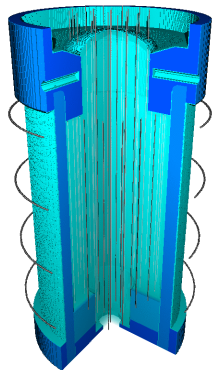
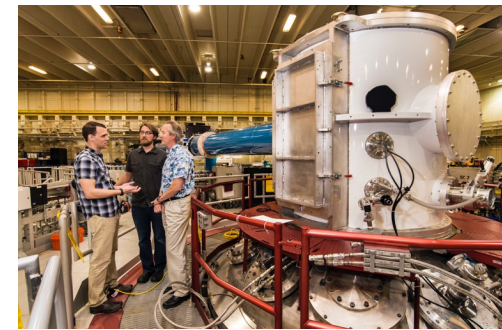
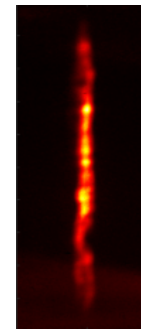
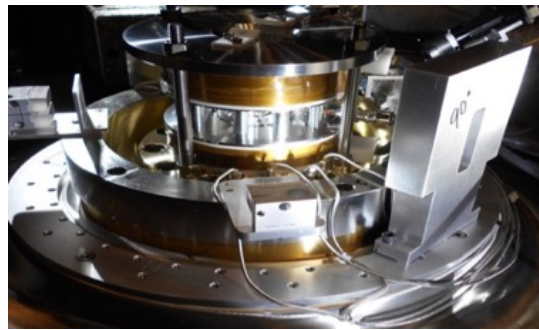
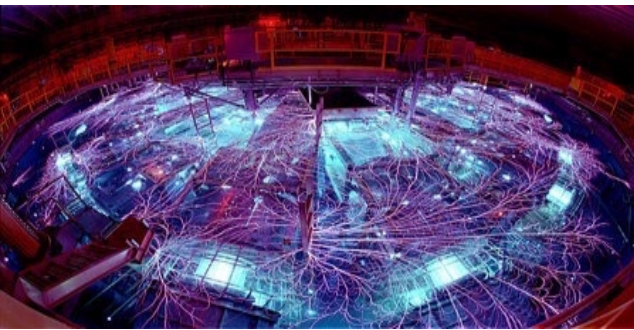


*Exceptional service in the national interest*



# Progress in Magnetized Liner Inertial Laser Fusion Research

Kyle Peterson

IFSA 2017



Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and 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-NA-0003525

# MagLIF is a broad collaboration

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

***Sandia National Laboratories***

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

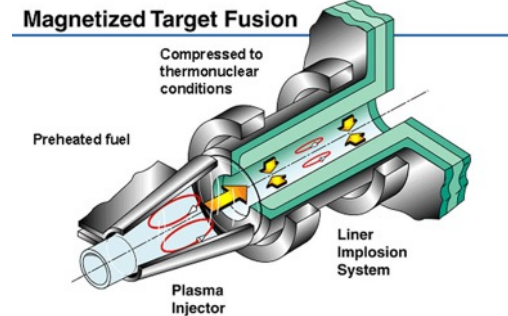
## ■ Strategy:

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

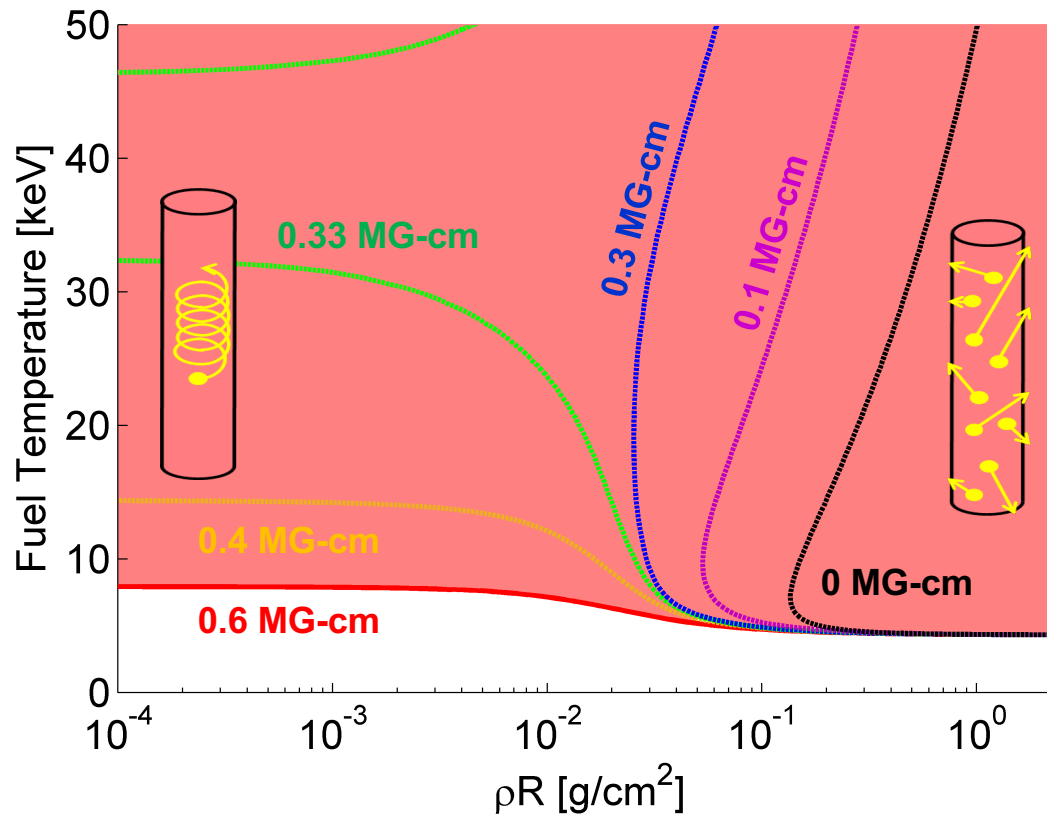
## ■ Requirements:

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

OC-100-0106 (11-99)

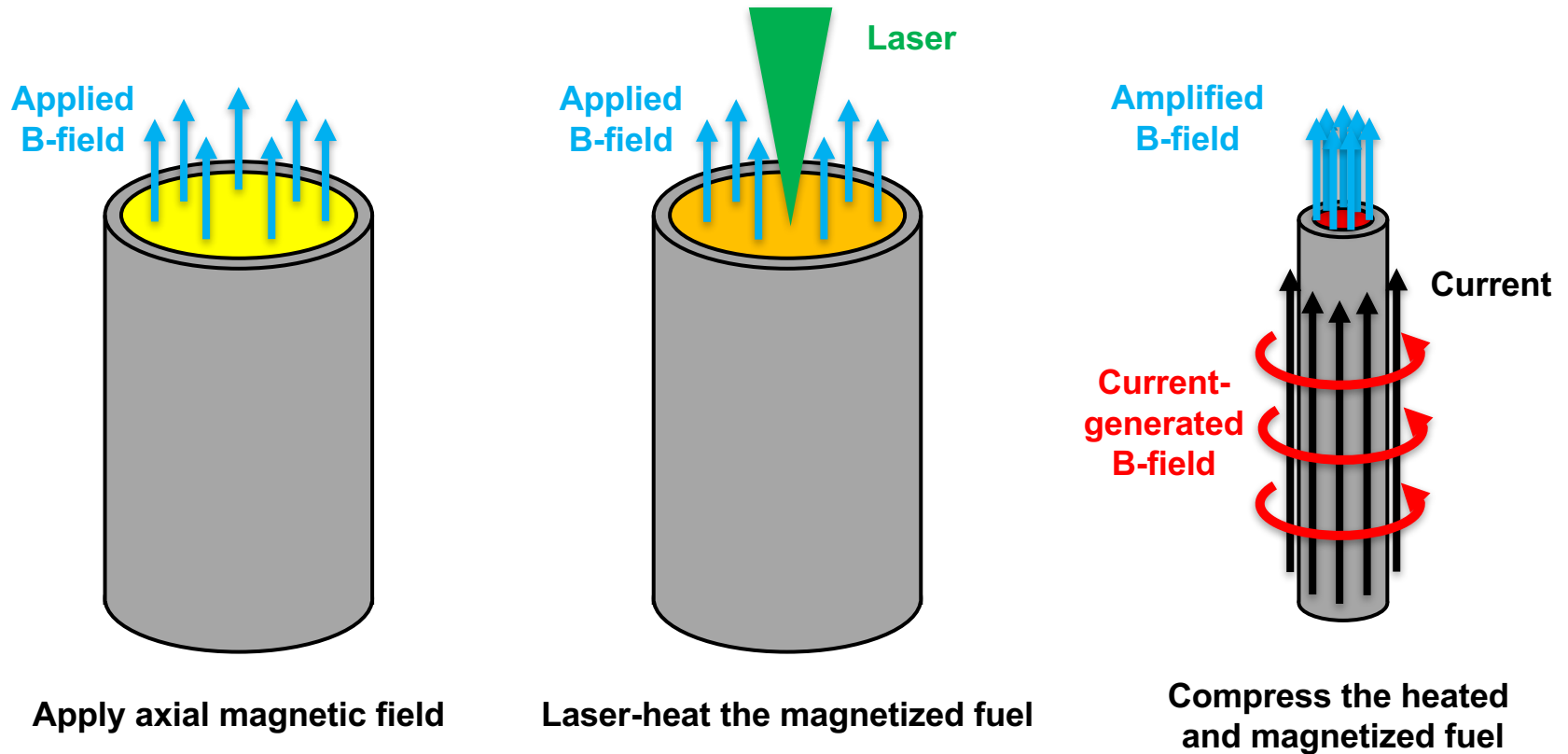


# Magneto-inertial fusion utilizes magnetic fields to relax the stagnation requirements of ICF

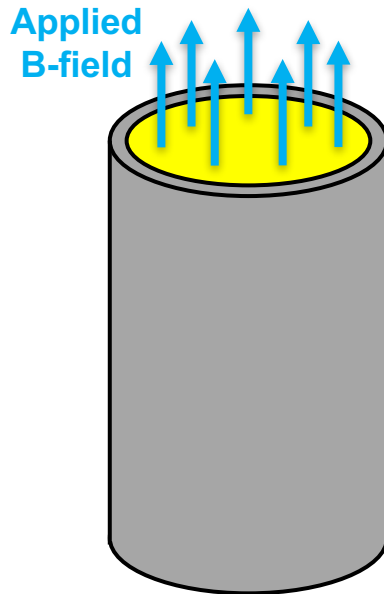


- With a high enough magnetic-field-radius product, charged fusion products become trapped
- This relaxes the areal density requirement of the fuel
- Good performance is possible over a much larger region of parameter space

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



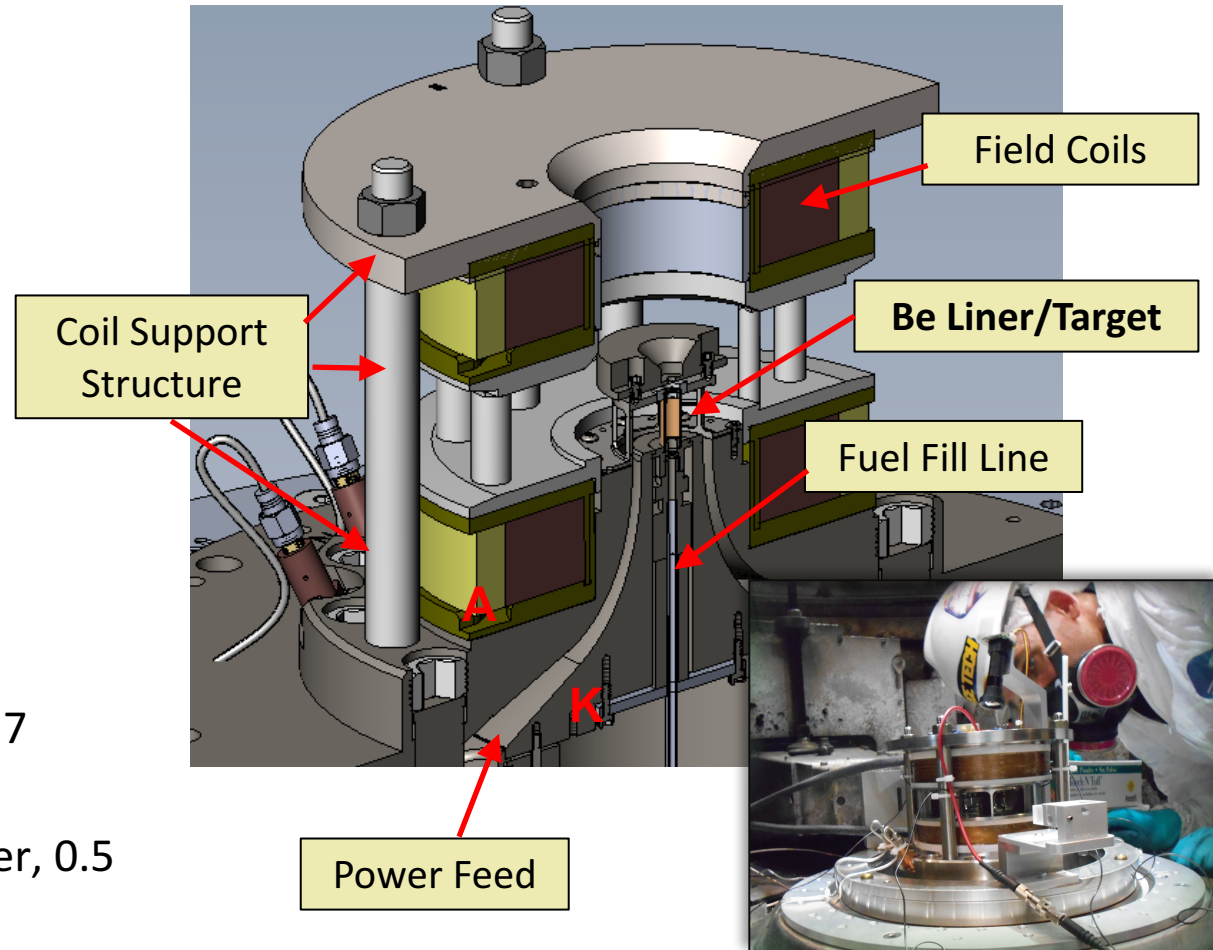
# An axial magnetic field is applied with external field coils before the implosion occurs



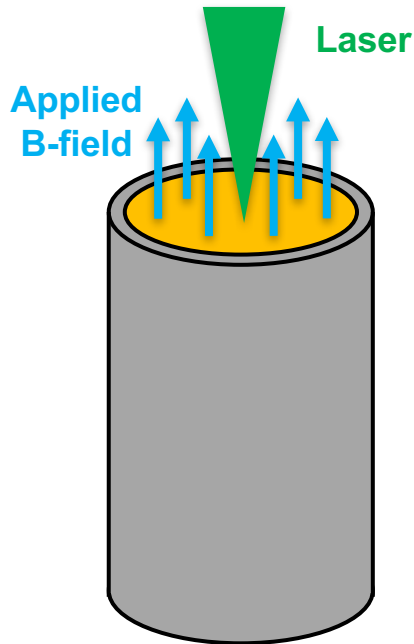
Apply axial magnetic field

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

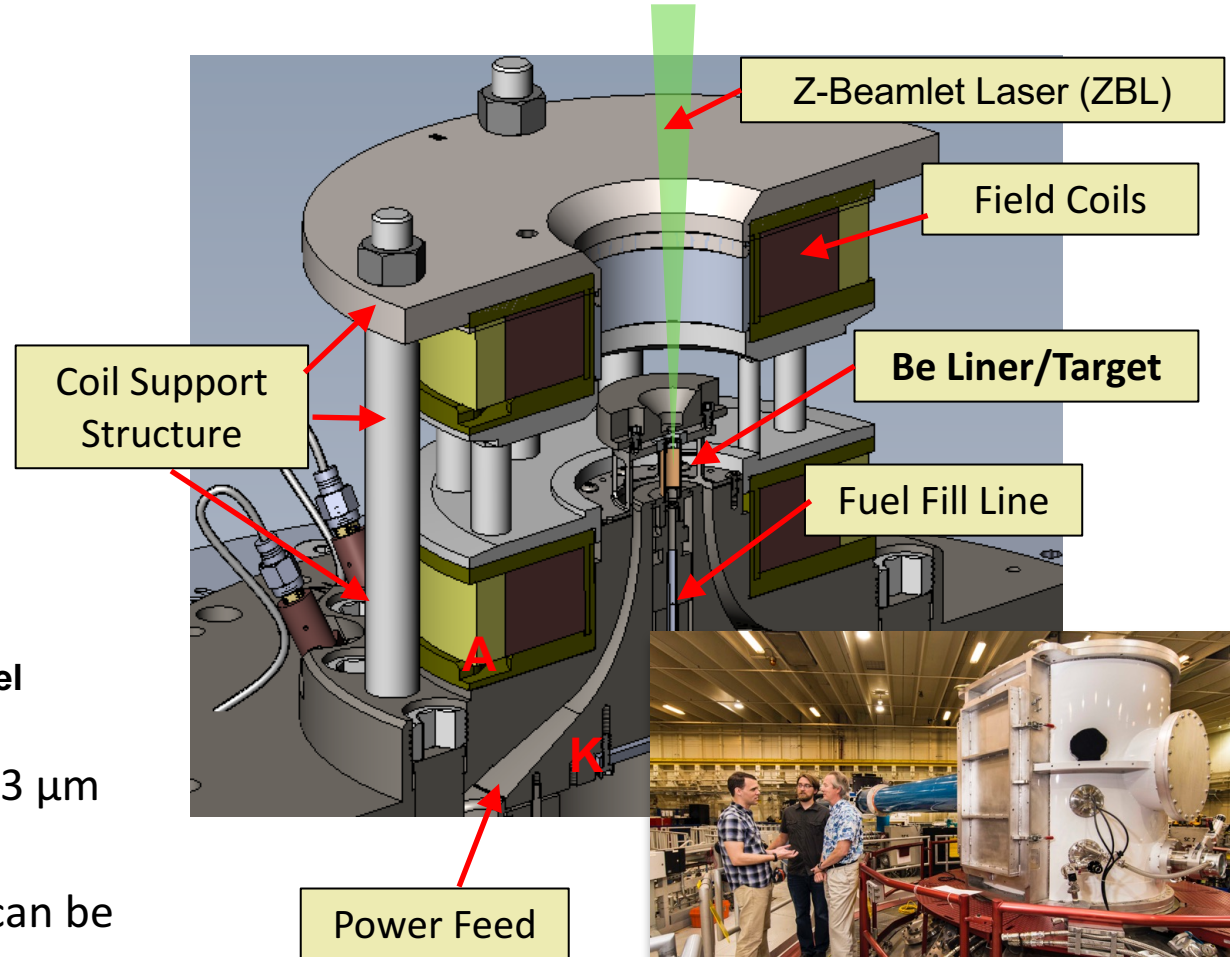
Helmholtz-like coils apply 10-30 T in 3.5 ms



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



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

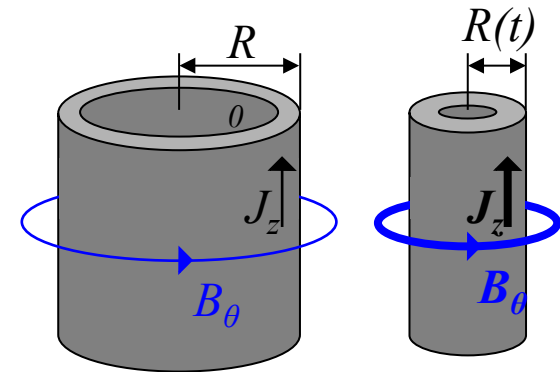
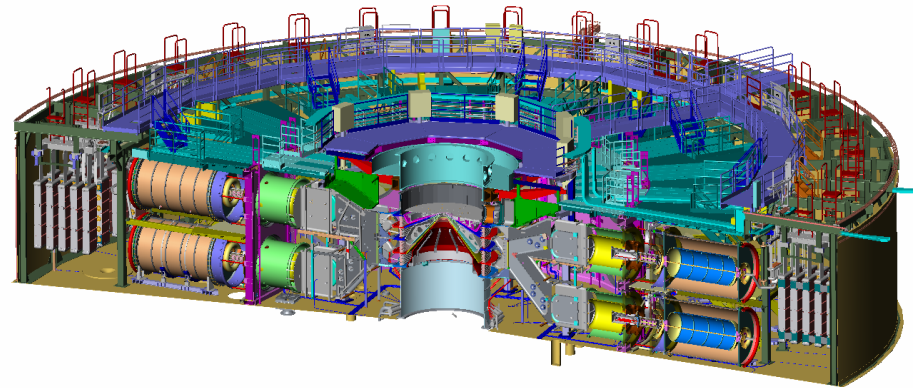
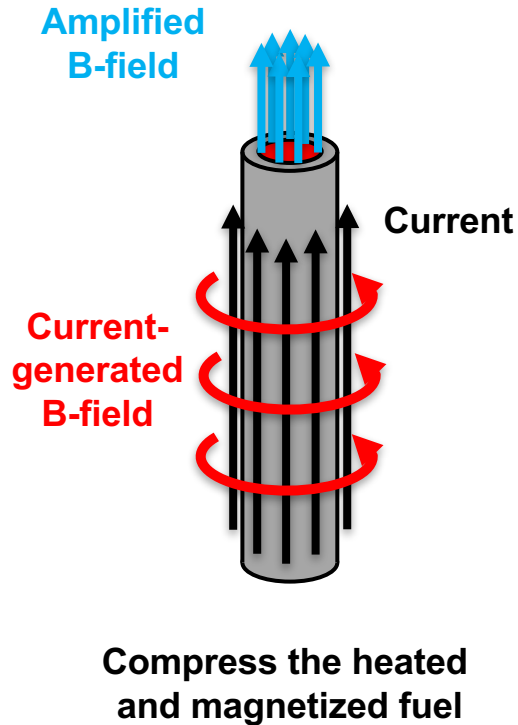


Laser-heat the magnetized fuel

- Laser must pass through 1-3  $\mu\text{m}$  thick plastic window
- Significant laser energy can be deposited in the plastic

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

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

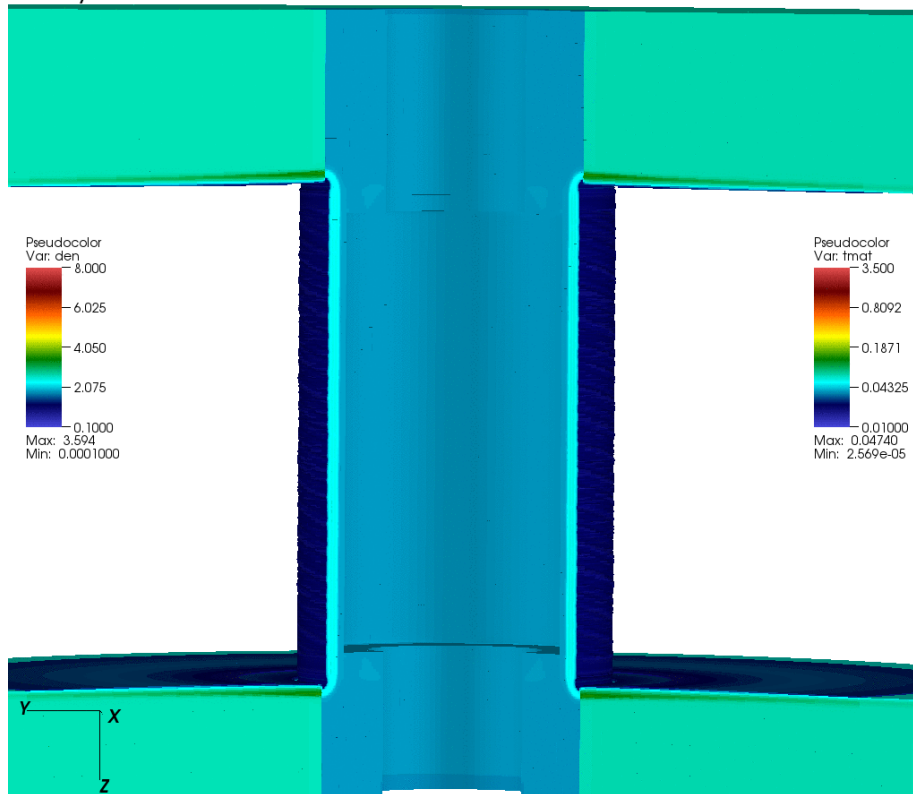


- Metal cylinder implodes at ~70 km/s
- Fuel is nearly adiabatically compressed
- Axial magnetic field is compressed to 1-10 kT

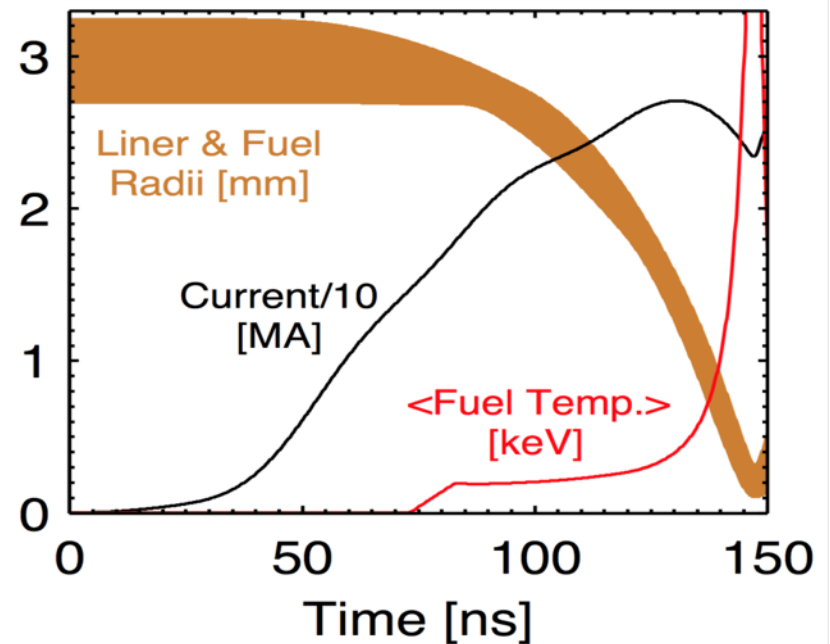
$$P = \frac{B^2}{8\pi} = 105 \left( \frac{I_{MA}/26}{R_{mm}} \right)^2 \text{ MBar}$$

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

DB: hydrg00333.root  
Cycle: 333 Time:0.065021



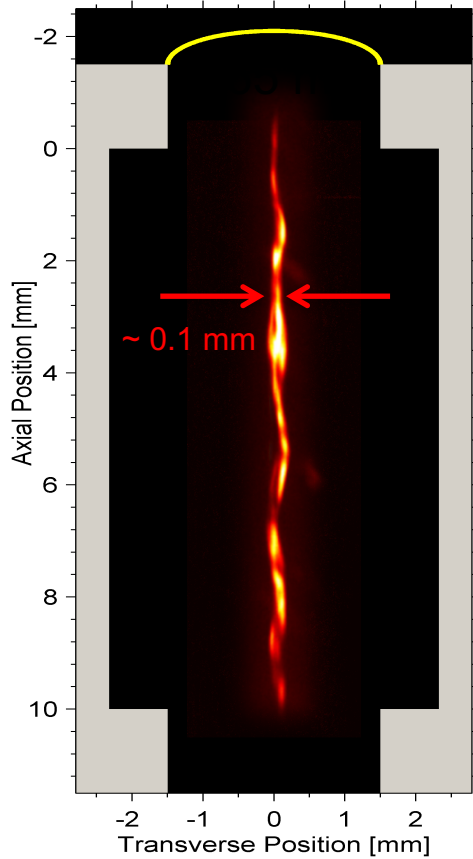
1-D picture\*



Simulation by A. Sefkow

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

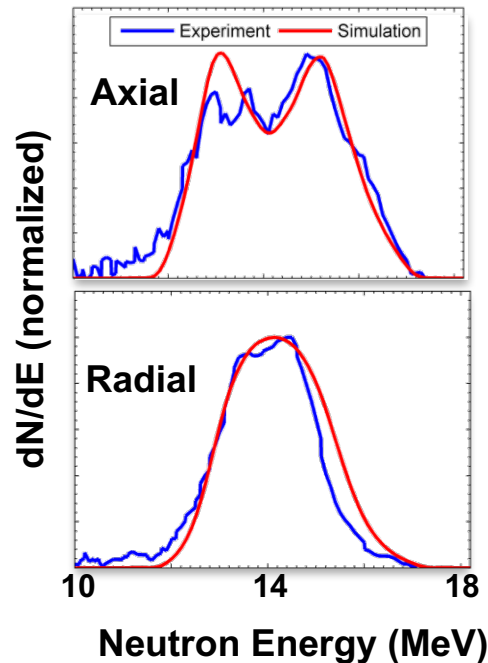
High Convergence Implosion



6+9 keV Emission Image  
CR > 40

B-field Flux Compression & Magnetic trapping of charged particles

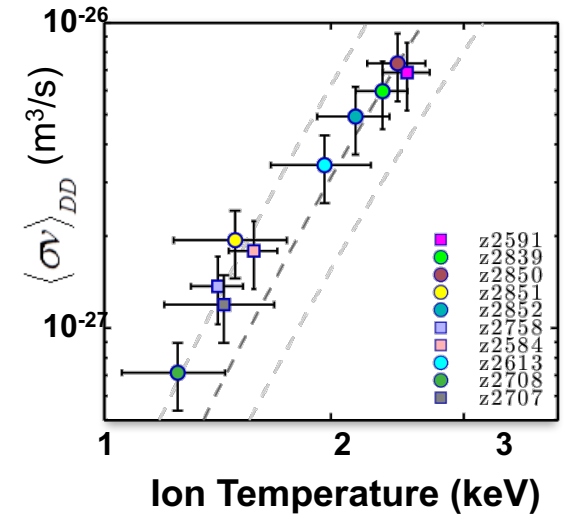
Secondary DT Spectrum



DT Secondary Spectra  
BR > 0.35 MG-cm

Thermonuclear Neutrons

Reactivity Scaling vs.  $T_i$



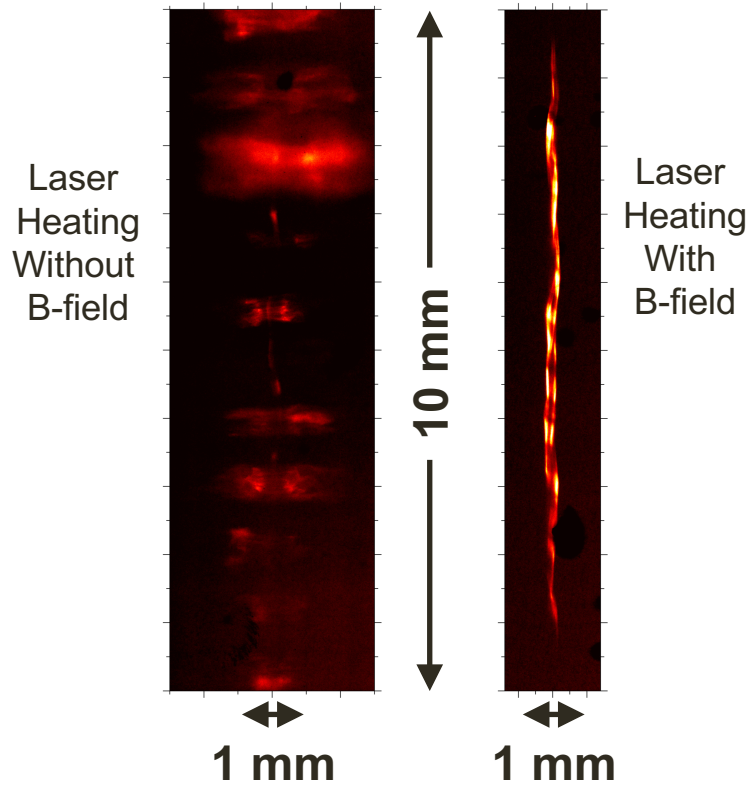
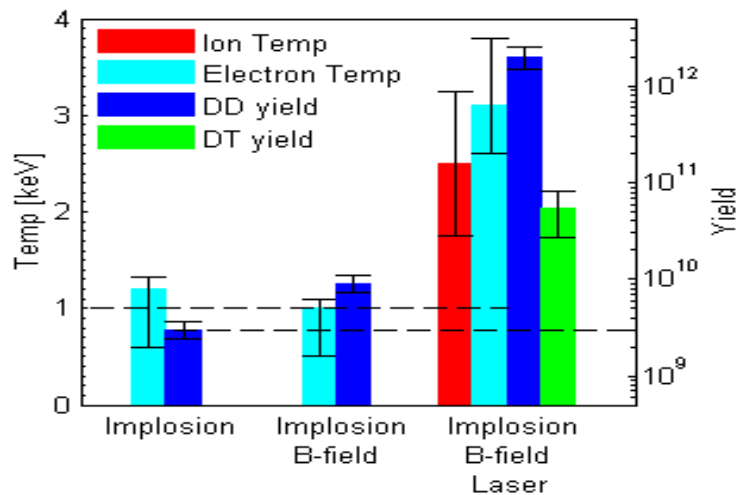
$$Y_{DD} = \frac{1}{2} n_D^2 \langle \sigma v \rangle_{DD} V \tau$$

Yield, Volume, Duration  
Consistent with DD reactivity

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

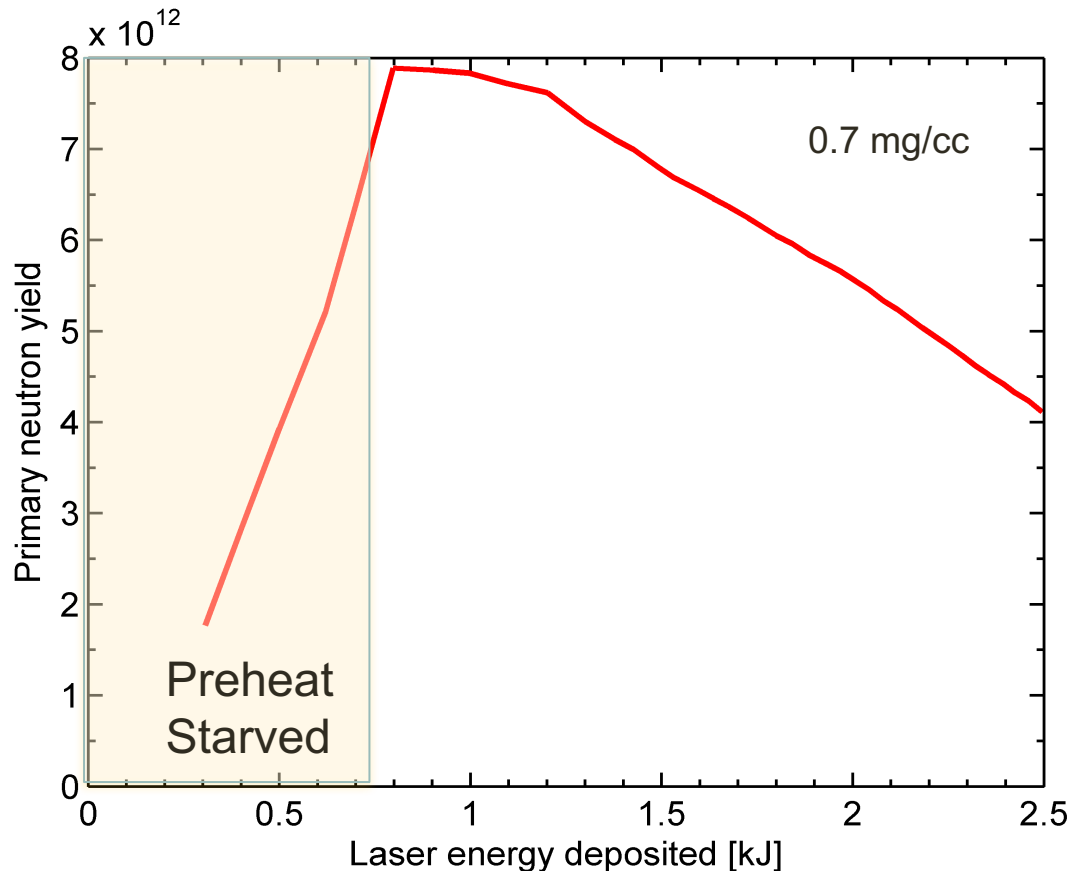
Significant yields and temperatures only w/ applied  $B_z$  and preheat

	No B-field	B-field	
No Laser Heating	$3 \times 10^9$	$1 \times 10^{10}$	DD Neutron yield
Laser Heating	$4 \times 10^{10}$	$3 \times 10^{12}$	



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

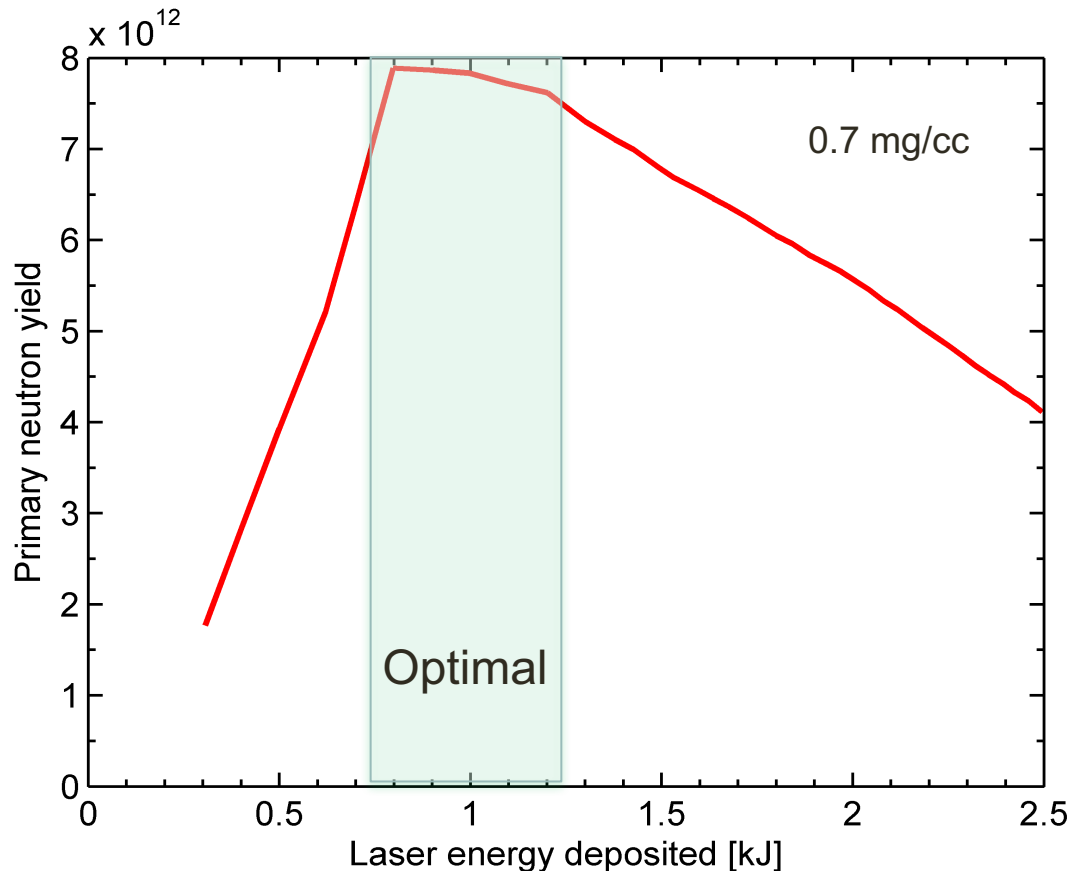
# Simulated primary neutron yields are highly sensitive to the coupled preheat energy



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

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

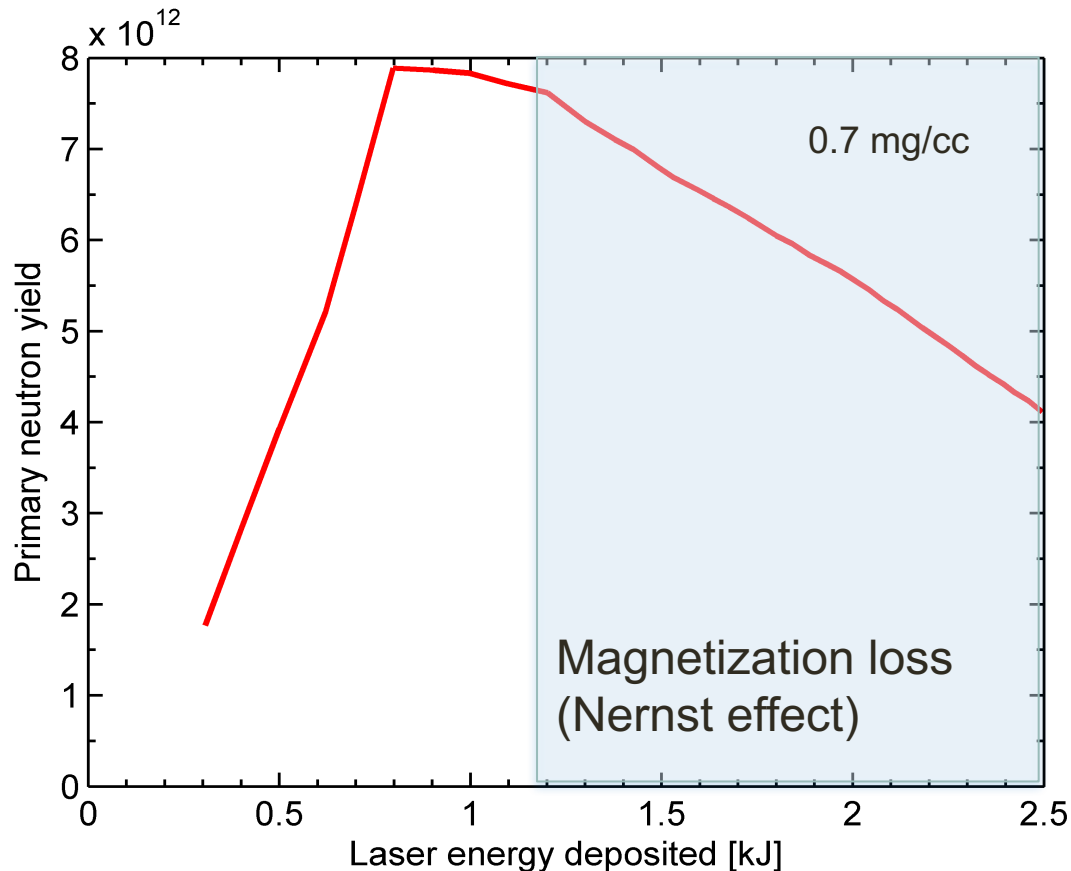
# Simulated primary neutron yields are highly sensitive to the coupled preheat energy



- With sufficient magnetization, yield is strong function of preheat energy
- Simulations predict maximum DD yields of  $6-8 \times 10^{12}$  (clean) with a coupled energy of  $\sim 1$  kJ

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

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



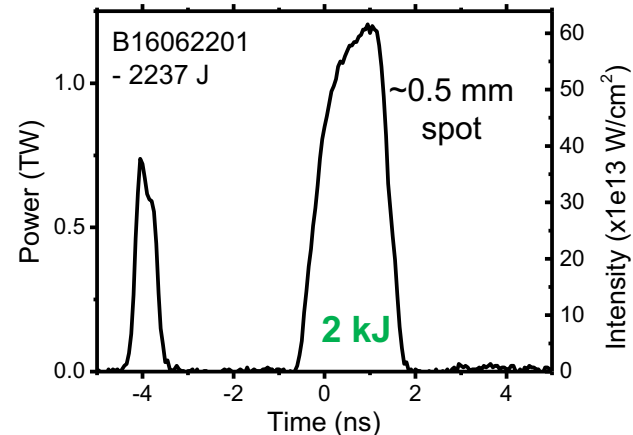
- With sufficient magnetization, yield is strong function of preheat energy
- Simulations predict maximum DD yields of  $6-8 \times 10^{12}$  (clean) with a coupled energy of  $\sim 1$  kJ
- Larger coupled energies reduce yield due to Nernst effect

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

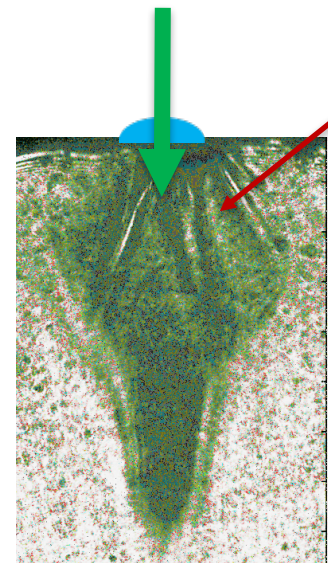
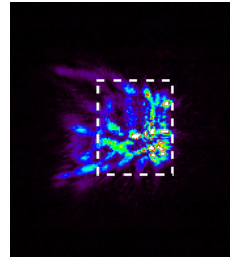
# Our initial experiments had significant uncertainty in the coupled laser energy

- Significant laser plasma interactions (LPI), not modeled in our codes
- No beam smoothing
- Several independent 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

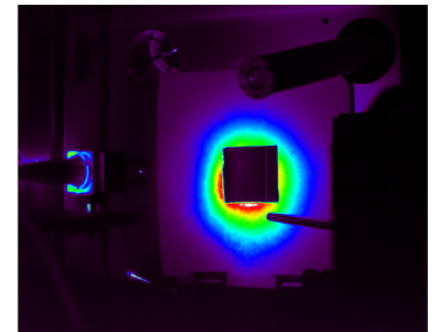


Beam Profile

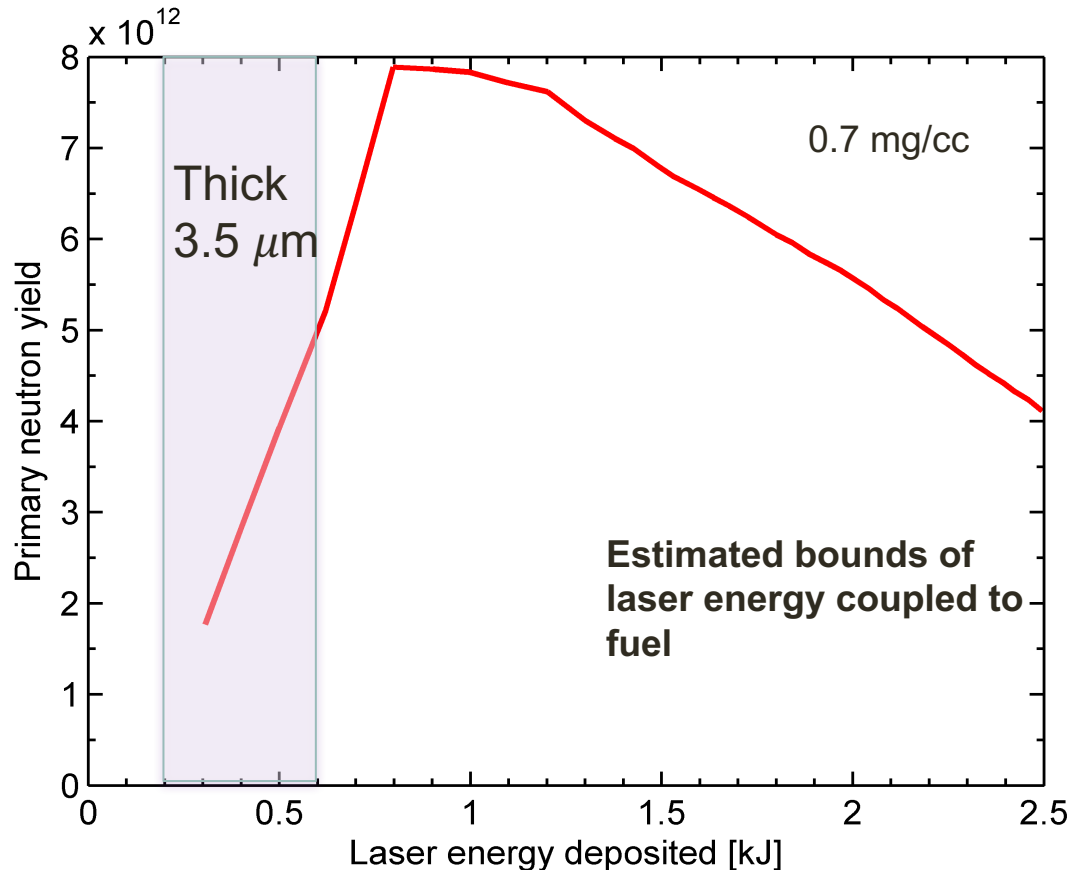


filamentation

Stimulated Brillouin Scattering: 900J !



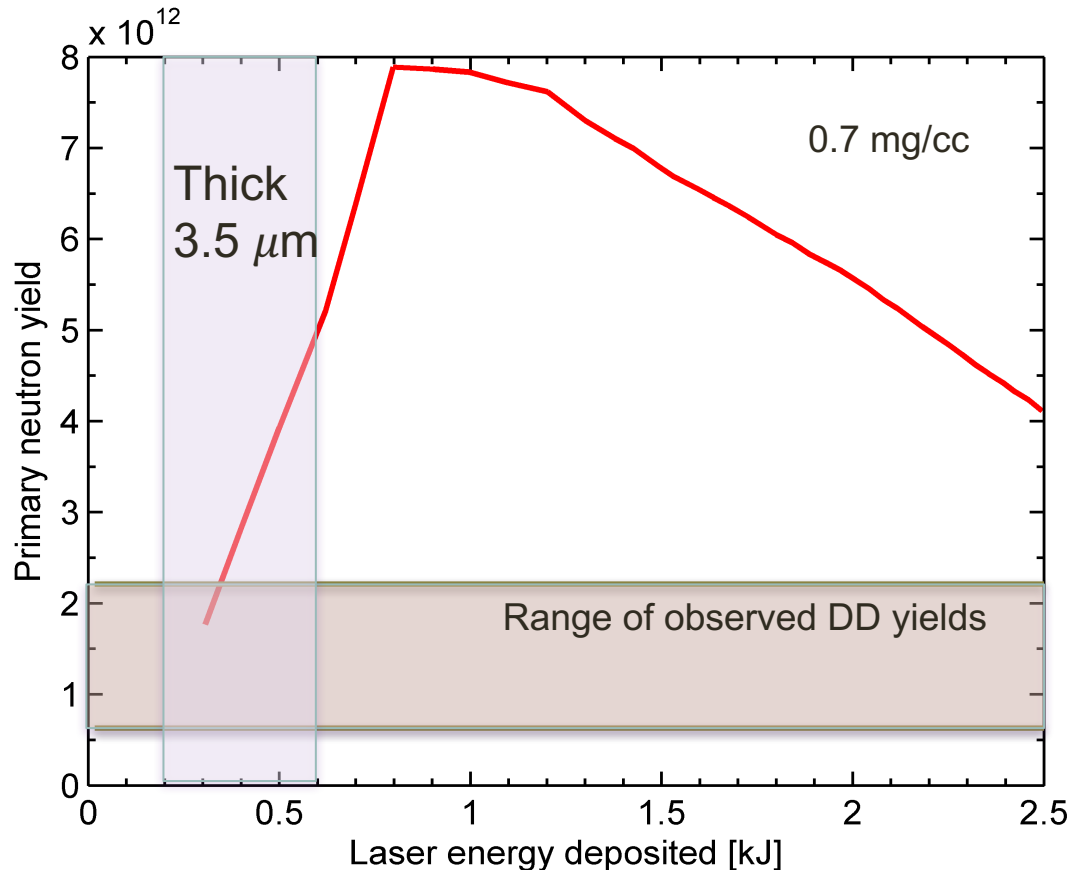
# 2D MHD simulations of our standard MagLIF configuration match experiments to within 2-3x



- 200-600J estimated coupled with thick (3.5  $\mu\text{m}$ ) windows

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

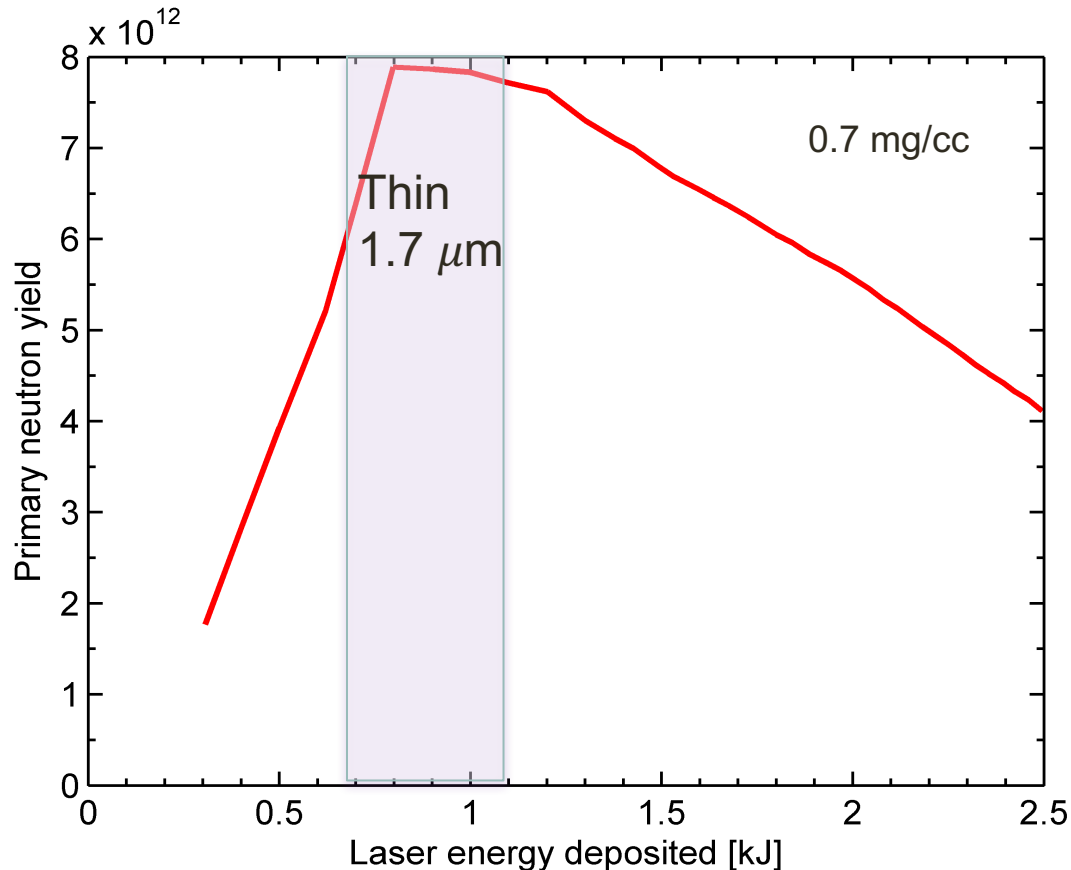
# 2D MHD simulations of our standard MagLIF configuration match experiments to within 2-3x



- 200-600J estimated coupled with thick (3.5  $\mu\text{m}$ ) windows
  - Initial experiments produced up to  $2 \times 10^{12}$  primary DD neutrons

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

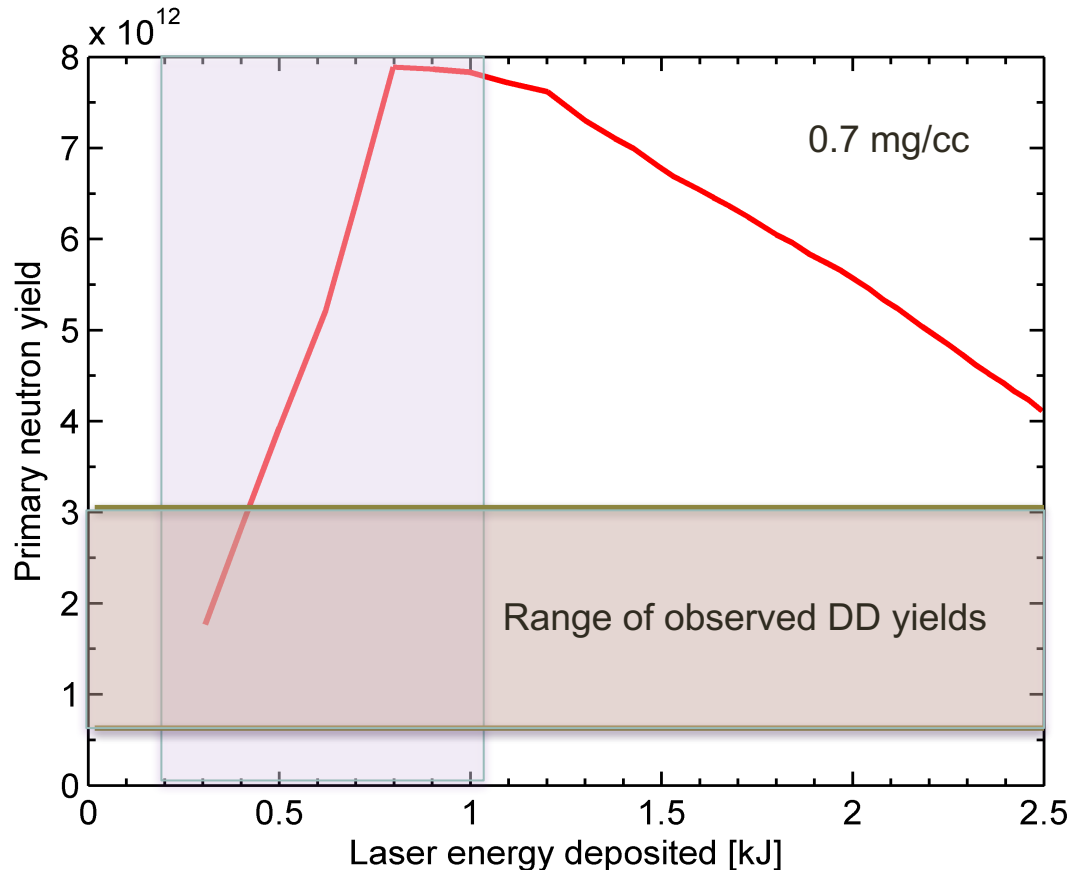
# 2D MHD simulations of our standard MagLIF configuration match experiments to within 2-3x



- 200-600J estimated coupled with thick (3.5  $\mu\text{m}$ ) windows
- 600-1200J estimated for thin windows (1.7  $\mu\text{m}$ )

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

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



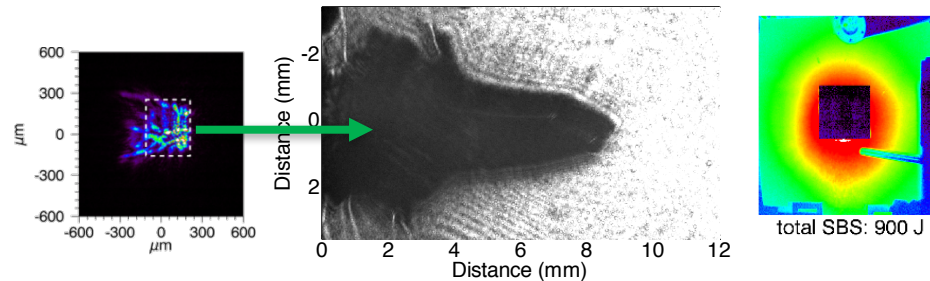
- 200-600J estimated coupled with thick ( $3.5 \mu\text{m}$ ) windows
- 600-1200J estimated for thin windows ( $1.7 \mu\text{m}$ )
- Similar performance obtained with both thin and thick windows
  - Thin windows more susceptible to high Z target components (mix)
  - Increased laser energy (4kJ) decreased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

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

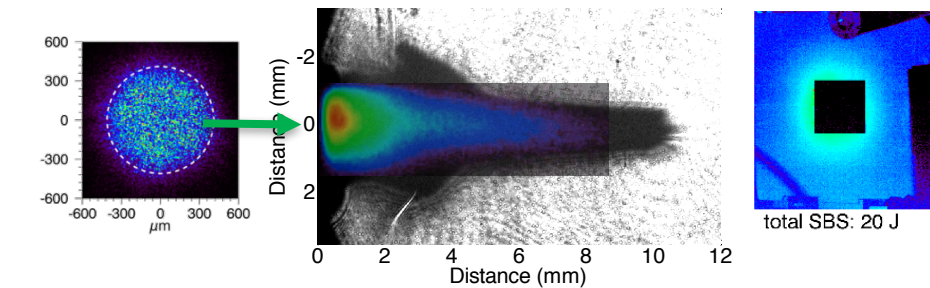
# New laser heating protocols were developed using phase plate smoothing and reduced intensities

## Optical Blastwave Measurements

### Original MagLiF Configuration



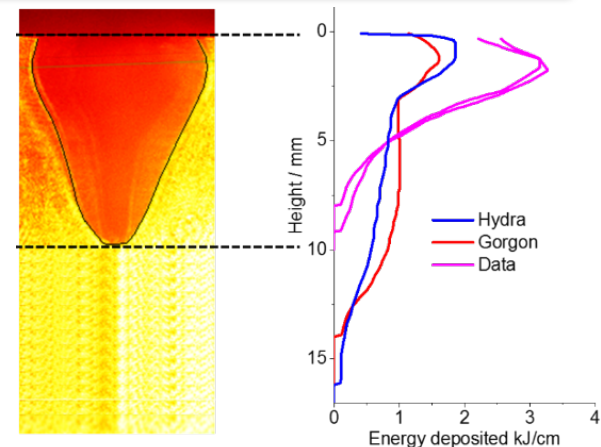
### Laser Config A



- 1100  $\mu\text{m}$  Distributed Phase Plate
- Lower laser intensity
- 80 J pre-pulse, 1500J 4ns main pulse

- Reduced SBS from  $\sim 50\%$  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

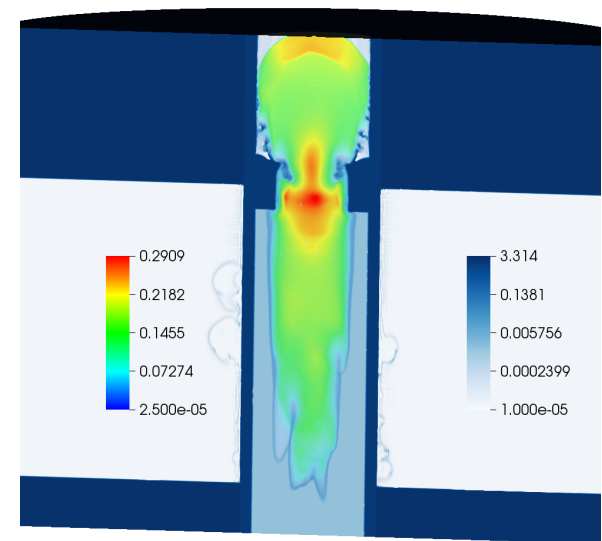
Simulations match total energy deposited, but not axial profile



# 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

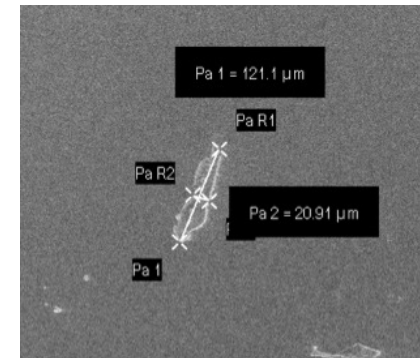
- Variation is significantly larger than observed in previous experiments
- The source of the large performance variation is currently being investigated
  - Laser preheat configuration ?
  - Liner instabilities (CR>40) ?
  - Mix cliff ?



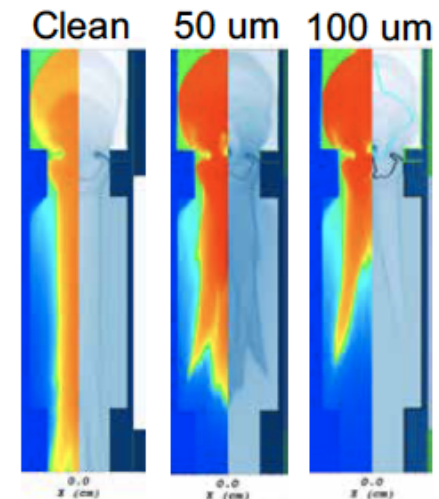
# Several potential sources of performance variation due to laser heating are being explored

- Dust is one of the leading hypotheses
- Simulations suggest  $>50 \mu\text{m}$  dust particles can substantially affect laser deposition
- Significant number of dust particles  $10\text{-}100 \mu\text{m}$  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

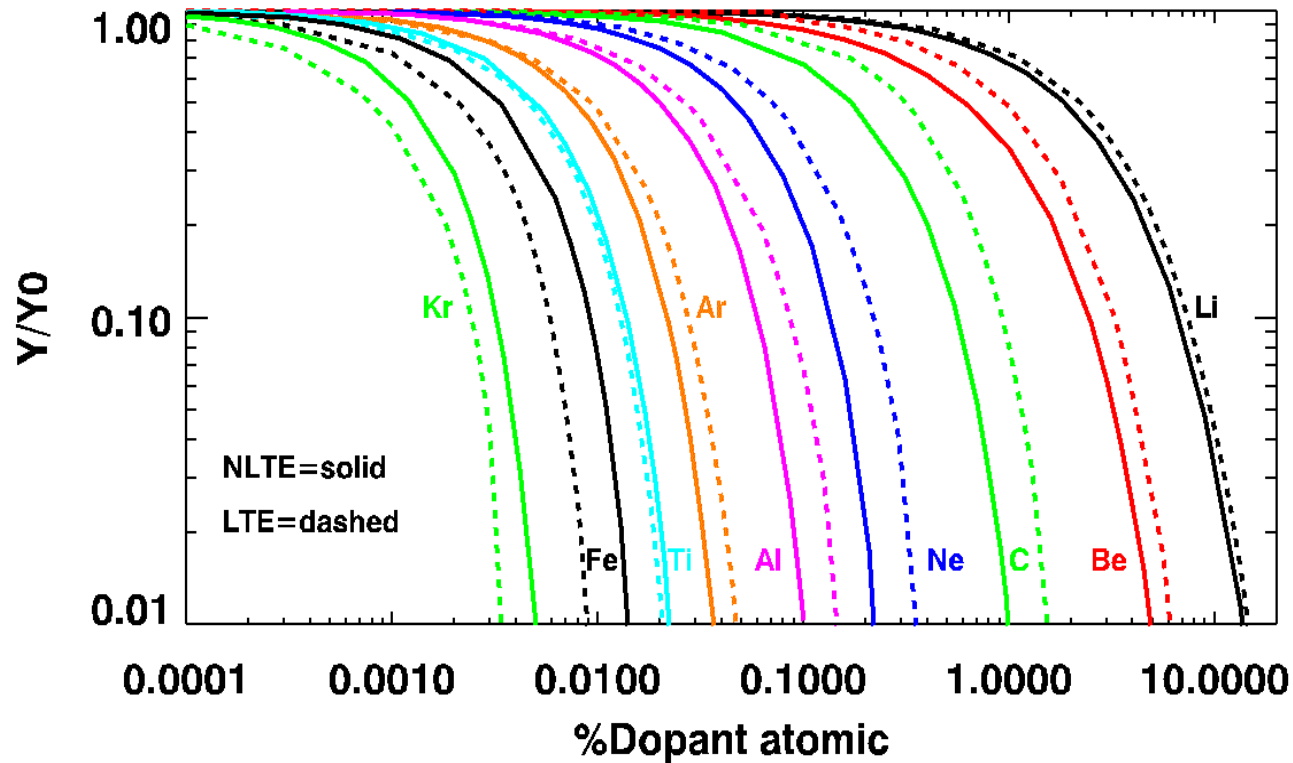
Dust particles measured on typical window



2D Hydra simulation



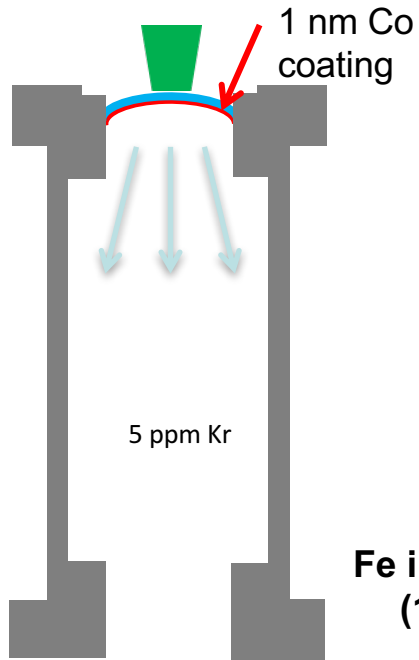
# With its long preheat stage, MagLIF is highly susceptible to fuel impurities (mix)



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

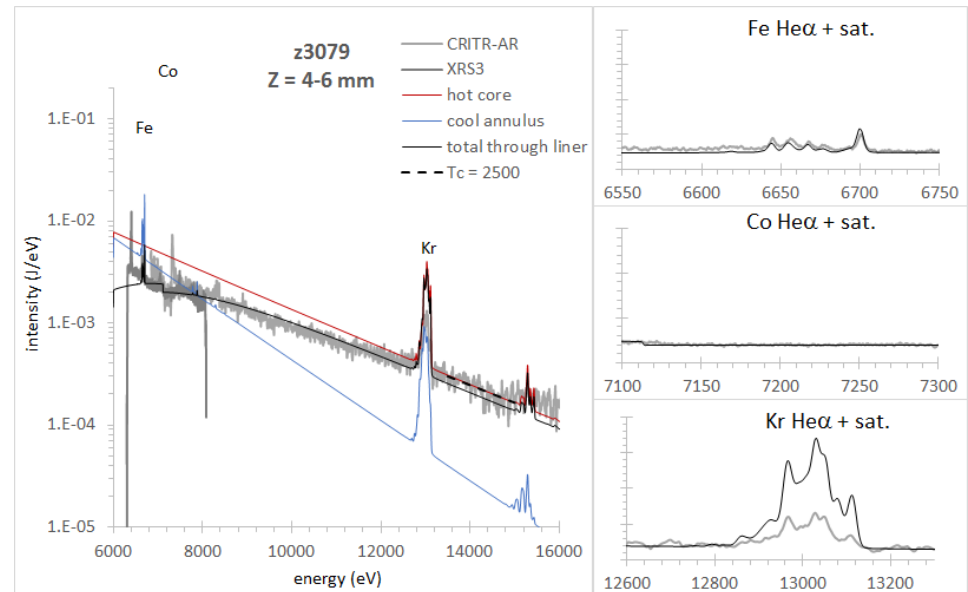
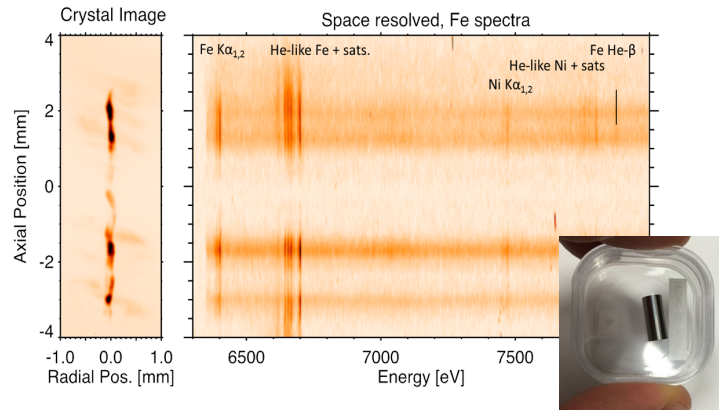
*Are we on a mix cliff?*

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

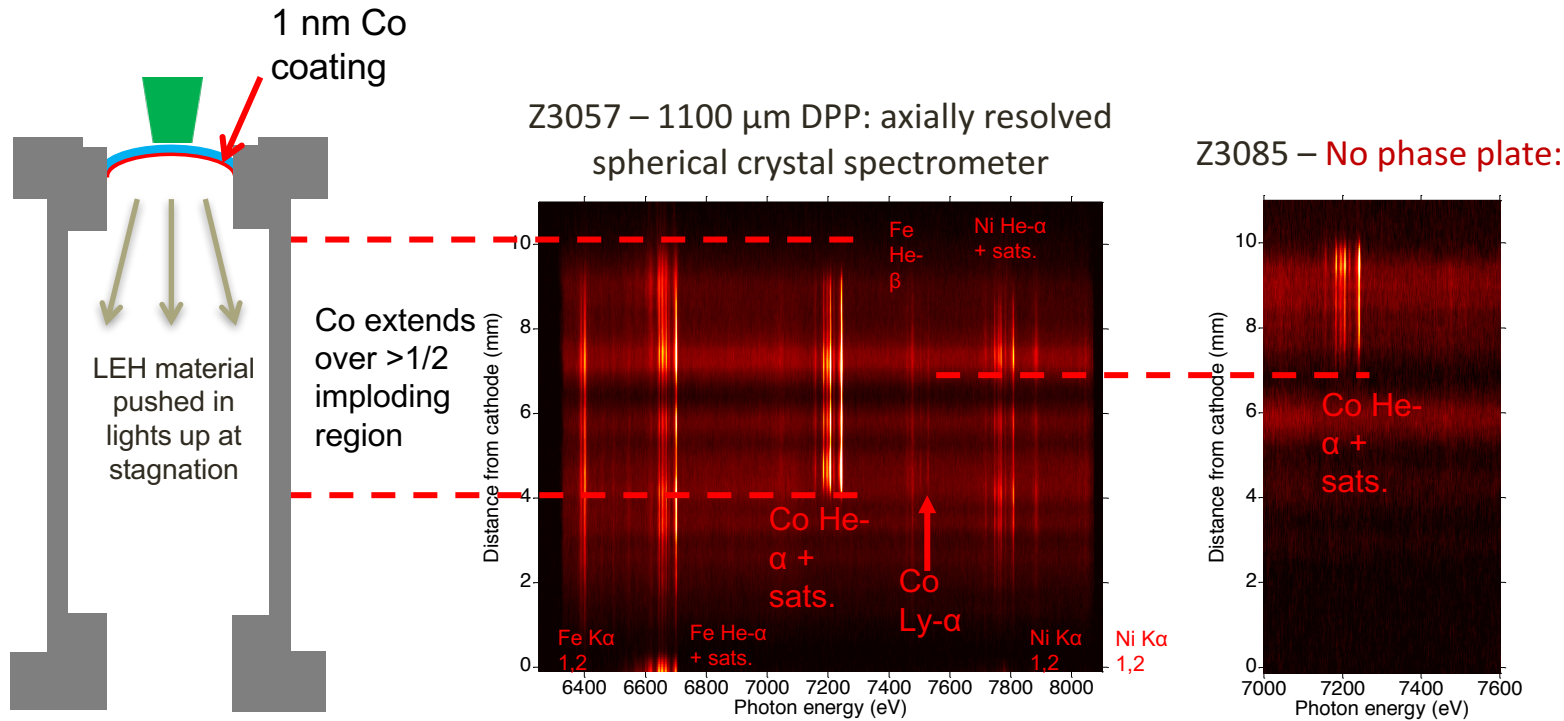


- Fe impurities from the Be liner/endcap mix into the stagnation column
- 5 ppm Kr dopant premixed into fuel
- Localized Co dopants

**Fe in S65 Be Liner (100 ppm Fe)**

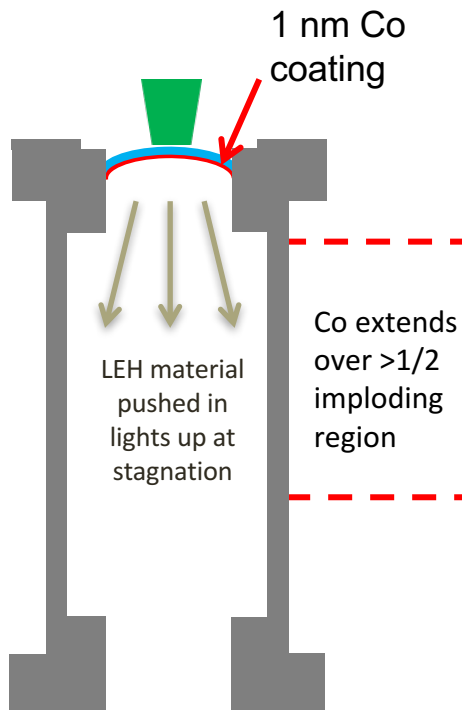


# Window mix has been observed experimentally and is transported further with the new laser heating protocols

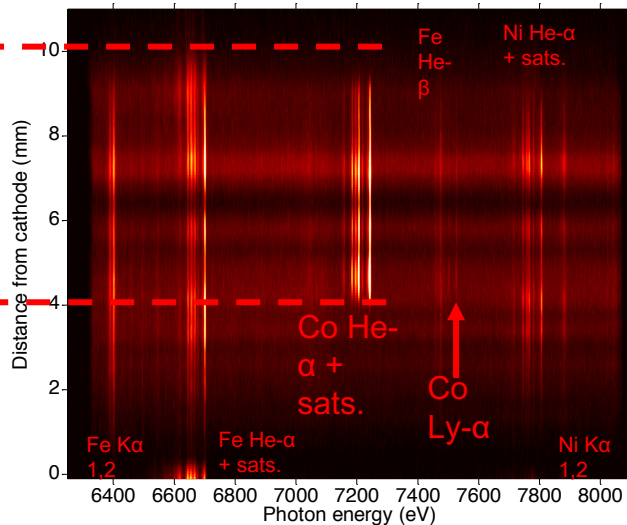


- We are developing uniformly doped windows to help better quantify window mix

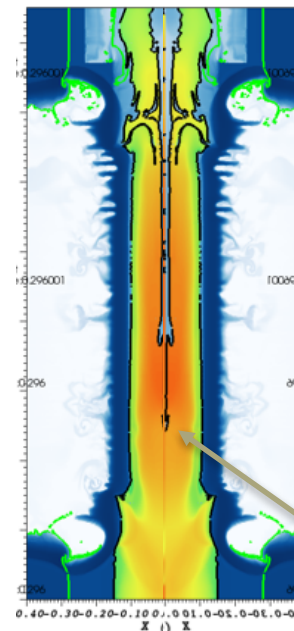
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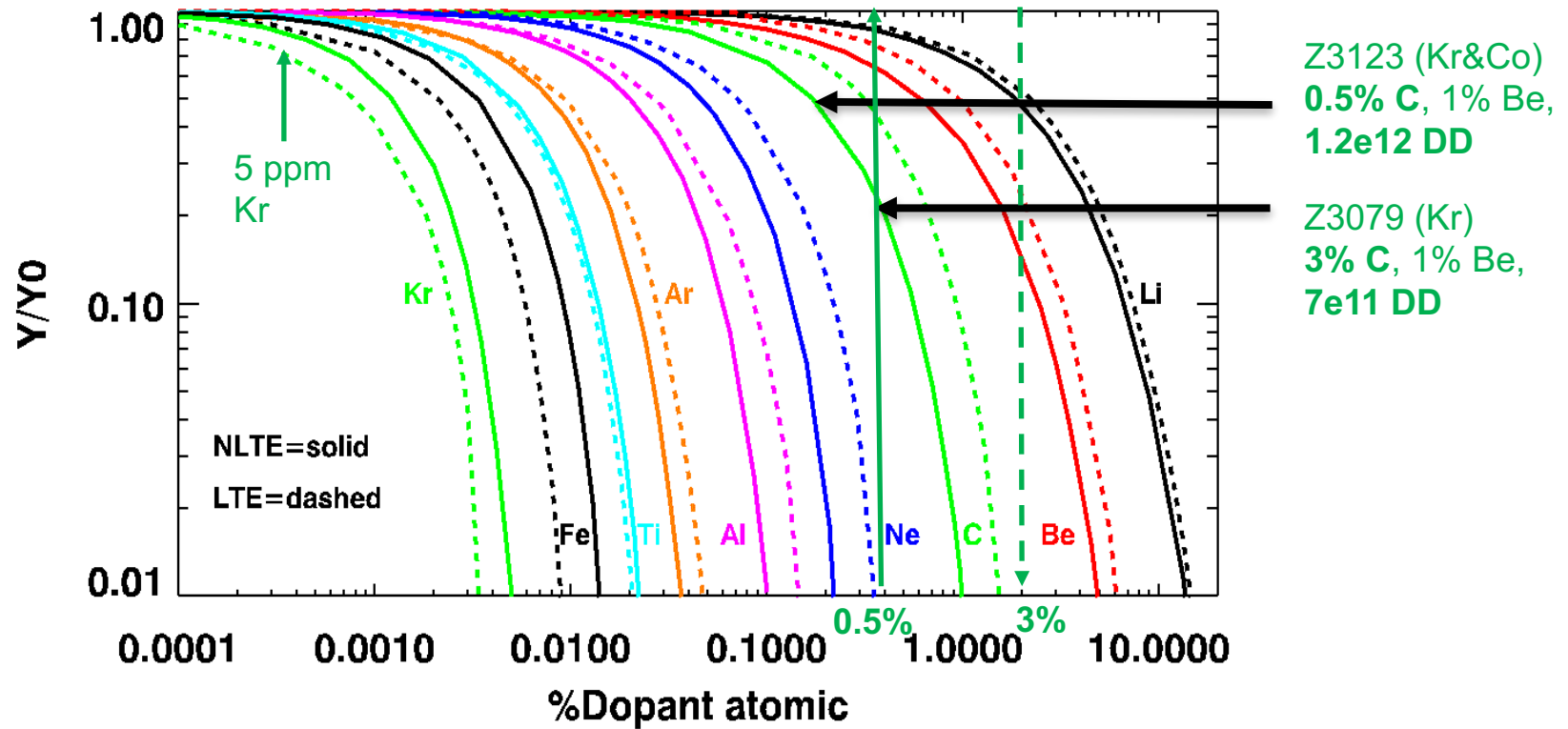
Z3057 – 1100  $\mu\text{m}$  DPP: axially resolved spherical crystal spectrometer



2D HYDRA Simulation



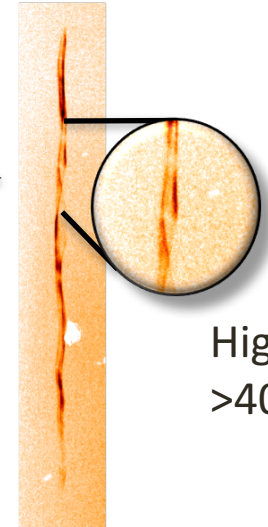
# Inferred fractions of Be and C mix trend with but are not completely consistent with expected yield variations



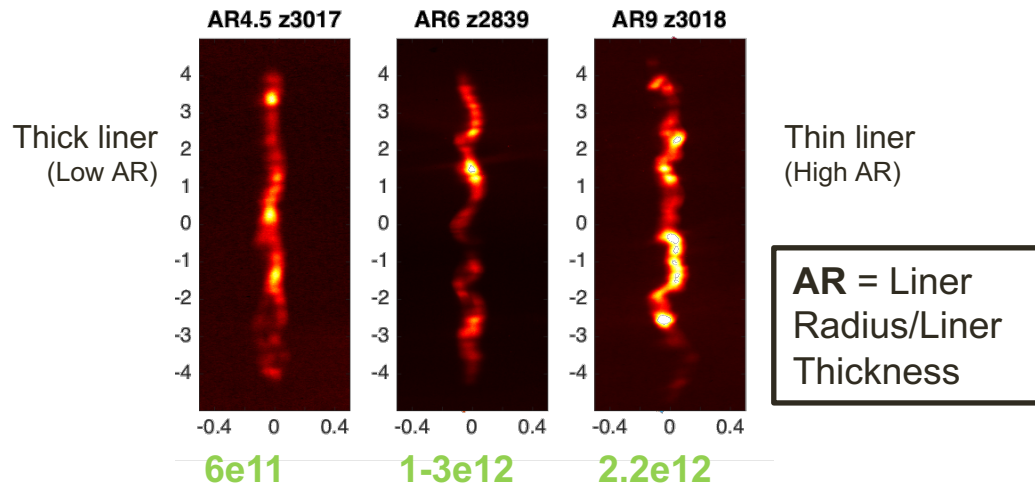
# The impact of 3D instabilities on performance is still uncertain

- 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



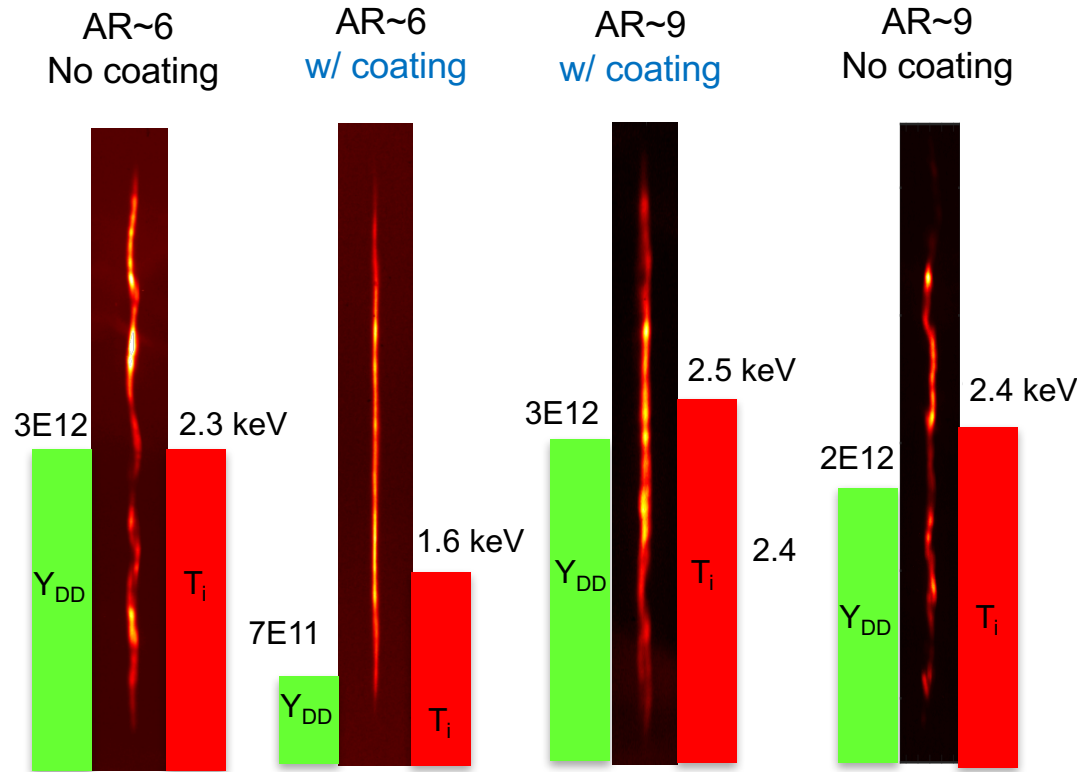
High CR  
>40!



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

>6keV X-ray self-emission stagnation images

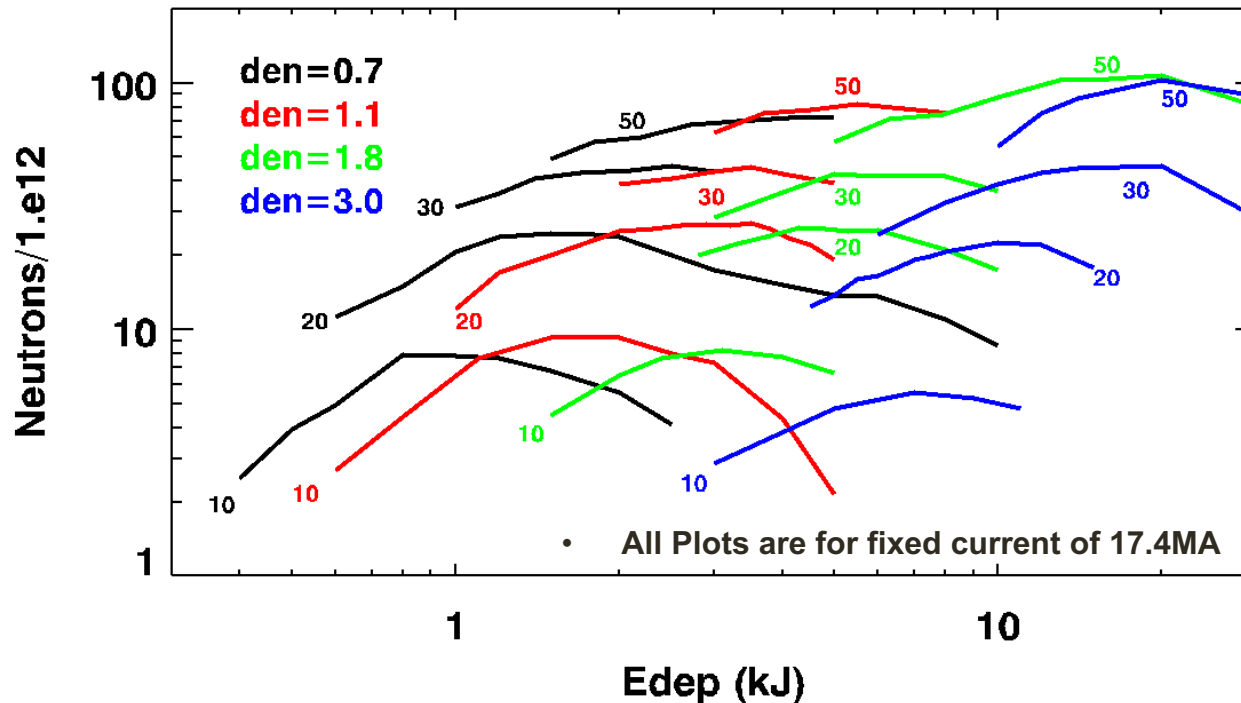
- Thick plastic coatings applied to outside surface mitigate electro-thermal instability growth
- Coated AR-9 targets have shown excellent stability and shot-to-shot reproducibility thus far (~15%)
  - Higher magnetization observed ( BR ~ 400 kG cm )
- Coated AR 6 targets show remarkable stability, but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



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

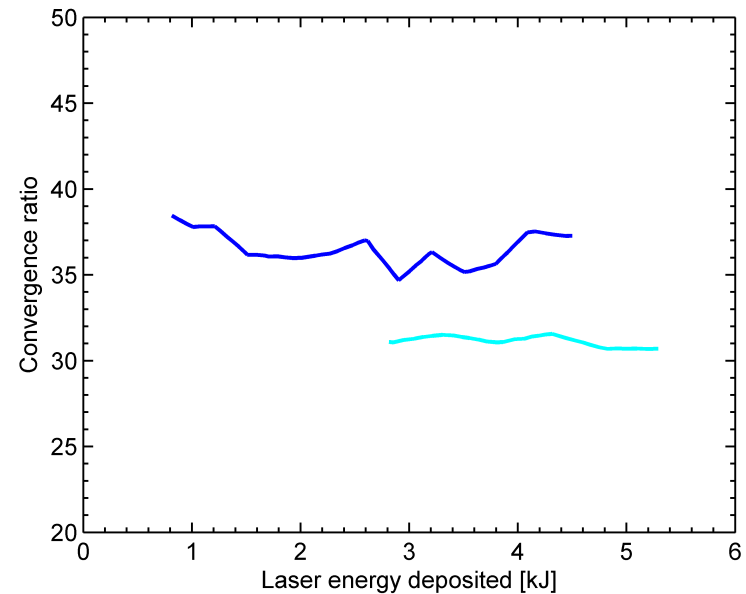
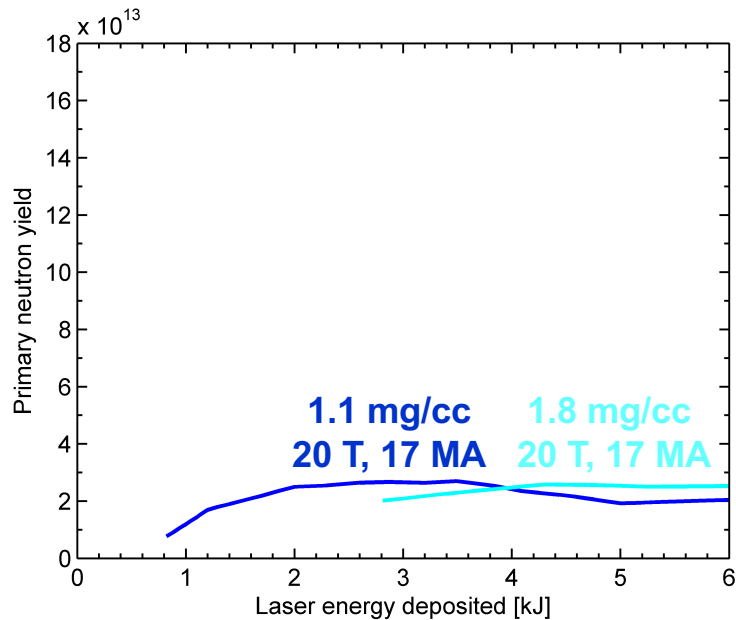
# Without more current, initial magnetization levels need to be increased to realize any significant increase in performance

Simulated scaling with  $B_z$  and laser energy deposited

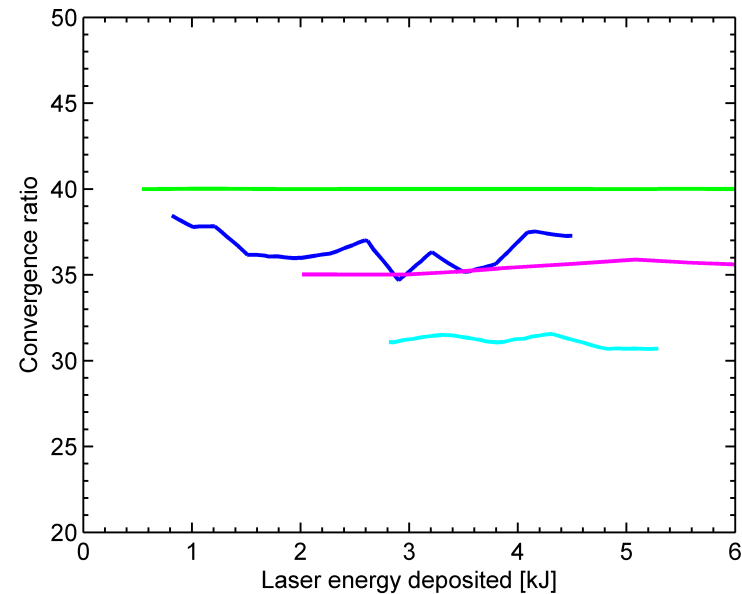
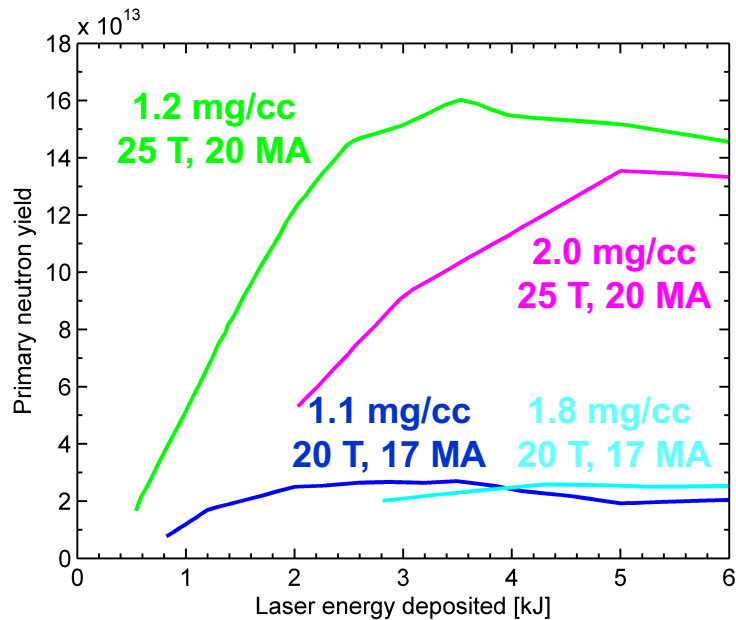


- Key MagLIF scaling issues can be studied without more drive current
- Larger fields increase the burn time
- Higher fuel densities lower convergence

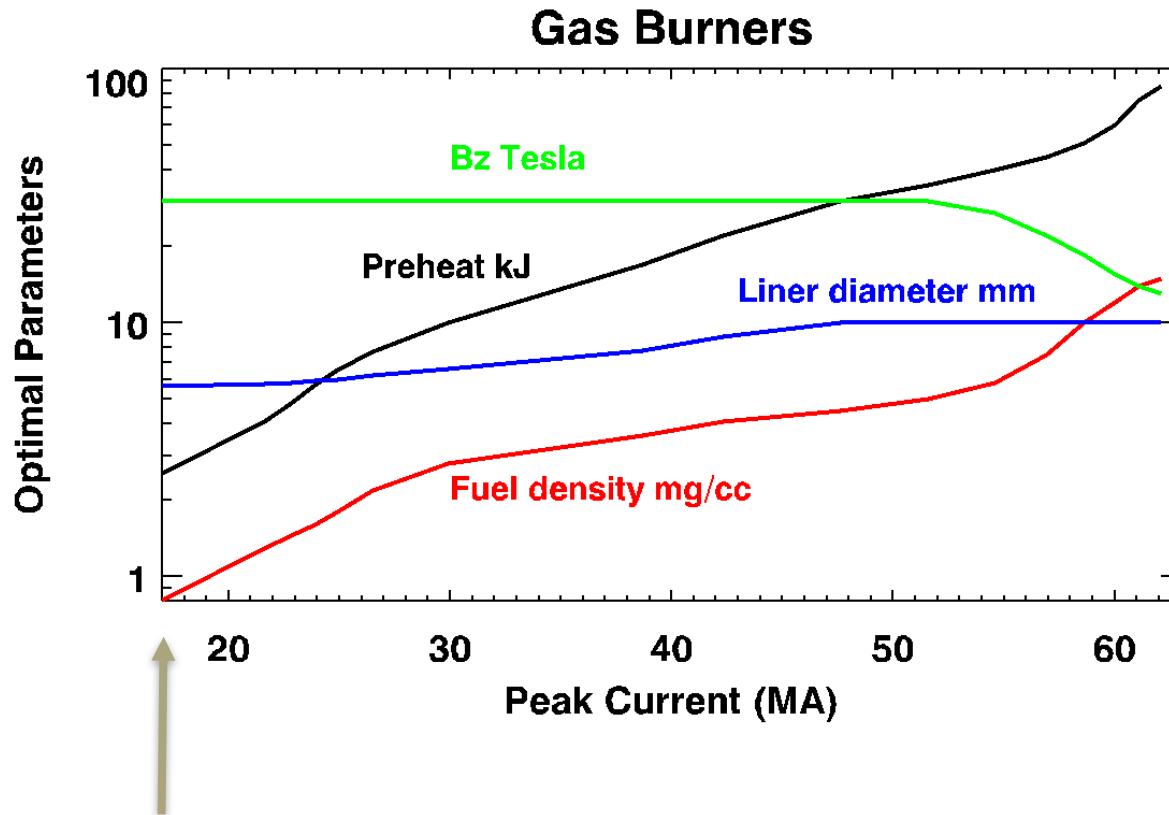
# Performance can also be improved with with increased load current, but the convergence ratio goes up



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



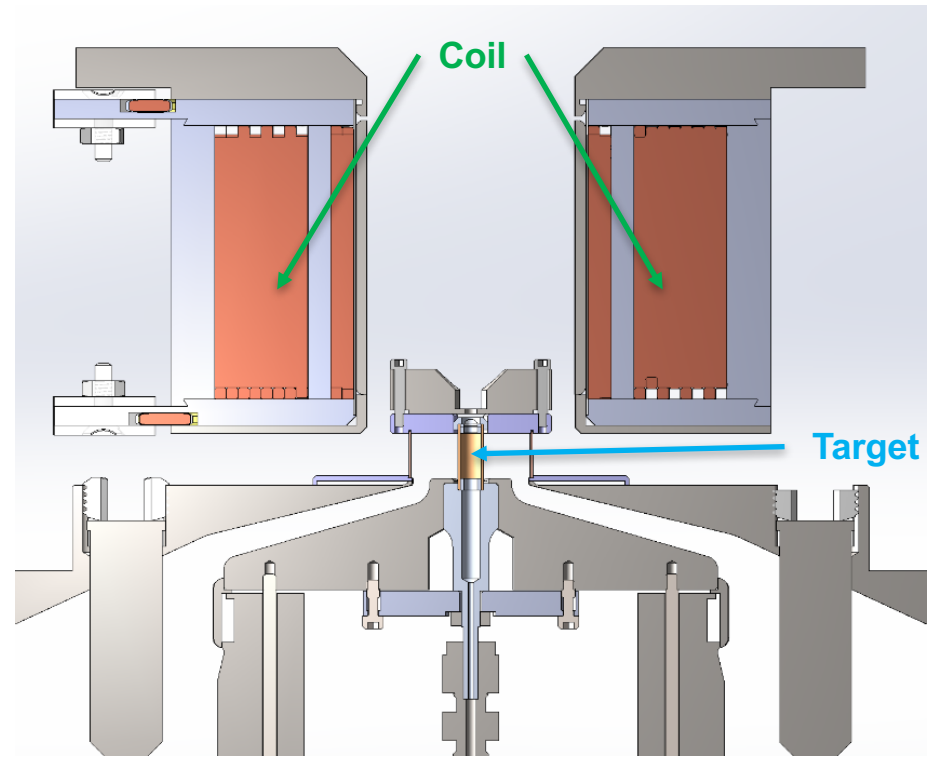
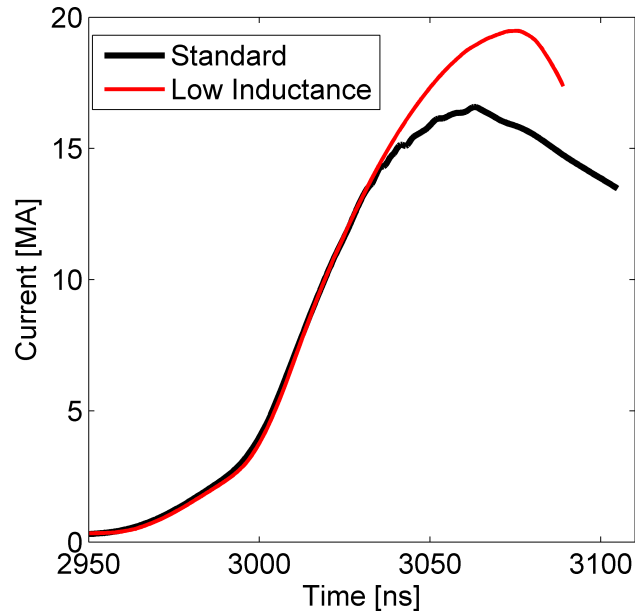
# Performance optimized scaling is only achieved when field, fuel density, preheat energy, and current are all scaled simultaneously



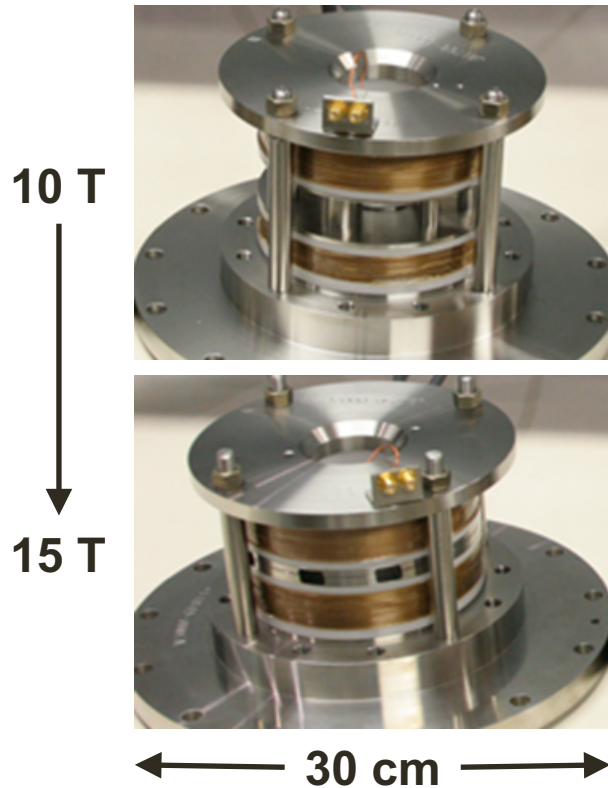
According to simulations, we have not yet been able to test optimal conditions yet on Z

# 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

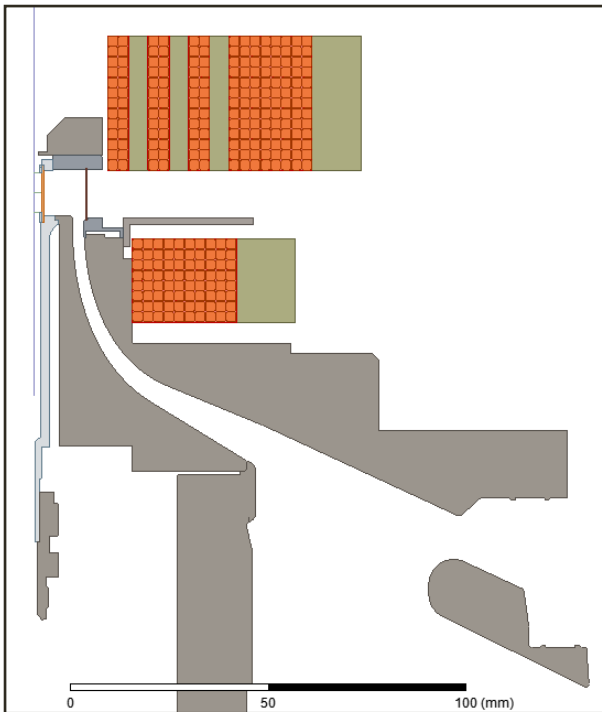


- Using standard coil, initial field can be increased to ~25T
  - 15 T Limited Diagnostic Access
  - 25 T No Diagnostic Access
  
- Completed the first commissioning tests at 15 T
  
- Increased magnetization and coupled preheat energy is predicted to improve performance (without an increase in drive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

Standard coil, high inductance feed,  
17MA peak current

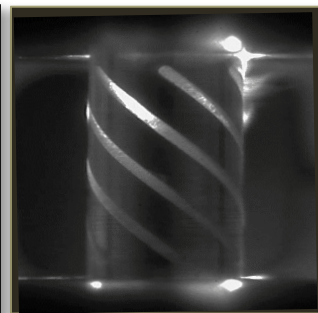
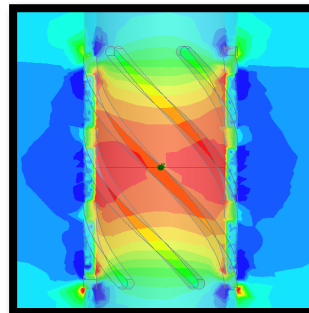
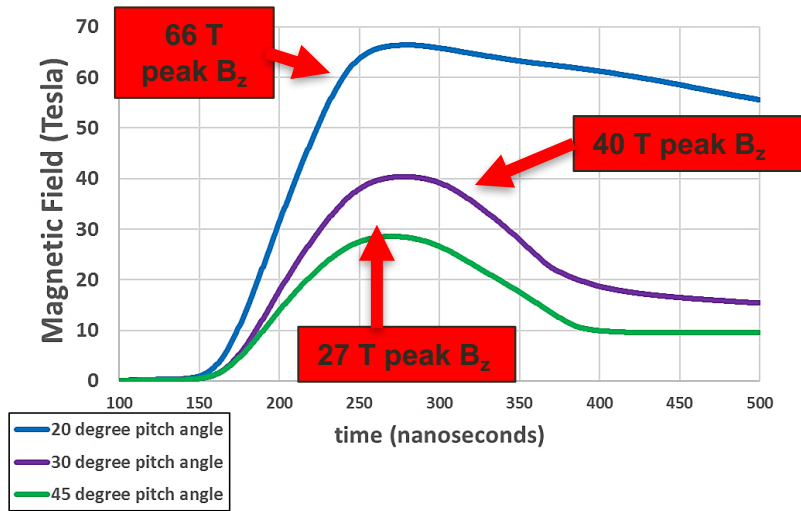
# We are also working to increase the initial applied B-field increase the applied B-field – Longer Term

New low inductance coil, operation up to 25 T



Coil design courtesy of Derek Lamppa

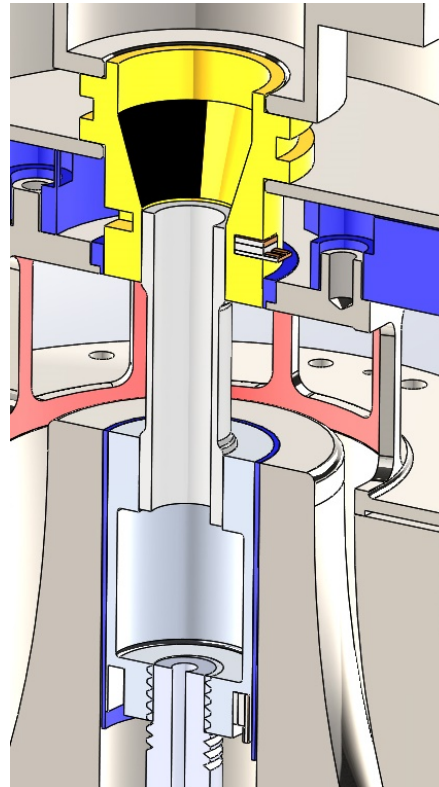
Slotted helical liners “Automag”



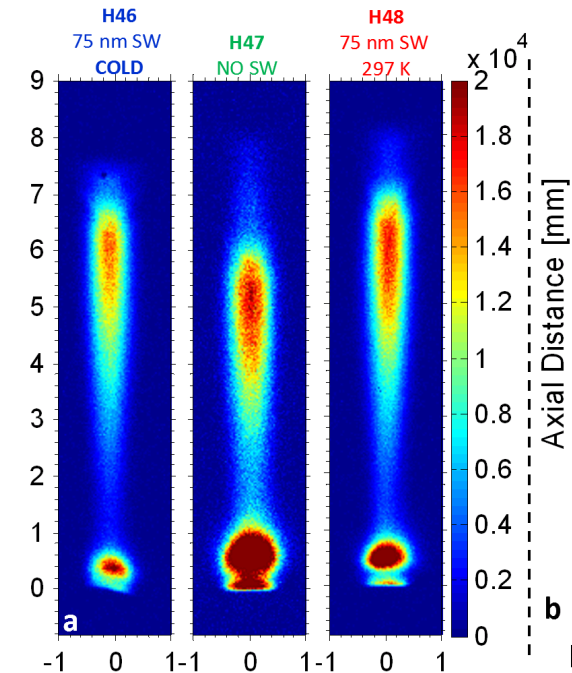
# We are working to minimize or eliminate the window mass from our experiments

## Cryogenic Targets

- 400 nm window cooled to  $\sim 30\text{K}$
- 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



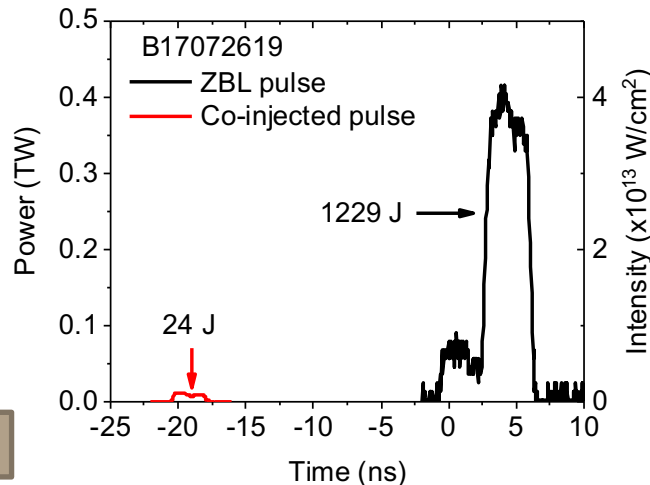
## Cryo laser heating tests



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

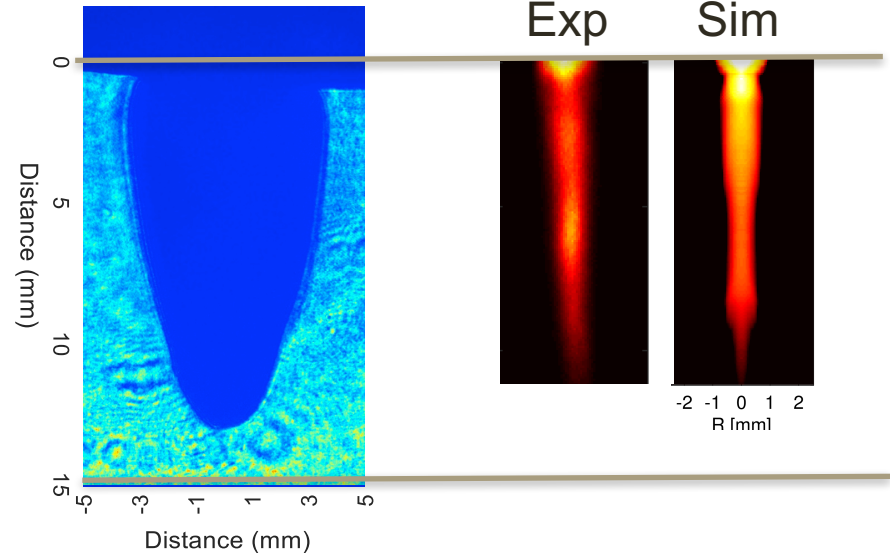
## Co-injection of Z Petawatt

- 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



Optical Shadowgraph @ +20ns

Time integrated pinhole camera

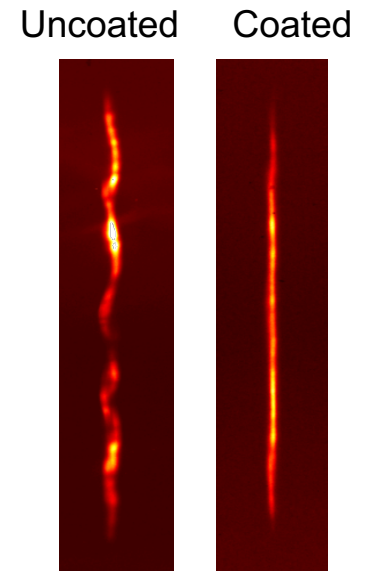
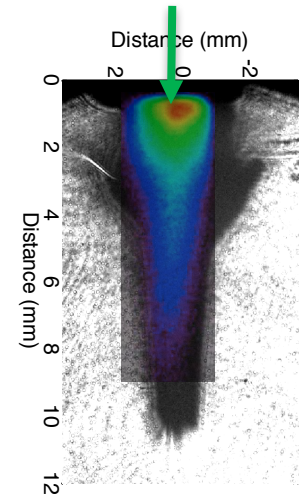


- Significantly improved agreement with simulations
- **First integrated test this week!**

# 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

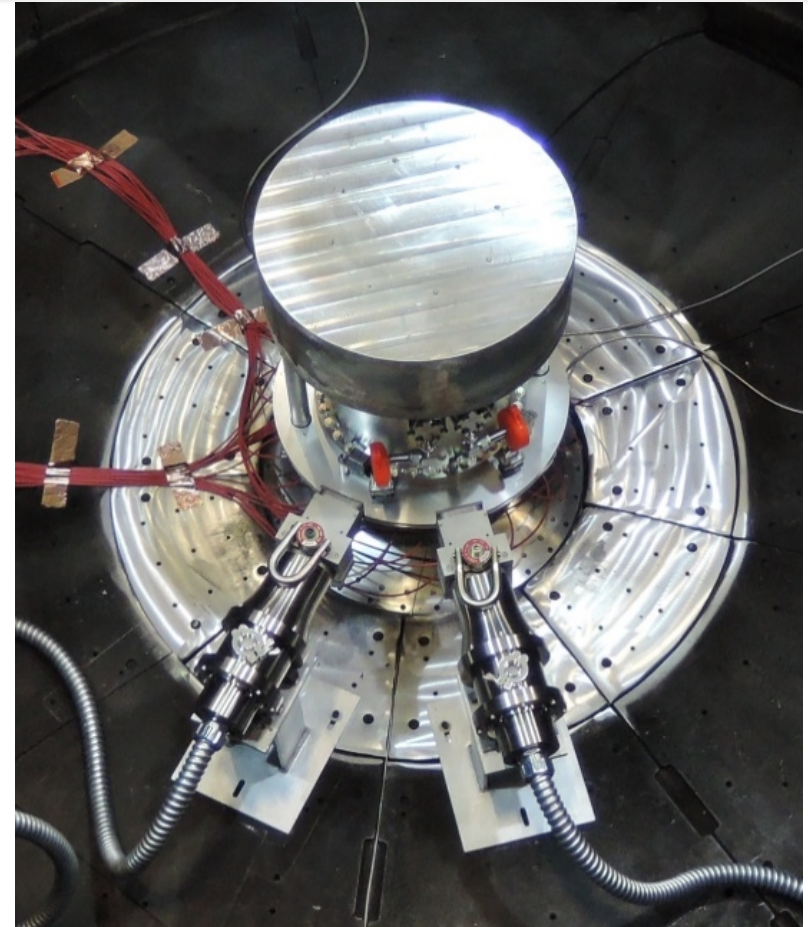
## ■ Going Forward

- Improve robustness and scalability of MagLIF targets on Z
  - Decrease convergence ratio to  $\sim 35$  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

- **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  $\sim 200$  J of laser energy coupled\* to the target

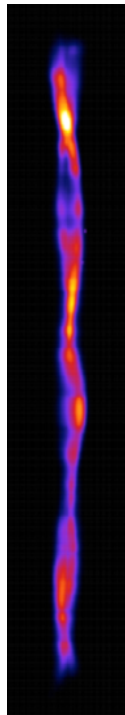
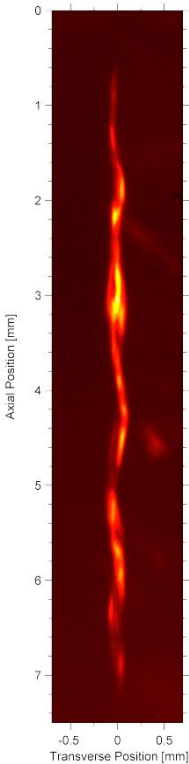
### Imaging

### Radiography

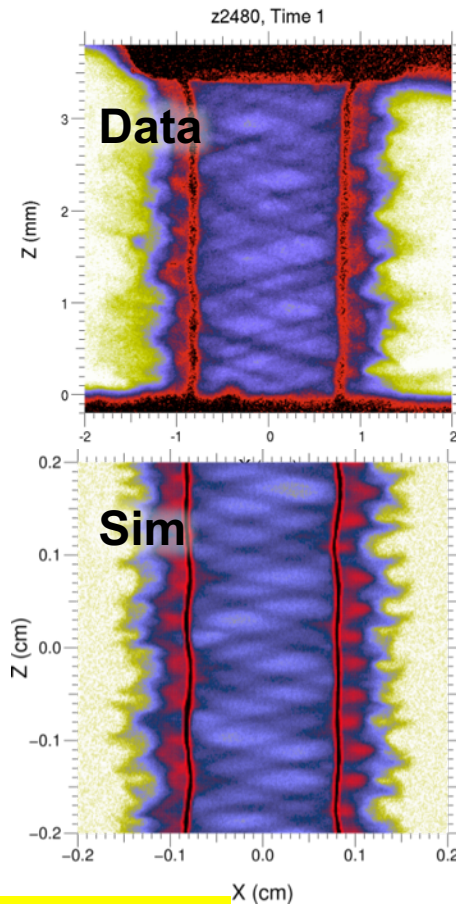
### Comparison to z2591 Observables

Data

Sim



Z2613



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

Delivered laser energy is 2.5 kJ

A. Sefkow simulations

\*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

## Imaging

## Radiography

## Comparison to z2613 Image

Data

Sim

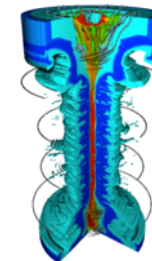
Data

Sim

Parameter	Measured/inferred	Post-shot simulations
FWHM	$91 \pm 40$ mm	$121 \pm 40$ mm

### Sim. Values:

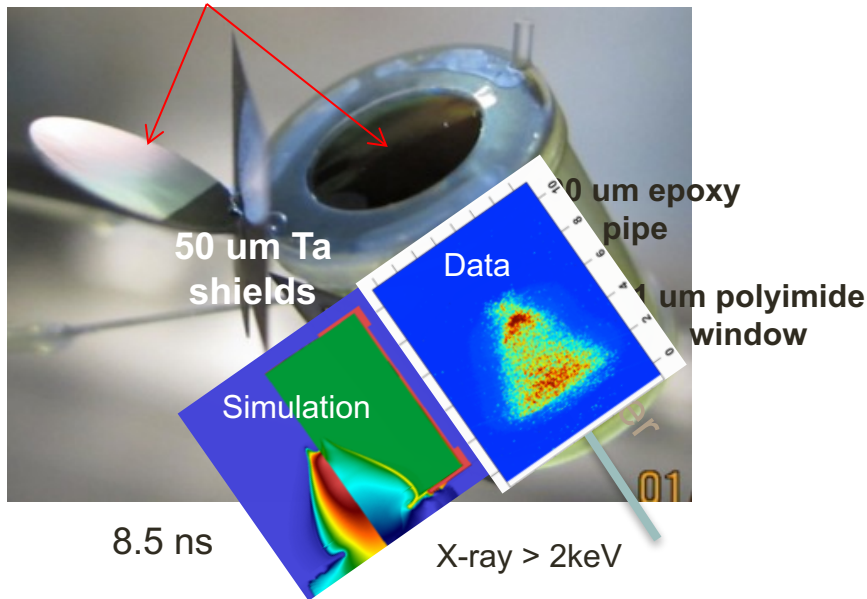
- Burn weighted, time integrated ion temp: **3.5 keV**
- Continuum emissivity (~9keV) weighted, time integrated electron temperature: **3.3 keV**
- Iron contaminant in Be emissivity weighted, time integrated electron temperature: **1.8 keV**
- Continuum emissivity (~9keV) weighted, time integrated fuel density:  **$0.33 \text{ g cm}^{-3}$**
- DD Yield:  **$4.e12$**
- FWHM neutron pulse: **1.7ns**
- Liner  $\rho R$  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.



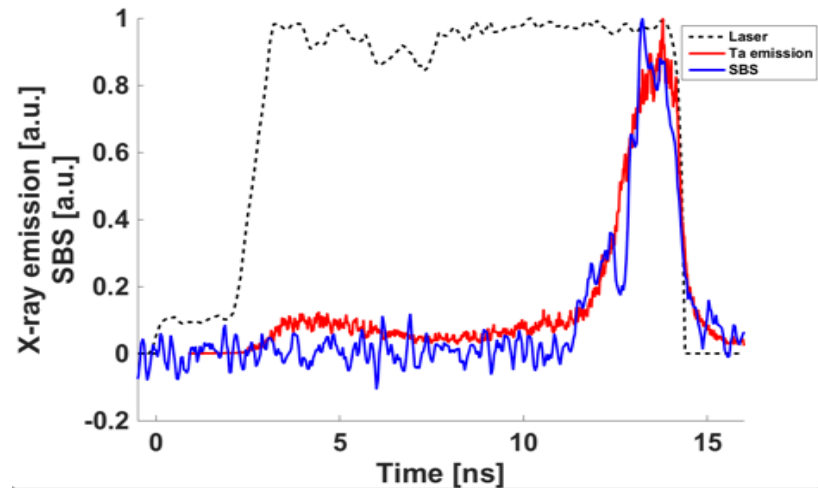
C. Jennings simulations

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

Pipe witness and calibration plates



SBS time history



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

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

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 ( $P\tau$ , BR) and identify important correlations

Hotspot Parameters

$$\{T_i\} = \{T_e\}$$

$$\{\tau_\nu^\ell\}$$

$$\{P_{HS}\}$$

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

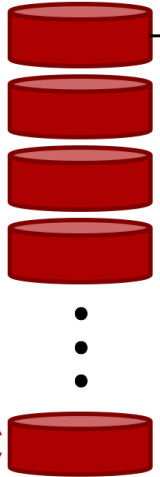
$$\{Z_{mix}\}$$

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

$$\overline{BR}$$

$$\tau_{burn}$$

$$\delta h$$



**X-ray Emission:**

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

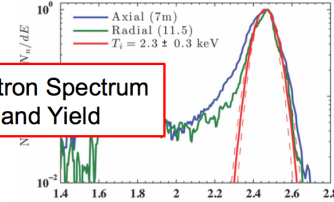
$$\tilde{j}_i \equiv \frac{j_i}{j_D} = Z_i^2 + \frac{A_{f-b} Z_i^A}{A_{f-f} T} e^{Ry Z_i^2/T}$$

**Neutron Emission:**

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

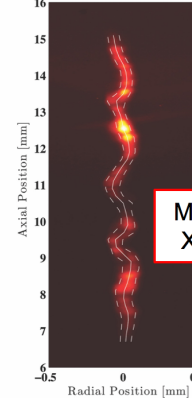
$$*I_o(E) = e^{-\frac{2E}{\sigma^2}(\sqrt{E}-\sqrt{E})^2}$$

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

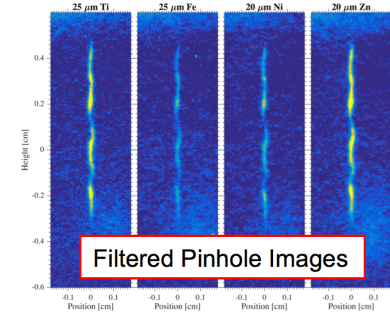


Neutron Spectrum and Yield

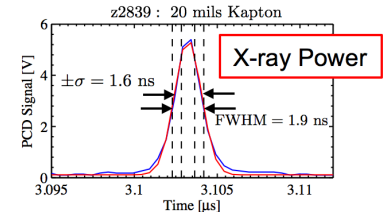
Ar Imager: Stagnation



Monochromatic X-ray Imaging



Filtered Pinhole Images



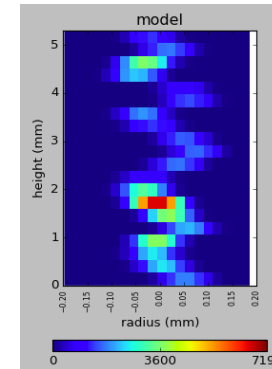
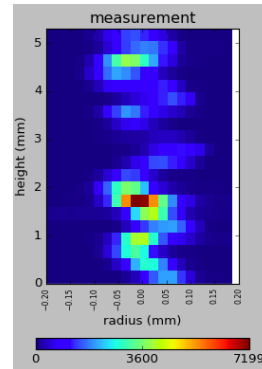
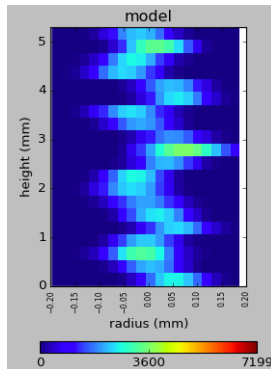
X-ray Power

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

Prior

Data

Posterior



Spherical Crystal Imager Example