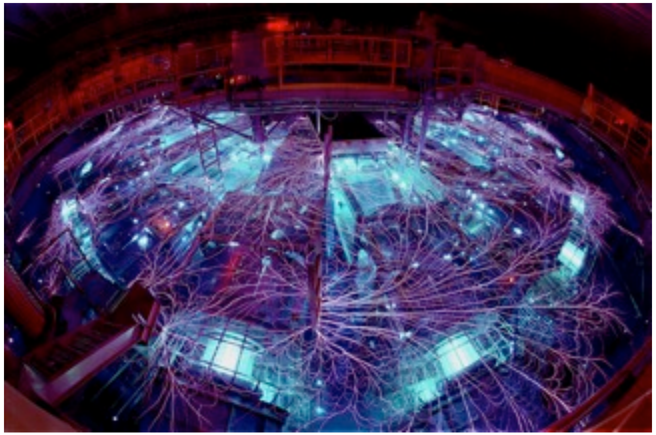
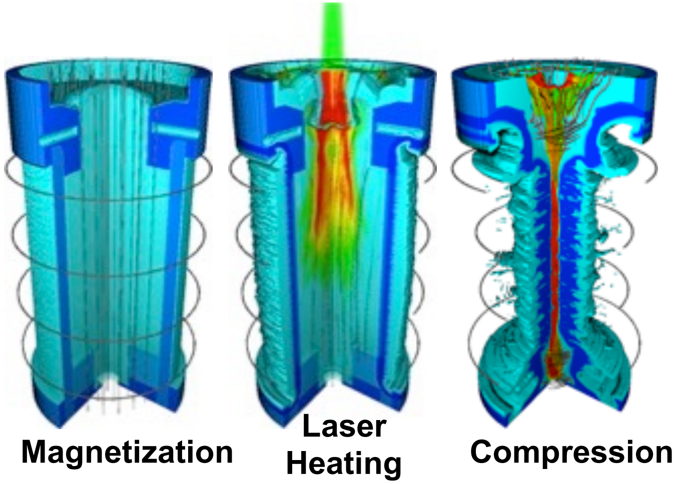
Exceptional service in the national interest





Review of observations, gaps, and hypotheses in MagLIF

Kyle Peterson

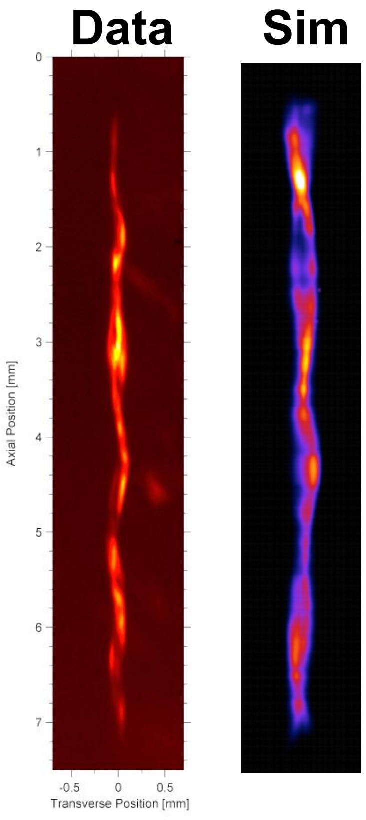
on behalf of the entire MagLIF team

Sandia National Laboratories,
Albuquerque, NM, USA

National Implosion Stagnation Physics Group,
Washington, DC
September 13-14

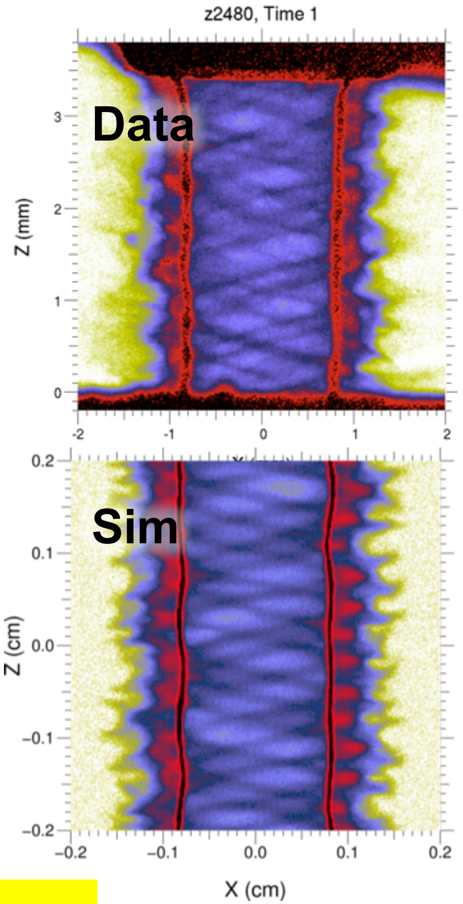
The observables are well modeled by 2-D and 3-D Hydra if we assume ~200 J of laser energy coupled to the target

Imaging



Z2613

Radiography



Comparison to z2591 Observables

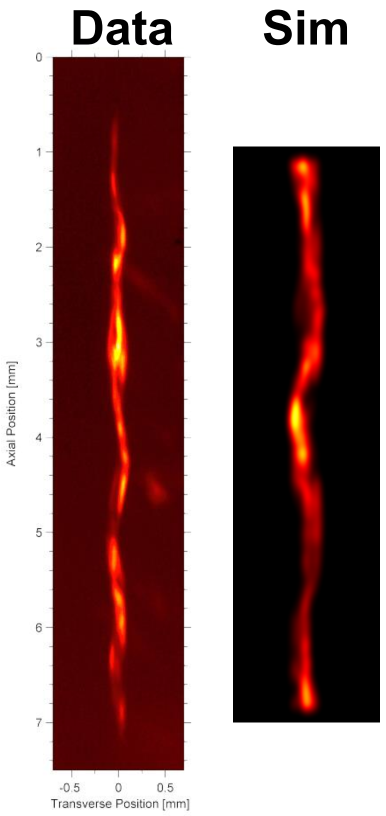
Parameter	Measured/inferred	Post-shot simulations
r_{stag}^{hot}	44 ± 13 μm	40 μm
$<T_i>^{DD}$	2.5 ± 0.75 keV	3.0 ± 0.5 keV
$<T_e^{spec}>$	3.0 ± 0.5 keV	2.7 ± 0.5 keV
ρ_{gas}^{stag}	0.3 ± 0.2 g cm^{-3}	0.4 ± 0.2 g cm^{-3}
ρR_{gas}	2 ± 1 mg cm^{-2}	2.6 ± 1.0 mg cm^{-2}
ρR_{liner}^{stag}	900 ± 300 mg cm^{-2}	900 mg cm^{-2}
$<P^{stag}>$	1.0 ± 0.5 Gbar	1.5 ± 0.3 Gbar
E_{gas}^{stag}	4 ± 2 kJ	7 ± 2 kJ
$<B_z^f r_{stag}>$	(4.5±0.5)e5 G cm	4.8e5 G cm
Y_n^{DD}	(2.0±0.5)e12	(2.5±0.5)e12
Y_n^{DD}/Y_n^{DT}	40 ± 20	41-57
t_{burn}^{FWHM}	1.5 ± 0.1 ns (x-ray)	1.6 ± 0.2 ns

A. Sefkow

*Thick window (3.5 micron experiments)

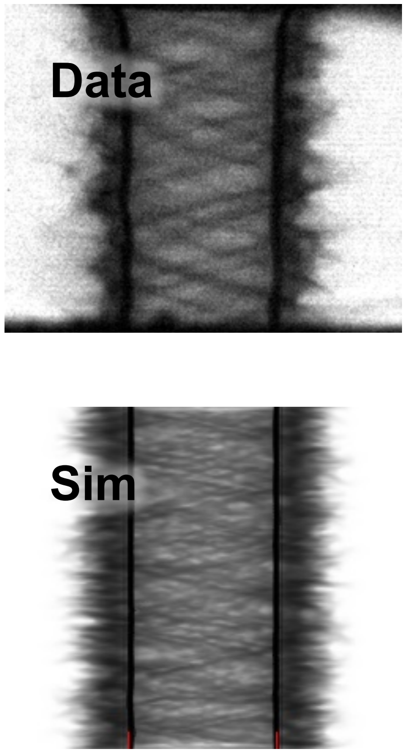
The observables are also well modeled by 3-D GORGON if we assume ~500 J of laser energy coupled to the target

Imaging



Z2613

Radiography

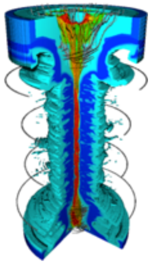


Comparison to z2613 Image

Parameter	Measured/inferred	Post-shot simulations
• FWHM	91 ± 40 mm	121 ± 40 mm

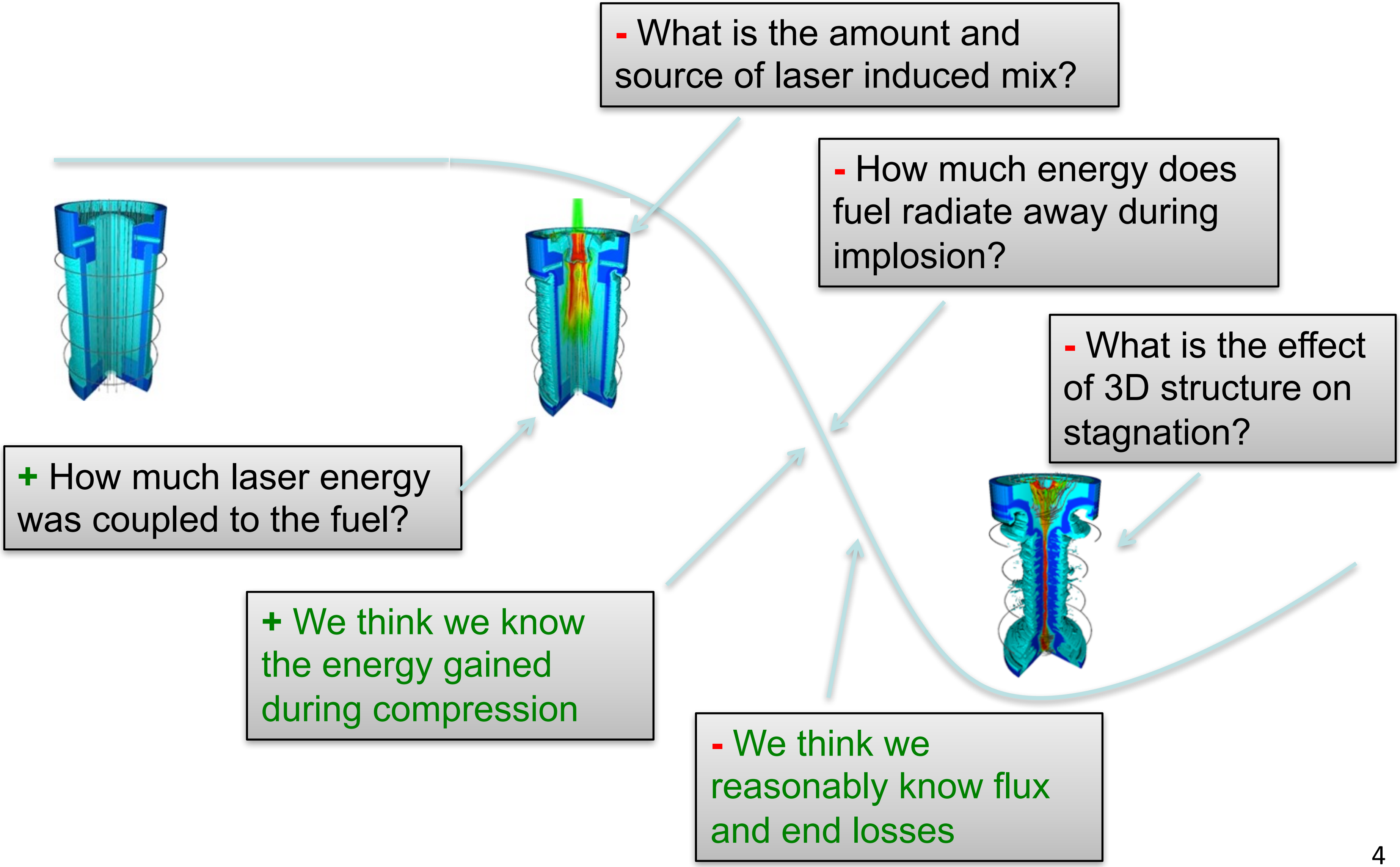
Sim. Values:

- Burn weighted, time integrated ion temp: **3.5 keV**
- Continuum emissivity (~9keV) weighted, time integrated electron temperature: **3.3 keV**
- Iron contaminant in Be emissivity weighted, time integrated electron temperature: **1.8 keV**
- Continuum emissivity (~9keV) weighted, time integrated fuel density: **0.33 g cm^{-3}**
- DD Yield: **4.e12**
- FWHM neutron pulse: **1.7ns**
- Liner ρR integrated along a single azimuth and axially averaged. Increases from **520 ± 60 mg cm^{-2}** to **980 ± 110 mg cm^{-2}** over the FWHM of the neutron pulse.



C. Jennings

Most of our ***stagnation/performance*** hypotheses are all related to energy balance.



- What is the amount and source of laser induced mix?

- How much energy does fuel radiate away during implosion?

- What is the effect of 3D structure on stagnation?

+ How much laser energy was coupled to the fuel?

+ We think we know the energy gained during compression

- We think we reasonably know flux and end losses

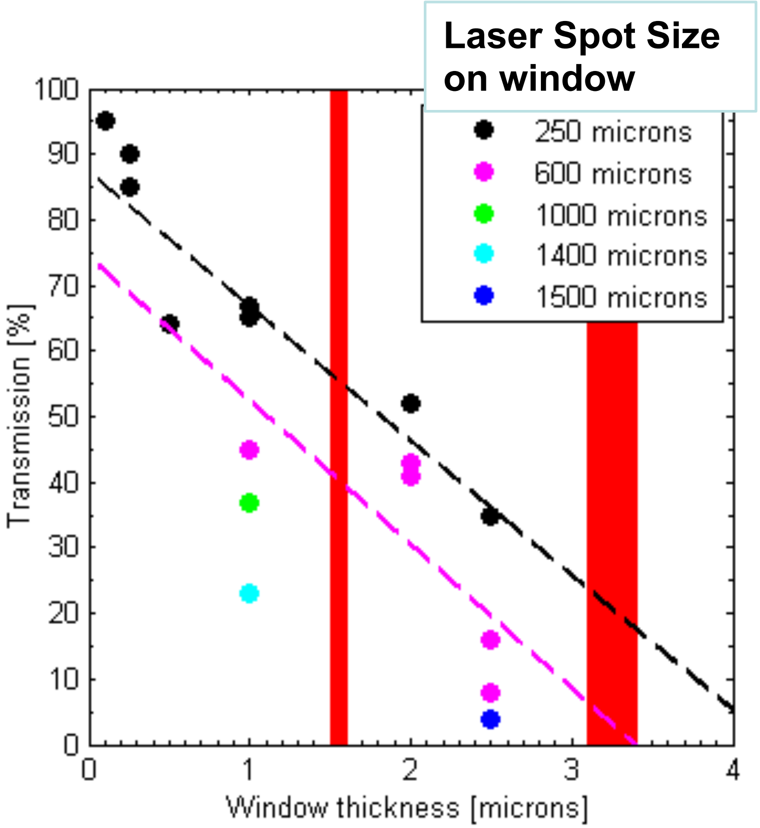
We are currently debating three different plausible stagnation pictures

- 1) Low coupling, low mix hypothesis
  - Little to no mix
  - Quasi-1D stagnation conditions
- 2) Moderate coupling, moderate laser induced mix
  - Moderate endcap/window/liner laser induced mix
  - Quasi-1D stagnation conditions when accounting for radiative loss
- 3) Moderate coupling, minimal laser induced mix
  - Minimal endcap/window/liner laser induced mix
  - 3D stagnation, inefficient thermalization

Hypotheses #1: Low laser energy coupling

Four sets of early laser data indicated poor laser transmission: Foil transmission

Transmission as fct. of thickness & spot size



Conclusions

400-500 micron spot size

>3 micron thick foil

5-20% transmission
(100-400 J)

400-500 micron spot size

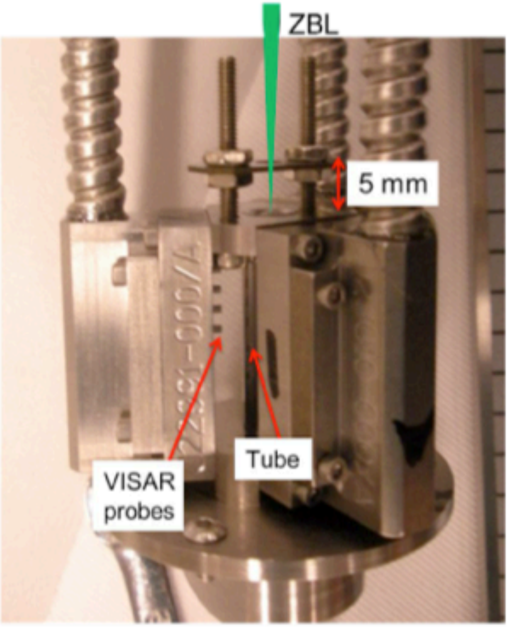
1.5 micron thick foil

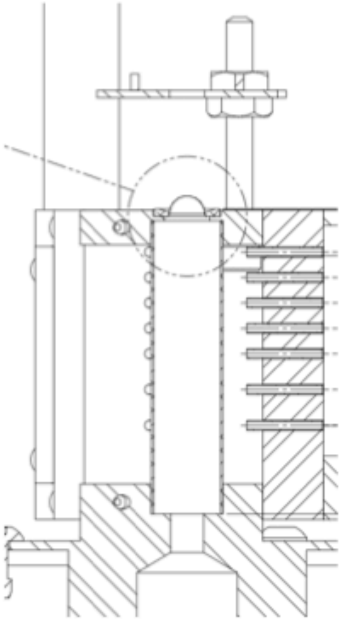
40-60% transmission
(0.8-1.2 kJ)

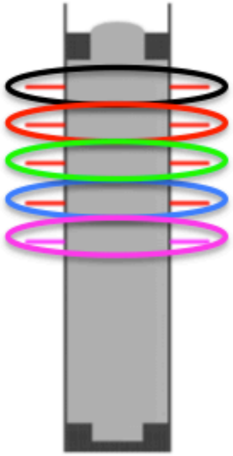
Note: PECOS experiments, 2.5 kJ, No phase plate, flat foil

Four sets of early laser data indicated poor laser transmission: Blast wave measurements

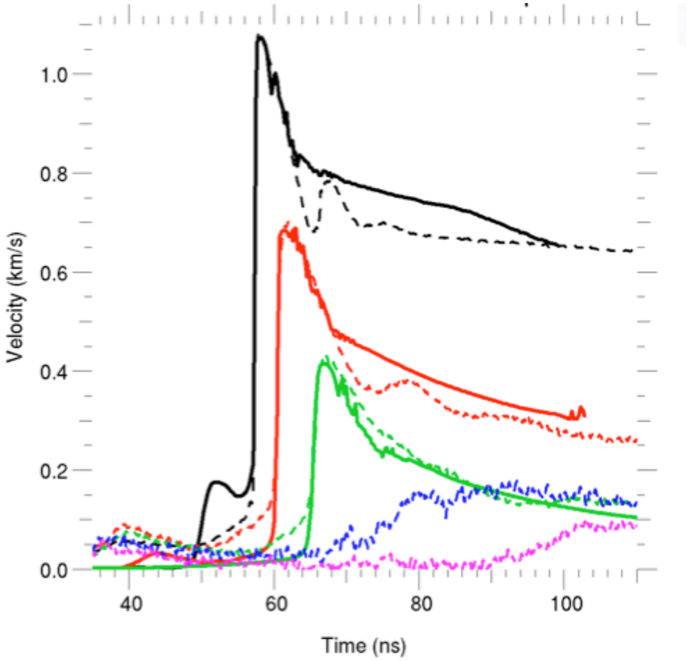
Inferred: 330 J or less coupled to the gas (of ~2.8 kJ)







Dashed: Data
Solid: HYDRA simulation

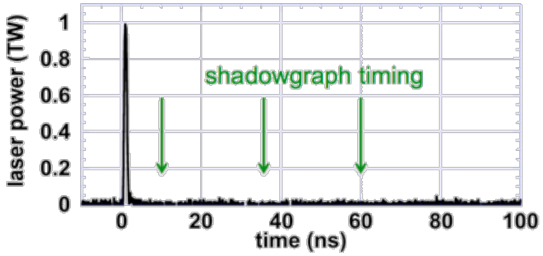


- Best focus on window ~**250** microns, MagLIF experiments **400-500** micron spot size
- Large azimuthal asymmetry observed in signals
- **120** psi DD gas (MagLIF experiments @**60** psi) and 3.5 μm LEH window

Four sets of early laser data indicated poor laser transmission: Blast wave shadowgraphy (~600 J*)

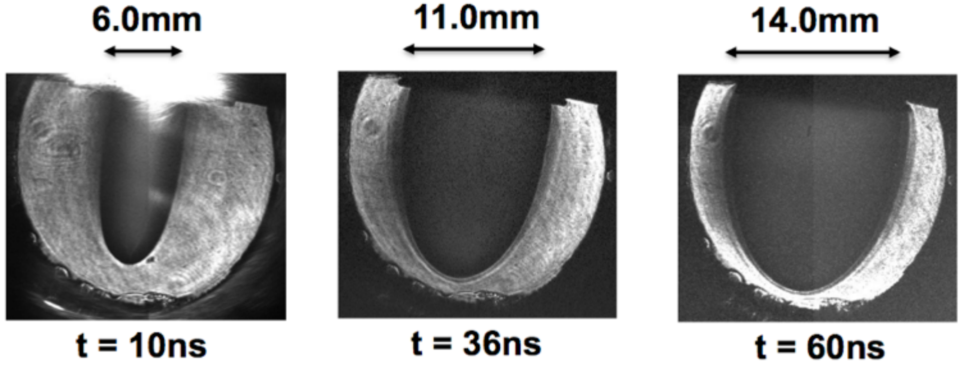
Shadowgraph measurements
Ne 250 Torr gas-cell shot, 10/6/2014

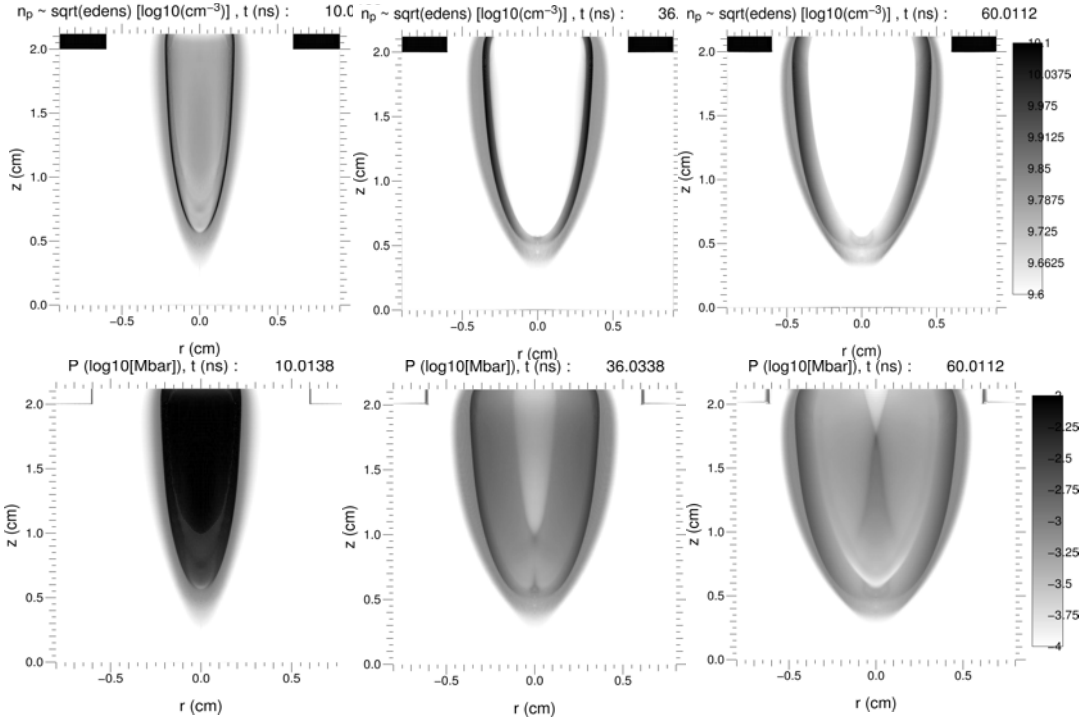
ZBL: 1.8kJ/2ns, 300J prepulse, 1mm dia. focus
Target: scale-2 gas cell, 1μm-thick Mylar LEH, 250 Torr neon gas fill



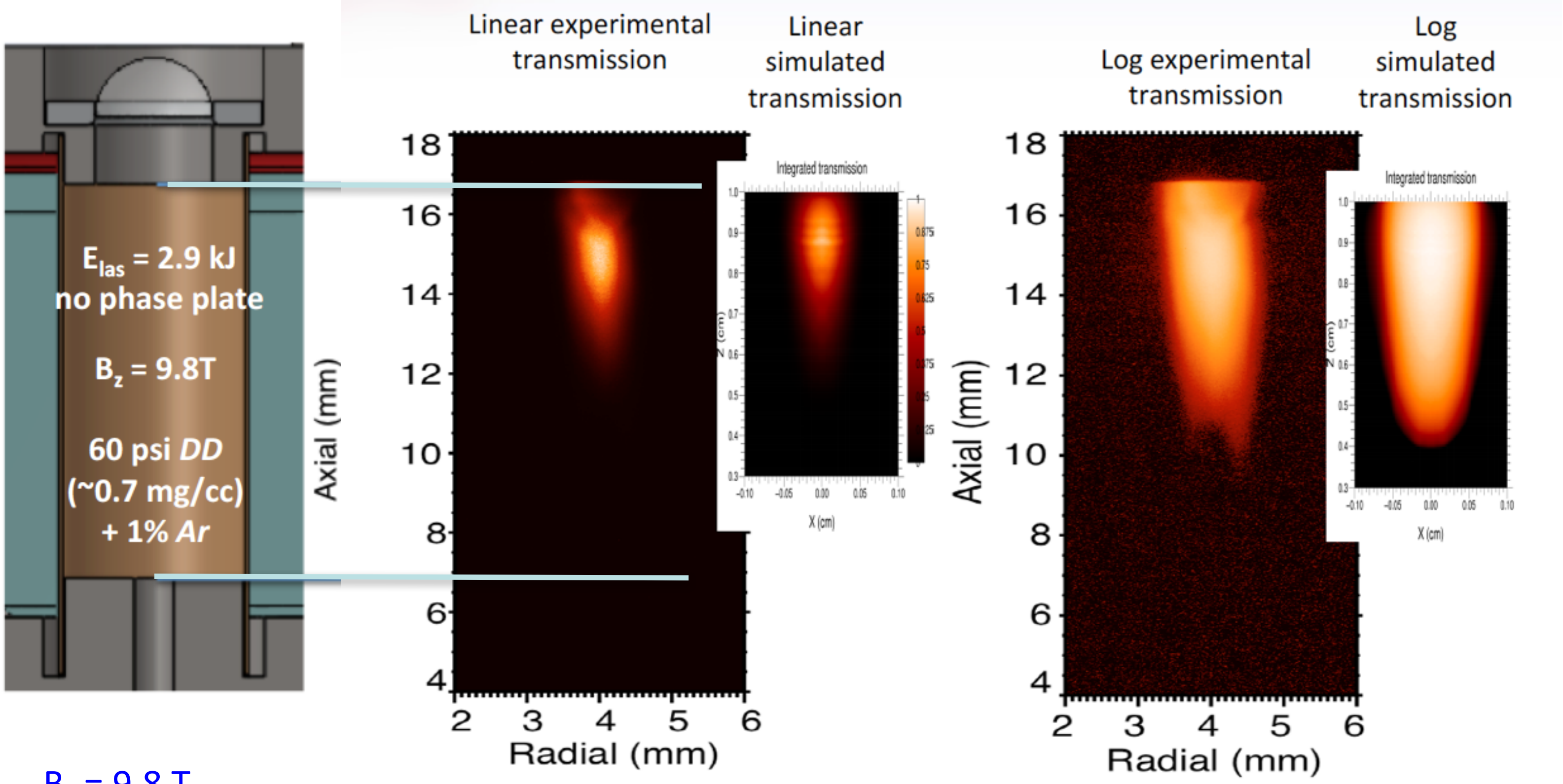
Shadowgraphs appear to measure the plasma's index of refraction n~$n_e^{0.5}$, which stays ~constant and captures shock and fuzzy edge radiation feature (whereas ρ, T_e, etc., vary and do not always capture features).

The $n_e^{0.5}$ profile tracks the plasma pressure very well, so the shadowgraphs are indeed measuring the laser absorption (the edge of where the plasma is hot).





Four sets of early laser data indicated poor laser transmission: Thin walled X-ray imaging with Bz on Z



Linear experimental transmission

Linear simulated transmission

Log experimental transmission

Log simulated transmission

E_{las} = 2.9 kJ
no phase plate

B_z = 9.8T

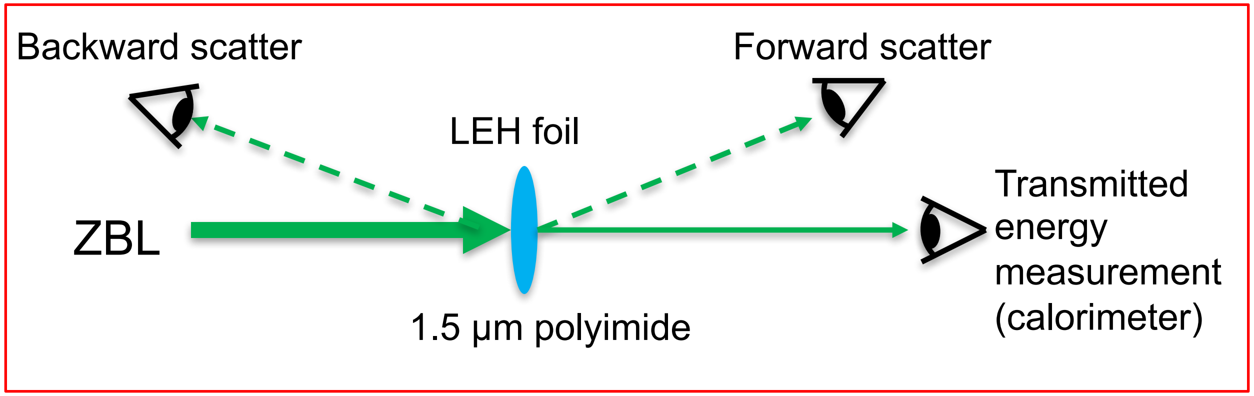
60 psi *DD*
(~0.7 mg/cc)
+ 1% *Ar*

- B_z = 9.8 T
- 1.89 µm polyimide stretched to **1.55** µm
- 100 µm thick *Be* liner + 1 µm thick *Ti* foil
- *KI* solution on top SS endcap
- 1 µm thick *V* foil + *CaCl*$_2$ solution on window
- E_{las} = 497 J (pre) + 2405 J (main)
- no phase plate

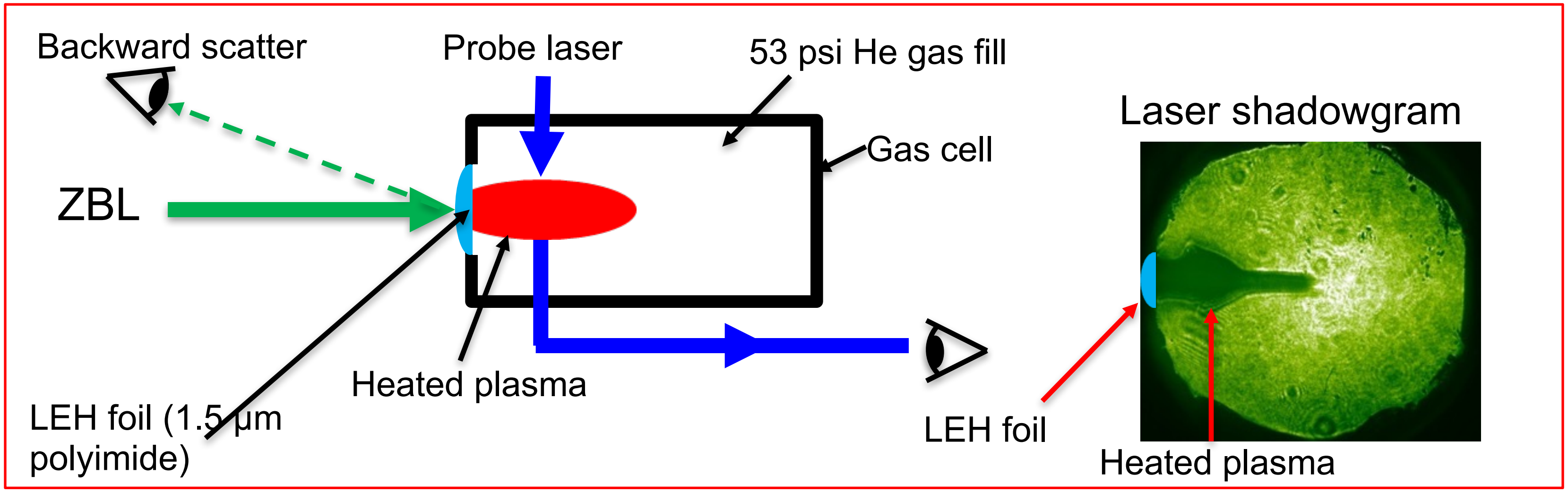
- **Measured energy is only 200J**
  - Diagnostic is not sensitive to regions below 250 eV
  - There could be 100s of J hidden
  - There is also unmeasured energy in the laser entrance channel

Improvements in PECOS have led to better measurements, surrogacy, and improved understanding

LEH transmission studies

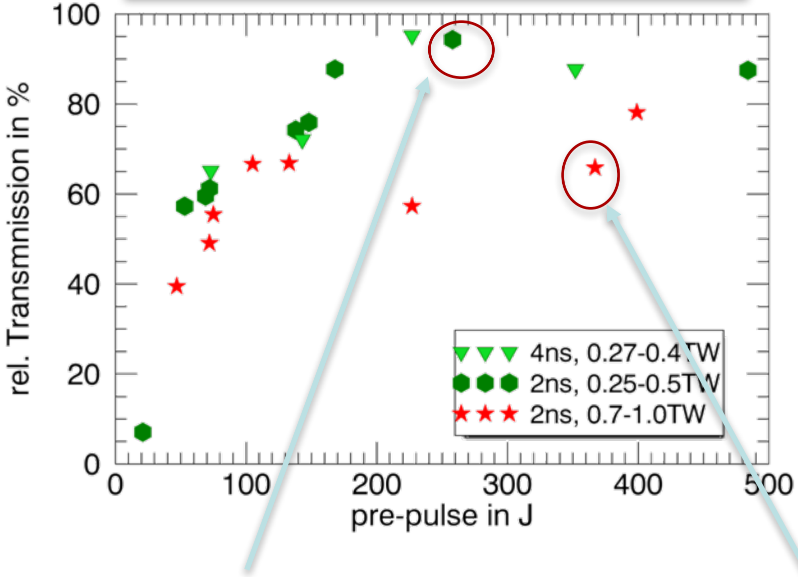


Gas cell experiments

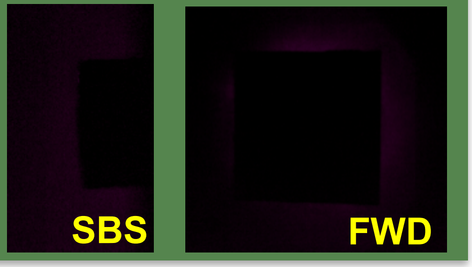


Significantly better transmission with higher prepulse energies and lower main pulse intensity

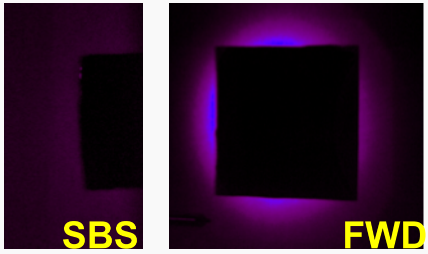
Transmitted main pulse energy
(1.47µm window DPP750



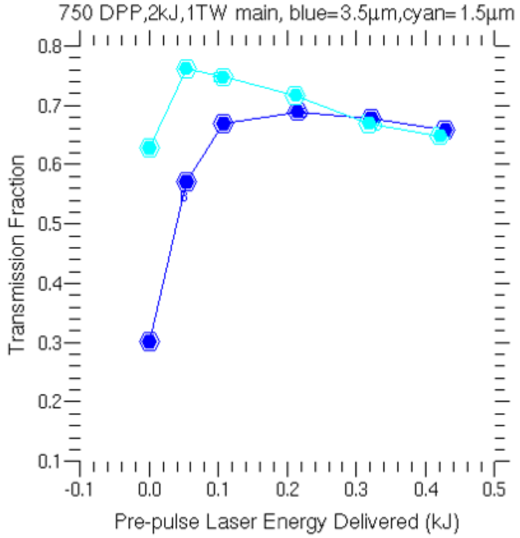
0.5 TW, 94% transmission
2 J backscatter (SBS)
5 J forward scatter



1.0 TW, 66% transmission
30 J backscatter (SBS)
70 J forward scatter



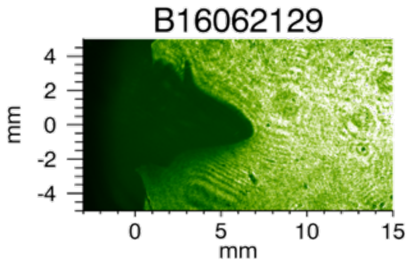
Hydra window only Sims
(1.47µm window DPP750)



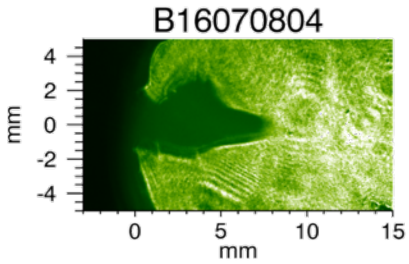
Reasonable agreement now obtained with simulations

Less backscatter, more cylindrical blast/thermal front with lowered intensity

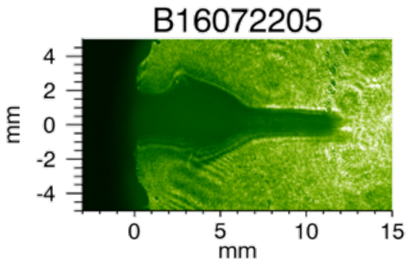
Full Intensity
no Phase Plate



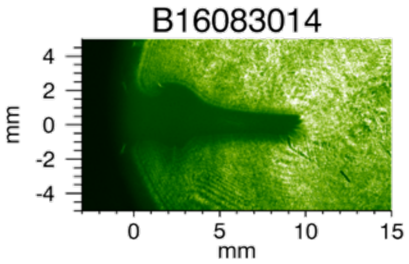
Full Intensity
750µm Phase Plate



Half-Intensity
750µm Phase Plate

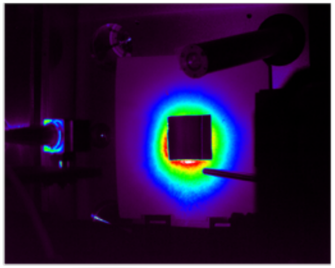


Quarter-Intensity
1100µm Phase Plate



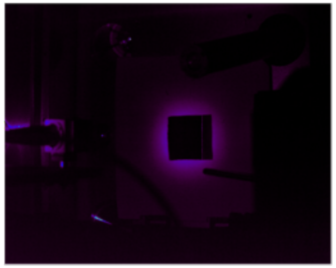
H39 Z-phase plate shot at about 1.6 x full intensity

LPI threshold



SBS: 900J

SBS: 300J



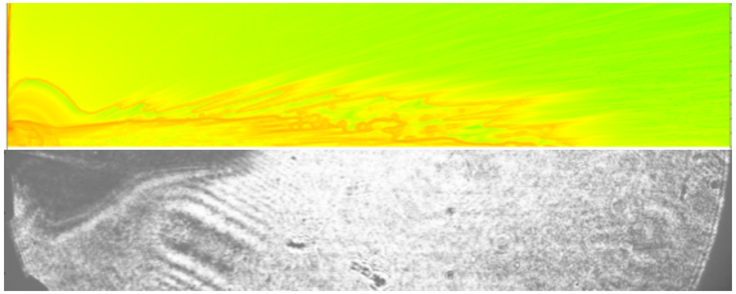
SBS: 70J

SBS: 20J

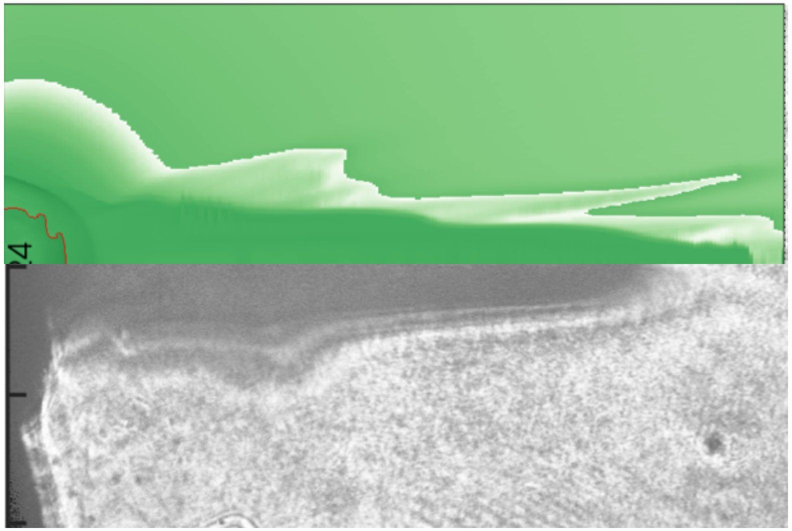
Intensity decreases - less backscatter - experiments match simulations better

Simulated optical blastwave radiography matches experiments significantly better at lower intensities

full intensity



quarter intensity

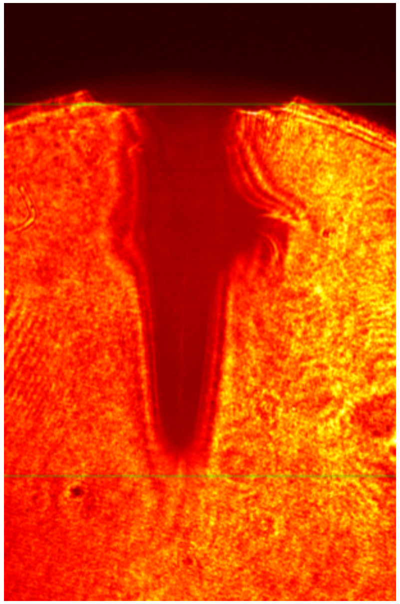


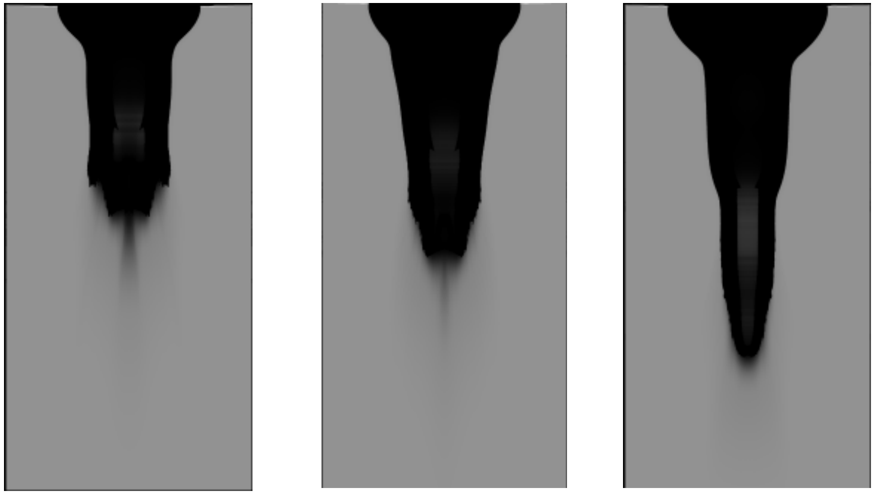
Recent PECOS results and HYDRA simulations: Preliminary Analysis

GORGON simulations show high degree of sensitivity to window deflection

3 different window deflections

700 µm win deflec. | 500 µm win deflec. | 300 µm win deflec.

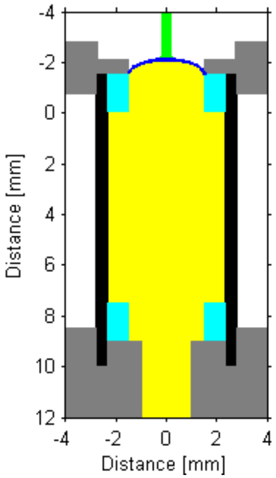




- HYDRA sims don’t exhibit nearly as much sensitivity
- Actual window deflection in experiments is uncertain

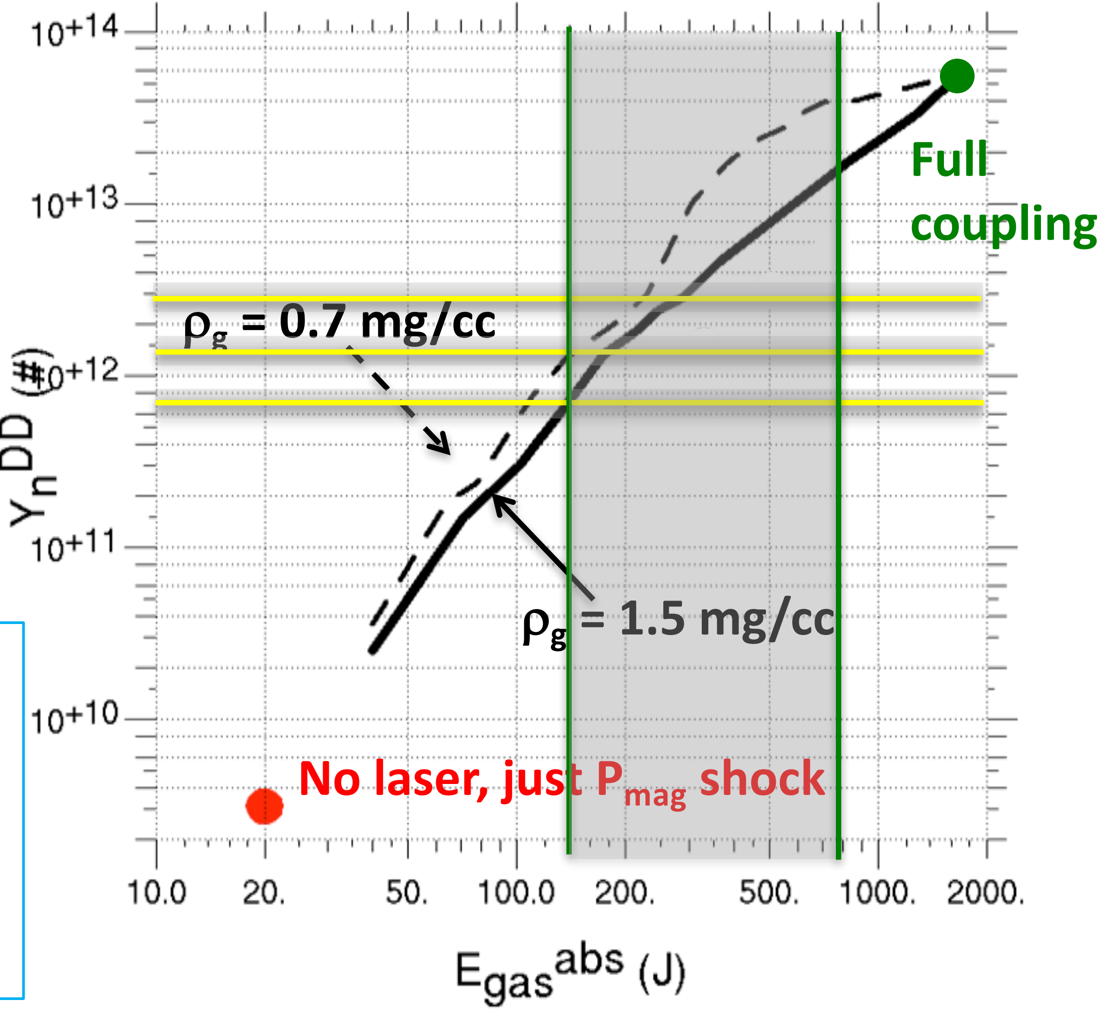
Recent PECOS measurements have help constrain deposited energy estimates in our baseline experiments

Baseline Target Parameters
Window thickness = 3.5 μm
Target height = 7.5 mm
Endcap material = aluminum



1.7×10^{12}
2.1 keV

2D Simulated MagLIF Performance



Energy Balance
Total Laser Energy = 2.5 kJ
Energy absorbed in window (sim) ~ 800 J
Estimated SBS losses ~ **900 J**
Energy coupled to fuel < 800 J
Minimum credible coupled energy ~ 150J

Y_{exp}/Y_{sim2D} (perfect laser coupling, no mix) = 0.08

A. B. Sefkow et al., Phys. Plasmas, 21 072711 (2014).

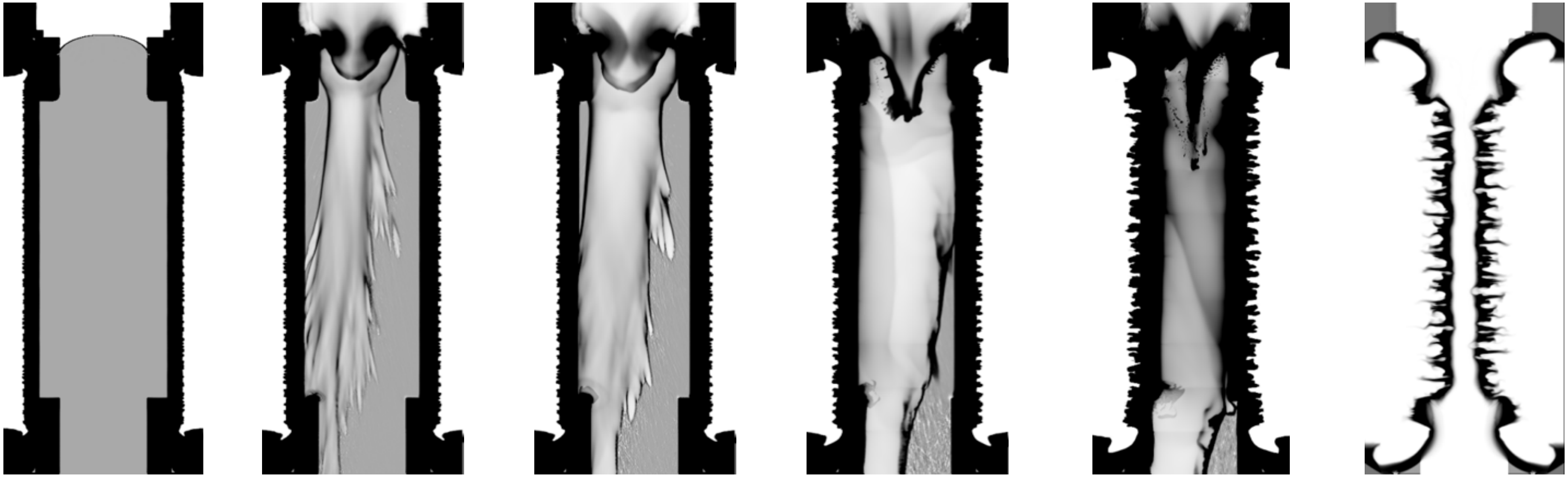
Summary of Low Laser Energy Coupling Hypothesis

- We don’t yet have a direct measurement of energy deposited in the fuel
- New measurements on PECOS have helped constrain estimates of deposited energy
  - Rev0 Integrated MagLIF configuration most likely have backscatter losses on the order of **at least** 900J (Z optical train is different)
  - 200-800J with thick (3.5 micron windows)
  - 600-1000J with thin (1.5 micron windows)
- New laser configurations with DPPs and low intensity show much better match to simulations and should allow for much less uncertainty in deposited laser energy

Hypotheses #2: Significant amount of mix

Models indicate mix can occur from multiple origins:

- Blast wave from laser preheat causes blowoff from liner wall and endcaps
- Laser can pass through the gas and cause blowoff from the bottom end cap
- Laser can deflect through LEH plasma and hit the liner/endcap causing blowoff
- The exploded LEH window can mix into the gas
- The liner is RT unstable



Laser deflected

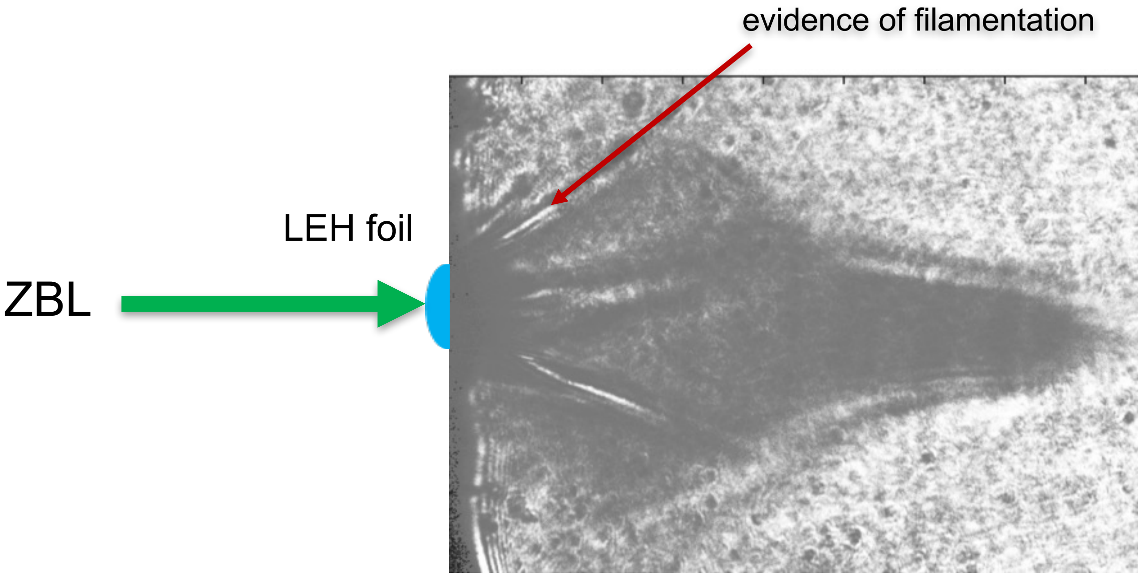
Laser on bottom cap

Blast Wave Reflected

LEH window injected

Unstable liner

In recent PECOS experiments, significant filamentation has also been observed with high intensities used in typical MagLIF experiments



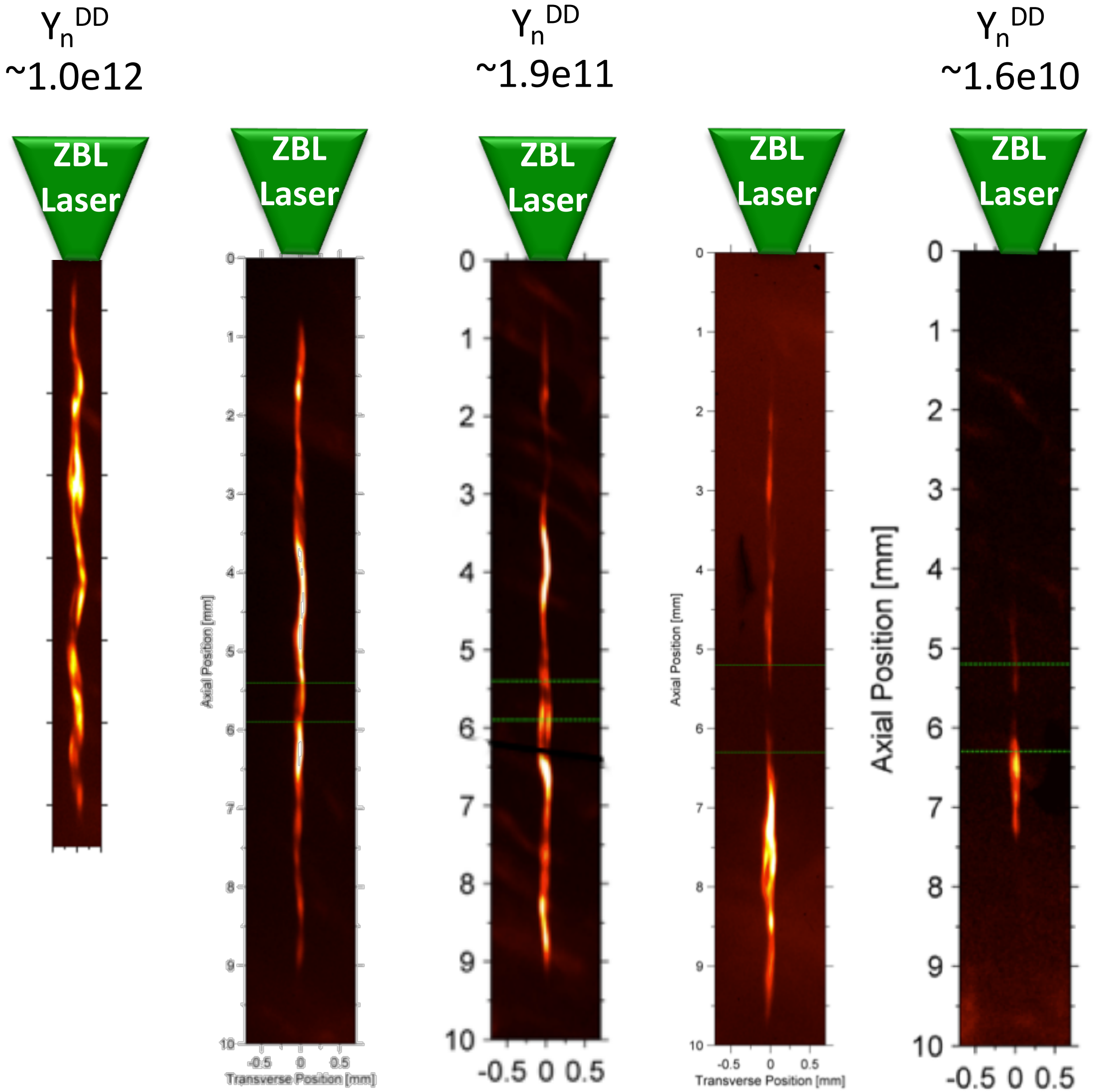
In general, increased laser energy has reduced yield, consistent with *Z*>1 mix from the window and LEH

Simulations:
Increasing laser energy (E_{laser}) should *dramatically increase* yield (in absence of mix)

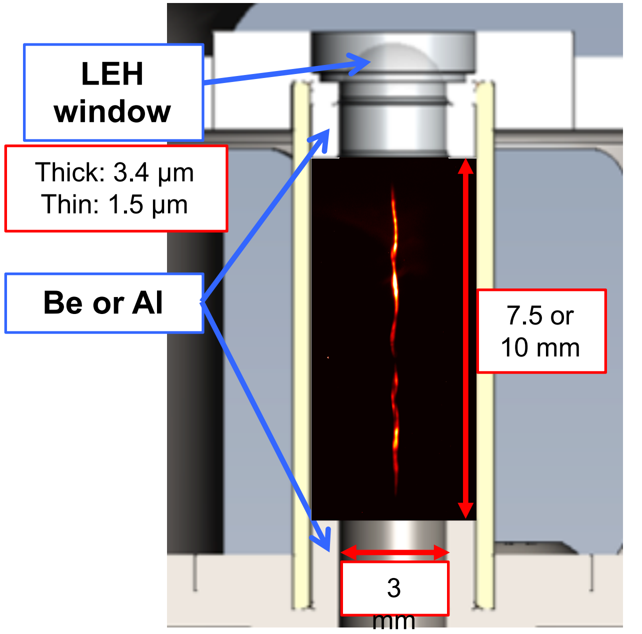
Experiments:
Target changes thought to *increase* laser absorption into gas have all *decreased* the yield.

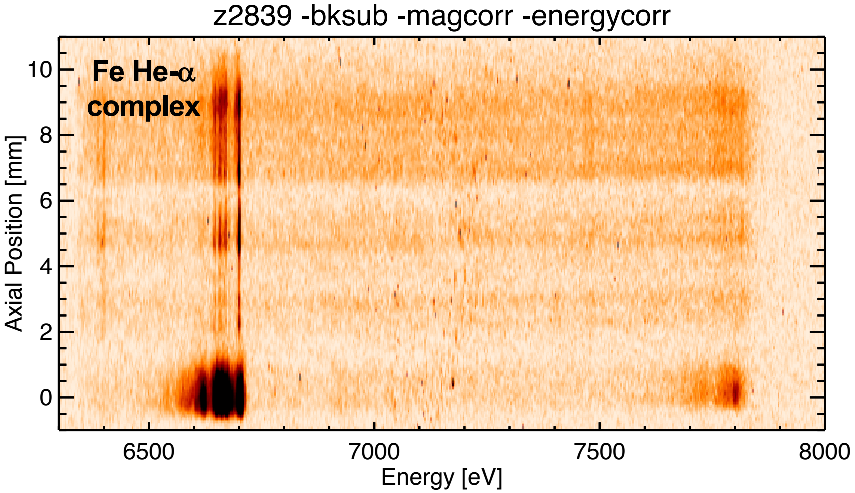
Laser-produced mix (direct or indirect via blastwave of radiation) appears to be the culprit.

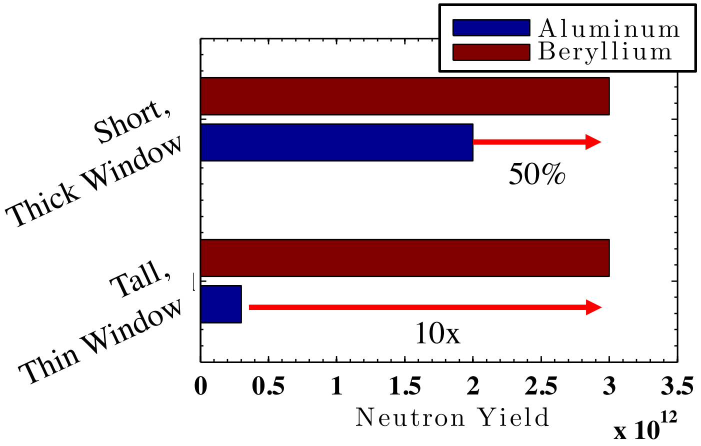
Must stay unmixed for ~50 ns!
We can dud the top of the stagnation plasma!



Changing to low Z endcaps with nominal laser coupling improves performance



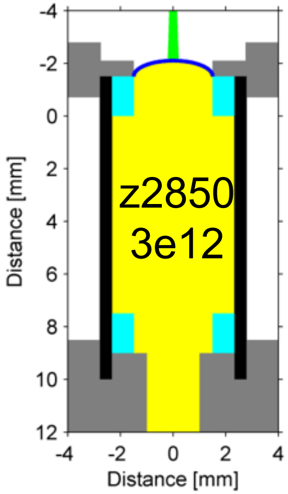


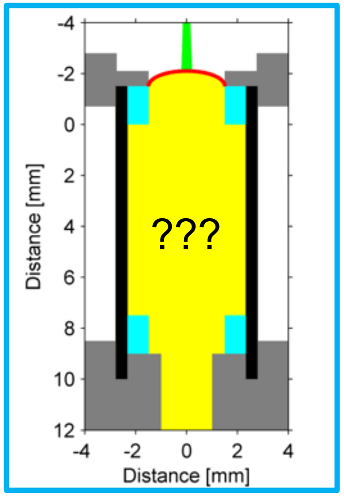


- Switching from Al to Be end caps improved the neutron yield in both thick and thin window cases
- Improvement is more dramatic in thin-window case
- Suggests mix is worse, possibly due to increased laser coupling with thin window

Marginal yield improvements are observed with increased laser coupling and drive current (when Be end caps are used)

Drive current (target height 10-7.5mm)



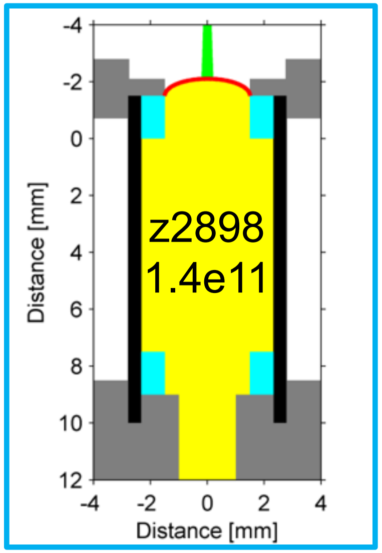


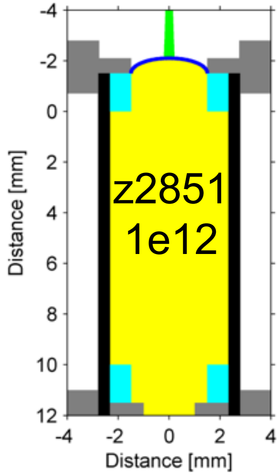
z2899
Pulsed Power Failure

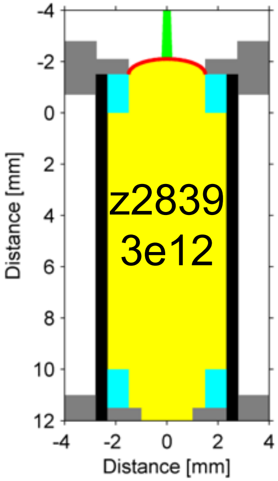
2-3x improvement?

Z2898
+0.75mm DPP

Additional Mix with DPP?



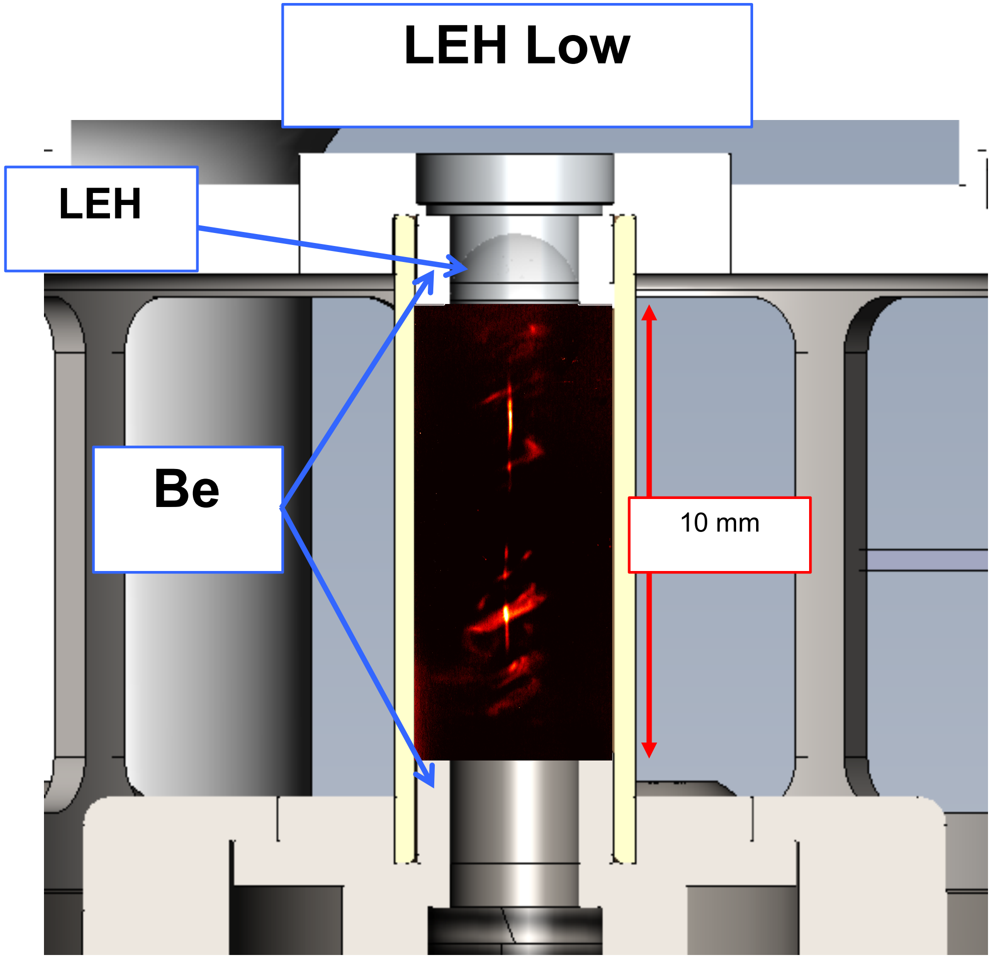


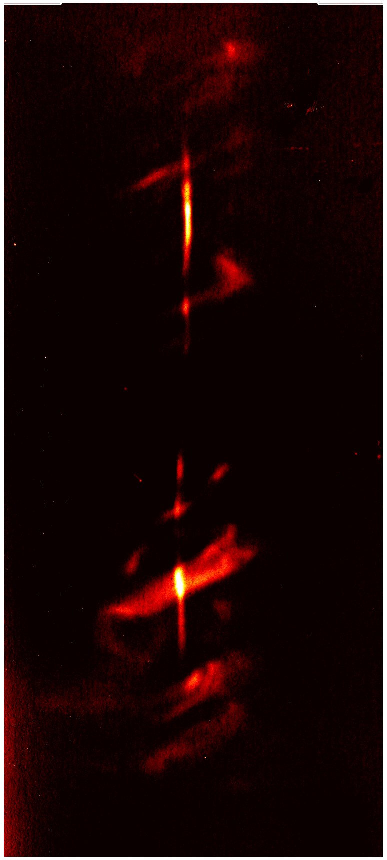


All targets have only Be components in contact with fuel

Laser coupling (window thickness, 3.5mm - 1.7mm)

Lowering the LEH window also significantly reduces performance

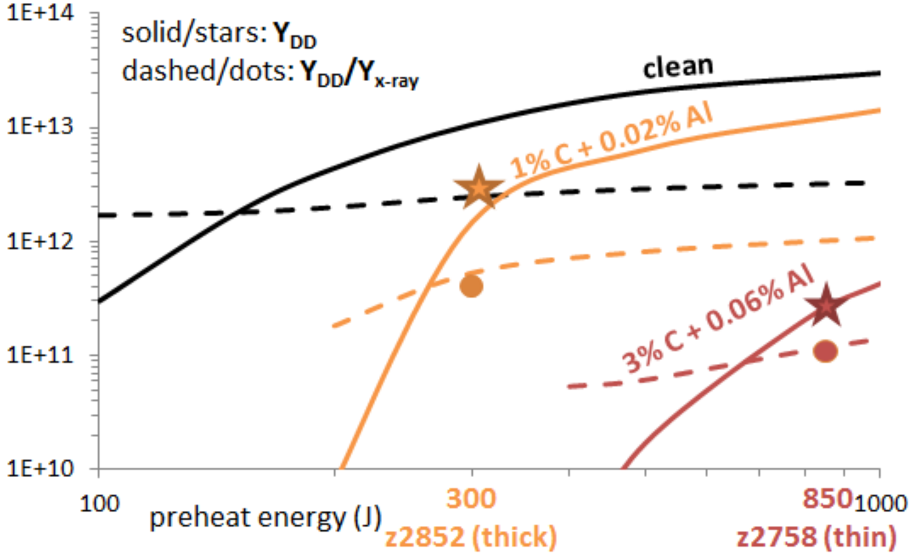


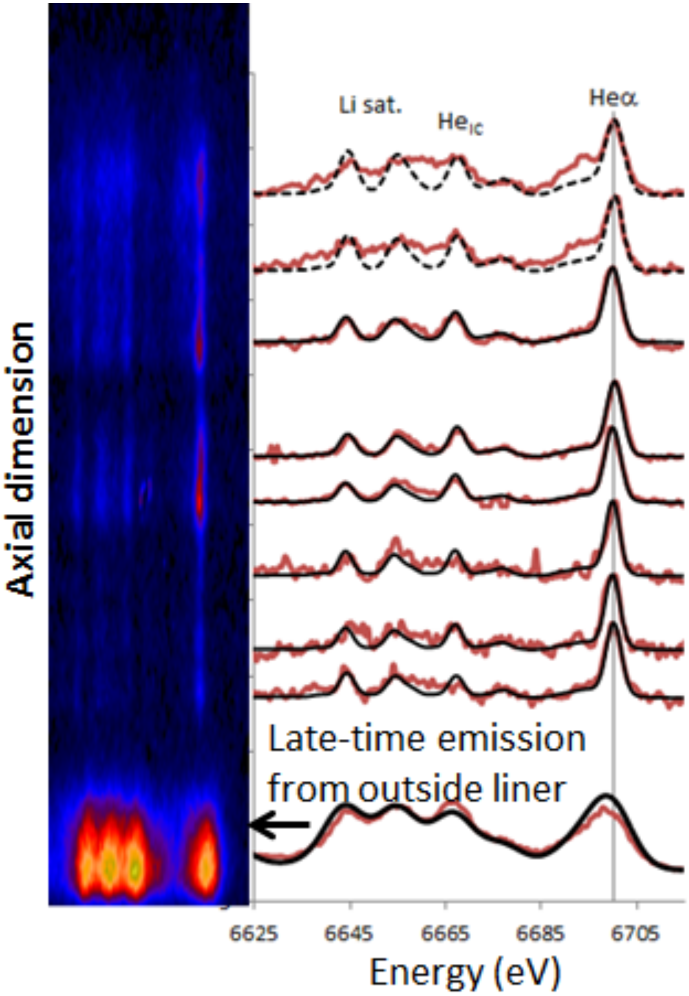

Y_{dd}=3.8e10 (~85x reduction)

Consistent with Window mix fuel contamination

Mix is measured by impurity line emission and absolute x-ray yields

- X-ray yields from filtered silicon diodes indicate $\rho_f \sim 0.3$ g/cc (with mix), dependent on Δt and volume
- XRS3 and CRITR impurity line emission intensities indicate ~few % Be from late-time instability mixing
- Ratios of neutron to x-ray yields indicate that endcap and possibly window mix increase with preheat energy





We recently completed a MagLIF series to investigate mix sources with localized Co dopant

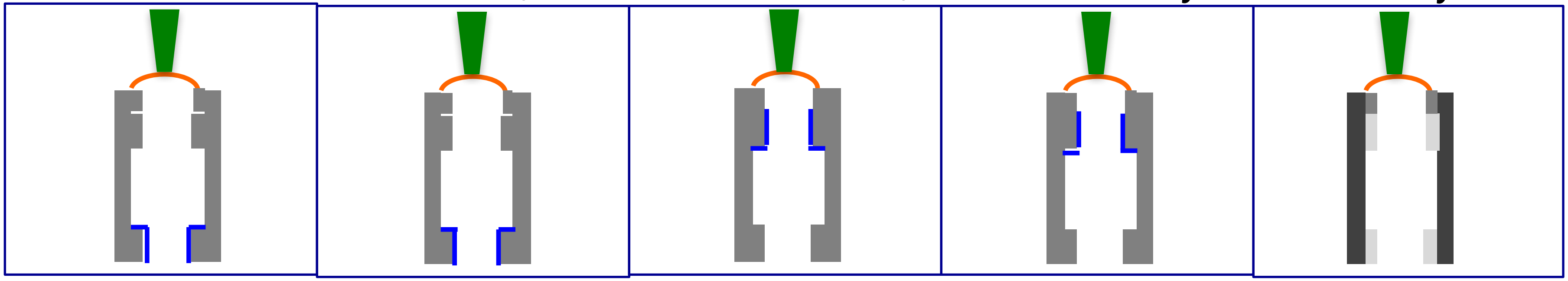
Monday

Tuesday

Wednesday

Thursday

Friday



Target 3
S-65 caps
S-65 body
Co on top cap

Target 3 (repeat)
S-65 caps
S-65 body
Co on bottom cap

Target 4
S-65 caps
S-65 body
Co on top cap

Target 4 (repeat)
S-65 caps
S-65 body
Co on top cap

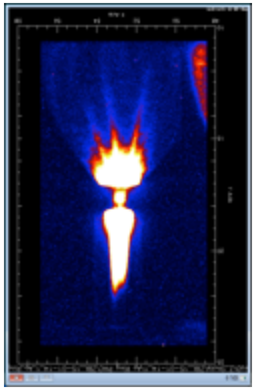
Target 2a or 2b
UHP caps
O-30 body

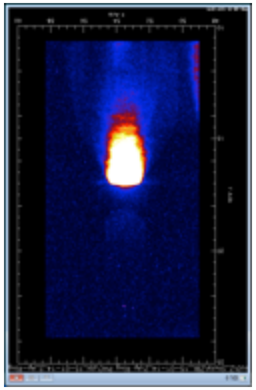
Results are still being analyzed.

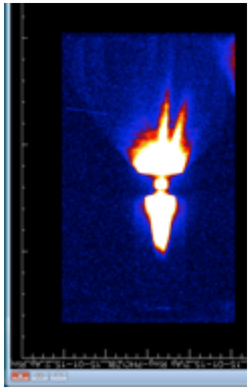
Only trace amounts of Co appear to have been observed

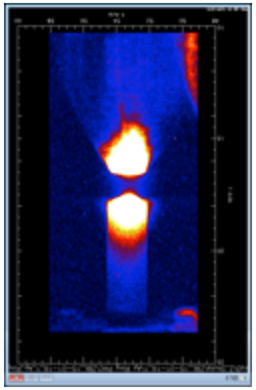
Laser only experiments on Z (with ~1.8mm DPP) **suggests *significant* window mix**

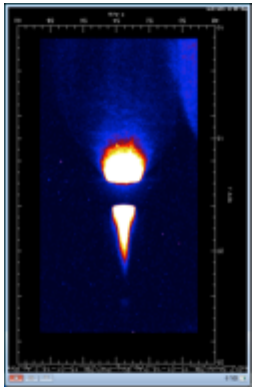
All pinhole images have similar intensities above washer

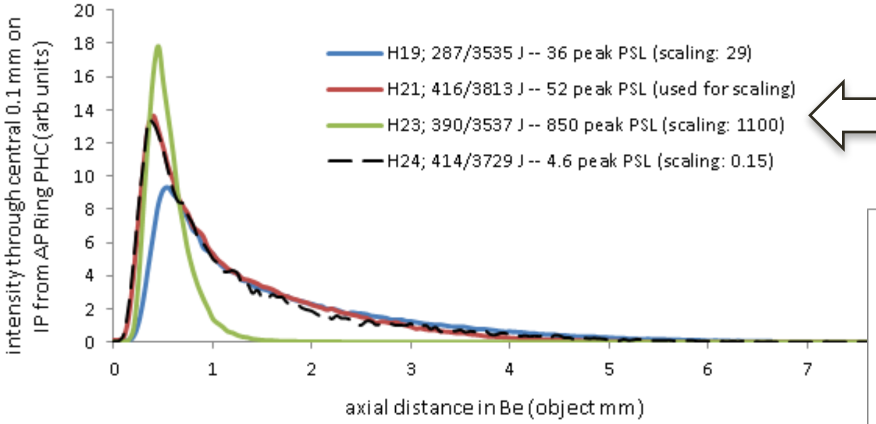

H19
45 psi, 0.5% Ar


H20
50 psi, Pure Ne


H22
60 psi, 0.5% Ar

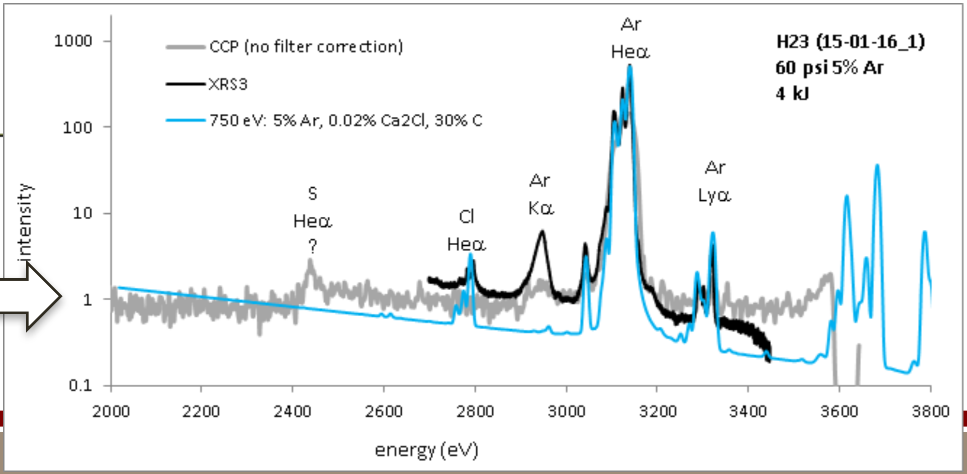

H23
60 psi , 5% Ar


H24
60 psi, pure D2



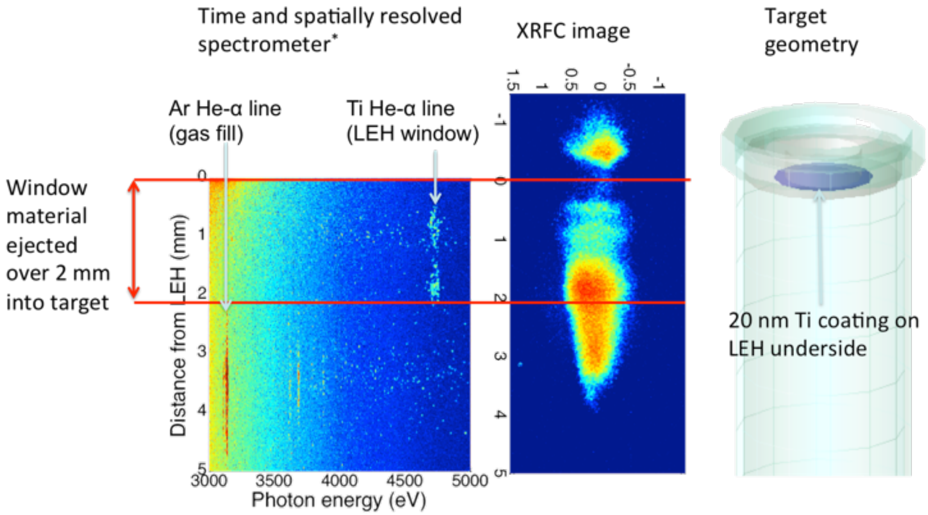
Axial lineouts below washer show similar profiles for low dopant fractions, with intensity scaling that suggests 10% carbon mix in pure D2 case (H22)

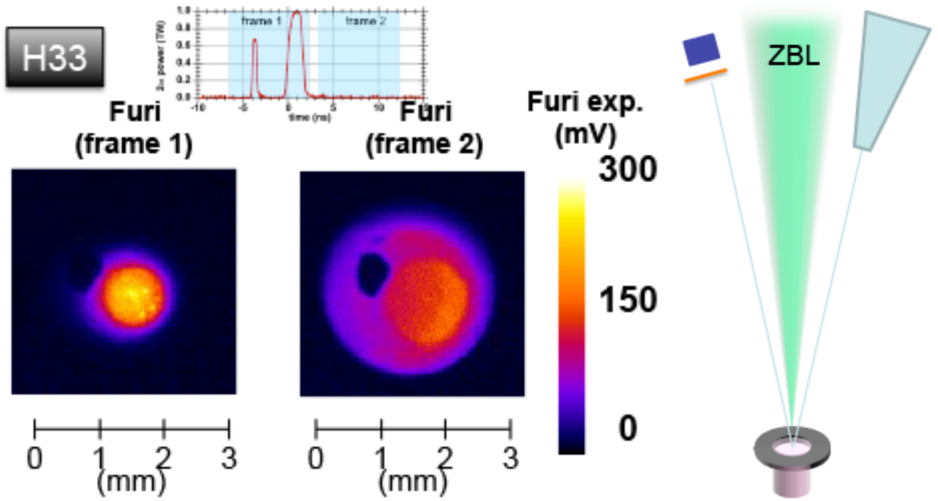
XRS3 spectra indicate fill temperatures of 0.6 – 0.8 keV, small (~0.02%) Cl mix fractions, and significant (>20%) low-Z mix

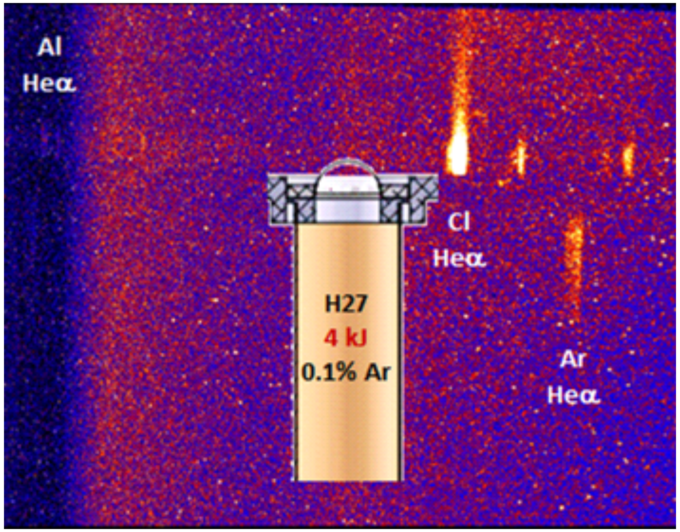


We have made progress in characterizing and mitigating fuel contamination as a result of the preheating method

- Window mix using Ti dopant coated on the LEH window at OMEGA-EP
- Localized Cl dopant on the LEH window, Al washers, we are assessing laser-induced mix using ZBL
- Developing time-gated axial imaging and spectroscopy to measure heating on integrated Z shots

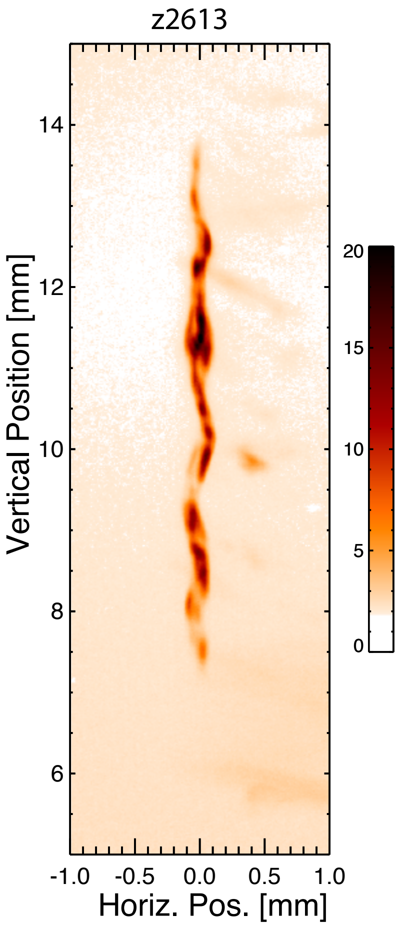




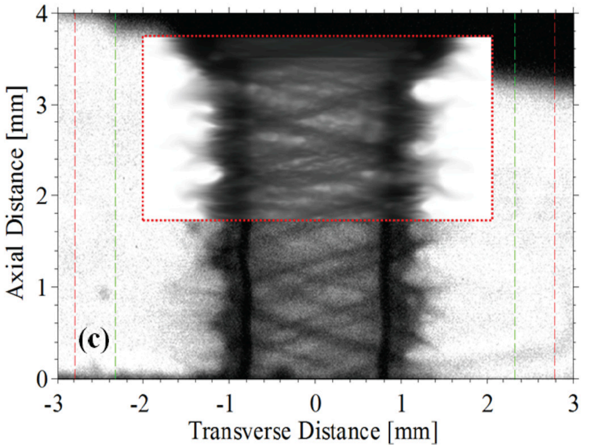


Hypotheses #3: Implosions deviate significantly from 1D (3D effects)

X-ray emission from the fuel shows a high aspect ratio stagnation column and helical structure



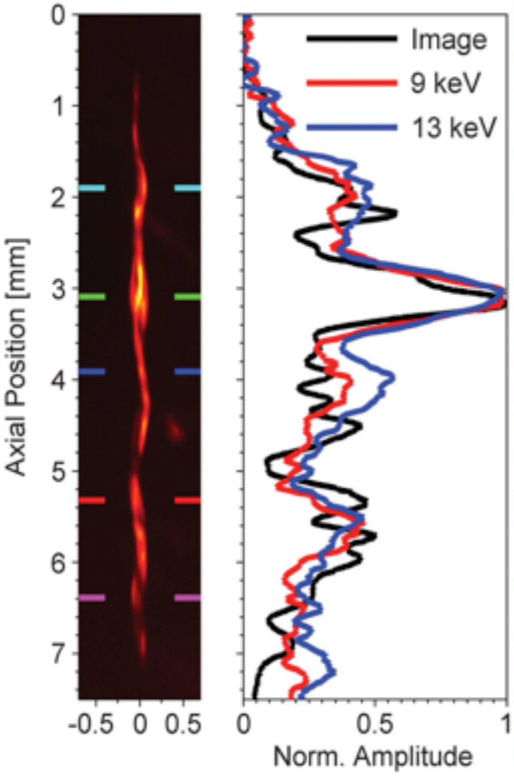
- **Combination of 6.2 and 9.4-keV emission**
- **Emission FWHM is 50-110 µm, height is > 6mm**
- **Axial intensity variations indicate variations in both the fuel conditions (temperature and density) and the liner opacity**
- **Helical structure consistent with structure observed in liner radiography experiments**



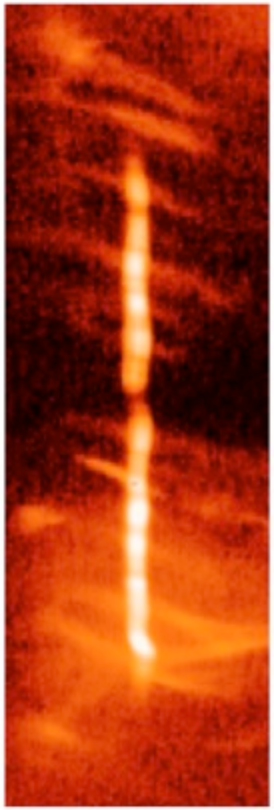
M. R. Gomez et al., PRL **113**, 155003 (2014); E. C. Harding et al., RSI **86**, 043504 (2015).

Variation in self-emission and liner opacity contribute to observed structure

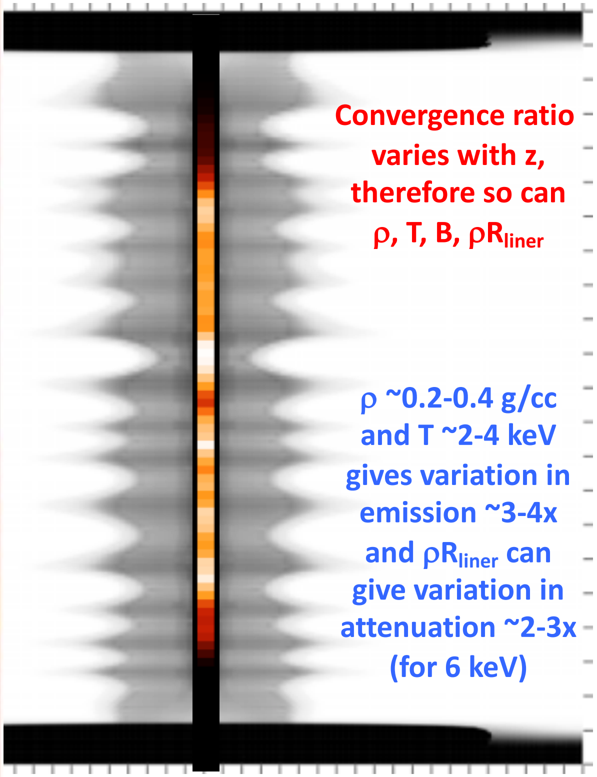
Data Example 1



Data Example 2



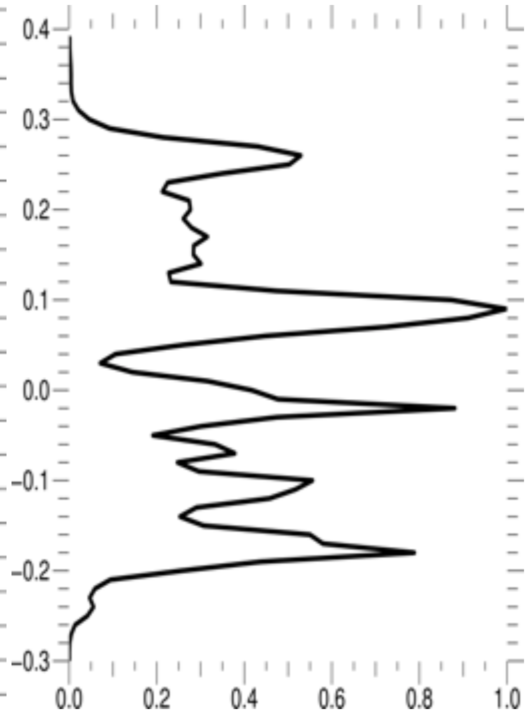
Example 2D simulated radiograph



Convergence ratio varies with z, therefore so can ρ, T, B, ρR_{liner}

ρ ~0.2-0.4 g/cc and T ~2-4 keV gives variation in emission ~3-4x and ρR_{liner} can give variation in attenuation ~2-3x (for 6 keV)

Integrated self-emission accounting for liner opacity and detector resolution



However, helical emission and radiographs require 3D simulations

A. B. Sefkow, et. al., *in preparation* (2015).

Five color pinhole imaging demonstrates consistency in temperature and opacity inferences

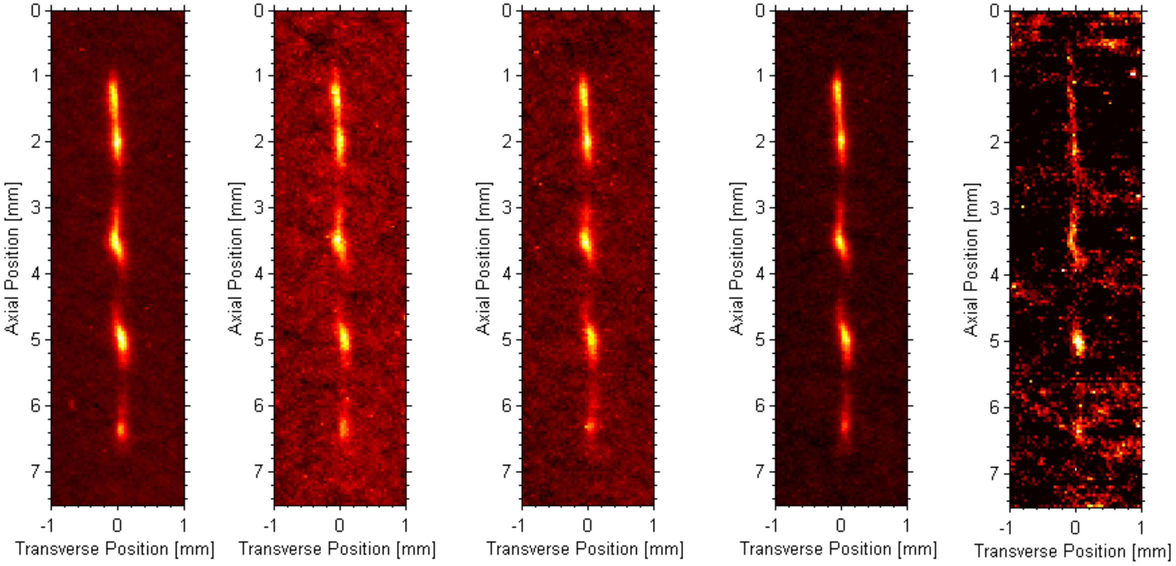
Image 1
Ti 22 μm

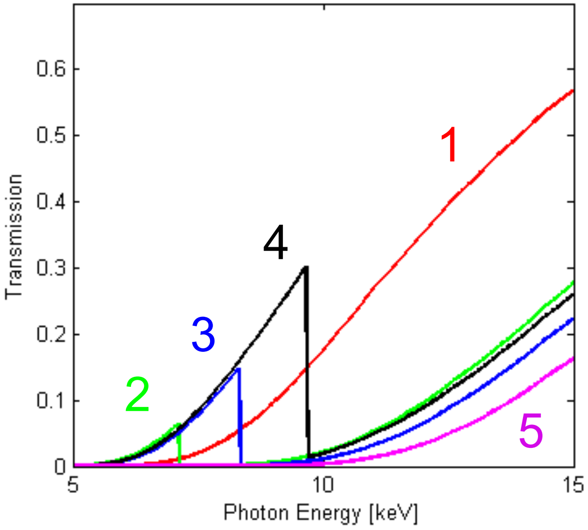
Image 2
Fe 24 μm

Image 3
Ni 20 μm

Image 4
Zn 20 μm

Image 5
Ti 101 μm



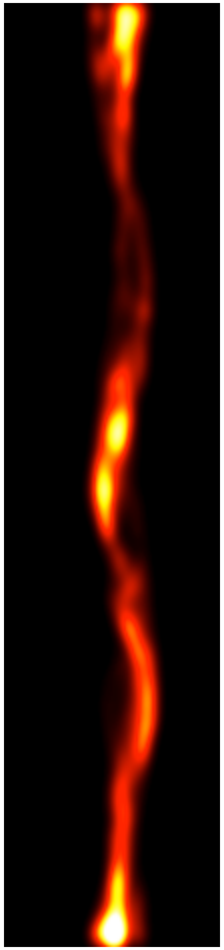


- Expected signal values for each filter are calculated assuming temperatures ranging from 0 to 8 keV and Be opacities ranging from 0 to 3 g/cm^2
- The ratio of the calculated signals are compared to the ratio of the measured signals at each axial location to find the best fit
- Temperatures range from 2 to 4 keV with an average of 3.1 keV
- Be opacities range from 0.3 to 2 g/cm^2 with an average of 1.2 g/cm^2

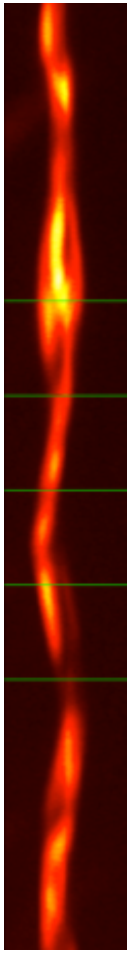
Implosion instabilities also have the potential to degrade neutron yield

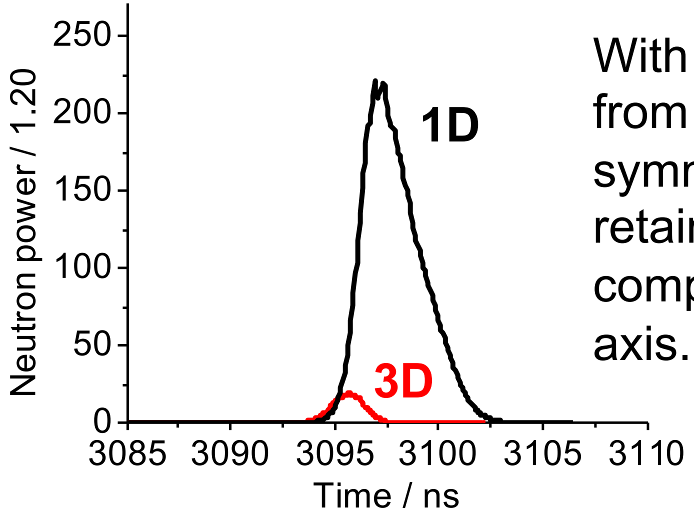
Density Profile at Peak Neutron Emission

Synthetic Ar Image



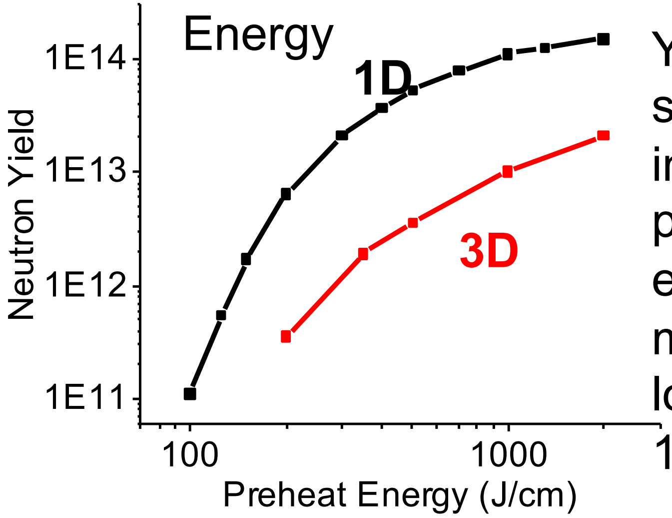
Z2613





With departures from cylindrical symmetry we retain only initial compression on axis.

Yield vs Preheat Energy



Yield still scales with increasing preheat energy, but magnitude lowered from 1D equivalent

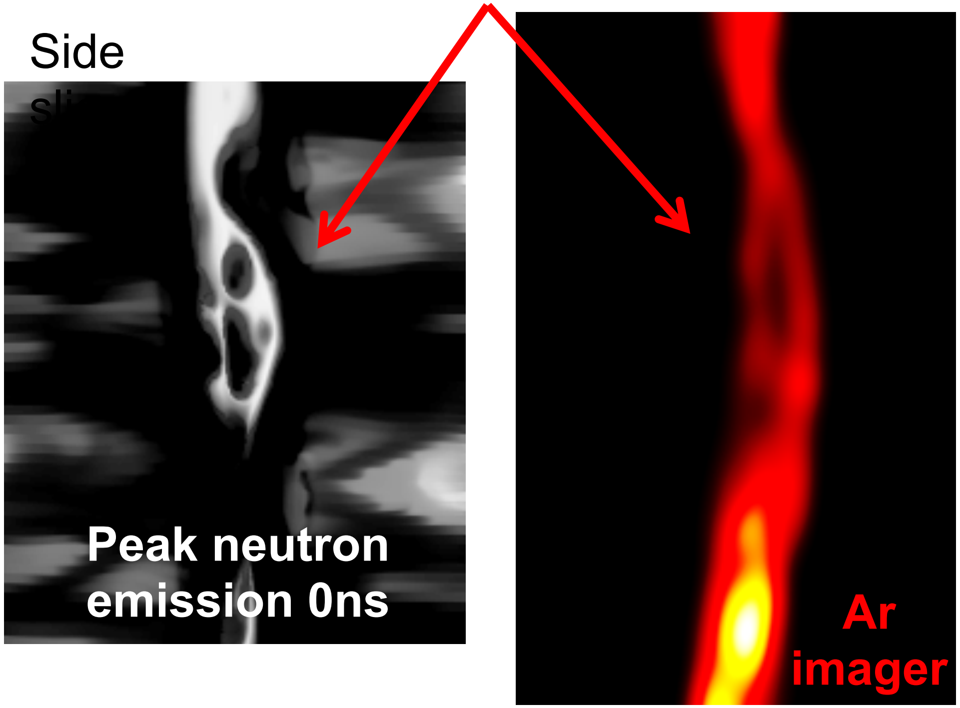
Azimuthal liner structure is not effectively decelerated against compressed fuel.

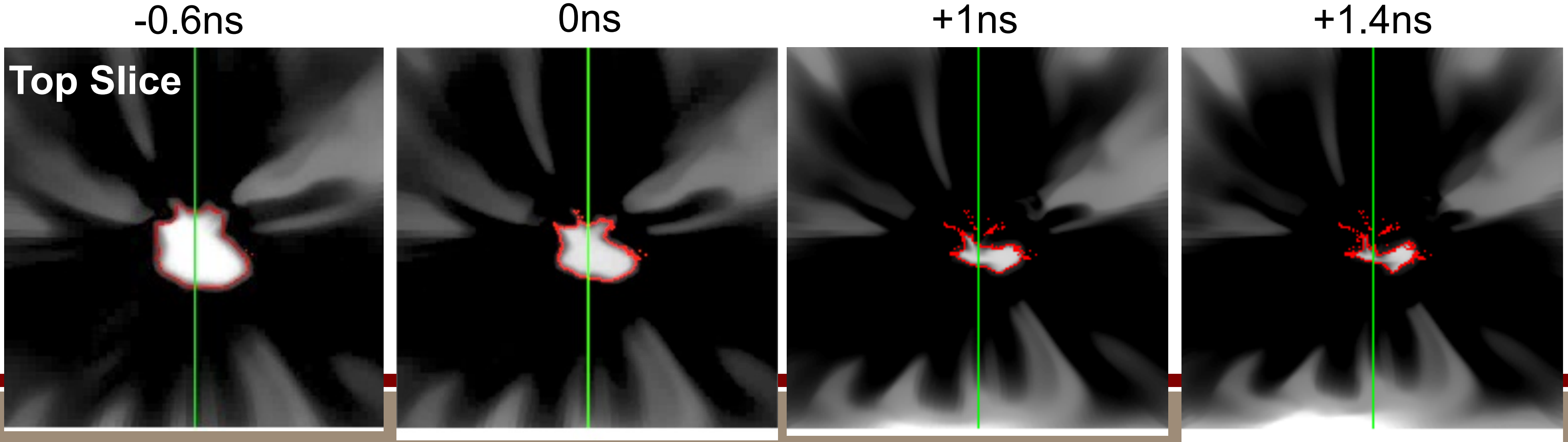
Spikes of liner material can penetrate through fuel

- Reduces fuel compression (liner can decelerate against liner)
- Increases surface area to thermal losses.
- Mixes cold fuel and liner material into hot fuel.

Fuel volume can be bisected creating bifurcated structures evident is some of the Ar imaging

Side

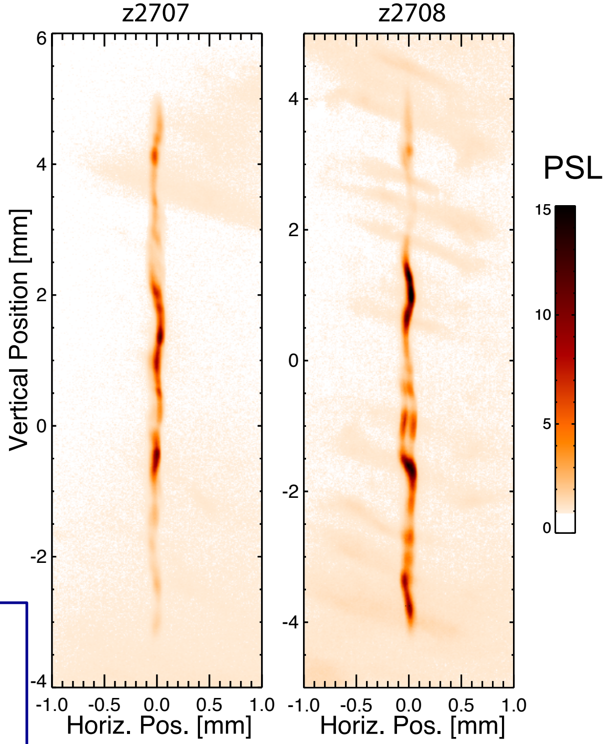


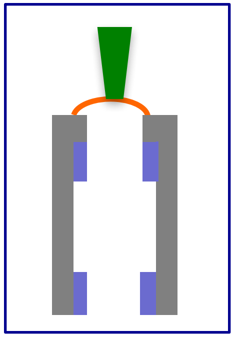


The emission morphology from nearly identical targets can vary, but DD yields are similar.

Y_{dd} = 2.8e11
I_{var} = 0.87
I_{ave} = 2.1 PSL

Y_{dd} = 1.8e11
I_{var} = 0.716
I_{ave} = 5.0 PSL

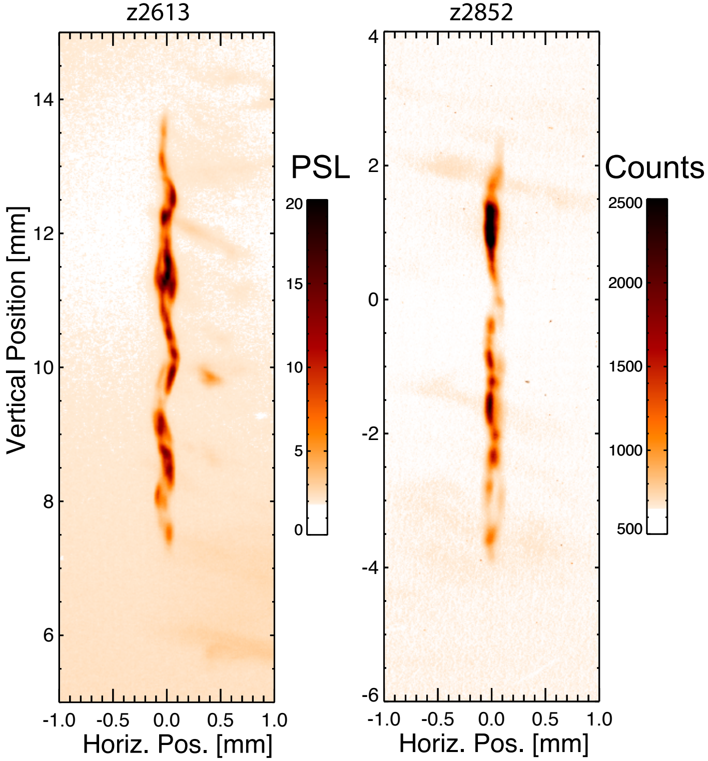


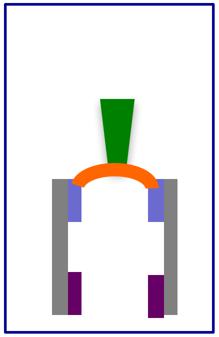


z2707 and 2708 were identical targets.
Long Be liner, thin window, and Al caps

Y_{dd} = 1.1e12
I_{var} = 0.541
I_{ave} = 5.3 PSL

Y_{dd} = 2.0e12
I_{var} = 1.0
I_{ave} = 528 counts

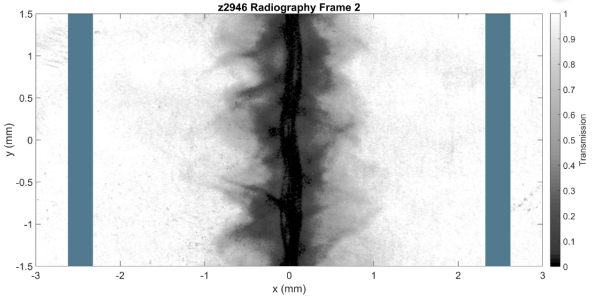


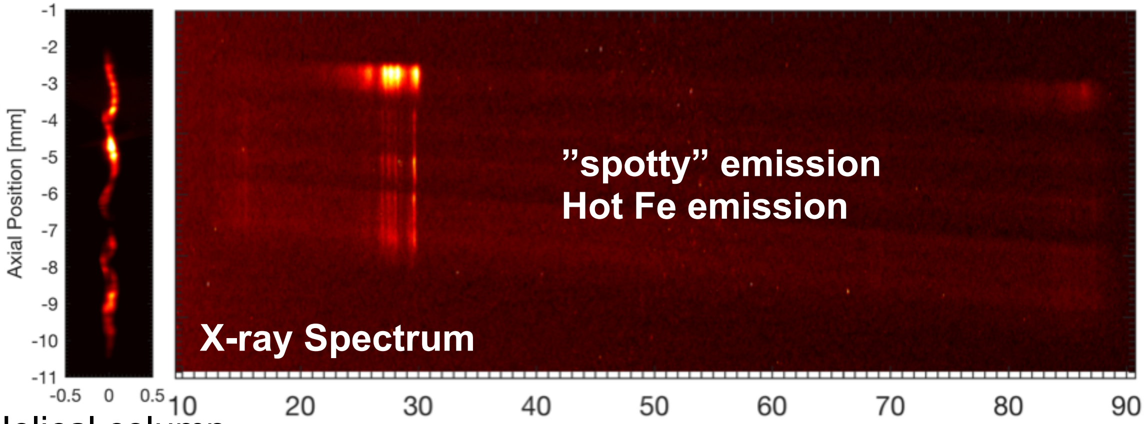


z2613 and 2852 were nearly identical.
Both were short liners with thick windows.
z2613: Al top cap, Nylon bottom, 2 mm exit hole
Z2852: Al top cap, Be bottom, 3 mm exit hole

ETI Coatings improve stagnation morphology, but reduce ion temperature and yield

No coating





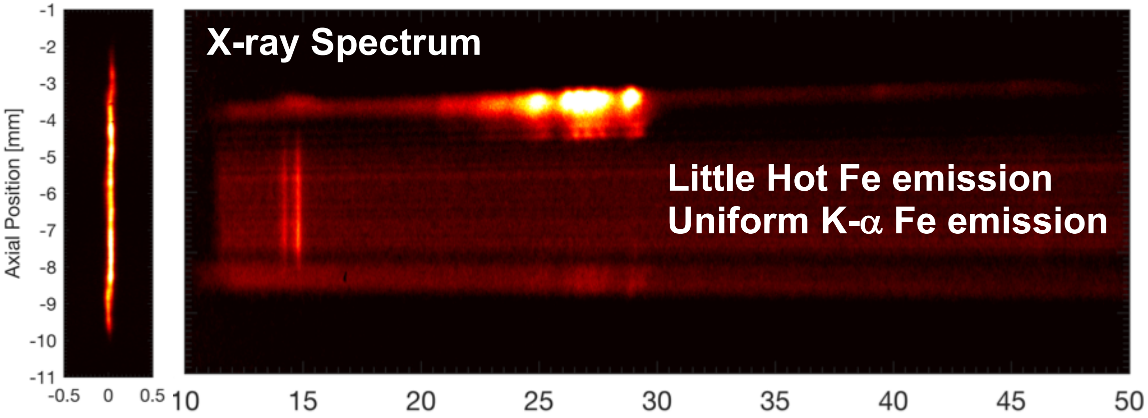
”spotty” emission
Hot Fe emission

X-ray Spectrum

Helical column
Highly variable intensity

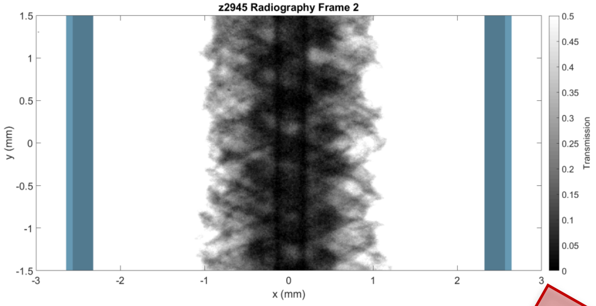
Despite ”improved” morphology, neutron yield and ion temperature decreased

Much straighter column
Uniform brightness



X-ray Spectrum

Little Hot Fe emission
Uniform K-α Fe emission



w/ dielectric coating

Implosion only experiments

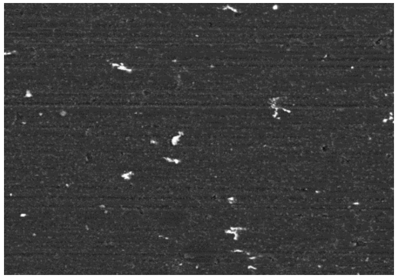
Integrated experiments

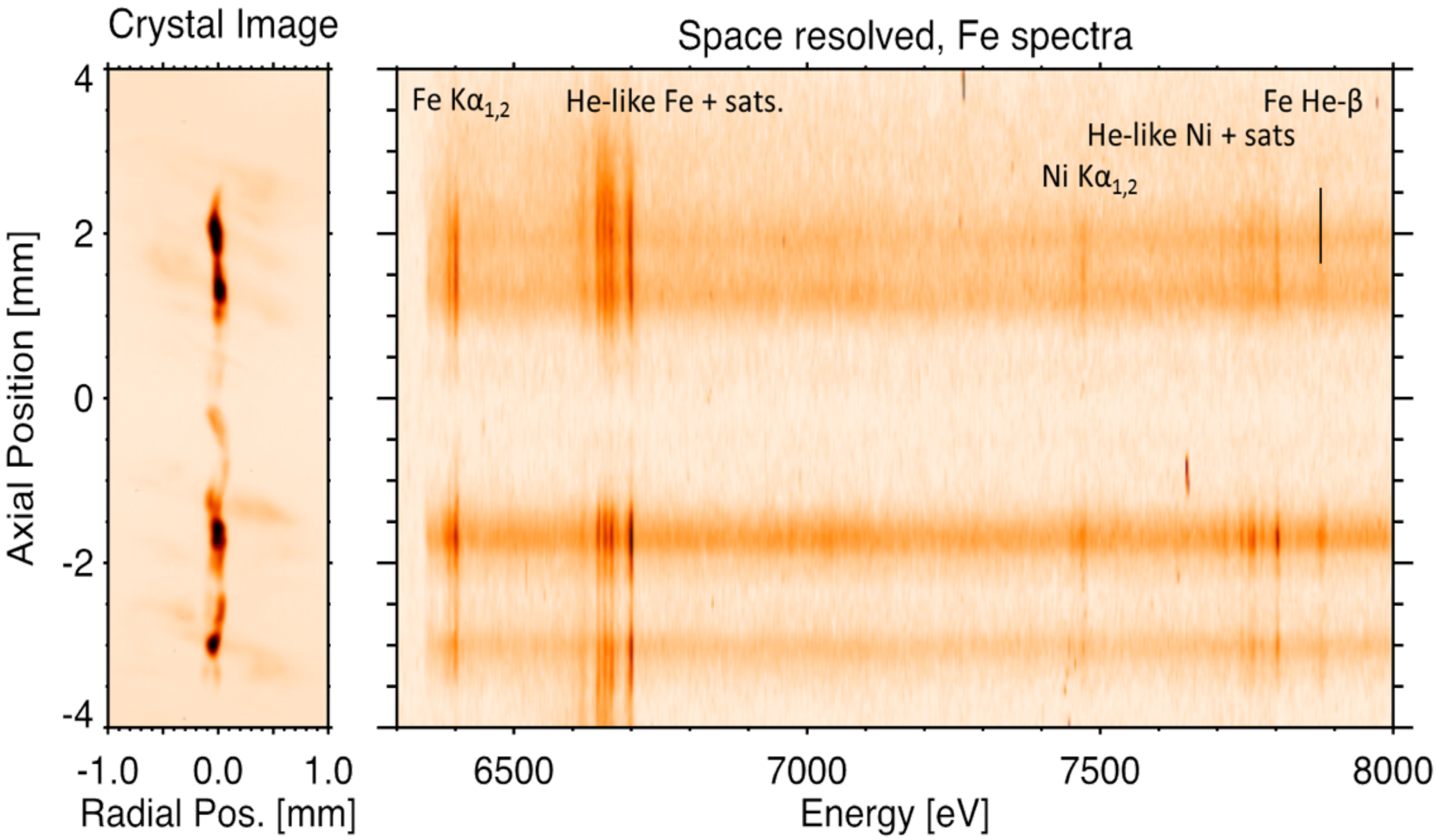
Radiographs provided by Tom Awe and Dave Ampleford

Fe impurities from the Be liner/endcap mix into the stagnation column and provide an axially-resolved diagnostic of the plasma.

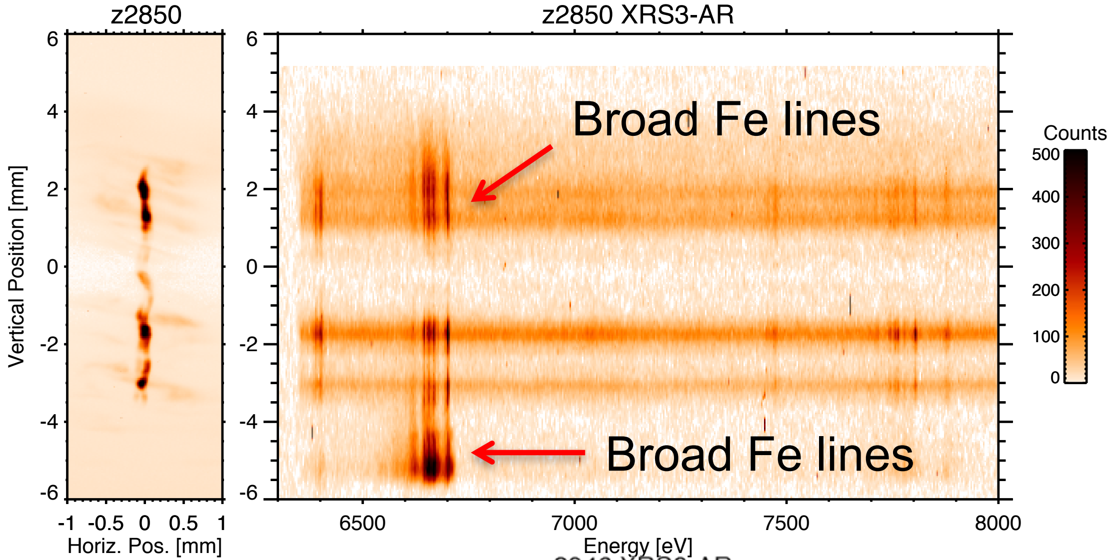
MagLIF liner machined out of S65 Be (100 ppm Fe)

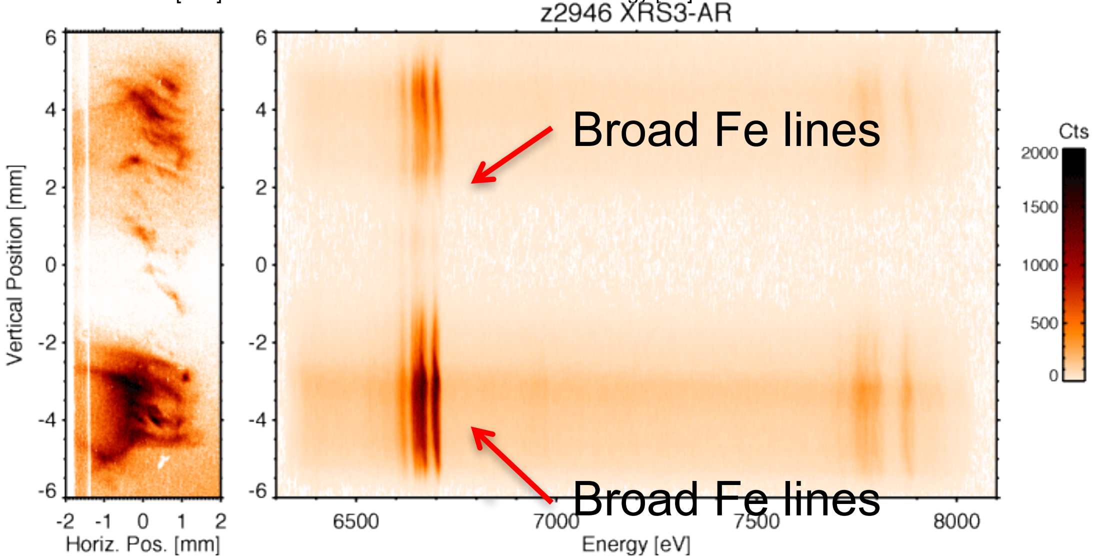
SEM image of the Be liner outer surface





We are seeing Fe emission from *outside* the liner. This emission occurs after stagnation and could be gated-out with 1 ns time resolution. Removing this emission would simplify the analysis of the Fe spectra from *inside* the liner.





Full MagLIF shot (z2850),Y_{DD} = 3e12:
Fe spectral lines near the top and bottom of the target appear broadened.

Implosion only shot (z2946), no laser heating:
No stagnation column but there are strong Fe signals appearing near the ends. This spatially broad source of Fe emission maybe contaminating other shots like z2850.

Backups