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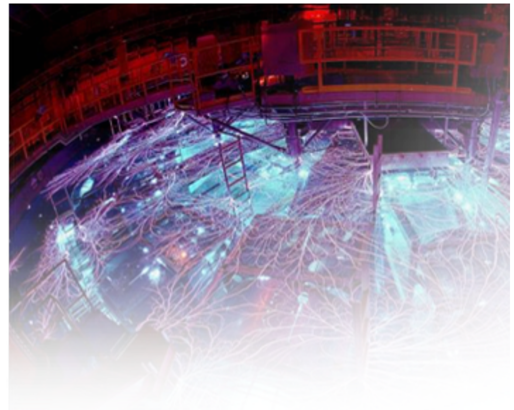
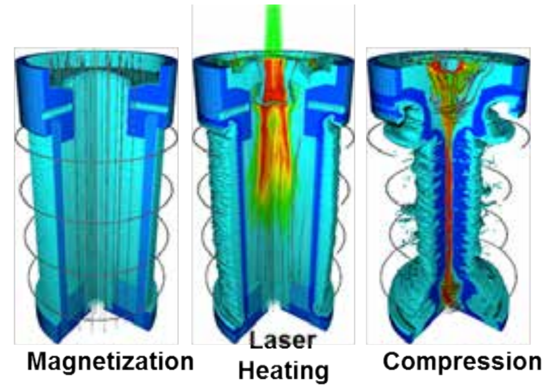

Magnetized Liner Inertial Fusion Research in the United States

Daniel B. Sinars, ICF Program Manager
Sandia National Laboratories

PLASMA 2017

U.S. DEPARTMENT OF ENERGY
NNSA National Nuclear Security Administration

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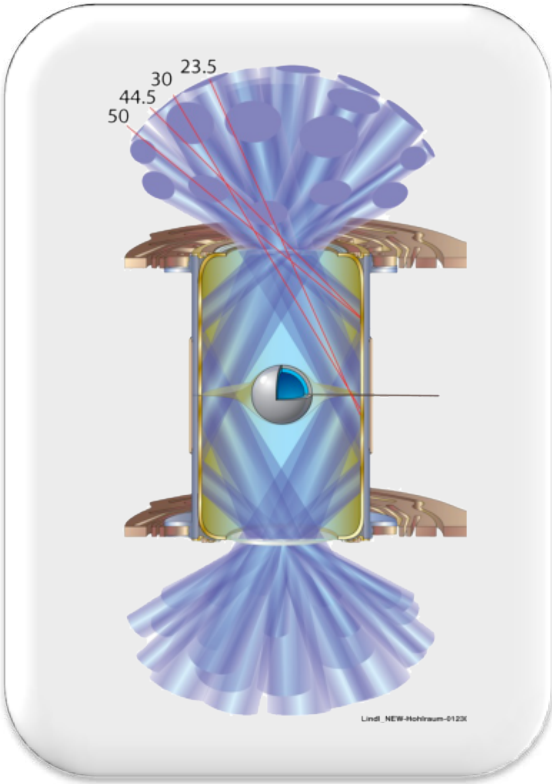
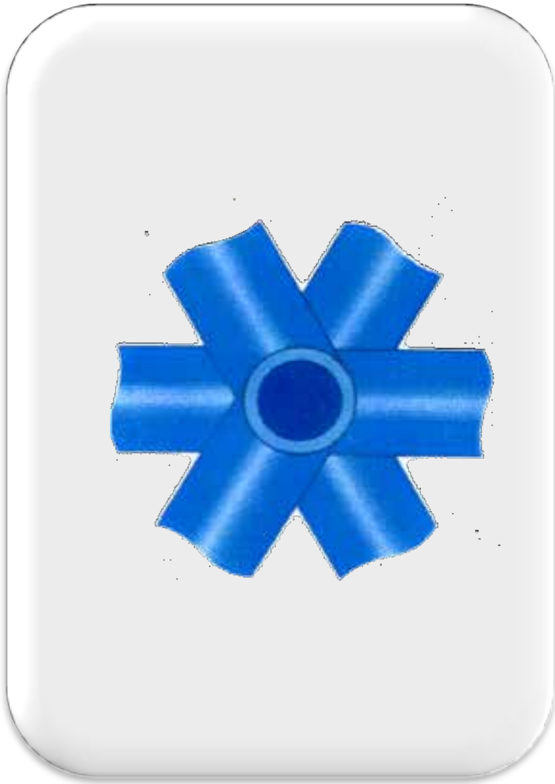
The US Inertial Confinement Fusion program is studying three main approaches to laboratory fusion

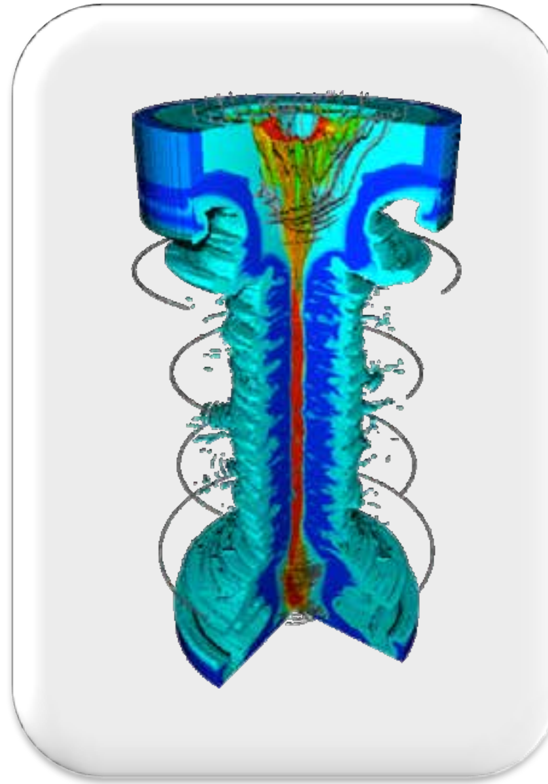
Laser Indirect Drive



Laser Direct Drive



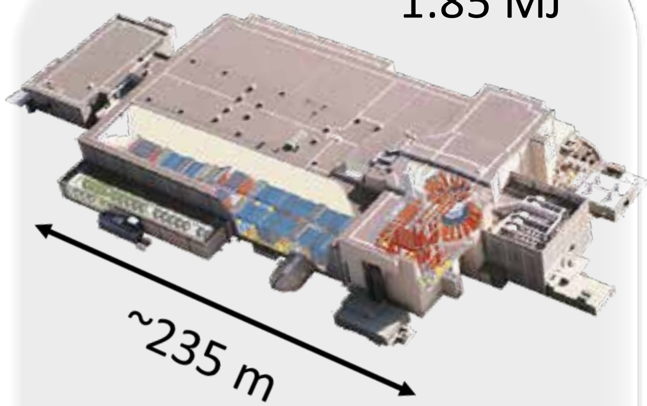
Magnetic Direct Drive



All three major US ICF facilities collaborate to provide critical data across all the major approaches

National Ignition Facility

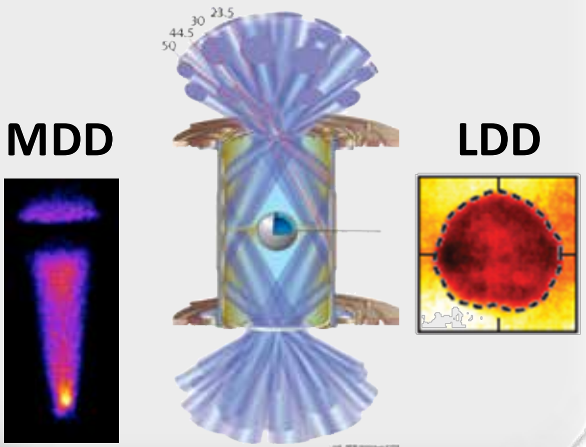
1.85 MJ



Laser Indirect Drive

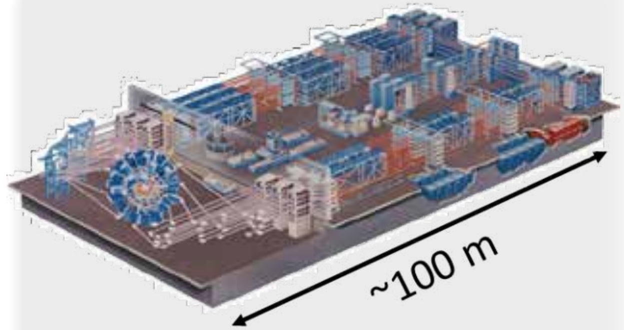
MDD

LDD



Omega Facility

26 kJ



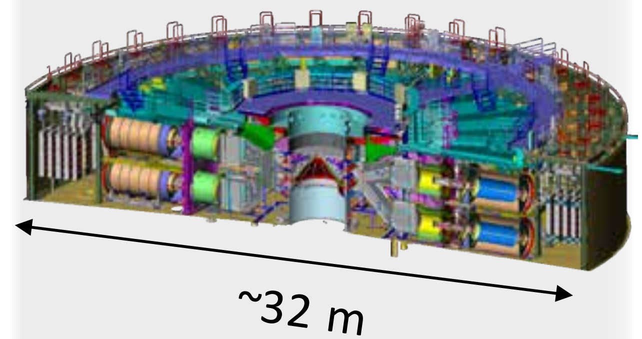
Laser Direct Drive

LID

MDD

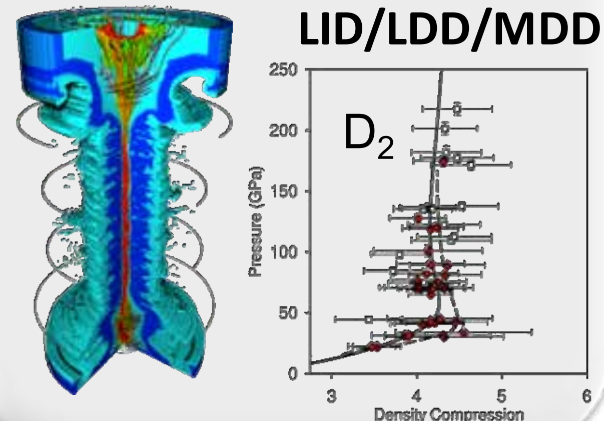
Z Facility

2 MJ

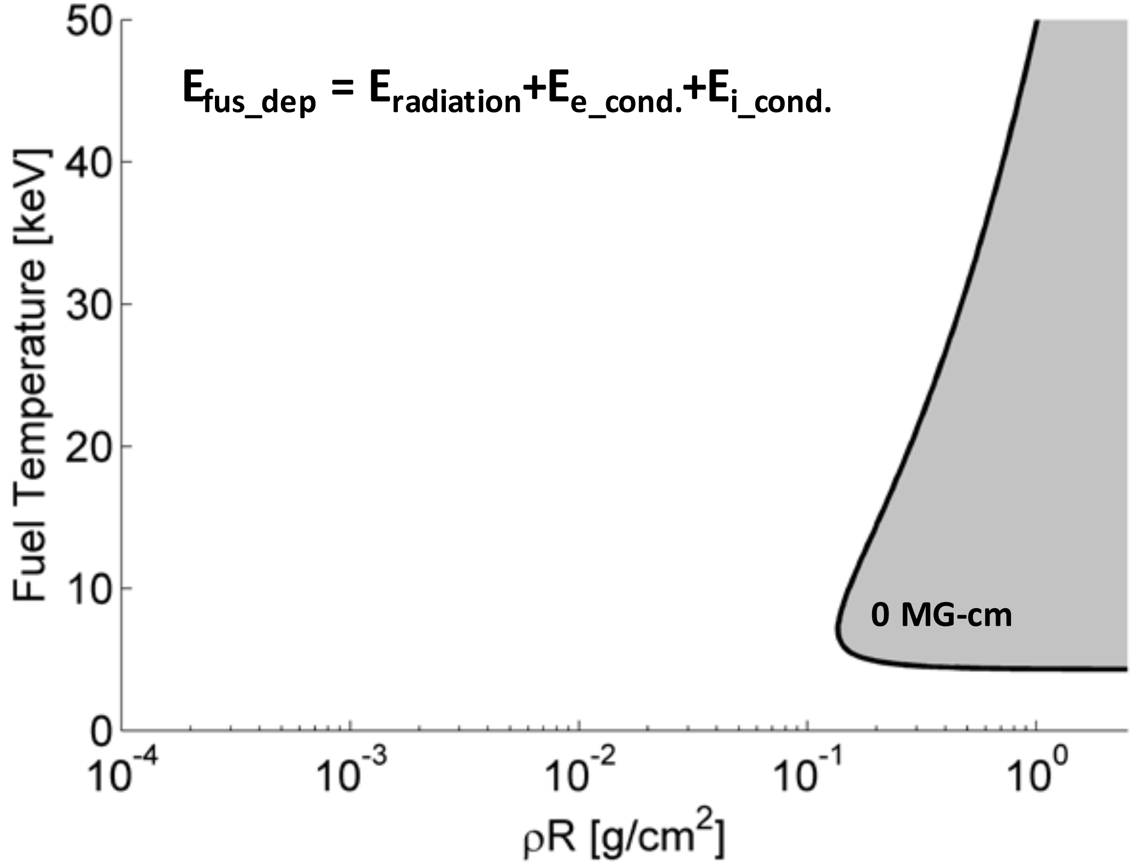


Magnetic Direct Drive

LID/LDD/MDD



ICF has requirements on stagnation conditions to propagate a burn wave (for high gain)



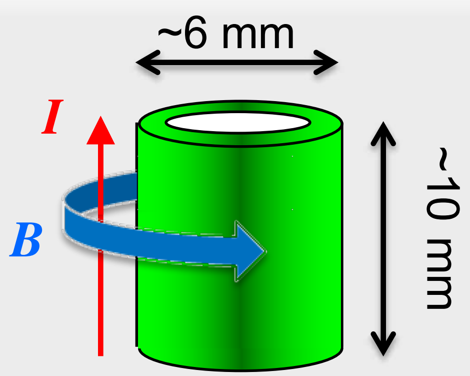
Room temperature ~0.025 eV

- There is a minimum fuel temperature of about 4.5 keV
  - This is where fusion heating outpaces radiation losses
- The minimum fuel areal density is around 0.2 g/cm^2
- Traditional ICF concepts attempt to operate in this minimum

P. F. Knapp, et al., Phys. Plasmas 22, 056312 (2015).

Magnetic direct drive provides an alternative way to do ICF using an axial B-field to reduce ρr requirements

Magnetic Direct Drive (MDD)



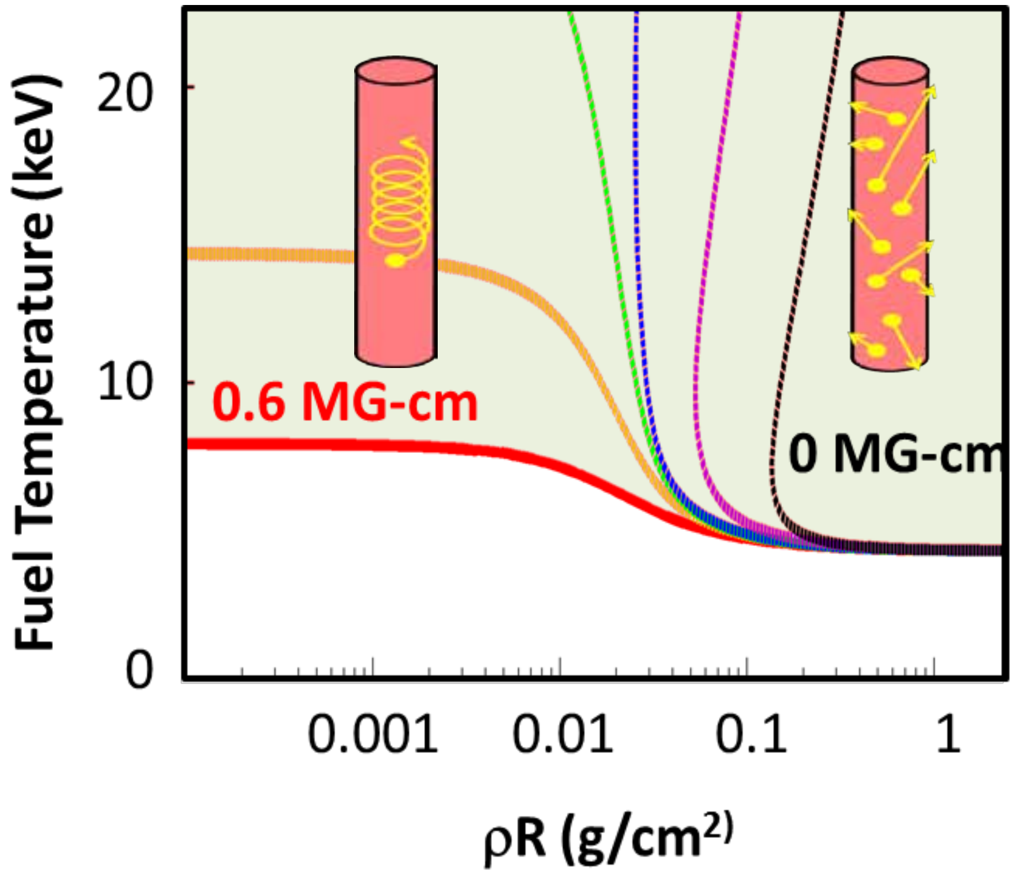
Drive Pressure

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

- Cylindrical convergence
  - Harder to achieve high ρr
- Thick liners (~500 μm)
  - Harder to achieve high velocity

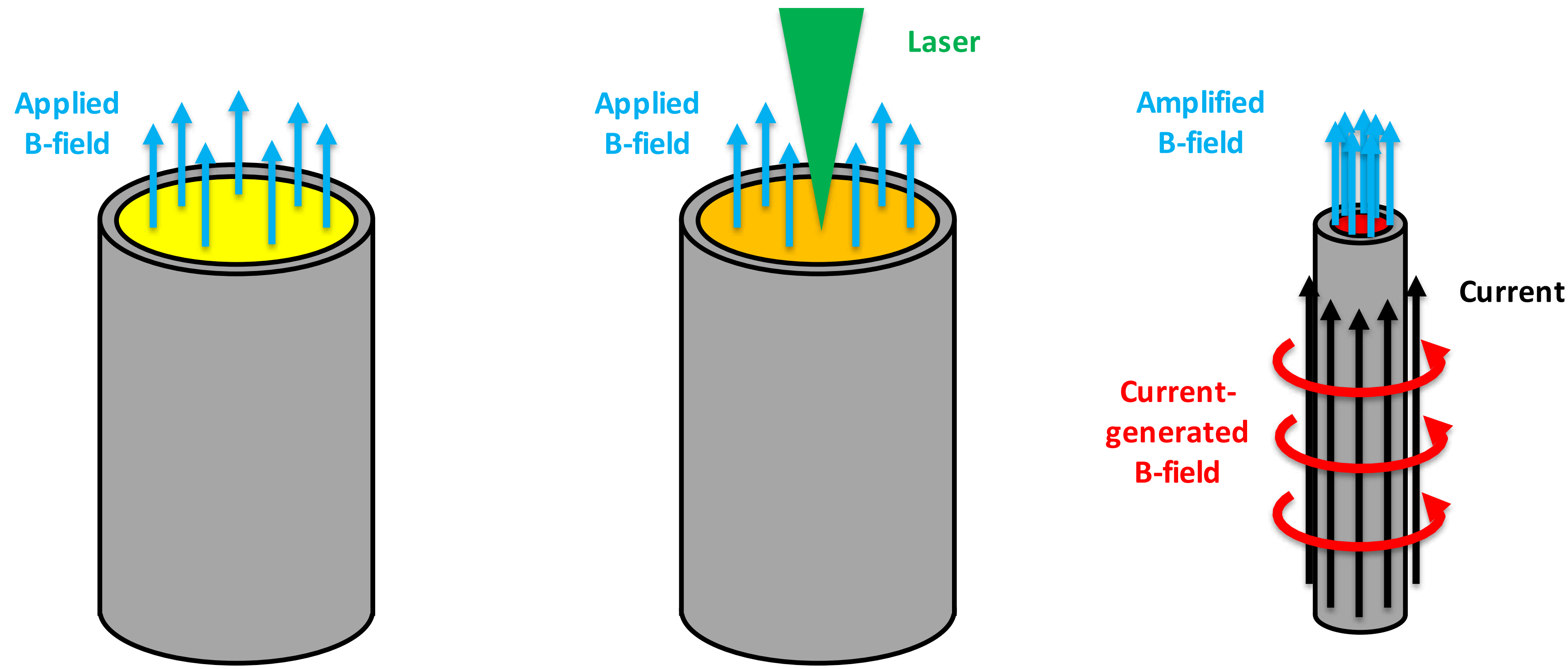
Imposing an axial B-field relaxes ρr requirements

Curves of self-heating from DT fusion alphas



Knapp, et al., POP 22 (2015).

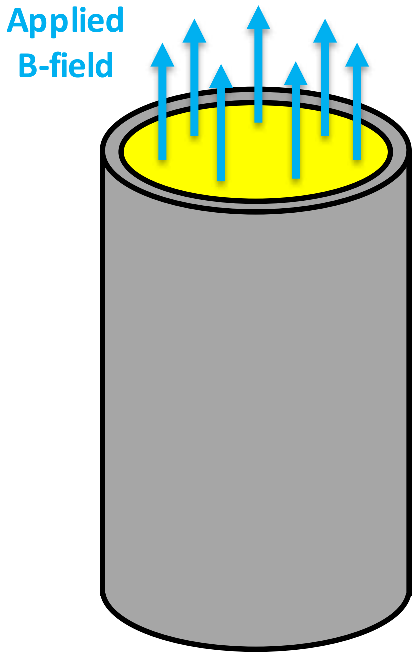
Magnetized Liner Inertial Fusion (MagLIF) relies on three stages to produce fusion relevant conditions



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).

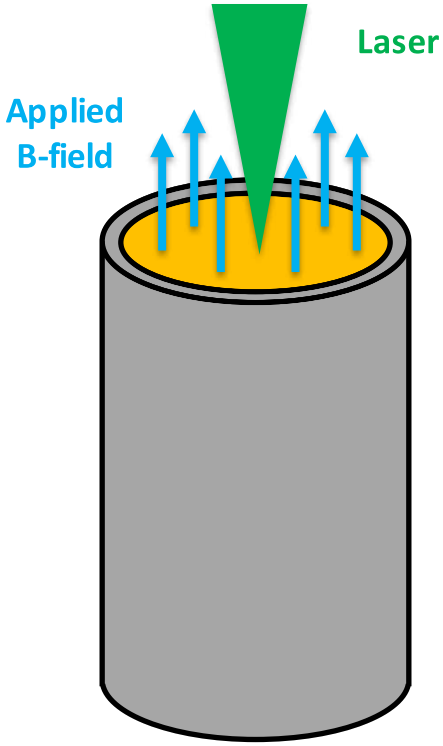
An axial magnetic field is applied to limit radial charged particle transport during the implosion



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
  - 3 ms risetime to allow field to diffuse through conductors

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

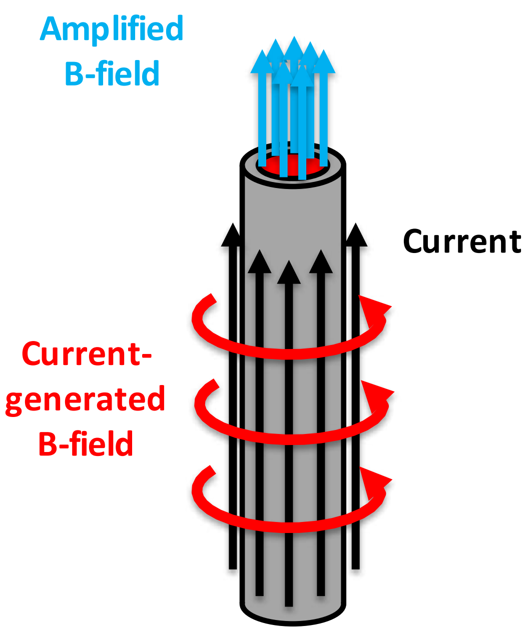


Laser-heat the magnetized fuel

- 527 nm, 2 ns, 2 kJ laser used to heat the fuel
- Laser must pass through 1-3 μm thick plastic window
  - Lose about half of the laser energy to the plastic
- Fuel is heated to ~100 eV
  - Recall the axial magnetic field limits thermal conduction in the radial direction

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

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

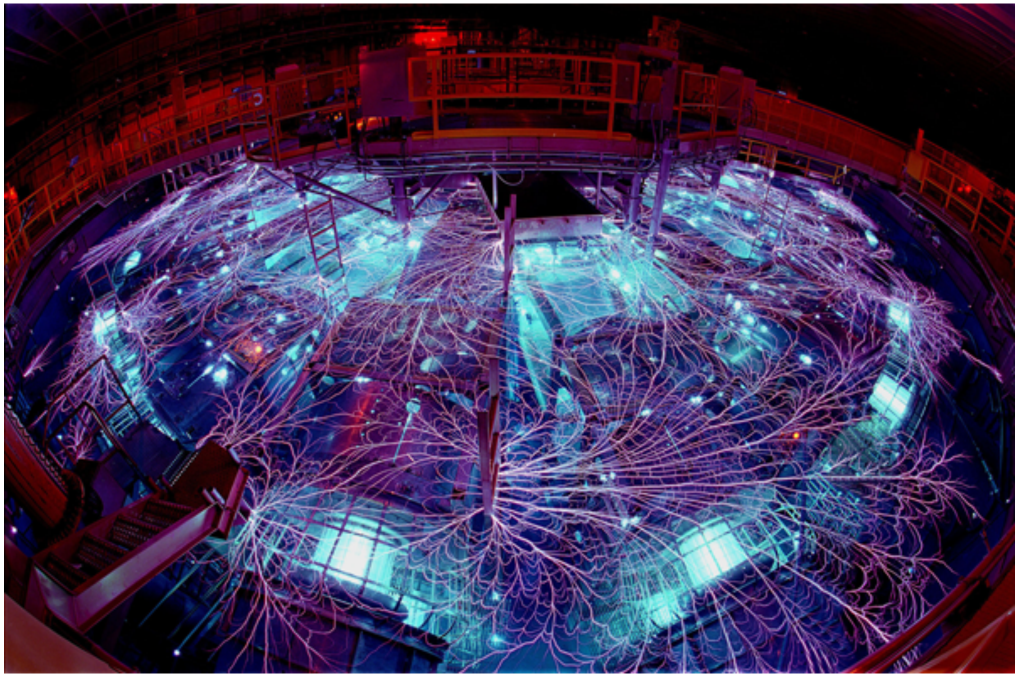


Compress the heated and magnetized fuel

- Axial current is ~17 MA, risetime is 100 ns
  - Generates ~3 kT azimuthal B-field
  - Metal cylinder implodes at ~70 km/s
- Fuel is nearly adiabatically compressed, which further heats the fuel to keV temperatures
- Axial magnetic field is increased to 1-10 kT through flux compression

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

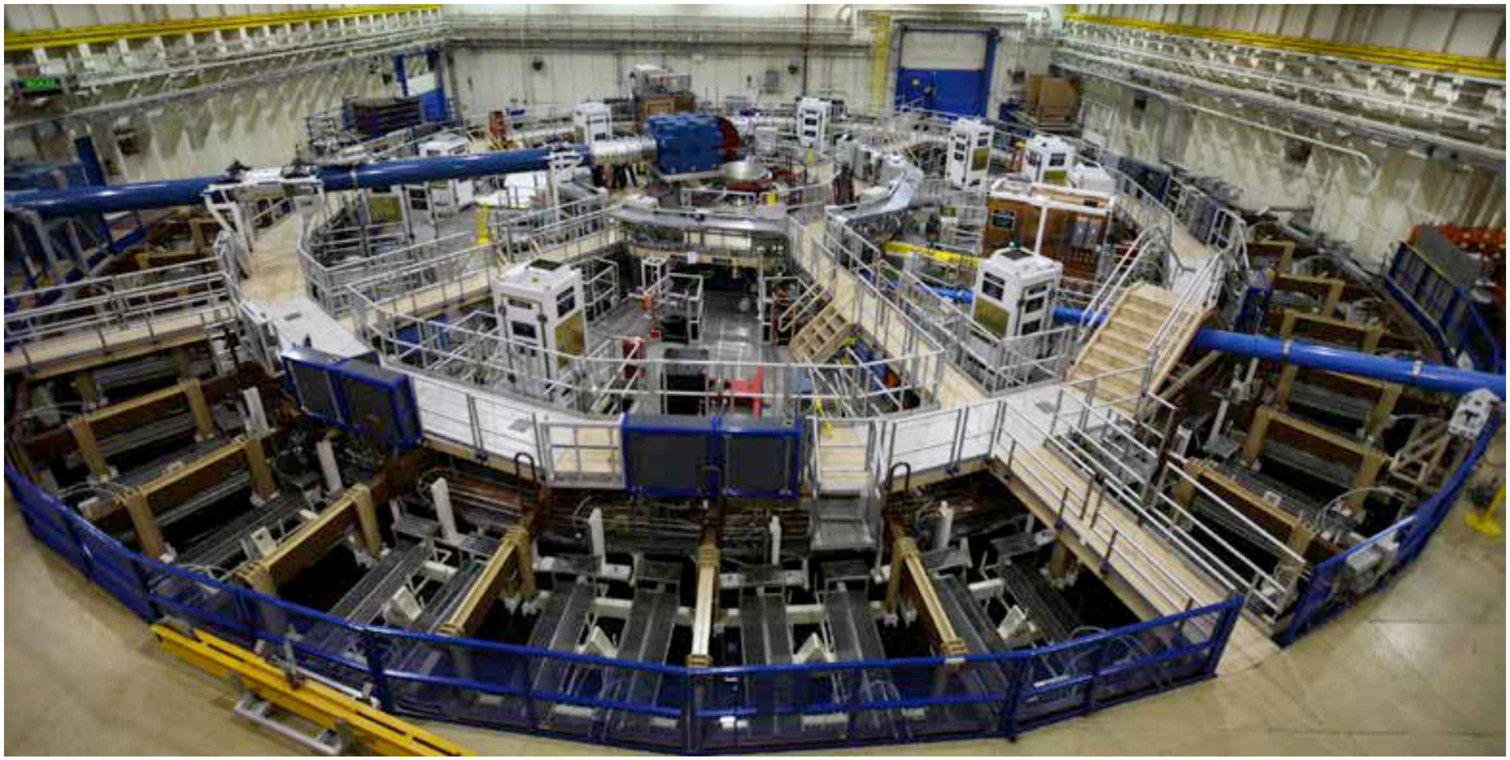
We use pulsed power to create high energy density matter



"Arcs and Sparks" photo of Z

- What is pulsed power?
  - Store energy over relatively long period of time (seconds to minutes)
  - Discharging over a relatively short period of time (ns to μs)
  - Compression in time of ~10^9
- Z stores about 20 MJ of energy over about 3 minutes
  - Average power ~ 100 kW
- Z delivers around 3 MJ of energy in a 100 ns risetime pulse to the experiment
  - Peak power ~80 TW

The energy of the Z machine is compressed in space as well as time



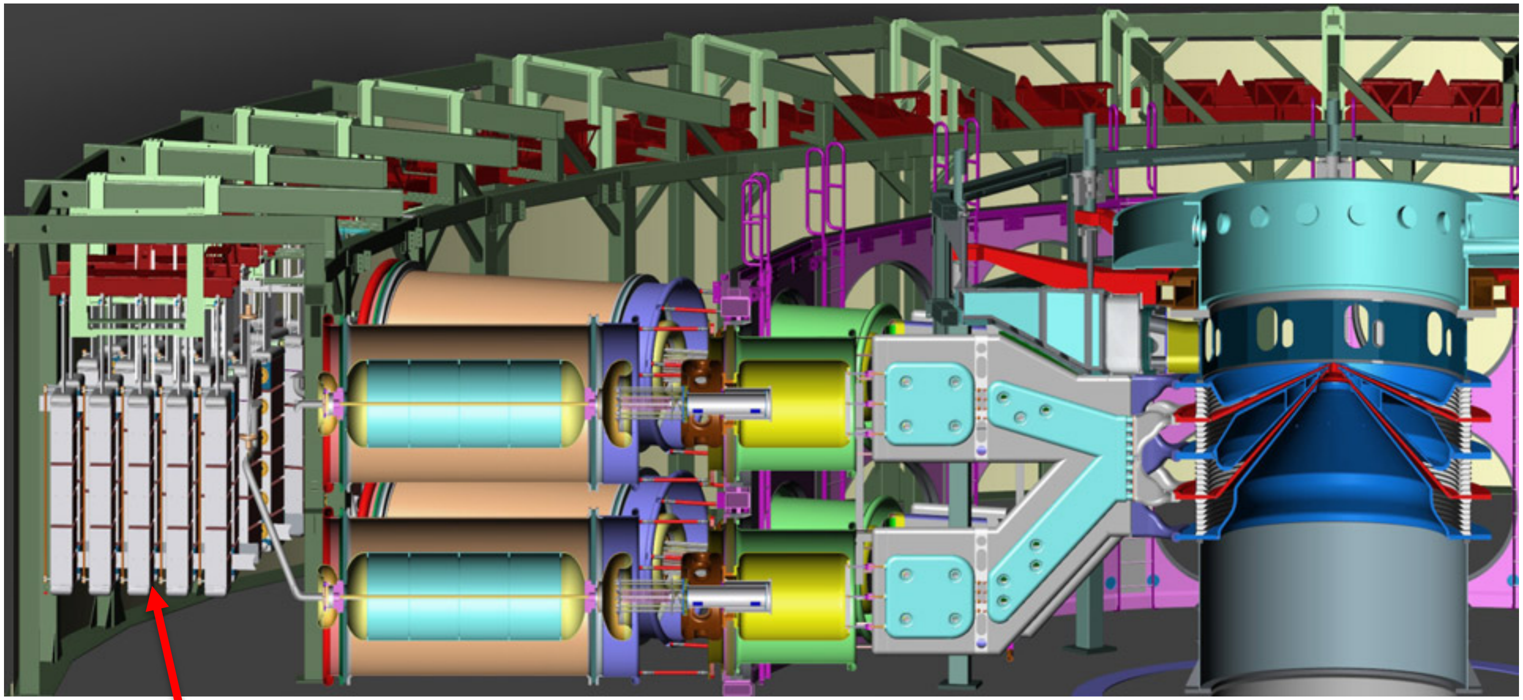
33 m

Energy storage volume is ~100 m^3

Target volume is ~0.1 cm^3

Compression in space is ~10^9

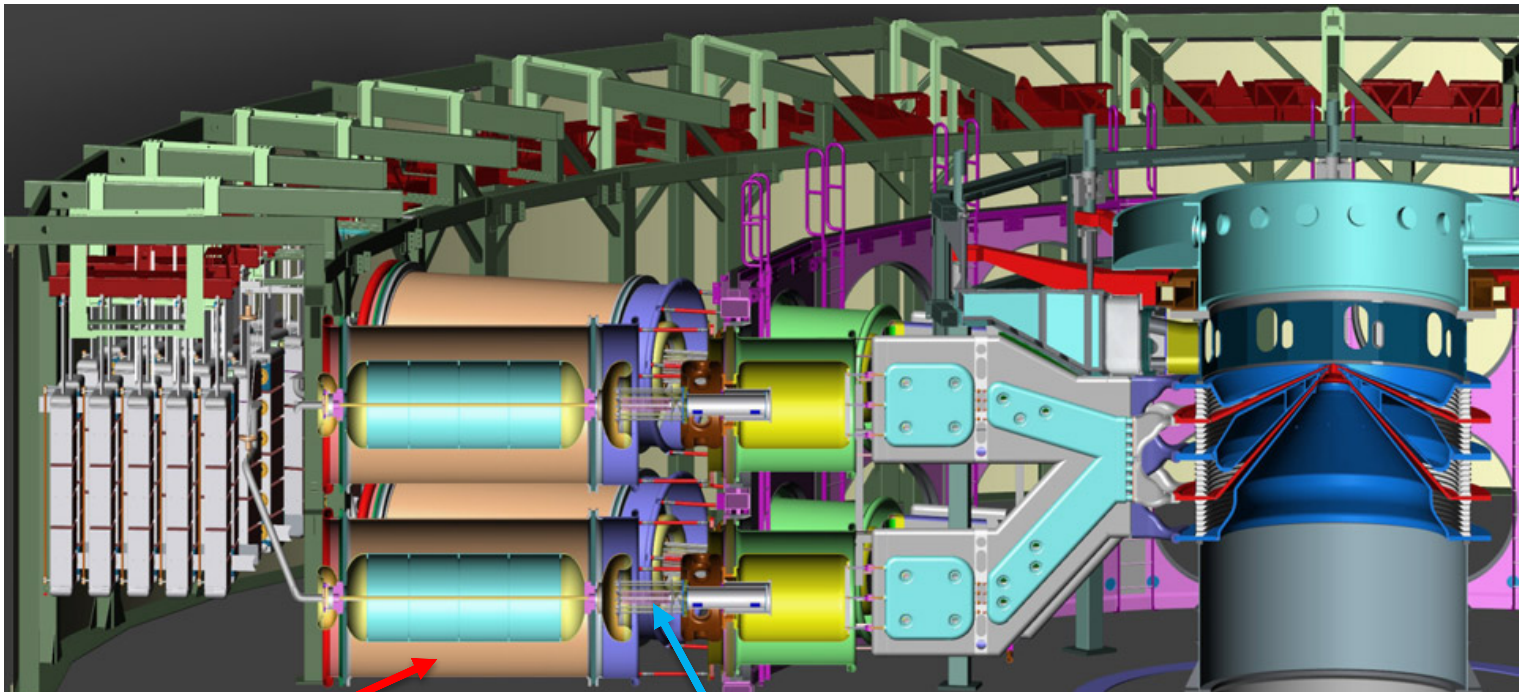
The Z machine uses Marx banks to generate high voltage electrical pulses



Marx bank

- Each Marx bank has 60 capacitors
- Each capacitor is charged to 85 kV
- **Output voltage is > 5 MV**
- 36 Mark bank outputs are parallelized to increase current

We use pulse compression stages to reduce the risetime of the current



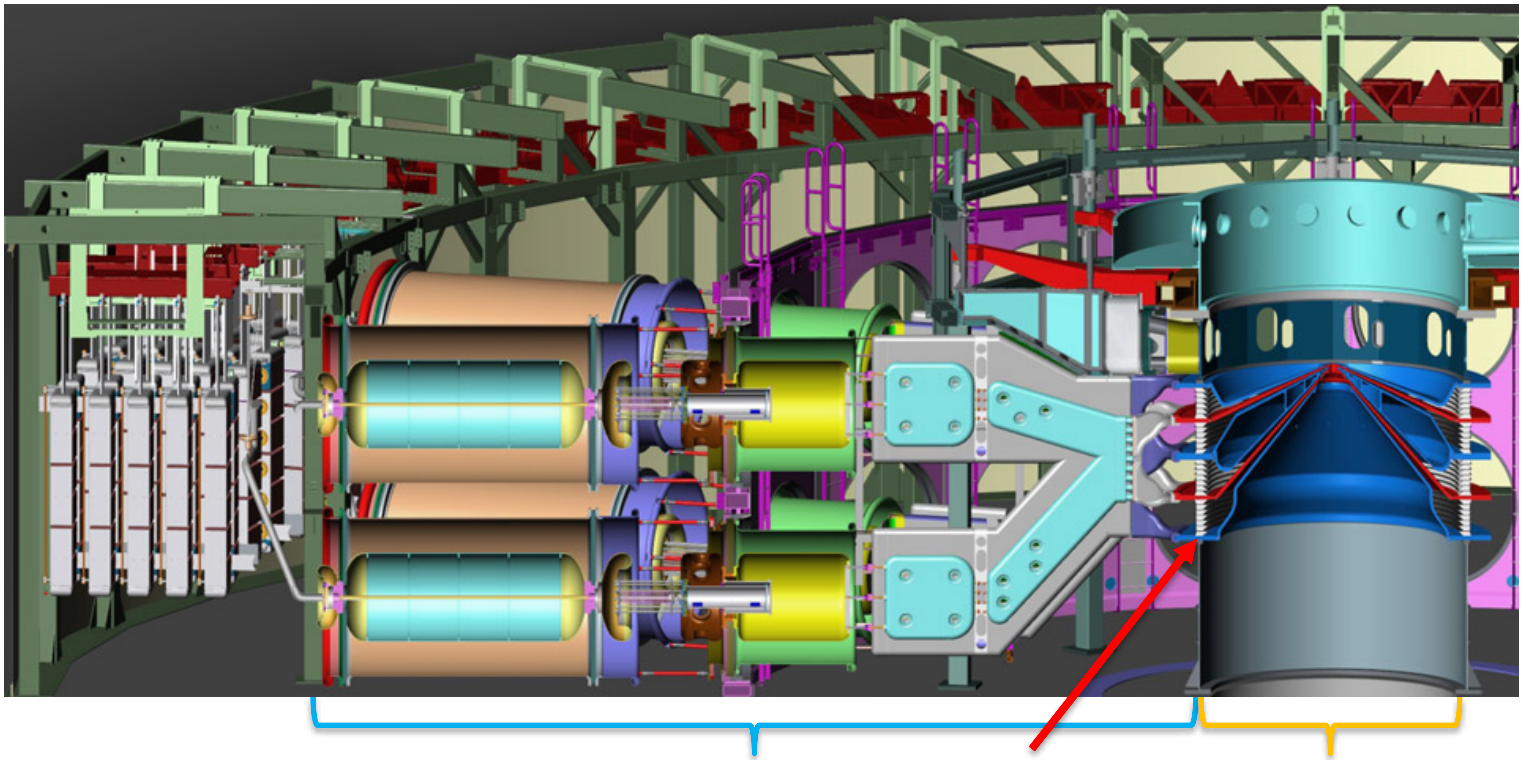
Water capacitor

Laser-triggered switch

- Water capacitors are used to temporarily store and the output of the Marx bank
- Electrical pulse is discharged through laser-triggered high voltage switch

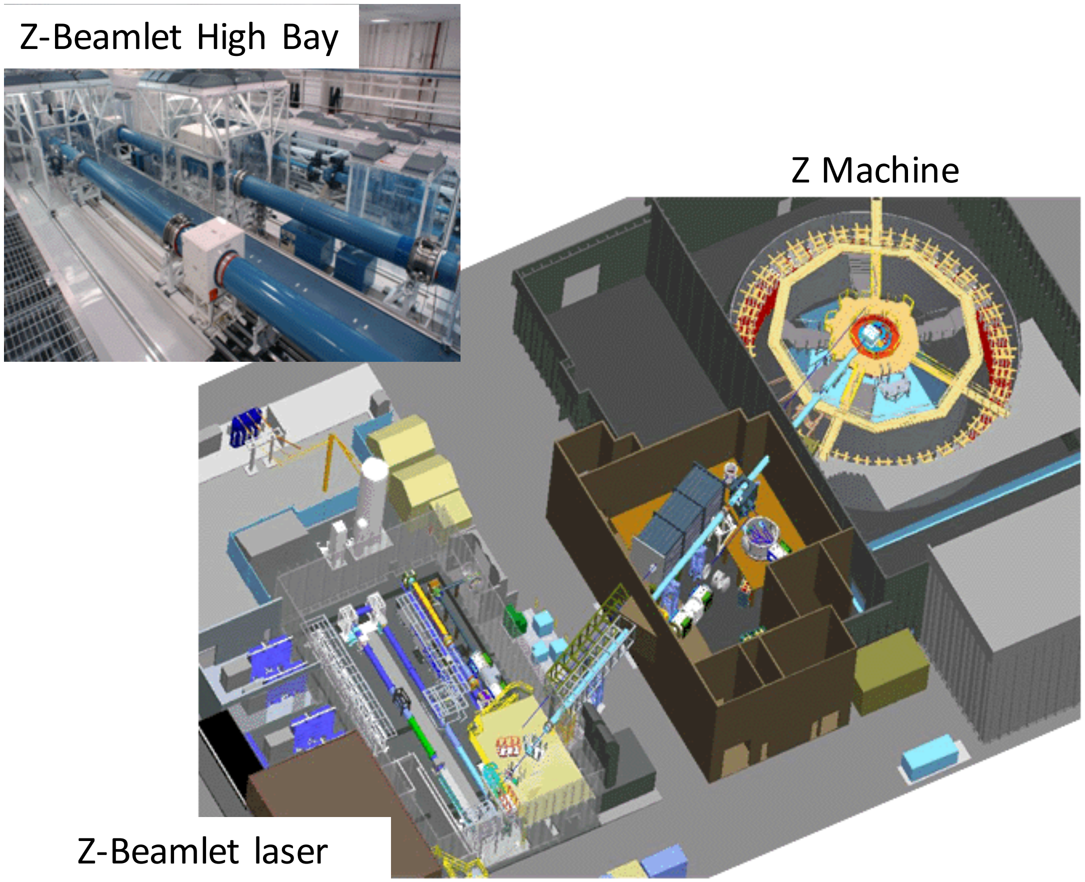
Electrical power reaches 80 TW

The compressed electrical pulse is transmitted into vacuum through an insulator stack



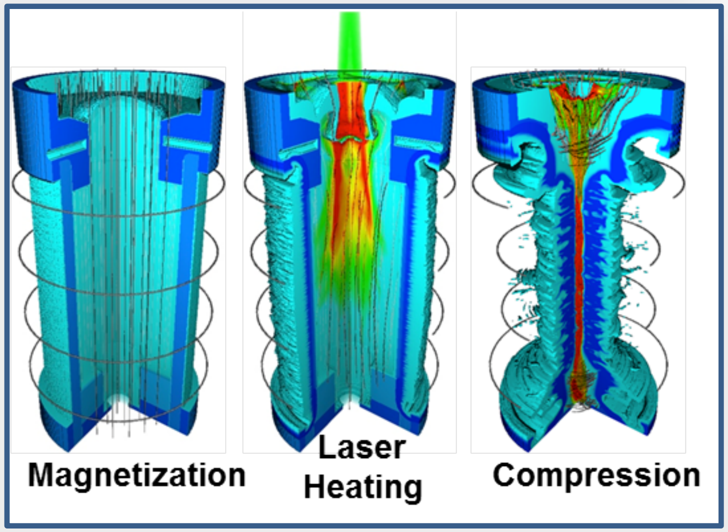
- Several transmission lines in parallel to reduce inductance
- Allows up to 26 MA to drive the experiment
- Electrical power at load is ~4x average global power usage

In addition to our pulsed power machine, we have a multi-kJ, TW-class laser



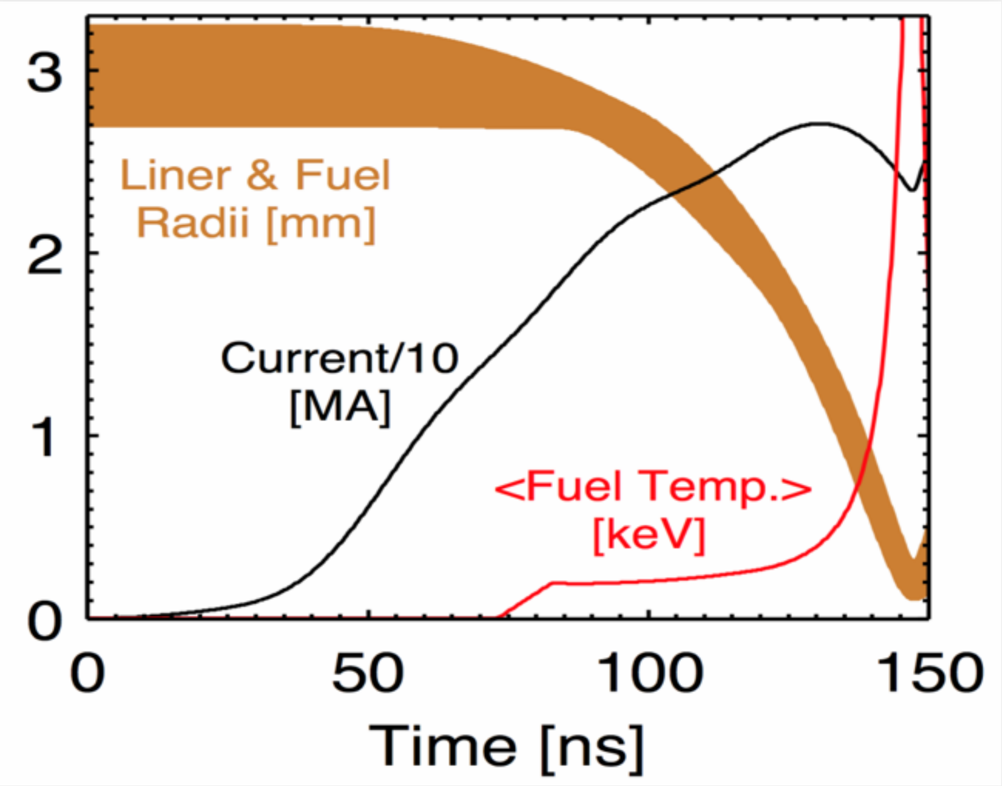
- Originally a prototype beamline for the NIF
- Up to 4.5 kJ at 1 TW of 527 nm
- Up to 3 shots per day (4 hour cool down)
- With the Z machine or in separate experiments

We use a variety of 1D, 2D, and 3D radiation-magneto-hydrodynamics tools to simulate MagLIF



- Length ~1 cm
- B_z = 10-30 T
- Laser Energy = 1-4 kJ
- T_0 ~ 100-200 eV
- CR ~ 35
- ρR ~ 0.003 g/cm^2
- P ~ 5 Gbar
- BR ~ 0.5 MG-cm

1-D picture*

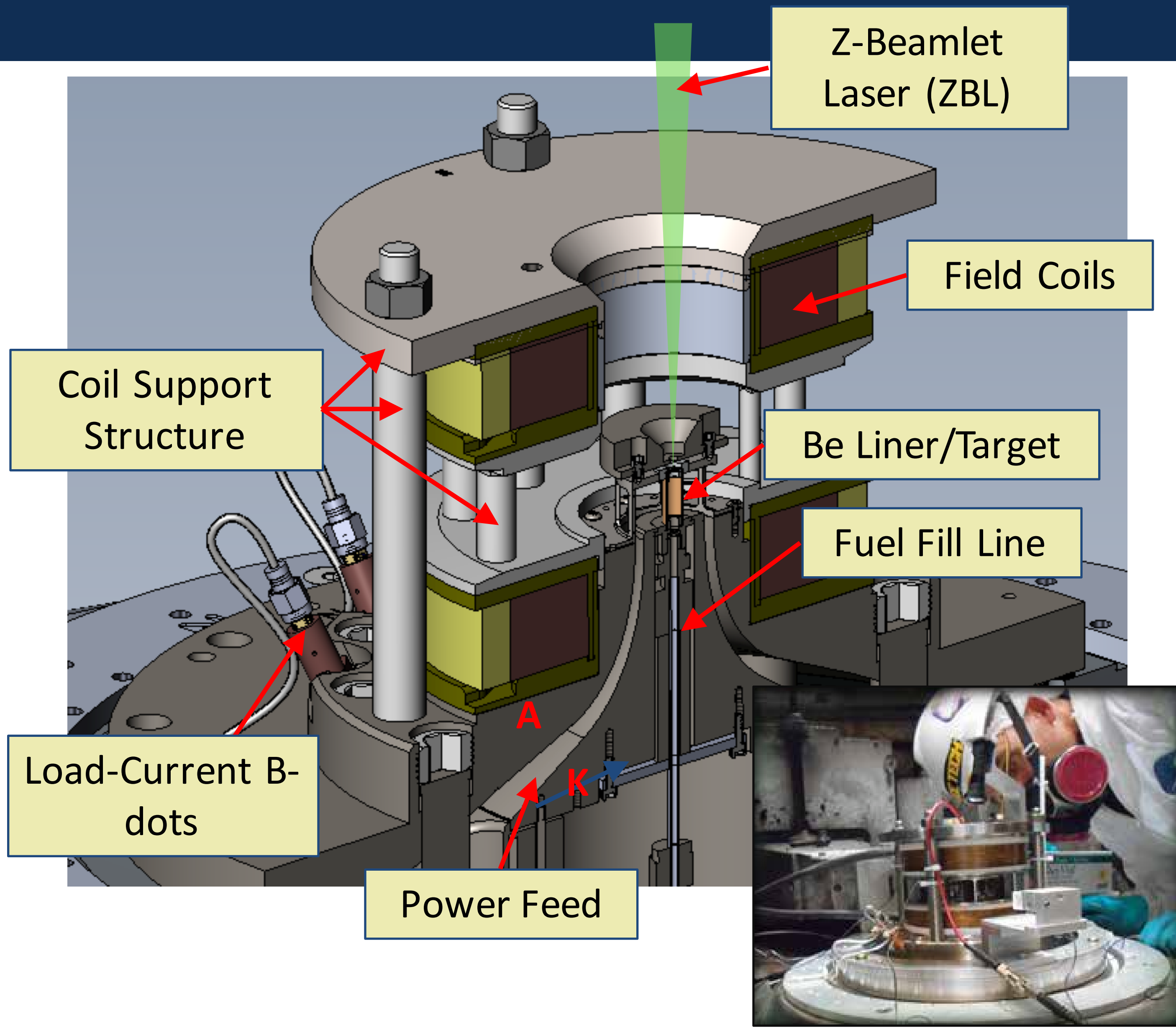


Fuel is quasi-adiabatically heated

Slutz et al., POP 17 (2010); Sefkow et al., 21 POP (2014). *R. D. McBride and S. A. Slutz, PoP 22, 052708 (2015)

Anatomy of a MagLIF Experiment

- **Field Coils**: Helmholtz-like coil 10-30 T axial field ~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)



All of this energy completely destroys the nearby components!

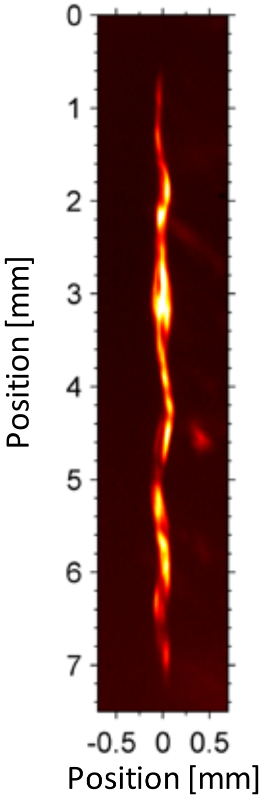
Before

After

- Debris impacts laser optics and diagnostics
- Clean up and reload limits us to 1 shot/day
- Diagnostic housings are 2.5 cm thick tungsten

We have demonstrated key aspects of magneto-inertial fusion on Sandia's Z facility

Well-behaved stagnation volume



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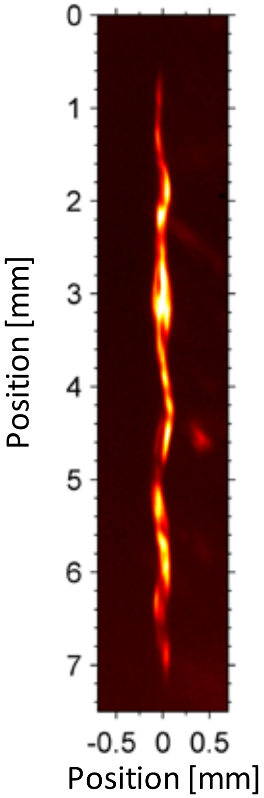
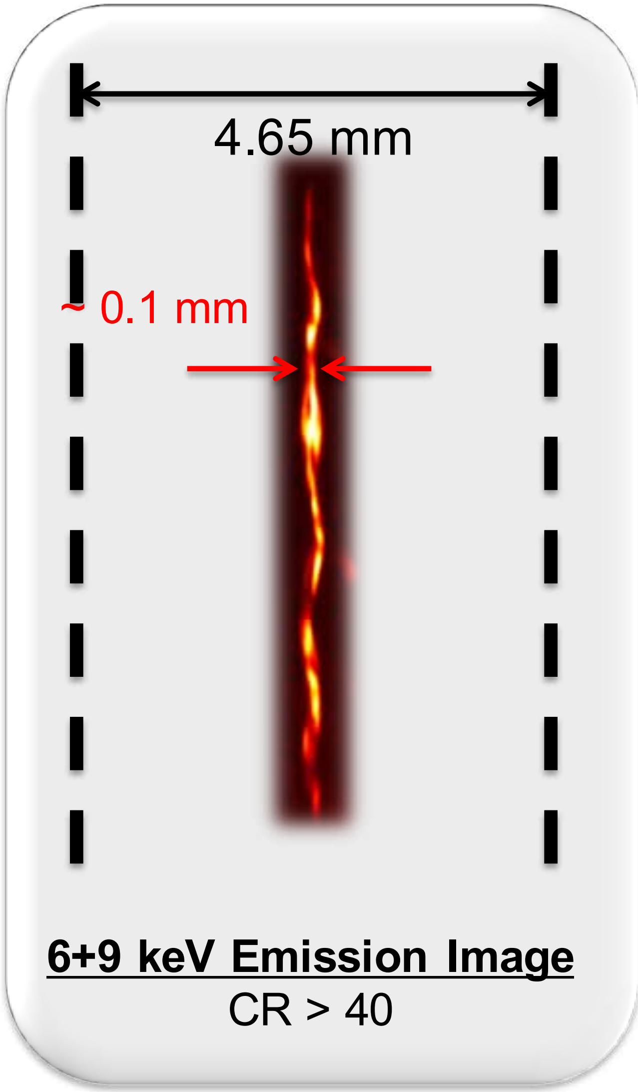


High Convergence Implosion



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

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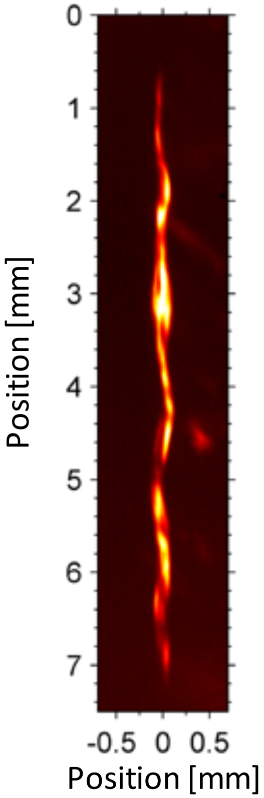
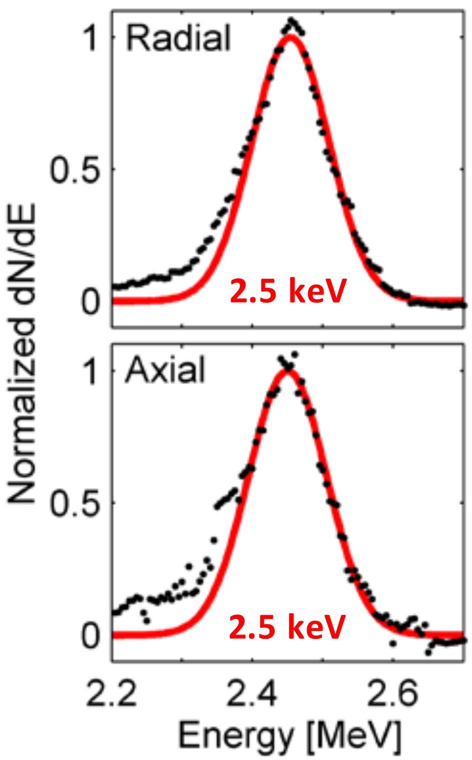


Relevant temperatures



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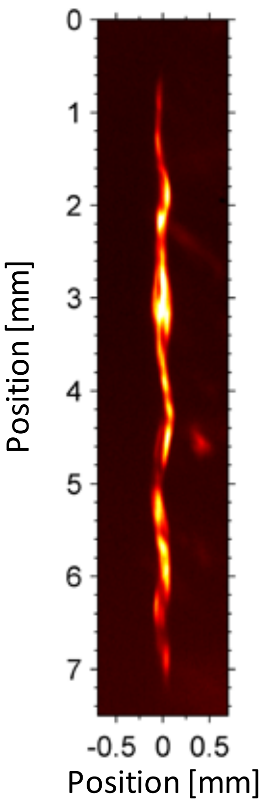

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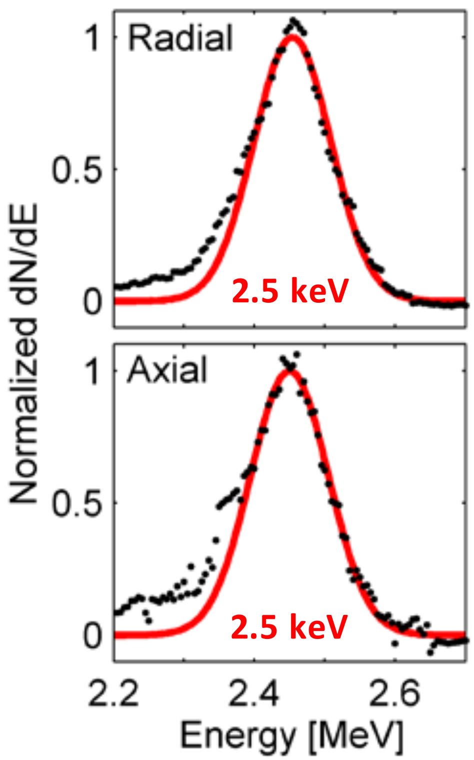
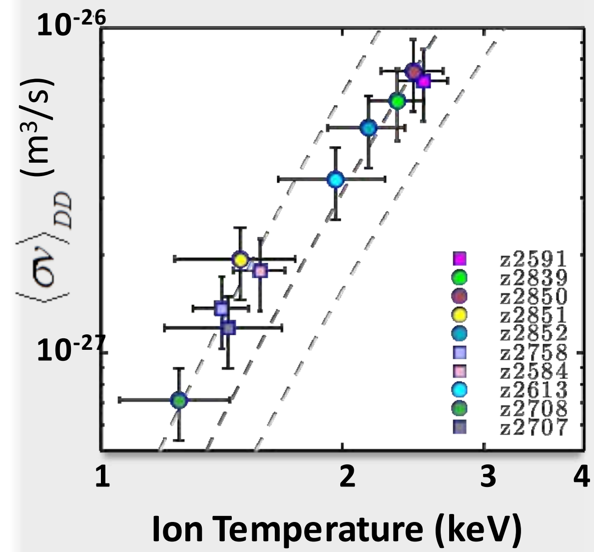


Thermonuclear Neutrons

Reactivity Scaling vs. T_i



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

<u>Yield, Volume, Duration</u>

Consistent with DD reactivity

M. R. Gomez, et al., Phys. Rev. Lett. 113, 155003 (2014); Hahn et al., RSI 85 (2014).

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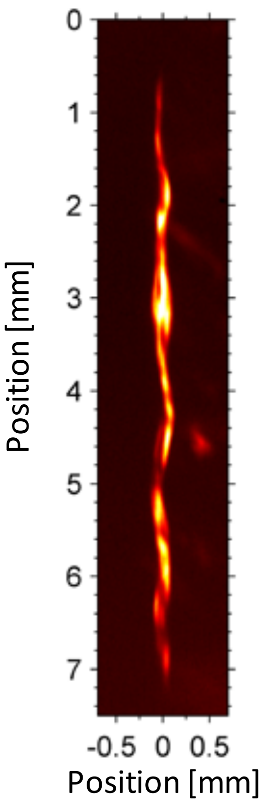

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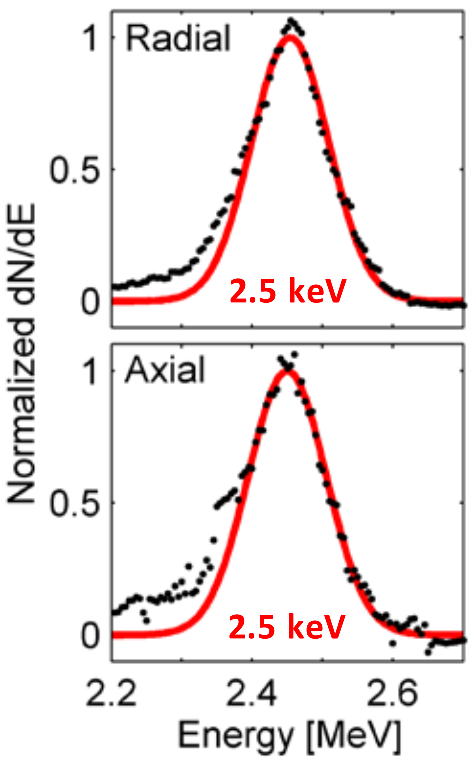
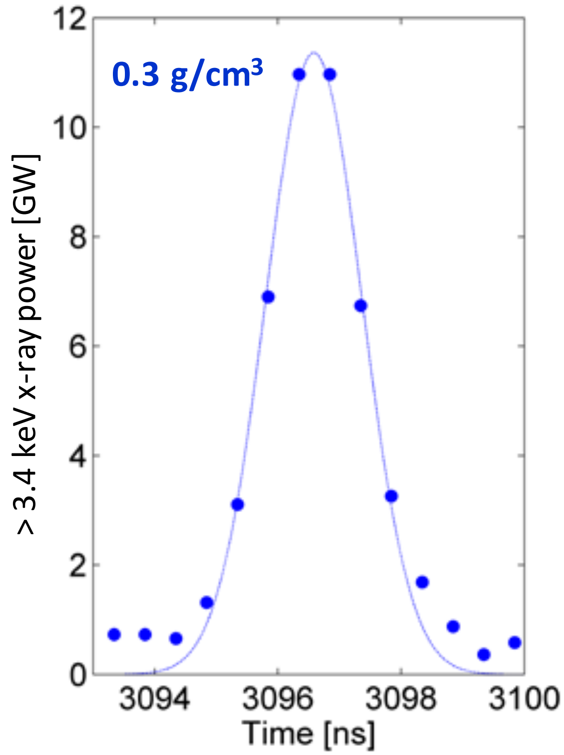


Relevant densities



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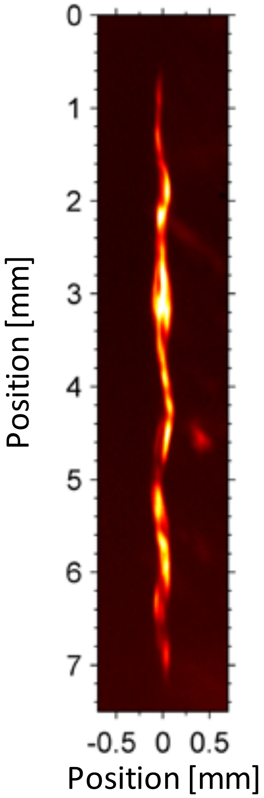

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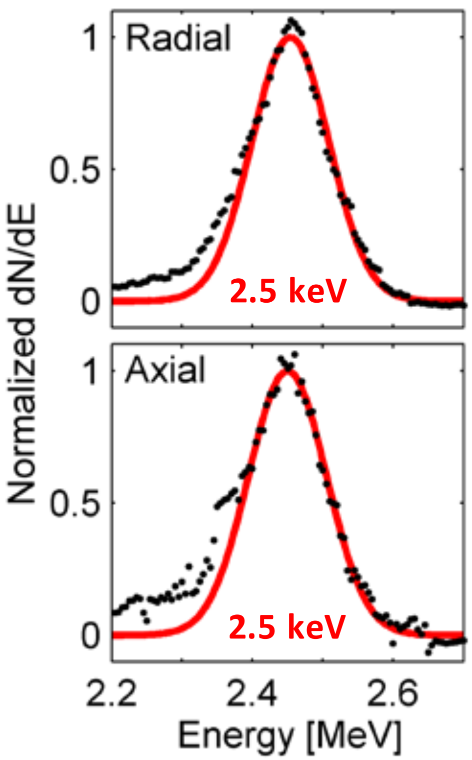
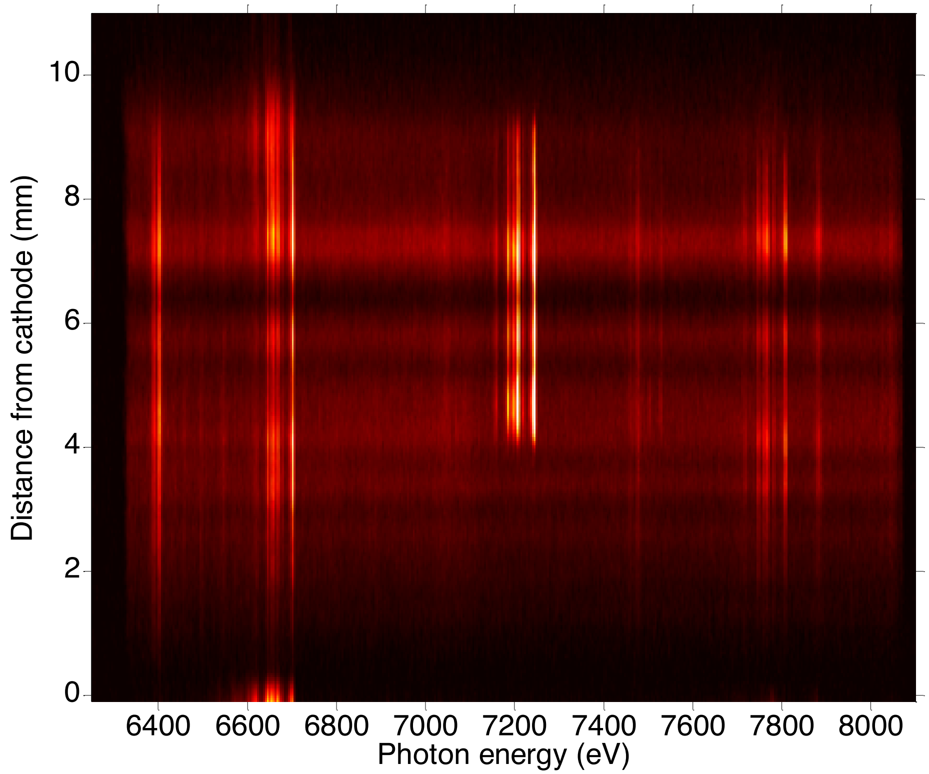


Inferred fuel temperatures and densities consistent with detailed x-ray spectroscopy



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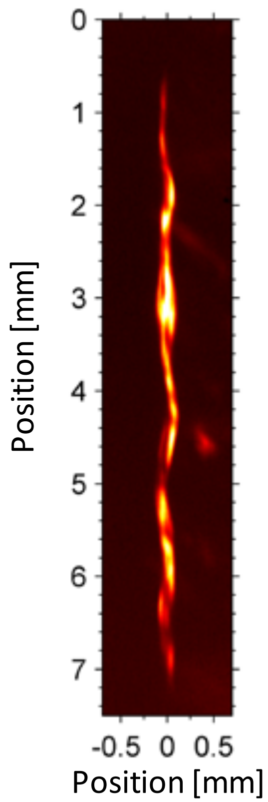
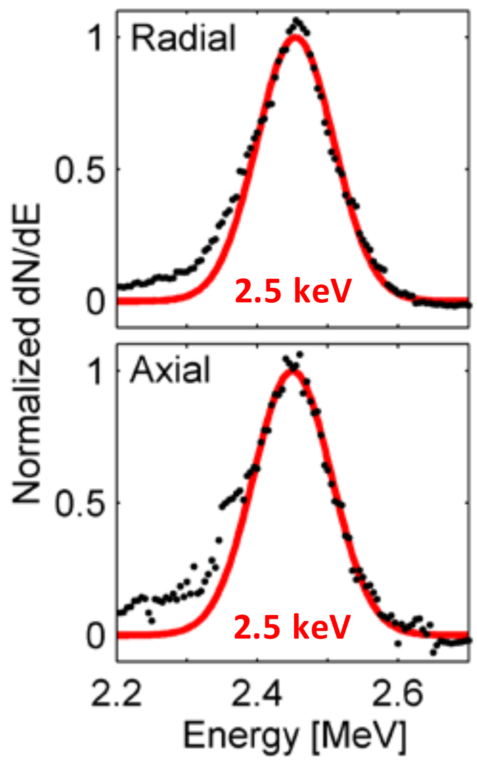


Relevant temperatures



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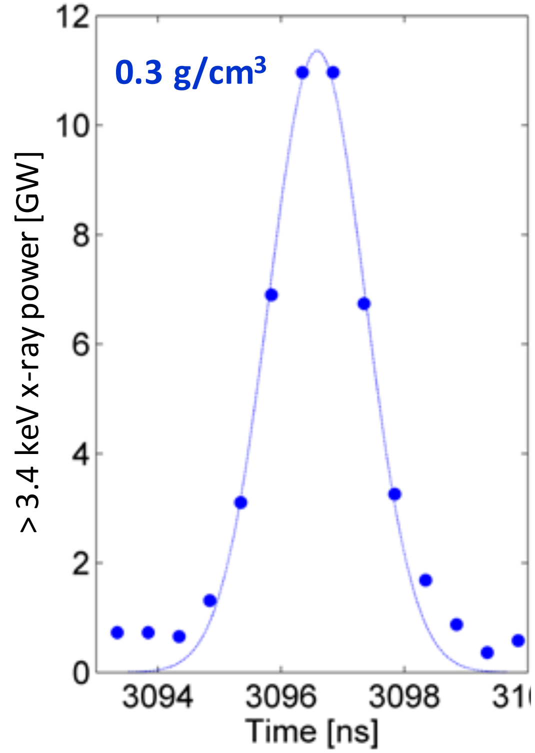
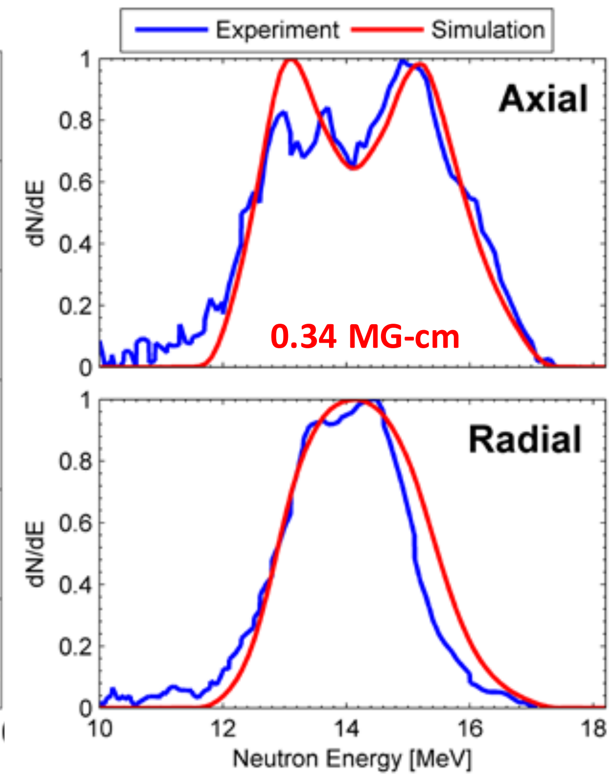


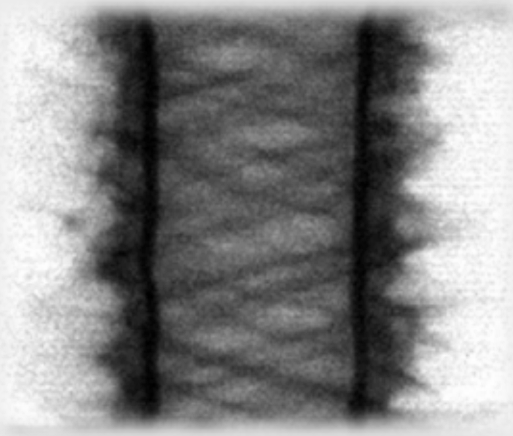
Relevant fuel magnetization



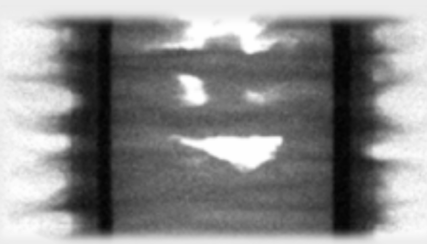
In MagLIF, the applied B-field induces 3-D liner features that imprint on the stagnation column at CR > 40.

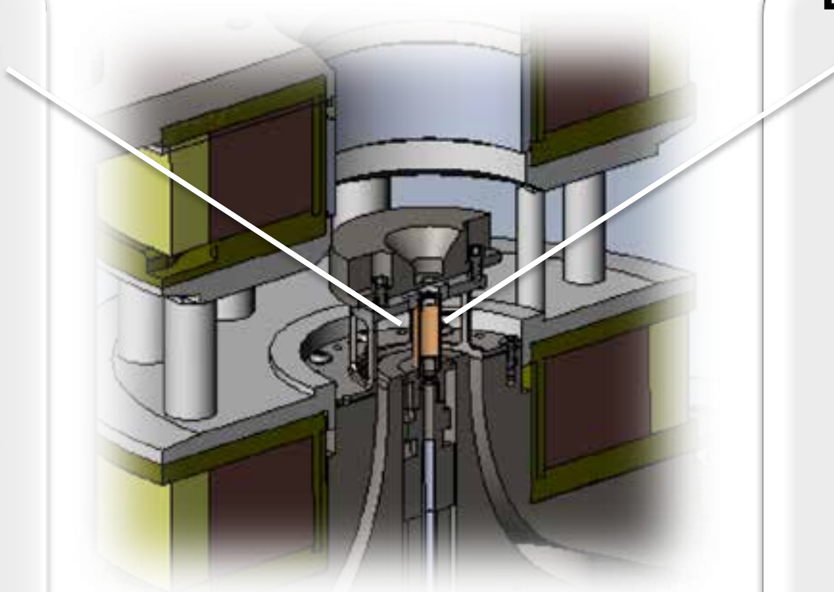
Backlit Radiographs

B_z = 7 T



No B_z





Helmholtz Coil Provides Axial Magnetic Field (B_z)

- Thermal insulation
- Trap fusion particles

X-ray Self Emission

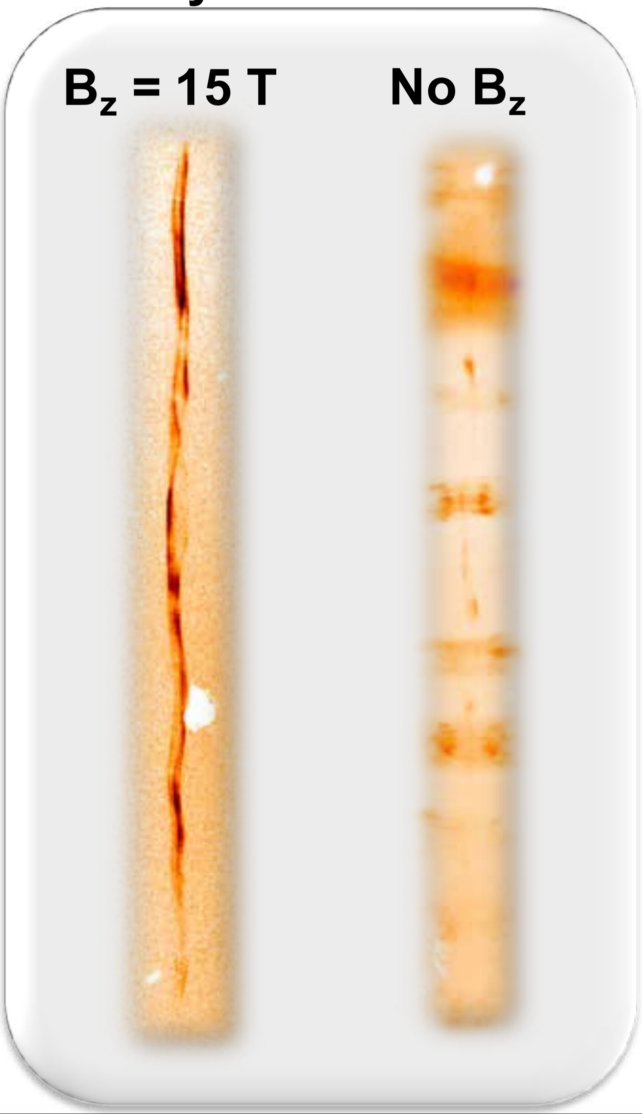
B_z = 15 T **No B_z**

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

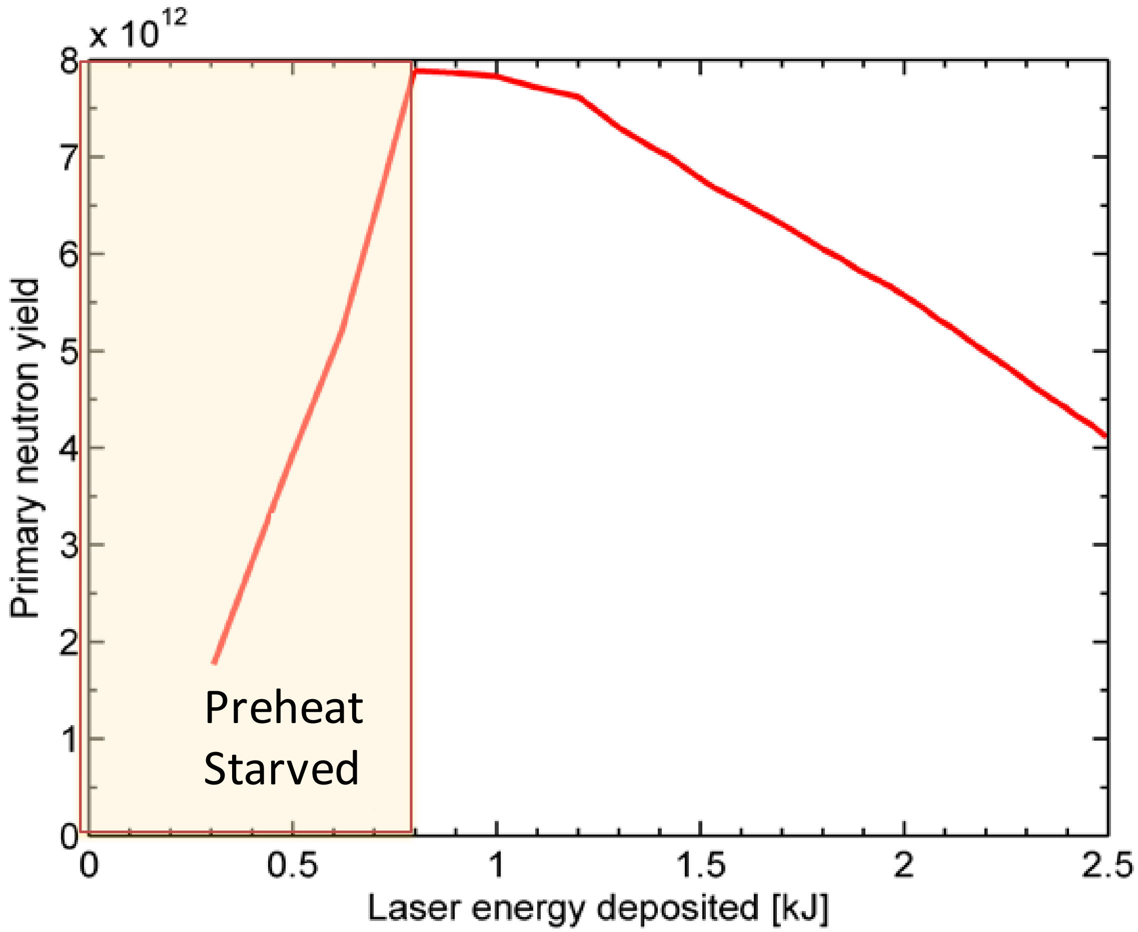
	No B-field	B-field
No Laser Heating	**$3x10^9$ (near-background)**	**$1x10^{10}$**
Laser Heating	**$4x10^{10}$**	**$3x10^{12}$**

$3x10^{12}$ is a DT-equivalent yield of ~0.6 kJ

X-ray Self Emission



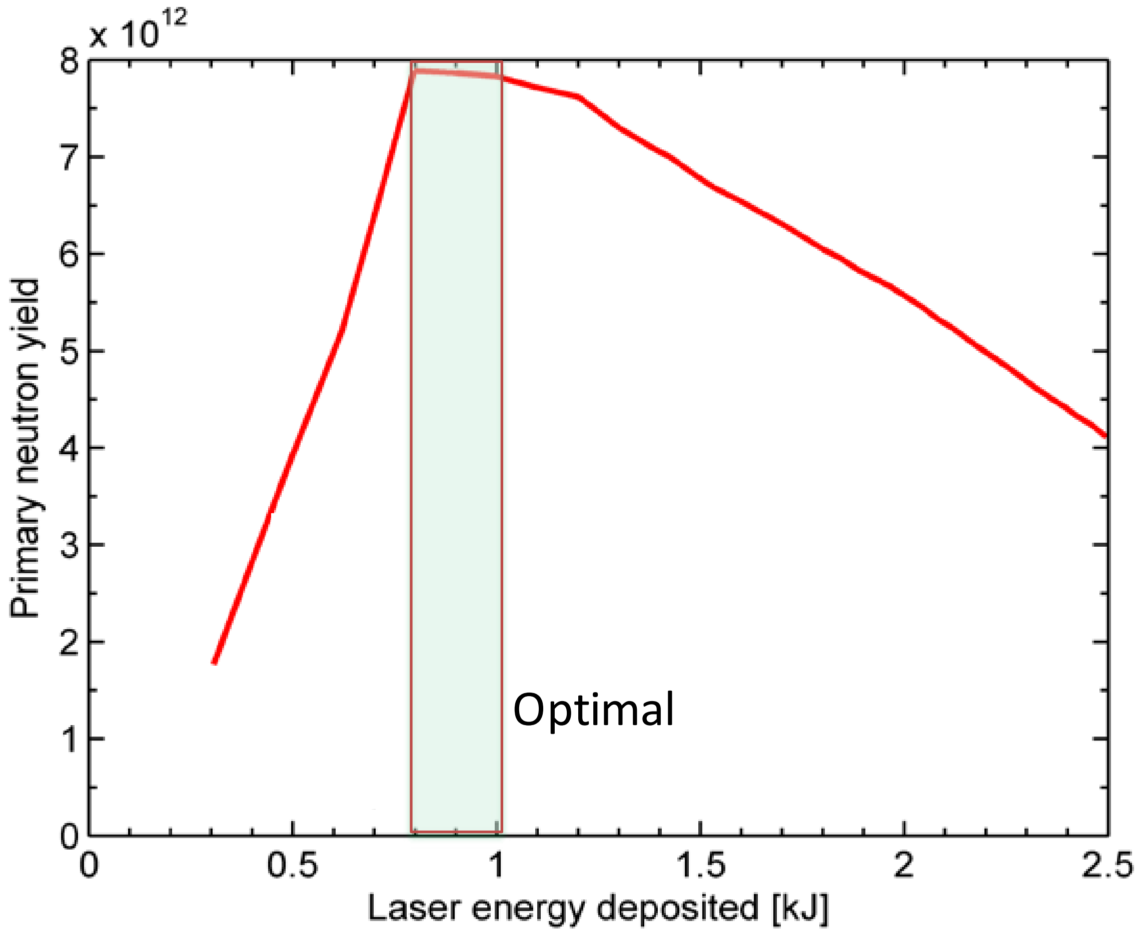
Simulated primary neutron yields are sensitive to the coupled preheat energy



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

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

Simulated primary neutron yields are 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

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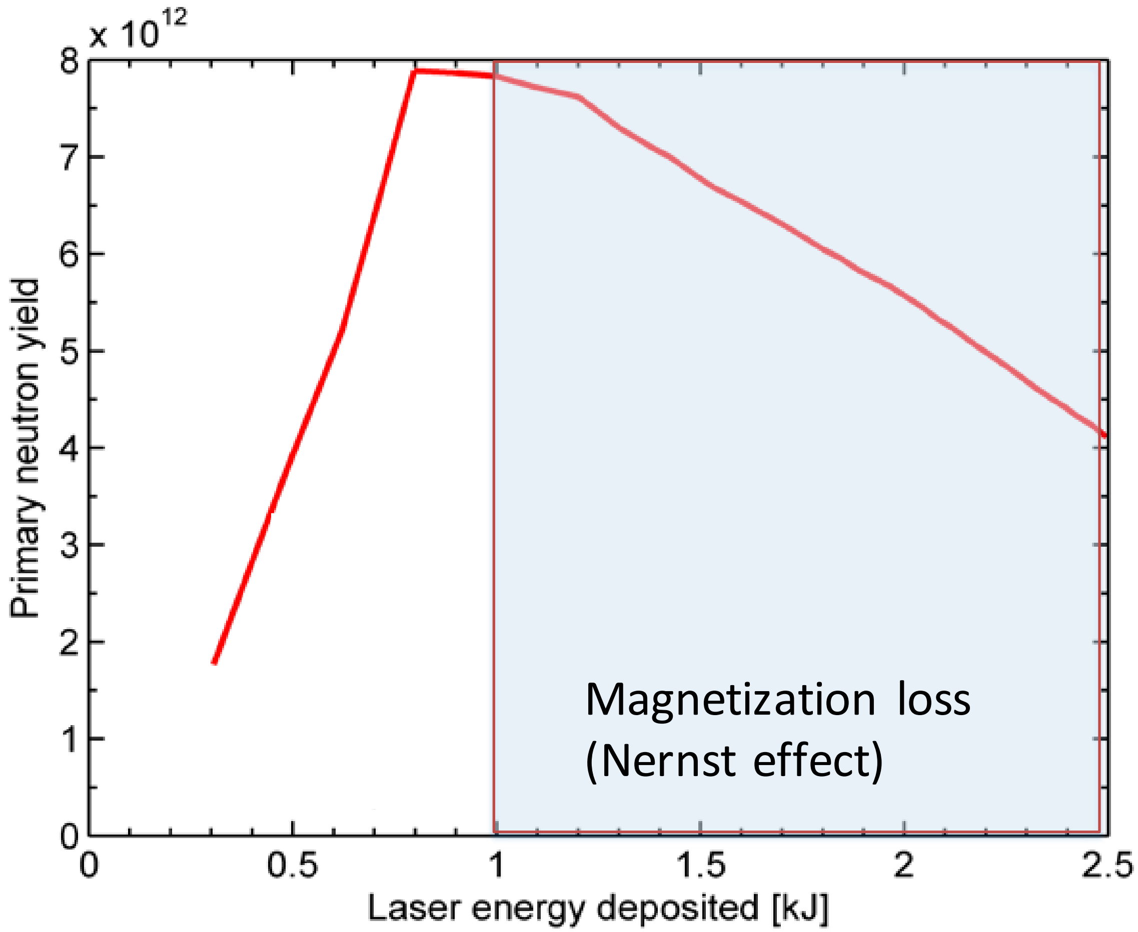
Simulated primary neutron yields are sensitive to the coupled preheat energy



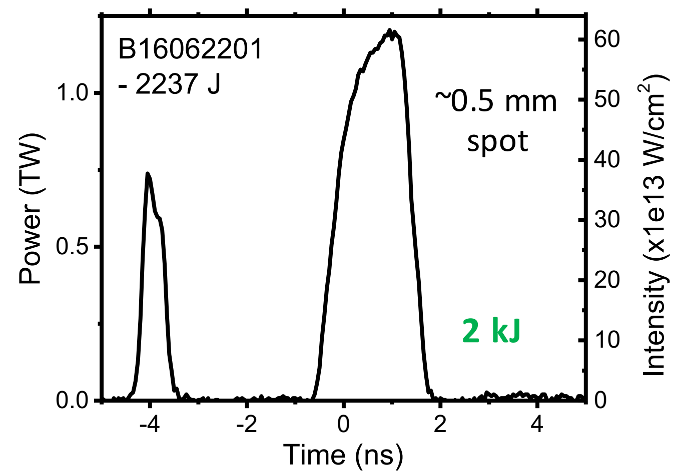
Assumes 10T, 17 MA, 2D clean implosion (No mix, 3D, etc)

- 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

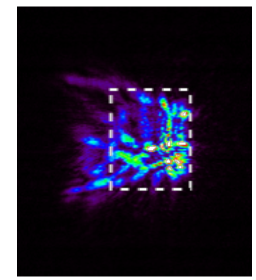
Our initial experiments had significant uncertainty in the coupled laser energy

- Laser configuration produced significant laser plasma interactions (LPI) not modeled in our codes
- No beam smoothing was employed
- Several independent laser heating experiments suggested low (200-600J) preheat coupling
  - Window transmission
  - X-ray emission
  - VISAR blastwave analysis
- Recent optical shadowgraphy measurements of blastwave in DD fuel suggest >600J

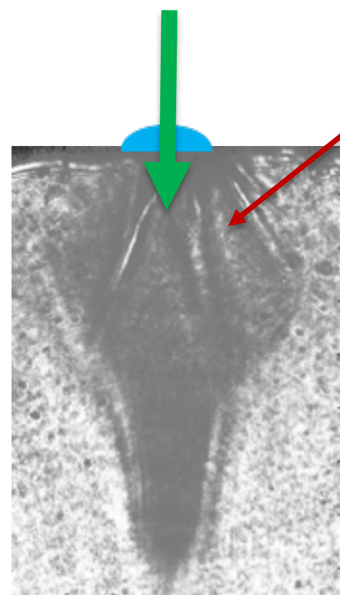
Original MagLIF laser pulse



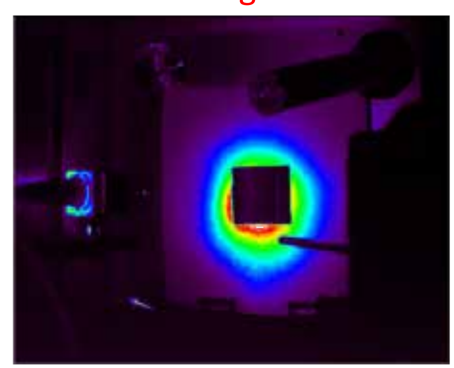
Beam Profile



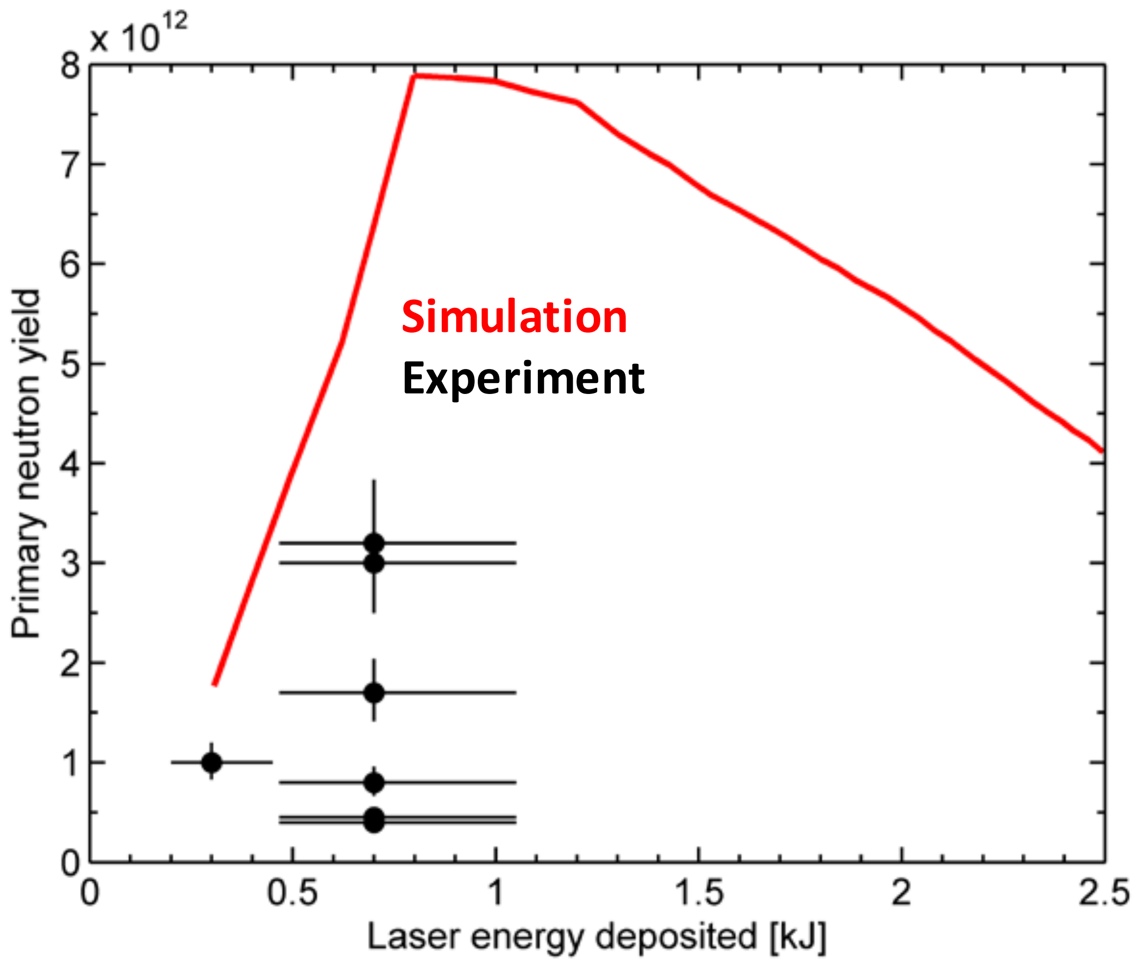
filamentation



Stimulated Brillouin Scattering: 900J !



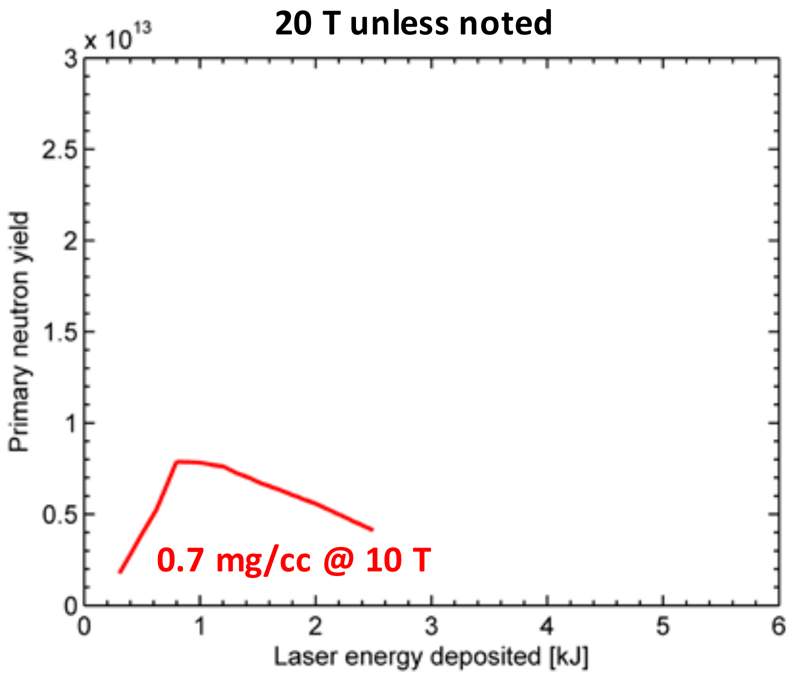
2D MHD Simulations of our initial MagLIF configuration match experiments to about 2-3x

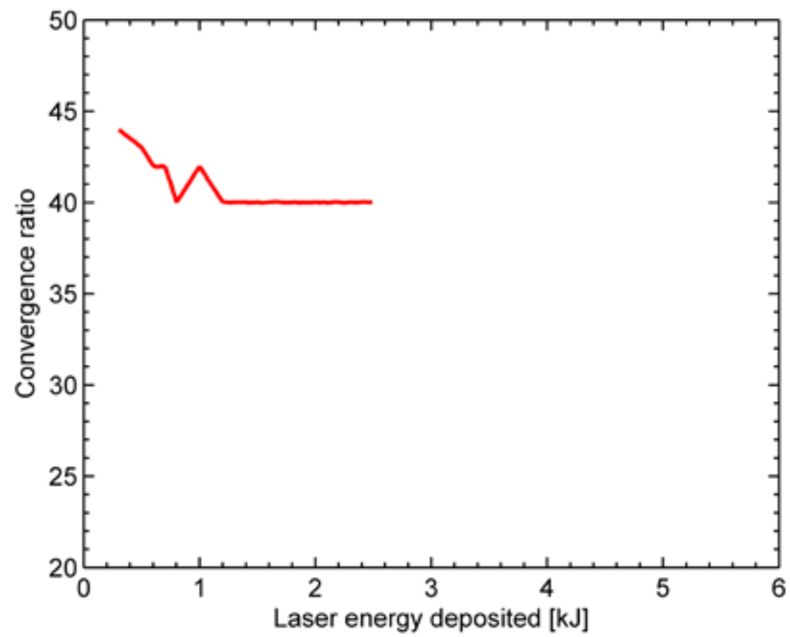


Assumes 10T, 17 MA, clean implosion (No mix, 3D, etc)

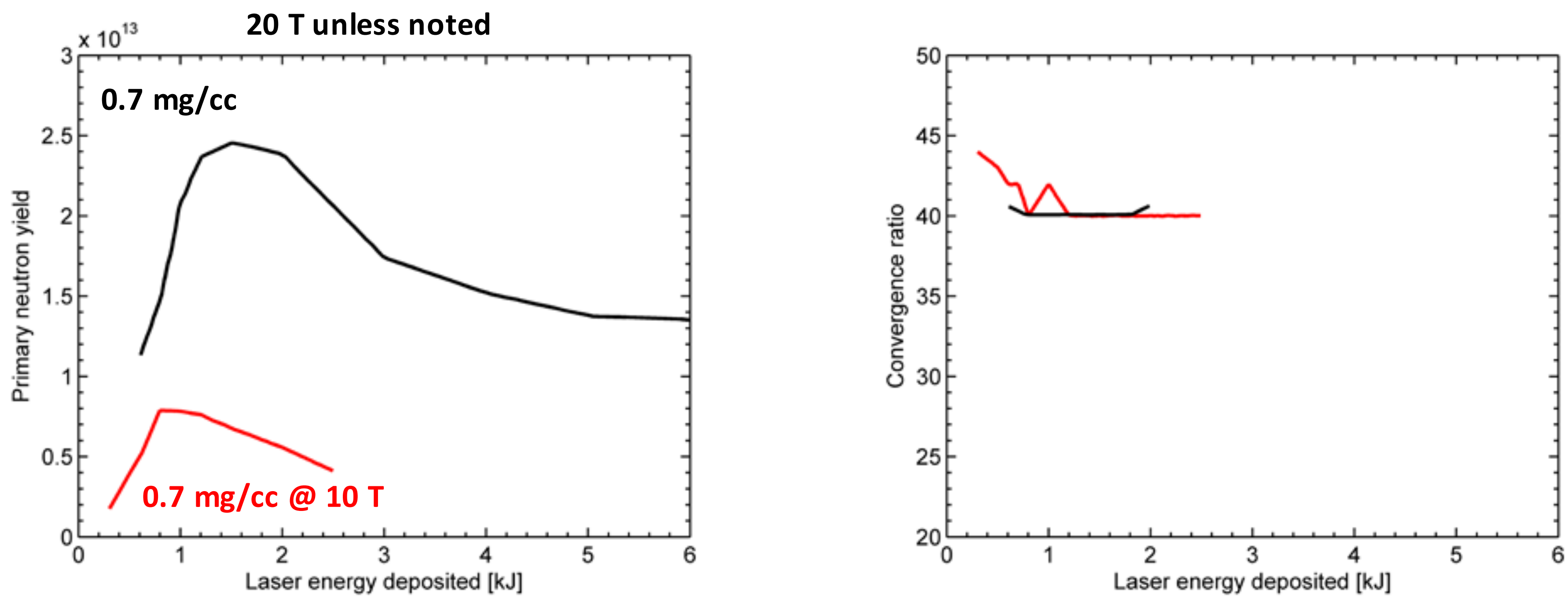
- 200-800J estimated coupled with thick (3.5 micron windows)
- 600-1200J estimated for thin window (1.5 micron)
- Experiments produced up to $3x10^{12}$ primary DD neutrons in this configuration
- Marginal improvement in yield observed with thinner windows

Simulations predict improved performance with higher B-field and laser energy deposition

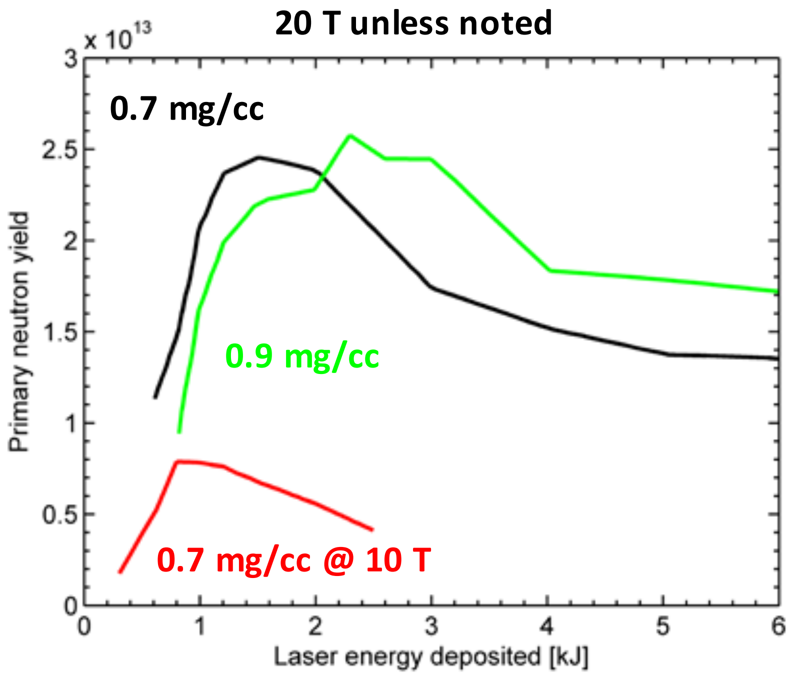


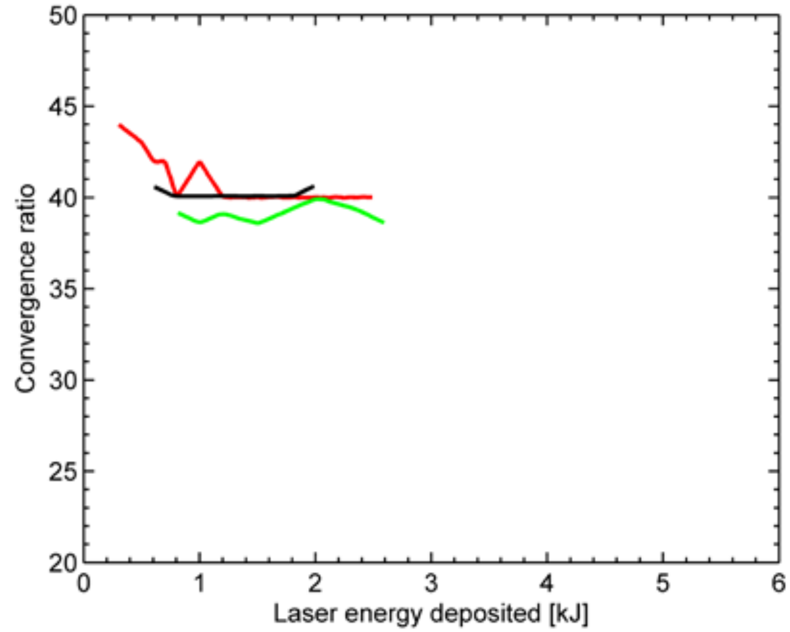


Simulations predict improved performance with higher B-field and laser energy deposition

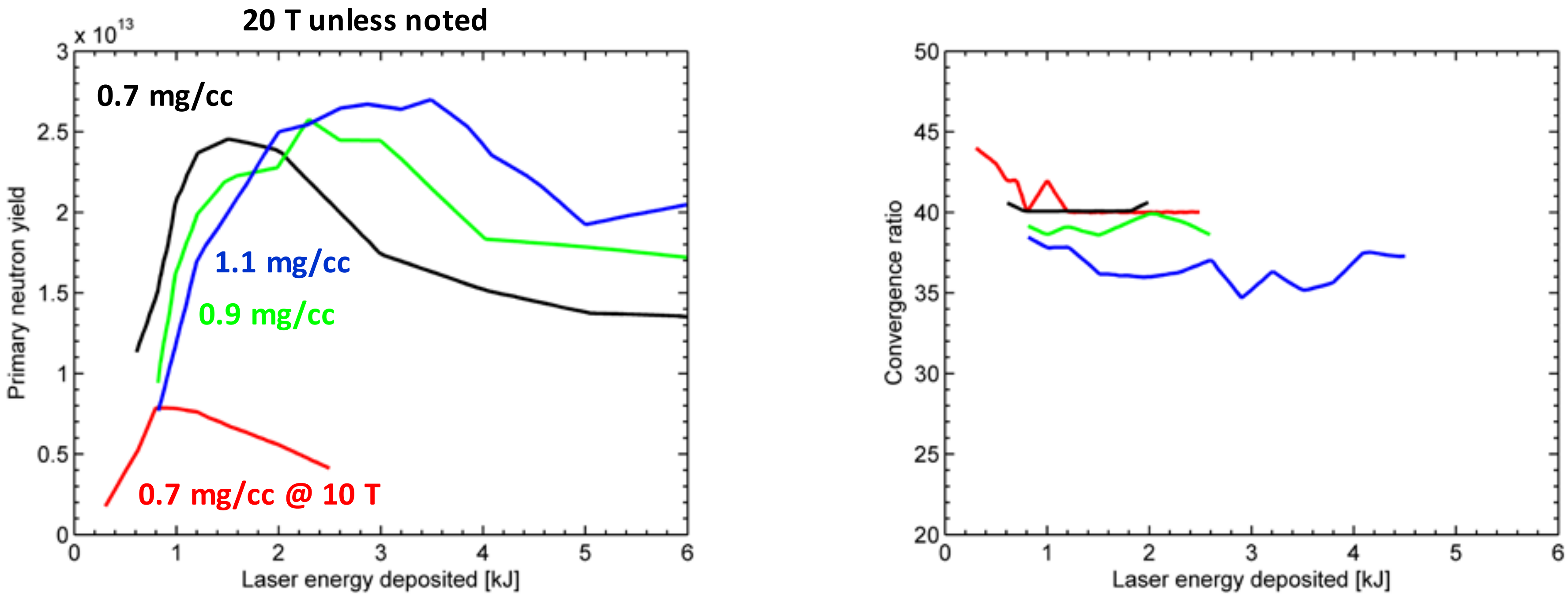


Simulations predict improved performance with higher B-field and laser energy deposition

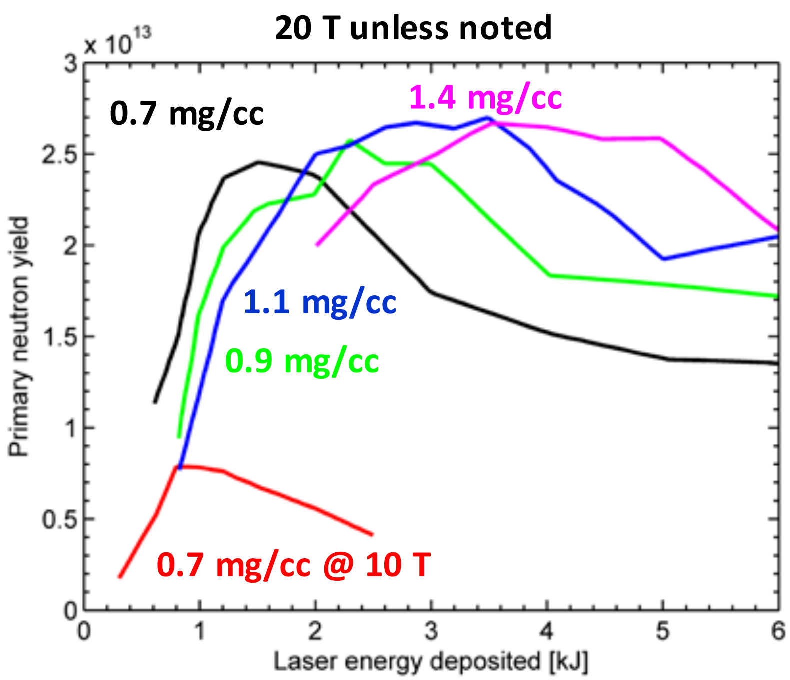


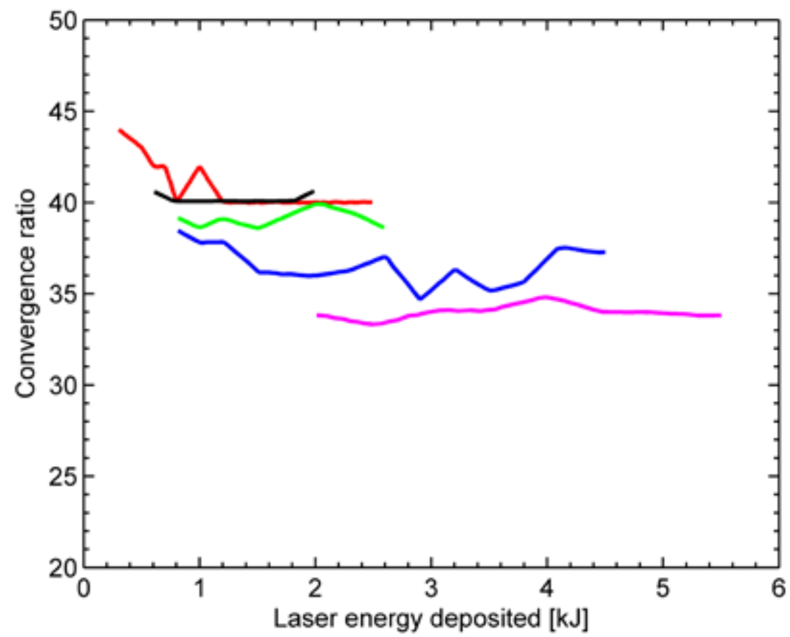


Simulations predict improved performance with higher B-field and laser energy deposition

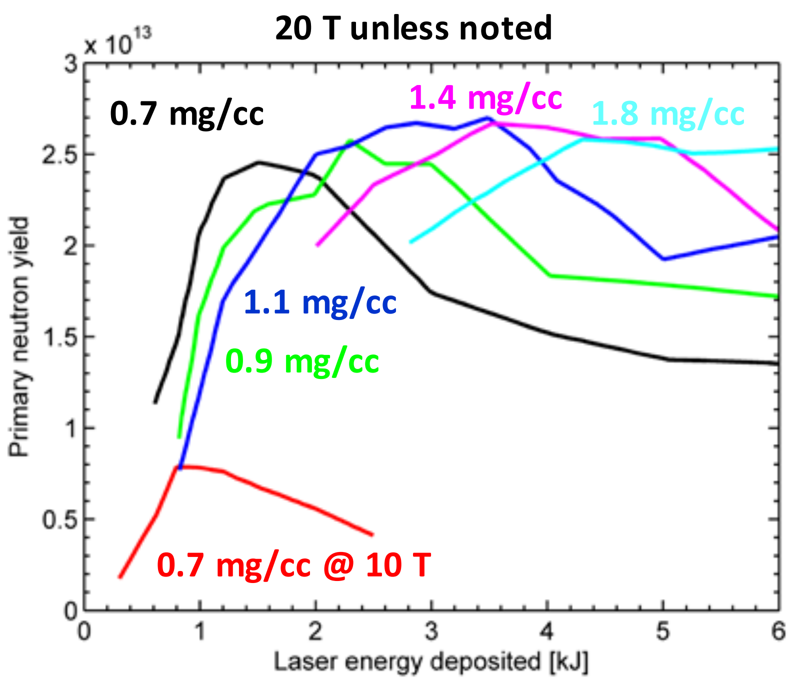


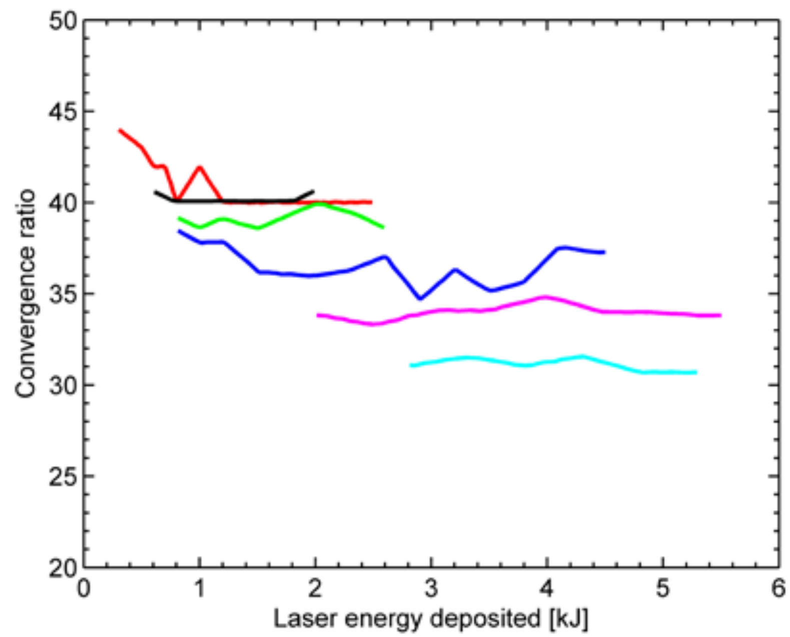
Simulations predict improved performance with higher B-field and laser energy deposition





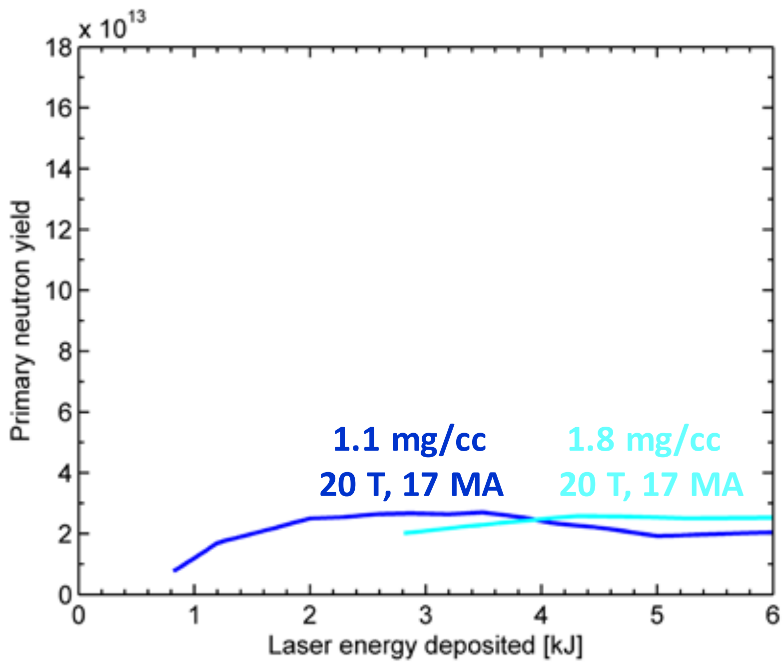
Simulations predict improved performance with higher B-field and laser energy deposition

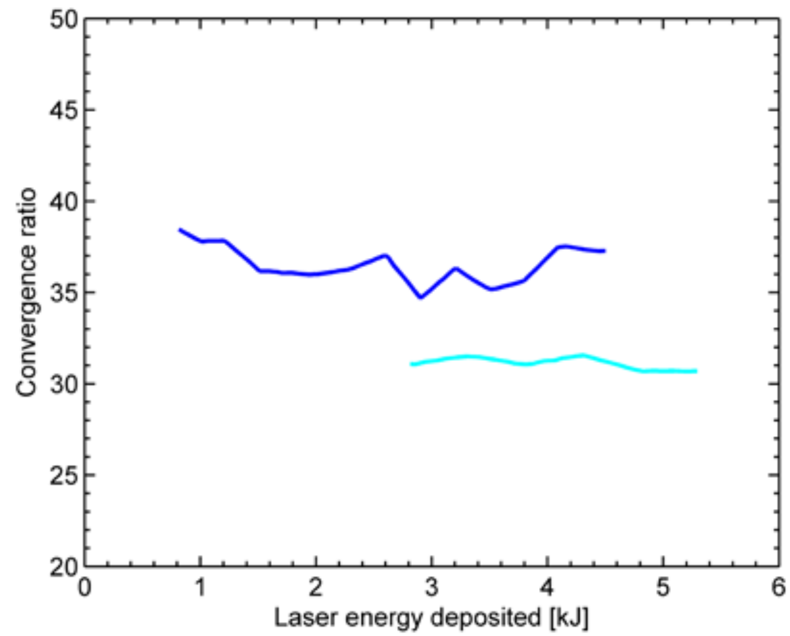




Increasing the B-field to 20 T and the fuel density is expected to reduce the convergence ratio and increase the neutron yield

Performance further improves with increased load current, but the convergence ratio goes up





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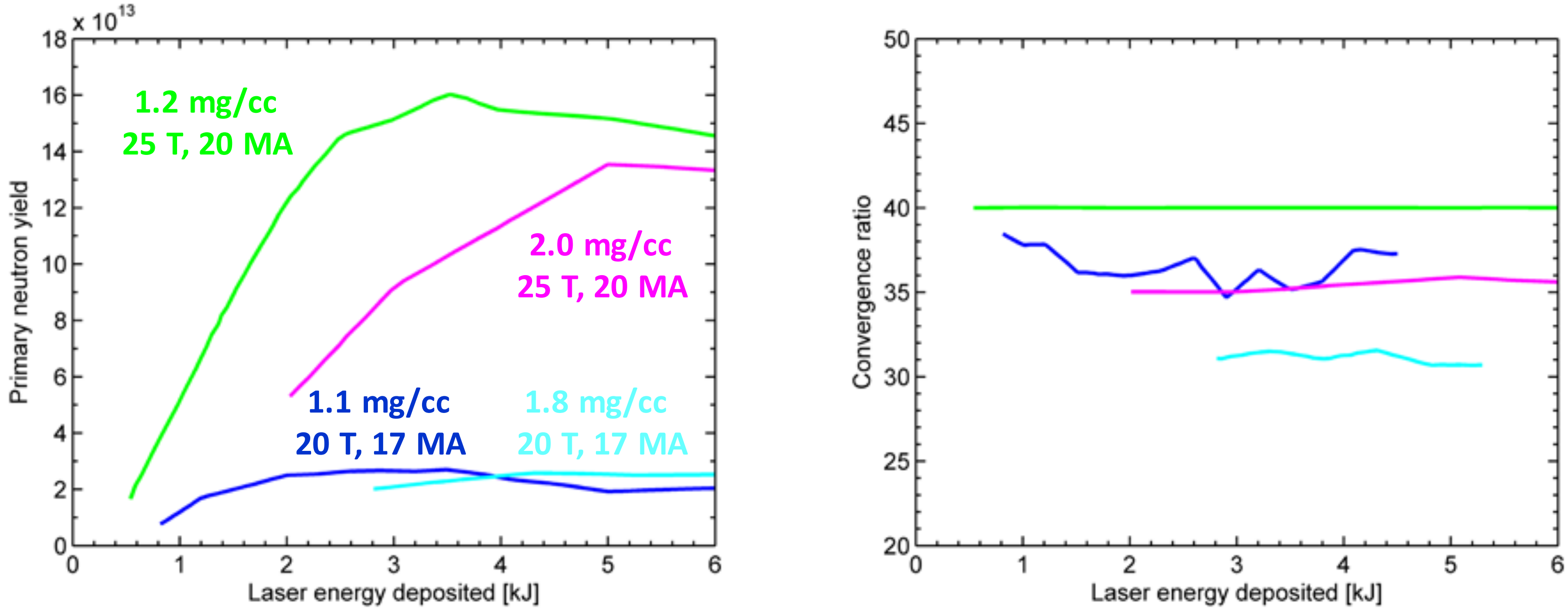


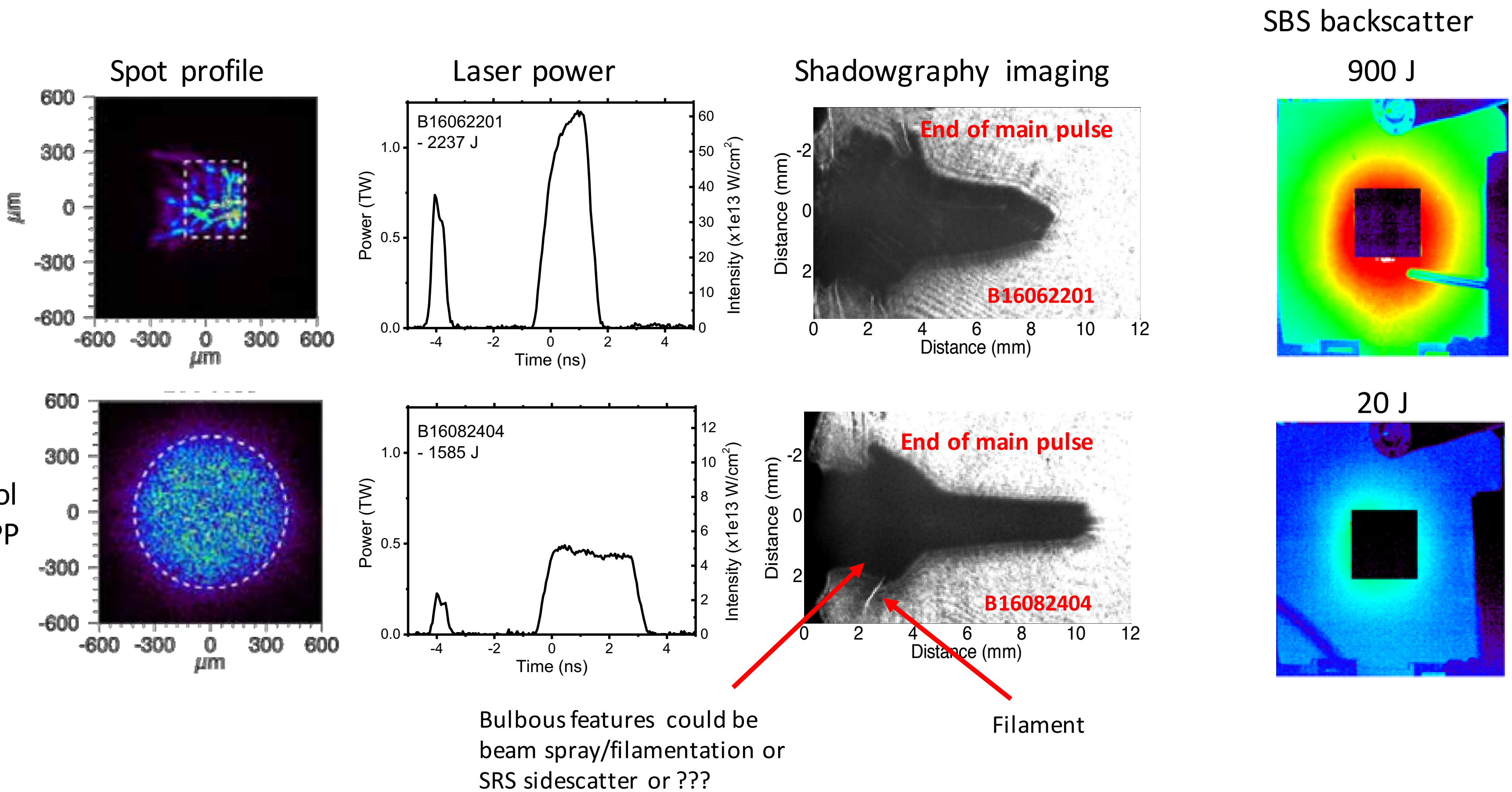
$5x10^{13}$ primary DD neutrons is roughly equivalent to 10 kJ DT

A new laser protocol was developed for Z-Beamlet that uses phase plate smoothing & lower laser intensity to reduce LPI and modeling uncertainties

Spot profile | Laser power | Shadowgraphy imaging | SBS backscatter

Old protocol
No DPP

New protocol
1100 µm DPP



With such huge amounts of energy being diverted into LPI in old configuration, no hope for HYDRA to accurately model preheat consistently

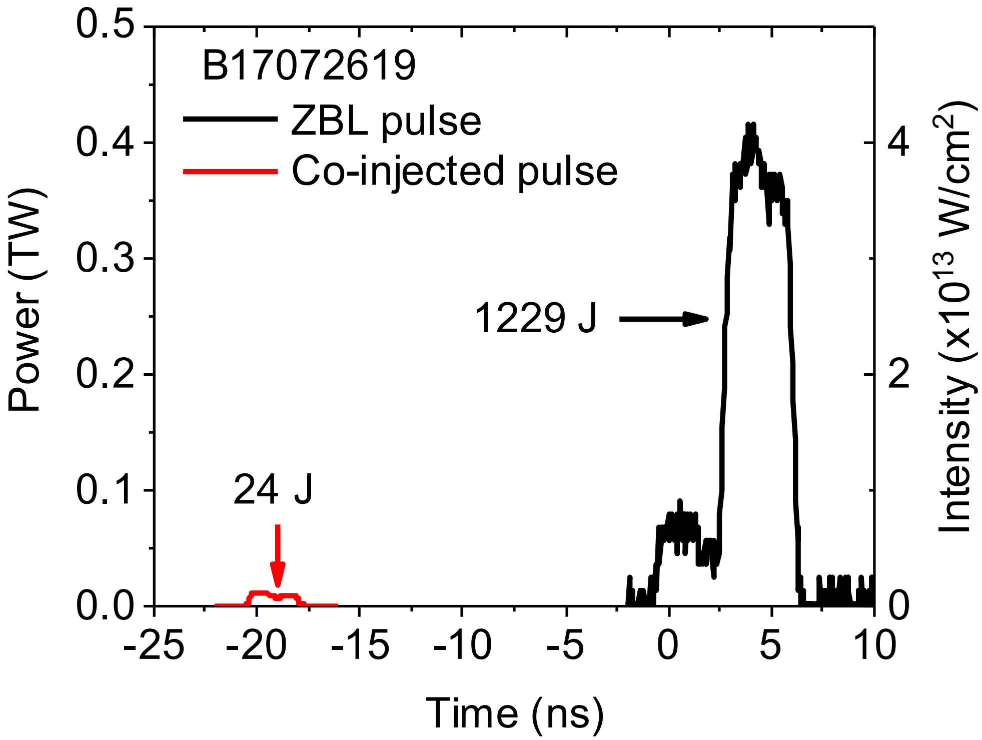
These new laser heating protocols have produced the highest MagLIF integrated yields thus far, but questions remain about reproducibility

	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**	Direct repeat of z3040.	Co coating on LEH

- The source of the large performance variation is currently being investigated
  - Variability in the laser heating configuration? (e.g., dust)
  - Variability in fuel convergence (due to high convergence ratio)

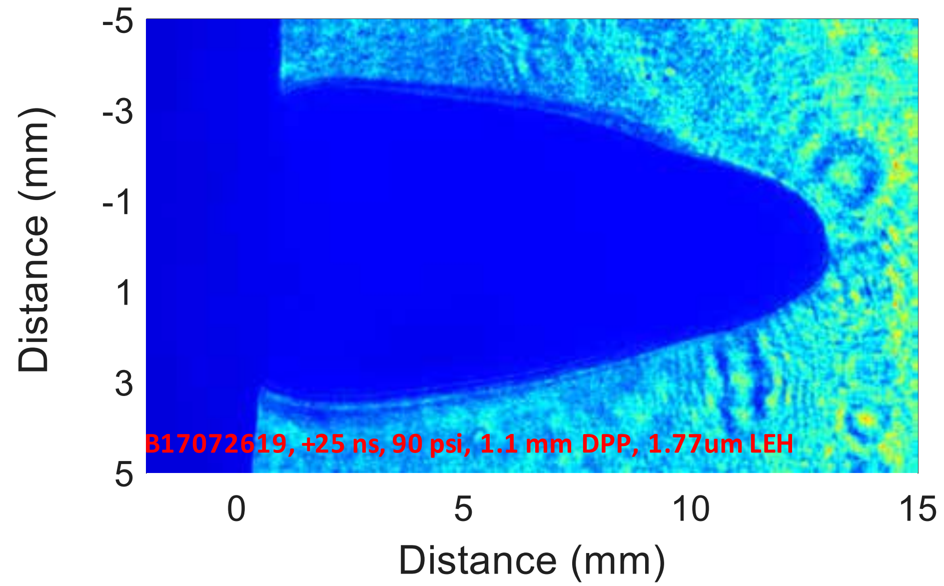
A new laser pulse shape more gently disassembles the window and allows the density to drop for ~ 20 ns, minimizing interaction with steep density gradients

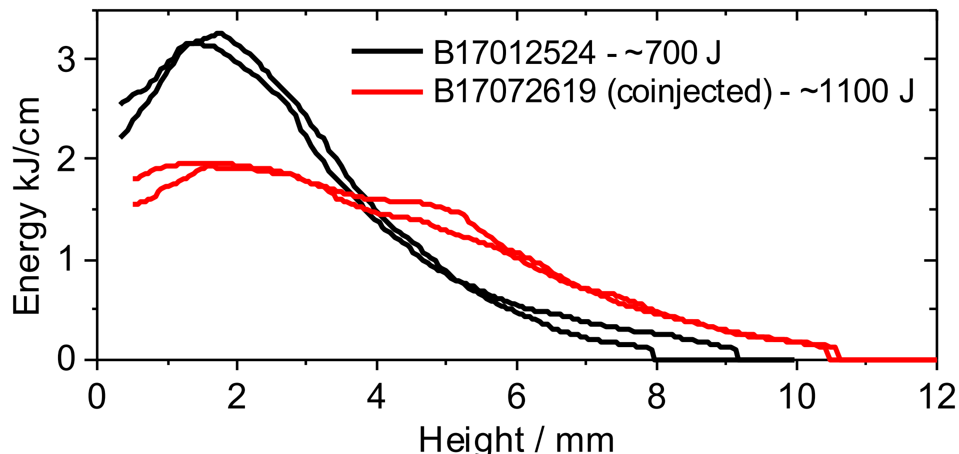
Independently timed prepulse



First integrated Z shot week of Sept. 9

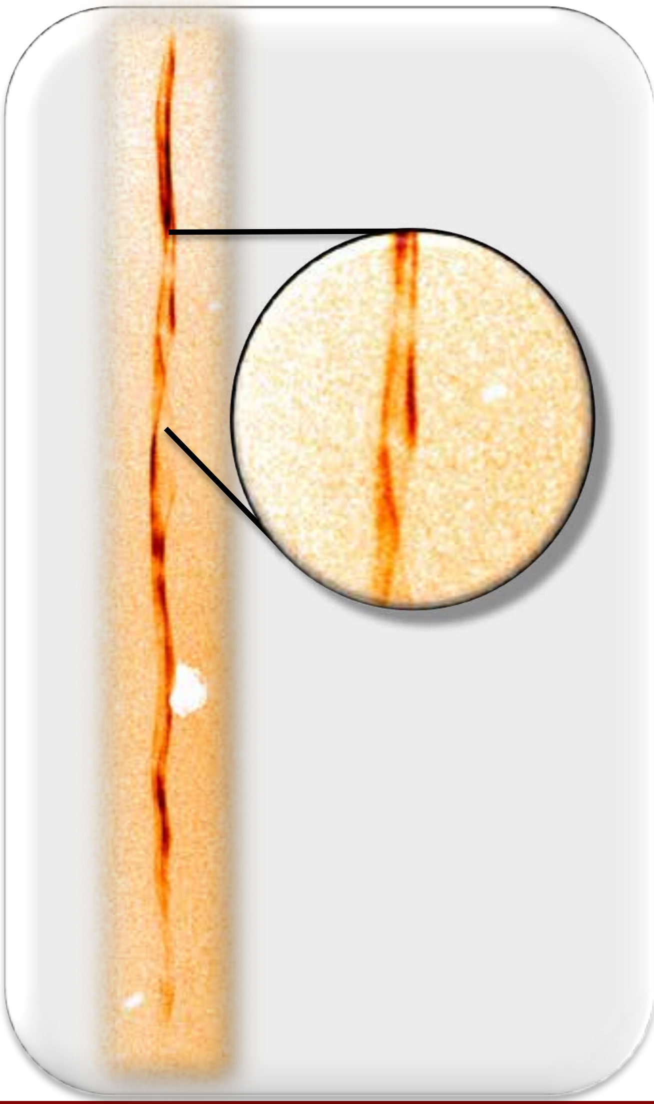
More uniform and deeper penetration



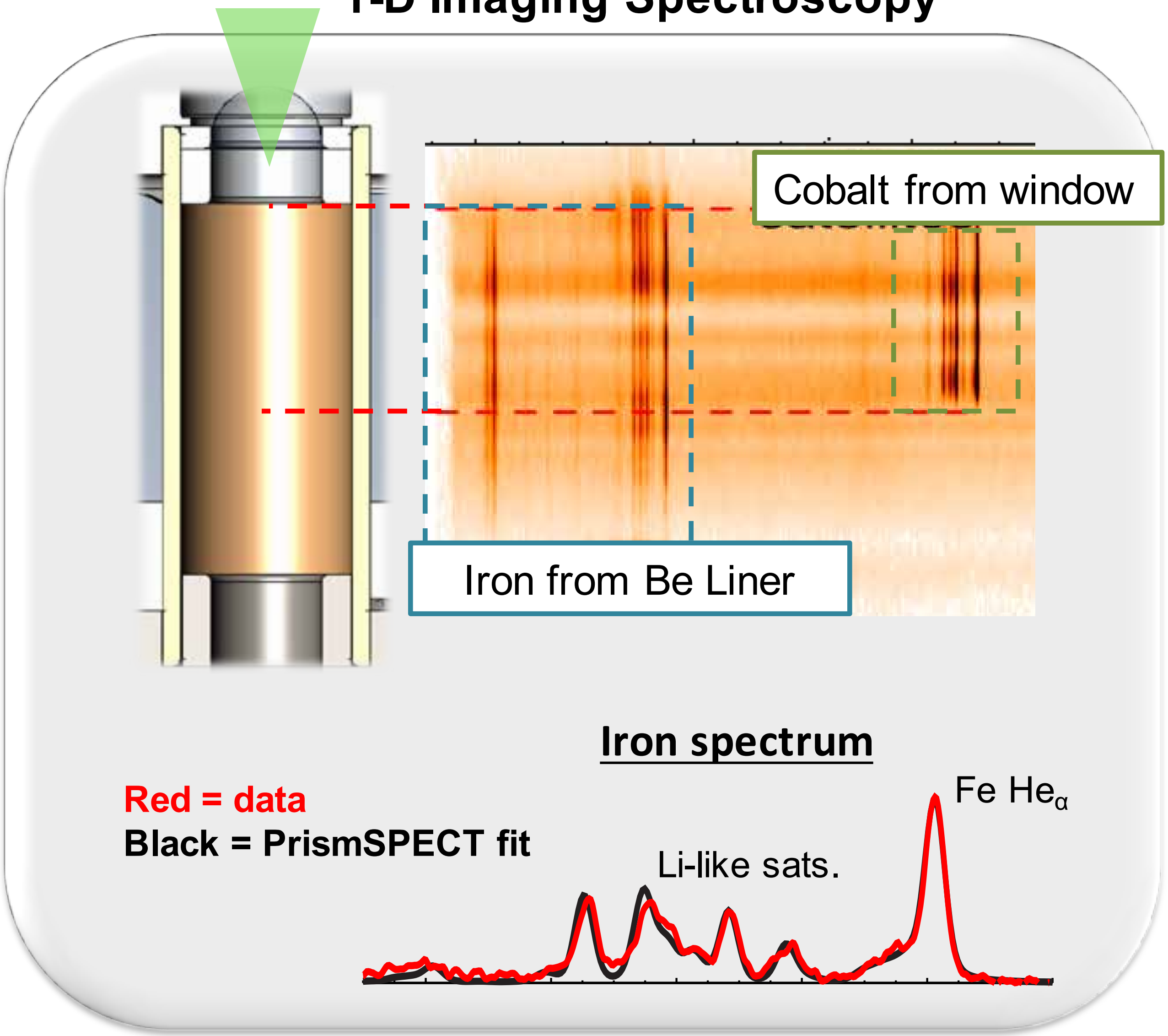


New high resolution diagnostics are providing important insight into the MagLIF stagnation morphology and mix

2-D Monochromatic Imaging



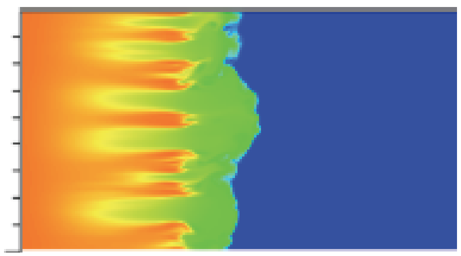
1-D Imaging Spectroscopy



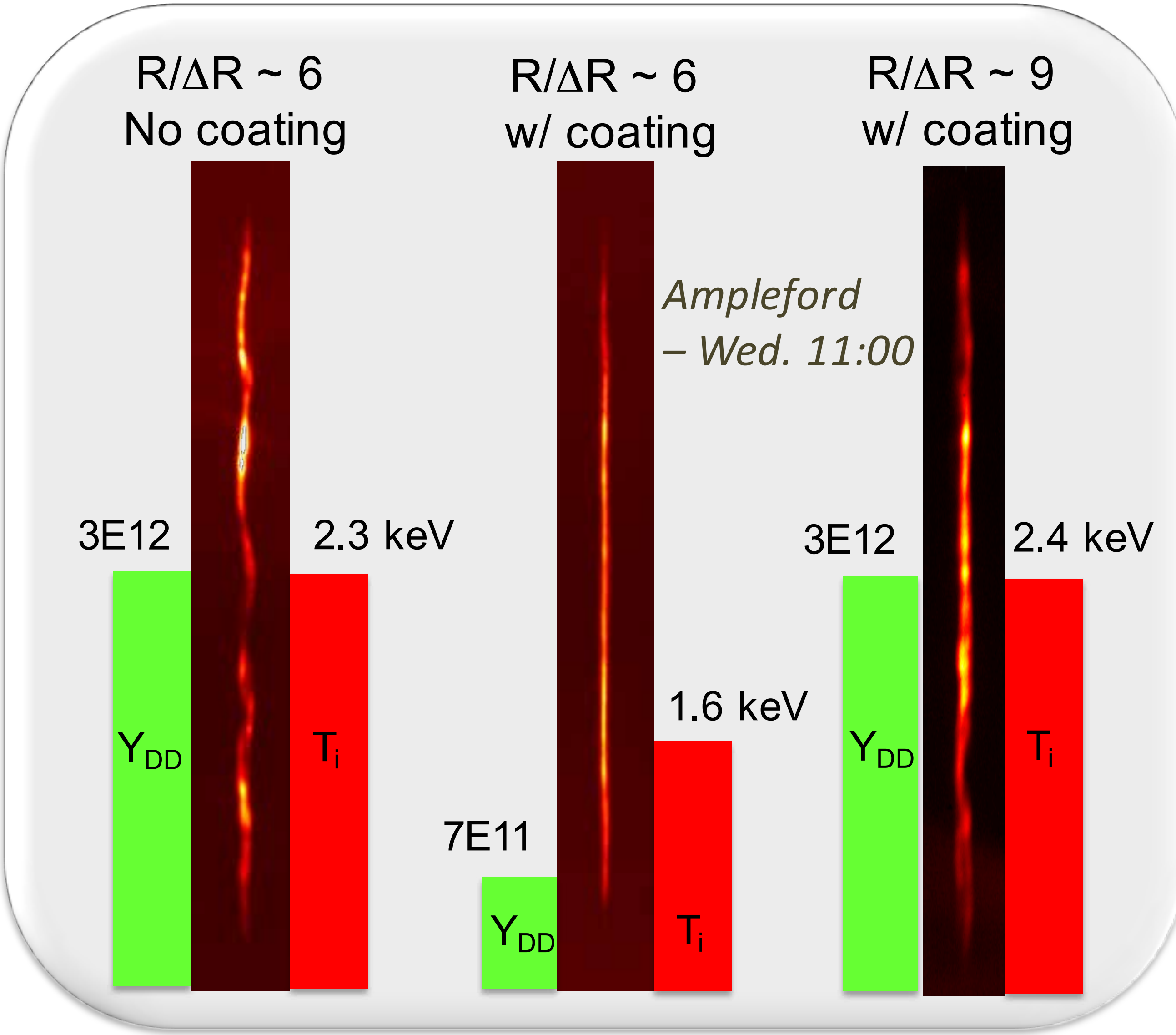
Dielectric liner coatings improve the stagnation shape but require a thinner liner to recover performance

Electrothermal Instability can be mitigated using epoxy coatings

No Coating



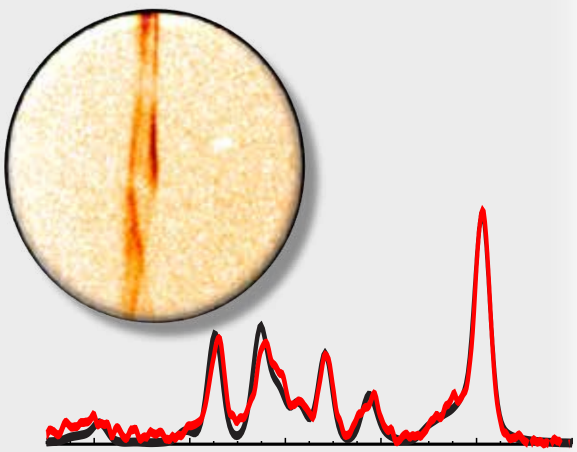
50 μm coating



MagLIF efforts are focused on improved performance at lower convergence by increasing capability in each phase

Implosion & Stagnation

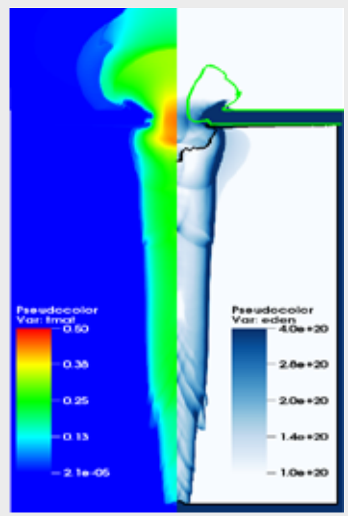
- Decrease CR to ~35 for a less structured and more repeatable stagnation.



- Achieve >10 kJ DT yield on Z with T > 4 keV and BR > 0.5 MG-cm

Laser Preheat

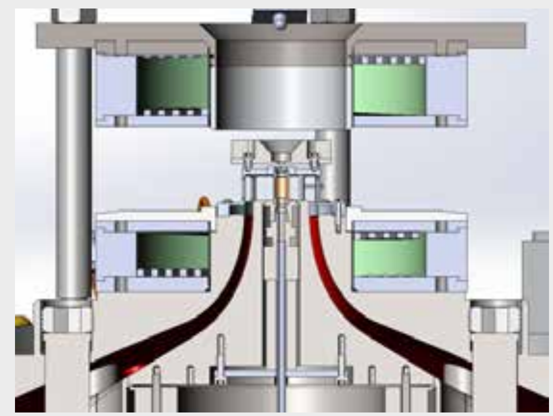
- Develop methods and validated models for more efficient laser preheat.



- Achieve >2 kJ preheat w/ minimal laser-induced mix

Power Flow

- Develop platforms and validated models for more efficient power flow compatible with High B_z



- Achieve >20 MA peak current w/ B_z ~ 25 T

We will test the combination of these three improvements over the next year

- Our main near term goal is to reduce the convergence of the system to produce a more reliable and easily-diagnosable stagnation
  - Increase the energy density of the fuel through more effective laser coupling, higher initial fuel density, and increased inhibition of thermal transport

- We have been operating at 10 T, 0.2-1 kJ, and 17 MA
- We expect to be operating at 15-20 T, 1-2 kJ, and 19-20 MA within the next year
- We think 20-30 T, 2-4 kJ, and 20+ MA is possible in the near future

- There are still many challenges to overcome, but there seems to be a clear path towards increased performance in Magnetized Liner Inertial Fusion

Thank you to my many coauthors

S. A. Slutz, C. A. Jennings, A. J. Harvey-Thompson, M. R. Weis, D. C. Lamppa, B. T. Hutsel, D. J. Ampleford, T. J. Awe, D. E. Bliss, G. A. Chandler, M. Geissel, M. Gomez, K. D. Hahn, S. B. Hansen, E. C. Harding, M. H. Hess, P. F. Knapp, G. Laity, M. R. Martin, T. Nagayama, D. C. Rovang, C. L. Ruiz, M. E. Savage, P. F. Schmit, J. Schwarz, I. C. Smith, R. A. Vesey, E. P. Yu, M. E. Cuneo, B. Jones, K. J. Peterson, J. L. Porter, G. A. Rochau, and W. A. Stygar

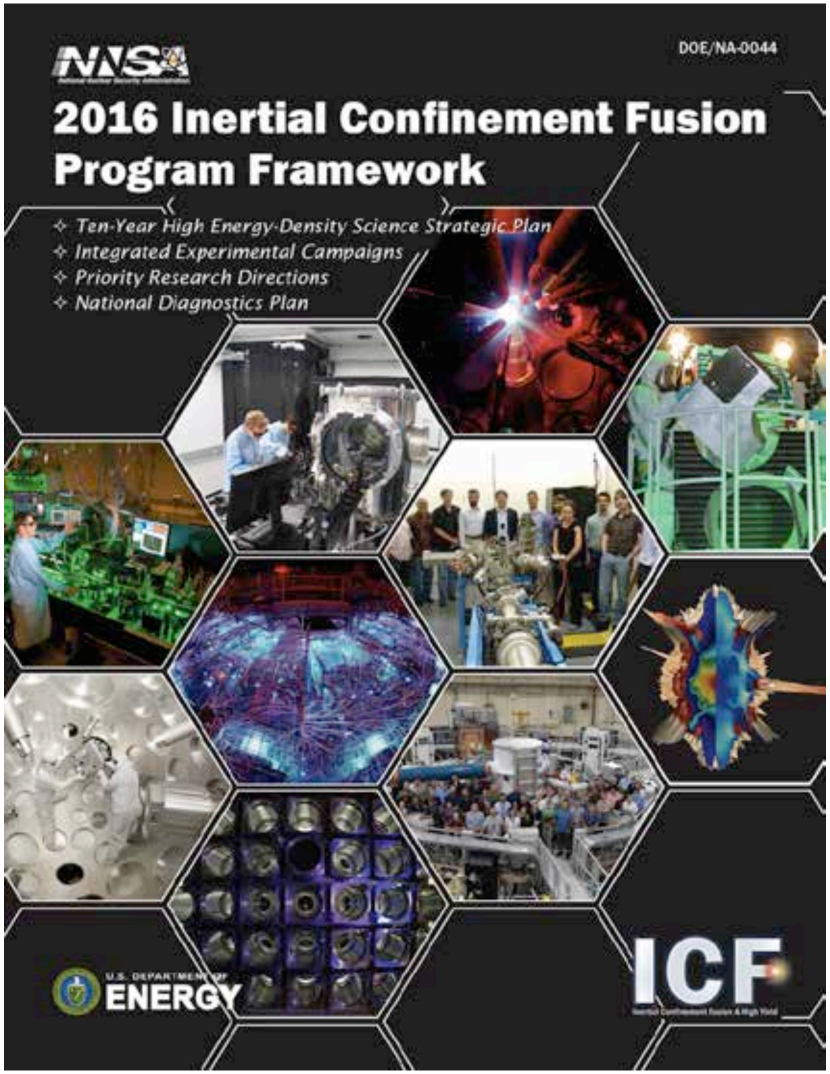
Backups

The goal of the US ICF program is to achieve multi-MJ fusion yields.

US National Program Goal: Determine the efficacy of reaching ignition on the NIF and of achieving credible physics scaling to multi-megajoule fusion yields for each of the three major ICF approaches

Organized around four framework elements:

- 10-year strategic plan for High Energy Density Science
- Integrated Experimental Campaigns
- Priority Research Directions (focused science)
- Transformative Diagnostics



Search 'ICF Framework NNSA' on Google