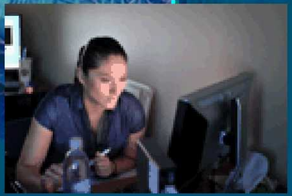
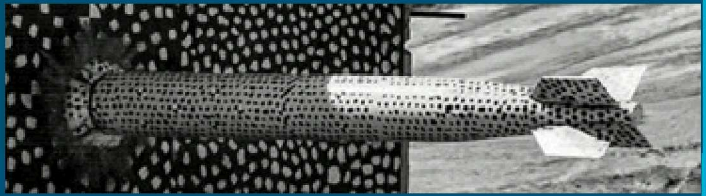
SAND2018-5782C

An overview of ICF and HEDP research on the Z machine at Sandia National Laboratories





PRESENTED BY

Patrick F. Knapp

May 24, 2018

Kinetic Effects in ICF Workshop, Santa Fe, NM

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Thanks to my many colleagues & collaborators:

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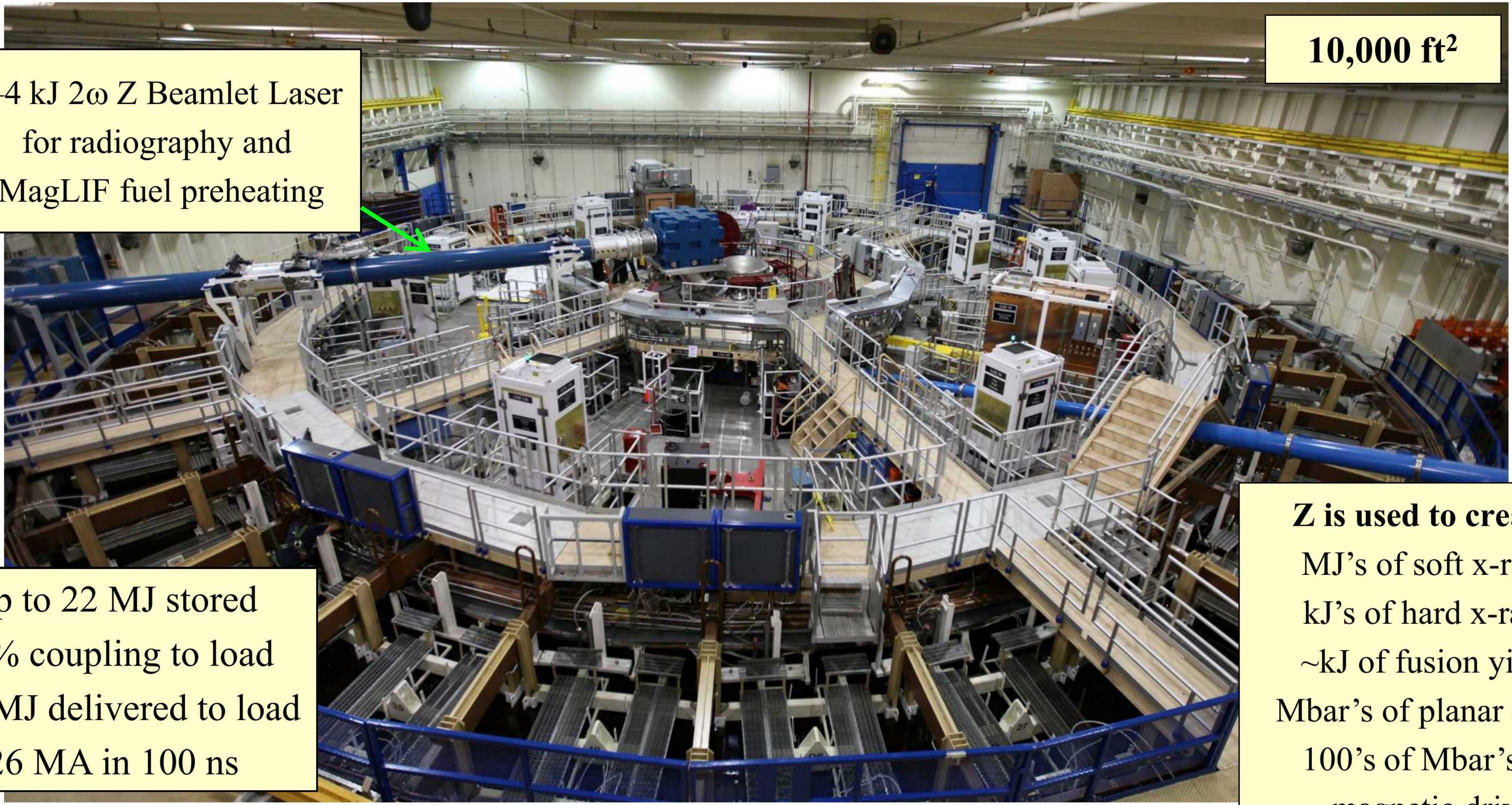
[10] General Atomics, San Diego, CA

Outline

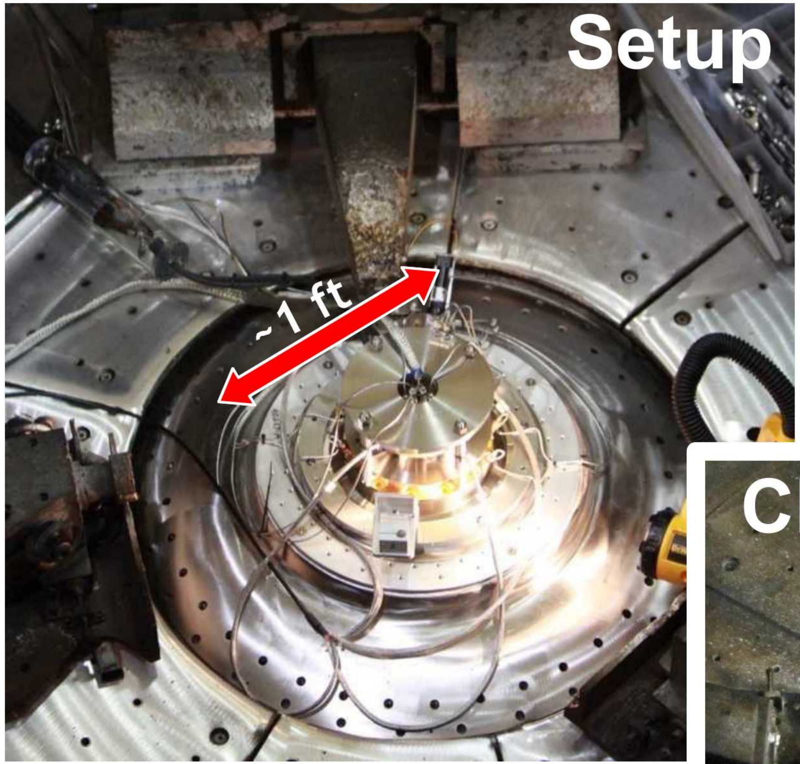
- Overview of the Z facility and Pulsed Power Driven HEDP
- Magnetized ICF research on Z
- Physics beyond MHD
  - Power flow
  - Non-thermal x-ray and neutron source
  - The physics of low density plasmas
  - Plasma transport

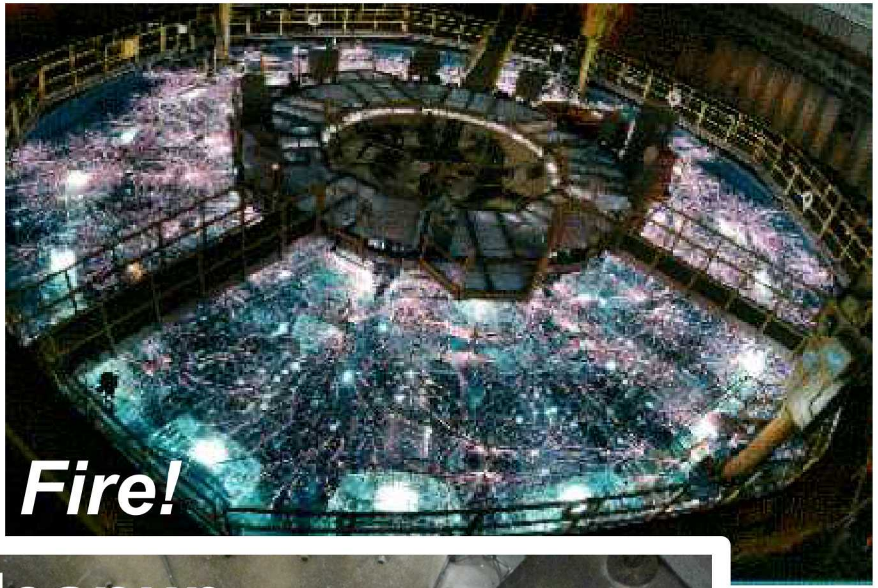
The Z facility combines the multi-MJ Z pulsed-power accelerator with the multi-kJ Z Beamlet Laser (ZBL)



Z is a fun and challenging place to conduct high impact experiments

Shot rate of ~1/day





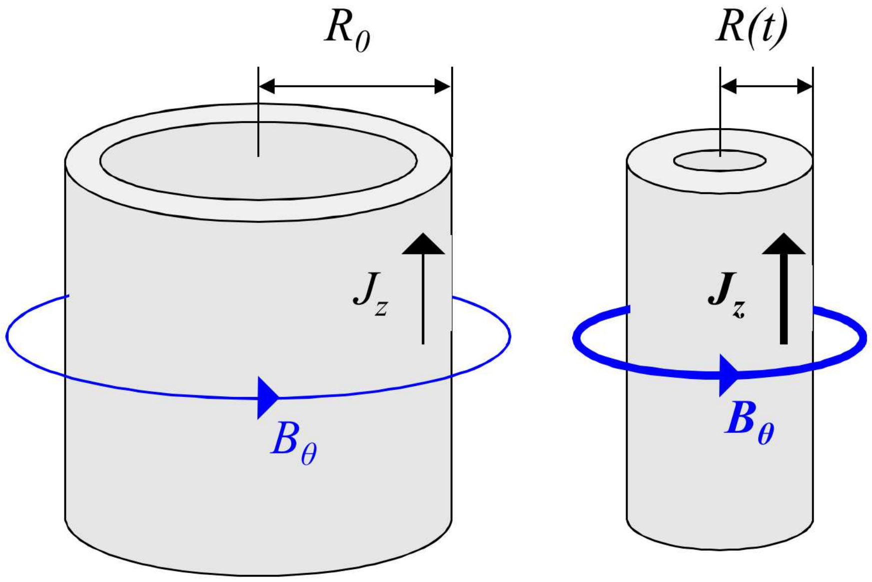
- MJ's of magnetic energy to the load
- Equivalent to detonating a few sticks of dynamite
- Harsh debris, shock, and radiation environment make fielding experiments unique and challenging

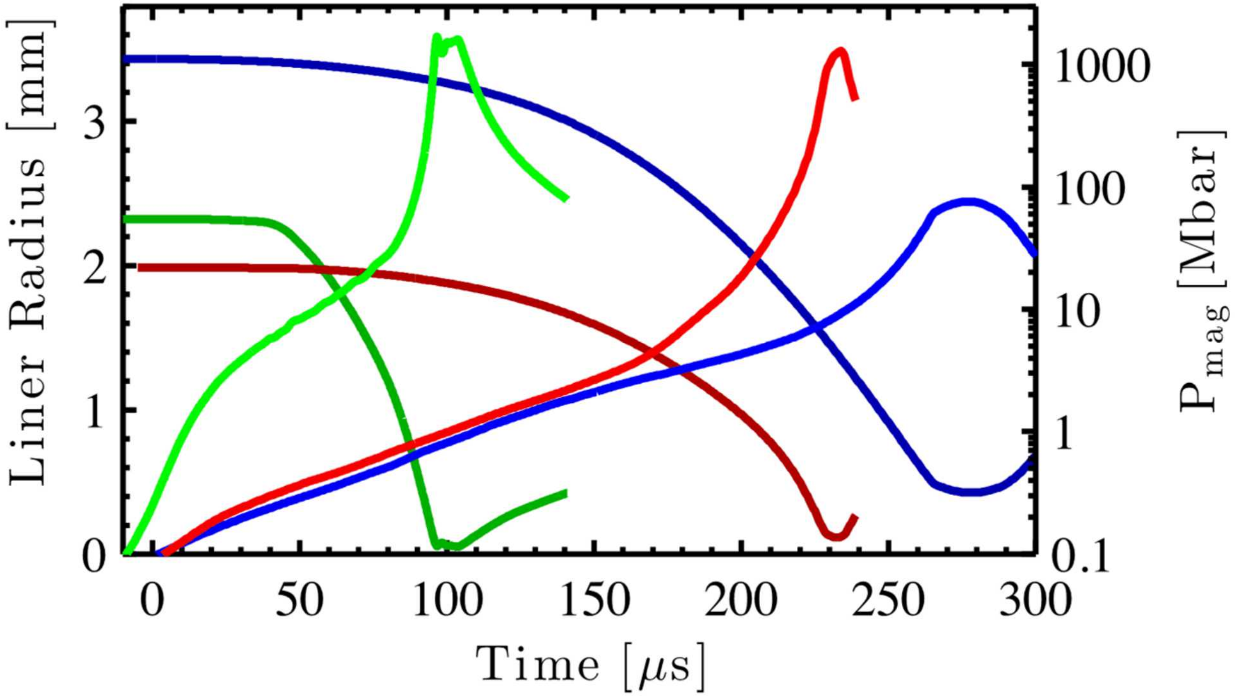
Magnetically-Driven Cylindrical Implosions are Efficient: Implosion Drive Pressure is Divergent!

$$P = \frac{B^2}{2\mu_o} = 140 \cdot \left(\frac{I_{[\mathrm{MA}]}/30}{R(t)_{[\mathrm{mm}]}} \right)^2 \quad [\mathrm{Mbar}]$$

$$\rho\left(\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u}\cdot\nabla)\mathbf{u}\right) = \frac{\mathbf{J}\times\mathbf{B}}{c} - \nabla P$$

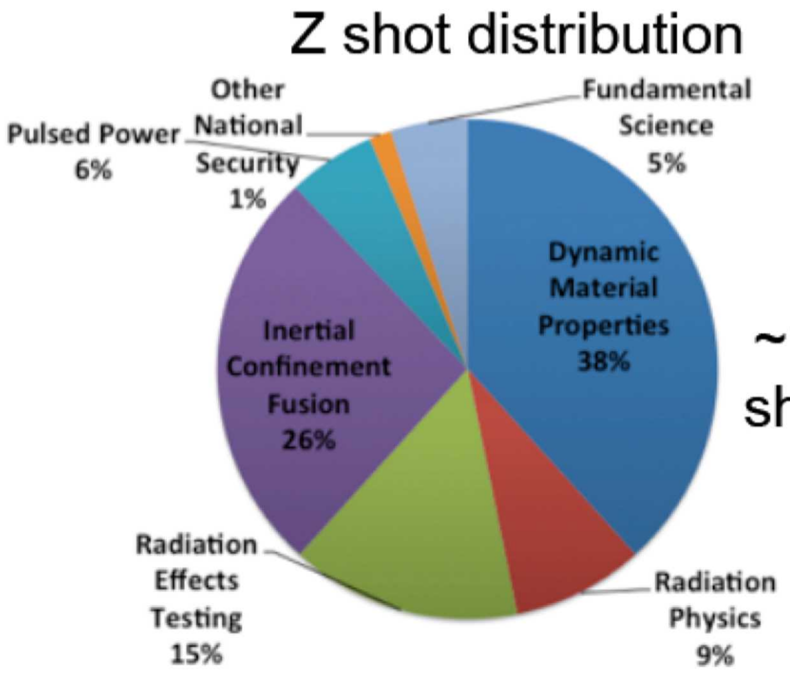
$\rho_f \approx 60\ \mathrm{g/cm^2}$
$T \approx 10\ \mathrm{eV}$
$\mathrm{P}_f \approx 2\ \mathrm{Gbar}$



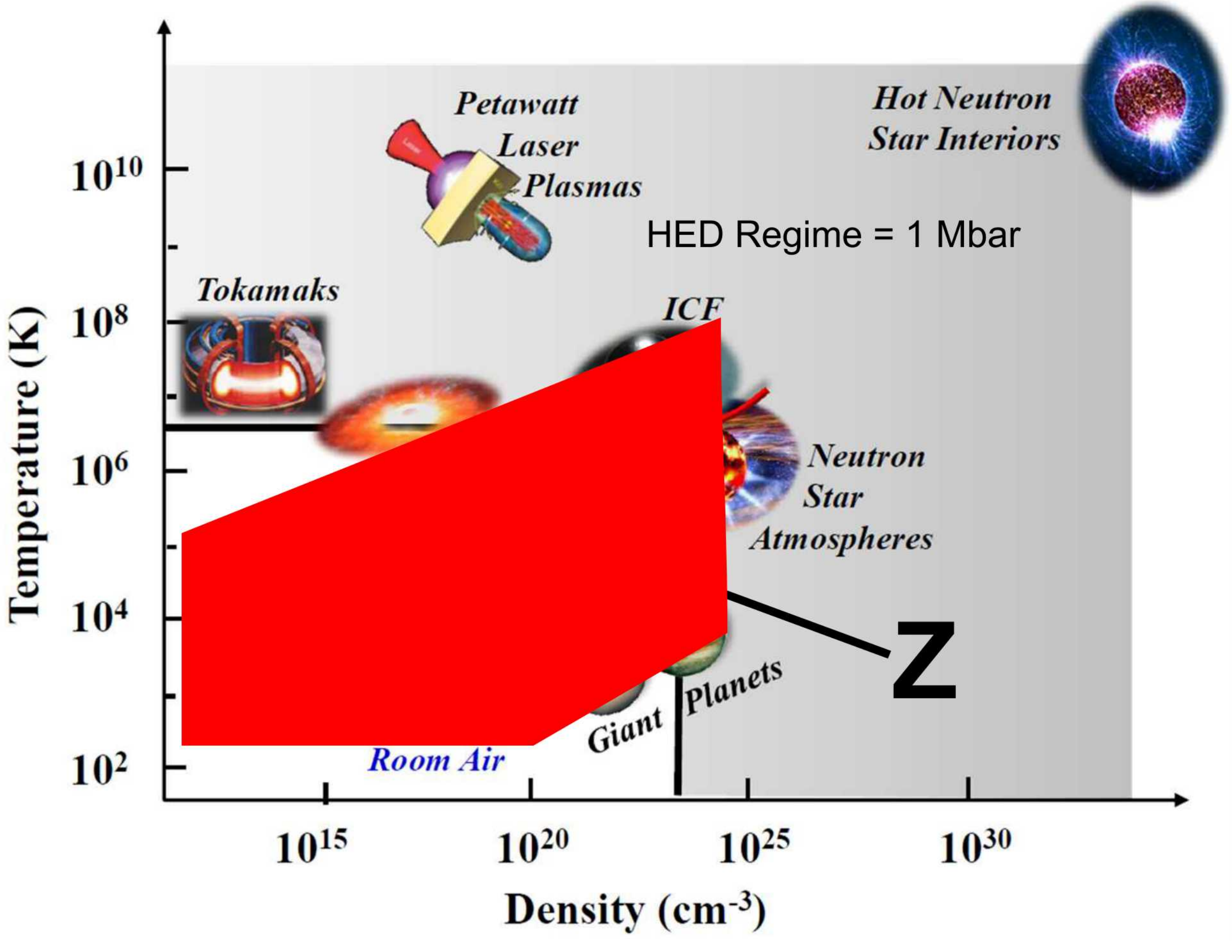


By varying the magnetic pressure pulse shape, liner dimensions, and duration of drive, Z can access a wide variety of end states

Experiments on Z support a diverse range of mission needs and a wide range of physics



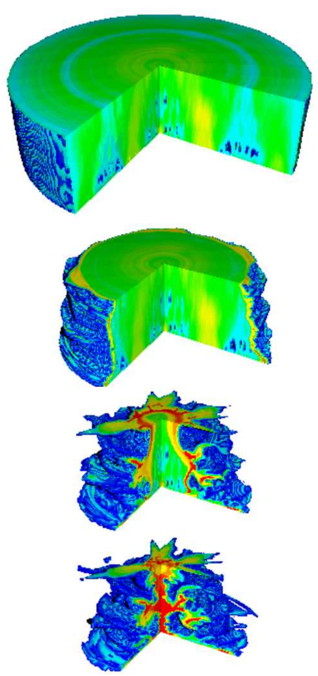
~150-200 shots/year

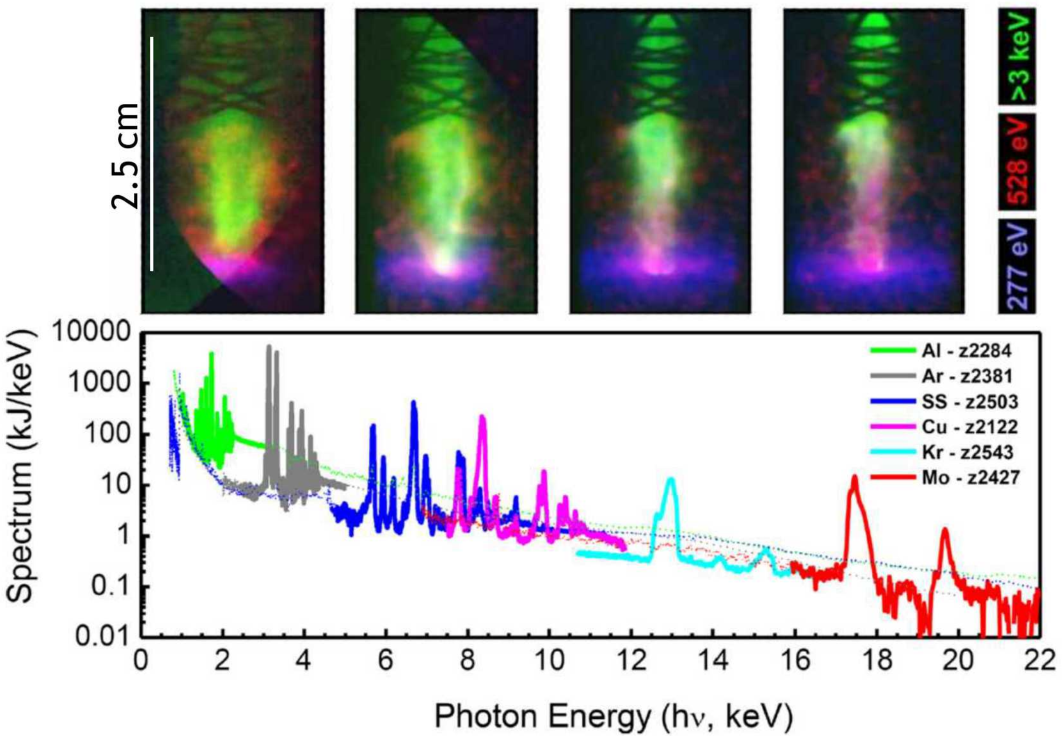


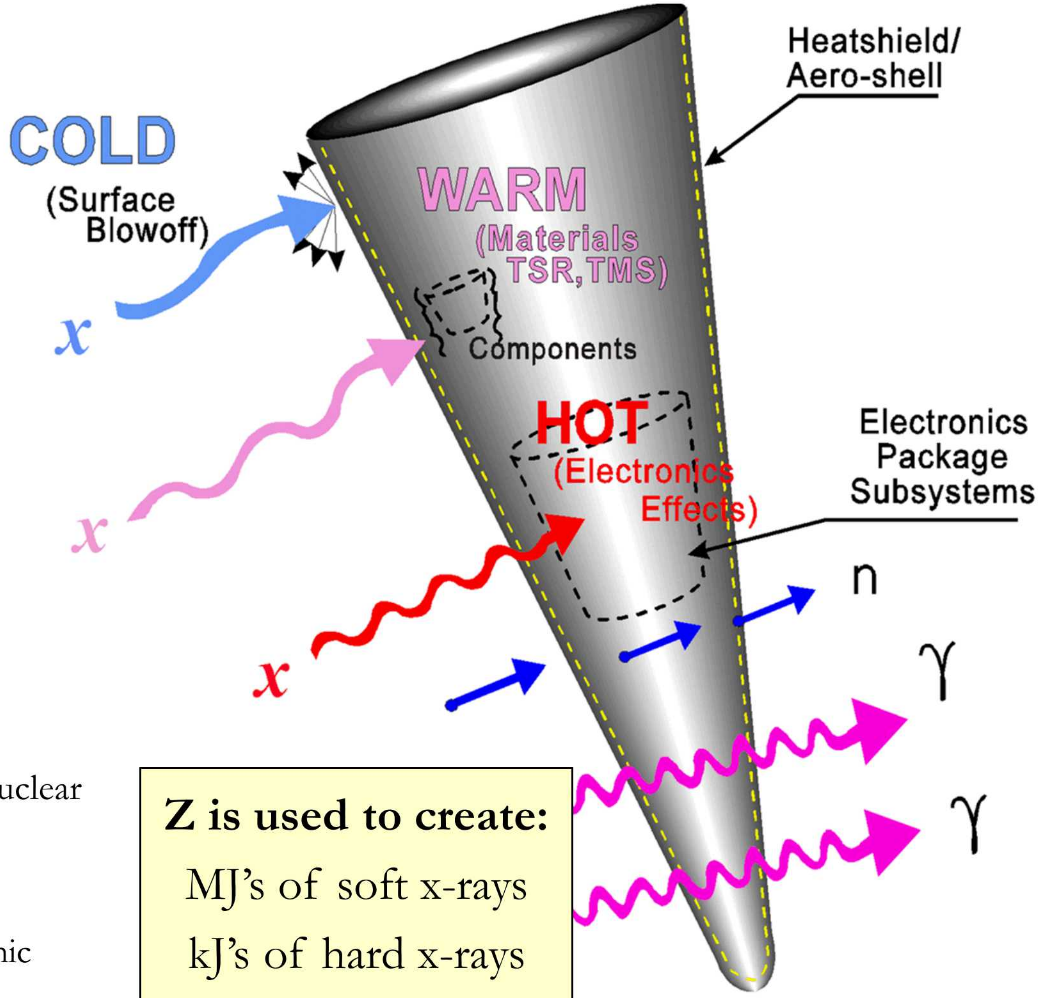
Z supports a large variety of missions

- Inertial Confinement Fusion
- Dynamic Material Properties
- Radiation Effects Testing
- Radiation Physics
- Pulsed Power Development
- Other National Security Applications
- …and more

Z is used to create extreme radiation environments for Stockpile Stewardship applications







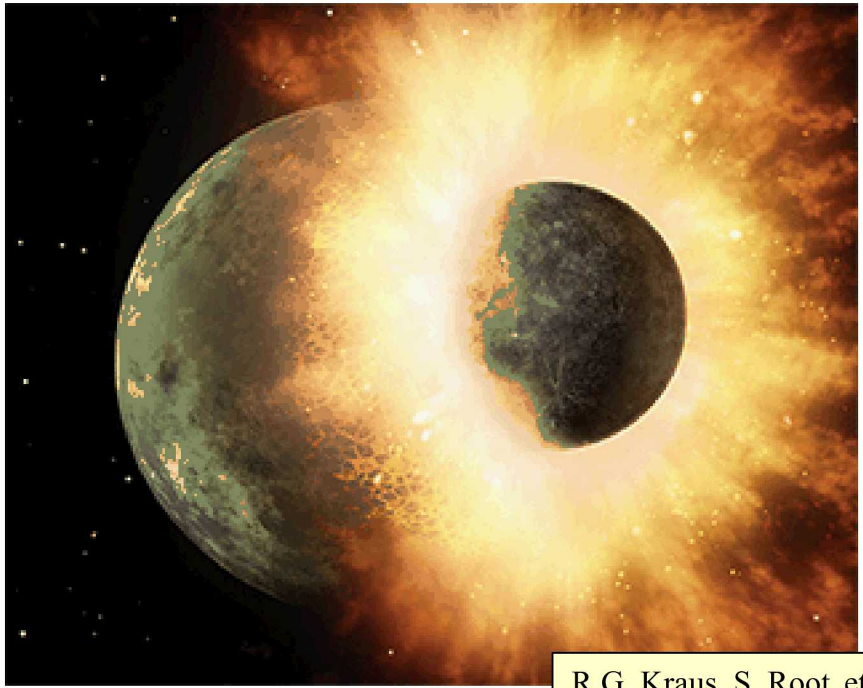
- Part of Sandia's national security mission is to understand how systems and materials in our nuclear weapons systems behave in extreme x-ray environments
- Z is the world's brightest x-ray source, e.g. 350 kJ of Ar K-shell yield above 3 keV photon energy
- Developing x-ray sources at Z requires expertise in pulsed power, z-pinch physics, plasma and atomic physics, spectroscopy and high-energy-density diagnostics, target fabrication, and radiation-MHD simulation

Z is used to create:
MJ's of soft x-rays
kJ's of hard x-rays
~kJ of fusion yield

Dynamic materials experiments are answering long standing questions in planetary science

How did collisions in the early solar system influence its current structure?

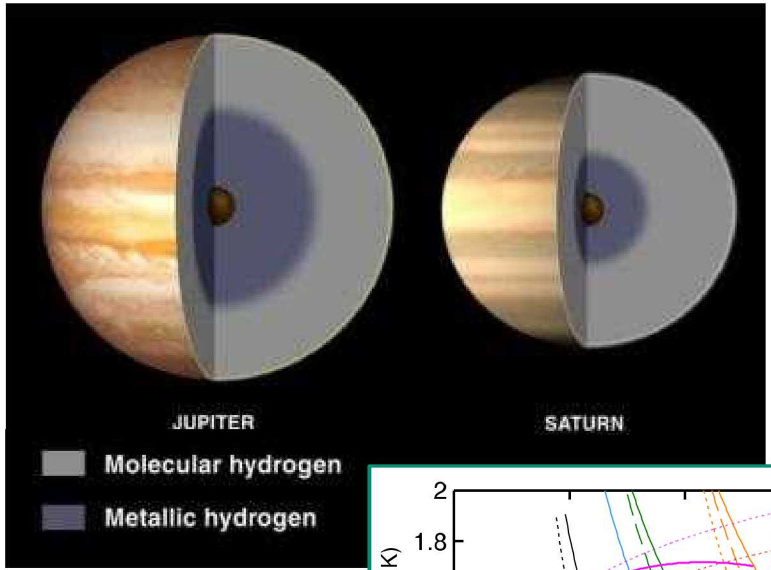
"Impact vaporization of planetesimal cores in the late stages of planet formation"

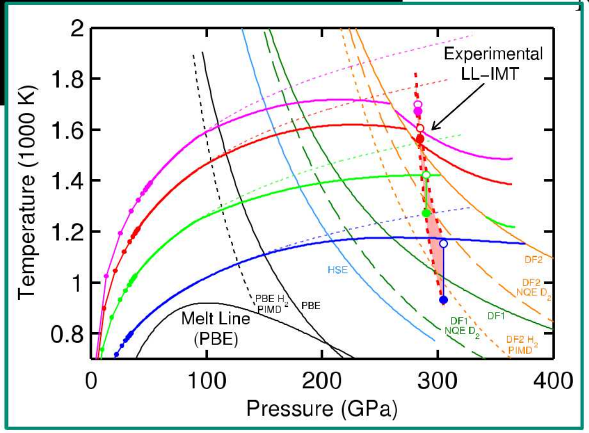


(Image Credit: NASA/JPL-Caltech)

R.G. Kraus, S. Root, et al., *Nature Geoscience* **volume 8**, pages 269–272 (2015)

Is there a Liquid-Liquid insulator to metal phase transition in H?





Present structure

- Layers of different composition while fulfilling observational constraints

Evolution

- Discrepancies in modeling the evolution of Jupiter and
- Why is Saturn so luminous?

Magnetic fields

- Origin of multi-polar fields in Neptune and Uranus

M.D. Knudson, M.P. Desjarlais, et al., Science 348 1455, 26 June 2015.

The ZAPP collaboration is uncovering exciting discrepancies with once accepted models


THIS WEEK

EDITORIALS

MENTORING The heavy responsibility to the next generation p.438

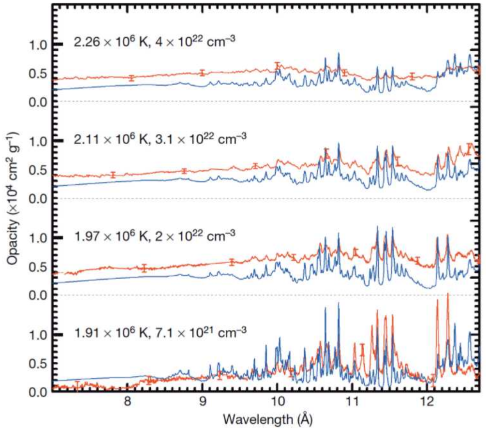
WORLD VIEW Beware the real risk of World Cup fever p.439

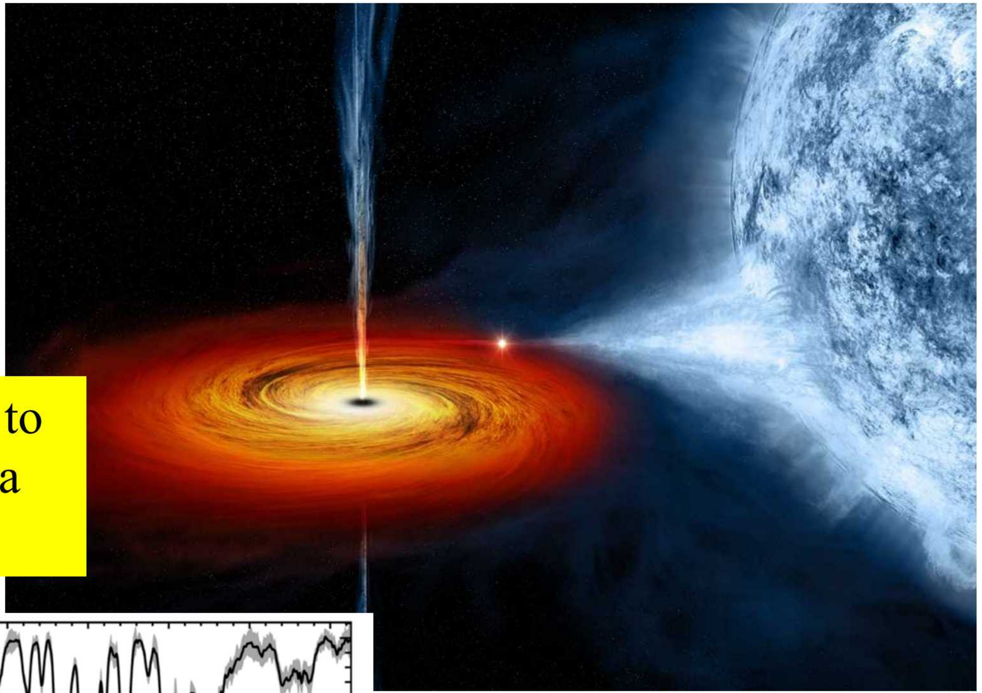
POISON Strawberry-frog parents give protection to kids p.441

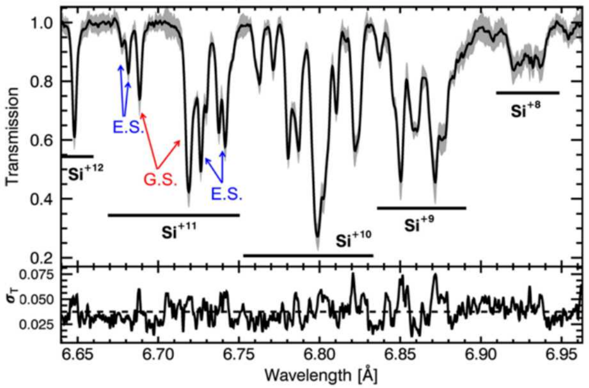
Nailing fingerprints in the stars

Laboratory-based experiments are sorely needed to complement the rapidly proliferating spectral data originating from observations by the latest space telescopes.

"Laboratory-based experiments are sorely needed to complement the rapidly proliferating spectral data originating from the latest space telescopes"



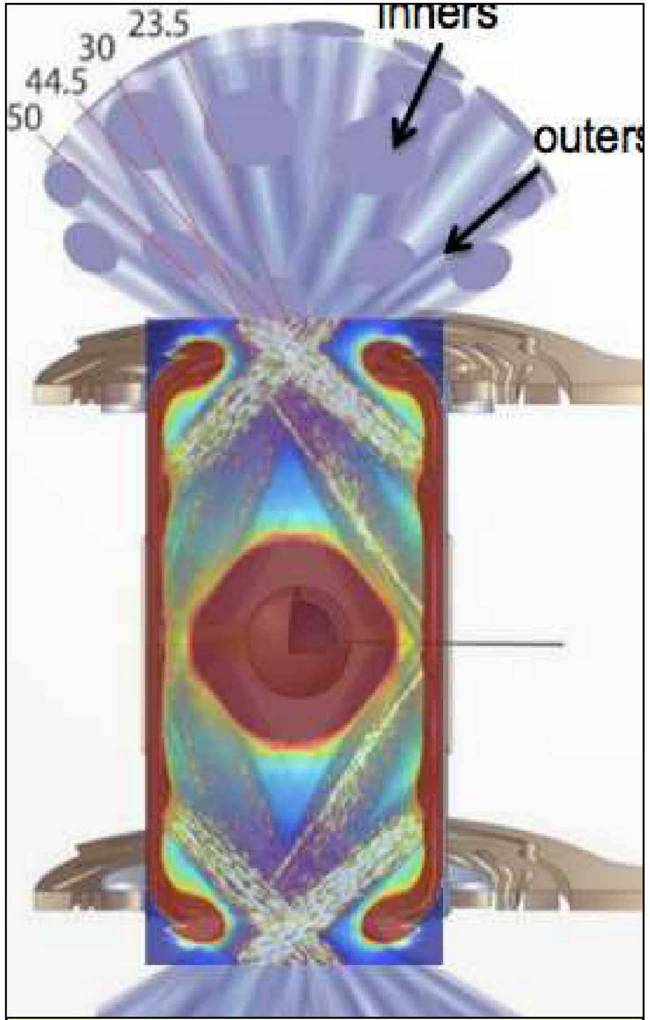
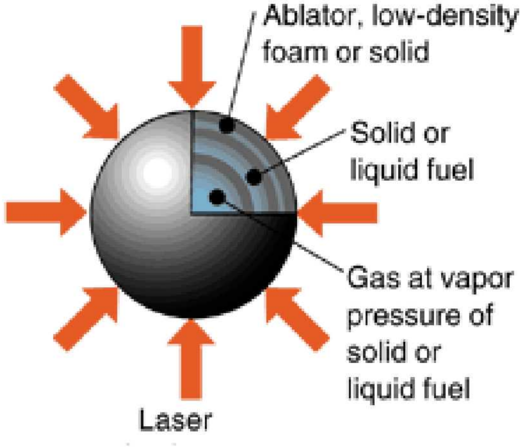
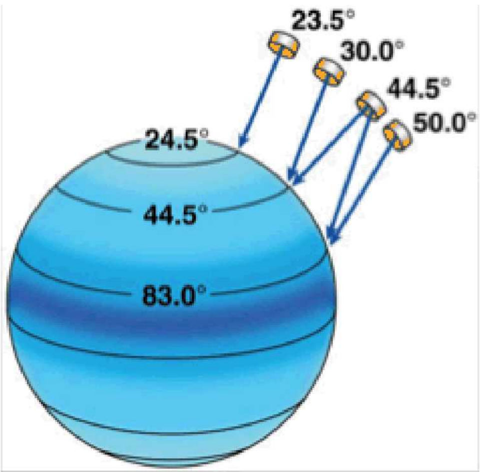
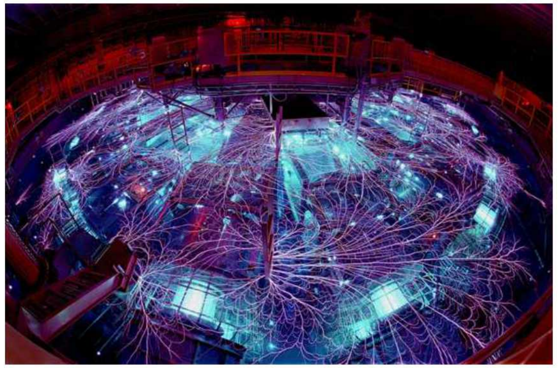
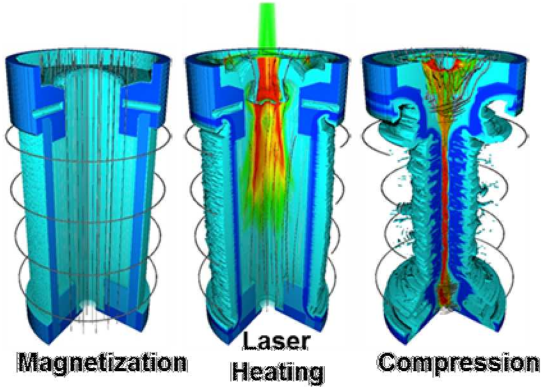




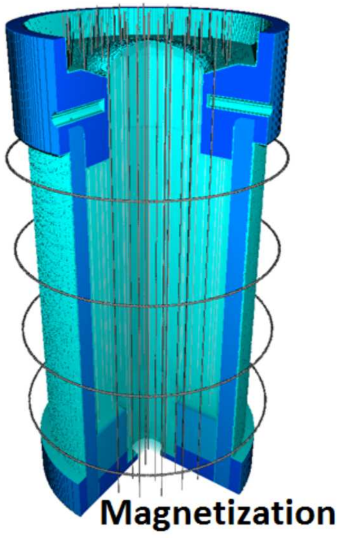
J. E. Bailey, T. Nagayama, G. P. Loisel et al., *Nature* 517, 56–59 (01 January 2015).
G.P. Loisel et al., Phys. Rev. Lett. **119**, 075001 (2017)

Magnetic Direct-Drive ICF on Z

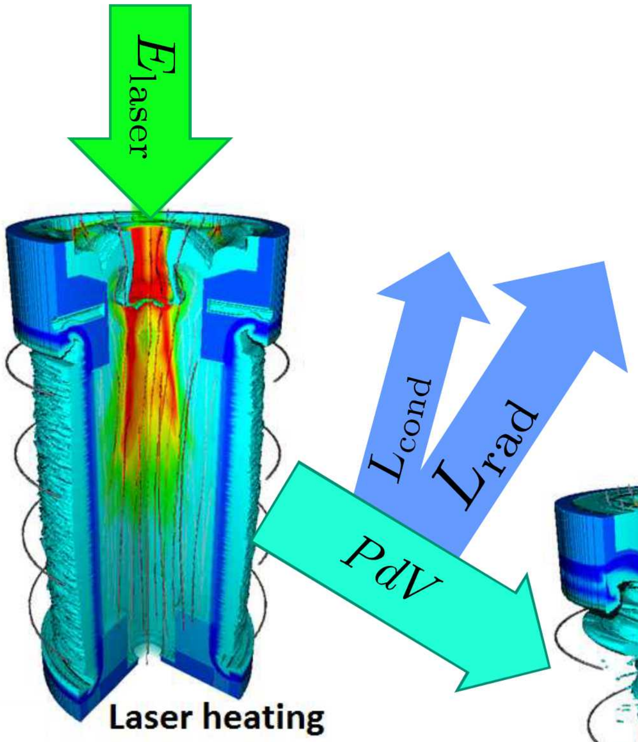
ICF research using magnetic direct drive is part of the mainline national program

Radiation-driven implosions	Laser-driven implosions	Magnetically-driven implosions
	 	 
NIF at LLNL	OMEGA laser at LLE	Z Facility at SNL

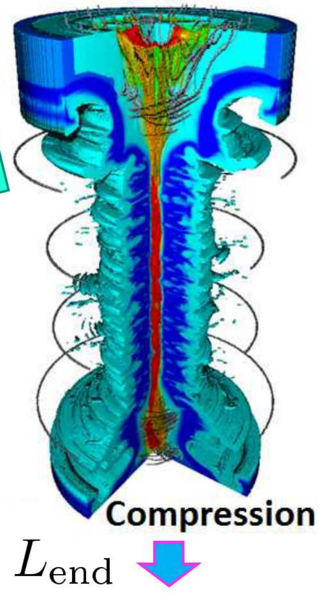
MagLIF uses preheat, magnetic insulation and adiabatic compression to achieve high pressure

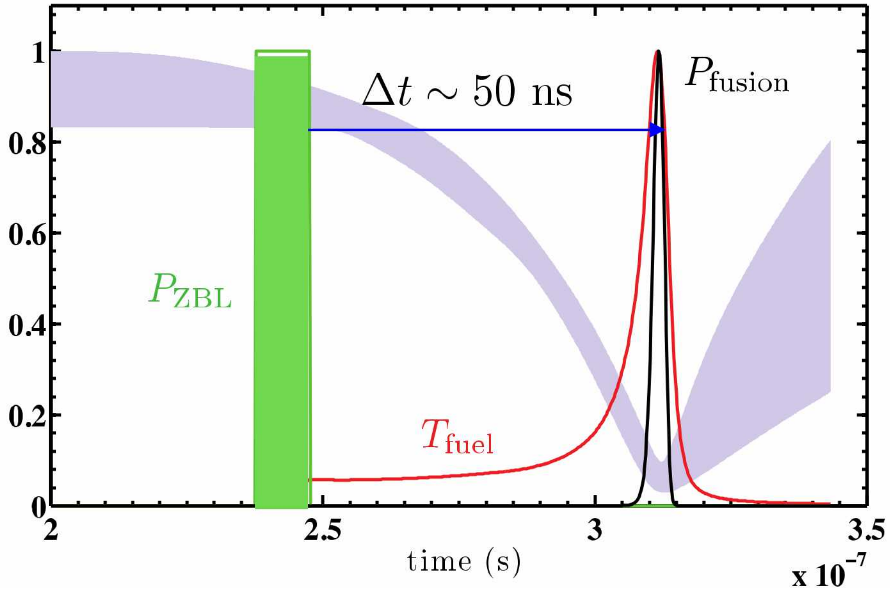


- D_2 gas ~ mg/cc
- 10-30 T, 3 ms risetime



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



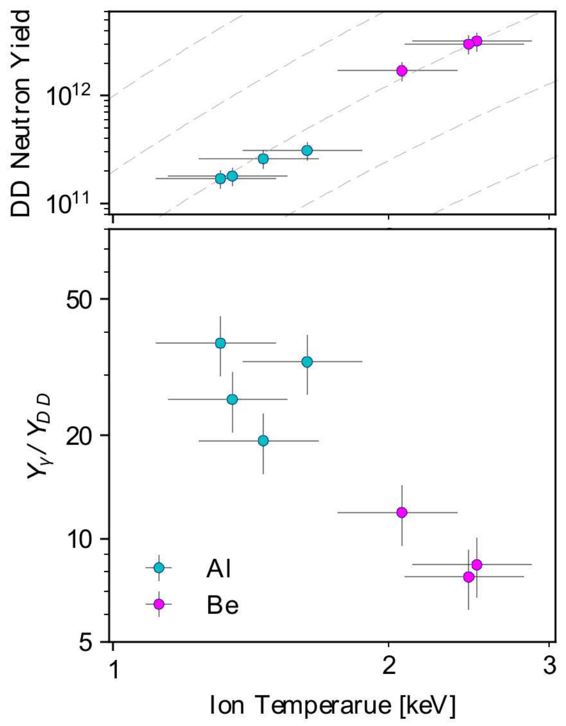


- Laser heating allows high pressures to be achieved with low implosion velocity (<100 km/s)
- Flux compression allows confinement of fusion products with low fuel ρR
- Calculations show MagLIF scales to high yield and gain

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

MagLIF experiments have successfully demonstrated key aspects of magneto-inertial fusion

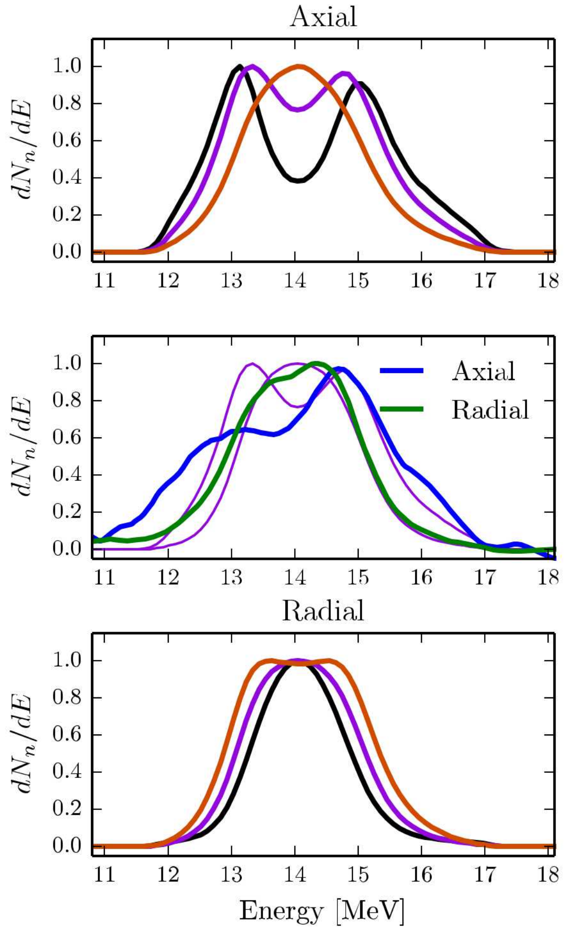
Thermonuclear neutron generation



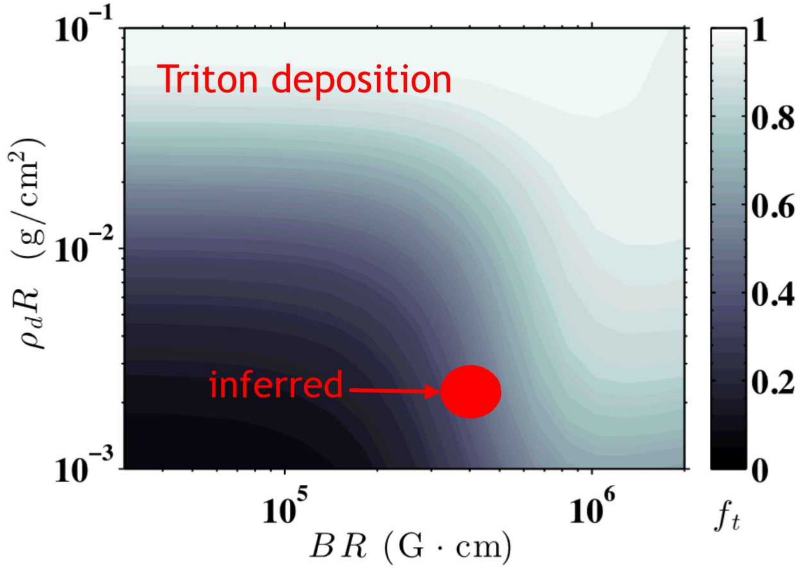
- Isotropic, Gaussian DD neutron spectra
- DD neutron yields = 1e13
- Ion temps = 2.5-3 keV
- Electron temps = 3.1 keV (from x-ray spectroscopy)

M.R. Gomez et al., Phys. Rev. Lett. **113**, 155003 (2014)

Magnetic flux compression



Confinement of fusion products



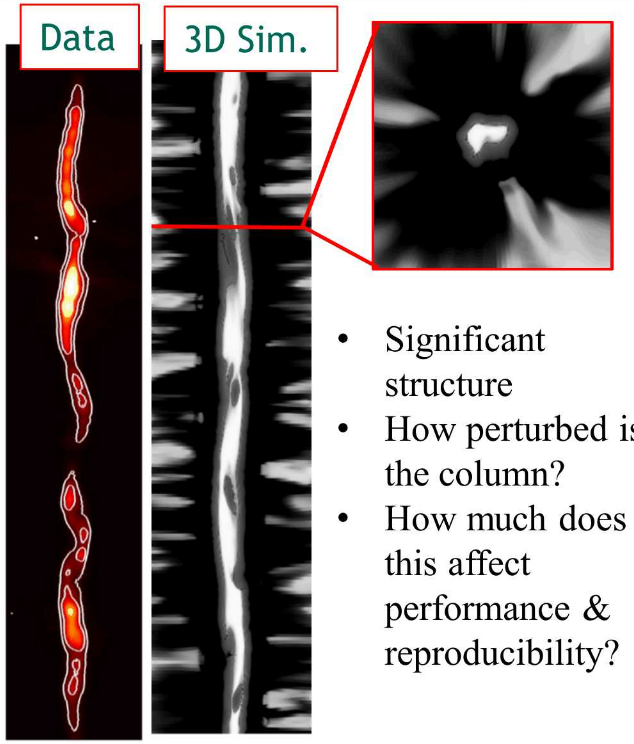
- BR = 0.25-0.35 MG*cm
- $R/R_{T,\alpha} \sim 1–2$
- Magnetized, trapped T's, α's!
- Important for scaling to ignition!

P.F. Knapp and P.F. Schmit et al., Phys. Plasmas, **22**, 056312 (2015)
P.F. Schmit and P.F. Knapp et al., PRL 113, 155004 (2014)

Despite promising early results, questions and concerns remain

Target performance is not as high as predicted, what are the primary causes and how do we mitigate them?

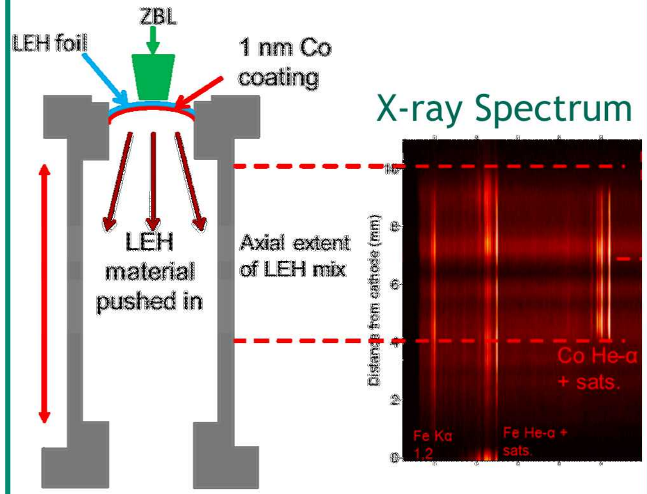
Implosion Stability



- Significant structure
- How perturbed is the column?
- How much does this affect performance & reproducibility?

Simulation courtesy C. Jennings

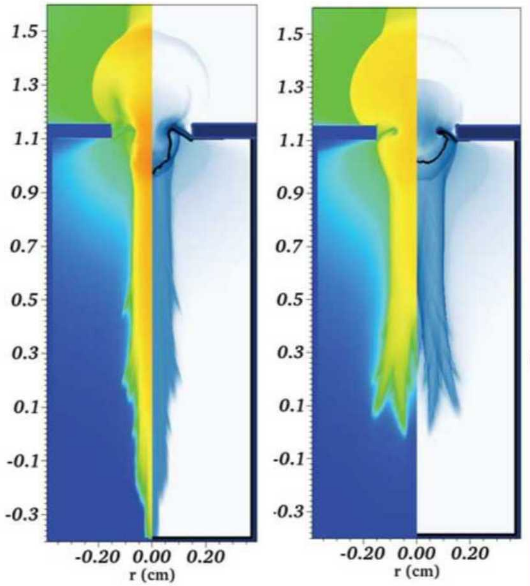
Mix



- Experiments show evidence of mix from multiple sources (liner/window)
- How bad is it?
- How do we mitigate mix?

Data courtesy A. Harvey-Thompson & E. Harding

Laser Energy Coupling

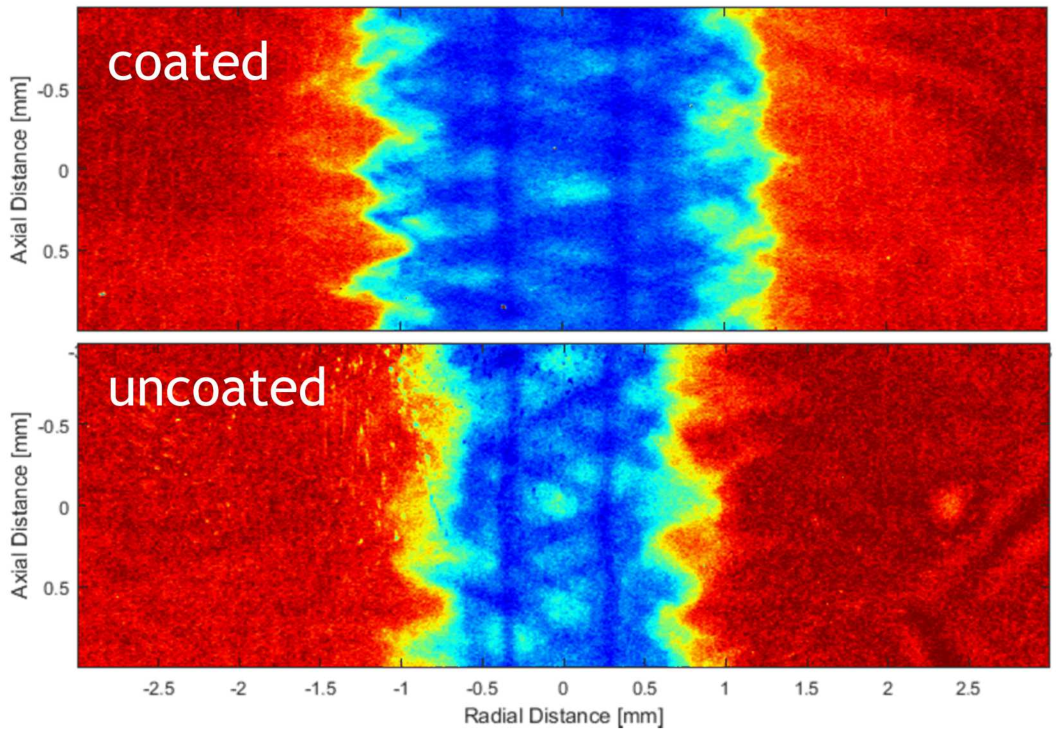


- How much energy?
- What is the optimum for good coupling w/ low mix
- How does performance scale w/ energy experimentally?

Simulations courtesy M. Weis

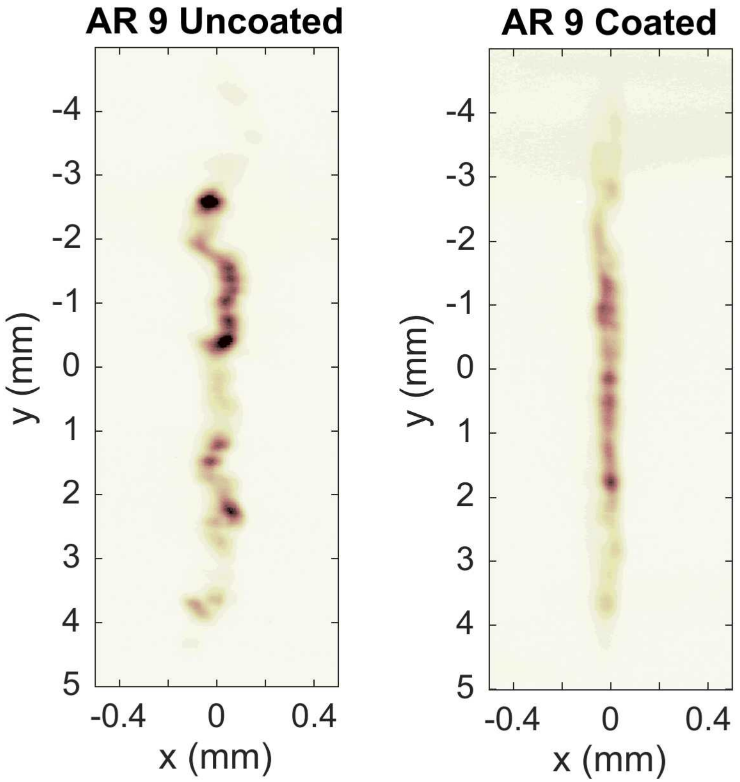
Adding a dielectric coating to the exterior of the liner appears to reduce instability amplitude and improve stagnation uniformity

Radiography



Data courtesy D. Ampleford and T. Awe

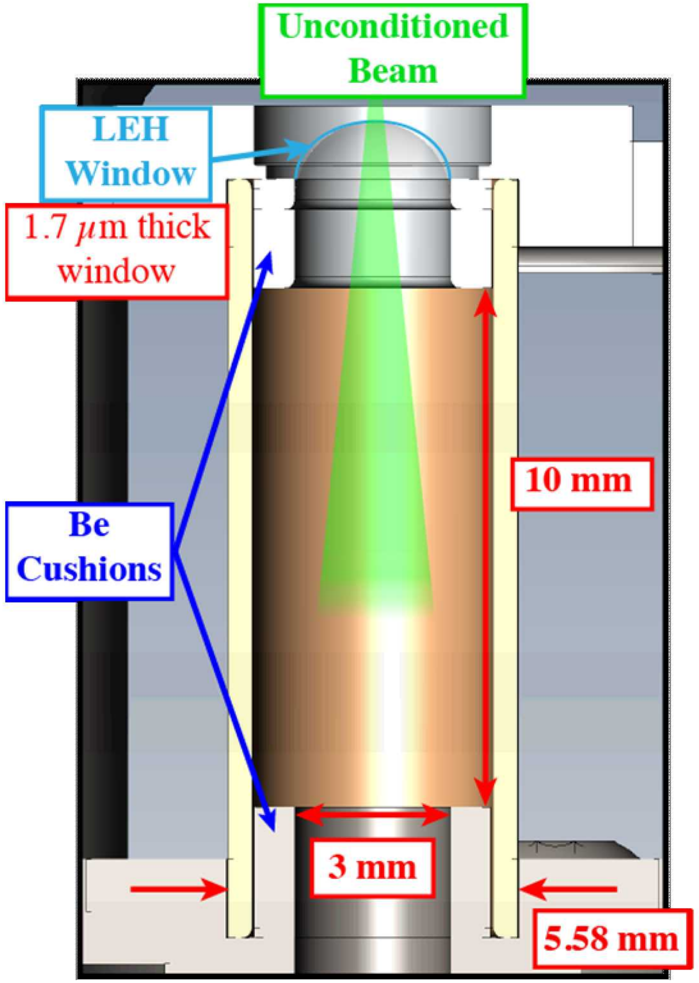
Self-Emission Imaging

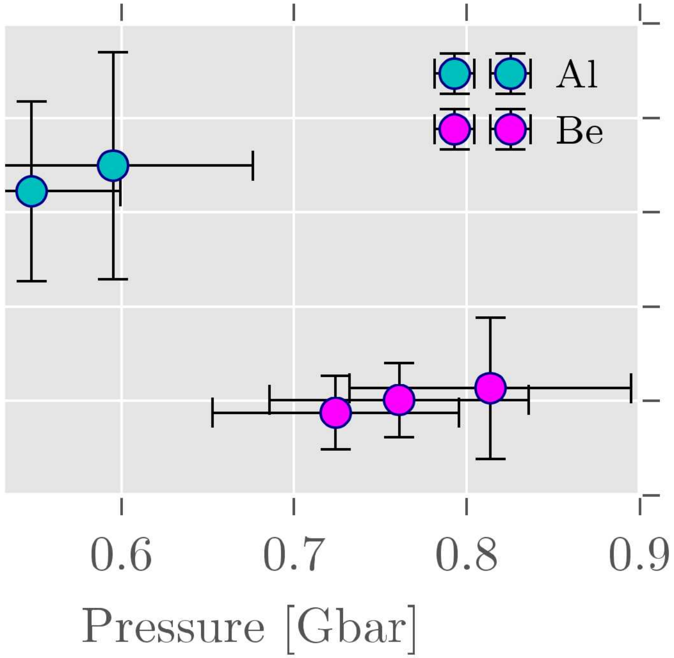


Data courtesy D. Ampleford and Eric Harding

- Radiographs of coated liners show reduced ρR perturbations and straighter inner wall, but mass is distributed to larger radius
- Stagnation images of coated targets are markedly straighter with less structure

When heating with an unconditioned beam, mix from plasma facing components is significant





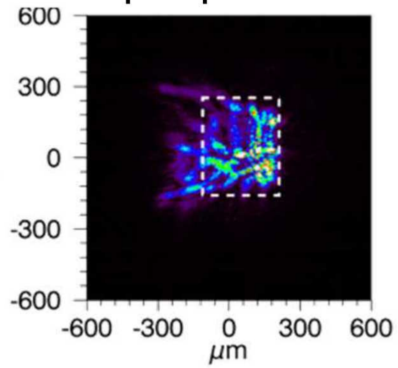
	Window	Cushion	Liner	E_{HS}
Al	0.5 %	0.5 %	2 %	7.7 kJ
Be	0.5 %	1.5 %	2 %	12 kJ

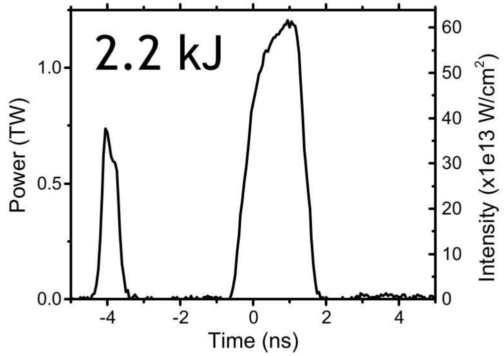
- Mix from the window is present
- Mix from the cushion is present and can have a significant impact on performance
  - Al cushion targets have ~40% lower T_i, 30% lower E_{HS}, and 10x lower yield
- Mix from the liner is present and is unlikely to be significantly affecting performance

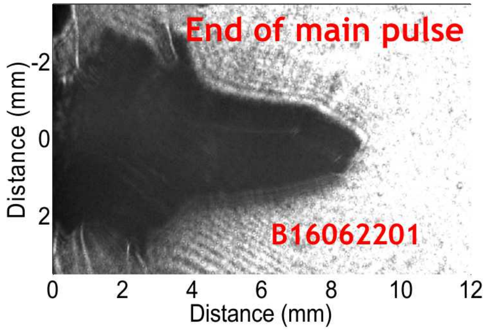
Dedicated 2ω laser heating experiments have lead to dramatic improvements in our ZBL protocols

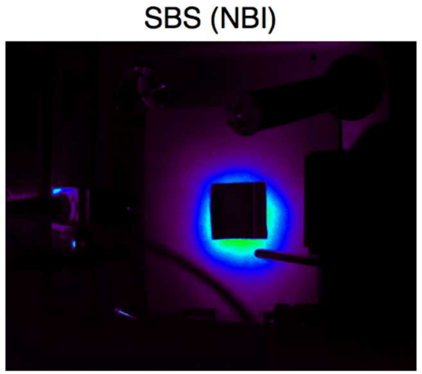
Spot profile | Laser power | Shadowgraphy imaging

Old protocol
No DPP
~ 2016



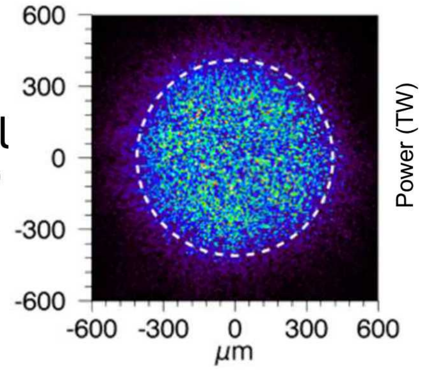


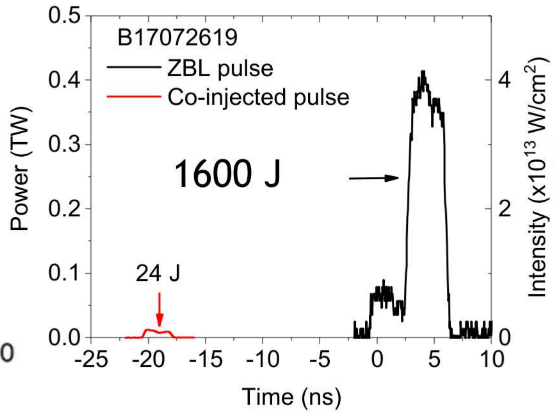


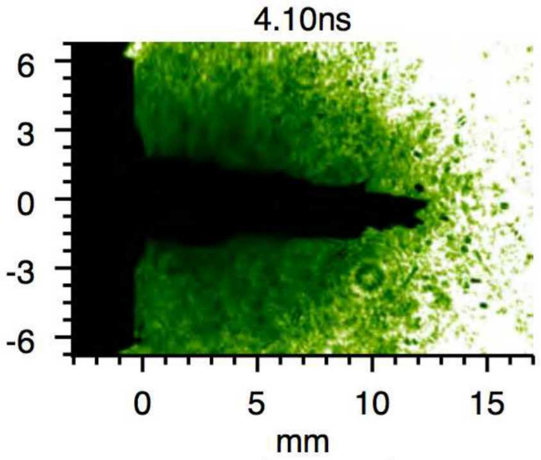


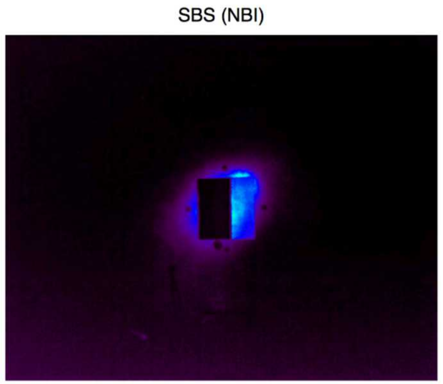
New diagnostics (multi-frame shadowgraphy, SBS, SRS diodes)
New capabilities (DPP smoothing, ZPW, D2)

New protocol
1100 μm DPP
~ 2018



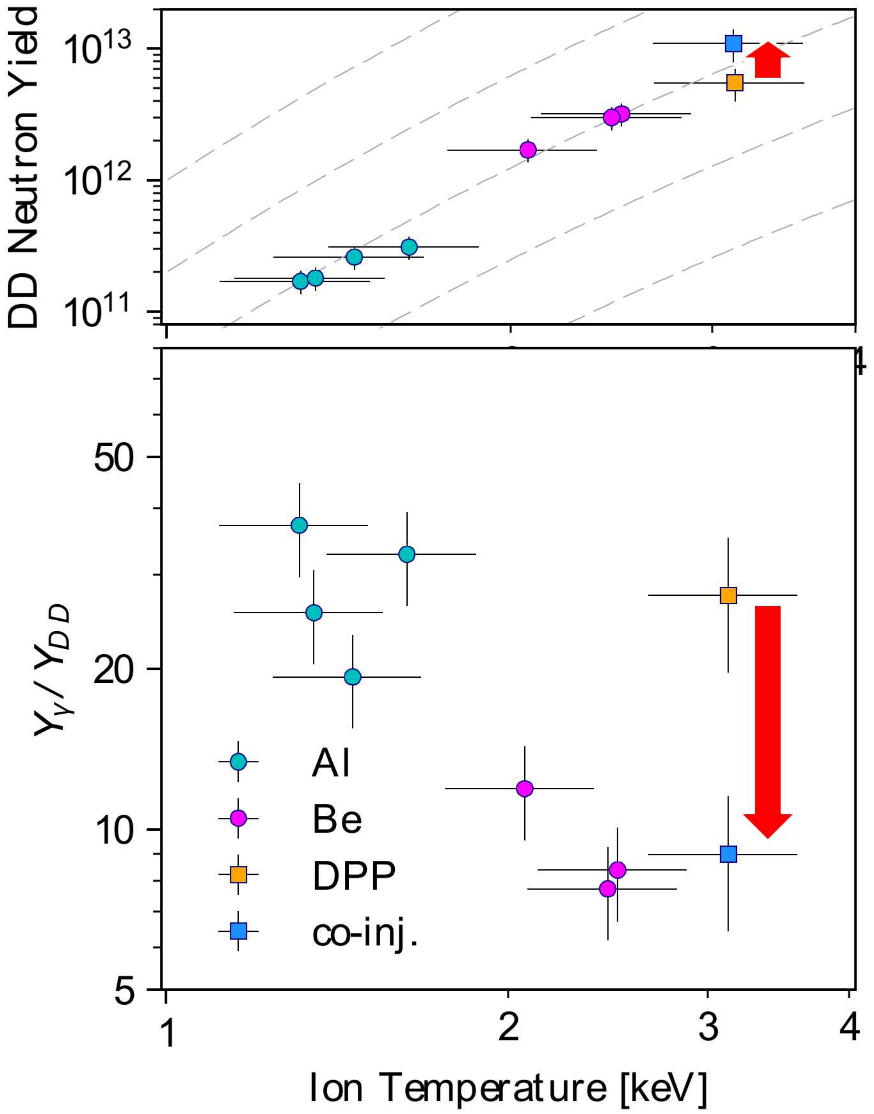






Backscatter is reduced by ~ an order of magnitude compared to the original unconditioned beam

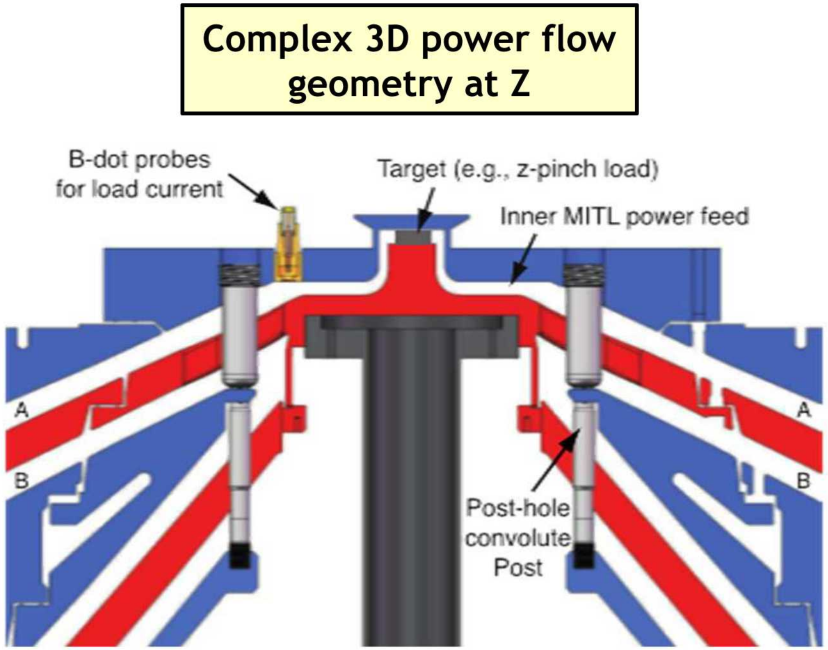
By combining several of these techniques, we have been able to substantially increase the peak neutron yield

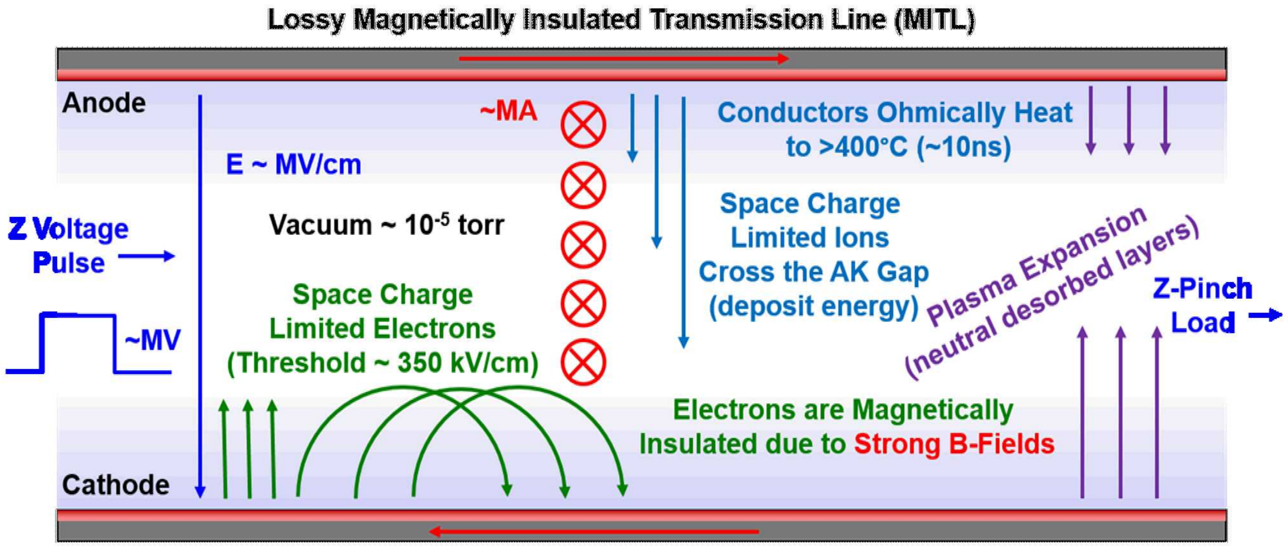


- Combining advanced laser heating protocols and dielectric coatings led to our highest performing experiment to date
  - 1.1×10^{13} DD neutrons, $T_i > 3$ keV (from nTOF)
  - Experiments designed and executed by A.J. Harvey-Thompson, M.R. Weis, & M. Geissel
- 3x Reduction in mix signature and 2x increase in yield going from DPP beam conditioning to co-injection + DPP beam conditioning

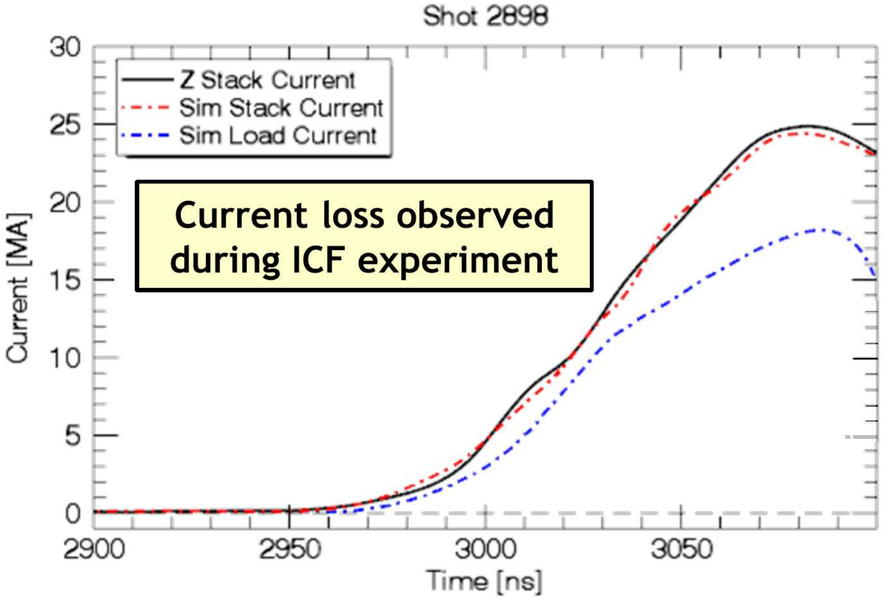
Power Flow Physics

Current loss can limit energy delivery to a variety of HED experiments at the Sandia Z Facility





- Targets designed for various HED programs (fusion research, radiation sources, materials experiments, pulse shaped loads) have different impedance parameters
- Low-inductance targets typically perform optimally at the Z Facility (e.g. DH wire arrays)
- Non-ideal current delivery could be caused by a variety of physics processes which are not fully understood at the predictive level

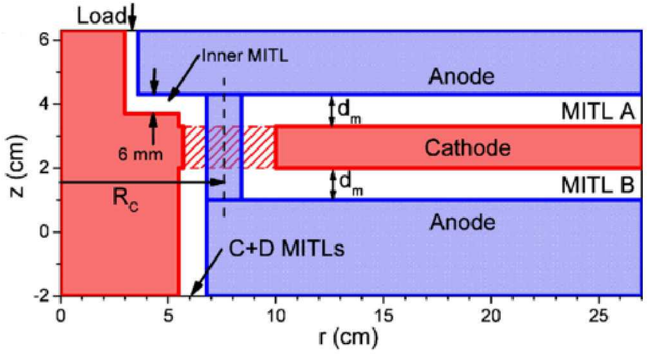


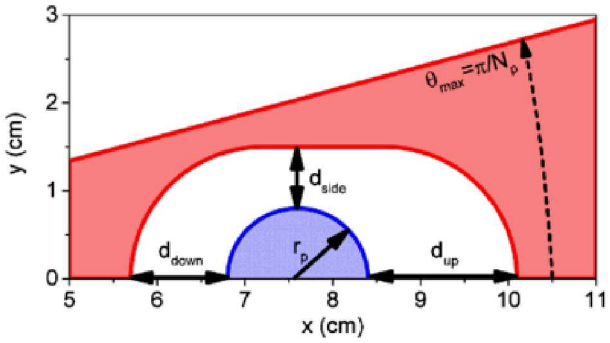
material provided by George Laity

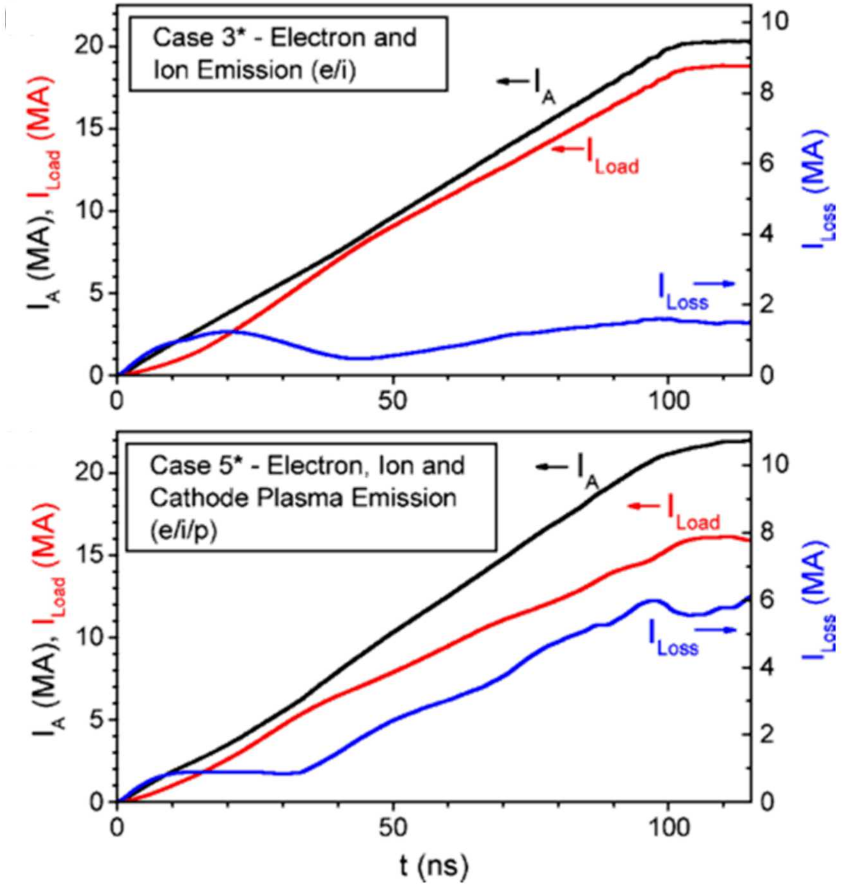
Modeling Challenges Exist for Advancing the Physics Understanding of Current Loss on Z

It is difficult to model (requires modeling large volume kinetic effects) the actual Z convolute geometry, therefore simple MITL geometries are used to understand scaling relationships and phenomenological physics:

- Space Charge Limited Electron Emission from Cathode Surfaces (>240kV/cm)
- Space Charge Limited Ion Emission from Anode Surfaces
- Neutral Desorption / Plasma Formation near Electrode Surfaces (>400°C)
- Negative Ion Emission / Generation in Anode-Cathode Gaps
- Magnetic Nulls in Convolute Geometries

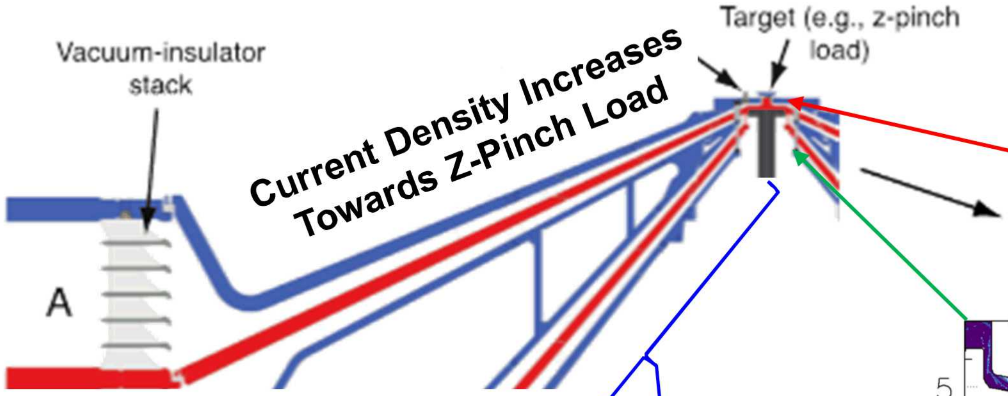




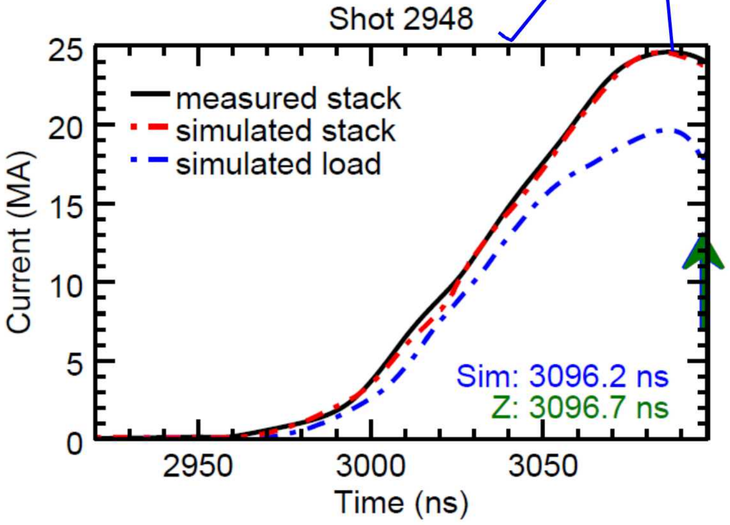


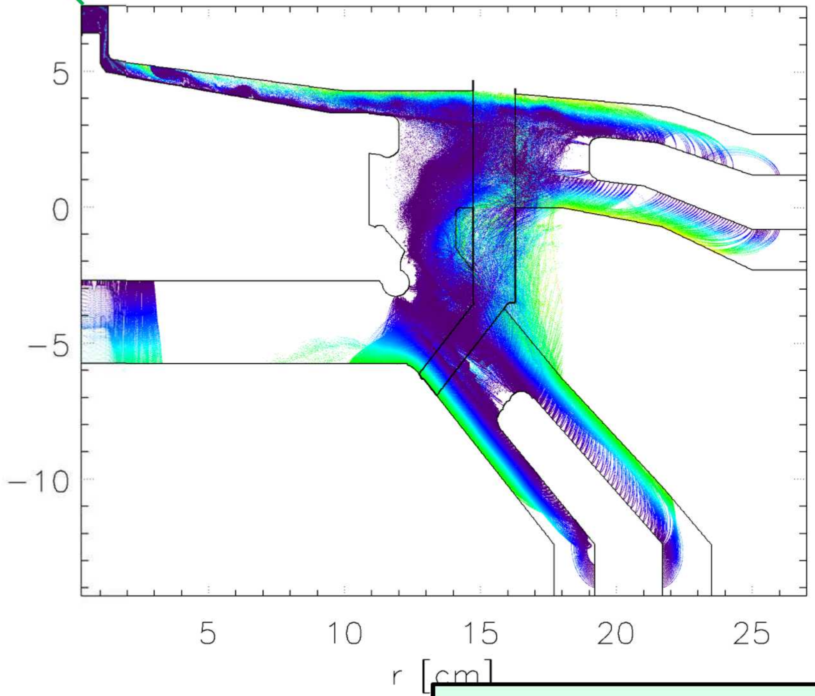
D. Rose et al., *Phys. Rev. ST Accel. Beams*, Vol. 18, 030402, (2015).

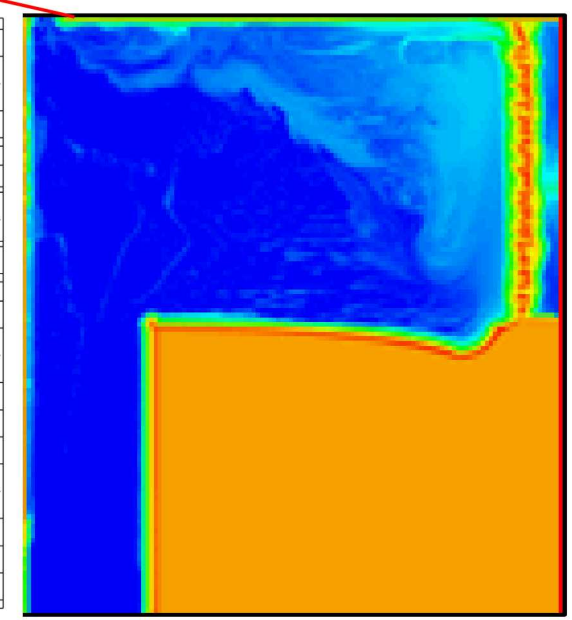
Sandia has multiple ongoing investments to rapidly improve understanding of power flow physics models



Matthew Martin (1641), C. Jennings (1684), et al.
Extended-MHD, Low-Density Plasma Effects
(Supported by FY18-20 REHEDS-LDRD)



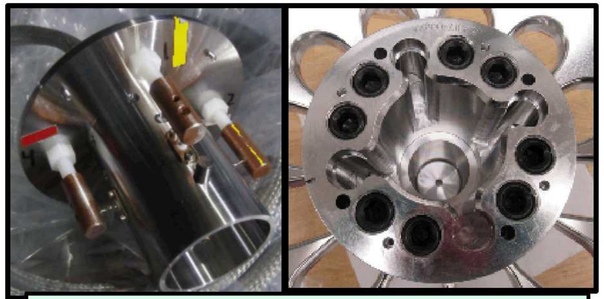




Brian Hutsel (1651), et al. *Semi-Analytical Transmission Line Models (Supported by FY16-18 REHEDS-LDRD, Published in Phys. Rev. Accel. Beams, 2018)*

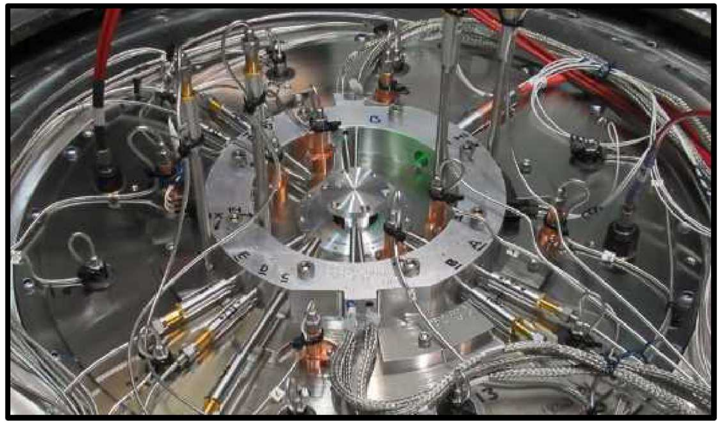
Nichelle Bennett (1684), David Rose (Voss), et al.
Improved Hybrid Kinetic-Fluid Models
(Supported by FY18-20 Grand Challenge LDRD)

Sandia is supporting rapid diagnostic development for experimental power flow validation

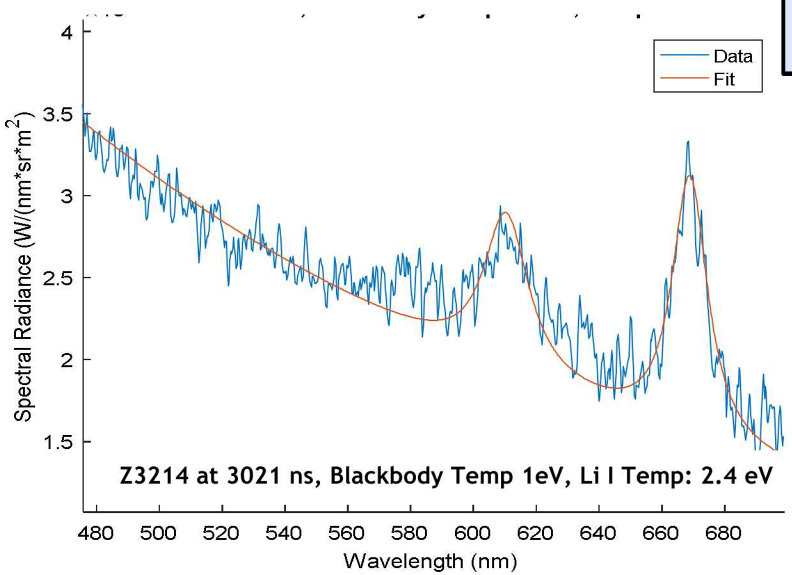


Tim Webb (1656), et al.
Cathode Ion Detectors on Z

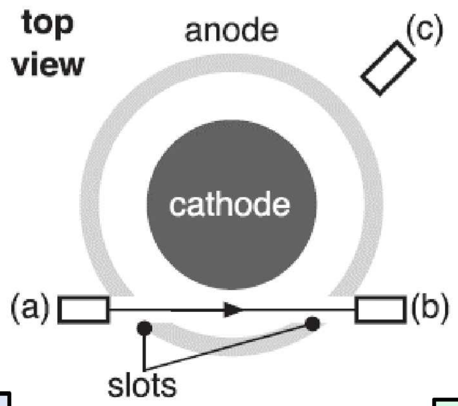
Derek Lamppa (5445), et al.
Mini Magnetic Ion Spectrometer

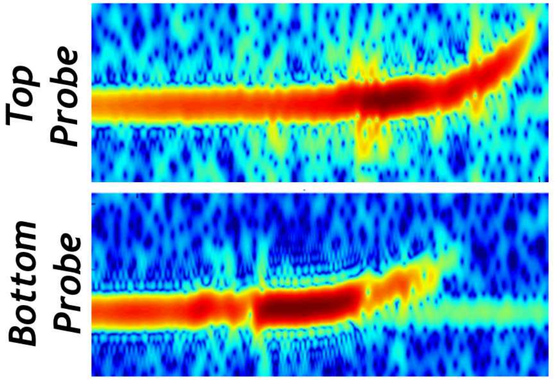


George Laity (1683), et al. *Dedicated Z Power Flow Experiments (80+ Measurements each, 12+ new diagnostics over the past 18 months)*



Sonal Patel (1656), Mark Johnston (1656), et al.
Higher Resolution Li Spectroscopy in Z Convolut
(Supported by FY15-17 REHEDS-LDRD)

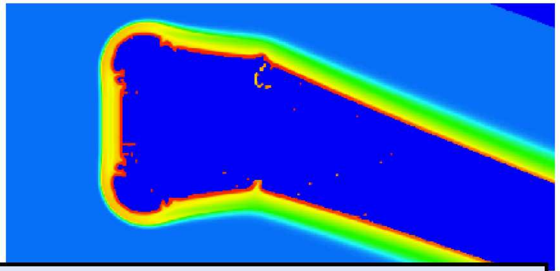




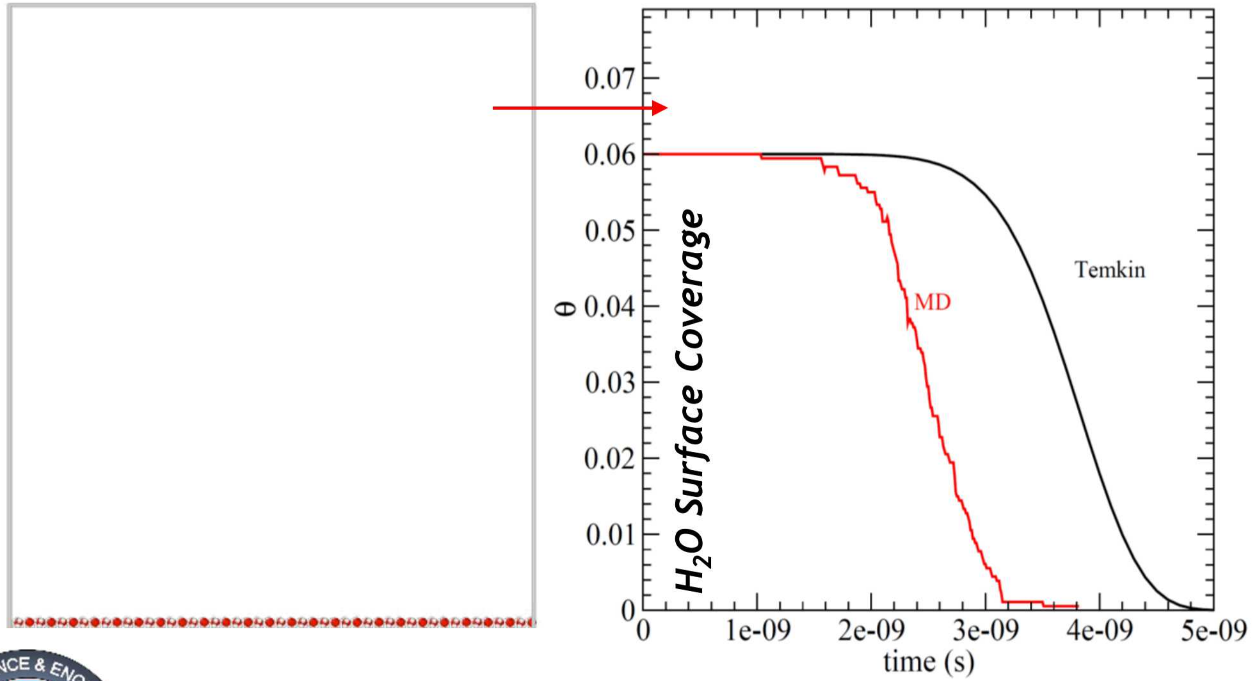
Dan Dolan (1646), A. Porwitzky (1641), et al.
Chordal PDV – Plasma Density Interferometer
(Published in Journal of Applied Physics, 2018)

The PLASMA GC LDRD is making rapid progress in new science-based models for vacuum power flow

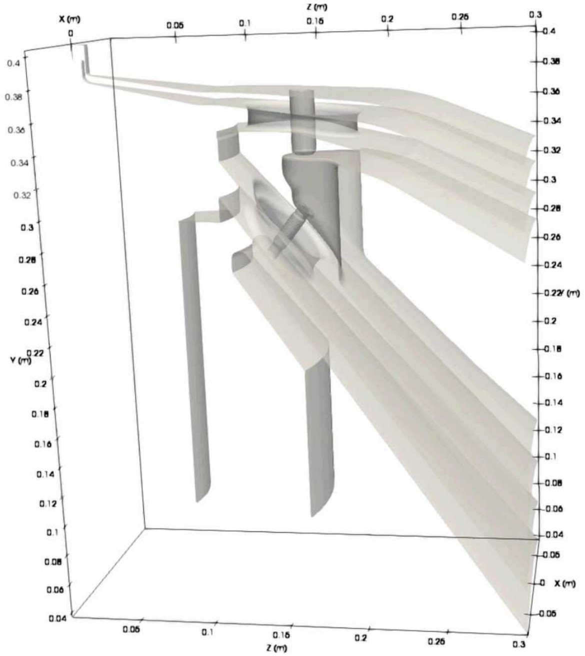
We are investing in Foundational S&T for:
- ✓ *Computational Plasma Physics Models*
- ✓ *3D Hybrid Kinetic-Fluid Simulation Methods*
- ✓ *Improvements in Algorithm Efficiency/Speed*
- ✓ *Models of Real Electrode Surfaces in the Lab*



Kyle Cochrane (1641), et al.
ALEGRA Surface Heating on Z-Next



Matthew Lane (1864), Kevin Leung (1864), et al.
MD Simulations of H_2O Desorption under Rapid Heating



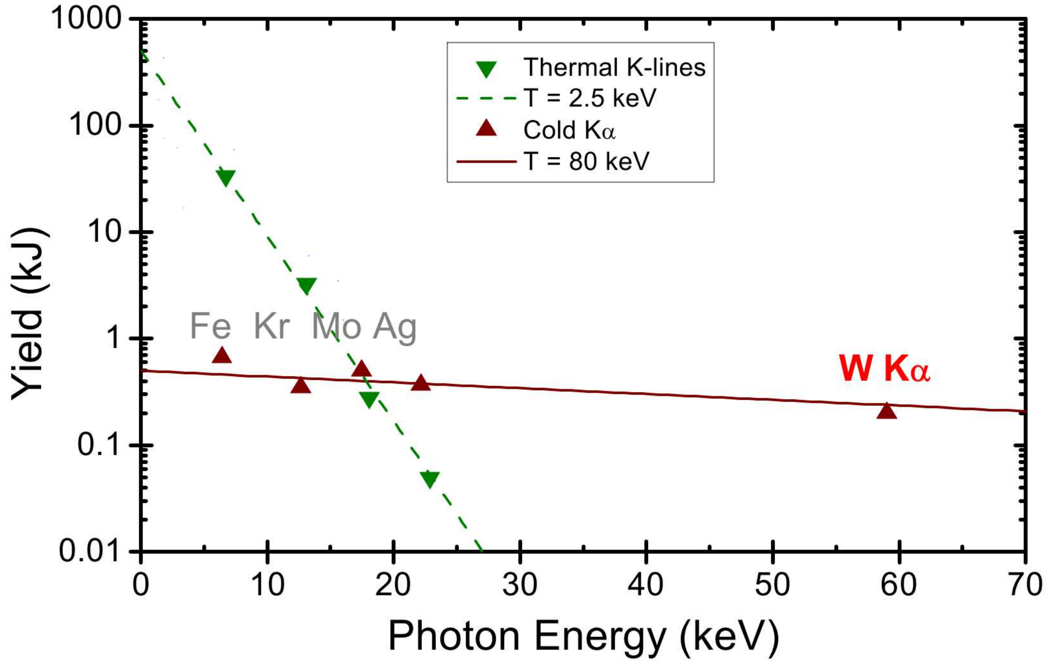
Andrew Fierro (1878), et al.
3D PIC Simulations of Z Convolute

Non-thermal X-ray and Neutron Sources

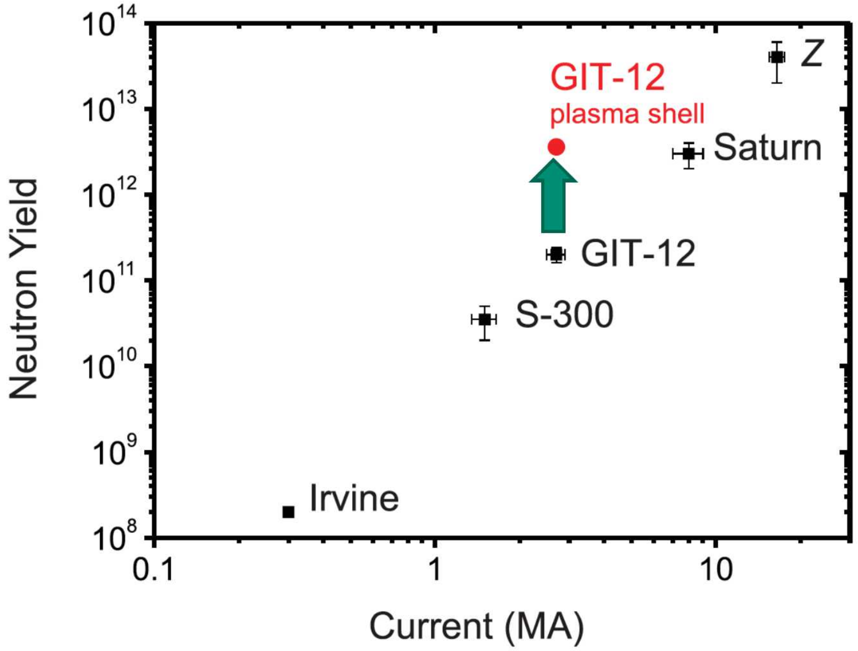
Driven by the RES mission need, we are exploring ways to enhance neutron and high energy photon yields with non-thermal populations

Z-pinches can effectively produce large E fields, driving non-thermal ion and electron populations

Optimizing Wire arrays for Kα emission*



Optimizing D2 Gas Puff @ 3 MA**



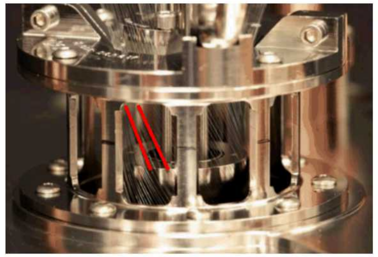
These efforts are largely (though not entirely) empirical because modeling is extremely difficult

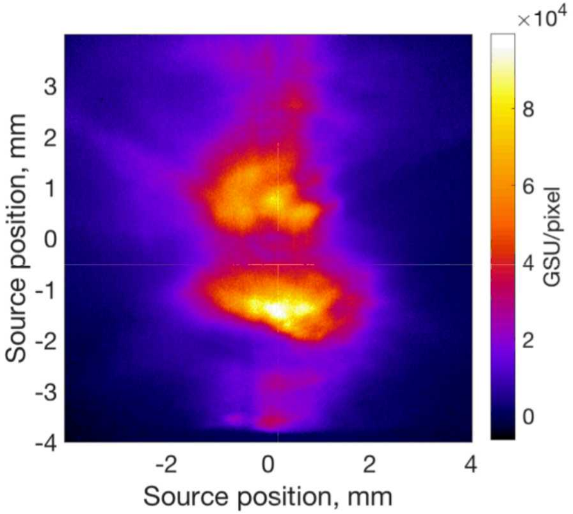
*D Ampleford et al. ICOPS 2016

**D Klir et al 2015 Plasma Phys. Control. Fusion 57

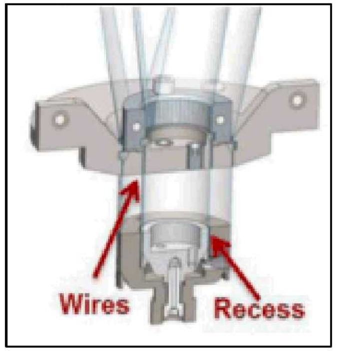
We are developing arrays to enhance Kα yield along with new diagnostics to improve our understanding

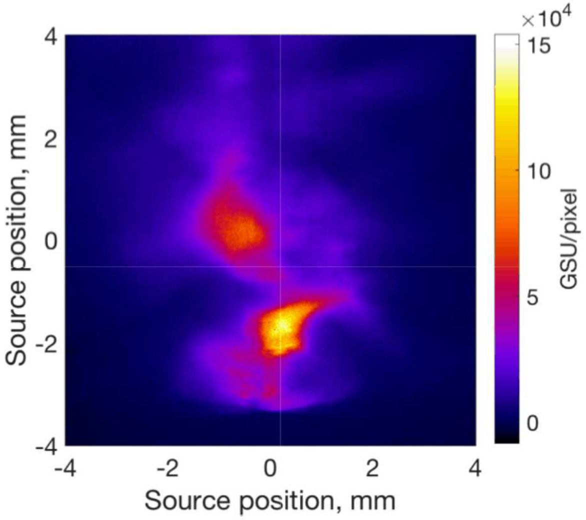
Twisted wire array





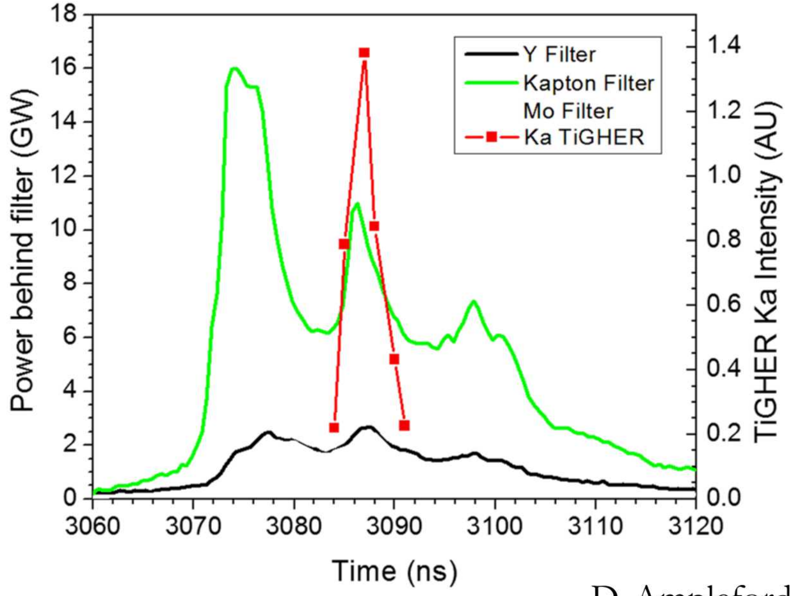
Straight wire array

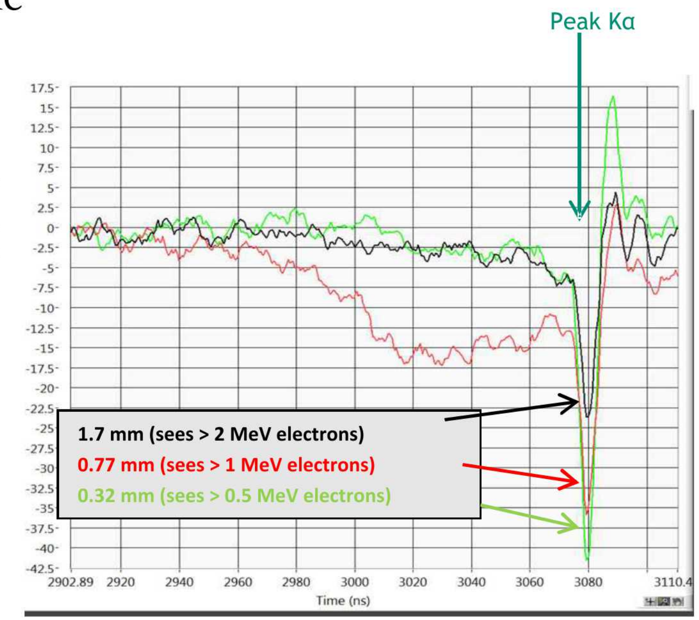




J. Fein et al., HTPD 2018

Mo Kα emission history corresponds well to electron beam history recorded using a faraday cup diagnostic

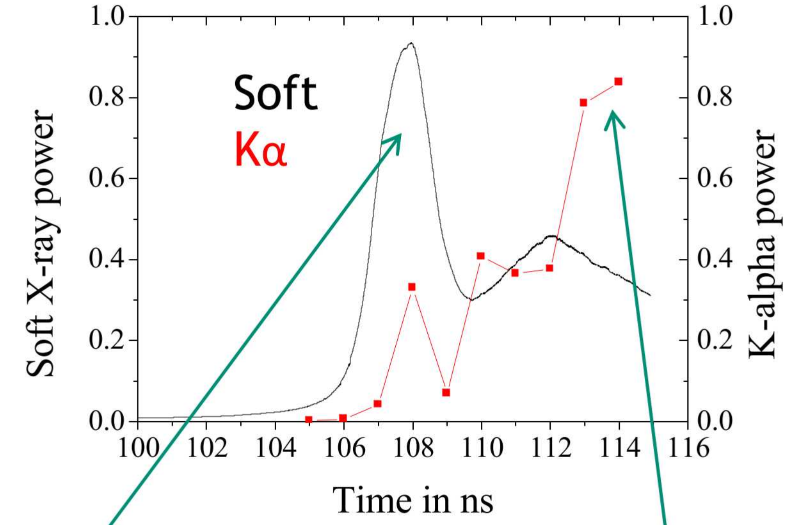


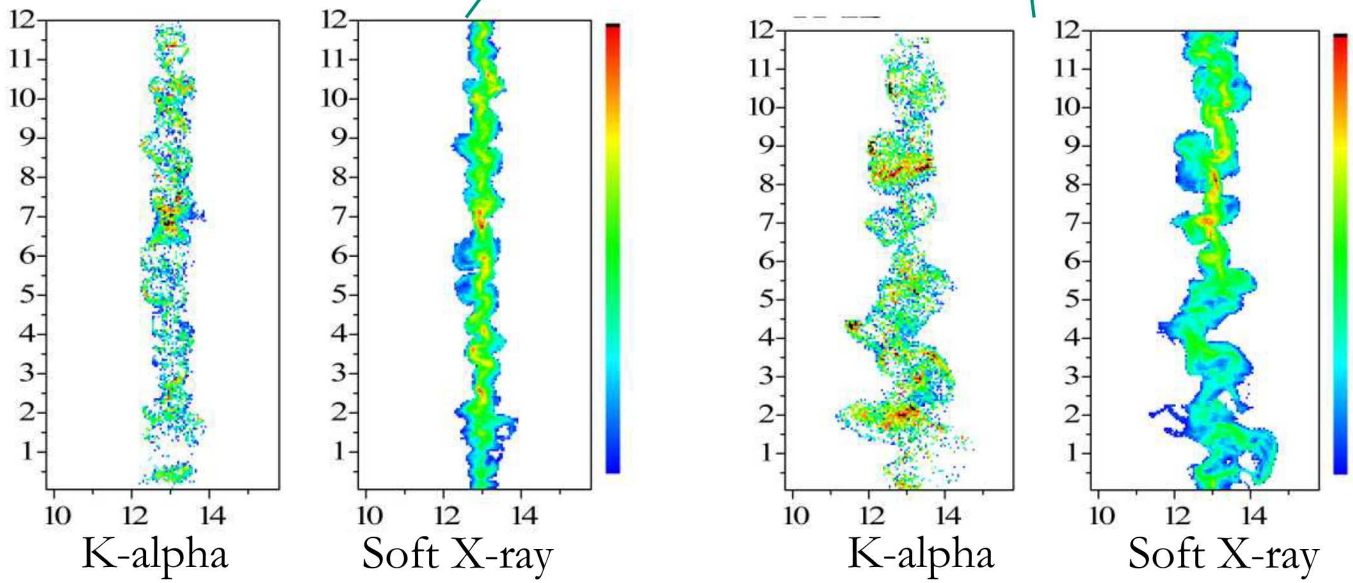


D. Ampleford et al. ICOPS 2016

- New wire array designs are being tested to enhance non-thermal x-ray yield
- A Wolter optic was developed and successfully fielded to image Mo Kα yield

Predictions of Kα emission from runaway electrons show peak after soft x-ray emission

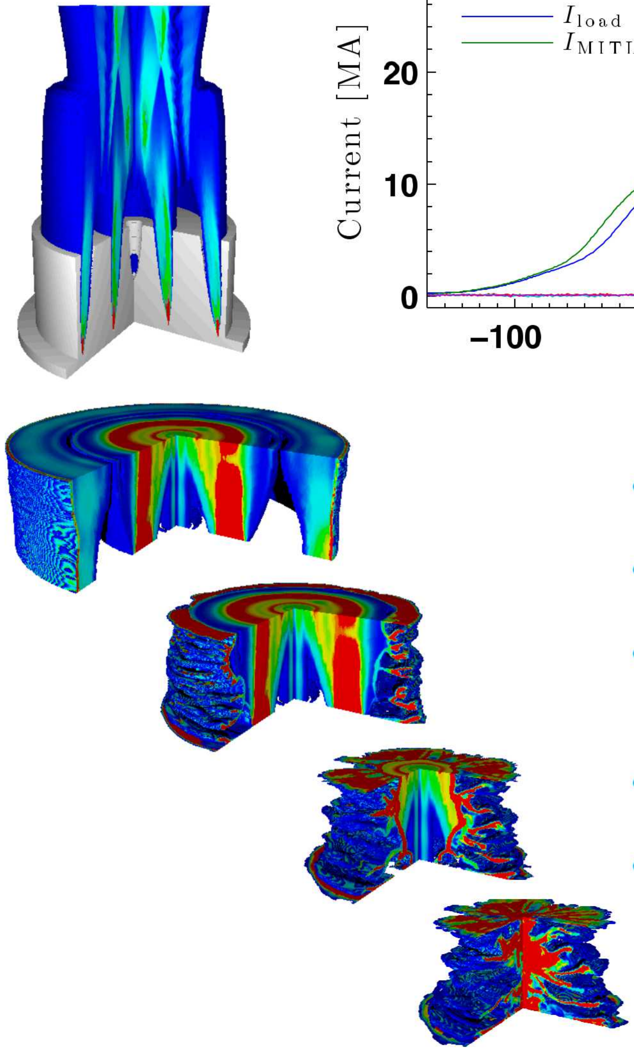




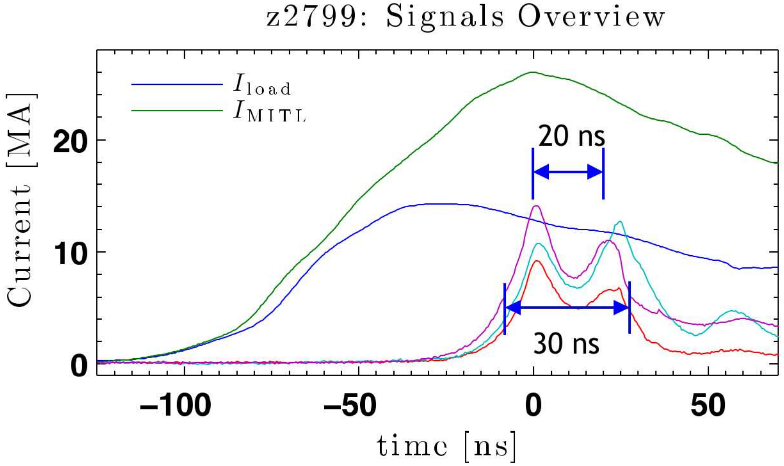
- Gorgon MHD run in tandem with 3D EM PiC code Melinda
- Electron runaway condition based on when $\underline{E} \cdot \underline{B} / |B|$ exceeds the Dreicer field
- Fast electron trajectories are tracked in evolving E and B fields predicted by MHD model
- Kα prediction based on
  - $n_{fast} \, v_{fast} \, n_i \, \sigma \, E_{k\text{-alpha}}$

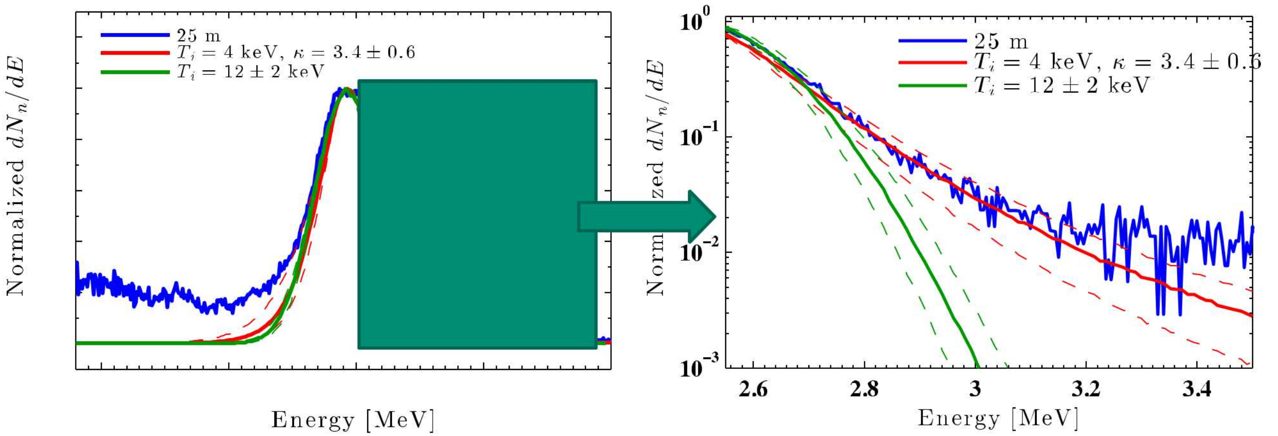
Simulations courtesy J. Chittenden, Imperial College of London

The D_2 gas puff is a bright, quasi-thermal neutron source



Calculation courtesy C. Jennings





- Spectroscopically inferred implosion velocity of 500-700 km/s
- Yields >3x10^{13}, with a long burn duration
- Cannot fit neutron spectrum with a Maxwellian plasma model, obtain reasonable fits using the Kappa distribution
- Source duration effects can impact spectrum, even at 25 m
- High energy tail contains important information, but noisy

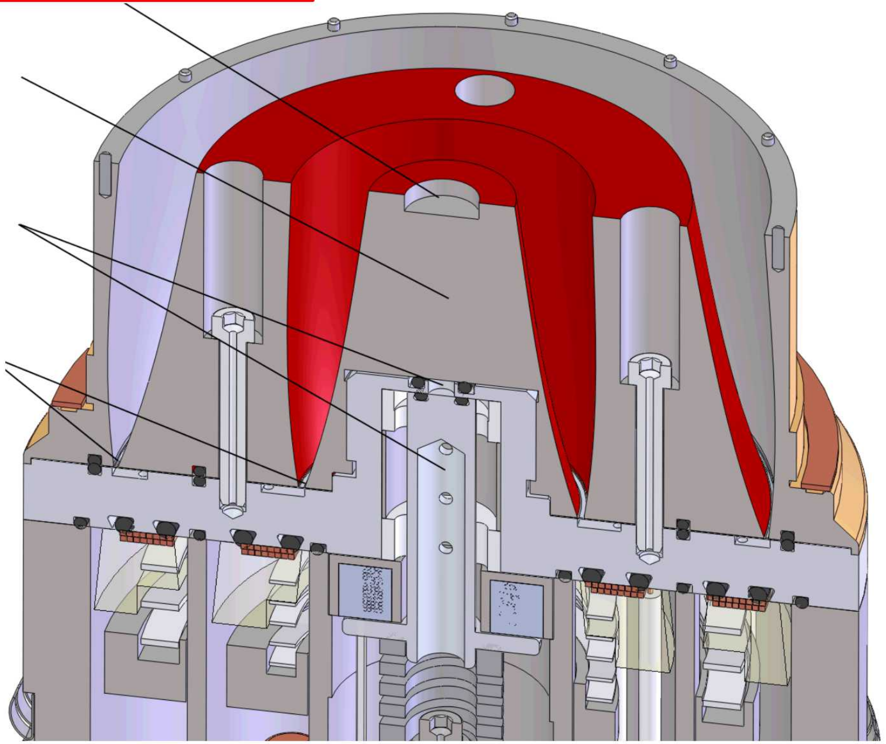
Need burn history to understand neutron spectrum more fully

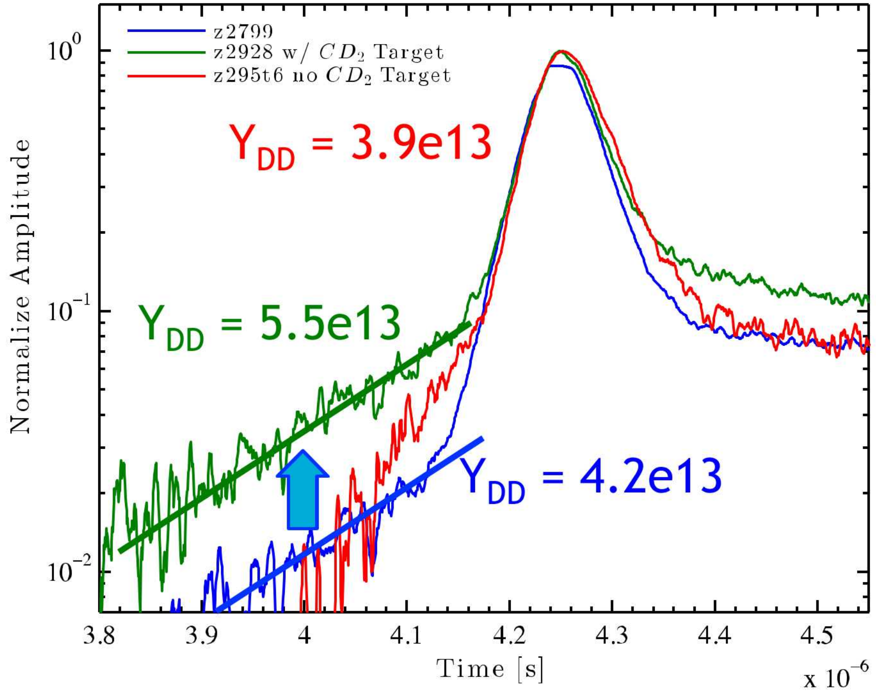
$$f_\kappa(v) = \frac{A_\kappa}{2\pi v_T^3}\left(1 + \frac{v^2}{(2\kappa - 3)v_T^2}\right)^{-(\kappa+1)}$$

$$A_\kappa = \frac{(2\kappa-3)^{-3/2}\Gamma(\kappa+1)}{\Gamma(\kappa-1/2)\Gamma(3/2)} \quad v_T = \sqrt{\frac{k_b T}{m}}$$

Putting a deuterated plastic target on the cathode increases the neutron yield and the high energy neutron population

On-axis CD_2 target location

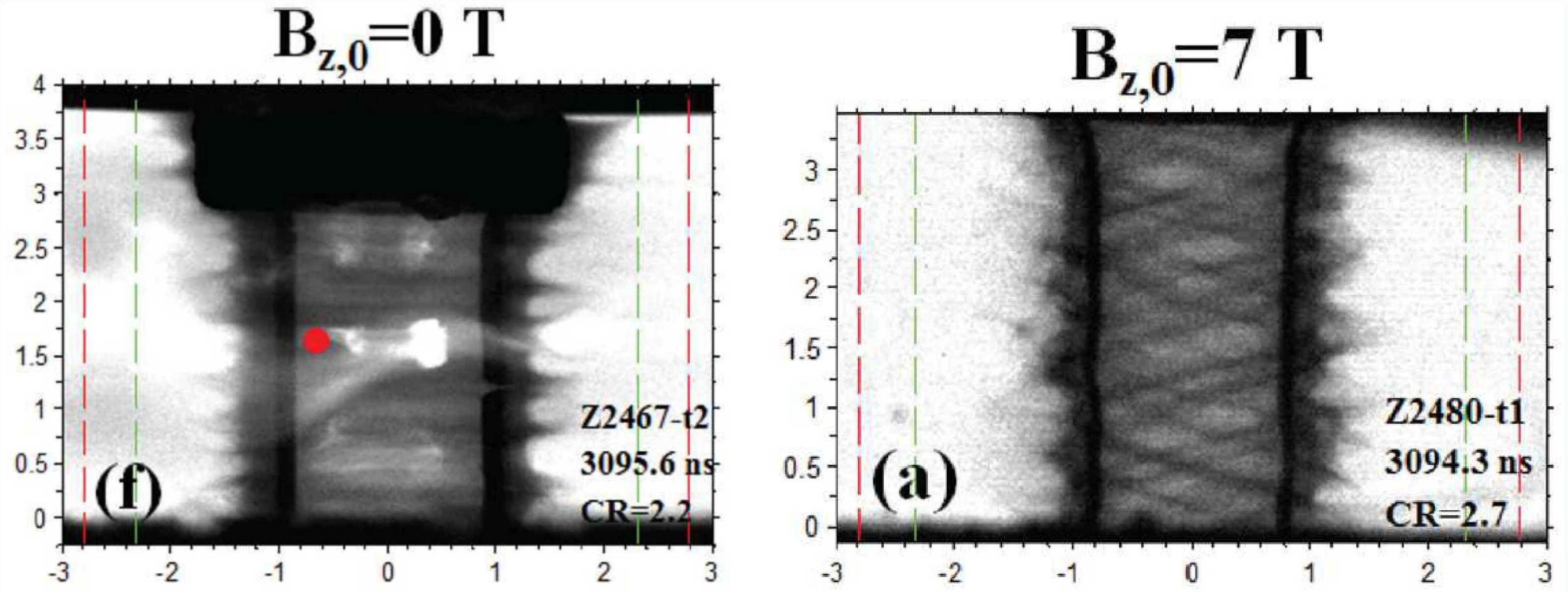




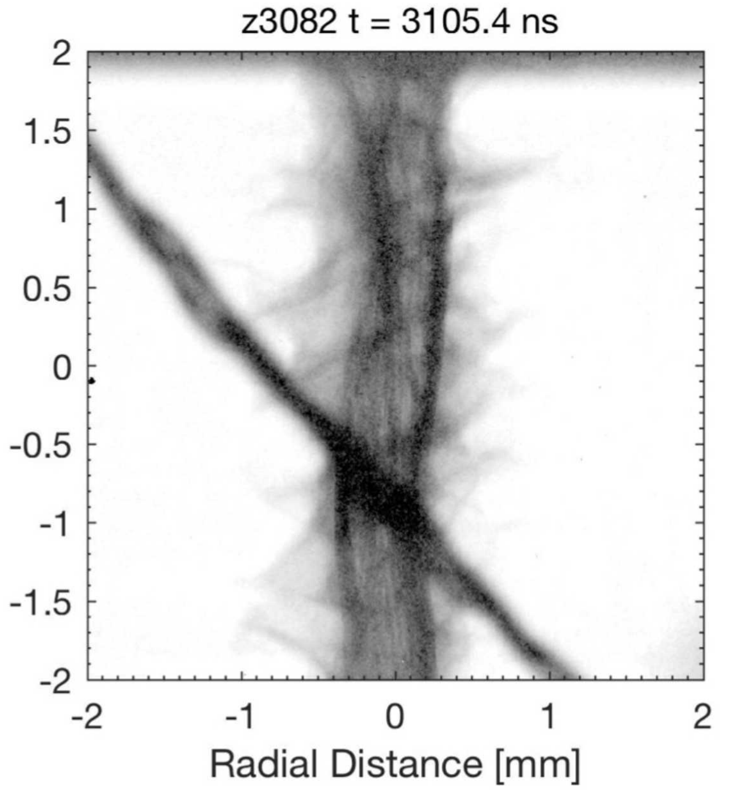
- CD_2 target in cathode provides a dense deuterium target for high energy deuterons to interact with
- If "beam" population is significant, expect large increase in neutron yield
- Observed a ~30% increase in yield
- Also observed increase in high energy neutron population w/ CD_2 target

Hall Physics and the Helical MRT mode

The presence of an initial axial field dramatically modifies the MRT structure



*T.J. Awe et al, Physics of Plasmas **21** , 056303 (2014)

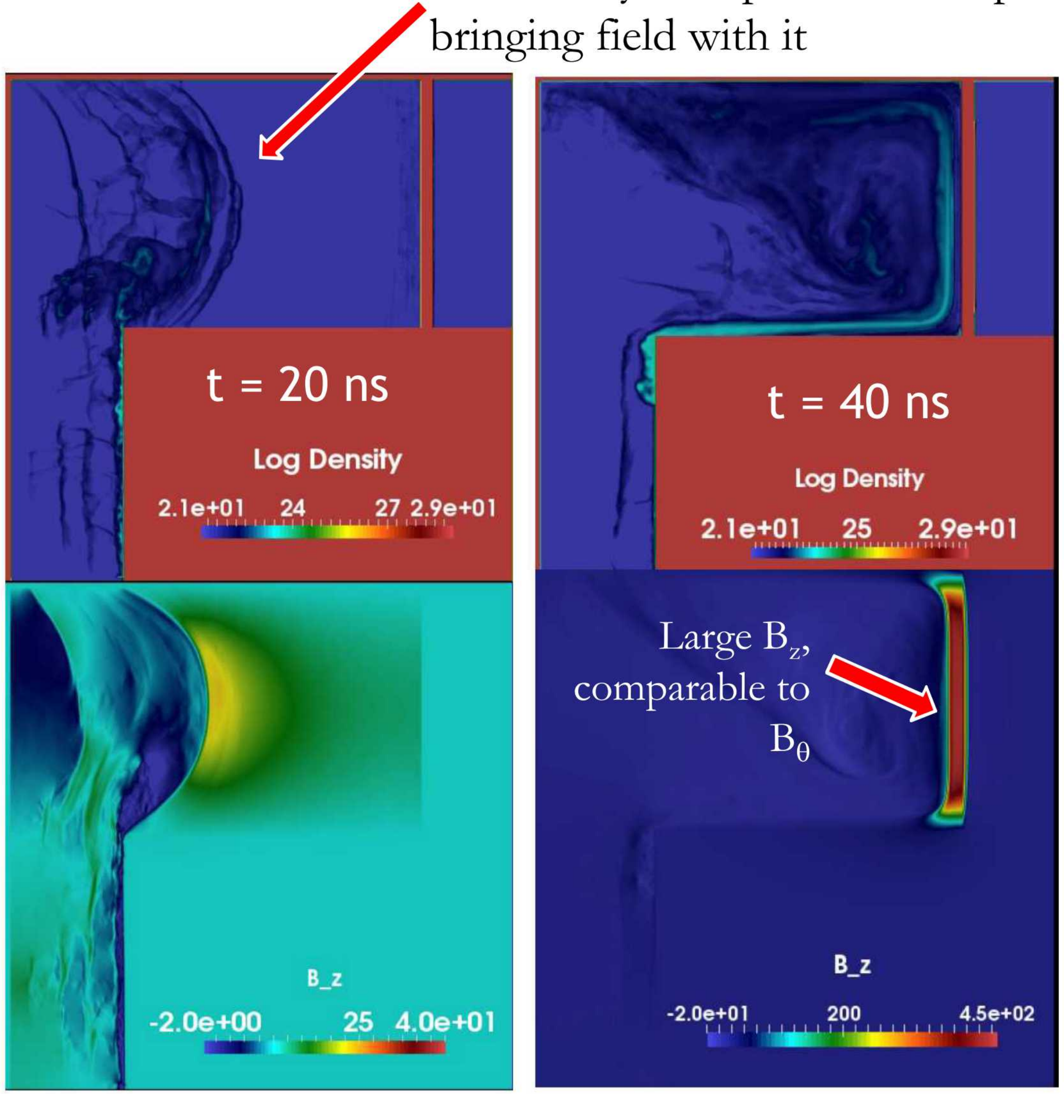


$B_{z,0} = 7$ T

- Radiographic studies of unmagnetized liner implosions show an m=0 structure
- Magnetized liner implosions reveal a surprising helical instability mode, m >> 1
- Pitch angle of 16 degrees (at CR=2.7), increases w/ CR and $B_{z,0}$
- k ⊥ **B** is the most unstable mode, but the pitch angle is too large given the ratio $B_{z,0}/B_\theta$
- Also observe large scale helical mode form during deceleration phase
- How and when is this mode seeded

Hall physics allows mass to permeate the feed gap and compress axial field to large initial amplitudes

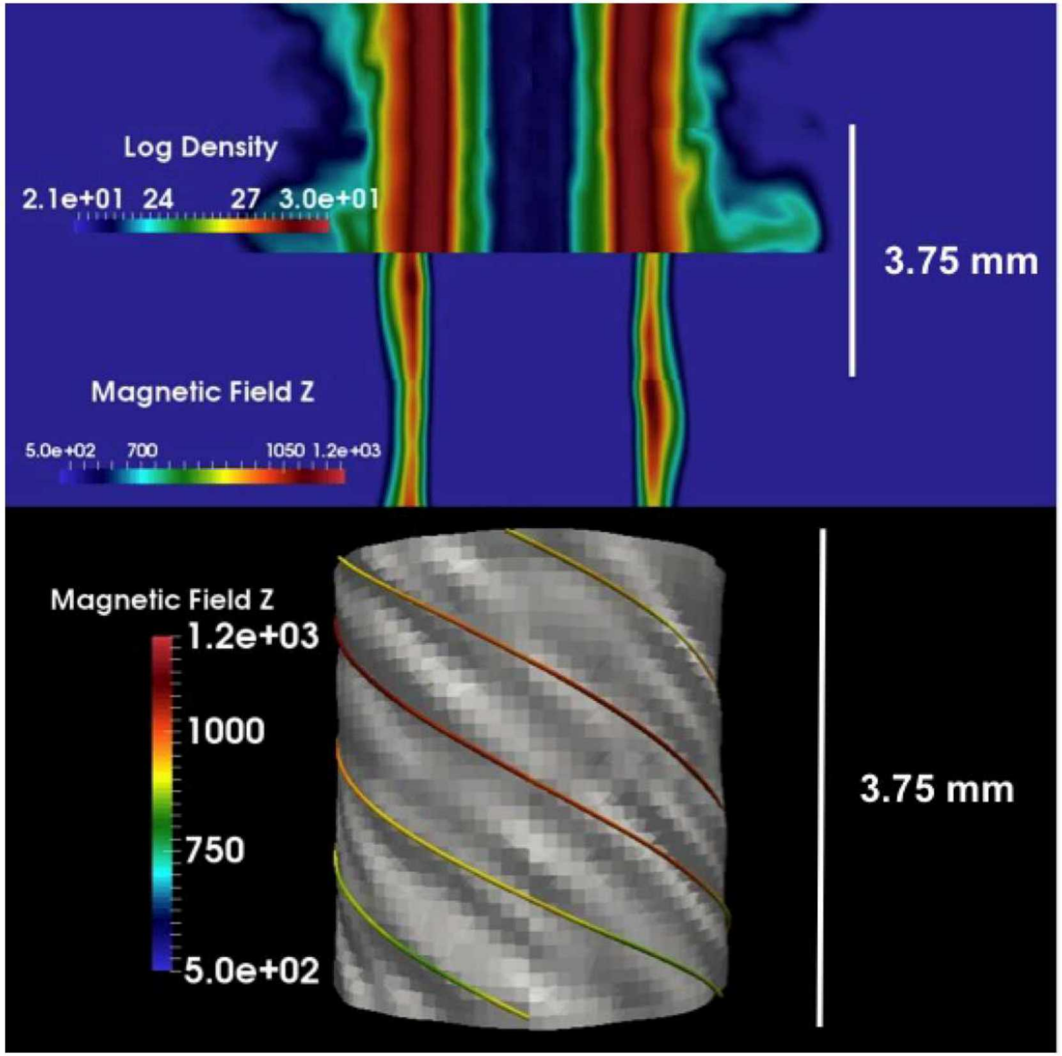
low density feed plasma is swept in, bringing field with it



- Incorporating the Hall term in the GOL allows low density plasma to carry current in a physical way
- Leads to compression of background plasma with entrained Bz
- Enhanced axial field on surface of liner allows helical force-free currents to form
- Resistive MHD with typical method of handling vacuum-plasma interface won't do this effectively, or at all

C.E. Seyler, M.R. Martin, N.D. Hamlin, **Helical Instability in MagLIF Due to Axial Flux Compression Low-Density Plasma**, Under Review

Field aligned perturbations grow to macroscopic scale late in time

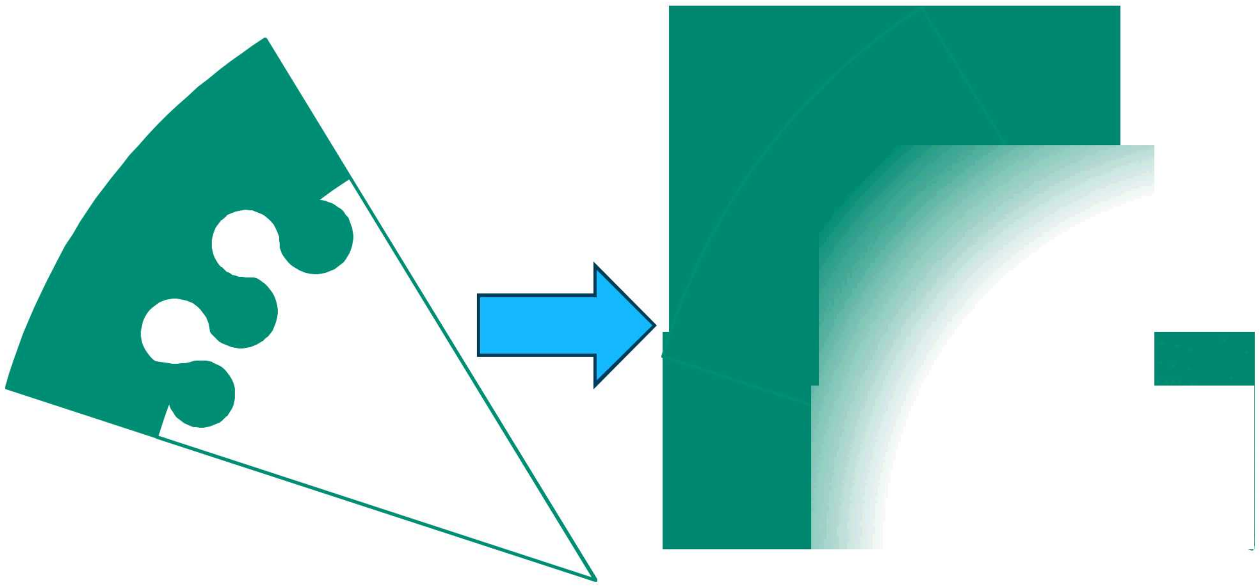


- Enhanced B_z-field on surface of liner produces a finite pitch total field
- This allows an MRT mode with **k⊥B** to form and lock in a density perturbation
- Helical density perturbation grows at constant pitch producing the large scale structures we see at stagnation

C.E. Seyler, M.R. Martin, N.D. Hamlin, **Helical Instability in MagLIF Due to Axial Flux Compression Low-Density Plasma**, Under Review in P.P.

Plasma Transport Experiments

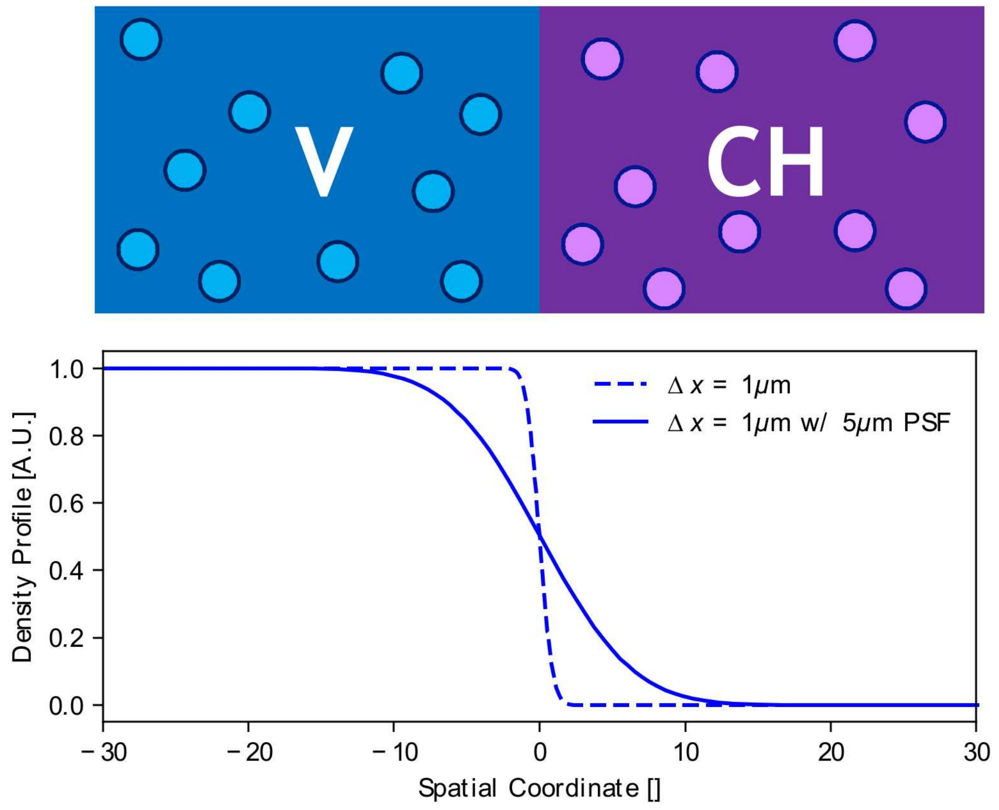
Understanding material transport across an interface is fundamentally tied to our understanding of mix

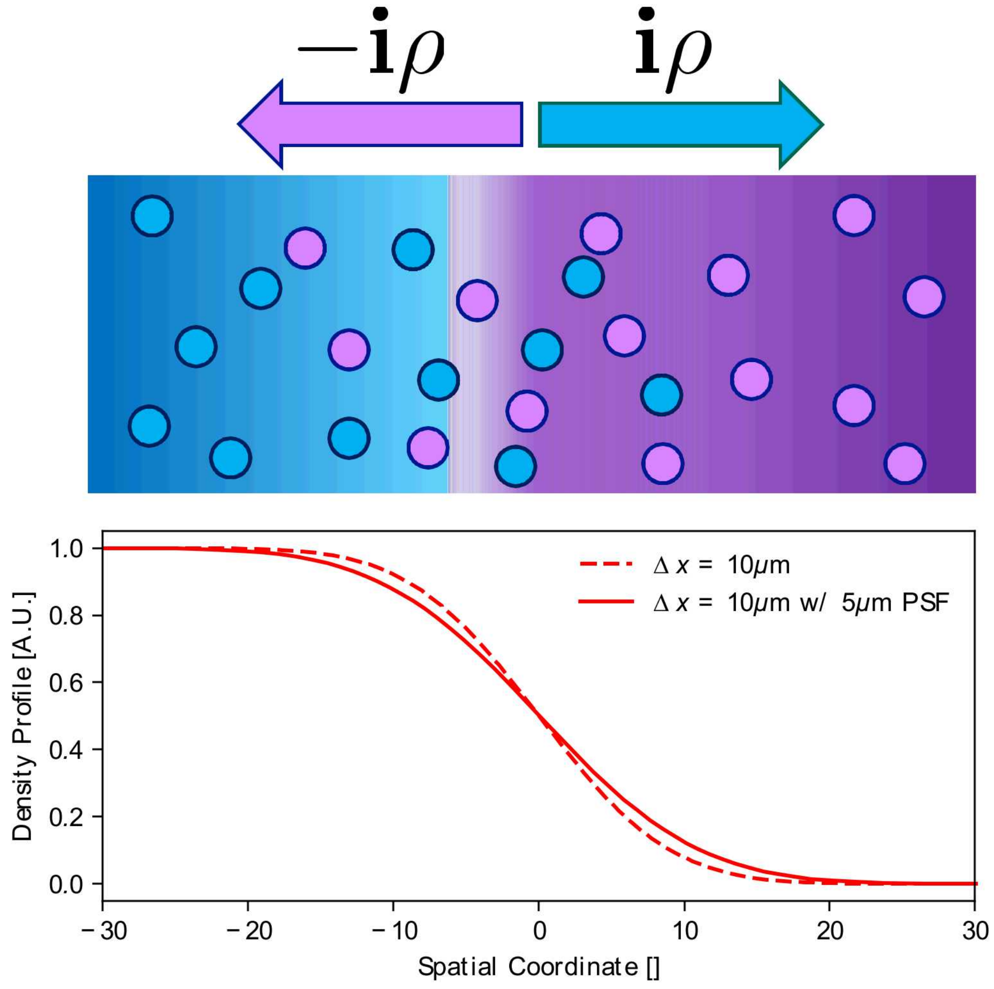


- How does an interface go from perturbed to mixed
- Is it just hydrodynamics stirring/turbulence?
- What role does diffusion play?

- In addition to distorting the hotspot shape and introducing vorticity, perturbations will
  - increase the surface area available for transport processes
  - decrease the scale length over which transport needs to operate to mix a volume
- Unfortunately fluid models don't account for transport processes well, particularly in strongly coupled plasmas

To explore this phenomenon we want to measure the "blurring" of an otherwise quiescent interface

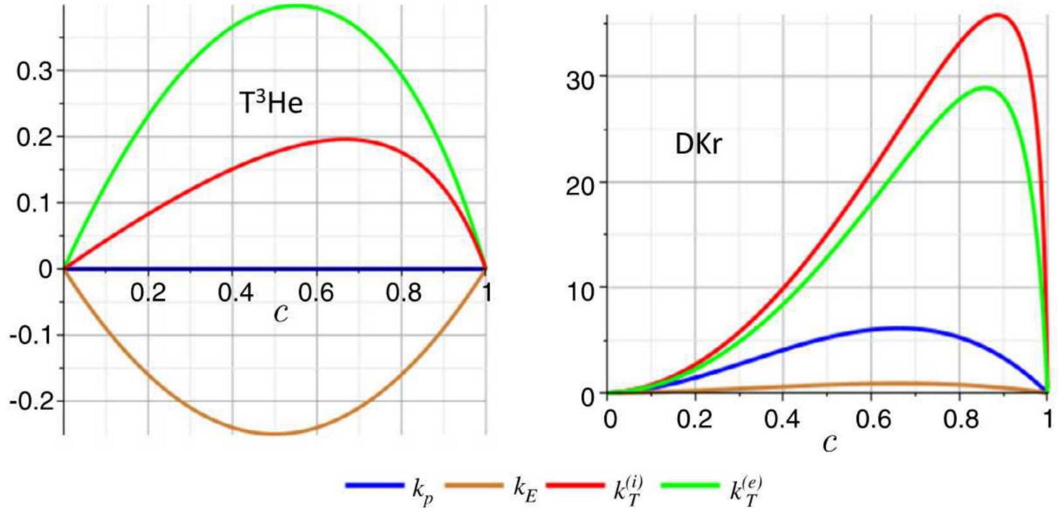


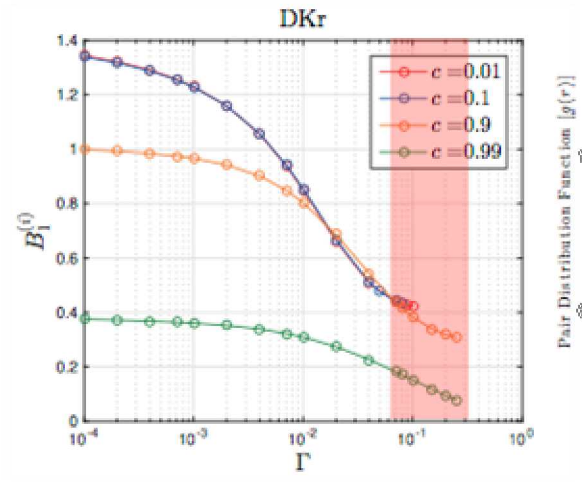


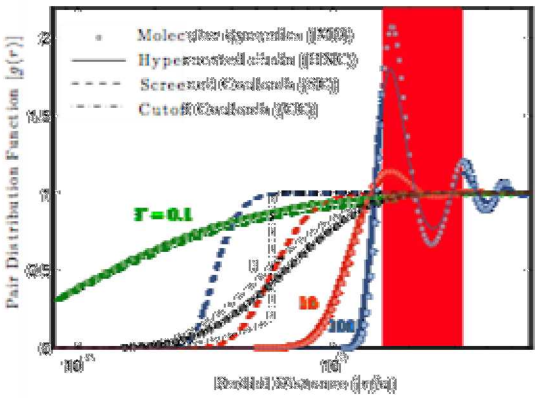
In a "hot" strongly coupled plasma, how does diffusion behave?

Weakly coupled theory says thermo-diffusion dominates for strongly asymmetric mixtures (Kagan and Tang, 2014)

EPT Formalism for strongly coupled plasmas (Kagan et al. 2016) says thermo-diffusion is negligible for asymmetric mixtures, but begins to break down at large Γ

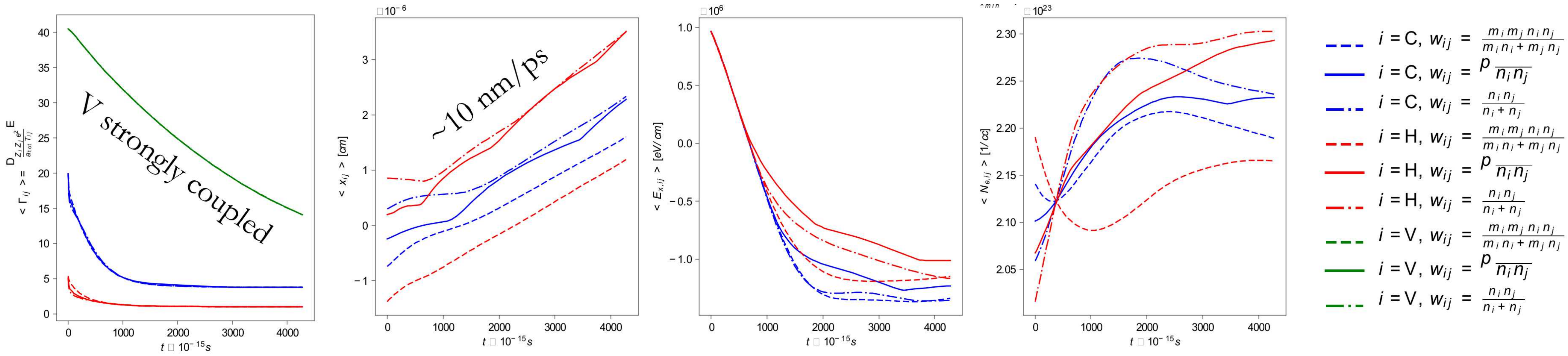






Direct Integration of multi-species VPBGK system can overcome the shortcomings of EPT theory

VPBGK (Haack et al.) Simulations of Plasma Transport at CHO-V Interface: Preliminary Results



Utilize multi-species VPBGK code to study plasma transport at CHO-V interface

Initial analysis of simulation data:

- Plasma regimes probed during experiment
- Average single species diffusion coefficients
- Interfacial interspecies diffusion
- Electric field evolution at interface

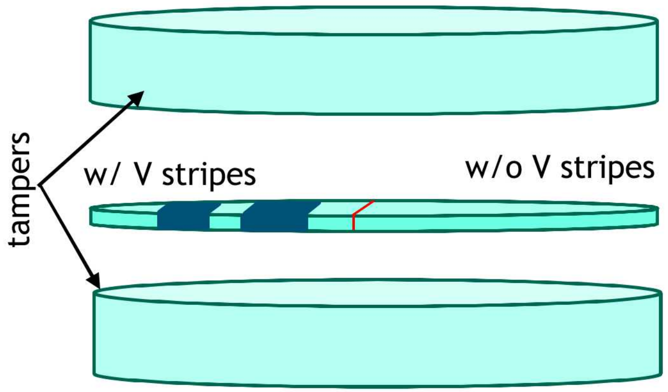
Preliminary conclusions:

- Vanadium plastic interface exhibits complex temporal history
- CH interface positions move into V at approx. similar rates, indicating little species separation
- Electric fields at each interface evolve in a dissimilar fashion due to ionization state changes

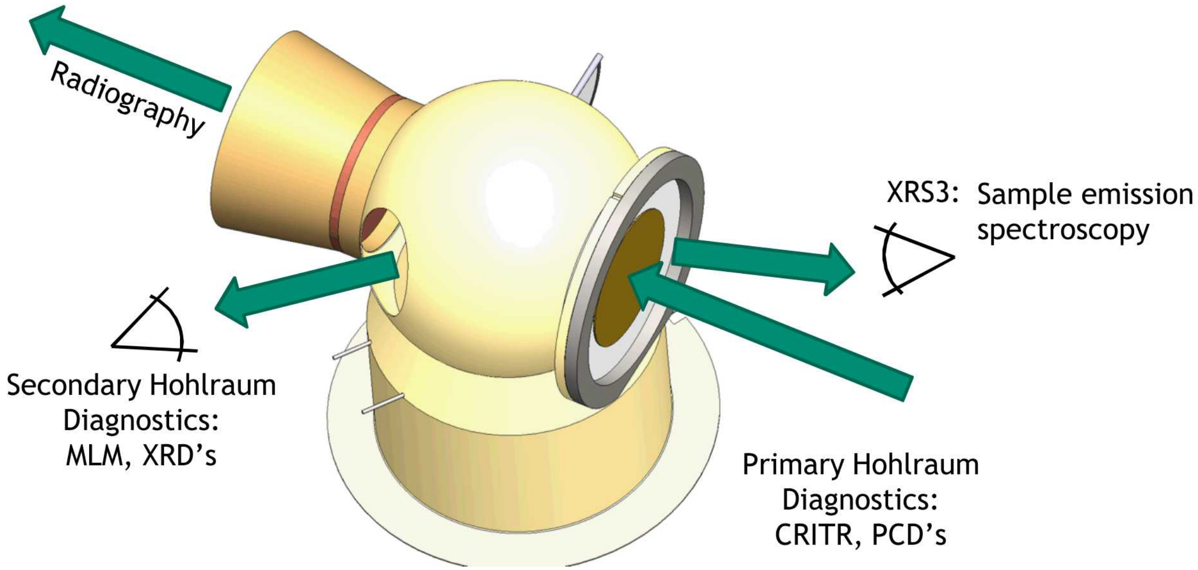
calculations performed by K. Beckwith

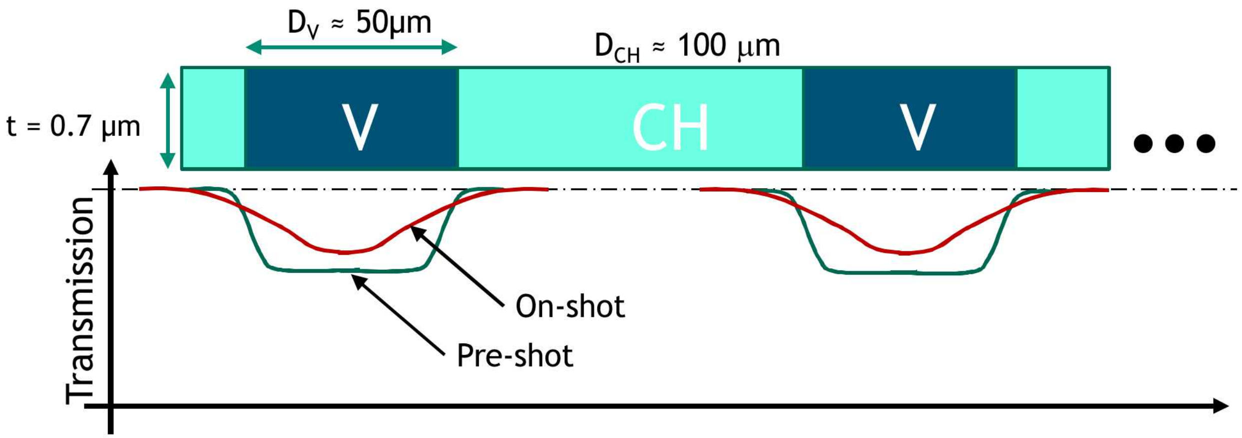
Plasma Transport Sample and experimental Concept

Conceptual Sample



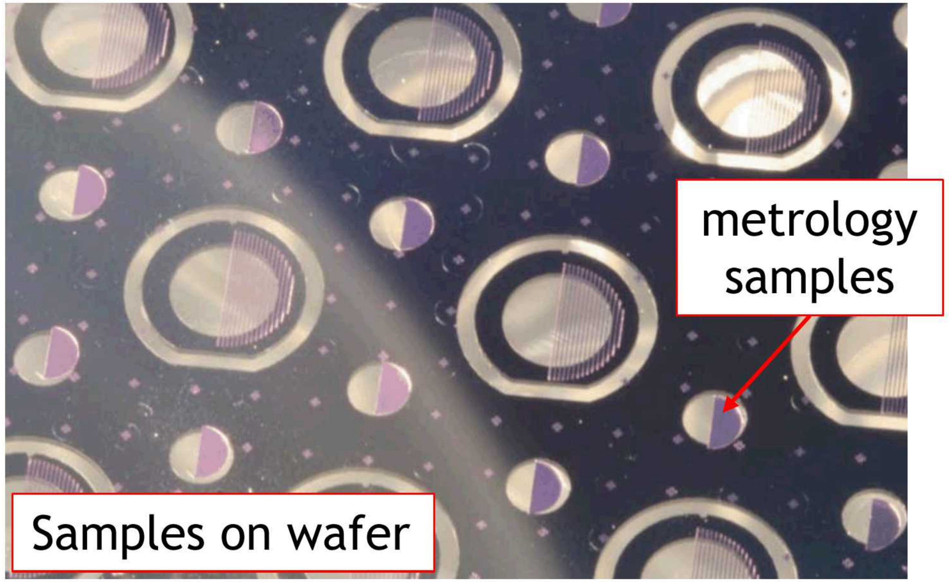
Experimental Setup

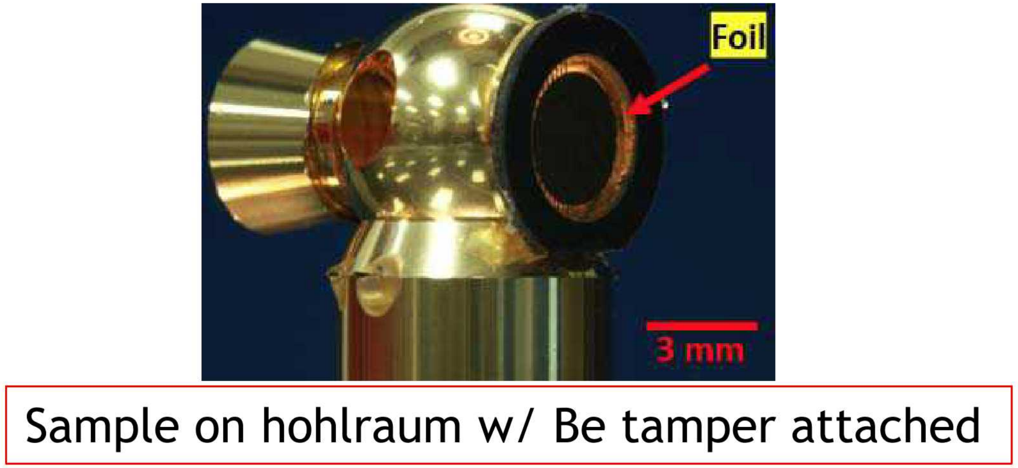


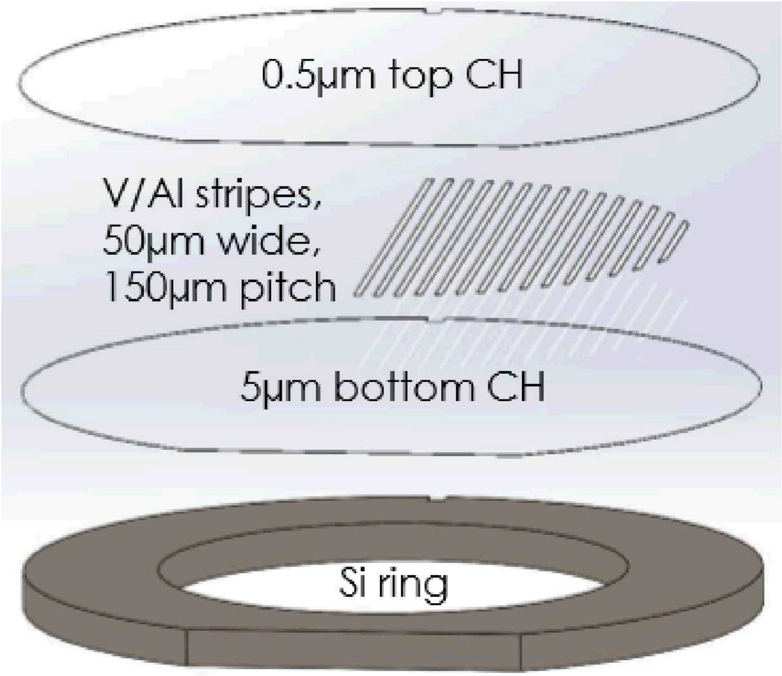


- Sample volumetrically heated using Hohlraum (T_r~180 eV, 5 ns rise) from one side to 150 eV, ~0.1x solid density
- Half moon sample allows transmission to be obtained from the attenuation
- Linear array of High-Z material allows integration of data along one dimension
- ZBL radiography used to image evolution of high Z strips

Fabrication of the sample required significant R&D by general atomics







- Requirement of very steep interface led to development of lithographic technique for coatings
- Lots of development in metrology for areal density, mixture properties, and edge widths

Material provided by Haibo Huang, General Atomics

We are attempting to optimize our Radiography capability for spatial resolution in one dimension

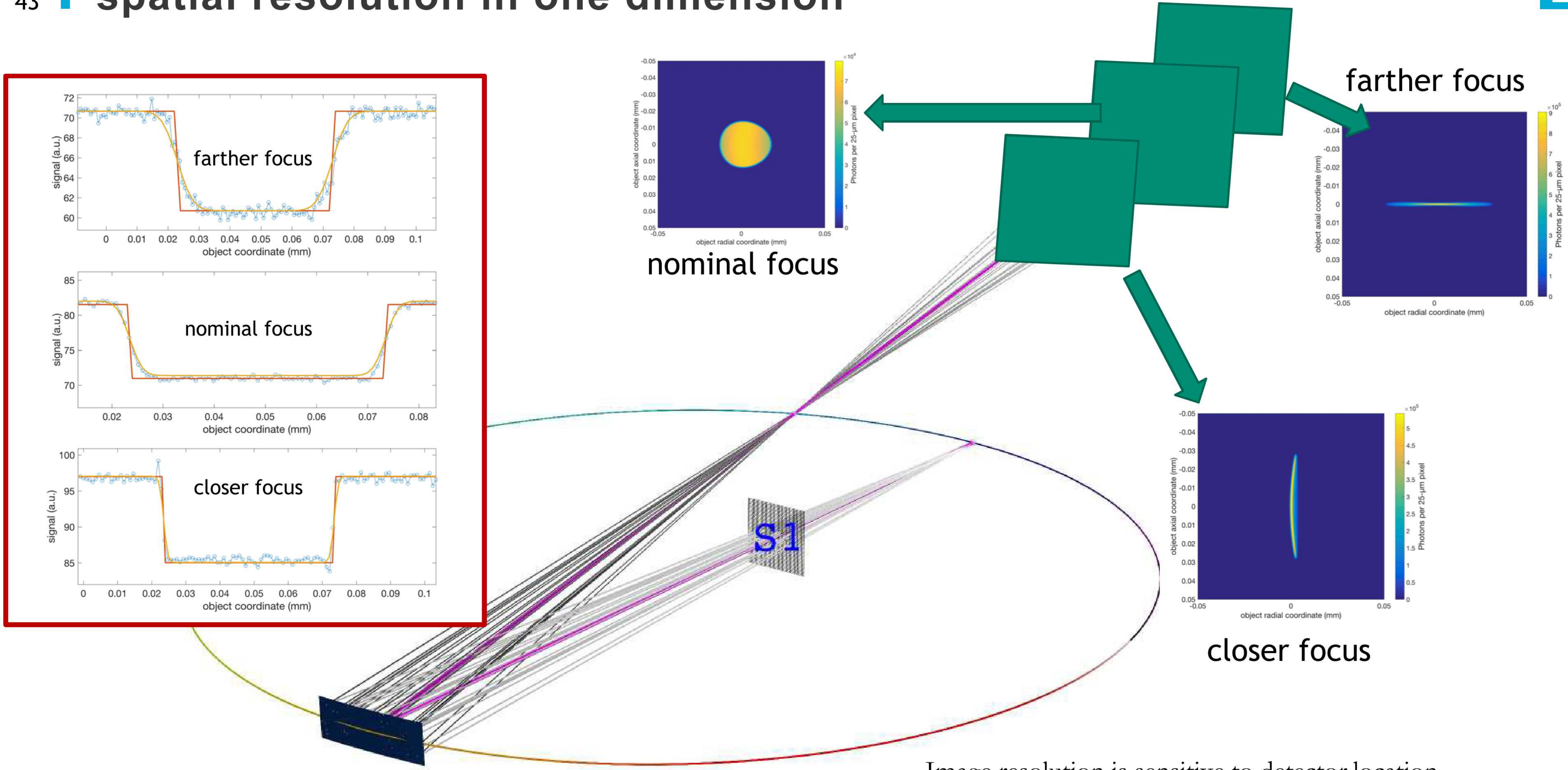
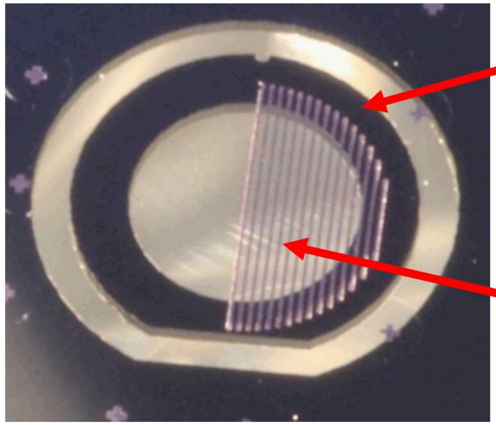


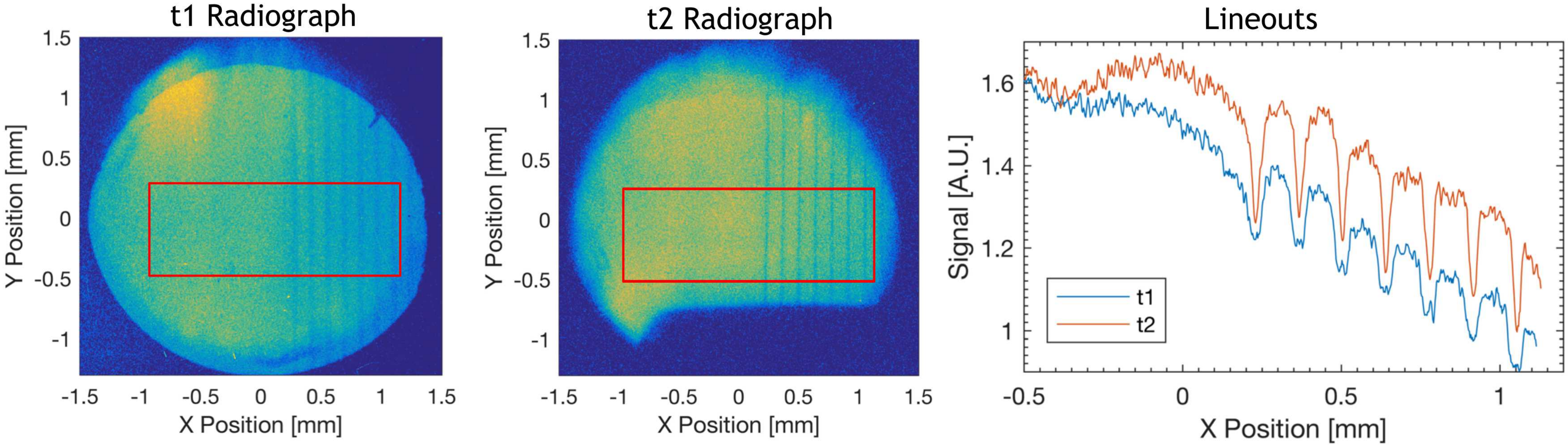
Image resolution is sensitive to detector location
Can optimize resolution in one dimension, sacrificing the other

Ray tracing performed by Marius Schollmeier

We have executed our first plasma transport experiments on Z demonstrating the feasibility of the proposed measurement

- Executed two experiments in March testing x-ray heating and diagnostics performance
- Demonstrated good contrast of the sample in the radiographs on shot z3220 (6.1 keV backlighter with detector placed at closer focal position)





Conclusions

- Z supports a diverse scientific portfolio
  - ICF
  - Radiation Effects Sciences
  - HEDP
  - Material Properties
- Non-fluid physics impacts our ability to conduct and understand our experiments
  - Current delivery to the target
  - Plasma environment near the target can impact instability growth
- We are exploiting the non-thermal nature of some Z-pinch plasmas to enhance outputs for RES applications
- We are currently developing theory, calculation, and experimental capabilities to study plasma transport in strongly coupled plasmas