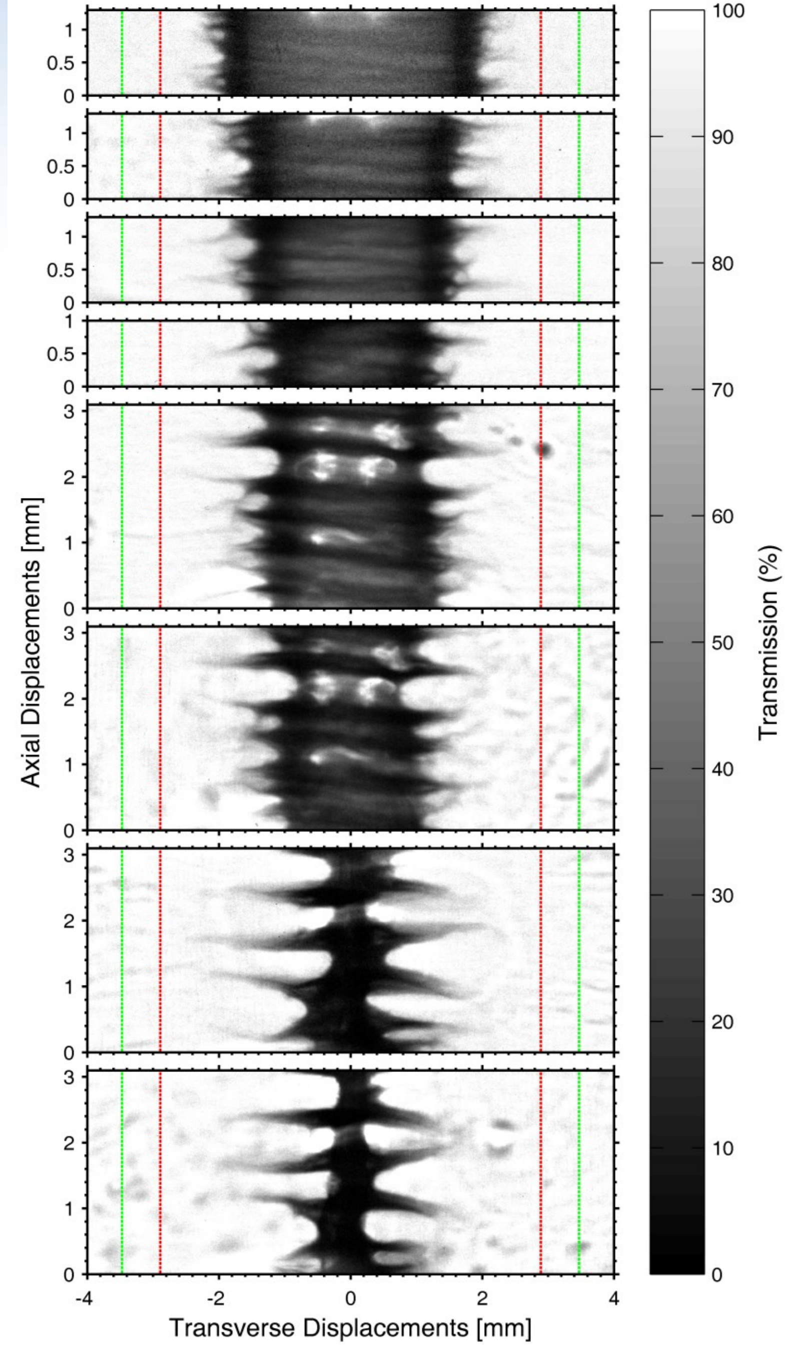
Experiments obtain high-quality radiographs of an imploding Be liner



AR=6:

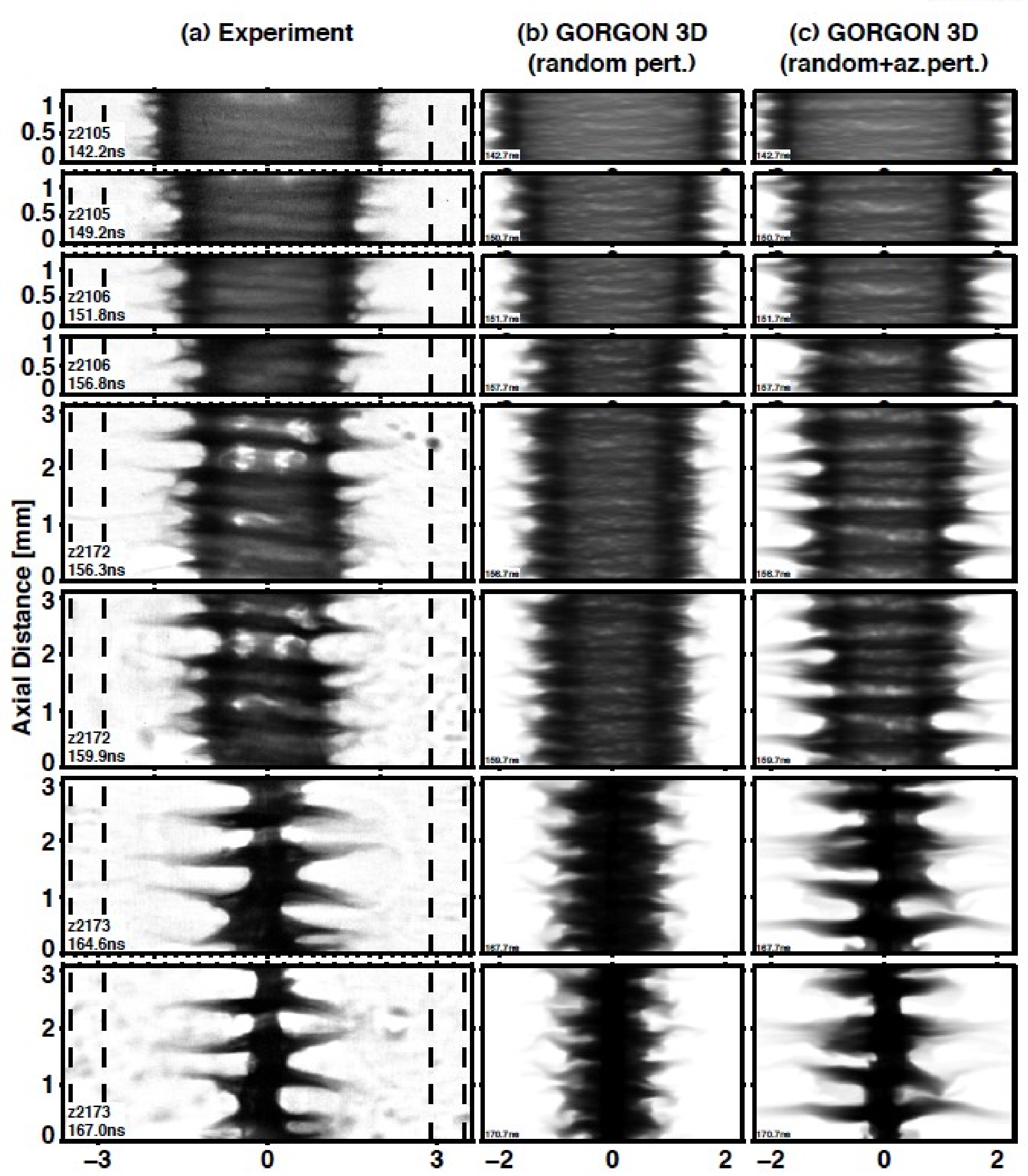
$R_{outer,0} = 3.47$ mm

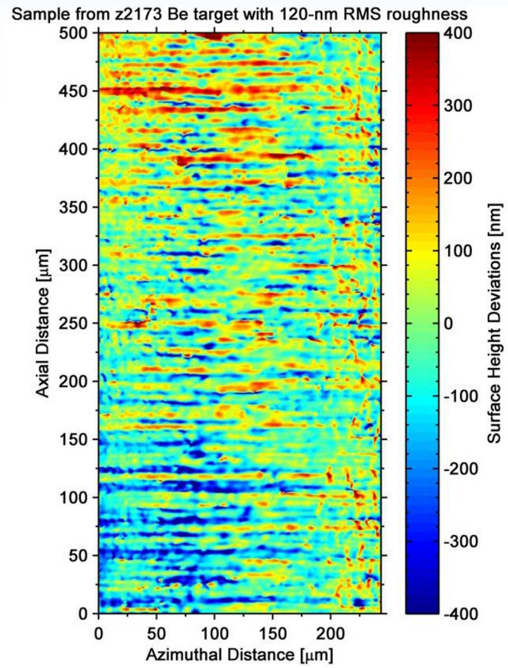
$R_{inner,0} = 2.89$ mm



R. D. McBride, S. A. Slutz, C. A. Jennings *et al.*, Phys. Rev. Lett. 109, 135004 (2012).

Experiments have focused on developing predictive capability of instability growth of imploding liners*

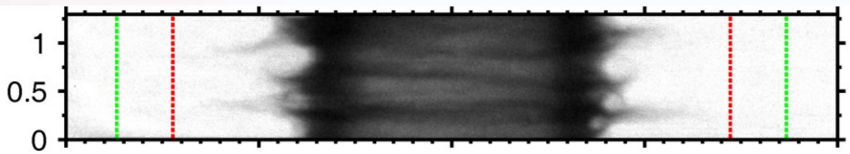


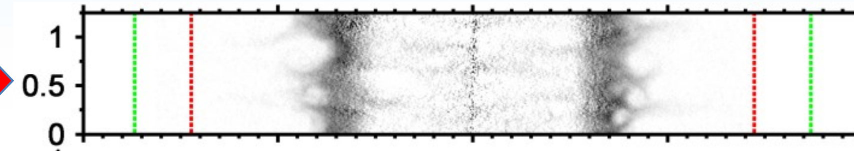


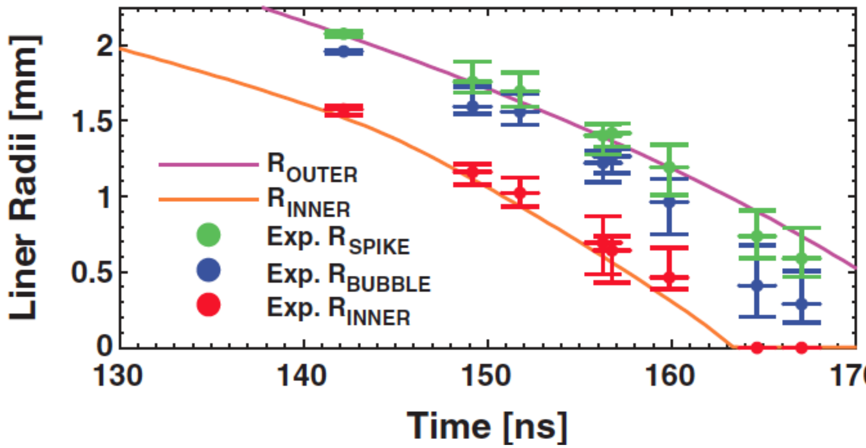
Azimuthal correlation consistent with liner surface characterization data must be incorporated into 3D simulations to capture late-time MRT instability growth

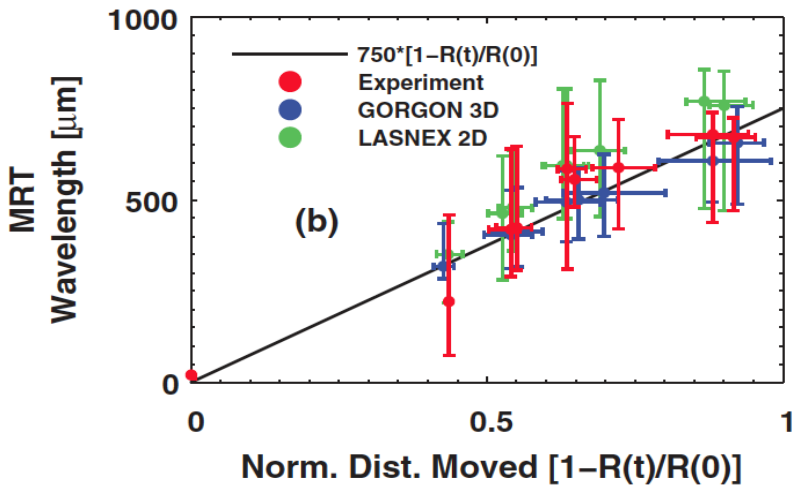
*R.D. McBride et al., PRL **109**, 135004 (2012)

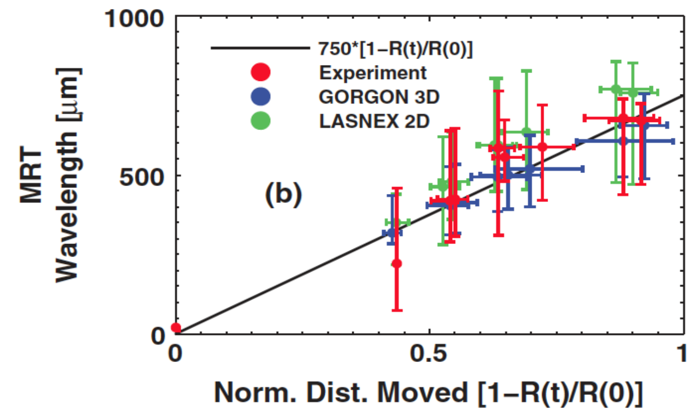
Abel inversion allows calculation of several important experimental parameters

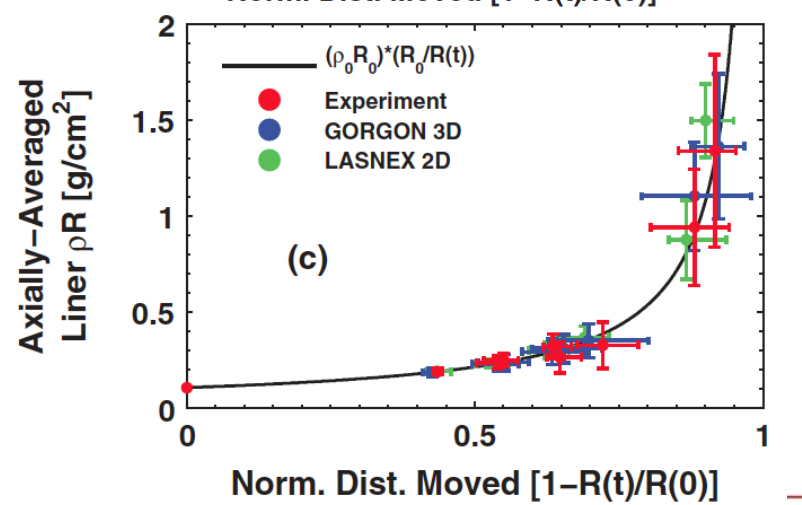












R. D. McBride, S. A. Slutz, C. A. Jennings *et al.*, Phys. Rev. Lett. 109, 135004 (2012).

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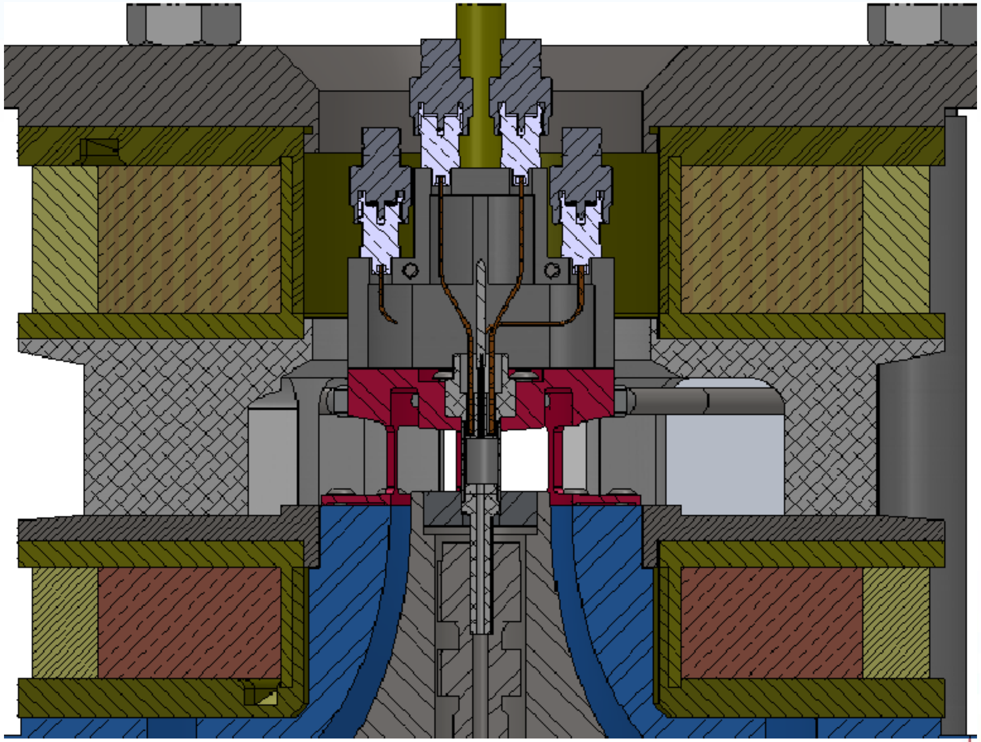
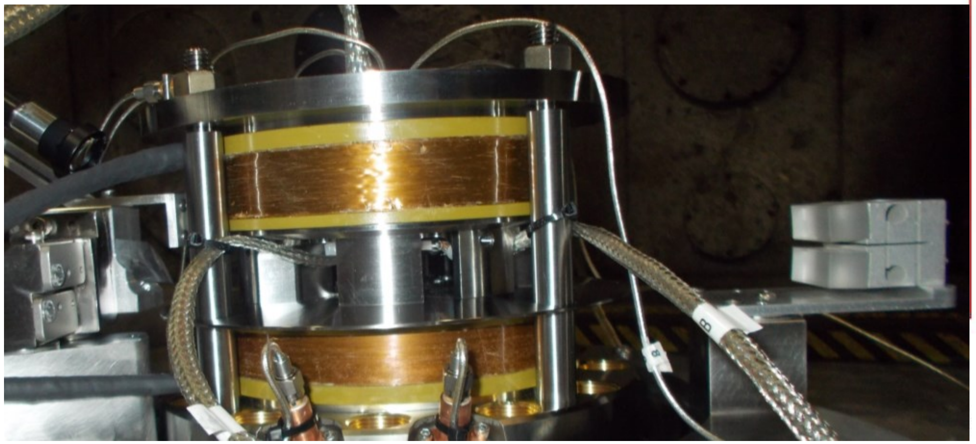
MagLIF Helmholtz-like coil pair first fielded on Z in February of 2013—All requirements met

Field strength requirements:
−10 T seed field with full diagnostic access
−30 T coils will have limited diagnostic access

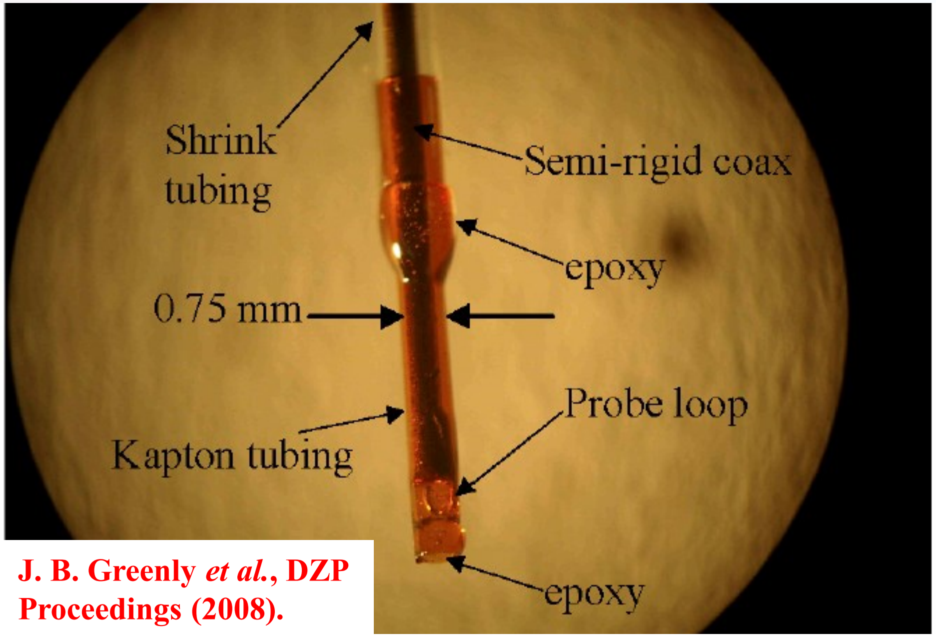
Pulse length requirement:
− Must not crush or buckle target or hardware
− Fully magnetize liner/fuel with uniform field
− 3.5 ms risetime used

Minimize increased inductance from required elongation of final feed

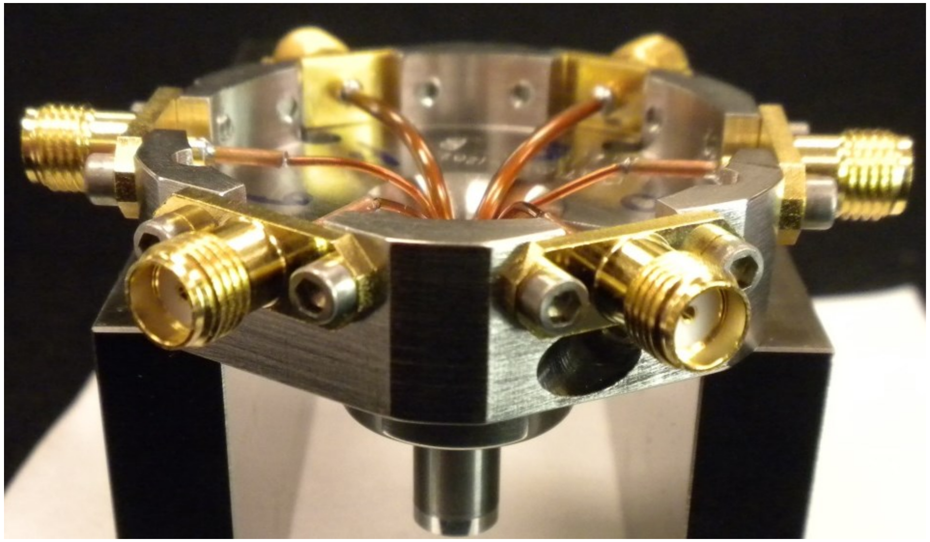


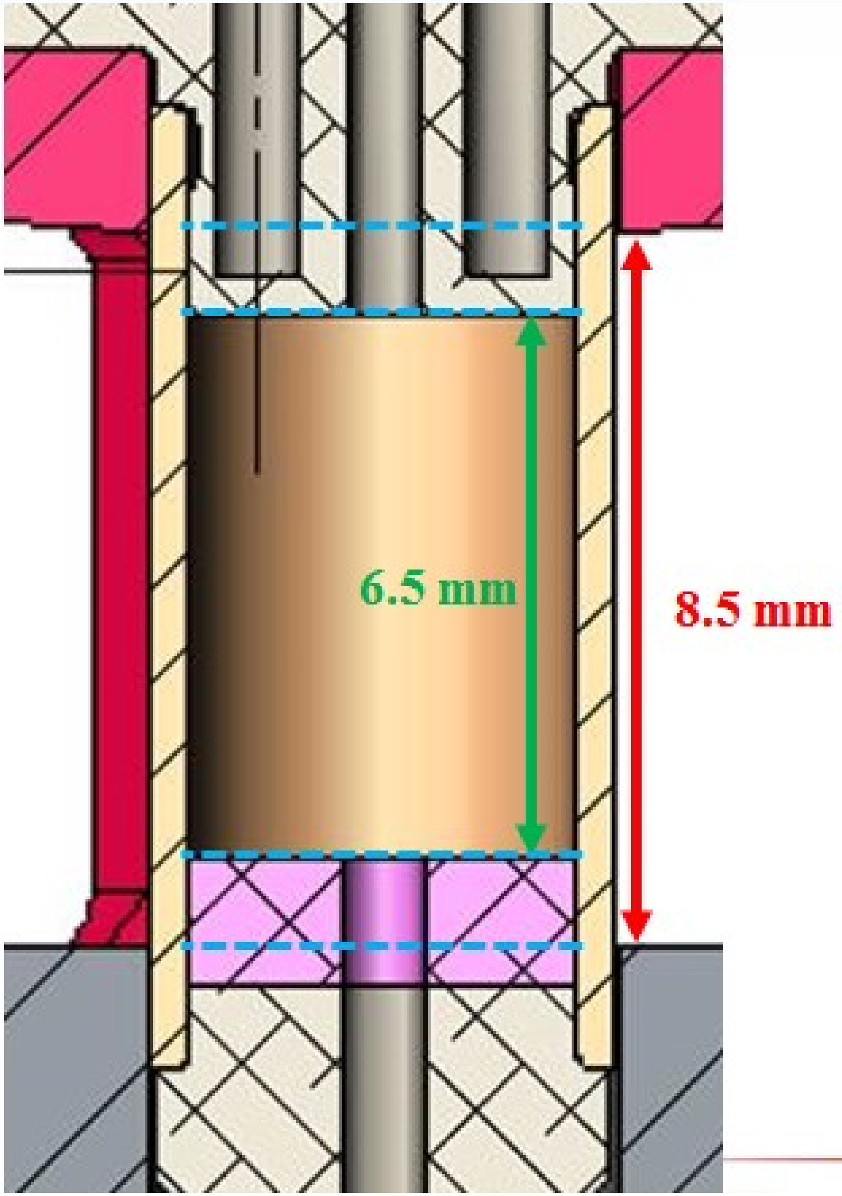


Experiments with "micro-Bdots" confirm B_Θ penetration through the liner, and B_z flux compression within the liner

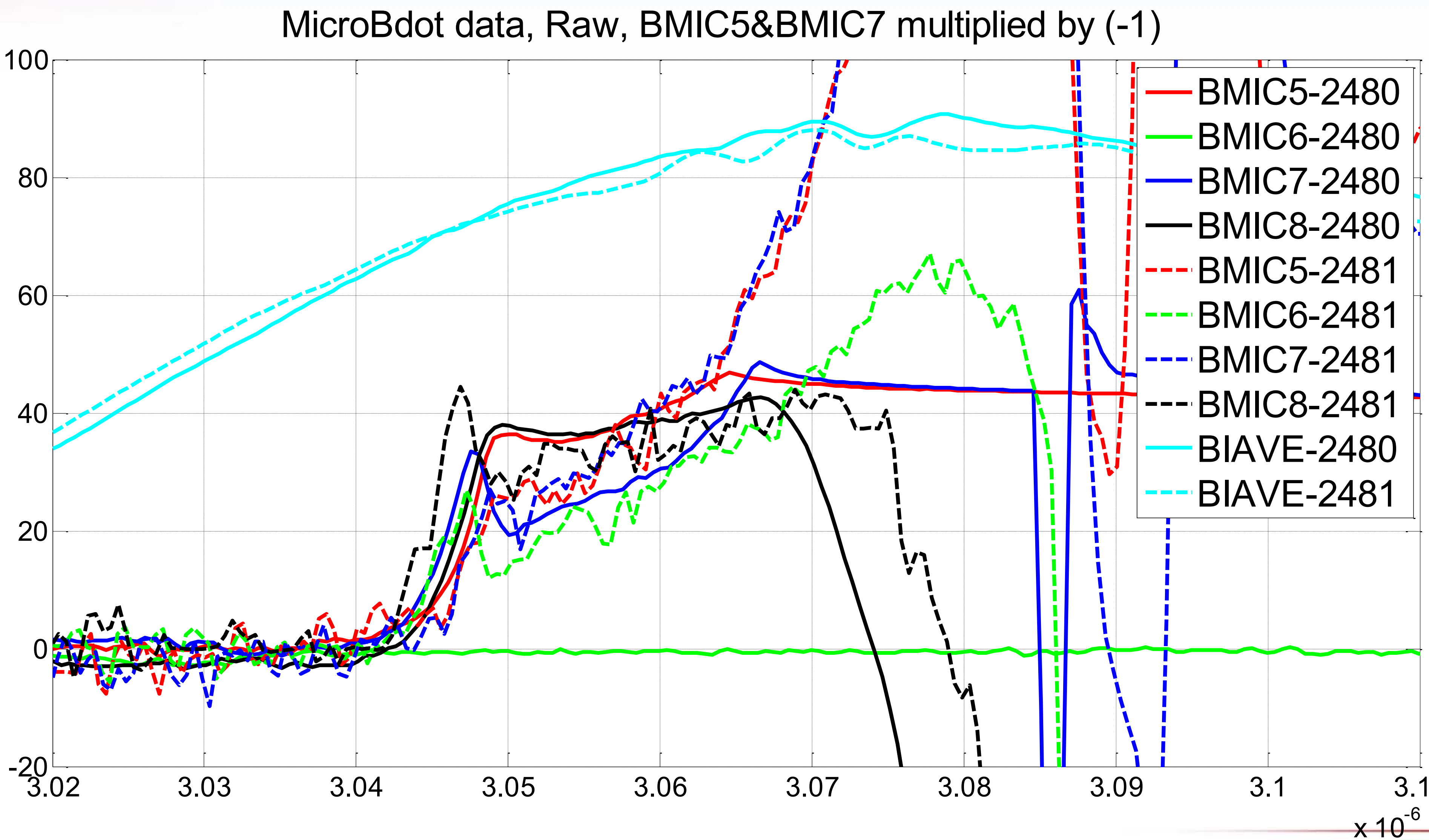


J. B. Greenly *et al.*, DZP Proceedings (2008).



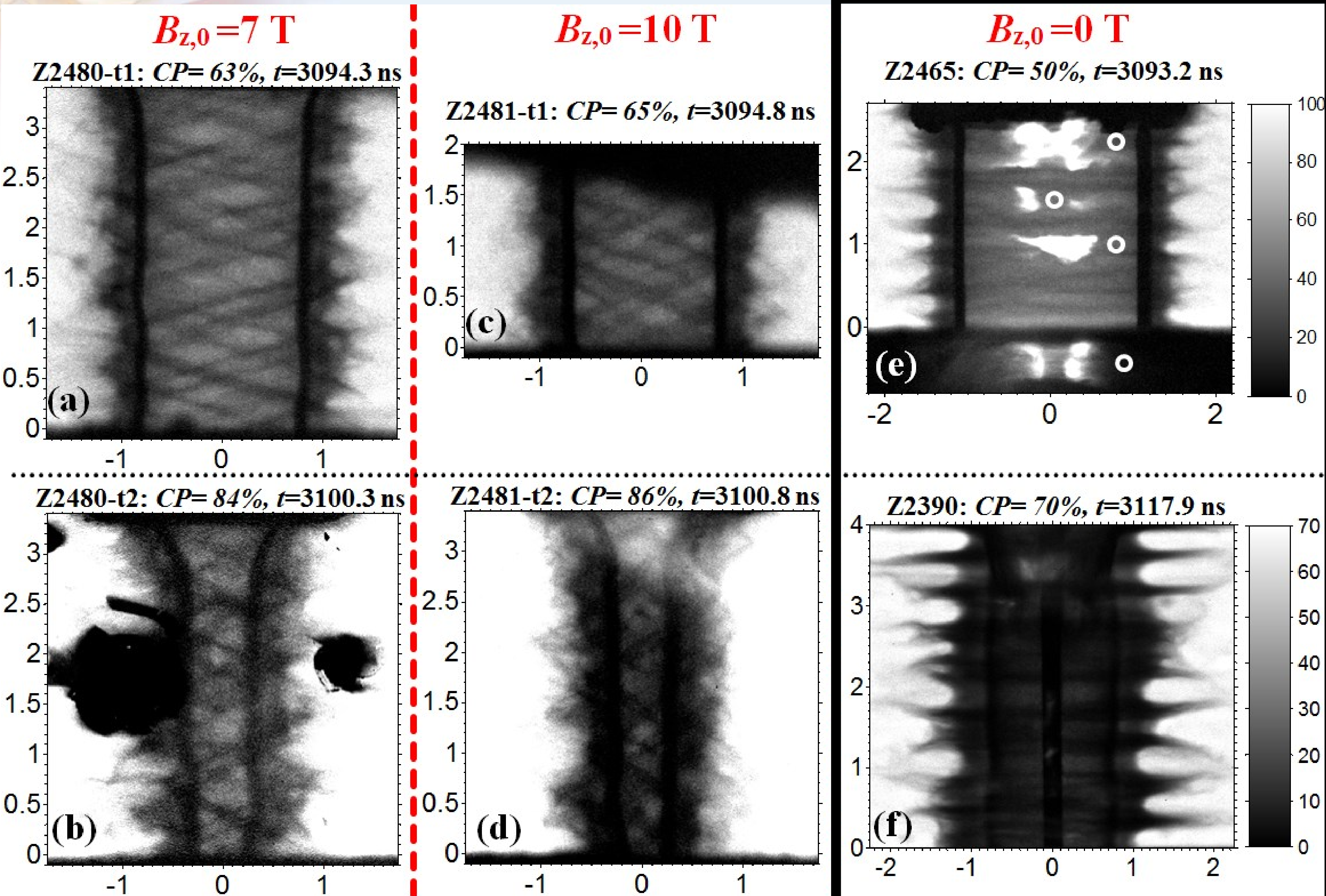


Compressed flux observed → MicroBdots (B_r) measure rising fringe fields above imploding liner



Electrode instabilities can cause jetting of liner material into fusion fuel; mitigated by nylon "cushions"

Helix-like instabilities develop on premagnetized liners



T.J. Awe et al., manuscript submitted to PRL

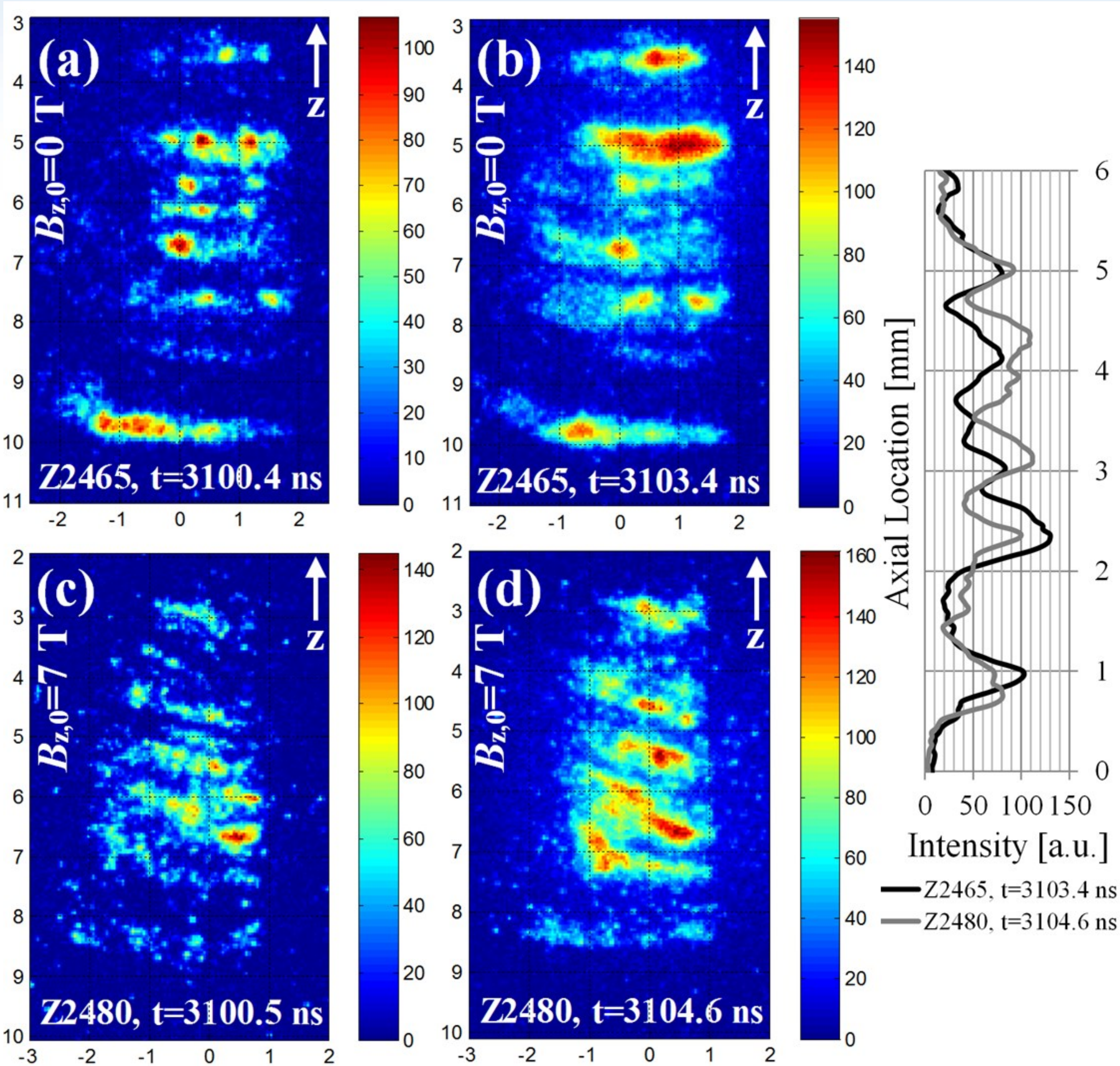
Gated X-ray Pinhole imaging

$B_{z,0}$=0 T cases:
horizontal structure

$B_{z,0}$=7 T cases:
Structures at 15 to 20 degrees to horizontal

****

Otherwise similar intensity and dominant perturbation wavelength

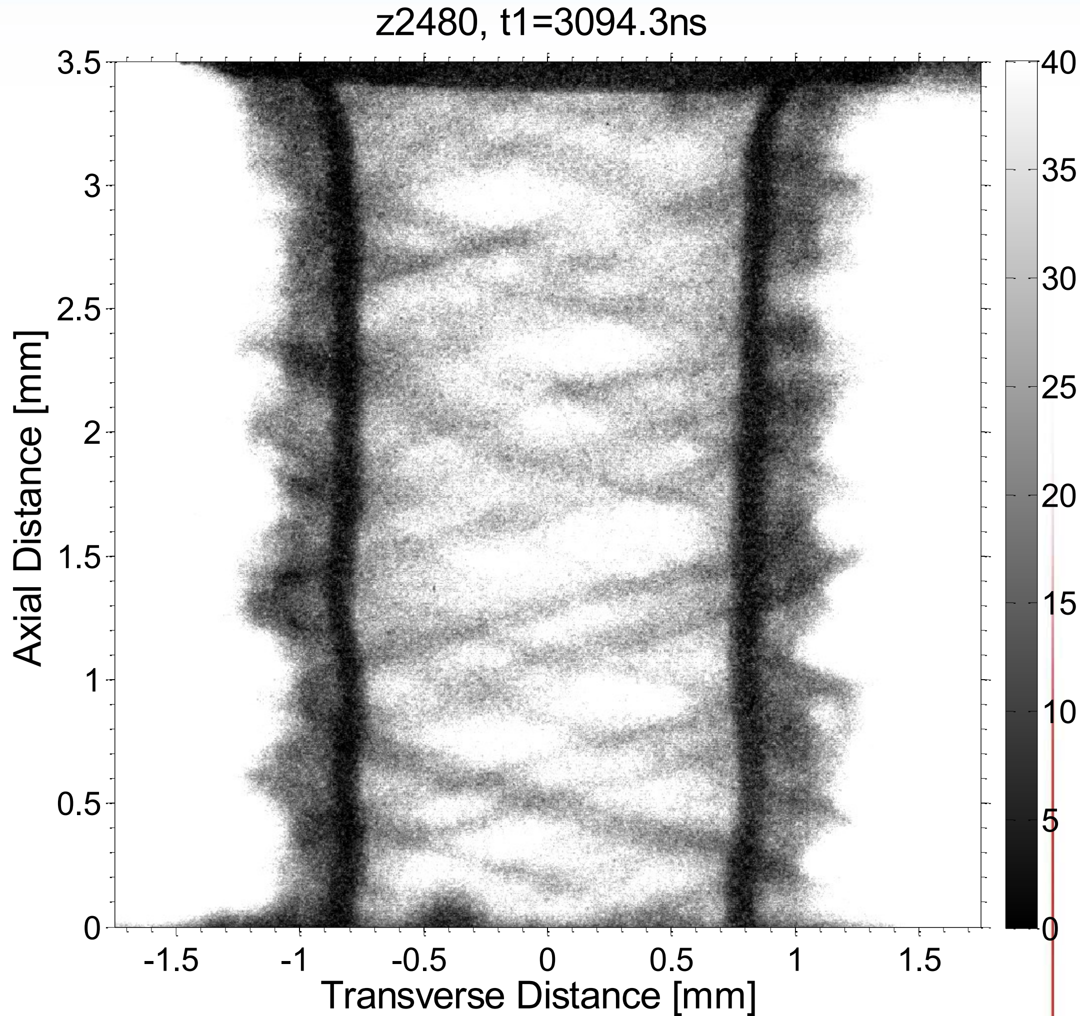


Helix-like instabilities are observed

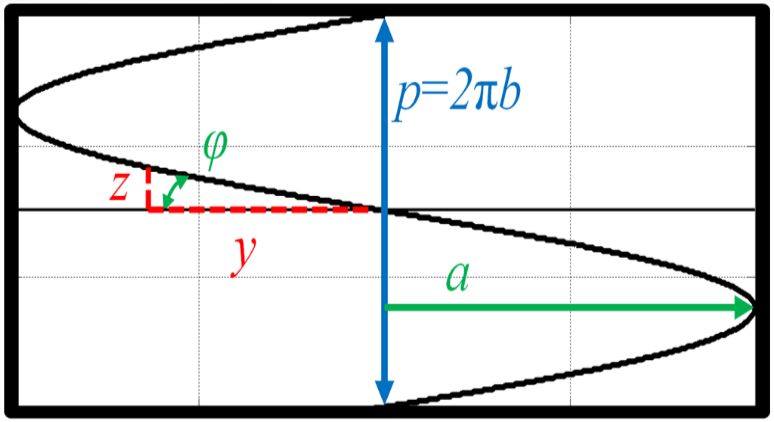
High-density structures are at large angle to the z axis

Penetrating radiography "sees" structures at "front" and "back" of liner, so structures with positive and negative slope are observe. This results in the observed cross-hatched pattern

Well-connected structures can be traced through multiple cycles



A simple cylindrical helix model fits the data well



Cylindrical helix model

$y(\theta)=a\cdot\sin(\theta)$

$z(\theta)=p\cdot\theta/2\pi$

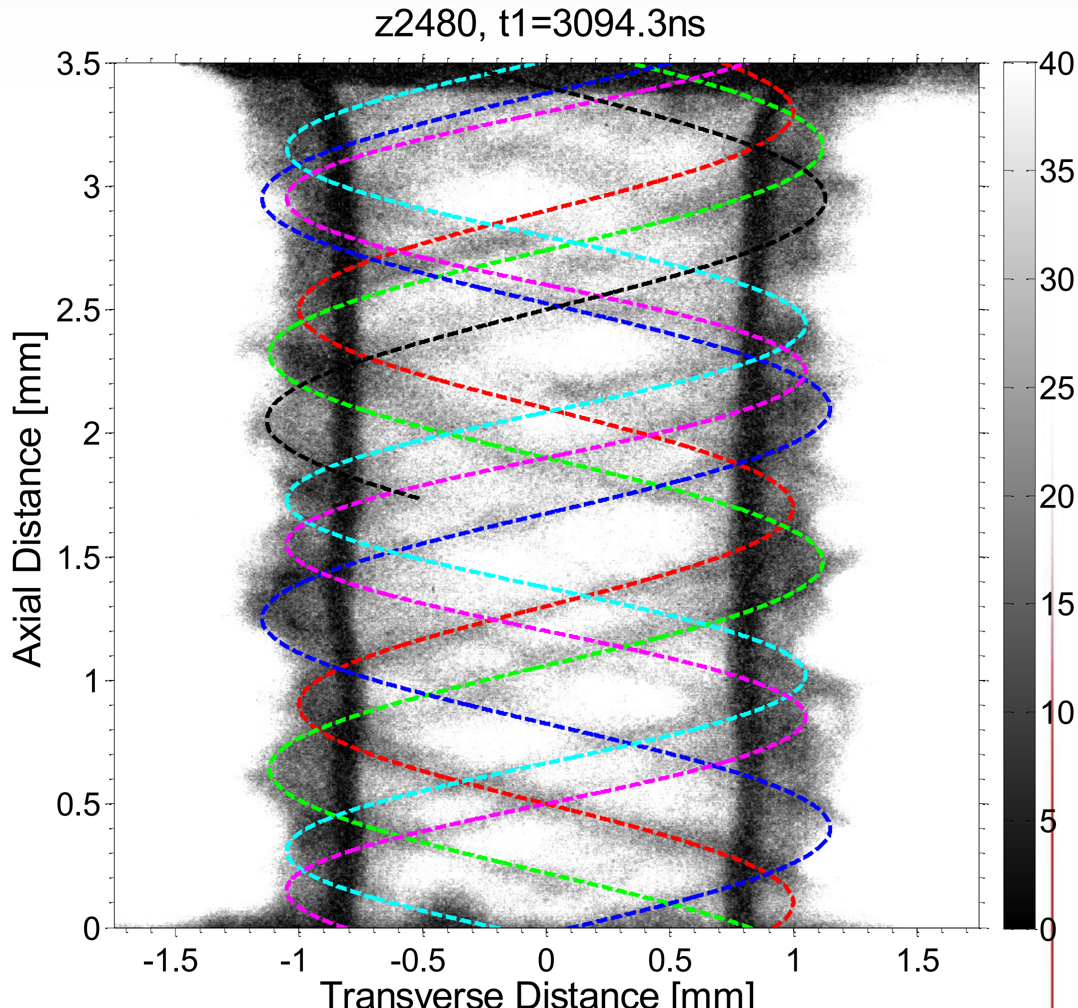
a =radius

p=pitch

"pitch angle"

$\varphi=\tan^{-1}(z/y)$

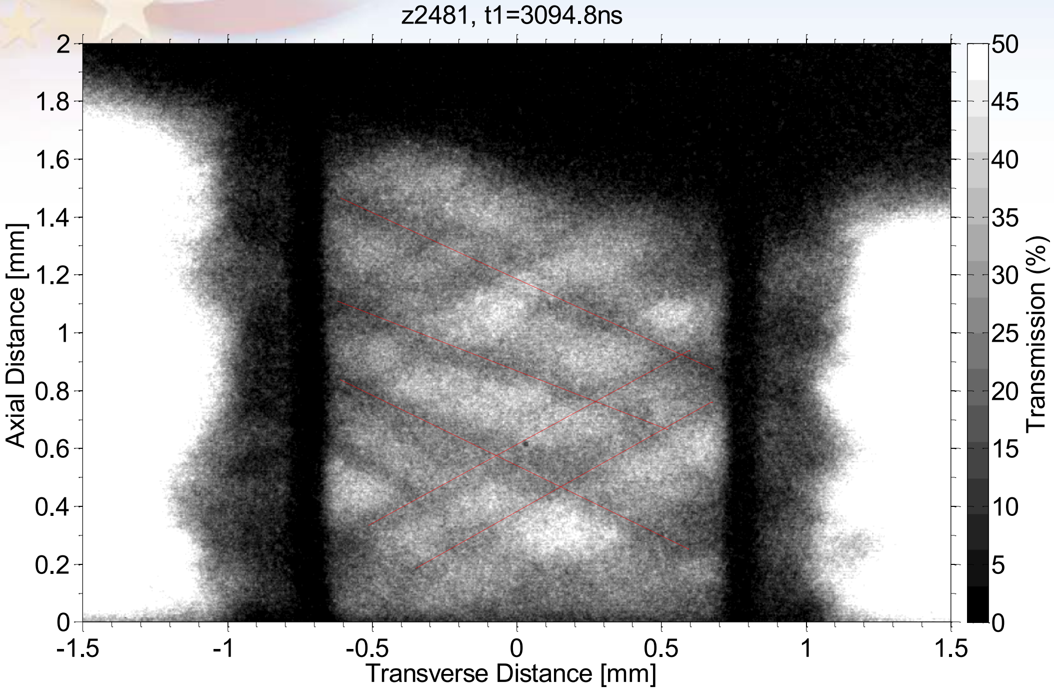
$\varphi\approx\tan^{-1}(p/2\pi a)$



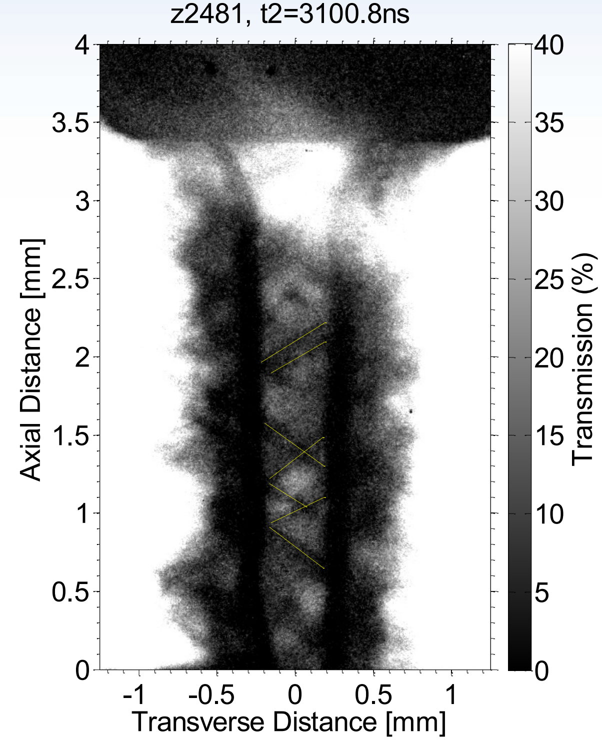
a_{avg}=1.07 mm

p_{avg}=1.56 mm

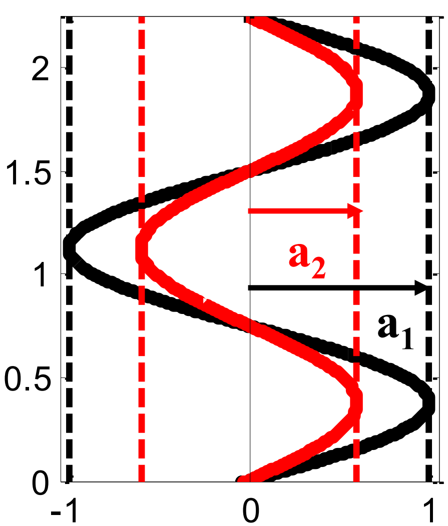
Pitch remains approximately constant as the liner implodes



φ_{avg}=26°



φ_{avg}=33°

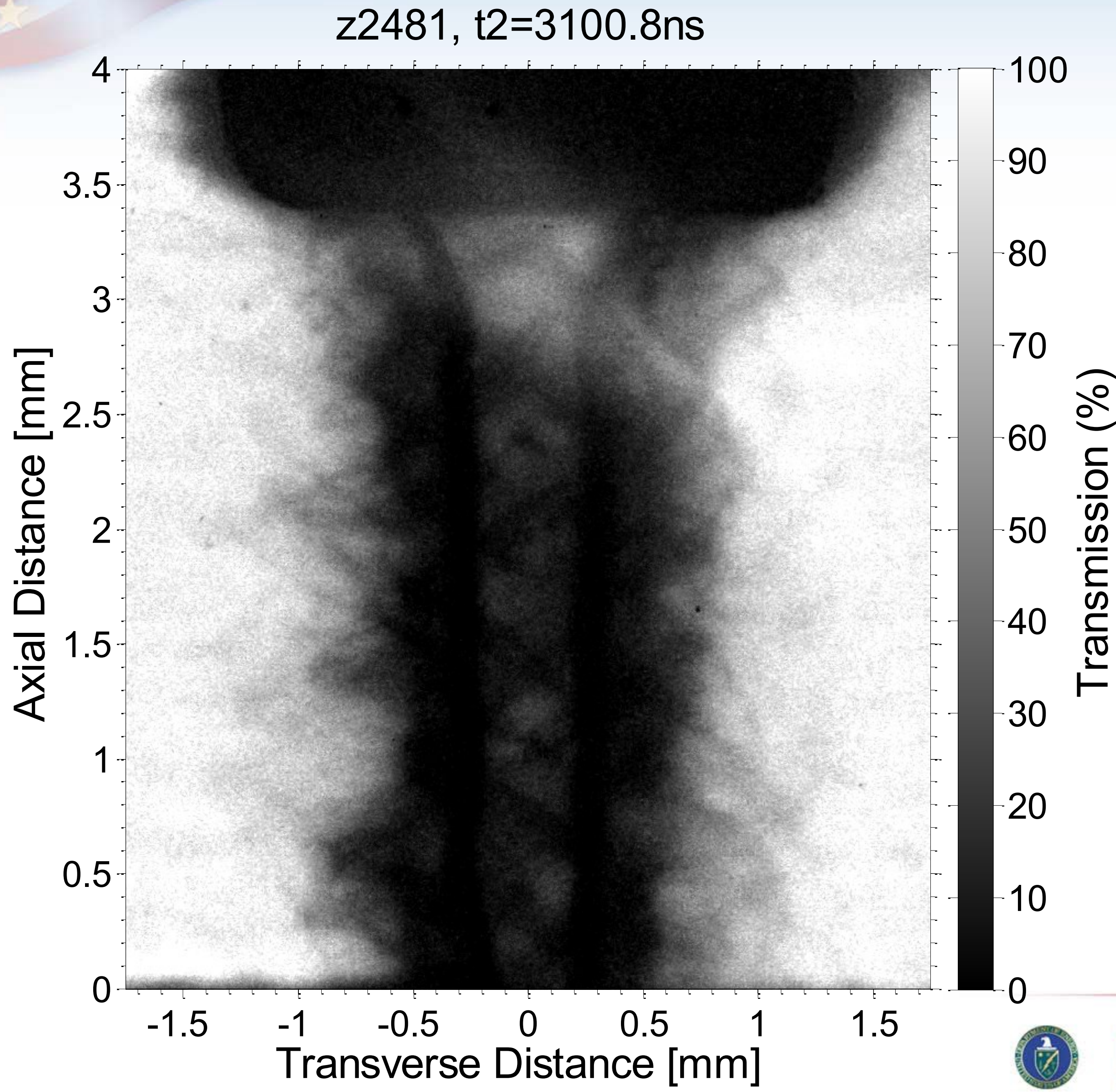


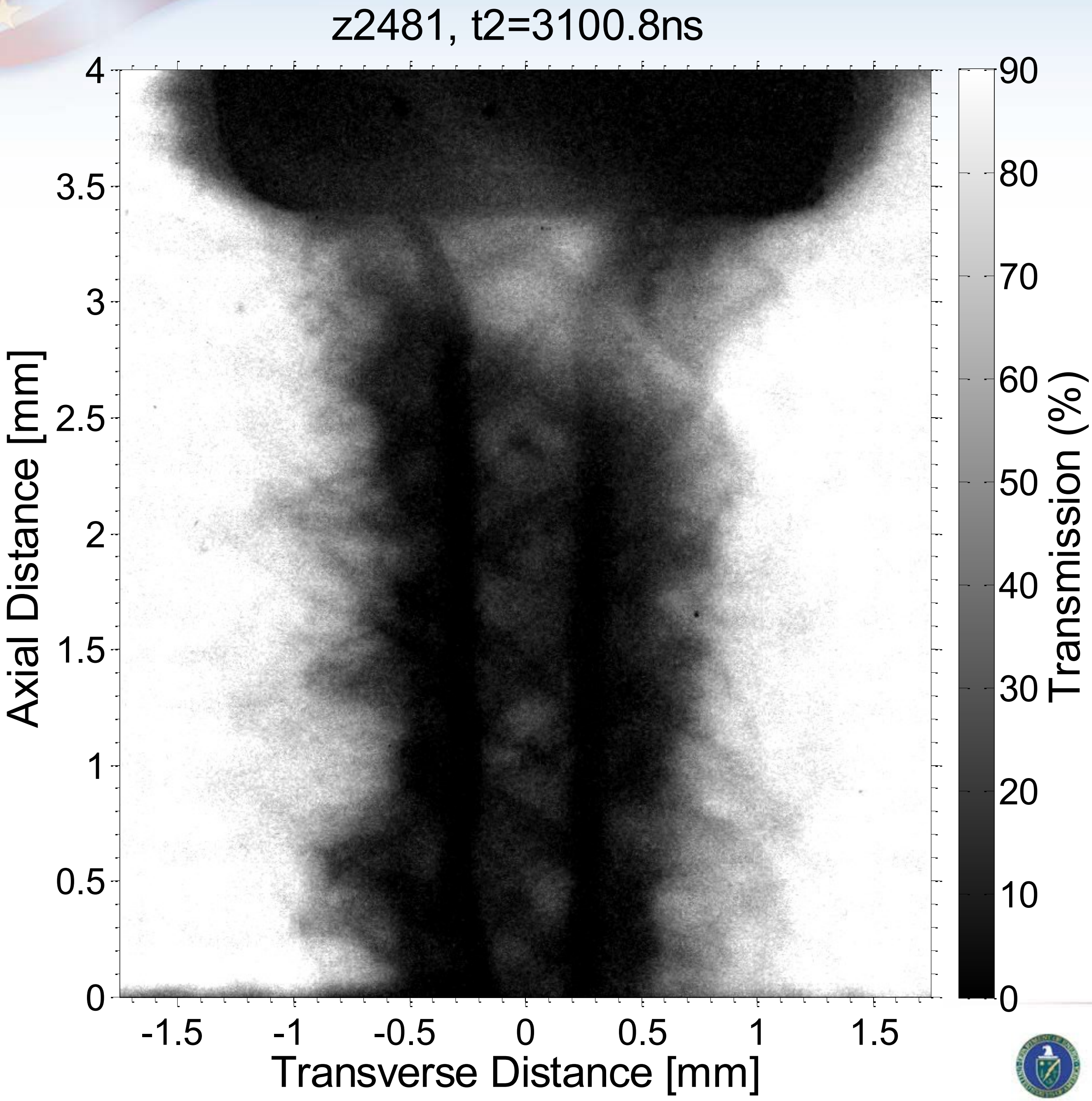
***p*≈constant**

C ≡ a_1/a_2

$$\varphi_{t2} = \tan^{-1}(C \cdot \tan(\varphi_{t1}))$$

Required 'C' matches contraction of 80-90% of liner mass


z2481, t2=3100.8ns
Axial Distance [mm]
4
3.5
3
2.5
2
1.5
1
0.5
0
-1.5
-1
-0.5
0
0.5
1
1.5
Transverse Distance [mm]
Transmission (%)
100
90
80
70
60
50
40
30
20
10
0



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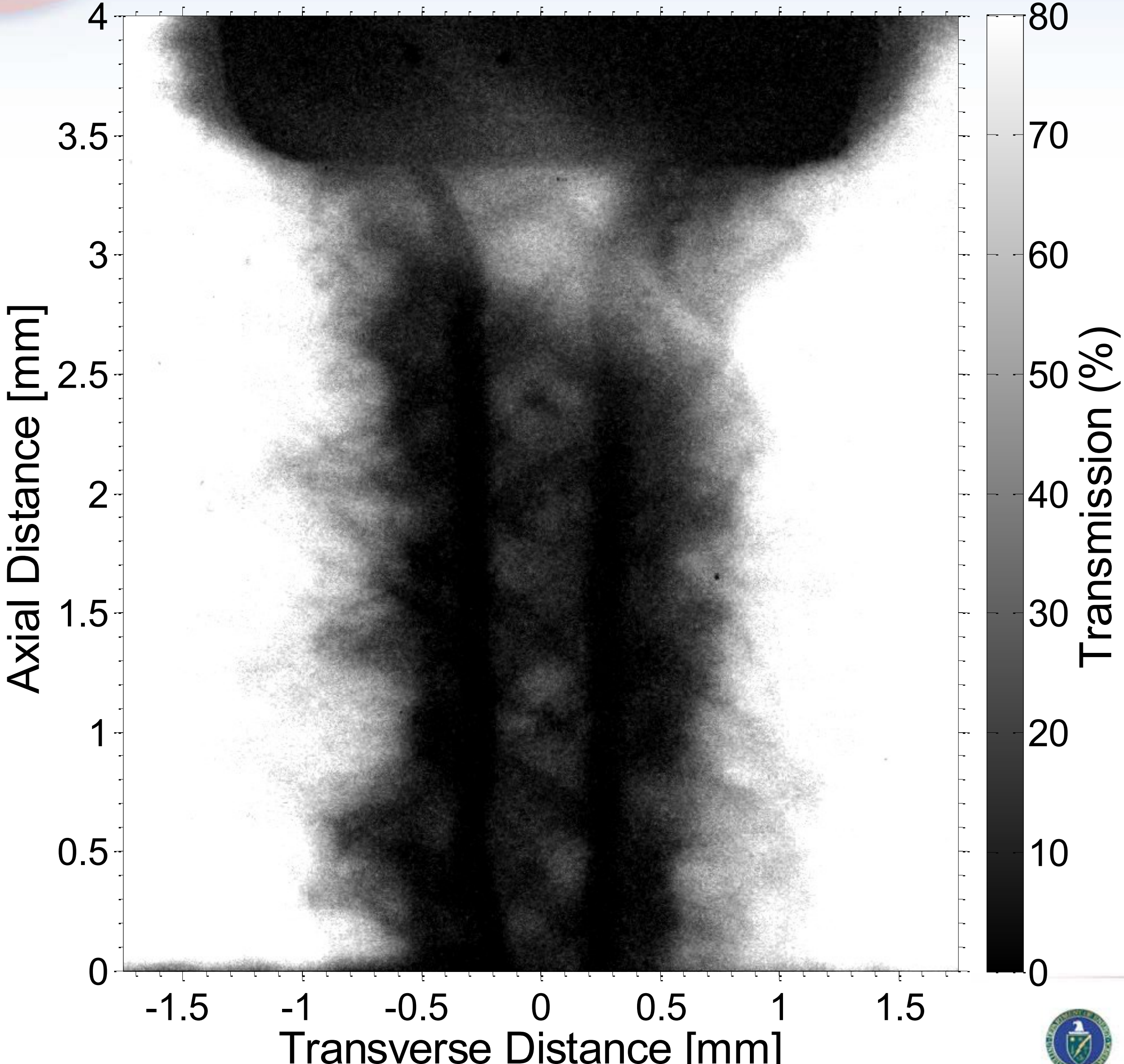
z2481, t2=3100.8ns



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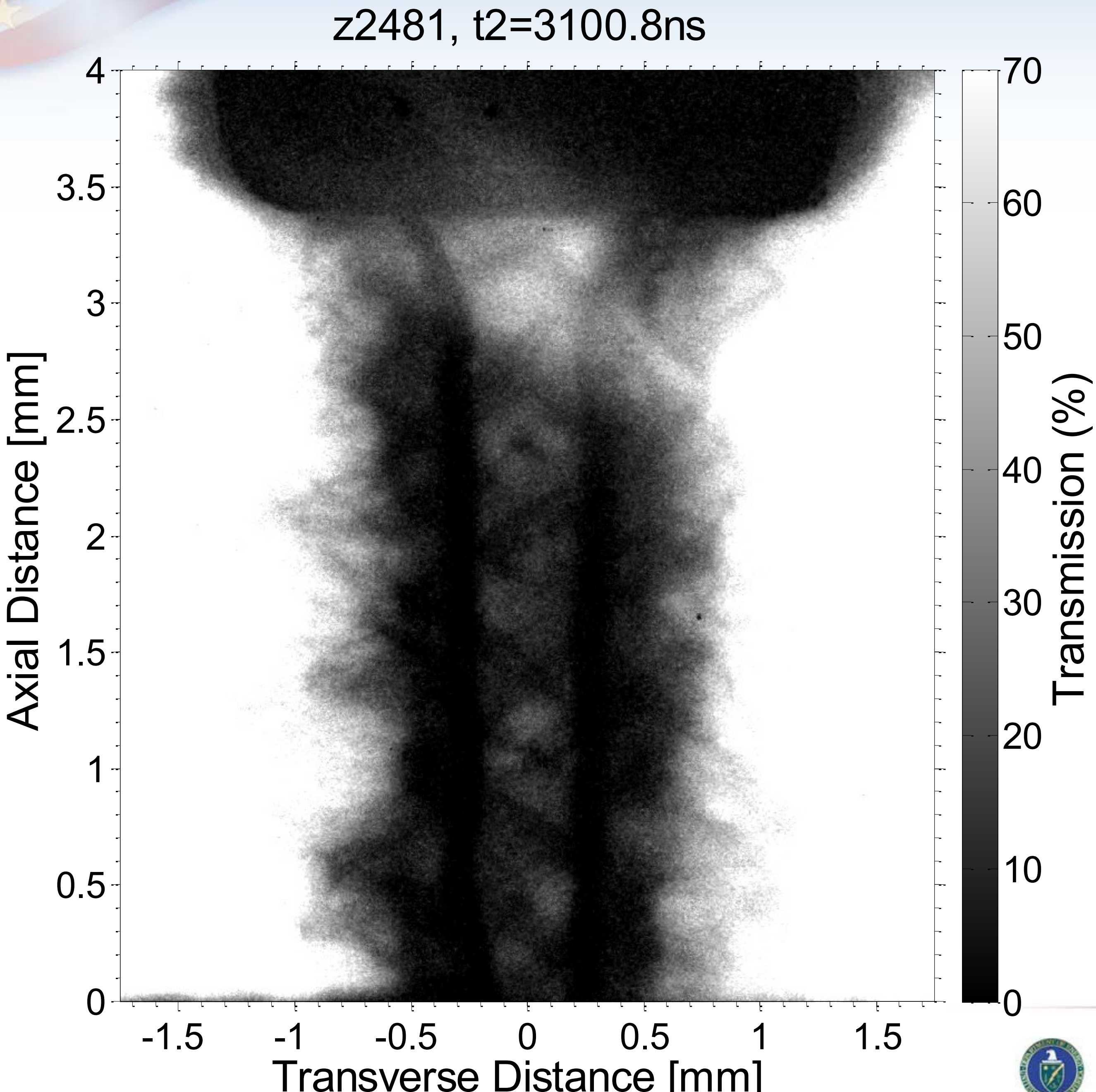
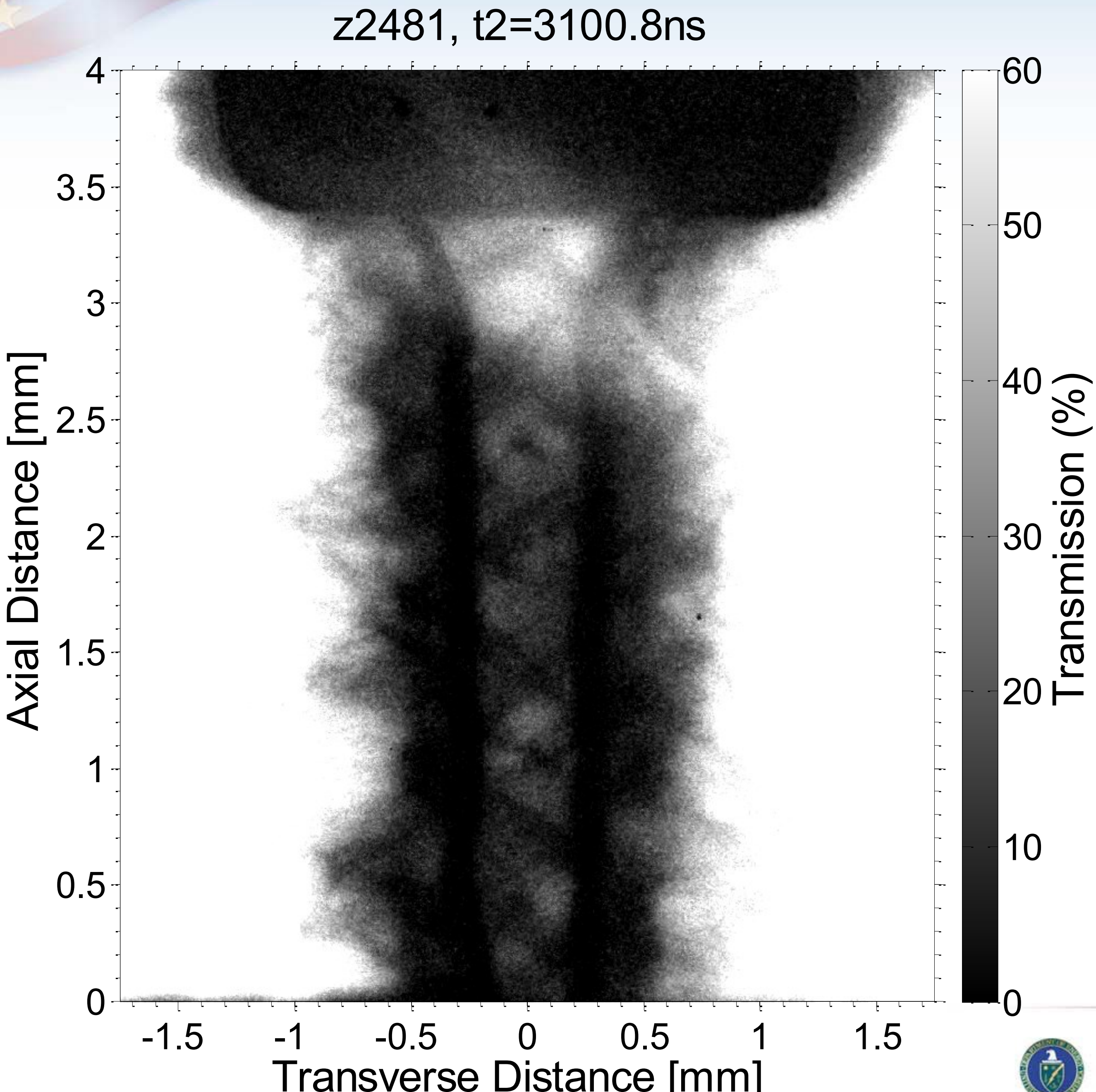


z2481, t2=3100.8ns
Axial Distance [mm]
Transverse Distance [mm]
Transmission (%)
4
3.5
3
2.5
2
1.5
1
0.5
0
-1.5
-1
-0.5
0
0.5
1
1.5
70
60
50
40
30
20
10
0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3.5
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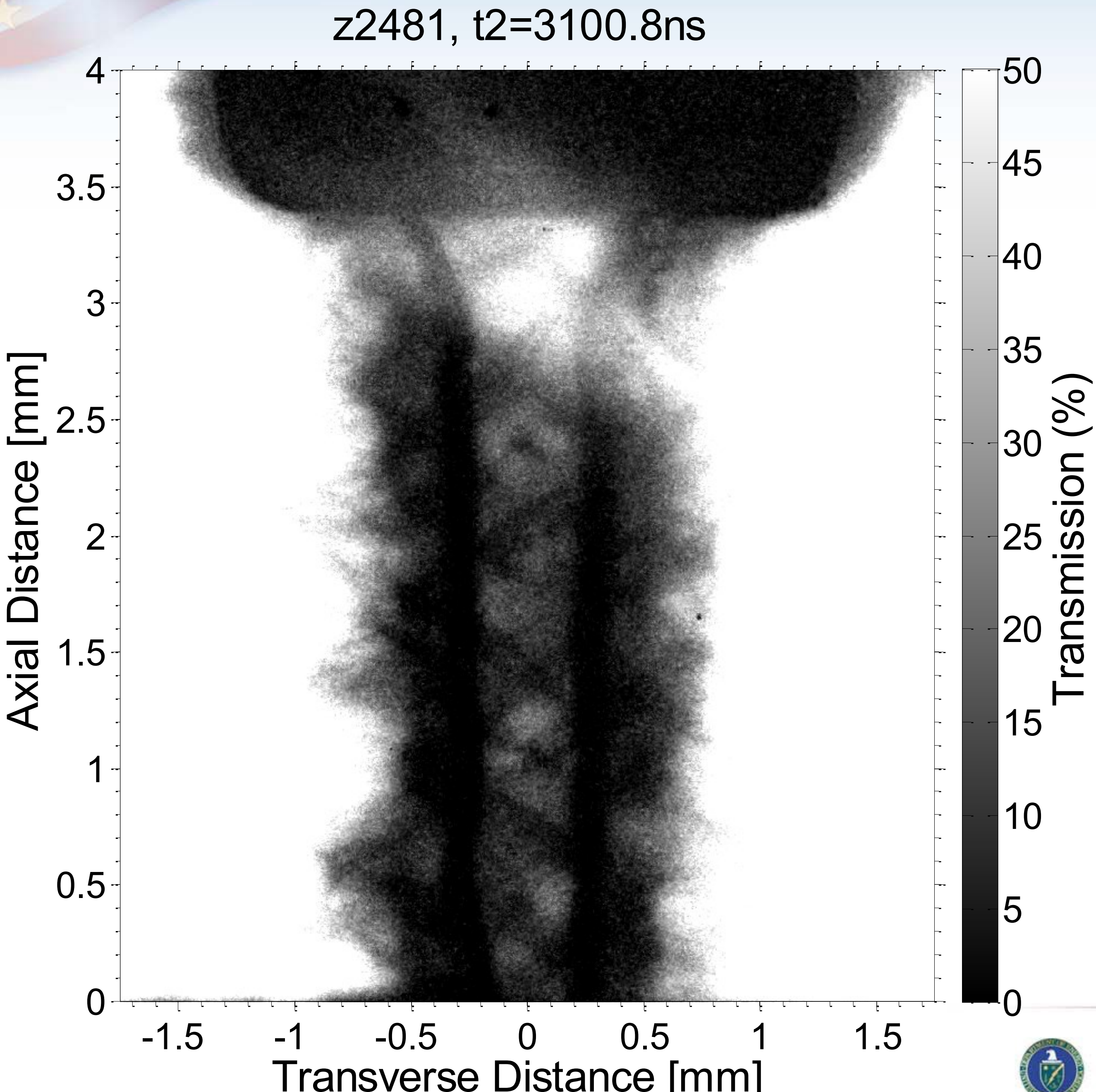
2.5
2
1.5
1
0.5
0
-1.5
-1
-0.5
0
0.5
1
1.5
Transverse Distance [mm]
Transmission (%)
60
50
40
30
20
10
0



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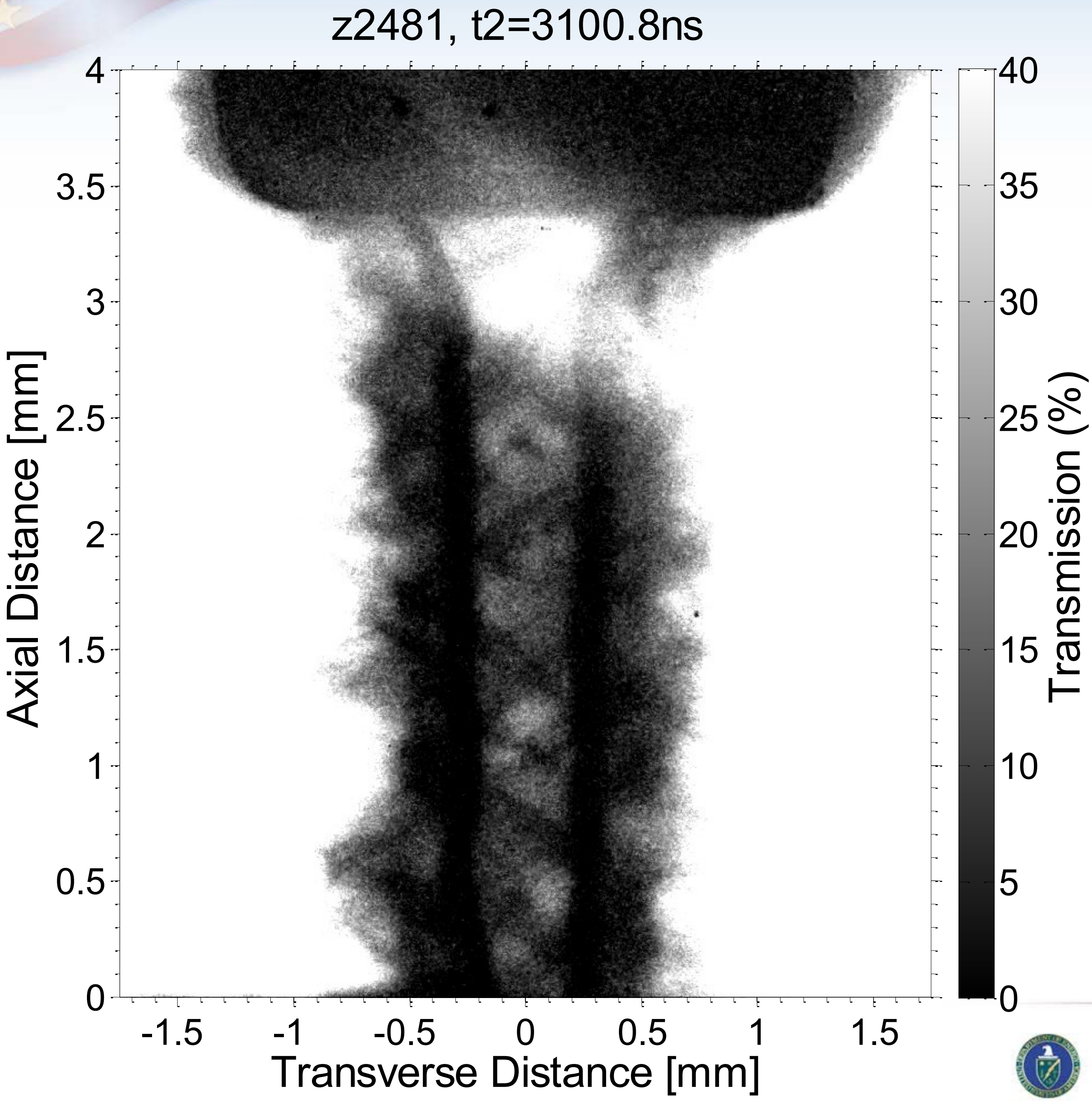
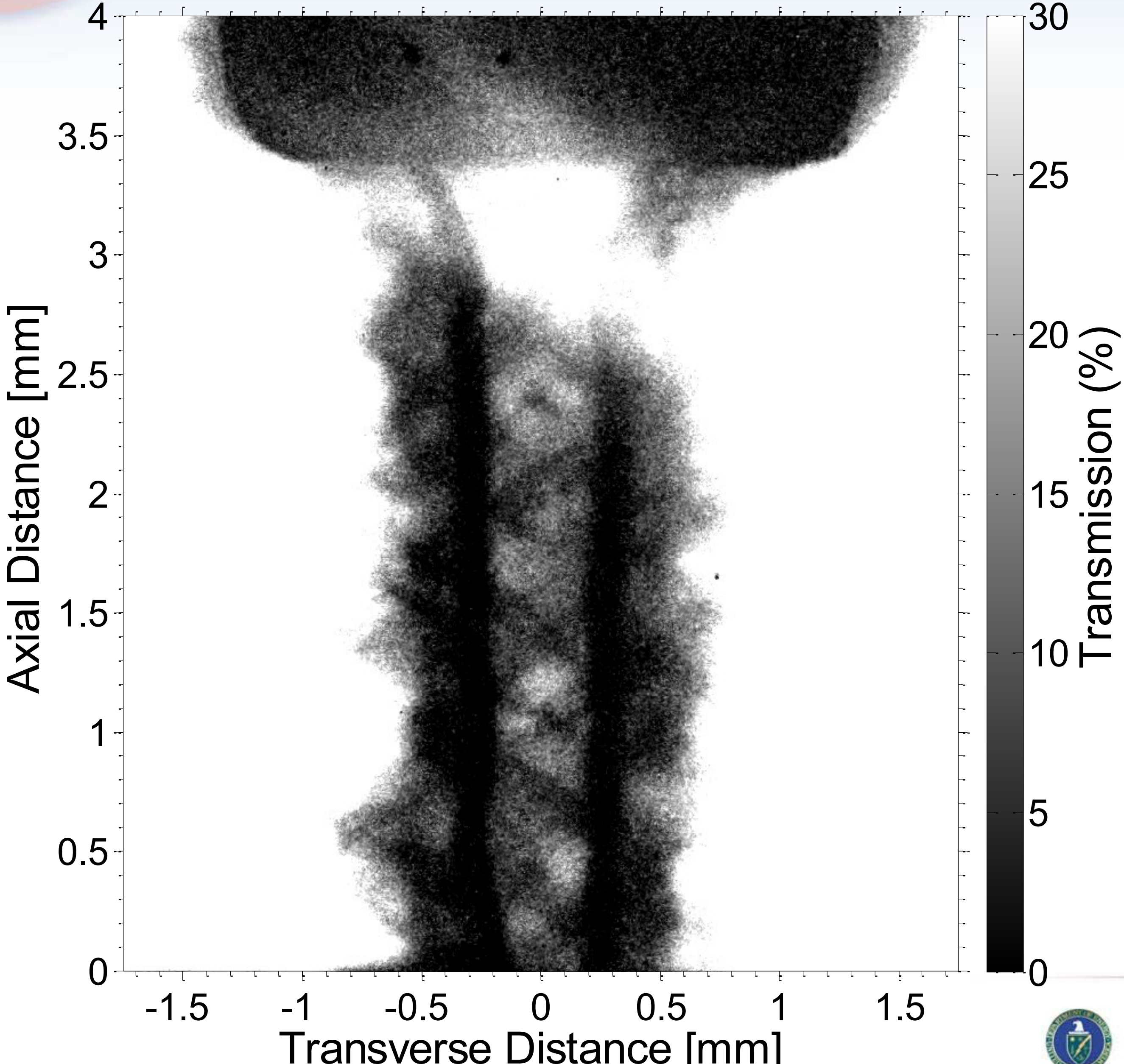
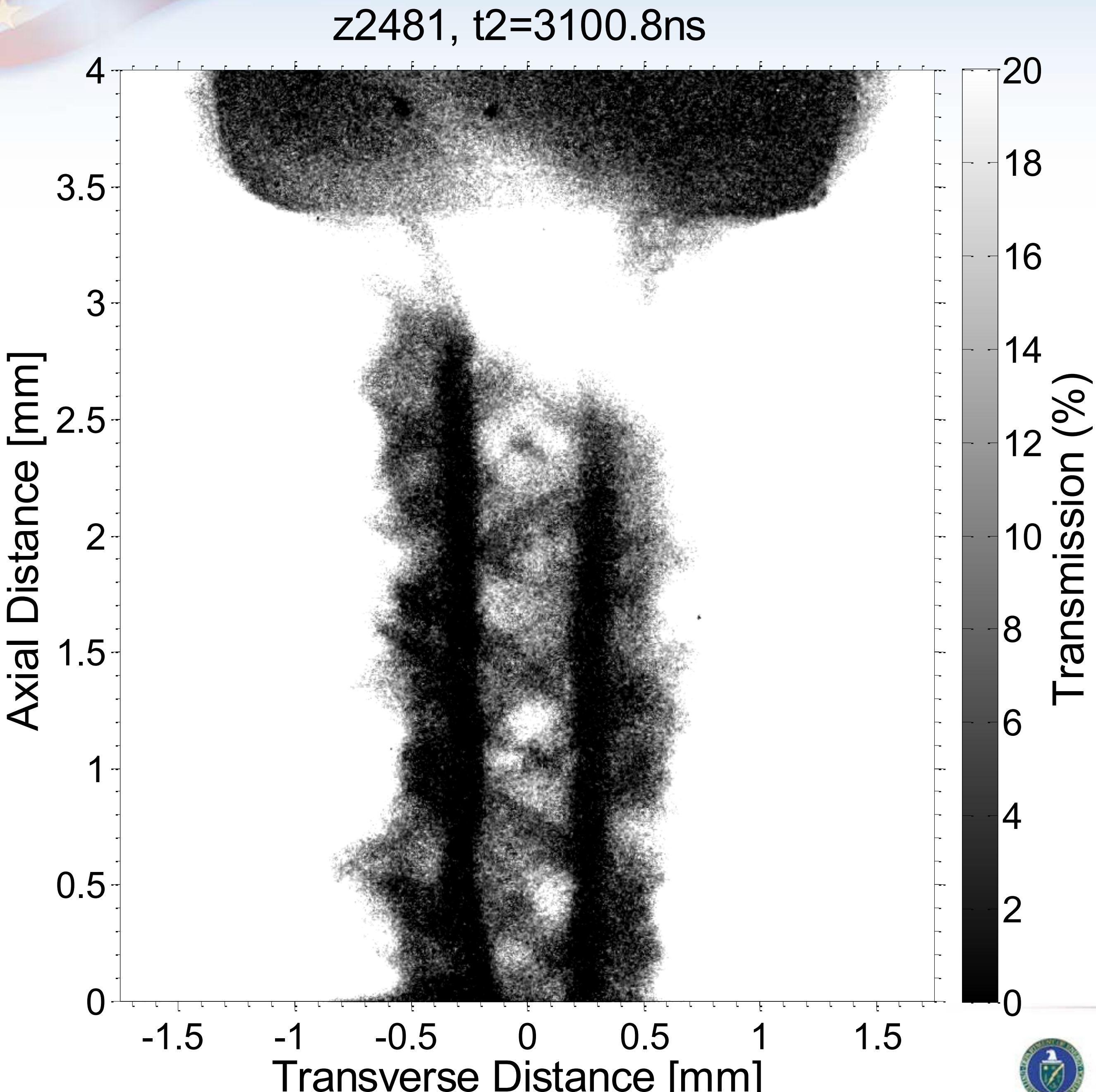
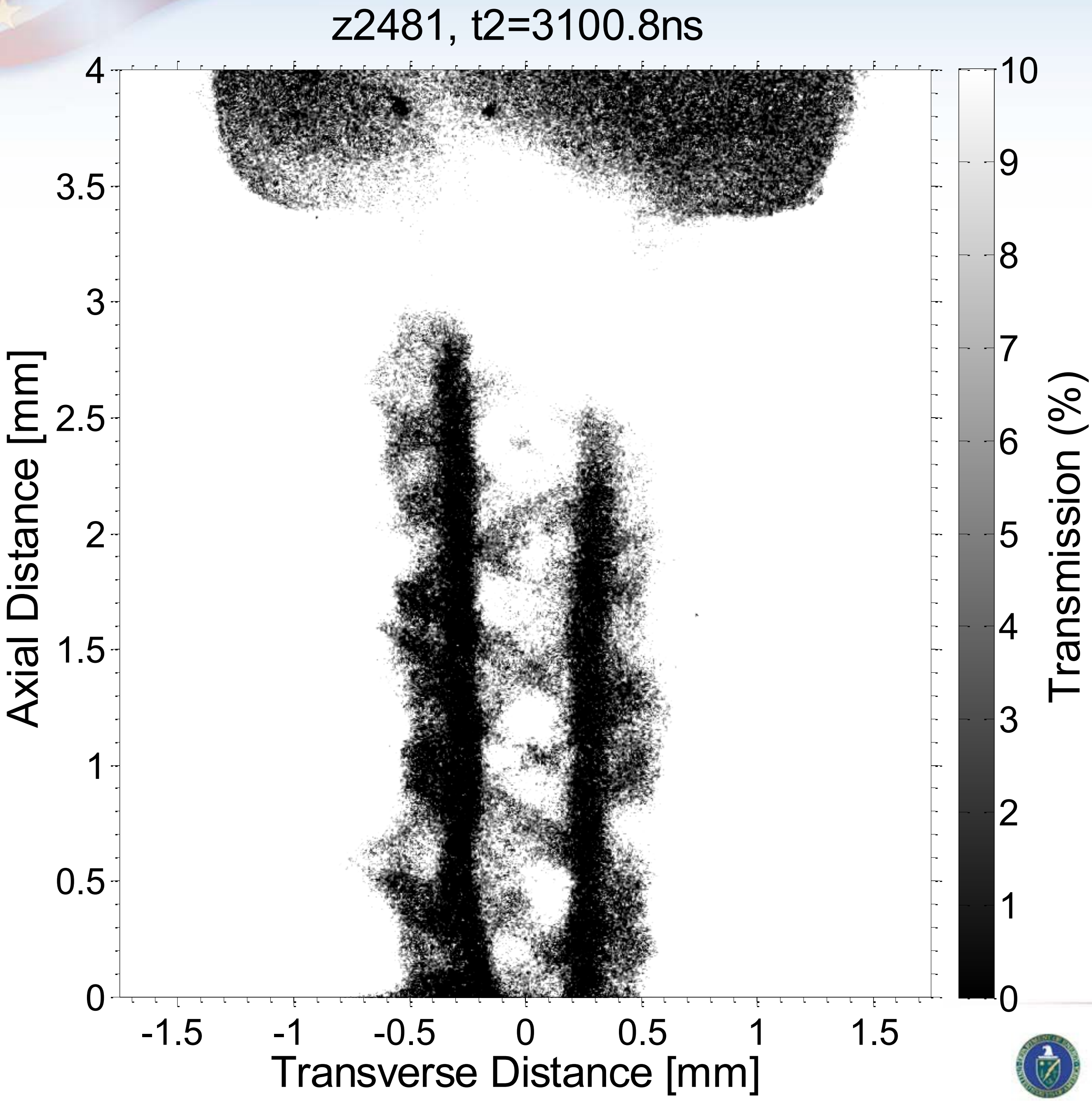


z2481, t2=3100.8ns
Axial Distance [mm]
Transverse Distance [mm]
Transmission (%)
4
3.5
3
2.5
2
1.5
1
0.5
0
-1.5
-1
-0.5
0
0.5
1
1.5
40
35
30
25
20
15
10
5
0

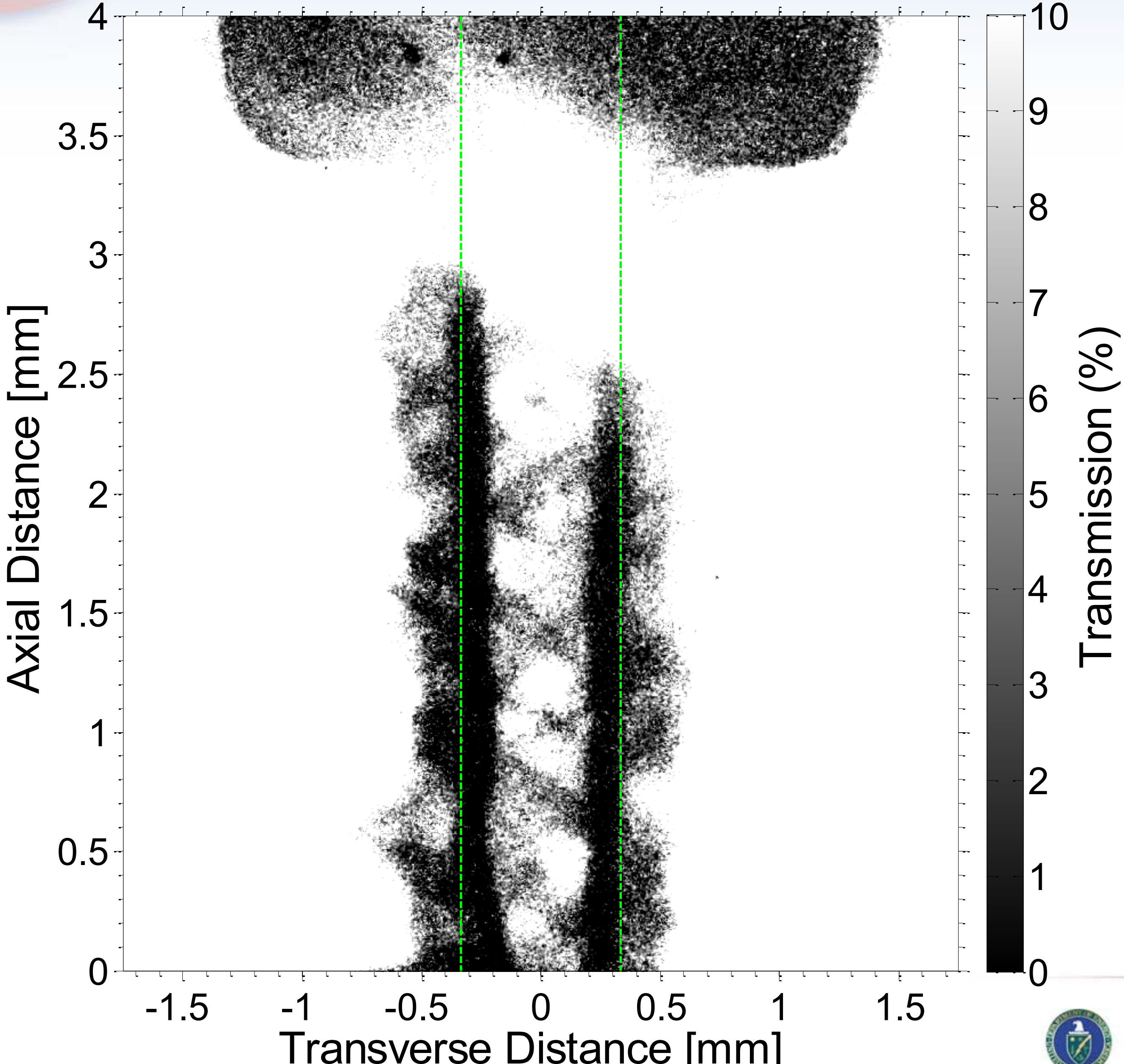
z2481, t2=3100.8ns



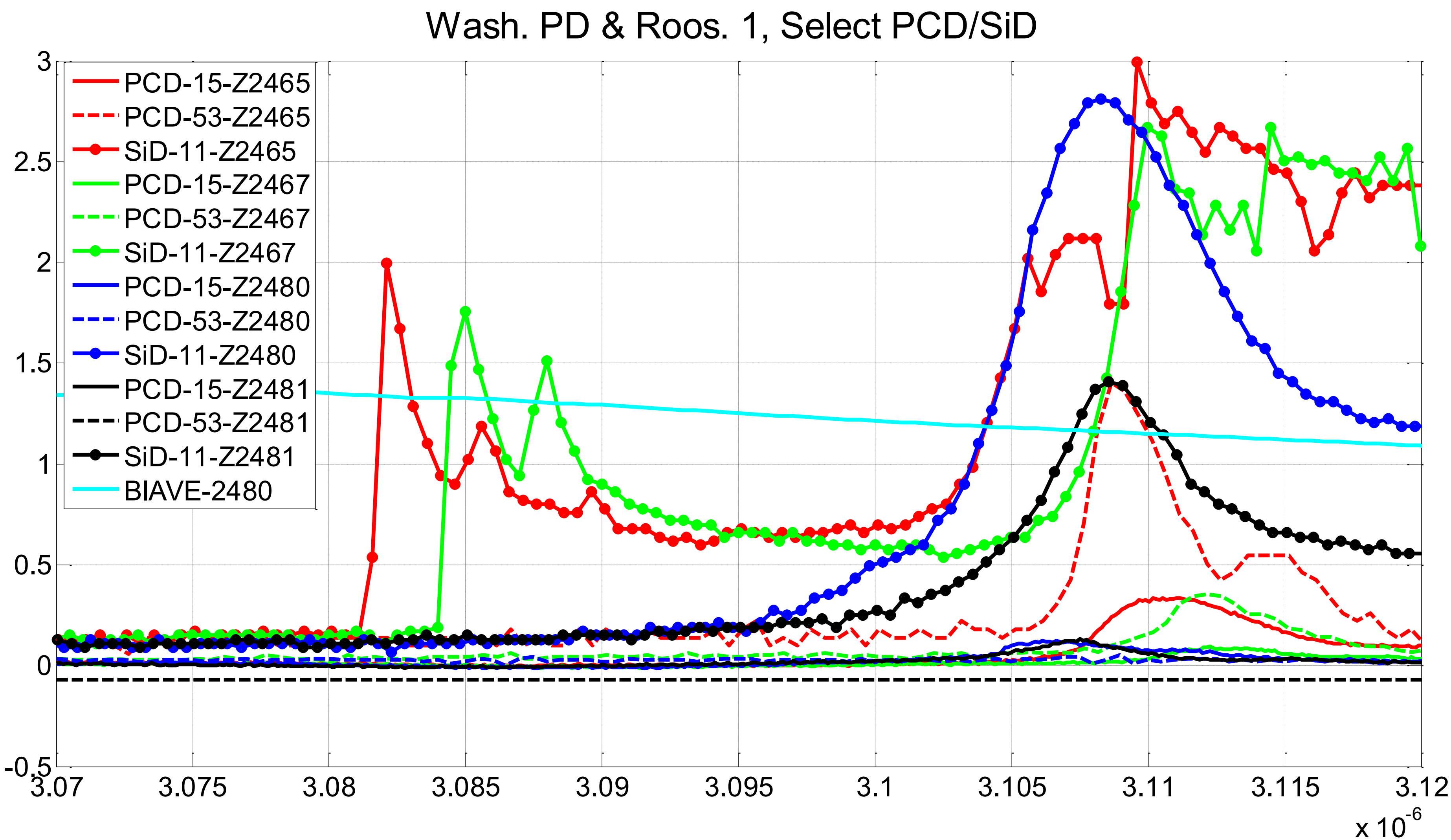

z2481, t2=3100.8ns
Axial Distance [mm]
Transverse Distance [mm]
Transmission (%)
4
3.5
3
2.5
2
1.5
1
0.5
0
-1.5
-1
-0.5
0
0.5
1
1.5
20
18
16
14
12
10
8
6
4
2
0


z2481, t2=3100.8ns
Axial Distance [mm]
Transverse Distance [mm]
Transmission (%)
4
3.5
3
2.5
2
1.5
1
0.5
0
-1.5
-1
-0.5
0
0.5
1
1.5
10
9
8
7
6
5
4
3
2
1
0

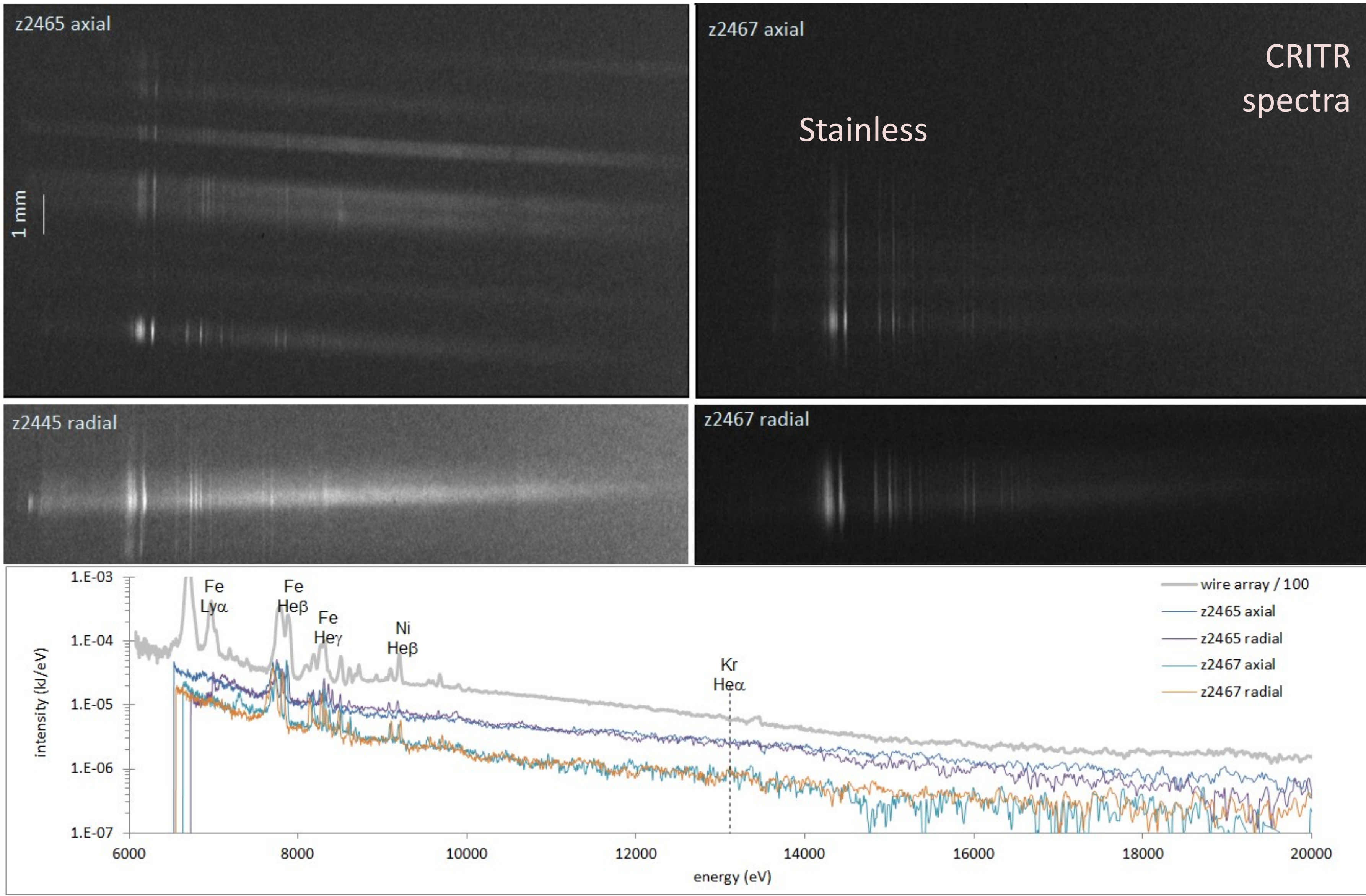
Implosion remains highly uniform at CR=7



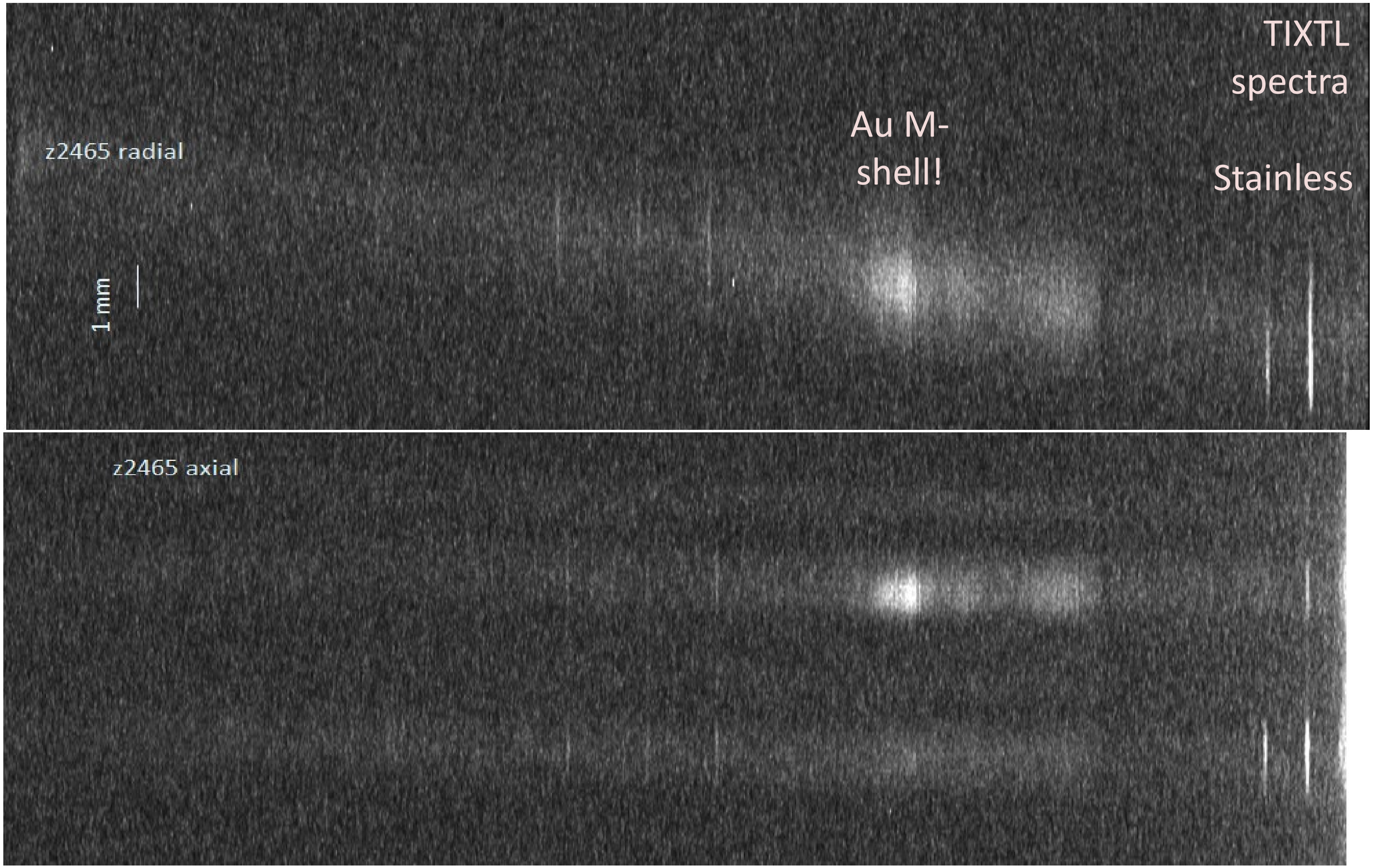
Silicon diode and PCD data may indicate enhanced stability



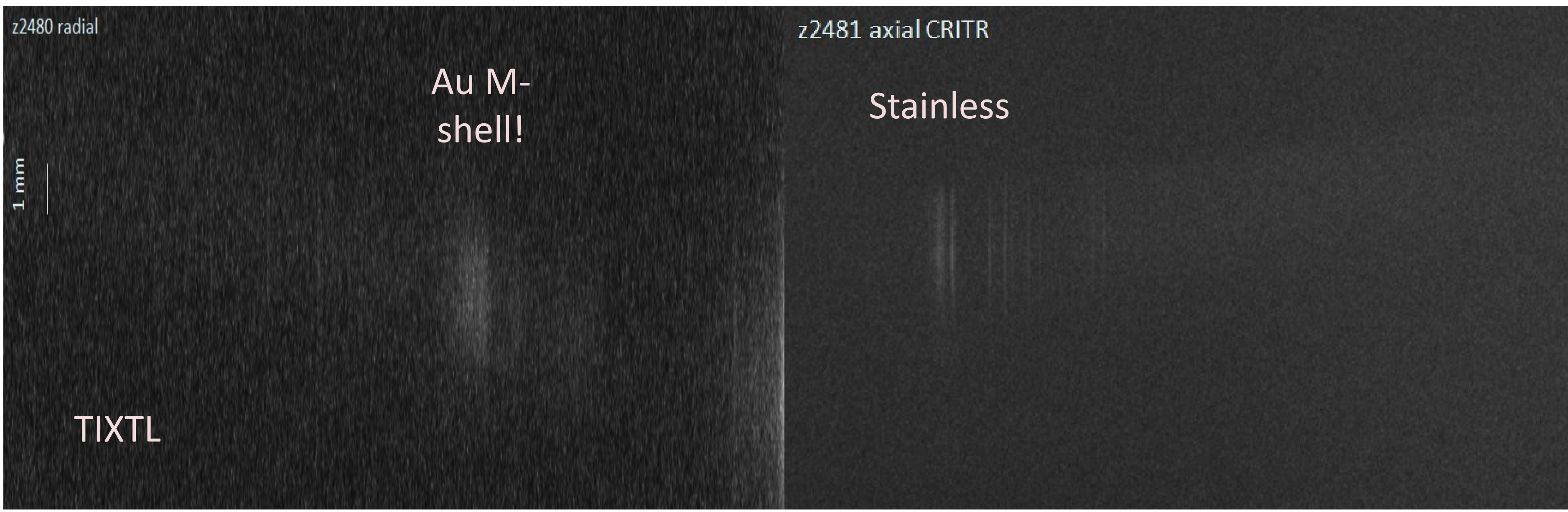
Stainless steel and gold emission were evident in spectra from Washington targets with no axial B-field



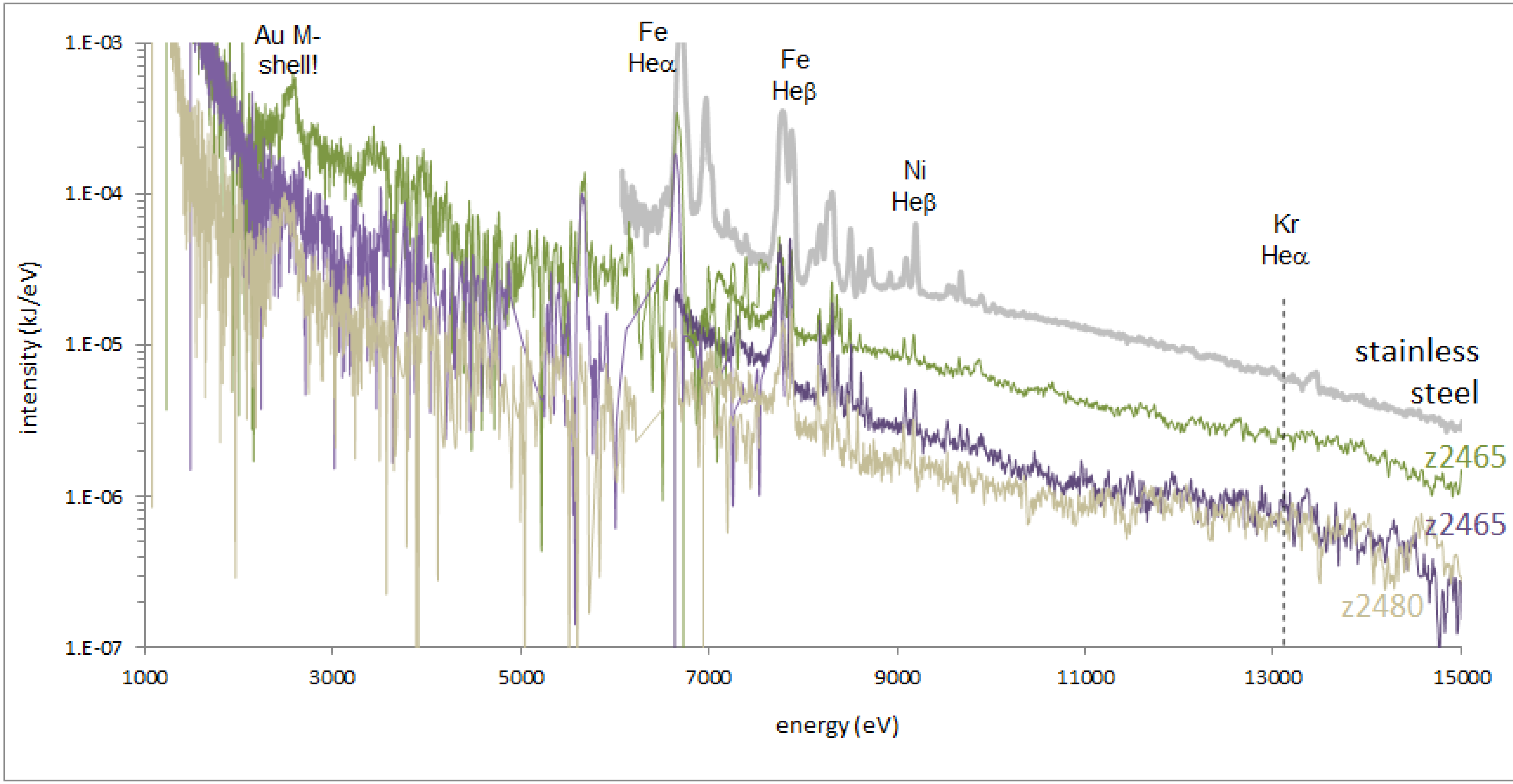
Stainless steel and gold emission were evident in spectra from Washington targets with no axial B-field



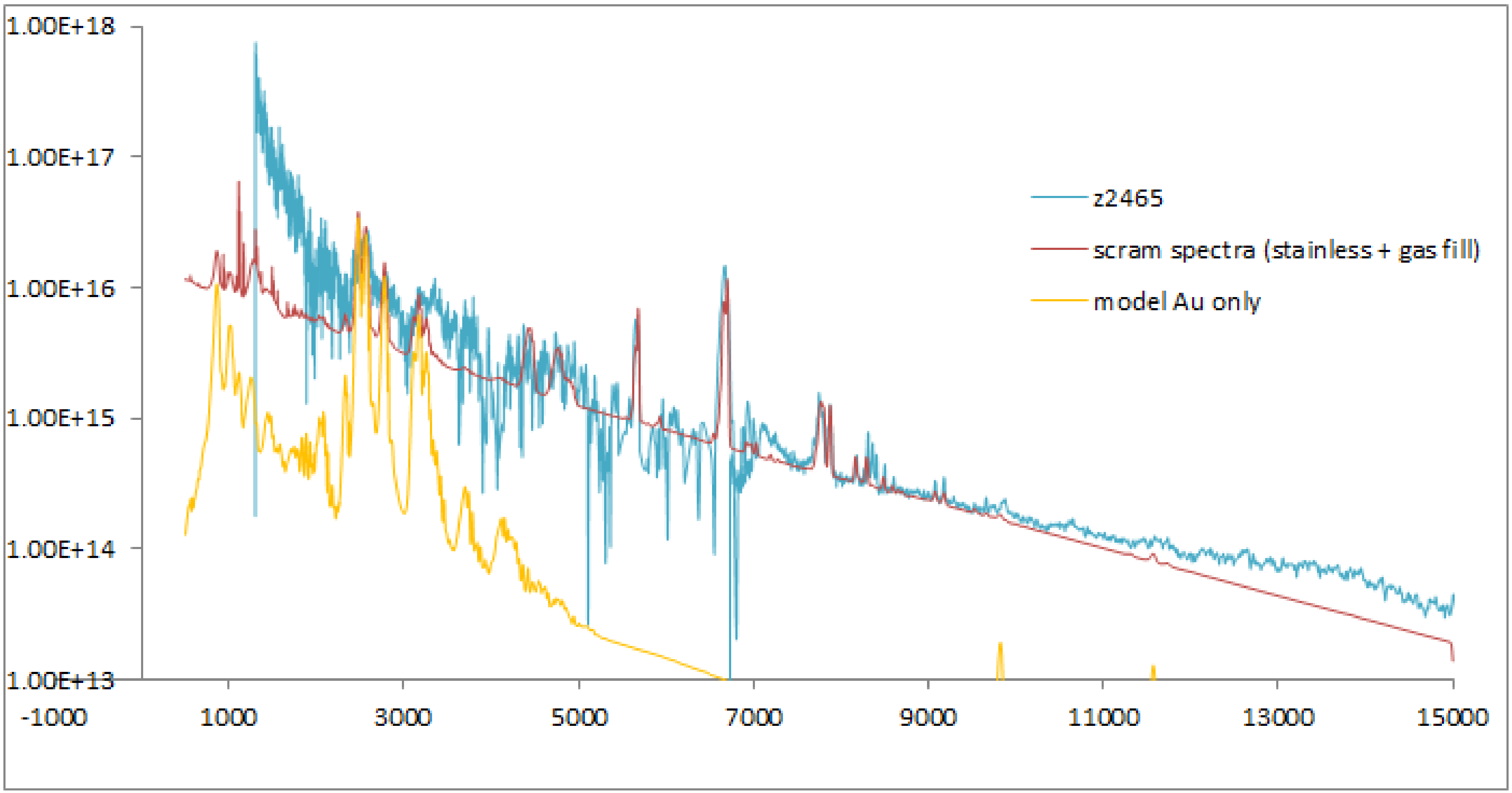
Stainless steel and gold emission were also evident, faintly, from Roosevelt shots!



Absolute intensities are very weak (0.1%) compared to stainless wire arrays, but line emission unambiguously signals stainless.



The Be liner, stainless, and Au appear to reach ~ 2 keV (lower T on the Roosevelt shots)



Summary & Conclusions

- Liner implosion & MRT studies using penetrating radiography have provided valuable data for benchmarking codes & characterizing a MagLIF-relevant liner implosion through to stagnation
- Radiographs with high-opacity tracer layers have allowed us to assess the stability of the imploding liner's inner surface more accurately and more directly than previously possible
- A radiograph of a liner at a convergence ratio of 7 shows that the liner's inner wall remains highly uniform
- Micro-Bdot measurements confirm flux compression by liners seeded with a uniform axial field
- In stark contrast to liner with no seed B_z field, pre-magnetized liners develop 3D helix-like surface instabilities

→**Evidence suggests that this may have a stabilizing effect**

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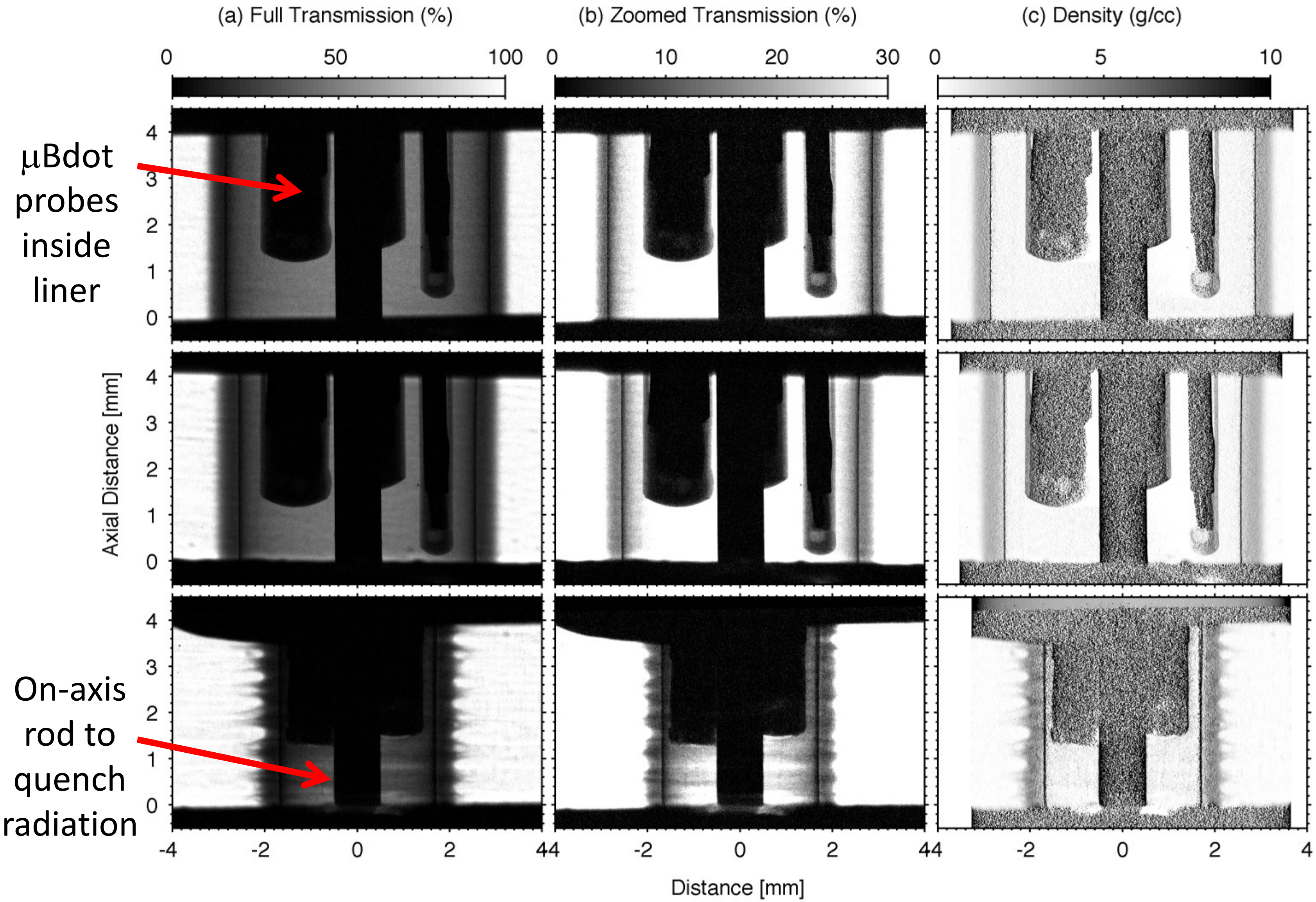
BACKUP

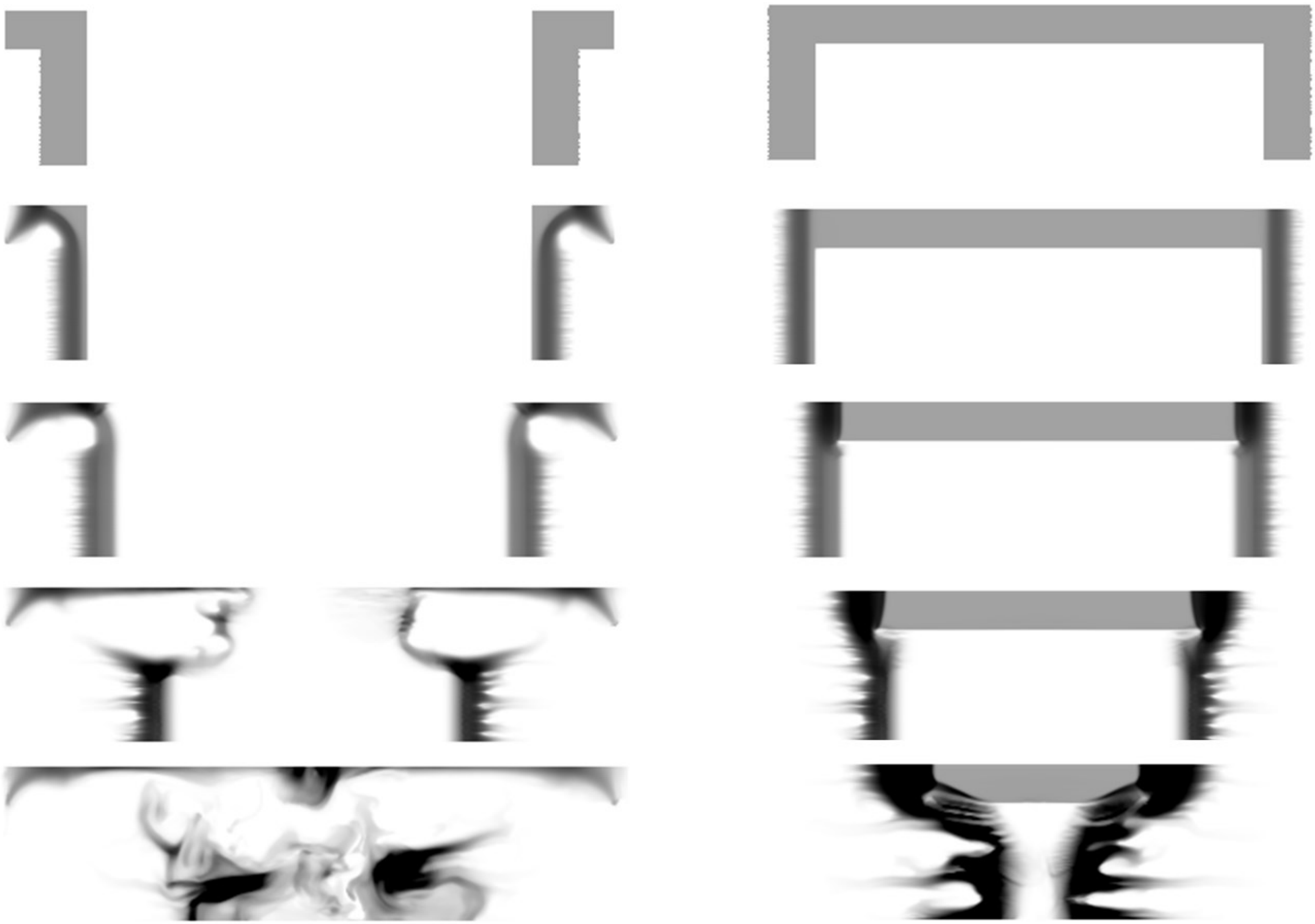
Recent experiments used 2.5 μm Al just inside the Be liner to enhance the contrast of the liner's inner surface*



*Thin Al layer to enhance contrast suggested by D.D. Ryutov

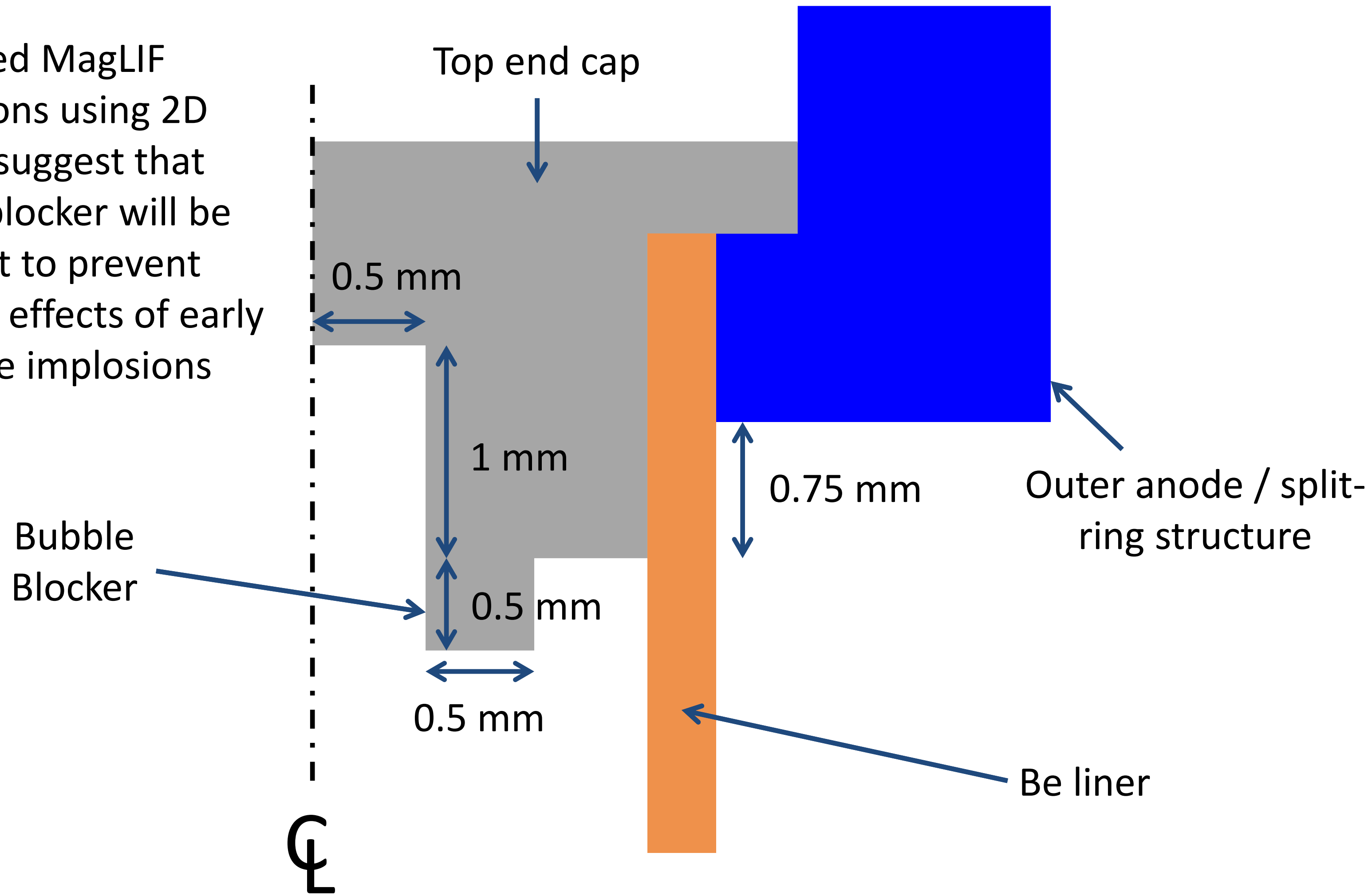
R. D. McBride *et al.*, invited manuscript in preparation for Phys. Plasmas (2013).

Simulations Suggest that the addition of a "cushion" feature to the end cap will mitigate this instability



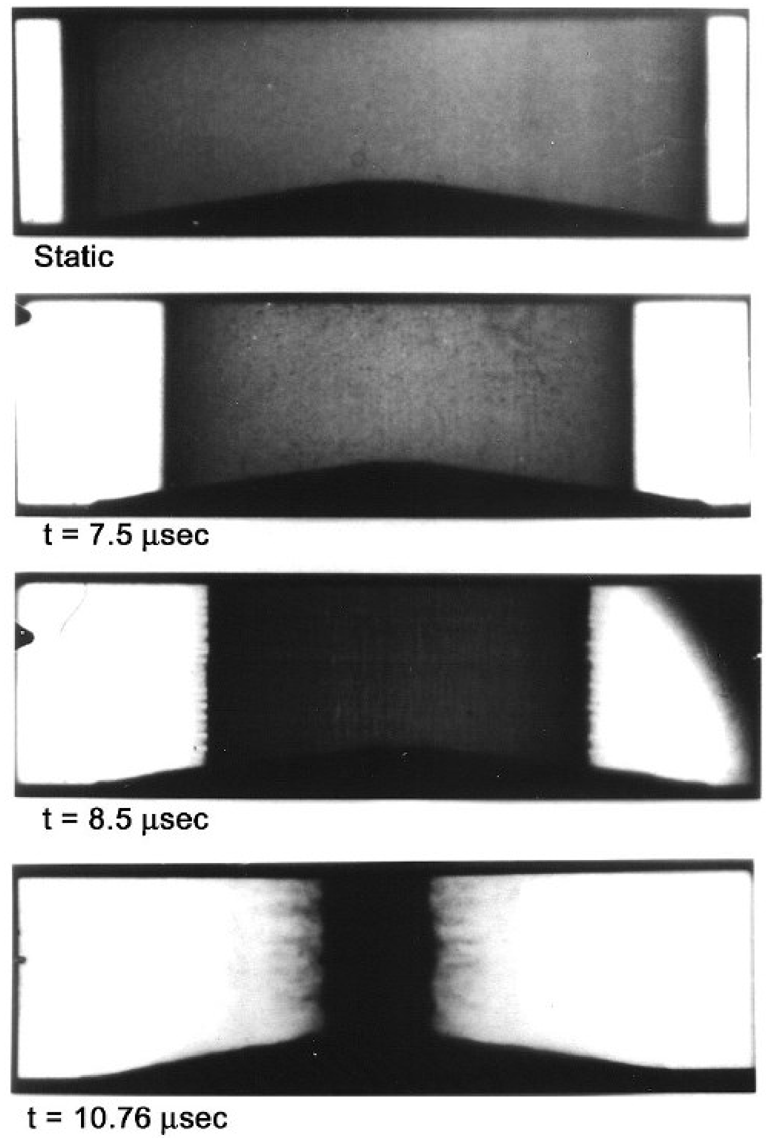
Experiments planned to test mitigation schemes:

Integrated MagLIF simulations using 2D LASNEX suggest that bubble blocker will be sufficient to prevent negative effects of early electrode implosions

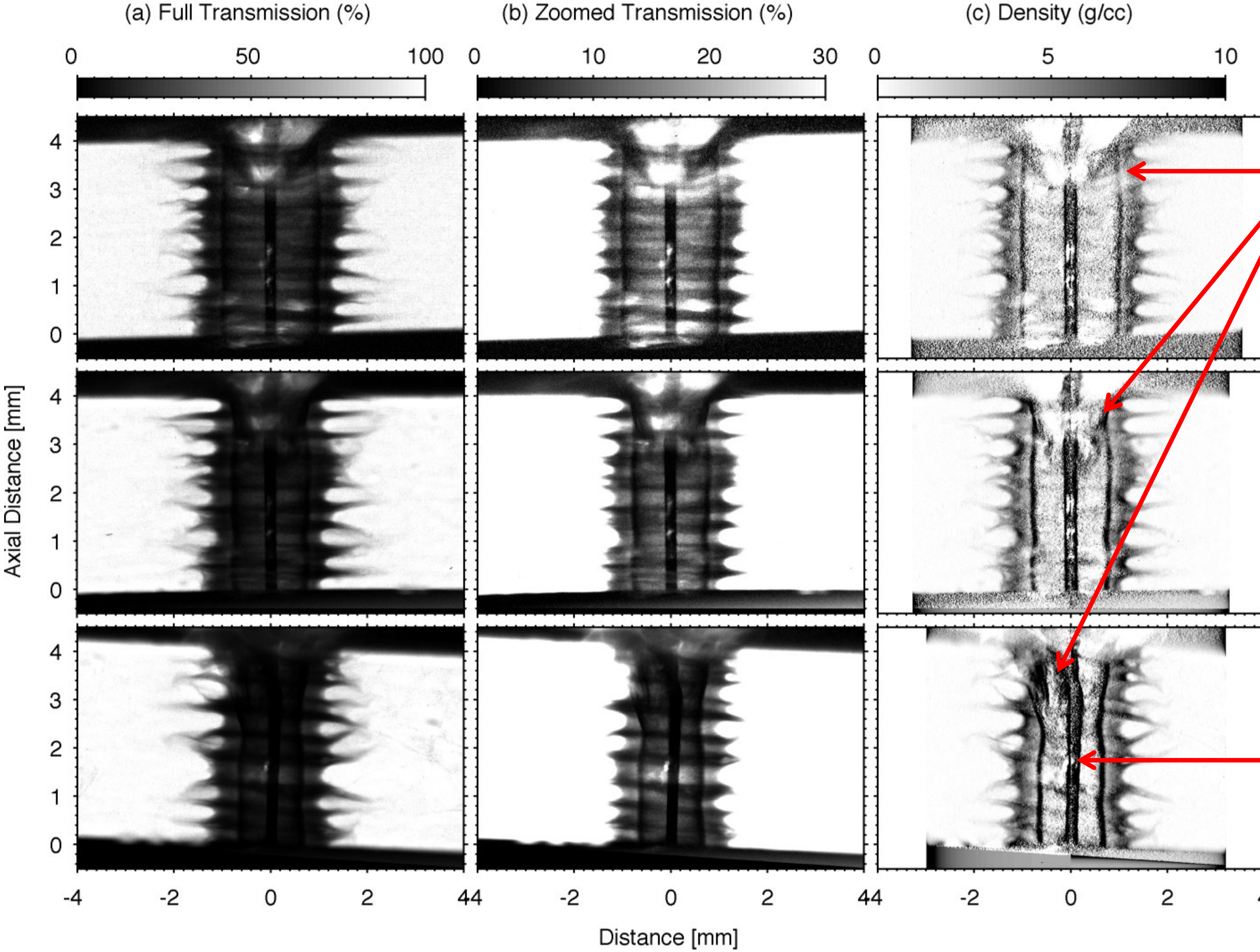


Other schemes that can be tested include:

Angled glide planes, as tested by Reinovsky *et al.*, IEEE Trans. Plasma Sci. (2002).



Radiographs at a convergence ratio of ~5 show remarkably good stability for inner liner surface



Note: Most disruption to liner stability caused by electrode end-effects and jetting material

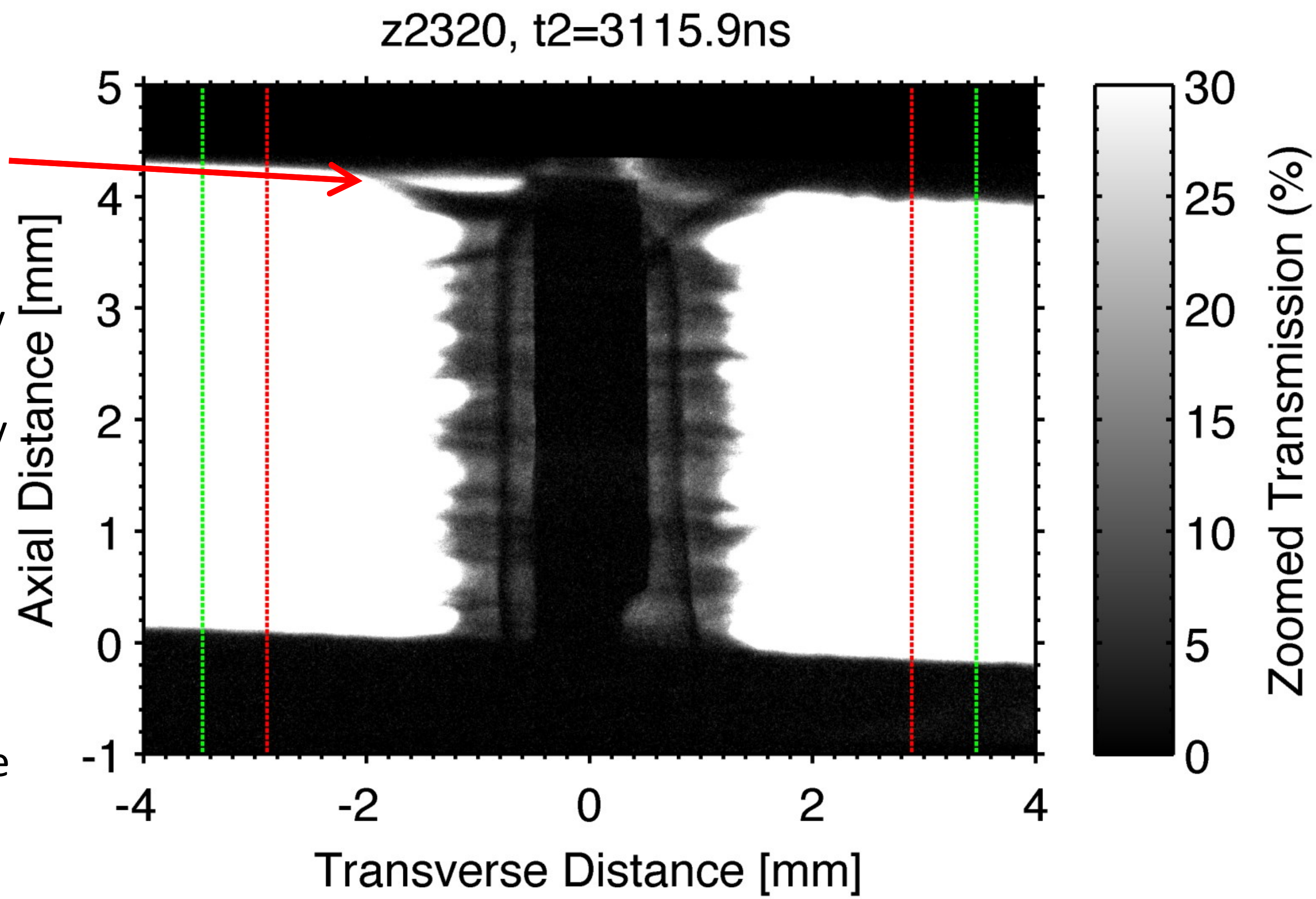
Note: MagLIF requires final compression to about diameter of on-axis rod

R. D. McBride *et al.*, invited manuscript in preparation for Phys. Plasmas (2013).

Most disruption to liner stability caused by electrode end-effects

Early anode implosion causes material to jet into imploding volume and disrupt liner stability

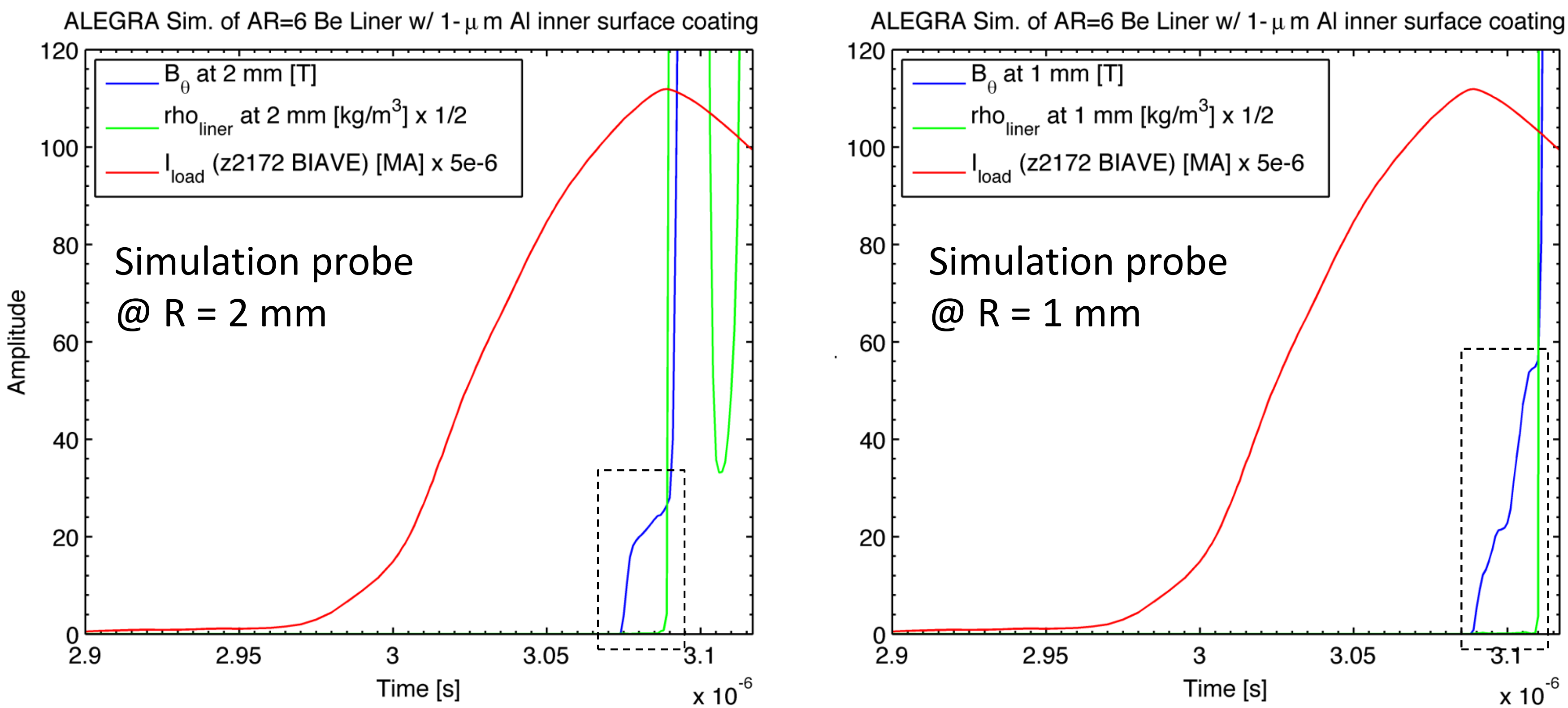
(Camera was fortuitously aligned high on this particular shot, allowing a partial view of the bubble near the anode surface; presumably this occurs along the cathode surface as well)



R. D. McBride *et al.*, invited manuscript in preparation for Phys. Plasmas (2013).

Micro-Bdot experiments:

1D ALEGRA simulations predicted magnetic field penetration (Z's B_θ drive field) into liner interior upon shock breakout:



ALEGRA simulations by M. R. Martin

R. D. McBride *et al.*, invited manuscript in preparation for Phys. Plasmas (2013).

Micro-Bdot experiments:

Micro-Bdot probes fabricated for use on Z by John Greenly at Cornell University

For probes from 0.020’’ semi-rigid co-ax, loop areas are about 0.1 mm^2

These probes are being considered for measuring the flux-compression component of the MagLIF concept (by measuring the fringe fields above the imploding liner)

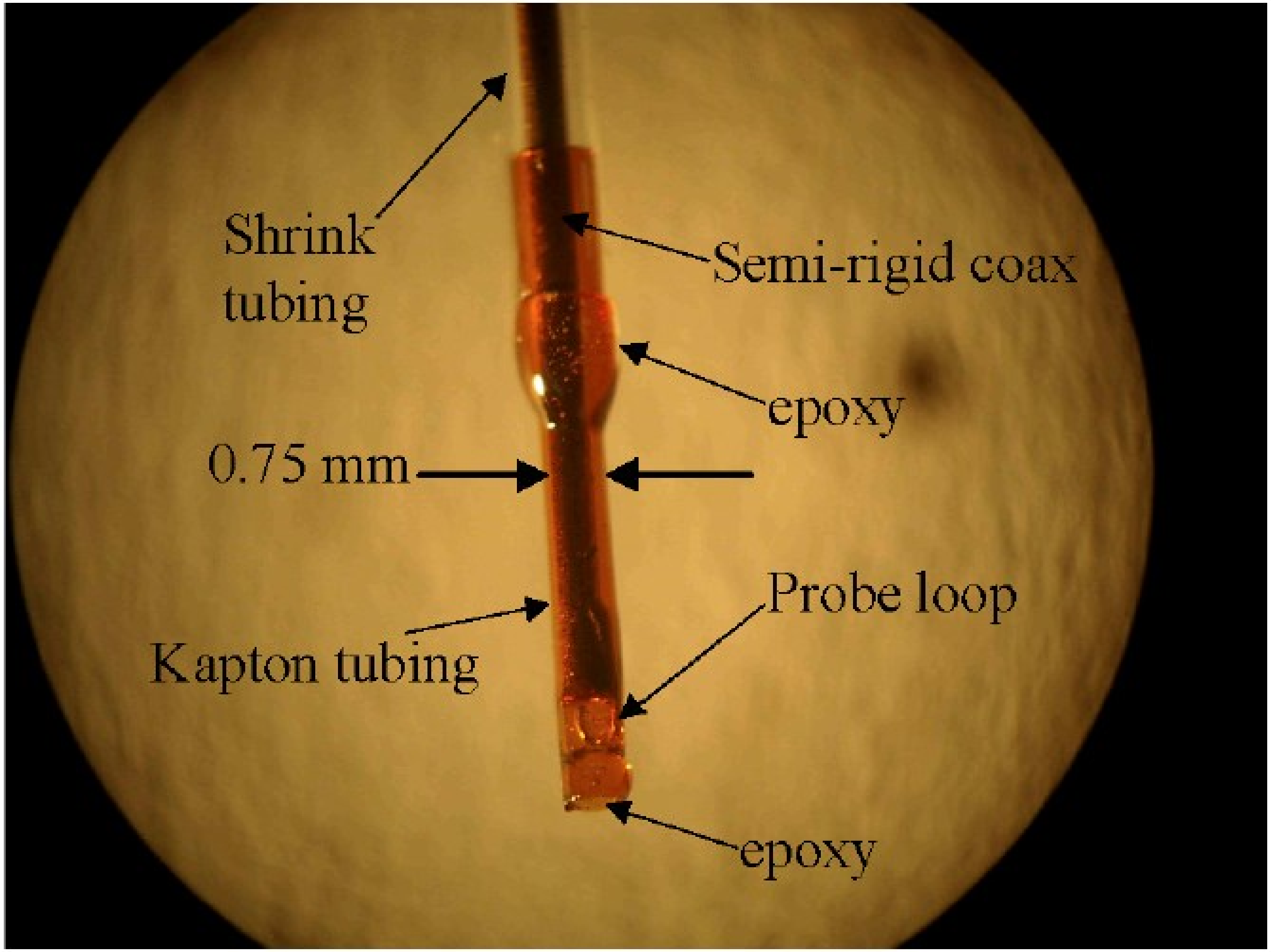
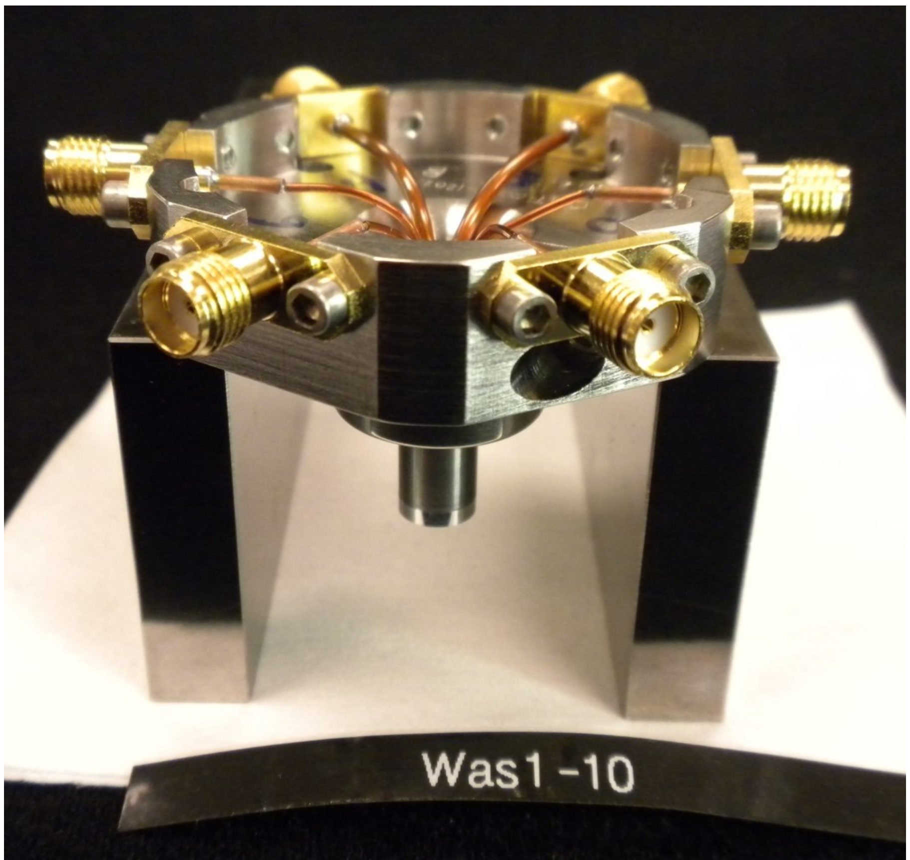
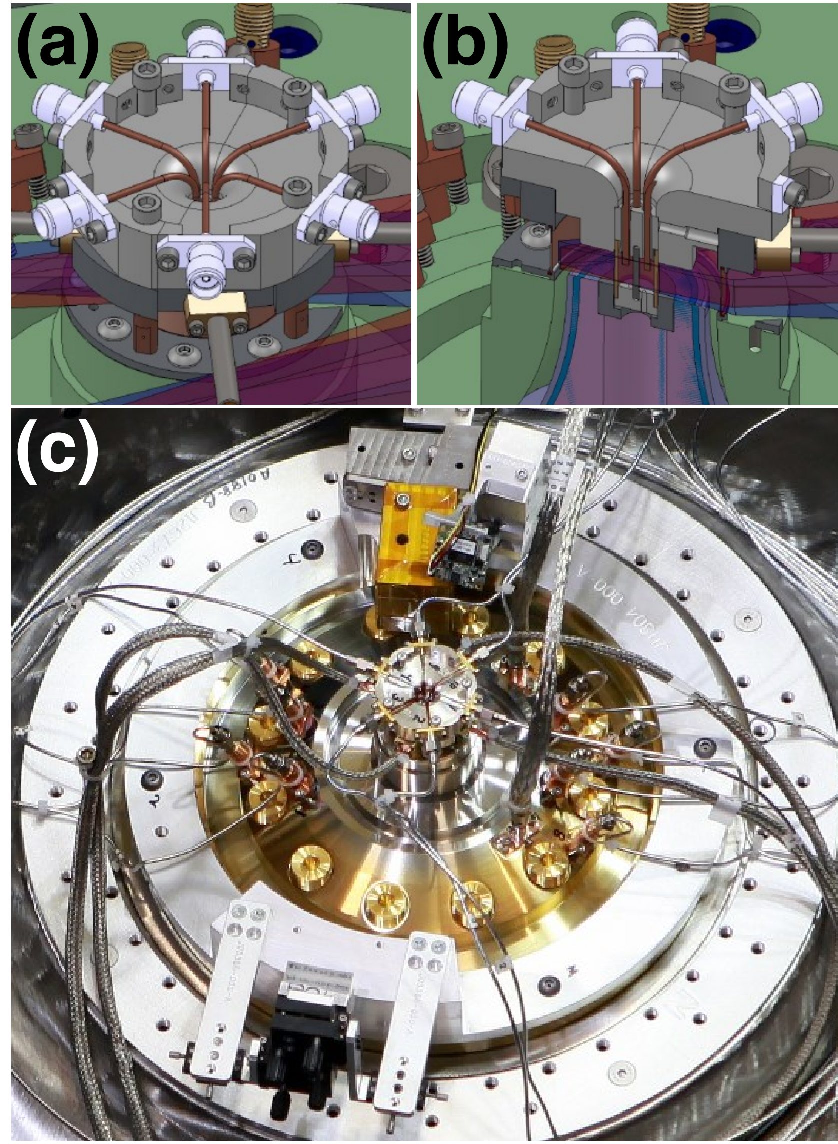


FIGURE 2. COBRA magnetic probe construction.

Micro-Bdot experiments:

Z load load hardware and liners modified to accept Greenly micro-Bdot probes

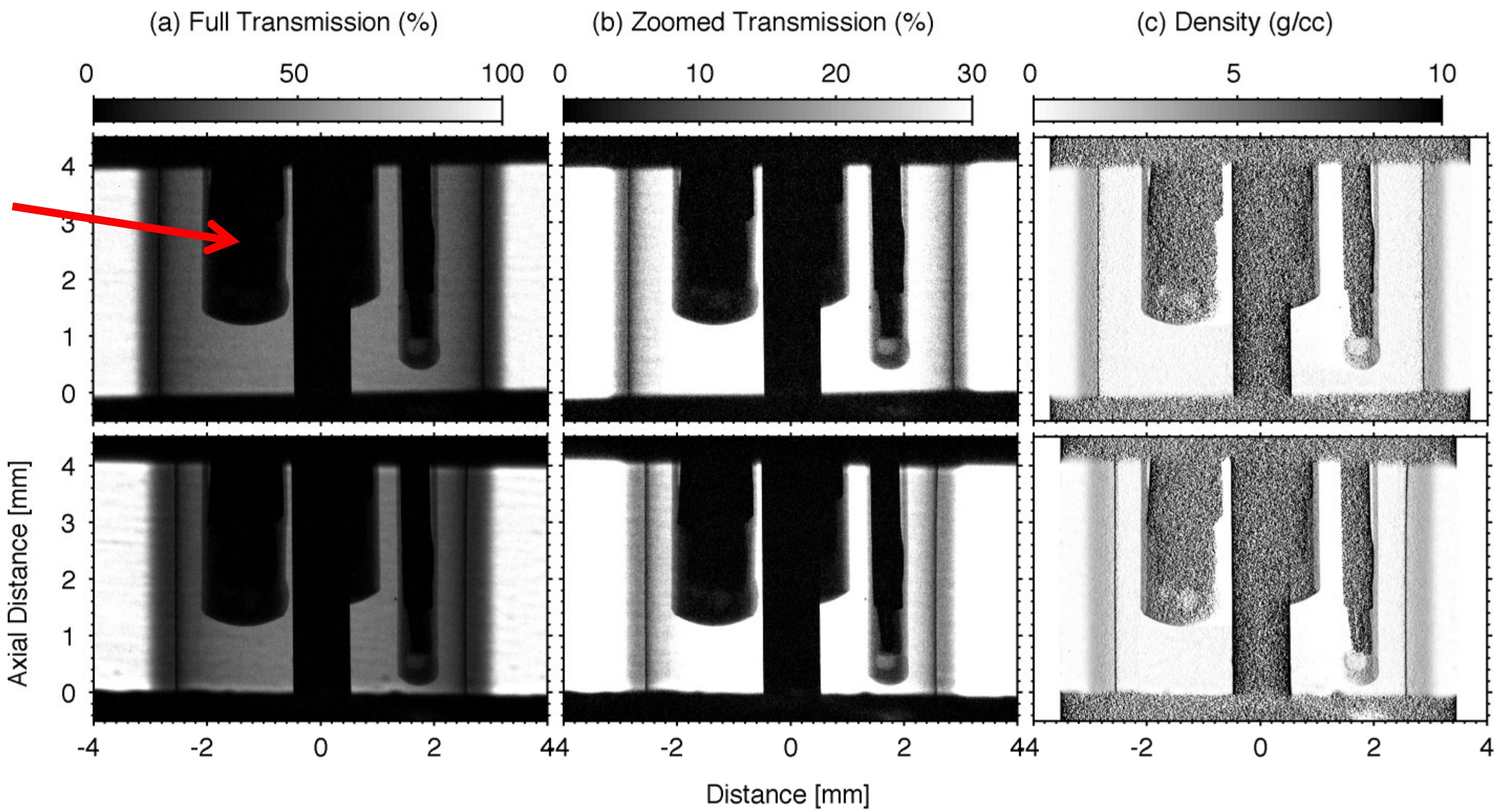




R. D. McBride *et al.*, invited manuscript in preparation for Phys. Plasmas (2013).

Micro-Bdot experiments:

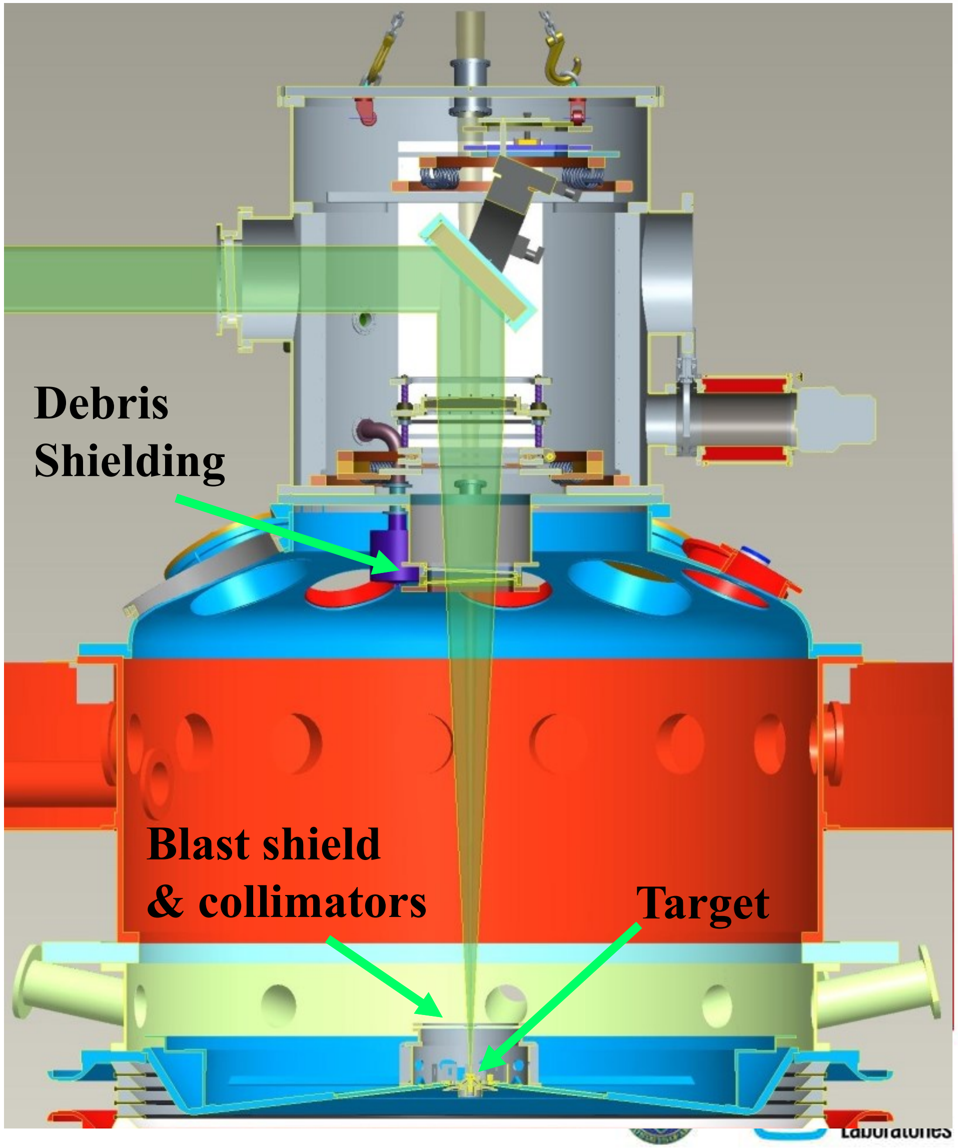
μBdot probes inside liner

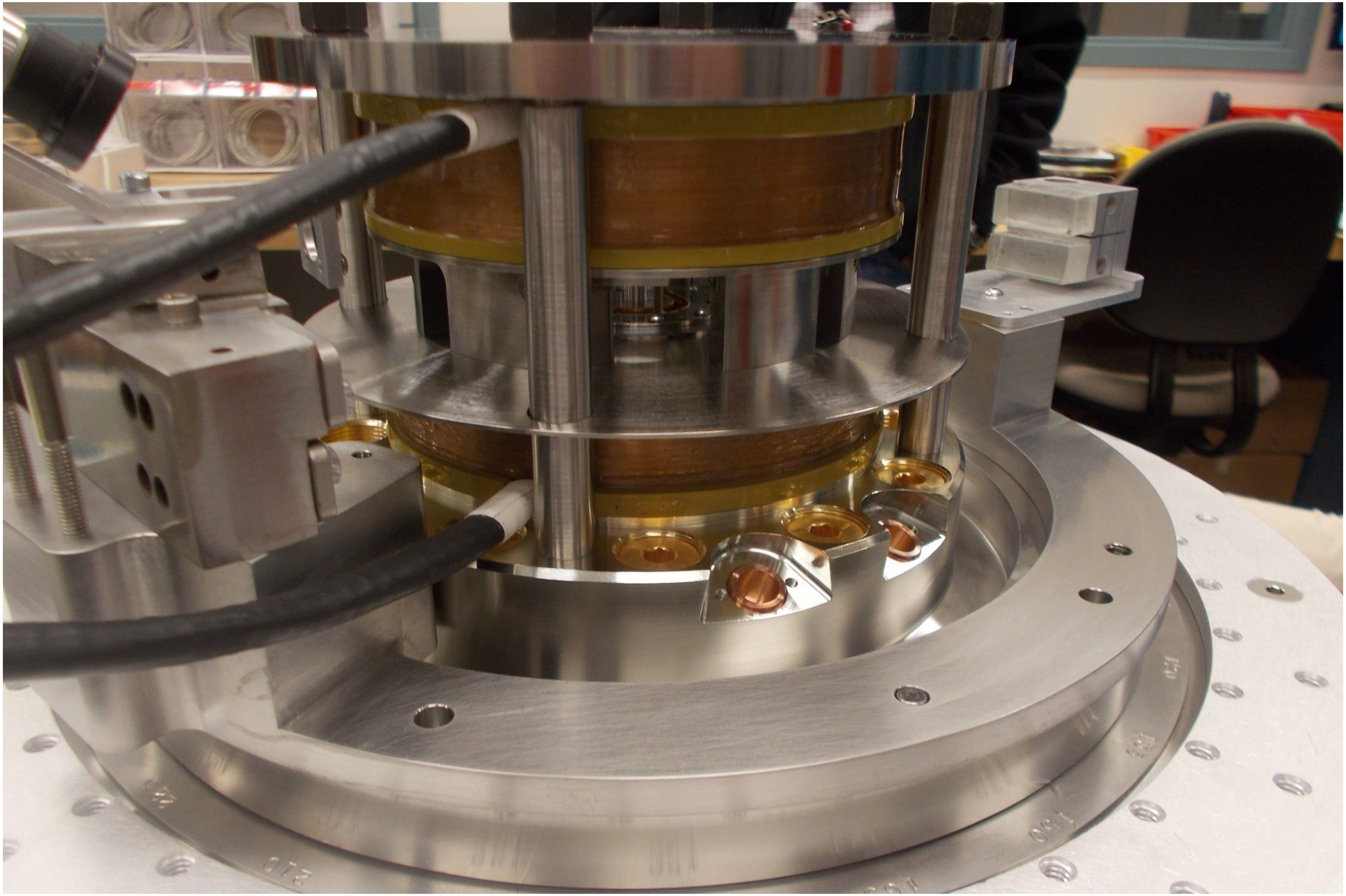


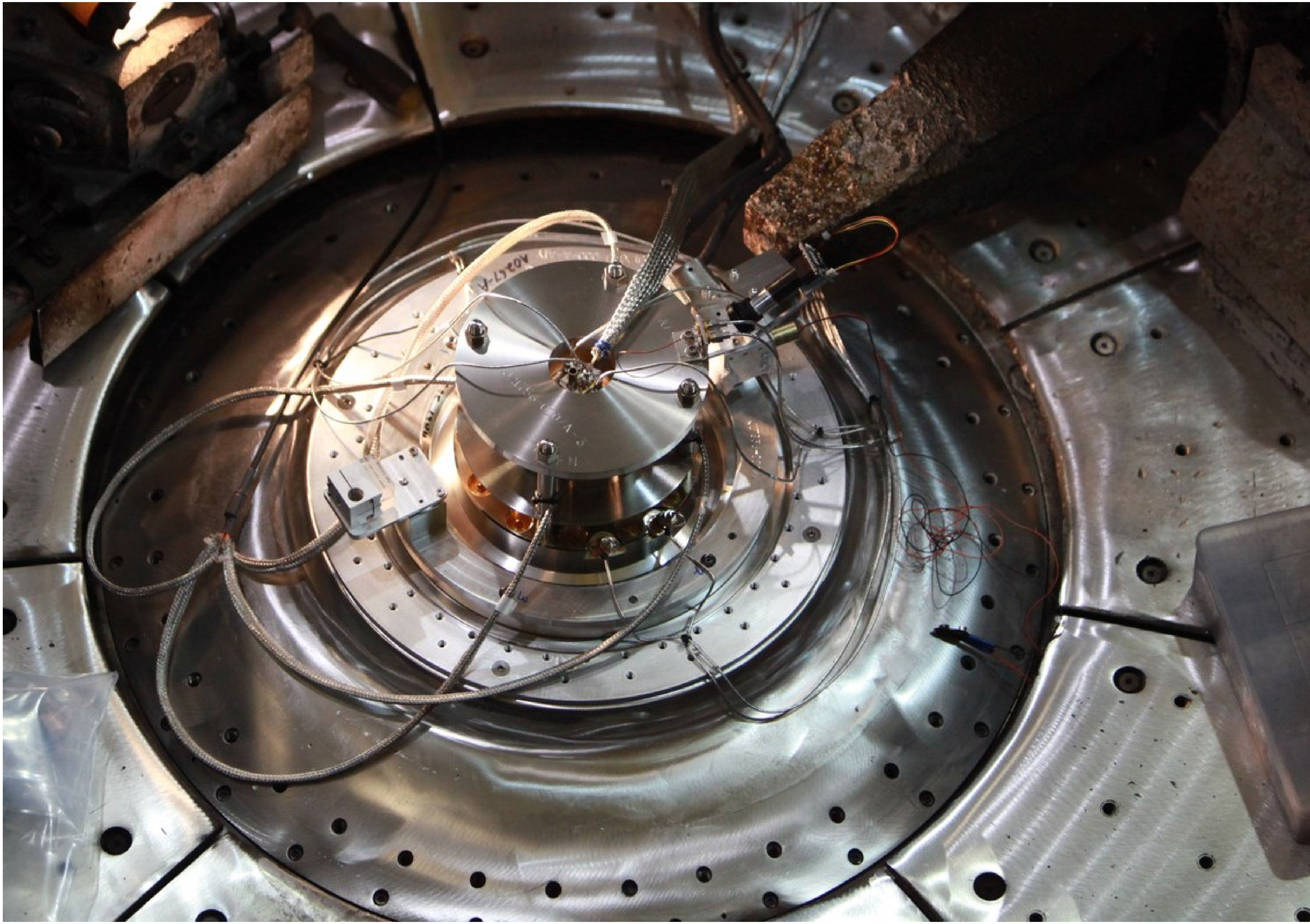
R. D. McBride *et al.*, invited manuscript in preparation for Phys. Plasmas (2013).

Laser preheating will be integrated into Z experiments in July 2013—Relevant physics will be assessed

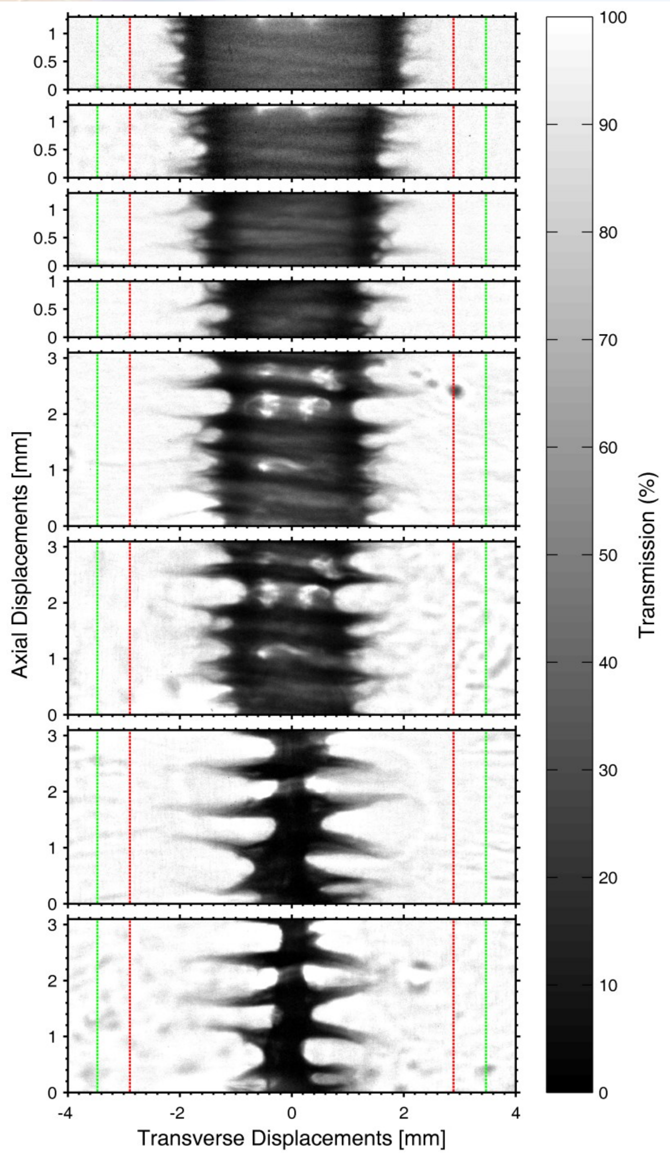
- Beam is delivered off-axis for radiography application
- Both MagLIF and X-ray Thomson Scattering (XRTS) require laser light to be delivered on or very close to the axis
- XRTS work resulted in engineering solutions to debris concerns
- Filling out booster amps increases energy to ~6 kJ

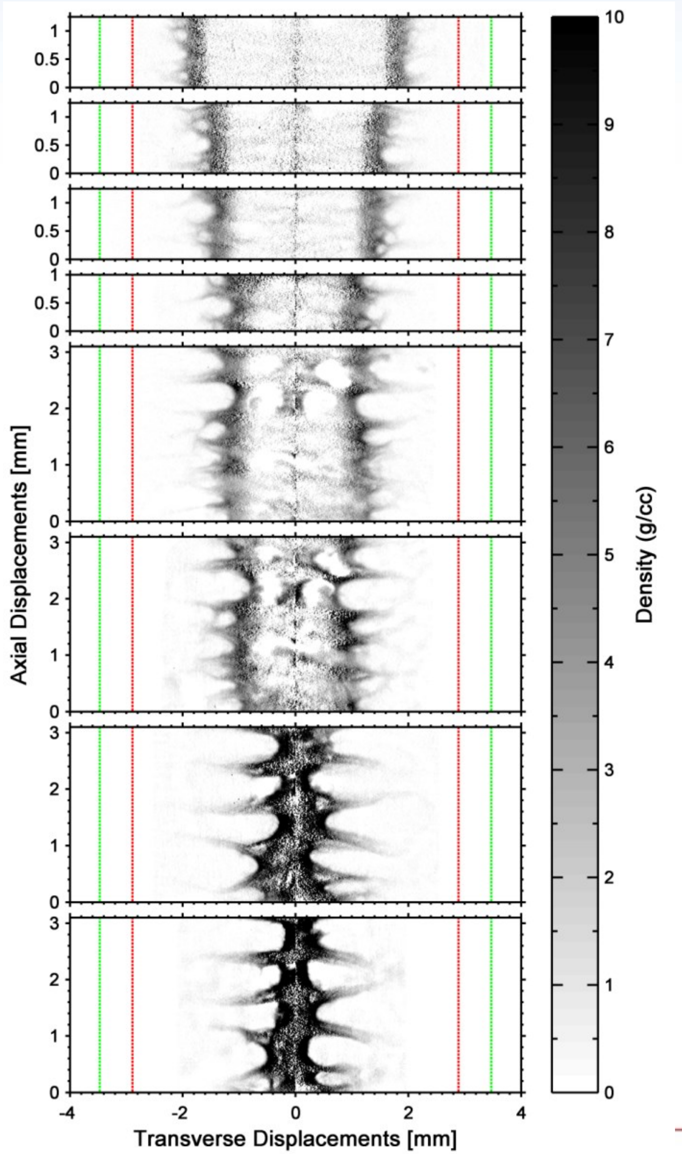






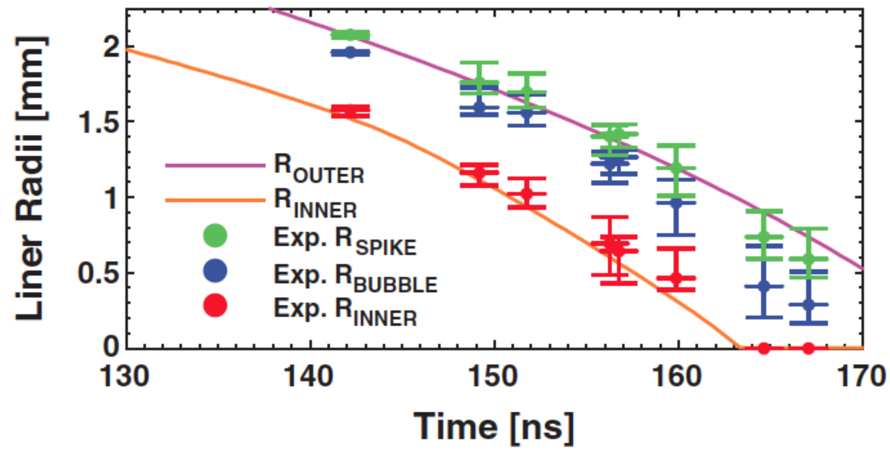
We can Abel invert the data line by line:



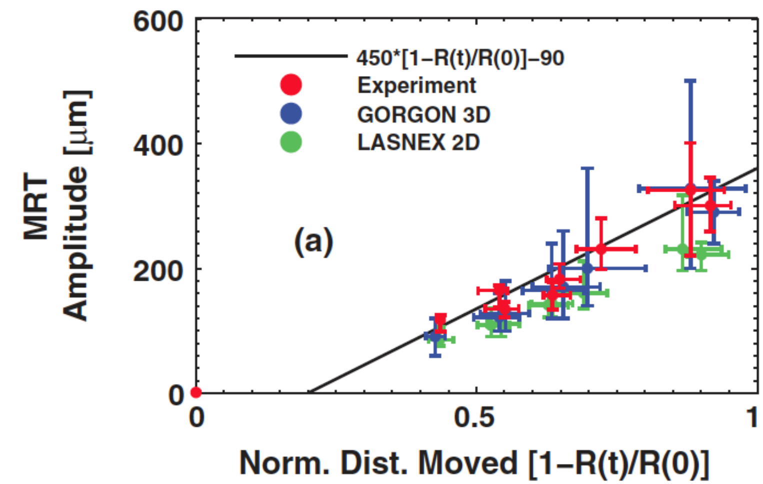


Sandia National Laboratories

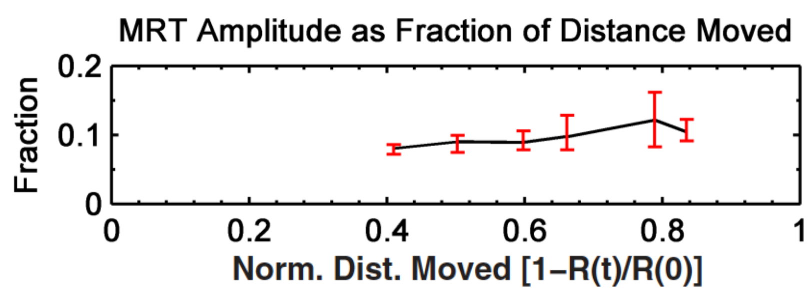
And compare implosion trajectories to 1D ALEGRA simulation:



Then define MRT amplitude as difference between bubble radius and spike radius



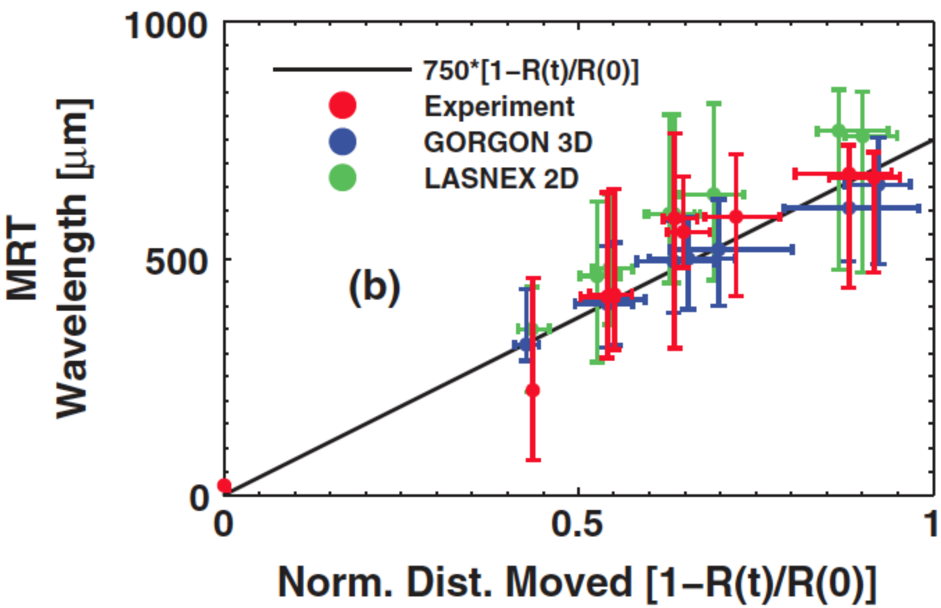
We find nearly linear growth with normalized distance moved

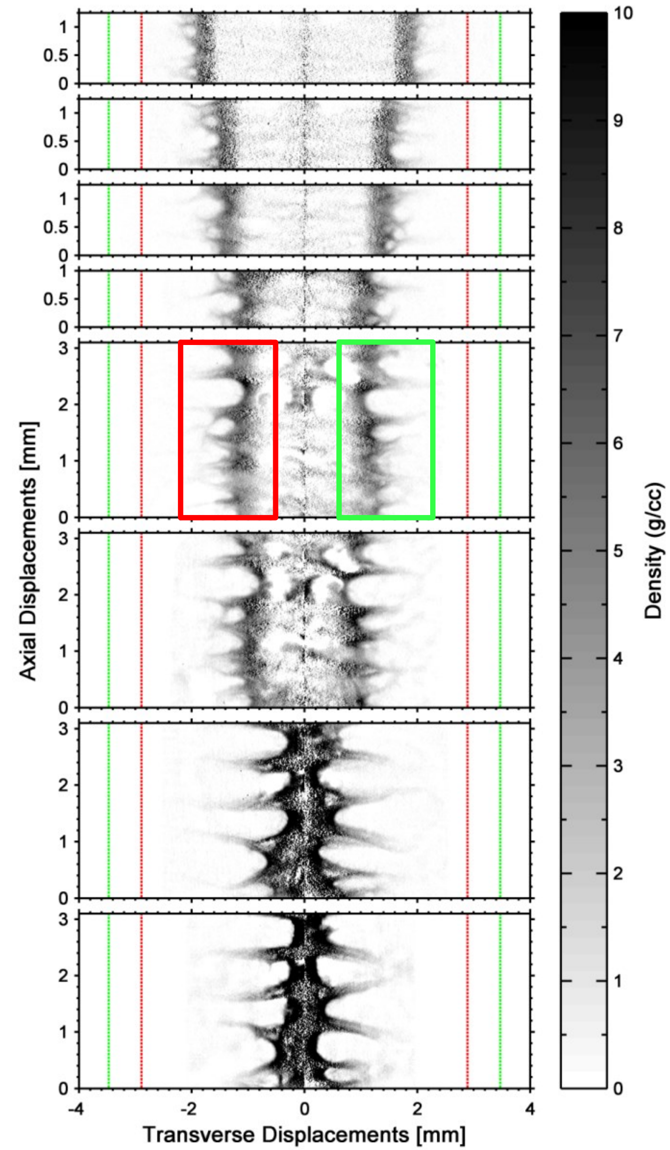


R. D. McBride, S. A. Slutz, C. A. Jennings *et al.*, Phys. Rev. Lett. 109, 135004 (2012).

Wavelength Growth from Abel Inverted data

Fourier Analysis:



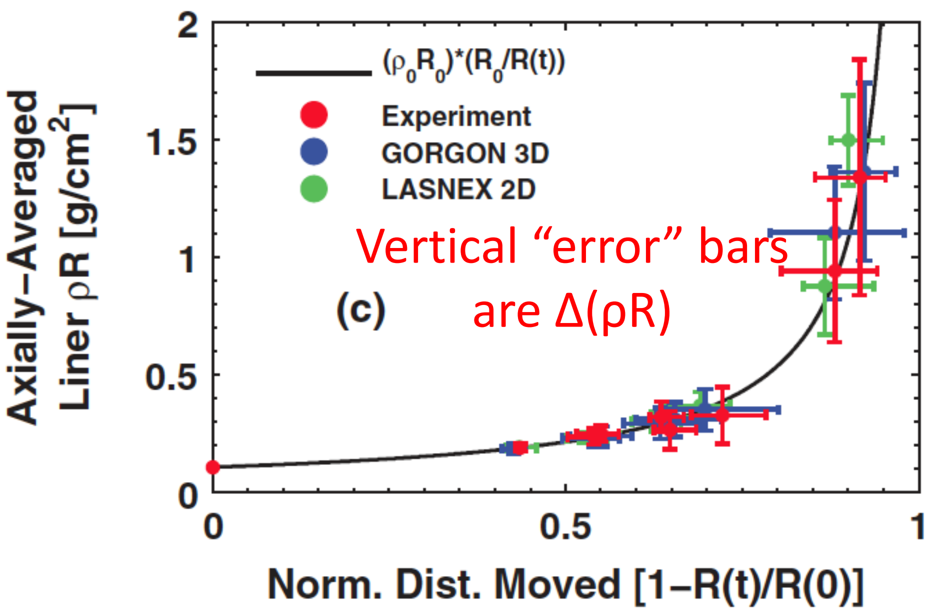


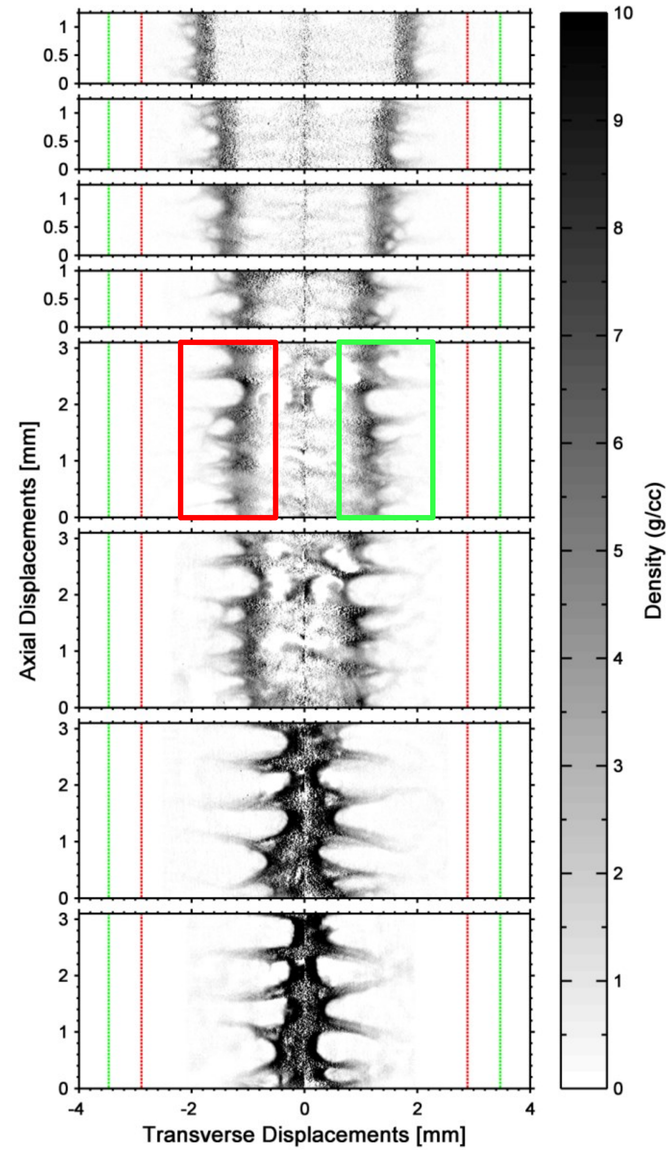
50% of the total fluctuation energy is in the wavelengths within the vertical “error” bars

R. D. McBride, S. A. Slutz, C. A. Jennings *et al.*, Phys. Rev. Lett. **109**, 135004 (2012).

Mean liner ρR and Δ(ρR)

From S. A. Slutz, et al., PoP (2010): $Q \sim (\rho R)^{1/2}$



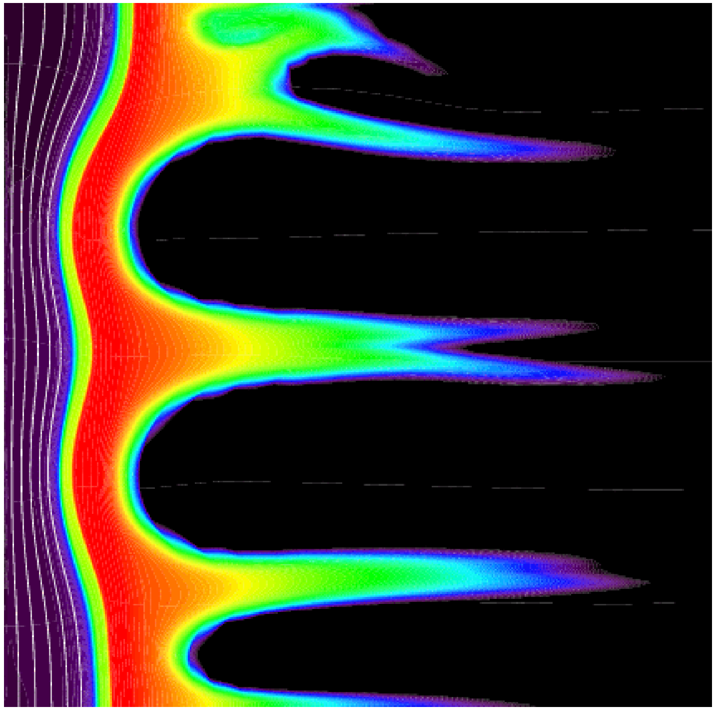


$\Delta(\rho R) < 30\% \rightarrow \Delta Q < 16\%$

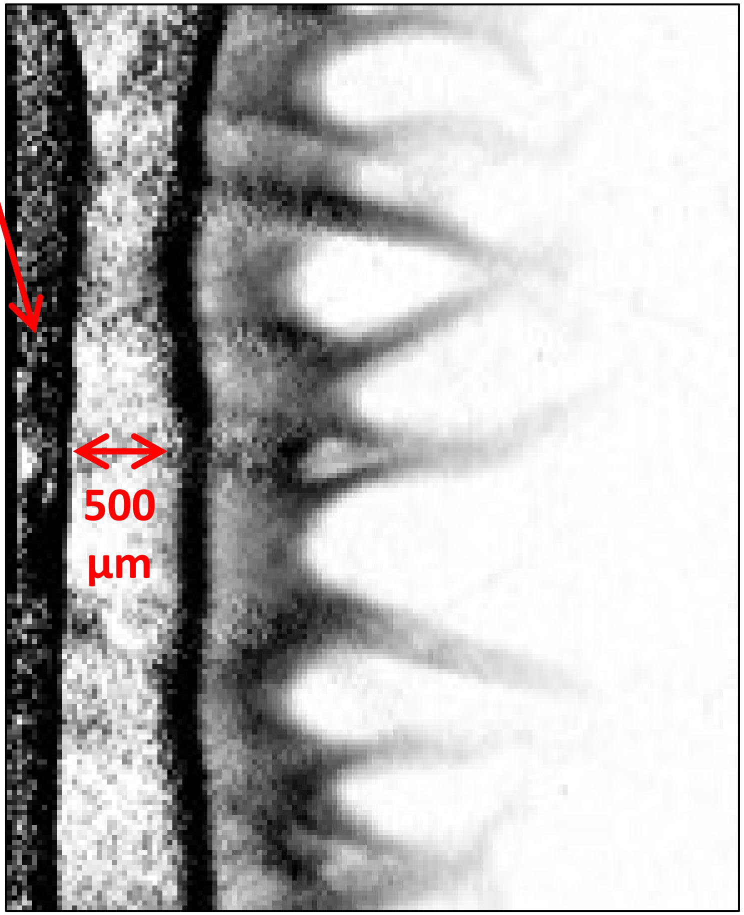
R. D. McBride, S. A. Slutz, C. A. Jennings *et al.*, Phys. Rev. Lett. **109**, 135004 (2012).

Radiographs at a convergence ratio of ~5 show remarkably good stability for inner liner surface

Note: MagLIF requires final compression to on-axis rod



LASNEX 2D from
S. A. Slutz, *et al.*, PoP (2010)



Experiment

R. D. McBride *et al.*, invited manuscript in preparation for Phys. Plasmas (2013).