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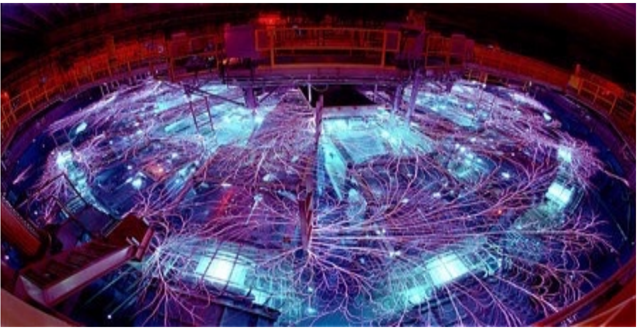

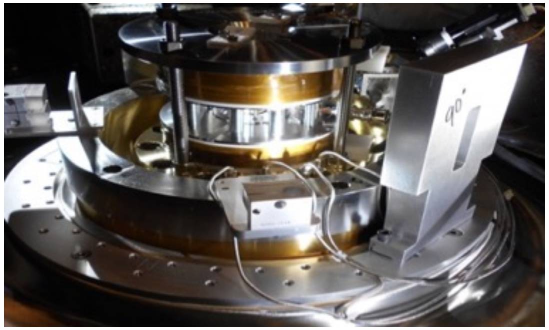

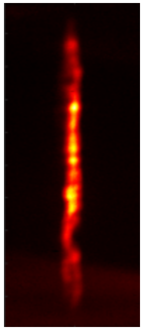

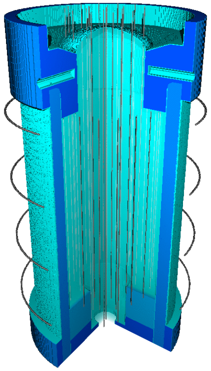

Progress in Magnetized Liner Inertial Laser Fusion Research

Kyle Peterson

IFSA 2017

U.S. DEPARTMENT OF ENERGY
NNSA National Nuclear Security Administration
LDRD LABORATORY DIRECTED RESEARCH & DEVELOPMENT

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MagLIF is a broad collaboration

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D. Appleford, T.J. Awe, C.J. Bourdon, G.A. Chandler, P.J. Christenson, M.E. Cuneo, M. Geissel, M. Glinsky, 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,, T.N. Nagayama, K.J. Peterson, J.L. Porter,P. Rambo, G.A. Rochau, D.C. Rovang, C.L. Ruiz, S.E. Rosenthal, M.E. Savage, P.F. Schmit,J. Schwarz, D.B. Sinars, S.A. Slutz, I.C. Smith, W.A. Stygar, R.A. Vesey, M. Weis, E.P. Yu., G. Logan

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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, A.B. Sefkow

Laboratory for Laser Energetics

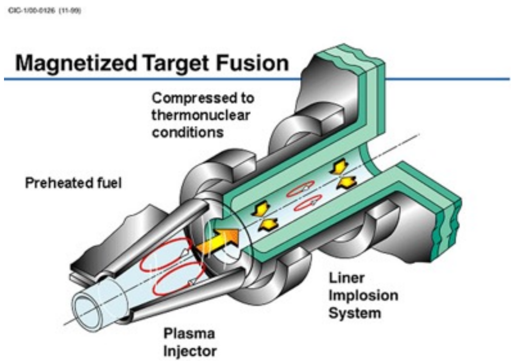
B. Pollock, D. Strozzi, C. Goyon, J. Moody, S. Khan, D. Hinkel, M.C. Herrmann

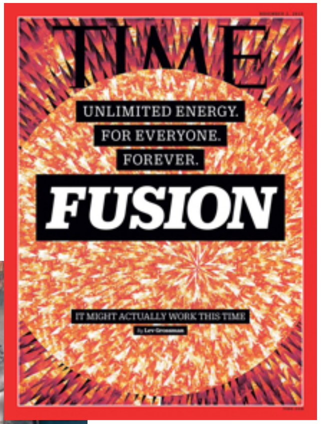
Lawrence Livermore National Laboratory

Magneto-inertial fusion attempts to operate in an intermediate fuel density space between MCF and ICF

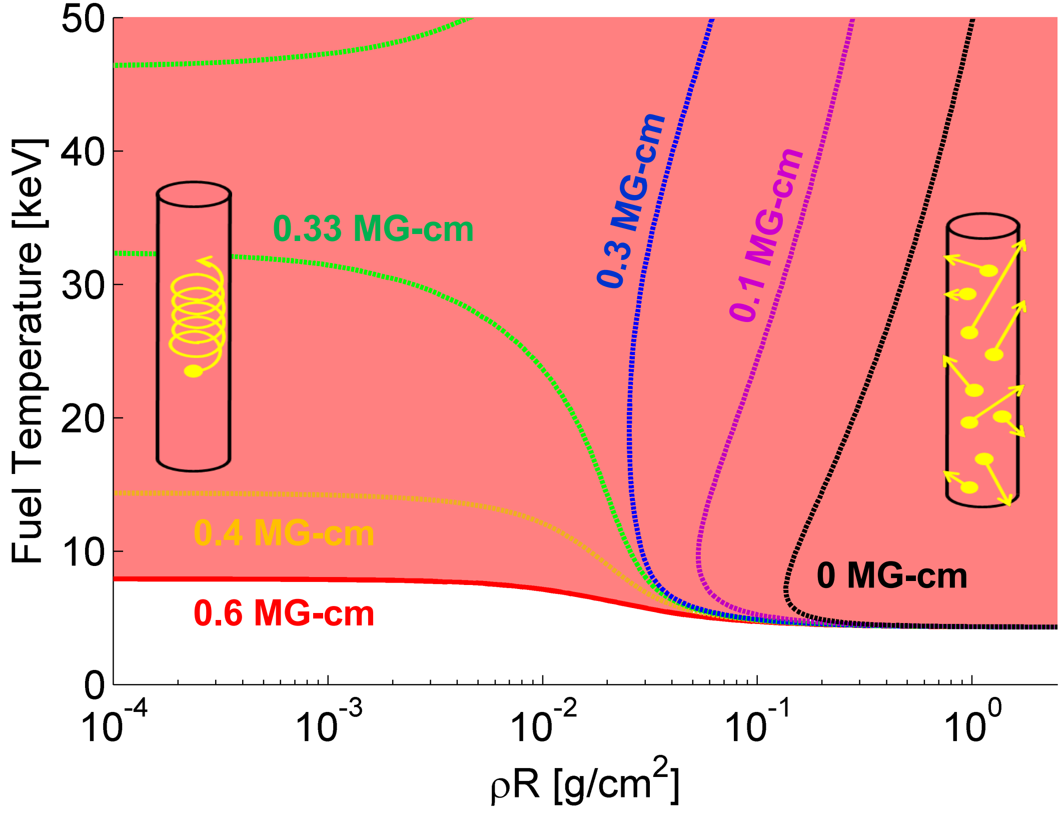
- **Strategy:**
  - Reduce fuel density to suppress radiation losses
  - Use a magnetic field to suppress the thermal conduction losses during compression
  - Reduce required target convergence

- **Requirements:**
  - Magnetized fuel
  - Pre-heated fuel
  - Compression system
    - Pre-heated and pre-magnetized plasma compressed until fusion is achieved





Magneto-inertial fusion utilizes magnetic fields to relax the stagnation requirements of ICF



- With a high enough magnetic-field-radius product, charged fusion products become trapped
- This relaxes the areal density requirement of the fuel
- Good performance is possible over a much larger region of parameter space

Magnetized Liner Inertial Fusion relies on three stages to produce fusion relevant conditions

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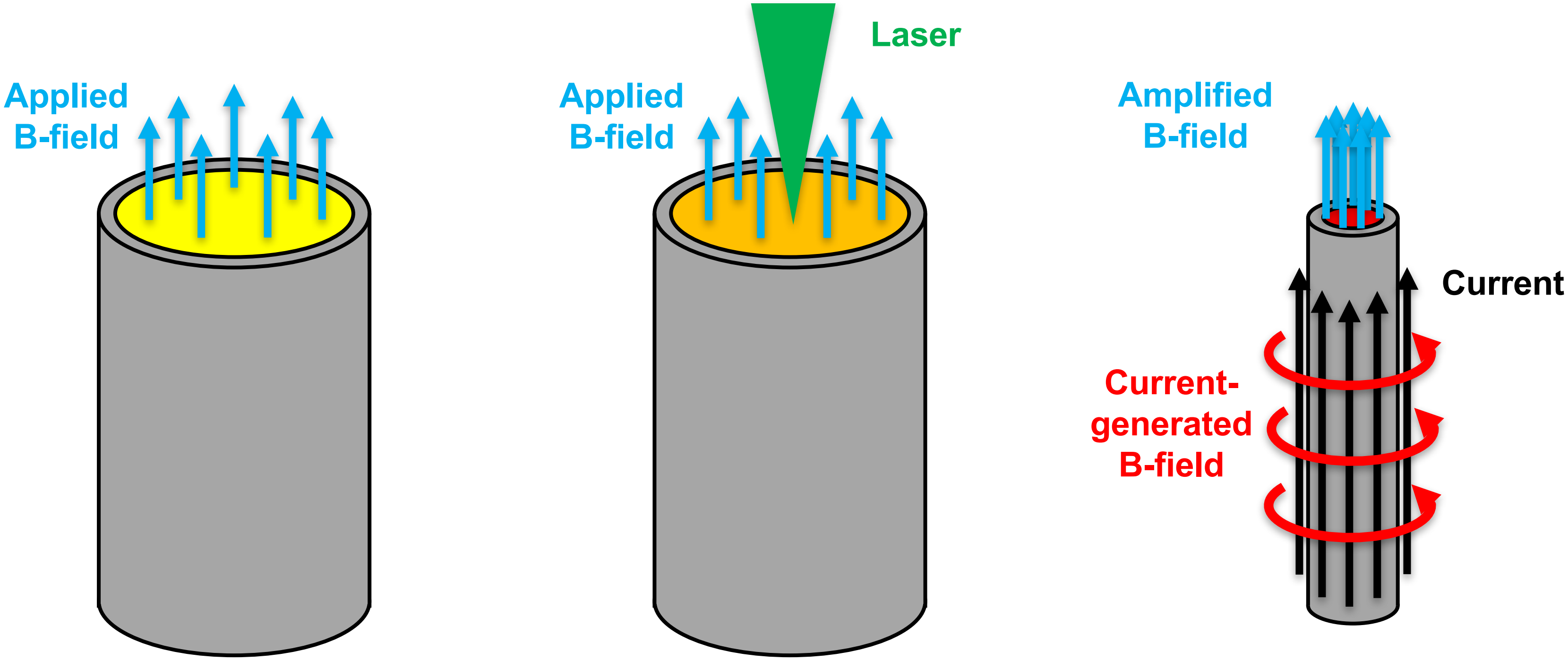


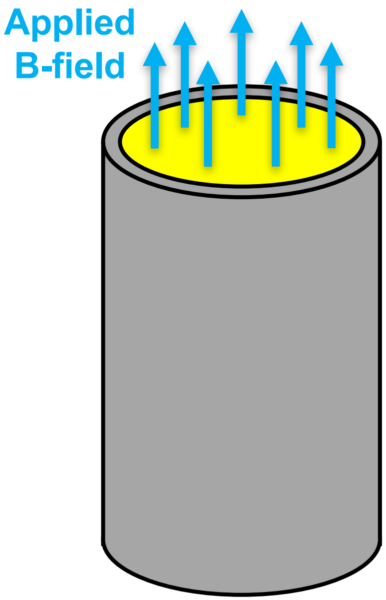
Apply axial magnetic field

Laser-heat the magnetized fuel

Compress the heated and magnetized fuel

S. A. Slutz, et al., Phys. Plasmas 17, 056303 (2010).

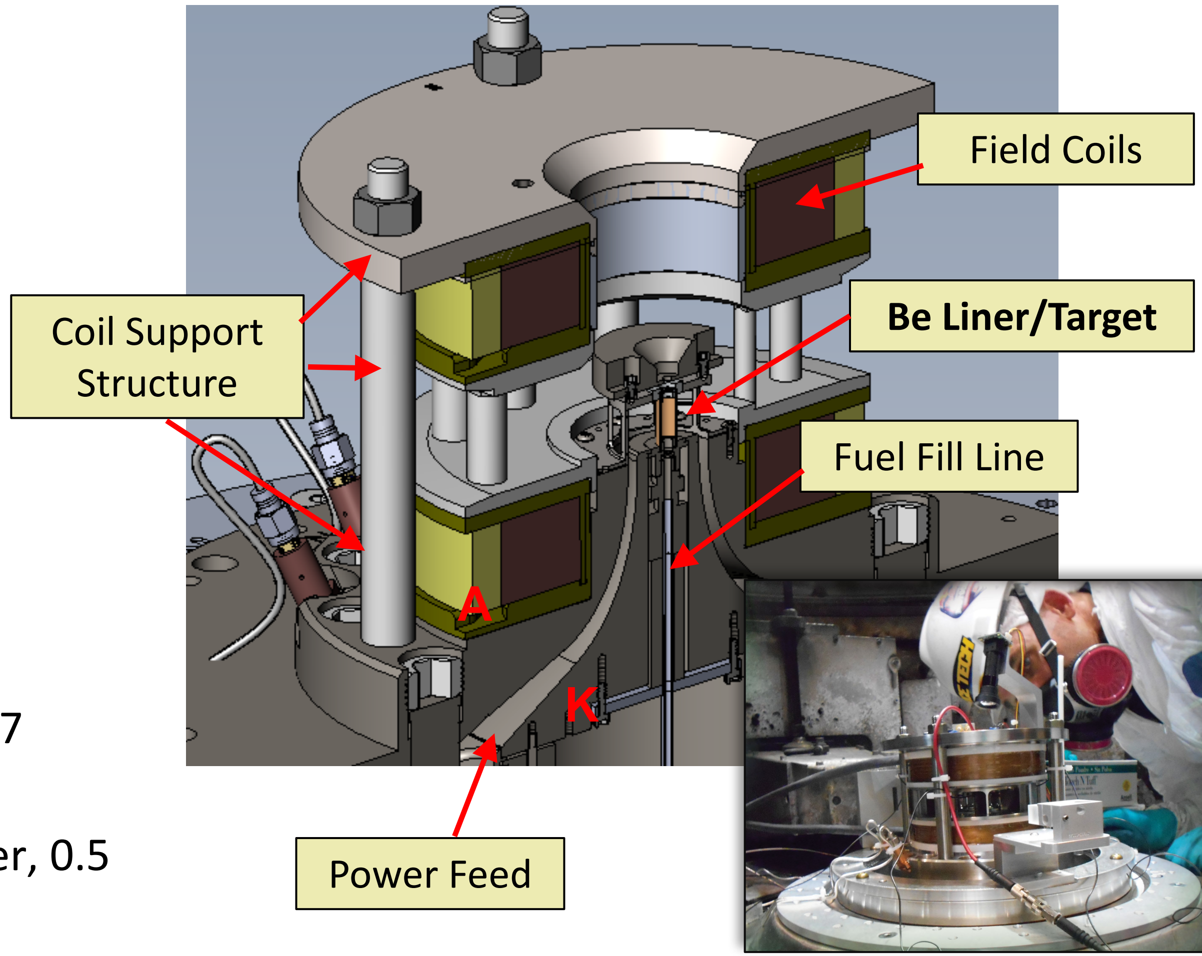
An axial magnetic field is applied with external field coils before the implosion occurs



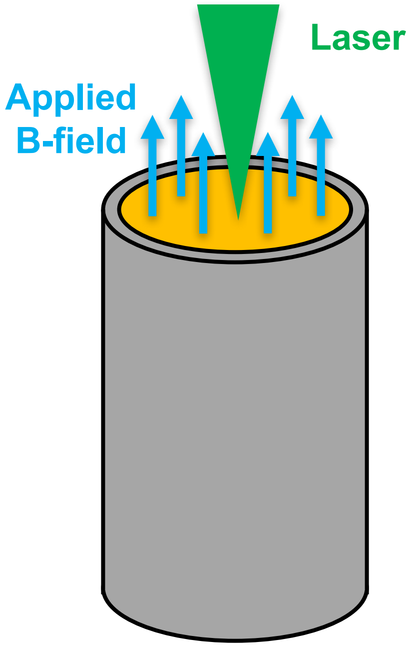
Apply axial magnetic field

- Metal cylinder contains 0.7 mg/cm^3 of deuterium gas
- 10 mm tall, 5 mm diameter, 0.5 mm thick

Helmholtz-like coils apply 10-30 T in 3.5 ms



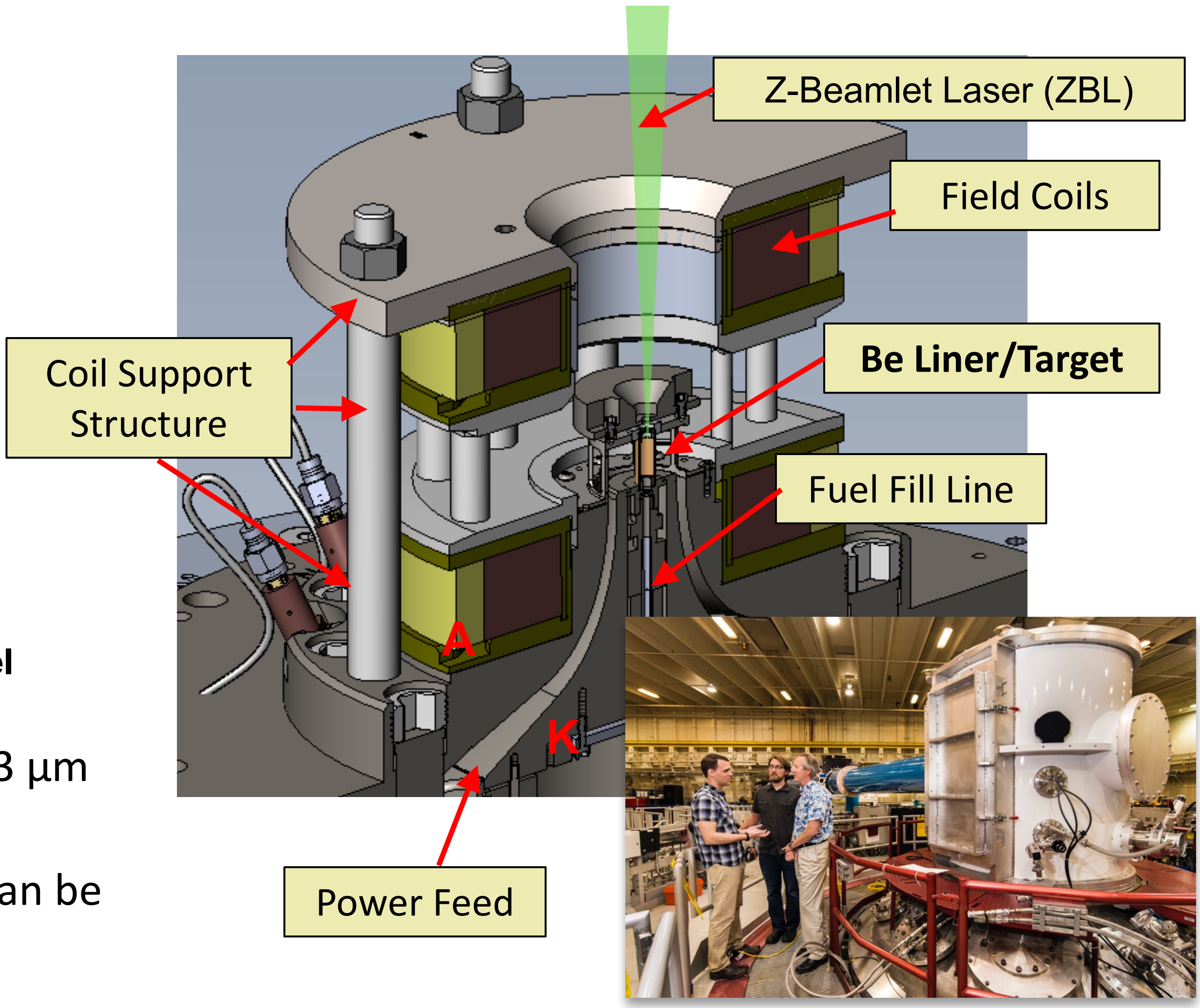
A laser is used to heat the fuel at the start of the implosion



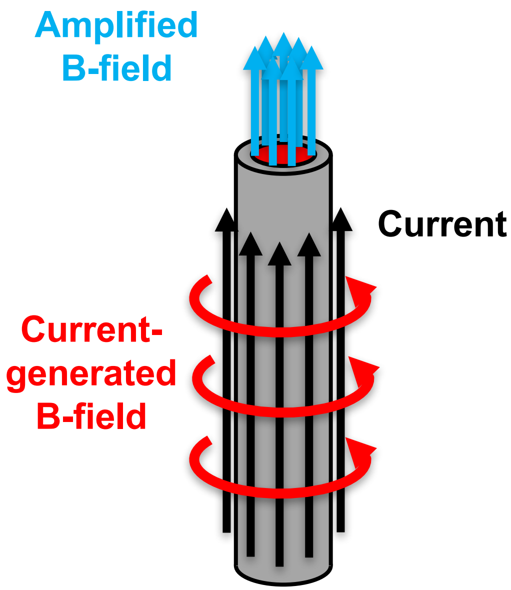
Laser-heat the magnetized fuel

- Laser must pass through 1-3 µm thick plastic window
  - Significant laser energy can be deposited in the plastic

527 nm, 2 ns, 1-4 kJ laser used to preheat the fuel

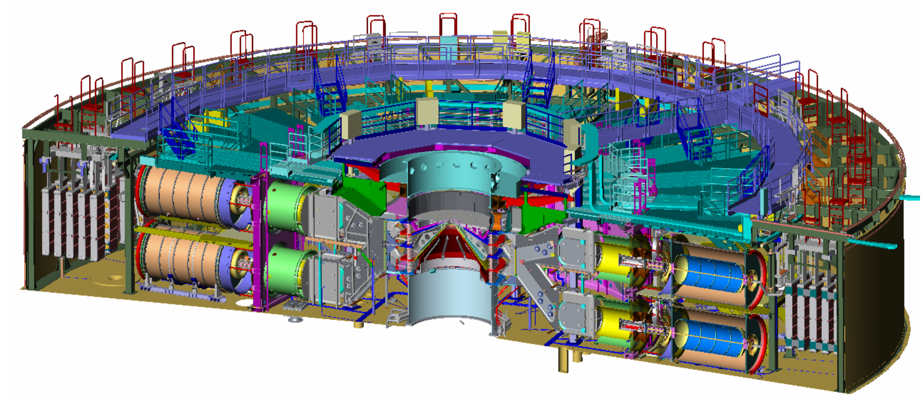


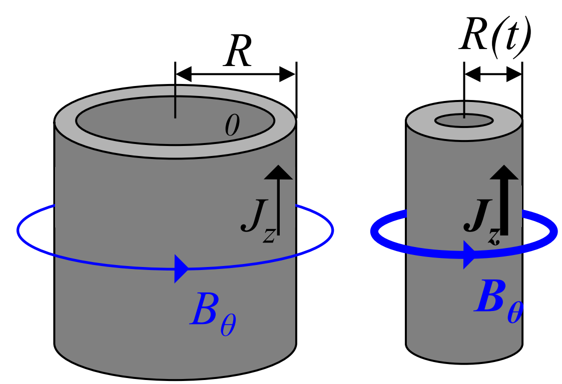
The current from the Z machine is used to implode the target



Compress the heated and magnetized fuel

Z drives axial ~17 MA axial current, risetime is 100 ns

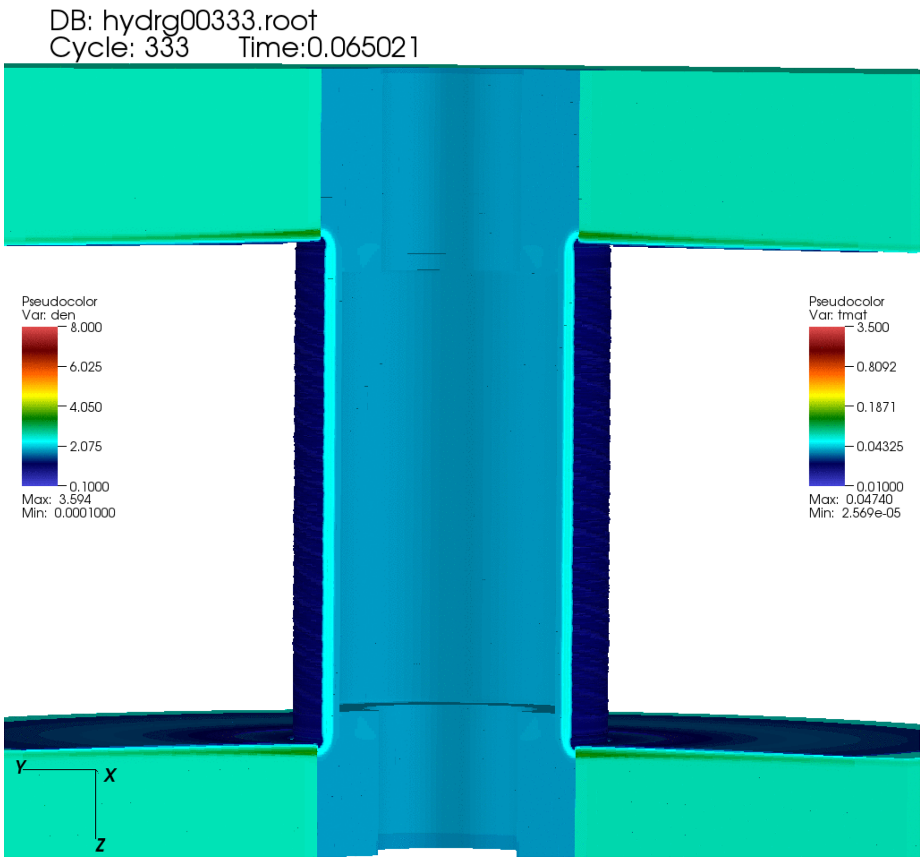




- Metal cylinder implodes at ~70 km/s
- Fuel is nearly adiabatically compressed
- Axial magnetic field is compressed to 1-10 kT

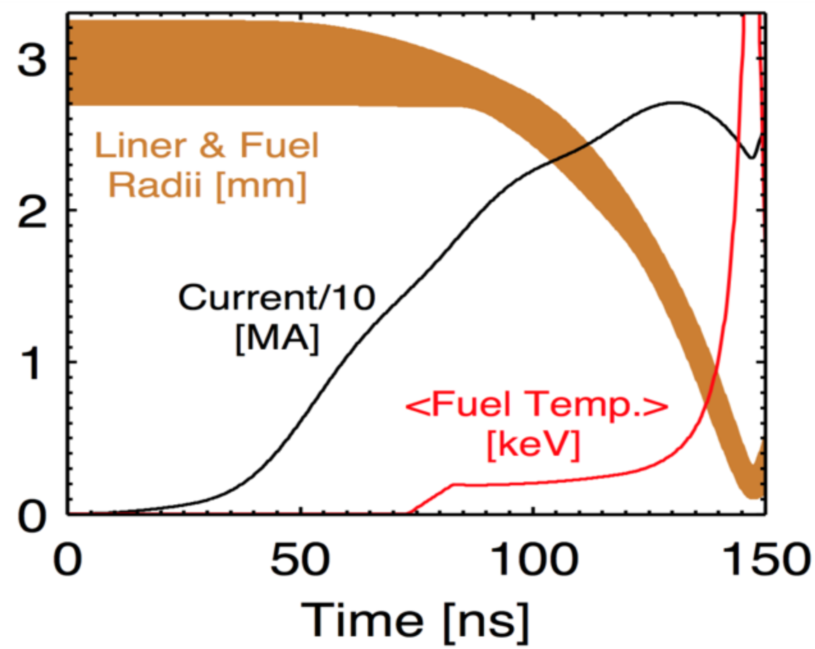
$$P = \frac{B^2}{8\pi} = 105\left(\frac{I_{MA}/26}{R_{mm}}\right)^2 \text{ MBar}$$

Fully-integrated (Bz+Laser+Z) 3-D HYDRA calculations illustrate the stages of a MagLIF implosion



Simulation by A. Sefkow

1-D picture*



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

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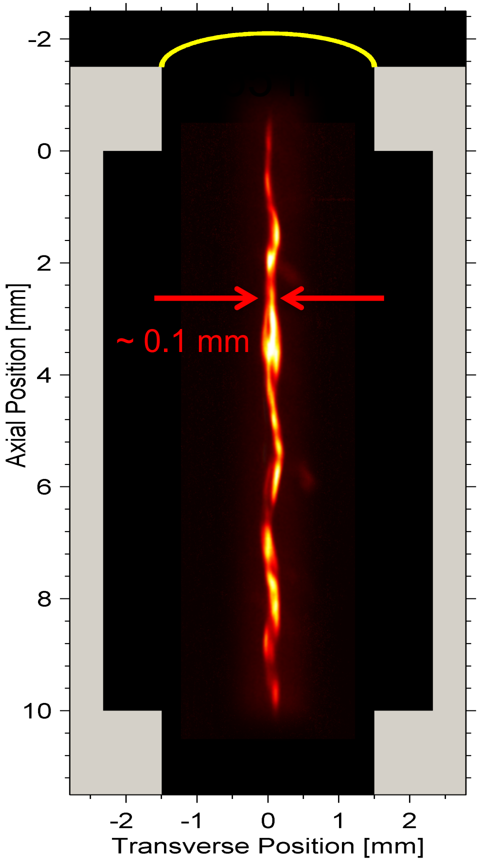
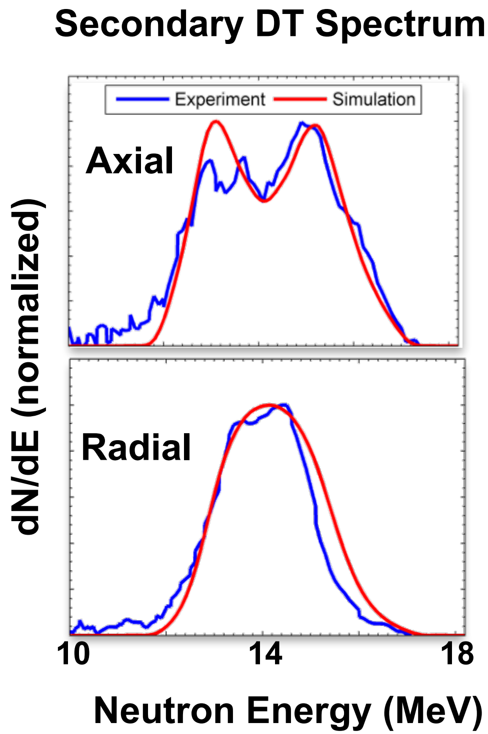
High Convergence Implosion



6+9 keV Emission Image

CR > 40

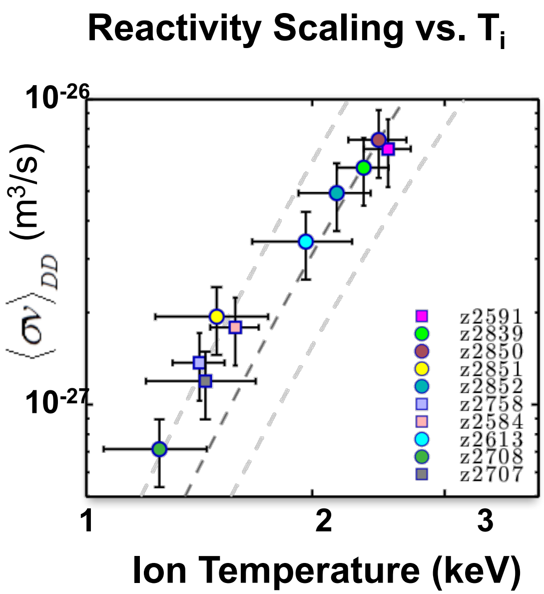
B-field Flux Compression & Magnetic trapping of charged particles



DT Secondary Spectra

BR > 0.35 MG-cm

Thermonuclear Neutrons



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

Yield, Volume, Duration

Consistent with DD reactivity

Gomez et al., PRL 113 (2014); Schmit et al., PRL 113 (2014); Hahn et al., RSI 85 (2014)

We have verified that good performance requires both applied B-field and laser heating

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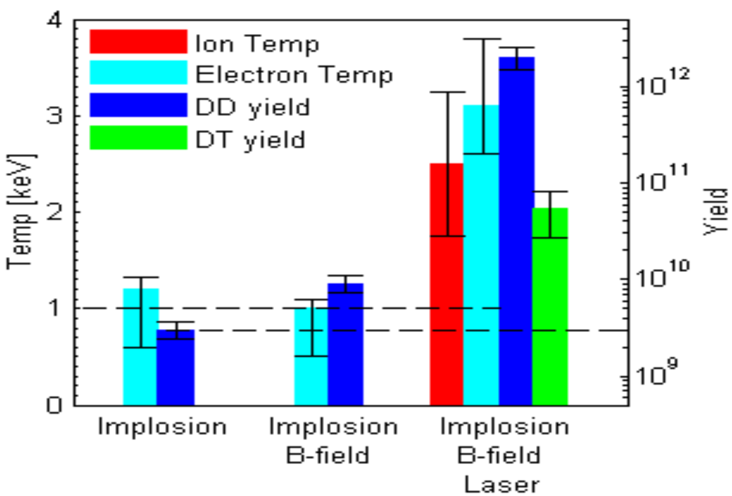
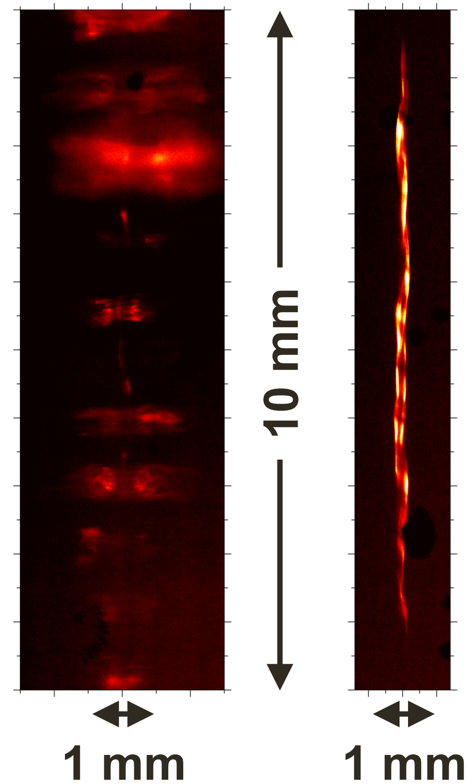
Significant yields and temperatures only w/ applied B_z and preheat

DD Neutron yield

	No B-field	B-field
No Laser Heating	3×10^{9}	1×10^{10}
Laser Heating	4×10^{10}	3×10^{12}



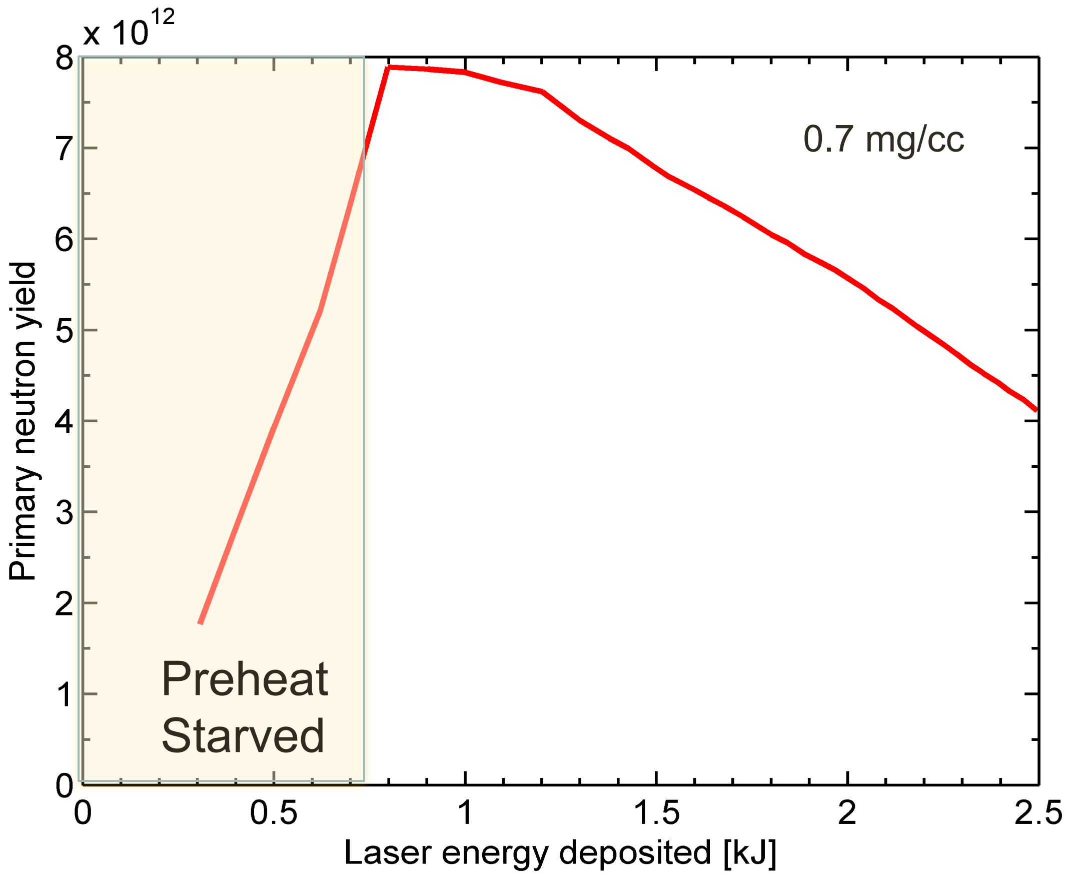
Laser Heating Without B-field



Laser Heating With B-field

3×10^{12} is a DT-equivalent yield of ~0.6 kJ

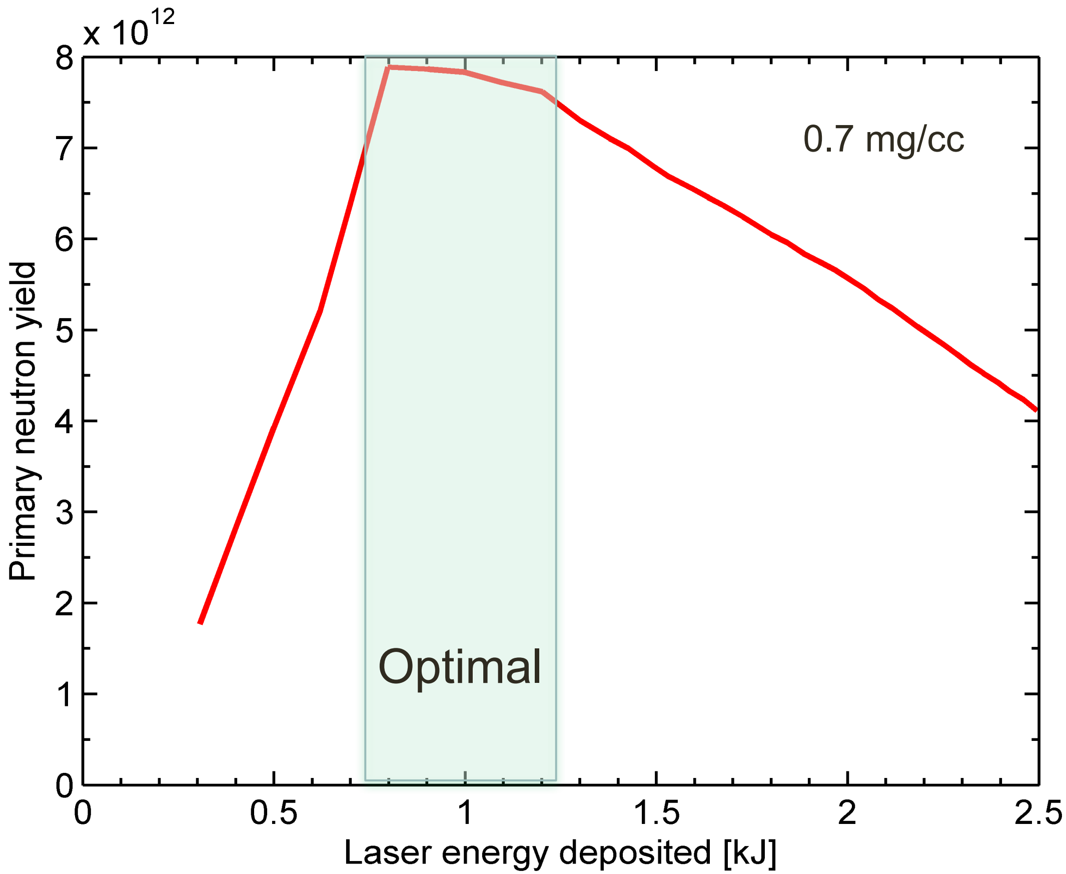
Simulated primary neutron yields are highly sensitive to the coupled preheat energy



- With sufficient magnetization, yield is strong function of preheat energy

Assumes 10T, 17 MA, 2D clean implosion (No mix, 3D, etc)

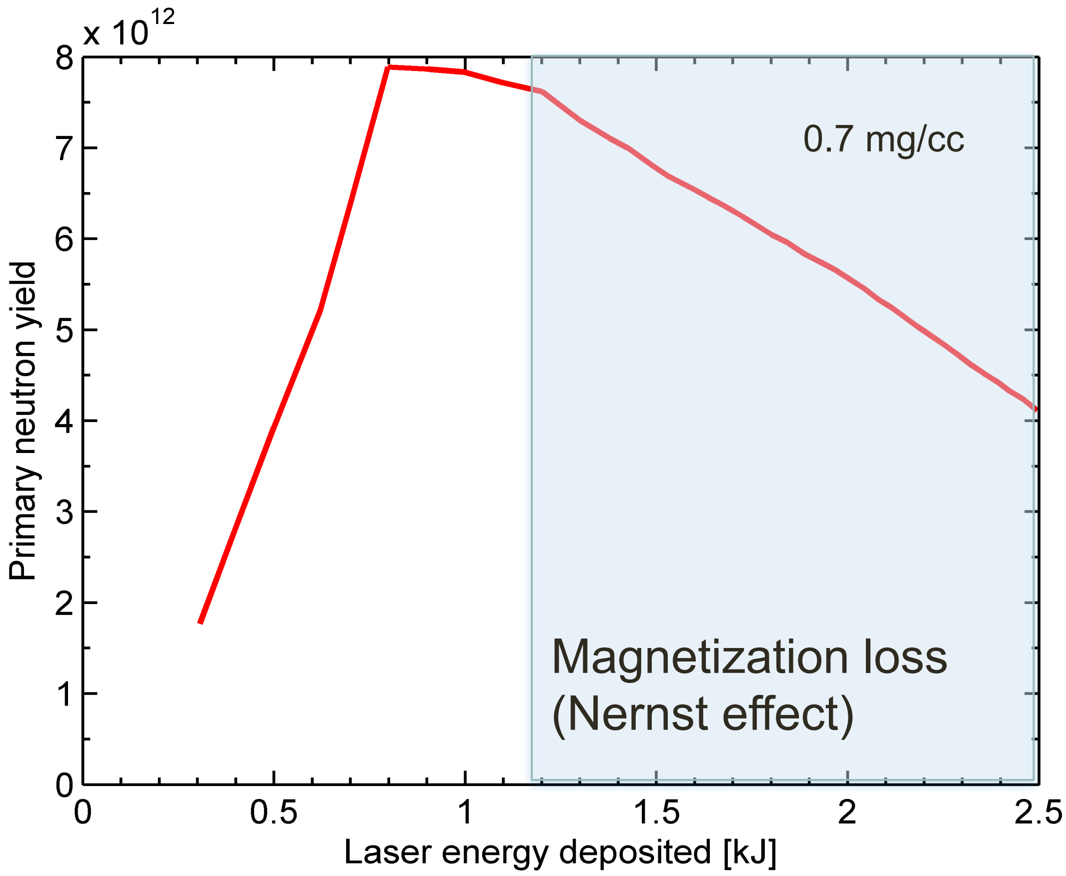
Simulated primary neutron yields are highly sensitive to the coupled preheat energy



- With sufficient magnetization, yield is strong function of preheat energy
- Simulations predict maximum DD yields of 6-8x10^{12} (clean) with a coupled energy of ~1kJ

Assumes 10T, 17 MA, 2D clean implosion (No mix, 3D, etc)

Simulated primary neutron yields are highly sensitive to the coupled preheat energy



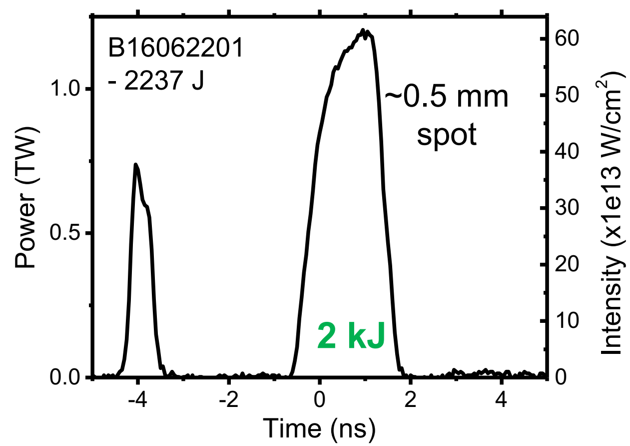
- With sufficient magnetization, yield is strong function of preheat energy
- Simulations predict maximum DD yields of 6-8x10^{12} (clean) with a coupled energy of ~1kJ
- Larger coupled energies reduce yield due to Nernst effect

Assumes 10T, 17 MA, 2D clean implosion (No mix, 3D, etc)

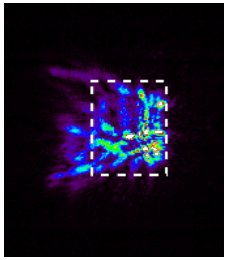
Our initial experiments had significant uncertainty in the coupled laser energy

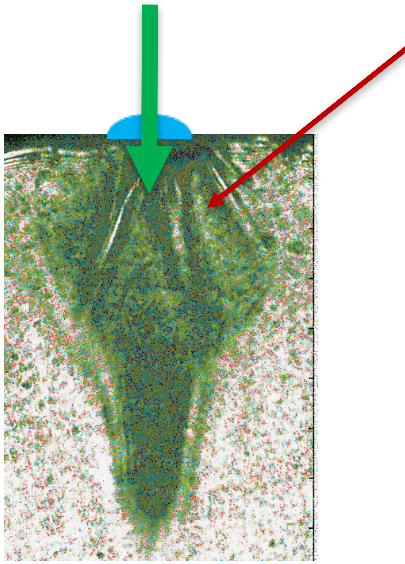
- Significant laser plasma interactions (LPI), not modeled in our codes
- No beam smoothing
- Several <u>independent</u> laser heating experiments suggested low laser energy coupling to fuel
  - Window transmission
  - X-ray emission
  - VISAR blastwave analysis
- Initial experiments assumed to be preheat starved

Original MagLIF laser pulse

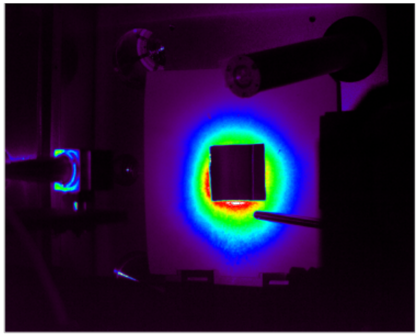


Beam Profile



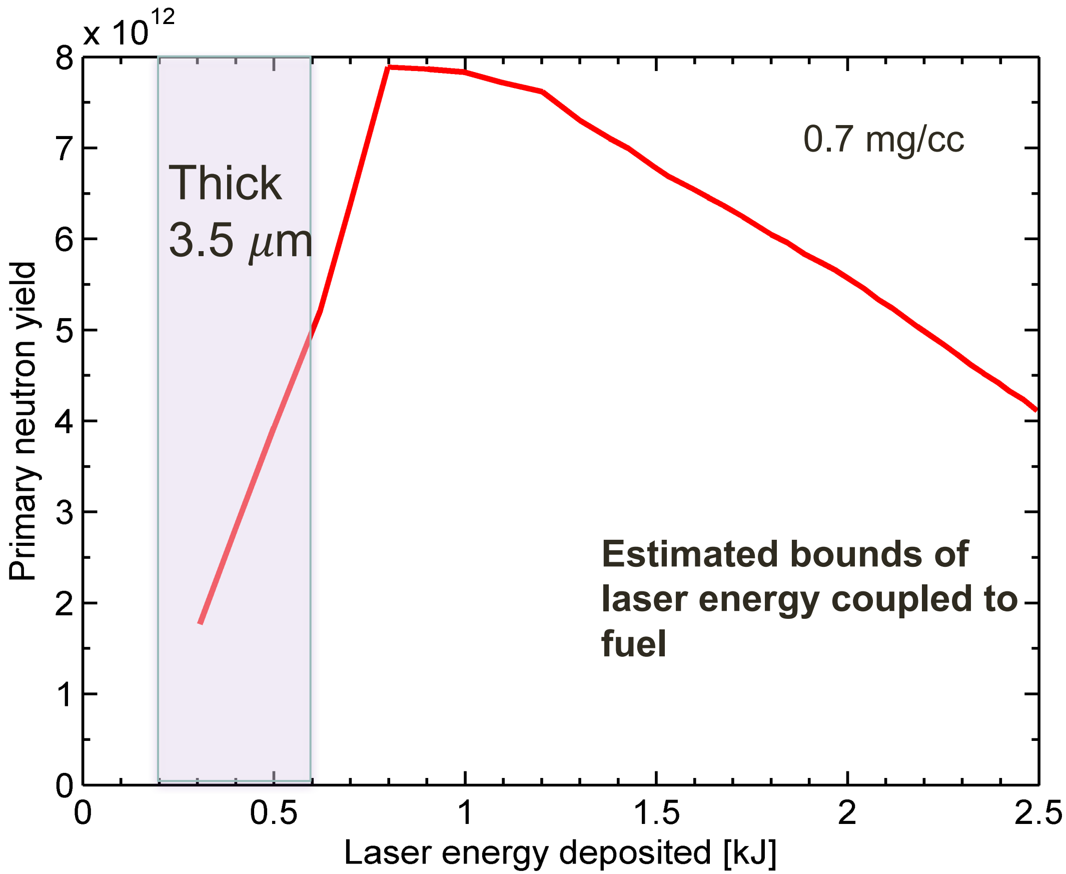


Stimulated Brillouin Scattering: 900J !



15

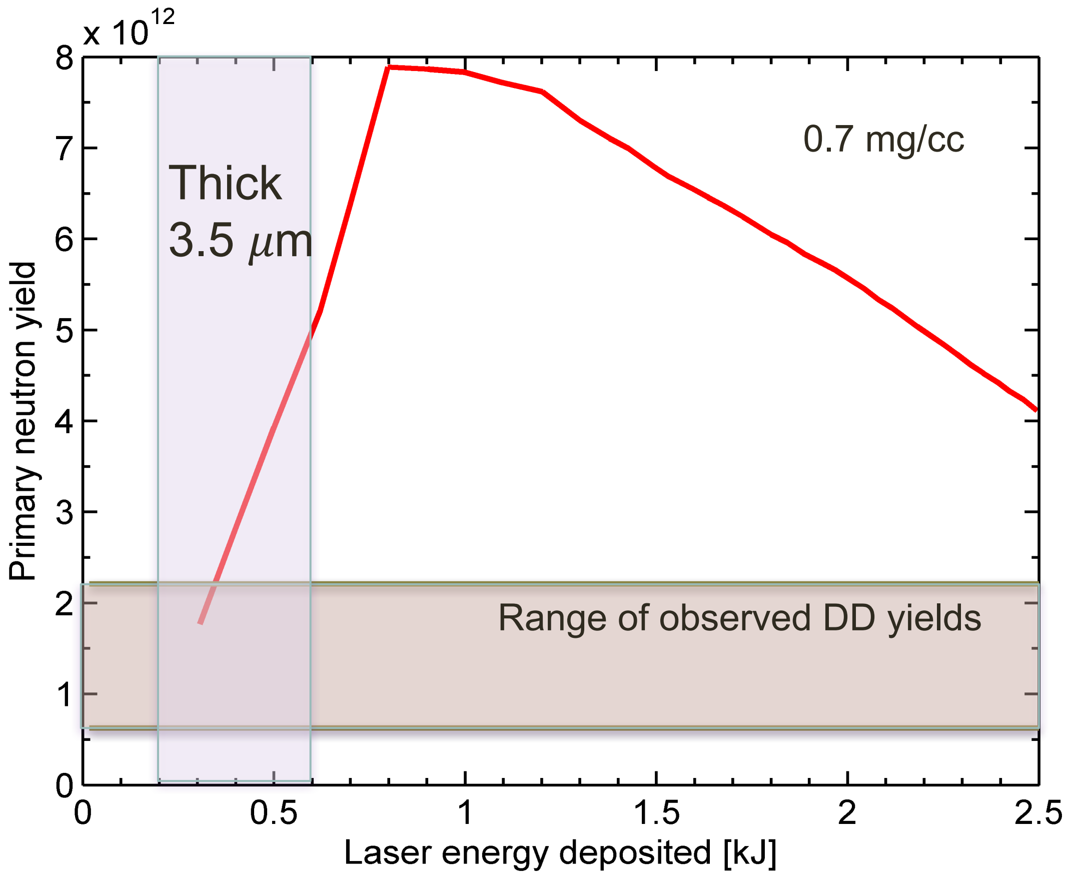
2D MHD simulations of our standard MagLIF configuration match experiments to within 2-3x



- 200-600J estimated coupled with thick (3.5 μm) windows

Assumes 10T, 17 MA, clean implosion (No mix, 3D, etc)

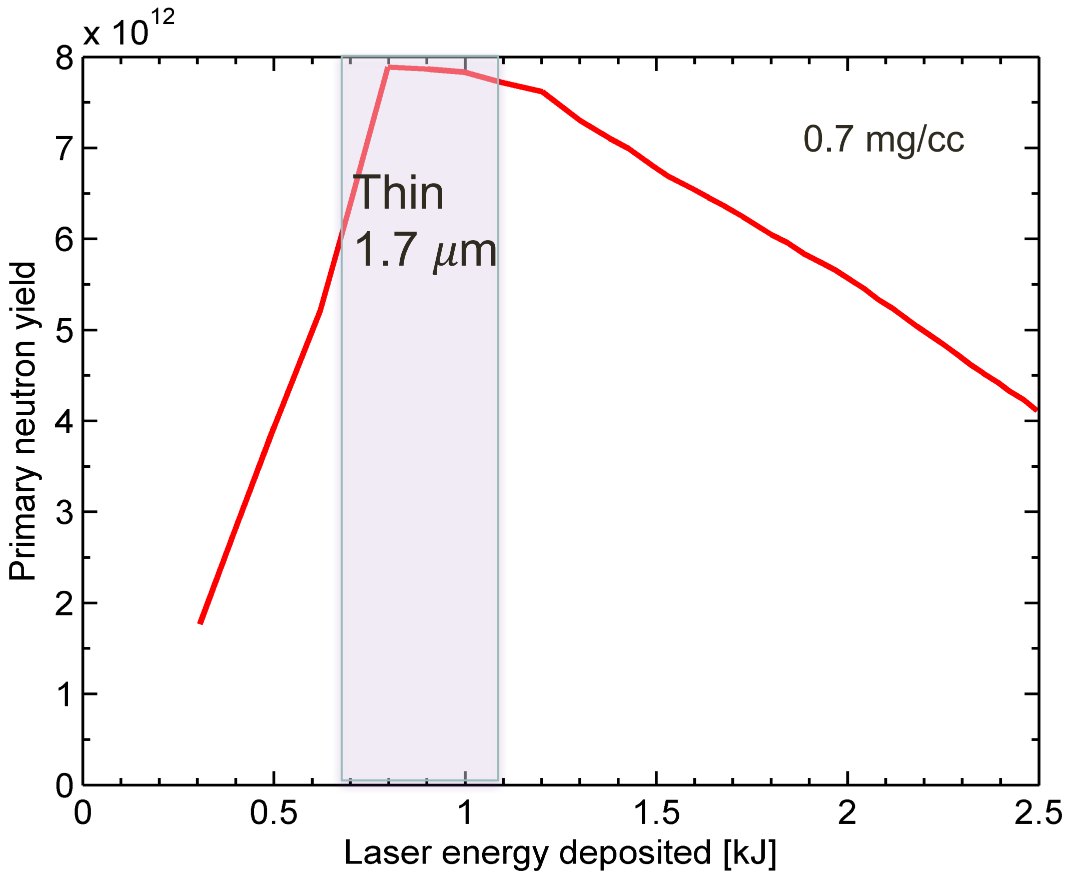
2D MHD simulations of our standard MagLIF configuration match experiments to within 2-3x



- 200-600J estimated coupled with thick (3.5 μm) windows
  - Initial experiments produced up to 2×10^{12} primary DD neutrons

Assumes 10T, 17 MA, clean implosion (No mix, 3D, etc)

2D MHD simulations of our standard MagLIF configuration match experiments to within 2-3x

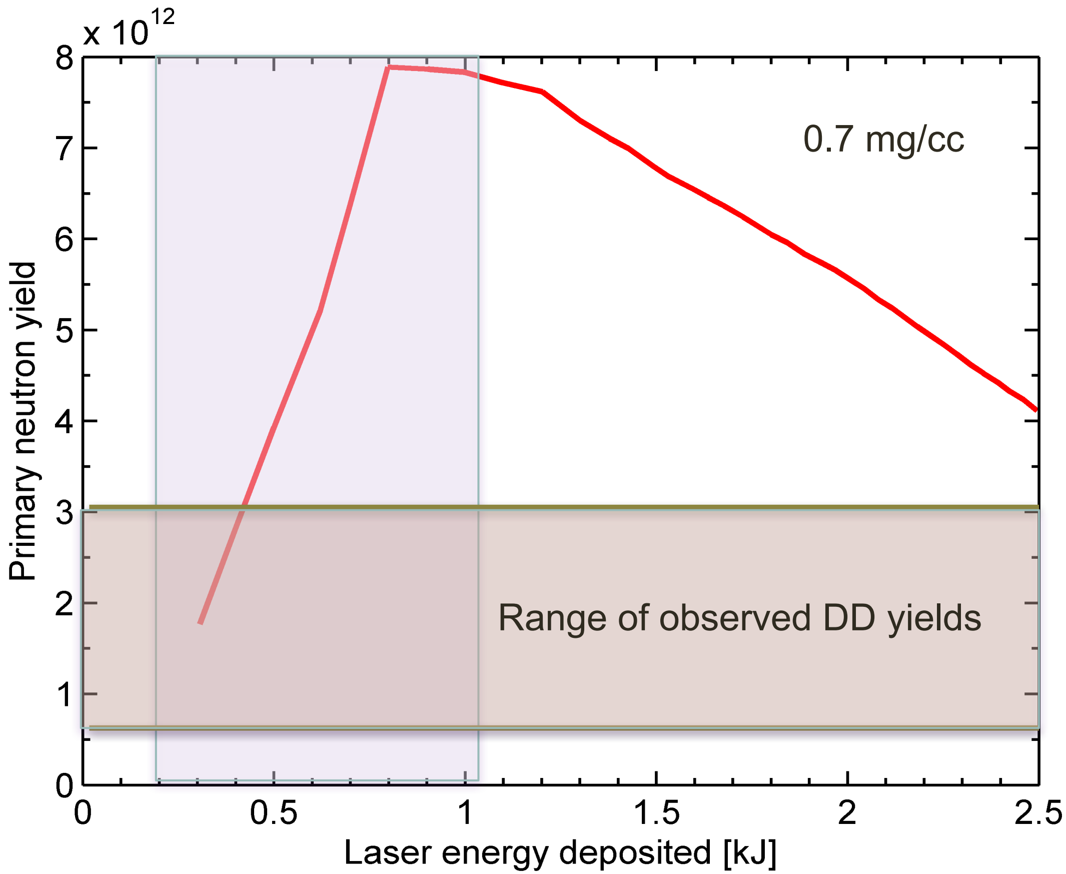


- 200-600J estimated coupled with thick (3.5 μm) windows
- 600-1200J estimated for thin windows (1.7 μm)

Assumes 10T, 17 MA, clean implosion (No mix, 3D, etc)

Simulations courtesy of S. A. Slutz

2D MHD simulations of our standard MagLIF configuration match experiments to within 2-3x



- 200-600J estimated coupled with thick (3.5 μm) windows
- 600-1200J estimated for thin windows (1.7 μm)
- Similar performance obtained with both thin and thick windows
  - Thin windows more susceptible to high Z target components (mix)
  - Increased laser energy (4kJ) decreased performance

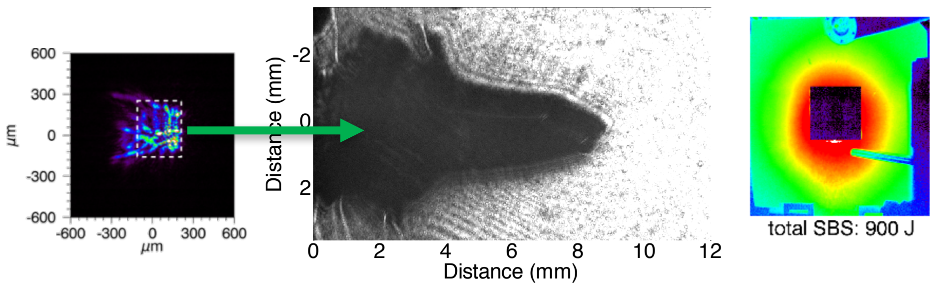
Assumes 10T, 17 MA, clean implosion (No mix, 3D, etc)

Simulations courtesy of S. A. Slutz

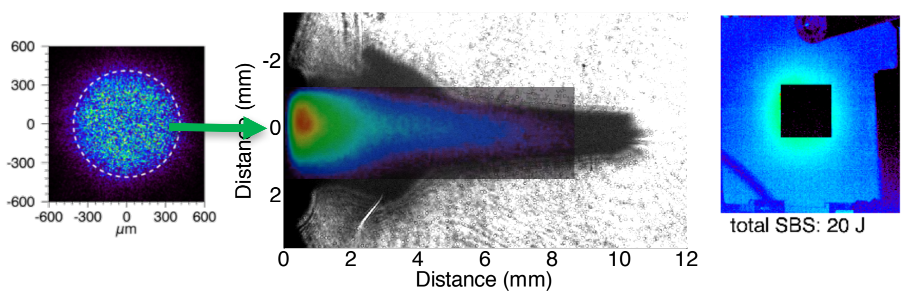
New laser heating protocols were developed using phase plate smoothing and reduced intensities

Optical Blastwave Measurements

Original MagLiF Configuration



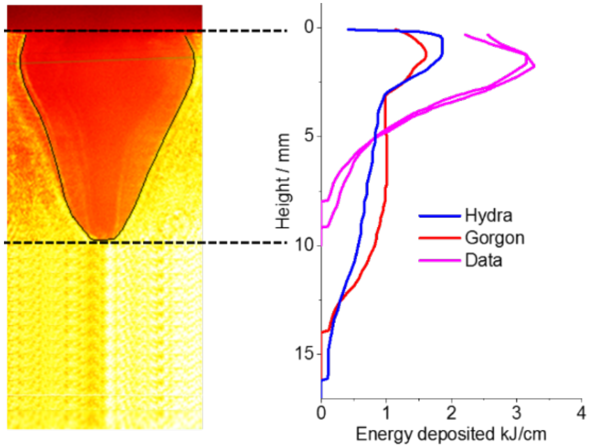
Laser Config A



- 1100 μm Distributed Phase Plate
- Lower laser intensity
- 80 J pre-pulse, 1500J 4ns main pulse

- Reduced SBS from ~50% to <3%
- Enhanced penetration depth with **reduced** laser energy
- Less conical and more cylindrical energy deposition
- Reduced energy uncertainty: 600-800J deposited in imploding region of fuel

Simulations match total energy deposited, but not axial profile

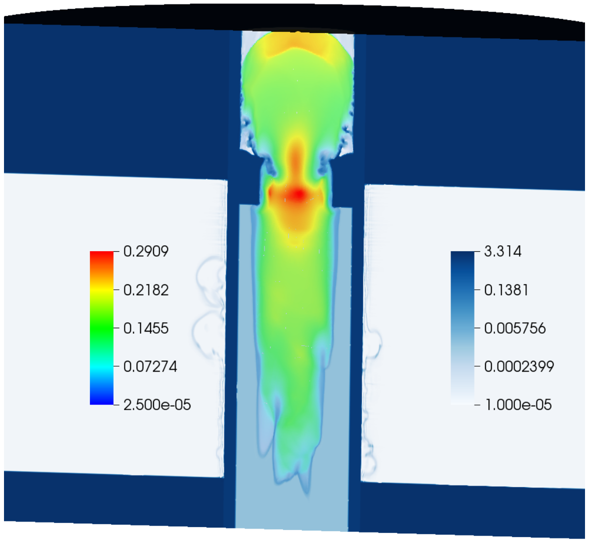


Geissel: O. Th.C1.1

These new laser heating protocols have produced the highest yields thus far, but questions remain about reproducibility

	z3040	Z3041	z3057
Laser energy	70 + 1460 J	73 + 1534 J	103 + 1283 J
Y_{DD}	4.1e12 ± 20%	3.2e11 ± 20%	2.0e12 ± 20%
Comments	**~50% of clean 2D sim**	Direct repeat of z3040	Co coating on LEH

- **Variation is significantly larger than observed in previous experiments**
- **The source of the large performance variation is currently being investigated**
  - Laser preheat configuration ?
  - Liner instabilities (CR>40) ?
  - Mix cliff ?

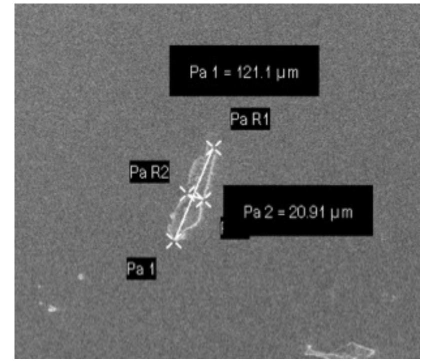


Several potential sources of performance variation due to laser heating are being explored

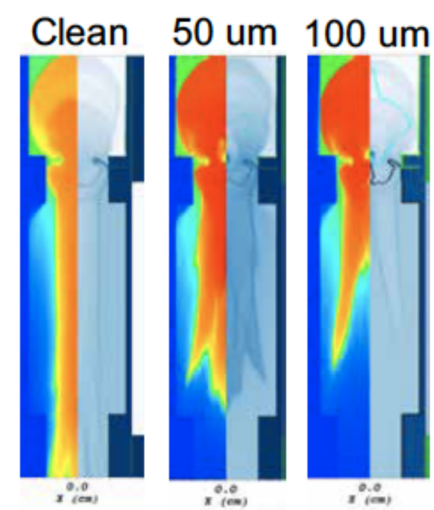
- Dust is one of the leading hypotheses
- Simulations suggest >50 μm dust particles can substantially affect laser deposition
- Significant number of dust particles 10-100 μm in size have been observed on windows
- Chances of interaction increase with larger laser spot size

- New protocols are being put in place to control and monitor dust in our experiments

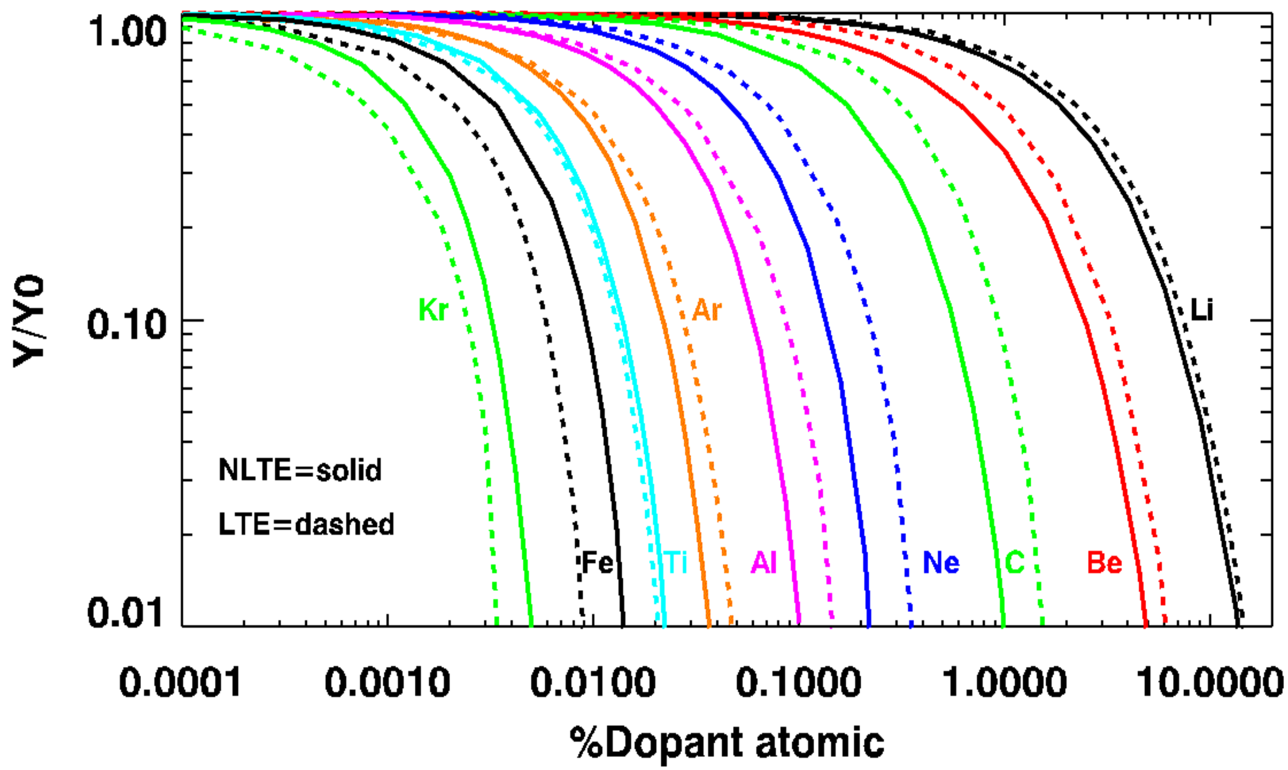
Dust particles measured on typical window



2D Hydra simulation



With its long preheat stage, MagLIF is highly susceptible to fuel impurities (mix)



Even small high-Z fractions lead to catastrophic radiative losses during the ~50 ns preheat stage.

Are we on a mix cliff?

Spectroscopy is being used to infer the plasma temperature, density, and mix fractions

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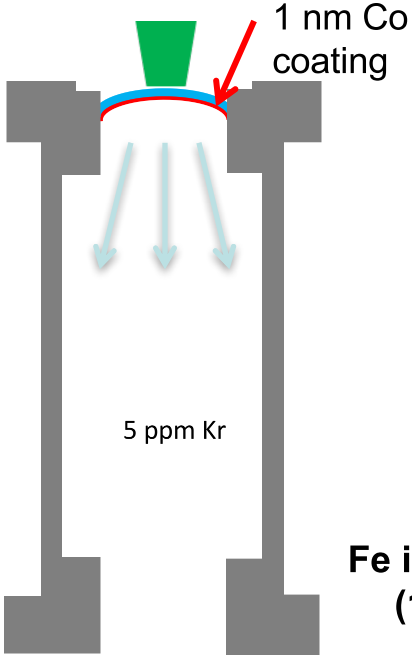
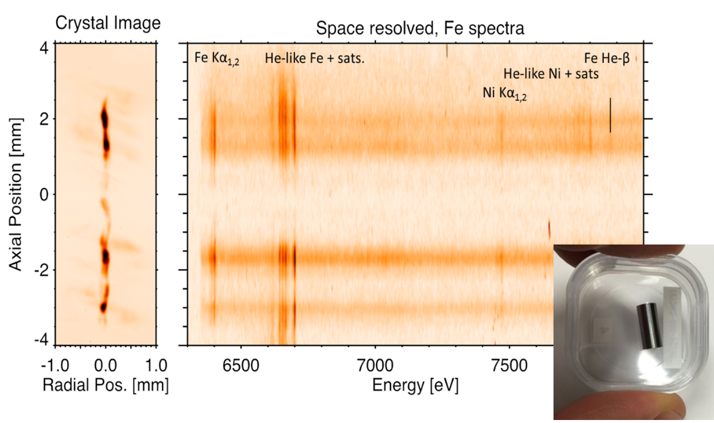
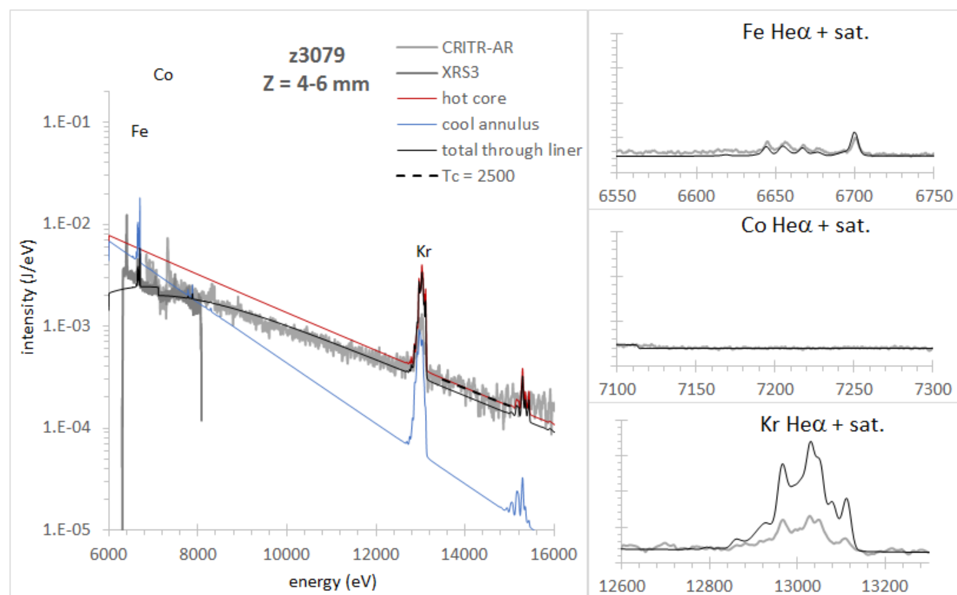


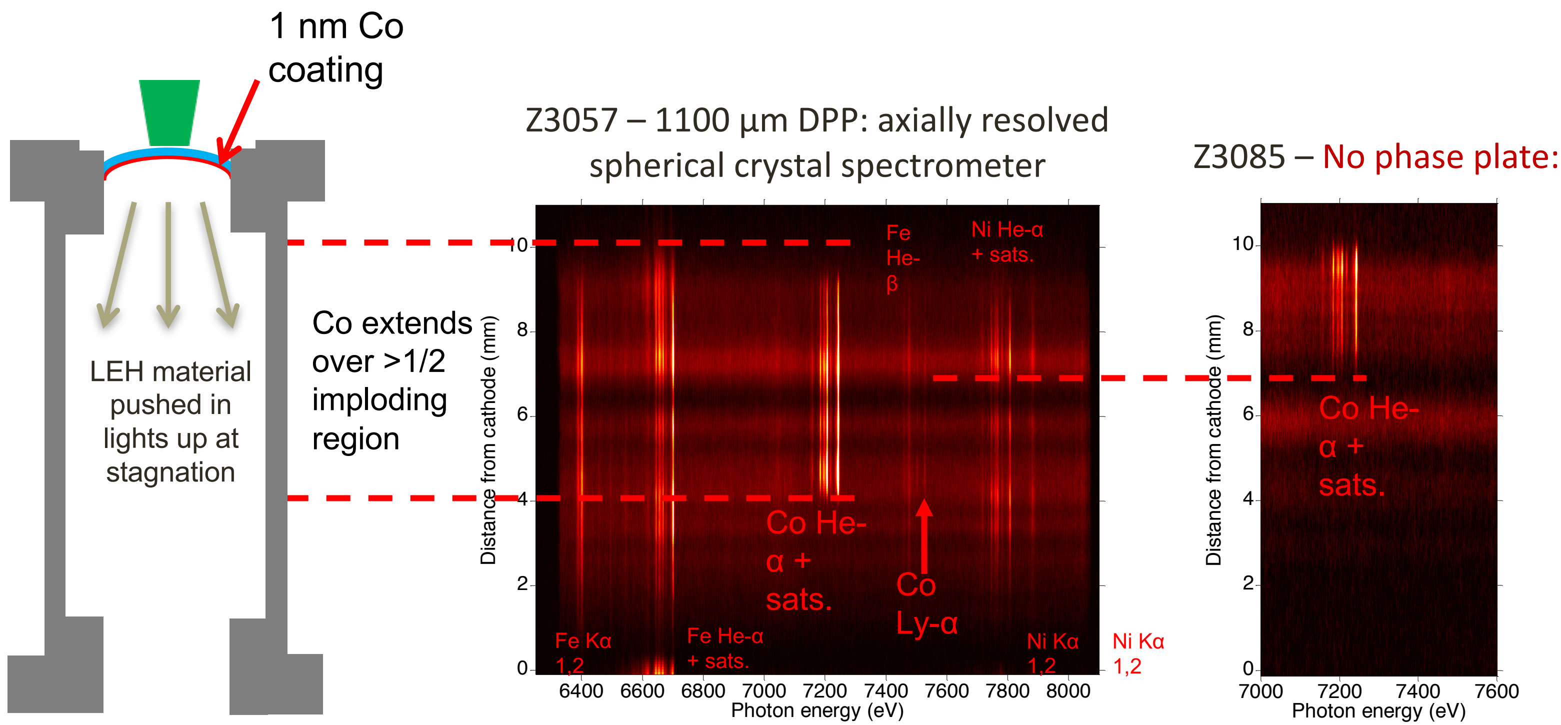
- Fe impurities from the Be liner/endcap mix into the stagnation column
- 5 ppm Kr dopant premixed into fuel
- Localized Co dopants

Fe in S65 Be Liner (100 ppm Fe)



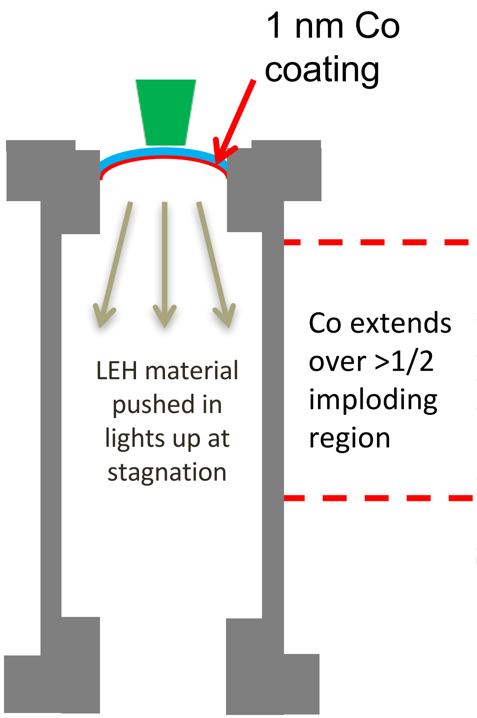


Window mix has been observed experimentally and is transported further with the new laser heating protocols

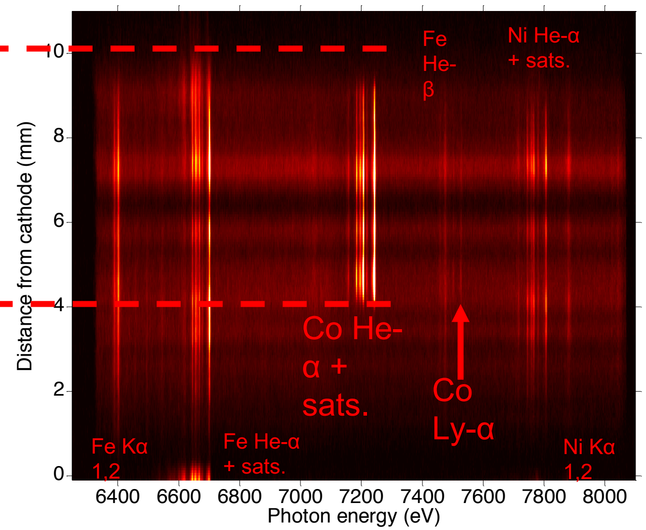


- We are developing uniformly doped windows to help better quantify window mix

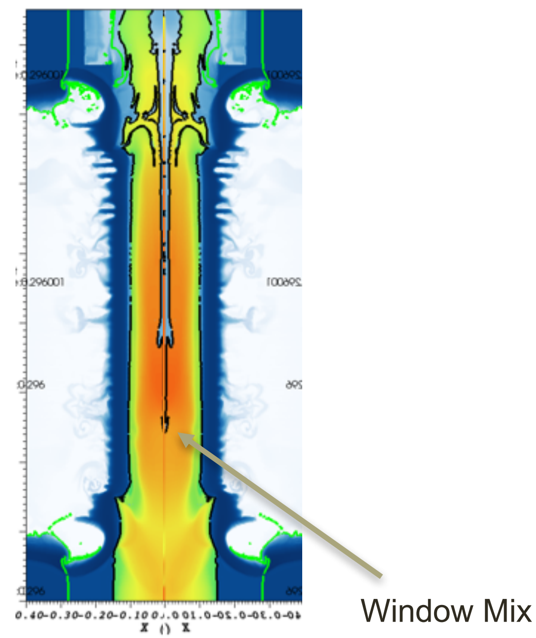
Window mix has been observed experimentally and is transported further with the new laser heating protocols



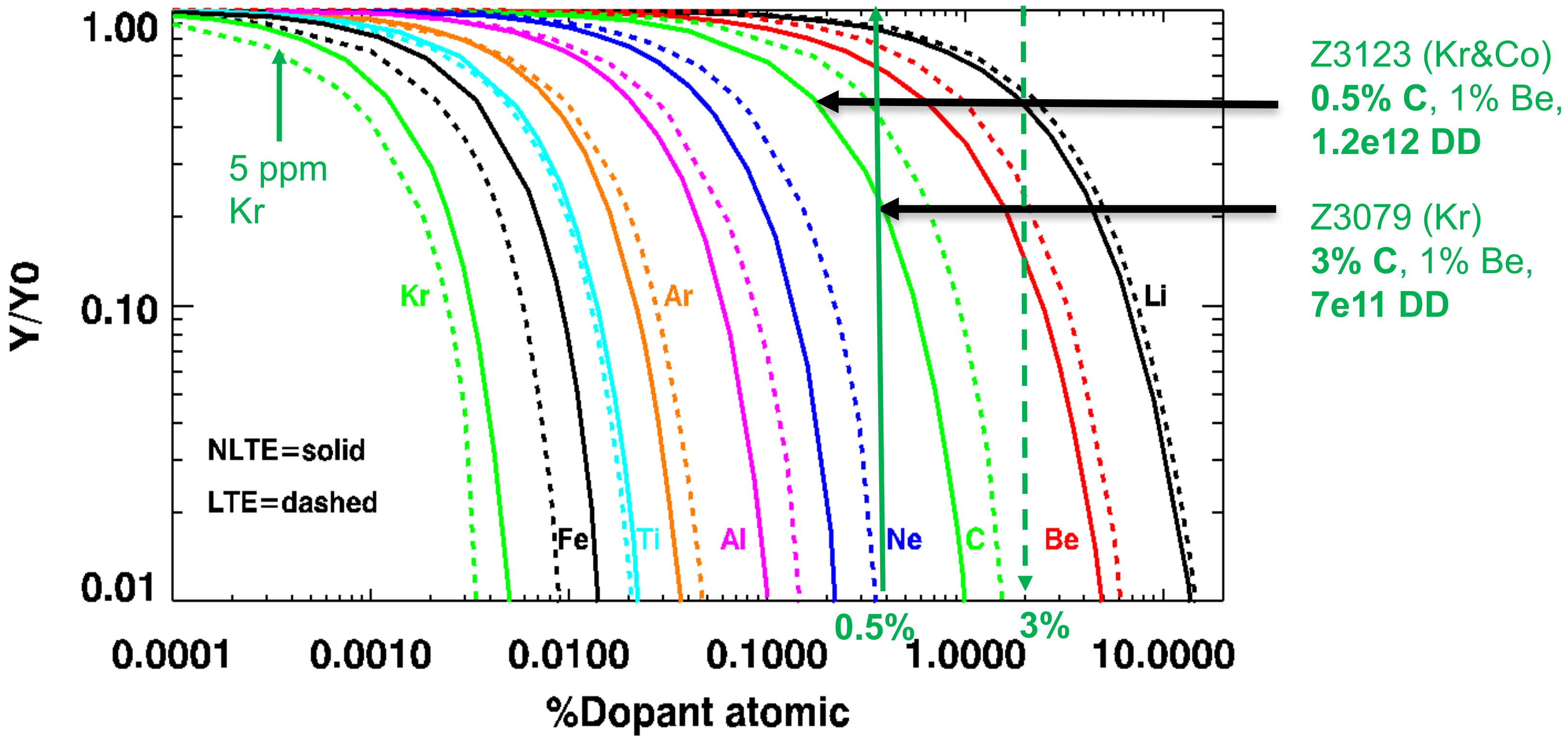
Z3057 – 1100 μm DPP: axially resolved spherical crystal spectrometer



2D HYDRA Simulation



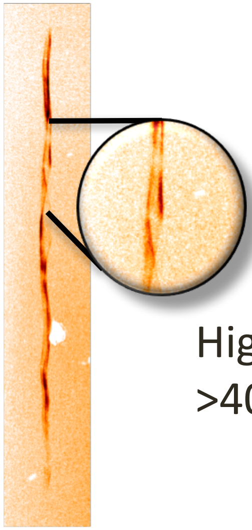
Inferred fractions of Be and C mix trend with but are not completely consistent with expected yield variations



The impact of 3D instabilities on performance is still uncertain

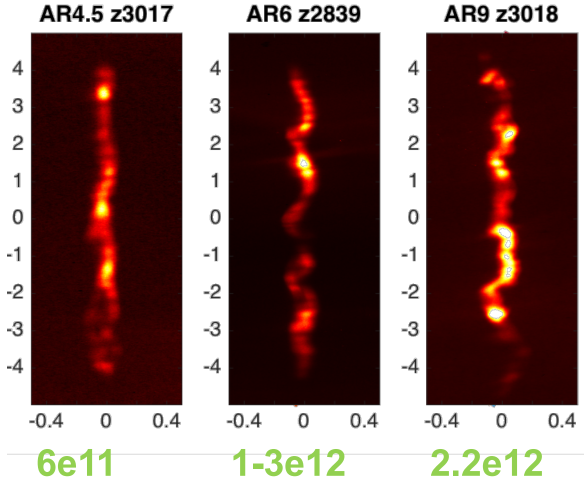
- Spectroscopic measurements suggest relatively high levels of mix
- Experiments with higher convergence generally have poorer performance
- Disruption due to instabilities?
- 3D simulations have matched experimental observables with quasi-2D pressure profiles
- Thicker liners (less feedthrough) have **decreased** performance

>6keV, time time integrated high resolution X-ray self-emission stagnation image



High CR >40!

Thick liner
(Low AR)



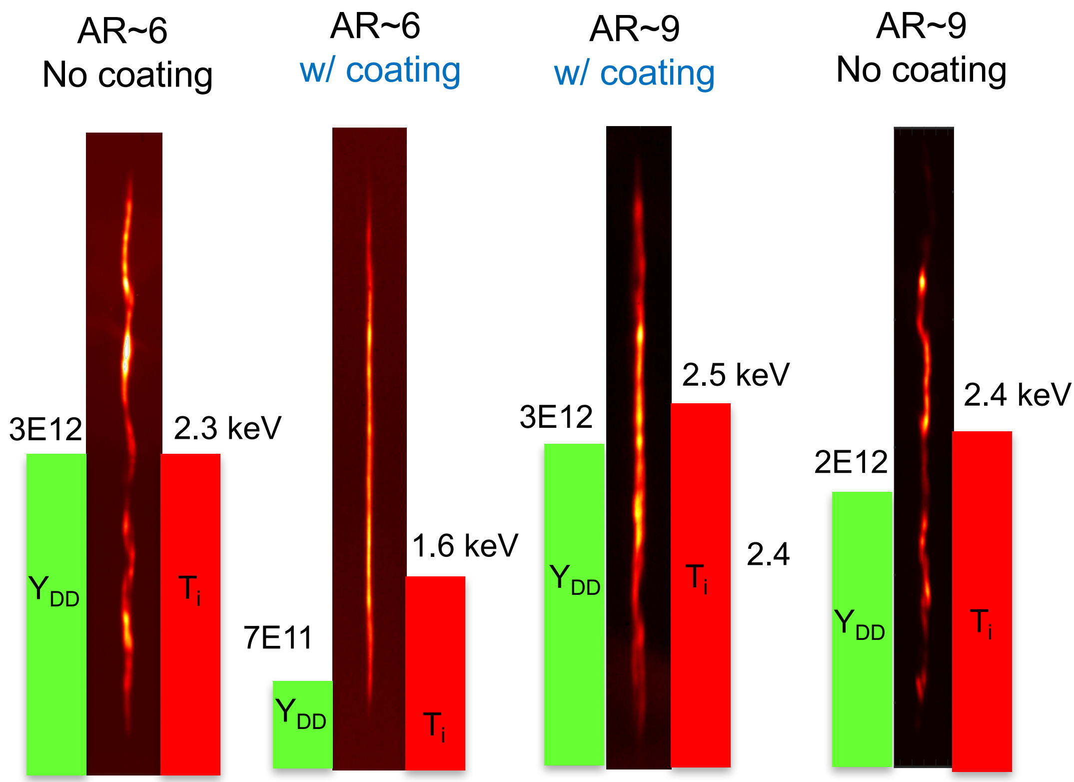
Thin liner
(High AR)

AR = Liner Radius/Liner Thickness

Significant improvements in liner stability have been demonstrated with thick dielectric coatings

- Thick plastic coatings applied to outside surface mitigate electro-thermal instability growth
- Coated AR-9 targets have shown excellent stability and shot-to-shot reproducibility thus far (~15%)
  - Higher magnetization observed (BR ~ 400 kG cm)
- Coated AR 6 targets show remarkable stability, but poorer performance
  - Possible effects of mass distribution, liner compression, etc.

>6keV X-ray self-emission stagnation images

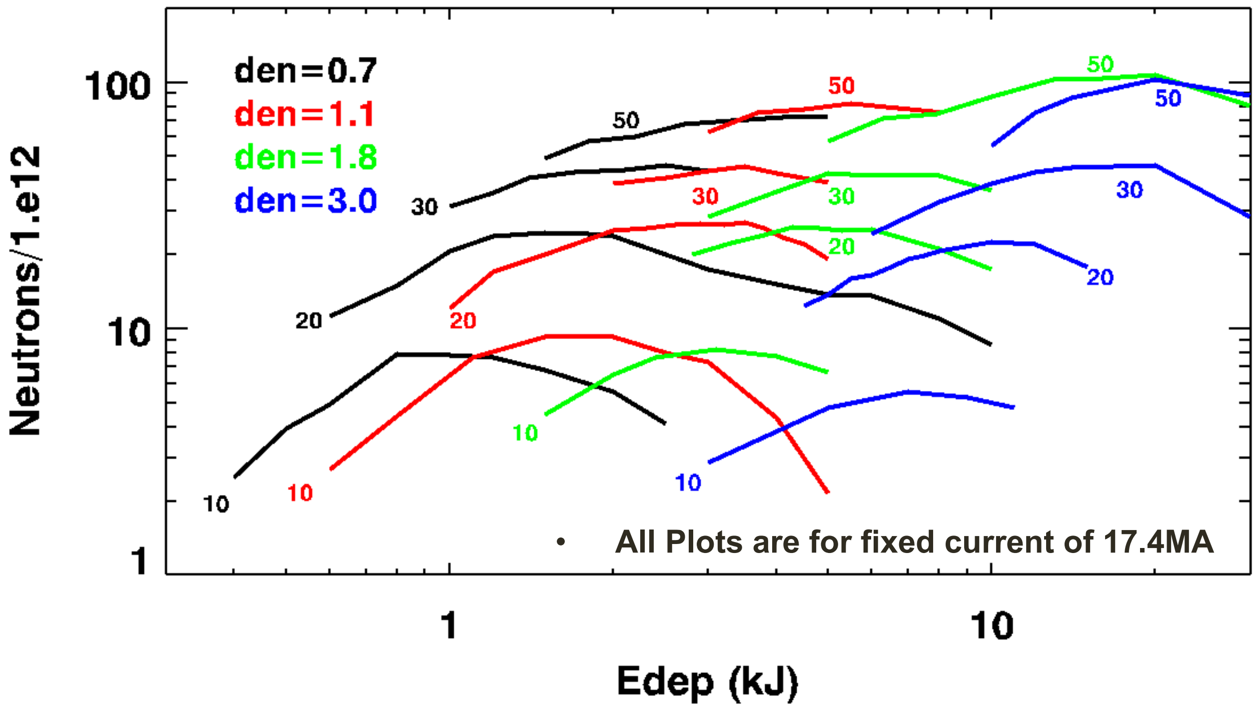


Observed differences in liner morphology do not appear to be strongly affecting stagnation performance

Ampleford: O. We.C1.4

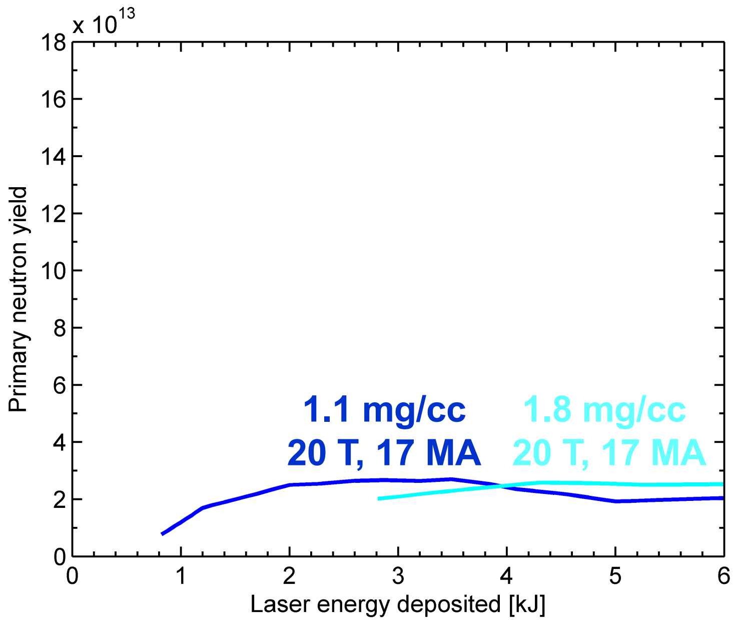
Without more current, initial magnetization levels need to be increased to realize any significant increase in performance

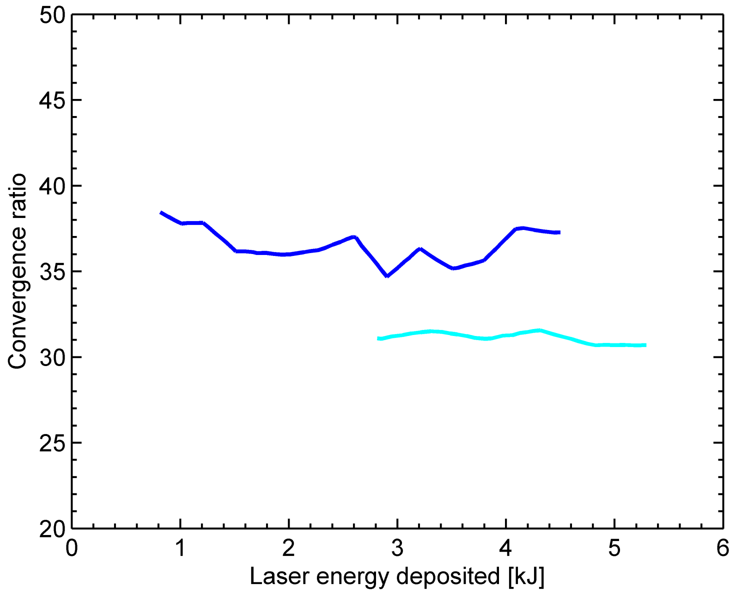
Simulated scaling with B_z and laser energy deposited



- Key MagLIF scaling issues can be studied without more drive current
- Larger fields increase the burn time
- Higher fuel densities lower convergence

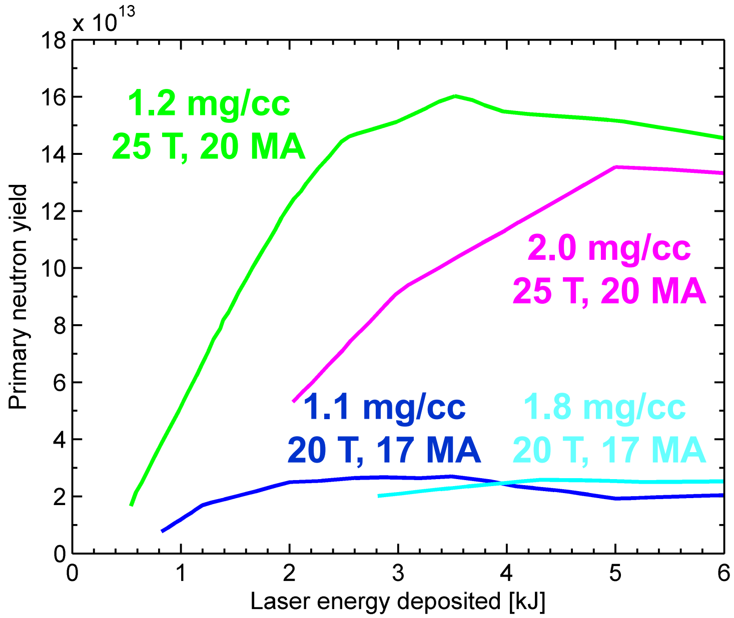
Performance can also be improved with with increased load current, but the convergence ratio goes up

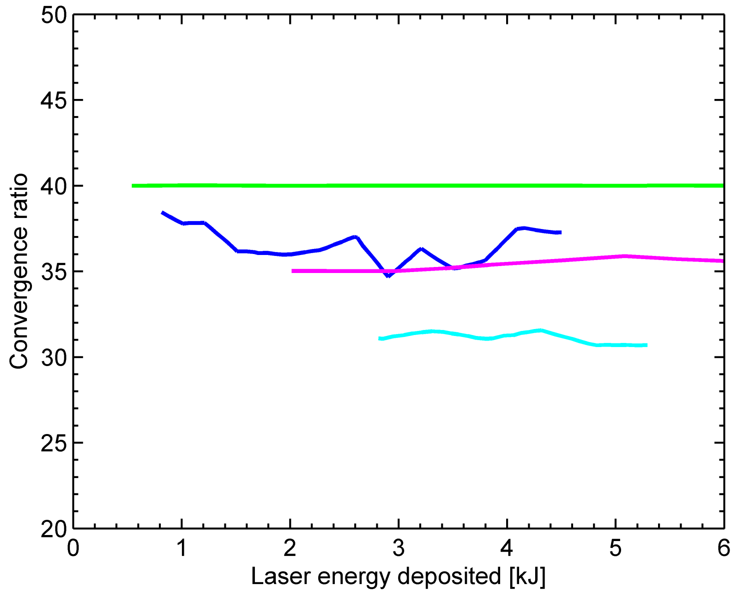




Simulations courtesy of S. A. Slutz

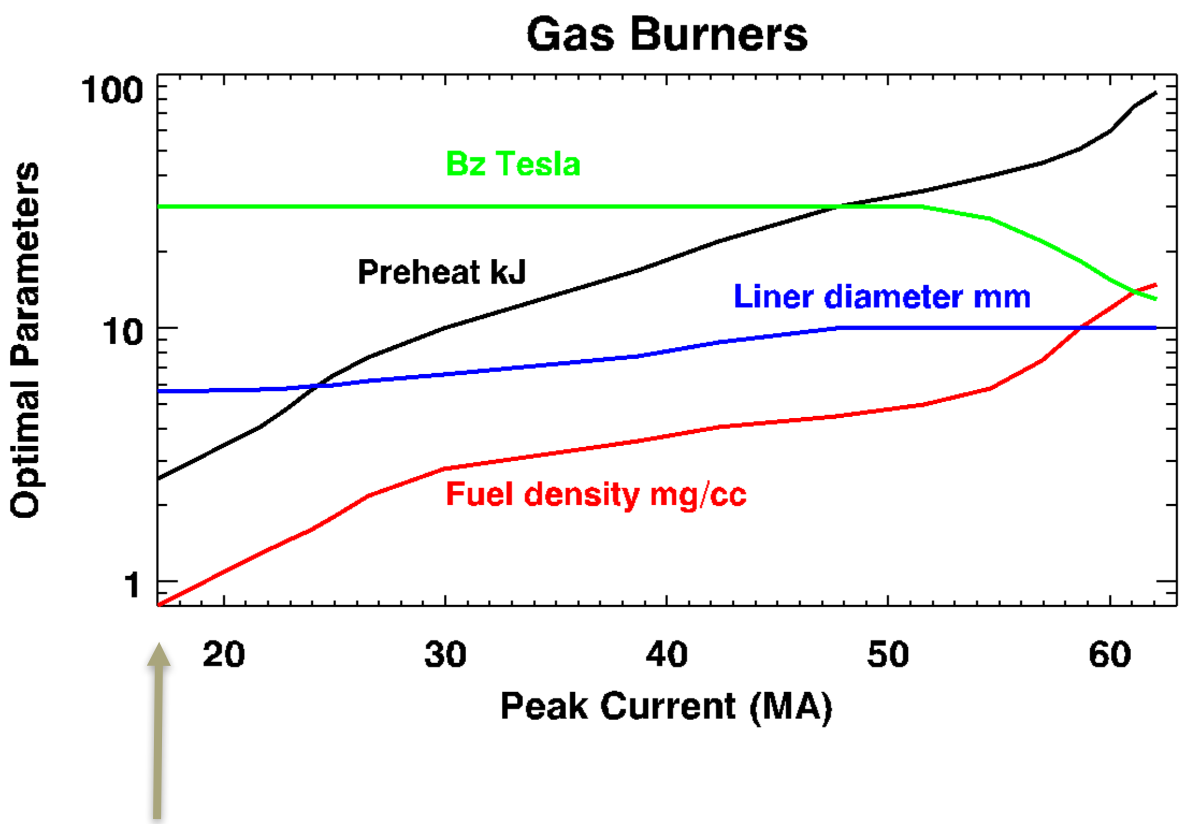
Performance can also be improved with with increased load current, but the convergence ratio goes up





Simulations courtesy of S. A. Slutz

Performance optimized scaling is only achieved when field, fuel density, preheat energy, and current are all scaled simultaneously

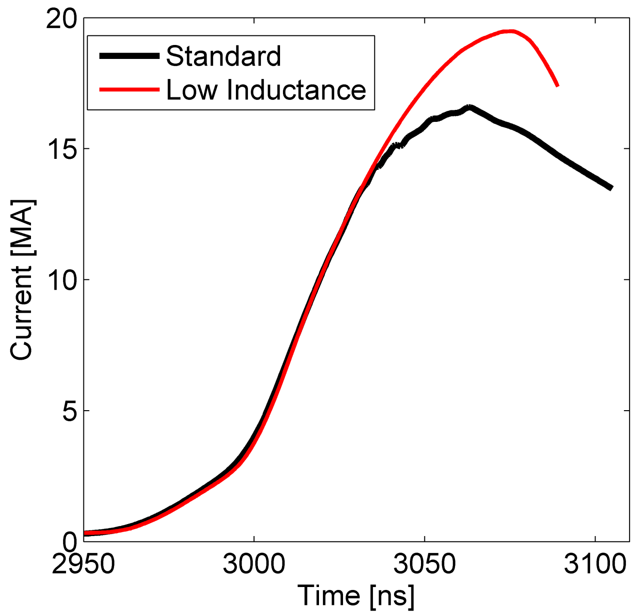


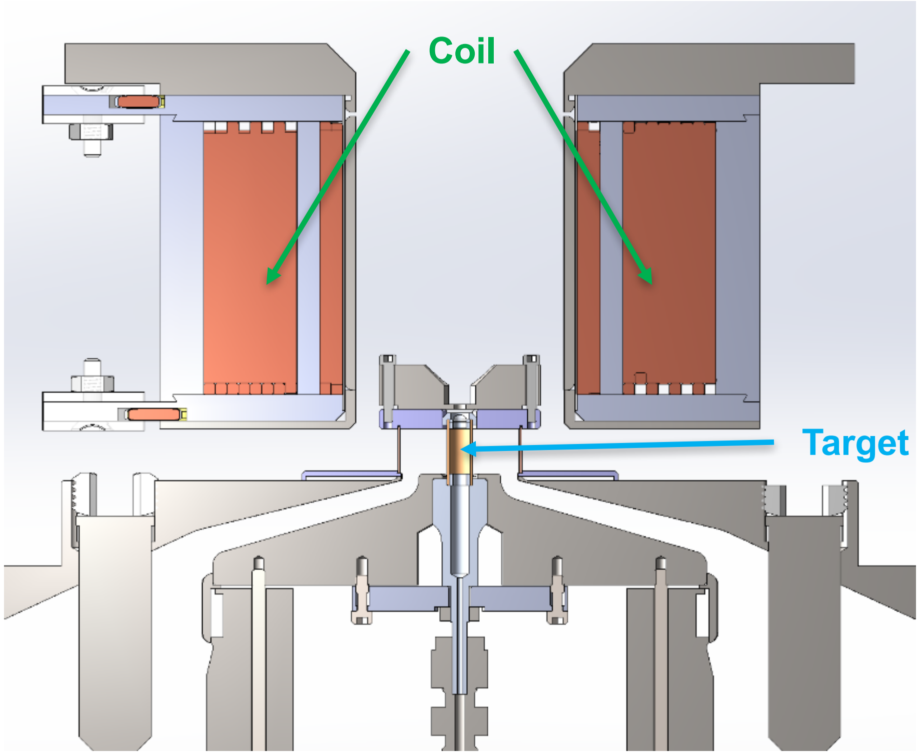
According to simulations, we have not yet been able to test optimal conditions yet on Z

Simulations courtesy of S. A. Slutz

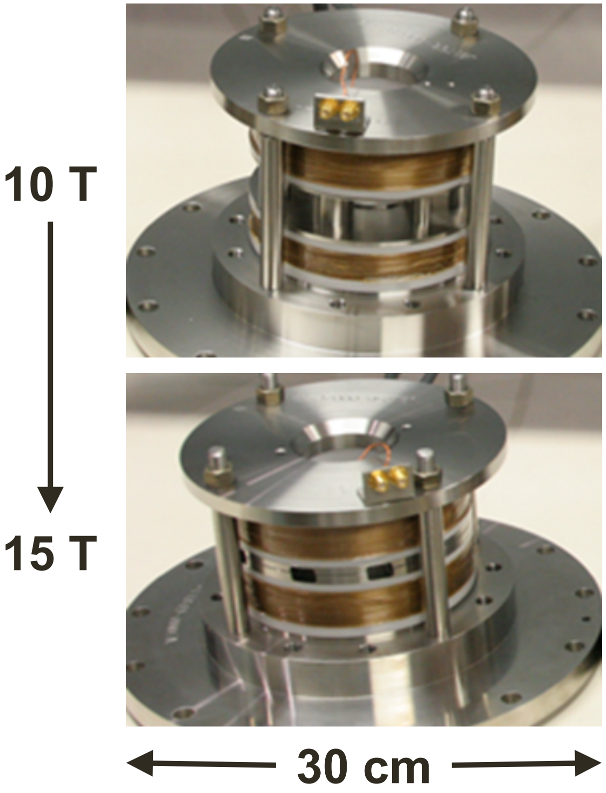
We are working towards scaling to higher drive currents which requires reducing the load inductance

- 10-20% increase in peak current has been demonstrated with 10 T
- 19+ MA, 13-17T fields (non-uniform)
- Initial integrated tests have not shown improvement in performance
  - Increased convergence





We are also working to increase the initial applied B-field

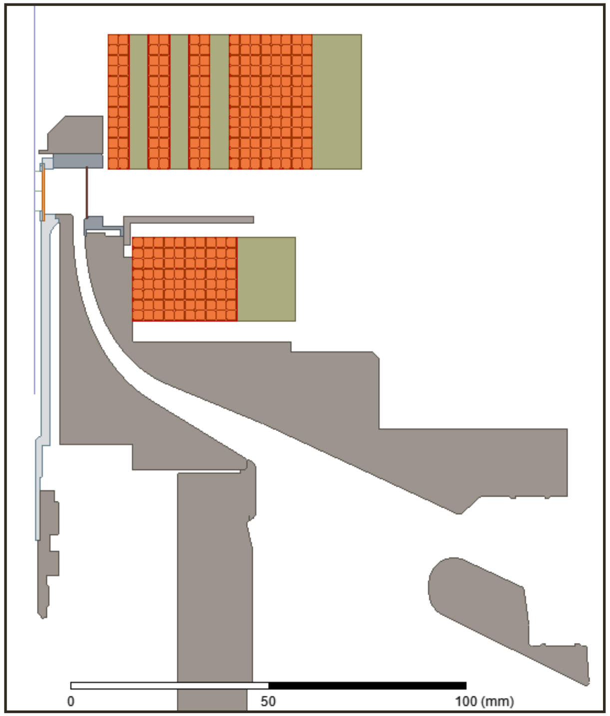


Standard coil, high inductance feed, 17MA peak current

- Using standard coil, initial field can be increased to ~25T
  - 15 T Limited Diagnostic Access
  - 25 T No Diagnostic Access
- Completed the first commissioning tests at 15 T
- Increased magnetization and coupled preheat energy is predicted to improve performance (without an increase in drive current)

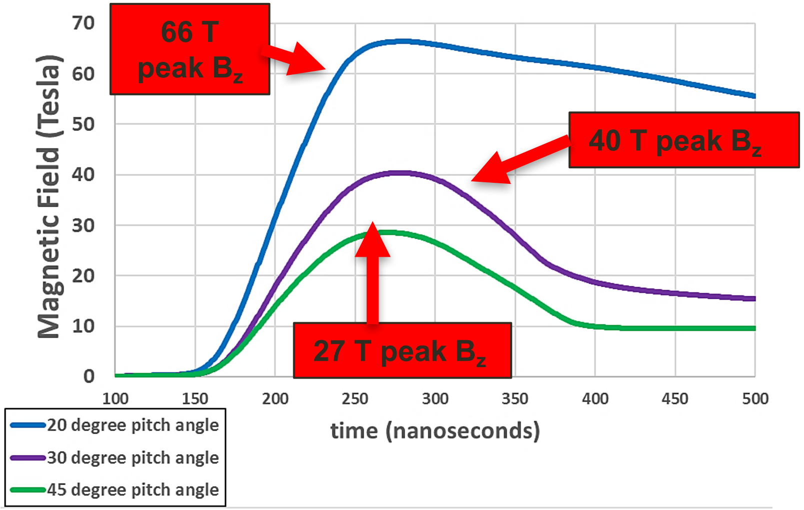
We are also working to increase the initial applied B-field increase the applied B-field – Longer Term

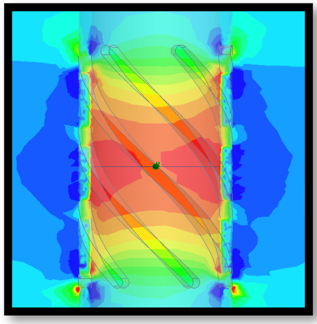
New low inductance coil, operation up to 25 T

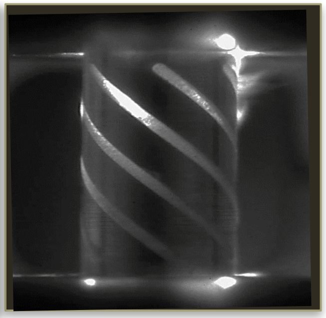


Coil design courtesy of Derek Lamppa

Slotted helical liners "Automag"





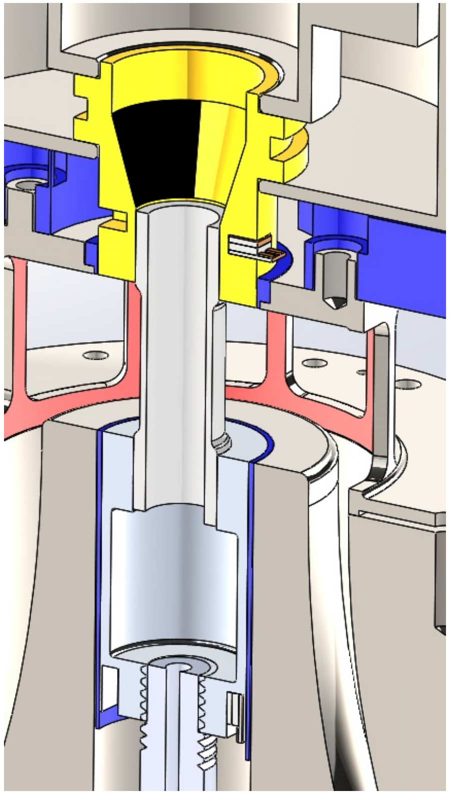


G. Shipley, T. Awe

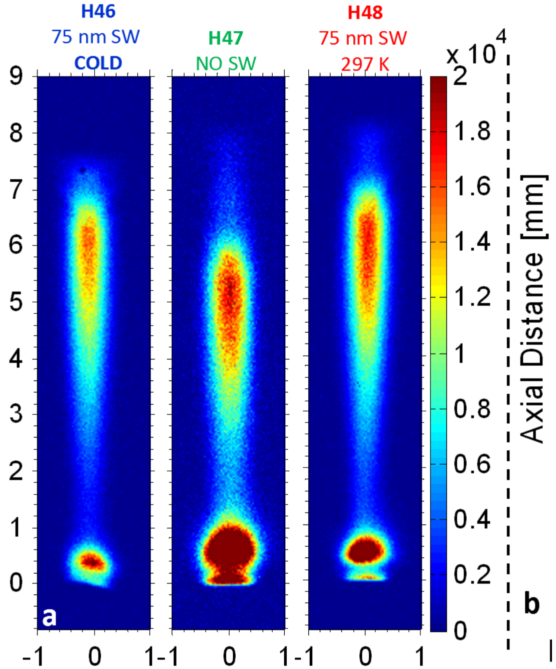
We are working to minimize or eliminate the window mass from our experiments

Cryogenic Targets

- 400 nm window cooled to ~30K
- First attempts performed poorly
  - Redesigned to minimize window ice
  - Potential issue with previous target design identified
- Excellent laser propagation and deposition observed with new design
- Two weeks ago, we had a successful integrated test of this design with nominal performance



Cryo laser heating tests

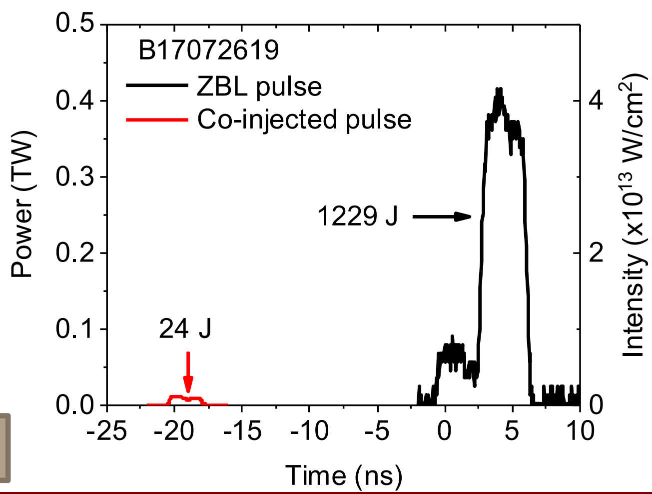


T. Awe, M. Weis, M. Glinsky, K. Shelton, A. York

We are working to minimize or eliminate the window mass from our experiments

Co-injection of Z Petawatt

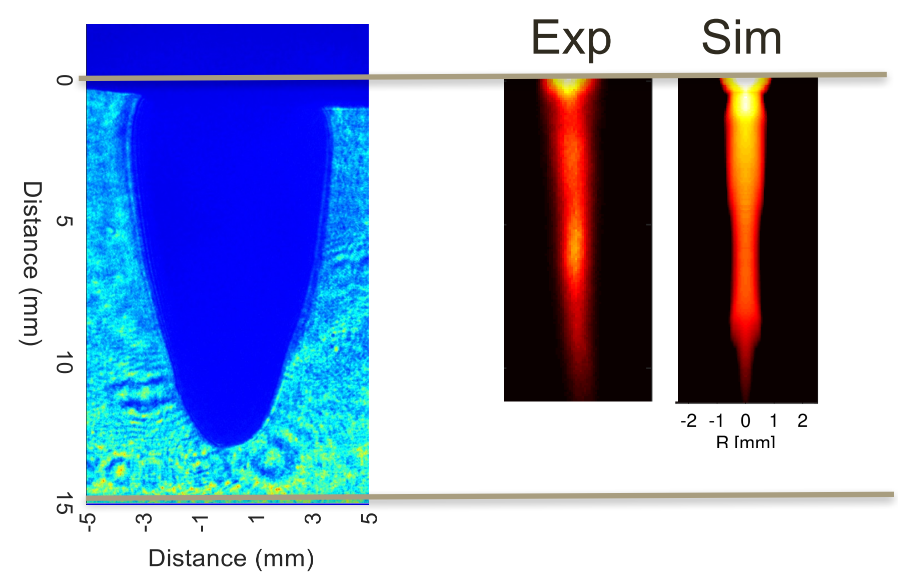
- New capability
- Utilize 10-20J Z-Petawatt laser pulse to disassemble window
- Entire 6 ns ZBL laser window available for fuel heating
- Initial results are promising! Significantly improved energy coupling and reduced LPI effects



Schwarz: P. Tu.25

Optical Shadowgraph @ +20ns

Time integrated pinhole camera

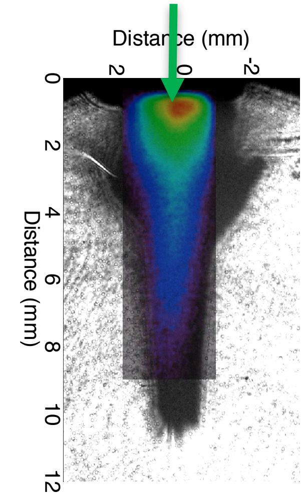


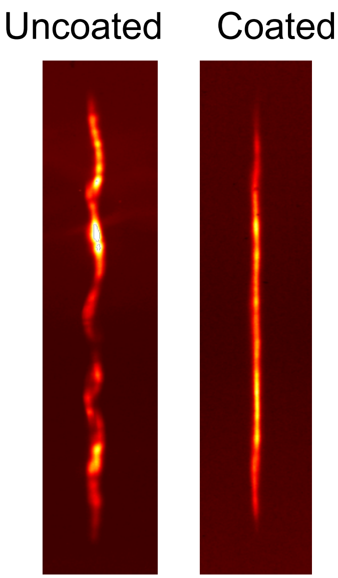
- Significantly improved agreement with simulations
- **First integrated test this week!**

A. Thompson, M. Geissel, M. Weis, J. Schwarz, I. Smith

Summary

- **Progress**
  - We have developed a new, significantly better understood, low LPI laser preheating platform that has produced record MagLIF performance, 4e12 (~50% of clean)
  - We have improved our understanding of mix sources and their impact on performance
  - Significant improvements in liner stability have been demonstrated
  - We are developing several new capabilities to test scaling (low inductance coils with increased field, cryogenic platform, co-injection, automag)





Summary

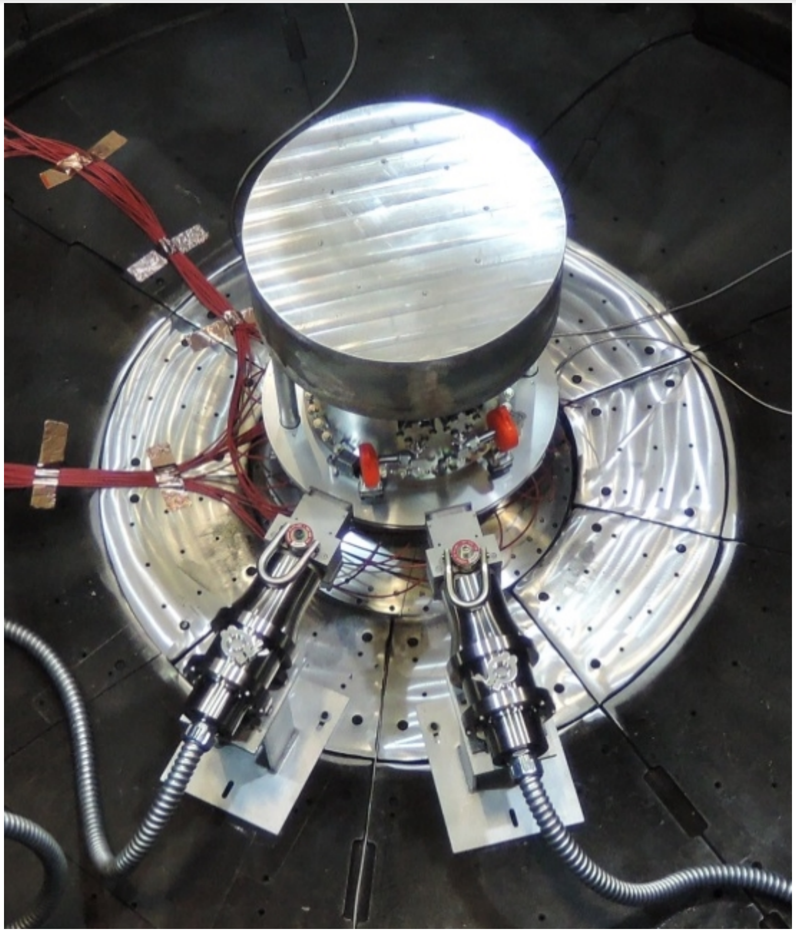
- **Going Forward**
  - Improve robustness and scalability of MagLIF targets on Z
    - Decrease convergence ratio to ~35 by increasing fuel mass
    - Minimize or eliminate laser entrance window mass and control dust
    - Understand sources of variability in integrated experiments
    - Develop more efficient power flow platforms compatible with higher Bz
  - Better quantify stagnation conditions and relative impact of both laser and liner mix on performance
  - Evaluate scaled laser energy coupling (30kJ) at NIF

Backups

First ever tritium experiment was conducted on Z in August 2016

Sandia National Laboratories

- **Motivation**: We need to develop experience with tritium and it can benefit our scientific understanding through higher yields (50 -100x) and higher energy spectrum neutrons (14 MeV)
- **Approach**: We safely conducted a tritium experiment on Z using a trace amount of tritium (0.1% T), applied engineering controls (e.g. containment) and thorough planning
- **Outcome**: Neutron diagnostics measured a primary DT neutron signal for the first time on Z and tritium was not detected above background levels using surface and airborne monitoring techniques



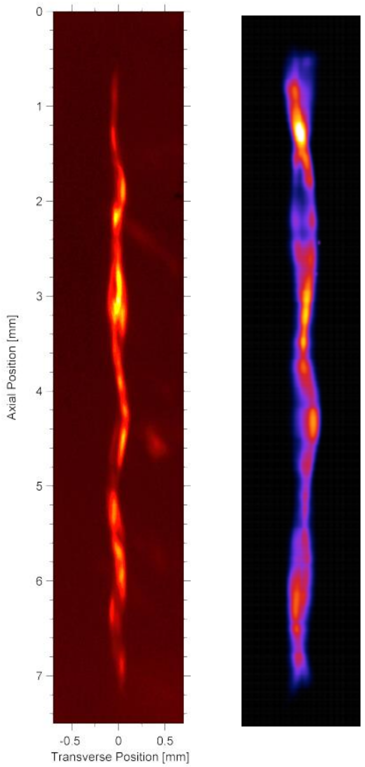
Experimental configuration for first ever tritium experiment on Z

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

Sandia National Laboratories

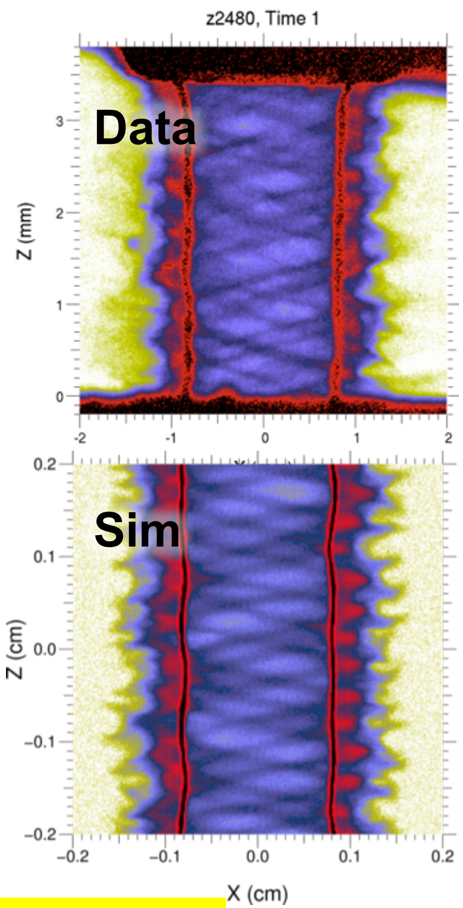
Imaging

Data **Sim**



Z2613

Radiography



A. Sefkow simulations

Comparison to z2591 Observables

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

Delivered laser energy is 2.5 kJ

*Thick window (3.5 micron experiments)

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

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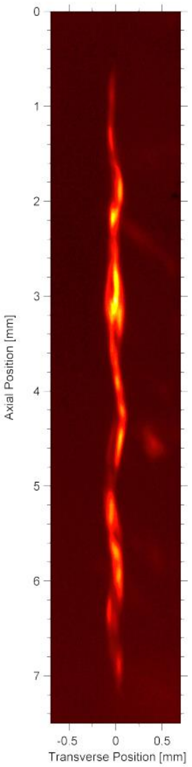
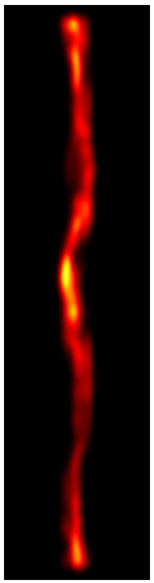
Imaging

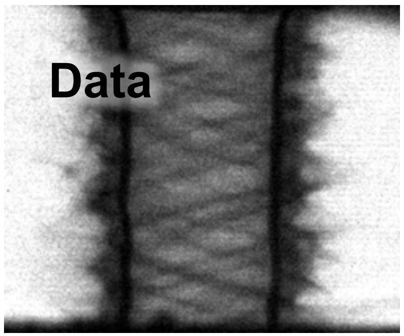
Data **Sim**

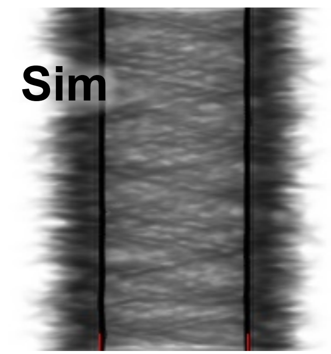




Z2613

Radiography





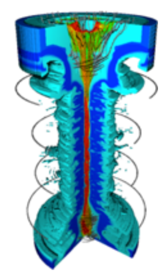
C. Jennings simulations

Comparison to z2613 Image

Parameter	Measured/inferred	Post-shot simulations
• FWHM	91 ± 40 mm	121 ± 40 mm

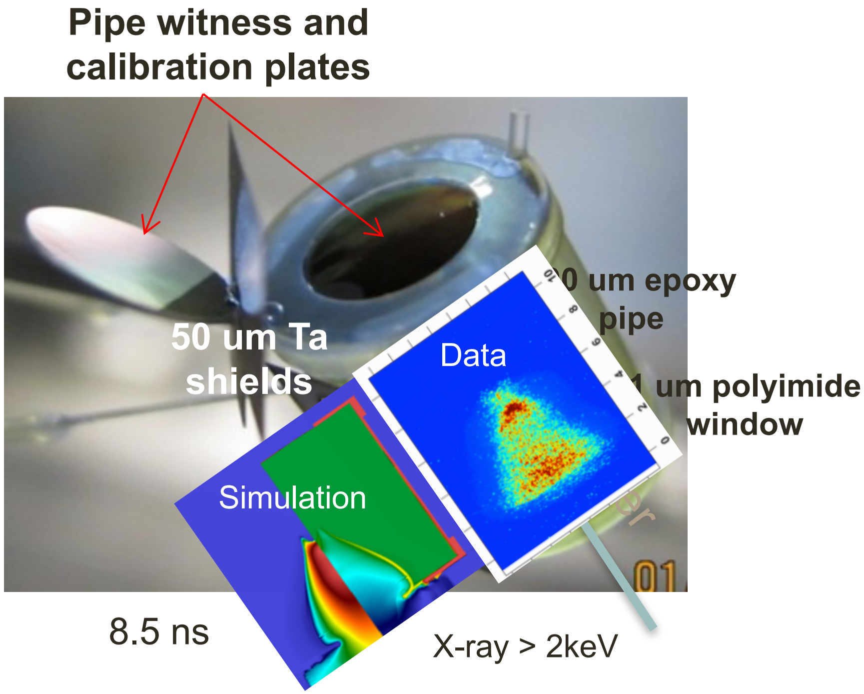
Sim. Values:

- 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 ± 60 mg cm^{-2}** to **980 ± 110 mg cm^{-2}** over the FWHM of the neutron pulse.



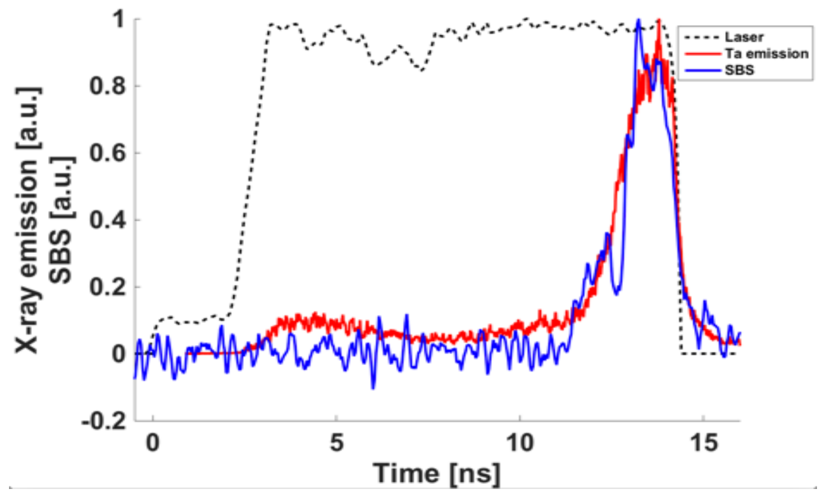
*Thick window (3.5 micron experiments)

Initial laser experiments at NIF have been favorable for scaled laser heating



Time dependent laser propagation is in remarkable agreement with pre-shot simulation predictions

SBS time history



Energy coupling is >98% with minimal backscatter during propagation within the gas-pipe!

Primary Objective: Assess whether or not laser preheating is a viable scaling path for magnetized target fusion (MagLIF)

Bayesian inference tools are now being applied to better quantify stagnation performance (Pτ, BR) and identify important correlations

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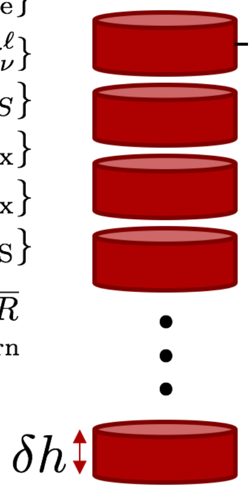
Hotspot Parameters

$$\{T_{\mathrm{i}}\} = \{T_{\mathrm{e}}\}$$
$$\{\tau_\nu^\ell\}$$
$$\{P_{HS}\}$$
$$\{f_{\mathrm{mix}}\}$$
$$\{Z_{\mathrm{mix}}\}$$
$$\{R_{\mathrm{HS}}\}$$
$$\overline{BR}$$
$$\tau_{\mathrm{burn}}$$



X-ray Emission:

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

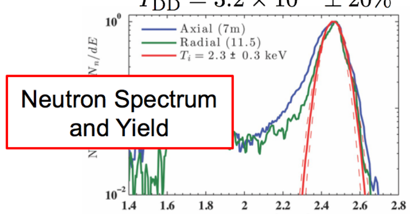
$$\tilde{j}_i \equiv \frac{j_i}{j_{\mathrm{D}}} = Z_i^2 + \frac{A_{f-b}}{A_{f-f}}\frac{Z_i^4}{T}e^{RyZ_i^2/T}$$

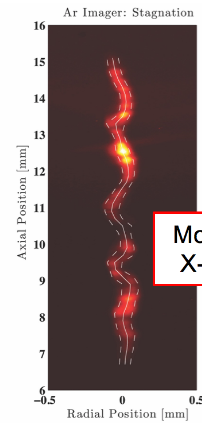
Neutron Emission:

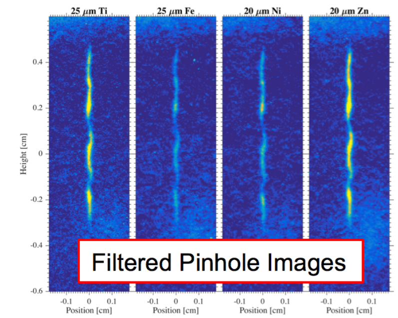
$$\frac{dN_{\mathrm{DD}}}{dE} = \sum_{n=1}^{\mathrm{N}}\frac{P_{\mathrm{HS}}^2 V\tau_{\mathrm{burn}}}{(1+\sum_i f_i Z_i)^2}\int_0^1 \tilde{r}d\tilde{r}\frac{\langle\sigma v\rangle_{\mathrm{DD}}}{T_{\mathrm{i}}^2}I_o(E)$$

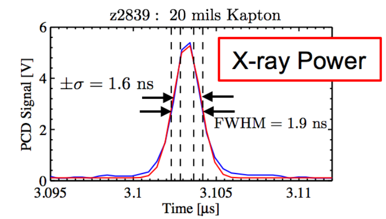
$$^*I_o(E) = e^{\frac{-2\bar{E}}{\sigma^2}(\sqrt{E}-\sqrt{\bar{E}})^2}$$

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





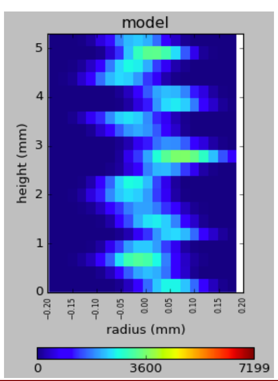




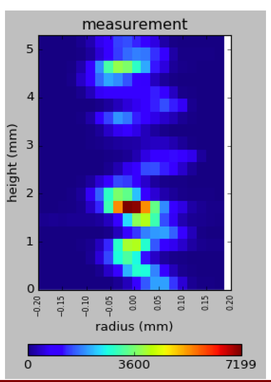
$$Y_\gamma = 10\ \mathrm{J} \pm 20\%$$

Spherical Crystal Imager Example

Prior



Data



Posterior