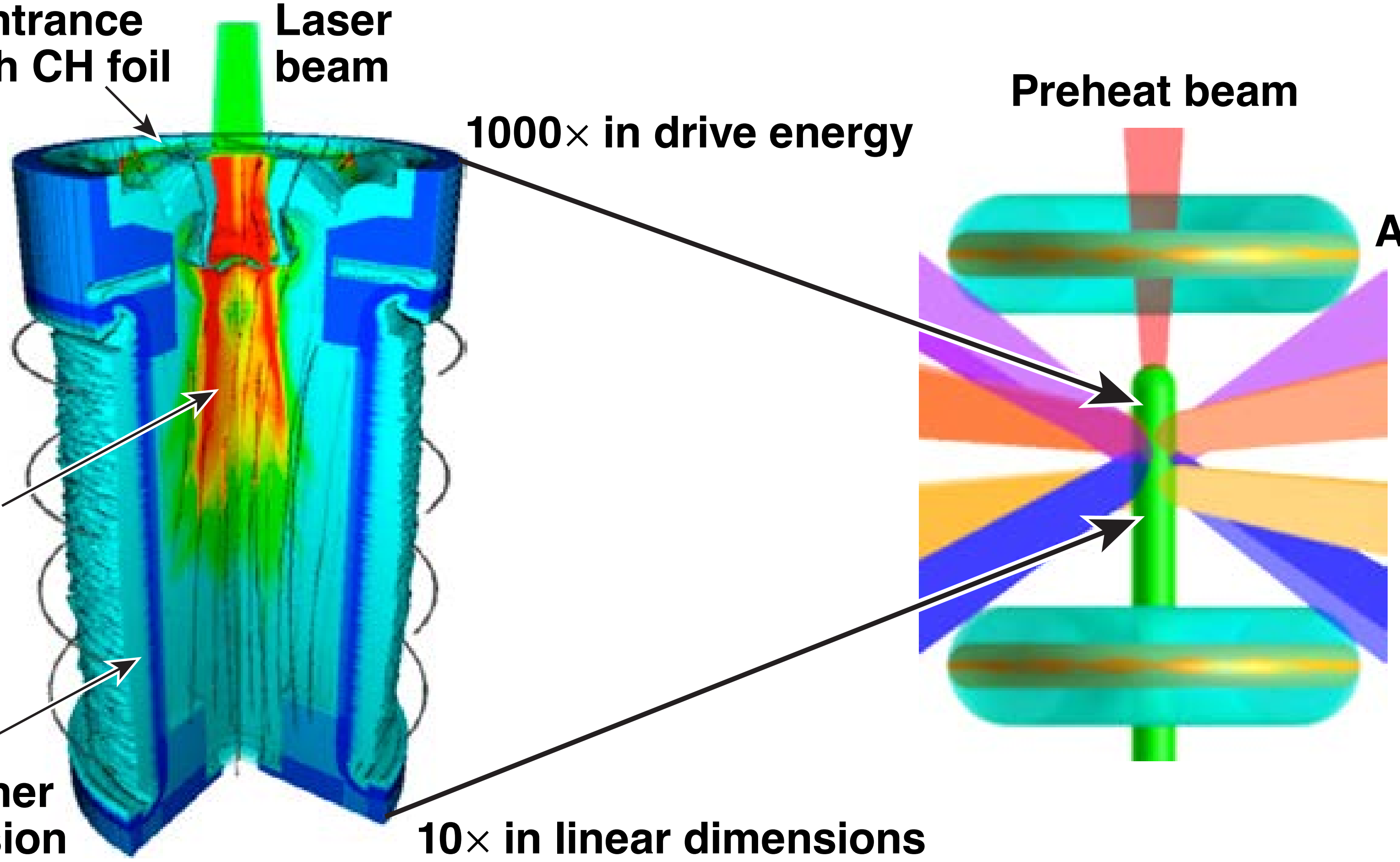
Laser-Driven Magnetized Liner Inertial Fusion on OMEGA



Laser entrance hole with CH foil

Laser beam

Axial-field coils not shown

Z: 19 MA
~1 MJ in target
r = 3 mm

Laser-heated fuel

Start of liner compression

1000× in drive energy

10× in linear dimensions

Preheat beam

Axial-field coils

40 beams for compression

OMEGA: 14.5 kJ
~1 kJ in target
r = 0.3 mm

J. R. Davies
University of Rochester
Laboratory for Laser Energetics

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American Physical Society
Division of Plasma Physics
Portland, OR
5–9 November 2018

Summary

OMEGA results confirm that magnetization and preheating increase yield and reduce convergence ratio

- Laser-driven MagLIF on OMEGA provides data at 1000× lower drive energy than Z with targets 10× smaller in linear dimensions
- OMEGA results indicate that initial magnetic fields >15 T and initial deuterium densities >1 mg/cm^3 planned for Z should significantly increase yields
- The results from OMEGA and Z will be compared to simulations with the same codes to increase confidence in extrapolating to energy gain

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MagLIF: magnetized liner inertial fusion

Collaborators

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University of Rochester
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Sandia National Laboratories

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[1] Now at LANL
[2] Now at NCKU, Taiwan

Outline

- What is MagLIF?
- Scaling down MagLIF from Z to OMEGA
- Preheat experiments
- Optimizing cylindrical compression
- Results

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- **What is MagLIF?**
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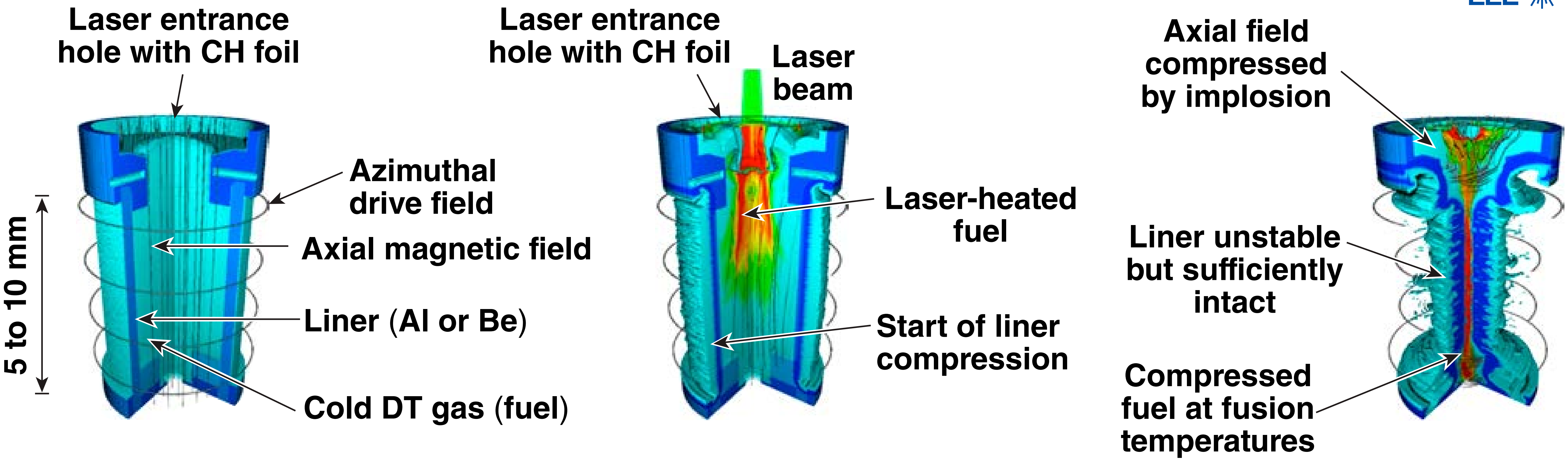
MagLIF is an inertial confinement fusion (ICF) scheme using magnetized, preheated fuel to allow for cylindrical implosions with lower velocities and lower convergence ratios than conventional ICF*



Laser entrance hole with CH foil

Azimuthal drive field

Axial magnetic field

Liner (Al or Be)

Cold DT gas (fuel)

5 to 10 mm

Laser entrance hole with CH foil

Laser beam

Laser-heated fuel

Start of liner compression

Axial field compressed by implosion

Liner unstable but sufficiently intact

Compressed fuel at fusion temperatures

- An axial magnetic field lowers electron thermal conductivity allowing a near-adiabatic compression at lower implosion velocities and confines alpha particles if BR > 0.6 T-m, allowing a lower areal density
- Preheating to ~100 eV makes it possible for >1 keV to be reached at a convergence ratio <30

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

Outline

- What is MagLIF?
- **Scaling down MagLIF from Z to OMEGA**
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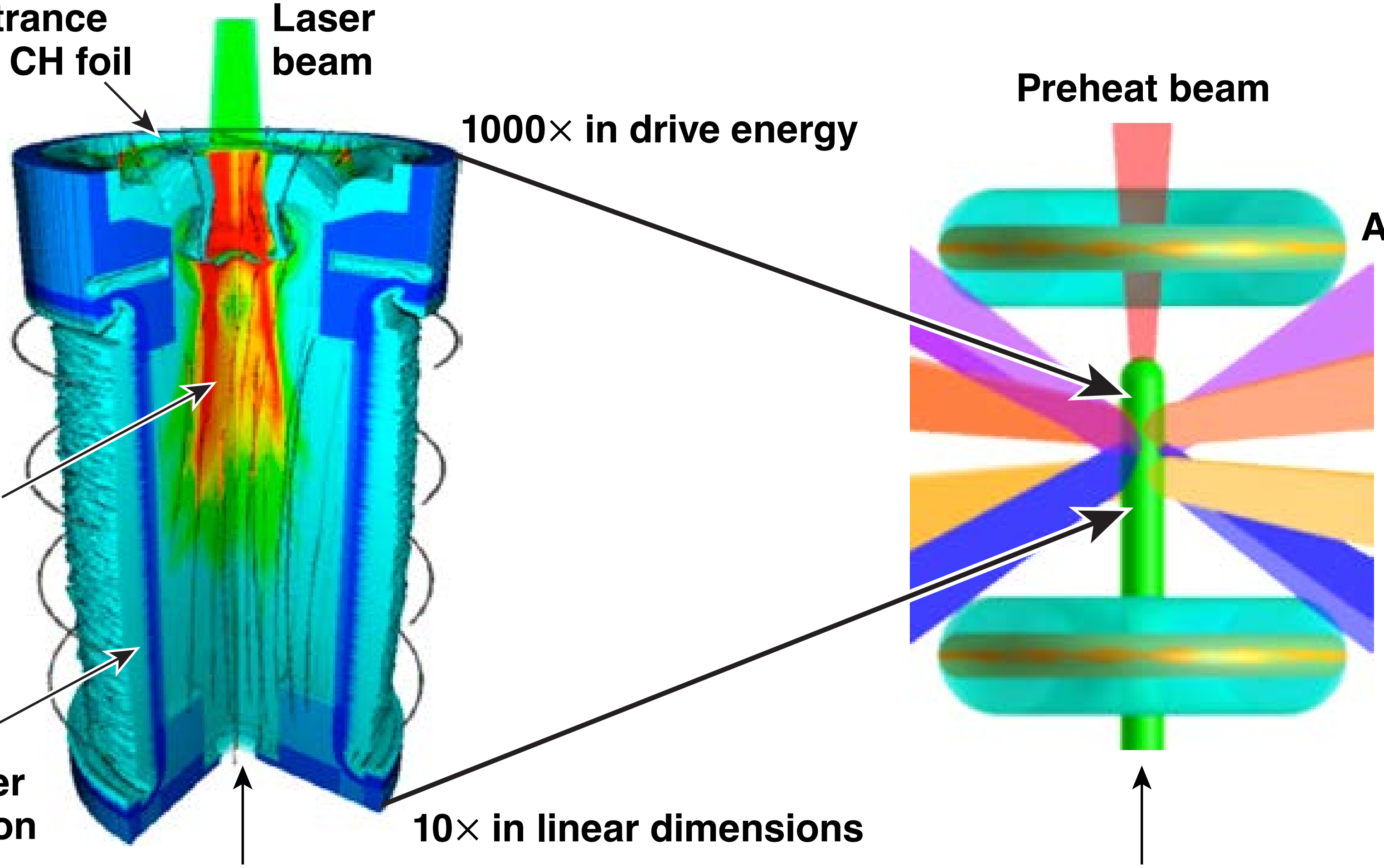
OMEGA can carry out magnetized, preheated, cylindrical compressions, allowing a scaled-down version of MagLIF on Z*

Point design: 30 T
Experiments: 10 T

Axial-field coils
not shown

Z: 19 MA
~1 MJ in target
r = 3 mm



Point design: T_0 = 250 eV
Experiments: $T_0 < 100$ eV

Laser entrance hole with CH foil

Laser beam

Laser-heated fuel

Start of liner compression

Point design: 3 mg/cm^3 DT
Experiments: 0.7 mg/cm^3 DD

1000× in drive energy

10× in linear dimensions

$T_0 \sim 200$ eV

Preheat beam

Initial design: 10 T

Axial-field coils

40 beams for compression

$\leq$2.7 mg/cm^3 DD

OMEGA: 14.5 kJ
~1 kJ in target
r = 0.3 mm

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*D. H. Barnak *et al.*, Phys. Plasmas 24, 056310 (2017).

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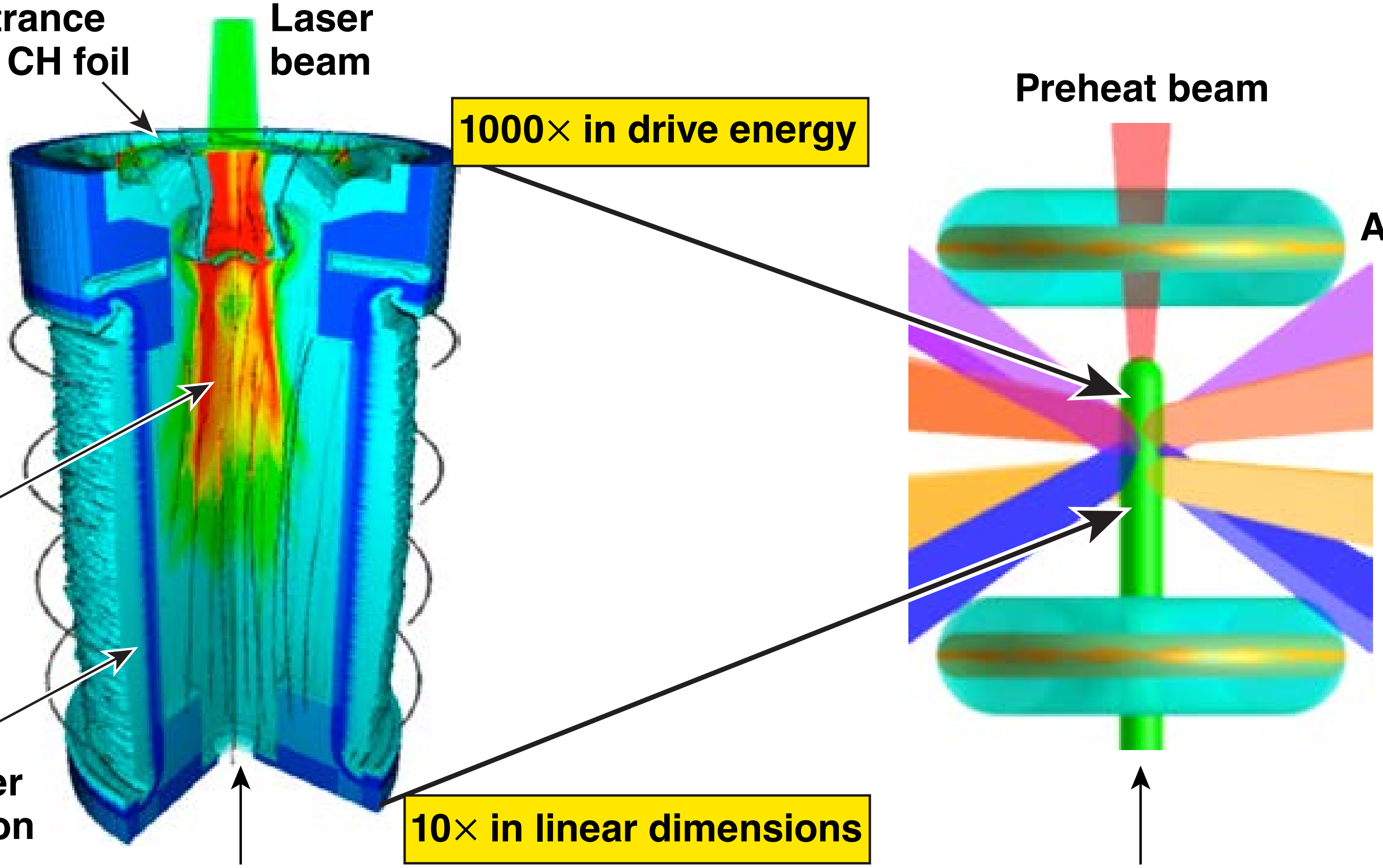

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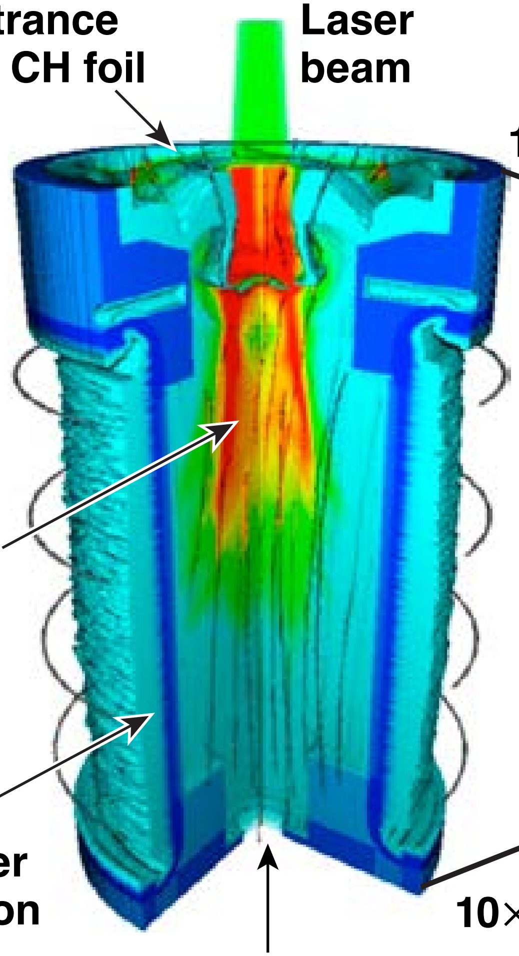
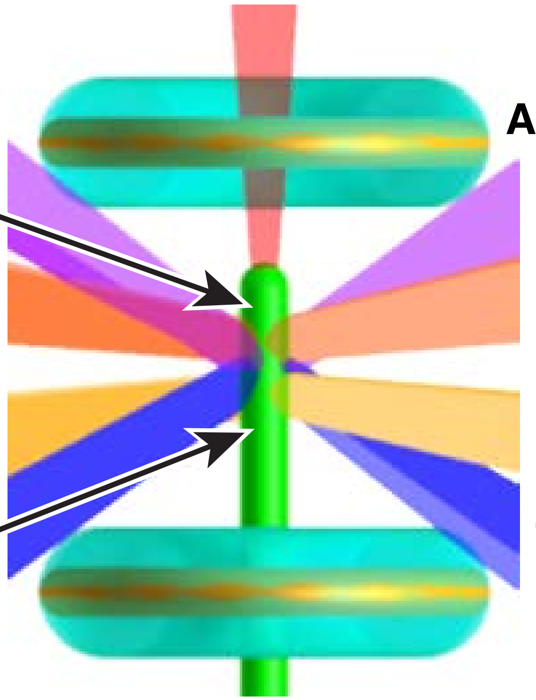


1000× in drive energy

10× in linear dimensions



Initial design: 10 T

OMEGA: 14.5 kJ
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E27821b

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*D. H. Barnak *et al.*, Phys. Plasmas 24, 056310 (2017).

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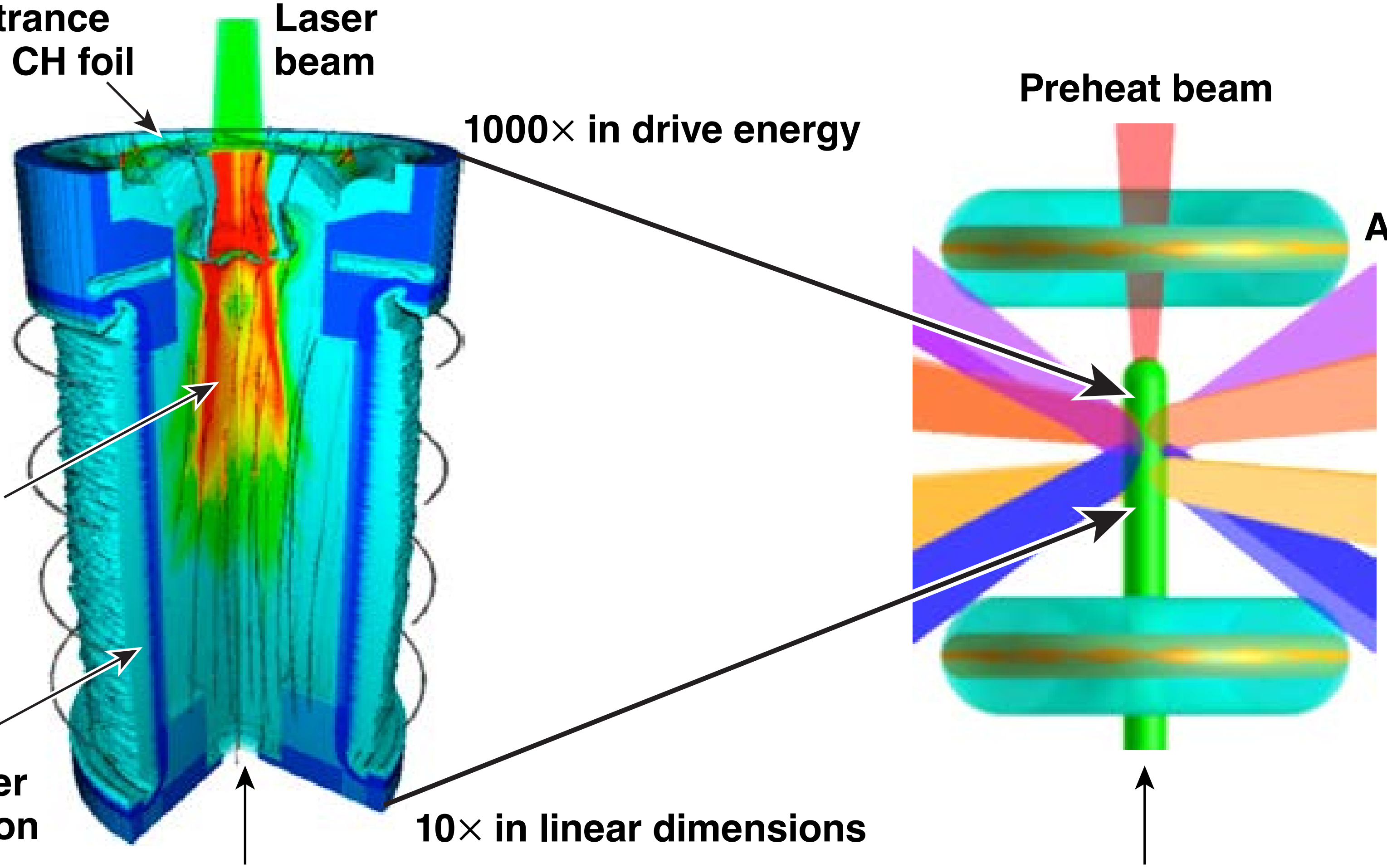

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$T_0 \sim 200$ eV

Initial design: 10 T

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~1 kJ in target
$r = 0.3$ mm

≤2.7 mg/cm^3 DD

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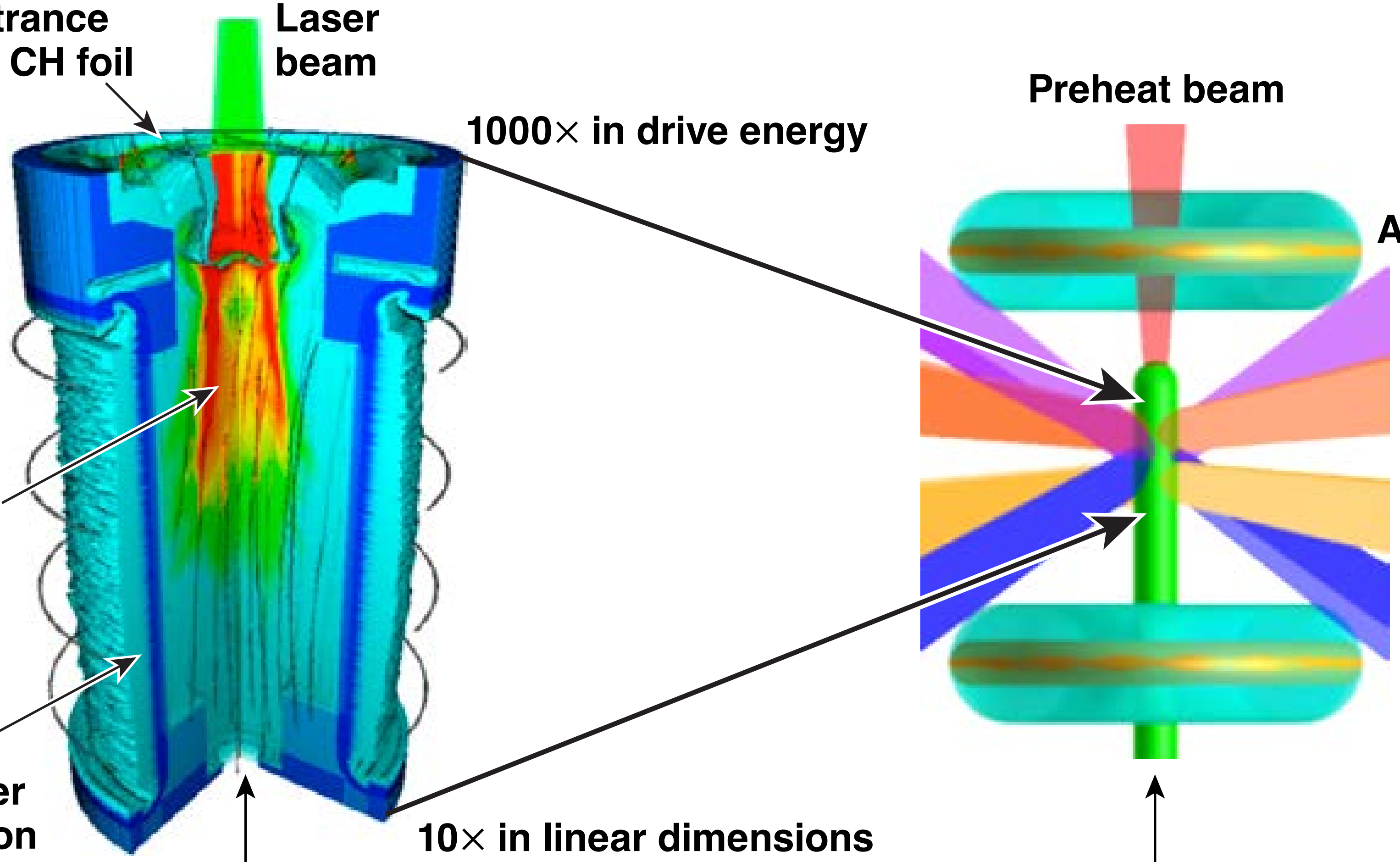

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*D. H. Barnak *et al.*, Phys. Plasmas 24, 056310 (2017).

E27821d

OMEGA targets will not achieve magnetic confinement of fusion products* and will have higher thermal and flux losses than Z

- Magnetic confinement of charged fusion products (T from DD fusion, He from DT fusion) is determined by the ratio of Larmor radius to fuel radius
  - increasing magnetic field 10× would lead to magnetic pressure, reducing convergence and heating
- The greater surface area to volume ratio in smaller targets will lead to greater heat loss
- Magnetic-flux loss will increase because diffusion time scales as r^2 and Nernst velocity as $1/r$
- Aim for a design with an implosion velocity at least twice that of the Z point design by increasing the shell aspect ratio
  - $v > 140$ km/s, aspect ratio > 6 (thickness $<50\ \mu$m)
  - estimate that $T_{\mathrm{final}} \propto (C\rho_0 r_0 v)^{2/5}$, assuming unmagnetized ion thermal conduction dominates heat loss during compression, where C is convergence ratio, ρ_0 is fuel density, r_0 is fuel radius, and v is implosion velocity, so doubling v will maintain T_{final} within a factor of 2
  - ablative stabilization of the Rayleigh–Taylor instability and the absence of magnetohydrodynamic (MHD) modes means that laser-driven MagLIF should allow a higher aspect ratio

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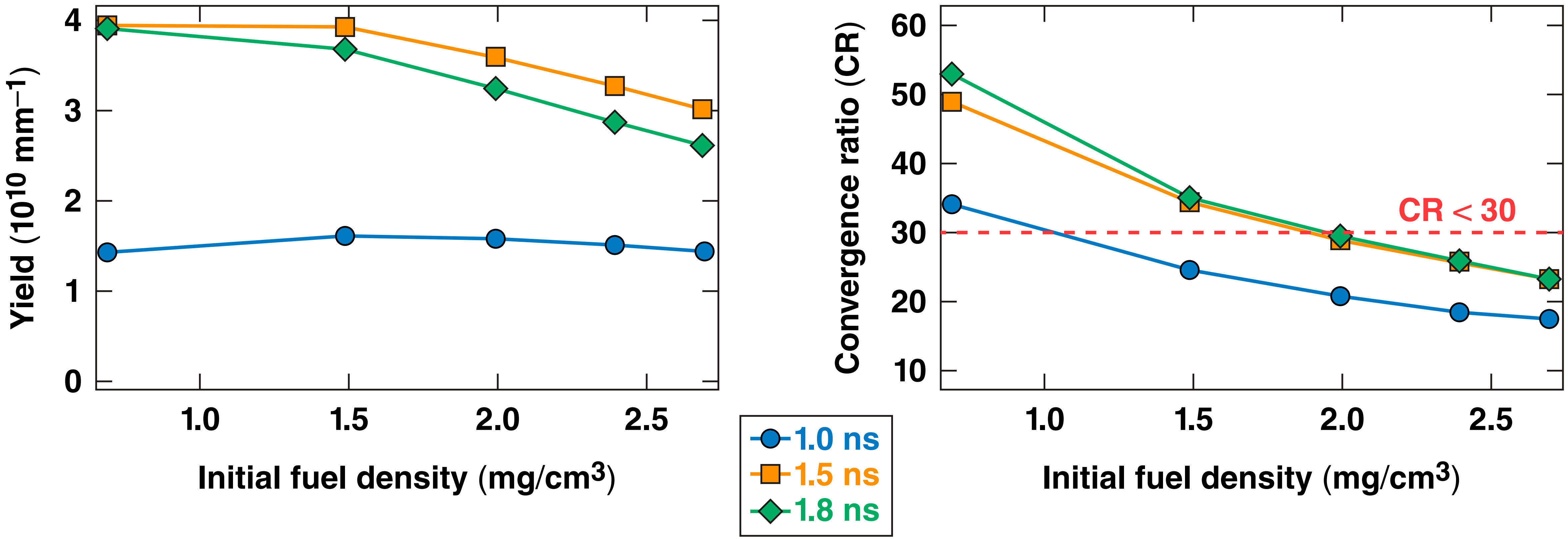
*P. F. Schmit *et al.*,Phys. Rev. Lett. 113, 155004 (2014).

One-dimensional *LILAC** simulations were used to choose the pulse length and fuel density for shell aspect ratios from 6 to 15**

Results for shell aspect ratio 10 (30-μm thick)



Aspect ratio ≥ 10, 1.5-ns pulse length, fuel density ≥ 2.4 mg/cm^3

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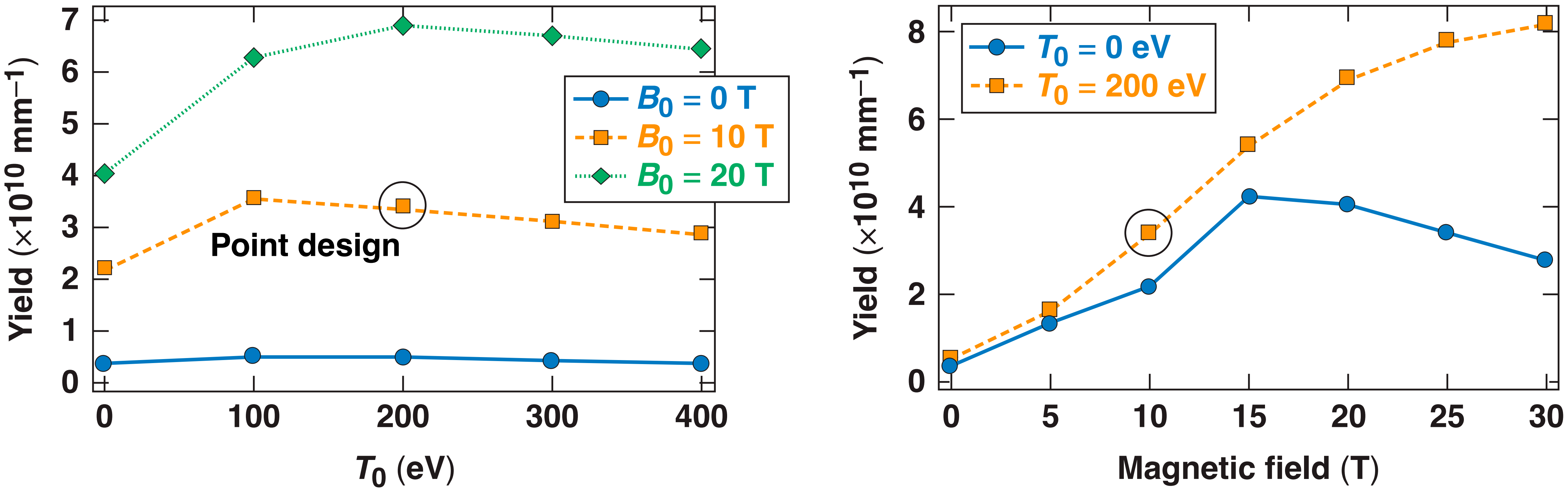
*J. R. Davies *et al.*, Phys. Plasmas 22, 112703 (2015).

**J. R. Davies *et al.*, Phys. Plasmas 24, 062701 (2017).

TC13141a

Scans of the preheat temperature and axial magnetic field showed a threshold preheat of ~100 eV and improved performance with fields up to 30 T

Results for shell aspect ratio 10 (30-μm thick)



E27823

Outline

- What is MagLIF?
- Scaling down MagLIF from Z to OMEGA
- **Preheat experiments**
- Optimizing cylindrical compression
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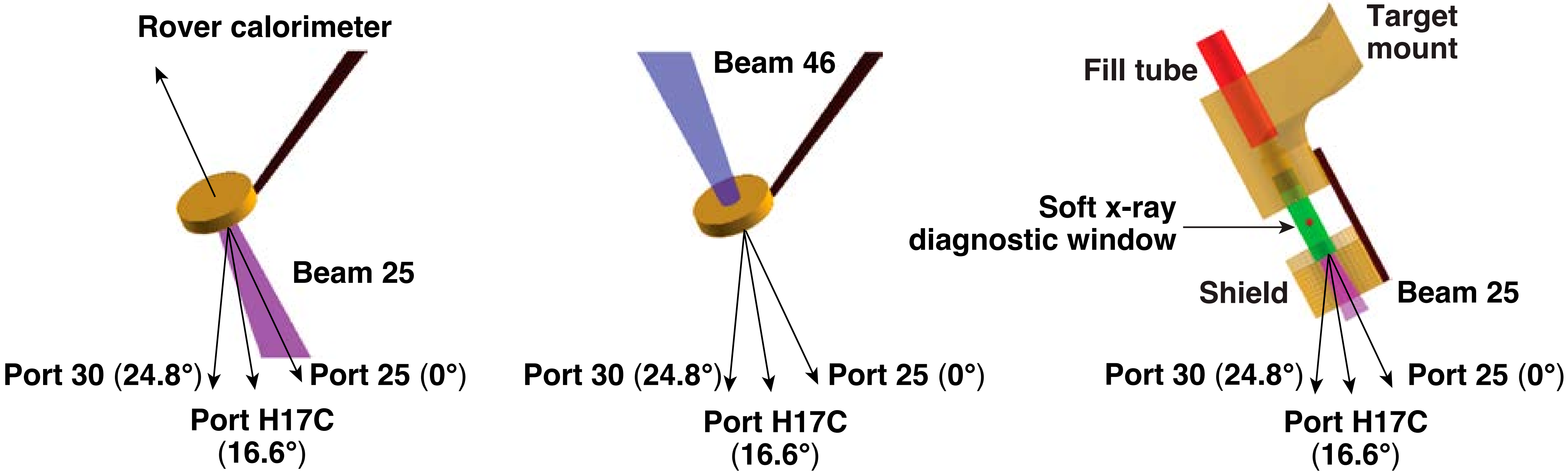
Laser transmission and reflection and soft x-ray emission were measured and compared to 2-D *DRACO* simulations

Laser entrance foil only targets (1.84-μm polyimide)

Full target

Foils on mounted washers



Rover calorimeter

Beam 25

Port 30 (24.8°)

Port 25 (0°)

Port H17C (16.6°)

Beam 46

Port 30 (24.8°)

Port 25 (0°)

Port H17C (16.6°)

Target mount

Fill tube

Soft x-ray diagnostic window

Shield

Beam 25

Port 30 (24.8°)

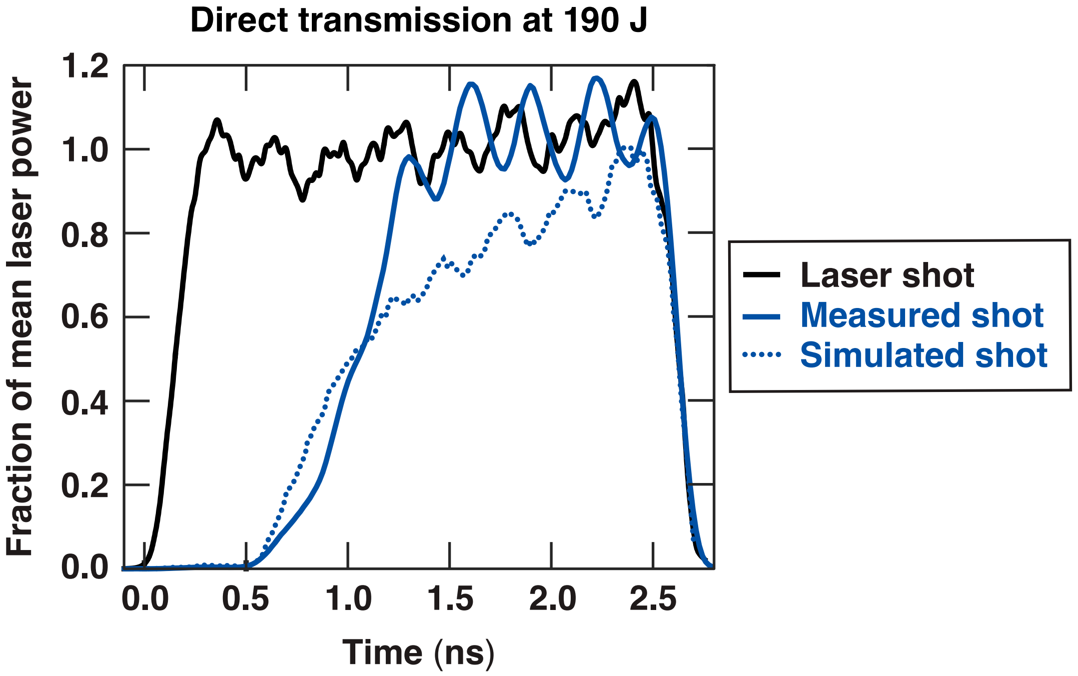
Port 25 (0°)

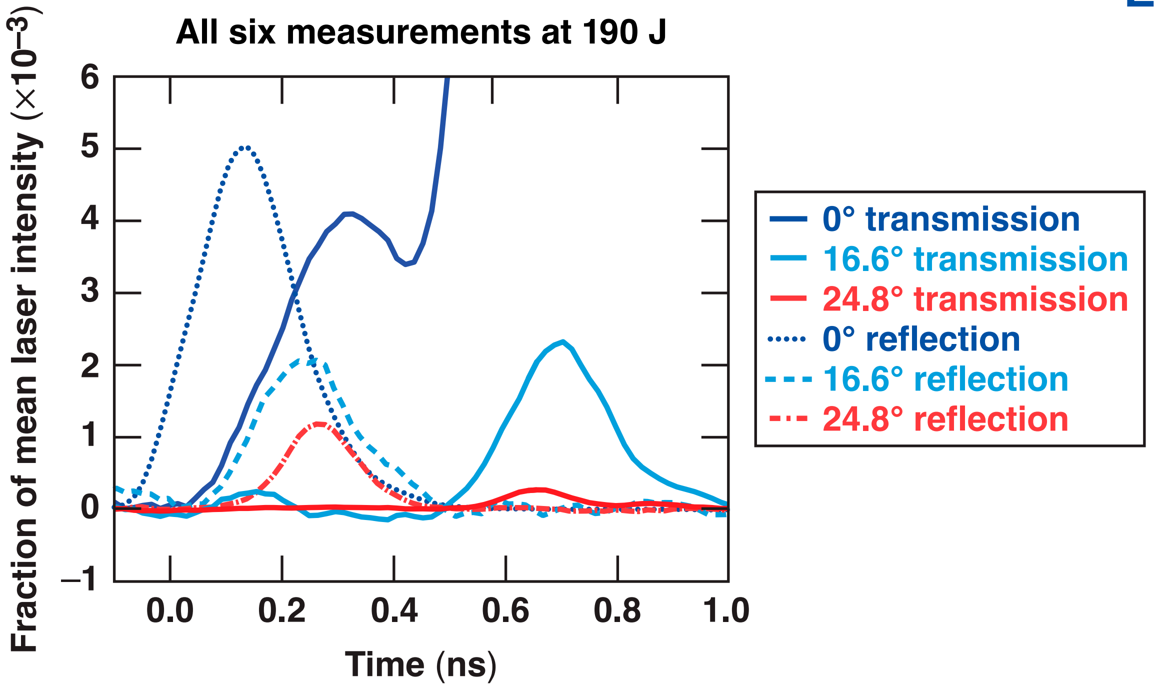
Port H17C (16.6°)

Ports 25, 30, and H17C collect time-resolved spectra of the laser light

TC12451c

Foil transmission exceeded simulations, sidescattered transmission and total reflection were negligible, and reflection from full targets was the same as for foils*





190 J:	Direct transmission	Sidescatter	Reflection	Foil absorption
Foil	65.5±2.0%	0.72±0.22%	0.61±0.10%	33.2±2.0%
Full targets	–	–	0.59±0.22%	–
Simulations	55.9%	0.0%	1.6%	42.4%

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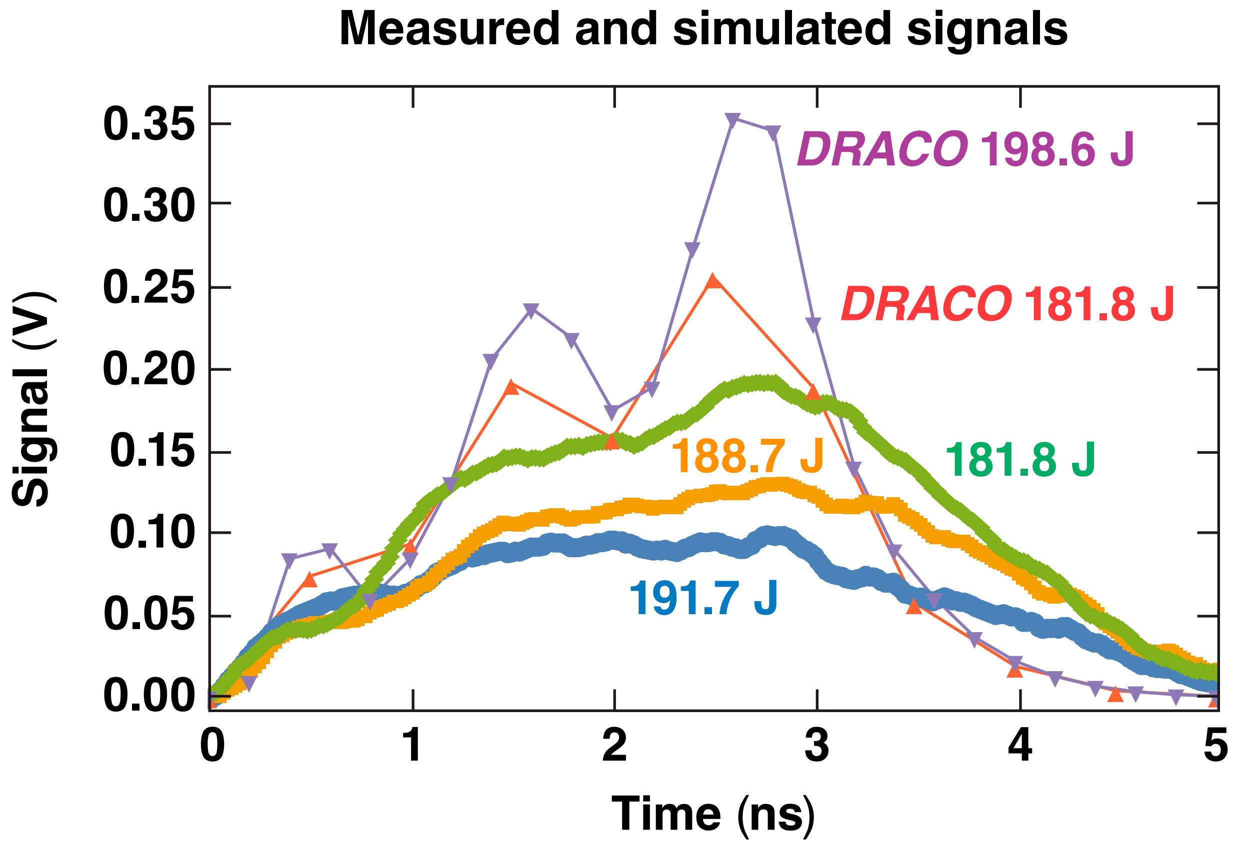
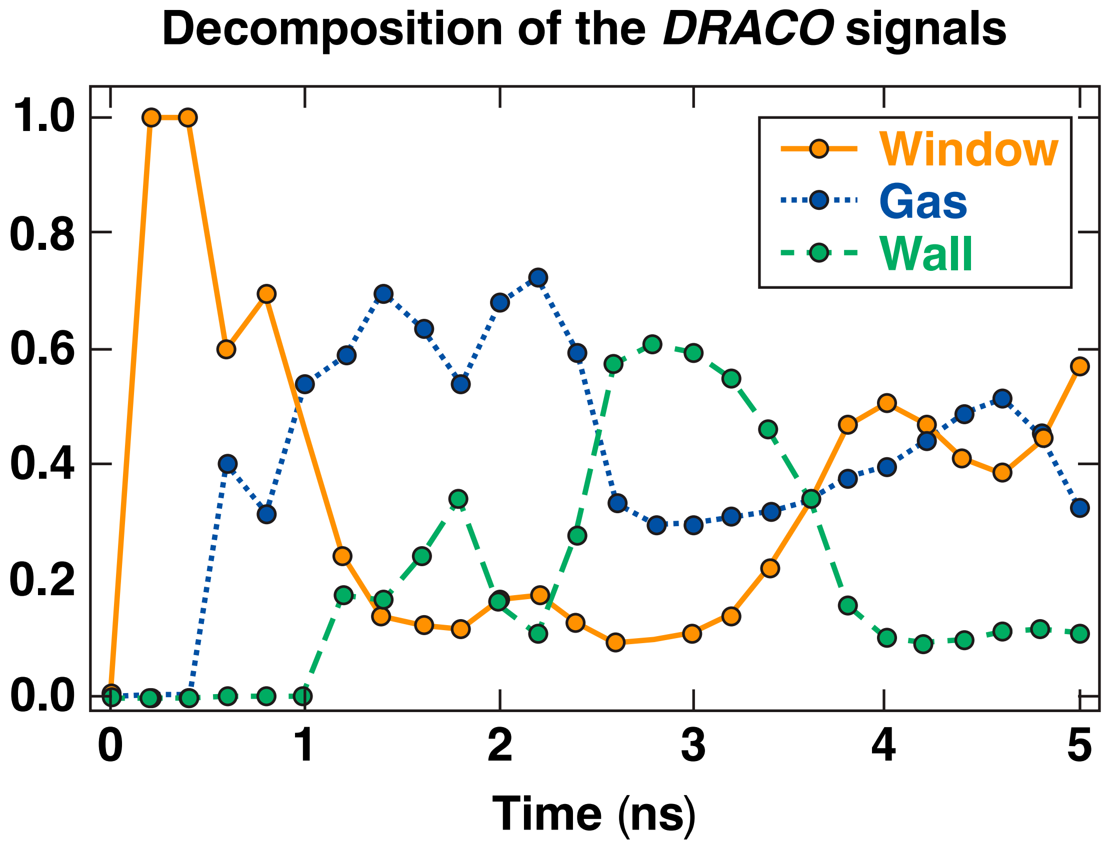
*J. R. Davies *et al.*, Phys. Plasmas 25, 062704 (2018).

Soft x-ray emission measurements showed that the gas was preheated in excess of 100 eV and that simulations overestimated the window emission

Sample channel (~keV) from the Dante spectrometer looking into the window of full target shots





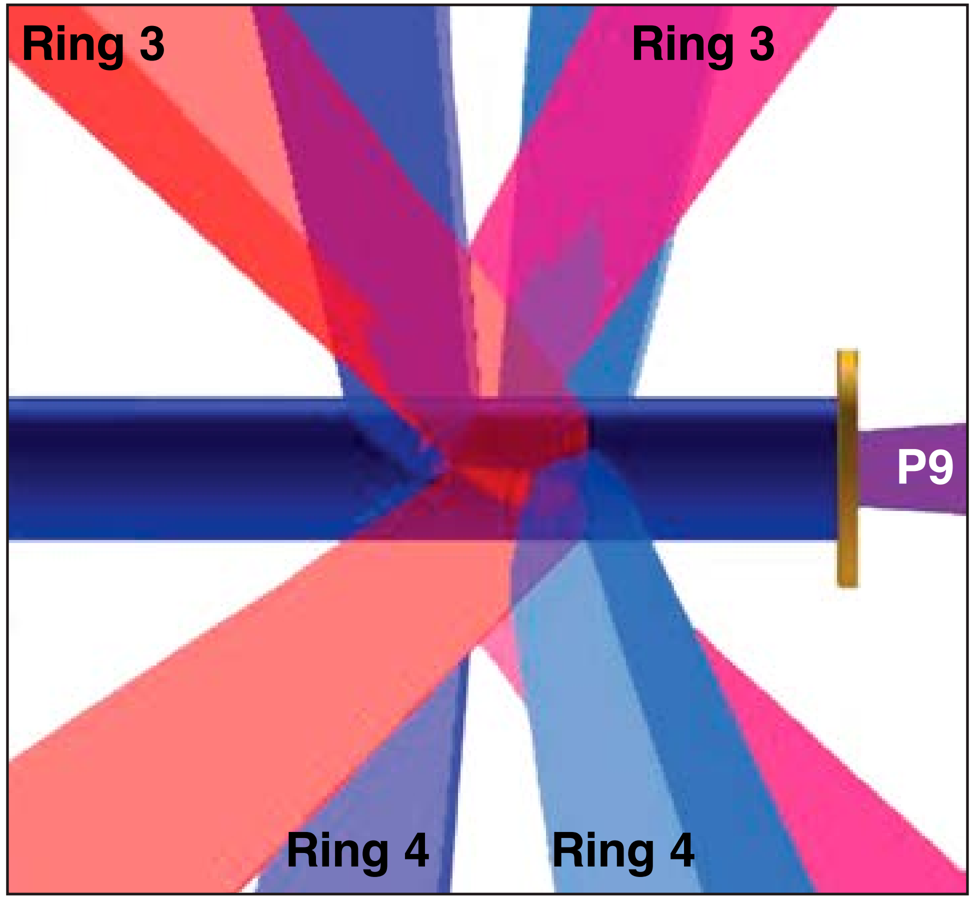
Simulations match the gas temperature to within 10 eV.

E27825

Outline

- What is MagLIF?
- Scaling down MagLIF from Z to OMEGA
- Preheat experiments
- **Optimizing cylindrical compression**
- Results

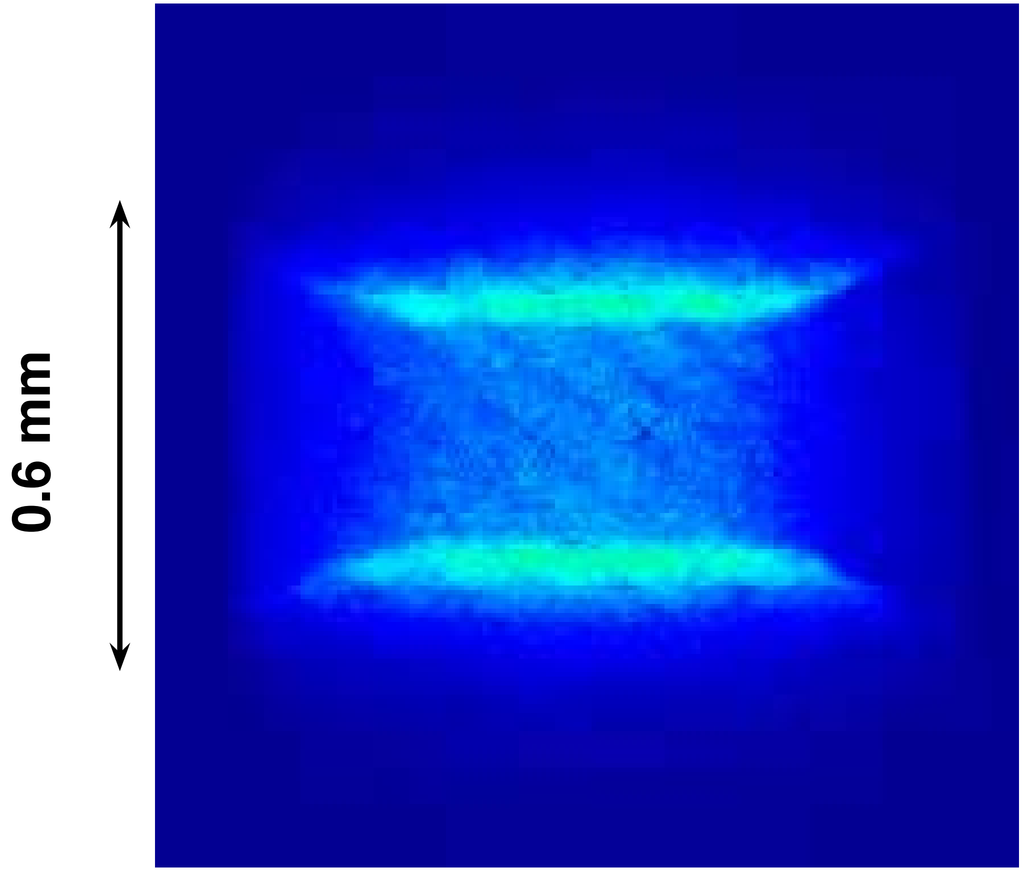
OMEGA is designed to distribute 60 beams uniformly over a sphere so it does not lend itself to uniform compression of a cylinder



- The cylinder is aligned with a pent axis to use the P9 beam port for the preheating beam
  - added a 3ω beam capability to P9 using a different beam for this project
- 20 beams (rings 1 and 2) cannot be used because they are at glancing angles of incidence
- The remaining 40 beams are arranged in rings of 10 at $\pm31.15°$ (rings 3) and $\pm8.75°$ (rings 4) to the cylinder axis
- Increasing angles to the axis lead to lower intensities on the target surface, to reflection in the corona at a lower density, and to the beams crossing different positions at different radii

X-ray framing-camera images of self-emission were used to determine implosion velocity and axial uniformity

X-ray emission from 1 to 1.8 ns



E27827

The separation and energy balance between rings 3 and 4 that maximize the uniformly imploded length were determined experimentally in three steps*

(1) Single-ring shots

Determine the intensity reduction required to reproduce the x-ray implosion velocity in 1-D simulations (normal to target axis)

$$I_{\text{R3-1D}} = 0.49\, I_{\text{laser}}$$
$$I_{\text{R4-1D}} = 0.89\, I_{\text{laser}}$$

E27828

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*E. C. Hansen *et al.*, Plasma Phys. Control. Fusion 60, 054014 (2018).

The separation and energy balance between rings 3 and 4 that maximize the uniformly imploded length were determined experimentally in three steps*

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(2) Initial pointing

Achieve uniform effective intensity by fully overlapping rings 3 at the center with rings 4 at the ends

Overdrive the center
Reduce ring 3 energy to obtain a uniform implosion

E27828a

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Reduce ring 3 energy to obtain a uniform implosion

(3) Repointing

Increase separation between the rings to reproduce the effect of reducing ring-3 energy while driving a longer region

Overdrive the ends
Reduce ring-4 energy to 83% (matches ring-3 intensity)

E27828b

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Increase separation between the rings to reproduce the effect of reducing ring-3 energy while driving a longer region

Overdrive the ends
Reduce ring-4 energy to 83% (matches ring-3 intensity)

The implosion velocity is 200±4 km/s over a region 0.6-mm long

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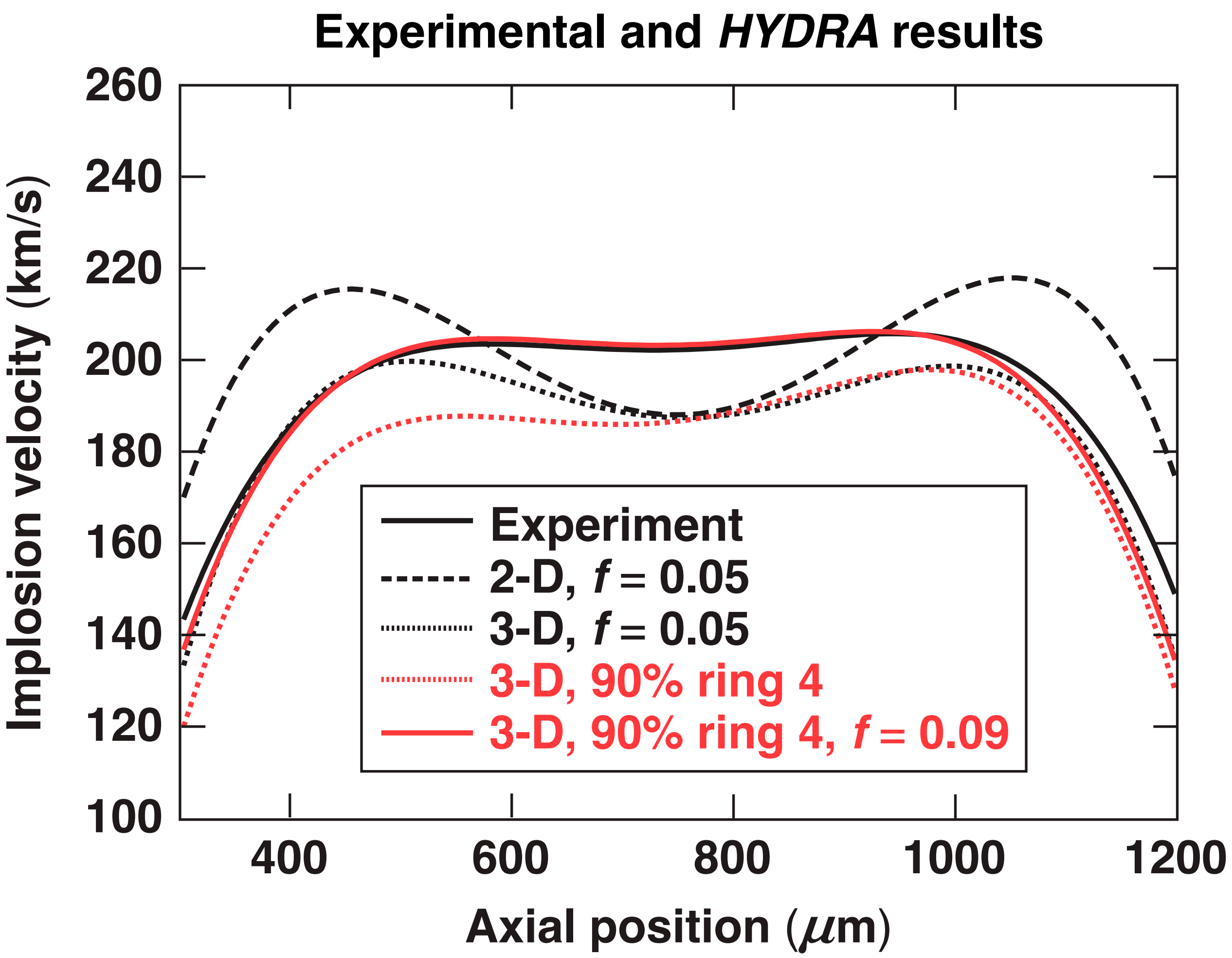
*E. C. Hansen *et al.*, Plasma Phys. Control. Fusion 60, 054014 (2018).

Three-dimensional *HYDRA* can reproduce the results with a 10% reduction in ring-4 energy and a flux limiter of 0.09



E. C. Hansen *et al.*, "Optimization of Laser-Driven Cylindrical Implosions on the OMEGA Laser," submitted to Physics of Plasmas.

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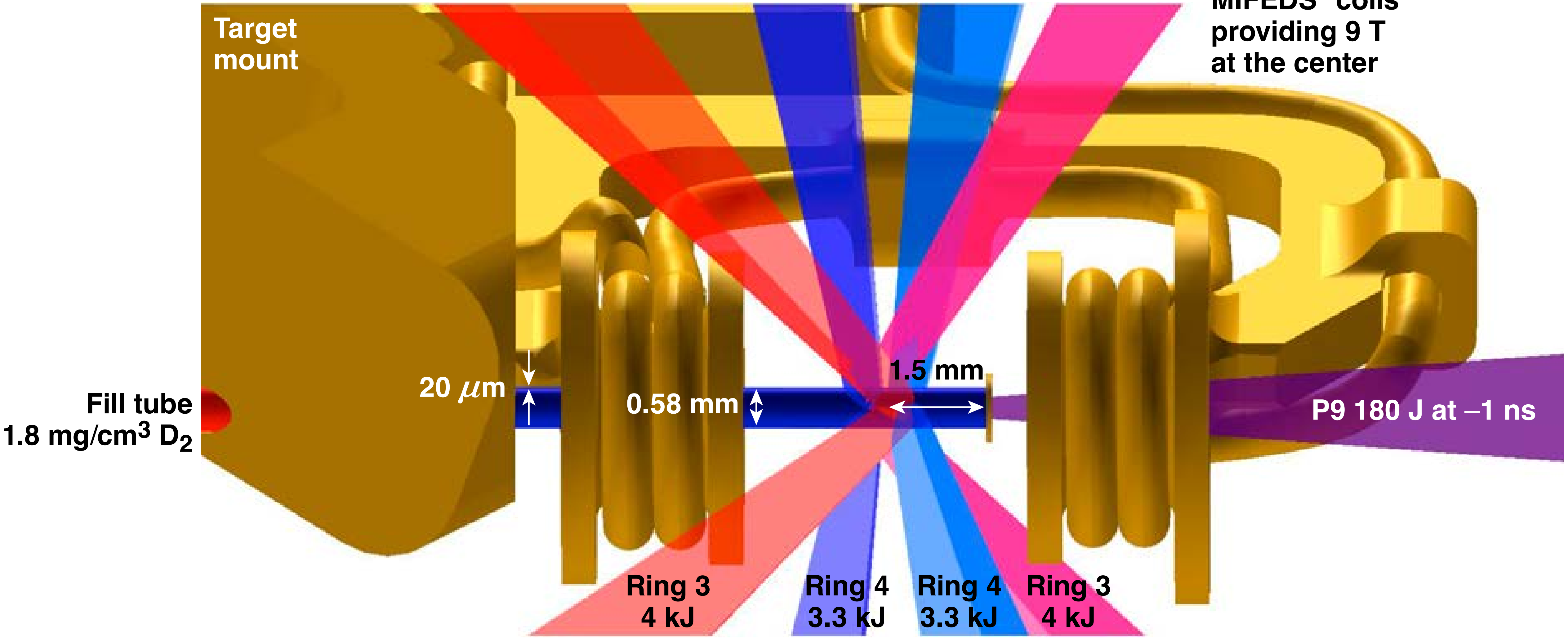
The baseline experimental setup uses a 20-μm-thick, 0.29-mm-radius parylene-N target, filled with 1.8 mg/cm^3 D$_2$, in a 9-T axial magnetic field driven by 1.5-ns-long square shaped pulses



E27832

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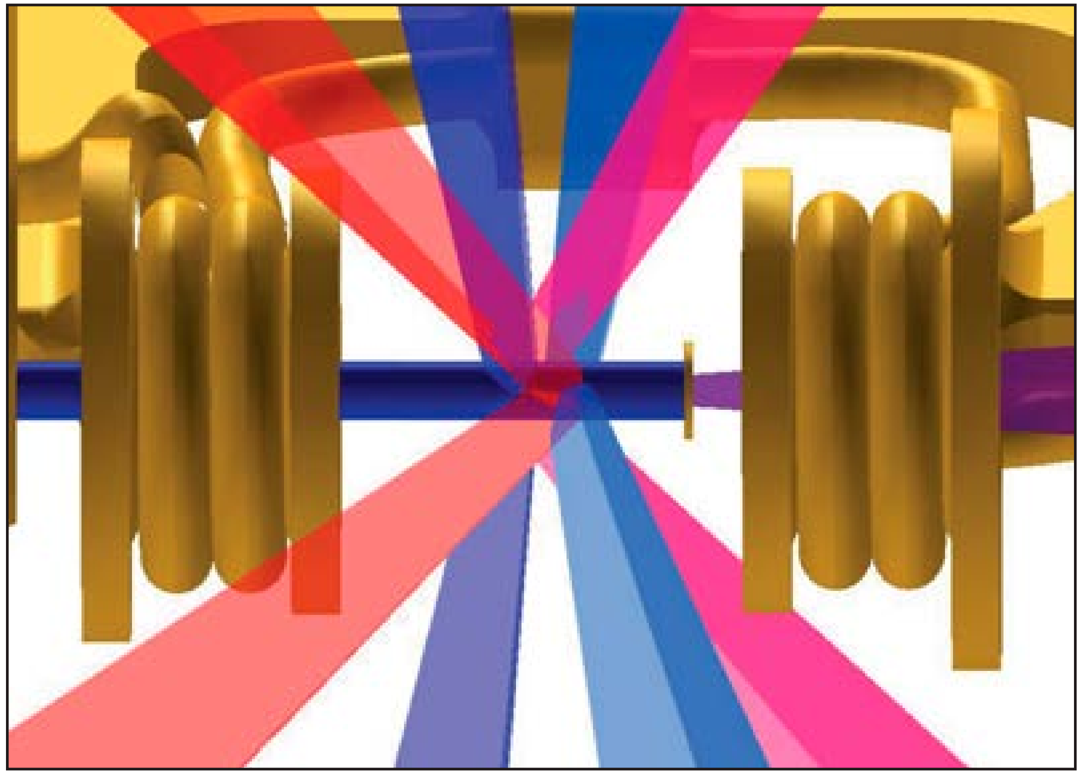
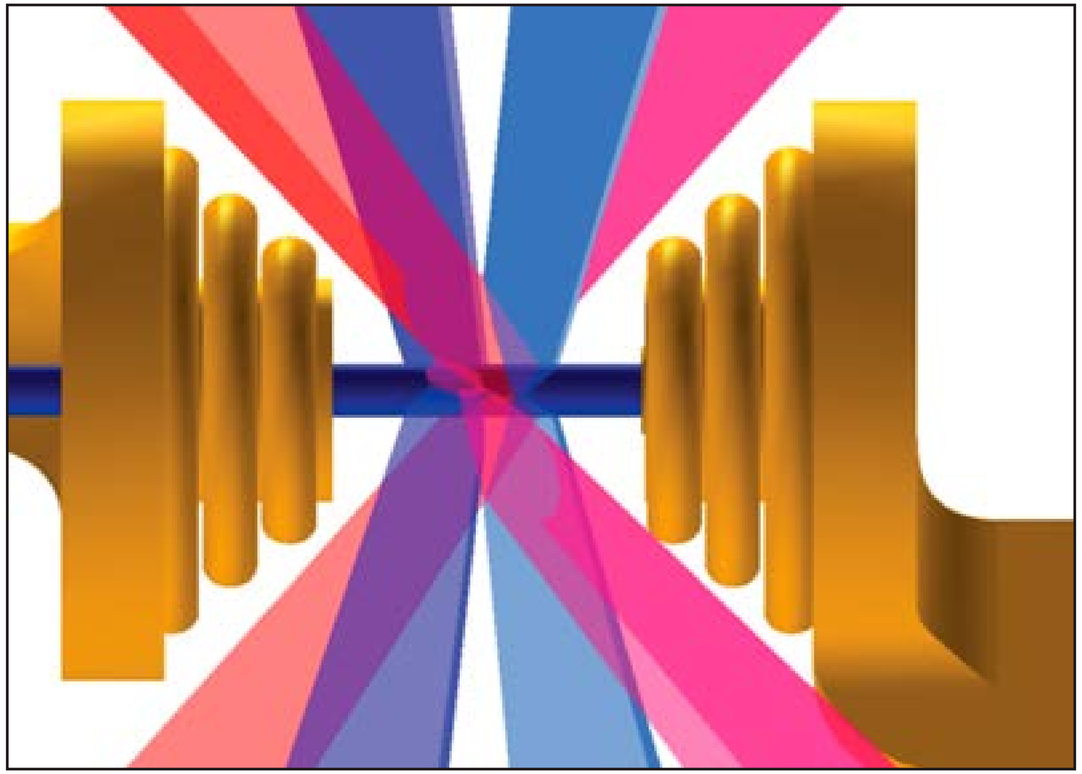
*Magneto-inertial fusion electrical discharge system

The initial axial magnetic field has been increased to 27 T by using two MIFEDS conical coils and thinner wire insulation with the wires glued to the holder

Old design, single MIFEDS, 9 T

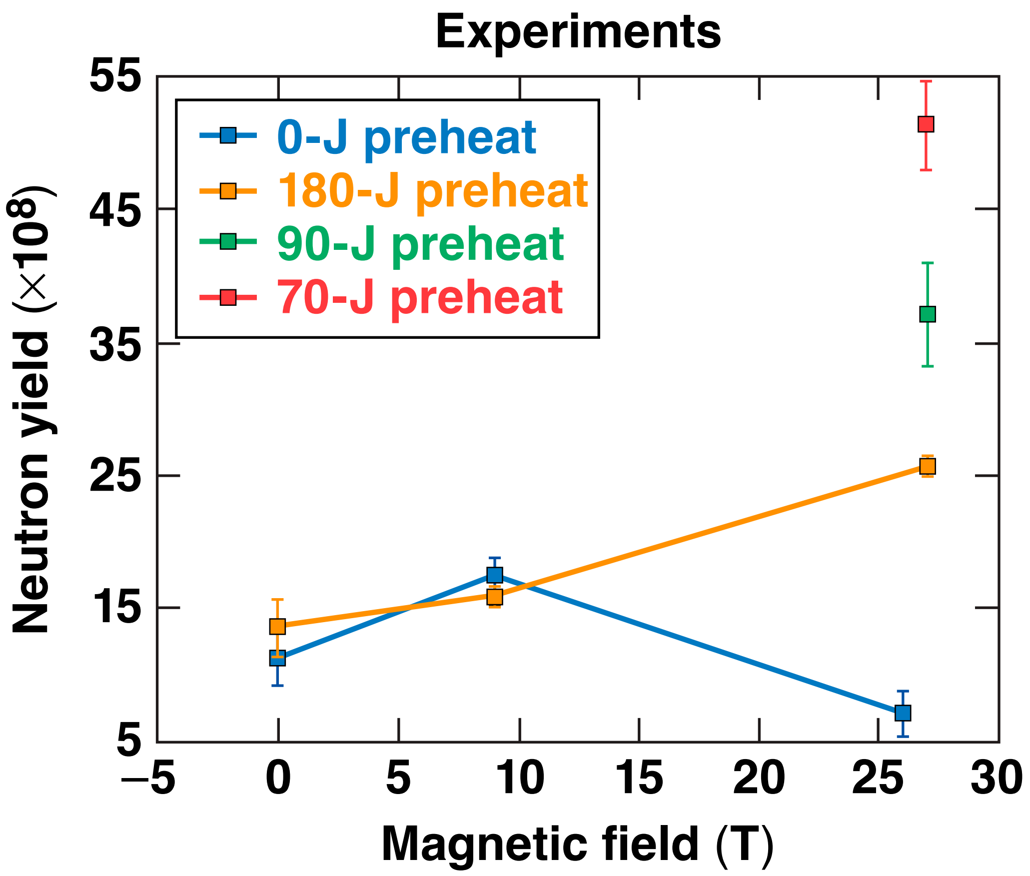


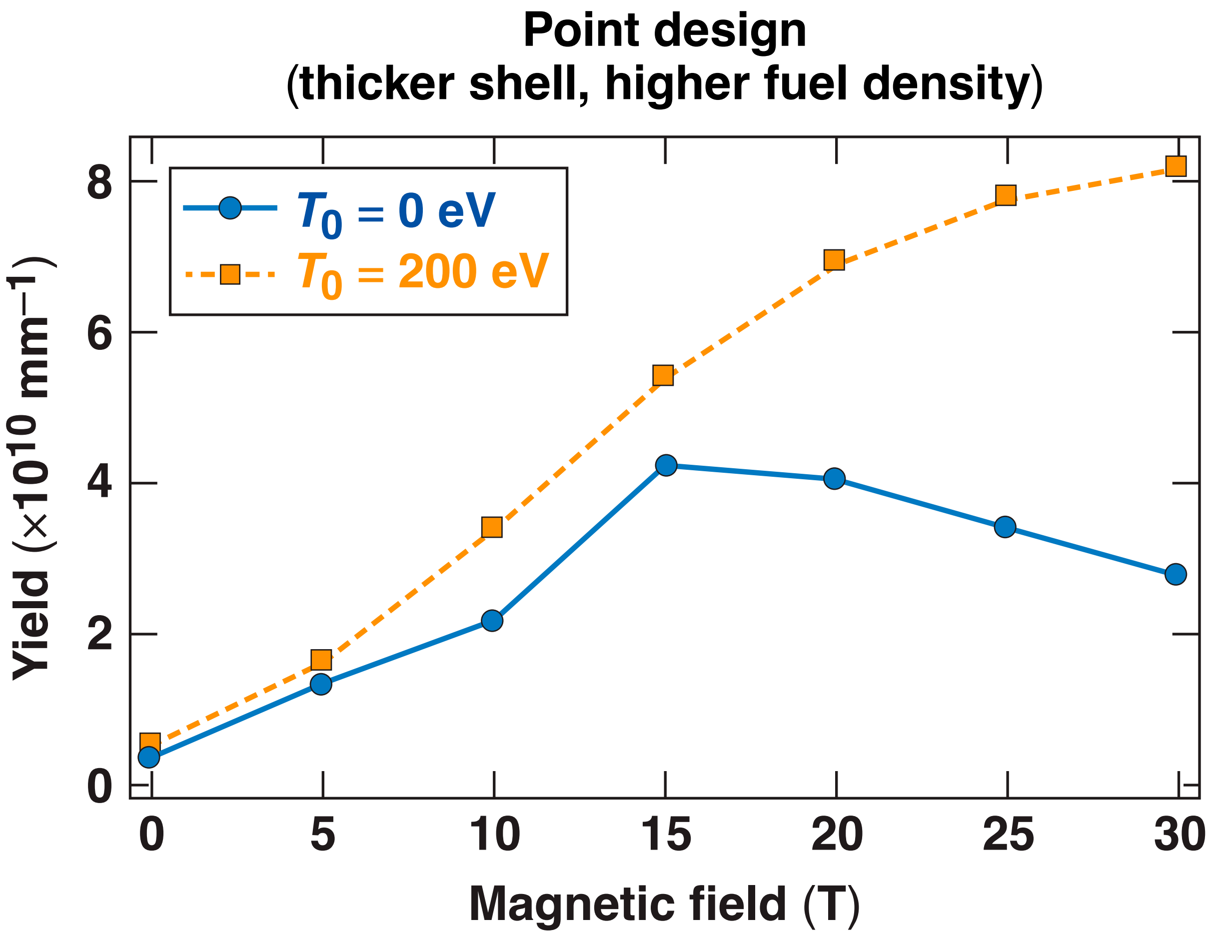
New design, dual MIFEDS, 27 T



E27833

Neutron yields are significantly increased by magnetization and preheat

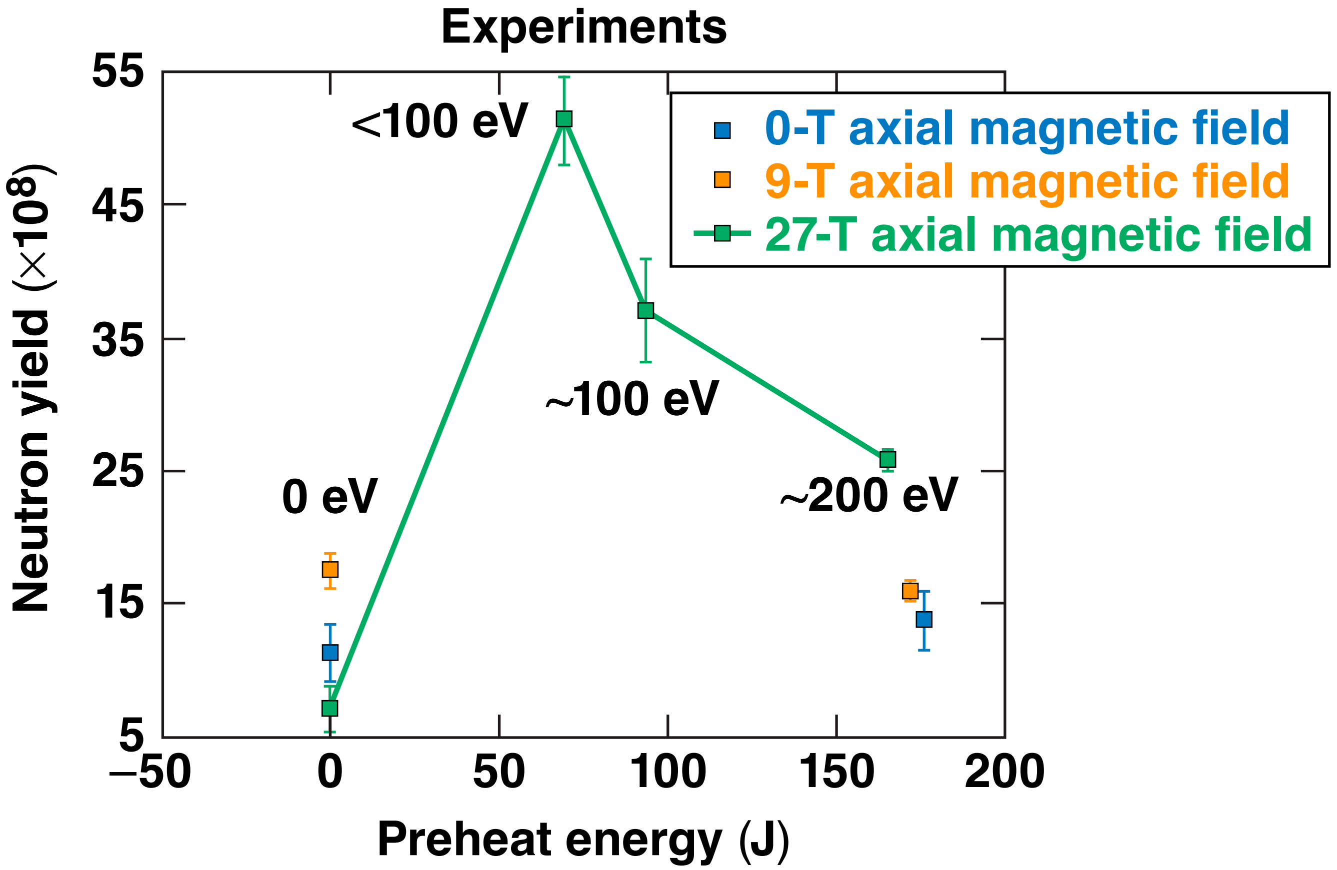


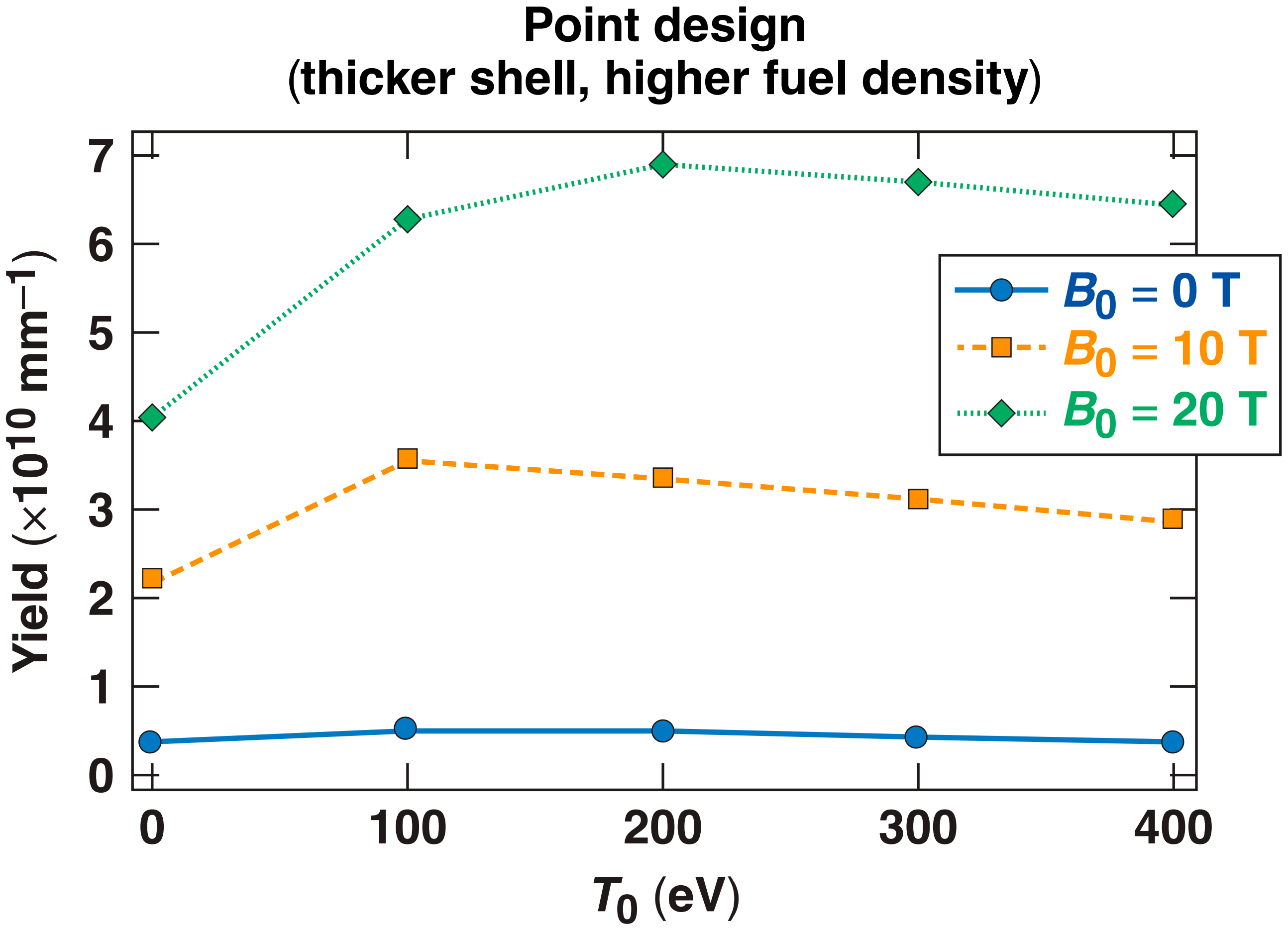


J. R. Davies *et al.*, Phys. Plasmas 24, 062701 (2017).

E27834

Optimum preheat energy is lower than expected and the fall in yield above optimum preheat is faster than expected

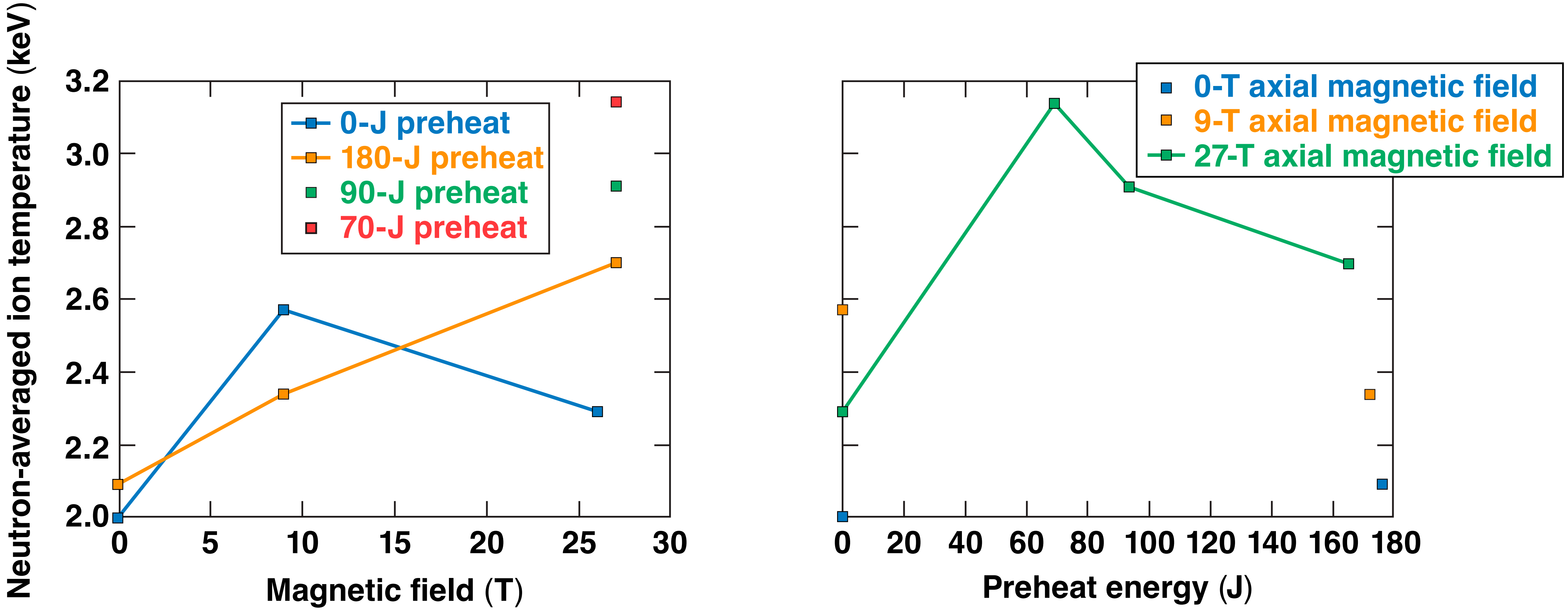




J. R. Davies *et al.*, Phys. Plasmas 24, 062701 (2017).

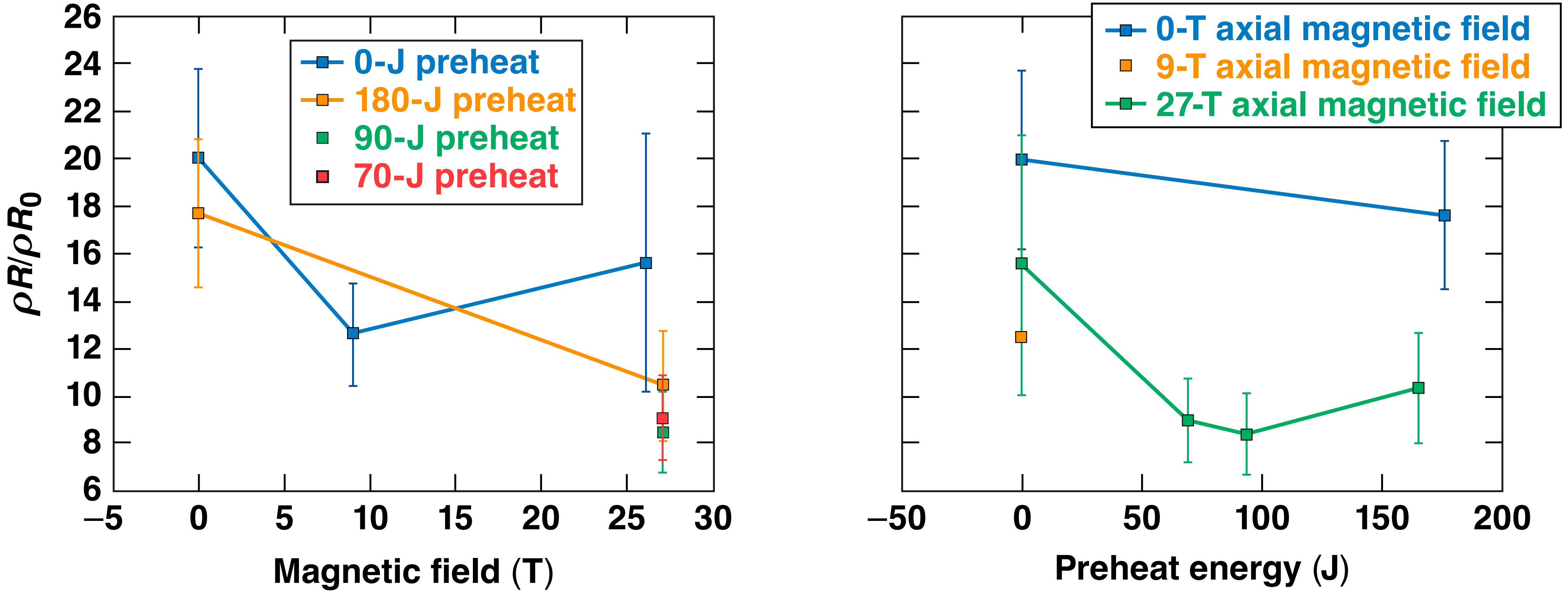
E27835

Neutron-averaged ion temperatures show the same trends as neutron yields



E27836

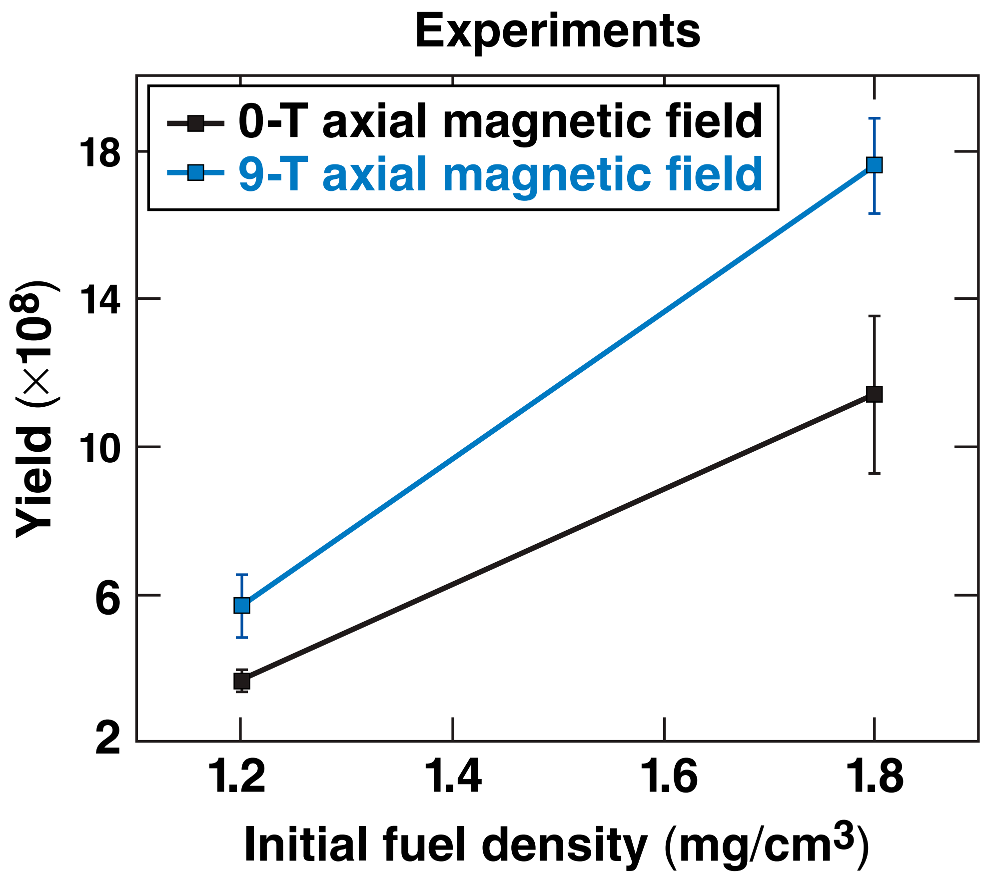
Fuel areal density ρR inferred from the secondary DT neutron yield is reduced by magnetization and preheat

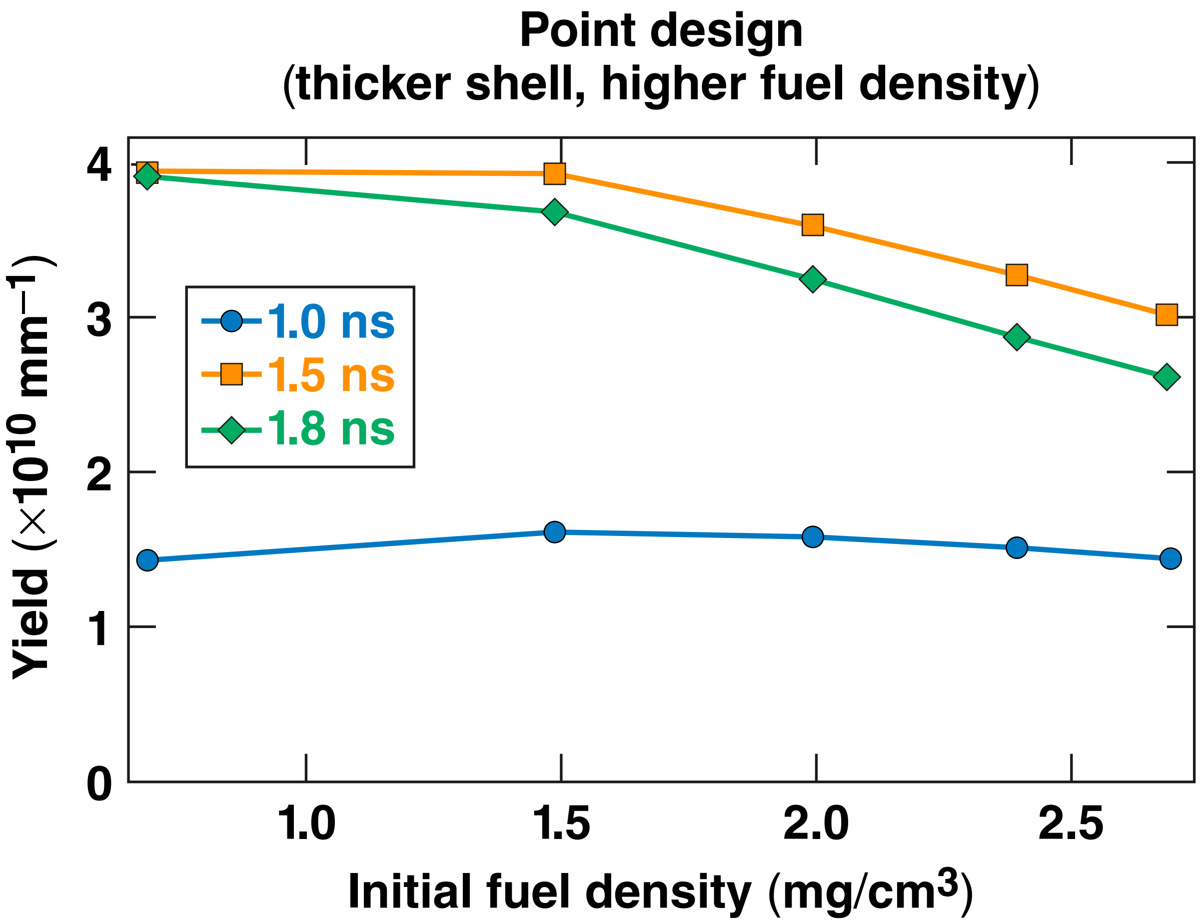


Magnetization and preheat give higher yield and higher temperature at lower convergence.

E27837

Lowering the fuel density closer to the 0.7 mg/cm^3 used on Z significantly lowered the yield



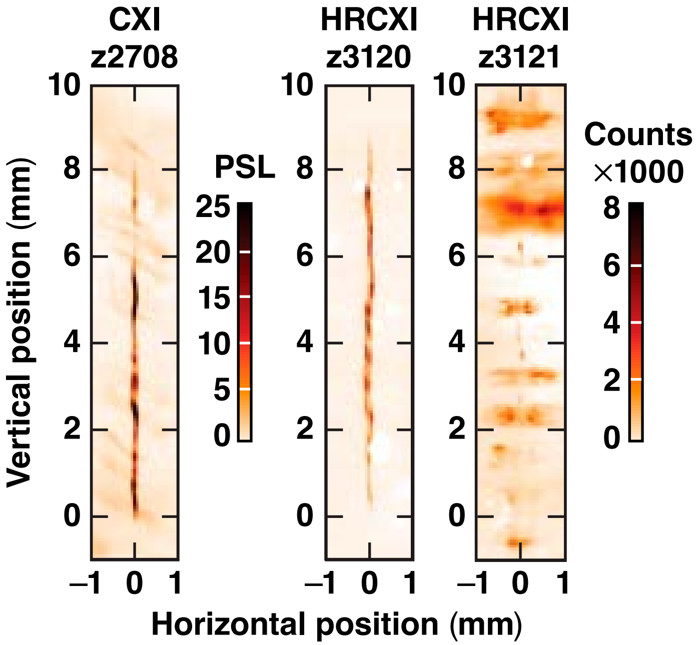


E27838

J. R. Davies *et al.*, Phys. Plasmas 24, 062701 (2017).

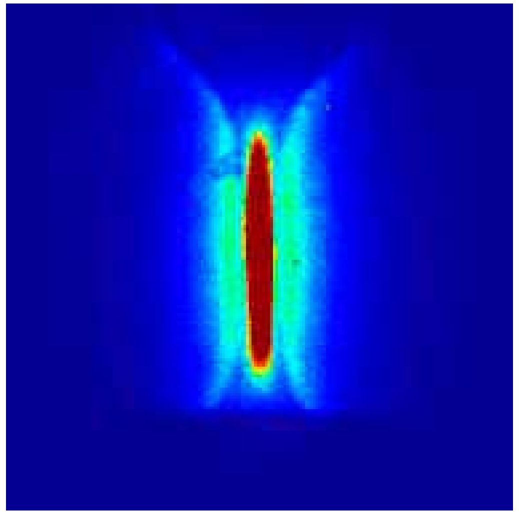
Compared to experiments on Z, the yield enhancements caused by magnetization and preheating are lower because the compression-only baseline is more stable

Z baseline experiments		
	$B_z = 0$ T	$B_z = 10$ T
No preheat	0.003×10^{12} ~1 keV	0.01×10^{12} ~1 keV
Preheat	0.04×10^{12} ~1 keV	3×10^{12} 2.5 keV



OMEGA baseline experiments		
	$B_z = 0$ T	$B_z = 10$ T
No preheat	1×10^{9} 2.0 keV	1.8×10^{9} 2.6 keV
Preheat	1.4×10^{9} 2.1 keV	1.6×10^{9} 2.3 keV

Any type of shot on OMEGA



E27839

Summary/Conclusions

OMEGA results confirm that magnetization and preheating increase yield and reduce convergence ratio

- Laser-driven MagLIF on OMEGA provides data at 1000× lower drive energy than Z with targets 10× smaller in linear dimensions
- OMEGA results indicate that initial magnetic fields >15 T and initial deuterium densities >1 mg/cm^3 planned for Z should significantly increase yields
- The results from OMEGA and Z will be compared to simulations with the same codes to increase confidence in extrapolating to energy gain

Mean D_2 density, magnetic field, preheat energy, DD neutron yield, neutron-averaged ion temperature, fuel areal density inferred from DT yield, and time of peak neutron emission by shot type

Type (number of shots)	ρ (mg/cm^3)	B (T)	E_{P9} (J)	Y_{DD} (10^8)	T_{i} (keV)	$\rho R/\rho R_0$	t_{p} (ns)
Compression only (4)	**1.85±0.03**	**0**	**0**	**11.4±2.1**	**2.00±0.5**	**22.5±4.7**	**1.57±0.15**
Preheated (3)	**1.81±0.02**	**0**	**176±3.1**	**13.8±2.2**	**2.09±0.5**	**19.6±3.9**	**1.54±0.08**
Magnetized 9 T (2)	**1.87±0.02**	**9**	**0**	**17.6±1.3**	**2.57±0.5**	**13.2±2.7**	**1.59±0.05**
Magnetized 26 T (2)	**1.63±0.14**	**25.5±1.5**	**0**	**7.24±1.7**	**2.29±0.5**	**17.0±6.8**	**1.58±0.04**
Integrated 9 T, 180 J (1)	**1.80**	**9**	**172**	**16.1±0.43**	**2.34±0.5**	**<13**	**1.37±0.17**
Integrated 27 T, 180 J (1)	**1.77**	**27**	**165**	**25.8±0.51**	**2.70±0.5**	**10.5±2.9**	**1.53±0.15**
Integrated 27 T, 90 J (2)	**1.78±0.03**	**27**	**93.3**	**37.1±3.9**	**2.91±0.5**	**8.08±2.14**	**1.43±0.19**
Integrated 27 T, 70 J (2)	**1.78±0.02**	**27**	**69.1±1.1**	**51.3±3.3**	**3.14±0.5**	**8.80±2.20**	**1.52±0.26**
Compression 1.1 mg/cm^3 (2)	**1.19±0.002**	**0**	**0**	**3.62±0.25**	**2.06±0.5**	**<82**	**1.50±0.15**
Magnetized 9 T, 1.1 mg/cm^3 (2)	**1.20±0.005**	**10**	**0**	**5.64±0.85**	**2.10±0.5**	**38.4±7.9**	**1.49±0.05**

Comparison of point design and experimental parameters for Z and OMEGA

Parameter	Z point design	Z experiments	Ω point design	Ω experiments
Aspect ratio Δ*r*/*r*	6	6 to 9	10 to 15	14.5
Fuel density (mg/cm^3)	3 (DT)	0.7 (DD)	2.4 to 2.7 (DD)	1.1 to 1.8 (DD)
Axial magnetic field (T)	30	0 to 15	10	0 to 27
Mean preheat (eV)	250	0 to 100	200	0 to 200
Implosion velocity (km/s)	70	~50	150 to 190	200
Fuel convergence ratio	25	~40	25	16 to 30
Neutron yield	–	Up to 10^{13}	–	Up to 5×10^9
Ion temperature (keV)	–	Up to 3	–	Up to 3