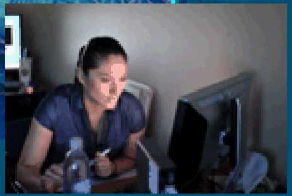
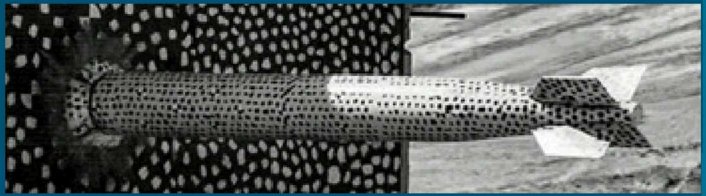
SAND2020-7367PE

Opportunities in HED physics research on Z: ICF, Data Science, Hydrodynamics, and more





PRESENTED BY

Patrick Knapp

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Thanks to my many colleagues and contributors

[1]M.E. Glinsky, [1]W. Lewis, [1]Kris Beckwith, [1]D.A. Yager-Elorriaga, [3]F.W. Doss, [1]C. A. Jennings, [1]M.A. Schauble, [1]K. Maupin, [4]M.R. Evans, [1]E. C. Harding, [1]A. J. Harvey-Thompson, [1]M. R. Gomez, [1]S. B. Hansen, [3]J. Haack, [2]K.D. Hahn, [1]G.A. Chandler, , [1]M. Geissel, [5]G. Cooper, [1]S. A. Slutz, [1]M. R. Martin, [1]K.D. Cochrane, [1]I.C. Smith, [1]M. Schollmeier, [6]J. Gunning, [1]T. J. Awe, [1]P. F. Schmit, [1]D. B. Sinars, [1]M. E. Cuneo, [1]M. Jones, [1]J. L. Porter, [1]G. A. Rochau, [1]K. J. Peterson, [1]W. A. Stygar, [1]D.J. Ampleford, [1]T.R. Mattsson, [1]M. K. Matzen,[1] ***and many more…***

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- National Security Programs
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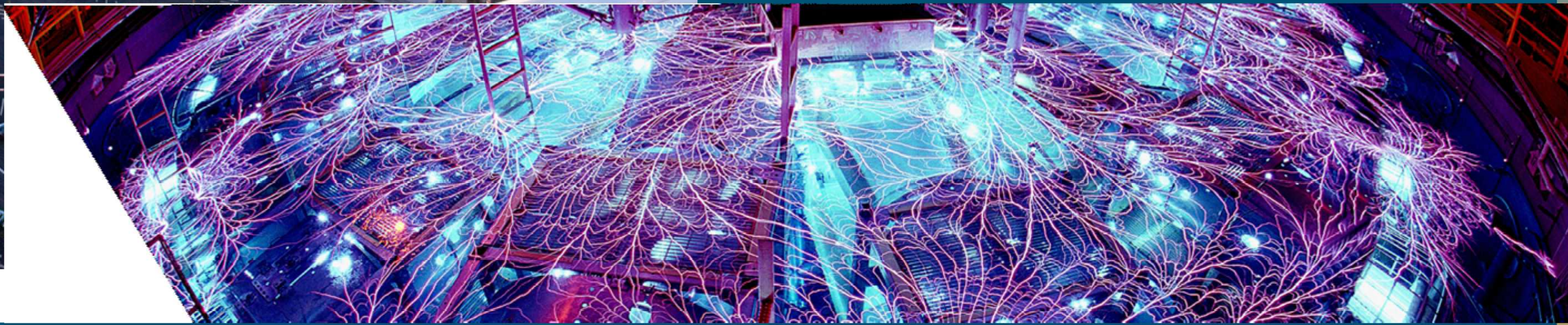
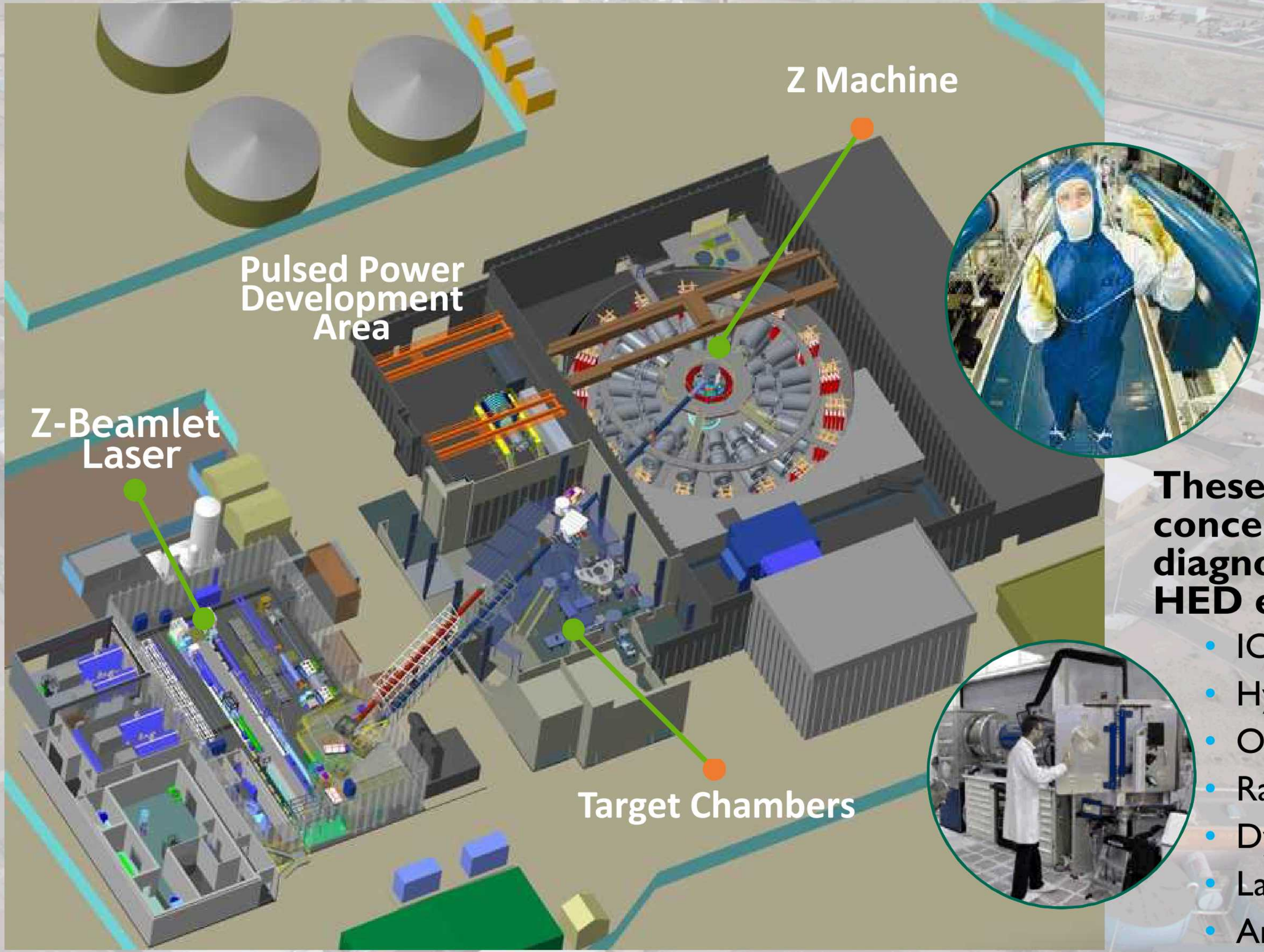


Sandia's Z Pulsed Power Facility

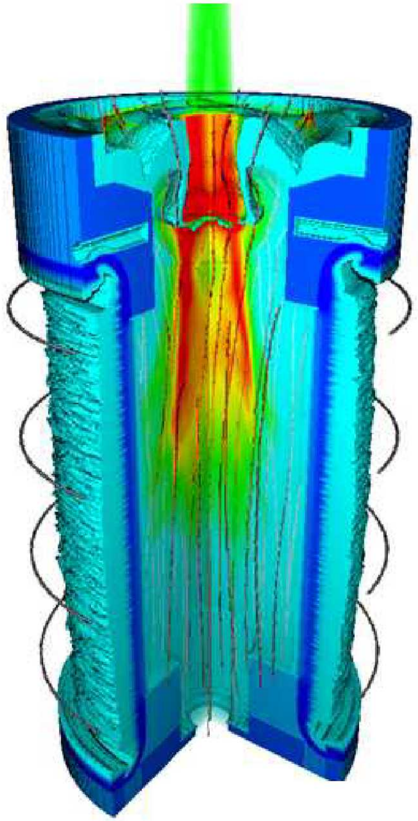
The Z facility is supported by the multi-kJ Z-Beamlet & Z-Petawatt lasers, which can also be operated independently



These facilities are used in concert to conduct and diagnose a wide range of HED experiments

- ICF and MIF
- Hydrodynamics
- Opacity
- Radiation Effects
- Dynamic Material Properties
- Lab-Astro
- And more…

P.K. Rambo *et al.*, Applied Optics 44 (2005); P. Rambo *et al.*, Proc. SPIE 10014 (2016).

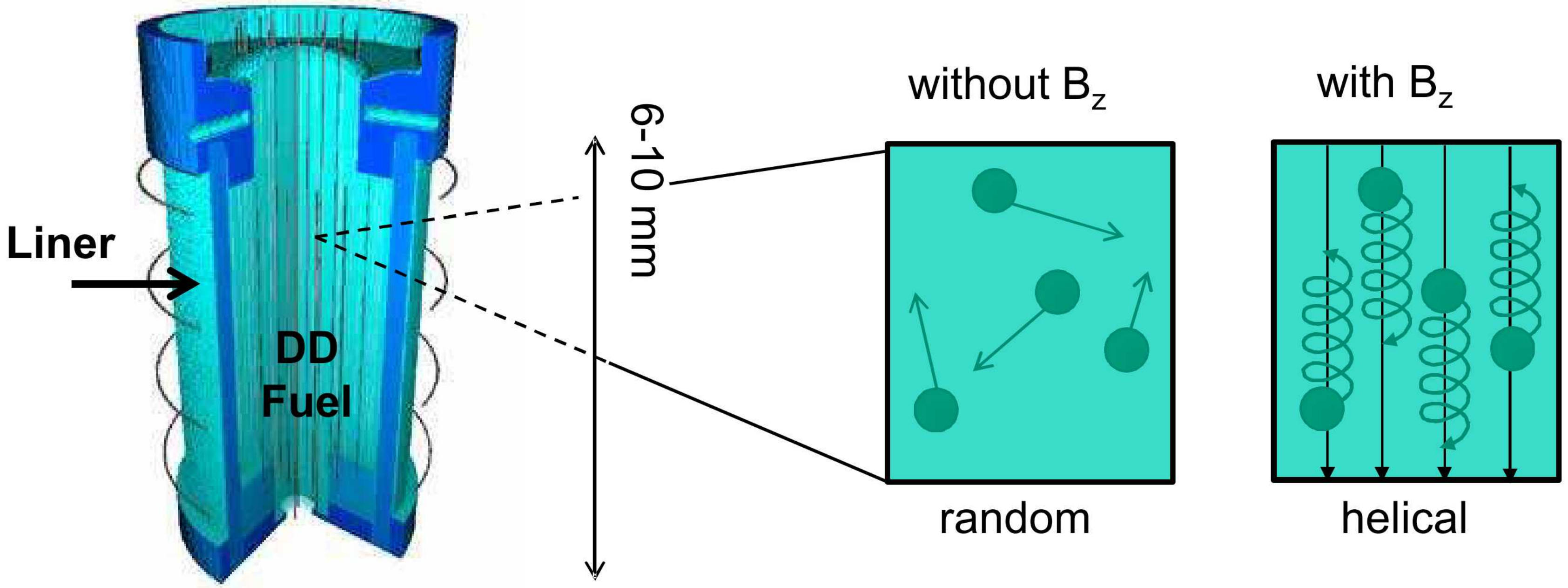


Magneto-Inertial Fusion Research on Z

MagLIF is a Magneto-Inertial Fusion (MIF) concept

Relies on three components to produce fusion conditions at stagnation

Use-Inspired



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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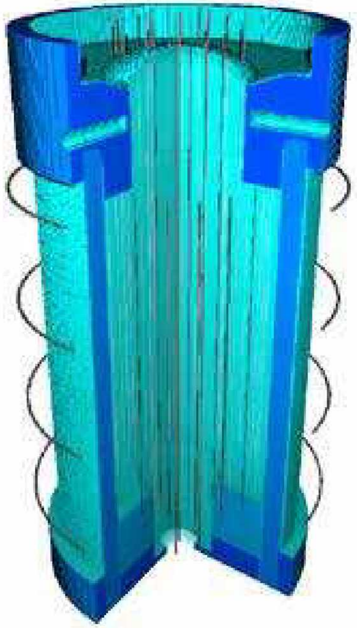

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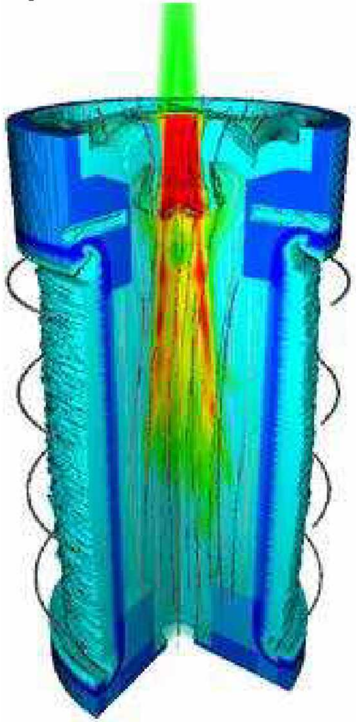

- **Laser preheat: 100-200 eV**
  - **Uses Z-Beamlet Laser (other heating methods possible)**
  - **Relax convergence requirement**
  - **$CR=R_{initial}/R_{final}$= 120 → 20-40**

Magnetization

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

Preheat

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

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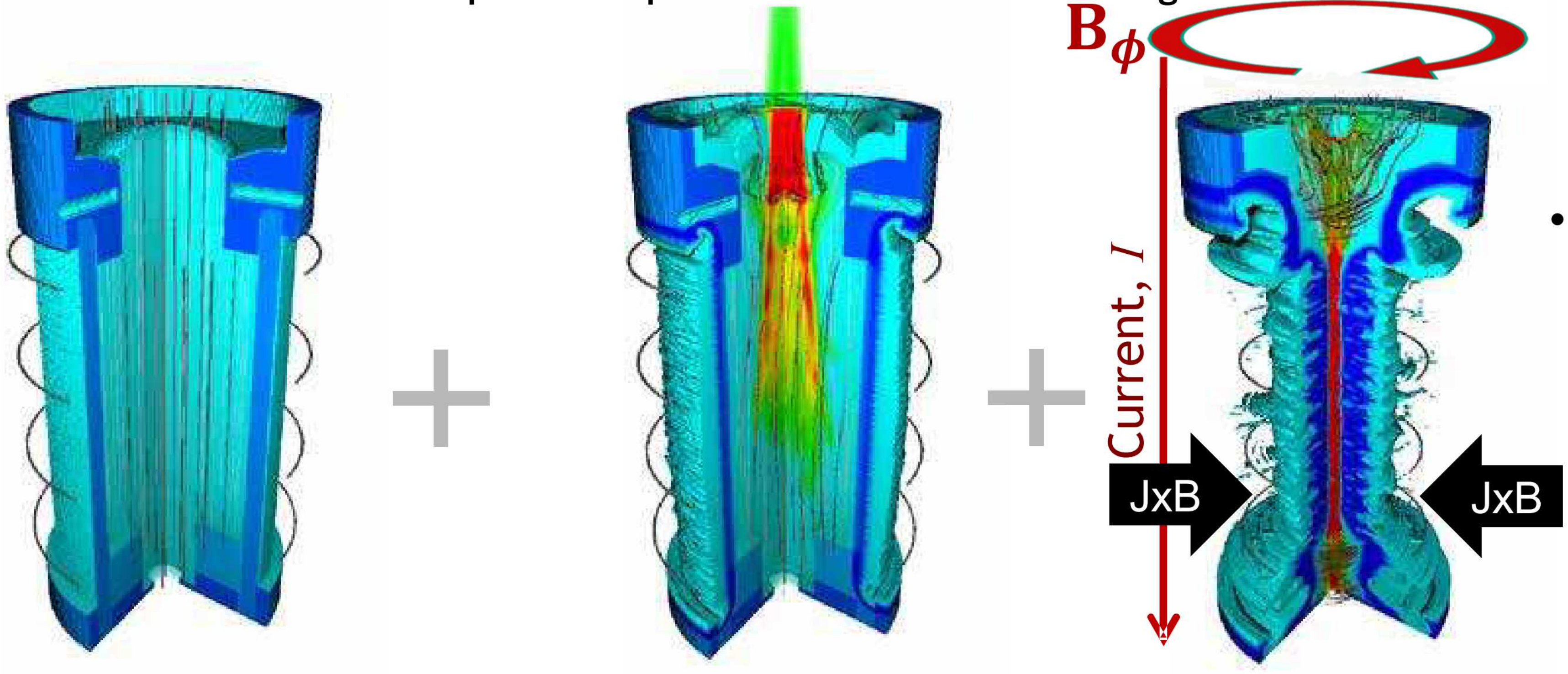

- **Magnetically Driven Implosion**
  - **"Only" ~100 km/s (vs. ~380 km/s on NIF)**
  - **B-field amplified to >few kT**

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

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

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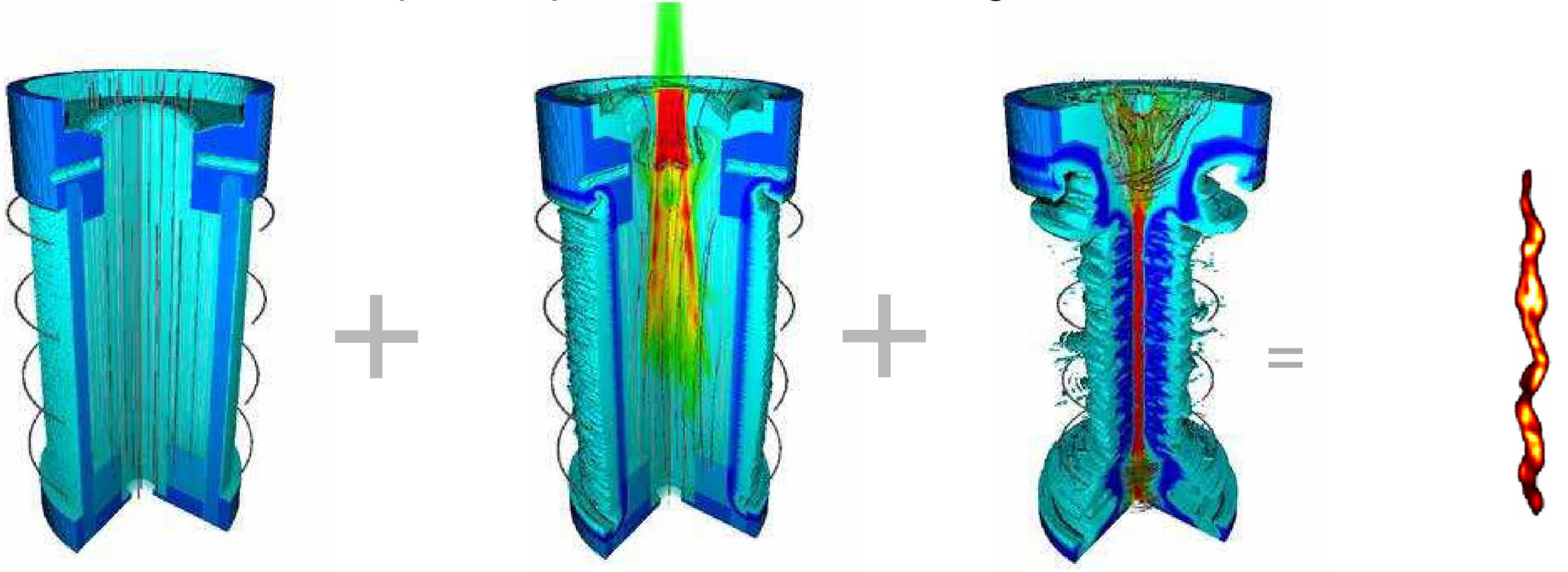

Magnetization
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Preheat
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Implosion
- PdV work to heat fuel
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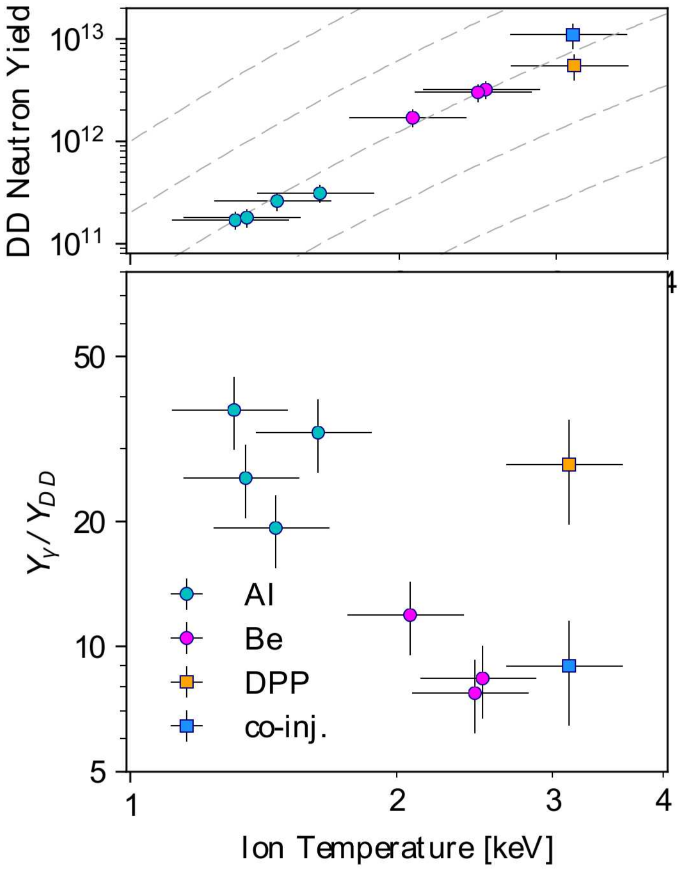
Stagnation
- Several keV temperatures
- Several kT B-field to trap charged fusion products

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 has demonstrated the key tenets of magneto-inertial fusion

In a target that would not produce significant yield without both heating and magnetization

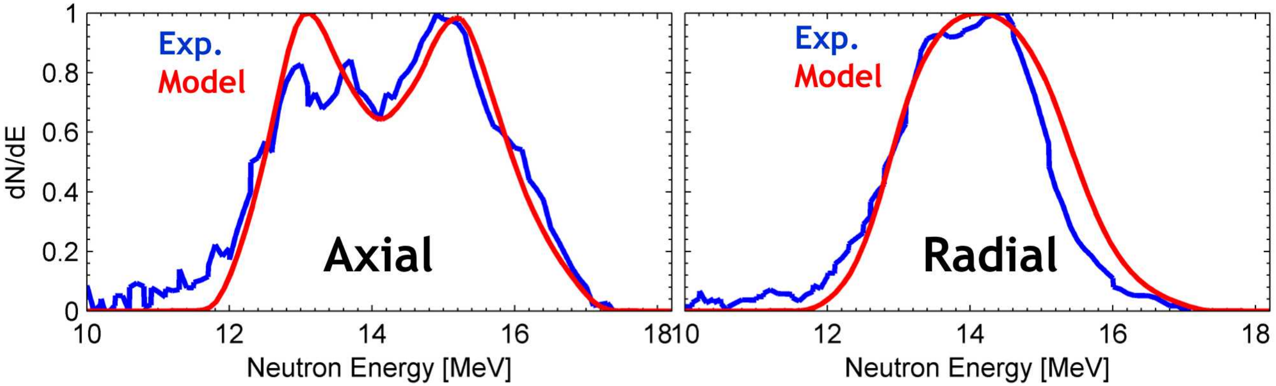


Achieved $>10^{13}$ DD neutrons
E_{ph} > 1 kJ, P_{HS} > 1 Gbar
T_{burn} ~3 keV

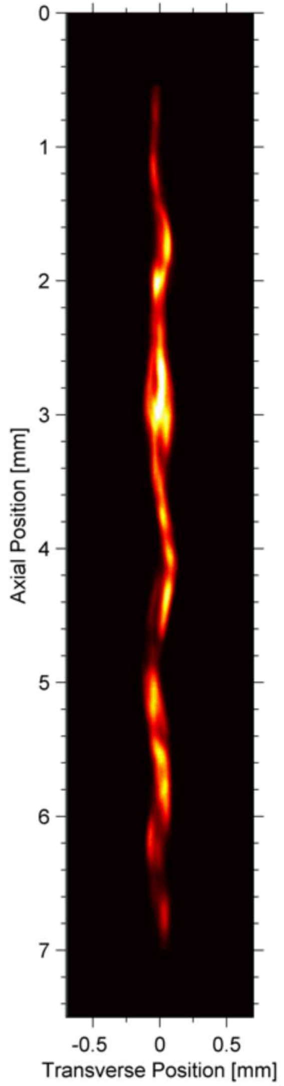
Thermonuclear neutron generation with fusion-relevant ion temperatures (2-3 keV)

High aspect ratio fuel column at CR > 30

Highly magnetized fuel at stagnation (>0.3 MG-cm)

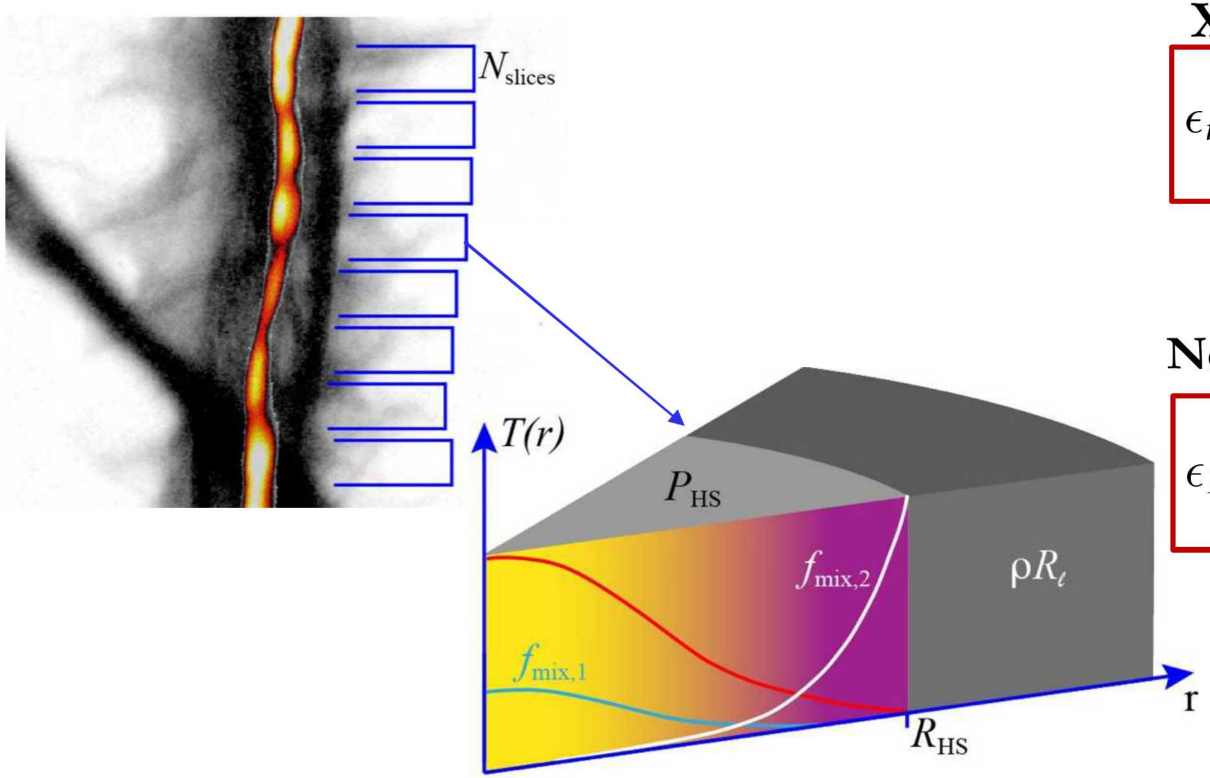


Secondary DT Neutron Spectra



M.R. Gomez *et al.*, Phys Rev Lett (2014); P.F. Schmit *et al.*, Phys Rev Lett (2014).

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



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)

Basic Model Parameters

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

$\{\rho R_\ell\}$

$\{P_{HS}\}$

$\{f_{\text{mix}}\}$

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

Global/hyper Parameters

Z_{mix}

τ_{burn}

h_{HS}

T_{exp}

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

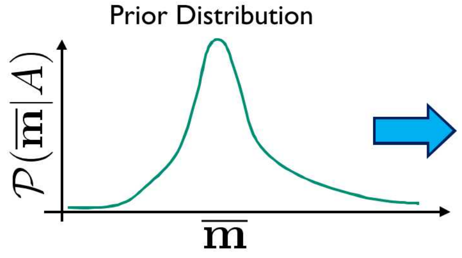
Bayesian inference allows us to integrate multiple sources of data using physics and diagnostic models to infer parameters

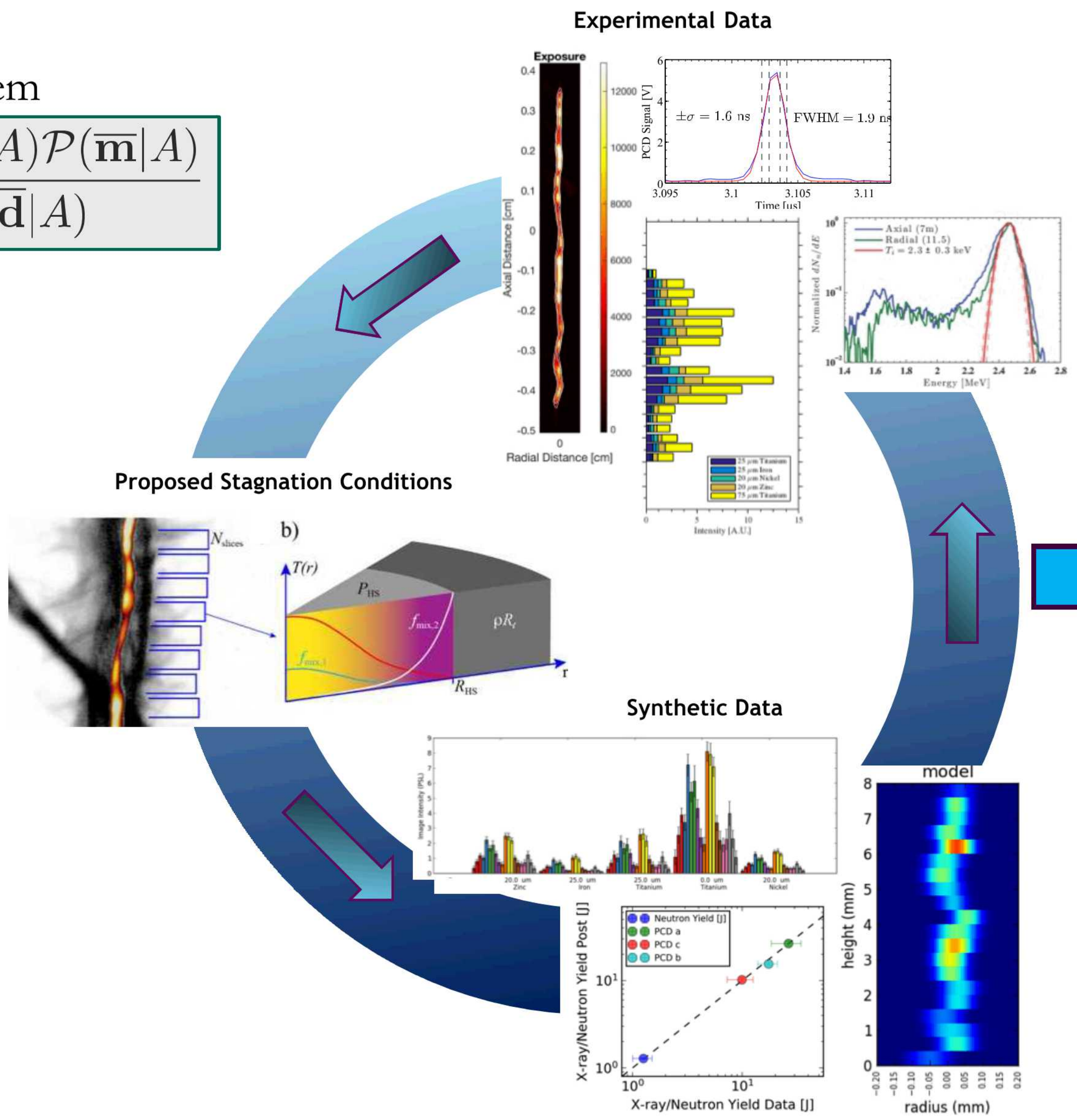
Bayes' Theorem

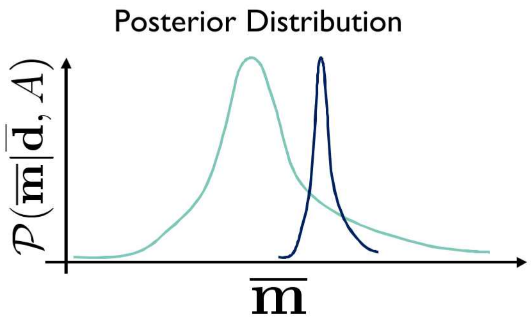
$$\mathcal{P}(\overline{\mathbf{m}}|\overline{\mathbf{d}}, A) = \frac{\mathcal{P}(\overline{\mathbf{d}}|\overline{\mathbf{m}}, A)\mathcal{P}(\overline{\mathbf{m}}|A)}{\mathcal{P}(\overline{\mathbf{d}}|A)}$$

Likelihood

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







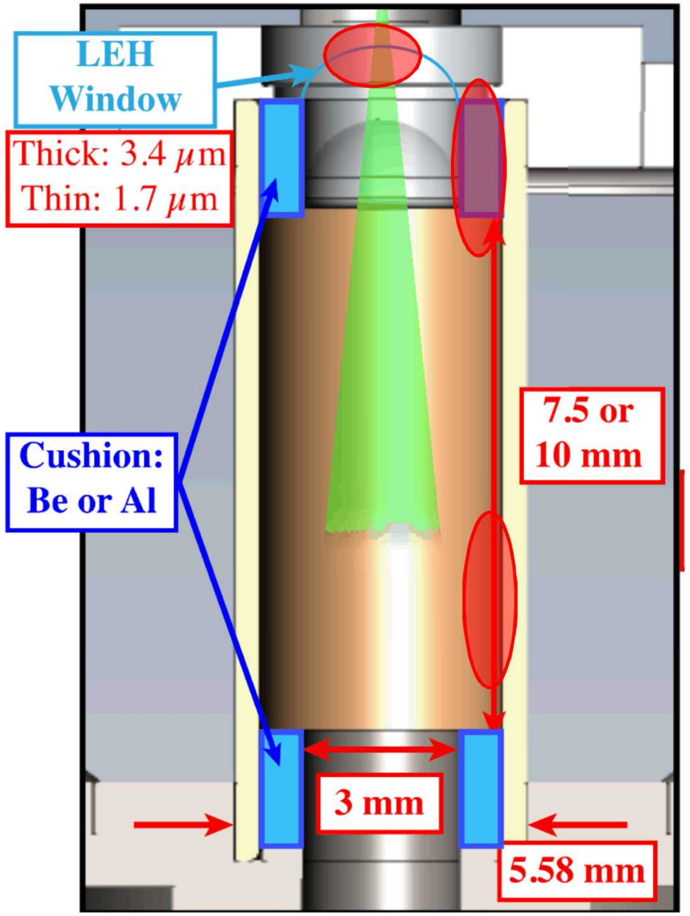
Model Parameters

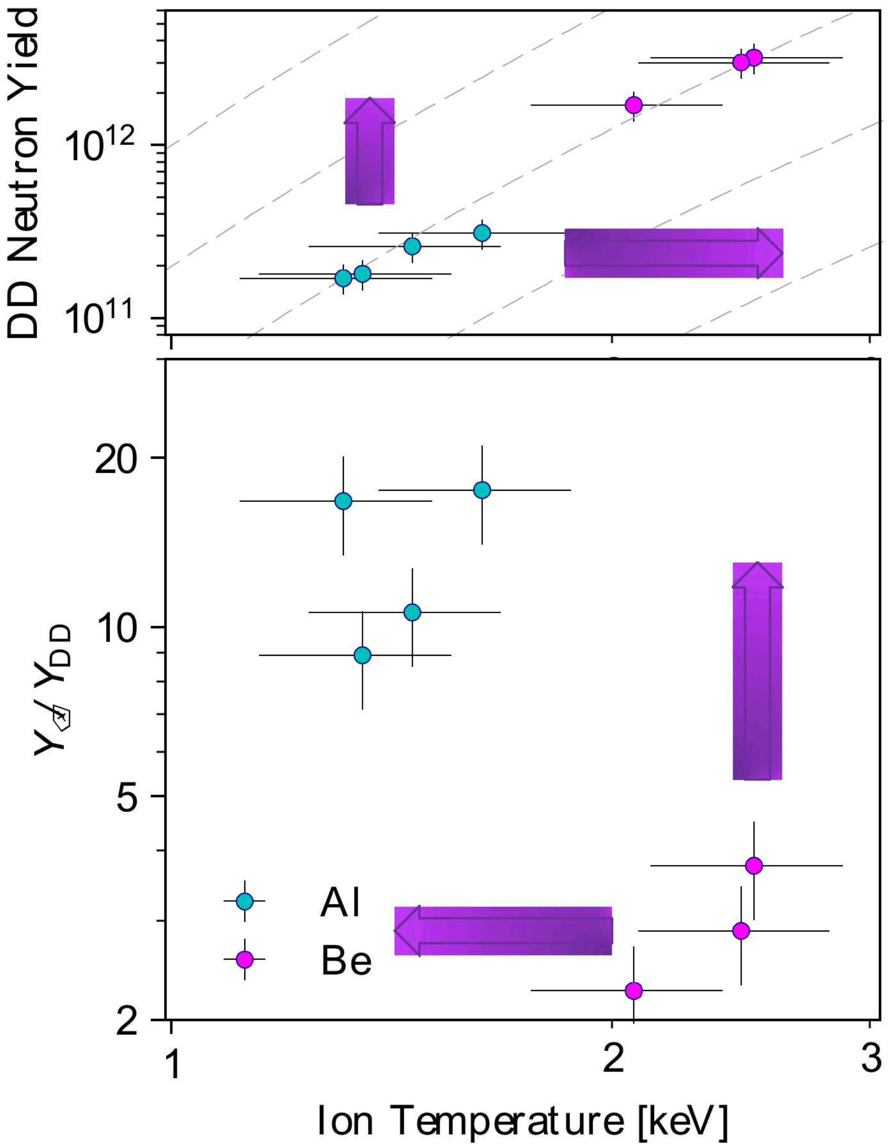
$$\overline{\mathbf{m}} = \begin{cases} P_{\mathrm{HS}} \\ T \\ f_{\mathrm{mix}} \\ R_{\mathrm{HS}} \\ \rho R_\ell \end{cases}$$

Outputs/Benefits:

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

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

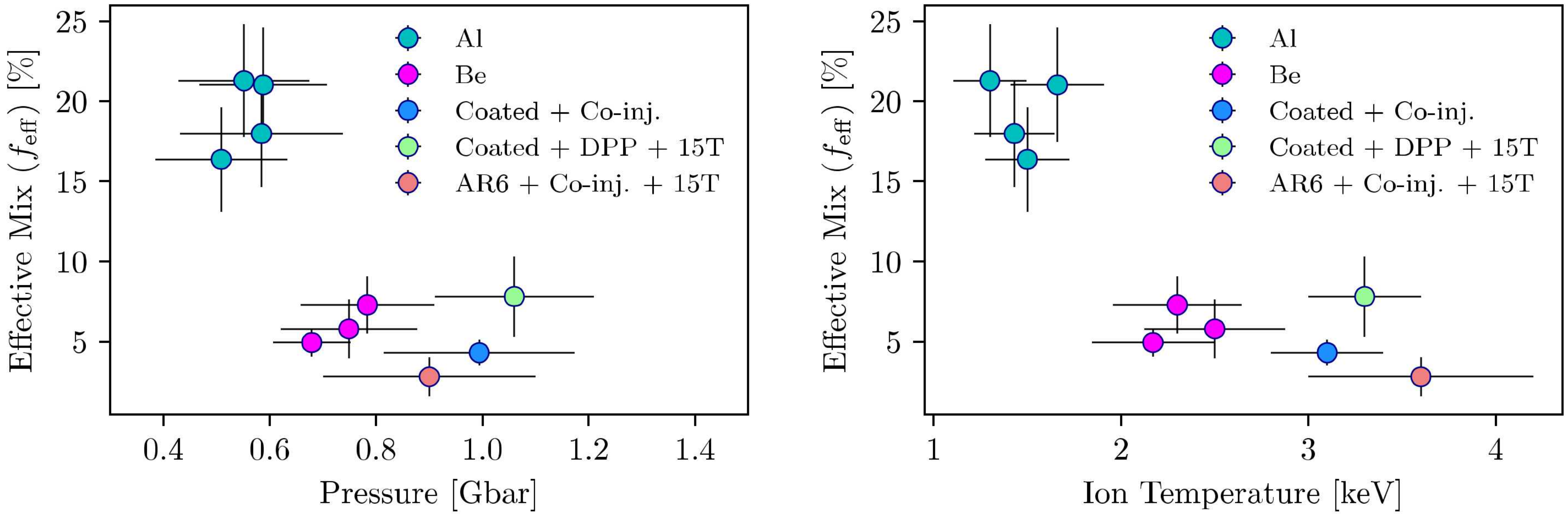




Main Contributors to mix

- Preheat
  - Window
  - Cushion
- Implosion
  - Liner

Using Bayesian analysis we can infer mix trends across a range of experiments with different implosion and laser heating features

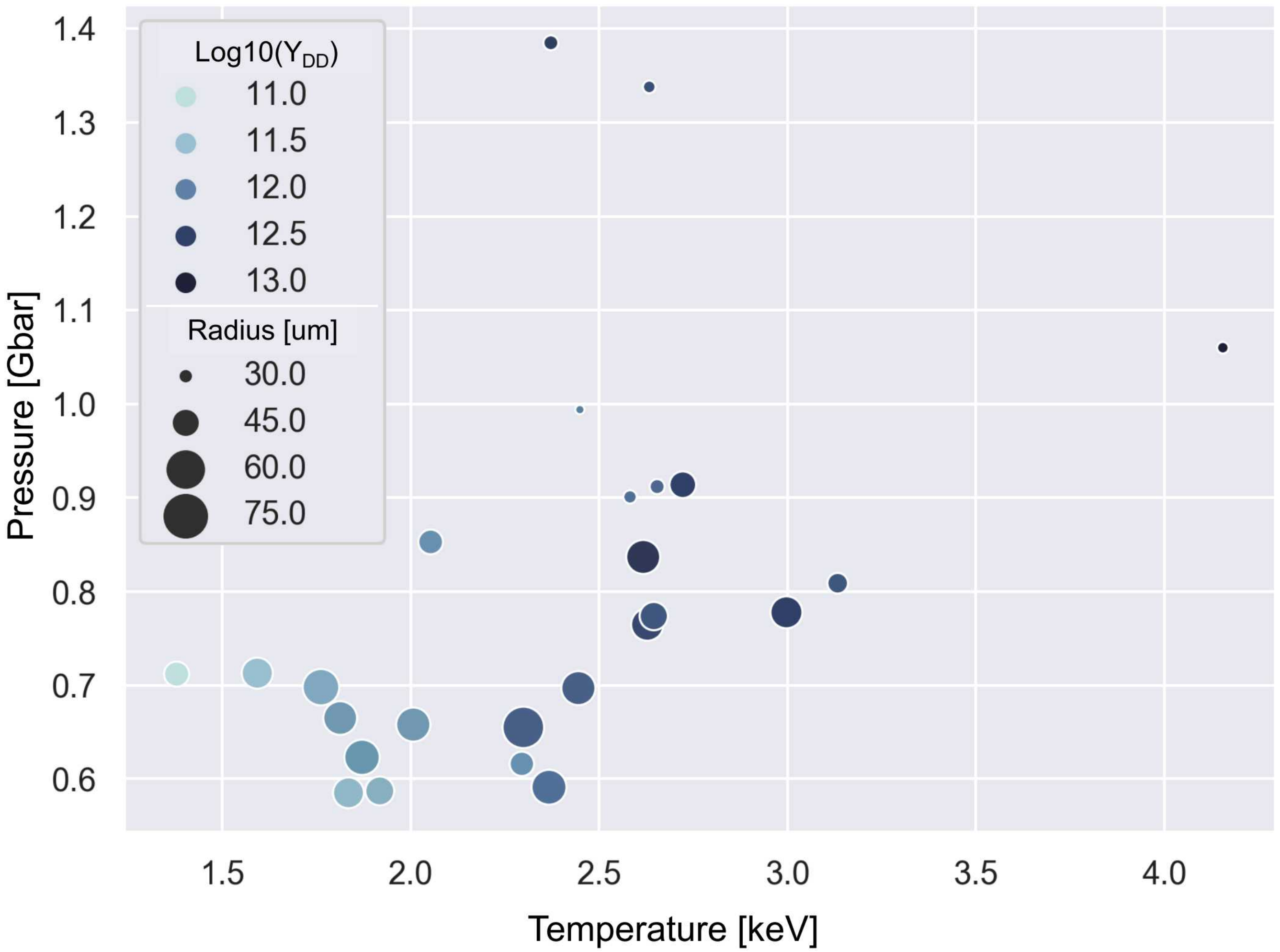


Including three of our highest yield shots in the "mix"

The major advancements here are improved laser heating protocols, higher B-field and higher current drive

- The use of co-injection (as opposed to just beam smoothing or no conditioning) reduces the effective mix present at stagnation
- It appears that higher B-field increases the stagnation temperature somewhat (more analysis needed)

We have begun mining data from a large database of MagLIF experiments to investigate broader trends



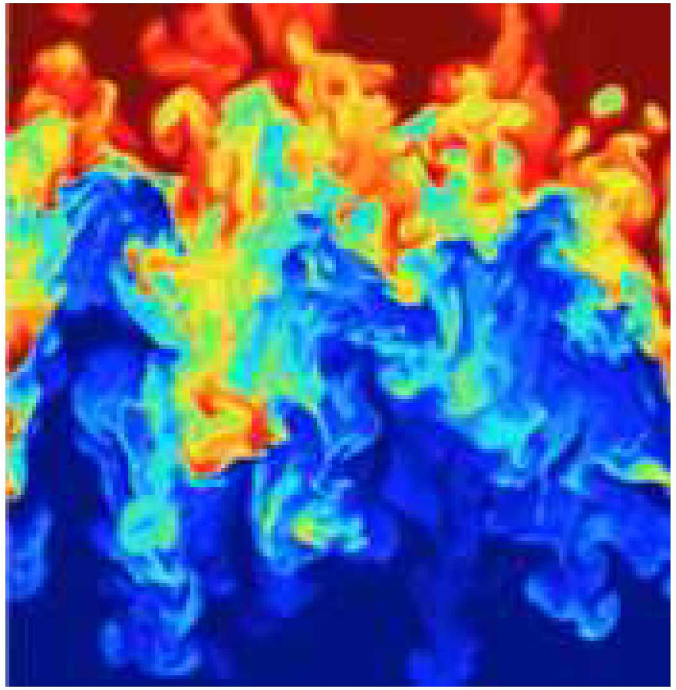
By determining all of the various model parameters simultaneously we can begin to examine trends across experiments

We see from this dataset that there are multiple ways to get the same yield e.g.

- moderate pressure, high temperature
- High pressure, moderate temperature

Central temperatures below ~2.3 keV are always associated with low performance

HED Hydrodynamics



Livescu et al, J. Phys. Conf. Ser. 318 (2011) 082007

We have developed a new platform to help benchmark modeling of instability driven mix in a converging geometry

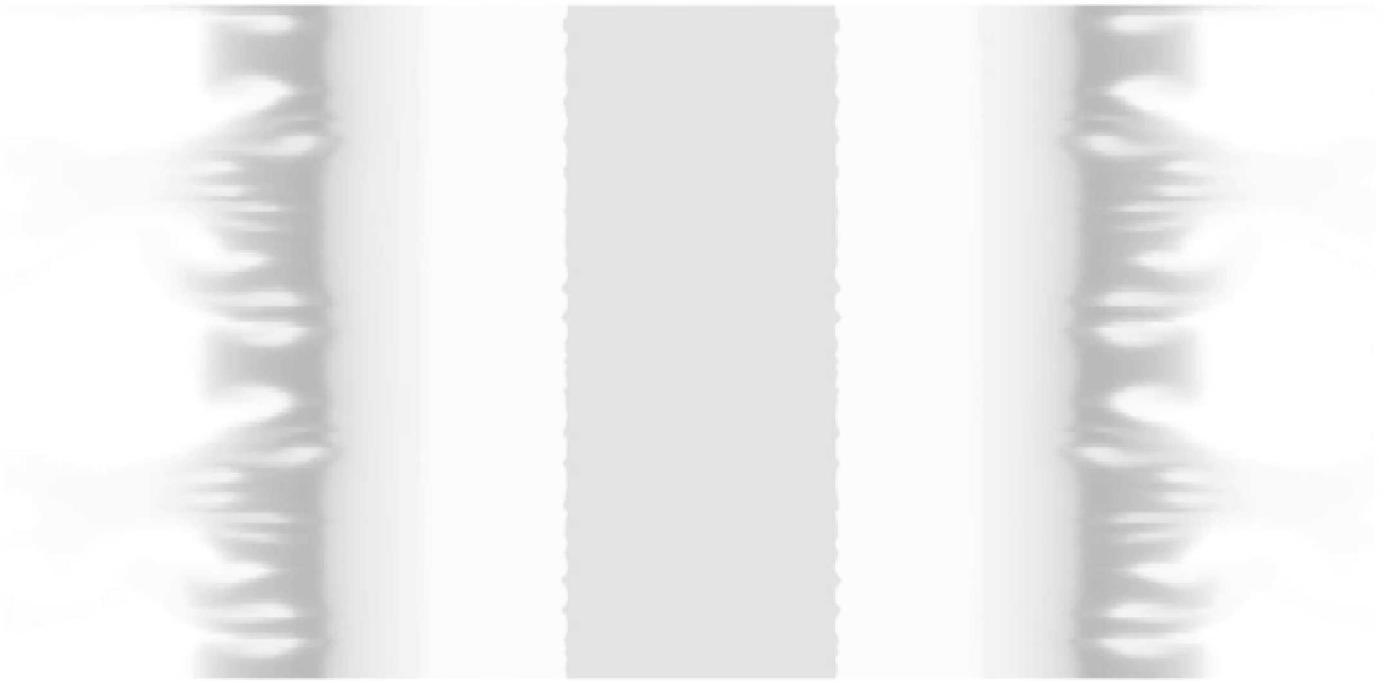
The platform is comprised of
- A Be liner
- A liquid D_2 fill
- An on-axis Be rod with machined perturbation

Z's current flows through the liner, causing it to implode

A strong shock is driven in the D_2

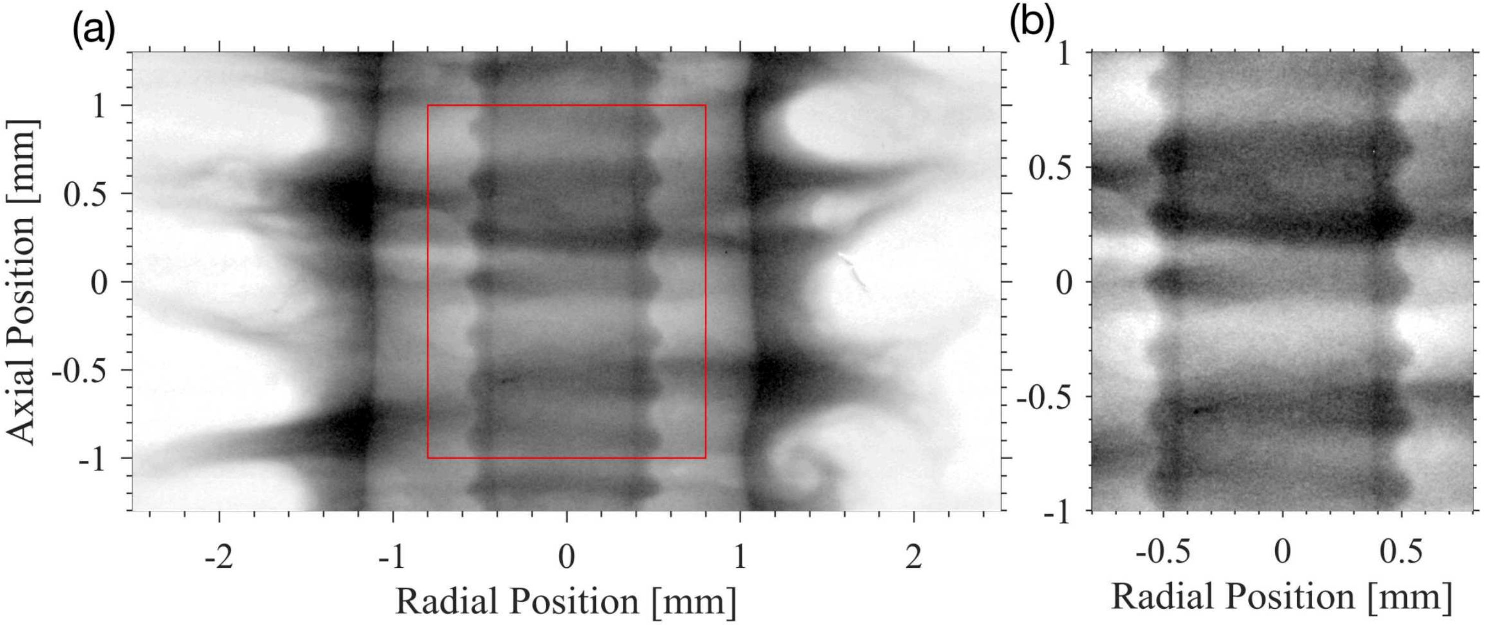
The shock impacts the rod, driving the RM process

The instability growth is diagnosed using x-ray BL



"RAGErunner" GORGON + xRAGE calculation

Abel inversion allows the density of the rod to be inferred without obstruction from the liner



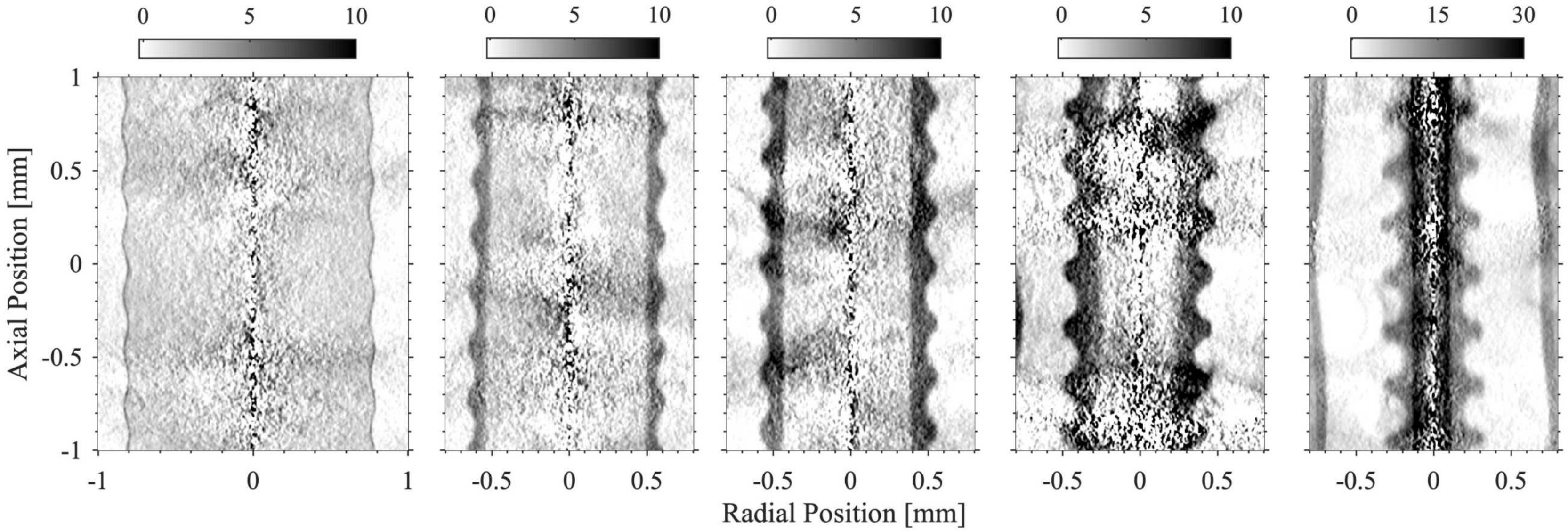
Radiographs are monochromatic at 1.85, 6.15, or 7.2 keV (we use 7.2 keV here)

full radiographic FOV is 4 mm x 12 mm

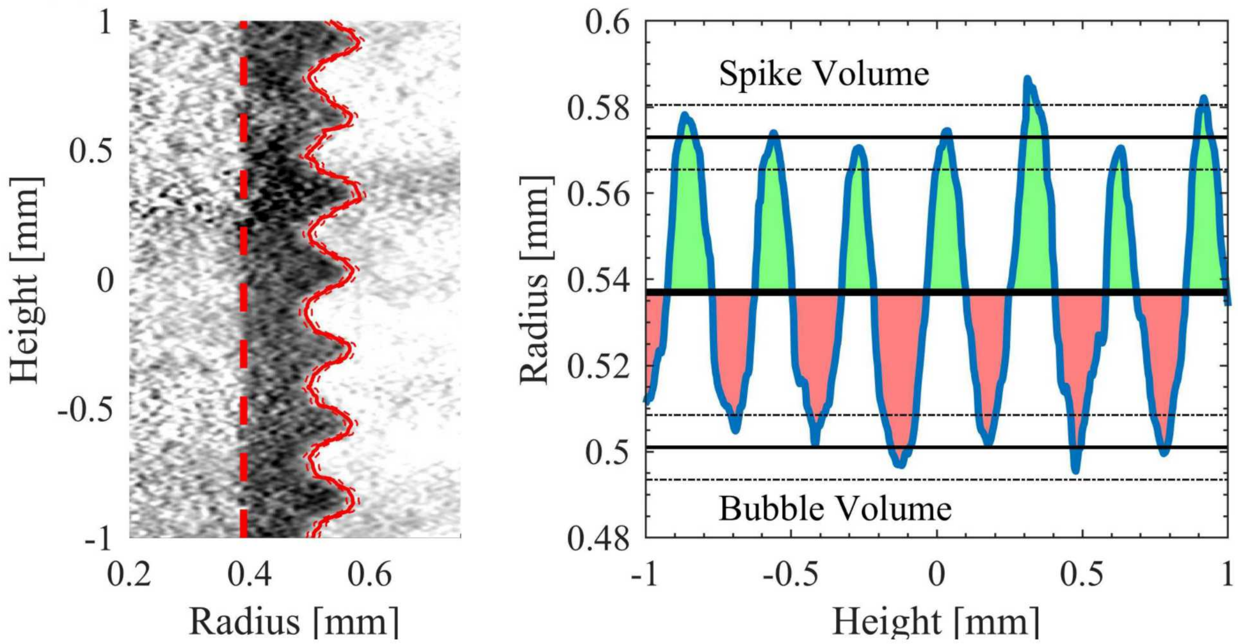
The spatial resolution is 12 μm

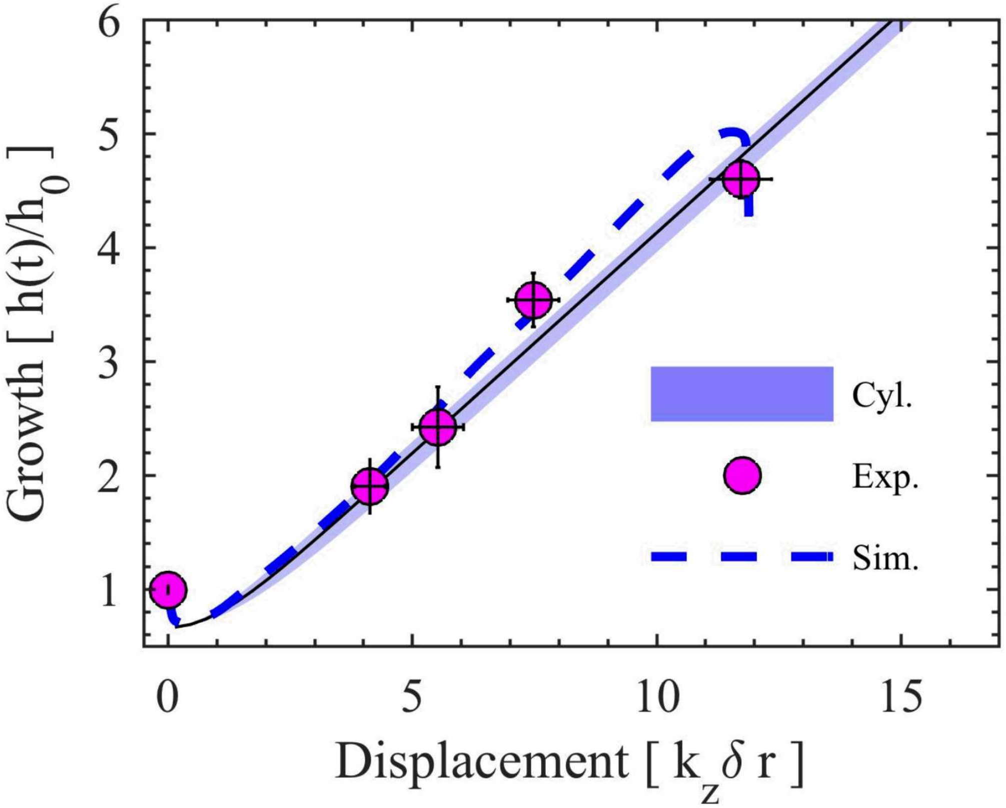
Contrast and SNR allow us to invert the data directly to obtain density

Abel invert to obtain ρ(r,z)



We can track the contour with high fidelity and measure the growth and mean interface position





The data agrees well with cylindrical theory from Lombardini et al. early on

Must include the shock proximity and compression effects

Late time behavior deviates from theory due to convergence effects

2D post-shot simulations were performed using a novel combination of the GORGON MHD and xRAGE rad-hydro codes

M. Lombardini et al., Physics of Fluids 21, 114103 (2009)

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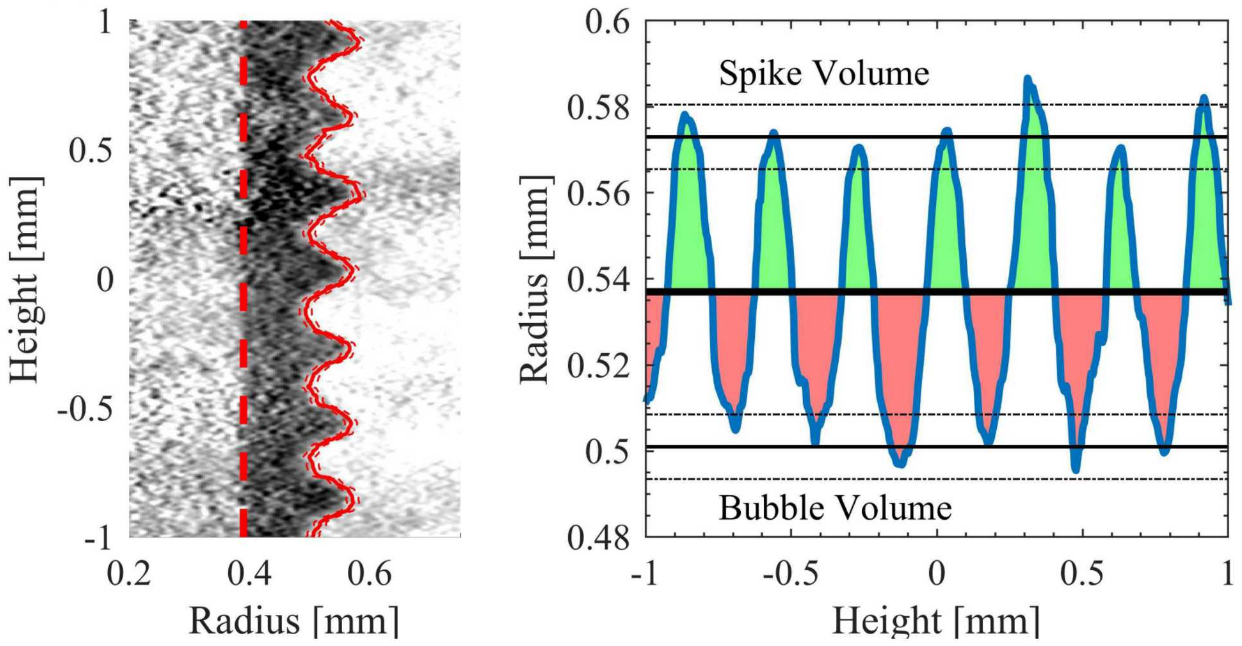

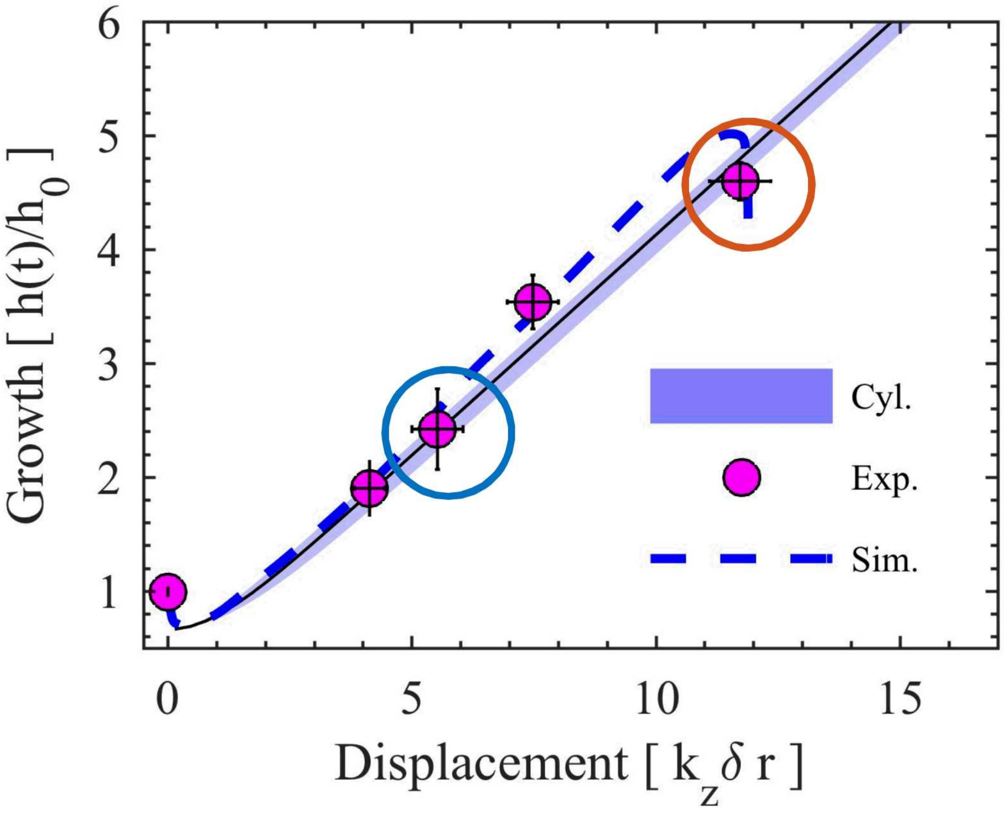

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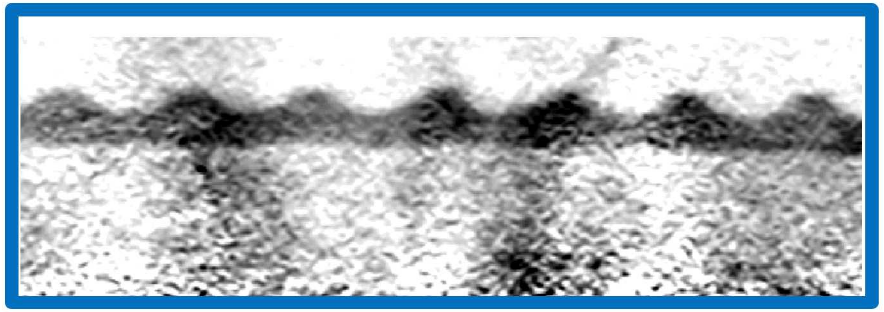
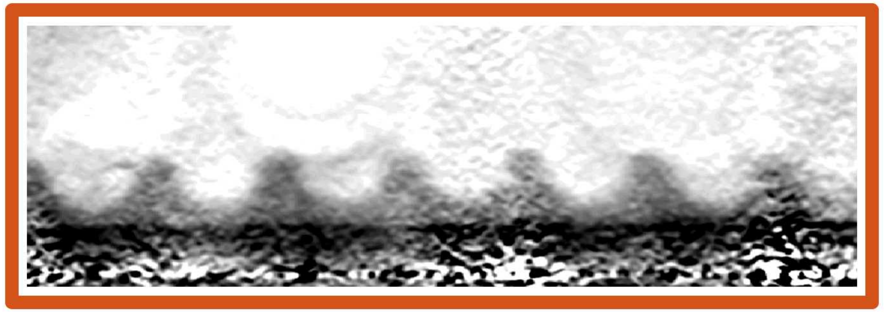
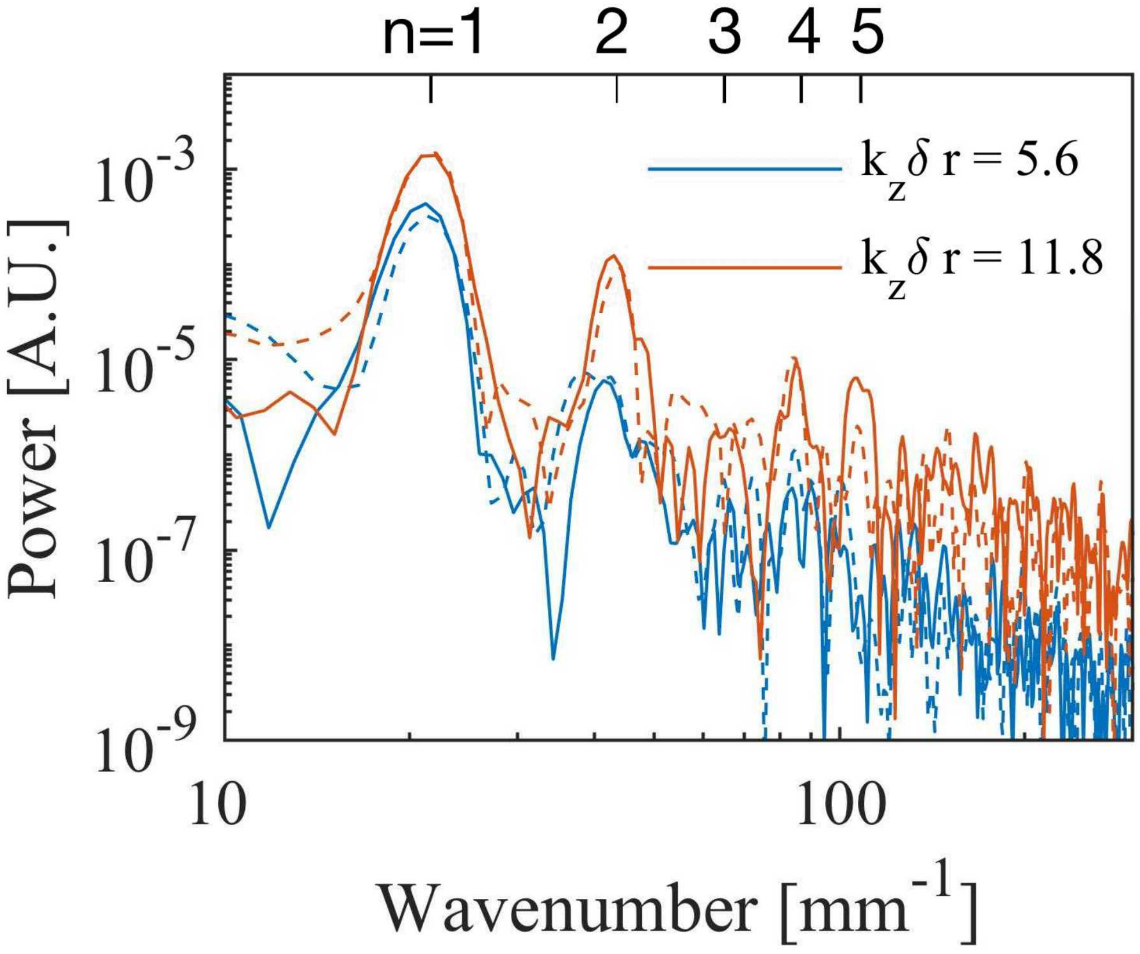
M. Lombardini et al., Physics of Fluids 21, 114103 (2009)

The high spatial resolution affords the possibility of performing detailed comparisons in the nonlinear growth phase

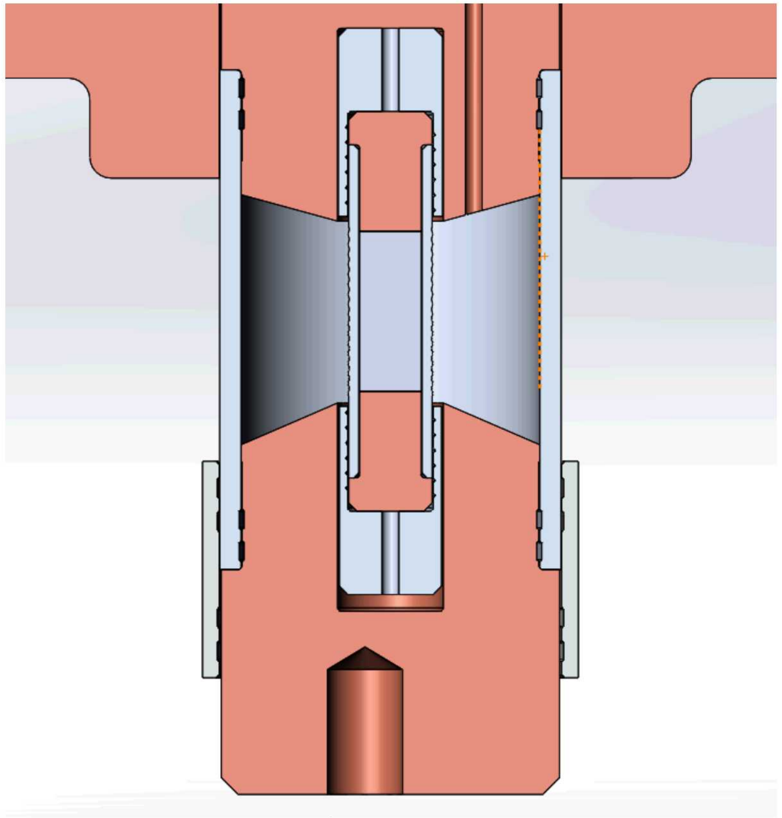




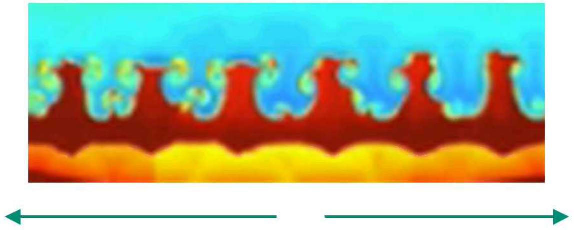


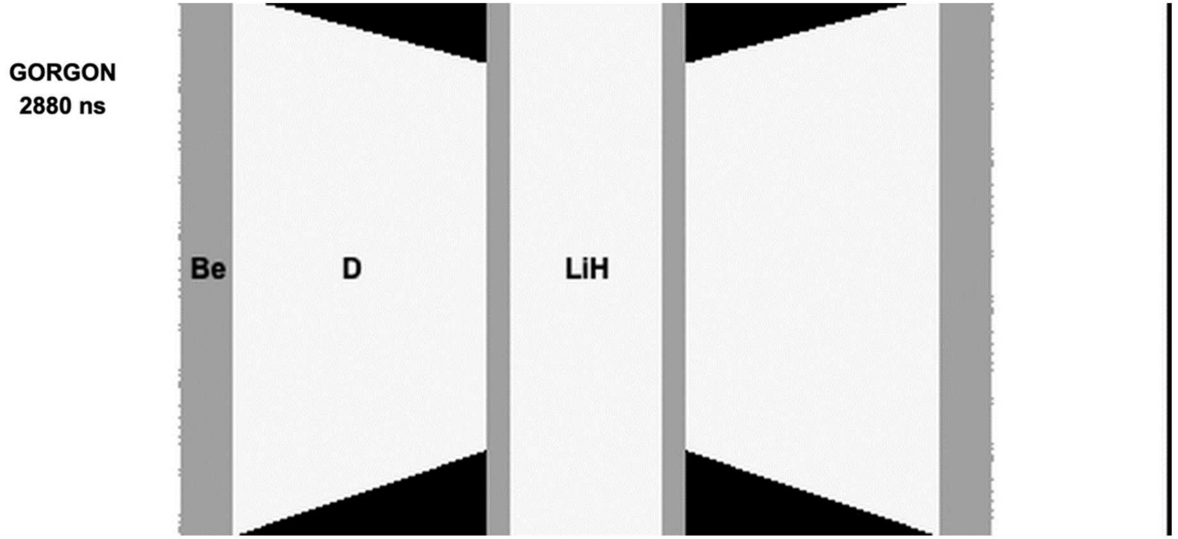
- With two frames on a single shot we can watch growth of modes n=1-5
- We see a distinct lack of energy around the 3rd harmonic
- This data is suitable for detailed comparisons with interfaces from 2D simulations

We are developing a Double Cylinder Platform to examine perturbation feedthrough and mixing in a convergent geometry



Target Design from CY20

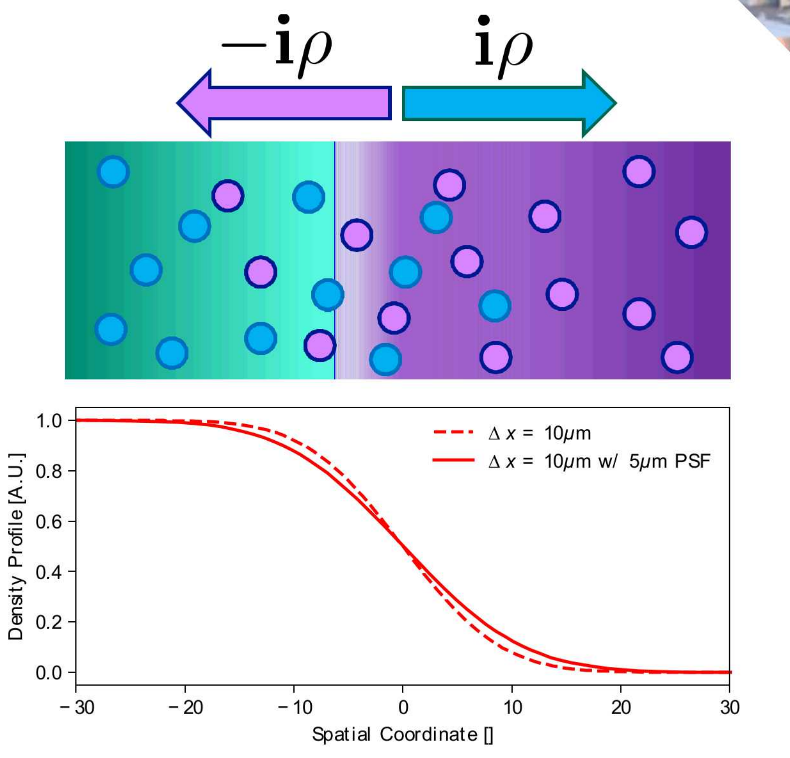




Predictions show that a smaller mode has negligible feedthrough compared to the larger "carrier" mode

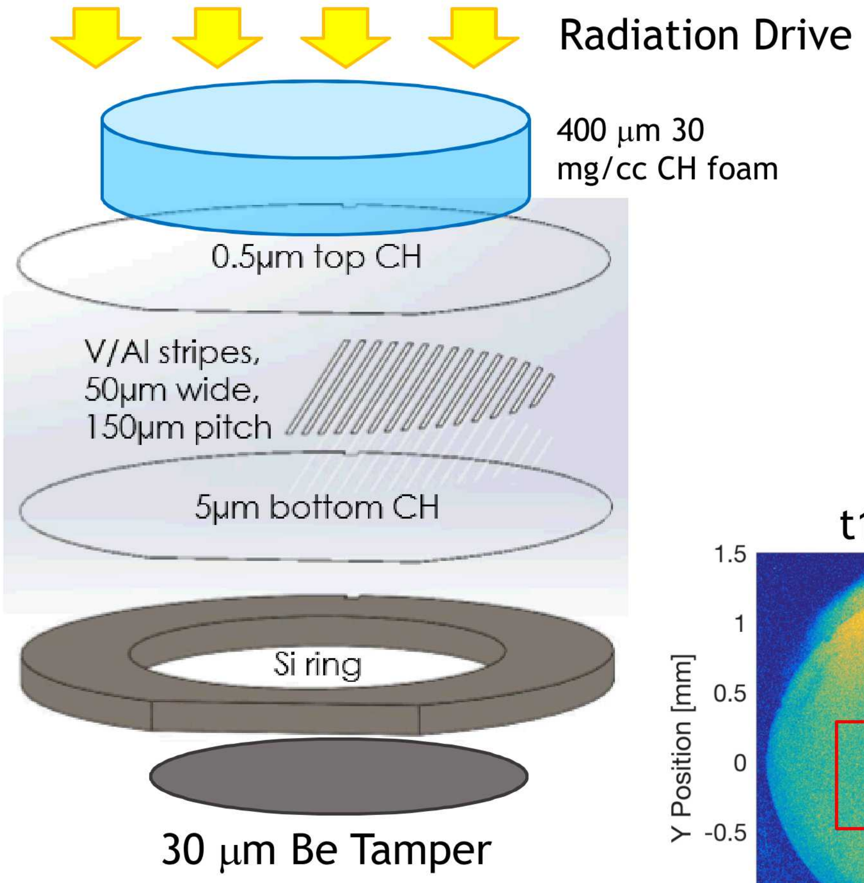
CY20 shot seeks to establish the platform and examine feedthrough with multiple modes

This platform allows long time-scale (>50 ns) feedthrough and mixing to be studied



Transport Physics in Strongly Coupled Plasmas

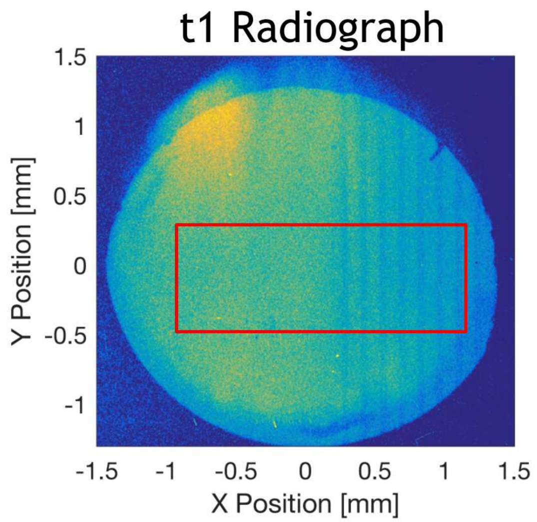
The plasma transport platform uses Z as a radiation source to drive a ionize a sample consisting of multiple interfaces

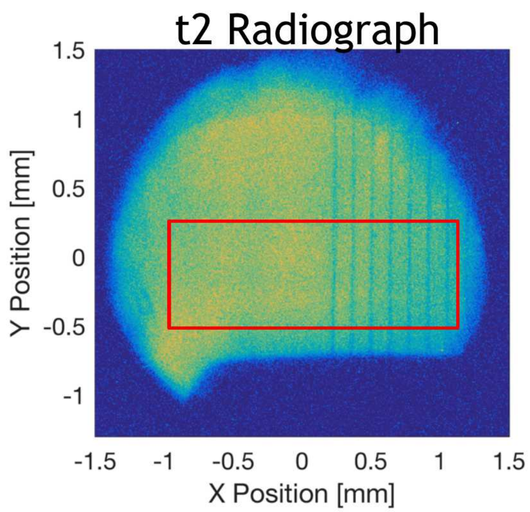


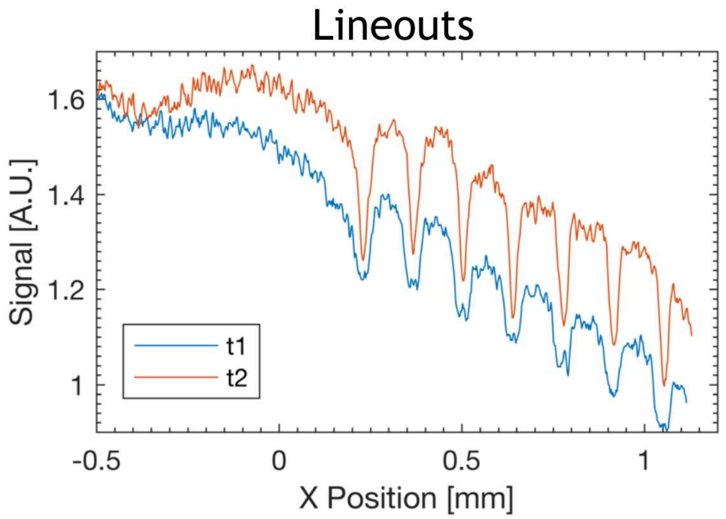
The radiation source drives an external sample into a strongly-coupled plasma state

The sample consists of a periodic array of V/CH "stripes"

Radiography is used to measure the "blurring" at the edges of the stripes caused by diffusion of the V into the CH



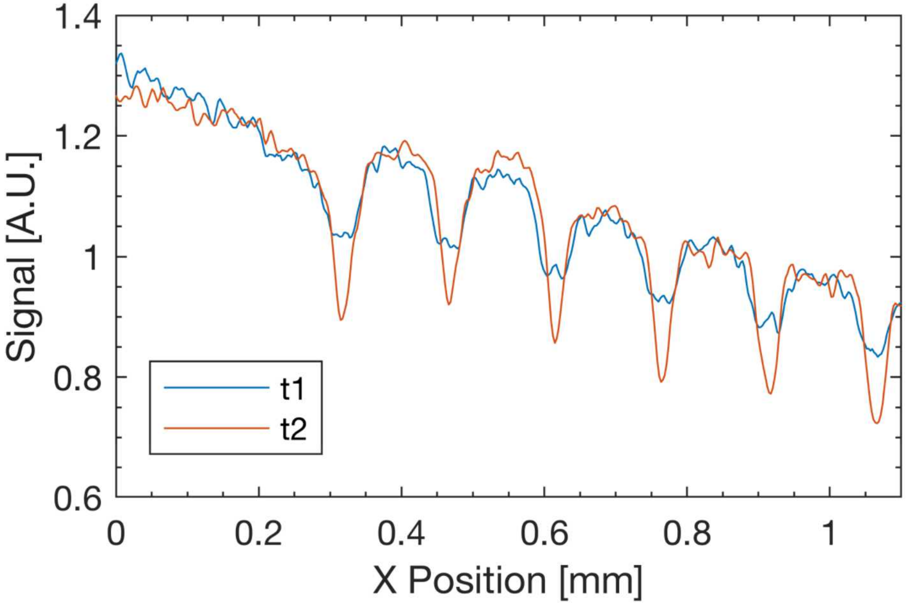


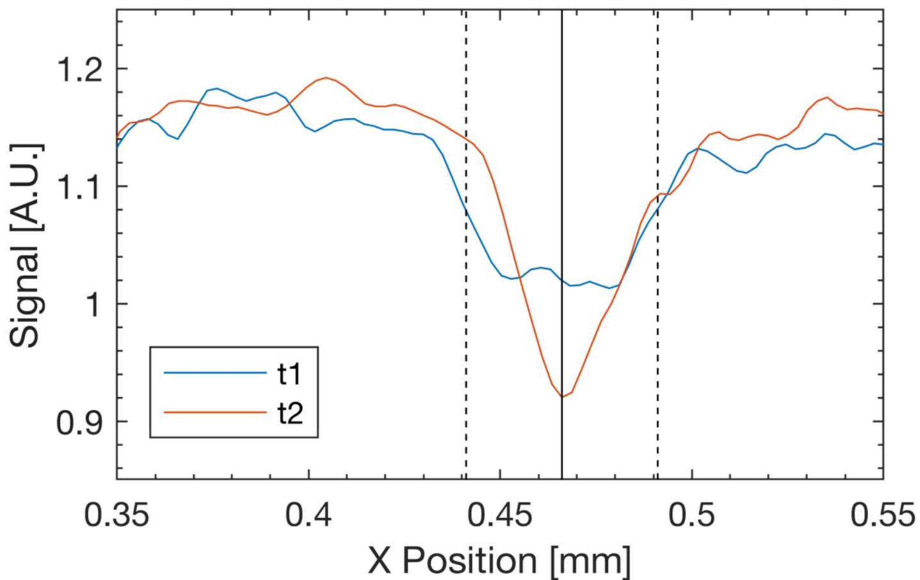


A closer look at the experimental data

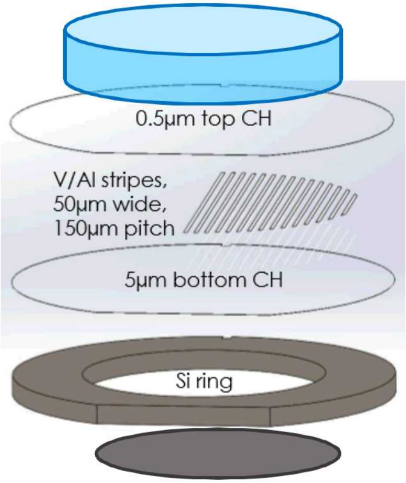
There is a clearly visible difference between the two frames

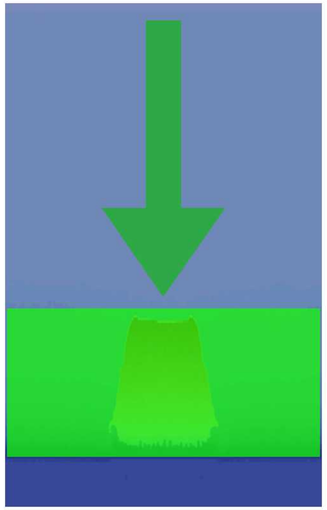
- The V strips appear to get "squeezed"
- There is a substantial absorption difference (hohlraum emission makes it difficult to assess this)
- A deeper look into rad-hydro and kinetic modeling sheds some light on these unexpected results

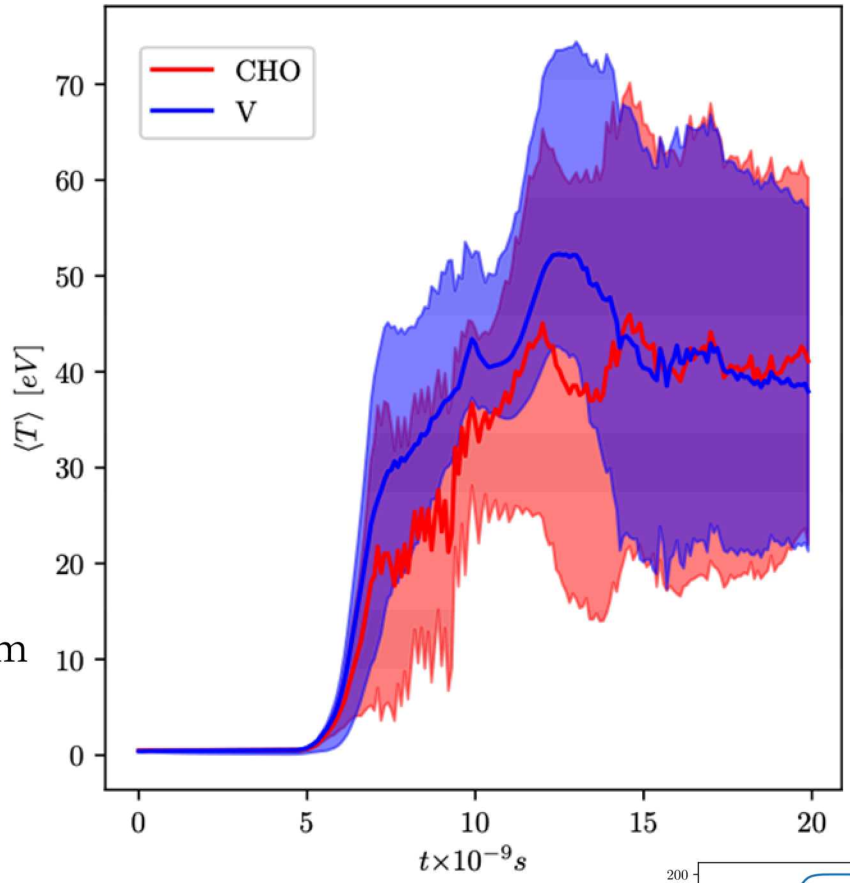


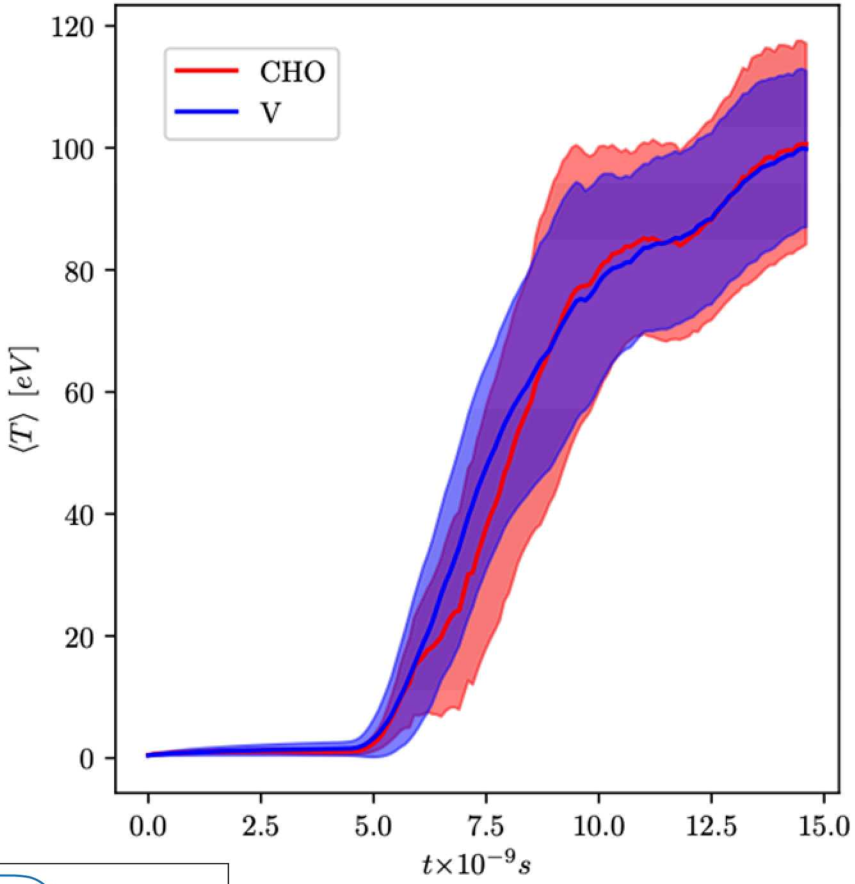


Radiation Hydrodynamics: How fast are we heating anyway?

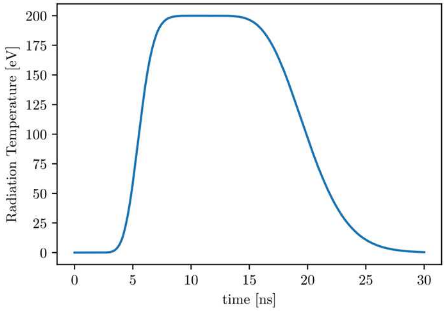








- Analyze time evolution of sample by integrating simulation along radiation path, over region adjacent to Vanadium
  - Heating strongly dependent on effective optical depth of foam
  - Foam @30 mg/cc: V & plastic only heat to 40eV
  - Foam @3 mg/cc: V & plastic heat to 80eV by 10ns and 100eV by 15ns
  - Impacts ionization state achieved



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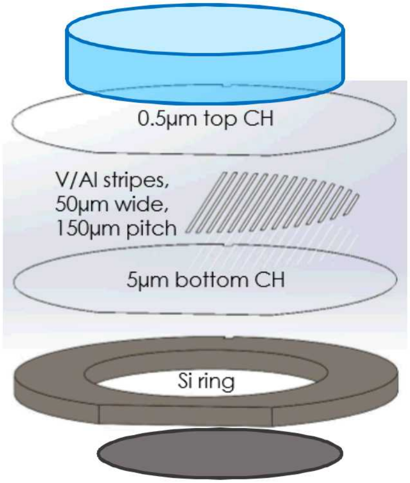
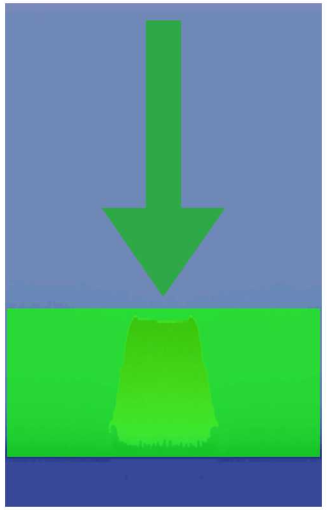
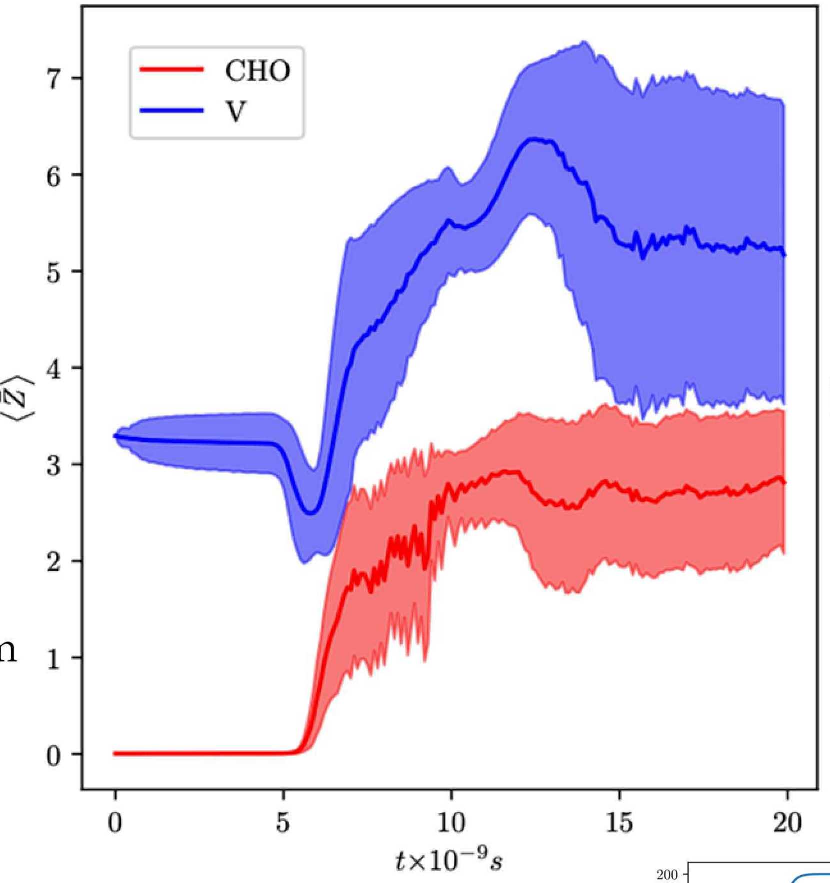
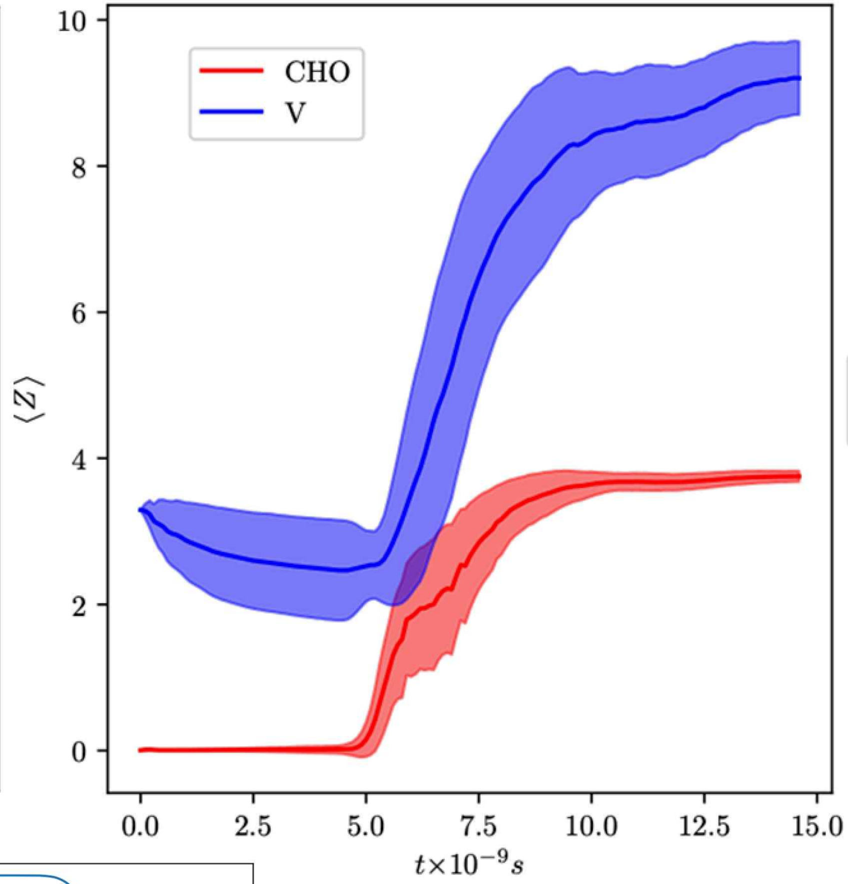


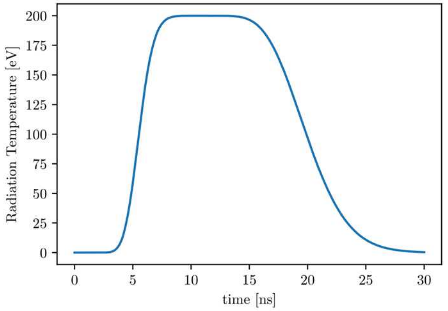


400 μm 30 mg/cc CH foam



400 μm 3 mg/cc CH foam





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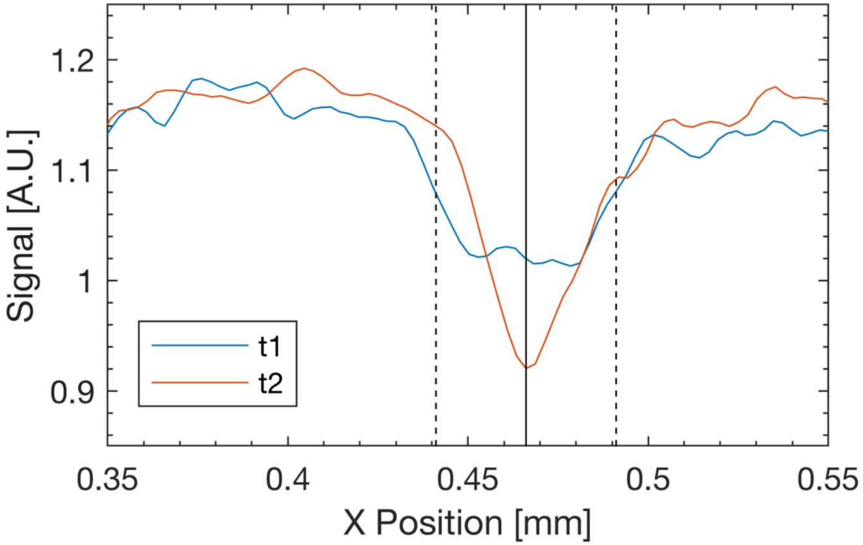
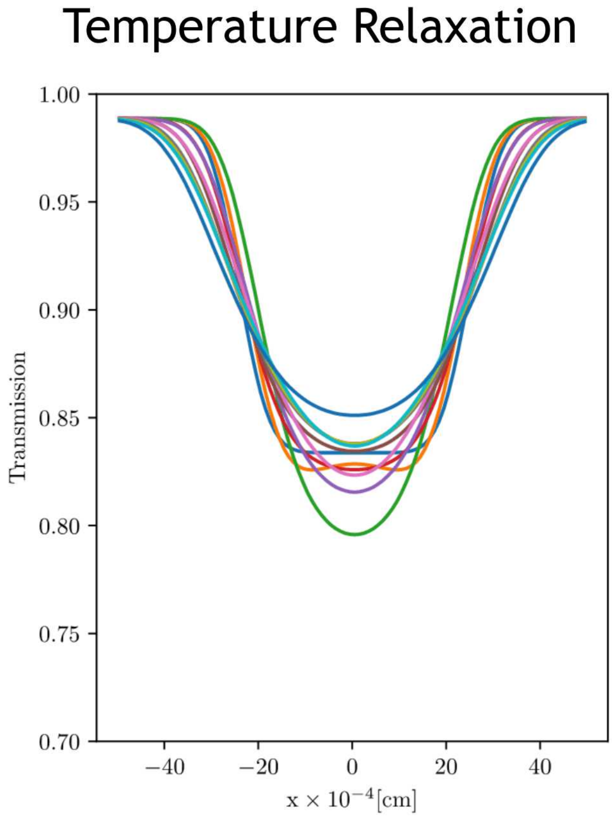
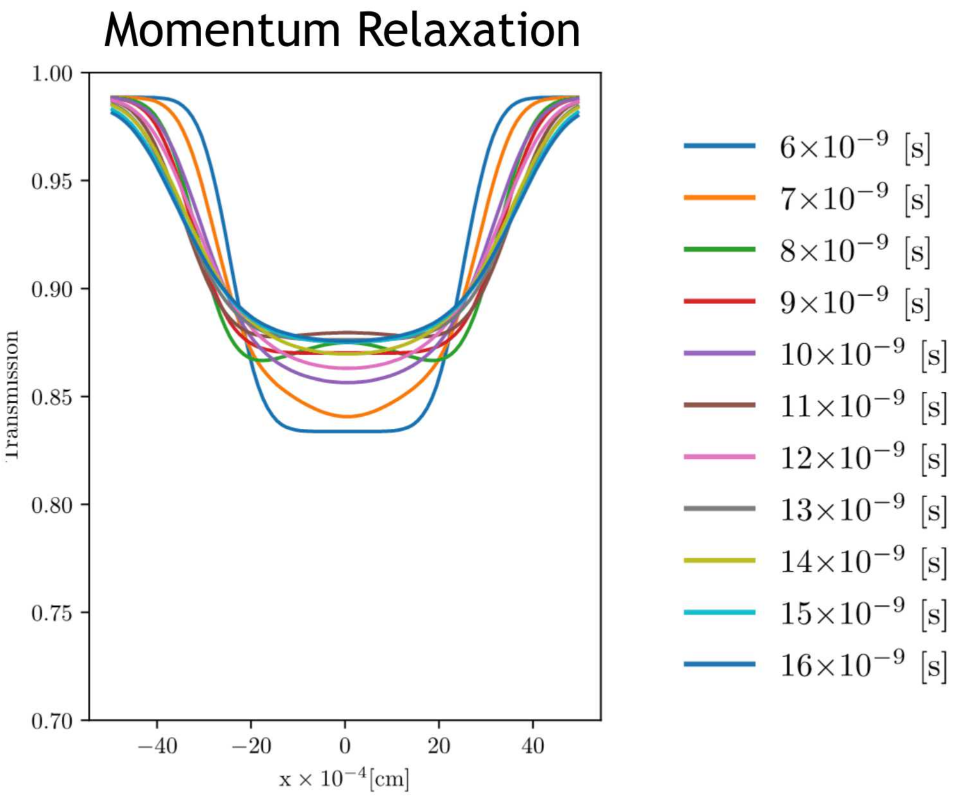
Kinetic Modeling of V/CH Interface: Synthetic Radiography

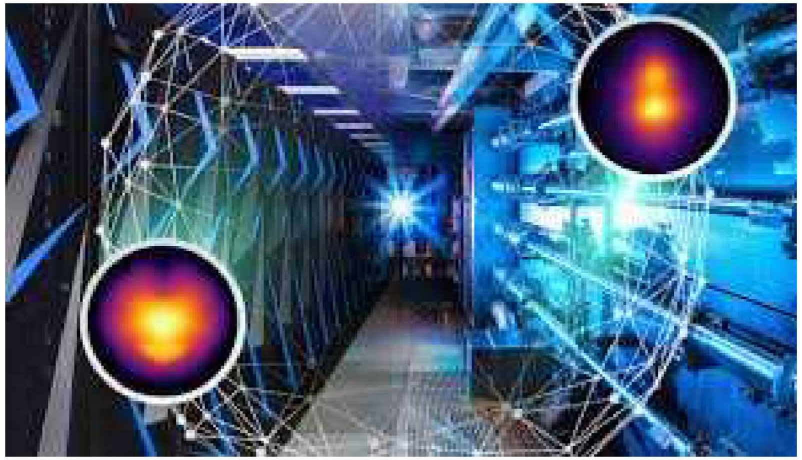






- Utilize electrostatic multi-species kinetic code to study plasma transport at CHO-V/Al interface
  - Thomas-Fermi Average Atom model for ionization state; Fermi-Dirac statistics for electrons
  - Comparing Temperature and momentum relaxation model for ion-ion collisions

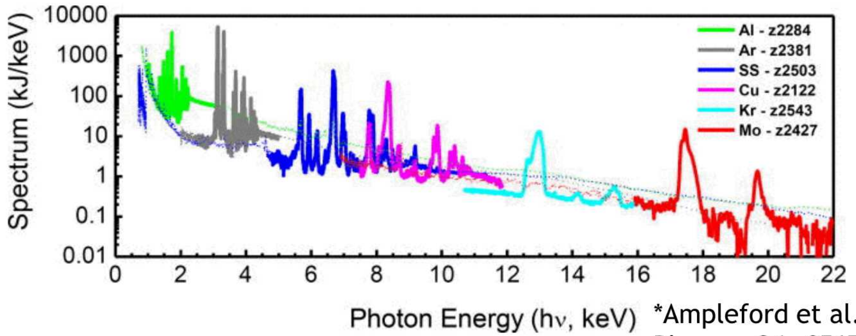
- Synthetic radiography:
  - In temp. relaxation case Transmission profile deepens and narrows prior to 8 ns, then widens
  - In mom. Relaxation case, the profile always widens
  - Effects of different diffusion treatments are observable with radiography!



LLNL press release, Jeremy Thomas

Data science applications

We are currently developing tools to bring the power of data assimilation to a variety of applications on Z



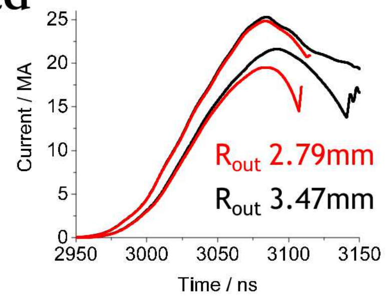
*Ampleford et al. Physics of Plasmas **21**, 056708 (2014)

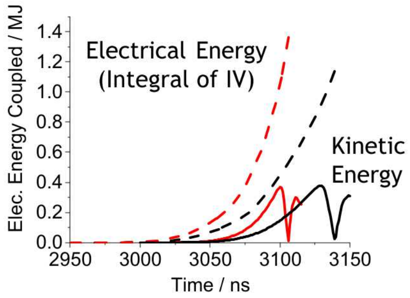
Improving measurements of x-ray output on Z by integrating

- X-ray power detectors (PCD's, XRD's, etc.)
- Total x-ray yield measurements (Calorimeter, bolometer)
- X-ray spectra from multiple independent instruments
- Driven by Radiation Effects Sciences (RES) needs

Use our knowledge of the Z circuit to constrain power delivery to the load and losses

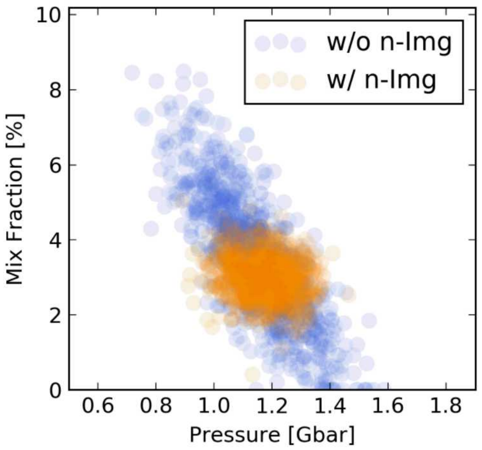
- Electrical measurements at multiple points in the Z circuit
- Load current velocimetry constrained by the circuit model and implosion model
- Driven by a need for better post-shot simulation capability and understanding of powerflow for scaling





Use the Bayesian formalism to design new diagnostics and optimize existing ones

- Output statistics give VOI which can be used to assess how much impact each diagnostic has on each parameter
- Synthetic data from simulation can be used to test new diagnostics to see which will have the most impact on the parameters of interest



We are developing a Bayesian engine to infer x-ray yields, and quantify & minimize uncertainties using detailed atomic physics

This will, by itself, likely reduce the uncertainty on the inference

More importantly, we are developing a tool that will allow us to interrogate what dominates the uncertainty and how we can improve our inference, quantitatively

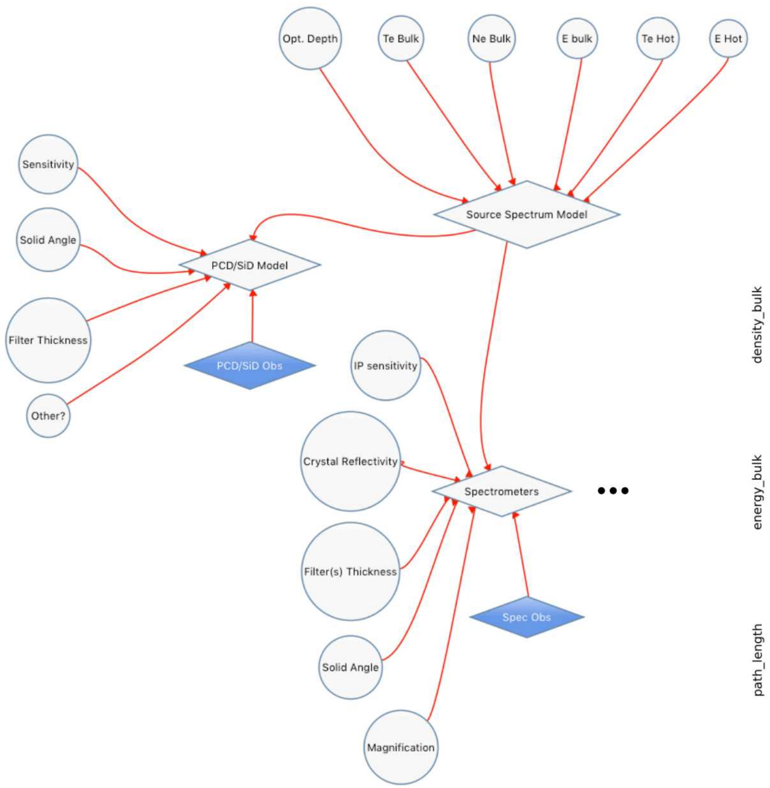
We can self consistently account for our (uncertain) knowledge of instrument response through priors on these parameters

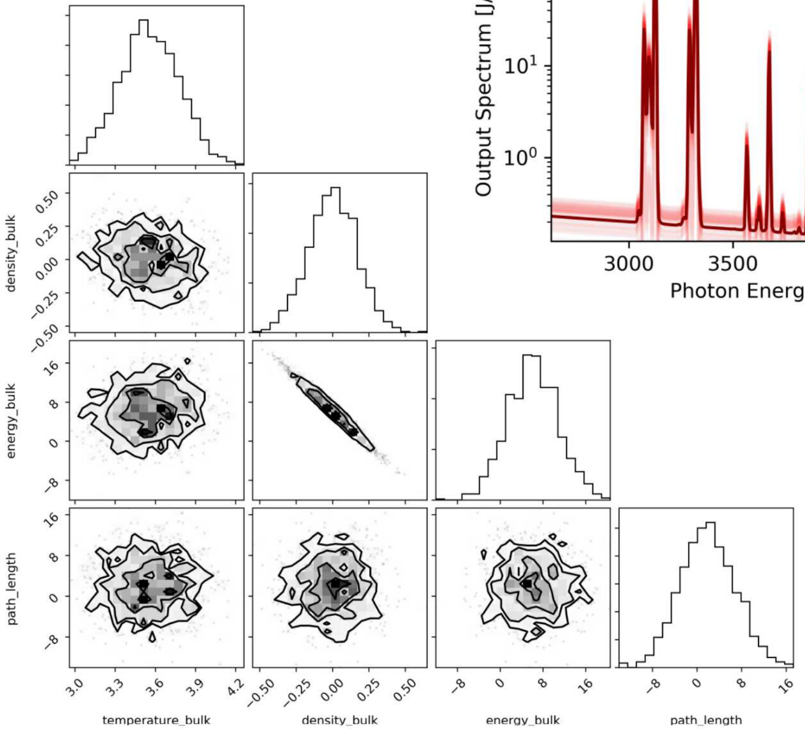
Big Questions

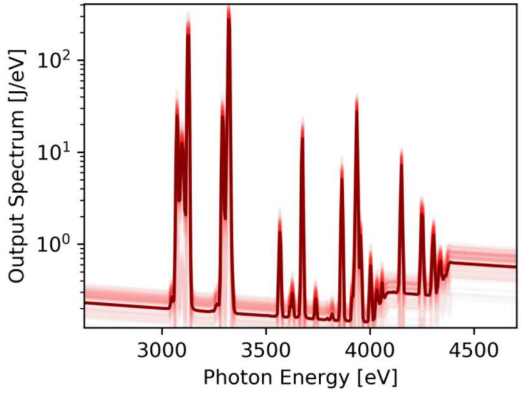
How would my inference change if I did something low cost like measuring all filters before use?

Something higher cost like recalibrating all the PCD's?

Something more drastic like adding a new diagnostic?



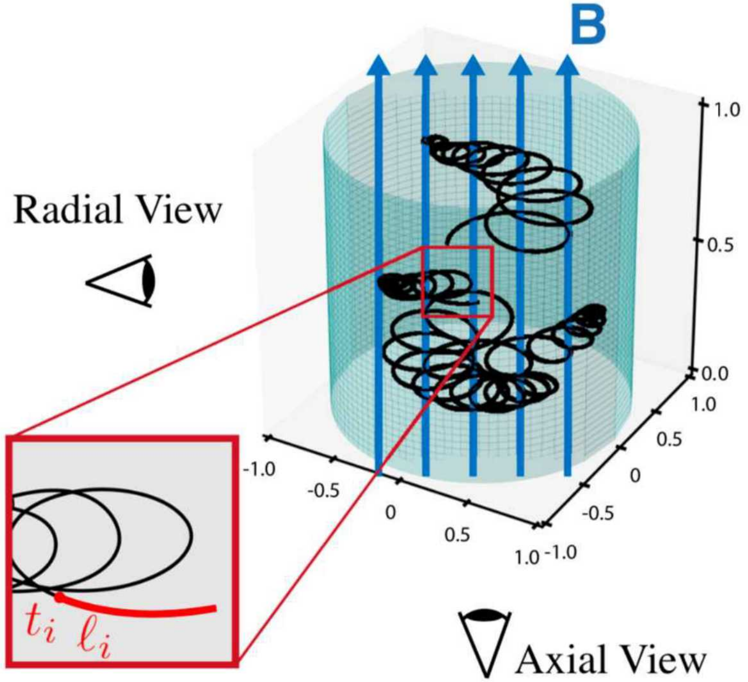




Secondary neutron yield and spectra are sensitive to BR and indicate a path toward measurement

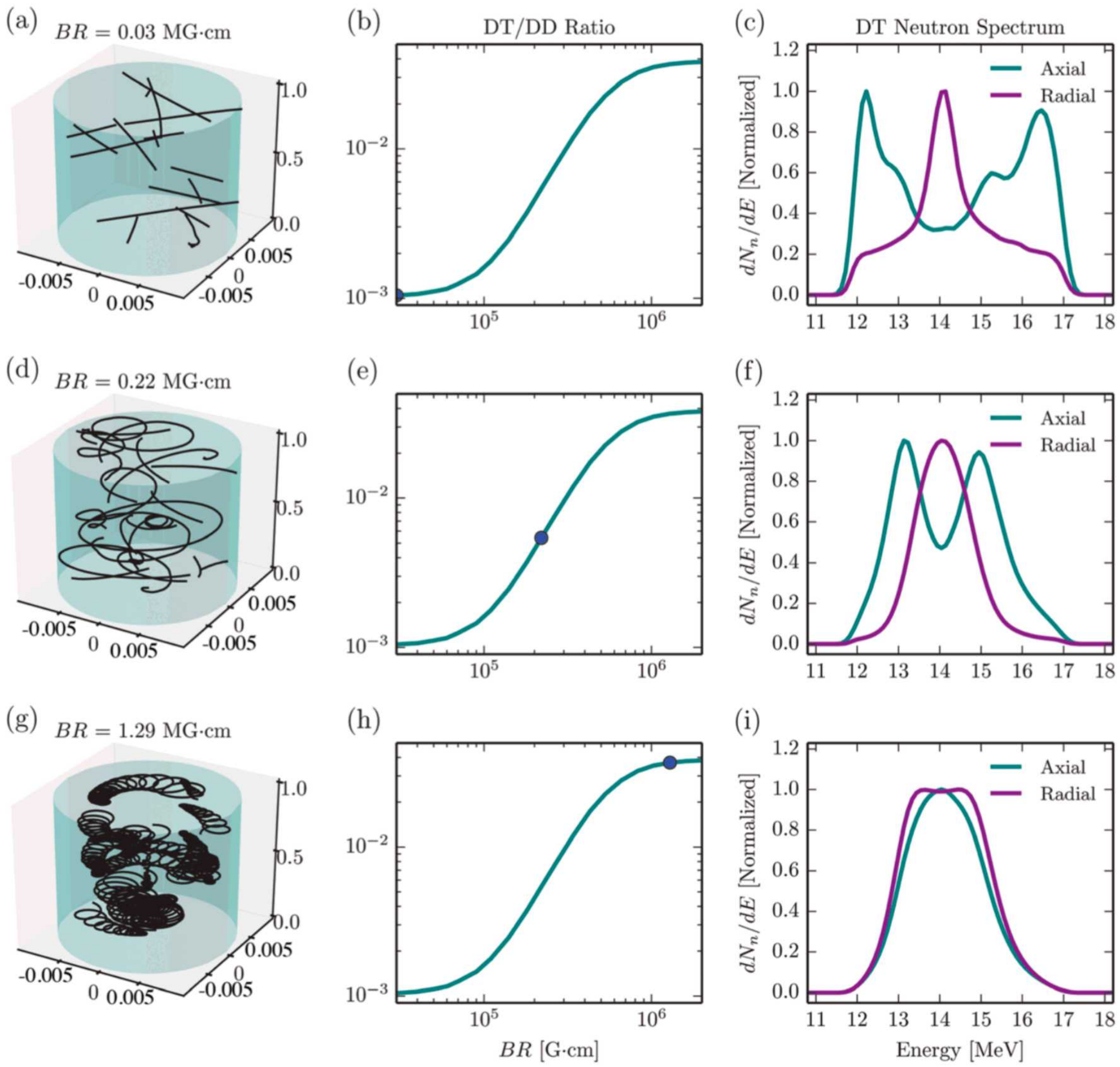
$$\text{Primary}: D + D \rightarrow \begin{cases} n + {}^3\text{He} & 2.45\ \text{MeV} \\ p + T, & 1.01\ \text{MeV} \end{cases}$$
$$\text{Secondary}: D + T \rightarrow n + \alpha. \quad 11.8\text{–}17.1\ \text{MeV}$$

$$\mathcal{P}_{DT} \propto \langle \rho_D \ell \rangle \sigma_{DT}$$



Magnetized →

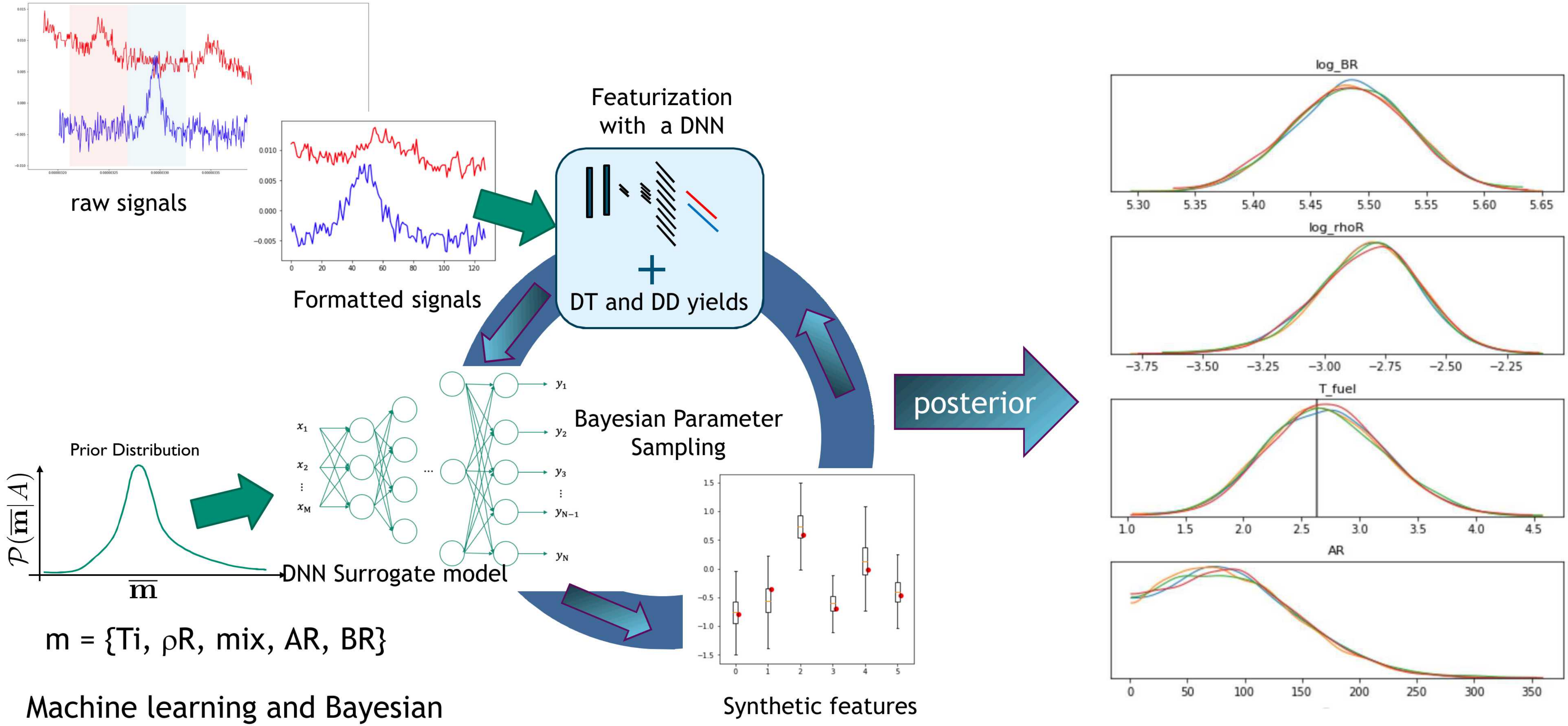
$\ell \propto f(BR)$



P.F. Knapp *et. al.*, PoP (2015)

We want to use these signatures to provide a fast inference of BR from experimental data

Using a combination of deep learning and Bayesian inference we have developed a nearly "push button" algorithm



m = {Ti, ρR, mix, AR, BR}

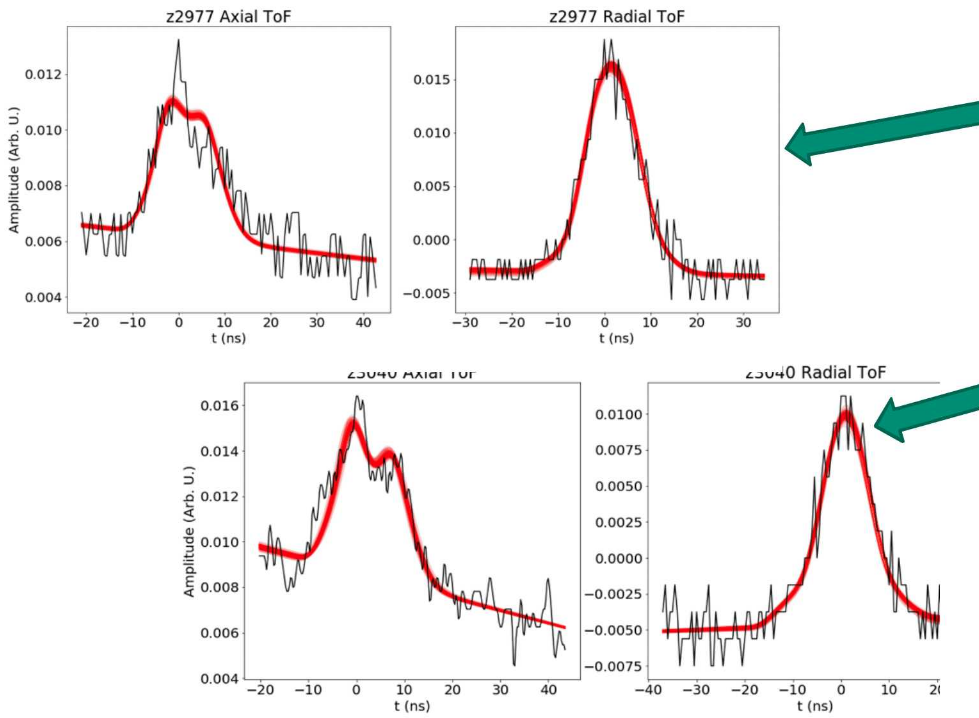
Machine learning and Bayesian inference with no human input

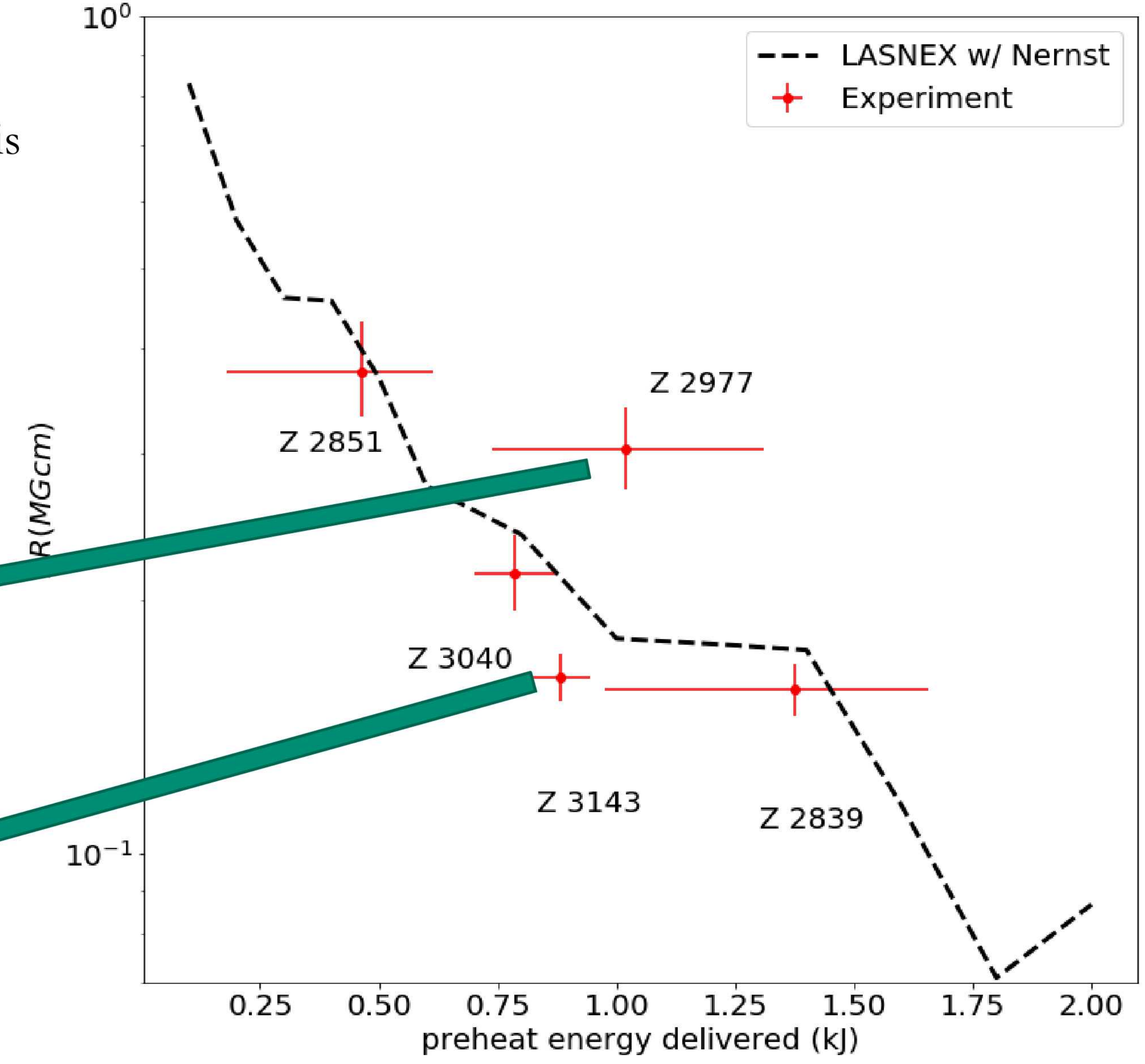
Measurements of magnetization on a range of experiments are consistent with predictions with the Nernst effect

LASNEX predictions with the Nernst effect predict reduced magnetization as preheat energy is increased

The higher energy deposition drives field out of the hotspot due to the Nernst effect

This capability has allowed us to verify this trend





Conclusions

There is wide range of exciting work happening on Z

- MagLIF is providing exciting opportunities to study magnetized ICF plasmas as well as an attractive path to high yield fusion
- The large available driver energy of Z provides unique opportunities in HED hydrodynamics in a converging geometry
- The bright x-ray sources produced by Z can be used to produce strongly coupled plasmas
- This platform is being developed to study kinetic diffusion processes important for mix in ICF
- These examples are just the ones that I am involved in, there is so much more!

Data science is playing an increasingly large role in how we process and analyze data as well as how we assimilate it with theory

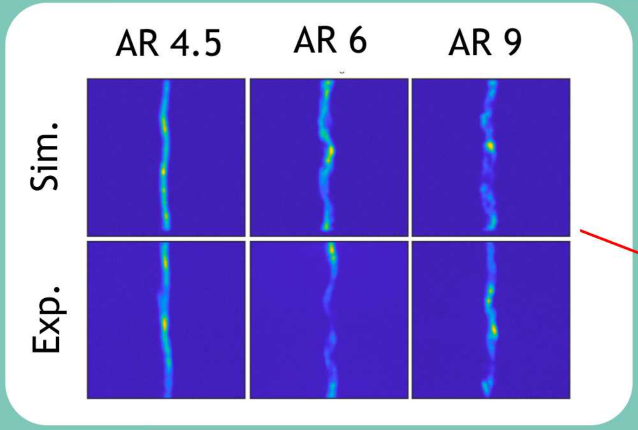
- Surrogate models enable fast sampling of expensive models for use in inference
- ML-based featurization of data can be used to reduce raw data in an automated and robust way
- The MST has been shown to allow robust classification and comparison of highly structured images
- Bayesian methods are being leveraged heavily for UQ and data assimilation

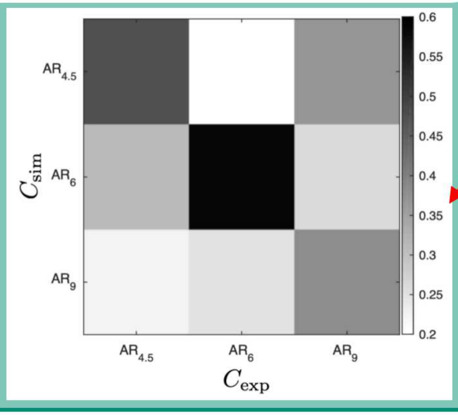
Mallat scattering transform for image quantification

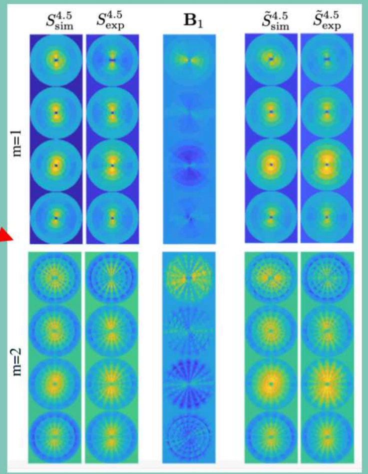
MST is a deep convolutional network with no free parameters

Computes information about local spatial frequencies in images as well as correlations between frequencies

Can be used as an image similarity metric

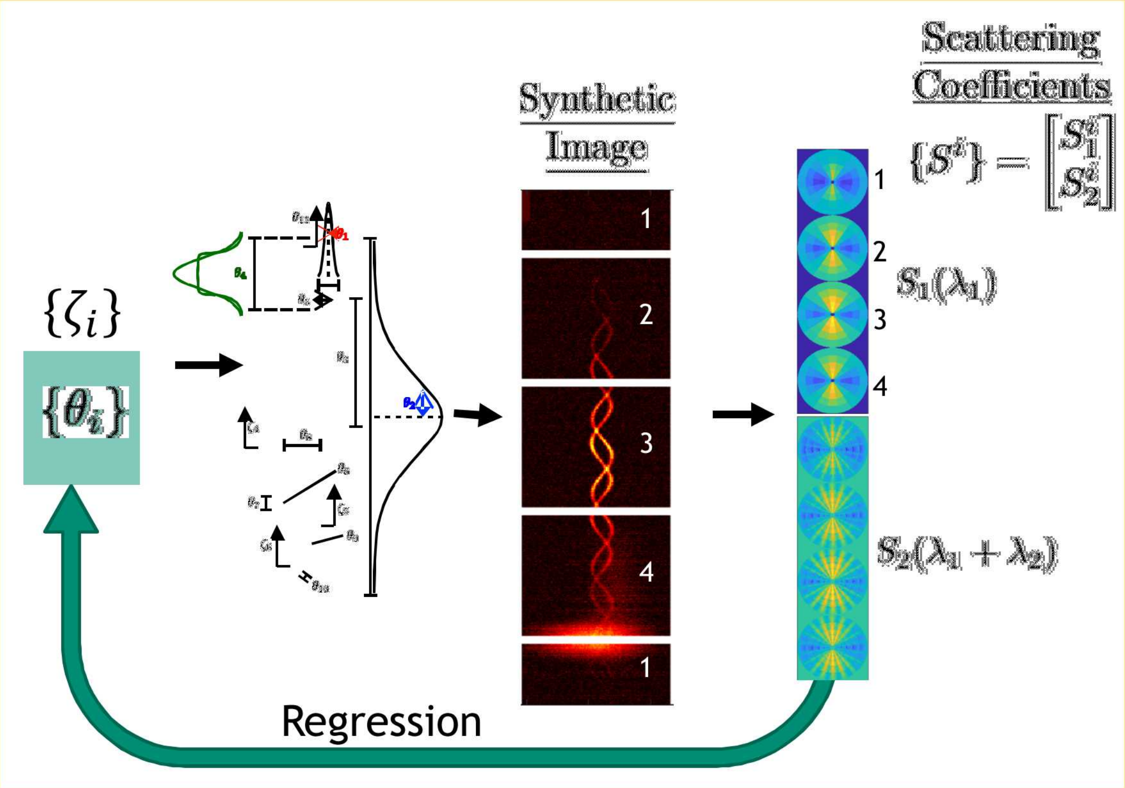






How similar are the simulated and measured images?

Used to estimate morphology of MagLIF stagnation images and quantitatively compare with experiments



What structures are present at what scales?
What does that say about stagnation physics?

Glinsky, Lewis, Moore, et al. submitted to PoP