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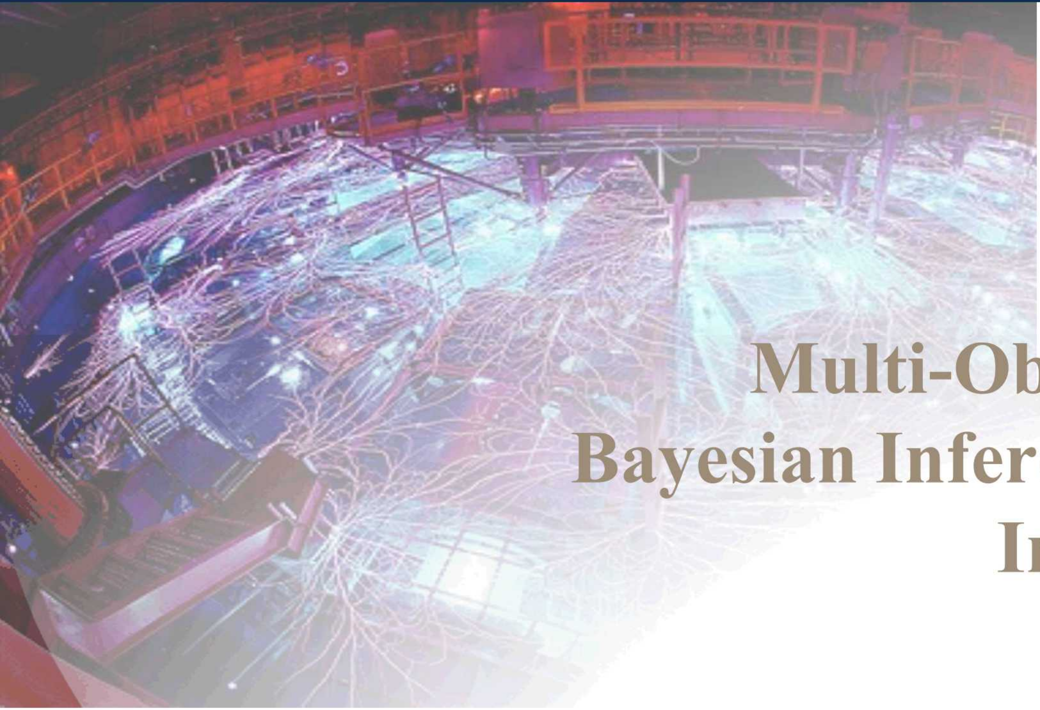

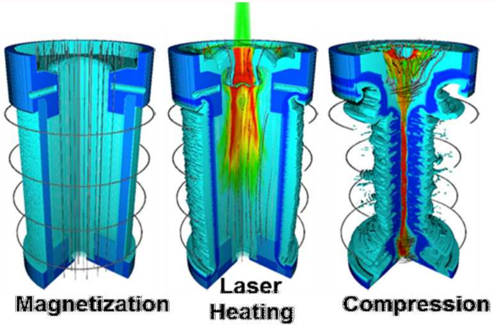

Multi-Objective data analysis using Bayesian Inference for Magnetized Liner Inertial Fusion experiments

Patrick Knapp

APS DPP 2017, Milwaukee WI

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This work represents the contributions of a large team

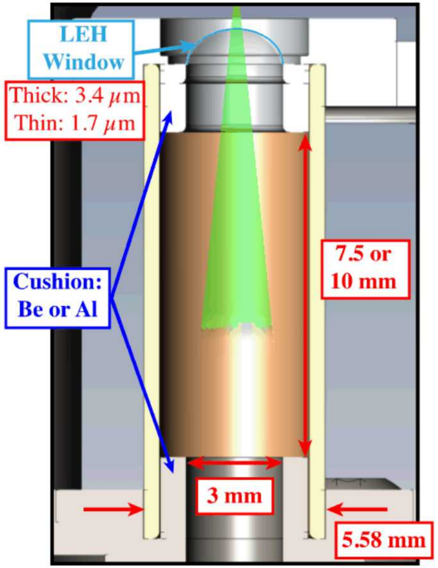
M.E. Glinsky[1], M. Evans[2], M.R. Gomez[1], S.B. Hansen[1], E.C. Harding[1], S.A. Slutz[1], K.D. Hahn[1], A. Harvey-Thompson[1], M. Geissel[1], D.J. Ampleford[1], C.A. Jennings, P.F. Schmit[1], I.C. Smith[1], J. Schwarz[1], K. Peterson[1], B.M. Jones[1], G.A. Rochau[1], D.B. Sinars[1]

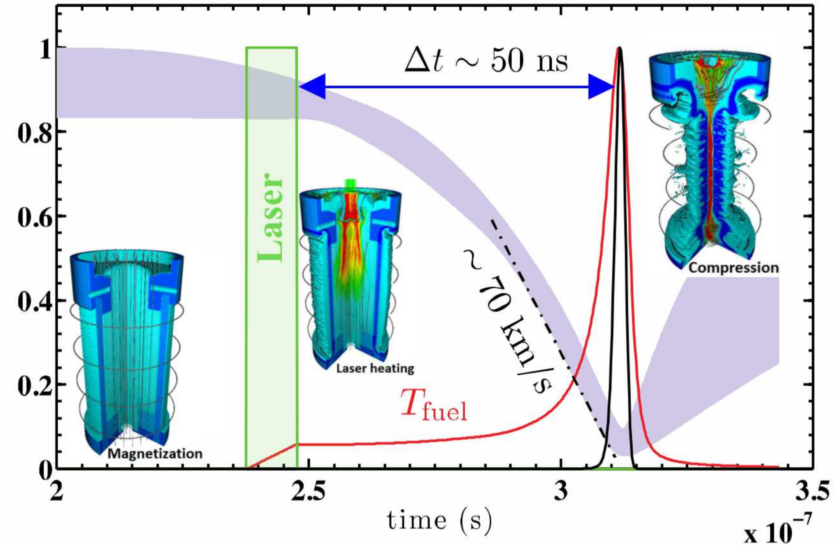
and many others…

[1]*Sandia National Laboratories, Albuquerque NM*

[2] *University of Rochester Department of Physics and Astronomy, Rochester NY*

Magnetized Liner Inertial Fusion is a promising concept being explored on Z

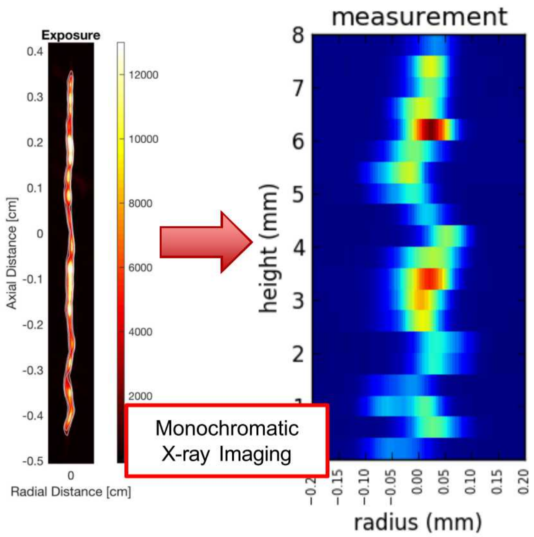


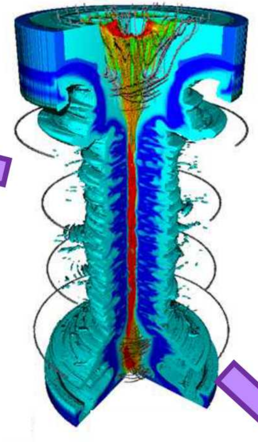


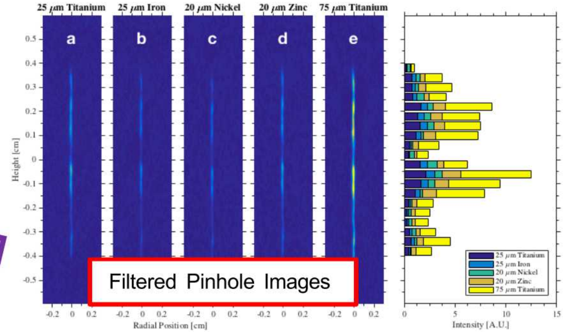
- Magnetization confines 3.5 MeV α-particles at lower ρR
- Preheating + magnetization allows ignition temperature to be reached at a lower implosion velocity[1]
- Calculations show MagLIF scales to high yield and gain[1,2]

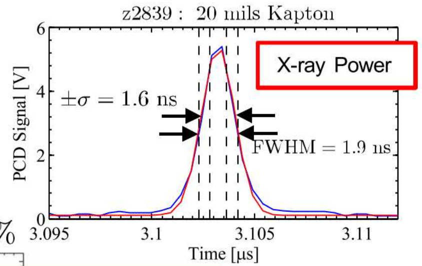
[1] S. A. Slutz, *et al.*, Phys. Plasmas **17** 056303 (2010)
[2] S. A. Slutz. and R.A. Vesey, PRL **108**, 025003 (2012)

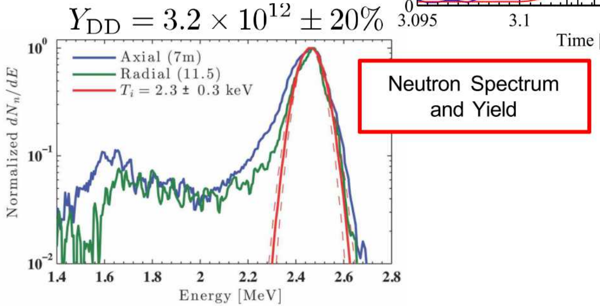
A suite of stagnation diagnostics are used to characterize performance





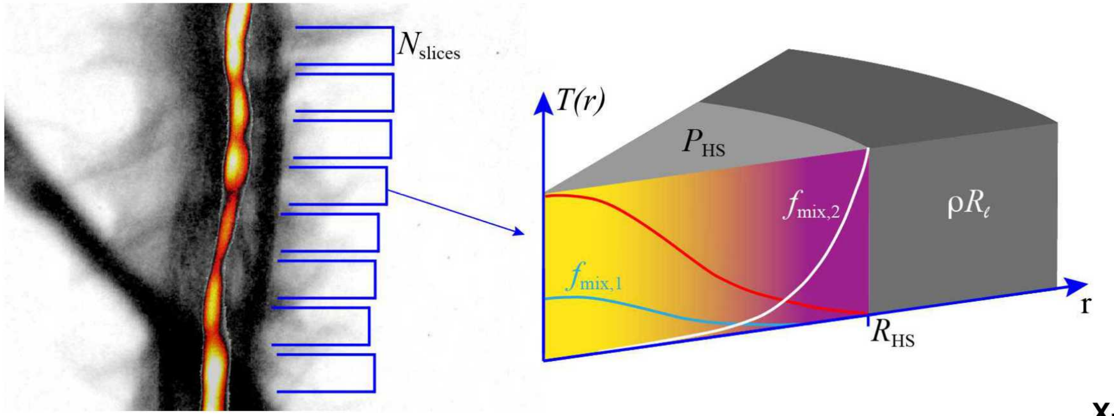






- Our extensive suite of diagnostics allow us to measure the fuel temperature, density, volume, magnetic field, and burn duration
  - Neutron yield and time-of-flight
  - X-ray imaging
  - Radiated power and energy

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



Model Parameters

$\{T_{\text{i}}\} = \{T_{\text{e}}\}$

$\{\tau_\nu^\ell\}$

$\{P_{HS}\}$ $\overline{BR}$

$\{f_{\text{mix}}\}$ τ_{burn}

$\{Z_{\text{mix}}\}$

$\{R_{\text{HS}}\}$

Assumptions:

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

X-ray Emission:

$$Y_\nu = A_{f-f} \sum_{n=1}^{N} e^{-\tau_\nu^\ell} \tau_{\text{burn}} 2V P_{\text{HS}}^2 \int_0^1 \tilde{r} d\tilde{r} \frac{g_{\text{FF}} \langle Z \rangle}{(1 + \langle Z \rangle)^2} \sum_i f_i \tilde{j}_i \frac{e^{-h\nu/T}}{T^{5/2}}$$

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

Neutron Emission:

$$\frac{dN_{\text{DD}}}{dE} = \sum_{n=1}^{N} \frac{P_{\text{HS}}^2 V \tau_{\text{burn}}}{(1 + \sum_i f_i Z_i)^2} \int_0^1 \tilde{r} d\tilde{r} \frac{\langle \sigma v \rangle_{\text{DD}}}{T_{\text{i}}^2} I_o(E)$$

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

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

The analysis is done use Bayesian Parameter estimation to determine the most likely hotspot parameters

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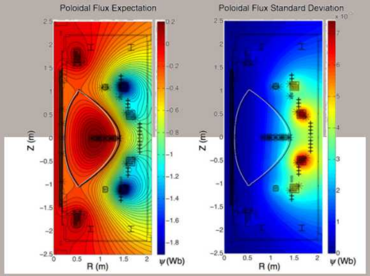
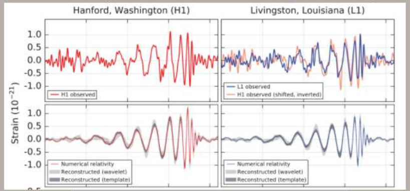
tokamak plasma profile estimation at installations such as JET and MAST



Svensson et al., Plasma Phys. Control. Fusion **50** 085002 (2008)
Von Nessi et al., J. Phys. **A46** 185501 (2013)

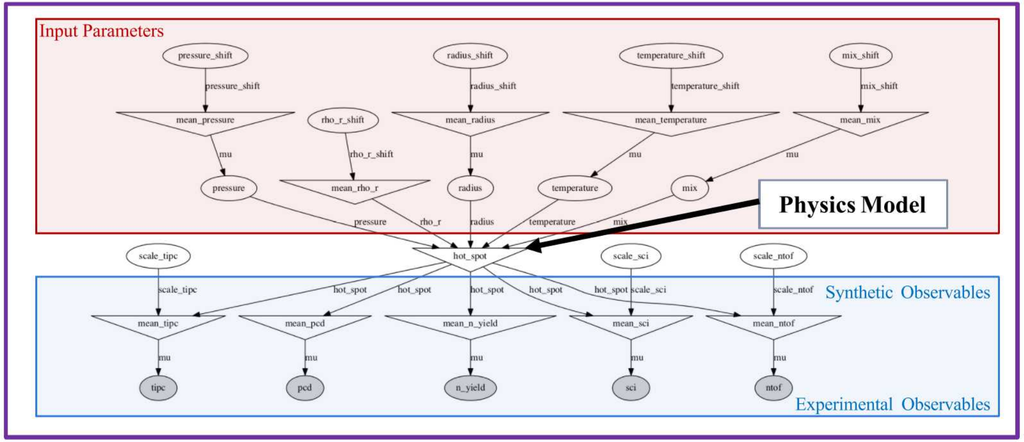
LIGO binary black hole merger analysis



Primary black hole mass	$36^{+5}_{-4} M_\odot$
Secondary black hole mass	$29^{+4}_{-4} M_\odot$
Final black hole mass	$62^{+4}_{-4} M_\odot$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	410^{+160}_{-180} Mpc
Source redshift z	$0.09^{+0.03}_{-0.04}$

Veitch et al., Phys. Rev. D **91** 042003 (2015)

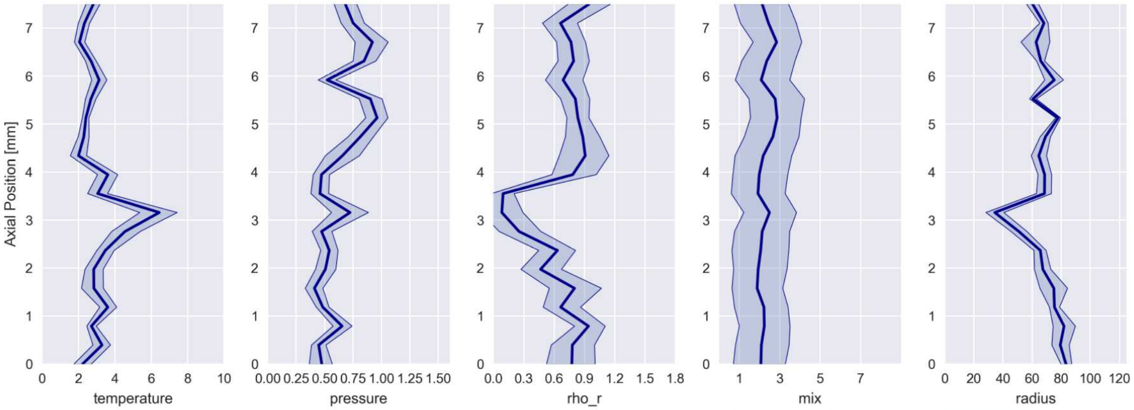
Bayesian Inversion Wrapper



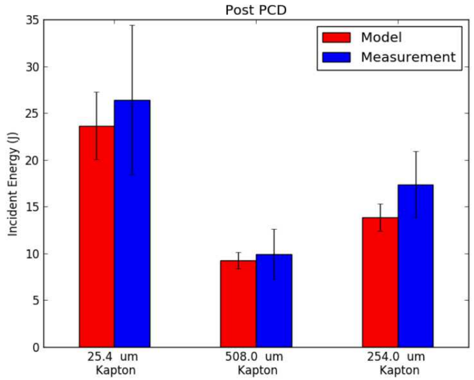
- Bayesian parameter estimation is a well-established technique used in a variety of fields
- Analysis can be used to infer most likely parameters, correlations between model parameters and/or data
- Can compute value of information to determine which data constrain which parameters and how well

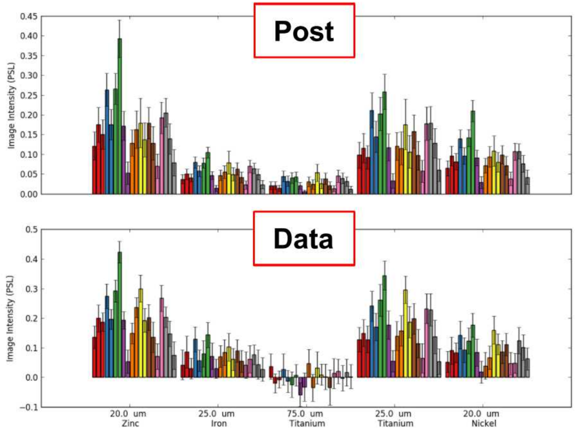
See Poster **BP11.00016**, by Matt Evans for details on validation of the inversion technique

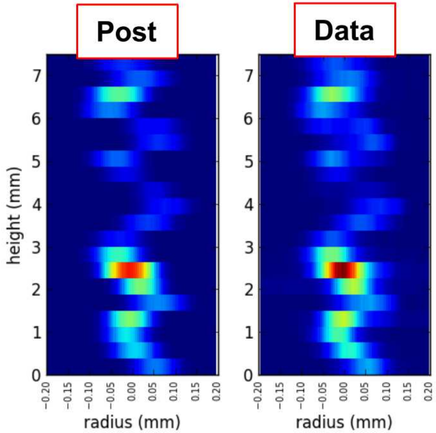
Analysis from z2839, the canonical MagLIF experiment



$$Y_{\mathrm{DD}}^{\mathrm{meas}} = 3.2 \times 10^{12} \pm 20\%$$
$$Y_{\mathrm{DD}}^{\mathrm{post}} = 3.1 \times 10^{12} \pm 10\%$$

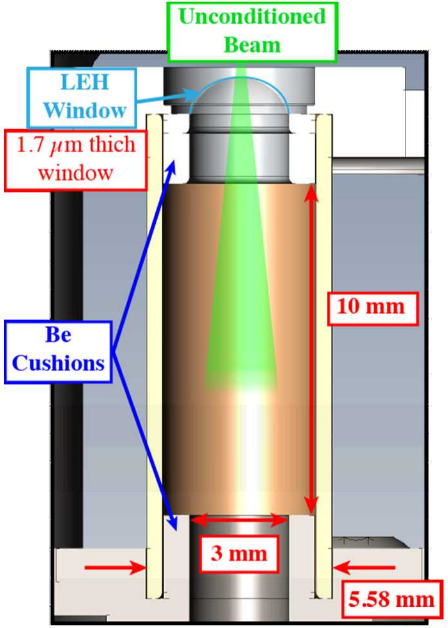


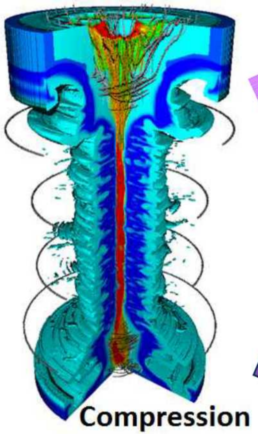




$$E_{\mathrm{HS}} = 10.8 \pm 1.1 \text{ kJ}$$
$$\langle P \rangle = 0.63 \pm 0.17 \text{ Gbar}$$

An ensemble of experiments have been performed to isolate sources of degradation and improve performance





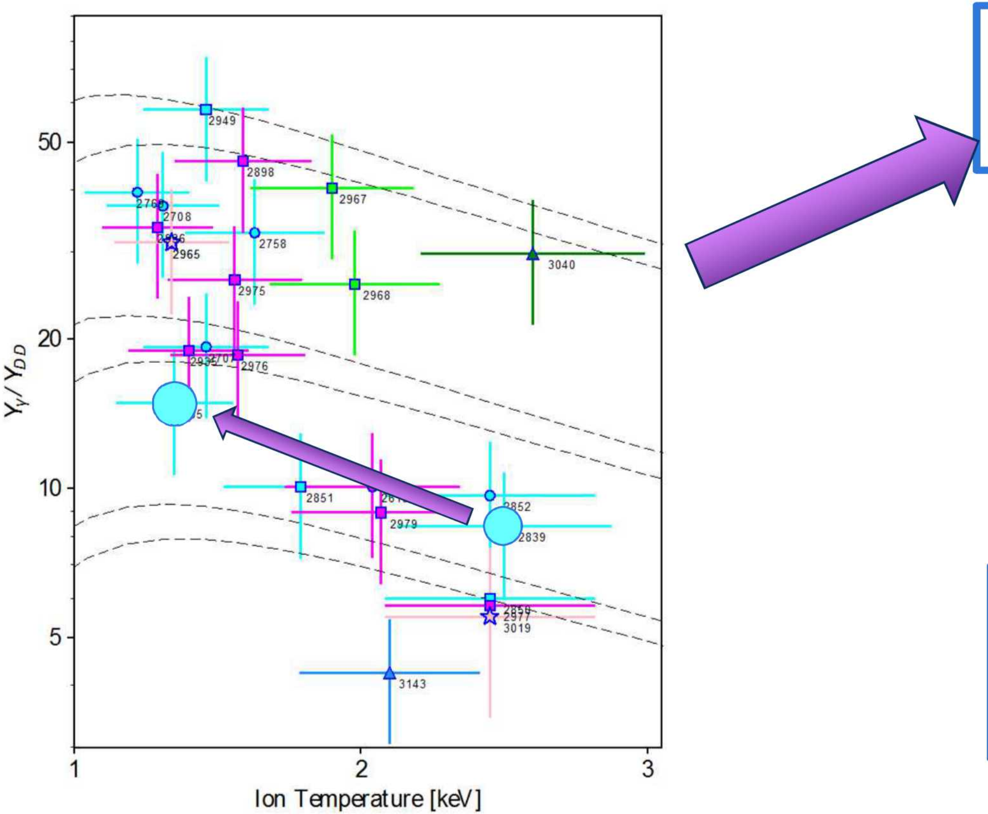
z2985: Al Cushions exacerbate impact of laser-induced mix

z3019: AR9 coated target to improve stagnation uniformity

z3040: Use DPP to condition beam and couple more energy to gas

z3143: 20 ns delay between 20J pre-pulse and 2kJ main pulse to reduce window mix

An ensemble of experiments have been performed to isolate sources of degradation and improve performance



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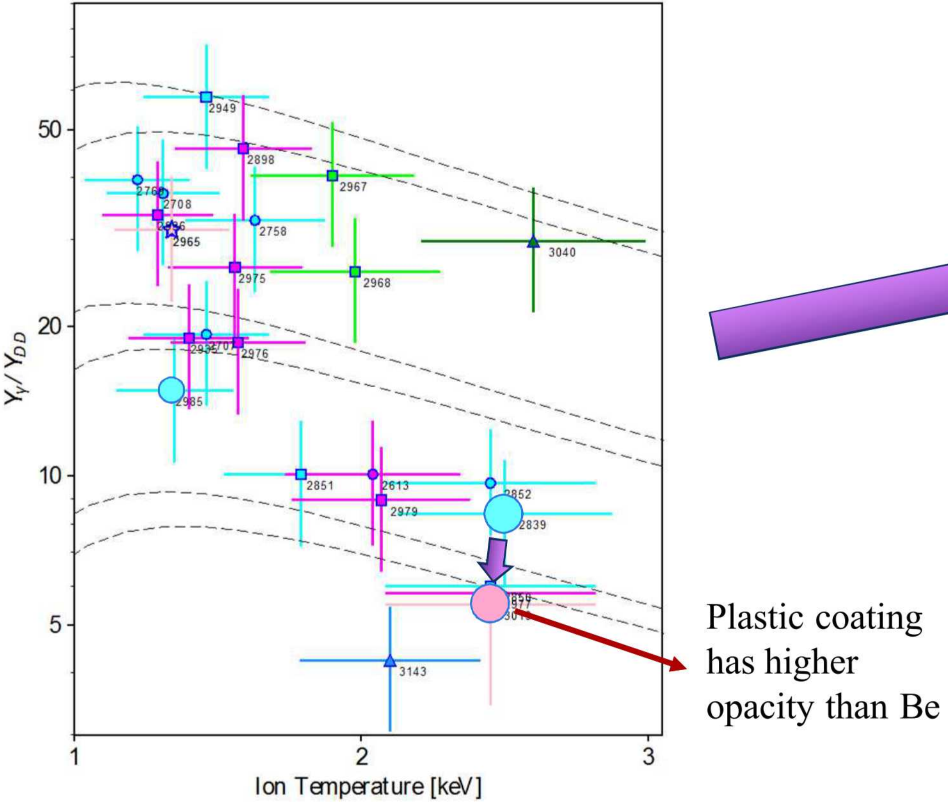

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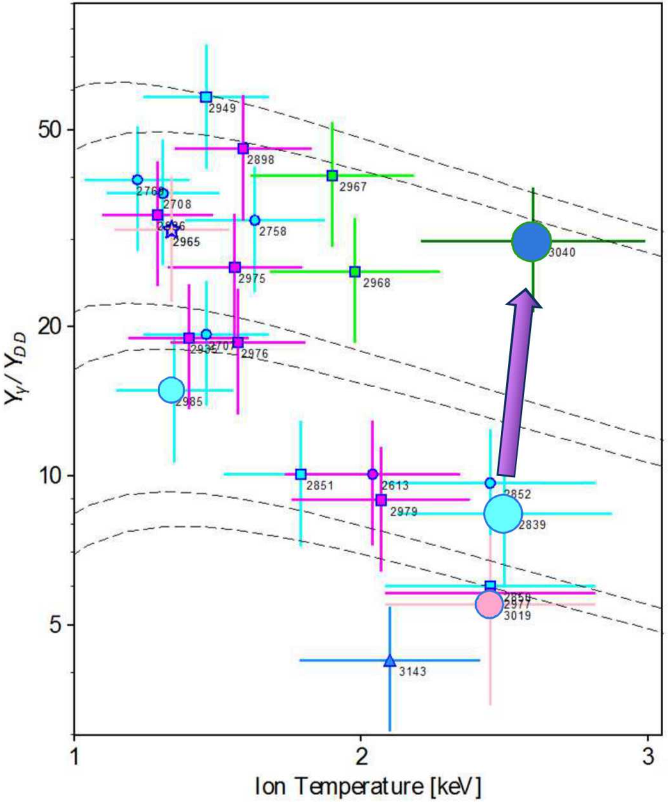
z3143: 20 ns delay between 20J pre-pulse and 2kJ main pulse to reduce w

For more information:

- Gomez: **PO8.00001**
- Jennings: **GI3.00004**
- Awe**: GI3.00006**
- Hutchinson**: PO8.00009**

An ensemble of experiments have been performed to isolate sources of degradation and improve performance



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- Weis: **PO8.00005**

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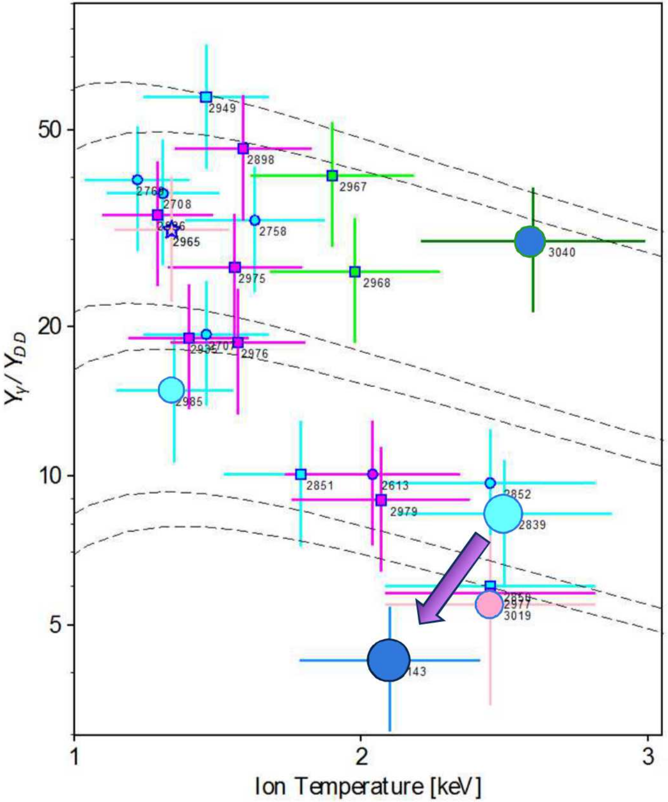

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- Geissel: **PO8.00004**
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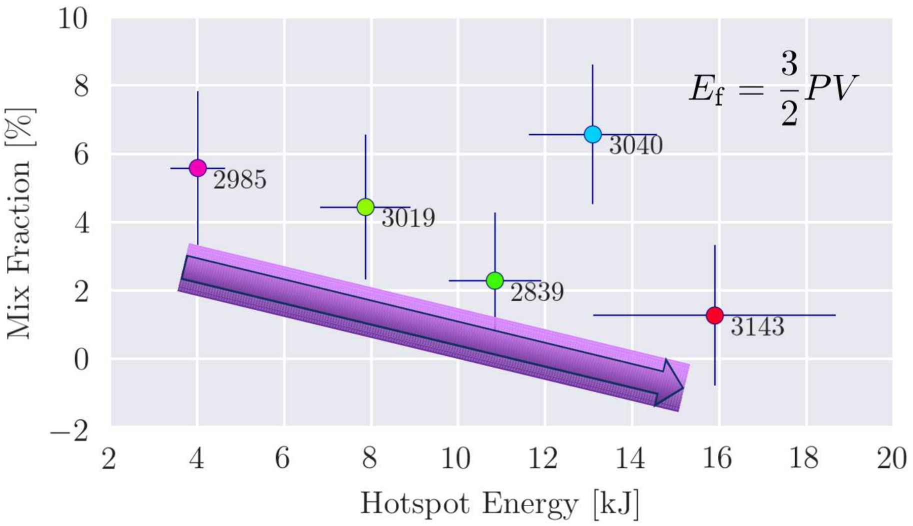
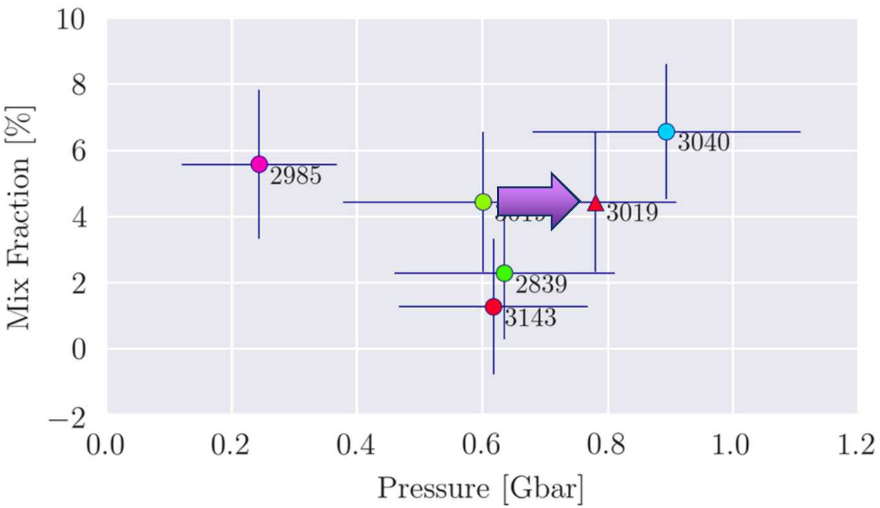
The fuel energy scales (mostly) inversely with the mix fraction

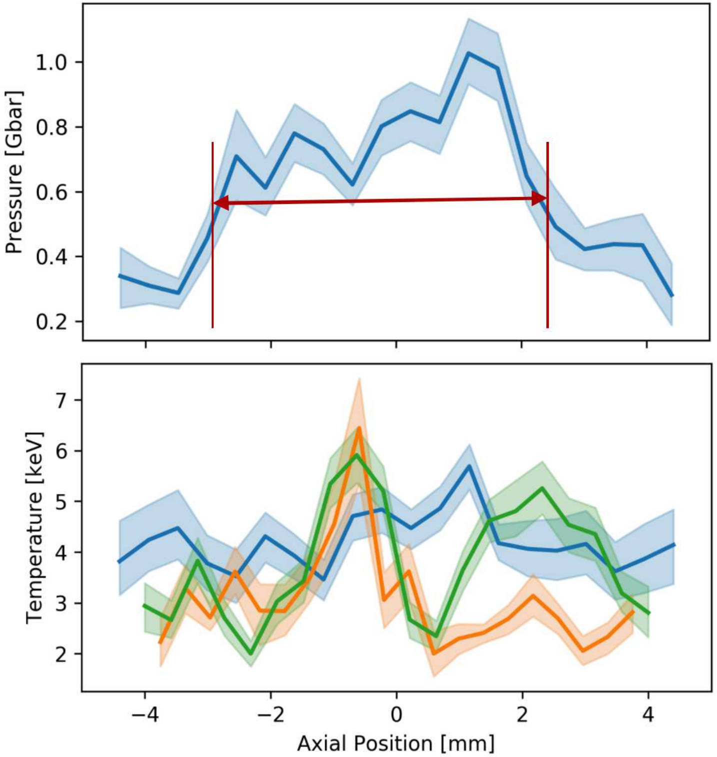


- In general, more mix means lower yield and less fuel energy at stagnation
- Experiment with DPP introduced significantly more mix, but performed better
- Co-injection shot w/ 90 PSI gas has more energy, less mix, but produced fewer neutrons
- Suggests sensitivity to *how* energy is deposited and mix is distributed

Mix fraction is CH equivalent

The ETI coating contributed to an elevated pressure over a fairly large portion of the column

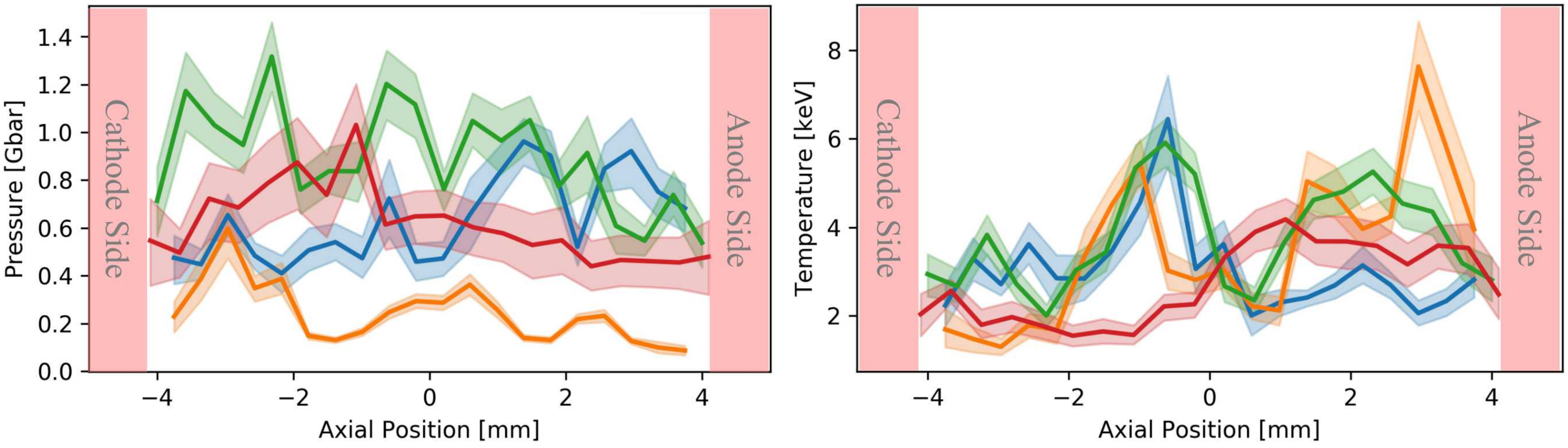




- Also exhibits more uniform temperature, radius, and liner areal density than other experiments
- All points to improved stability at stagnation

Mix fraction is CH equivalent

Axial pressure and temperature profiles reveal significant structure and presence of hotspots



- Large variations in temperature and pressure
- No evidence of end effects in pressure profiles without coating

We can constrain the relative window and cushion mix fractions by comparing experiments

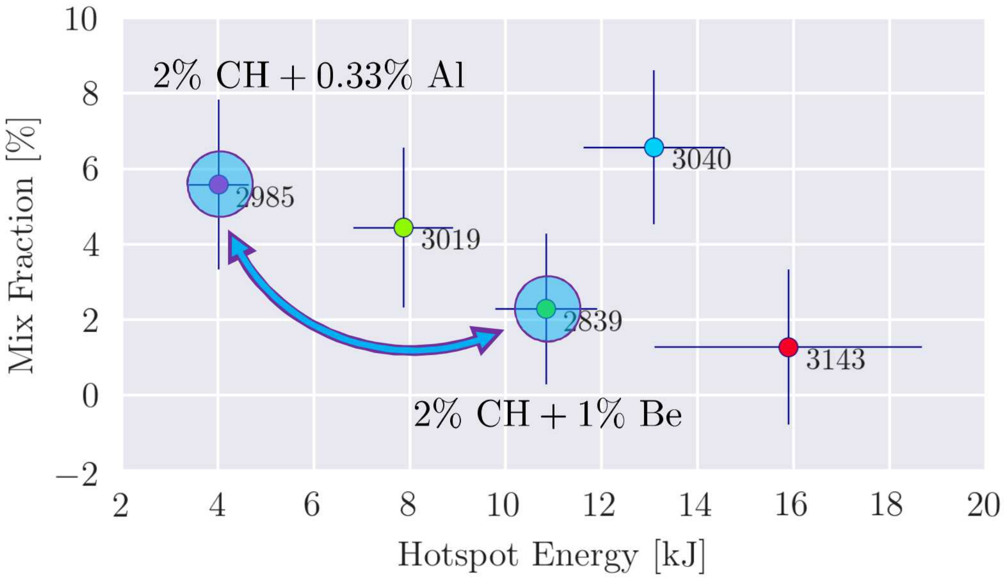
In our approximation, the losses due to mix scale as

$$\sim f Z^{5/2}$$

Assume the same mass of Al and Be are scraped off during preheat

$$f_{\mathrm{Al}} = \frac{1}{3} f_{\mathrm{Be}}$$

$$f_{\mathrm{eff}} Z_{\mathrm{eff}}^{5/2} = f_{\mathrm{Be,Al}} Z_{\mathrm{Be,Al}}^{5/2} + f_{\mathrm{CH}} Z_{\mathrm{CH}}^{5/2}$$



The Al-mixed hotspot radiates less energy than the Be-mixed hotspot, due to lower pressure

Radiation at stagnation cannot account for the energy deficit

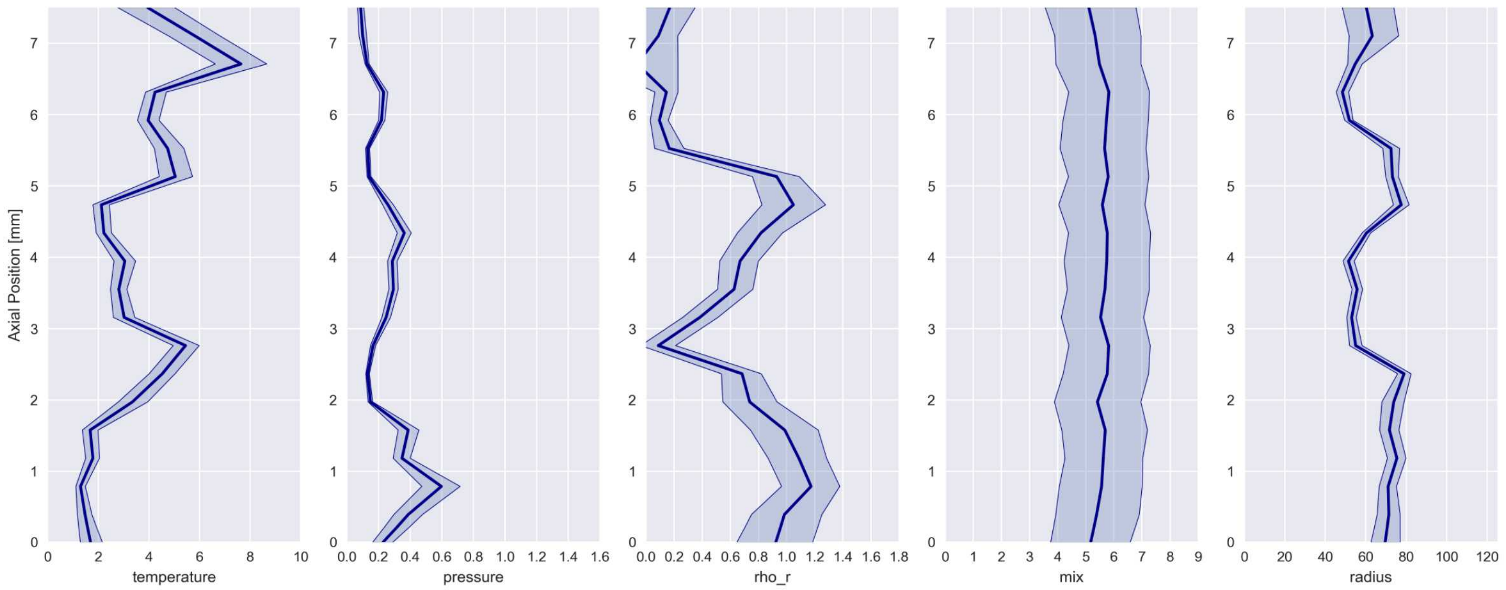
Conclusions

- A multi-objective, Bayesian parameter estimation technique was used to infer stagnation conditions in a range of MagLIF experiments
- Stagnation pressure, mix fraction, temperature and hotspot energy were seen to change with changes in experimental configuration
- Mix fraction ranges from 1-7% for different configurations and has a large impact on target performance
- An experiment with a dielectric coating shows much better axial uniformity in temperature, pressure, and liner areal density than the uncoated experiments

Backups

z2985

$$Y_{\mathrm{DD}} = 1.8 \times 10^{11}$$

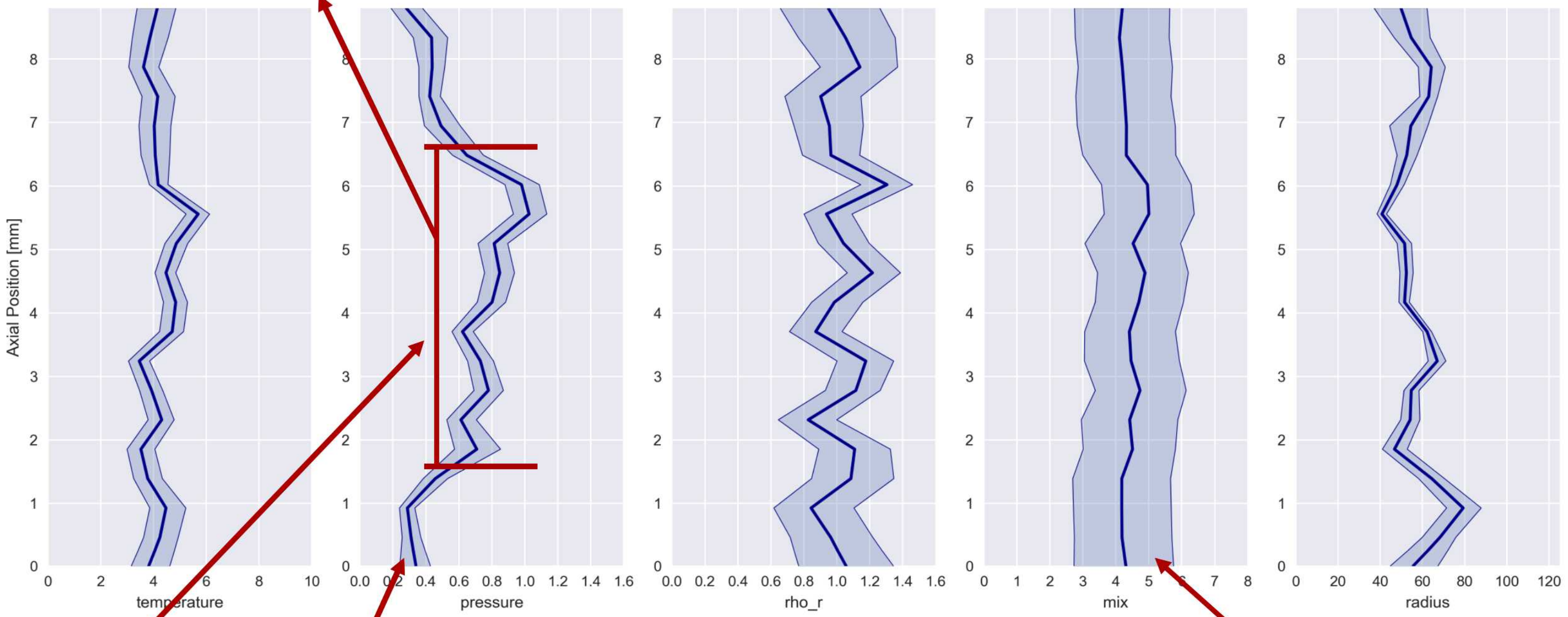


$$E_{\mathrm{HS}} = 4 \pm 0.6 \text{ kJ}$$

$$\langle P \rangle = 0.24 \pm 0.1 \text{ Gbar}$$

z3019 $Y_{\mathrm{DD}} = 3.0 \times 10^{12}$

$\langle P \rangle = 0.78 \pm 0.13 \text{ Gbar}$



Relatively uniform plateau

Low pressure at ends

End losses?

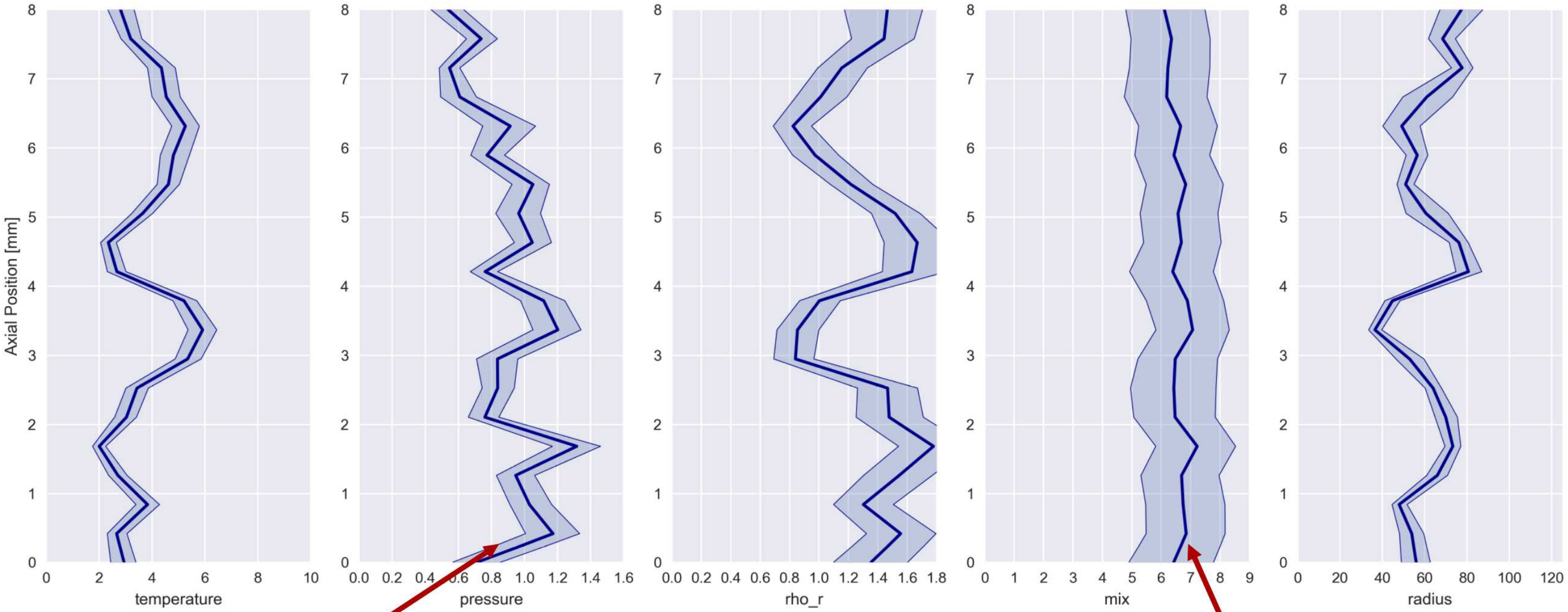
$E_{\mathrm{HS}} = 7.9 \pm 1 \text{ kJ}$

$\langle P \rangle = 0.6 \pm 0.22 \text{ Gbar}$

Moderate mix

z3040

$$Y_{\mathrm{DD}} = 4.1 \times 10^{12}$$



High Pressure!

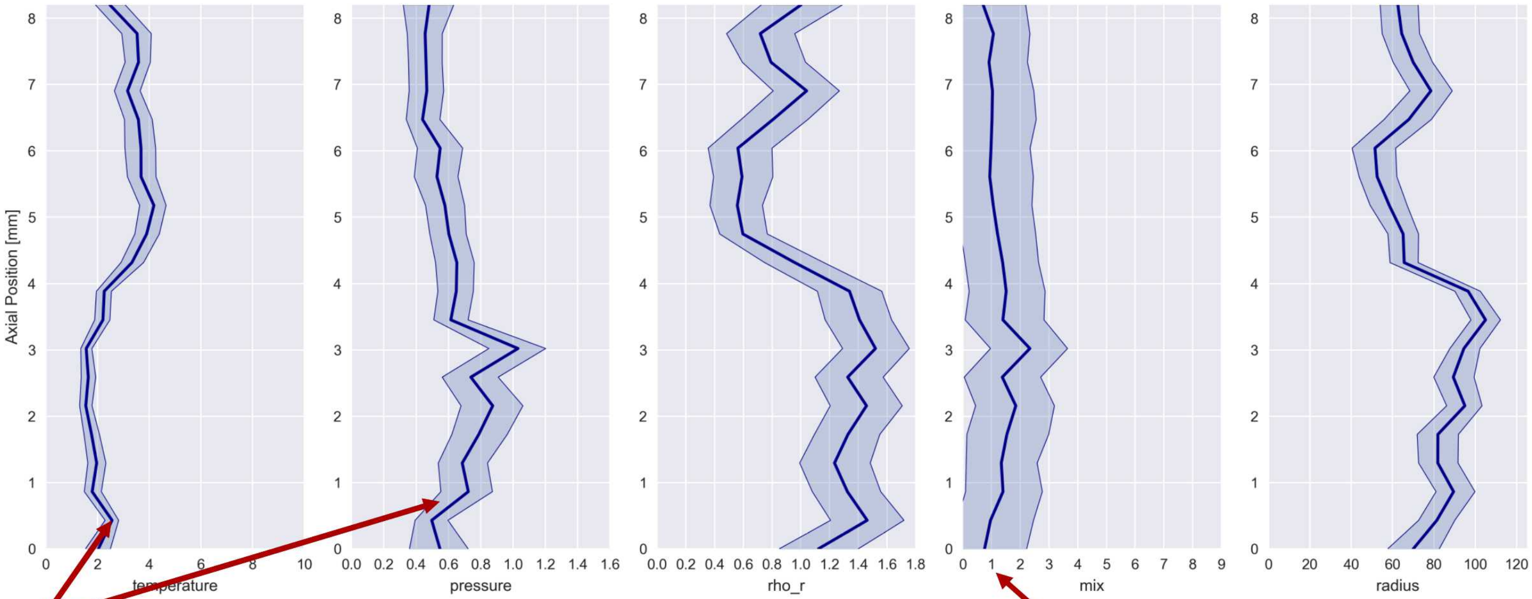
High Mix!

$$E_{\mathrm{HS}} = 13.1 \pm 1.5\ \mathrm{kJ}$$

$$\langle P \rangle = 0.9 \pm 0.2\ \mathrm{Gbar}$$

z3143

$$Y_{\mathrm{DD}} = 2 \times 10^{12}$$



Moderate temperature, pressure

$$E_{\mathrm{HS}} = 15.9 \pm 2.8 \ \mathrm{kJ}$$
$$\langle P \rangle = 0.62 \pm 0.15 \ \mathrm{Gbar}$$

Low to negligible mix