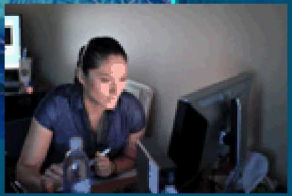
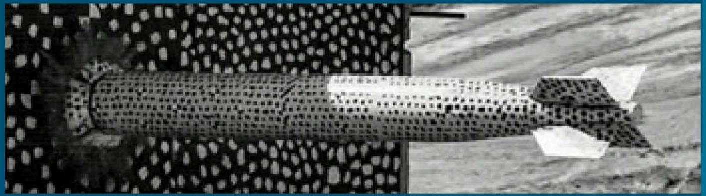
SAND2019-13732PE

Magneto Inertial Fusion (MIF) Hotspot Diagnostics and analysis





PRESENTED BY

Patrick Knapp

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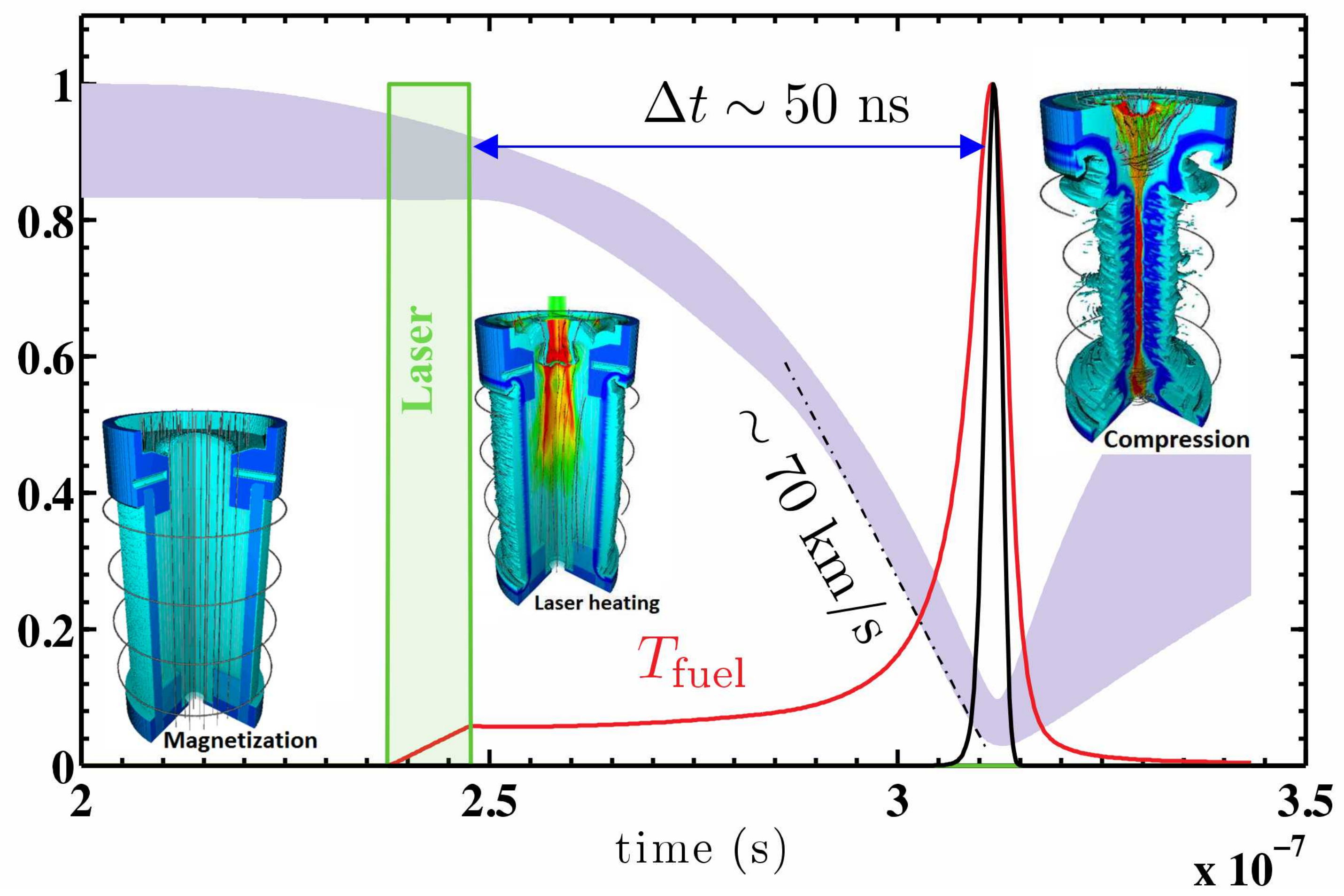
Magnetization and preheat reduce peak velocity required for ignition compared to traditional ICF



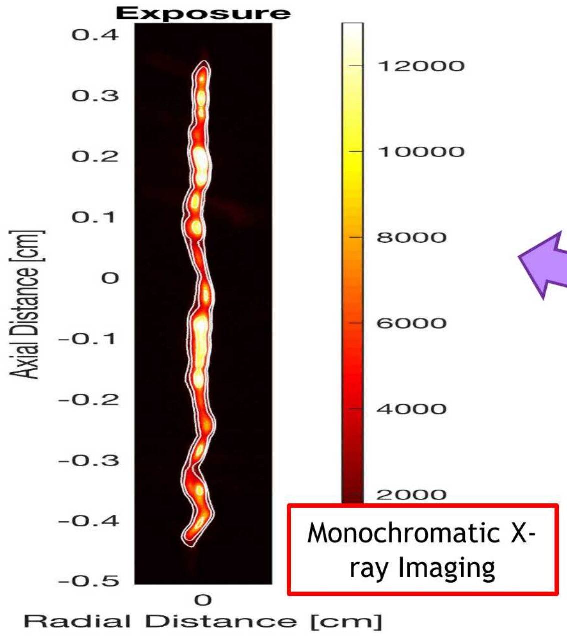
Magnetization confines 3.5 MeV α-particles at lower ρR

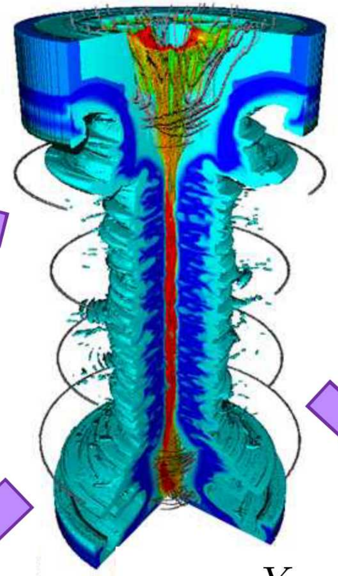
Preheating + magnetization allows ignition temperature to be reached at a lower implosion velocity[1]

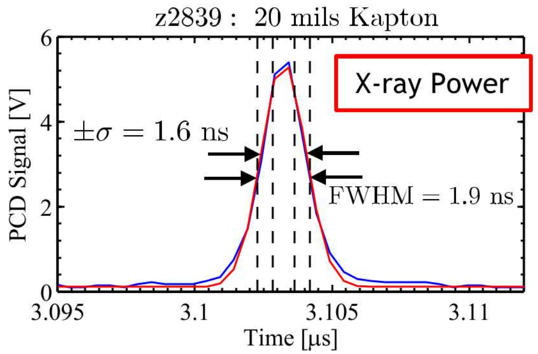
Calculations show MagLIF scales to high yield and gain[1,2]

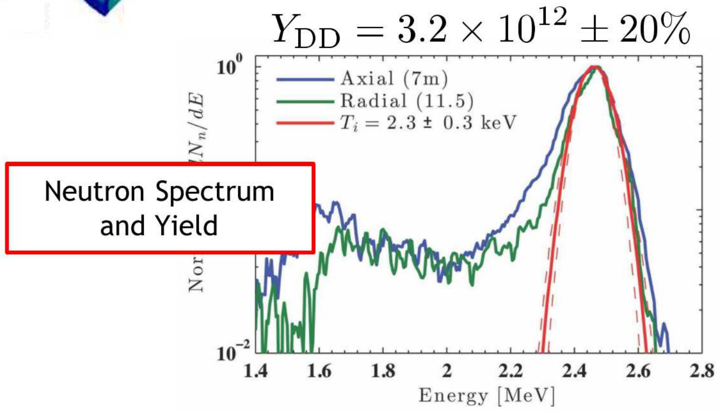
[1] S. A. Slutz, *et al.*, Phys. Plasmas **17** 056303 (2010)
[2] S. A. Slutz. and R.A. Vesey, PRL **108**, 025003 (2012)

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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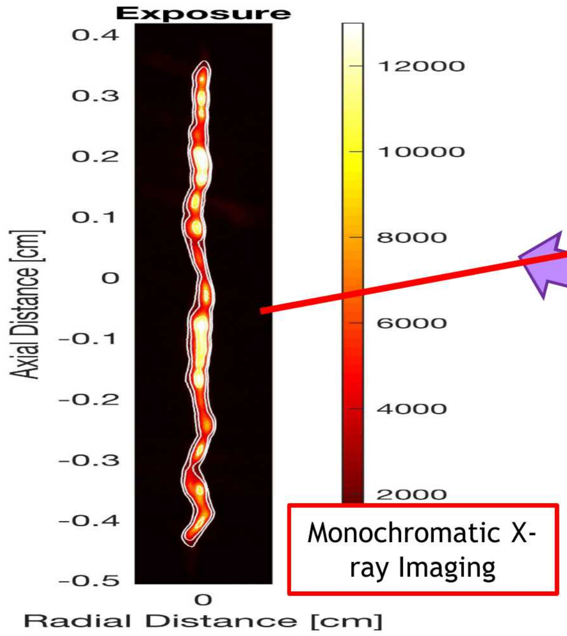
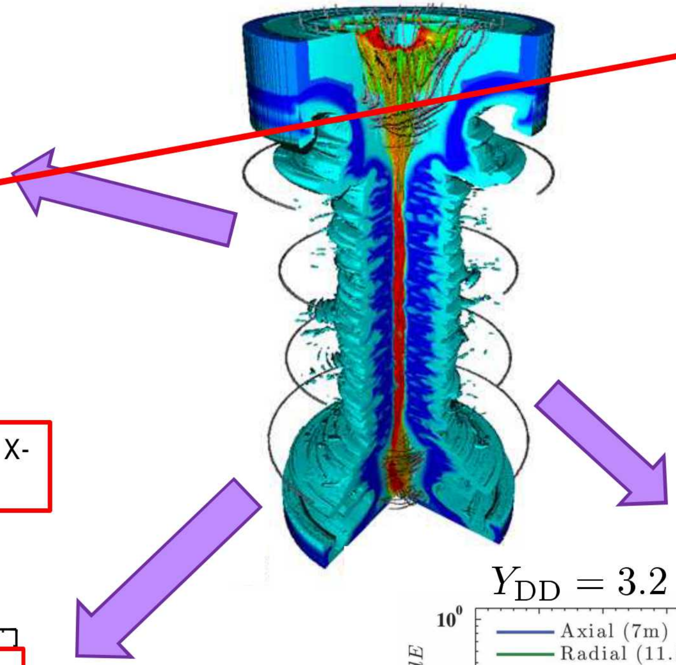
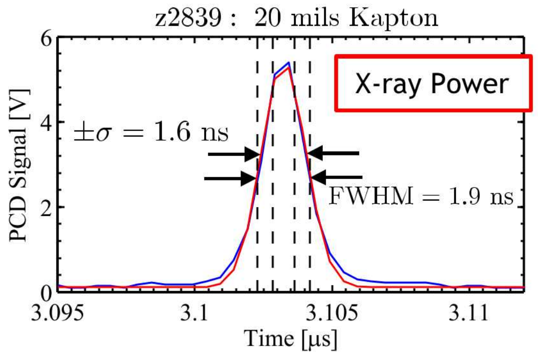
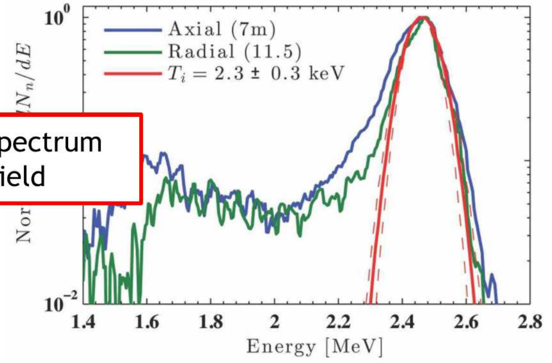




- Hotspot Volume: $V_{\mathrm{HS}} \pm \sigma_V$
- X-ray Yield:
- Burn Duration:
- Neutron Yield:
- Burn Temperature:



$Y_{\mathrm{DD}} = 3.2 \times 10^{12} \pm 20\%$



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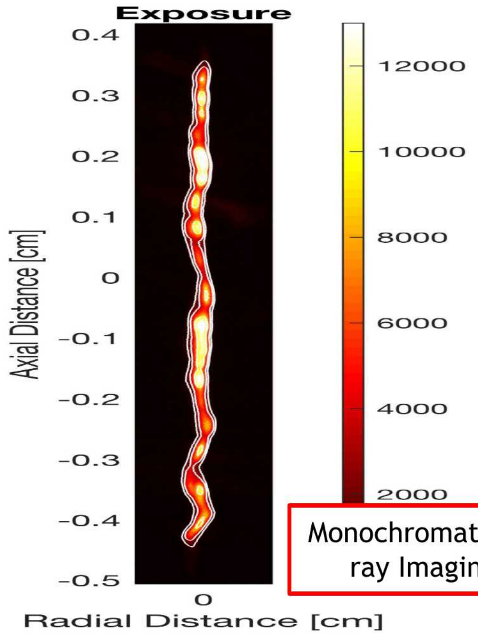
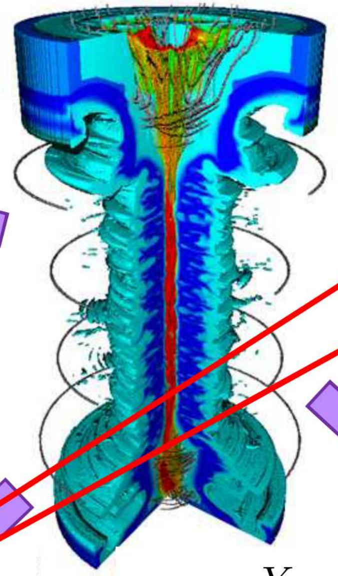
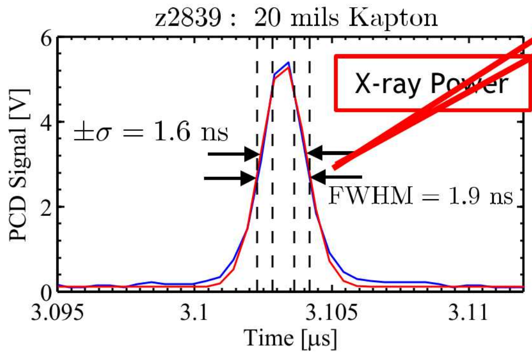


Monochromatic X-ray Imaging

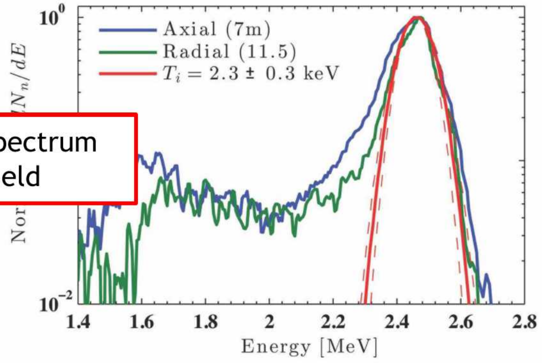


- Hotspot Volume: $V_{\mathrm{HS}} \pm \sigma_V$
- X-ray Yield: $Y_{\mathrm{PCD}} \pm \sigma_{Y_x}$
- Burn Duration: $\tau_{\mathrm{b}} \pm \sigma_{\tau}$
- Neutron Yield:
- Burn Temperature:



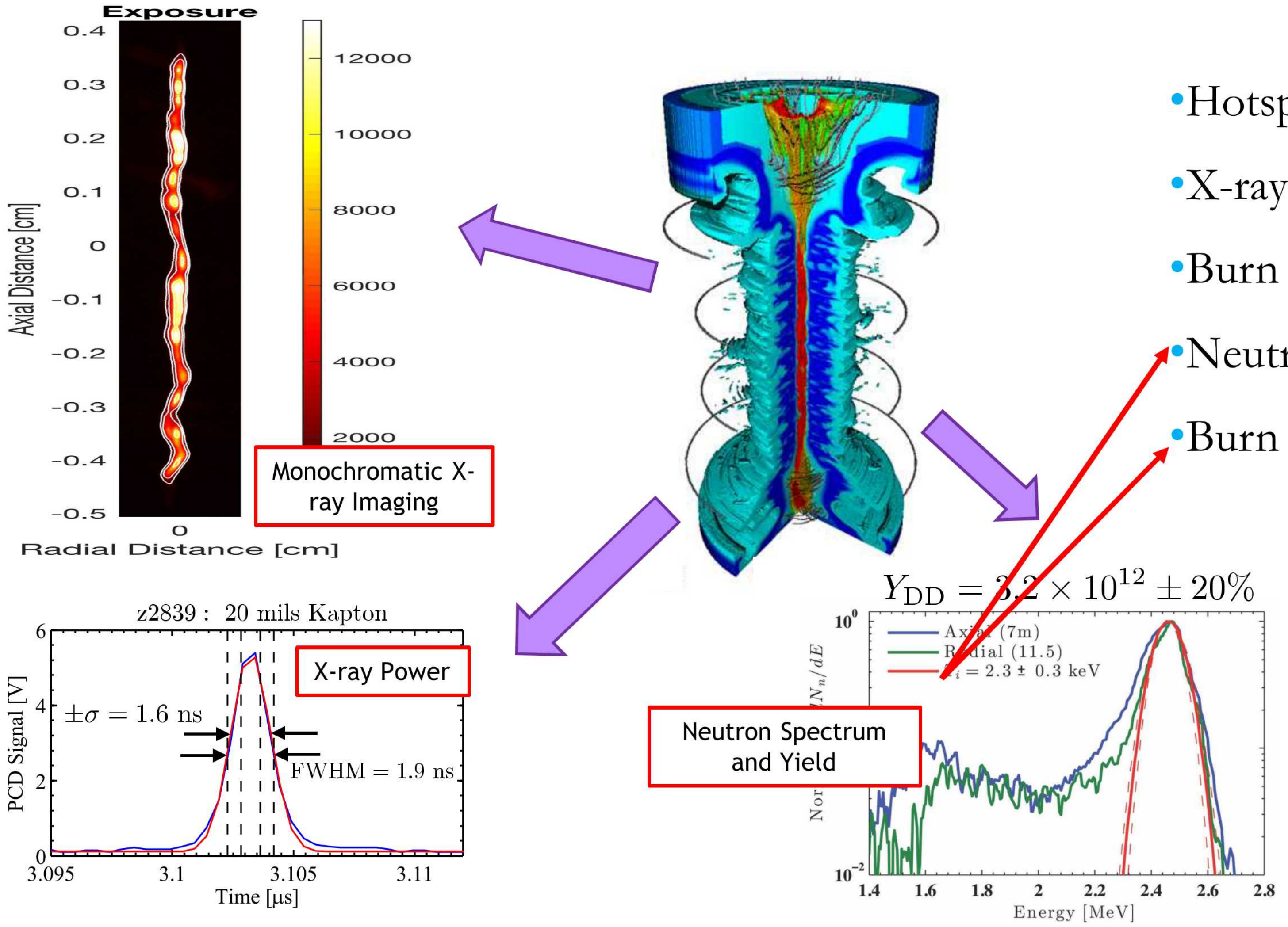
X-ray Power

$Y_{\mathrm{DD}} = 3.2 \times 10^{12} \pm 20\%$



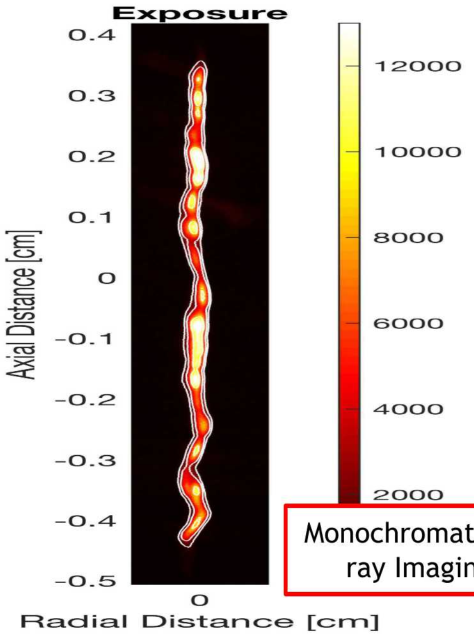
Neutron Spectrum and Yield

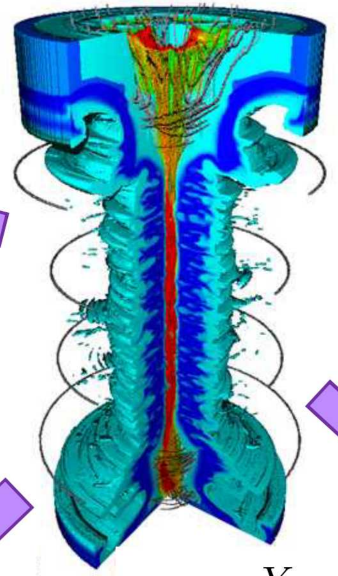
Using the available data we can completely constrain the quantities required to infer bulk stagnation pressure and mix fraction



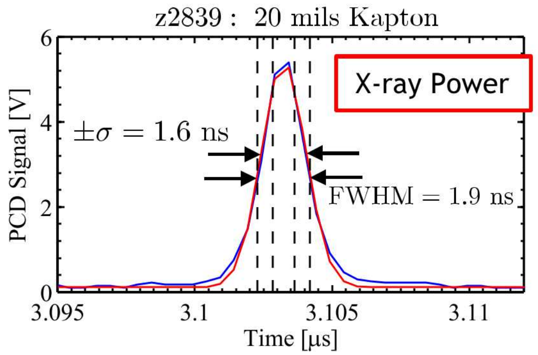
- Hotspot Volume: $V_{\mathrm{HS}} \pm \sigma_V$
- X-ray Yield: $Y_{\mathrm{PCD}} \pm \sigma_{Y_x}$
- Burn Duration: $\tau_{\mathrm{b}} \pm \sigma_\tau$
- Neutron Yield: $Y_{\mathrm{DD}} \pm \sigma_{Y_n}$
- Burn Temperature: $T_{\mathrm{c}} \pm \sigma_T$

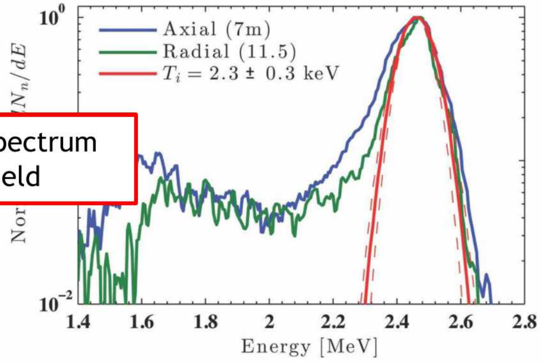
Using the available data we can completely constrain the quantities required to infer *bulk* stagnation pressure and mix fraction





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





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

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

X-ray Yield

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

Neutron Yield

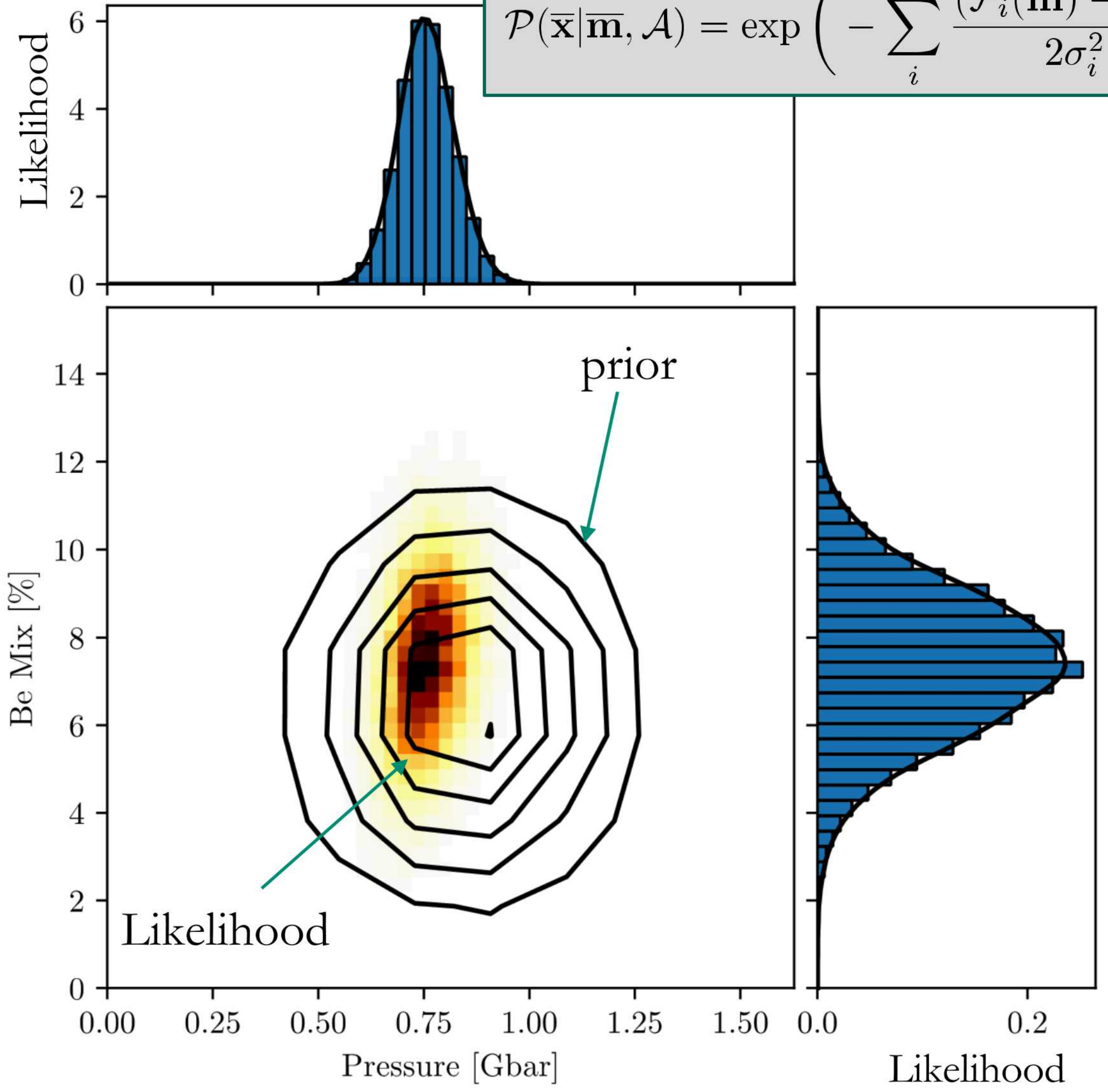
$$Y_{\mathrm{DD}} = \frac{1}{2} P_{\mathrm{HS}}^2 \tau_{\mathrm{b}} \int_{V_{\mathrm{HS}}} \frac{\langle \sigma v \rangle_{\mathrm{DD}}}{(1+\langle Z \rangle)^2 T_{\mathrm{i}}^2} dV$$

Three unknowns (P, mix, ρR_ℓ)

- 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

Likelihood

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



Bayesian inference allows us to use more data by employing a physics model and synthetic diagnostics

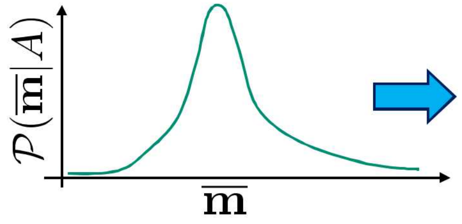
Bayes' Theorem

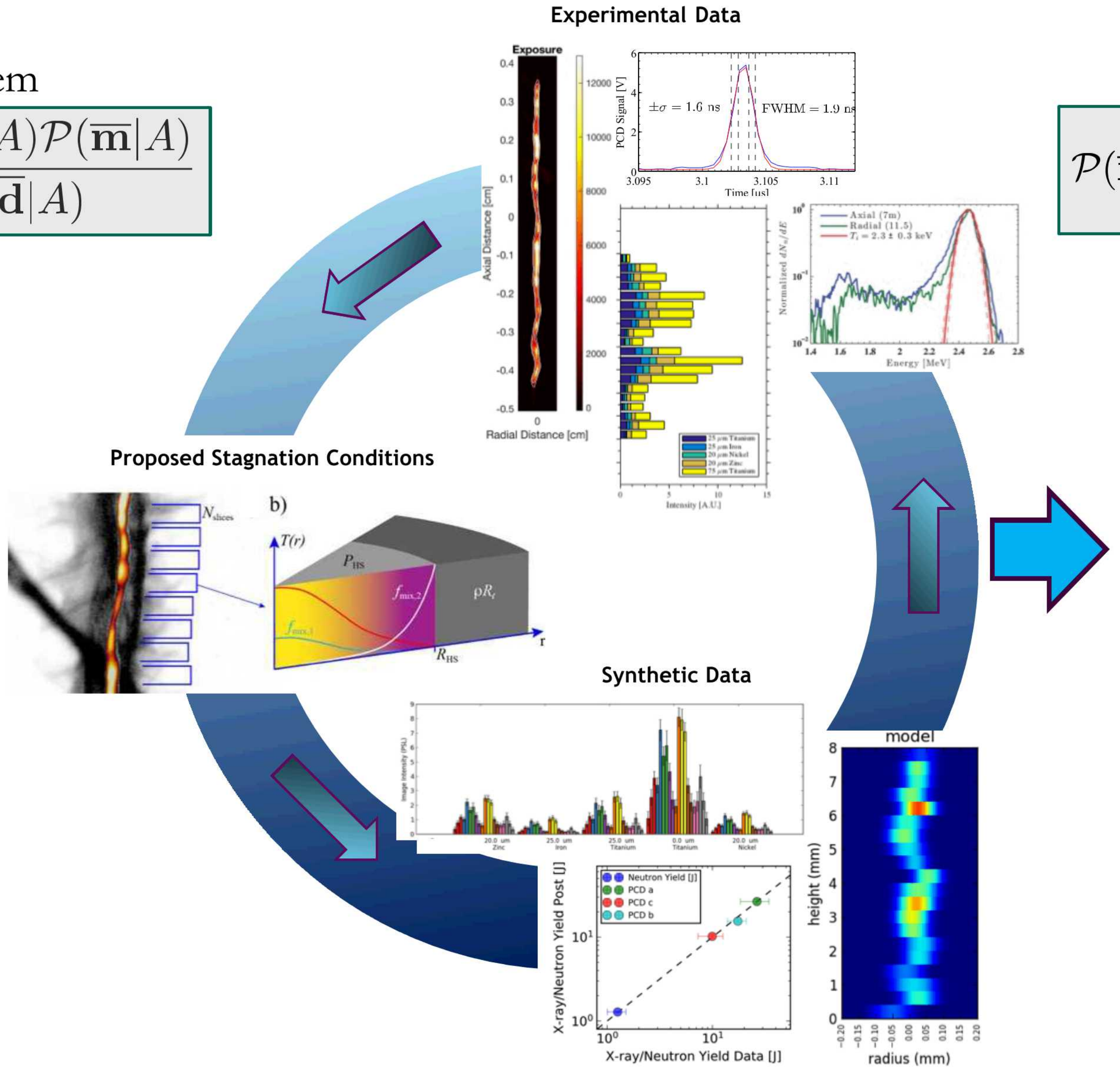
$$\mathcal{P}(\overline{\mathbf{m}}|\overline{\mathbf{d}}, A) = \frac{\mathcal{P}(\overline{\mathbf{d}}|\overline{\mathbf{m}}, A)\mathcal{P}(\overline{\mathbf{m}}|A)}{\mathcal{P}(\overline{\mathbf{d}}|A)}$$

Likelihood

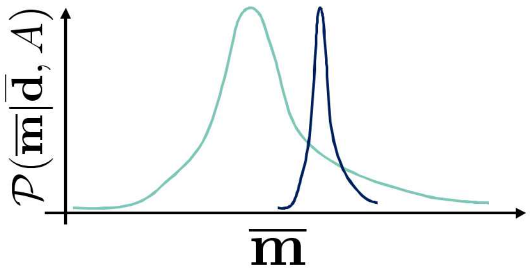
$$\mathcal{P}(\overline{\mathbf{x}}|\overline{\mathbf{m}}, \mathcal{A}) \propto \prod_{i=1}^{N} \exp\left(- \frac{(\mathcal{F}_i(\overline{\mathbf{m}}) - x_i)^2}{2\sigma_i^2} \right)$$

Prior Distribution





Posterior Distribution



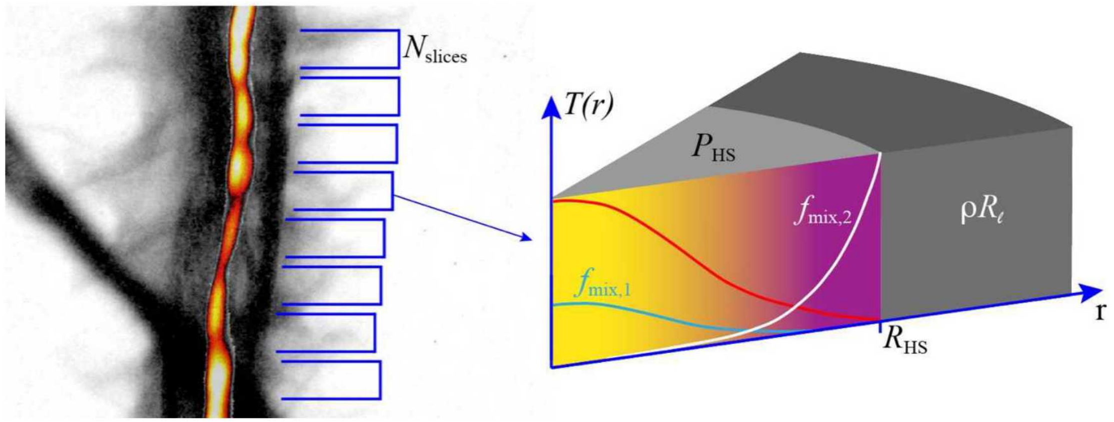
Model Parameters

$$\overline{\mathbf{m}} = \begin{cases} P_{\mathrm{HS}} \\ T \\ f_{\mathrm{mix}} \\ R_{\mathrm{HS}} \\ \rho R_\ell \end{cases}$$

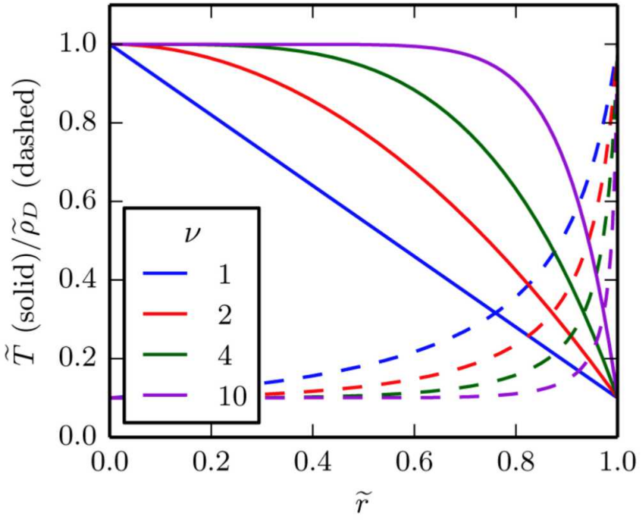
Outputs/Benefits:

- most likely parameter values
- confidence intervals
- correlations
- Value of information

We have developed a forward model that allows direct, quantitative comparison of the data with synthetic diagnostics



$$T(r) = T_c\left[1 - \left(\frac{T_w}{T_c}\right)\left(\frac{r}{R}\right)^{\nu}\right]$$



Model Parameters

$$\{T_{\mathrm{i}}\} = \{T_{\mathrm{e}}\}$$
$$\{\rho R_\ell\}$$
$$\{P_{HS}\}$$
$$\{f_{\mathrm{mix}}\}$$
$$\{Z_{\mathrm{mix}}\}$$
$$\{R_{\mathrm{HS}}\}$$

Assumptions:

- Each slice has its own independent parameters characterizing a static, isobaric hot spot surrounded by a liner
- Ideal gas EOS: $P_{\mathrm{HS}} = (1 + \langle Z \rangle) n_{\mathrm{i}} k_B T$
- All elements have same burn duration
- Electron and ion temperatures are equal
- X-ray emission is dominated by continuum (BF & FF)

X-ray Emission:

$$\epsilon_\nu = A_{f-f} e^{-\rho R_\ell \kappa_\nu} \tau_{\mathrm{b}} P_{\mathrm{HS}}^2 \frac{g_{\mathrm{FF}}\langle Z \rangle}{(1+\langle Z \rangle)^2} \sum_i f_i \tilde{j}_i \frac{e^{-h\nu/T}}{T^{5/2}}$$

$$\tilde{j}_i \equiv \frac{j_i}{j_{\mathrm{D}}} = Z_i^2 + \frac{A_{f-b}}{A_{f-f}} \frac{Z_i^4}{T} e^{RyZ_i^2/T}$$

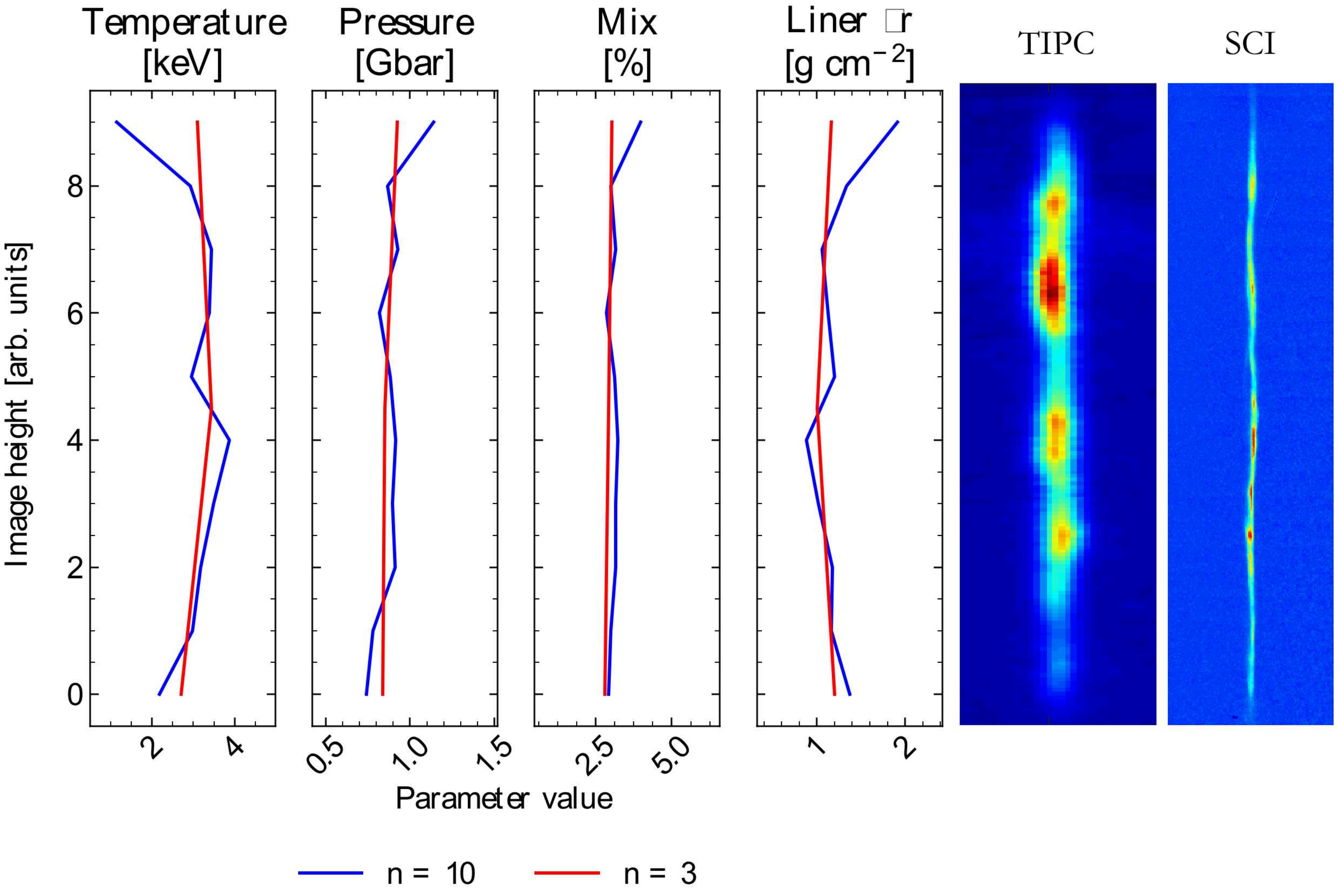
Neutron Emission:

$$\epsilon_E = \frac{P_{\mathrm{HS}}^2 \tau_{\mathrm{b}}}{1 + \delta_{1,2}} \frac{f_1 f_2 \langle \sigma v \rangle}{(1 + \langle Z \rangle)^2 T_{\mathrm{i}}^2} I_o(E)$$

$$^{*}I_o(E) = e^{\frac{-2\bar{E}}{\sigma^2}(\sqrt{E}-\sqrt{\bar{E}})^2}$$

*Ballabio et al., NUCLEAR FUSION, Vol. 38, No. 11 (1998)

This method allows us to infer axially varying stagnation parameters



Currently this method is most reliable for coarse variations

When increasing the resolution the 3D structure of the column begins to significantly impact the inference

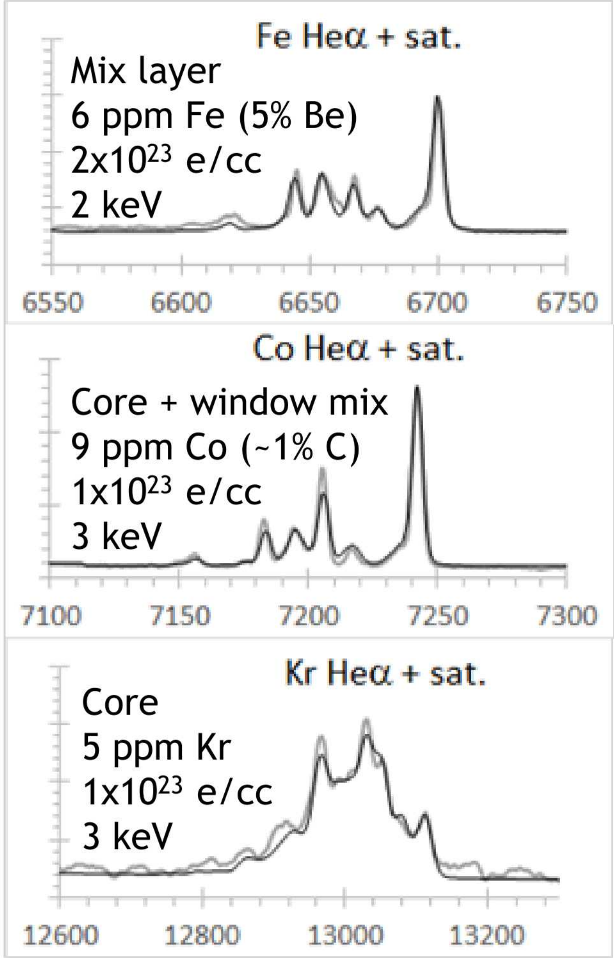
E.g. the 2D nature of the model introduces bias into the solution

We are evaluating the limits of this method using 3D MHD simulations

We are currently developing a more sophisticated model to employ in this analysis

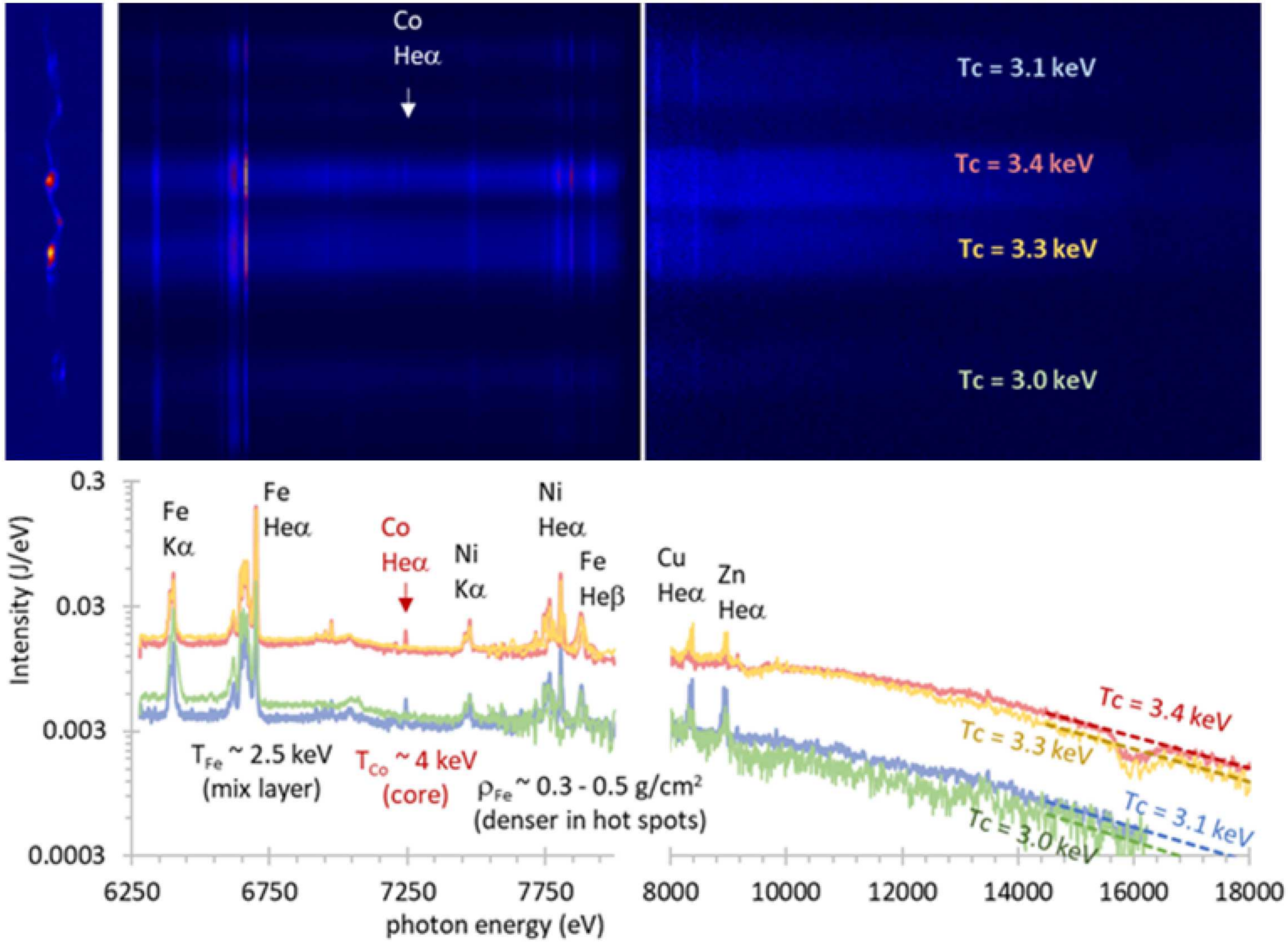
X-ray spectroscopy gives a strong independent opinion on stagnation parameters and deeper insight into mix

High-resolution spectra of dopants from liner, window, and fuel give Te, ne, & mix fractions (z3057 & z 3123)



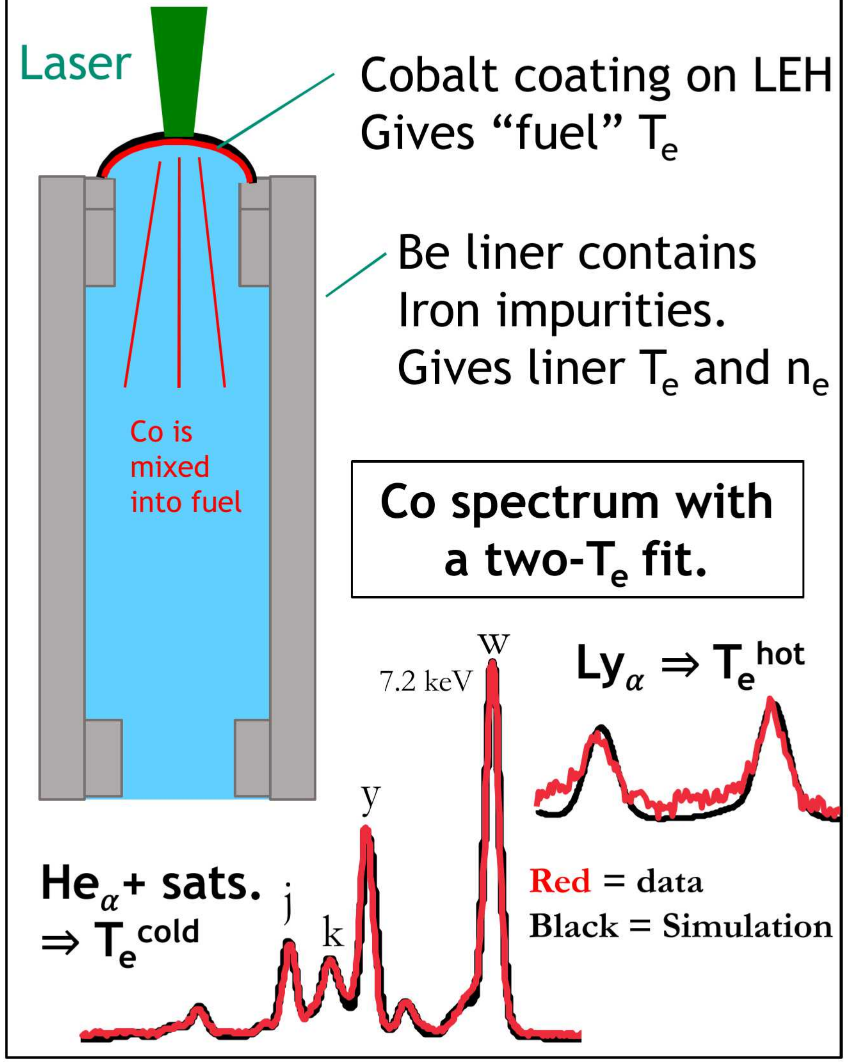
photon energy (eV)

Axially resolved spectra trace preheat mix & assess axial uniformity (z3289)



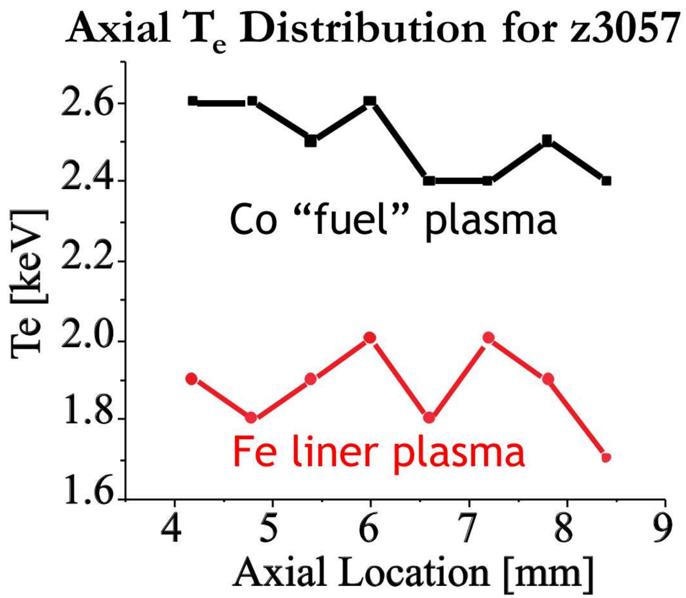
We have measured T_e and n_e by performing detailed fits to highly-resolved x-ray spectra. Gradients (ΔT_e and Δn_e) were observed.*

MagLIF shot z3057



Important Results

- The Co "fuel" plasma has T_e^{ave}~2.6 keV with ΔT_e~2 keV and is hotter than the liner plasma.
- Fe liner plasma is has T_e^{ave} ~1.8 keV. On similar shot, z2977, ΔT_e ~ 1 keV .
- Co n_e is lower than Fe n_e (>2x). Fe n_e is typically 1.5 - 2e23 cm^{-3} (measured using He_β)



*Work done in collaboration with the Weizmann Group (Maron *et. al.*)

There is much work left to do

We are developing a GRH for Z (in conjunction with LANL) to make nuclear burn history measurements

We have a 1D neutron imager that is operational, but is low resolution. We are investigating options for 2D imaging with DD and DT neutrons