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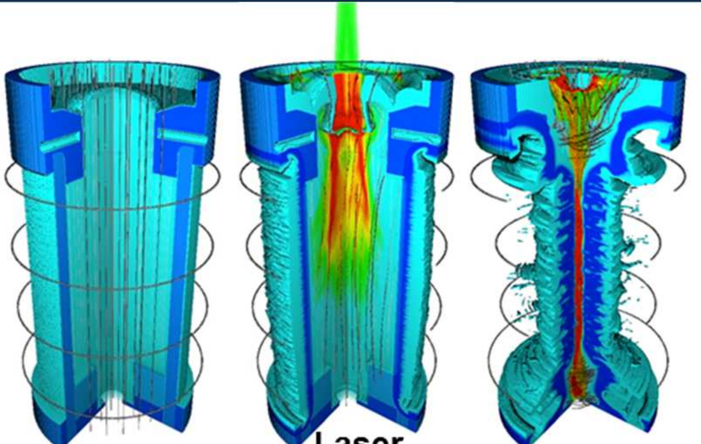

Shell morphology and kinetic energy in magnetic direct drive

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Addressing Common Challenges in ICF

Santa Fe, NM

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Overview

- Differences and commonalities in pusher physics between MDI's and traditional ICF
- Our current state of knowledge
- Focused physics investigations
- Important questions

There is significant overlap of pusher physics in magnetically driven implosions, but the differences are important

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Differences

- Adiabatic compression of fuel leads to a non-impulsive deceleration phase
- Much lower velocity (70-100 km/s), makes it difficult to assess residual kinetic energy
- Thick liner with low IFAR, potentially not all mass participating in confinement
- Drive pressure continues to increase w/ convergence (assuming good current coupling)

Similarities

- Liner areal density and ram pressure asymmetries must be minimized/controlled
- Liner kinetic energy must be efficiently converted to fuel internal energy

Overview

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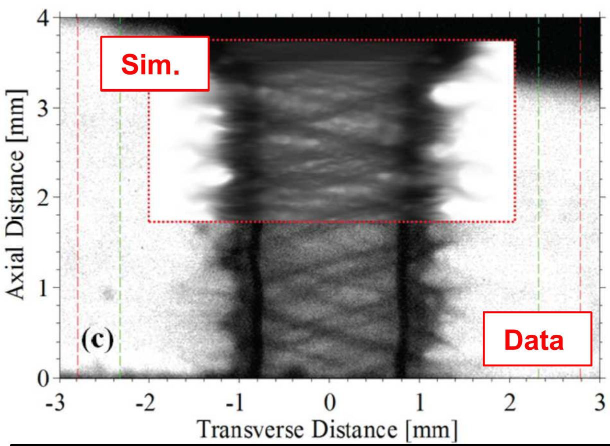
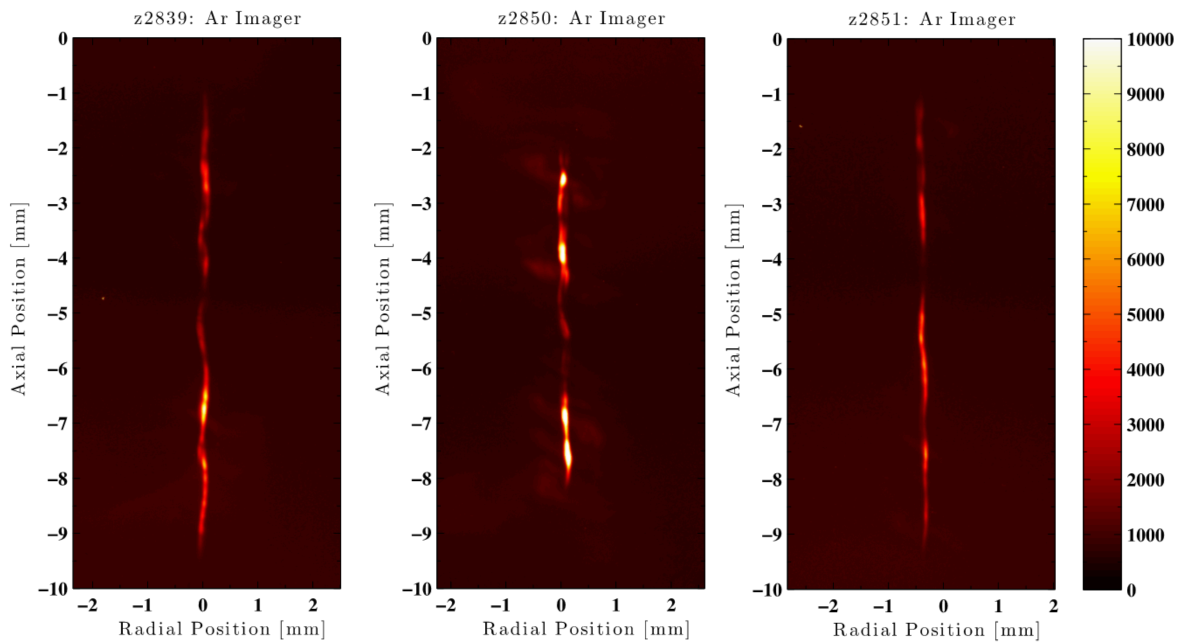
Existing data on the state and dynamics of the liner during stagnation in integrated experiments is limited

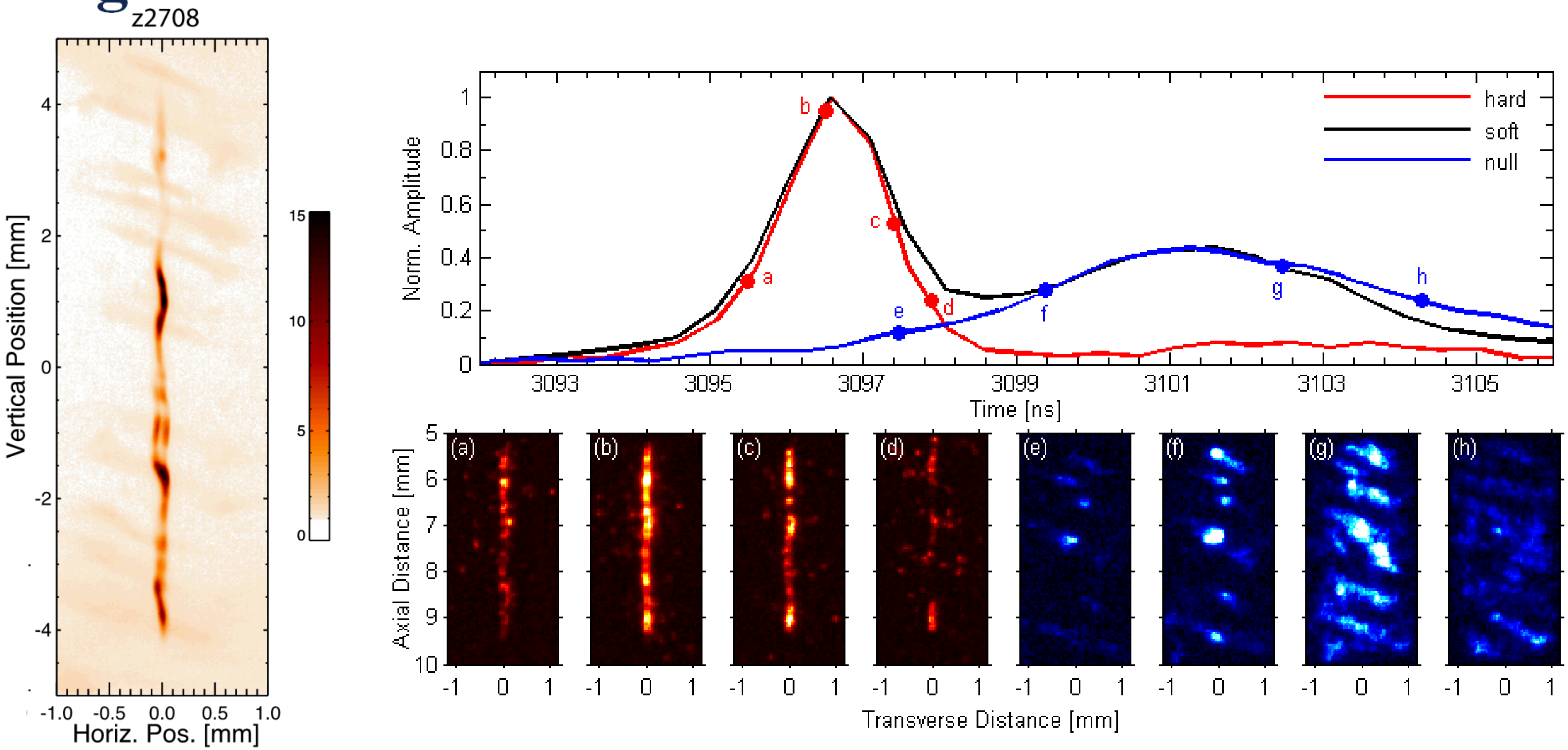


Radiograph from T. J. Awe *et al., Phys. Plasmas,* **21**, 056303 (2014) showing the modified MRT structure in flight along with synthetic radiograph from a GORGON calculation (inset).



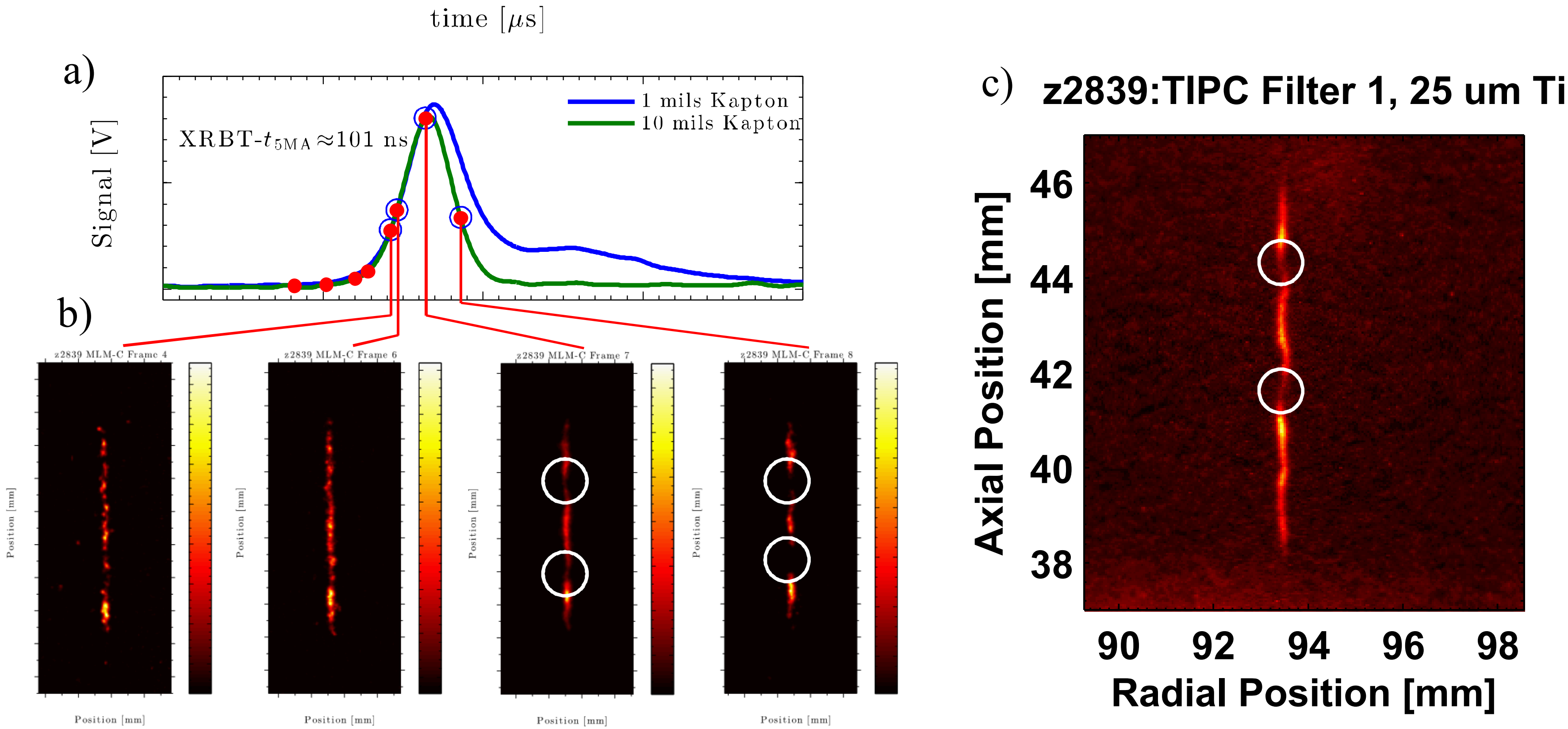
- In flight radiography reveals helical instability structure on the the liner
- Emission of stagnation column has helical structure

Emission from liner material at large radius shows that the helical structure persists through stagnation



- Helical striations in self-emission come from late time compression of outer liner material (~4-5 ns after stagnation)
- Not obviously connected to the helical structure of the column

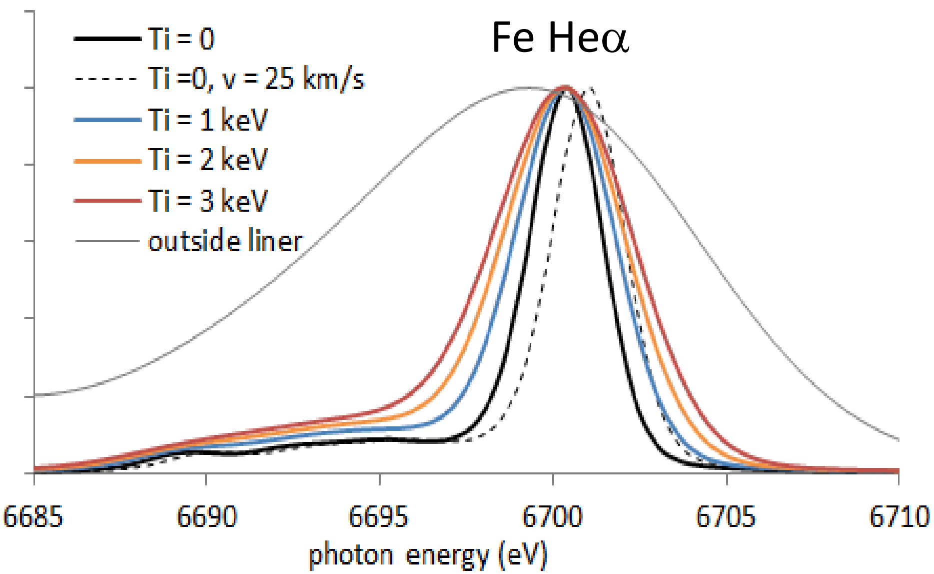
In some experiments we can see evolution of “breaks” in the emission column



- The gaps are consistent with those seen in higher energy, time integrated imaging
- Could be caused by locally high liner areal density or by gaps in hot fuel

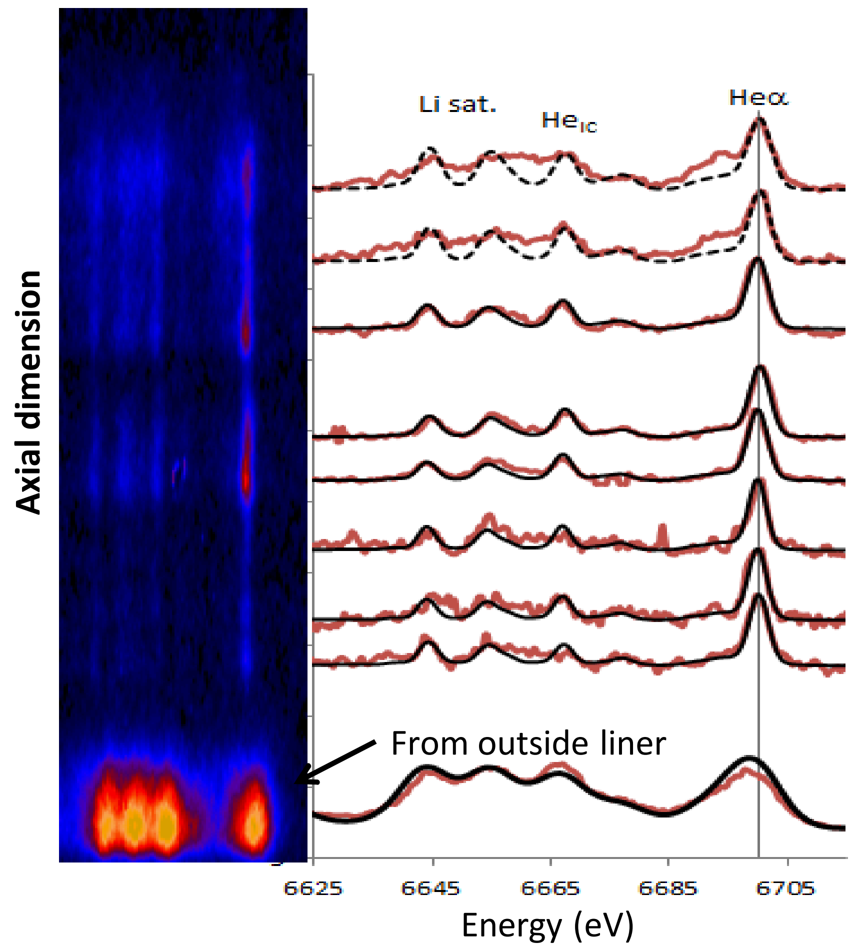
Residual motion > ~15 km/s can be detected with high-resolution spectroscopy

XRS3 instrument with $E/\Delta E \sim 3500$ detects K-shell emission from Fe impurities in Be liner from plasma with $T_e > 1$ keV



Line ratios, shifts, and widths provide information on source T_e, n_e, T_{ion}, v_{bulk}, & r. Line widths indicating $T_{ion} > T_e$ might reveal turbulent residual velocities, but have not yet been observed.

Assuming no crystal deformation, modest line shifts indicate $v_{bulk} < \sim 15$ km/s



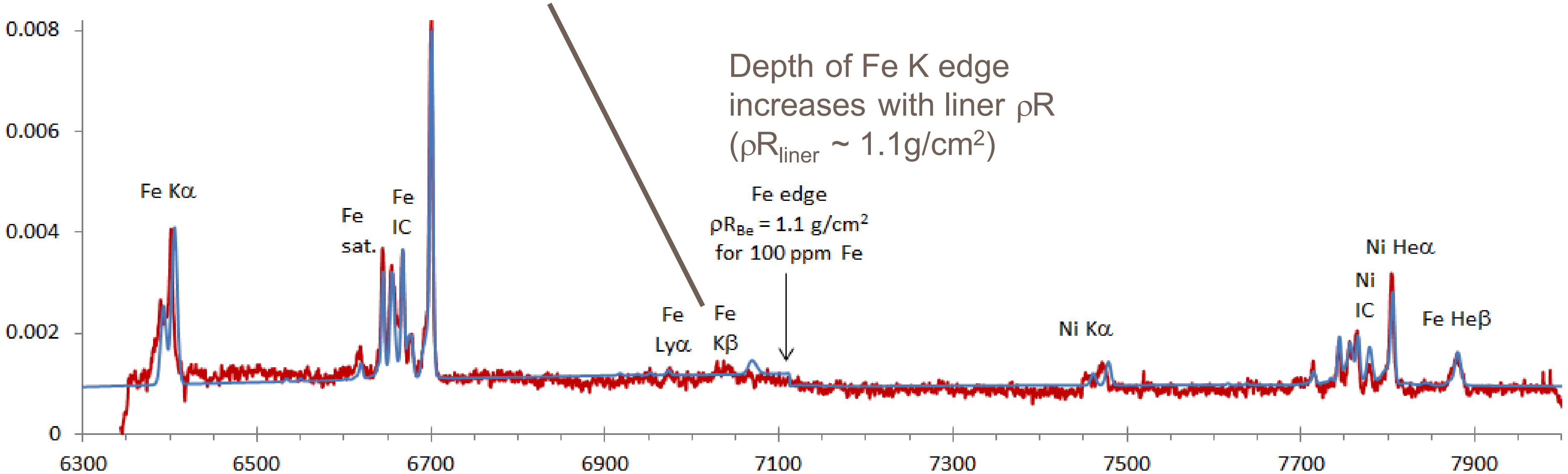
*E.C. Harding et al., Rev. Sci. Inst. 86, 043504 (2015)

Liner conditions are determined in multiple ways

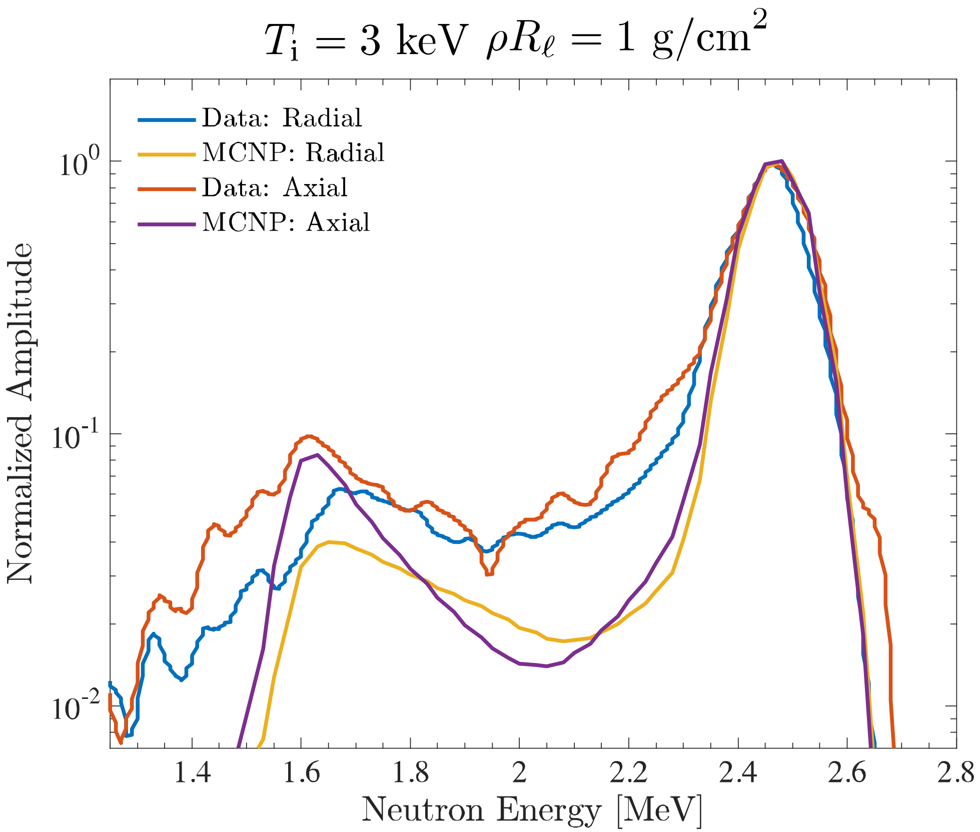
- Late-time images of emission from outside liner constrains final radius to ~0.8 mm; *assuming no mass loss* this indicates liner ρR ~ 1 g/cm^2 and liner ρ ~ 20 g/cm^3
- Differentially filtered diodes show similar peak powers through 10 and 30 mils kapton, indicating significant liner absorption (for Te = 3 keV, liner ρR ~ 1 g/cm^2)
- Differentially filtered hard-x-ray pinhole images indicate ρR = 0.9 g/cm^2
- Absorption edge depths from Fe impurities in cold Be indicate liner ρR = 0.9 g/cm^2
- Shape of absorption edge indicates T ~ 20 eV
- Plasma polarization shift of Fe Kβ fluorescence lines indicates liner ρ ~ 19 g/cm^3

While ionization of 3d electrons can cause small redshifts in Kα, only enhanced screening (plasma polarization) can cause redshifts in Kβ

Depth of Fe K edge increases with liner ρR (ρR_{liner} ~ 1.1g/cm^2)



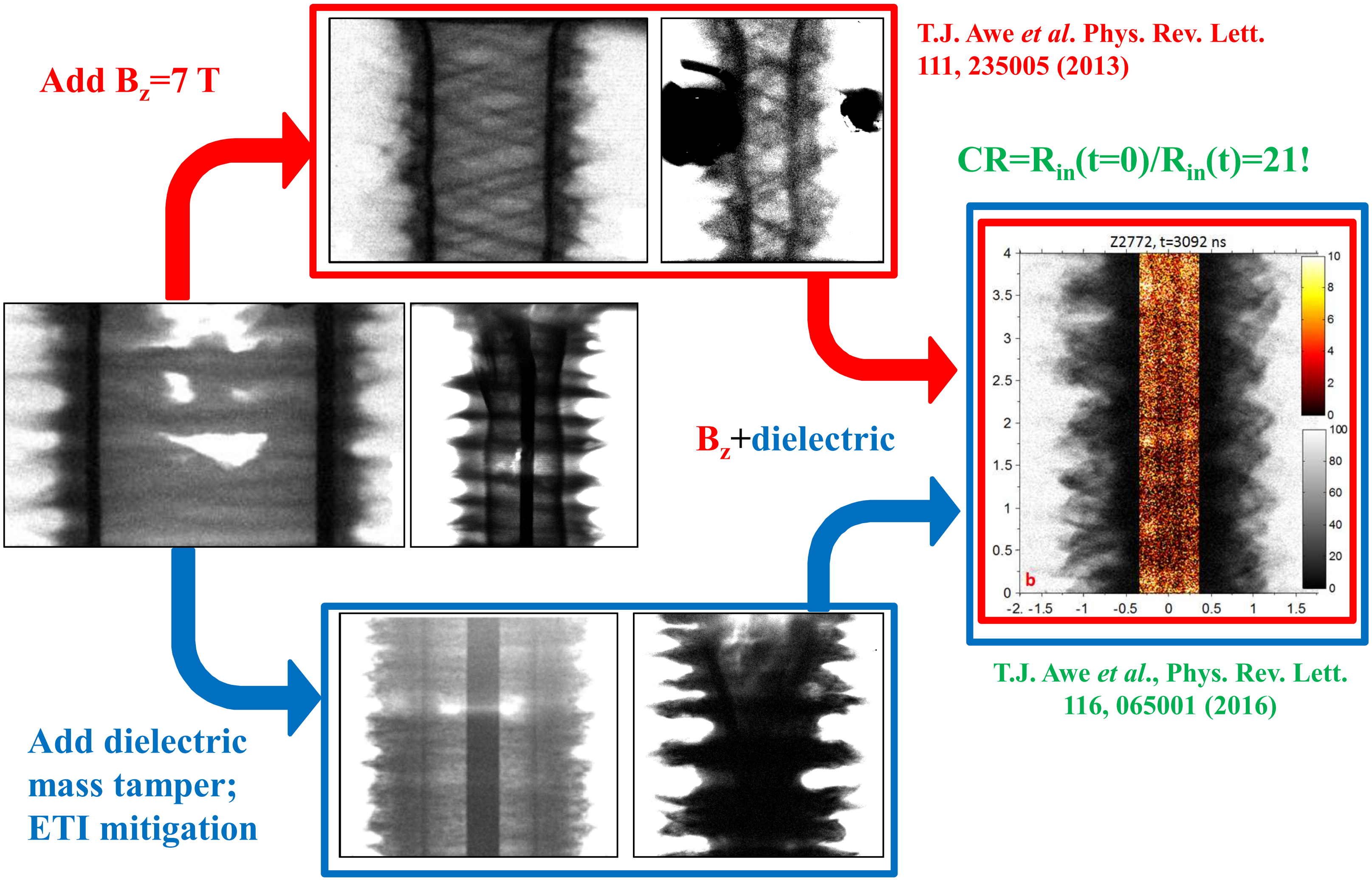
Clear indication of Be downscatter seen in nTOF data



*Data and calculations provided by K.D. Hahn

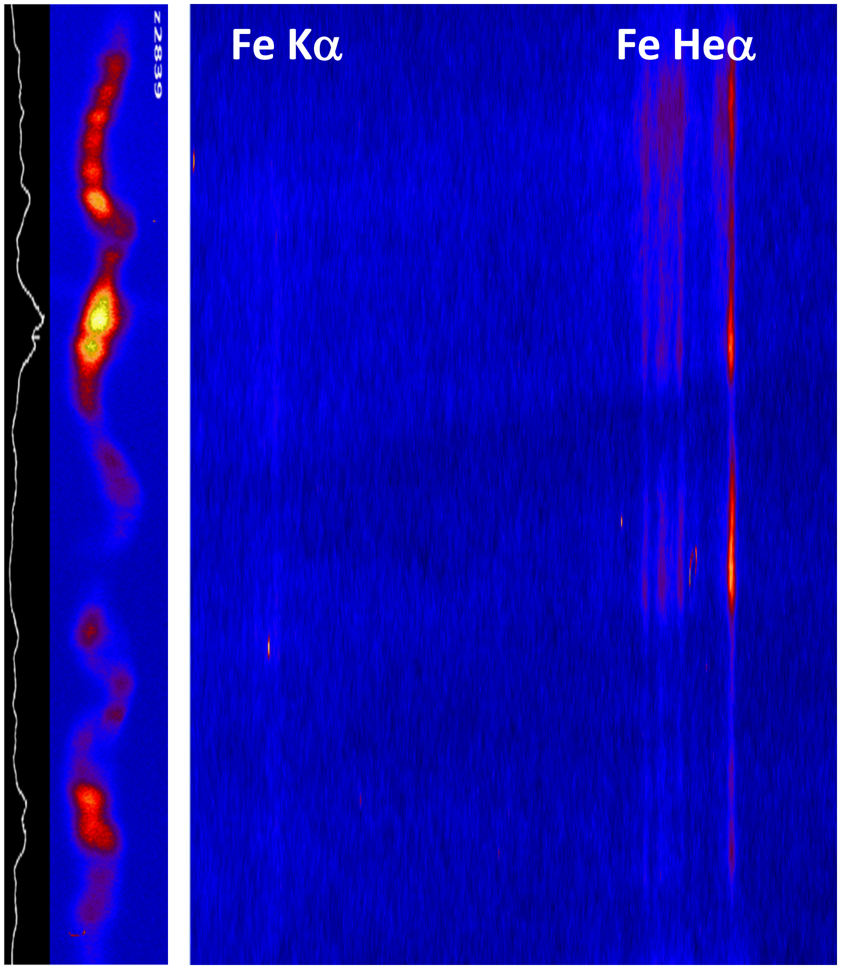
- Data is consistent with ~1 g/cm^2 Be at stagnation
- In the same range as inferred via x-ray data
- Significant scatter background makes quantitative determination challenging
  - Work in progress to better characterize detector response and scattering environment
  - We need the communities help to resolve this issue

Combining axial pre-magnetization with a dielectric tamper results in enhanced in-flight liner stability

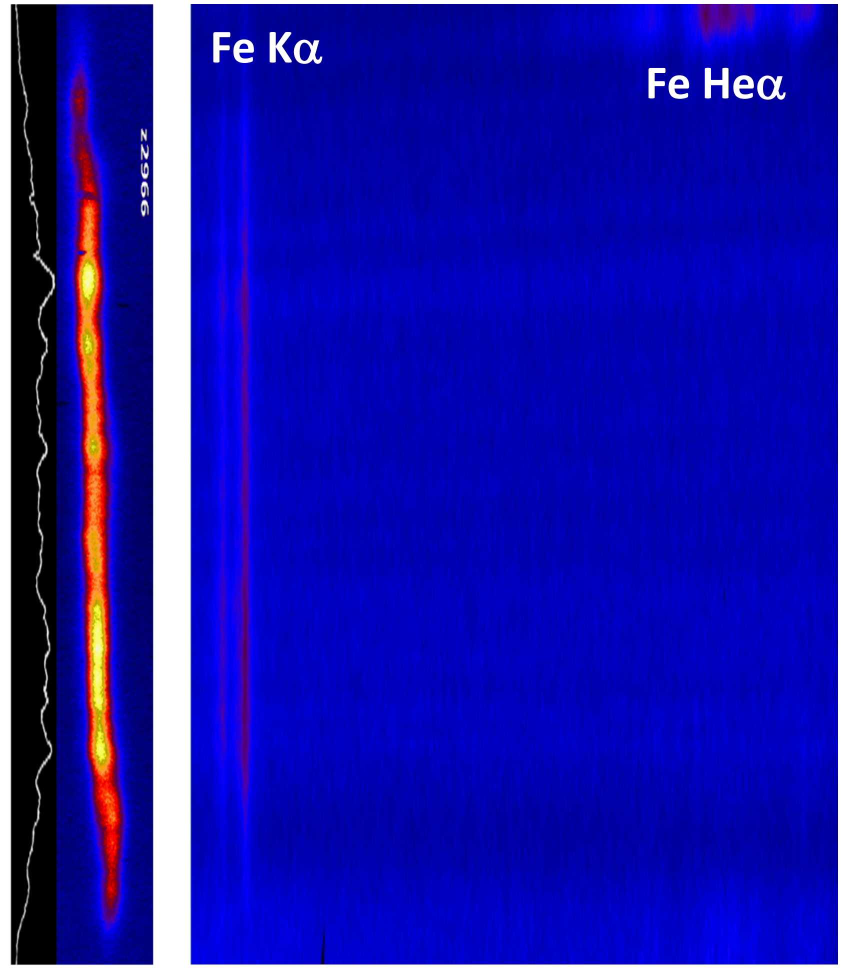


Employing coated liners in a recent integrated experiment has demonstrated improved symmetry and reduced mix

Uncoated: significant axial variation and Fe impurity emission → ~1% late-time Be



Coated: improved axial uniformity; Fe impurity emission → <0.1% late-time Be



Overview

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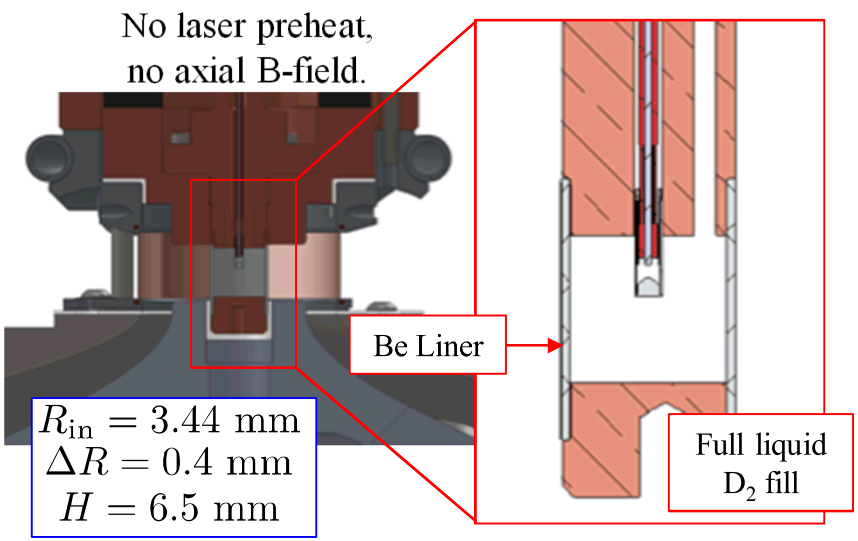
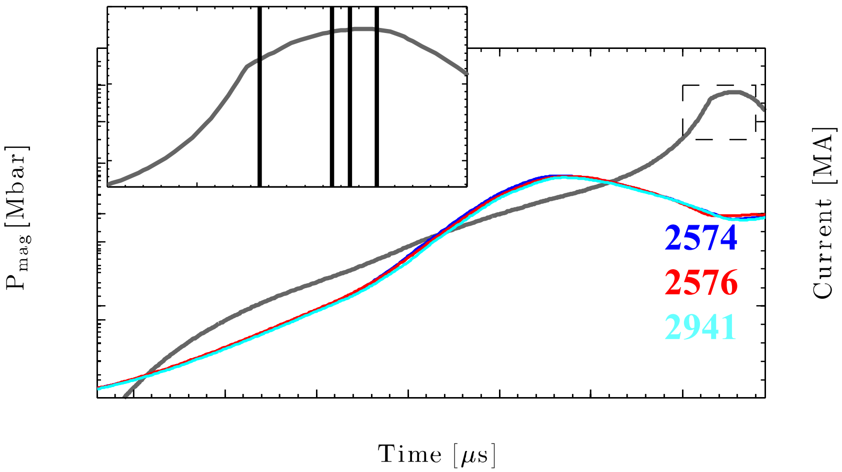
Slow, cold liner implosions are useful for directly probing confinement of high pressure fuel (~100 Mbar) in an ideal scenario





- Radiography is used to measure the
  - CR at stagnation
  - Confinement time
  - Liner areal density
  - Uniformity of stagnation column
- Low current (12 MA), long pulse allows
  - stagnation at large radius (400-500 μm)
  - Good resolution across stagnation column
  - Long dwell time to minimize motional blurring and jitter issues
- Atwood number is low at stagnation (~0.1), minimizing mix and deceleration phase instability growth

$$R_{\mathrm{stag}} = 450\ \mu\mathrm{m} \quad \Theta = k_B T / E_{\mathrm{F}} \approx 0.05$$
$$\rho_D = 10\ \mathrm{g/cm^3} \quad \Gamma = z e^2 / a k_B T \approx 6$$

We were able to capture a radiographic sequence of the entire stagnation phase in a magnetically driven liner implosion

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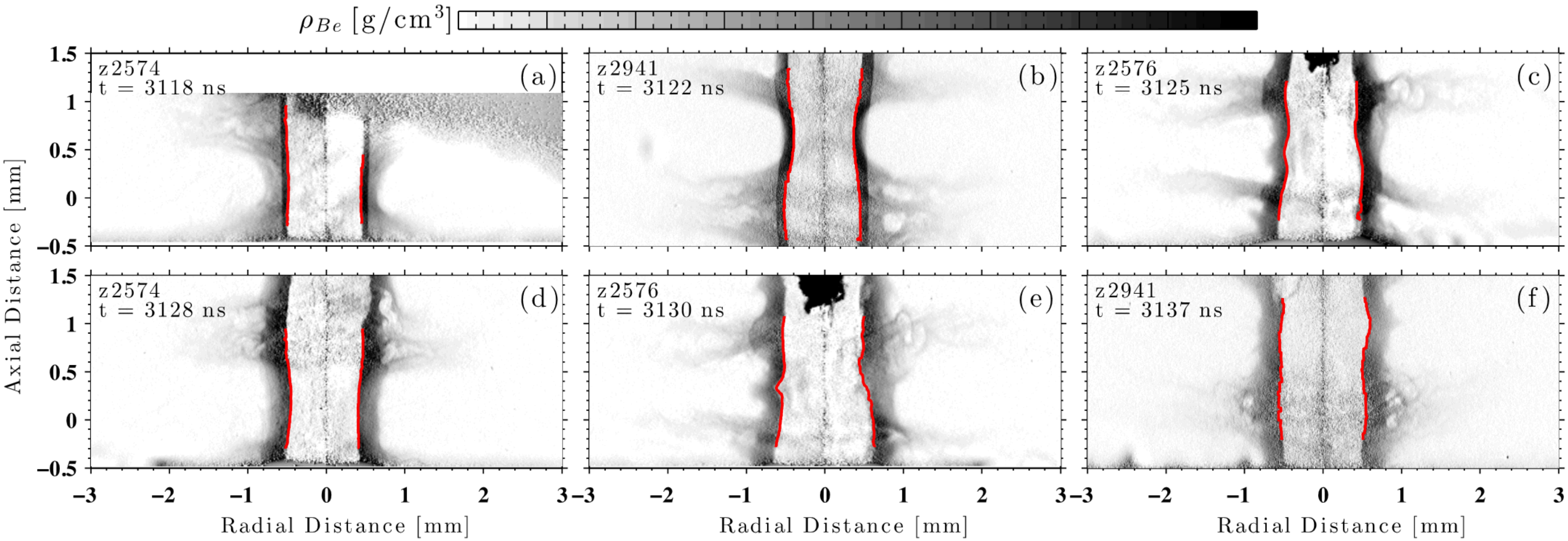
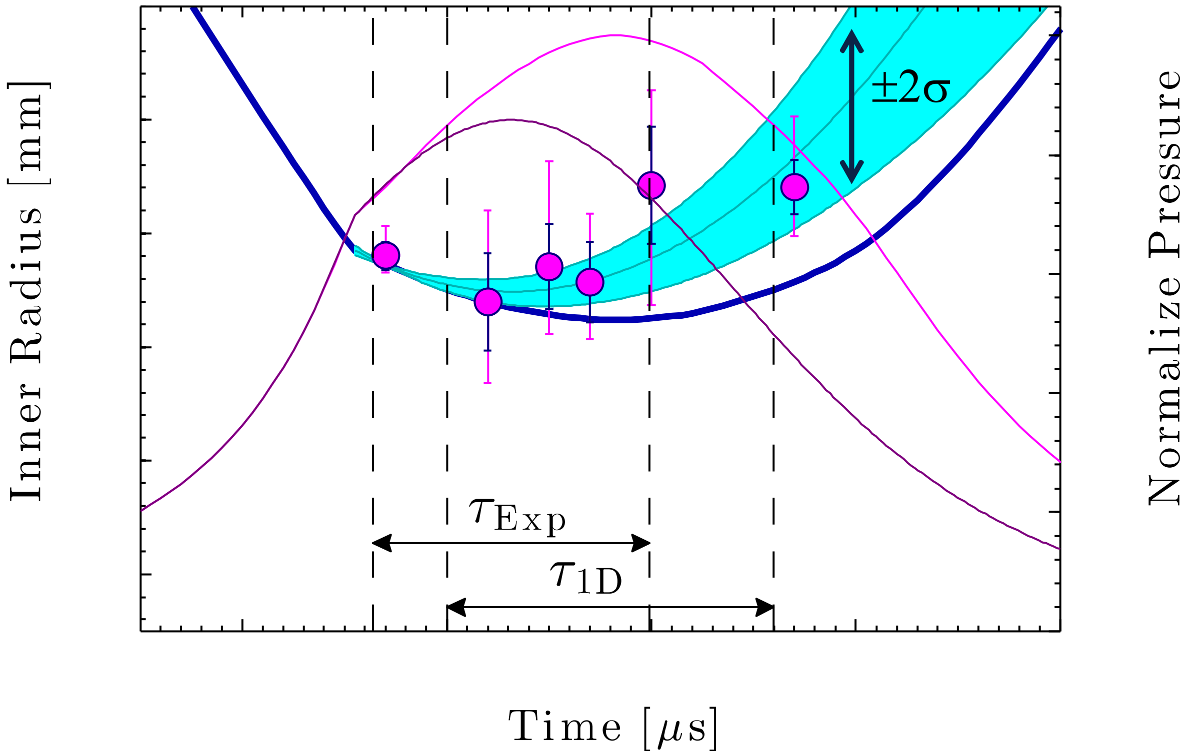


$$\frac{R_o}{R_{\min}} = 7.7 \qquad \langle \rho_D \rangle_{\text{final}} = 10\ \text{g/cm}^3$$

The confinement time and stagnation pressure are degraded compared to 1D simulation



Blue interval is the 2σ interval fitting the data, including a ± 1 ns uncertainty in radiograph timing

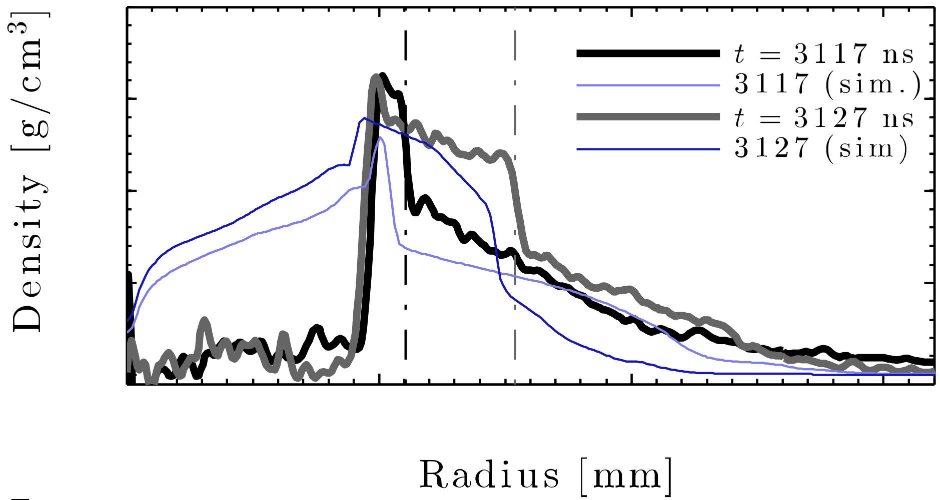
$$P_{\mathrm{hs}} \propto \mathcal{C}R^{2\gamma}$$

- Assume $\gamma=4/3$
- Confinement metric: $P \geq 0.85 * P_{max}$
- τ_{1D} = 16 ns
- τ_{Exp} =13.5±1.5 ns
- 17% reduction in confinement time and 14% reduction in Pressure
- Gives ~25% reduction in Pτ

$$\tau = f_{\mathrm{T}} R / C_{\mathrm{s}}$$

$$f_{\mathrm{T}}^{1\mathrm{D}} = 1.45 \quad f_{\mathrm{T}}^{\mathrm{Exp}} = 1.2$$

Do our codes accurately reproduce the liner density profile at stagnation?

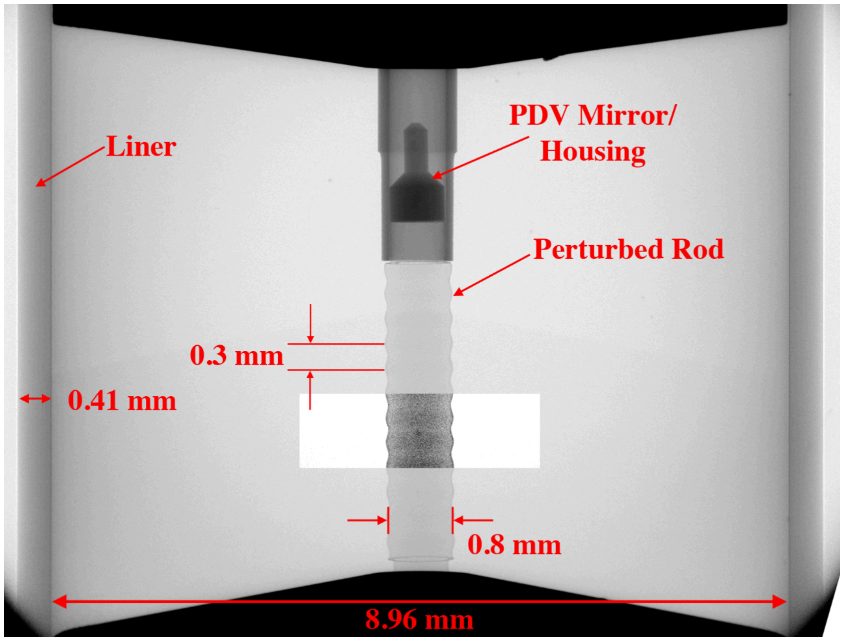


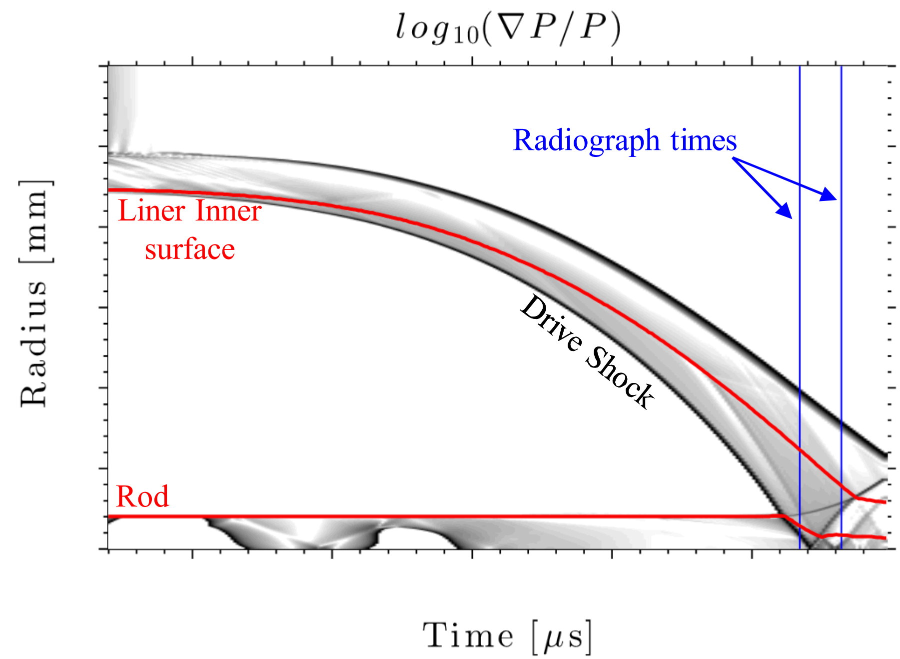
What is the dominant cause of degraded confinement?

- 1D Physics (e.g. EOS, ram pressure profile)
- Drive physics (current distribution at late time, current losses at late time)
- 3D physics not captured in current calculations

- Even though Alegra matches the 1D trajectory very well before disassembly, the radial density profiles don't match
- Is this significant?
  - May mean ram pressure profile is different, can degrade confinement, cause shock to traverse liner faster, etc.
  - May mean distribution of current is different than expected

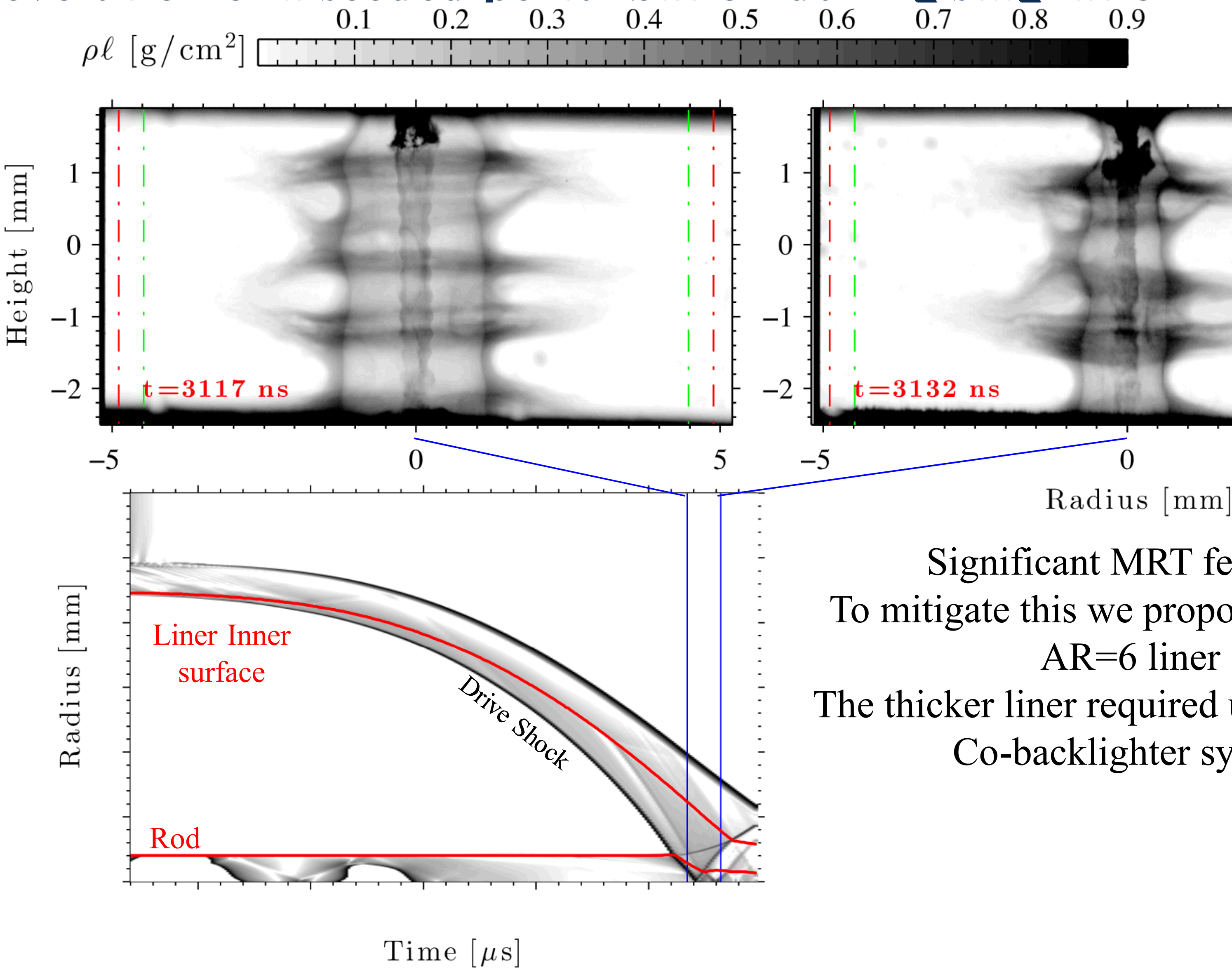
Convergent re-shock experiments are shedding light on the non-ideal nature of stagnation instability growth





- A Be rod with a pre-imposed sinusoidal perturbation is placed on axis
- The target is filled with liquid D2
- The liner launches a shock in the D2 which grows and strikes the rod/fuel interface
- Interface is unstable to RM and RT
- After reflection, shock (now ~300 Mbar) crosses the interface again

Two excellent radiographs have been obtained showing the evolution of a seeded perturbation during stagnation



Significant MRT feedthru

To mitigate this we proposed using an AR=6 liner

The thicker liner required using the new Co-backlighter system

Fourier Analysis shows growth of smaller wavelength modes

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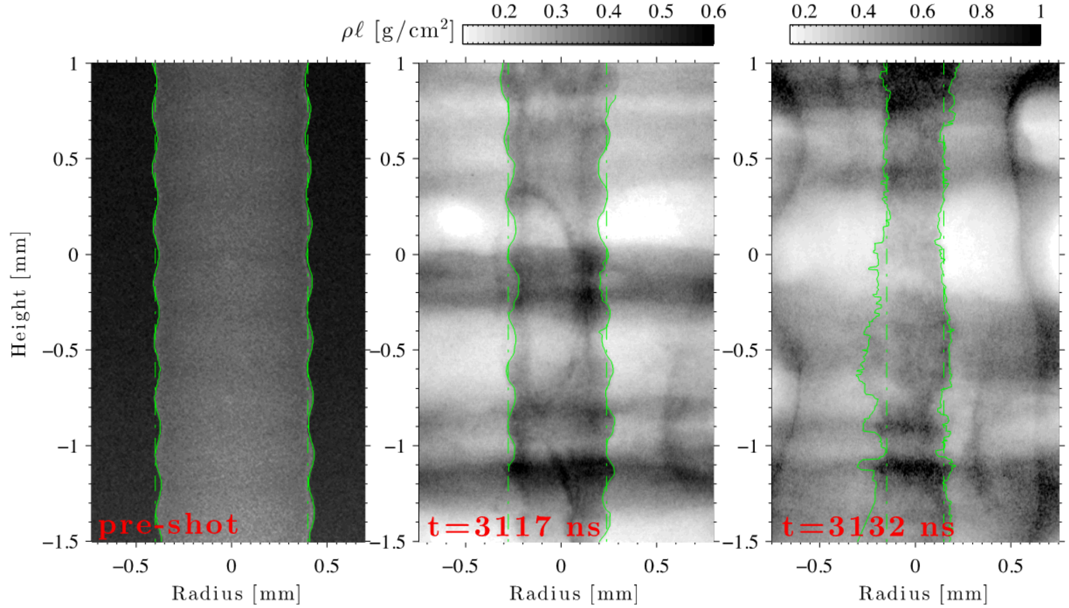
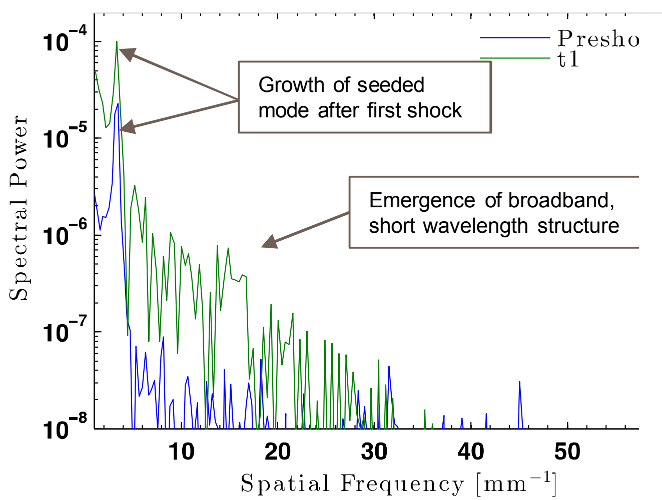
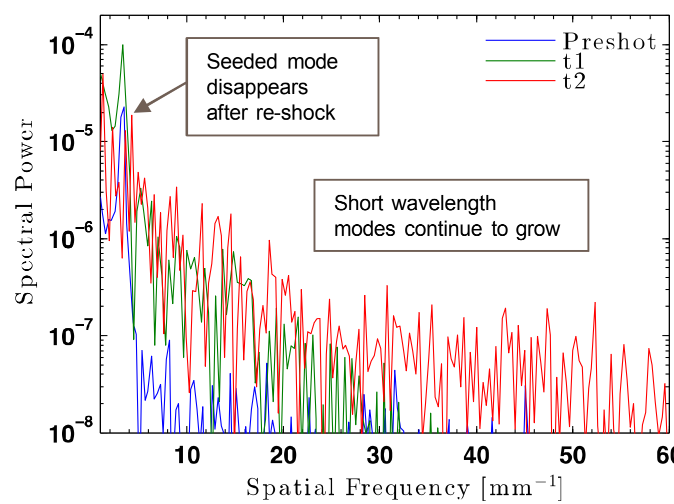
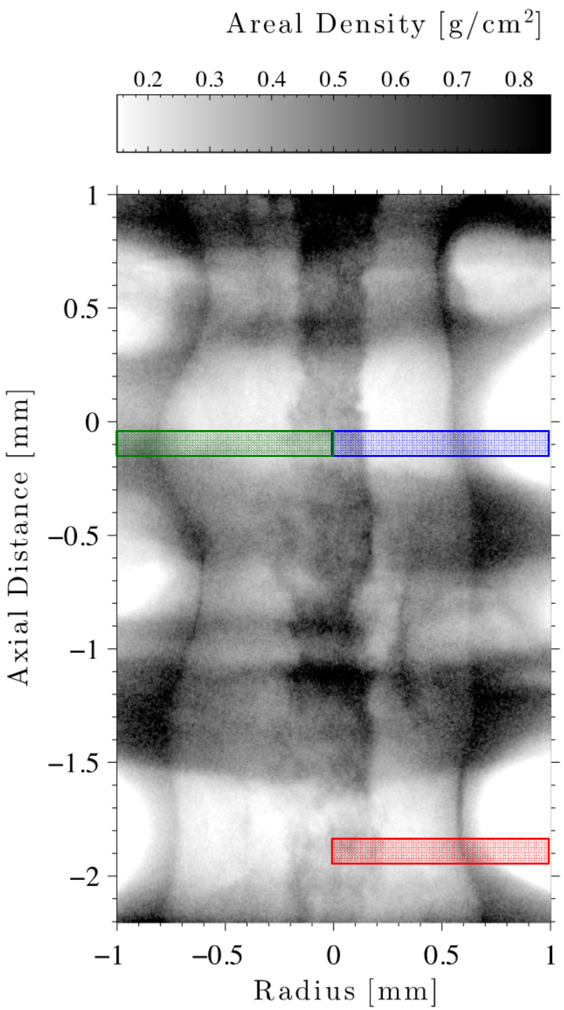


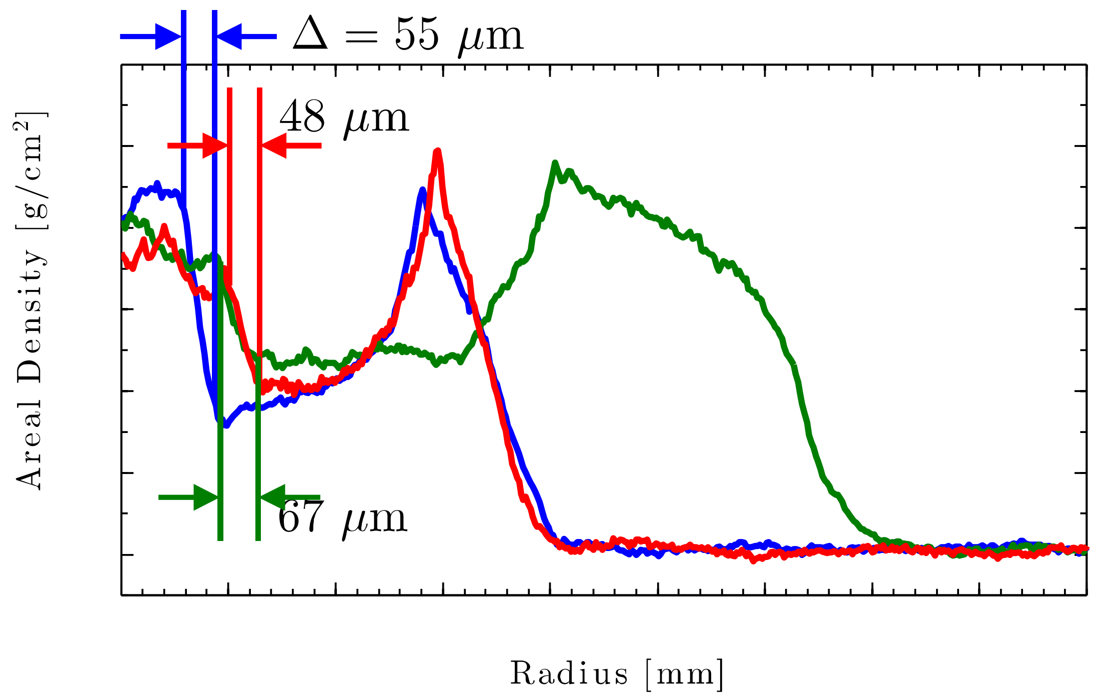
- Initial mode grows after 1st shock
- Unseeded, small scale perturbation appear
- After 2nd shock, initial mode is erased (RM phase inversion?)
- Small scale, highly 3D structures dominate





Preliminary attempts to determine a "mix width" are encouraging





- The deuterium is transparent
- The width of the transition from the Be rod to the region that is attenuated only by the liner is denoted as the "mix" width (~10-90% width)
- Abel inversions are noisy, it is best to attempt this analysis with the raw data
- More sophisticated analysis will attempt to "remove" the liner attenuation using fit to analytic profile

Remaining questions are significant

- How does the helical MRT mode inflight couple to the helical morphology of the fuel at stagnation
  - How does this evolve dynamically? Need developments in theory and experiment
  - What significance does this have in terms of integrated performance metrics
- How symmetric is the liner ram pressure?
  - We need to measure the axially resolved liner areal density
    - More sensitive x-ray spectrometer
    - 1D space resolved nTOF?
  - Can down-scattered neutron imaging help us or will it be too complicated to interpret?
  - The evolution of azimuthal asymmetries is a major unknown
- How severely are the observed non-uniformities impacting performance?
- How can we leverage the "focused" experiments to help our understanding of the integrated experiments?
- Can we make the focused experiments even more 1D to help elucidate the detailed physics related to late time drive, ram pressure profiles, EOS, etc.