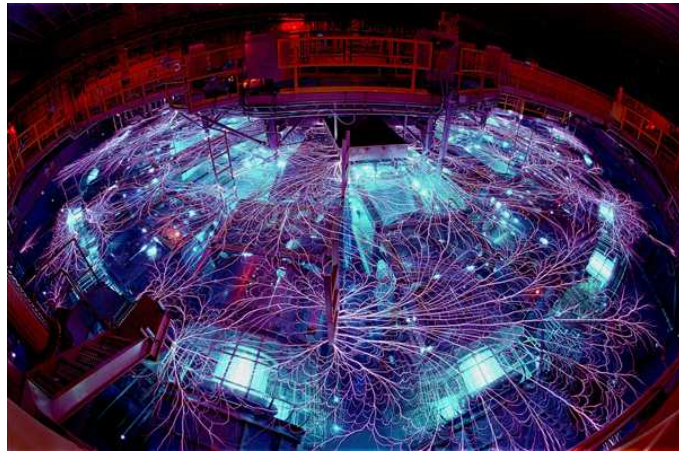


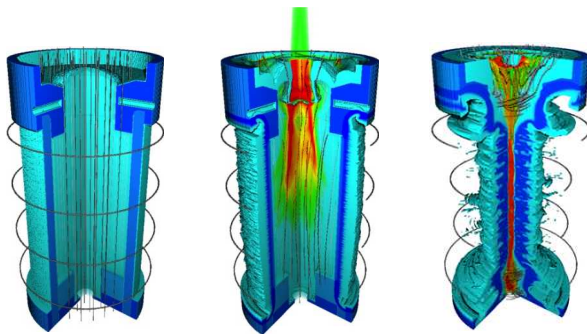
Exceptional service in the national interest



MagLIF research directions and progress

Kyle Peterson

Manager, Radiation and ICF Target Design



Sandia National Laboratories

Z Fundamental Science Program Workshop

Albuquerque, NM, August 1-3, 2016



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MagLIF is a broad national collaboration



T.J. Awe, C.J. Bourdon, G.A. Chandler, P.J. Christenson, M.E. Cuneo, M. Geissel, M.R. Gomez, K.D. Hahn, S.B. Hansen, E.C. Harding, A.J. Harvey-Thompson, M.H. Hess, C.A. Jennings, B. Jones, M. Jones, P.F. Knapp, D.C. Lamppa, J.S. Lash, M.R. Martin, R.D. McBride, L.A. McPherson, T.N. Nagayama, K.J. Peterson, J.L. Porter, G.A. Rochau, D.C. Rovang, C.L. Ruiz, S.E. Rosenthal, M.E. Savage, P.F. Schmit, A.B. Sefkow, D.B. Sinars, S.A. Slutz, I.C. Smith, W.A. Stygar, R.A. Vesey, E.P. Yu

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B.E. Blue, R. Paguio, K. Tomlinson, H. Huang, M.S. Wei

General Atomics

J. Davies, R. Betti, P.-Y. Chang, G. Fiksel, D. Barnak, V. Glebov, E.M. Campbell

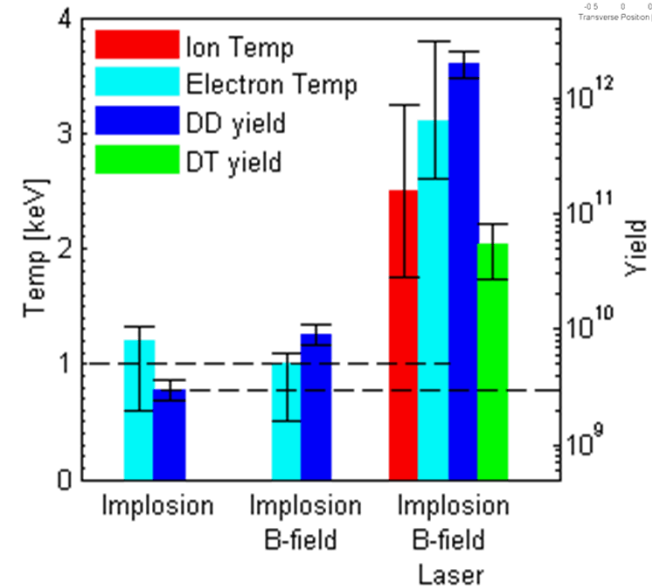
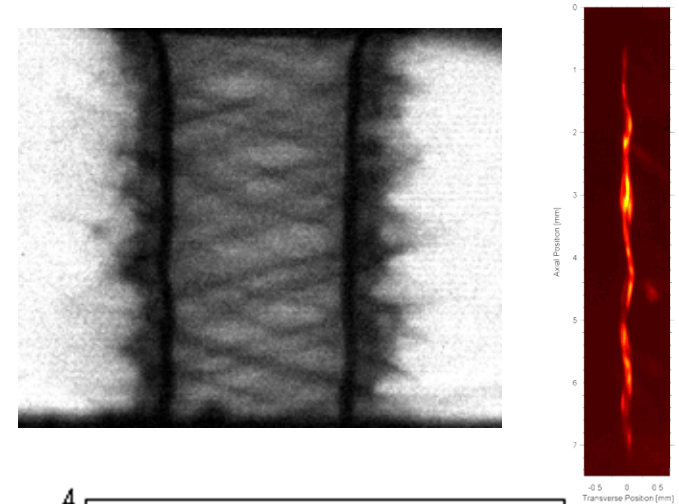
Laboratory for Laser Energetics

B. Pollock, M.C. Herrmann, J. Moody, D. Strozzi, C. Goyon, S. Khan, D. Hinkel, G. Logan

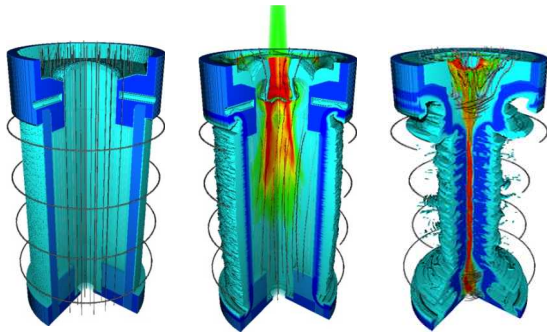
Lawrence Livermore National Laboratory

Summary: Initial experiments have demonstrated the fundamental MagLIF concept, and PRD-led experiments are now focused on understanding the science and future scaling.

- Initial MagLIF experiments have demonstrated the basic concepts of preheat and fuel magnetization to achieve thermonuclear fusion.
 - Max DD yields of $\sim 3E12$
- We have organized our program around 5 Priority Research Directions, and focused experiments will provide the understanding to scale to ignition and high yield.
 - Driver-Target Coupling (Current coupling)
 - Preconditioning (Laser preheat and B-fields)
 - Implosion (Liner stability)
 - Stagnation (Measurements)
 - Modeling, Simulation, & Scaling

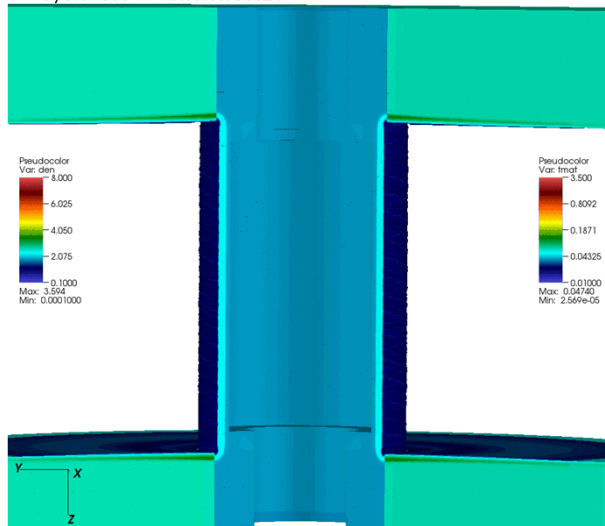


Magnetized Liner Inertial Fusion (MagLIF) is well suited to pulsed power drivers and may reduce fusion requirements



- **Axial magnetization of fuel/liner ($B_{z0} = 10\text{-}30\text{ T}$)**
 - Inhibits thermal conduction losses and traps alphas ($\beta: 5\sim 80$; $\omega\tau > 200$ at stagnation)
- **Laser heating of fuel (2 kJ initially, 6-10 kJ planned)**
 - Reduces radial fuel compression needed to reach fusion temperatures (R_0/R_f about 25, $T_0 = 150\text{-}200\text{ eV}$)

DB: hydrg00333.root
Cycle: 333 Time: 0.065021



3D HYDRA Simulation, A. Sefkow

- **Liner compression of fuel (70-100 km/s, $\sim 100\text{ ns}$)**
 - Low velocity allows use of thick liners ($R/\Delta R \sim 6$) that are robust to instabilities and have sufficient ρR at stagnation for inertial confinement
- This combination allows fusion at $\sim 100\times$ lower fuel pressure than traditional ICF ($\sim 5\text{ Gbar}$ vs. 500 Gbar)
- 2-D Simulations suggest 100 kJ DT yield may be possible on Z in future
 - Requires upgrades from our present system e.g., $10\text{ T} \rightarrow 30\text{ T}$; $2\text{ kJ} \rightarrow >6\text{ kJ}$; $19\text{ MA} \rightarrow >24\text{ MA}$

After demonstrating the fundamental concept of MagLIF, we are now focusing on understanding the science and developing the requirements for ignition and high yield.

~85% of
total effort
(Z,Ω,NIF)

- **Study the underlying science of MDDs, emphasizing MagLIF**
 - Primarily accomplished by the Priority Research Direction teams
 - Teams have dedicated experiments on multiple facilities (e.g., Z, Z-Beamlet, Omega, Omega-EP, universities, NIF)

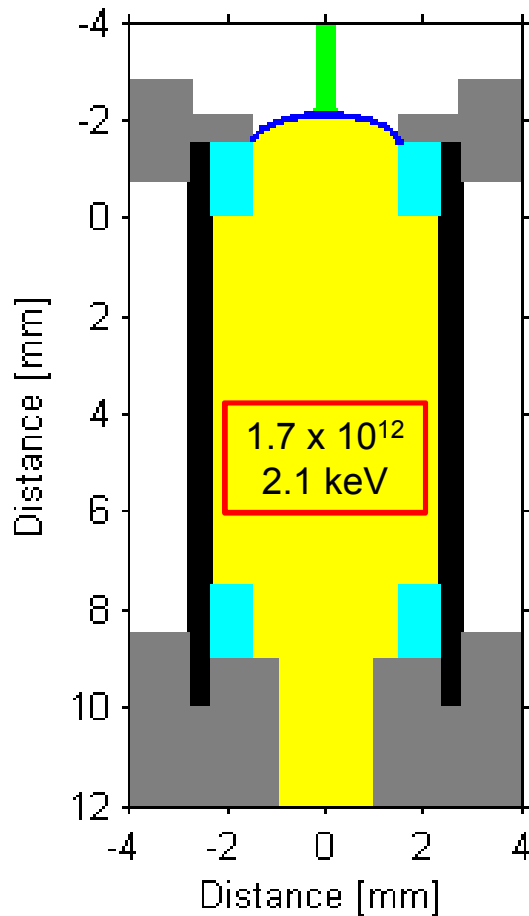
~10% of
effort

- **Demonstrate target performance over available range of conditions**
 - Primarily accomplished through integration experiments on Z
 - **100 kJ DT yields; P-tau > 5 Gbar-ns; BR > 0.5 MG-cm**

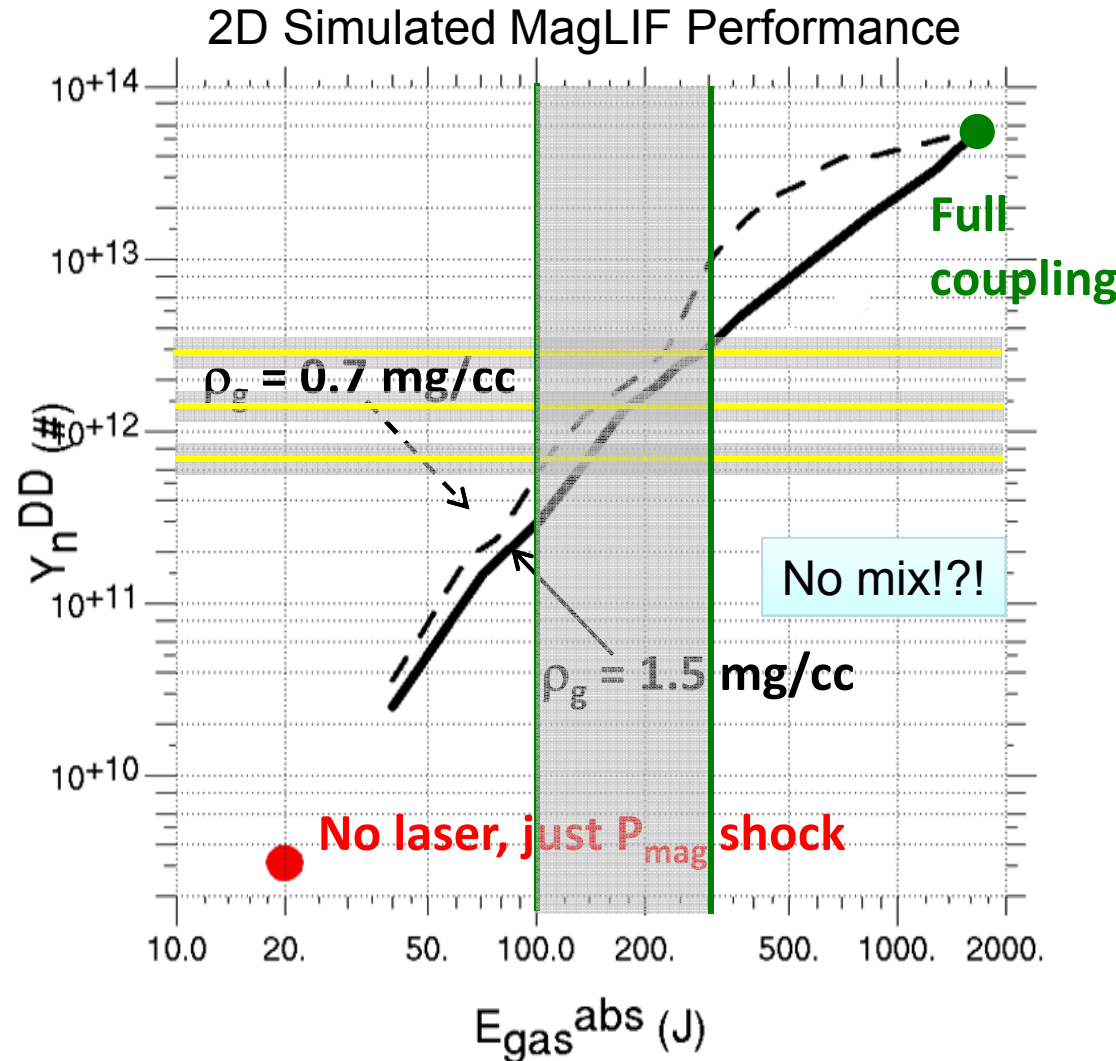
~5% of
effort

- **Develop a path to ignition and beyond, and assess its credibility**
 - Define credible gas (~5 MJ) and ice burning (~ 1GJ) ignition designs
 - Demonstrate “at-scale” fuel heating on NIF relevant to MagLIF
- **Update the mission needs for ignition and high yield**
 - Why does the nation need a facility capable of ~1 GJ/shot?

The baseline MagLIF experiments produced interesting stagnation conditions



Baseline Target Parameters
 Window thickness = 3.5 μm
 Target height = 7.5 mm
 Laser energy = 2.5 kJ
 Endcap material = aluminum

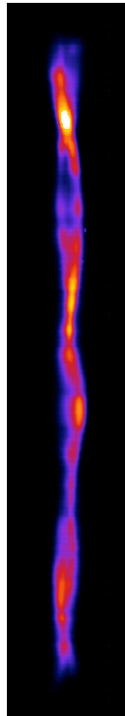
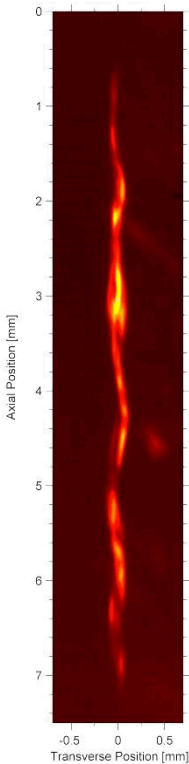


The observables are well modeled by 2-D and 3-D Hydra if we assume ~ 200 J of laser energy coupled to the target

Imaging

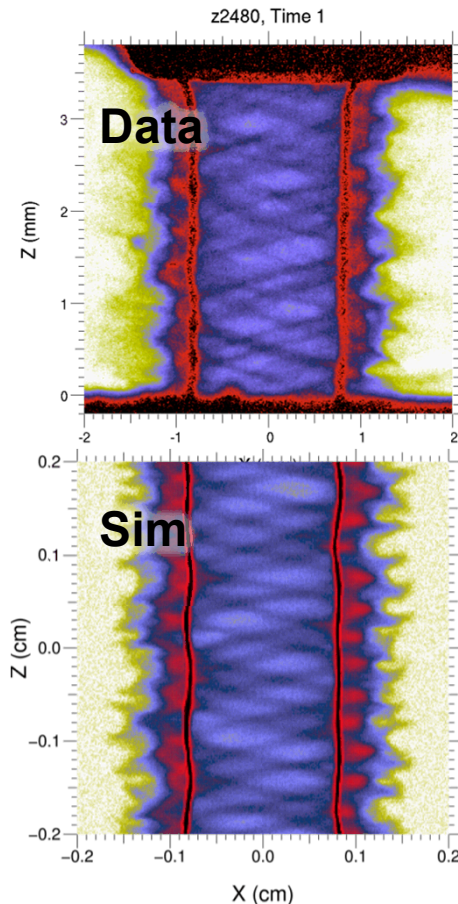
Data

Sim



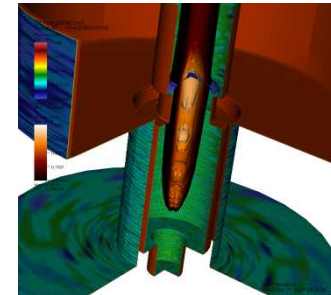
Z2613

Radiography



Comparison to z2591 Observables

Parameter	Measured/inferred	Post-shot simulations
$r_{\text{stag}}^{\text{hot}}$	$44 \pm 13 \mu\text{m}$	$40 \mu\text{m}$
$\langle T_i \rangle^{\text{DD}}$	$2.5 \pm 0.75 \text{ keV}$	$3.0 \pm 0.5 \text{ keV}$
$\langle T_e^{\text{spec}} \rangle$	$3.0 \pm 0.5 \text{ keV}$	$2.7 \pm 0.5 \text{ keV}$
$\rho_{\text{gas}}^{\text{stag}}$	$0.3 \pm 0.2 \text{ g cm}^{-3}$	$0.4 \pm 0.2 \text{ g cm}^{-3}$
ρ_{Rgas}	$2 \pm 1 \text{ mg cm}^{-2}$	$2.6 \pm 1.0 \text{ mg cm}^{-2}$
$\rho R_{\text{liner}}^{\text{stag}}$	$900 \pm 300 \text{ mg cm}^{-2}$	900 mg cm^{-2}
$\langle p_{\text{stag}} \rangle$	$1.0 \pm 0.5 \text{ Gbar}$	$1.5 \pm 0.3 \text{ Gbar}$
$E_{\text{gas}}^{\text{stag}}$	$4 \pm 2 \text{ kJ}$	$7 \pm 2 \text{ kJ}$
$\langle B_z^f r_{\text{stag}} \rangle$	$(4.5 \pm 0.5) \text{e5 G cm}$	4.8e5 G cm
γ_n^{DD}	$(2.0 \pm 0.5) \text{e12}$	$(2.5 \pm 0.5) \text{e12}$
$\gamma_n^{\text{DD}} / \gamma_n^{\text{DT}}$	40 ± 20	$41-57$
$t_{\text{burn}}^{\text{FWHM}}$	$1.5 \pm 0.1 \text{ ns (x-ray)}$	$1.6 \pm 0.2 \text{ ns}$



A. Sefkow

The observables are also well modeled by 3-D GORGON if we assume ~500 J of laser energy coupled to the target

Imaging

Radiography

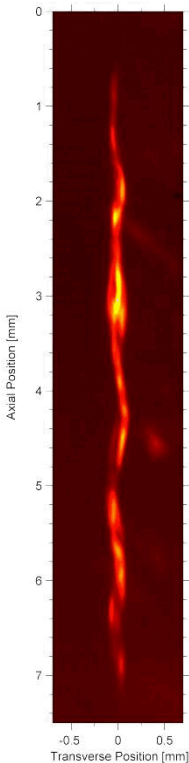
Comparison to z2613 Image

Data

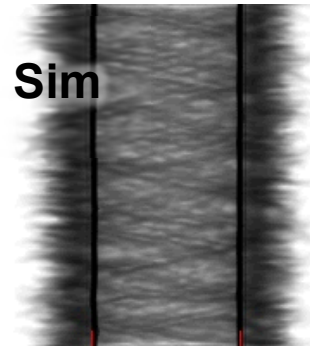
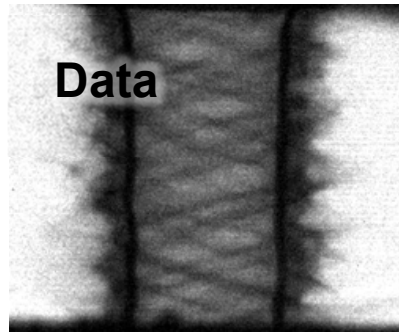
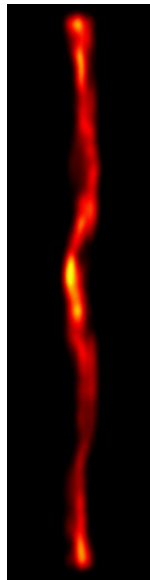
Sim

Data

Sim



Z2613

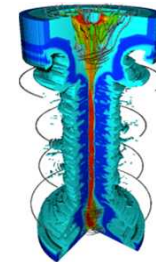


Parameter	Measured/inferred	Post-shot simulations
-----------	-------------------	-----------------------

- FWHM 91 ± 40 mm 121 ± 40 mm

Sim. Values:

- Burn weighted, time integrated ion temp: **3.5 keV**
- Continuum emissivity (~9keV) weighted, time integrated electron temperature: **3.3 keV**
- Iron contaminant in Be emissivity weighted, time integrated electron temperature: **1.8 keV**
- Continuum emissivity (~9keV) weighted, time integrated fuel density: **0.33 g cm^{-3}**
- DD Yield: **$4.e12$**
- FWHM neutron pulse: **1.7ns**
- Liner ρR integrated along a single azimuth and axially averaged. Increases from **$520 \pm 60 \text{ mg cm}^{-2}$** to **$980 \pm 110 \text{ mg cm}^{-2}$** over the FWHM of the neutron pulse.



C. Jennings

We established teams and team leaders for the science organized around the Priority Research Directions. They are focused on 5-year science & performance goals.

Research Group	Team Leaders
Driver-Target Coupling	Bill Stygar, Mike Cuneo
Target Pre-conditioning	Kyle Peterson
Implosion	Ryan McBride
Stagnation & Burn	Greg Rochau and Brent Jones
Intrinsic & Transport Properties	(treated as subset of next category)
Modeling, Simulation, & Scaling	Kyle Peterson and Thomas Mattsson

- Team leaders responsible for organizing the program of work for each of the research groups, including coordinating national research in each area
- The following slides summarize our progress to date and our key goals for the next five years in these areas

Driver-Target Coupling: 5 year goals

Scientific goals

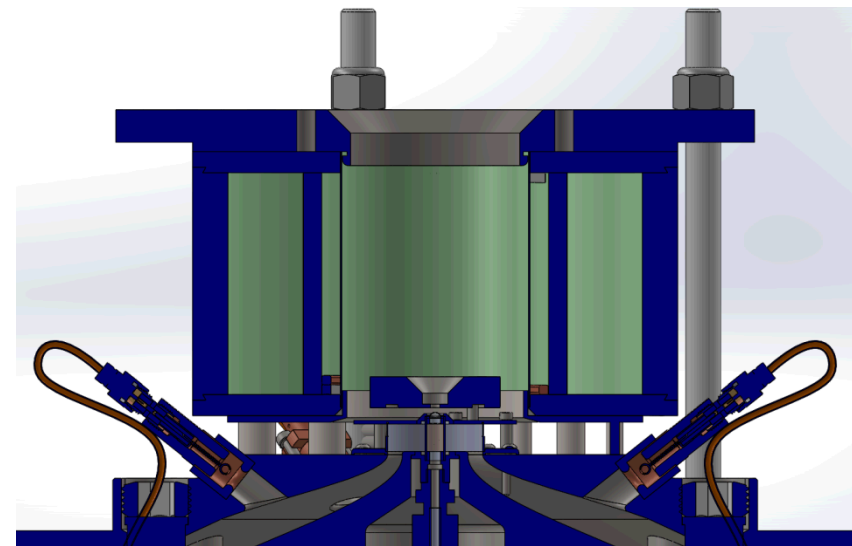
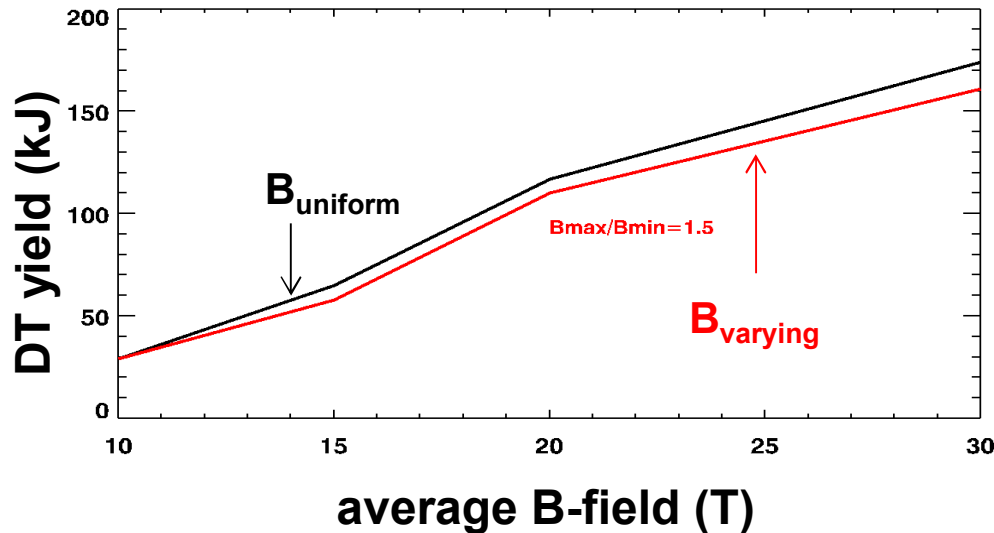
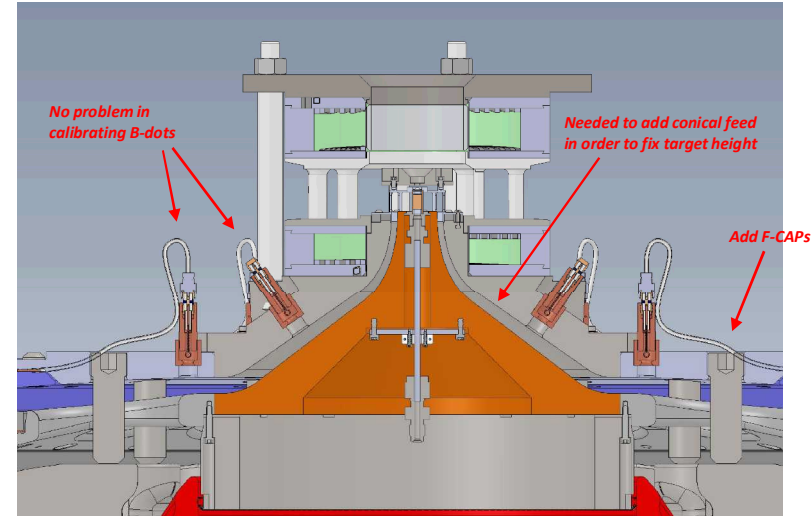
- Develop predictive (~5%) circuit and PIC models of load current coupling.
- Conduct scaled power-flow experiments under conditions similar to those of Z Next.
- Quantify the benefits to ICF loads of current-pulse shaping.
- Quantify the benefits of longer implosions.

Programmatic goals

- Deliver 22-24 MA to a MagLIF target on Z.
- Develop a point *pulsed-power* design of a MagLIF target for Z Next that achieves a net target gain of 1 (Likely, Yield $\sim E_{\text{target}} \sim 3\text{-}5$ MJ).

The DTC team is exploring new designs as a way to increase the current and test our predictive circuit models

- Uniform B-field requires high inductance loads that only achieve peak currents of ~ 18 MA.
- A non-uniform B-field allows lower-inductance hardware.
- Experiments in May demonstrated ~ 20 MA coupled to a MagLIF target.



Pre-Conditioning: Over the next five years, we seek to accomplish the following goals:

Scientific goals

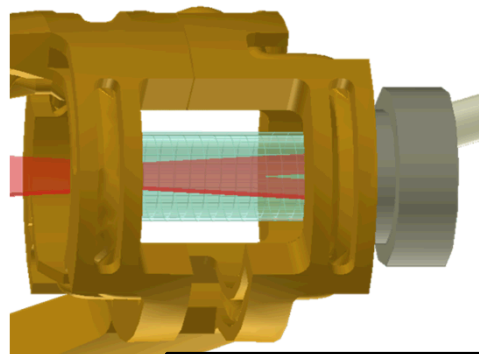
- Demonstrate a method for reproducibly coupling >2 kJ into magnetized fuel
- Characterize & mitigate any fuel contamination as a result of the heating method
- Minimize the likelihood and impact of laser-plasma interactions

Programmatic goals

- Improve Z-Beamlet to be capable of a multi-ns, >6 kJ, well-characterized “smoothed” beam profile (including an optimized pulse shape)
- Demonstrate 30 kJ heating on the NIF

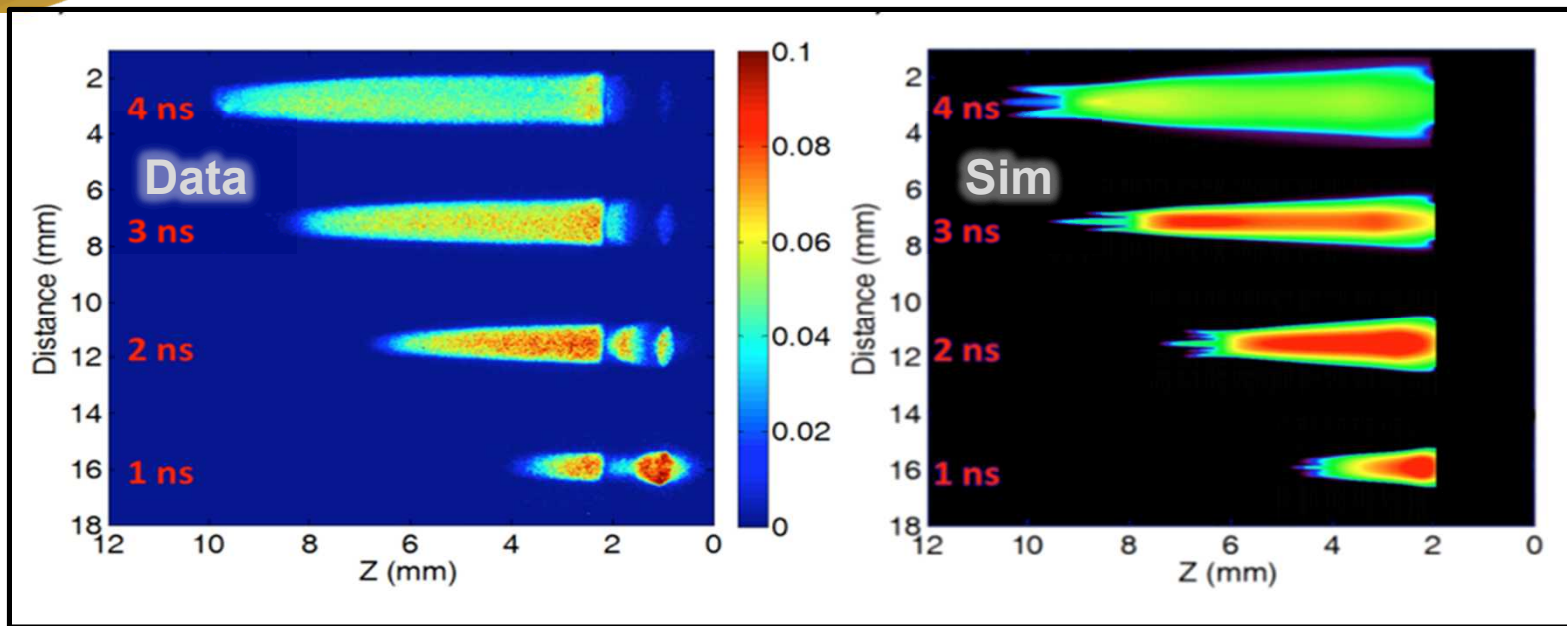
OMEGA-EP experiments are being conducted to develop understanding of laser energy transport & deposition.

Rexolite (CH) tube
(6.5-10 mm long)



Current topics of interest for OMEGA-EP Experiments

- Effect of LEH thickness
- Effect of gas fill density
- Effect of laser intensity
- Effect of magnetization
- How and where does mix occur?
- At what conditions does LPI become important?



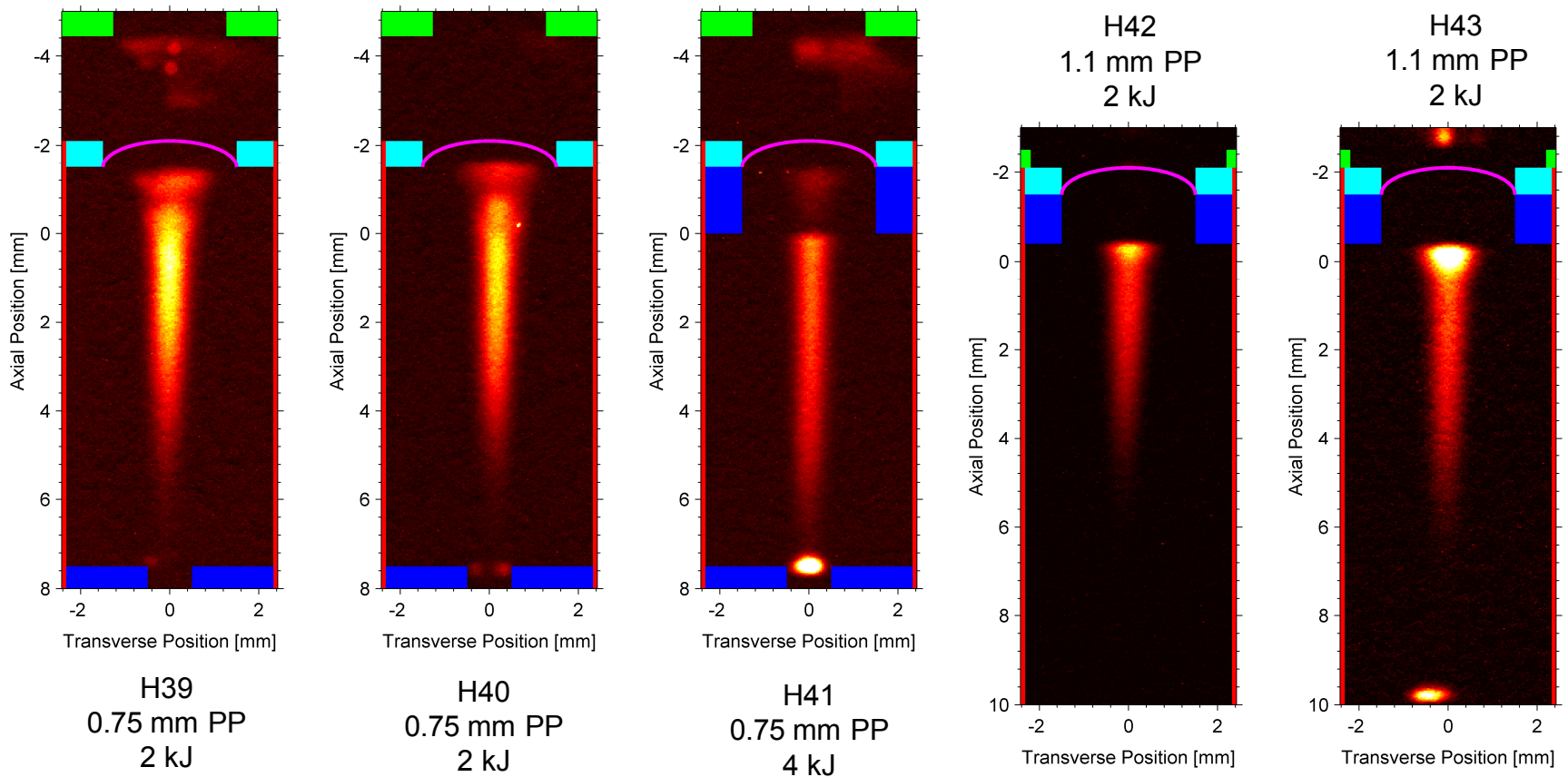
We have made inexpensive improvements to Z-Beamlet to support MagLIF experiments in the near term

- Activated Booster Amplifier
 - Added 400J of 2ω energy (4.5kJ total)
- Upgraded Final Optics Assembly (FOA)
 - Motorized up/down motion of focusing lens
- Activating co-injection to combine ZBL with sub-aperture (16 cm dia.) ZPW laser in long-pulse (2ns) mode
 - Front-end modifications complete for long-pulse operation
 - Installed optics and mounts to combine ZBL and ZPW beams
- Commissioning applied B-field system for laser experiments in Phase C target area
 - Working reliably at 100kA level to produce 4T in scale-2 targets, and 8T in scale-1 targets

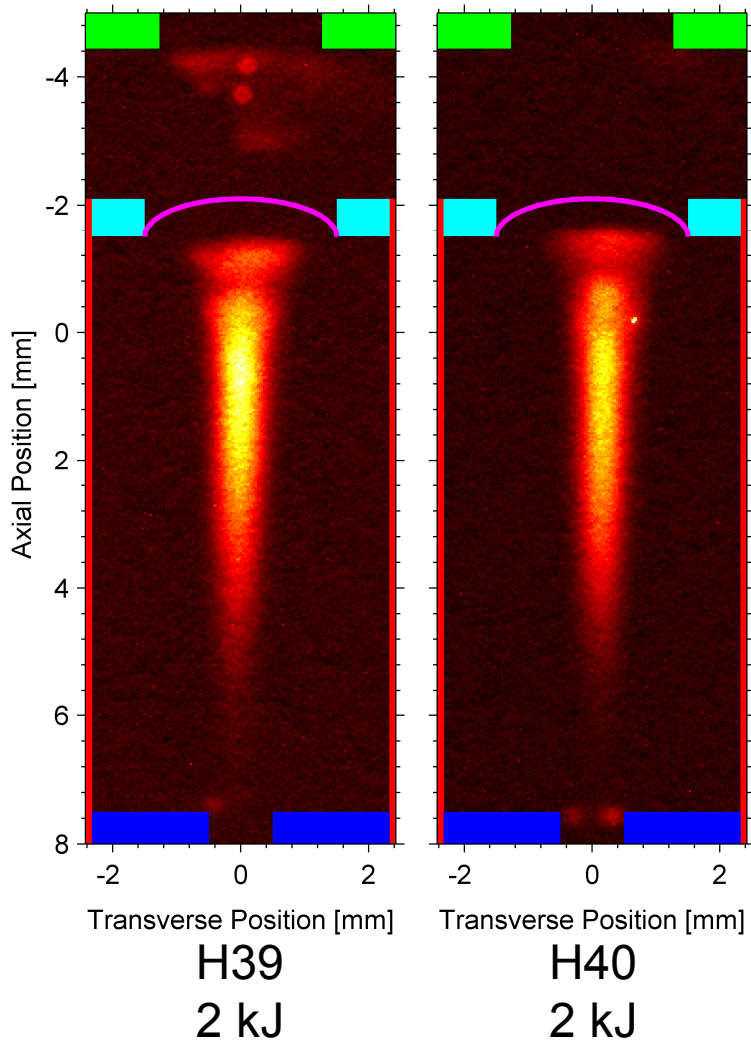


In January we conducted successful laser heating experiments in Z using phase plates to condition the beam

- 0.75 and 1.1 mm distributed phase plates have been procured, coated, conditioned, and characterized. Shots as high as 4 kJ with prepulse have been performed on Z using the DPPs.



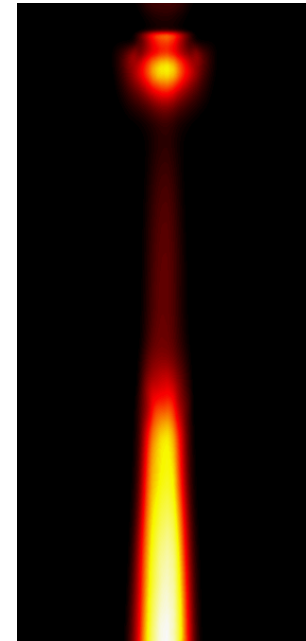
Even with phase plates, qualitative discrepancies with simulations remain for Z experiments



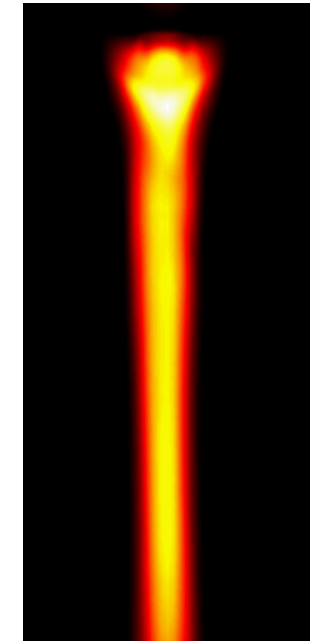
2D HYDRA
2 kJ



3D GORGON
2 kJ (70%)

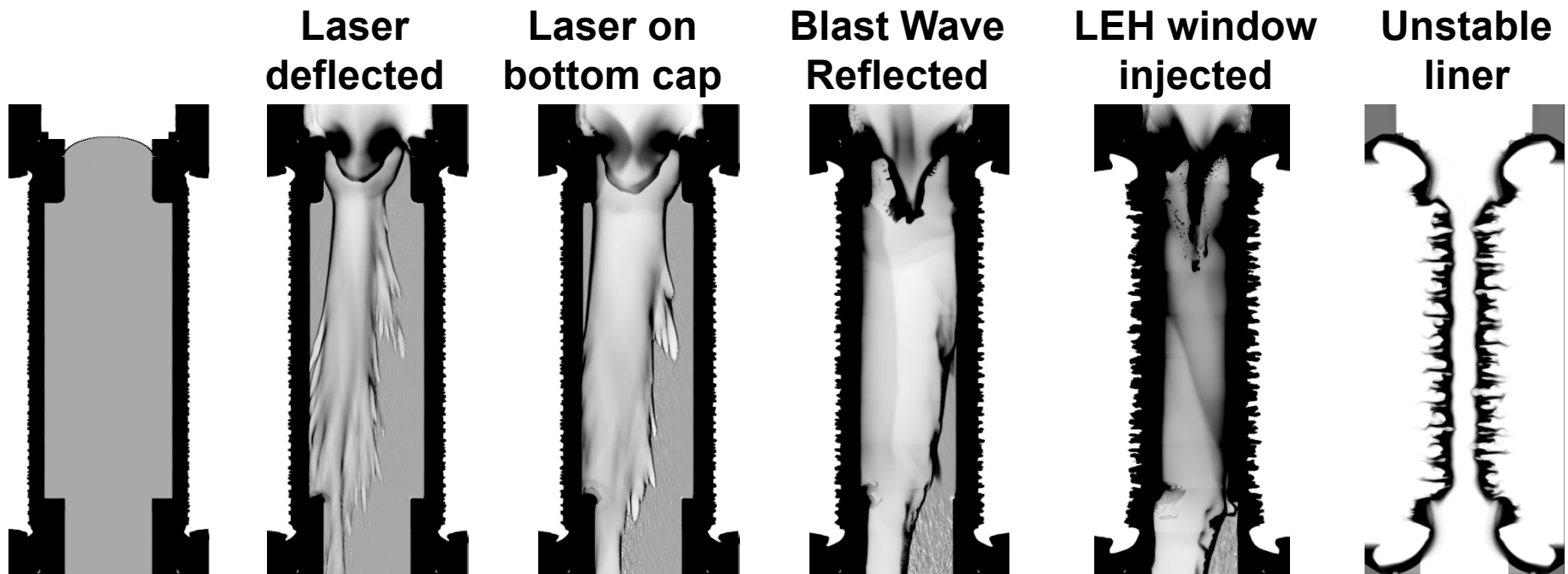


3D GORGON
2 kJ (70%,
 $1.5x \phi$)



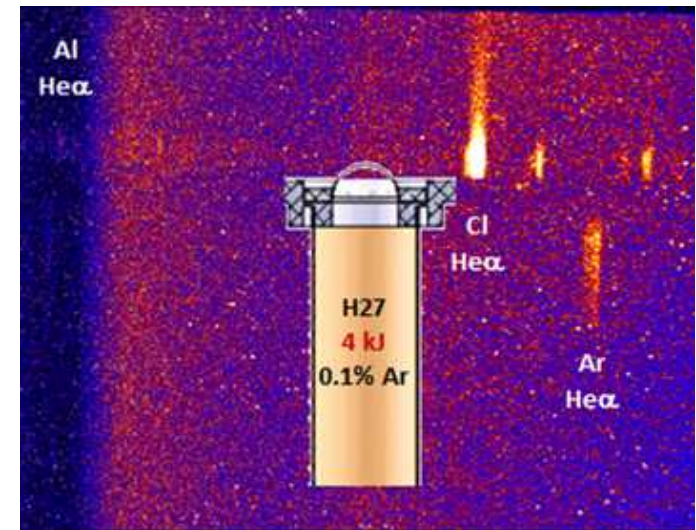
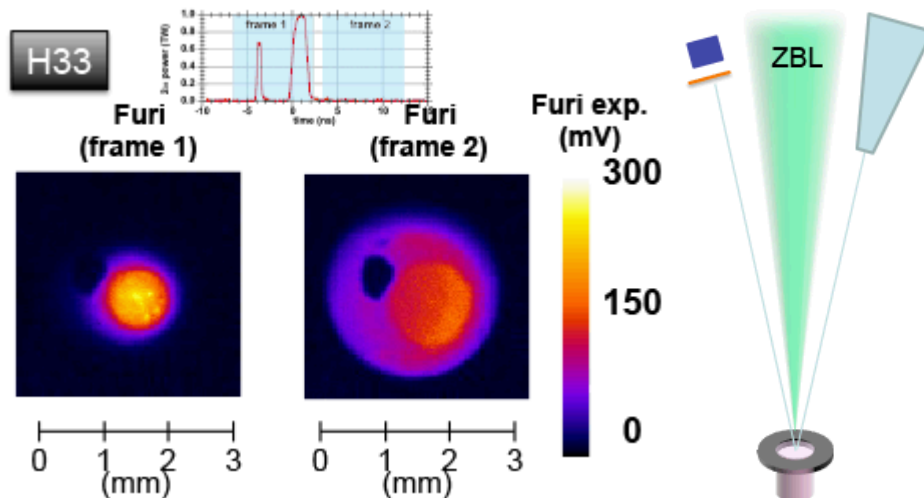
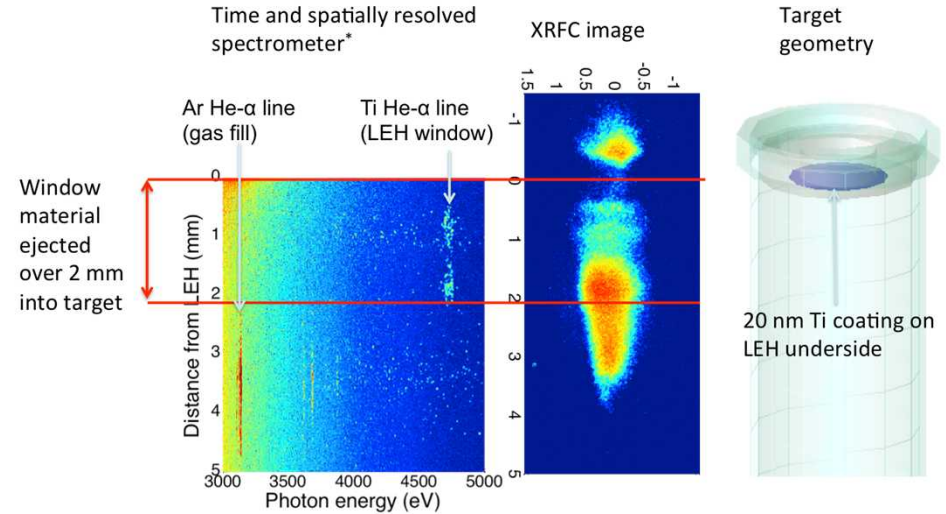
Models indicate mix can occur from multiple origins:

- Blast wave from laser preheat causes blowoff from liner wall and endcaps
- Laser can pass through the gas and cause blowoff from the bottom end cap
- Laser can deflect through LEH plasma and hit the liner/endcap causing blowoff
- The exploded LEH window can mix into the gas
- The liner is RT unstable



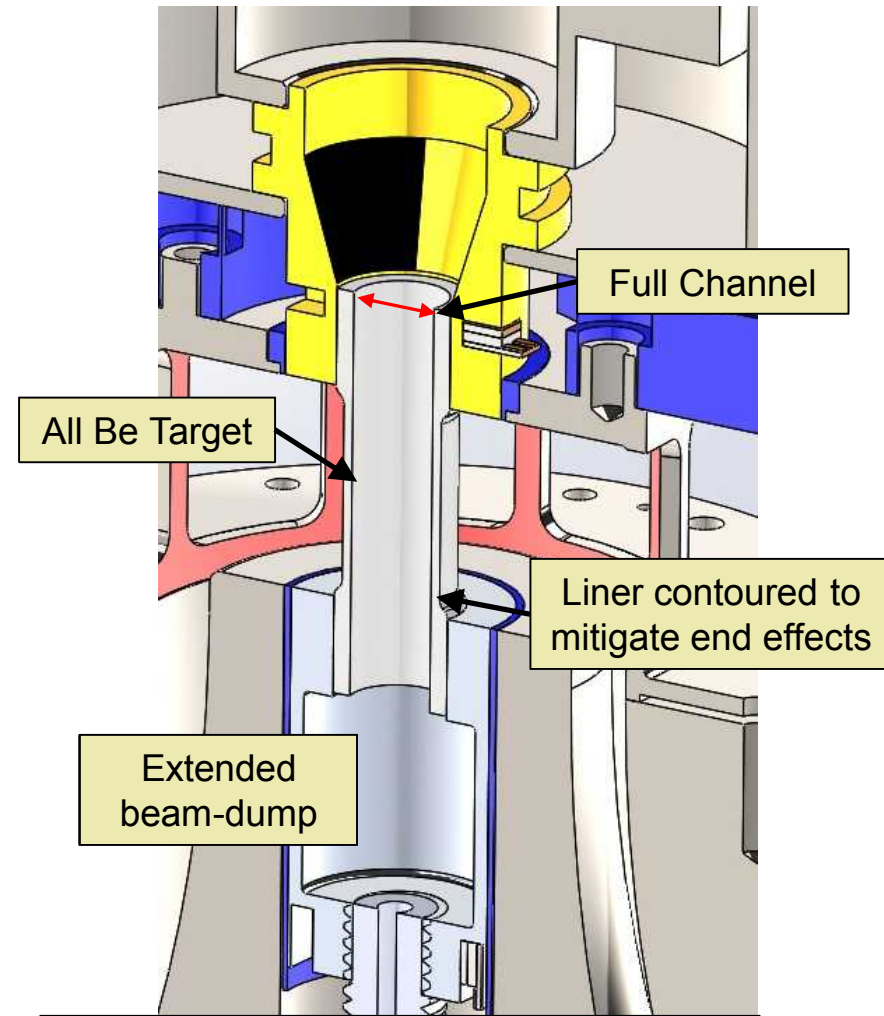
We have made progress in characterizing and mitigating fuel contamination as a result of the preheating method

- Window mix using Ti dopant coated on the LEH window at OMEGA-EP
- Localized Cl dopant on the LEH window, Al washers, we are assessing laser-induced mix using ZBL
- Developing time-gated axial imaging and spectroscopy to measure heating on integrated Z shots



A cryogenic target has been designed to help mitigate the laser interaction issues

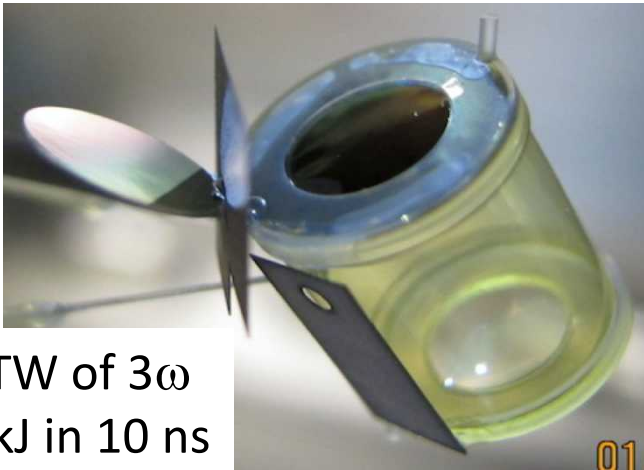
- Same gas density ($\sim 0.7 \text{ mg/cm}^3$) at much lower pressure (15 PSI @ 70 K)
- Thinner LEH windows with larger diameter
- Less energy invested in disassembly AND less mass injected into the target
- Bigger window diameter should reduce likelihood of laser interactions with the wall
- Long-term future development:
 - (1) frozen anti-mix layers
 - (2) frozen fuel layers for high-gain MagLIF



This design concept will be tested in Oct.

Design work done by Tom Awe, Adam Sefkow, and Keegan Shelton

NIF experiments are targeted at understanding laser transport and deposition at the 30 kJ predicted to be needed for high yields

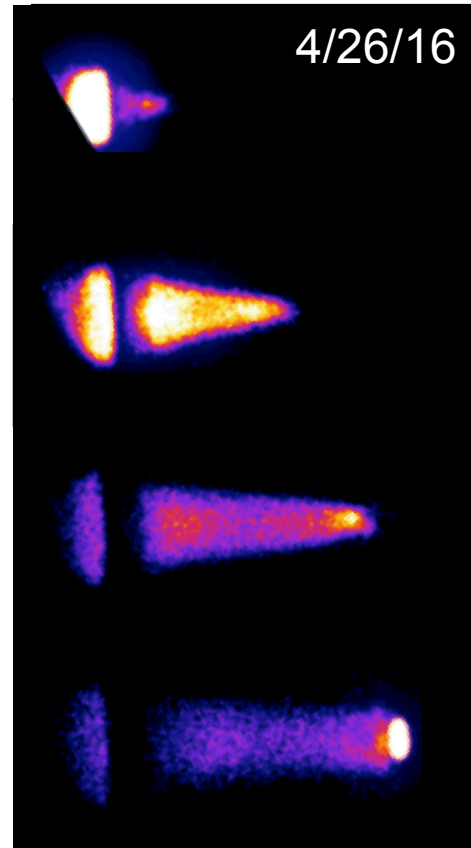


3 TW of 3ω
30 kJ in 10 ns

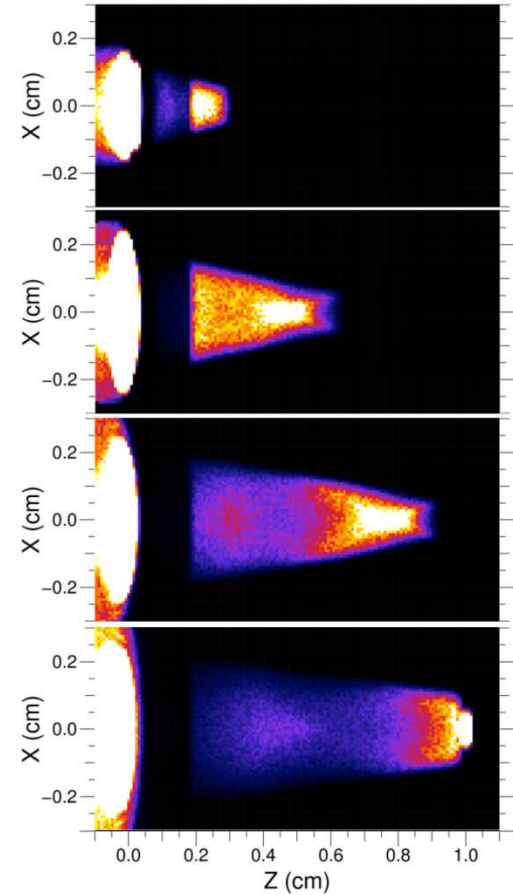
Objective : Measure laser propagation through a 1 cm gas pipe

- 1 cm long by 0.845 cm gas pipe
- Gas fill: 1 atm of C_5H_{12} at room temp., doped with 1% Ar
- 100 μm thick epoxy tube
- 0.75 μm polyimide LEH window

GXD Data



Hydra Sim



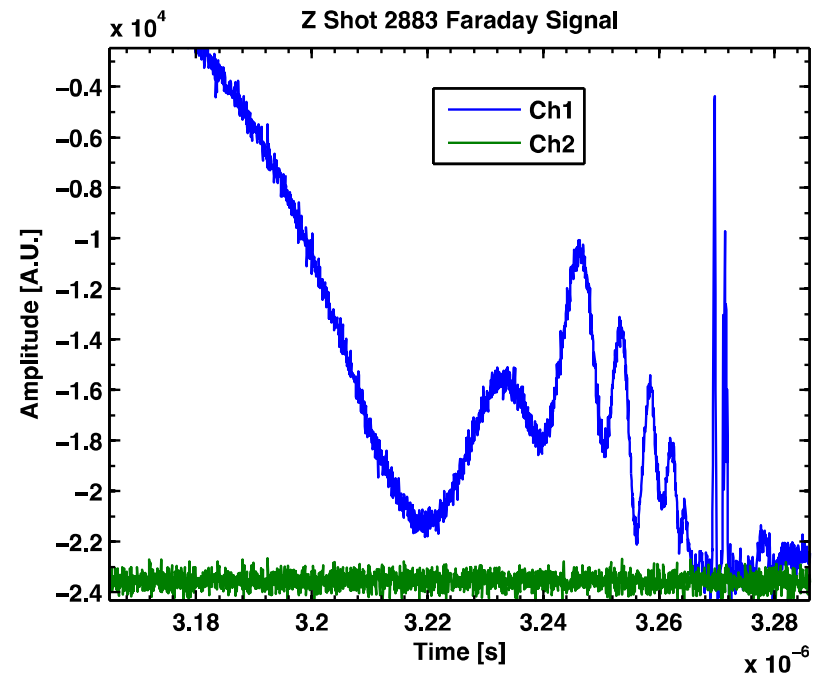
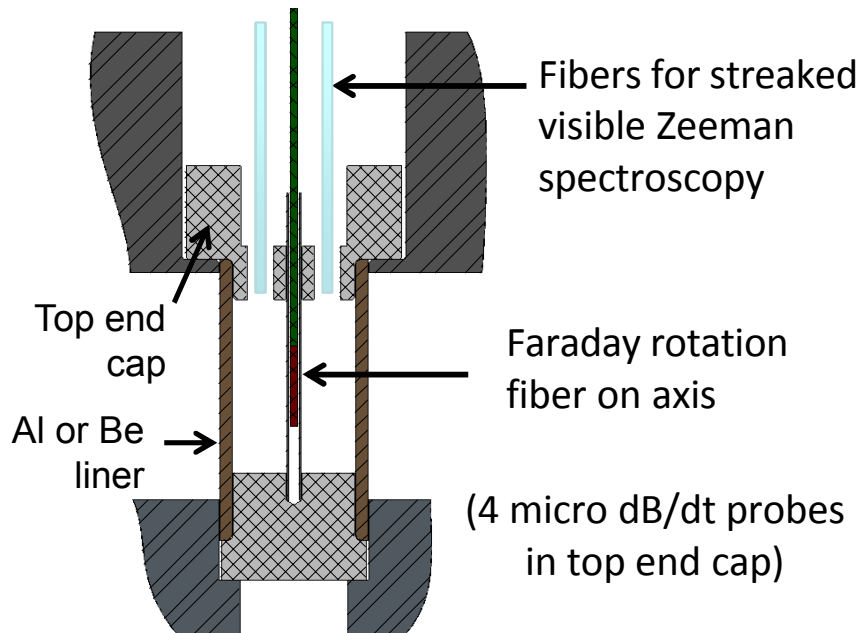
Implosion: 5 year goals

- Determine the dominant seeds for observed acceleration and deceleration instabilities, and strategies to mitigate against them
- Demonstrate the ability to model the evolution of 2D & 3D instability structures in codes used to predict the integrated target performance
- Measure the spatial distributions for temperature, density, B_z , and any contaminants in the fuel after heating and through at least CR=5
- Experimental demonstration of a magnetized liner implosion resulting in a diagnosable, ignition-relevant stagnation pressure-tau product of > 5 Gbar ns

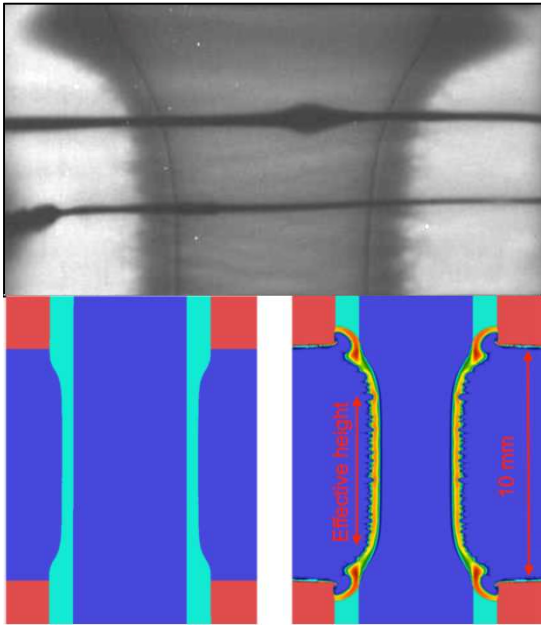
Magnetic flux compression experiments in November may have directly measured >1000 T fields (initial $B=17$ T)

- Three Z shots (z2882, z2883, z2885) used an on-axis Faraday rotation fiber to measure flux compression in a vacuum-filled liner implosion (topic of an invited talk at the HTPD conference this June).
- Analysis underway, preliminary work suggests >1000 T
- LDRD-funded initiative; also included micro Bdot development efforts

Platform developed for magnetic flux compression experiments on Z



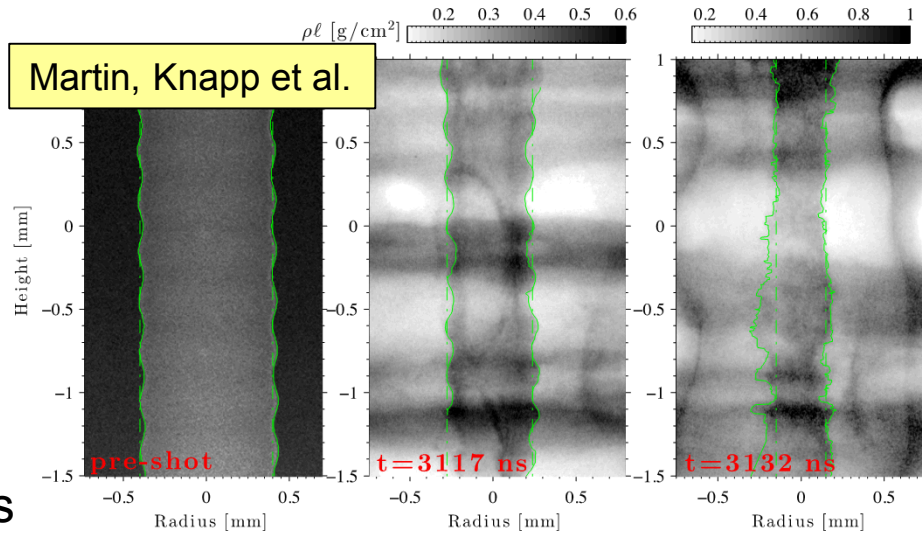
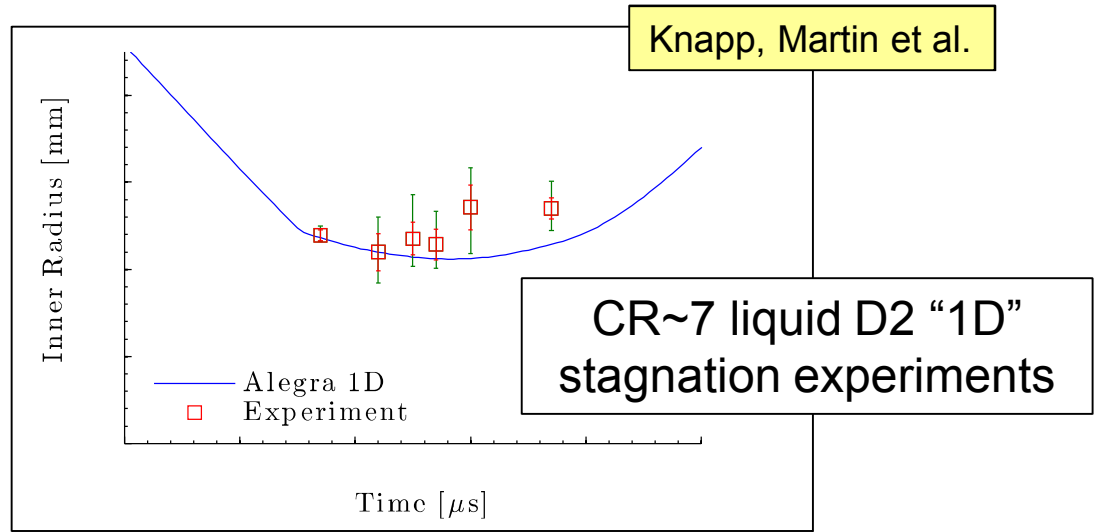
Implosion shots this year will continue to address several of our 5-year objectives



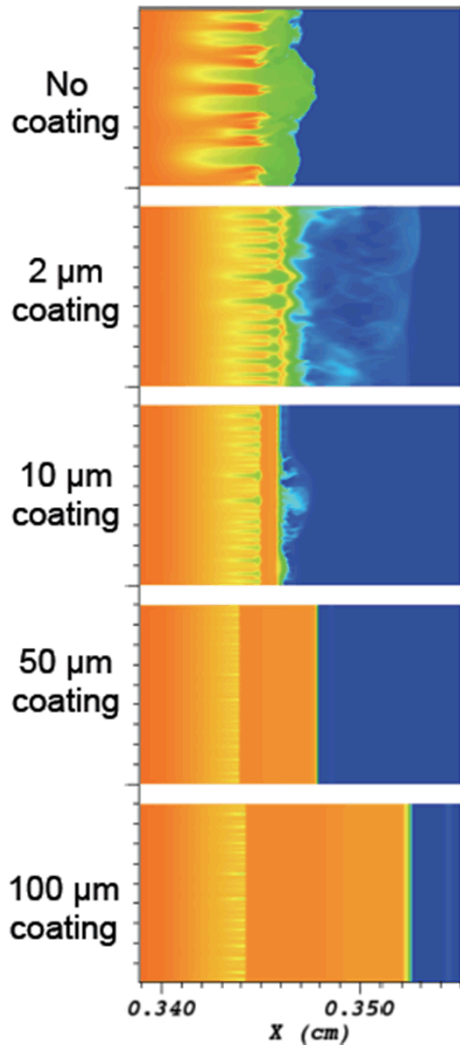
Shaped liners to control electrode/end effects

Sefkow, Ampleford et al.

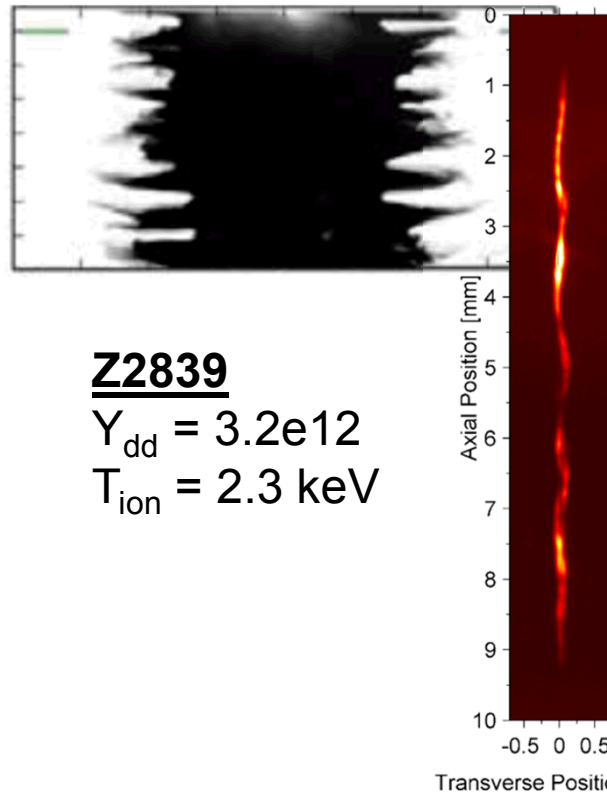
On-axis rods to study deceleration instabilities



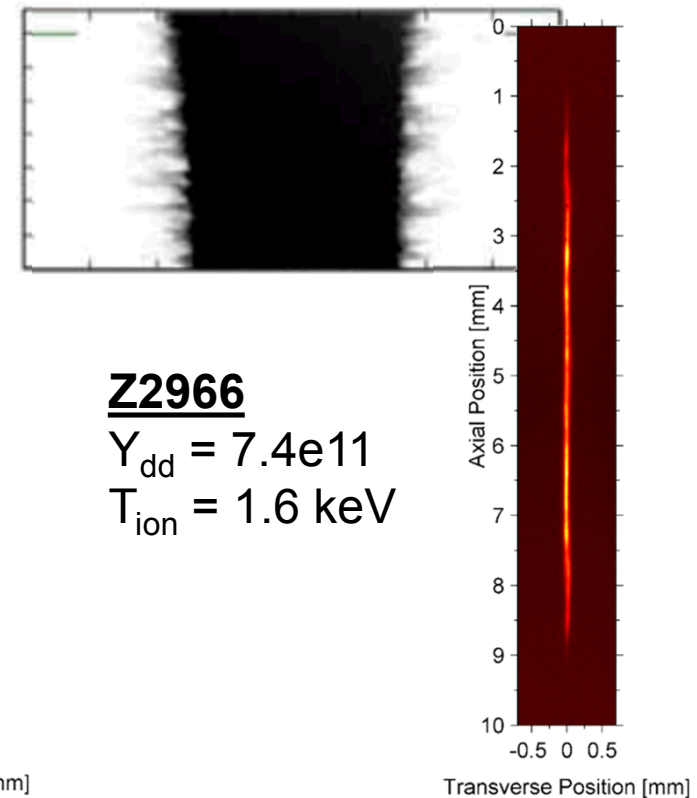
Recent experiments have demonstrated the efficacy of dielectric coatings on improving the stagnation morphology.



Uncoated Liners



Coated Liners



Thick dielectric coatings suppress liner instabilities that are seeded by the electro-thermal instability

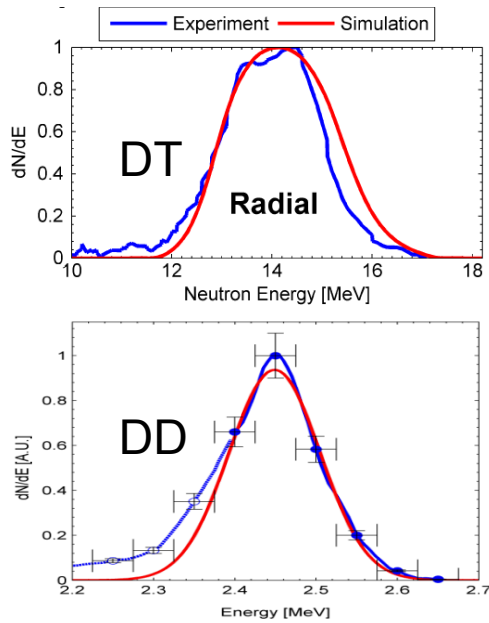
Stagnation: 5 year goals

- Achieve a burn-averaged ion temperature of >4 keV (robust burn threshold)
- Achieve a BR > 0.5 MG-cm ($R/r_\alpha > 2$)
- Achieve fuel pressure > 5 Gbar and $P_\tau > 5$ Gbar-ns
- Minimize and mitigate against radiation loss from high-Z contamination
- Demonstrate a continuous, ~uniform stagnation column at $CR > 20$
- Determine the non-thermal component of the fusion yield.

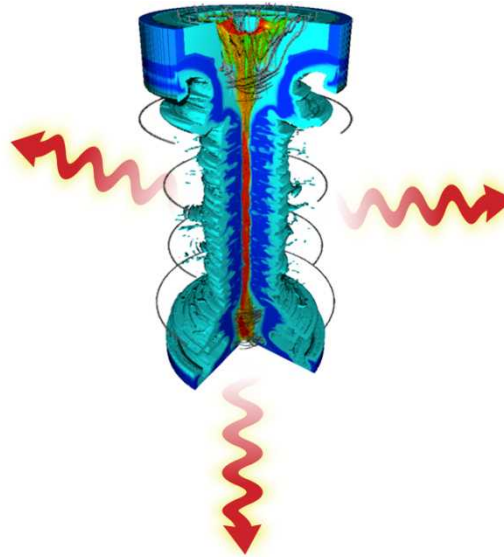
Implicit in these goals is developing the ability to make these measurements, which is where we are spending a lot of effort today

We use a combination of x-ray and neutron diagnostics to assess the performance of MagLIF implosions.

Neutron spectra

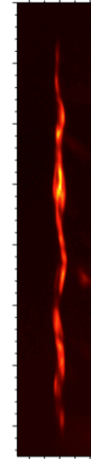


MagLIF Z pinch

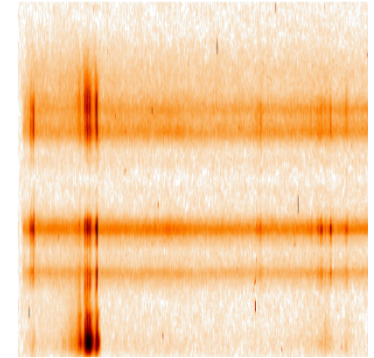


X-ray

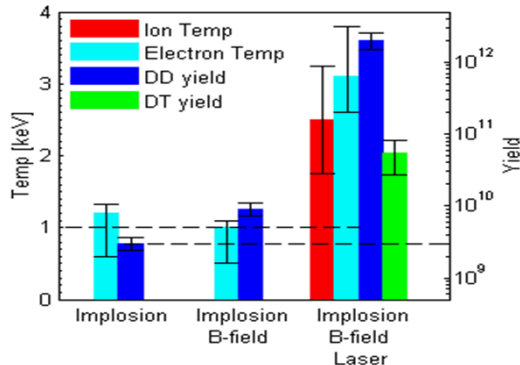
Imaging



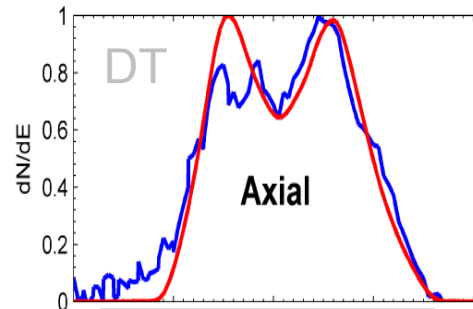
Spectra



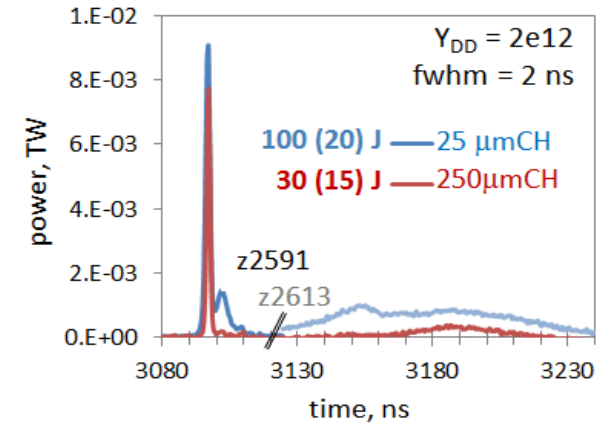
Nuclear Activation



Neutron spectra



X-ray Power

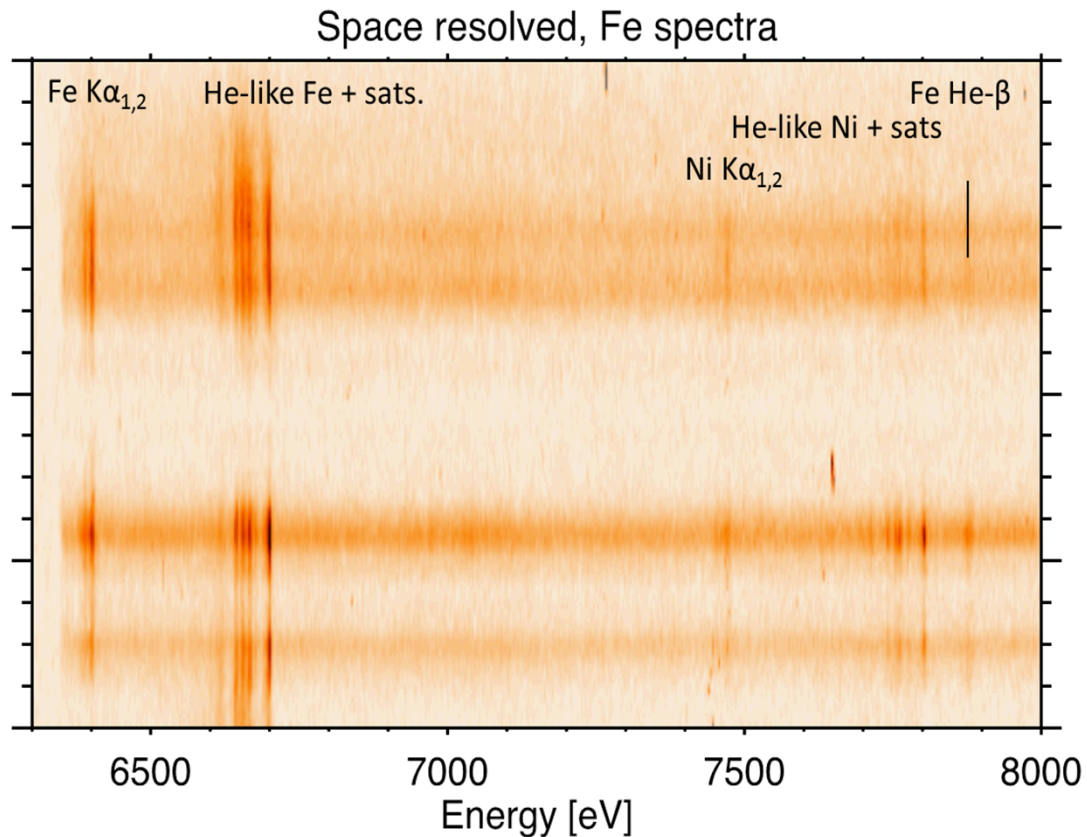
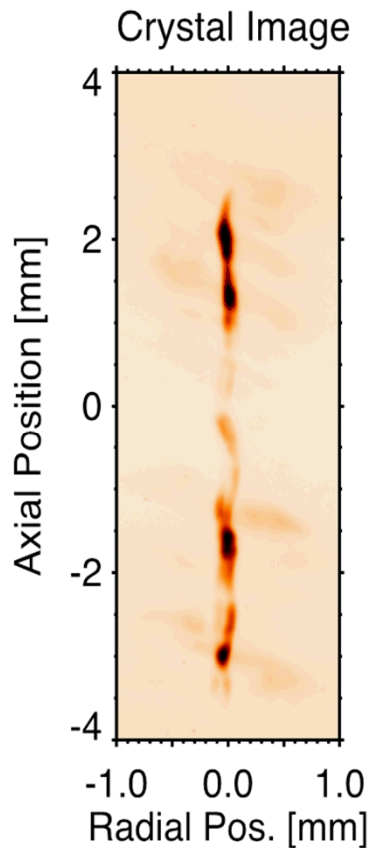
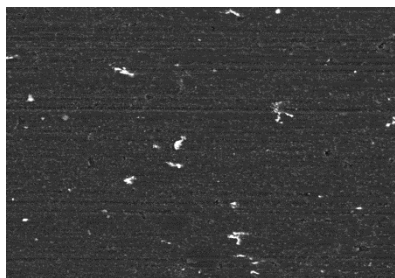


Fe impurities from the Be liner/endcap mix into the stagnation column and provide an axially-resolved diagnostic of the plasma.

MagLIF liner machined
out of S65 Be
(100 ppm Fe)



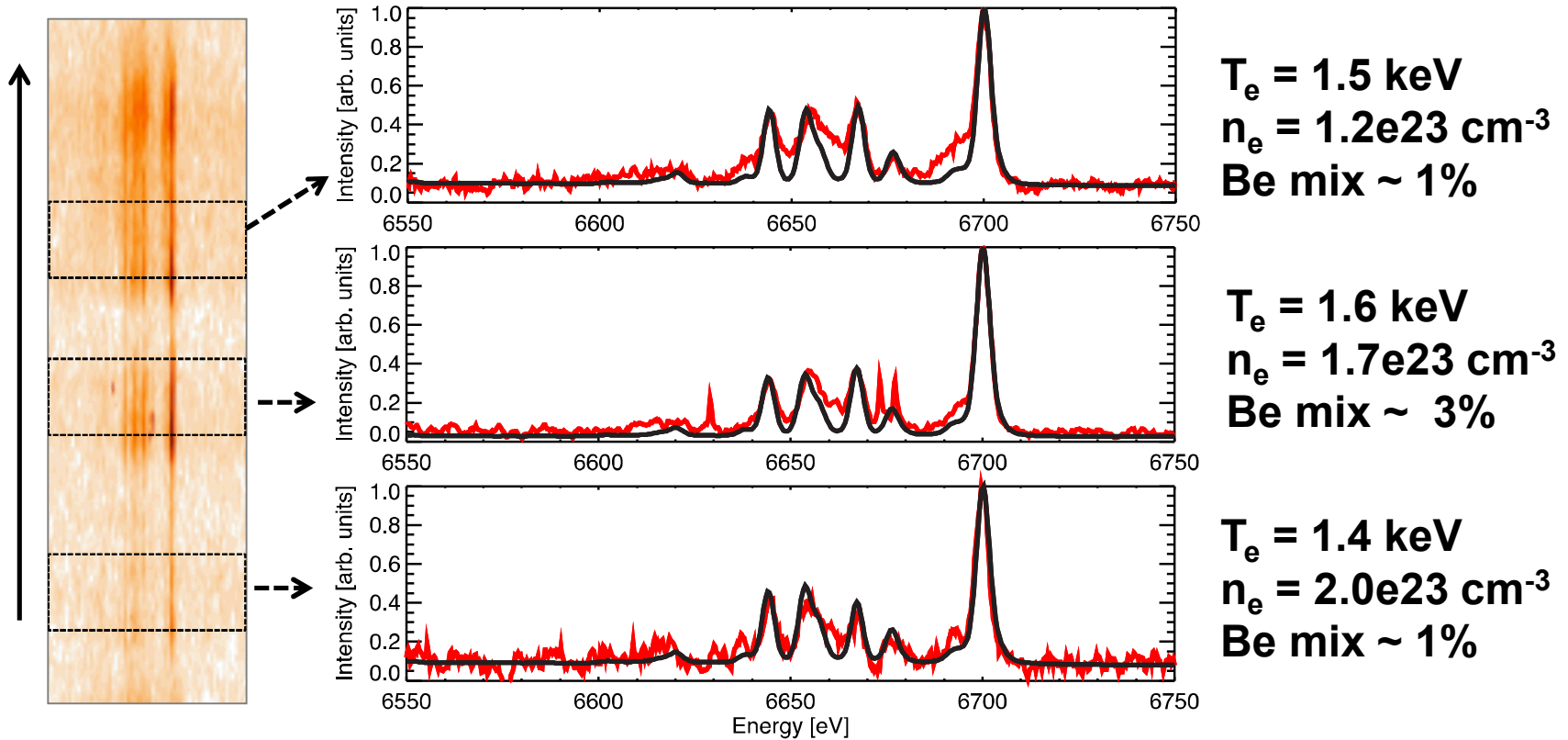
SEM image of the Be
liner outer surface



The Fe spectra can provide information on the plasma temperature, density, and mix fraction.

Experimental spectra fitted with PrismSPECT simulations using $E/\Delta E = 3000$.

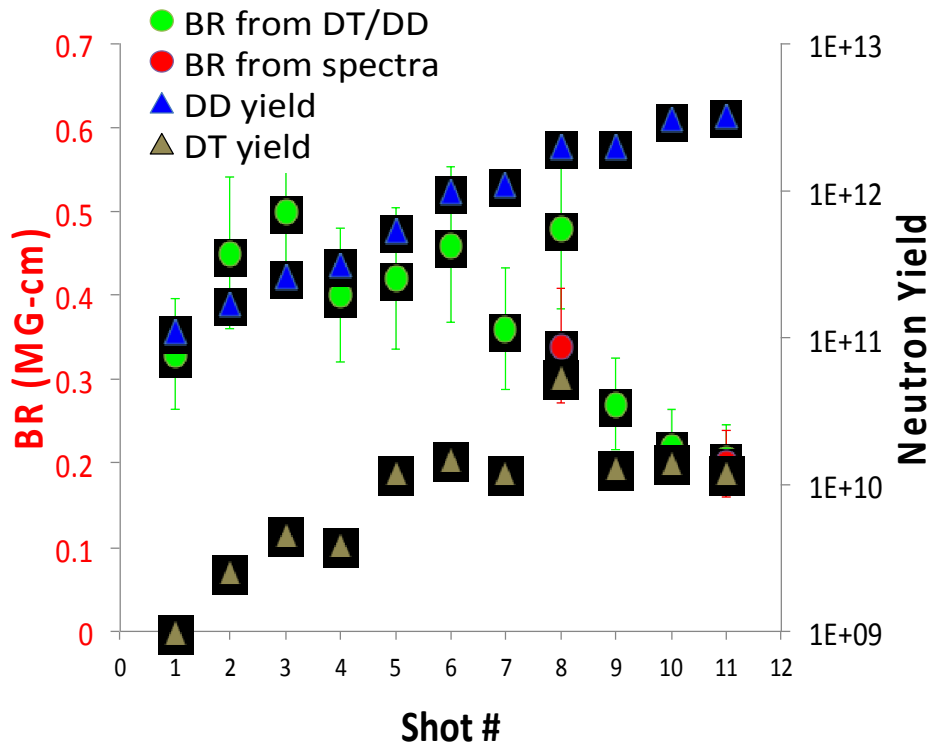
Preliminary
Inferred values



Much more work needs to be done to validate the model assumptions

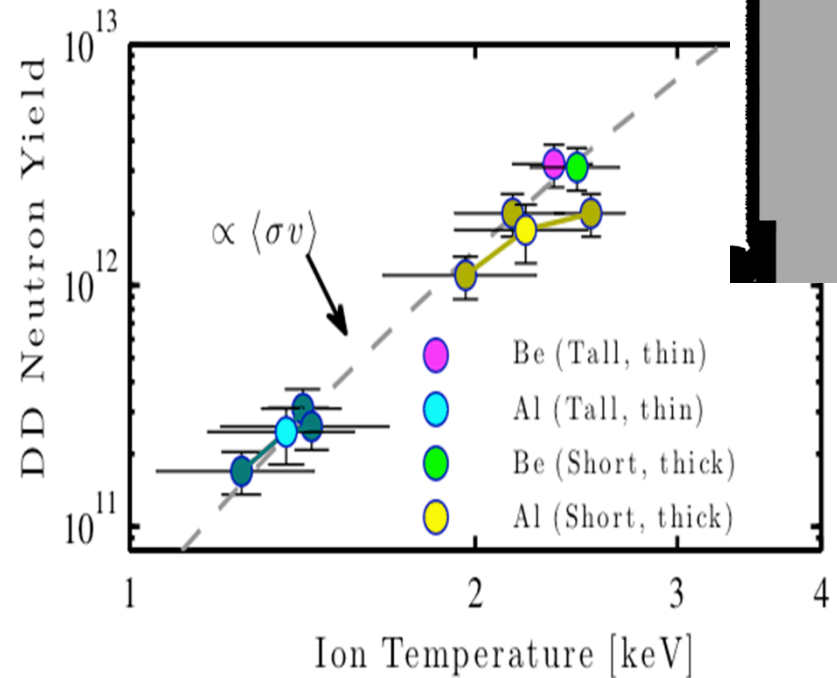
We are starting to collect enough data to study trends in the interplay between the various physical processes of MagLIF.

BR, DD, and DT yield comparisons



Note: Plot is sorted by increasing DD yield, not time.

Y_{DD} vs. T_i

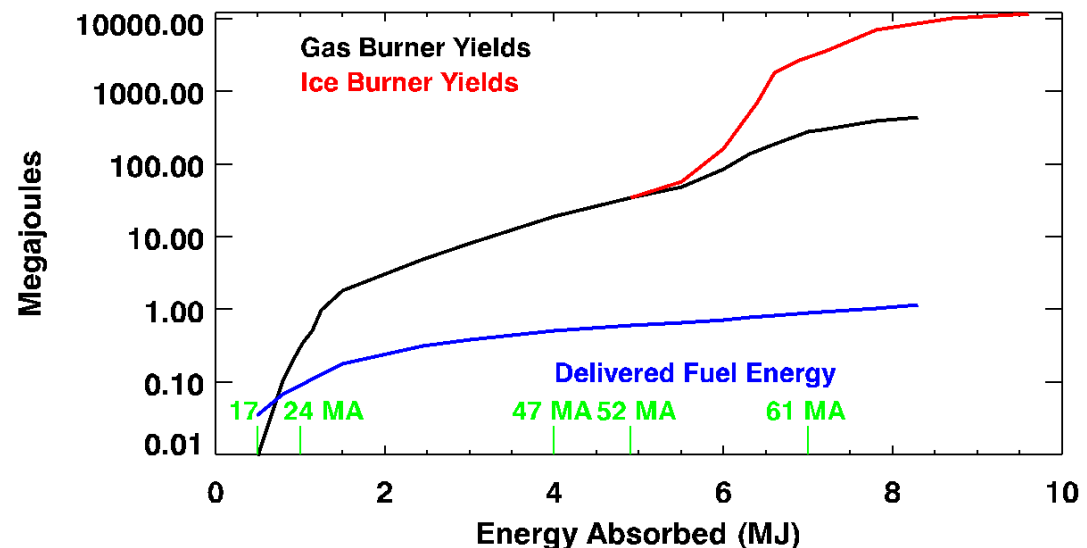
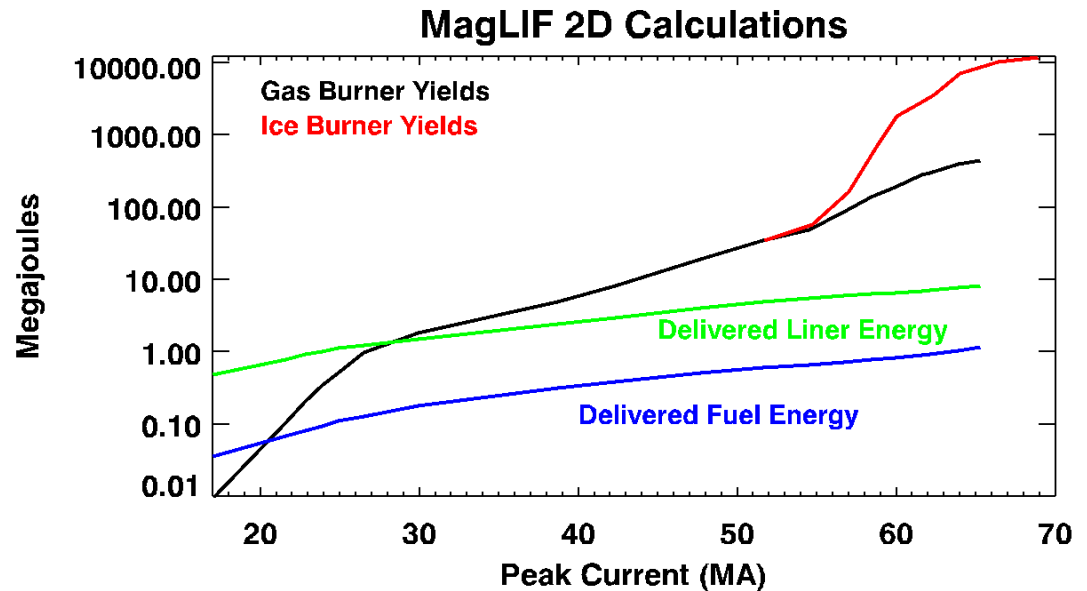


Over the next five years, we seek to accomplish the following goals related to modeling, simulation, & scaling:

- **Improve our existing codes capable of fully-integrated simulations by upgrading the MHD-based models in them**
 - All of the codes benchmarked to date as being useful for simulating all aspects of magneto-inertial fusion are based on fluid-like MHD approximations
 - Additions to the models are needed to capture more of the relevant physics, including magnetic flux loss (Nernst, Ettinghausen) and current flow in low-density plasma (“extended MHD”)
- **Investigate hybrid particle-in-cell codes as an alternative approach to fully-integrated simulations**
 - Traditional particle-in-cell codes do not scale well to the high particle densities typical of inertial confinement fusion
 - Hybrid fluid/particle calculation techniques may allow some codes to bridge the gap into this area (e.g., LSP or other ASC codes)
- **Develop tools and experiments for validating our simulations**
 - Theoretical test problems (e.g., magnetic Noh problem)
 - Highly-specialized test codes with better physics models

We are still working on validating our 2D calculations of MagLIF to understand whether they credibly scale

- Today's MagLIF experiments couple 17-18 MA (~ 0.5 MJ) to the target
- At 24 MA, an optimized target design with 30 T and >6 kJ of preheat is predicted by 2D LASNEX calculations to produce >100 kJ DT yield
- Obtaining all of these parameters simultaneously on Z will be a challenge!



We need to make rapid progress in the next 5 years to evaluate the science and general efficacy of MagLIF and establish credible requirements for ignition and high yield.

FY17 ■ Develop a methodology for inferring B-r and P- τ as quantitative performance metrics from integrated MagLIF experiments.

■ Demonstrate >1 kJ of laser energy coupled to the MagLIF fuel

■ **Develop and characterize a MagLIF baseline at ≥ 20 T, ≥ 20 MA, and ≥ 2 kJ**

■ Quantify the amount and relative origins of Mix

■ **Develop and characterize an enhanced MagLIF baseline at 30 T, 22-24 MA, and ≥ 6 kJ**

■ Provide credible physics extrapolation to ignition

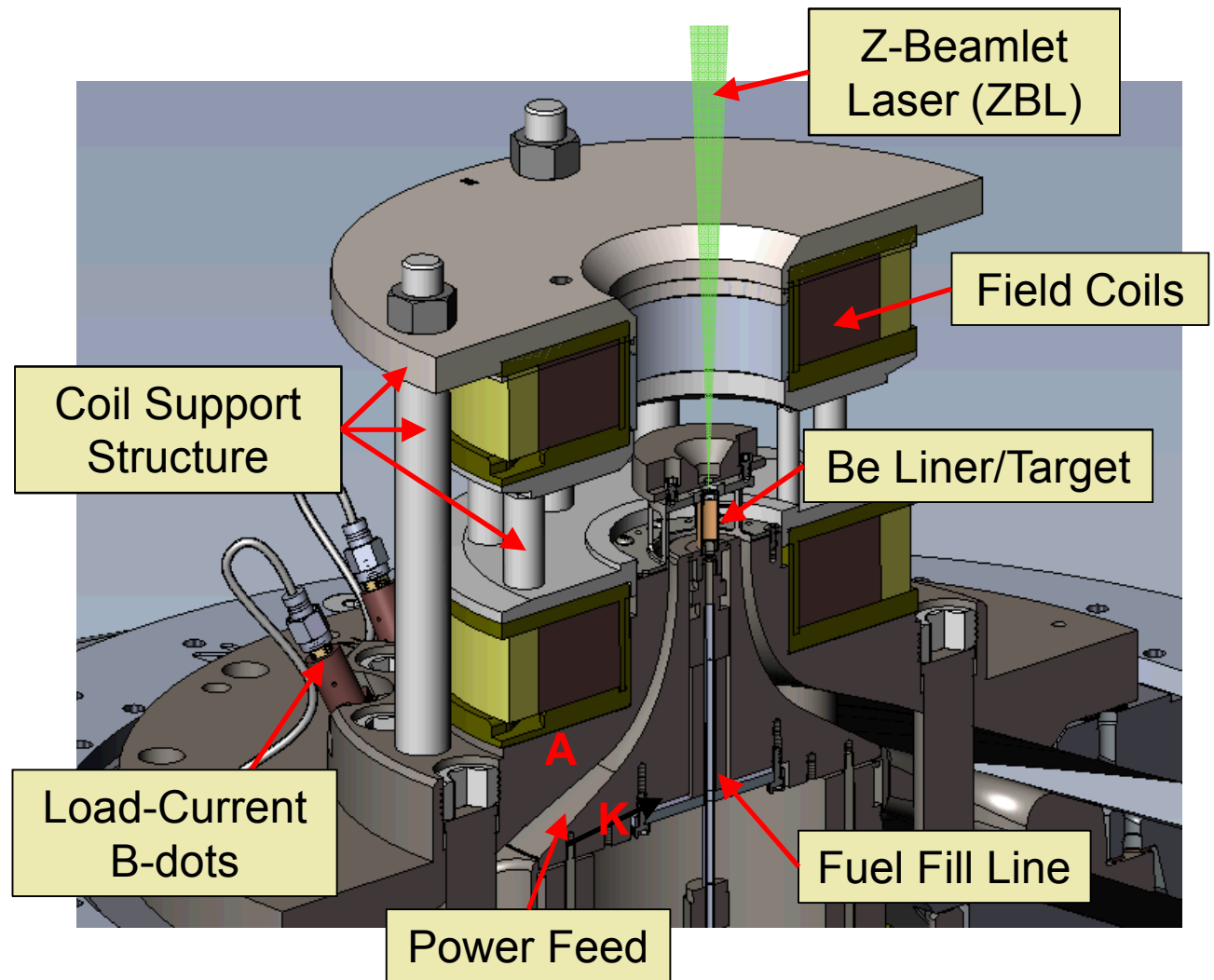
■ Demonstrate 30 kJ heating on NIF

FY20

Extra

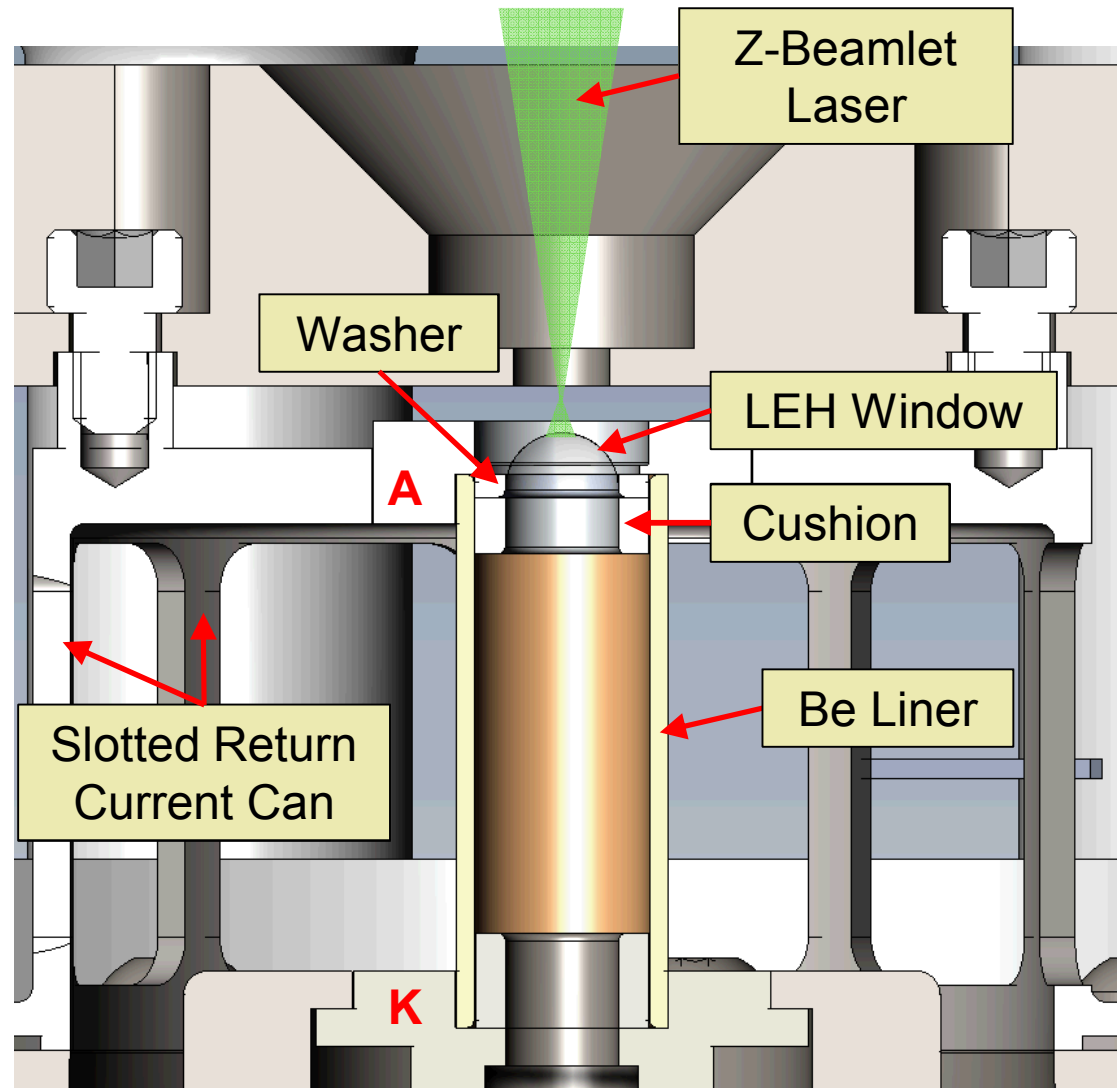
Anatomy of a MagLIF Experiment

- **Field Coils:**
Helmholtz-like coil pair produce a 10-30 T axial field w/ ~3 ms rise time
- **ZBL:** 1-4 kJ green laser, 1-4 ns square pulse w/ adjustable prepulse (prepulse used to help disassemble laser entrance window)



Anatomy of a MagLIF Target

- **Be Liner:** OD = 5.58 mm, ID = 4.65 mm, h = 5–10 mm
- **LEH Window:** 1-3 μm thick plastic window. Supports 60 PSI pure D₂ gas fill.
- **Washer:** Metal (Al or Be) washer supporting LEH window
- **Cushion:** Al or Be structure used to mitigate the wall instability. Also reduces LEH window diameter to allow thinner windows
- **Return Can:** Slotted for diagnostic access



Preliminary diagnostic development plan for Magnetic Direct Drive effort on Z

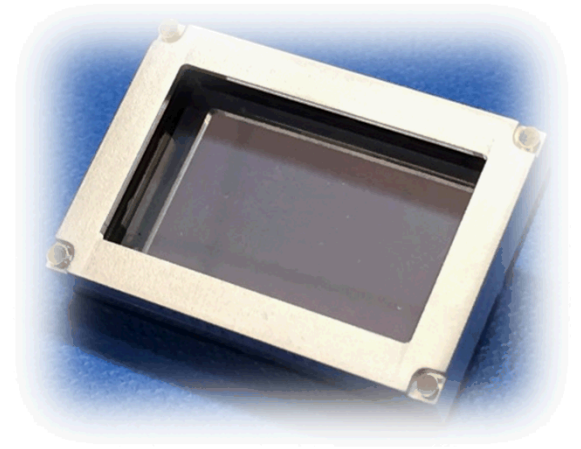
Stagnation	Te(t), ne(t)	hCMOS focusing spectrometer	FY17
		MLM continuum diodes	FY17
		SLOS focusing spectrometer	?
	X-ray Morphology(t)	MCP in-chamber pinhole	FY16
		SLOS crystal imager	?
	T_brysk	Gated nTOF	FY16
		Far-field nTOF	FY19
	MRS (Tritium)	?	
	Fusion Morphology	MagLIF n-Imaging (Tritium?)	FY17-18
	Burn History	GRH (Tritium)	FY18-19
Implosion	Liner stability at high convergence	>7keV radiography	FY16
		4-frame hCMOS radiography	FY17
	Liner stability on integrated shots	Tandem radiography	FY17
		Down-scattered n-imaging (Tritium)	?
	3-D liner stability	Multi-view radiography	FY19-20
Preheat	Te(t), ne(t) of preheat	hCMOS LEH imaging	FY16
		hCMOS LEH spectrometer	FY17
		Thomson scattering (NIF/ Ω)	FY18-19
Driver-Target Coupling	Load Current	PDV/VISAR	FY16
		Line VISAR	FY17
	Plasma and field strength in feed	Streaked visible spectroscopy	FY16-17

The Priority Research Directions are also helping to define the main diagnostic needs for the MDI effort

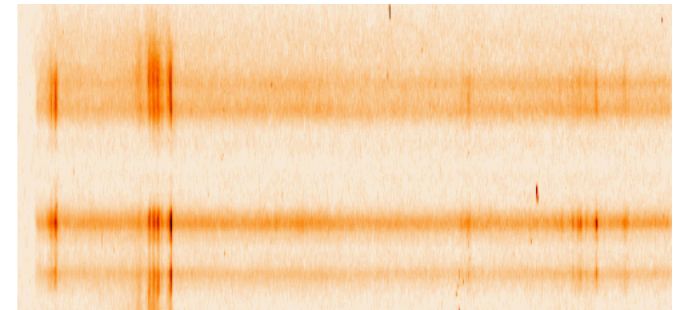
Stagnation & Burn Diagnostic Needs

- Time-gated high resolution spectra
 - hCMOS-based focusing spectrometer (1-2 years)
 - SLOS-based focusing spectrometer (3-5 years)
- Time-gated high resolution imaging
 - MCP-based in-chamber pinhole (this year)
 - SLOS-based crystal imager (3-5 years)
- Neutron Spectrum
 - Gated nTOF (this year)
 - CRS/MRS (requires tritium)
- Neutron Imaging (1-3 years)
- Reaction History (requires tritium)
- Continuum Spectroscopy
 - Mirrored diodes (1 year)

Multi-frame hCMOS Sensor



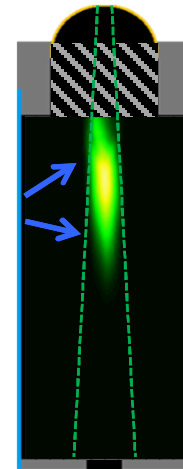
Space-Resolved Fe Spectra from MagLIF stagnation



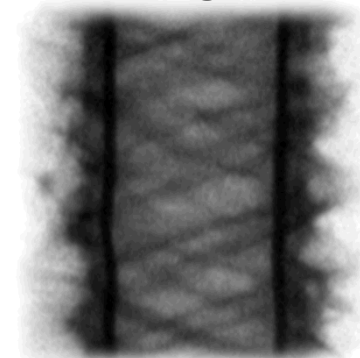
The Priority Research Directions are also helping to define the main diagnostic needs for the MDI effort

- **Implosion diagnostic needs**
 - Tandem radiography (1 year)
 - 4-frame hCMOS-based radiography (1-2 years)
- **Preheat diagnostic needs**
 - Thomson Scattering (Omega & NIF)
 - Gated LEH Imaging with hCMOS (this year)
 - Gated LEH Spectroscopy with hCMOS (1 year)
- **Driver-target coupling diagnostic needs**
 - PDV/VISAR (this year)
 - Visible spectroscopy for current flow (LDRD)

Monochromatic Preheat Image



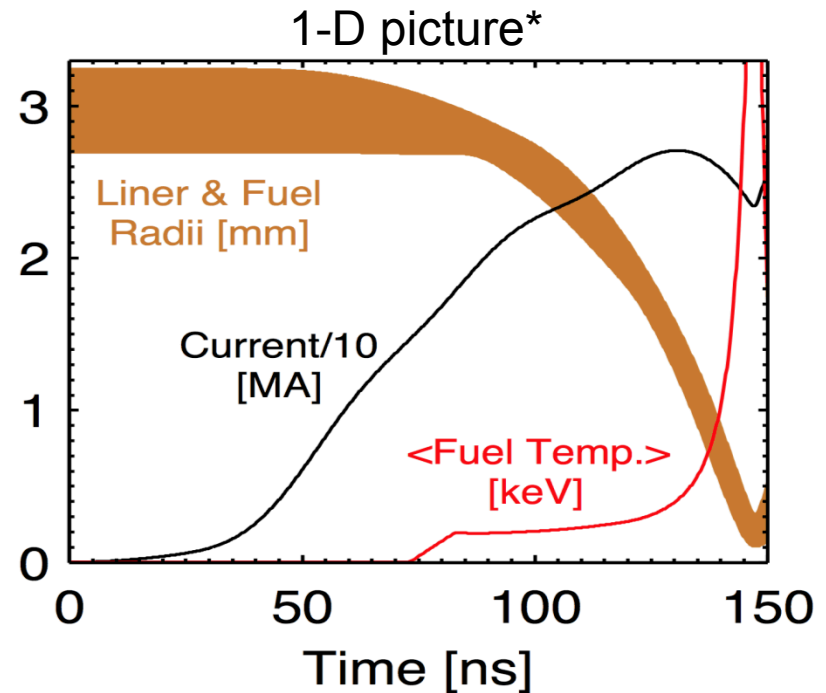
Monochromatic Implosion Radiograph



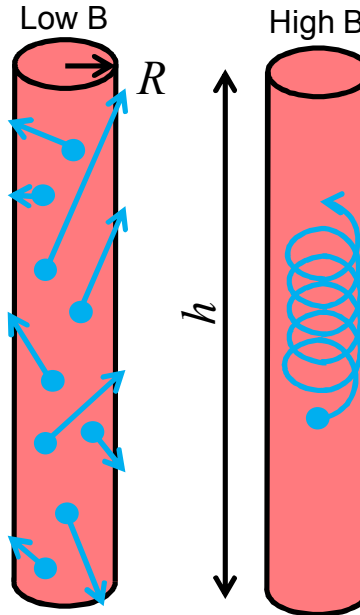
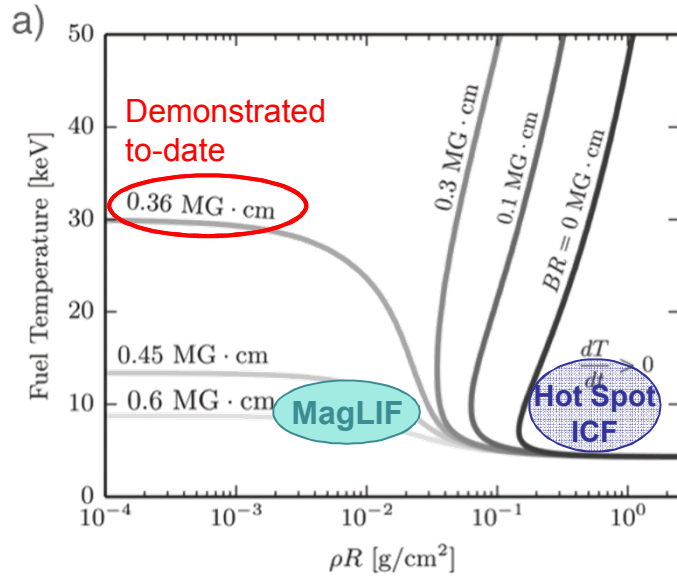
MagLIF has conservative fuel compression characteristics, but relies on largely unvalidated magneto-inertial fusion principles

Metric	X-ray Drive on NIF	100 kJ MagLIF on Z
Pressure	~140-160 Mbar	26 MA at 1 mm is 100 Mbar
Force vs. Radius	Goes as R^2	Goes as $1/R$
Peak velocity	350-380 km/s	70-100 km/s
Peak IFAR	13-15 (high foot) to 17-20	8.5
Hot spot CR	35 (high foot) to 45	25
Volume Change	43000x (high) to 91000x	625x
Fuel ρ -R	$>0.3 \text{ g/cm}^2$	$\sim 0.003 \text{ g/cm}^2$
Liner ρ -R	n/a	$>0.3 \text{ g/cm}^2$
BR	n/a	$>0.5 \text{ MG-cm}$
Burn time	0.15 to 0.2 ns	1 to 2 ns
T_{ion}	$>4 \text{ keV}$	$>4 \text{ keV}$

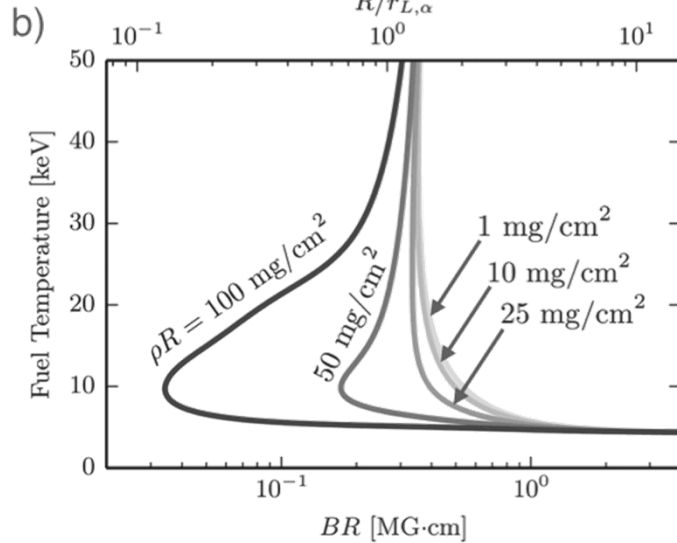
- Low Velocity Implosion
- Low IFAR
- Low convergence ratio / volume compression / fuel ρR



Magnetization (“BR”) reduces rho-R requirements and minimizes electron heat losses



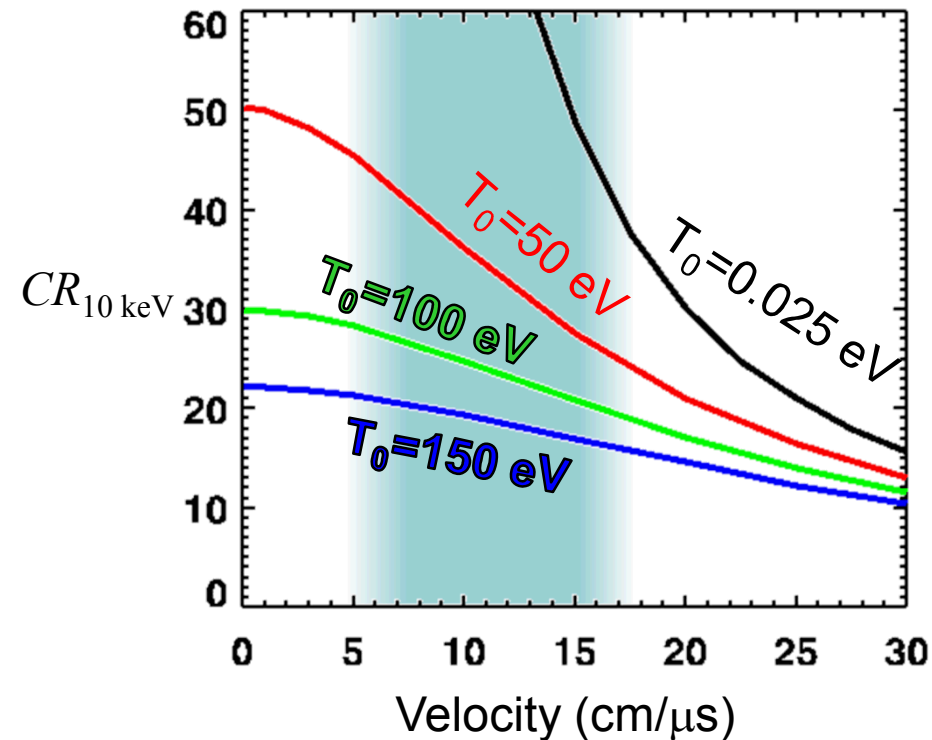
- Fraction of trapped α 's (tritons) is a function of **BR**
- At BR > 0.5 MG-cm the effects saturate (particles are well confined).
- Measurements to date suggest > 0.3 MG-cm



$$\frac{R}{r_{\alpha}} = \frac{BR [T \cdot \text{cm}]}{26.5} = \frac{BR [G \cdot \text{cm}]}{2.65e5} \approx 4BR [MG \cdot \text{cm}]$$

Preheating the fuel reduces the requirements on implosion velocity and convergence

Simulated CR necessary to achieve $T = 10 \text{ keV}^*$



Temperature rise for an ideal adiabatic cylindrical compression

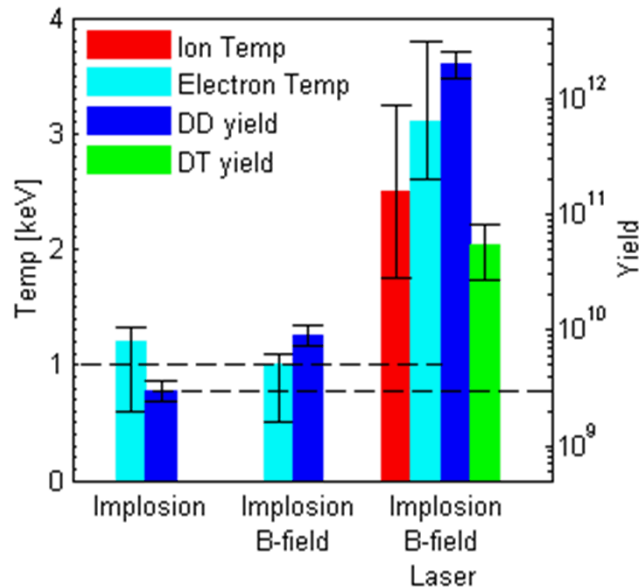
$$T = T_0 \underbrace{(r_0/r_f)^{4/3}}_{CR}$$

- Laser heating of fuel (6-10 kJ) offers one way to reach pre-compression temperatures of $\sim 200 \text{ eV}$
- Detailed simulations suggest we can reach fusion temperatures at $CR = 25$

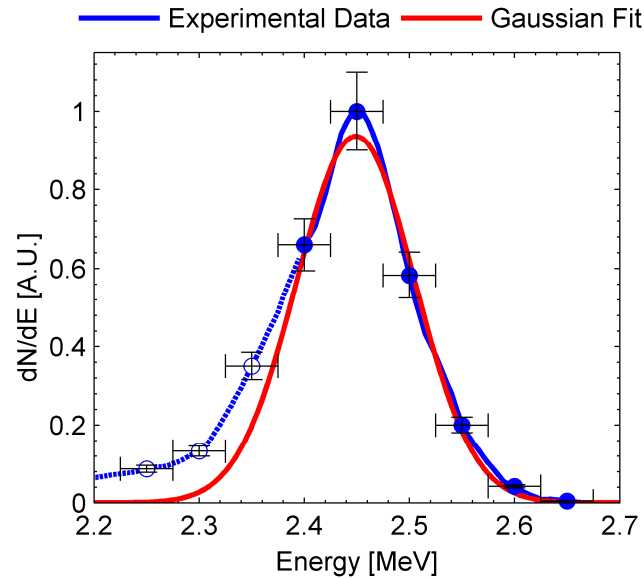
*Constant velocity cylindrical implosion of D_2 gas assuming no radiation or conductivity losses

Initial integrated experiments on Z demonstrated that the fundamental concepts of MagLIF work.

Significant yields and temperatures only w/ applied B_z and preheat

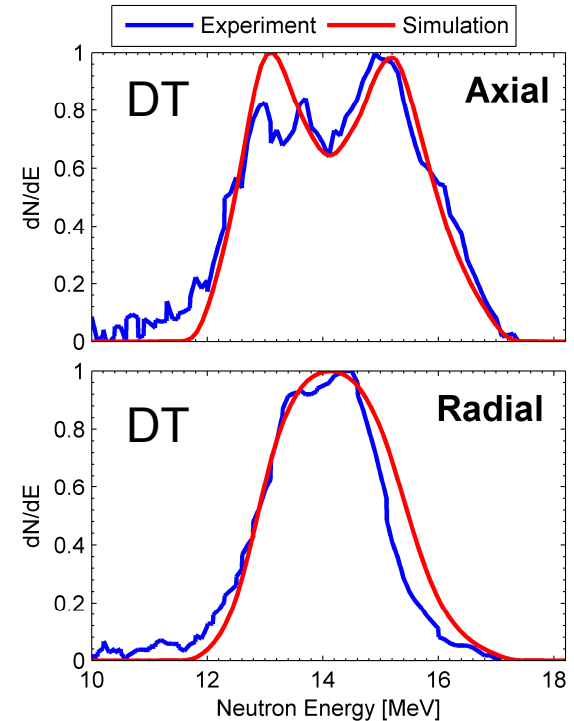


Thermonuclear neutron generation



Isotropic, 'Near-Gaussian' DD neutron spectra

Magnetic trapping of charged particles



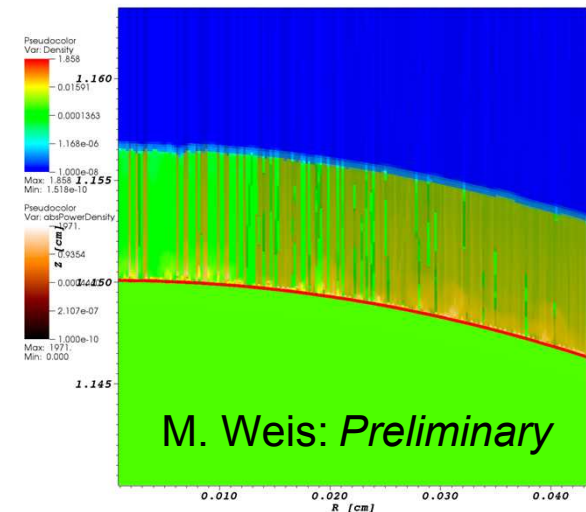
BR = 0.35 MG-cm

Max DD neutron yield = 3×10^{12}
Max ion temp = 2.5 keV

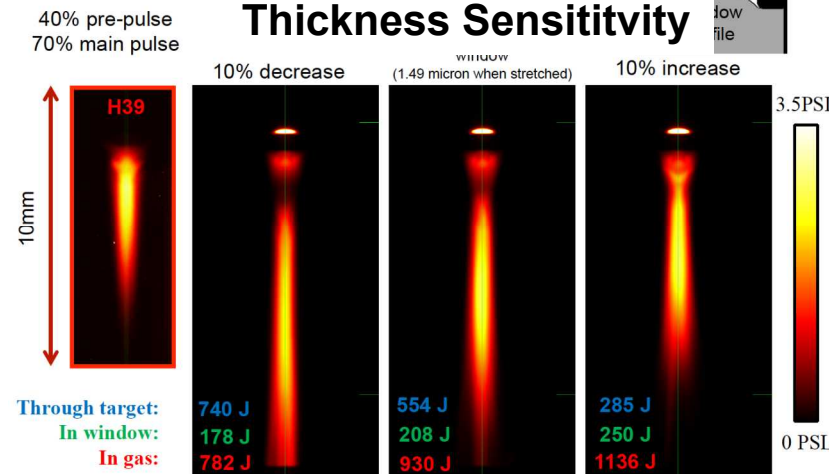
We are addressing simulation discrepancies in two ways

- How well do we really know our initial conditions?
 - Laser focus, delivered energy, etc.
 - Could IR Amplified Spontaneous Emission (ASE) be pre-disassembling LEH window?
 - What is level of laser scatter due to LPI? (2ω , $2.5e14$ W/cm²)
 - Does firing the magnetic field coils change initial state of window or target?
 - Is the laser interacting with the focusing target?
- Are the physics models in our hydrodynamic codes sufficient to model laser heating?

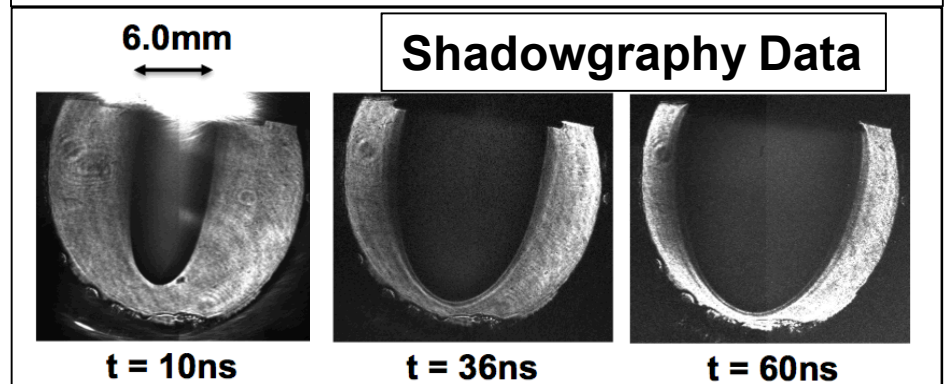
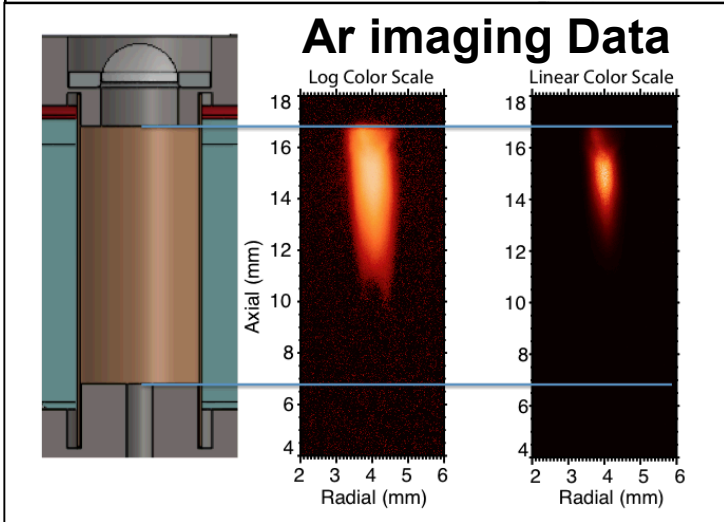
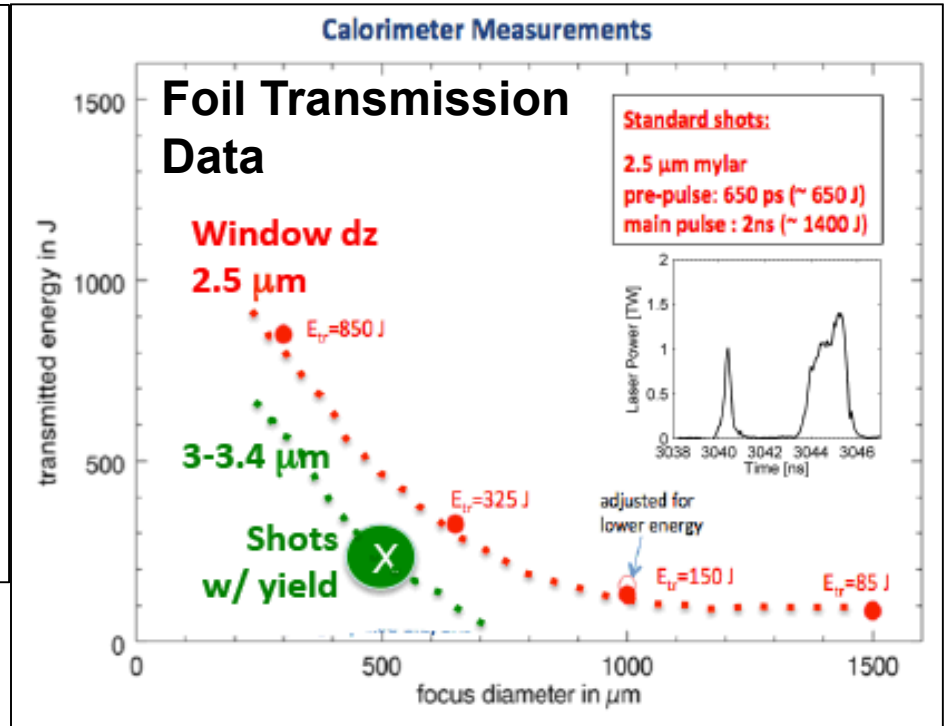
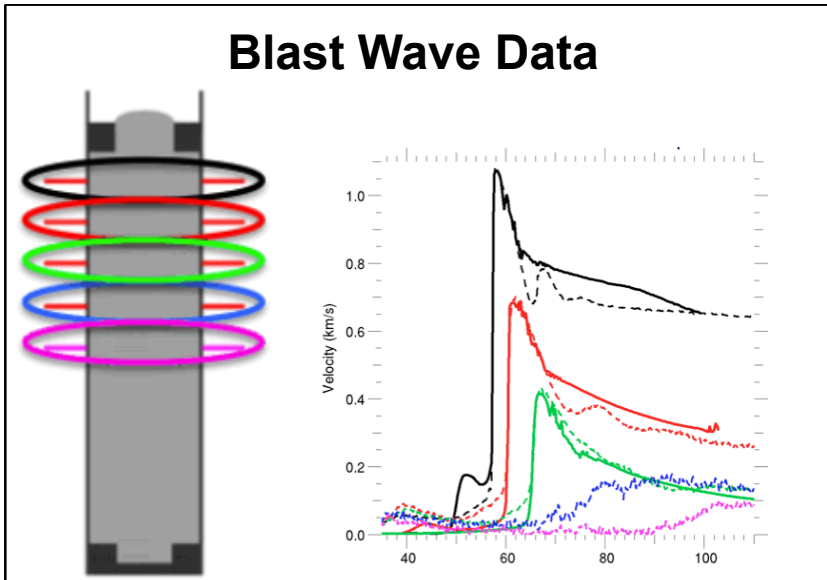
ASE: 20 mJ IR over 20 ns



Thickness Sensitivity

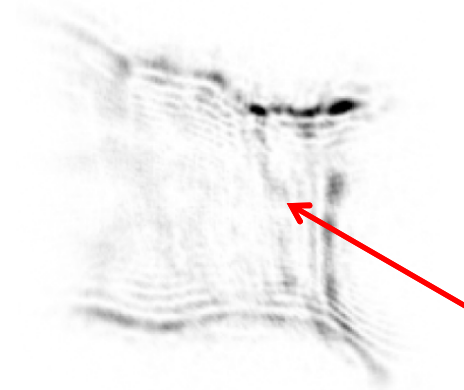


Energy coupled to the fuel in separate laser heating experiments appears to be less than originally expected.



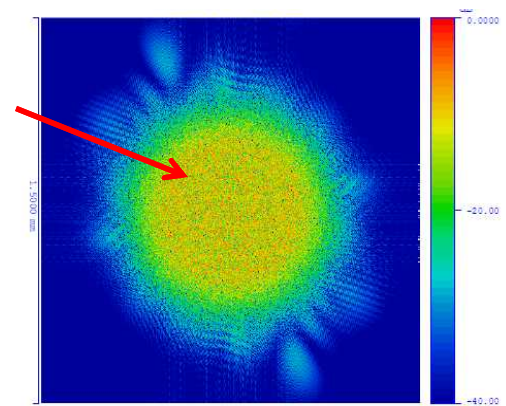
The Z-Beamlet beam spot quality may be one reason that we are not coupling as well to the fusion fuel as predicted

Z-Beamlet currently does not use any beam smoothing techniques adopted by the laser community

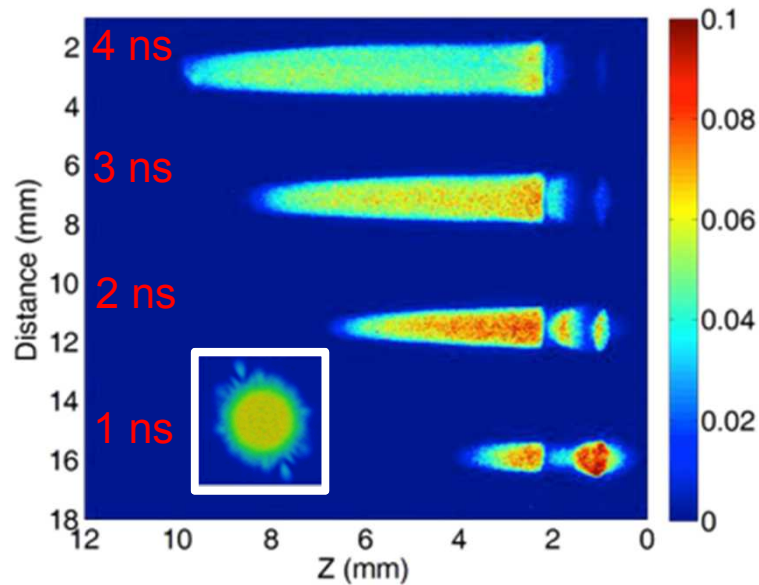


OMEGA-EP
750um DPP

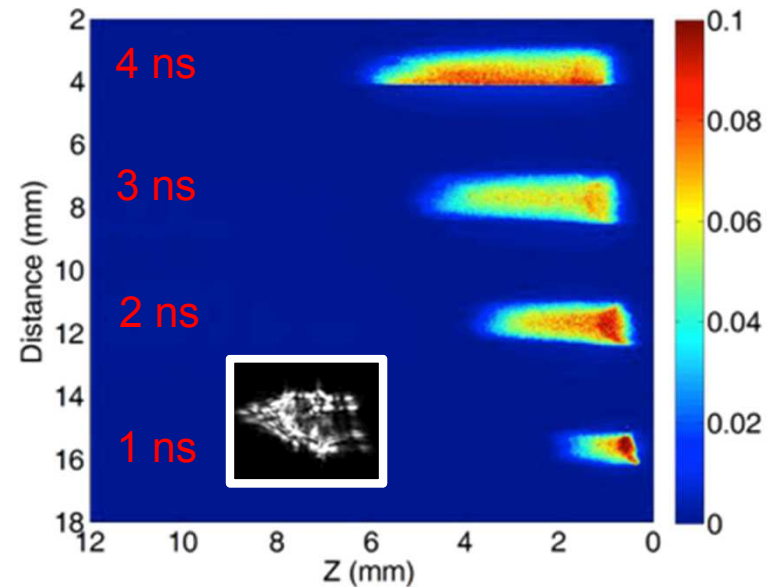
ZBL: No DPP
(representative)



4 ns/3.1 kJ, 2 μm LEH, no prepulse
with DPP (SNL Omega-EP data)



4 ns/2.93 kJ, 2 μm LEH, no prepulse
without DPP (SNL Omega-EP data)



It took until 2013 to develop the B-field and laser optics subsystems necessary to test the MagLIF concept.

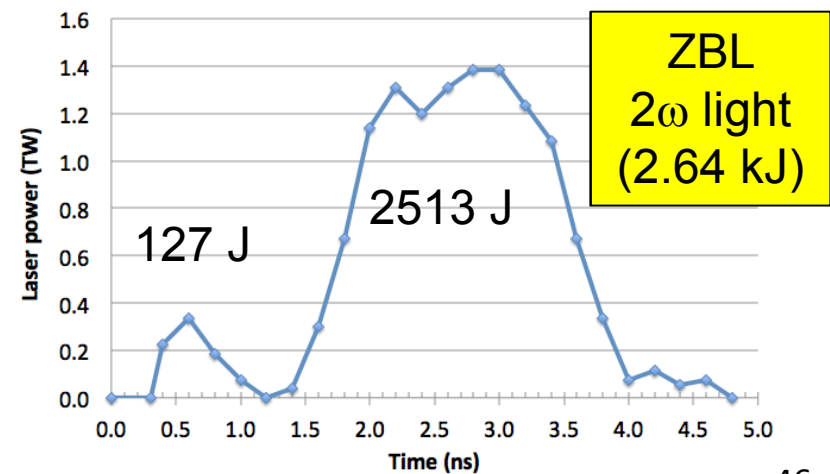
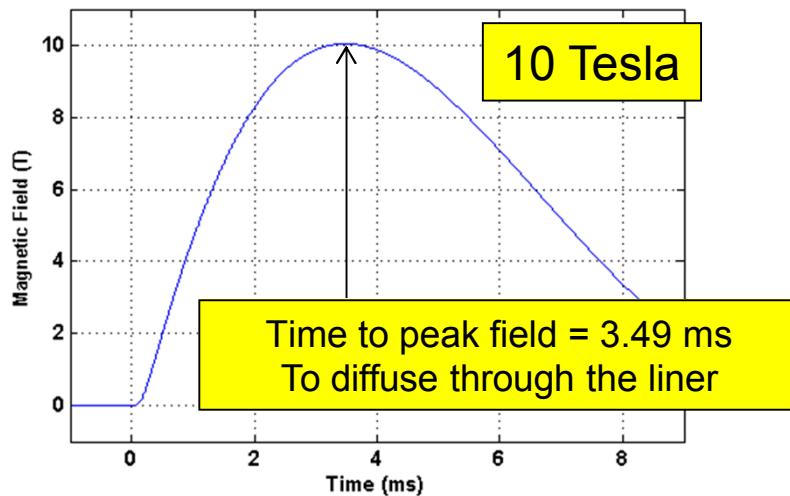
Capacitor bank system on Z
900 kJ, 8 mF, 15 kV



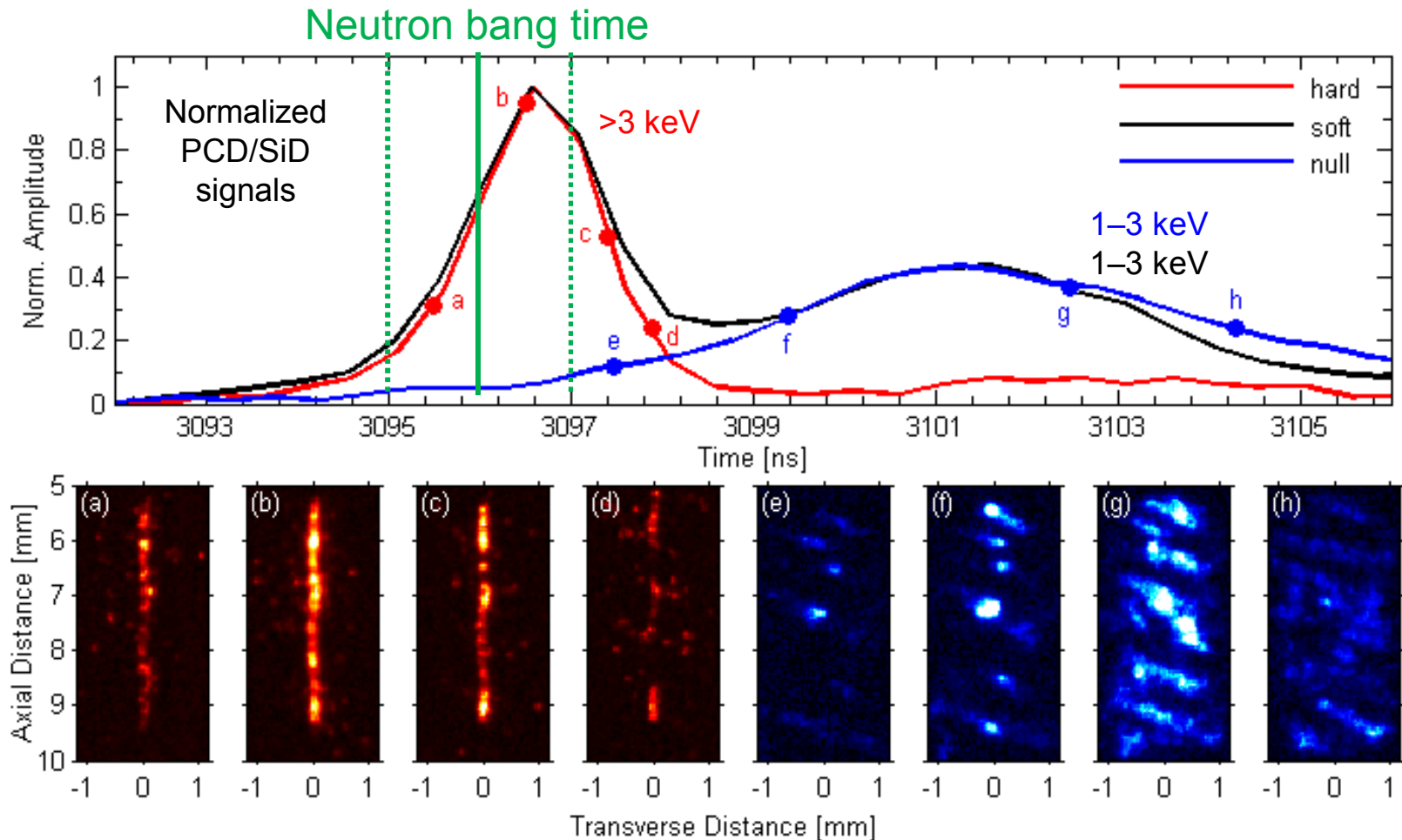
Z-Beamlet Vacuum Final Optic Assembly



10T Shot #17, SN001



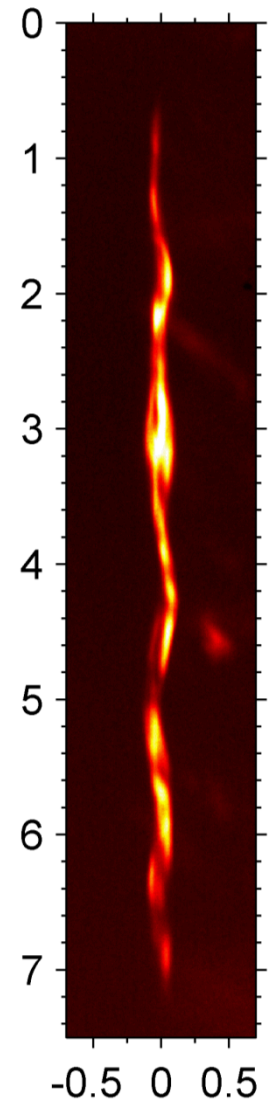
We observe a high-energy x-ray pulse from the stagnation column followed by late-time, lower energy liner emission.



- Narrow x-ray emission column observed at neutron bang time
- Emission from exterior of liner is observed with and without laser and B-field

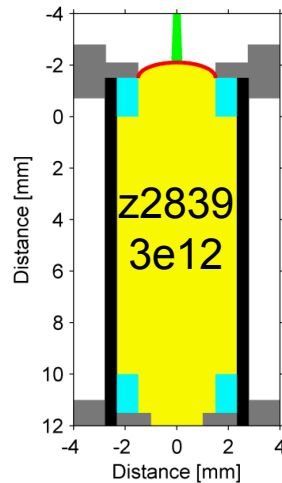
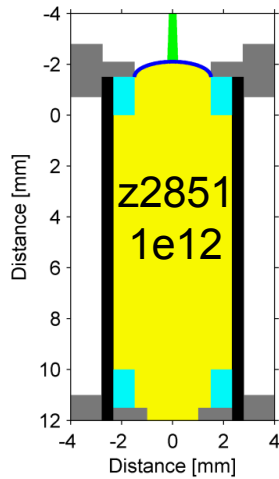
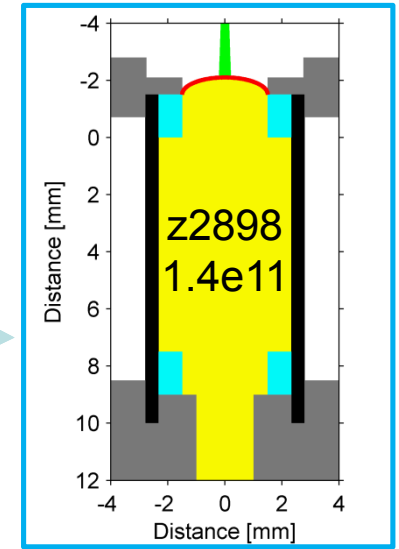
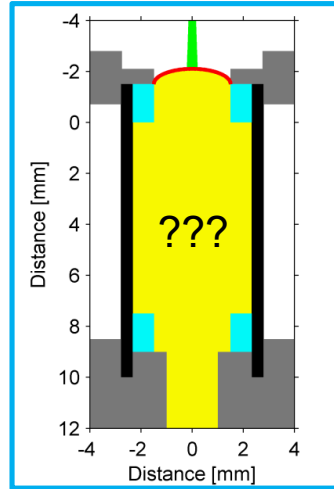
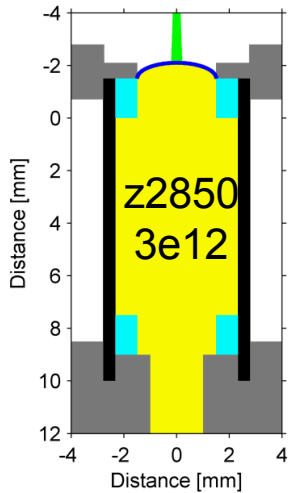
X-ray emission from the fuel shows a high aspect ratio stagnation column

- Image was produced by a time-integrated x-ray crystal optic system, and it is a combination of 6.2 and 9.4-keV emission
- Emission region does not define the fuel-liner boundary, but defines the hottest region of the fuel
- Emission FWHM is 50-110 μm
- Emission height is $> 6\text{mm}$ (approximately 80% of target height)
- Axial intensity variations indicate variations in both the fuel conditions (temperature and density) and the liner opacity
- Stagnation column appears weakly helical



The configuration of our first phase plate test was largely driven by empirical progress with the unconditioned beam

Drive current (target height 10-7.5mm)

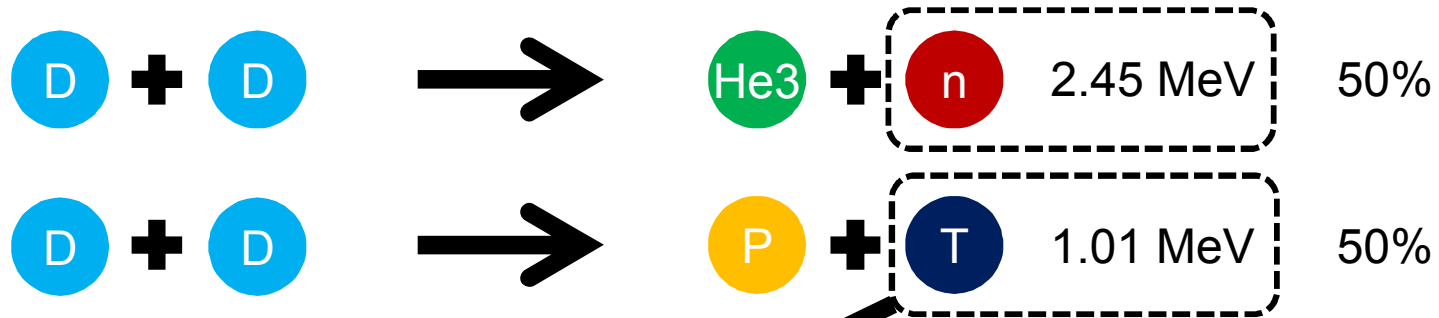


All targets have only Be components in contact with fuel

Laser coupling (window thickness, 3.5mm - 1.7mm)

All of our experiments have used deuterium gas as the fusion fuel

- Primary reactions



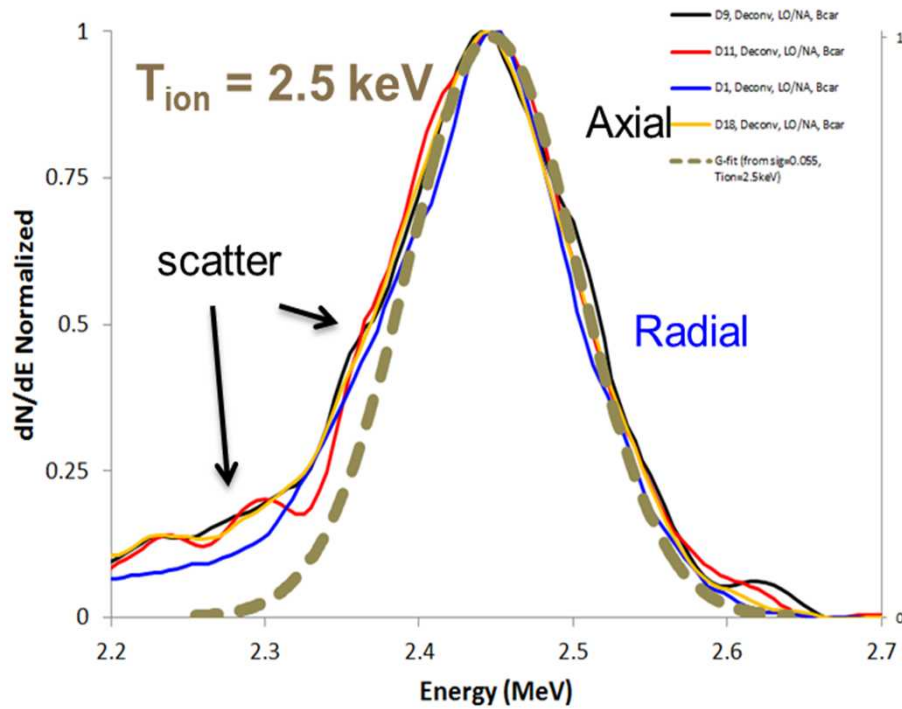
- Secondary reactions



- Triton may still retain fraction of birth energy when reacting

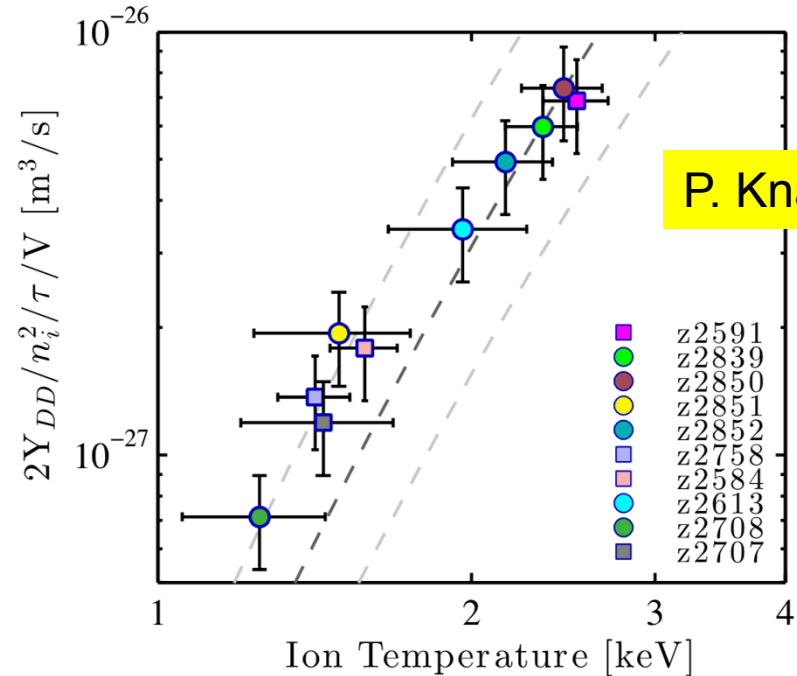
DD nTOF spectra provide a measure of T_{ion} and yield scales roughly as we expect from a thermonuclear process.

DD nTOF spectra provide one interpretation of T_{ion}



K. Hahn

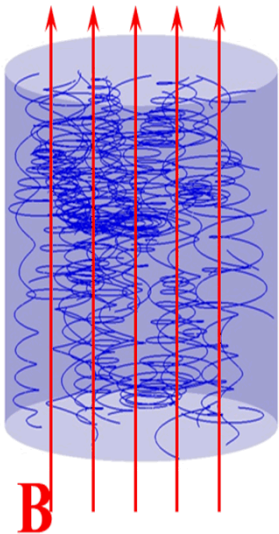
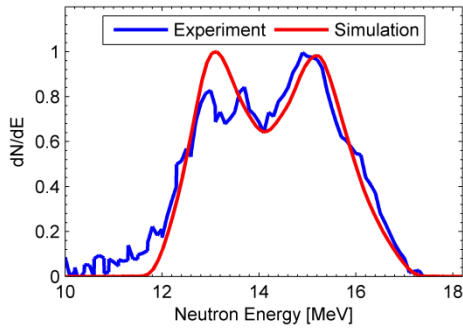
Various targets have spanned a range of ion temperatures and produce yields that are consistent with the thermonuclear cross section



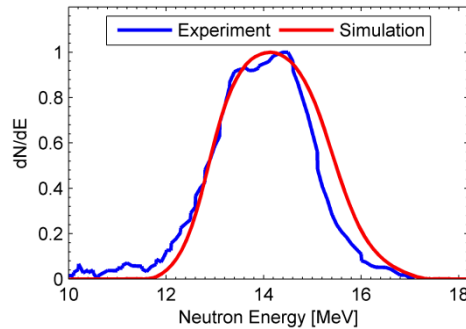
$$Y_{DD} = \frac{1}{2} n_D^2 \langle \sigma v \rangle_{DD} V \tau$$

Secondary DT yield and nTOF spectra indicate significant flux compression and resulting fuel magnetization.

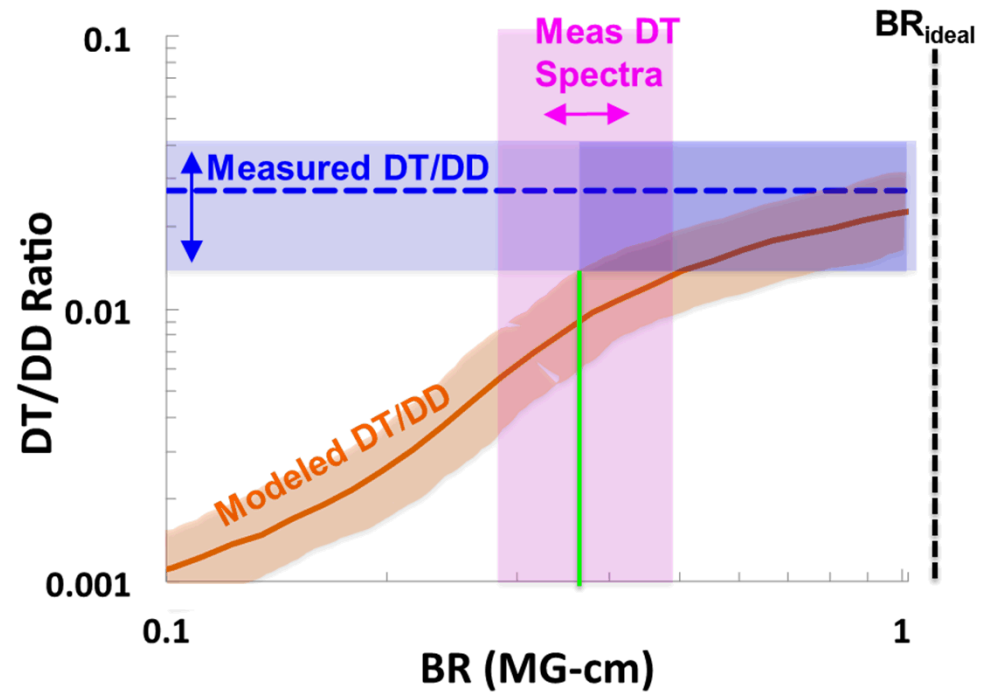
Axial DT Spectrum



Radial DT Spectrum



DT/DD Yield Ratio

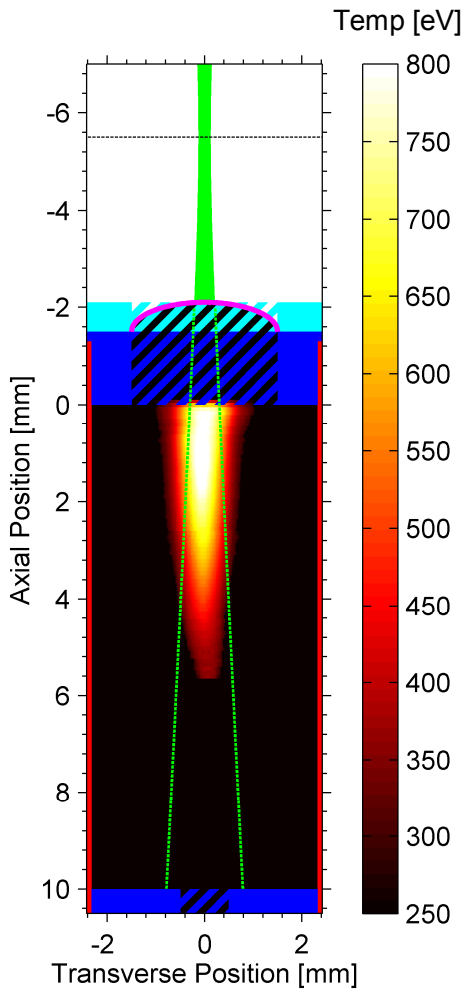


BR = 0.34 +40/-18% MG-cm

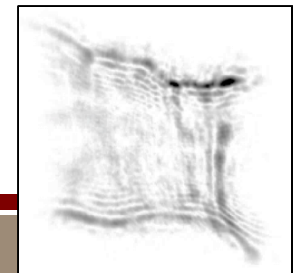
$$r_t \approx 1.1r_\alpha$$

$$\omega_{ci}T_{ie} \approx \omega_{ce}T_{ee}$$

Energy coupled to the fuel in separate laser heating experiments appears to be less than originally expected.

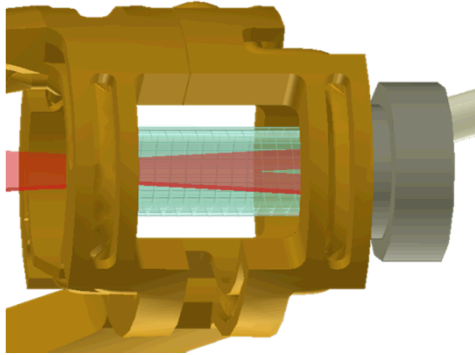


- Predicted greater than 1 kJ would be delivered to fuel
 - Energy inferred from x-ray image is only about 100-300 J
- Self-emission diagnostic is not sensitive to regions below 250 eV
 - There could be hundreds of Joules hidden
 - New target and diagnostic designs are needed to access lower temperature regions
- Energy deposition appears to increase towards the top of the target
 - There is unmeasured energy in the laser entrance channel
- Beam is unconditioned (not a smooth profile) which can substantially affect energy deposition
 - phase plates are under investigation



OMEGA-EP experiments are being conducted to develop understanding of laser energy transport & deposition.

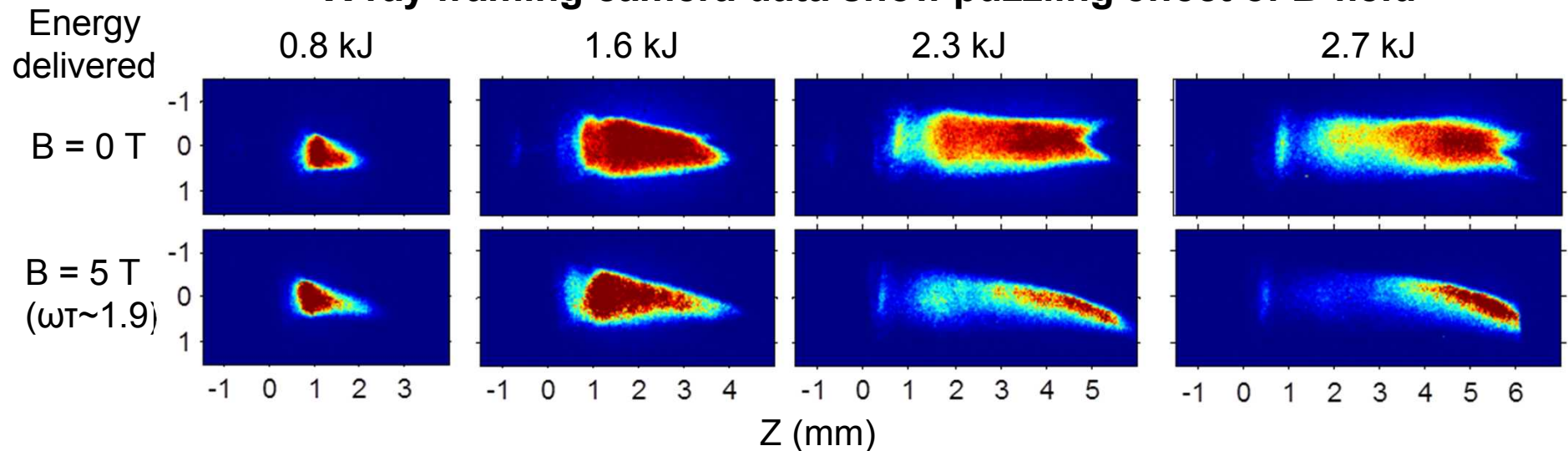
Rexolite (CH) tube
(6.5-10 mm long)



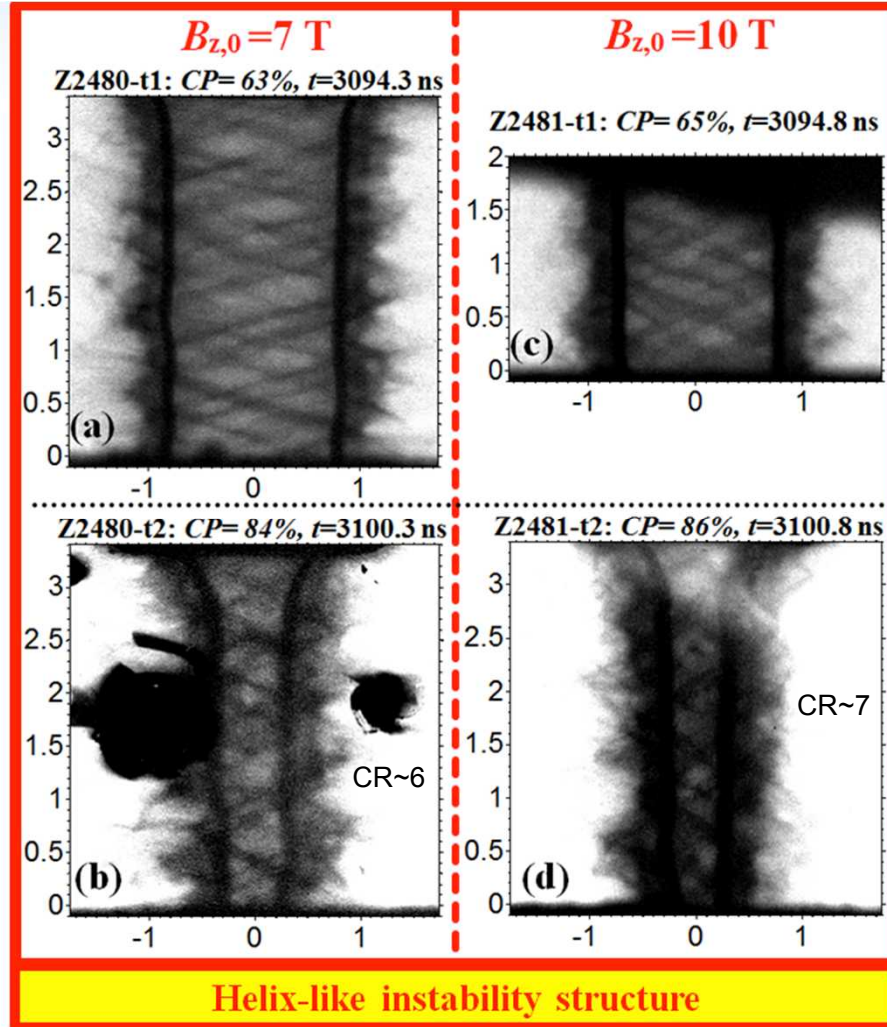
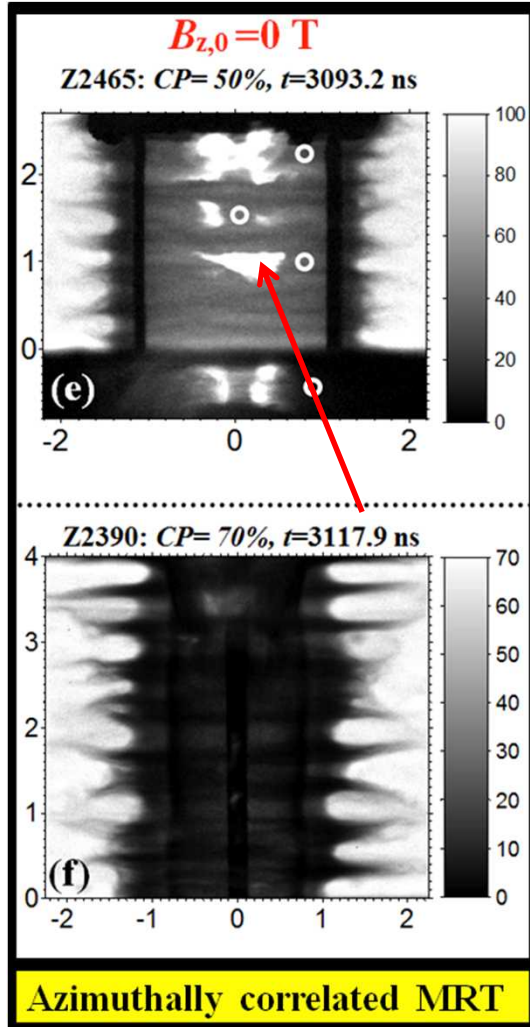
Current topics of interest for OMEGA-EP Experiments

- Effect of LEH thickness
- Effect of gas fill density
- Effect of laser intensity
- Effect of magnetization
- How and where does mix occur?
- At what conditions does LPI become important?

X-ray framing camera data show puzzling effect of B-field



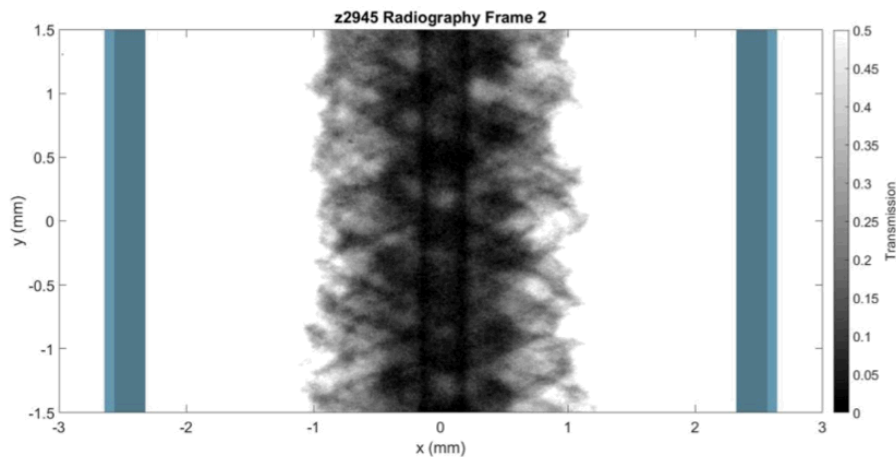
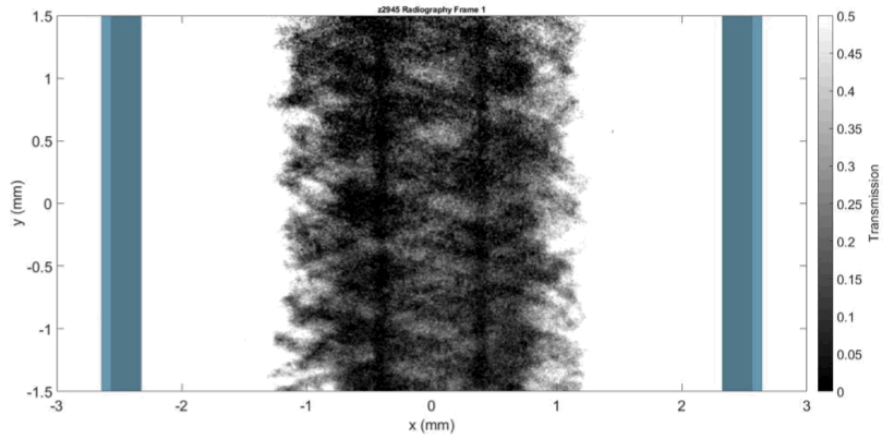
The addition of a ~ 10 T axial magnetic field produces a dramatic change in the structure of the liner instabilities



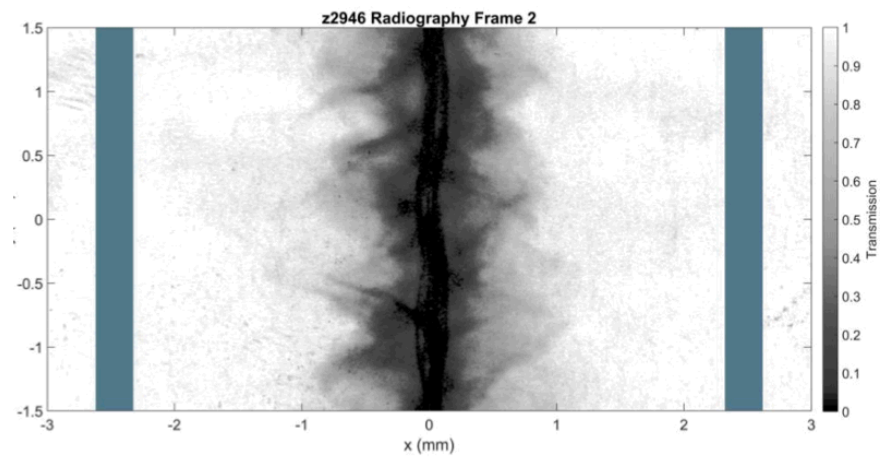
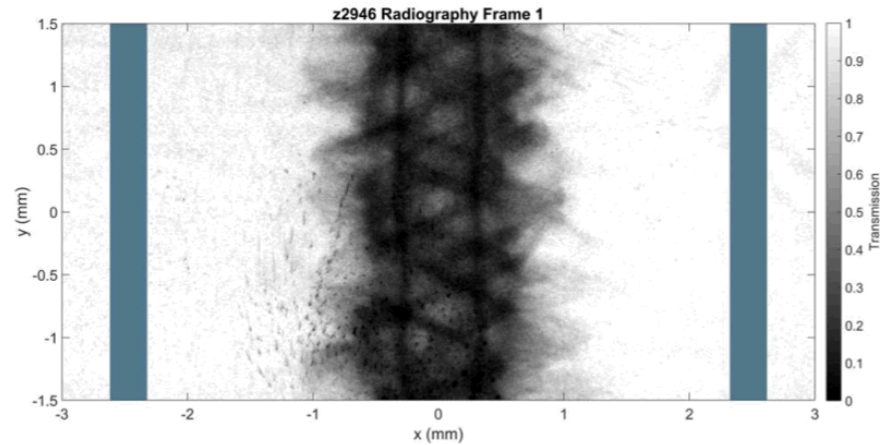
- Rather than cylindrically symmetric structures, we see helical structures
- Magnetic field reduced multi-keV x-rays associated with late-time instabilities

Late time radiography demonstrates that high aspect ratio liners can achieve more stable implosions with coatings

Coated liner

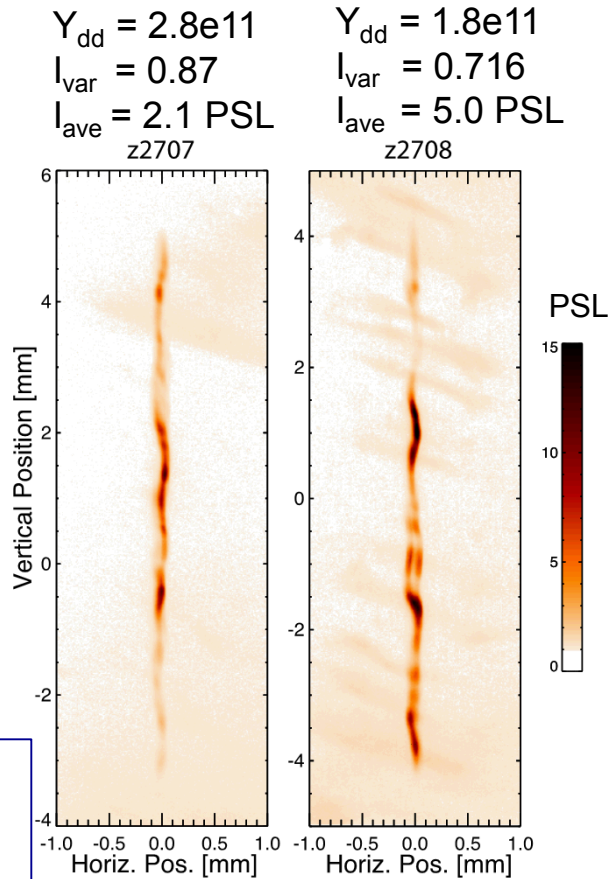


Uncoated liner

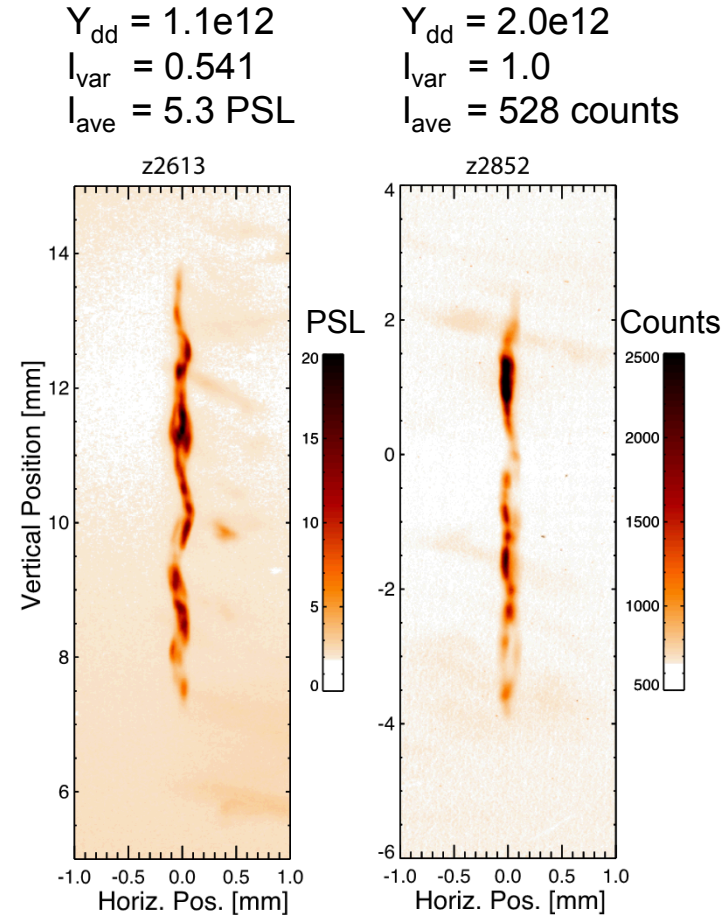
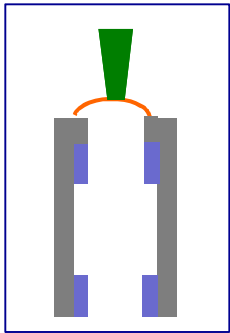


Ampleford, Rosenthal, Jennings et al.

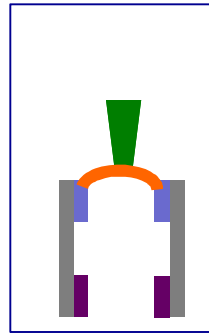
The emission morphology from nearly identical targets can vary, but DD yields are similar.



z2707 and 2708 were identical targets.
Long Be liner, thin window, and Al caps



z2613 and 2852 were nearly identical.
Both were short liners with thick windows.
z2613: Al top cap, Nylon bottom, 2 mm exit hole
z2852: Al top cap, Be bottom, 3 mm exit hole



We are investigating laser preheating on a number of different facilities.

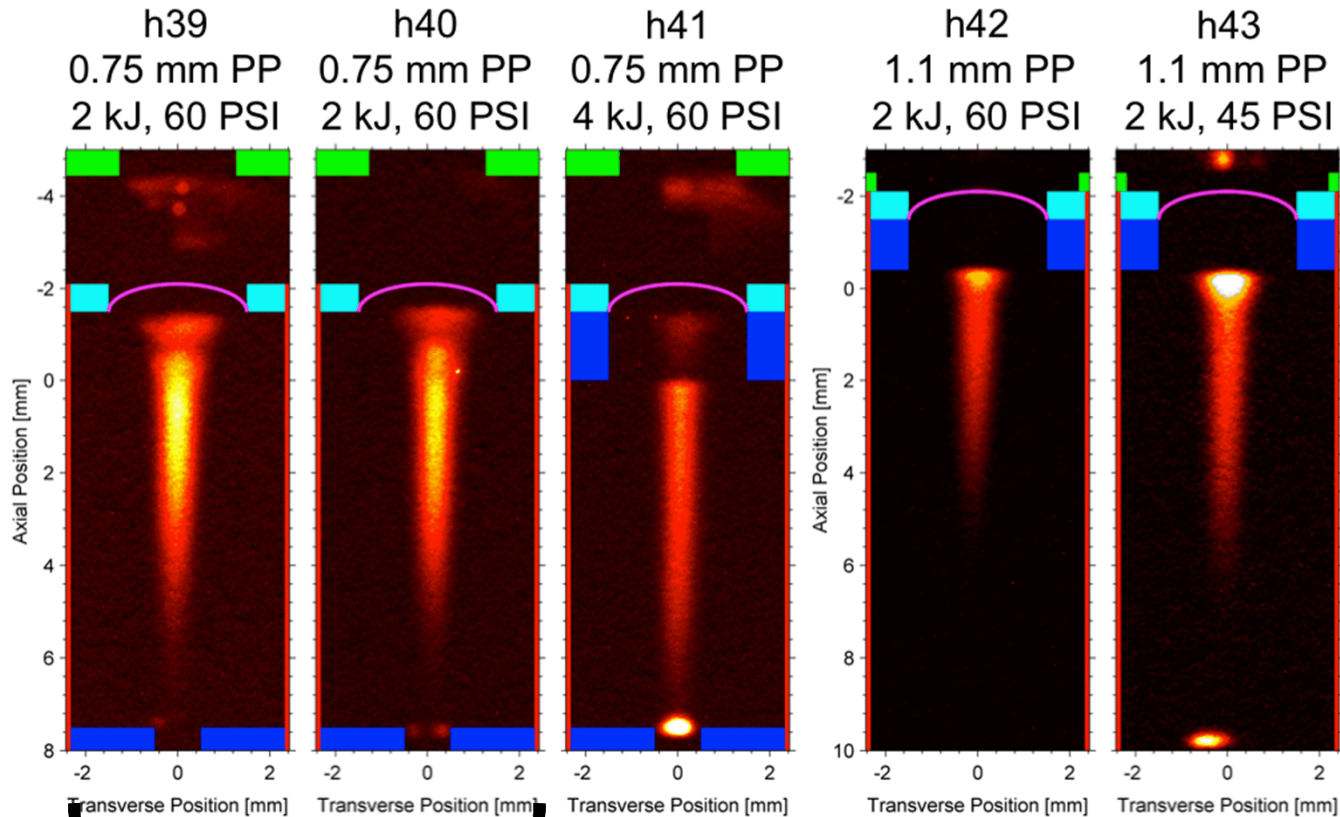
Facility	ZBL (Pecos)	ZBL (in Z)	OMEGA-EP	OMEGA	NIF
Collaborator	none	Some w/ LLNL	GA & LLE	LLE	LLNL
Shots/day	Up to 3	Up to 2	Up to 9	Up to 12	Up to 4
Shots/year	>150	15-20 (FY15)	18 to 27	18 to 36	TBD
Energy (1-beam)	4.5 kJ	4.5 kJ	2-2.5 kJ	0.4-0.6	<u>8-10 kJ</u>
Wavelength	2ω	2ω	3ω	3ω	3ω
Beam Smoothing	None yet	None yet	Very good	<u>Excellent</u>	Very good
Spectroscopy diagnostics	Limited, time-integrated	<u>Extensive</u>	Streaked	Limited	TBD
Imaging diagnostics	Shadowgraphy	<u>Monochromatic & Gated MLM</u>	Gated pinhole	Gated pinhole	Gated pinhole
Back scatter diagnostics	Diodes	None	None	<u>Excellent</u>	<u>Excellent</u>
B field capability	30 T single-coil	<u>30 T ABZ System</u>	<u>30 T MIFEDS</u>	<u>30 T MIFEDS</u>	Conceptual LDRD
Pre-pulse options	<u>8 ns window, soon arbitrary</u>	<u>8 ns window, soon arbitrary</u>	Limited (2nd beam)	None	TBD
Cryogenics?	Development	Development	None yet	None yet	TBD

We have made modest progress in our modeling, simulation, & scaling goals

- **Improve our existing codes capable of fully-integrated simulations by upgrading the MHD-based models in them**
 - Progress: A workshop was held at LLNL last fall in which various potential code improvements were discussed. We have not yet held a follow-on workshop, however, so it is unclear whether we are making progress.
- **Investigate hybrid particle-in-cell codes as an alternative approach to fully-integrated simulations**
 - Progress: We are proposing a ~\$4.5M/year internal “Grand Challenge LDRD” at Sandia that would combine elements of our ASC program with scientists at Voss Scientific to produce an exascale-compatible hybrid PIC code. The primary emphasis would be driver-target coupling, but it could be expanded later to include target physics modeling.
- **Develop tools and experiments for validating our simulations**
 - Progress: Collaborators at the NRL continue to work on test problems and theoretical/modeling research on these topics.
- **We will not invest significant effort in modeling laser-plasma interactions**
 - We are attempting to leverage existing expertise at LLE and NIF to characterize backscatter data from Z.

New phase-plates have been implemented for ZBL, but initial shot shows a negative effect on the integrated performance; Mix?

X-ray pinhole camera images of fuel emission



>10x decrease in n-yield (1 shot)

Compared to same pulse-shape w/out phase plate

Target Pre-conditioning

We believe that we need to demonstrate tritium use on Z to do better science & prepare for the future

- **Even at small percentages, tritium can enhance our scientific understanding and productivity on Z**
 - In ICF, could leverage more of the diagnostics and experience developed by the larger community that is centered on measuring 14 MeV neutrons, as well as demonstrating understanding in going from pure DD to few %T
 - In effects testing work, could benefit from enhanced yields and changes in energy spectrum to test our understanding of new testing platforms under development
- **We need to develop processes and experience**
 - Tritium has never been used on a large-scale pulsed power facility
 - Multiple missions for any next-step pulsed power facility will likely require the use of tritium
 - Multi-MJ fusion yields for Inertial Confinement Fusion
 - Combined neutron/photon effects testing
 - Science campaign experiments (e.g., boost)
 - Not all of the experience with using tritium on large laser facilities is relevant—we cannot rely solely on those experiences to define requirements for a next-step facility

We plan to work towards a key decision in late 2017 regarding future tritium operations on Z

	2015	2016	2017	2018	2019	2020	2021
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We believe the existing infrastructure would allow an estimated 2- 4 tritium experiments / yr. at up to 3% T

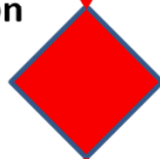
Option 0 would sustain 2 – 4 experiments / yr. Limited uncontained experiments

Contained	D2, He3	0.1% T	1% T	3% T	3% T	3% T	3% T
Uncontained	D2, He3	D2	0.1% T	1% T	3% T	3% T	3% T

Potential systems requiring upgrades for options 1 & 2 include:

- Center section purging/ventilation
- MITL tent
- HVAC
- Neutron shielding
- Tritium dedicated hardware
- Tritium capture system
- Tritium fill station

Key Decision for Tritium Operations on Z



Upgrade Option 1

Option 1
Upgrades contained experiments to 50/50
Unlimited uncontained experiments @ 3% T

Contained	10% T	50% T
Uncontained	3% T	3% T

Upgrade Option 2

Option 2
Upgrades all T experiments to 50/50

Contained	10% T	50% T
Uncontained	10% T	50% T

- Tests using light gas surrogates suggest a containment efficiency of 0.98. Measurements of recovery (0.99) and decontamination (0.99) give a combined 0.999998 removal efficiency
- 1st trace tritium test (contained) on Z in August