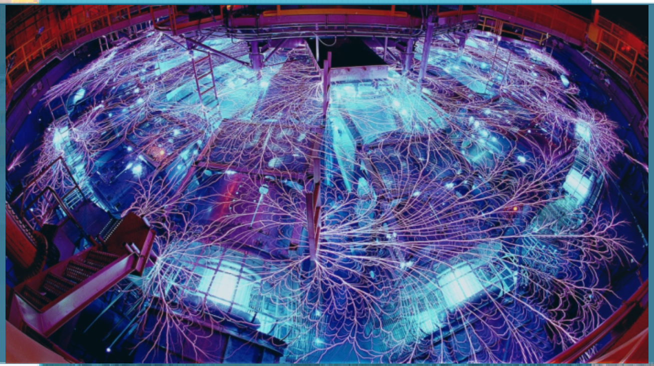
SAND2021-13948C

Sandia National Laboratories

Simultaneous inference of multiple stagnation performance metrics in MagLIF Experiments using Bayesian Data Assimilation



Patrick F. Knapp

63rd Annual Meeting of the APS Division of Plasma Physics

Monday November 8, 2021

Pittsburgh, PA

U.S. DEPARTMENT OF ENERGY NNSA

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Thanks to my many colleagues and contributors

[1]M.E. Glinsky, [1]M. A. Schaeuble, [1]C. A. Jennings, [1]E. C. Harding, [1]S. B. Hansen, [1]T. Nagayama, [2]J. Gunning, [1]A. J. Harvey-Thompson, [1]M. R. Gomez, [1]M. R. Weis, [1]P. F. Schmit, [1]D. E. Ruiz, [1]D. J. Ampleford, [4]M. Evans, [1]M. Geissel, [5]Shailaja Humane, [1]M. Mangan, [1]G.A. Chandler, [1,3]G. Cooper, [1]S. A. Slutz, [1]I.C. Smith, [1]T. J. Awe, [1]K. Beckwith, [1]D. B. Sinars, [1]M. E. Cuneo, [1]M. Jones, [1]J. L. Porter, [1]G. A. Rochau, [1]K. J. Peterson, [1]T.R. Mattsson, [1]M. K. Matzen,[1] ***and many more…***

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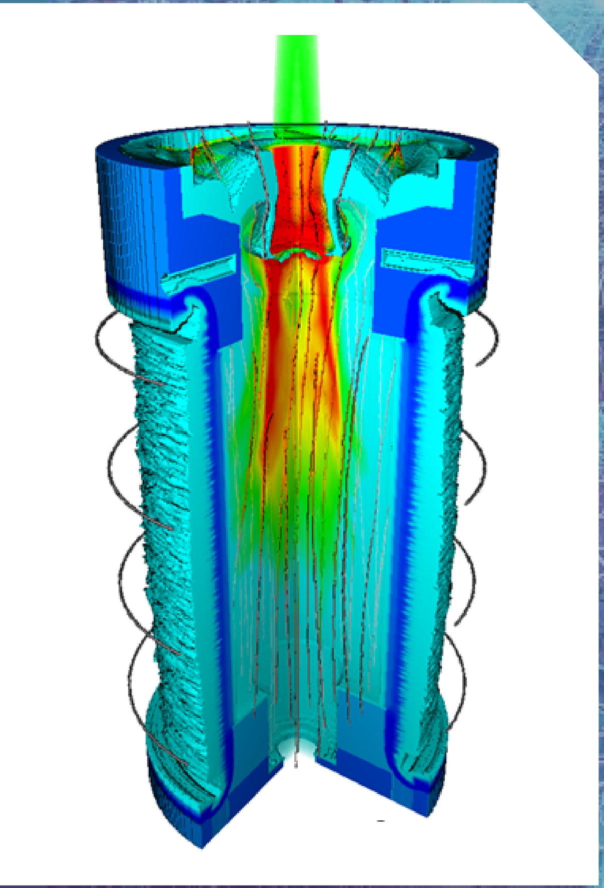
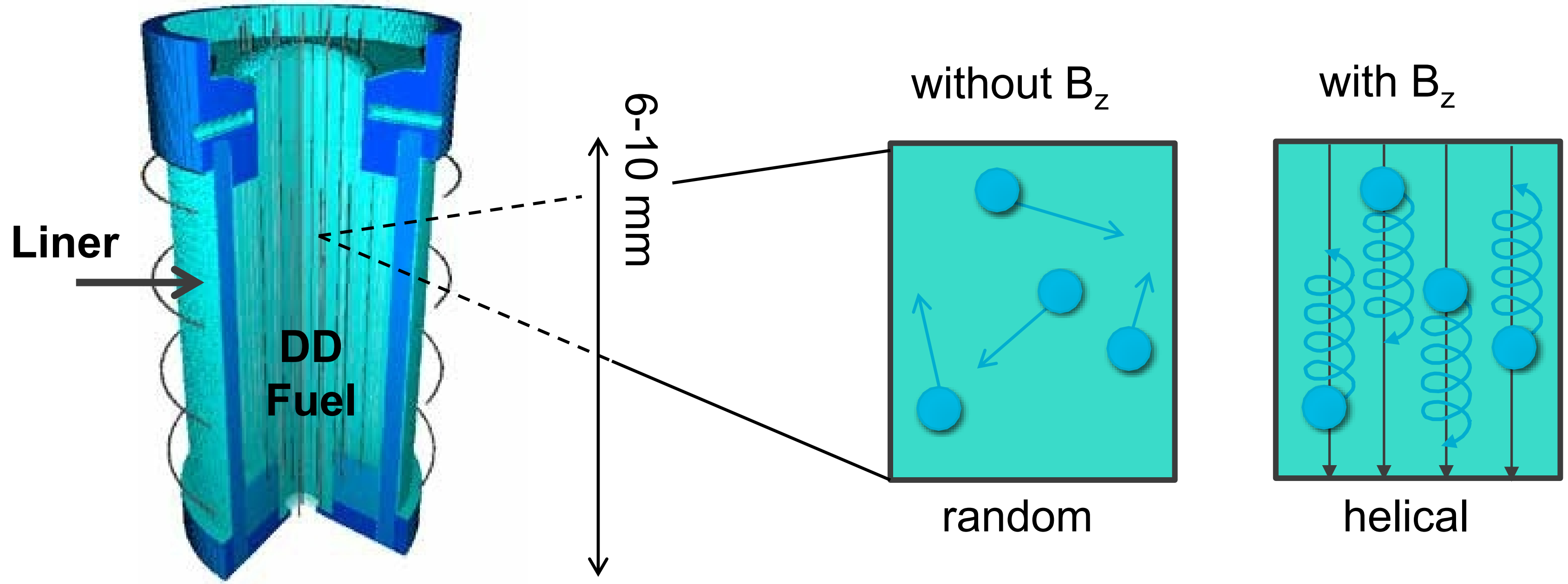
Outline



- What is Magnetized Liner Inertial Fusion
- Bayesian Data Assimilation
- Methodology and Validation
- Bulk Performance Analysis
- Scaling to larger drive current

MagLIF is a Magneto-Inertial Fusion (MIF) concept

Relies on three components to produce fusion conditions at stagnation



Magnetization: 10-30T at t=0

- **Reduces electron heat loss during implosion**
- **Traps charged particles at stagnation**

Magnetization

- Suppress radial thermal conduction losses
- Enable slow implosion with thick target walls

S.A. Slutz *et al.*, Phys. Plasmas (2010); A.B. Sefkow *et al.*, Phys. Plasmas (2014); S.A. Slutz *et al.*, Phys. Plasmas (2018).

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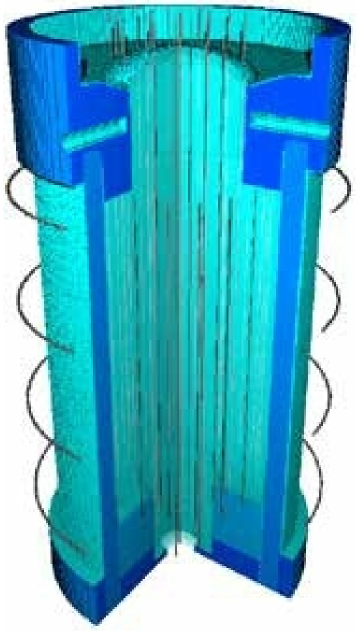
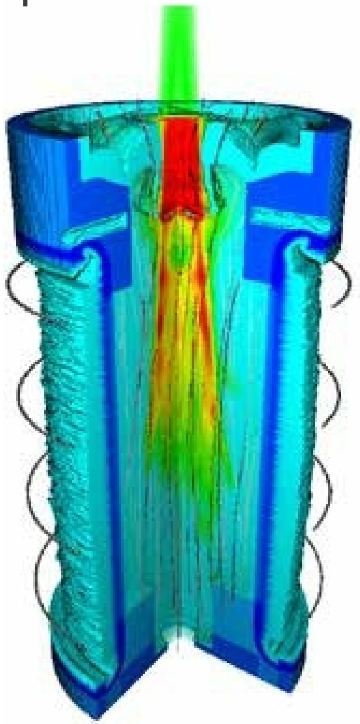
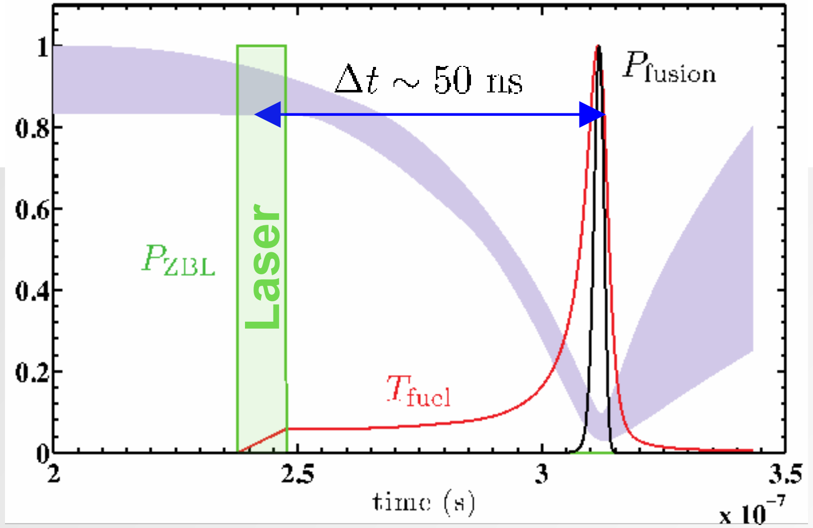




- **Laser preheat: 100-200 eV**
  - **Uses Z-Beamlet Laser**
  - **Relax convergence requirement**
  - **$CR=R_{initial}/R_{final}$= 120 → 20-40**



Magnetization

- Suppress radial thermal conduction losses
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Preheat

- Ionize fuel to lock in B-field
- Increase adiabat to limit required convergence

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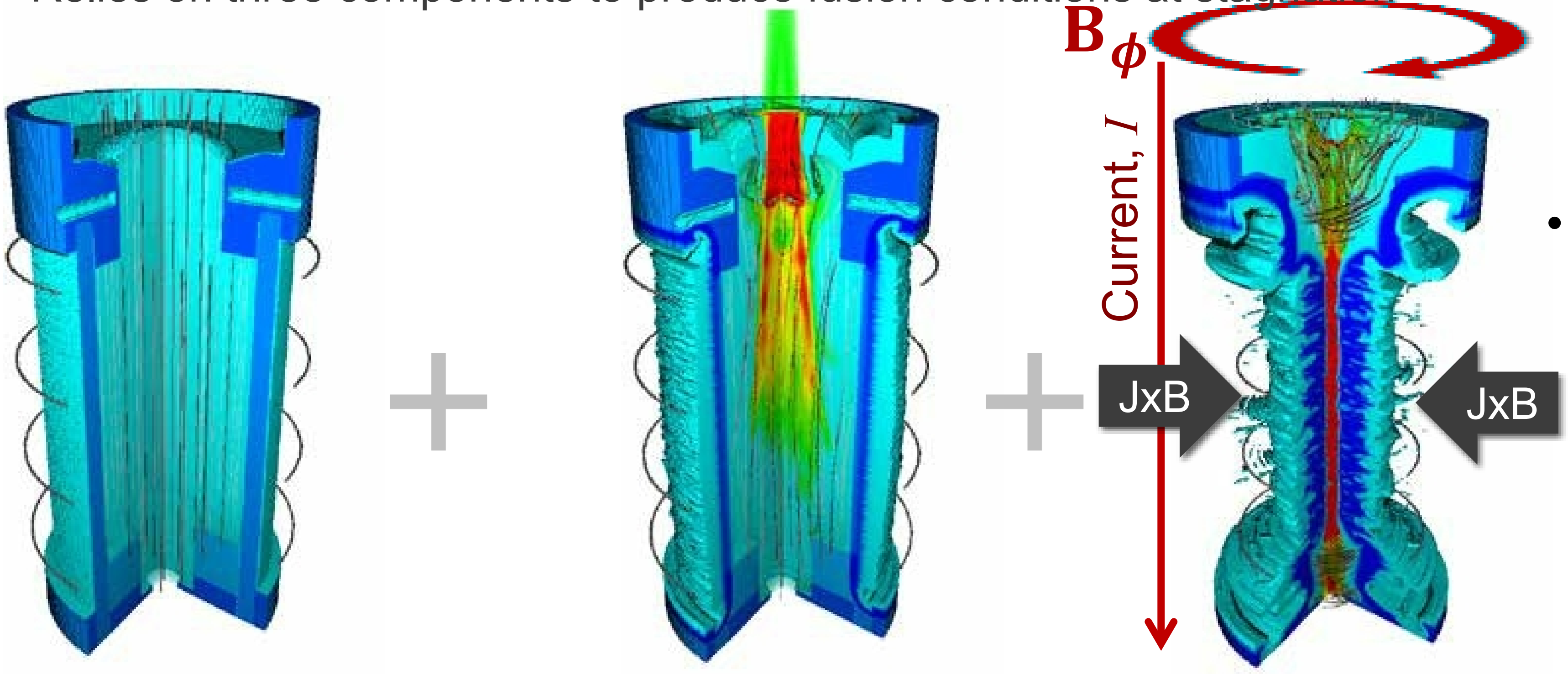

- **Magnetically Driven Implosion**
  - **Relatively low implosion velocity ~100 km/s**
  - **B-field amplified to >few kT**

Magnetization
- Suppress radial thermal conduction losses
- Enable slow implosion with thick target walls

Preheat
- Ionize fuel to lock in B-field
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Implosion
- PdV work to heat fuel
- Flux compression to amplify B-field

S.A. Slutz *et al.*, Phys. Plasmas (2010); A.B. Sefkow *et al.*, Phys. Plasmas (2014); S.A. Slutz *et al.*, Phys. Plasmas (2018).

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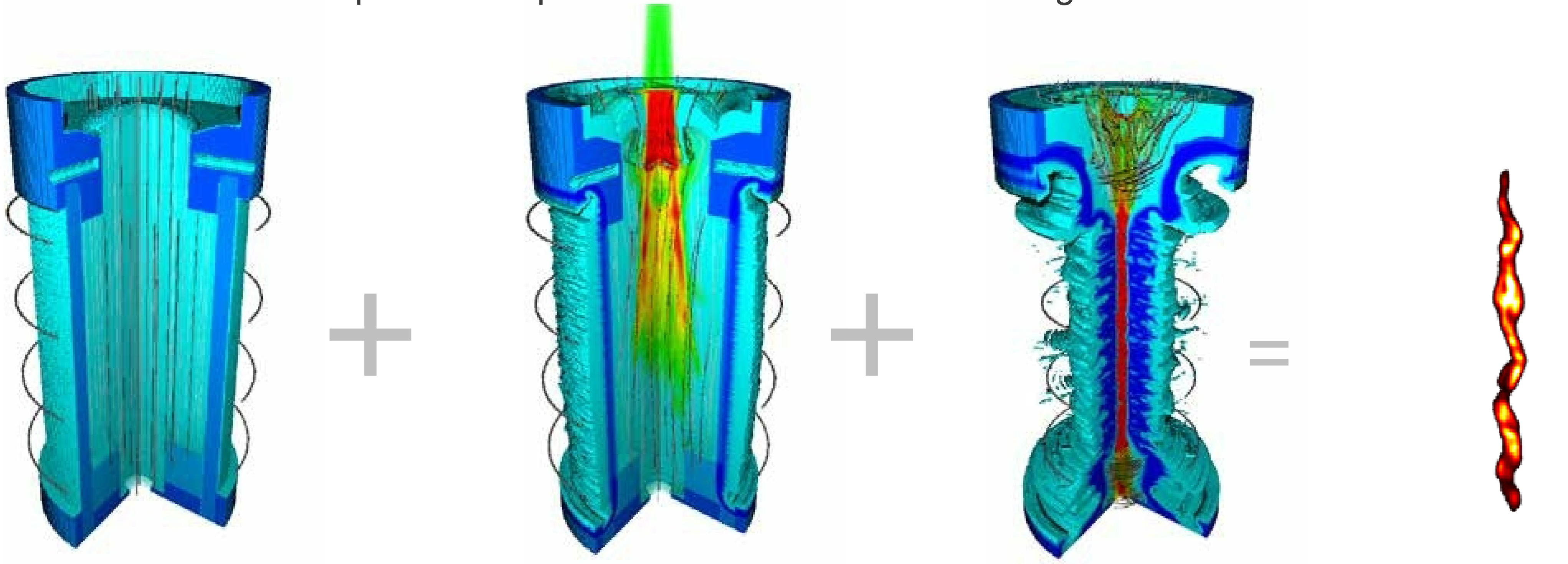

Magnetization

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Implosion

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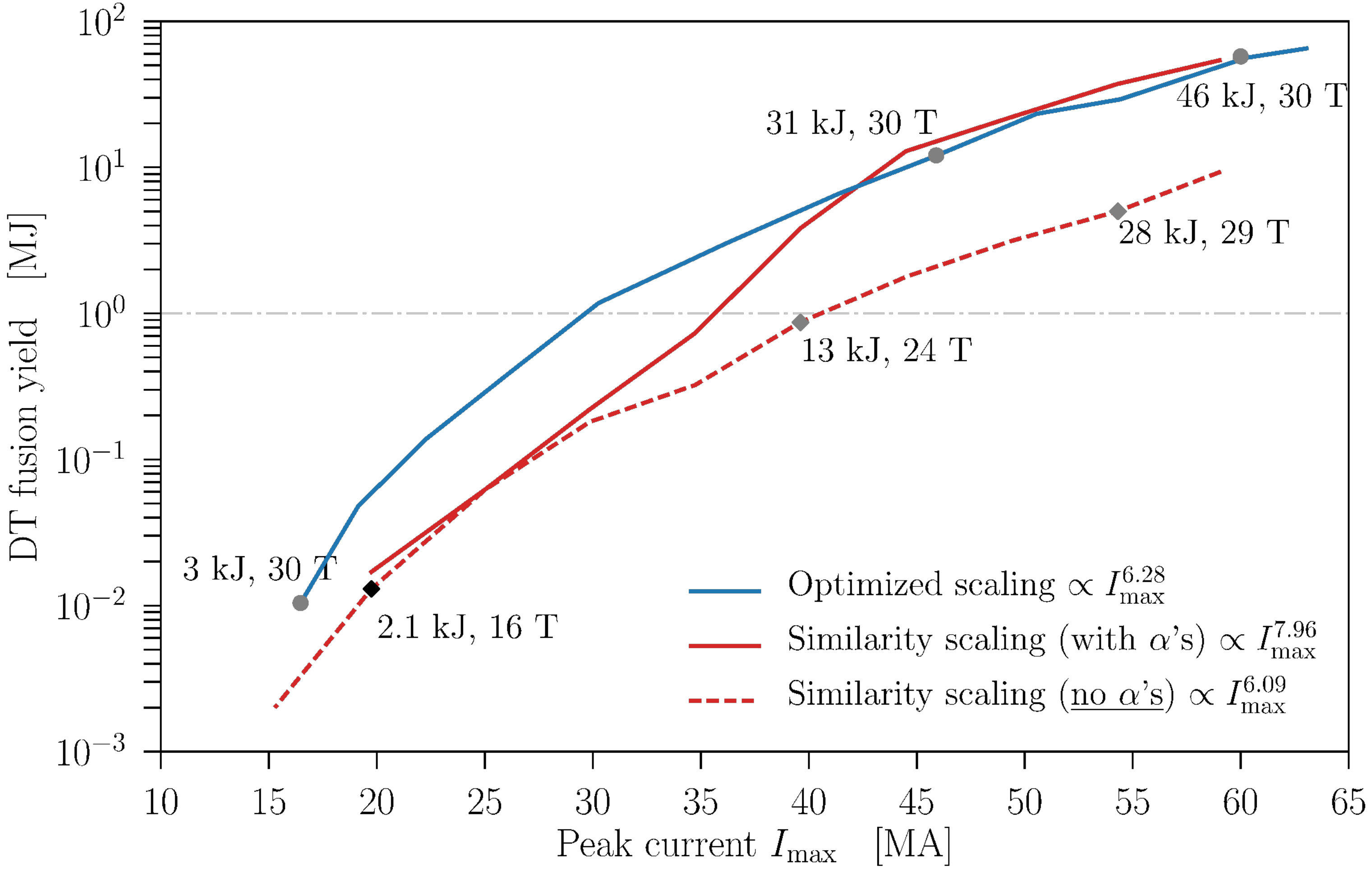
Stagnation

- Several keV temperatures, ~1 g/cm^3 fuel density
- Several kT B-field traps charged fusion products

S.A. Slutz *et al.*, Phys. Plasmas (2010); A.B. Sefkow *et al.*, Phys. Plasmas (2014); S.A. Slutz *et al.*, Phys. Plasmas (2018).

MagLIF shows promise for scaling to high Yields at larger driver energy

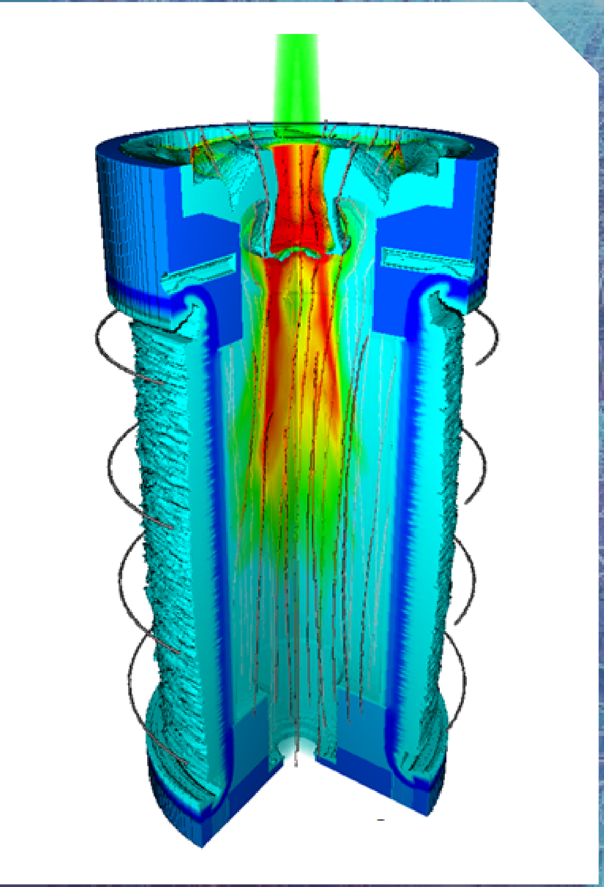


- Both numerically optimized[1] and analytically scaled[2] approaches show potential for 10's of MJ of yield
- Cryogenic layered target concepts could vastly exceed these estimates[3]
- Scaling requires larger preheat, more initial field, and more fuel in addition to higher currents
- Effects of alpha heating could be observed at currents <40 MA
- In order to understand scaling we must have a firm grasp on performance today

[1]S.A. Slutz *et al.*, Phys. Plasmas (2018), [2]P.F. Schmit and D.E. Ruiz., Phys. Plasmas (2020), [3]S.A. Slutz and R.A. Vesey, PRL (2012)

NP11.00075: D.E. Ruiz Wed. Morning

Outline



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Previous attempts to infer performance metrics were prone to large uncertainty and bias

Indium Activation measurement

Mix?

$$P_{\mathrm{HS}} = (1 + \langle Z \rangle)\sqrt{\frac{2Y_{\mathrm{DD}}}{V \tau_b S(T)}}$$

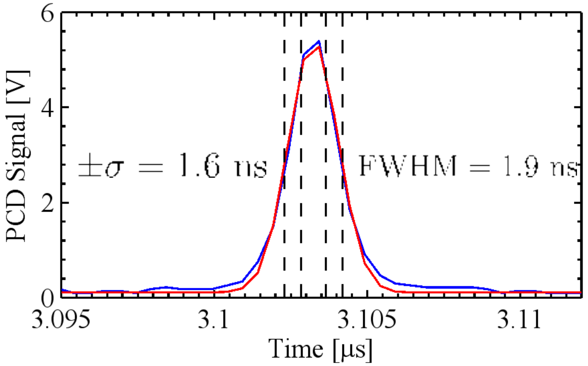
Fuel pressure cannot be directly measured, so often we use a combination of diagnostics to measure pressure using the reaction rate equation

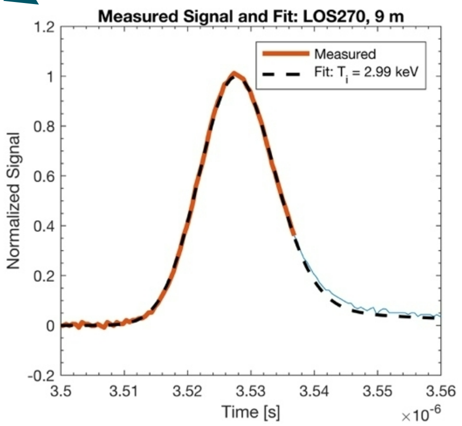
But this relies on making separate inferences from multiple nuclear and x-ray diagnostics

- Prone to bias since it is not possible to enforce consistency
- Does not extend to the addition of new diagnostic information (e.g. spectroscopy) as it becomes available

Volume:
X-ray Imaging

Time: X-ray Power

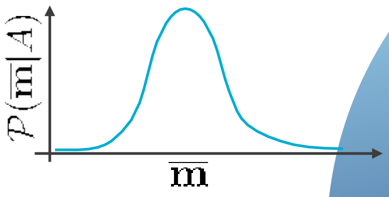


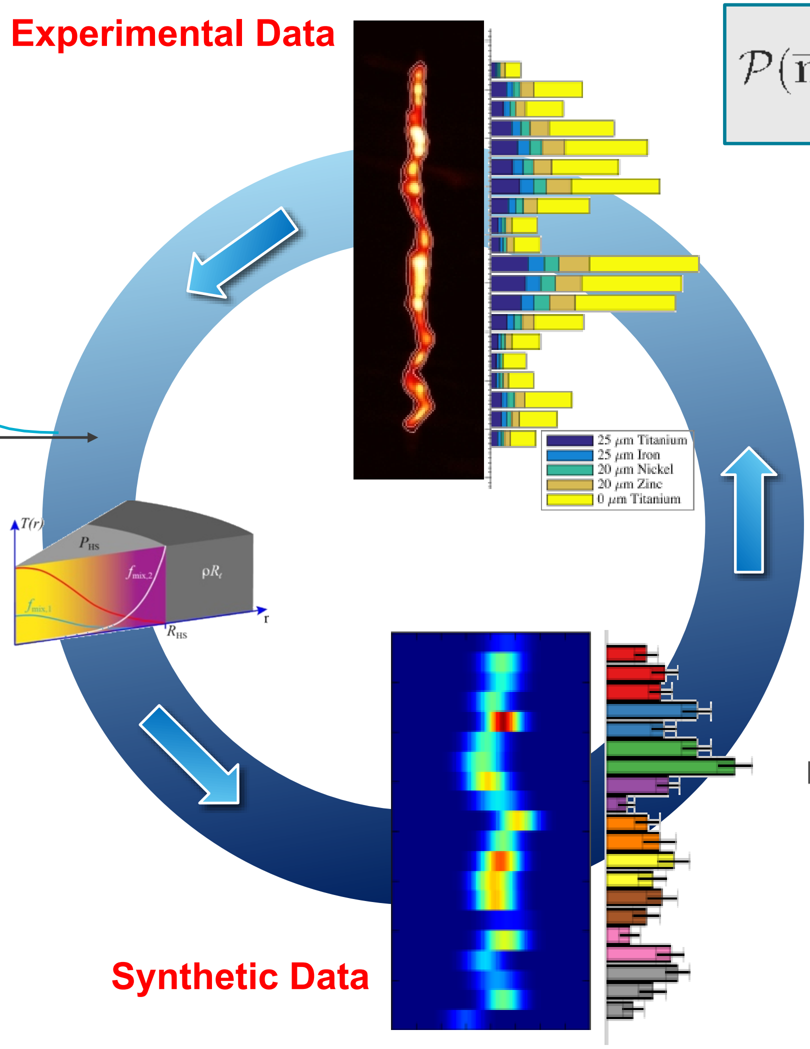


Temperature:
nTOF

Bayesian Data Assimilation allows us to find the solution that *simultaneous* matches all observables

Prior

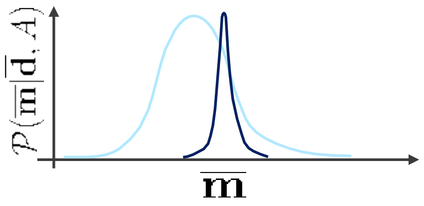




Bayes' Theorem

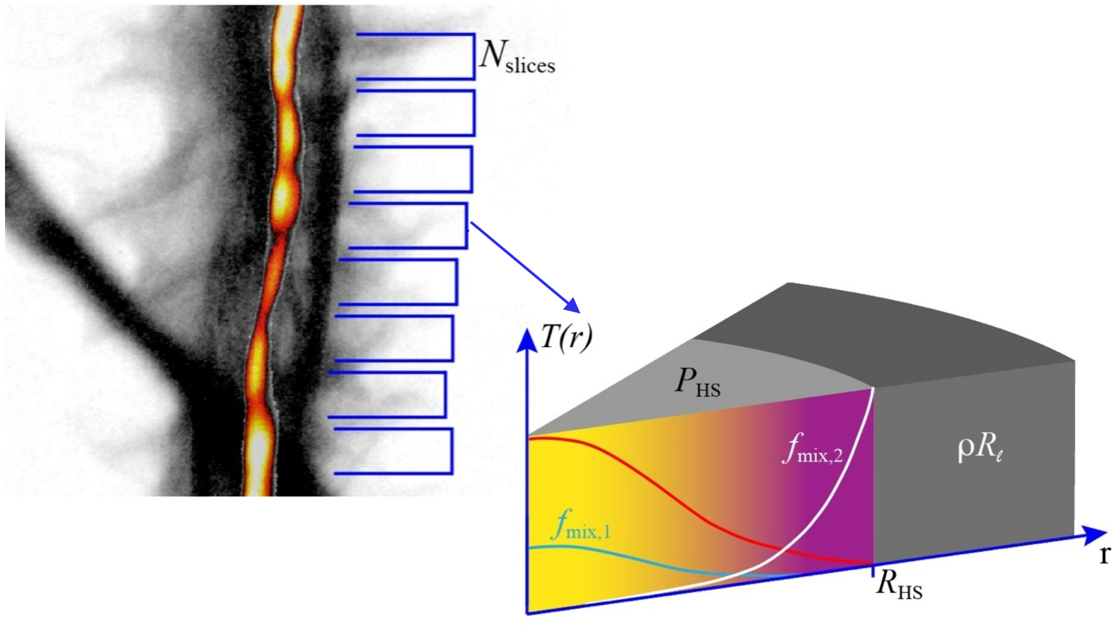
$$\mathcal{P}(\overline{\mathbf{m}}|\overline{\mathbf{d}}, A) = \frac{\mathcal{P}(\overline{\mathbf{d}}|\overline{\mathbf{m}}, A)\mathcal{P}(\overline{\mathbf{m}}|A)}{\mathcal{P}(\overline{\mathbf{d}}|A)}$$

Posterior



- Using a forward model of the plasma and diagnostics allows us to self-consistently reproduce all observables
- Prior distributions on model parameters allow us to regularize the solution
- The solution is not a point estimate, but a distribution of model parameters
- The distribution provides insights into uncertainties, correlations, sensitivities, and more

Our model computes neutron and x-ray emission from a cylindrical plasma column



X-ray Emission:

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

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

Neutron Emission:

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

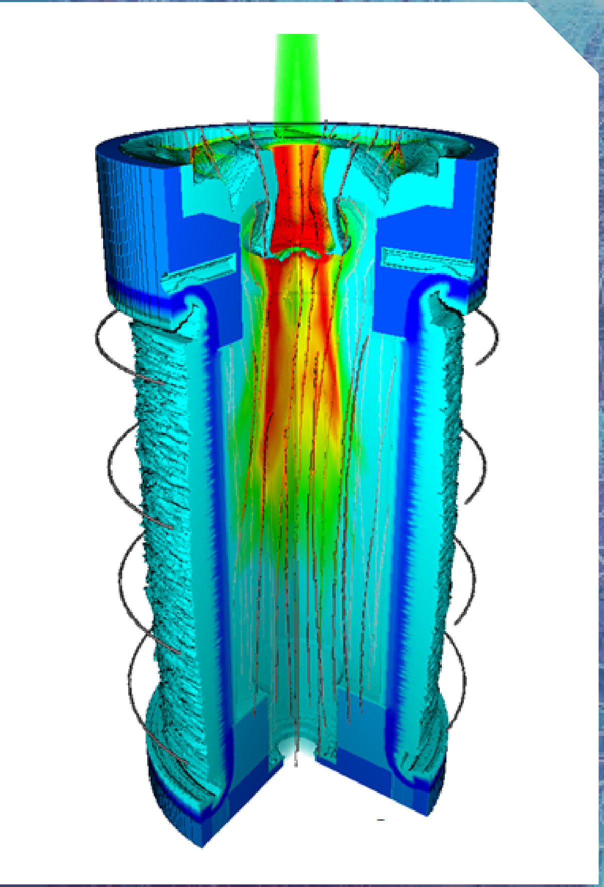
$$^{*}I_o(E) = e^{\frac{-2\bar{E}}{\sigma^2}(\sqrt{E}-\sqrt{\bar{E}})^2}$$

Assumptions:

- Each slice is a static, 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
- X-ray emission is dominated by continuum (BF & FF)
- X-ray and neutron emissivities are use to compute synthetic diagnostics

Model Parameters	Diagnostics
$\{T_{\text{i}}\} = \{T_{\text{e}}\}$	X-ray Yield
$\{\rho R_\ell\}$	Neutron Yield
$\{P_{HS}\}$	Pinhole Imager
$\{f_{\text{mix}}\}$	Crystal Imager
$\{R_{\text{HS}}\}$	nTOF

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



Outline

- What is Magnetized Liner Inertial Fusion
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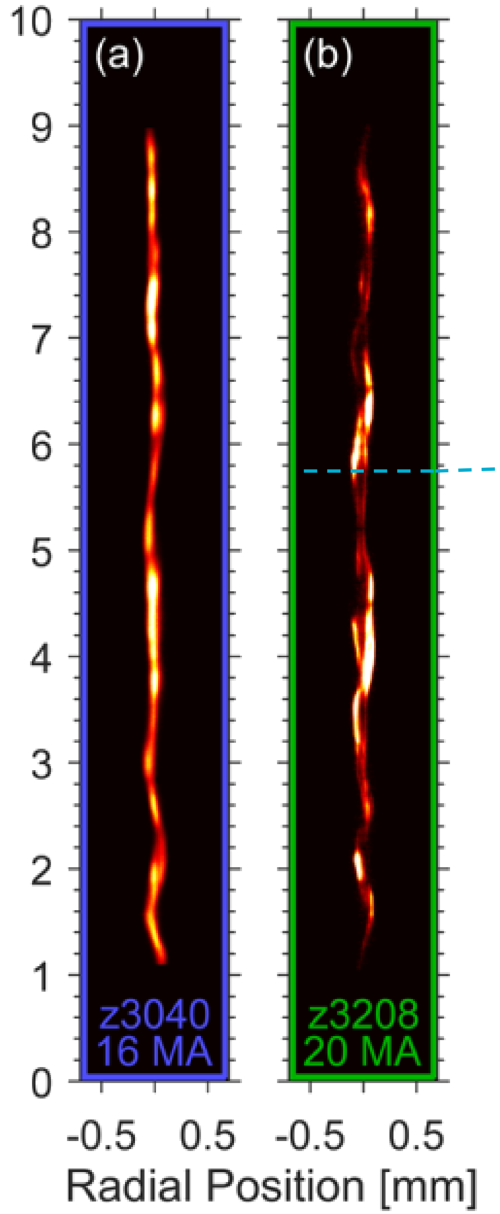
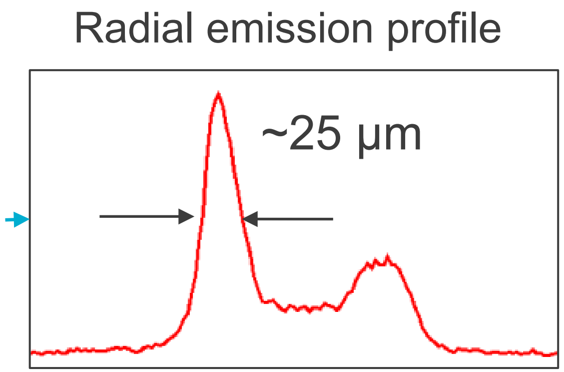
In order to infer bulk stagnation metrics we must establish that our analysis is robust to 3D structure





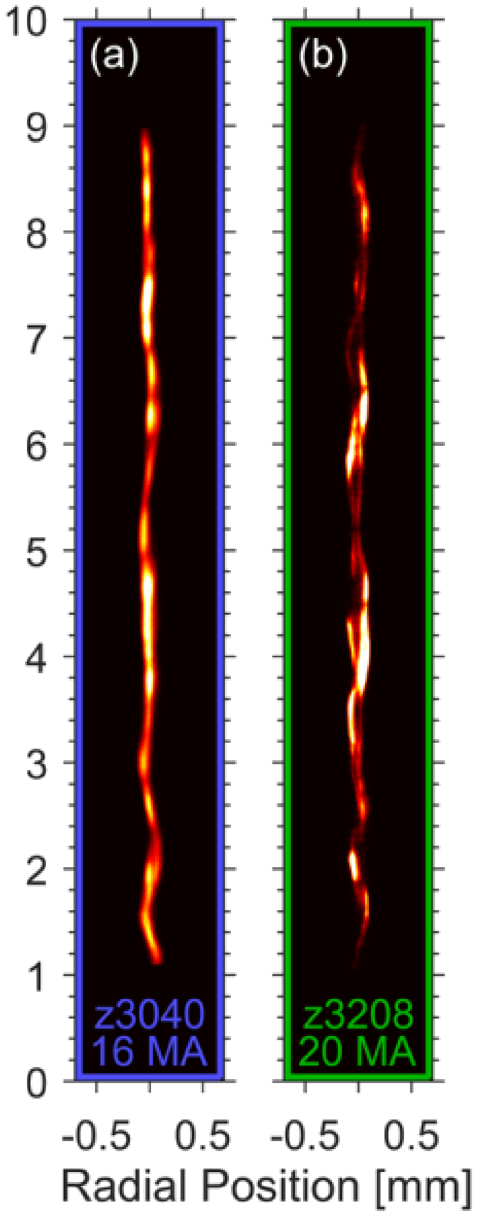
We observe highly structured stagnation columns that vary with initial conditions and drive current

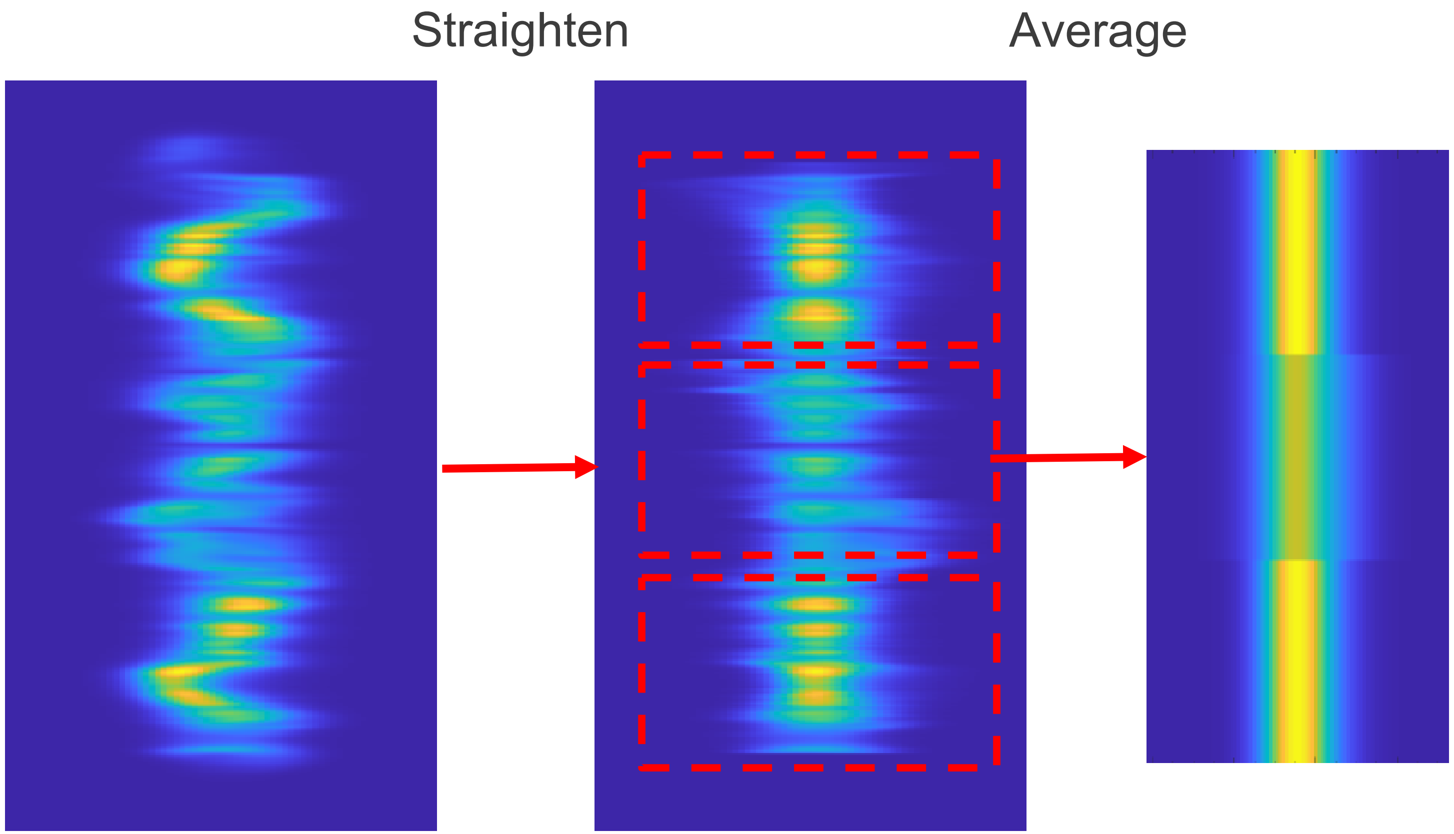
Higher resolution imaging reveals a multi-stranded helical structure on some experiments

These structures cannot be fit with a cylindrical model

In order to utilize our model to infer bulk performance metrics we must reduce our imaging data by “straightening” the column, averaging over the height, and symmetrizing it in a flux-preserving manner

In order to infer bulk stagnation metrics we must establish that we are robust to 3D structure

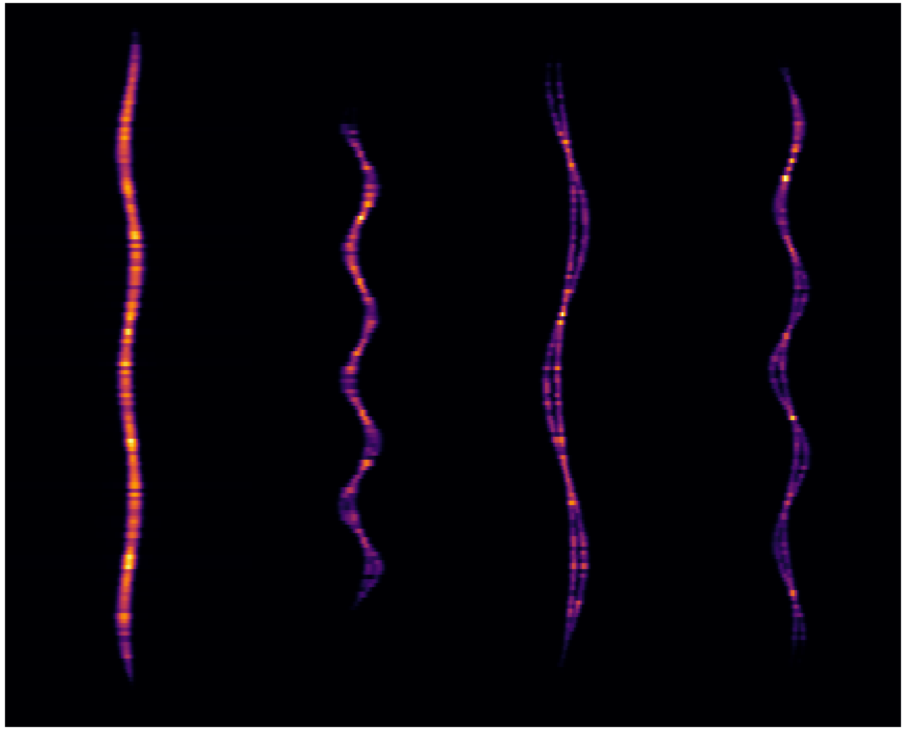


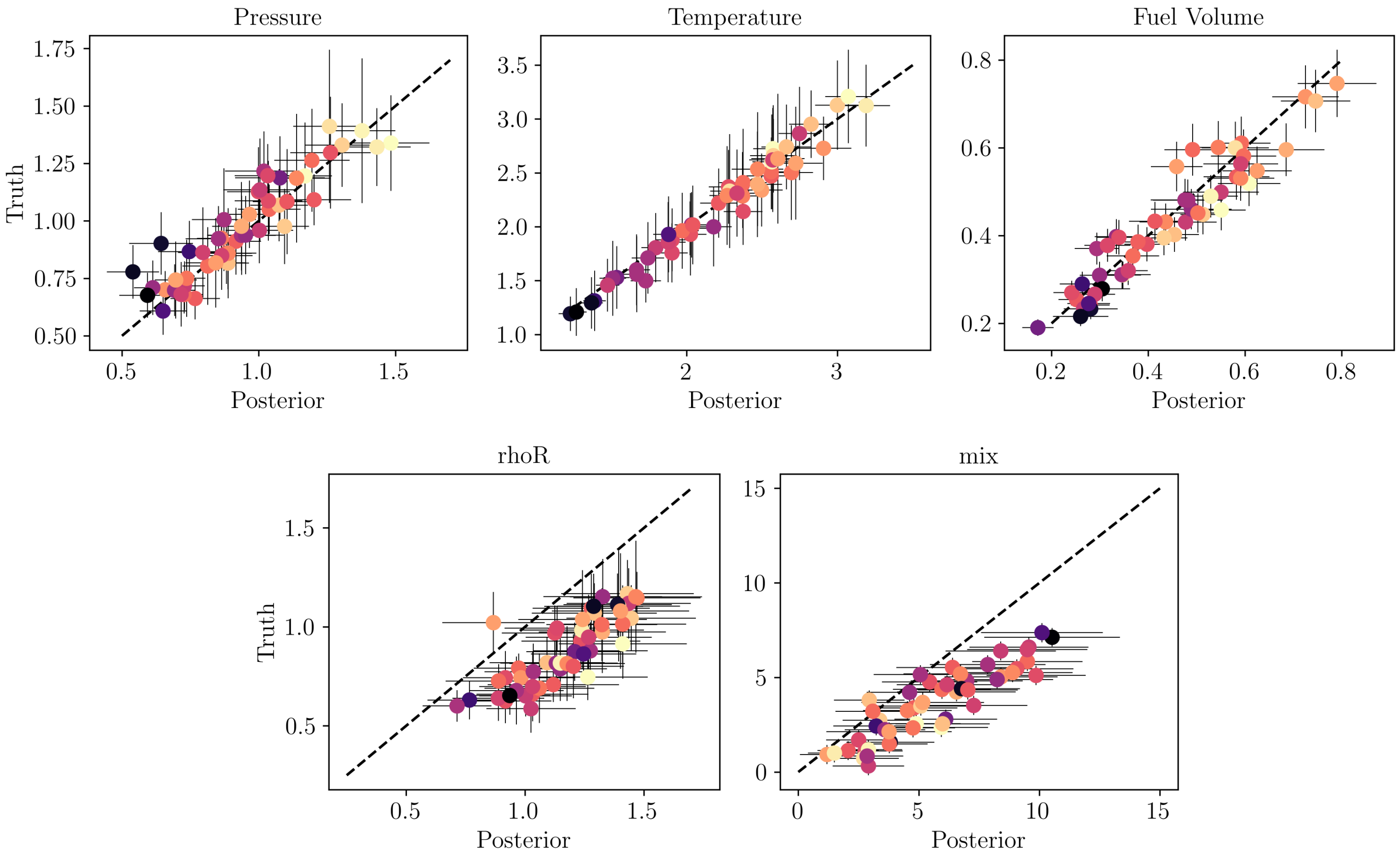


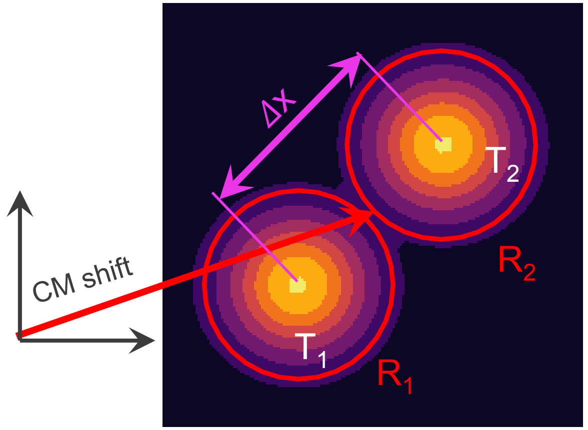
Once the images are straightened, we average them to perform analysis using a "3 slice" model

This is intended only to capture the largest axial variations

A Double Helix toy model was constructed to validate this analysis approach





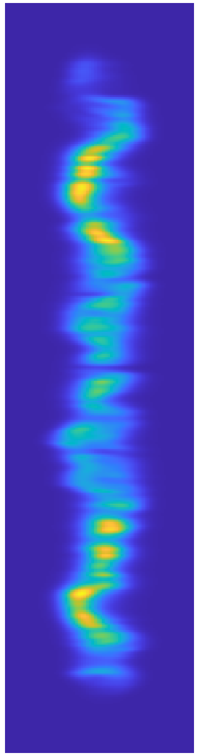


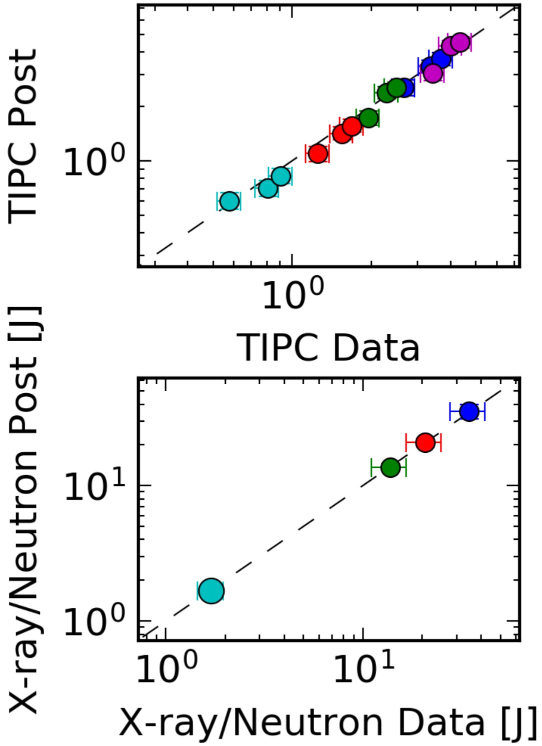
We are able to accurately infer the fuel pressure, temperature and volume

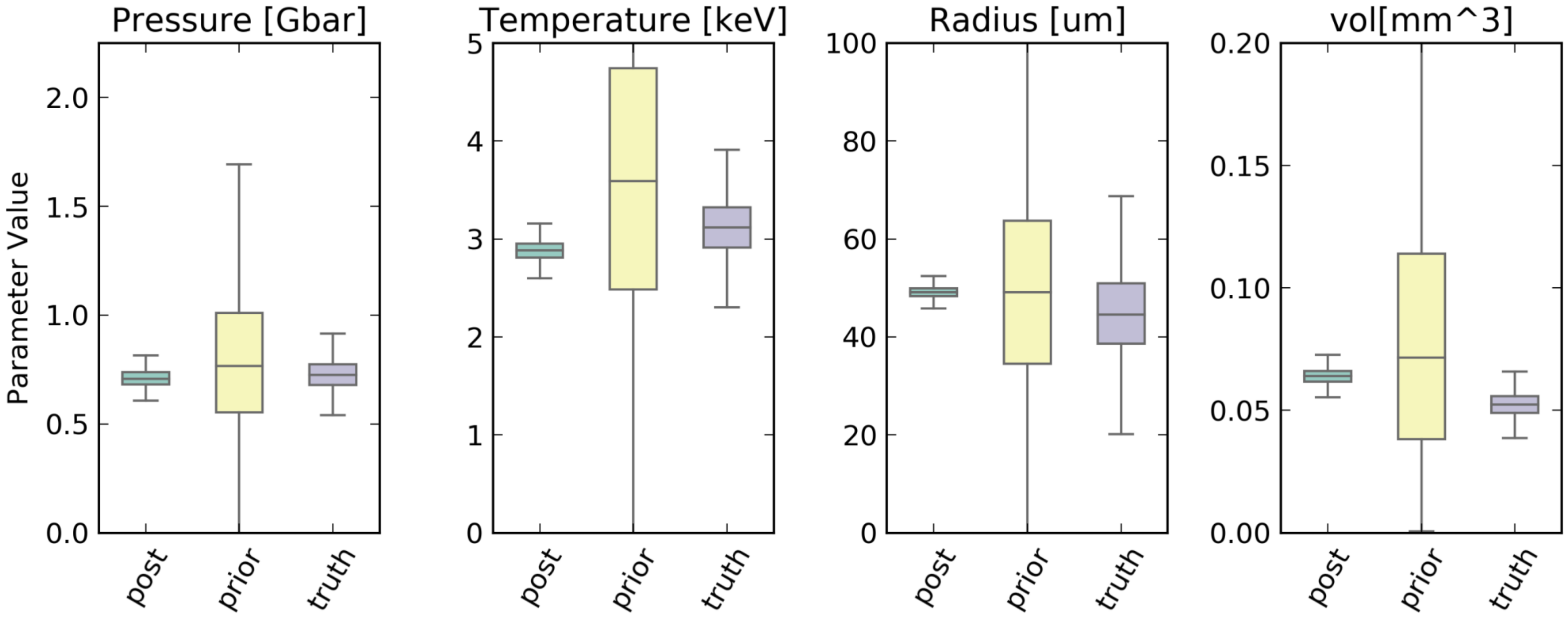
There is some bias in mix and liner areal density, however

- We have poor sensitivity to these parameters anyway
- The relative trends are still useful

Further validation was conducted using 3D GORGON simulations to provide more realistic structures and conditions



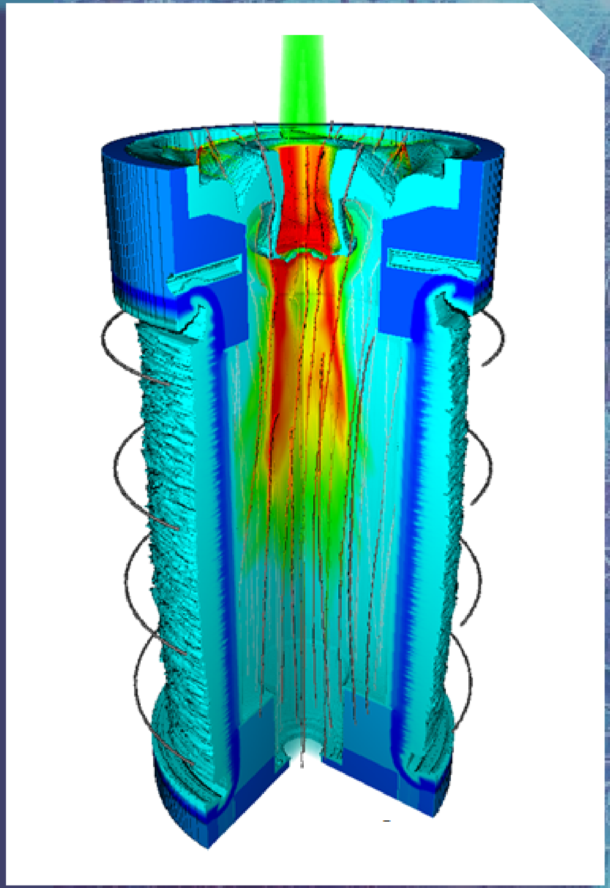




Inference on 3D GORGON simulation data compares well with bulk quantities in the presence of significant 3D structure

Inferred radius and volume compare well to the 99% neutron emission volume in GORGON

Outline



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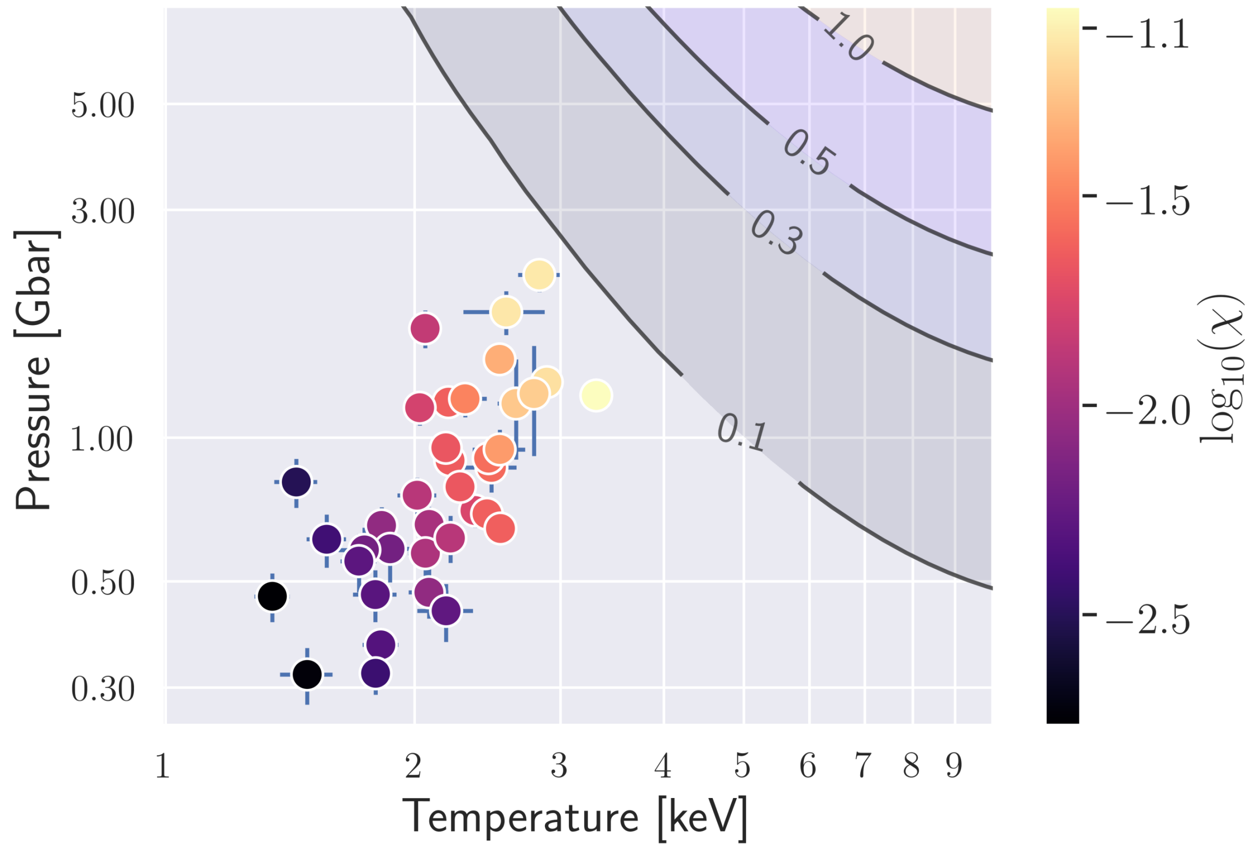
Results: Stagnation conditions



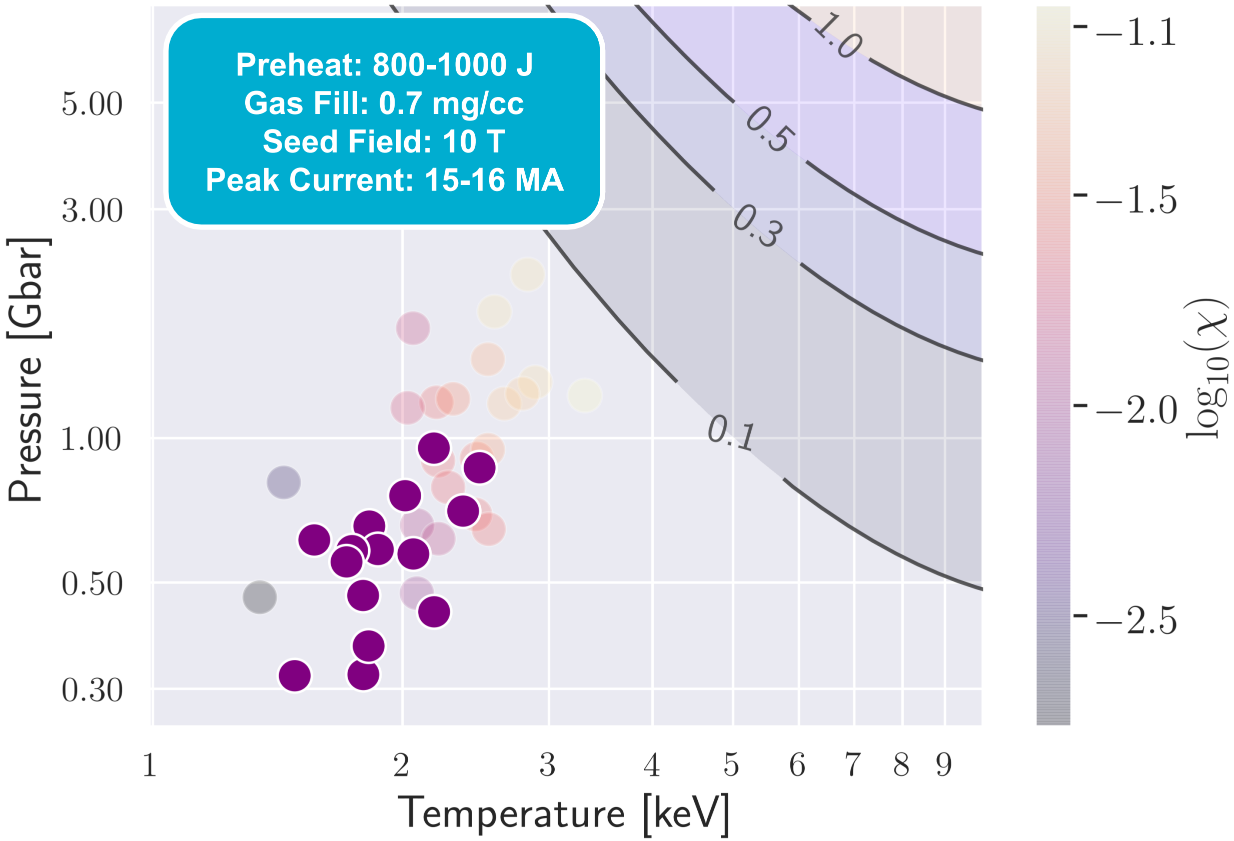
We analyzed a database of 36 MagLIF experiments dating back to 2015

Includes a wide range of neutron yields, preheat configurations, initial magnetic field strengths, fill densities, etc.

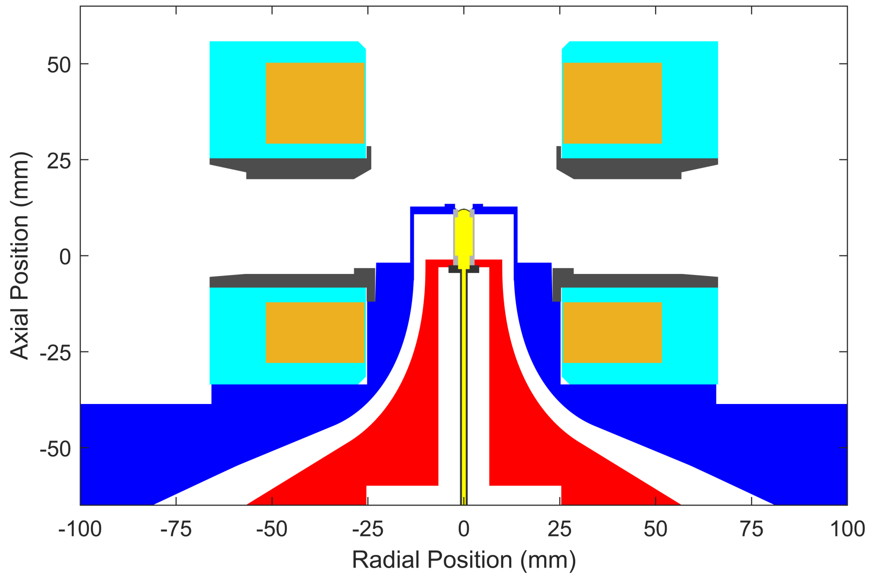
$$\chi = \frac{\varepsilon_\alpha}{24} P_{\mathrm{HS}} \tau_{\mathrm{E}} \frac{\langle \sigma v \rangle_{\mathrm{DT}}}{T^2}$$

Simultaneously increasing all input parameters provides the largest performance improvements

Uncoated AR6



CO05.00001 M.R. Gomez et al.
CO05.00004 A. J. Harvey-Thompson et al.
CO05.00006 M. Geissel et al.
CO05.00012 M.R. Weis et al.



Original MagLIF experiments used an extended power-feed to accommodate coils needed to produce a uniform axial field

This feed limited current delivery to ~16 MA

Coupling ~1 kJ with minimal conditioning is correlated with mix and variability

M.R. Gomez et al, PRL (2020)

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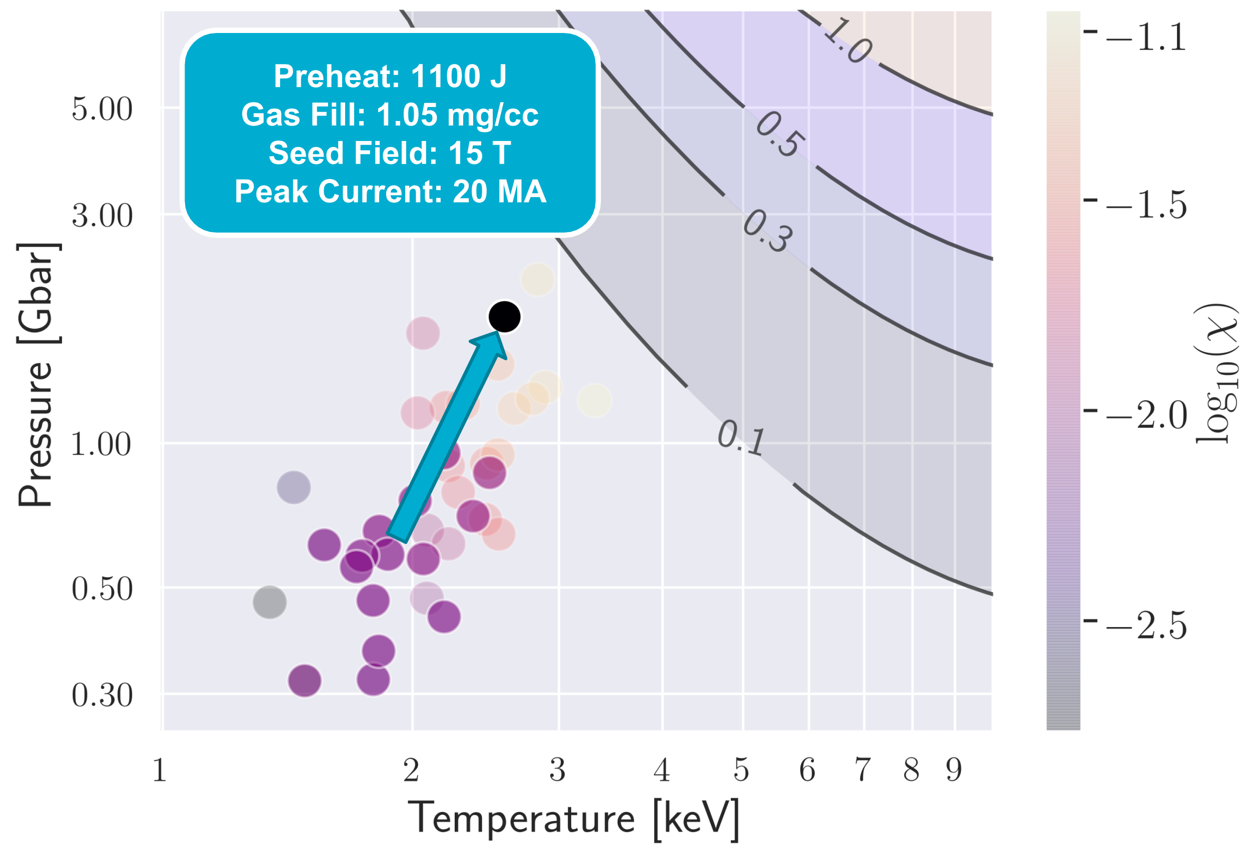

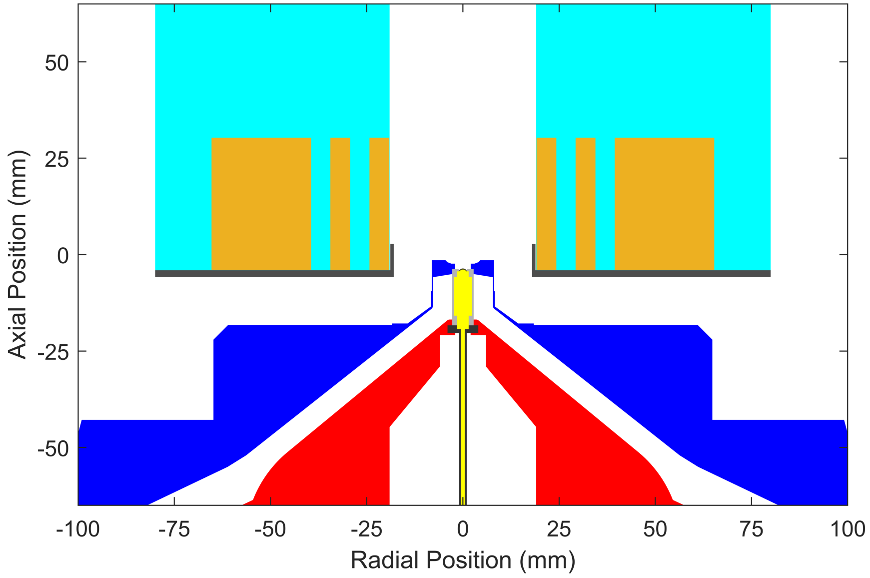

The power feed and coils were modified allow more current to be delivered to the target

The single-coil produces an average 15 T axial field with relaxed uniformity requirement

Improved laser heating protocols and higher fuel density were used to increase coupling

CO05.00001 M.R. Gomez et al.
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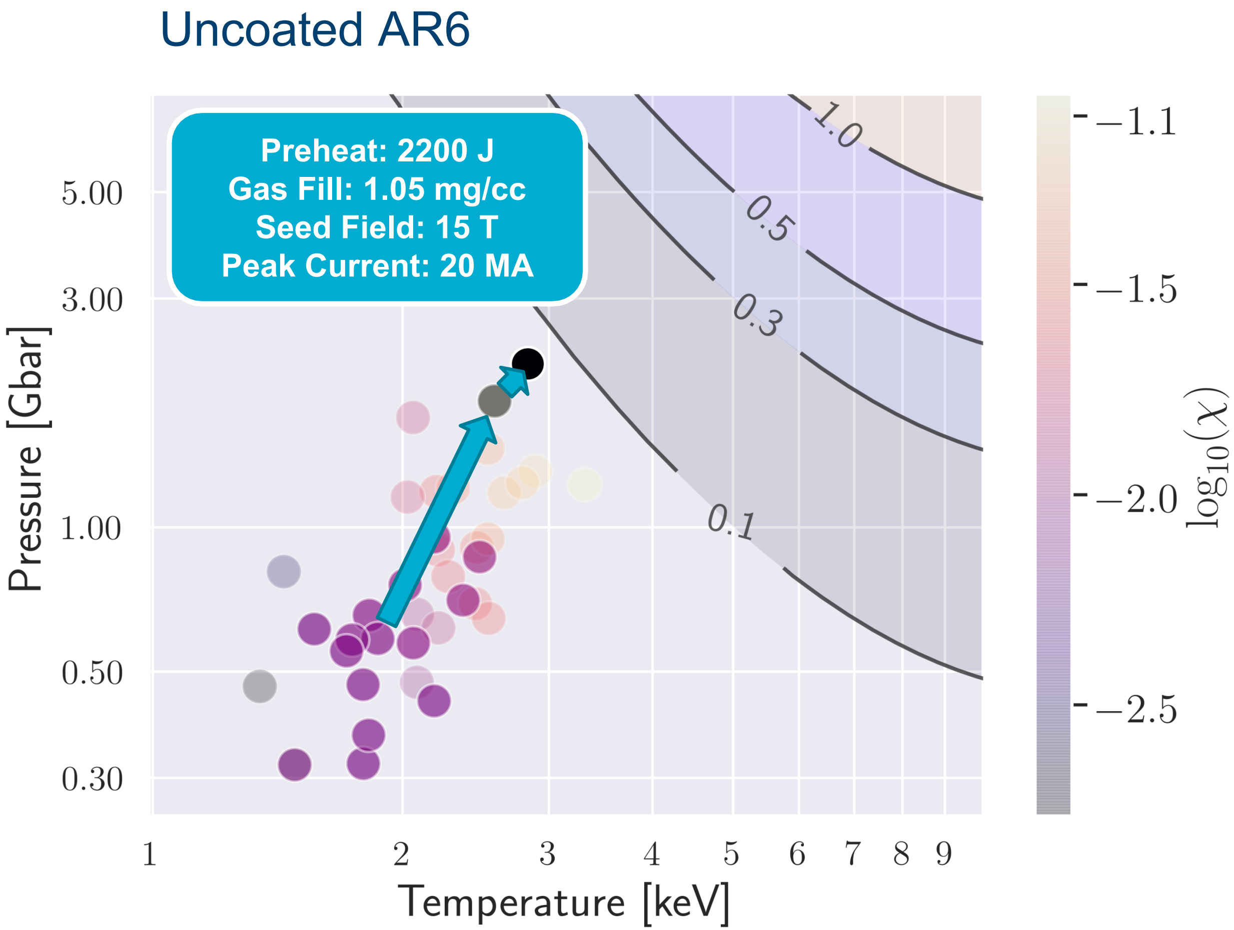

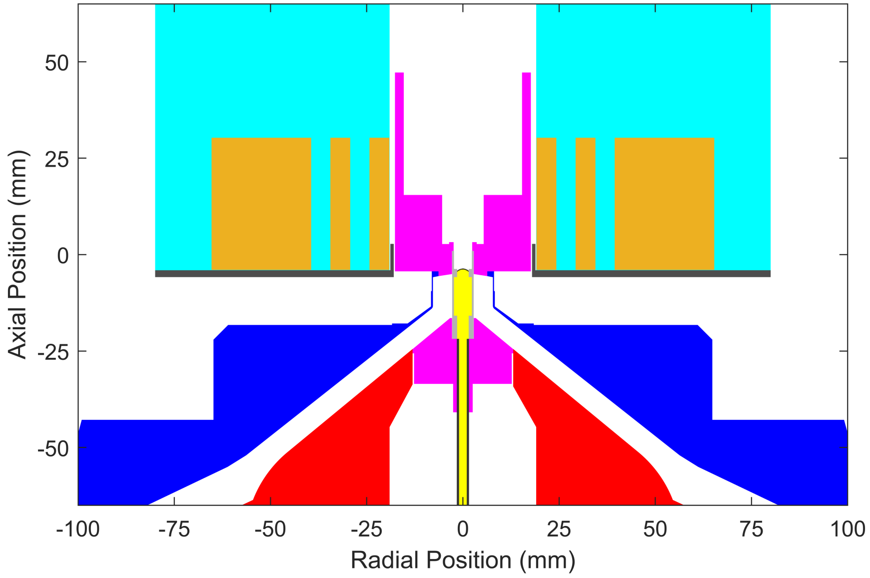

Further improvements to the laser heating were introduced

Cryogenic cooling of the target allowed the use of thinner LEH windows, improving laser coupling to the fuel and reducing mix

Together provide highest coupled preheat to date

CO05.00001 M.R. Gomez et al.
CO05.00004 A. J. Harvey-Thompson et al.
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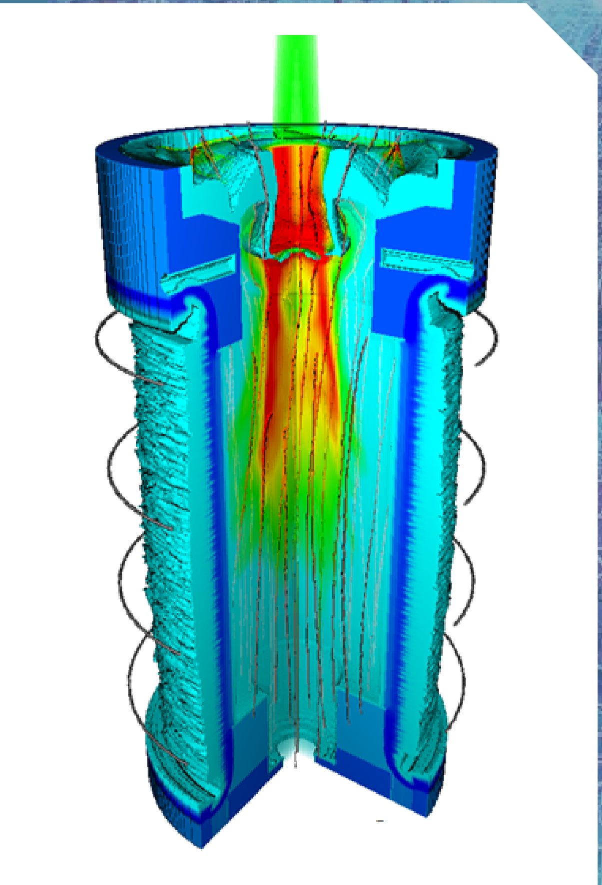

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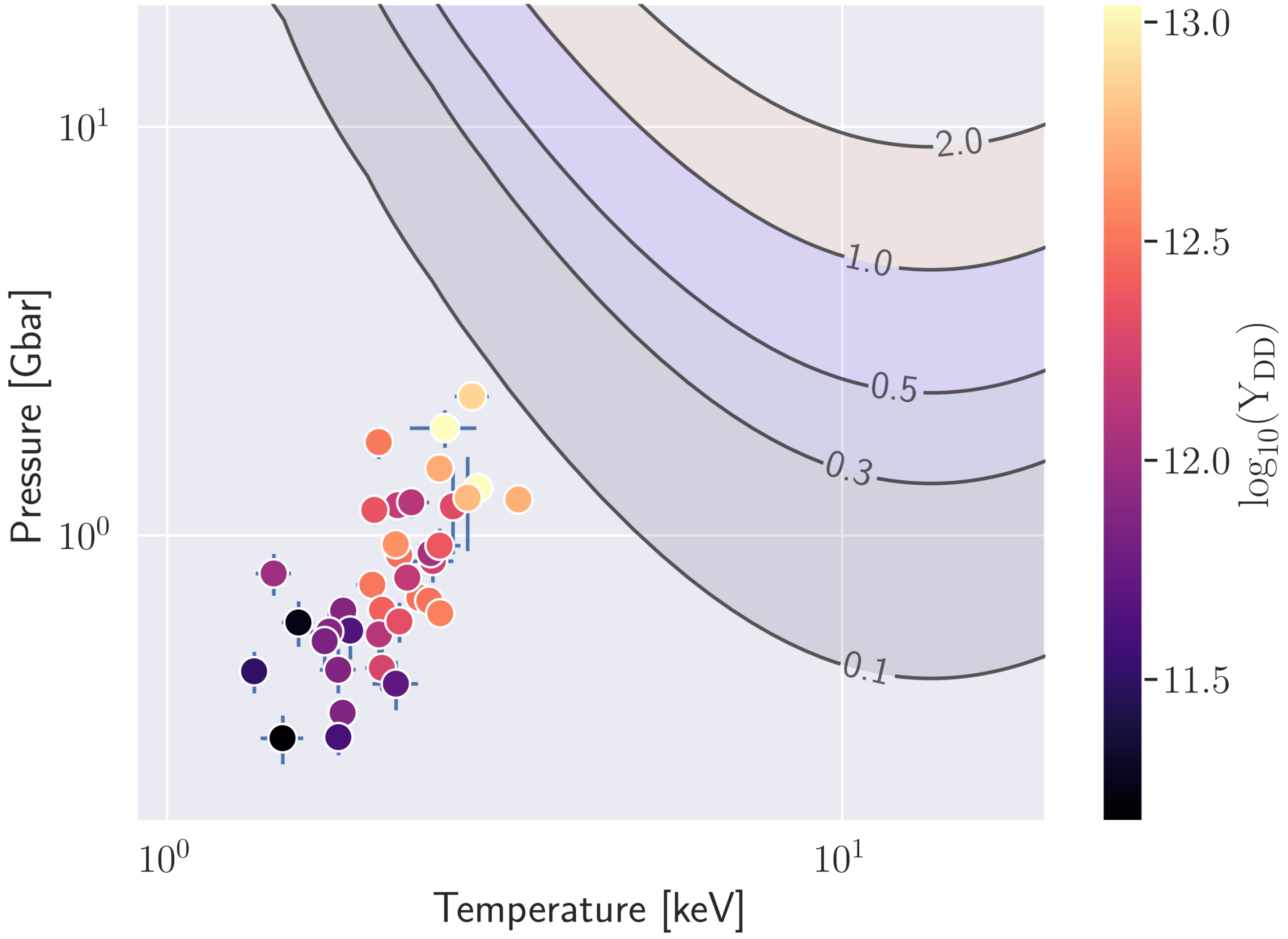
Multiple *existing* data points show the ability to scale to self-heating at realizable drive current



Using analytic scaling theory, we can assess the performance of experimental data points at larger driver energy

We choose a scaling path that preserves implosion time, radiation losses, ion-conduction losses, and end-losses

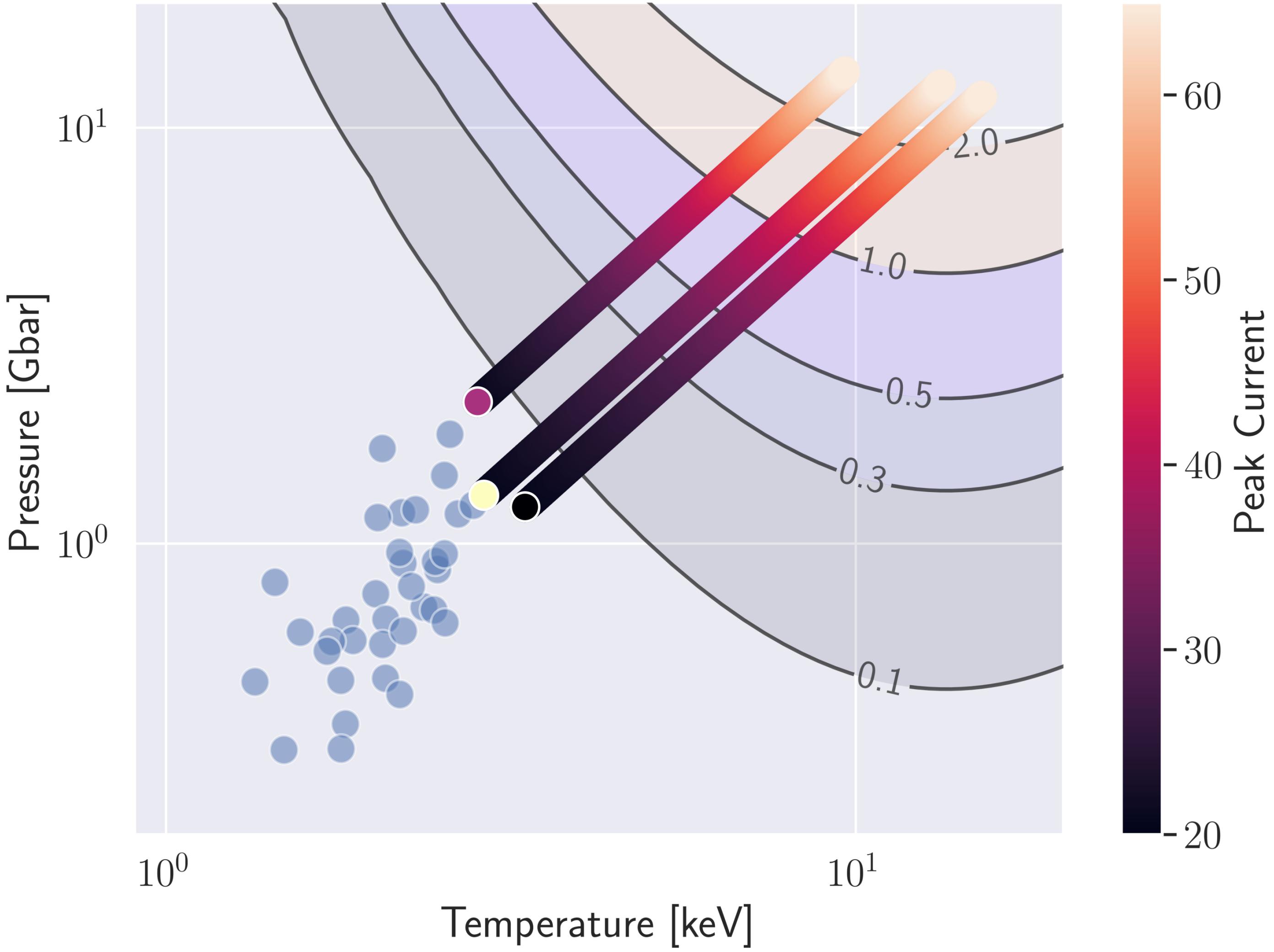
$$P_{\mathrm{no}-\alpha} \propto I_{\mathrm{peak}}^{1.5}$$

$$T_{\mathrm{no}-\alpha} \propto I_{\mathrm{peak}}$$

$$Y_{\mathrm{no}-\alpha} \propto I_{\mathrm{peak}}^{6.2}$$

P.F. Schmit and D.E. Ruiz., Phys. Plasmas **27**, 062707 (2020)

Multiple *existing* data points show the ability to scale to self-heating and multi-MJ yields at realizable drive current



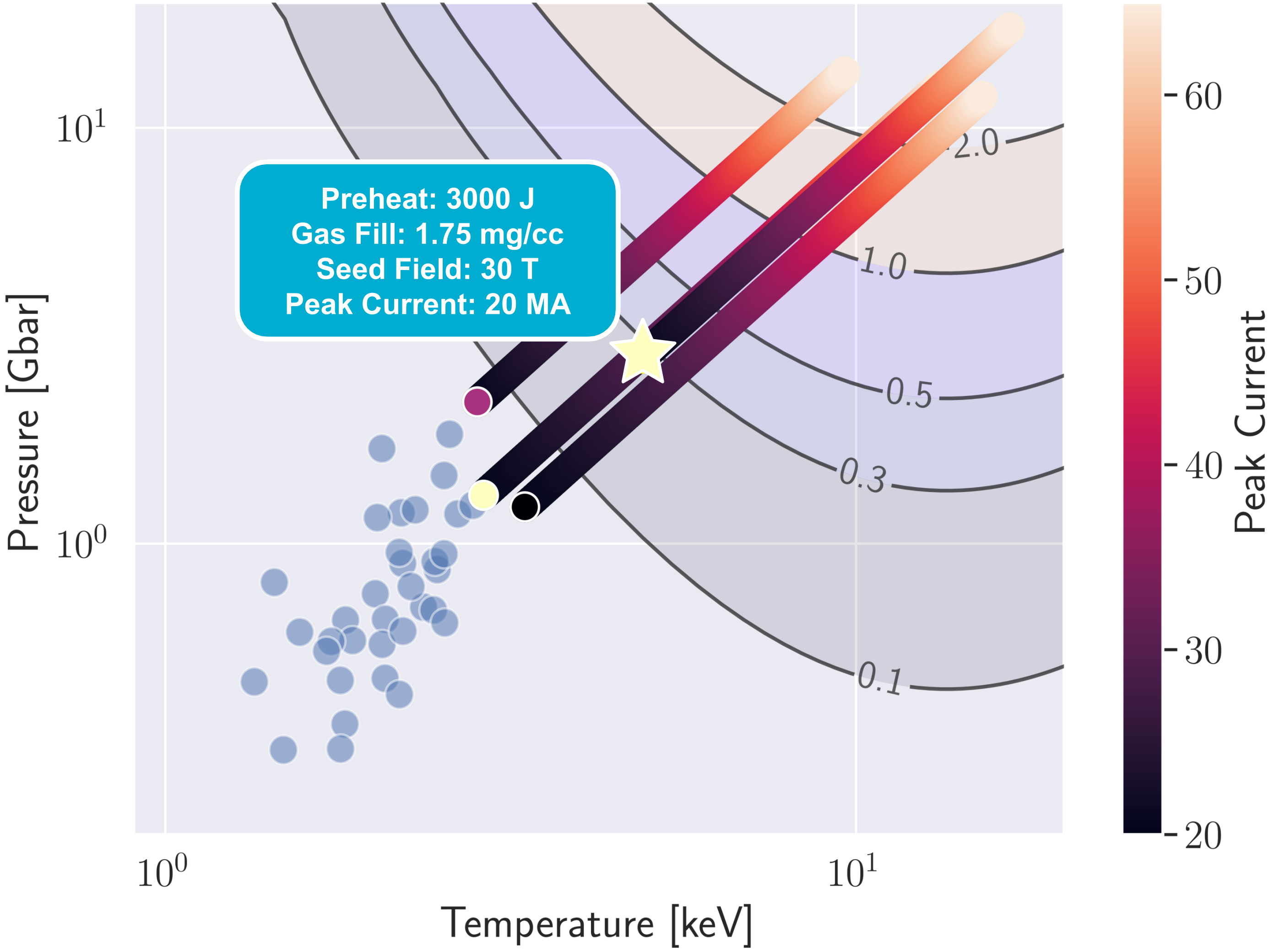
shot	Y_{DD} [10^{13}]	$X_{no\text{-}\alpha}$=1	$Y_{no\text{-}\alpha}$=1 MJ	Y_{α} [MJ]
z3179	0.5	40 MA	49 MA	6-10
z3236	1.1	38 MA	44 MA	5-9
z3576	0.7	45 MA	62 MA	5-10

- Existing targets exceed 1MJ no-α yield at currents >44 MA
- Yield amplification due to α-heating is >5x
- At 60 MA our best scaling target produces 50-100 MJ

P.F. Schmit and D.E. Ruiz., Phys. Plasmas **27**, 062707 (2020)

NP11.00075: D.E. Ruiz Wed. Morning

A design utilizing optimized input parameters on Z scales to hundreds of MJ's



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z3576	0.7	45 MA	62 MA	5-10
*Opt.	21	28 MA	41 MA	3-4.2

- The optimized target exceed $Y_{no-\alpha}$=1 MJ at the lowest drive current
- Yield amplification due to α-heating is 3-4x
- At 60 MA this target produces >40 MJ

*S.A. Slutz, et al., Physics of Plasmas **23**, 022702 (2016)

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Conclusions and future work

A Bayesian data assimilation technique was developed and used to analyze an ensemble of MagLIF experiments spanning a wide range of performance and input conditions

Applying analytic scaling theory shows existing data points scale to 100’s kJ no-α Yield and show potential for self-heating at 40-45 MA

- We have room to improve performance on Z by simultaneously increasing all input parameters

2D and 3D calculations of the scaled targets will help further assess their performance

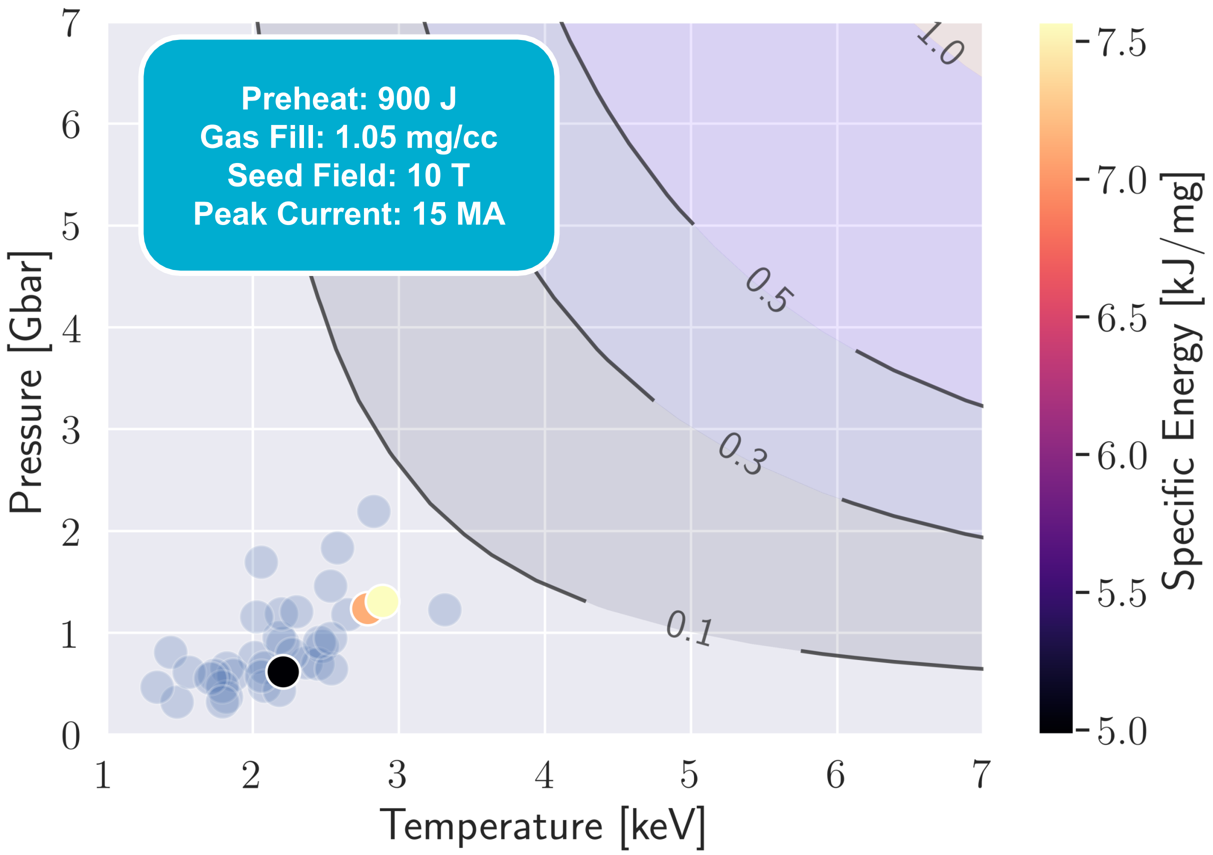
Further improving the quality of our inferences will require a model that explicitly treats the 3D structure

- Such a model has been developed and is being tested, but the optimization is strongly non-convex

Backups

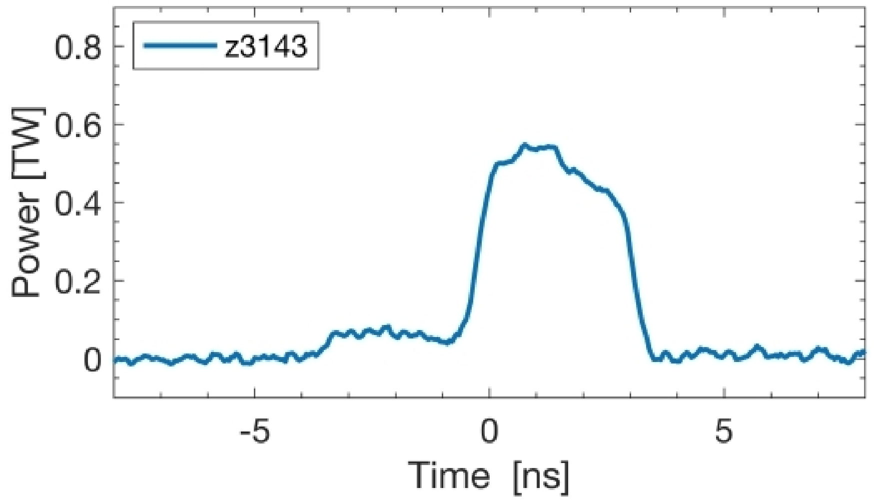
Improving laser heating protocols and increasing energy coupled shows improvements in performance

Coated AR9



CO05.00001 M.R. Gomez et al.
CO05.00004 A. J. Harvey-Thompson et al.
CO05.00006 M. Geissel et al.
CO05.00012 M.R. Weis et al.

Coated AR9 targets provide reproducible baseline from which to assess changes in preheat



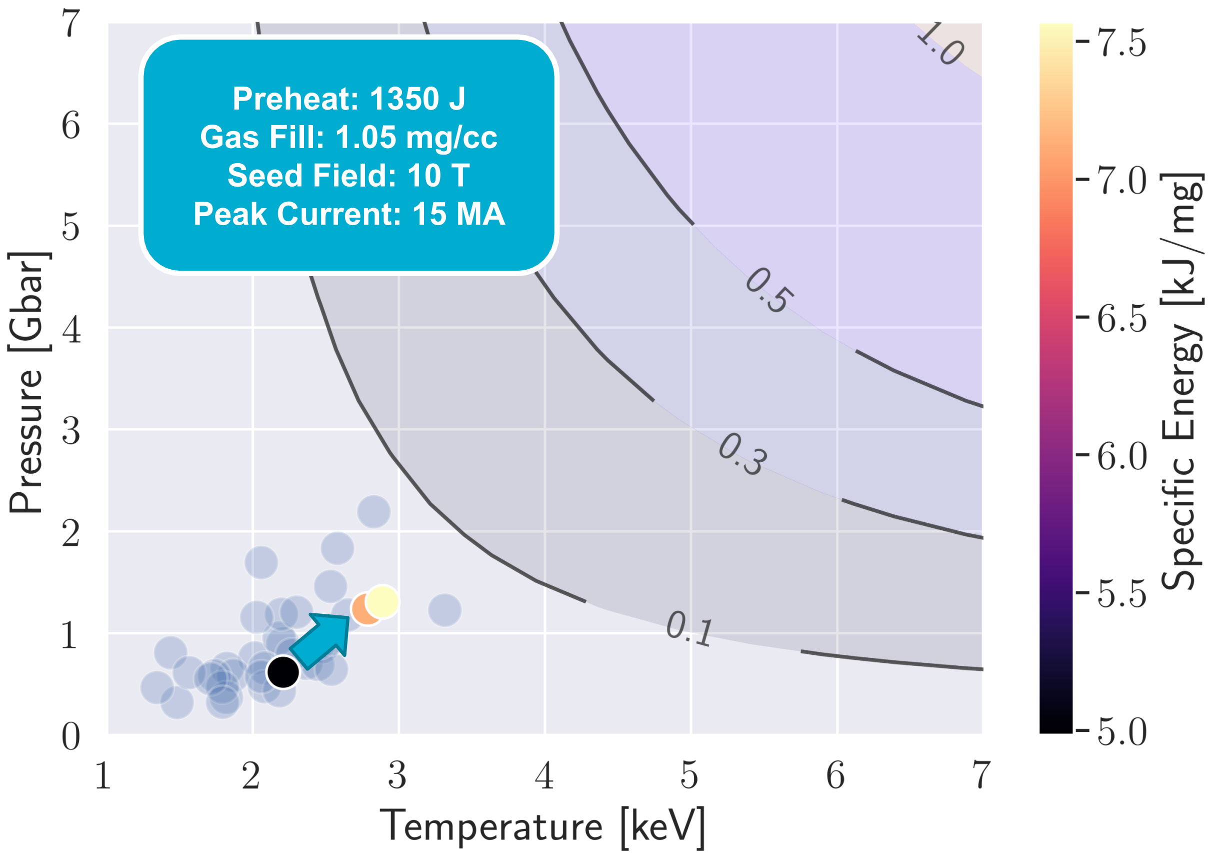
An 1100 um diameter DPP is used to smooth the wavefront, reducing high intensity spots

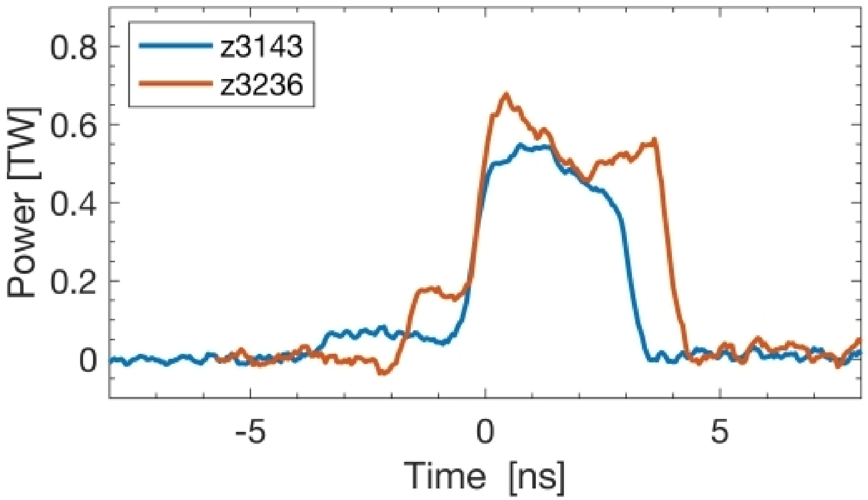
An early time ~20J pre-pulse is used to blow down the window

A foot pulse is used to re-ionize the LEH window with a modest intensity main pulse to limit LPI

Improving laser heating protocols and increasing energy coupled shows improvements in performance

Coated AR9





CO05.00001 M.R. Gomez et al.
CO05.00004 A. J. Harvey-Thompson et al.
CO05.00006 M. Geissel et al.
CO05.00012 M.R. Weis et al.

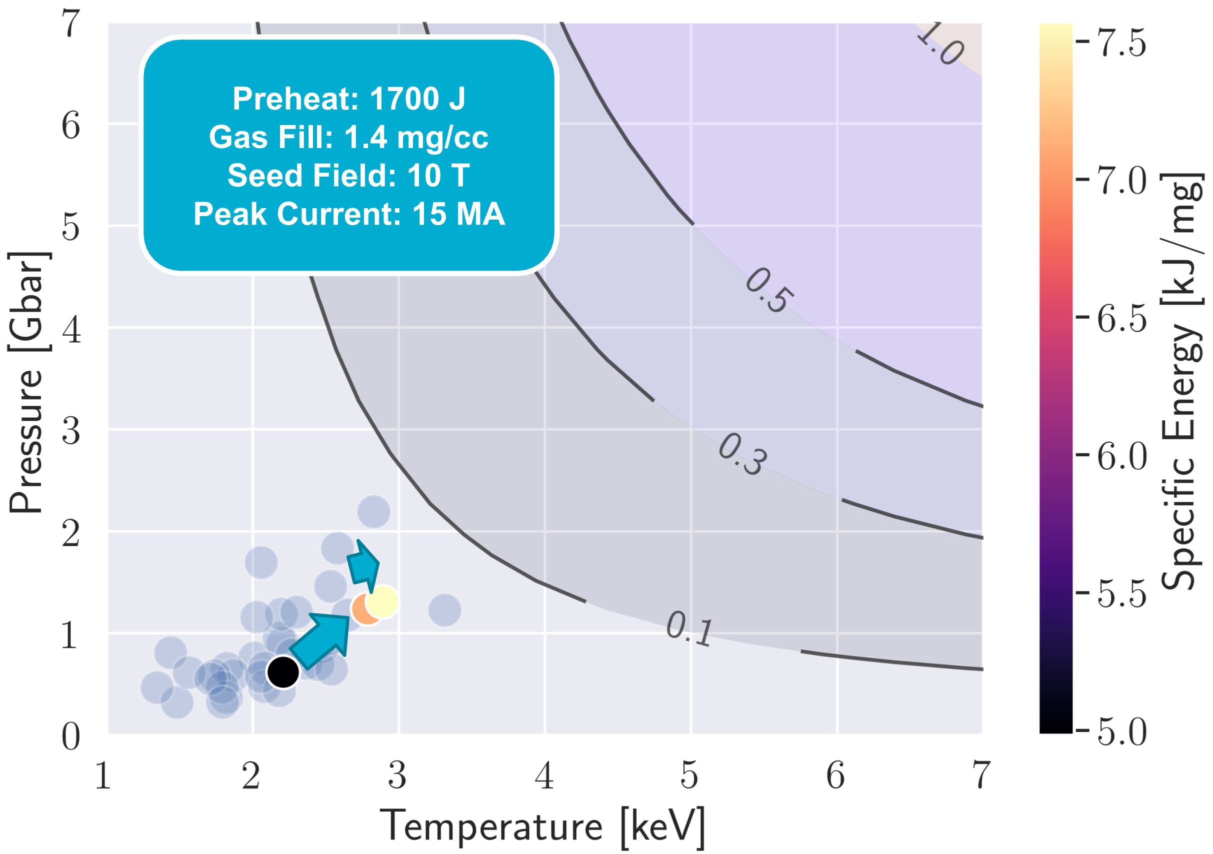
Guided by simulations, the foot pulse was increased in intensity and reduced in length

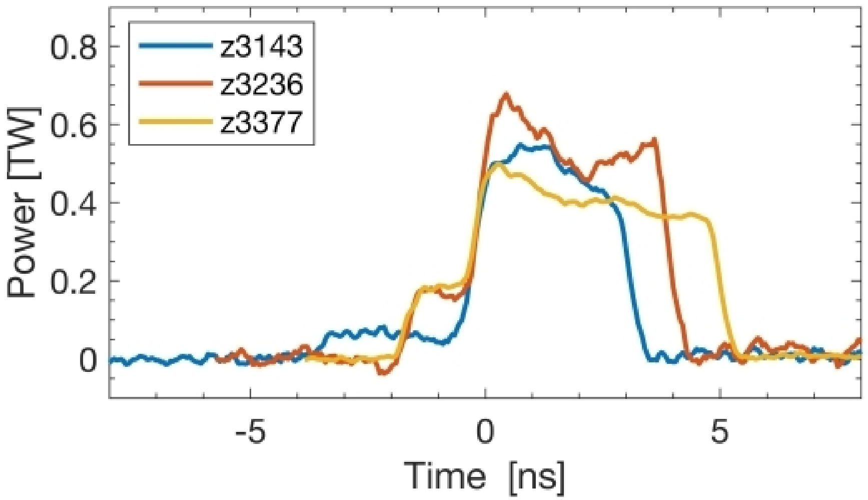
Main pulse was lengthened to increase energy deposition

Observed a substantial improvement in performance

Improving laser heating protocols and increasing energy coupled shows improvements in performance

Coated AR9





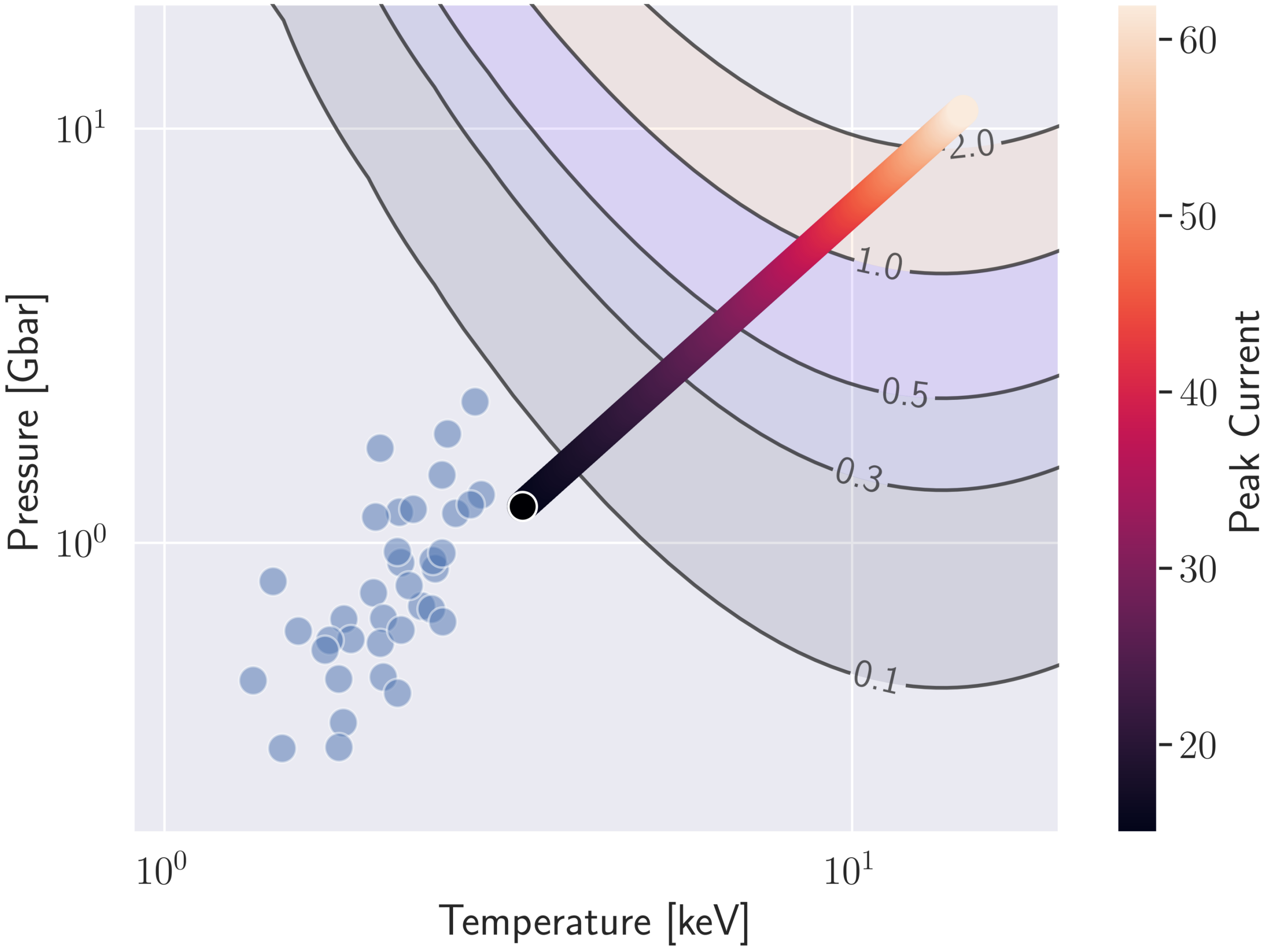
Main pulse was lengthened further to increase energy deposition

Gas density was increased to accommodate absorption from longer pulse

Achieved modest increases in specific energy deposited and performance

CO05.00001 M.R. Gomez et al.
CO05.00004 A. J. Harvey-Thompson et al.
CO05.00006 M. Geissel et al.
CO05.00012 M.R. Weis et al.

Multiple *existing* data points show the ability to scale to self-heating at realizable drive current



@15 MA, shot 3179

- B_z = 15 T, ρ_g = 0.7 mg/cm^3
- E_{dep} = 0.95 kJ
- T = 3.3 keV, P = 1.2 Gbar
- Y_{DD}=0.5x10^{13} → 1 kJ DT-equiv.

@40 MA χ = 1

- B_z = 26 T, ρ_g = 1.2 mg/cm^3
- E_{dep} = 11.6 kJ
- $T_{no\alpha}$ = 9.1 keV , $P_{no\alpha}$ = 5.6 Gbar
- $Y_{no\alpha}$ = 280 kJ

P.F. Schmit and D.E. Ruiz., Phys. Plasmas **27**, 062707 (2020)

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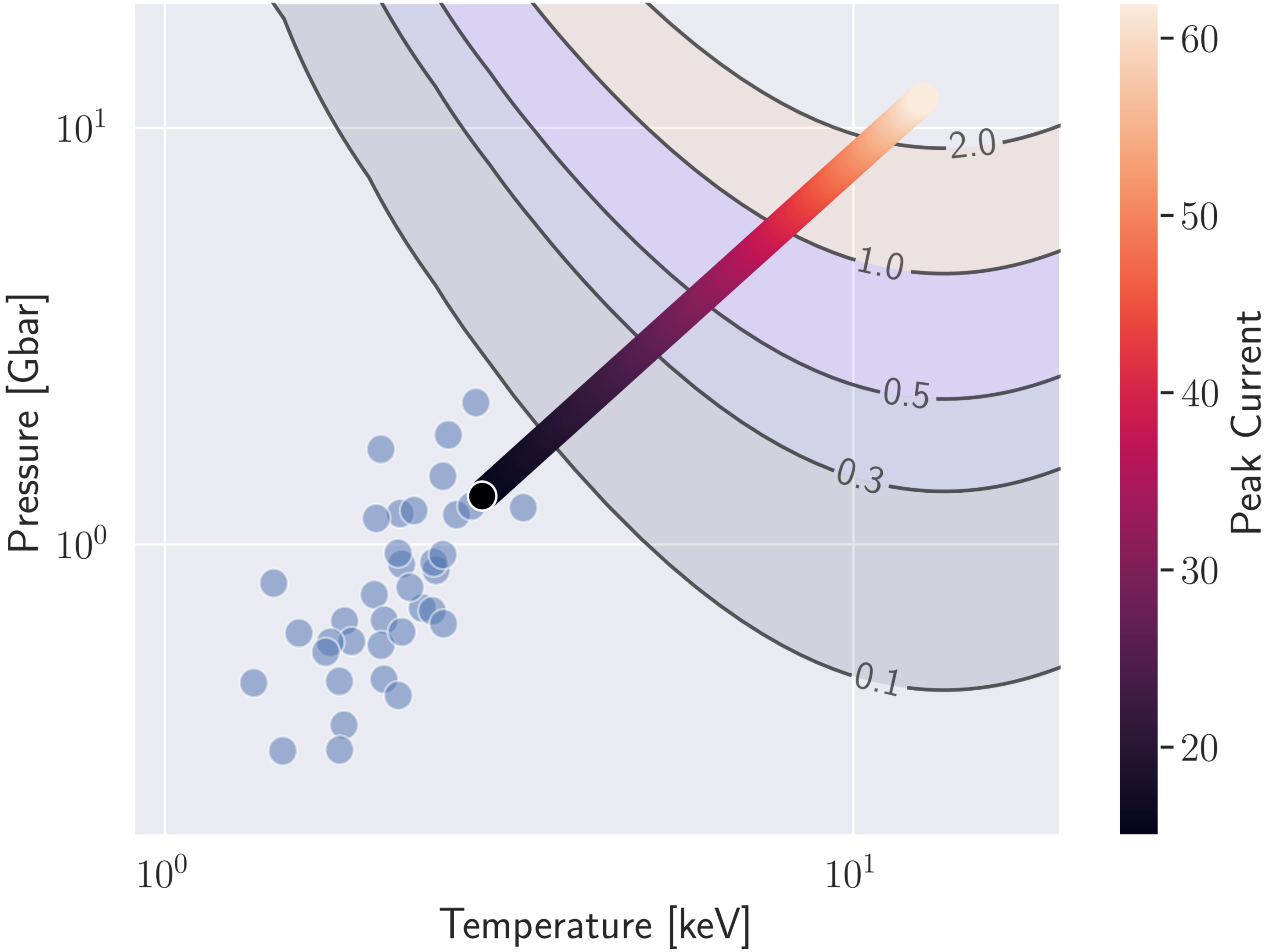
Multiple *existing* data points show the ability to scale to self-heating at realizable drive current



@20 MA, shot 3236

- B_z = 10 T, ρ_g = 1 mg/cm^3
- E_{dep} = 1.3 kJ
- T = 2.9 keV, P = 1.2 Gbar
- Y_{DD}=1.1x10^{13} → 2 kJ DT-equiv.

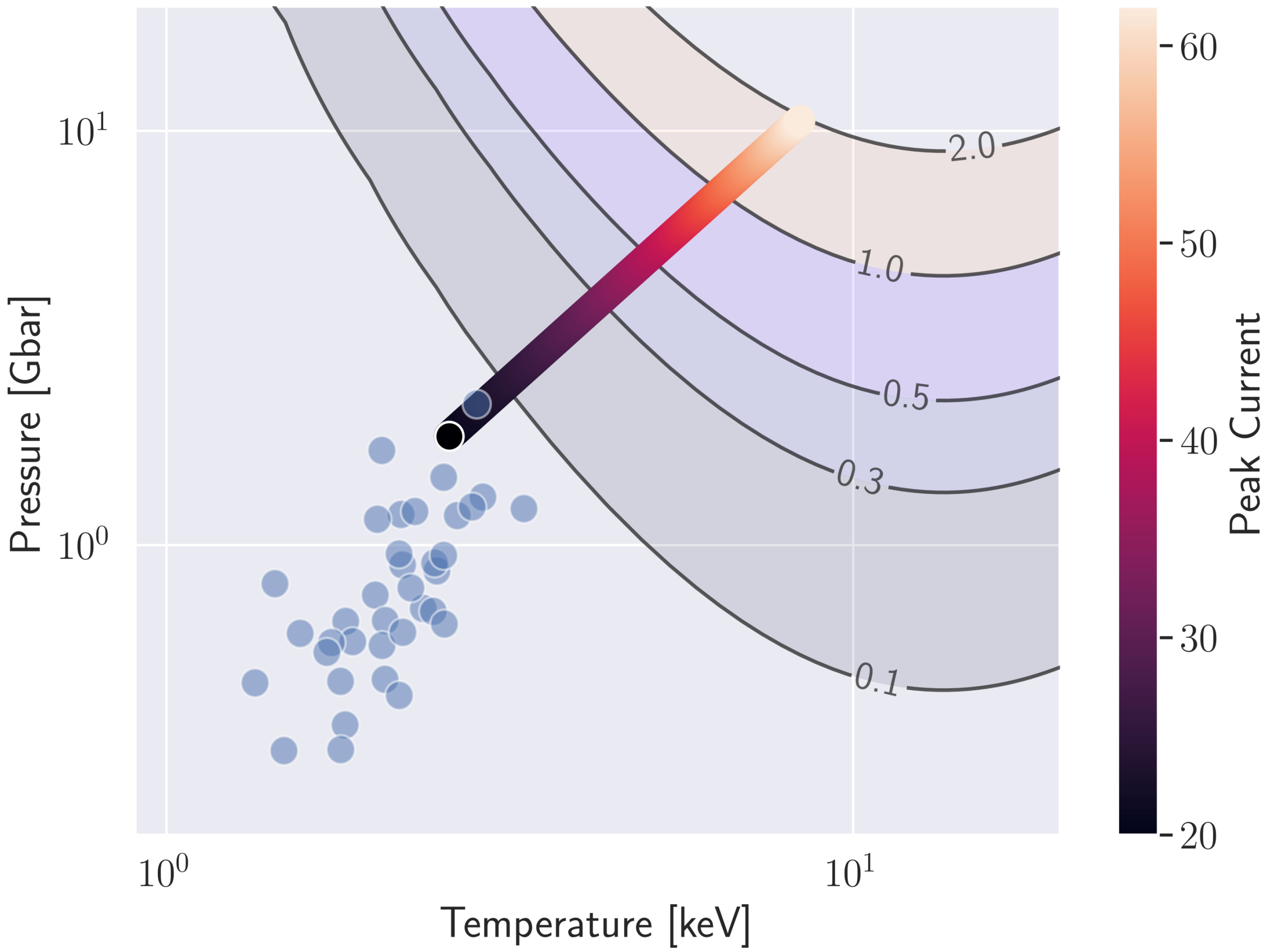
@38 MA χ = 1

- B_z = 17 T, ρ_g = 1.7 mg/cm^3
- E_{dep} = 15 kJ
- $T_{no\alpha}$ = 7.7 keV , $P_{no\alpha}$ = 5.6Gbar
- $Y_{no\alpha}$ = 436 kJ

P.F. Schmit and D.E. Ruiz., Phys. Plasmas **27**, 062707 (2020)

NP11.00075: D.E. Ruiz Wed. Morning

Multiple *existing* data points show the ability to scale to self-heating at realizable drive current



@20 MA, shot 3289

- B_z = 15 T, ρ_g = 1 mg/cm^3
- E_{dep} = 1.1 kJ
- T = 2.6 keV, P = 1.8 Gbar
- Y_{DD}=1.1x10^{13} → 2 kJ DT-equiv.

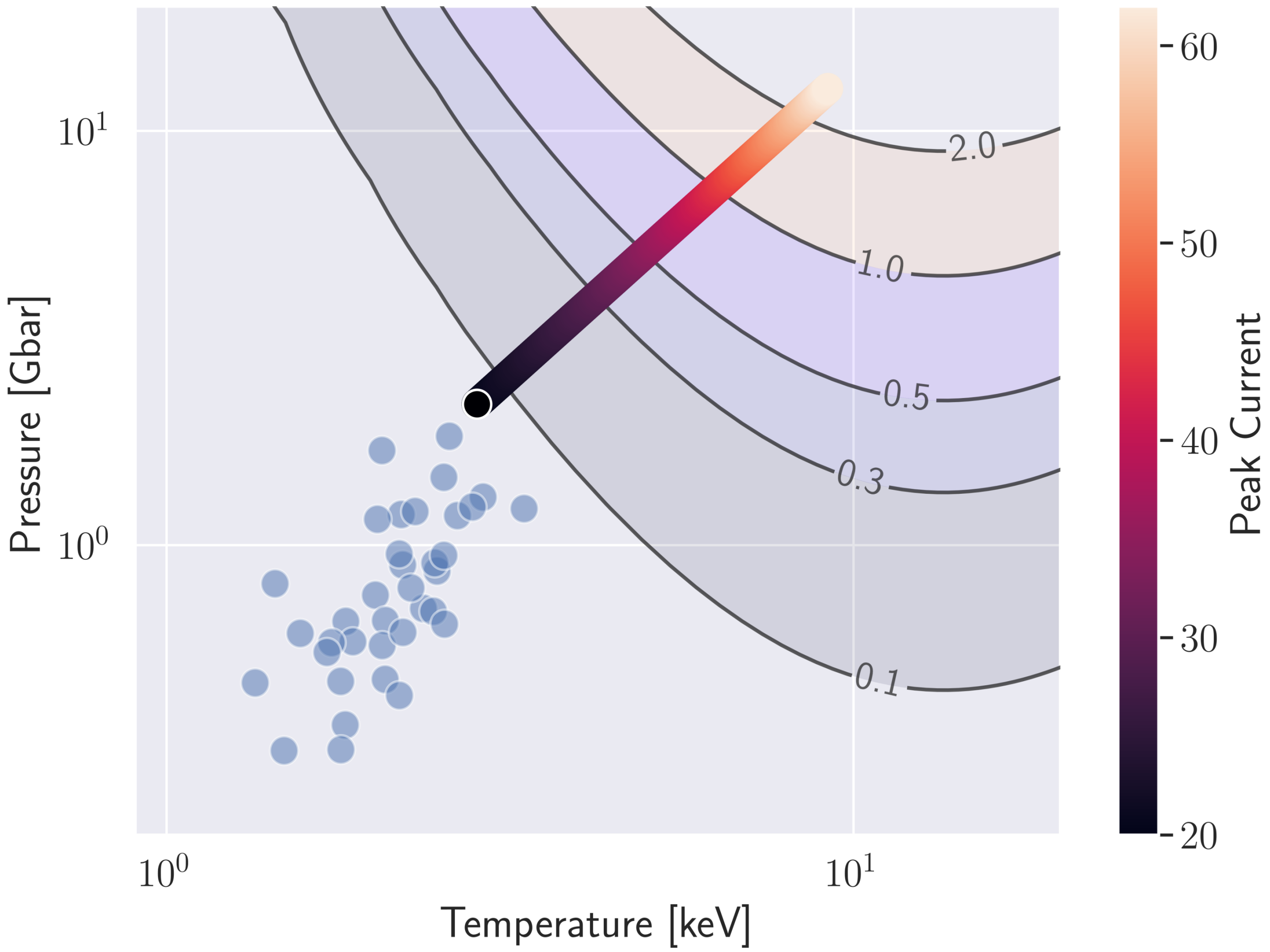
@48 MA χ = 1

- B_z = 26 T, ρ_g = 1.6 mg/cm^3
- E_{dep} = 11 kJ
- $T_{no\alpha}$ = 6.4 keV , $P_{no\alpha}$ = 7.1 Gbar
- $Y_{no\alpha}$ = 295 kJ

P.F. Schmit and D.E. Ruiz., Phys. Plasmas **27**, 062707 (2020)

NP11.00075: D.E. Ruiz Wed. Morning

Multiple *existing* data points show the ability to scale to self-heating at realizable drive current



@20 MA, shot 3576

- B_z = 15 T, ρ_g = 1 mg/cm^3
- E_{dep} = 2.2 kJ
- T = 2.8 keV, P = 2.2 Gbar
- Y_{DD}=0.76x10^{13} → 1.4 kJ DT-equiv.

@45 MA χ = 1

- B_z = 24 T, ρ_g = 1.6 mg/cm^3
- E_{dep} = 18 kJ
- $T_{no\alpha}$ = 6.6 keV , $P_{no\alpha}$ = 7.8 Gbar
- $Y_{no\alpha}$ = 143 kJ

P.F. Schmit and D.E. Ruiz., Phys. Plasmas **27**, 062707 (2020)

NP11.00075: D.E. Ruiz Wed. Morning