SAND2022-5815C

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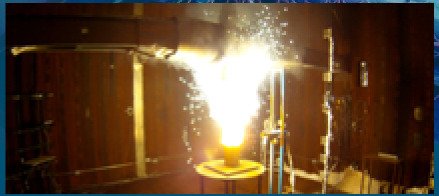
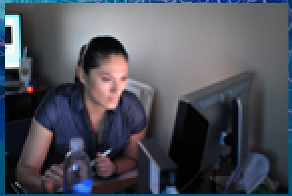
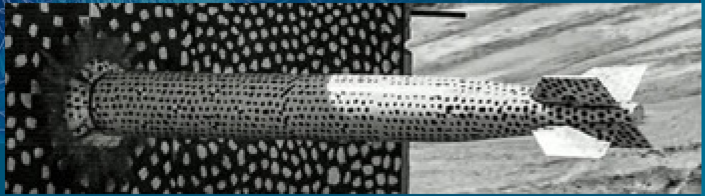
Assessment of Mix in MagLIF Experiments using an Analytic Hotspot Model







PRESENTED BY

Patrick F. Knapp

November 5, 2018

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Thanks to my many colleagues and contributors

[1]M.E. Glinsky, [5]M.R. Evans, [1]C. A. Jennings, [1]E. C. Harding, [1]A. J. Harvey-Thompson, [1]M. R. Gomez, [1]S. B. Hansen, [1]K.D. Hahn, [1]G.A. Chandler, , [1]M. Geissel, [1,7]C. Ruiz, G. Cooper, [1]S. A. Slutz, [1]R. W. Lemke, [1]M. R. Martin, [1]K.D. Cochrane, [1]I.C. Smith, [1]M. Schollmeier, [1]P.K. Rambo, [1]R. A. Vesey, [4]A. B. Sefkow, [6]R. D. McBride, [1]T. J. Awe, [1]P. F. Schmit, [1]D. B. Sinars, [1]M. E. Cuneo, [2]M. C. Herrmann, [3]C. W. Nakhleh, [2]B. E. Blue, [4]E. M. Campbell, [1]M. Jones, [1]J. L. Porter, [1]G. A. Rochau, [1]K. J. Peterson, [1]W. A. Stygar, [1]T.R. Mattsson, [1]M.P. Desjarlais, [1]J. S. Lash, [1]M. K. Matzen,[1] ***and many more…***

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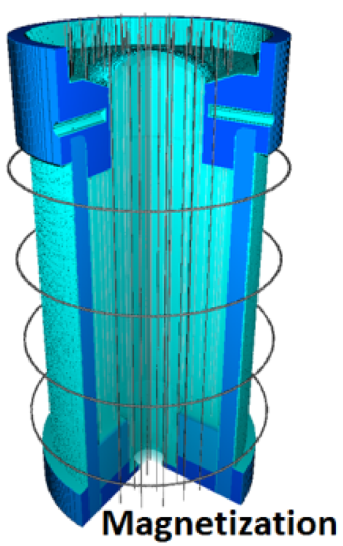
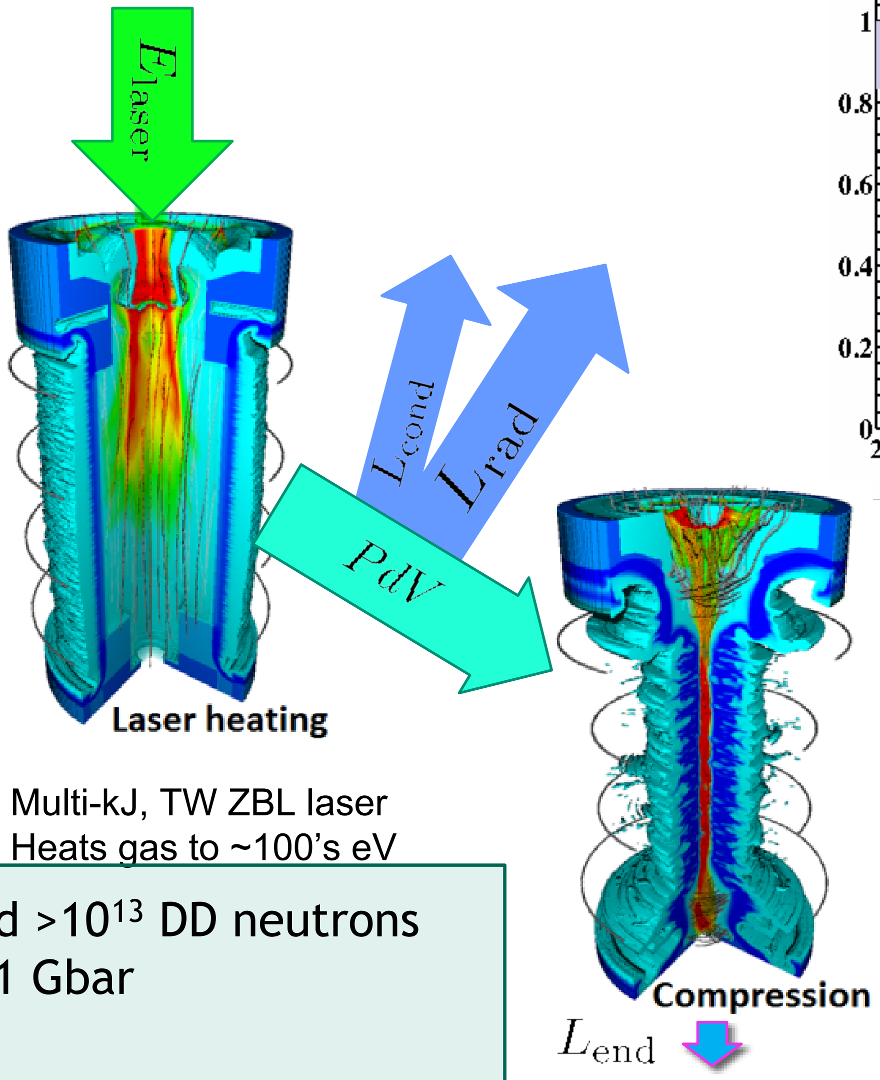
[7]Nuclear Engineering Department, University of New Mexico, Albuquerque, NM

MagLIF uses preheat, magnetic insulation and adiabatic compression to achieve high pressure

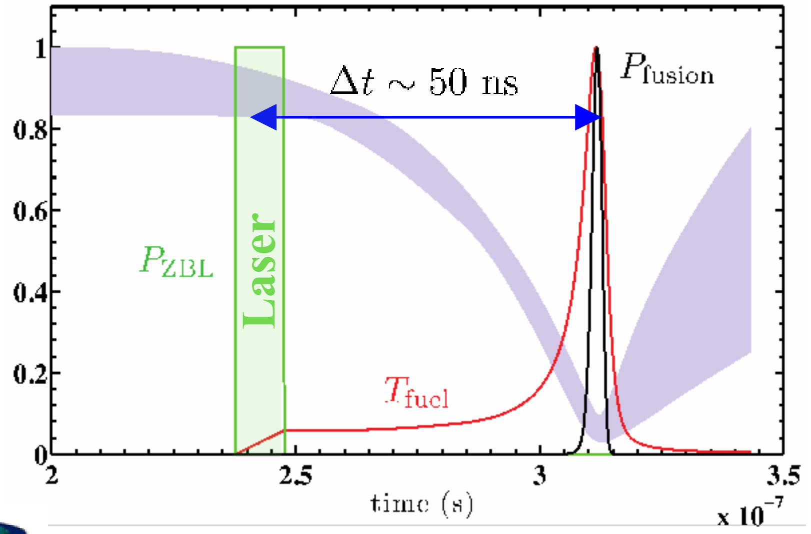


- D_2 gas ~ mg/cc
- 10-30 T, 3 ms risetime



- Multi-kJ, TW ZBL laser
- Heats gas to ~100's eV

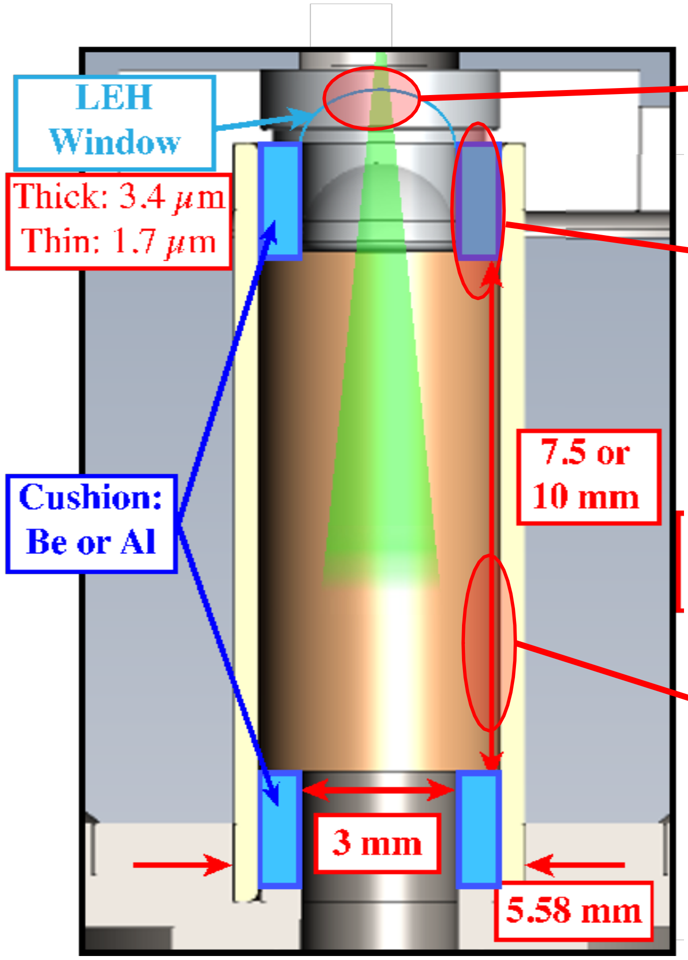
Recently achieved >10^{13} DD neutrons
E_{ph} > 1 kJ, P_{HS} > 1 Gbar
T_{burn} ~3 keV



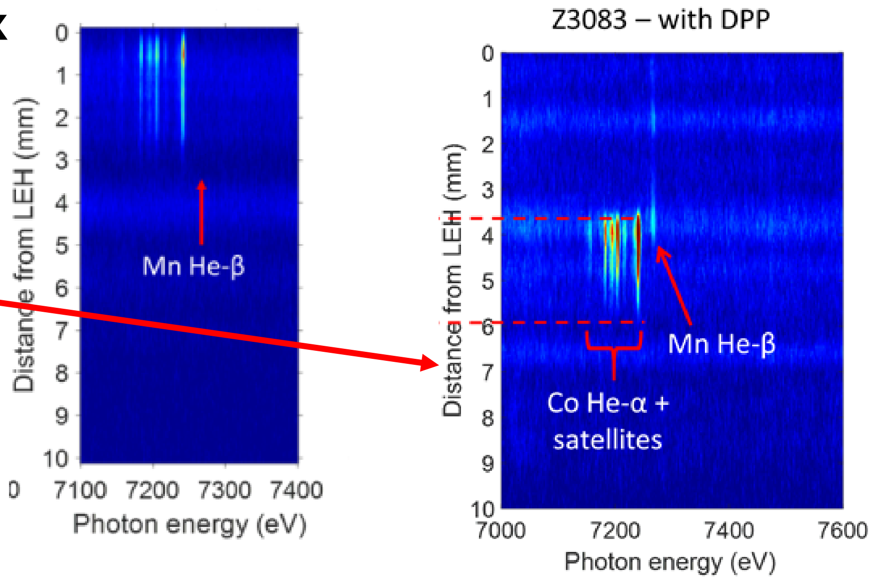
- Laser heating allows high pressures to be achieved with low implosion velocity (<100 km/s)
- Preheat energy is contained during implosion via magnetic insulation
- Flux compression allows confinement of fusion products with low fuel ρR
- Long dwell time between preheat and stagnation makes us sensitive to early time mix

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

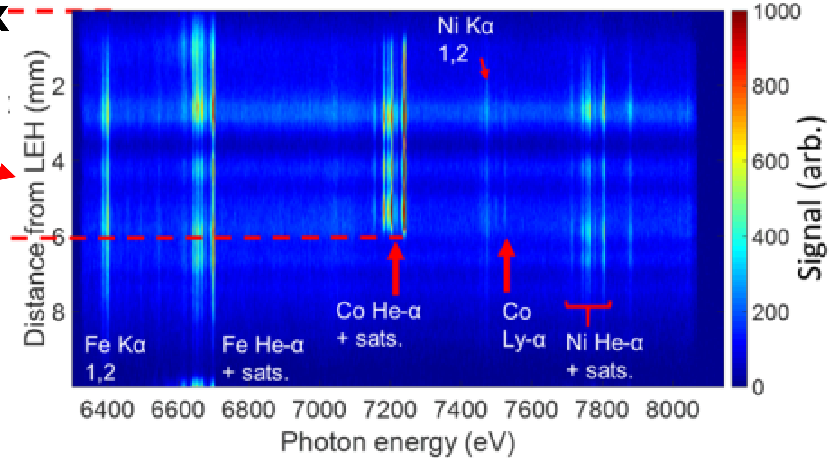
Mix is known to occur, but the total amount and relative contributions from potential sources is poorly understood



Co coatings used to analyze window and cushion mix



Fe impurity in Be used to analyze liner mix



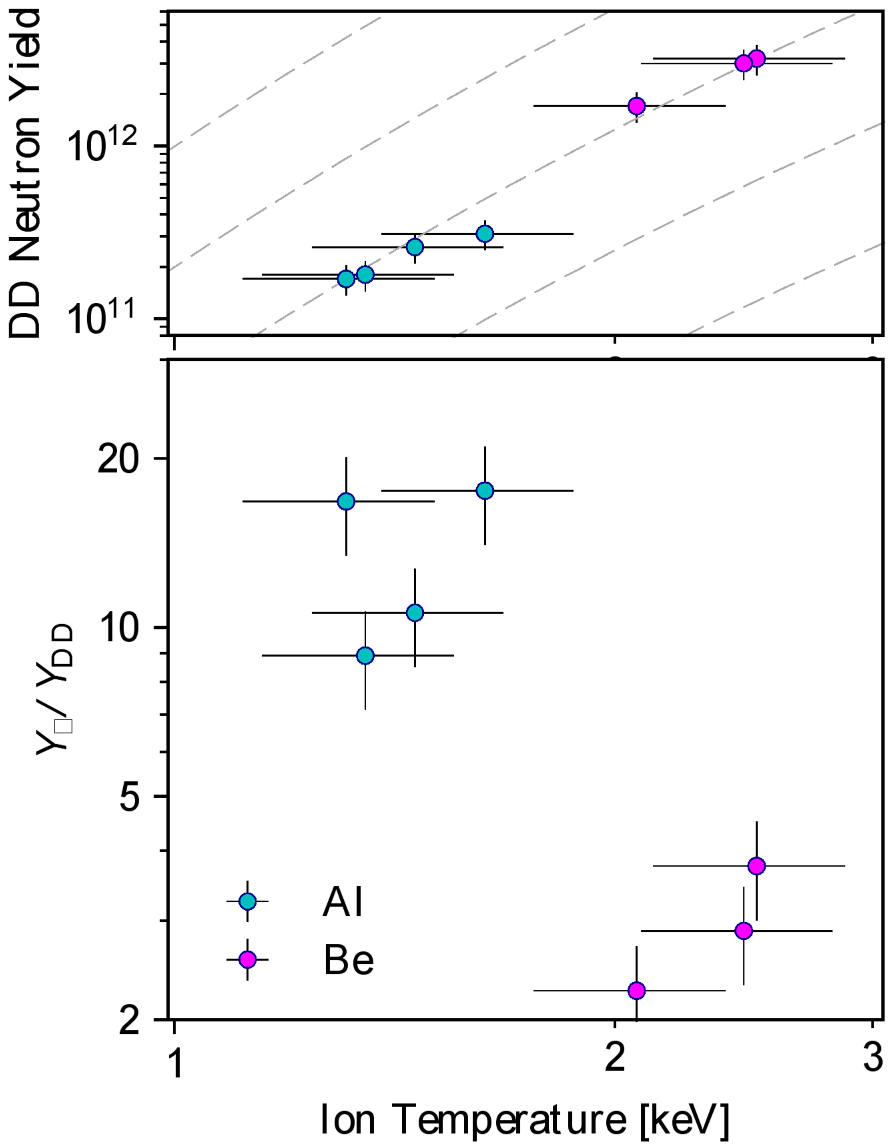
Main Contributors to mix

- Preheat
  - Window
  - Cushion
- Implosion
  - Liner

See related presentations
KI3.00002: Adam Harvey-Thompson
GP11.00126: Matthias Geissel

Harvey-Thompson et al., Phys. Plasmas (accepted)

We have analyzed a series of experiments that isolate the effect of mix from the cushions

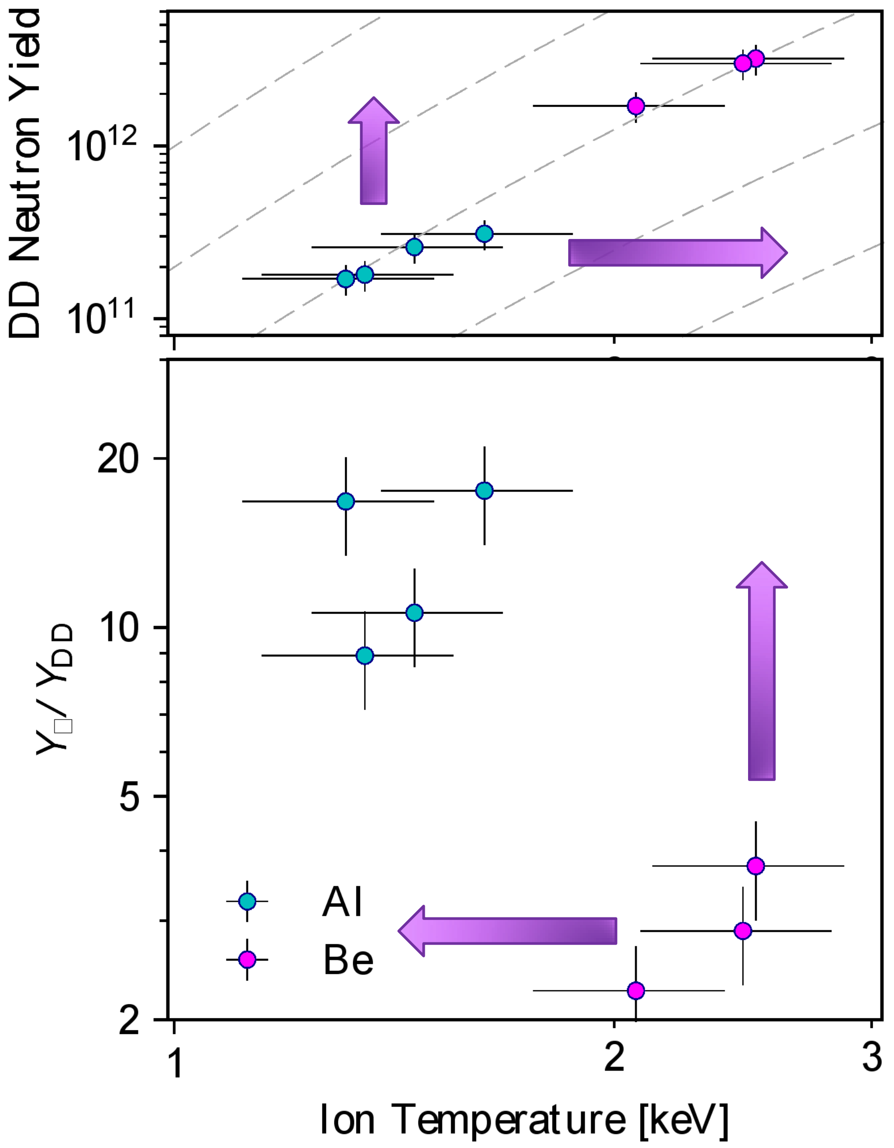


No DPP, 10 mm tall target, 1.7 μm thick window 60 PSI D_2 fill

Z Shot #	Cushion Material	E_{PH} [kJ]	Y_{DD} (±20%) $\times 10^{12}$	Y_{ν} [J]	T_i [keV]
z2707	Al	0.3+1.8	0.3	3.1	1.5
z2708	Al	0.4+2.3	0.2	3.2	1.3
z2758	Al	0.4+1.8	0.3	6.1	1.6
z2985	Al	0.6+2.1	0.2	1.8	1.4
z2839	Be	0.4+2.3	3.2	13.5	2.3
z2977	Be	0.4+2	3.0	9.7	2.5
z2979	Be	0.3+1.8	1.7	4.3	2.2

- Increased neutron yield is strongly correlated with higher temperatures
- Increased x-ray yield relative to neutron yield is strongly correlated with lower temperatures
- Be cushion experiments (magenta) are clustered in the higher yield, higher T, lower x-ray yield range
- Al cushion experiments are clustered in the opposite space
- All strongly suggests cushion mix in the Al case is a major contributor to the degraded performance

In this configuration there is a significant difference in performance between the Al and Be cushion cases



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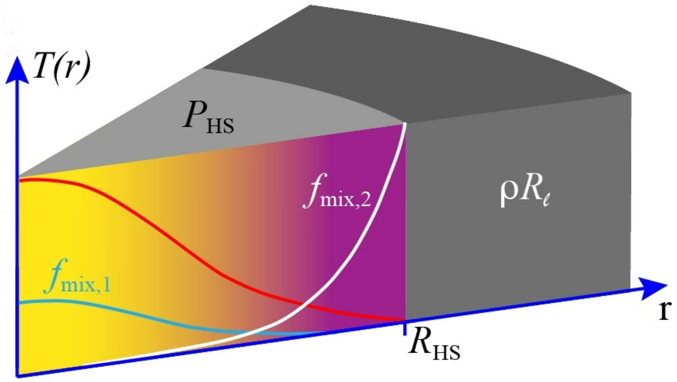
We have developed an analytic hotspot model to analyze and interpret these results

Model the stagnation as a 1D isobaric cylinder



Model Parameters

T_c

P_{HS}

V_{HS}

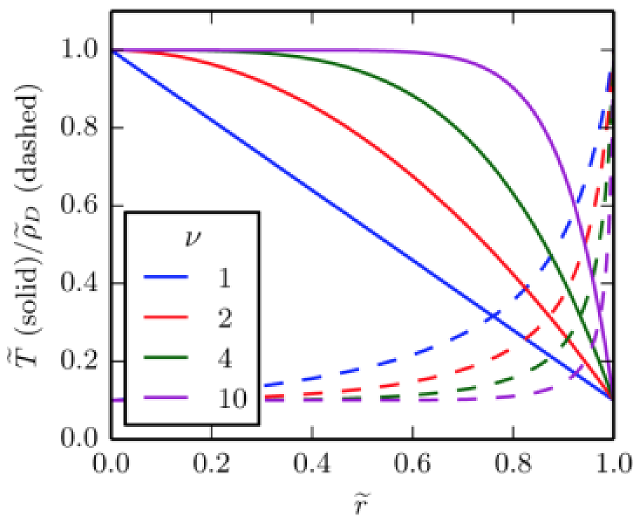
f_{mix}; Z_{mix}

τ_ν^ℓ

τ_{burn}

- In order to infer the stagnation parameters, we must account for the x-ray and neutron emission consistently
- By defining an isobaric cylinder with a prescribed (physically motivated) temperature profile (T_i=T_e)we can calculate all of the required diagnostic outputs

Prescribed temperature profile



$$P_\nu = A_{ff} 4\pi P_{HS}^2 e^{-\tau_\nu^\ell} \int_{V_{HS}} \frac{\langle Z\rangle g_{FF}}{(1+\langle Z\rangle)^2} \sum_i f_i \tilde{j}_i \frac{e^{-h\nu/T_e}}{T_e^{5/2}} dV$$

$$\tilde{j}_i \equiv j_i/j_D = Z_i^2 + (A_{fb}/A_{ff})\left(Z_i^4/T_e\right) e^{Ry Z_i^2/T_e}$$

$$Y_{DD} = \frac{1}{2} P_{HS}^2 \tau_b \int_{V_{HS}} \frac{\langle \sigma v\rangle_{DD}}{(1+\langle Z\rangle)^2 T_i^2} dV$$

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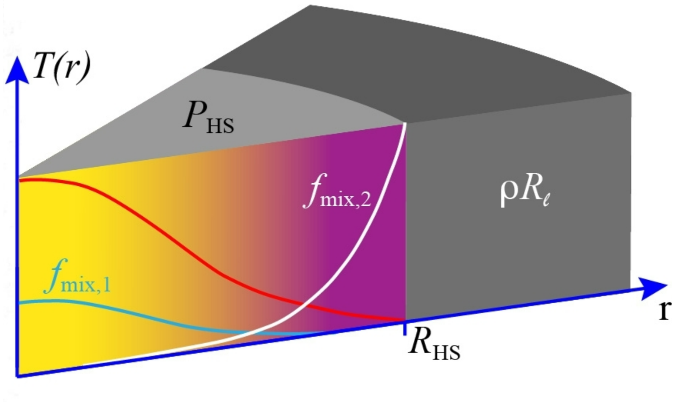

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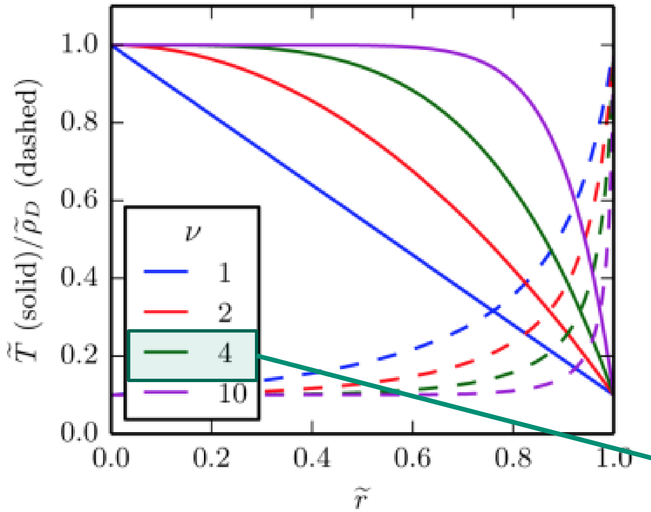

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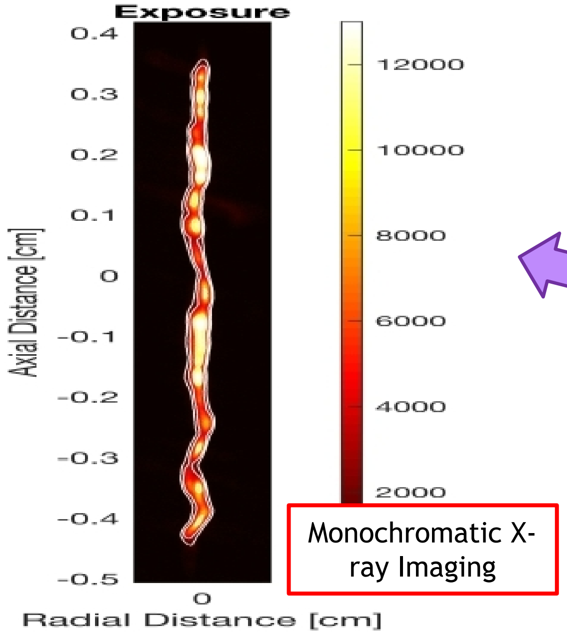
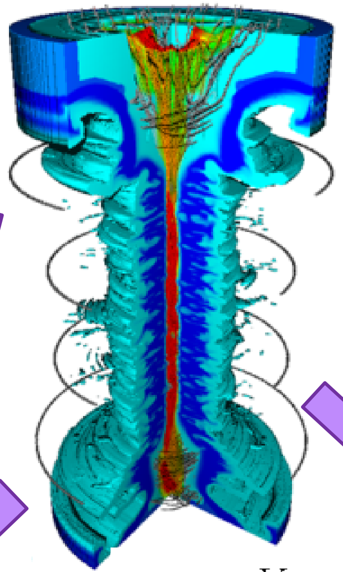
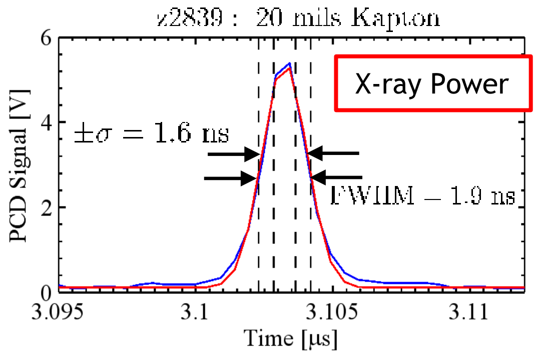
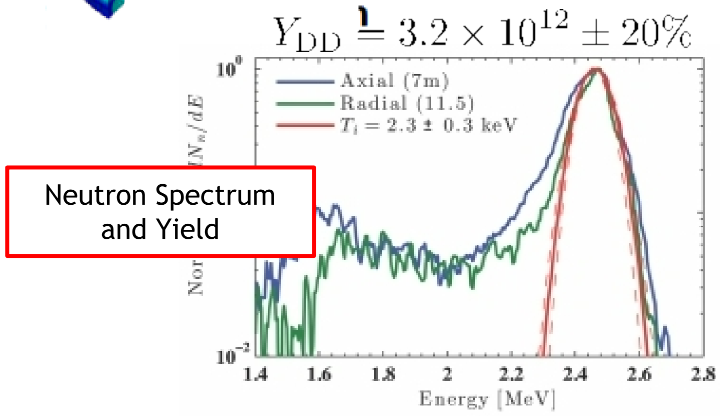
Based on comparison with MHD simulations

Using the available data we can completely constrain the quantities required to infer *bulk* stagnation pressure and mix fraction









- Hotspot Volume:
- X-ray Yield:
- Burn Duration:
- Neutron Yield:
- Burn Temperature:

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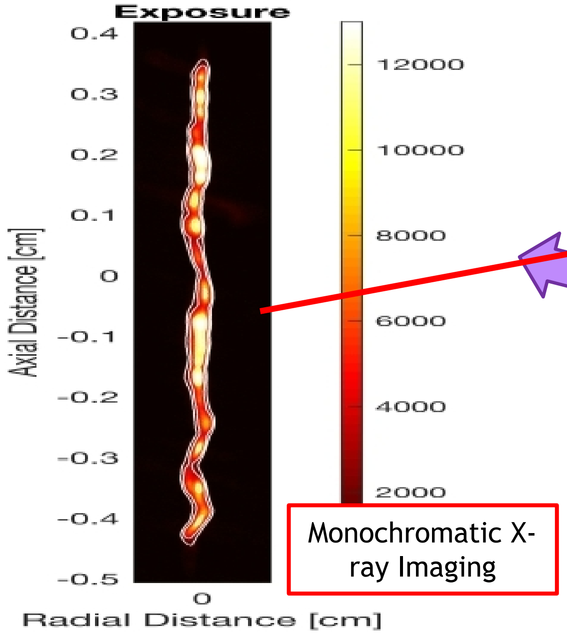

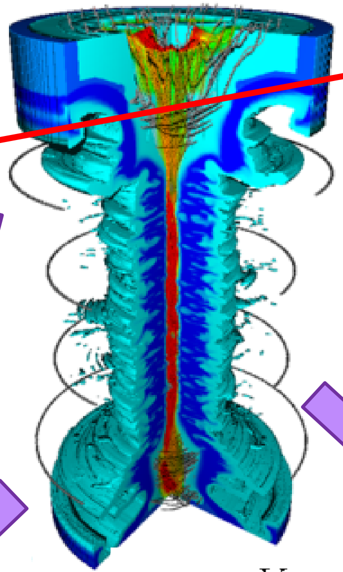

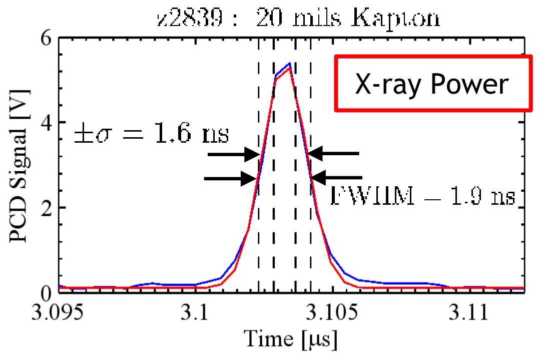

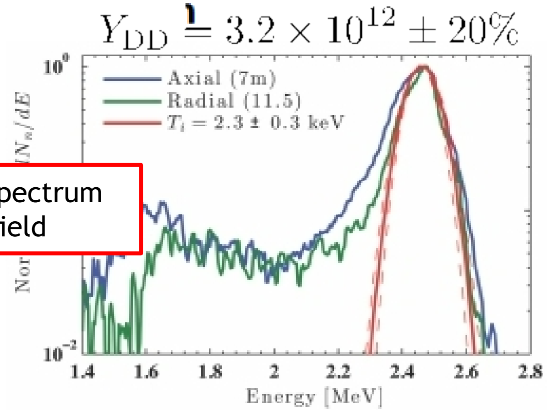

- Hotspot Volume: $V_{HS} \pm \sigma_V$
- X-ray Yield:
- Burn Duration:
- Neutron Yield:
- Burn Temperature:

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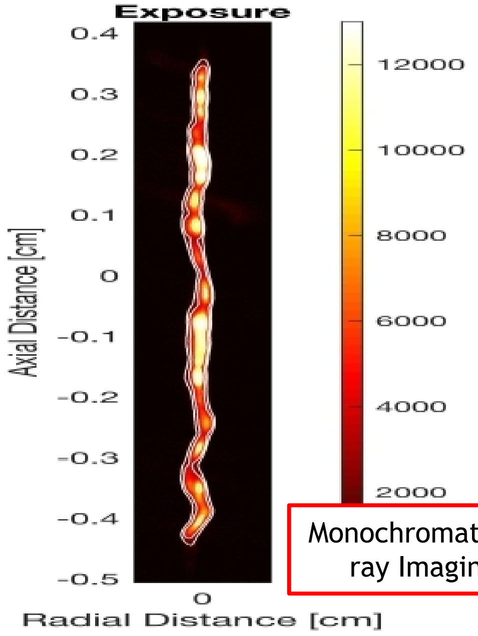
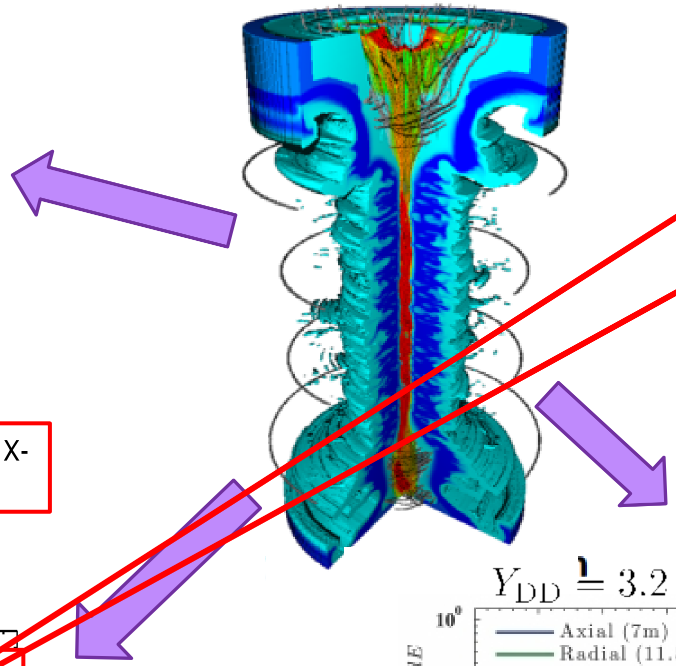
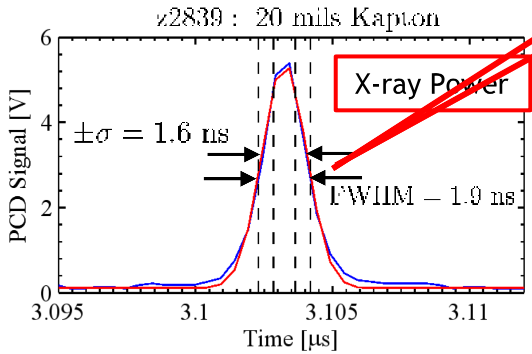
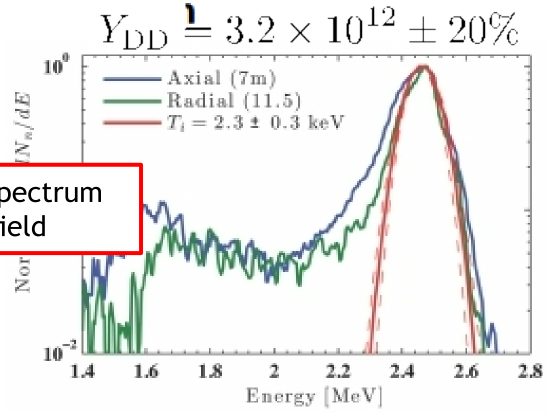


Monochromatic X-ray Imaging





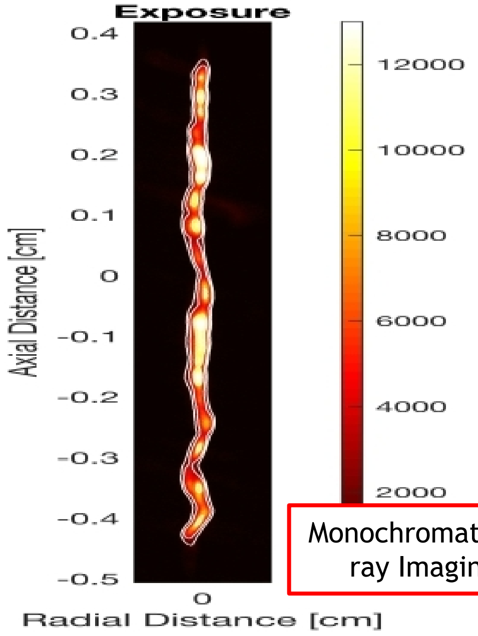
X-ray Power



Neutron Spectrum and Yield

- Hotspot Volume: $V_{HS} \pm \sigma_V$
- X-ray Yield: Y_{PCD}
- Burn Duration: $\tau_b \pm \sigma_\tau$
- Neutron Yield:
- Burn Temperature:

Using the available data we can completely constrain the quantities required to infer *bulk* stagnation pressure and mix fraction



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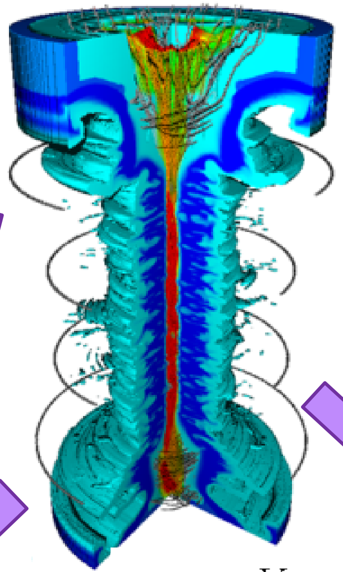
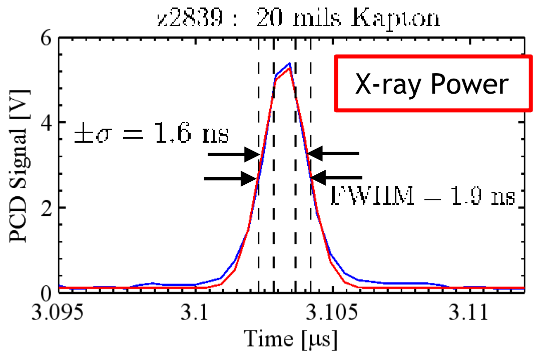


- Hotspot Volume: $V_{\mathrm{HS}} \pm \sigma_V$
- X-ray Yield: Y_{PCD}
- Burn Duration: $\tau_{\mathrm{b}} \pm \sigma_\tau$
- Neutron Yield: Y_{DD}
- Burn Temperature: $T_{\mathrm{c}} \pm \sigma_T$



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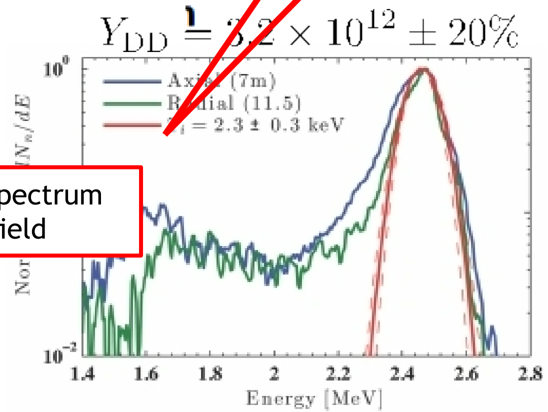

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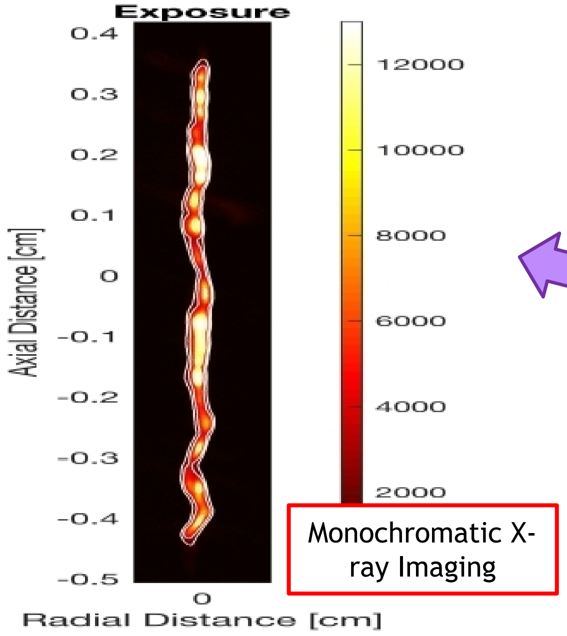
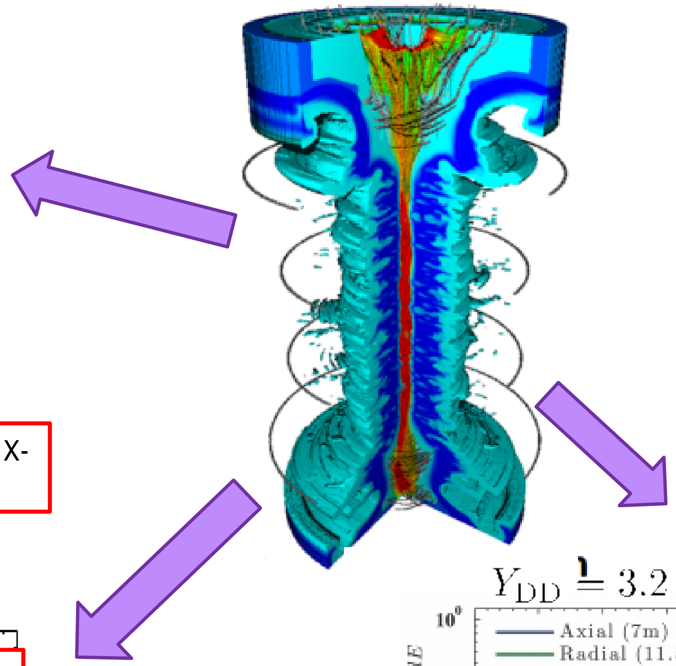
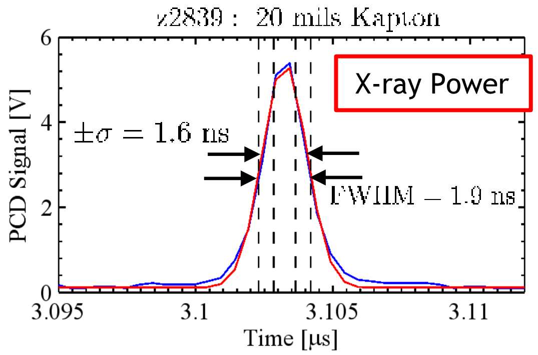
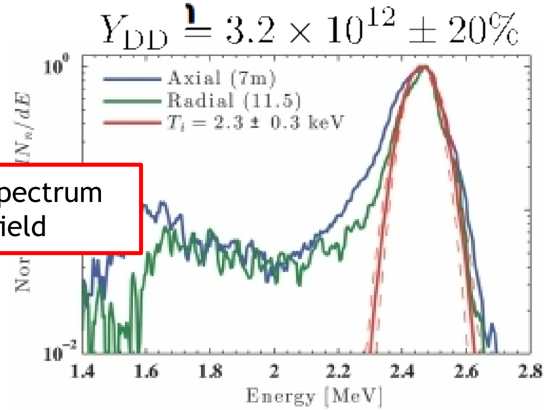








- Hotspot Volume: $V_{HS} \pm \sigma_V$
- X-ray Yield: Y_{PCD}
- Burn Duration: $\tau_b \pm \sigma_\tau$
- Neutron Yield: Y_{DD}
- Burn Temperature: $T_c \pm \sigma_T$

$$\rho R_\ell \pm \sigma_{\rho R}$$

Liner areal density taken as a nominal value from spectroscopic measurements*

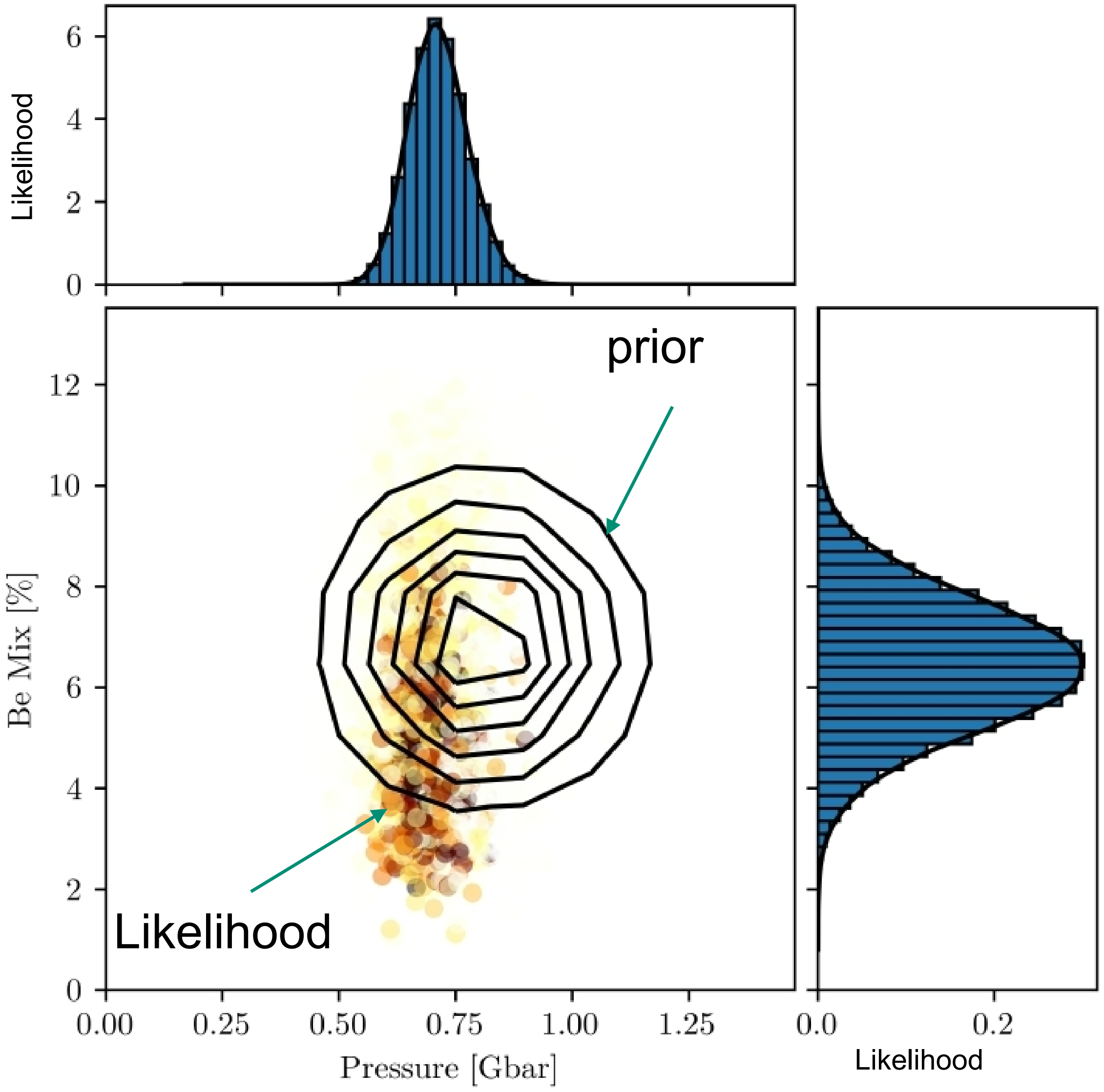
*Hansen et al., Phys. Plasmas 22, 056313 (2015)

By sampling the space of uncertain input parameters we determine the maximum likelihood solution for pressure and mix

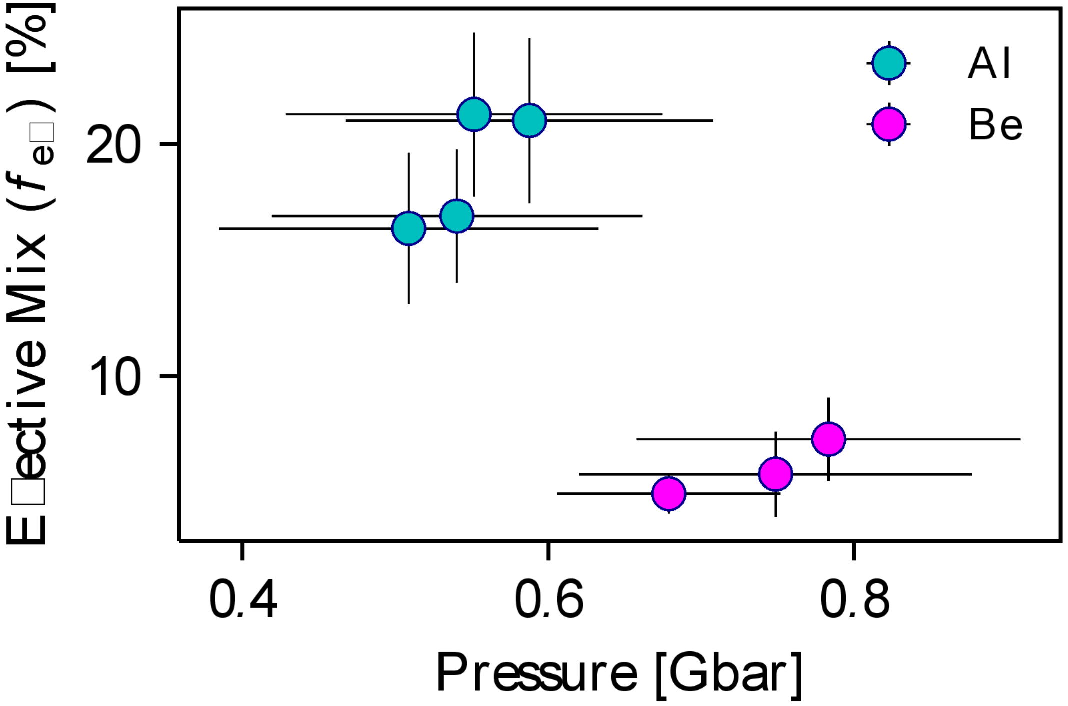
Likelihood

$$\mathcal{P}(\overline{\mathbf{x}}|\overline{\mathbf{m}},\mathcal{A}) = \exp\left(-\sum_i \frac{(\mathcal{F}_i(\overline{\mathbf{m}}) - x_i)^2}{2\sigma_i^2}\right)$$

- The likelihood is defined as the probability of observing the measurement given a particular set of model parameters and our prior knowledge of the system
- This method allows us to efficiently sample a wide range of parameter values, constrained by additional measurements
- Correlations are contained in the likelihood distribution



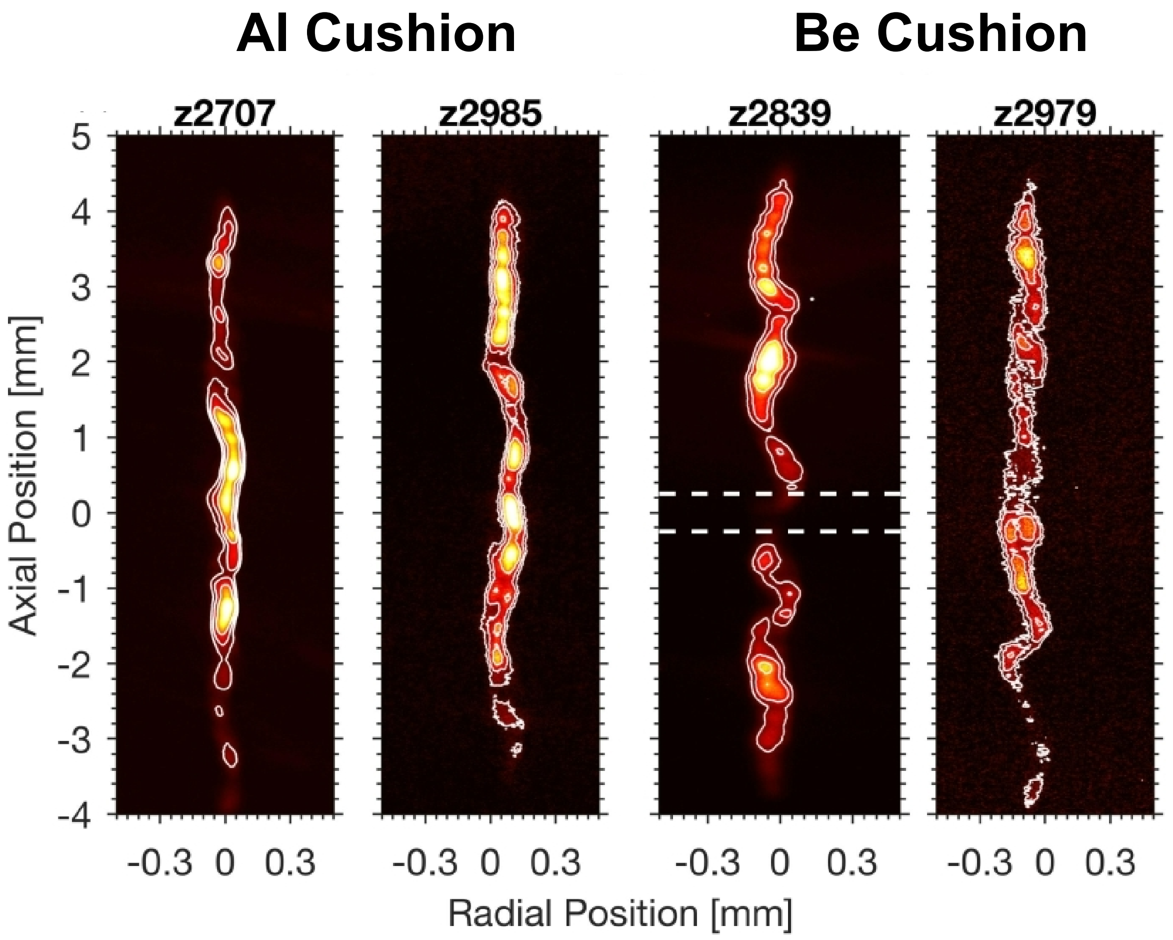
This analysis shows that low mix is strongly correlated with high pressure and the Al and Be cushion shots are clustered



- This analysis determines the stagnation pressure and an *effective* mix fraction (assuming mix is 100% Be)
- The Be cushion shots have, on average
  - 3x less effective mix fraction
  - ~40% higher pressure
- The average hotspot energy is ~50% higher in the Be cushion experiments

$$\langle E_{\mathrm{HS}}^{\mathrm{Al}} \rangle = \langle \frac{3}{2} P_{\mathrm{HS}} V_{\mathrm{HS}} \rangle \approx 7.6 \text{ kJ} \qquad \langle E_{\mathrm{HS}}^{\mathrm{Be}} \rangle = \langle \frac{3}{2} P_{\mathrm{HS}} V_{\mathrm{HS}} \rangle \approx 11.4 \text{ kJ}$$

We can use the similarities between the Al and Be experiments to deconvolve the mix sources from the integrated results



- The morphology and evolution of stagnation appear to be very similar between the high mix and low mix experiments
- Volumes are the same to +/- 20%
- τ_{burn} is the same to +/- 10% (measured with x-rays)
- Laser pulses and LEH windows are nominally identical
- Radiation losses are the only term significantly modified by mix

Exploiting these similarities we can break the mix contribution into three sources and constrain each

$$N_W \approx (500\ \mu m)^2 * \ 1.77\ \mu m \ * n_{ion} \approx 4 \times 10^{16}$$

Mix total: Window + Cushion + Liner

$$f_{eff}^{Be} Z_{Be}^3 = f_W \bar{Z}_{poly}^3 + f_C^{Be} Z_{Be}^3 + f_D Z_{Be}^3$$ Be Cushion

$$f_{eff}^{Al} Z_{Be}^3 = f_W \bar{Z}_{poly}^3 + f_C^{Al} Z_{Al}^3 + f_D Z_{Be}^3$$ Al Cushion

$$N_{fuel} = \frac{P}{kT} \approx 8 \times 10^{18}$$

$$f_W = 0.5 \pm 0.2\%$$

- f_W and f_D are assumed to be the same in the two cases
- 2 equations, four unknowns
  - Constrain f_W using the window thickness and laser spot size
  - Define a relationship between fractions of cushion mix in each case
- The system is fully defined and we can solve for each contribution using the ensemble averages for f_{eff}

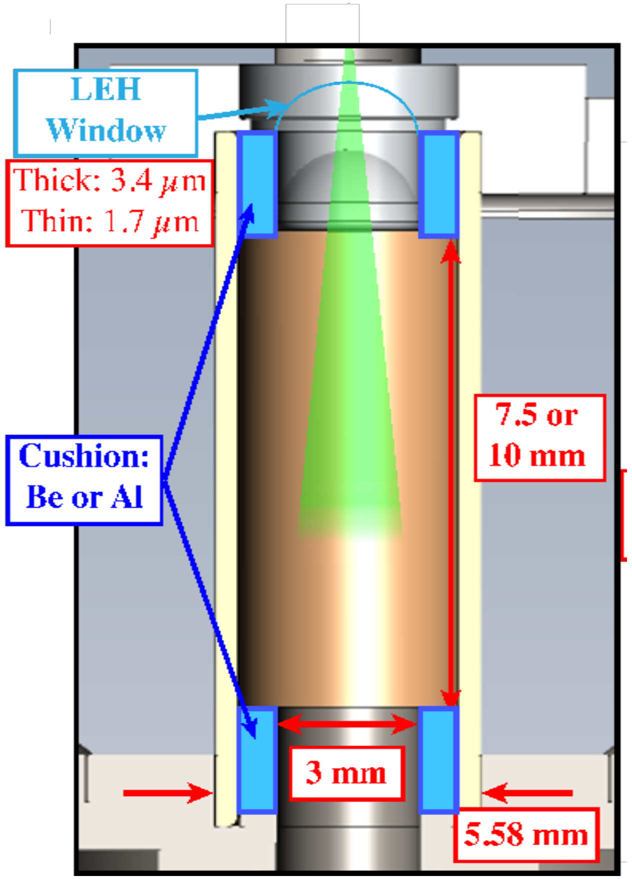
Equal cushion scrape-off mass

$$f_C^{Al} = \frac{1}{3} f_C^{Be}$$

Equal cushion scrape-off volume

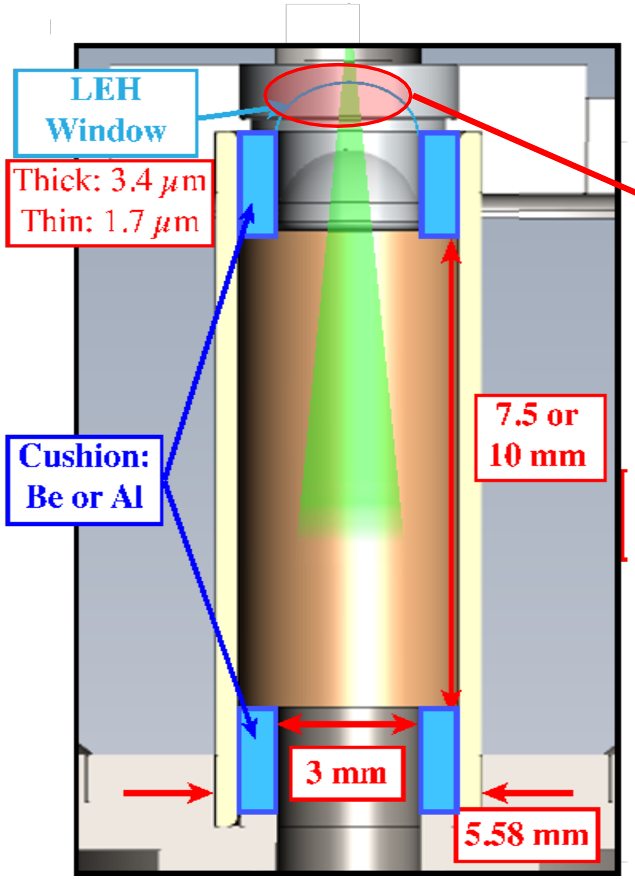
$$f_C^{Al} = \frac{1}{2} f_C^{Be}$$

Summary of contributions from the three potential sources of mix



	Aluminum Cushion at %	Beryllium Cushion at %	mass %
Window	0.5 %	0.5 %	1.8 %
Cushion	0.57 %	1.5 %	6.7 %
Liner	2.6 %	2.6 %	12 %

Summary of contributions from the three potential sources of mix



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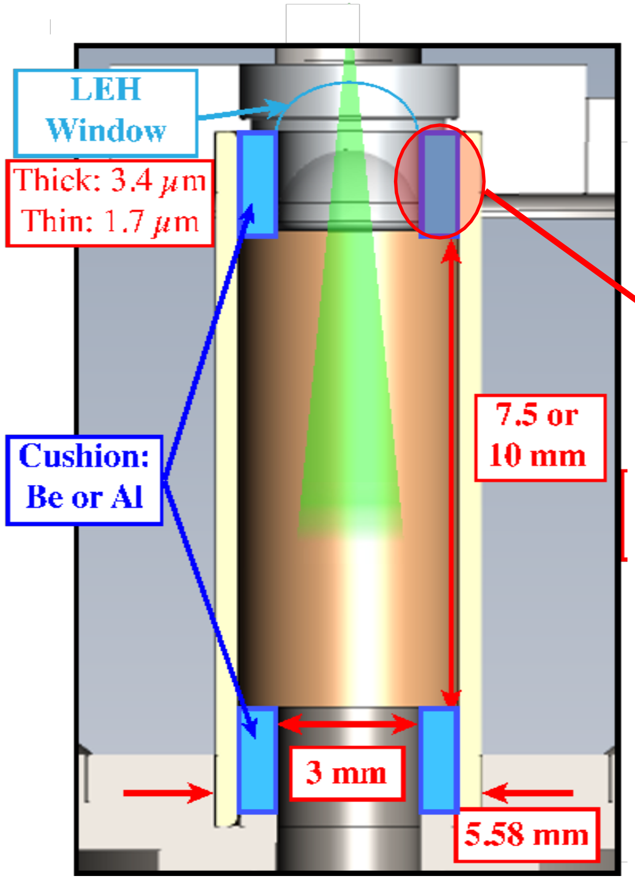
Cushion	0.57 %	1.5 %	6.7 %
Liner	2.6 %	2.6 %	12 %

Summary of contributions from the three potential sources of mix



	Aluminum Cushion at %	Beryllium Cushion at %	mass %
Window	0.5 %	0.5 %	1.8 %
Cushion	0.57 %	1.5 %	6.7 %
Liner	2.6 %	2.6 %	12 %

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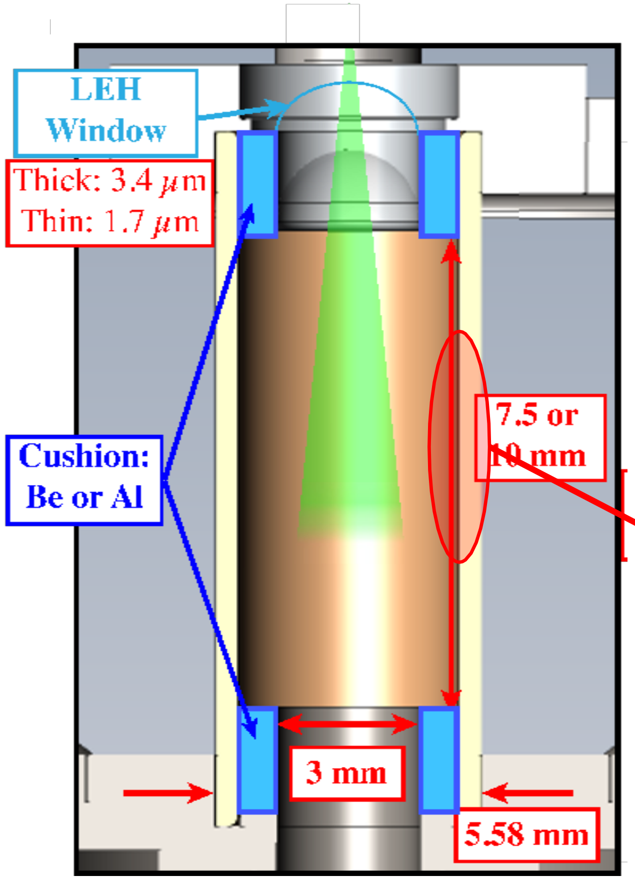

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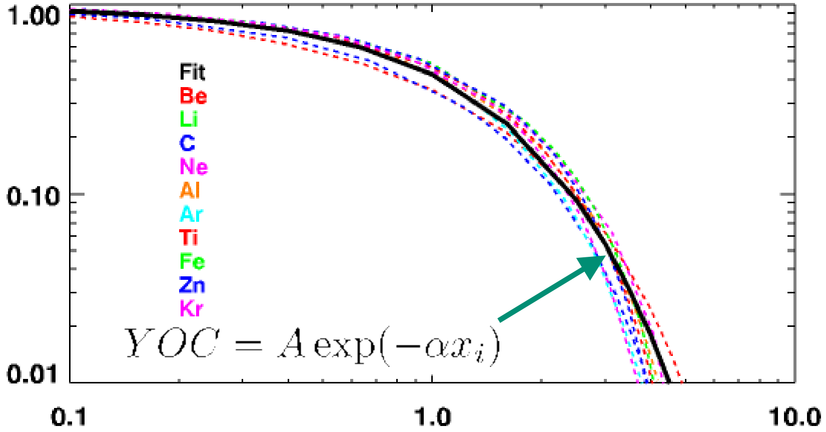
Cushion	0.57 %	1.5 %	6.7 %
Liner	2.6 %	2.6 %	12 %

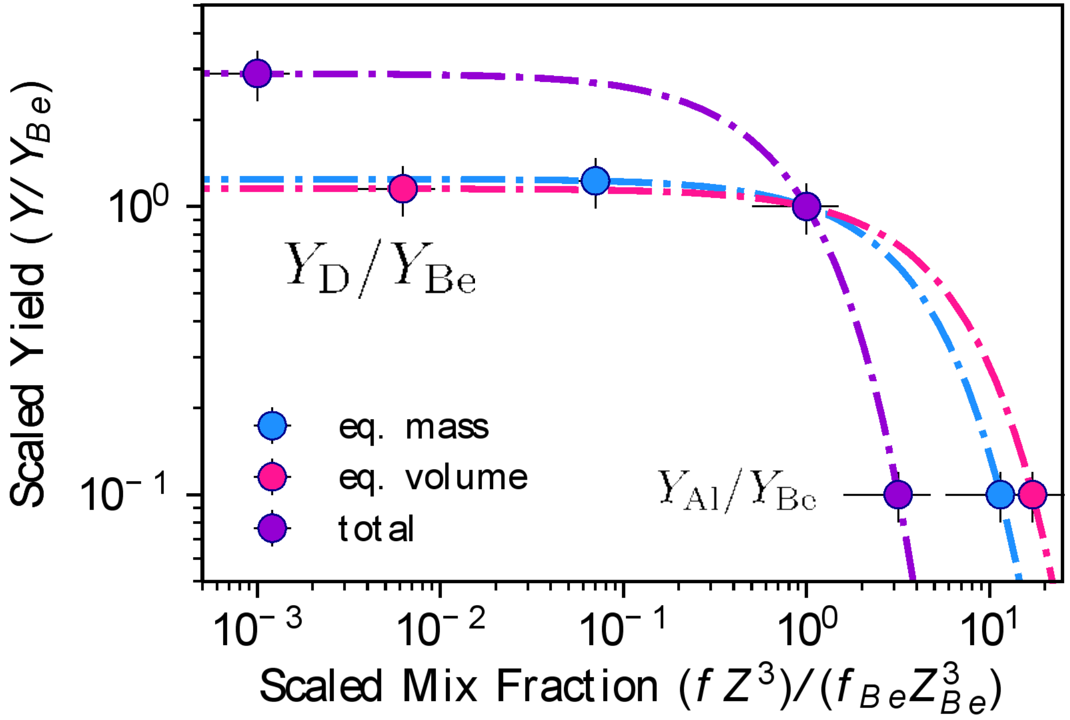
- When cushions are made of Al, they overwhelmingly dominate the degradation
- Liner accounts for >50% of the mix (by atom)
- Simple Z^3 scaling suggests liner mix and window mix are comparable in terms of losses at stagnation
- Window mix is almost certainly worse than liner mix since it is introduced earlier

How much impact does the observed mix fraction have on target performance?



$$x_i = (f_i Z_i^3)/(f_{\mathrm{Be}} Z_{\mathrm{Be}}^3)$$

$$Y_i/Y_{\mathrm{Be}} = A\exp(-\alpha x_i)$$



- Using calculations for pre-mix YOC from Slutz et al. we back out the trend under various assumptions
- We find that replacing the inferred cushion mix with D gives only 15—25% increase in yield
- Removing the entire observed effective mix fraction gives ~3x increase in yield
- Suggests that Be cushion mix in thin window, tall target, unconditioned beam case is not severely limiting performance, but overall mix is

Slutz et al., Phys. Plasmas (accepted)

Conclusions and Future work

- We find that mix is a significant factor in determining target performance
  - When the cushion is made of Be instead of Al yield was increased by ~10x, ion temperature by ~40% and pressure by ~40%
- Mix from the interaction with the laser (cushion + window) accounts for <50% of the observed total
- Here we have inferred bulk averaged quantities, but we know there is significant variation along the stagnation column
  - We are undertaking a detailed analysis of the data that attempts to account for 2D and 3D variations using the Bayesian Analysis*
  - We are working on incorporating 1D neutron imaging into the analysis**
  - A high fidelity nuclear burn history measurement would be a valuable addition
- We expect that mix from different sources will be distributed differently. We will address the *radial* and axial distributions of mix as part of the ongoing effort

*NP11.00138: Patrick Knapp (Wednesday)
**GP11.00094 : Jeremy Vaughan (Tuesday)
**GP11.00132: Dave Ampleford (Tuesday)