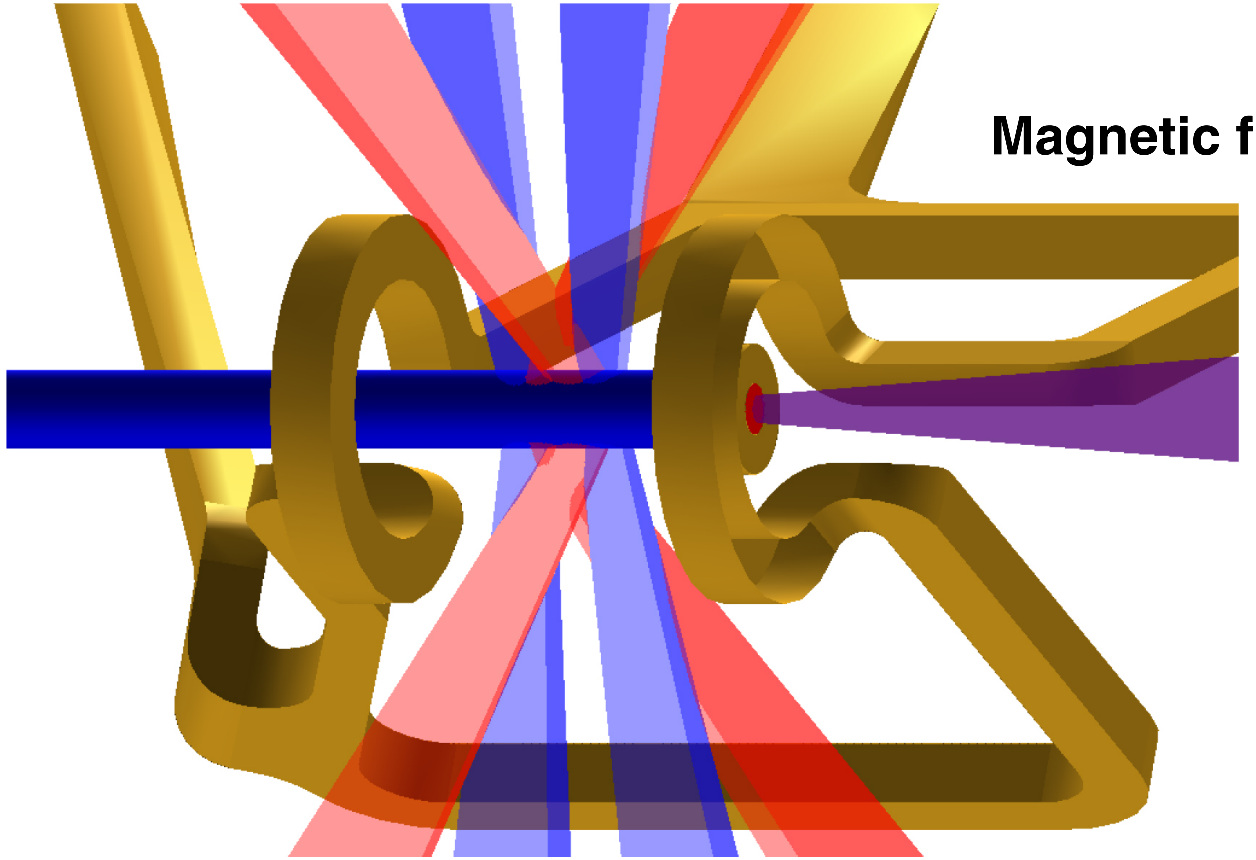
Magnetized Liner Inertial Fusion on OMEGA



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Summary

Laser-driven magnetized liner inertial fusion (MagLIF) on OMEGA is providing the first experimental data on scaling

- A point design for MagLIF on OMEGA was developed using 1-D and 2-D magnetohydrodynamic (MHD) simulations
- Focused experiments for separately optimizing preheating and implosion uniformity demonstrated the viability of the point design
- Preliminary integrated MagLIF experiments show an increase in neutron yield with preheating and magnetization

Laser-driven MagLIF will accelerate progress of MagLIF on Z.

TC13137

Collaborators

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Outline

- Introduction to MagLIF/Motivation
- OMEGA-scale MagLIF point design
- Preheat experiments
- Implosion-optimization experiments
- Integrated-MagLIF implosions on OMEGA
- Future projects

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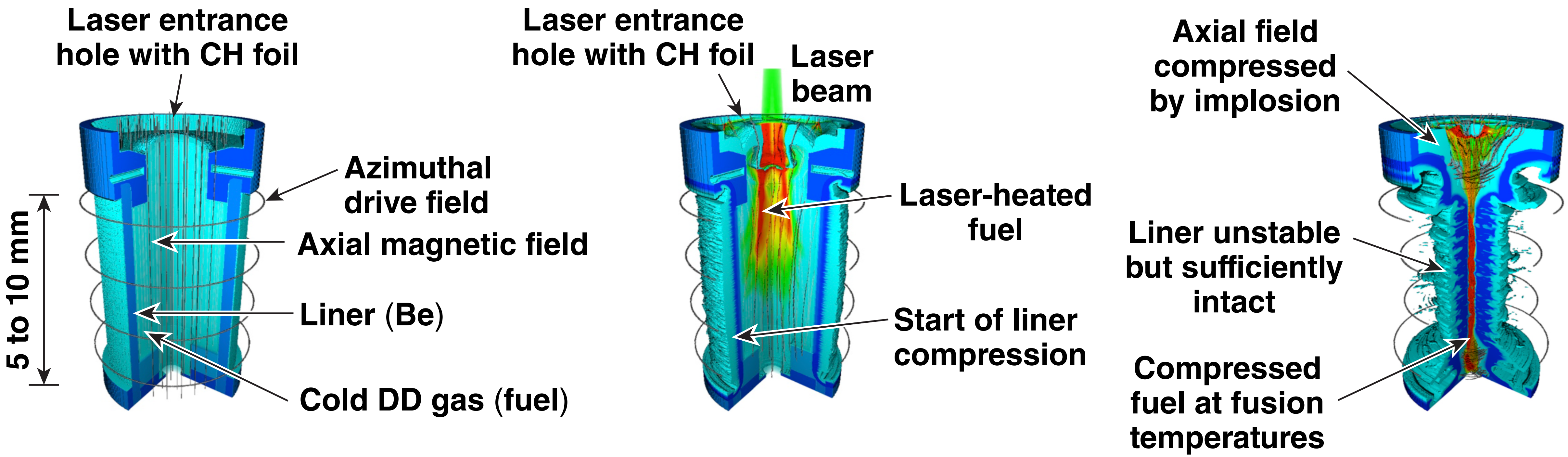
MagLIF uses a Z-pinch driven implosion, laser preheating, and magnetization to reduce radial conduction losses and confine alpha particles



Laser entrance hole with CH foil

Azimuthal drive field

Axial magnetic field

5 to 10 mm

Liner (Be)

Cold DD gas (fuel)

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 for a near-adiabatic compression at lower implosion velocities and confinement of alpha particles
- Laser 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).

MagLIF implosions on OMEGA provide a platform for studying the physics principles and scalability of the concept

- A faster shot cycle allows for more shots, better statistics, and wider scans of the MagLIF parameter space
- Better diagnostic access allows for measurements that cannot be performed at the Z scale
  - magnetic-field/Nernst-effect measurements, shell trajectories
- OMEGA-scale experiments provide code validation over 1000× in energy
  - ultimately, we will have the confidence in extrapolating to ignition-scale designs

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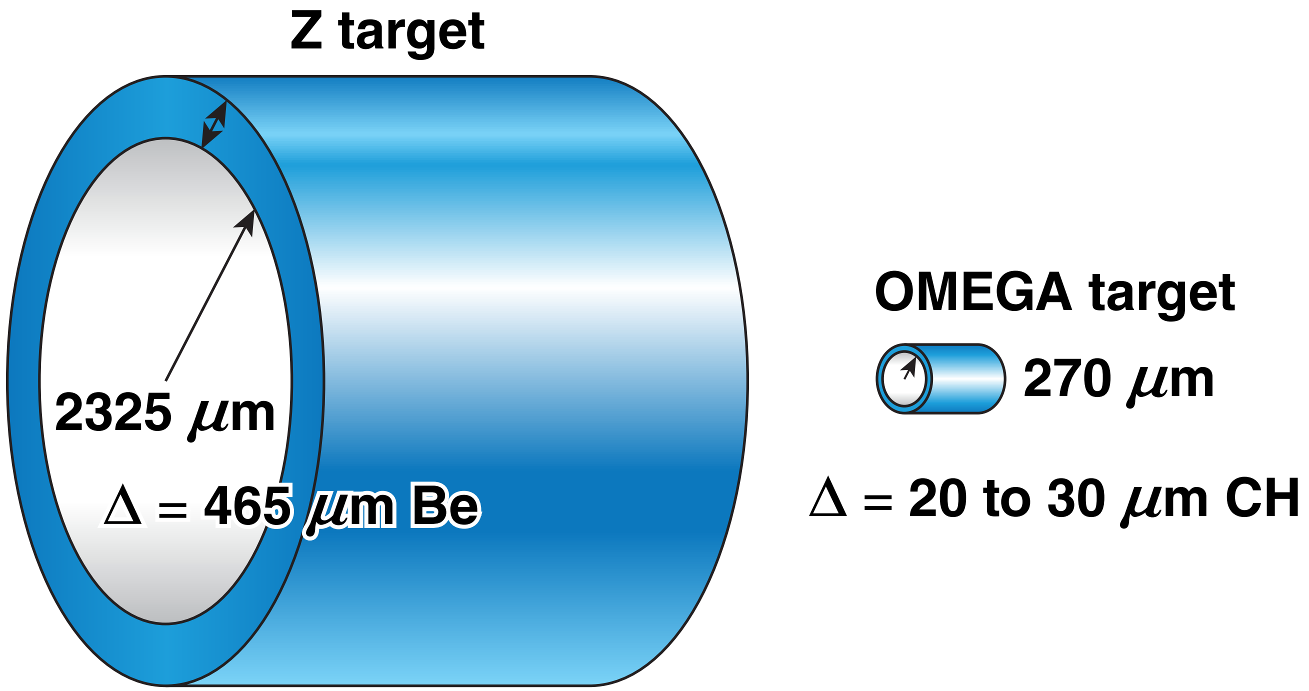
The OMEGA point design is energy scaled from the Sandia/Z 27 MA point design



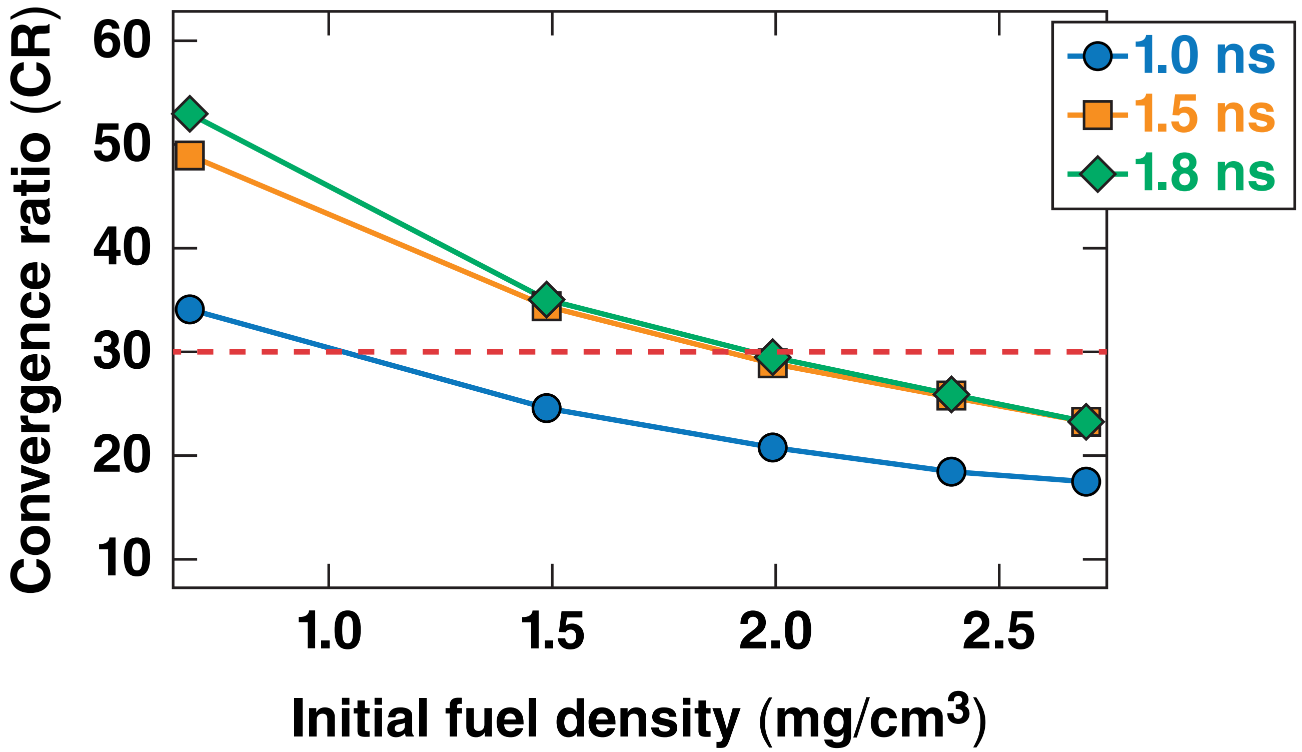
Z	OMEGA
100-ns drive	1.5-ns drive
L = 7.5 mm	L = 0.7 mm
B_0 = 10 T	B_0 = 10 T
ρ = 0.7 ~ 1.5-mg/cm^3 D_2	ρ > 1.5-mg/cm^3 D_2
E/L = 1.00 MJ/cm	E/L = 0.01 MJ/cm

- OMEGA will couple ~0.01 MJ cm^{-1} to a cylindrical shell
  - shell aspect ratio tuned to increase implosion velocity and mitigate end losses
  - fuel density tuned to limit convergence ratio (CR) to ~25

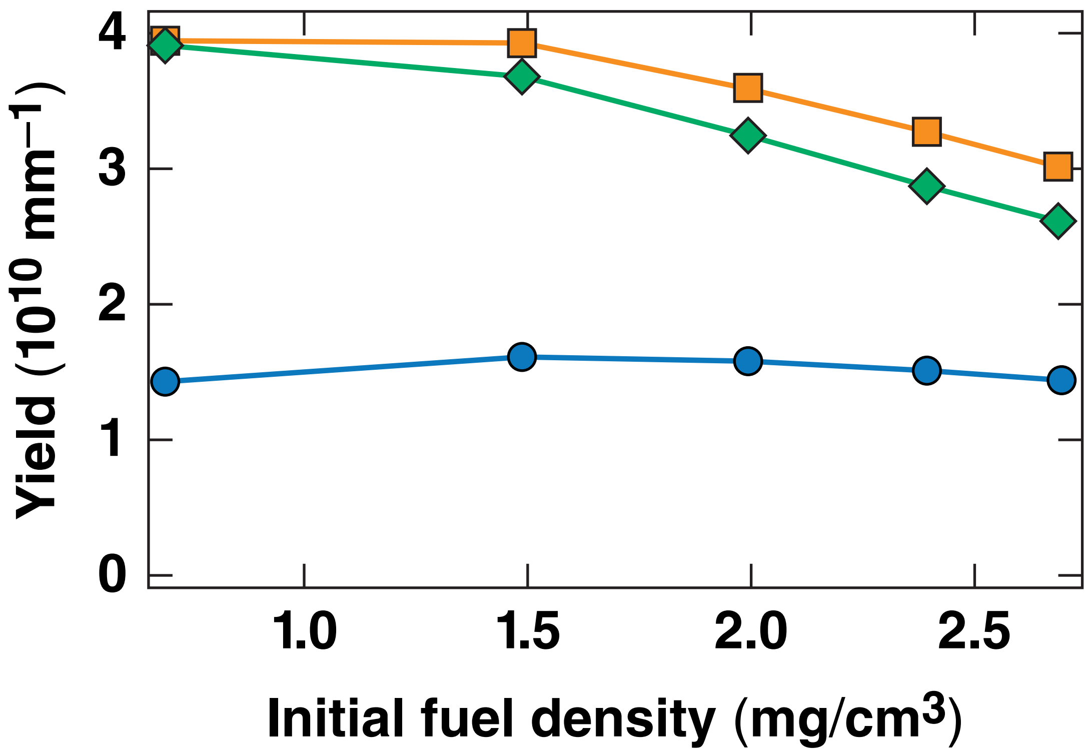
1-D *LILAC*-MHD modeling was used to optimize the OMEGA MagLIF design

- Pulse length, shell thickness, and fuel density were varied for a fixed 10-T magnetic field and 200-eV preheat temperature

30-μm shells



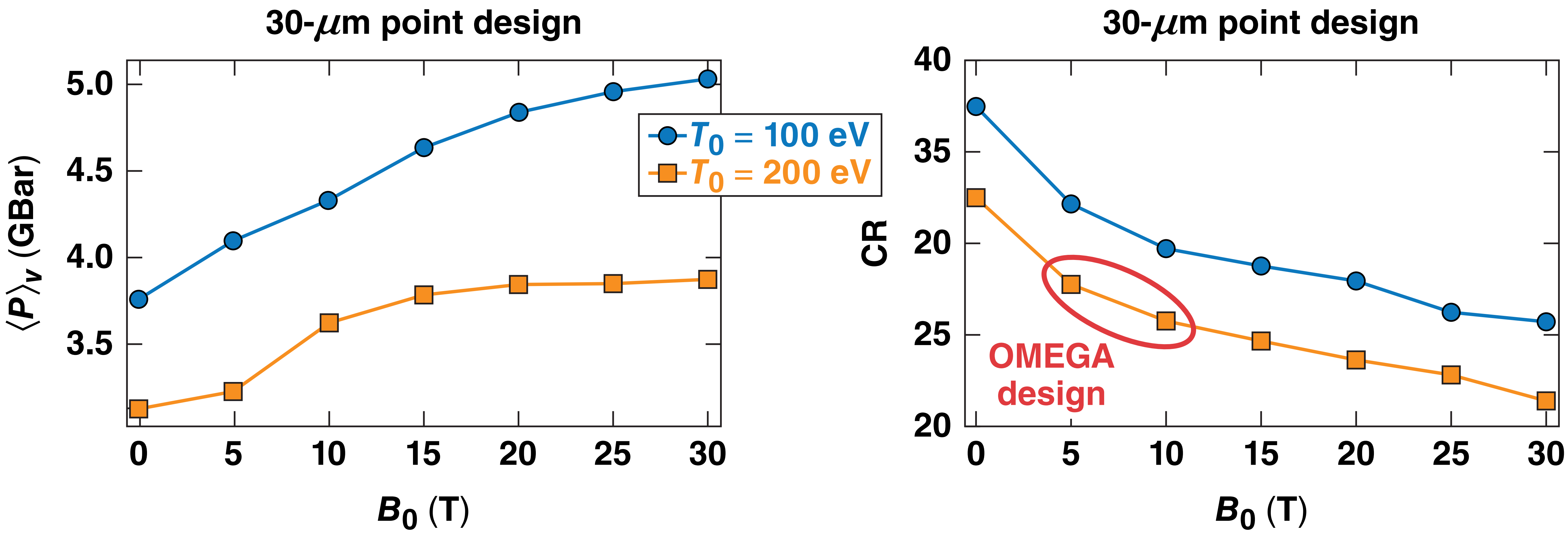
30-μm shells



A pulse length of 1.5 ns and a fuel density above 1.5 mg/cm^3 gives the maximum yield within the constraint of CR < 30.

Magnetic field and preheat reduce convergence ratio and implosion speed and provide a more stable cylindrical implosion

- **Higher core pressures are achieved because of the suppression of radial conduction loss by the magnetic field**



30-μm point design

30-μm point design

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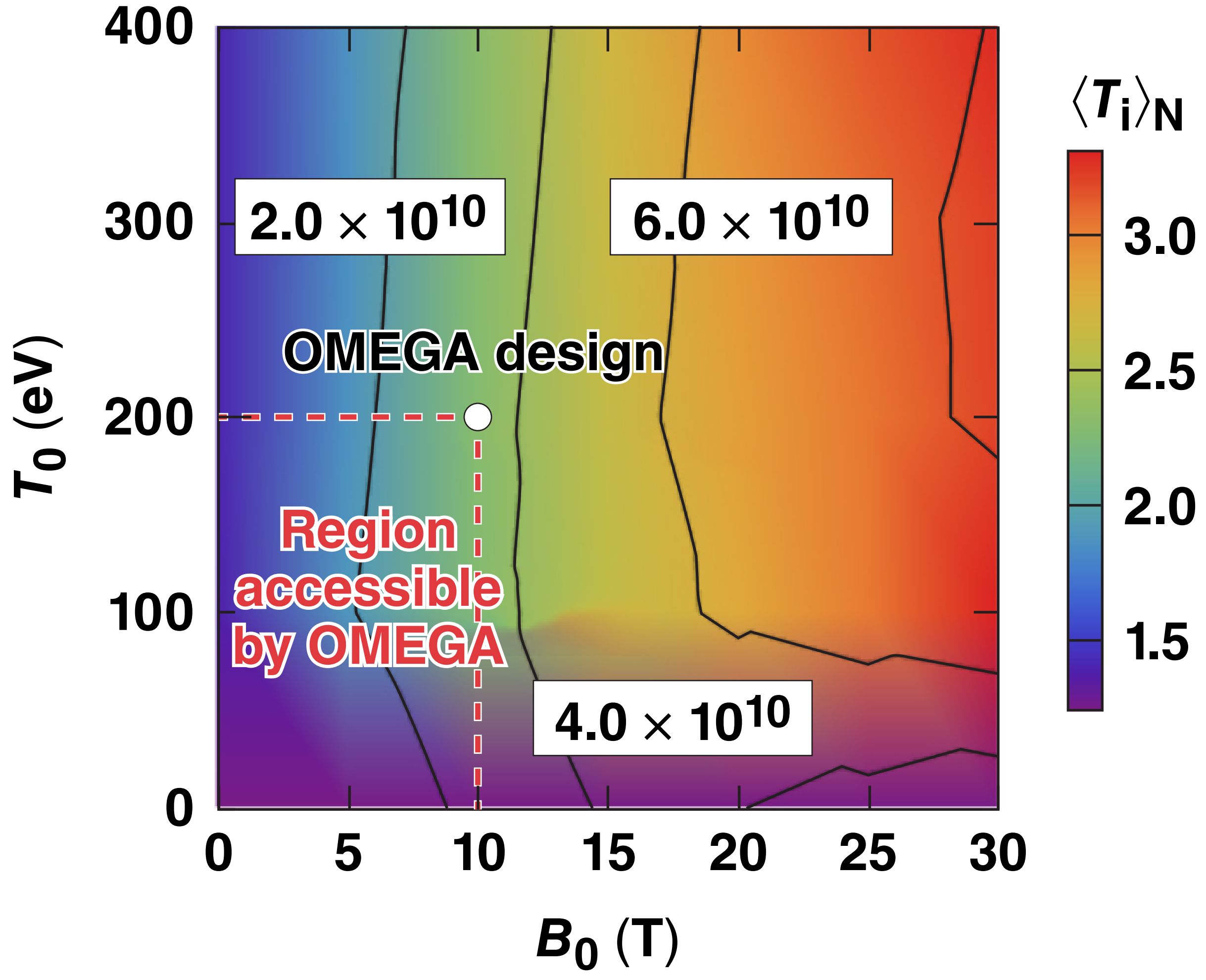
A minimum preheat temperature of 100 eV is required for a significant increase in neutron yield for any shell thickness and magnetic field at a CR < 30

30-μm point design



LILAC MHD results

B_0 (*T*)	T_0 (eV)	$\langle T_i \rangle_N$ (keV)	Y_N ($\times 10^{10}$/mm)	CR
0	0	1.24	0.393	49
0	100	1.37	0.528	37
10	100	2.27	3.560	30
10	200	2.28	3.360	26

Higher magnetic fields will be explored in future experiments.

TC12795a

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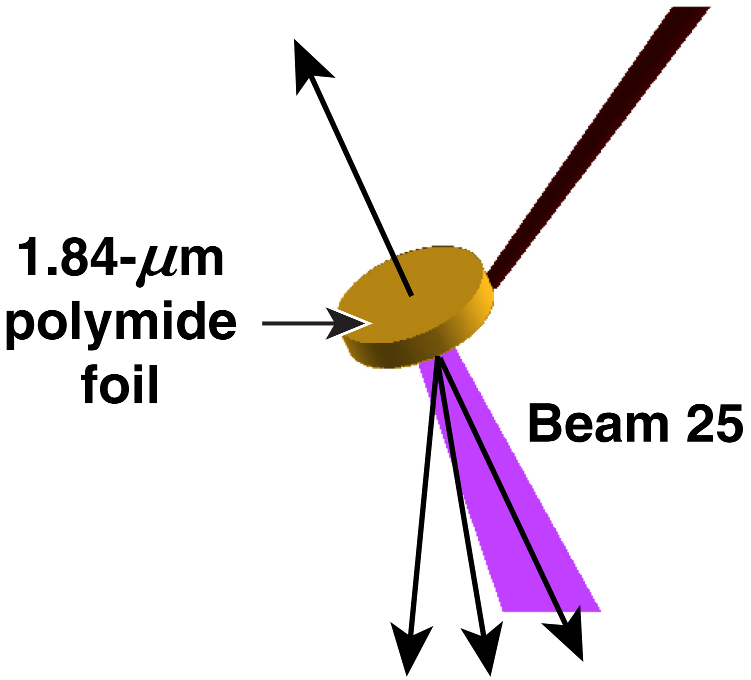
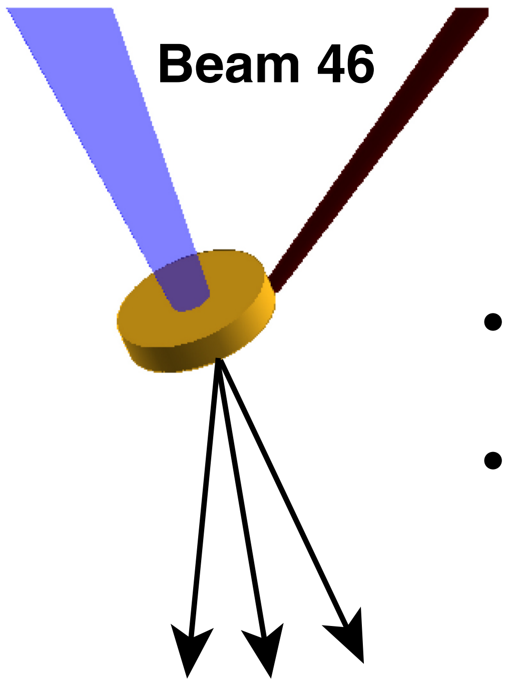
The preheat experiments measured LEH window transmission and gas heating using a single OMEGA beam

Up to 200 J of 3ω light was used to study preheat

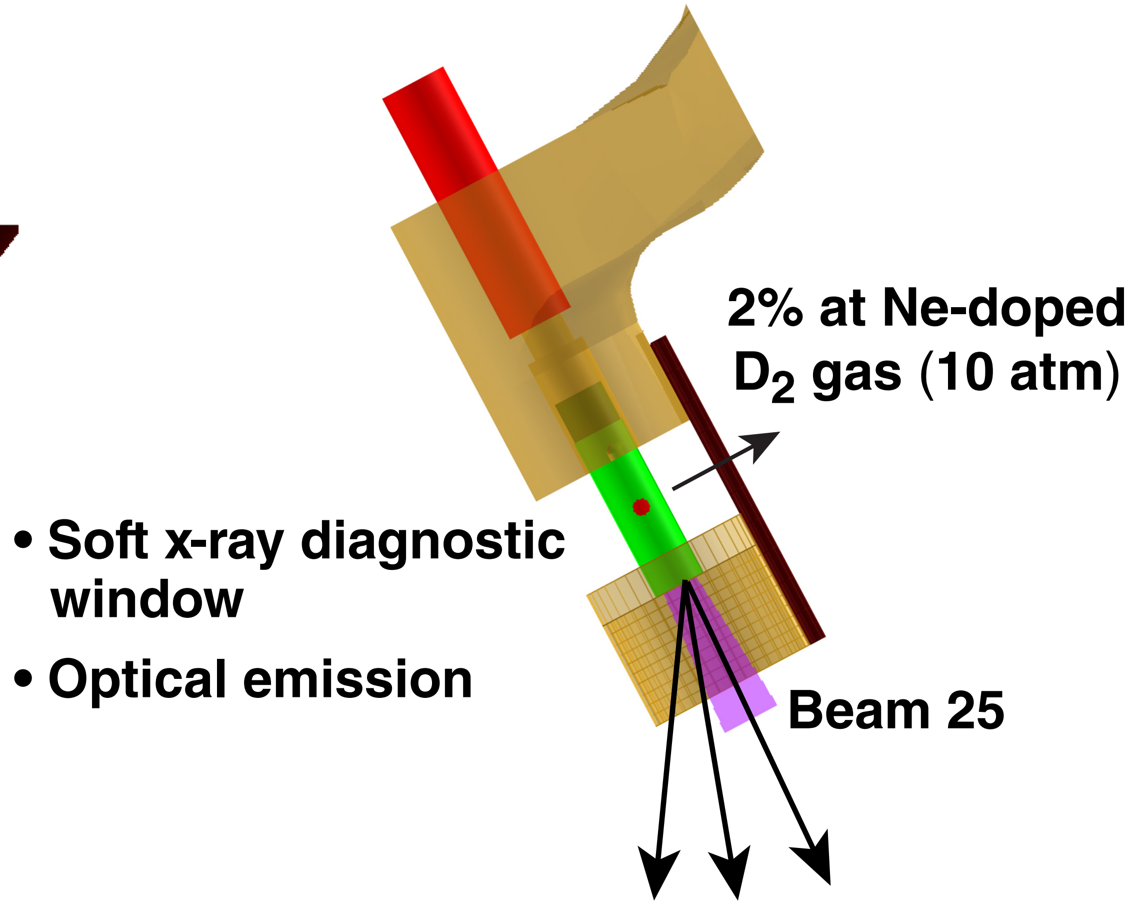
- Soft x-ray emission
- Optical emission



Backscatter measurements



Forward-scatter measurements



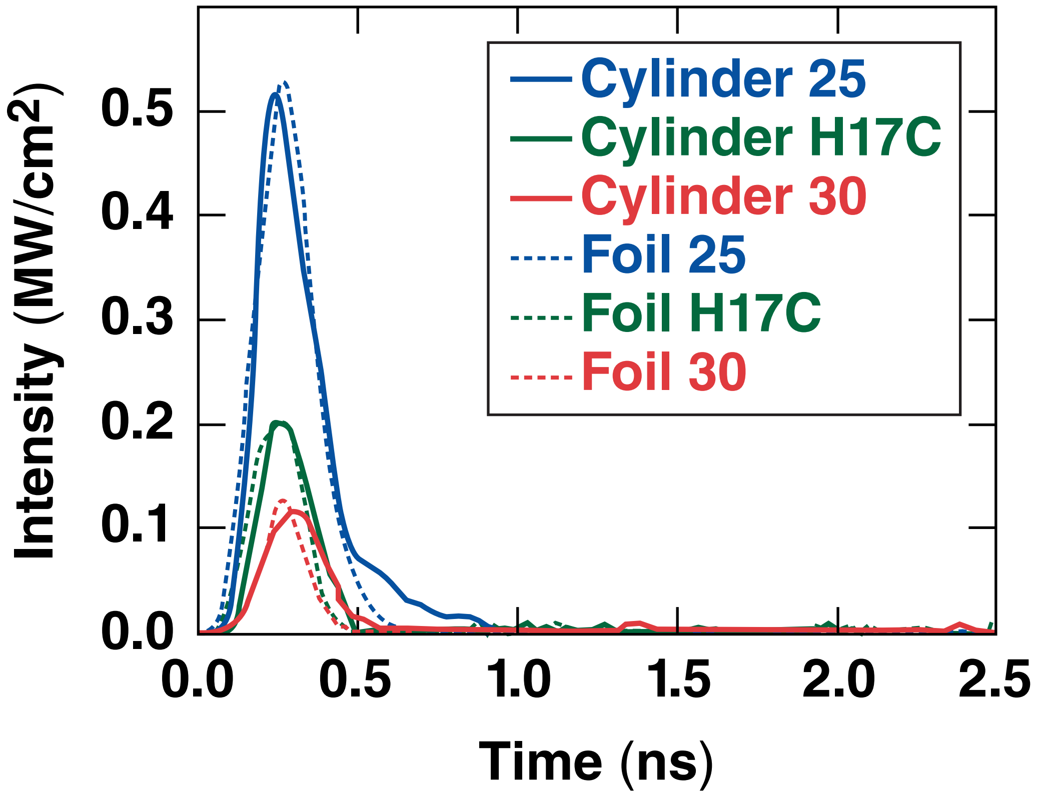
- Soft x-ray diagnostic window
- Optical emission

Backscatter measurements

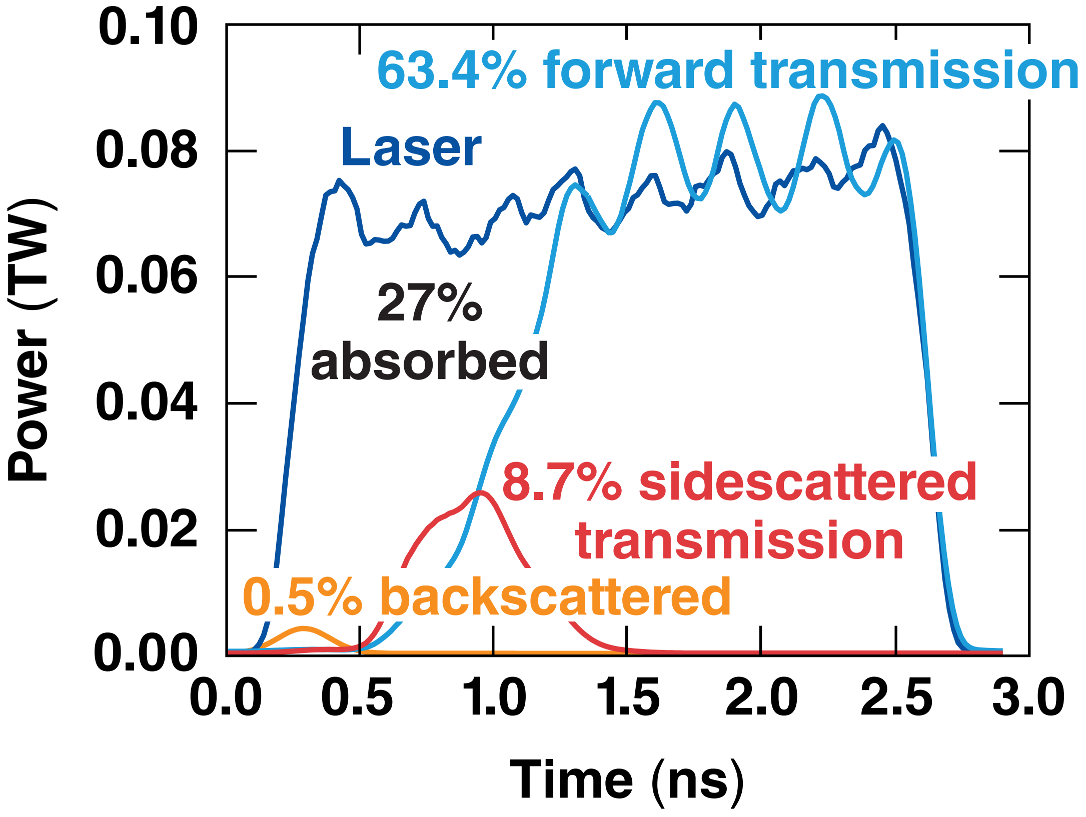
TC12451b

Foil transmission exceeds 50% with no backscatter from the gas and less than 10% sidescatter of transmitted light

Backscattered intensities measured for a full target and a foil



Total transmitted and backscattered powers calculated from two foil shots

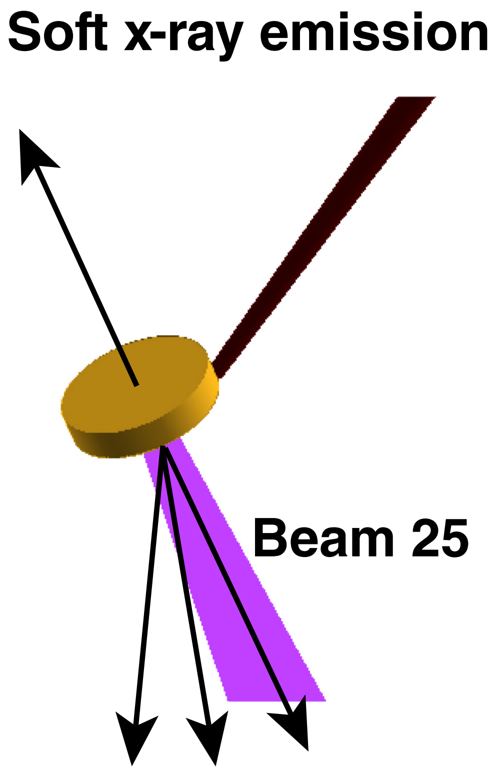


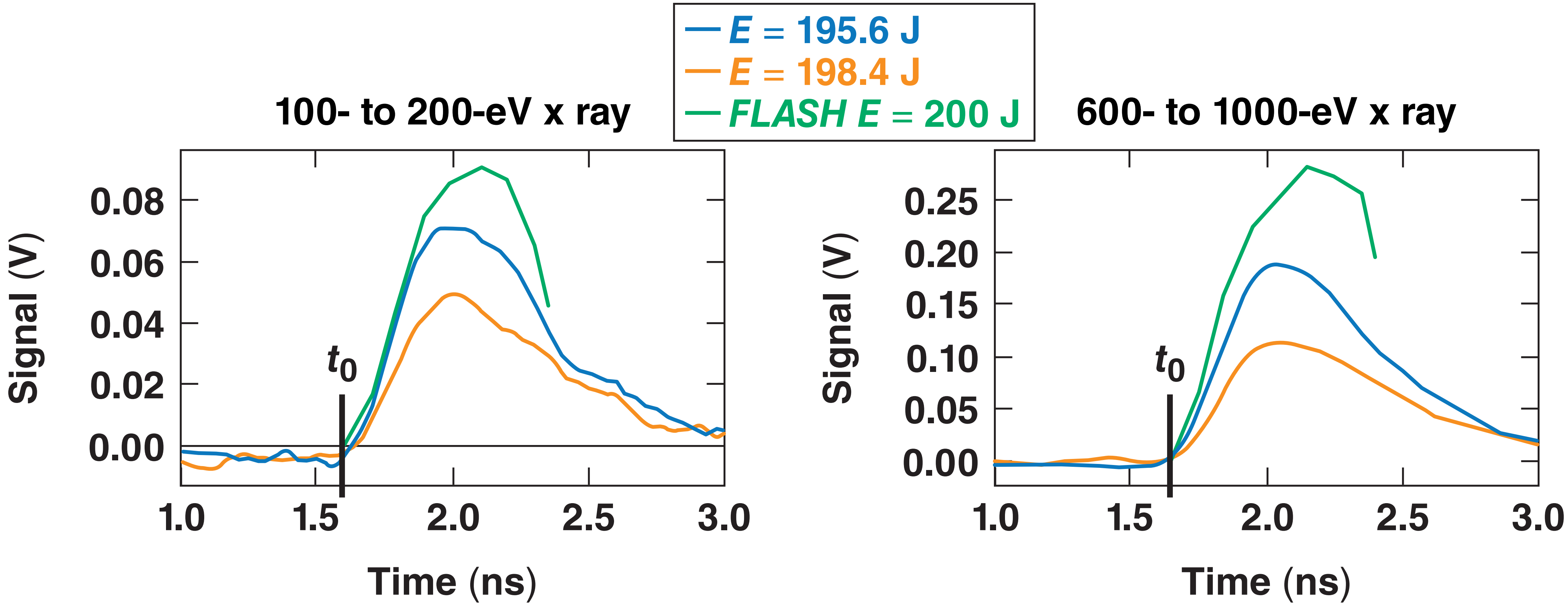
Backscatter from foils and from full targets are very similar and contain a negligible amount of the laser energy.

TC12456b

X-ray measurements of the LEH window disassembly is in good agreement relative to shot-to-shot variation with the 2-D hydrodynamics code *FLASH**

- Output from the *FLASH* code is post-processed using *Spect3D* atomic modeling to generate simulated filtered x-ray diode traces





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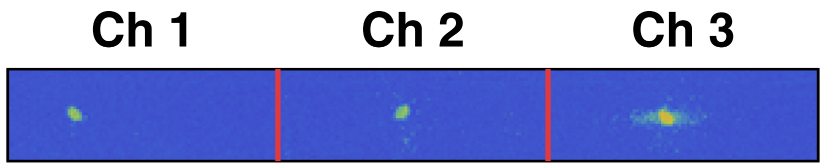
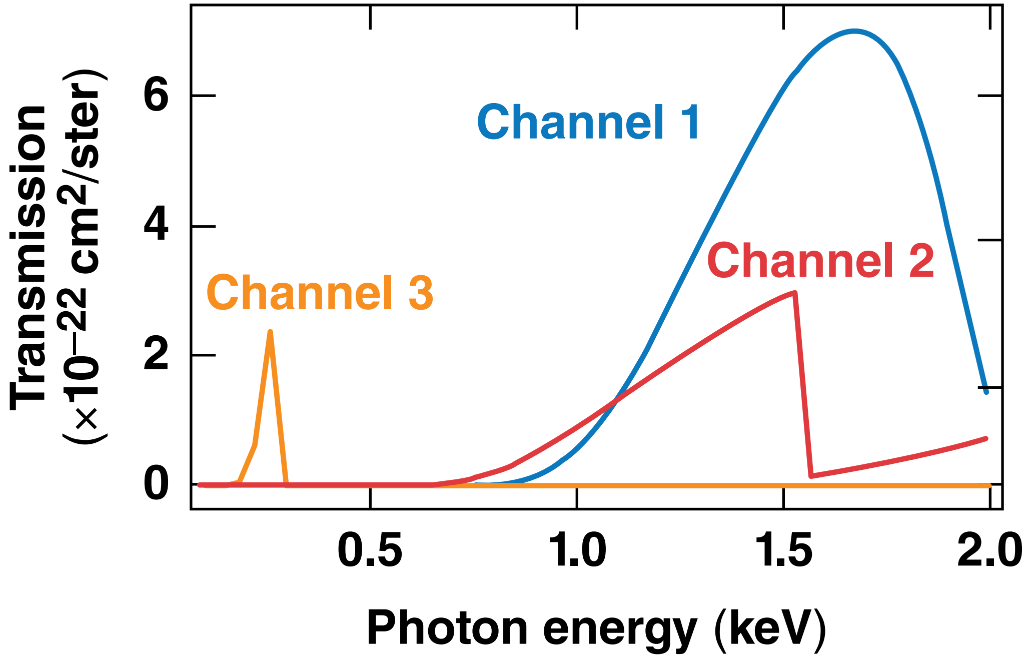
*B. Fryxell *et al.*, Astrophys. J. Suppl. Ser. 131, 273 (2000).

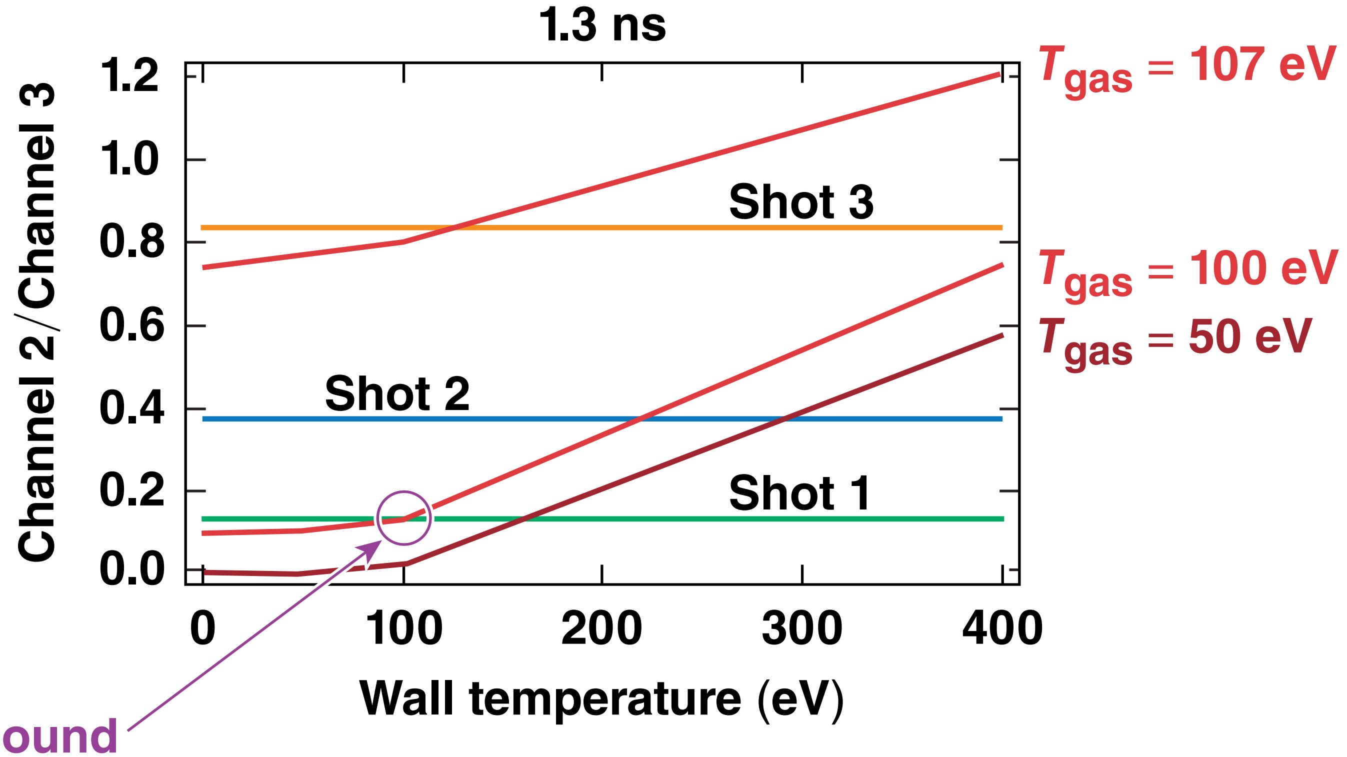
Analysis of soft x rays from the side window infer a minimum possible gas temperature of 100 eV at 1.3 ns into the laser pulse

Raw soft x-ray data



SXR response





Lower bound solution

The minimum preheat requirement can be routinely achieved.

SXR: soft x-ray framing camera

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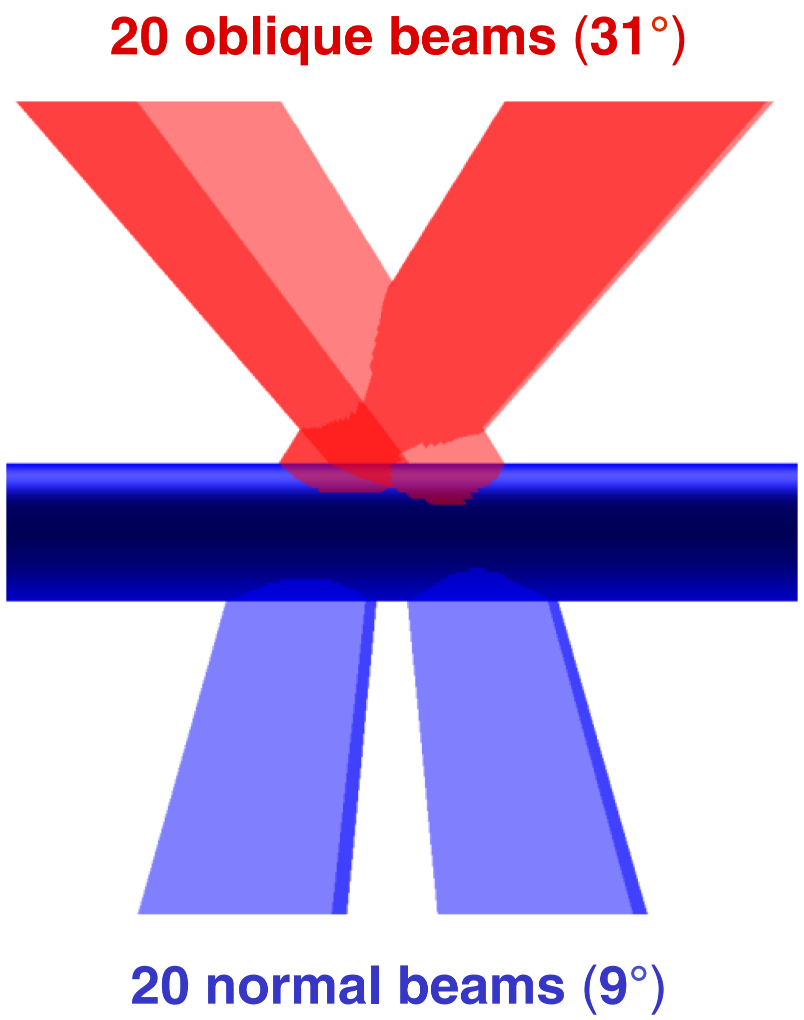
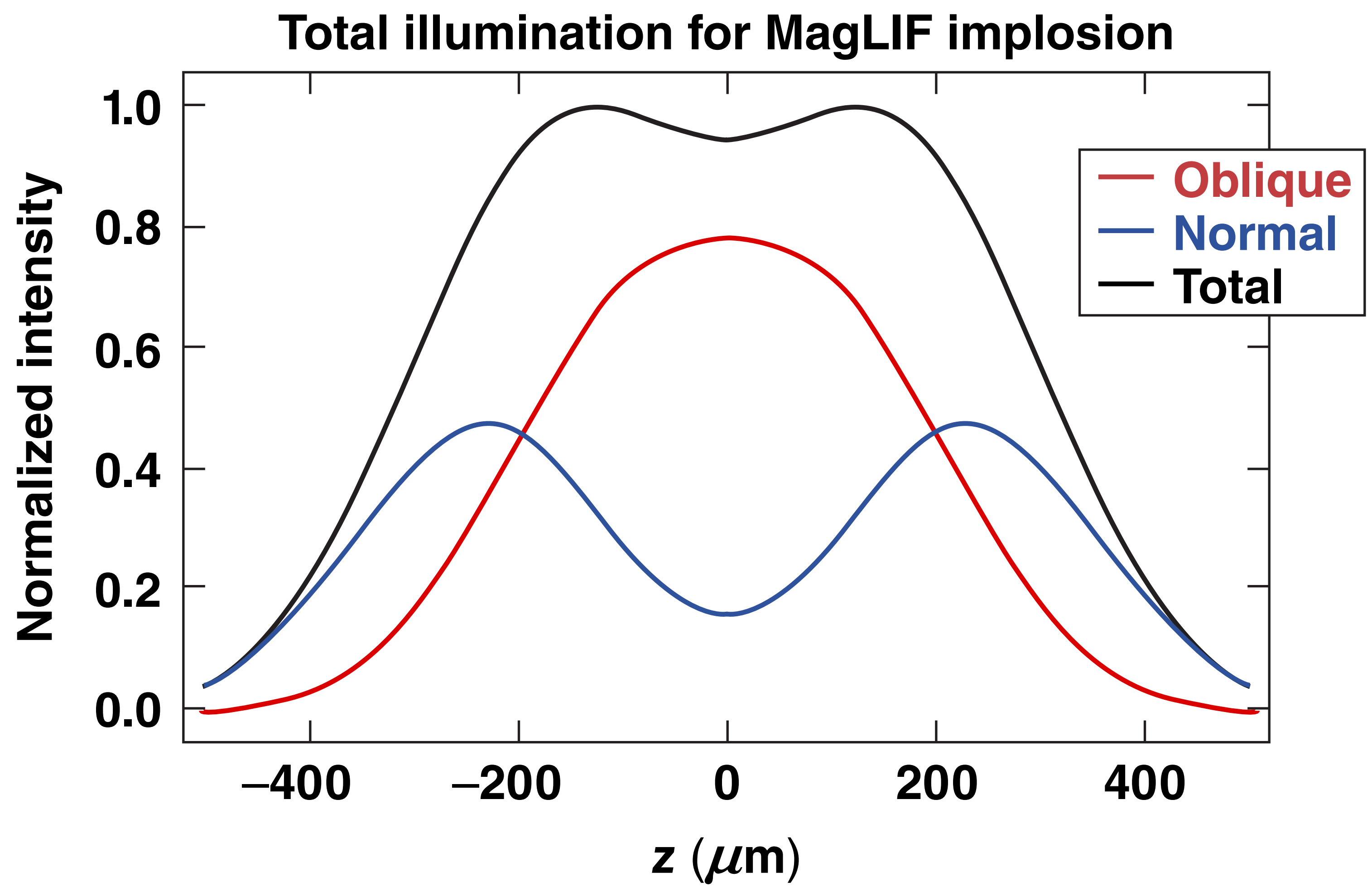
Implosion-only experiments were used to optimize the beam pointing and balance between normal and oblique beams

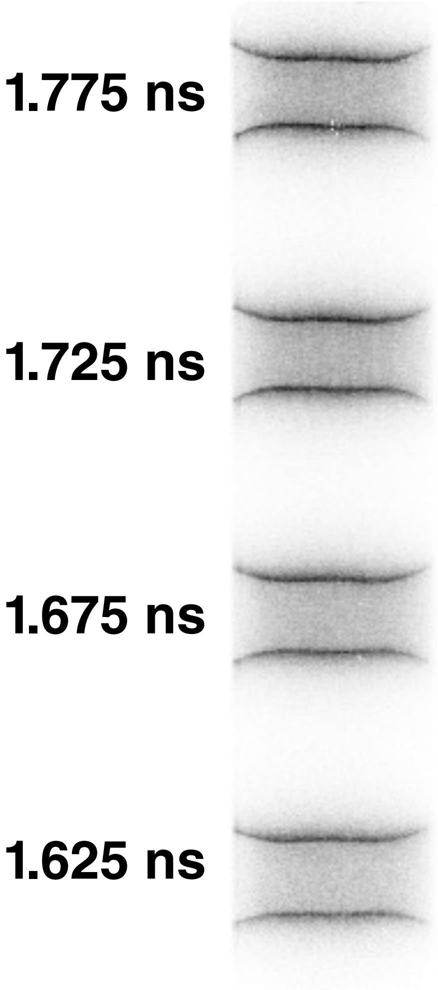


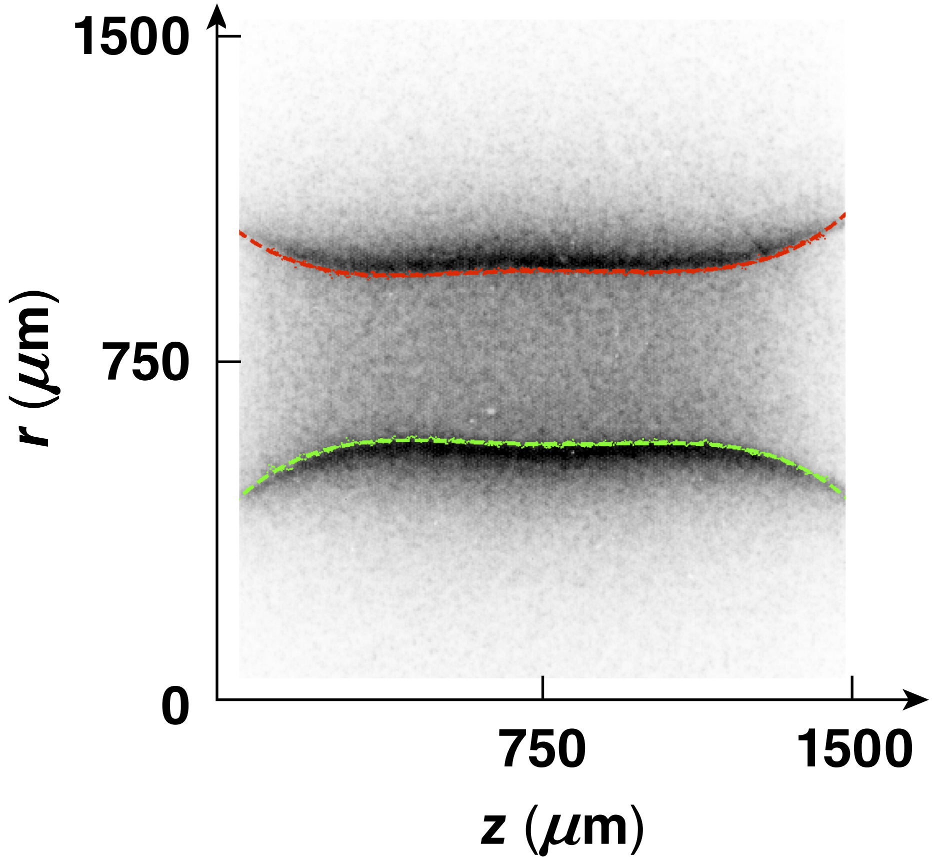


TC13144

X-ray self-emission images show that obtaining a uniform implosion over the maximum length requires reduced energy in the normal beams

- **Each image is curve fit to find the shell shape in terms of polynomial coefficients**
- **The ratio of *b*/*a* determines whether the shell ends are over/underdriven**



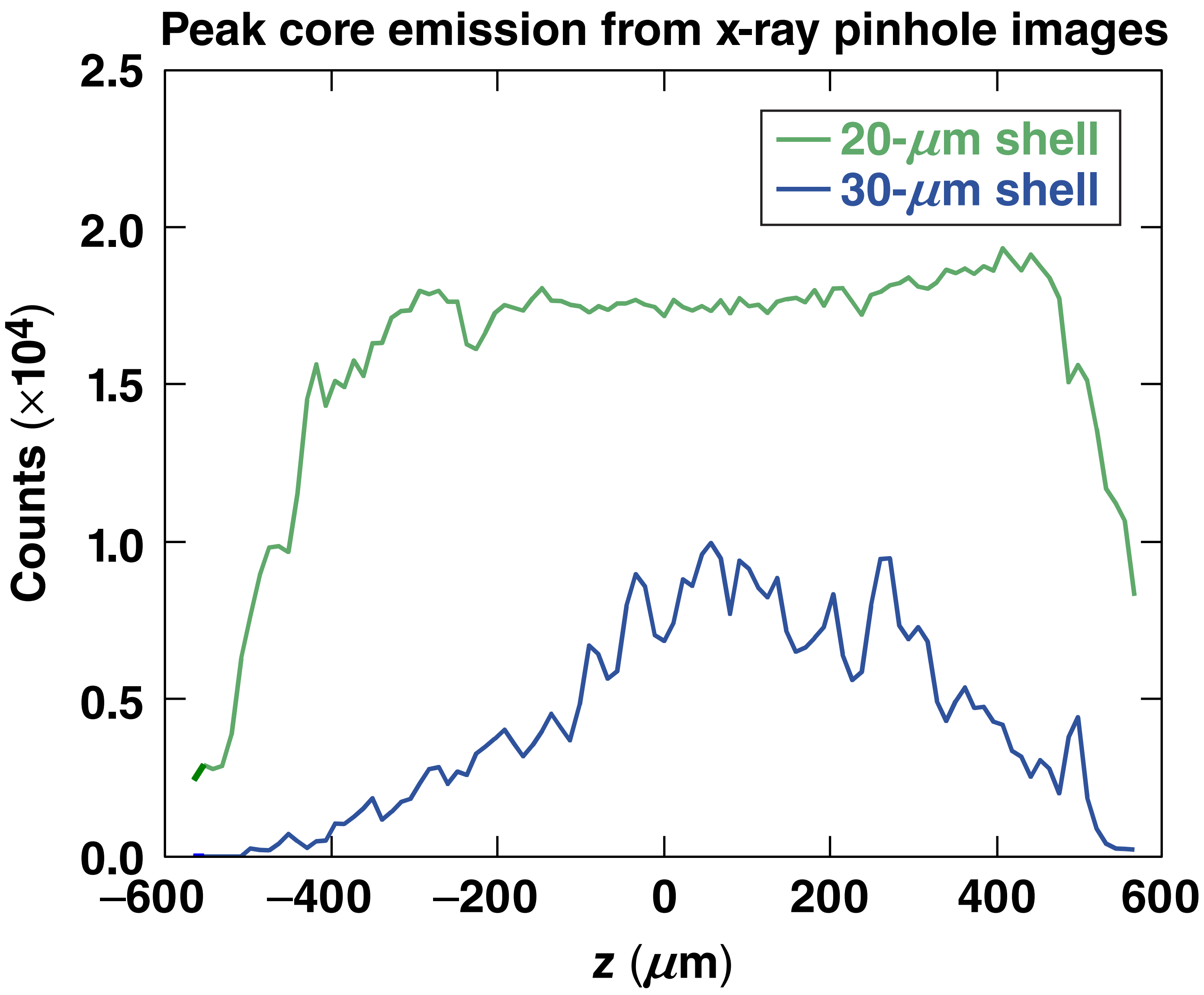


Fitting function:

$$R(z) = a + b\,(z - z_0)^2 + c\,(z - z_0)^4$$

TC13145

Time-integrated x-ray pinhole lineouts demonstrate that thinner shells provide a more uniform core



- For a thinner shell with the same nominal drive, the core emission becomes longer and flatter

- This suggests that a faster implosion is needed at the OMEGA scale to mitigate end losses

E13146

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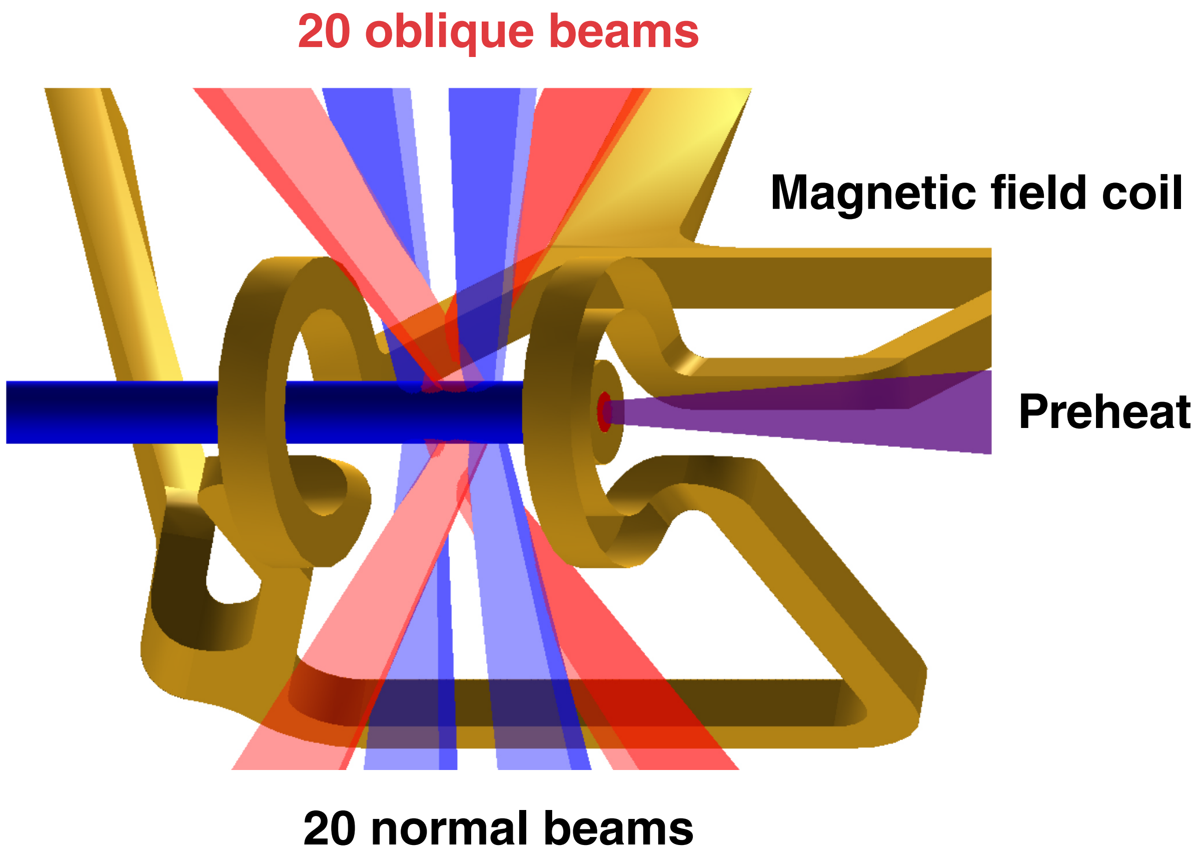
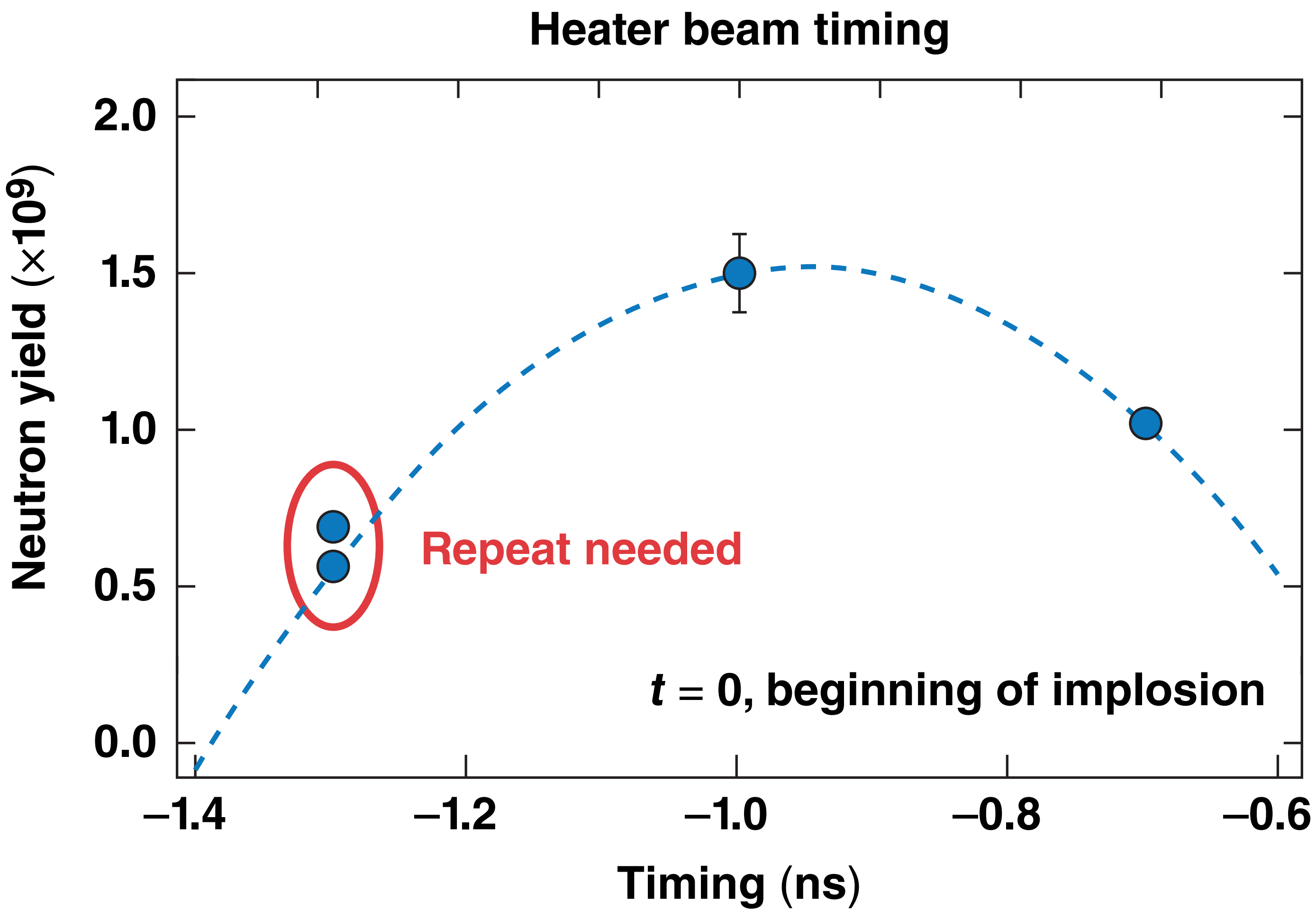
The first integrated MagLIF experiments scanned preheat beam timing

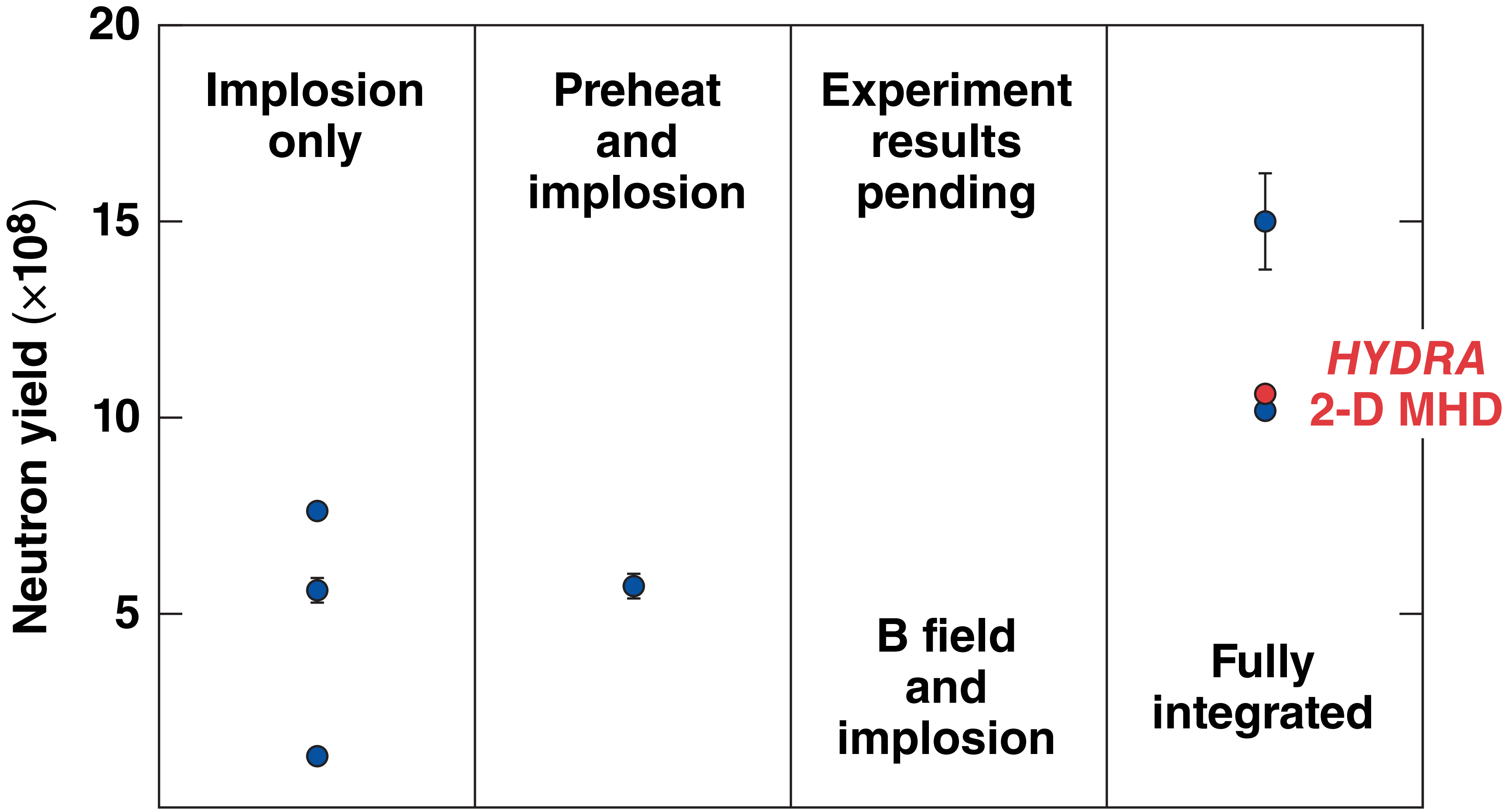
- The optimum preheat timing appears to be around 1 ns before the drive beams, in agreement with simulations
  - must repeat 1.3-ns shots because of poor implosion quality





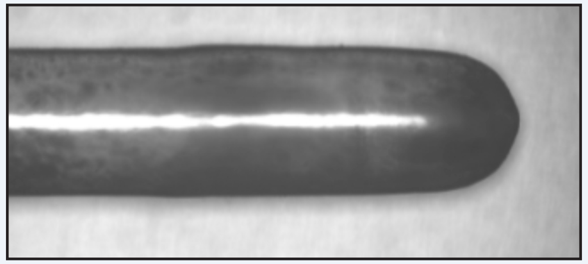
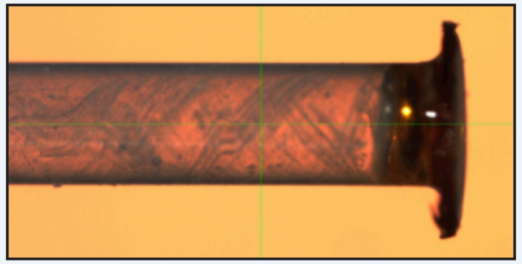
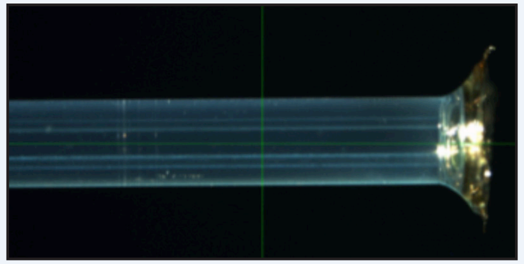
TC13147

Yield enhancement from both preheat and magnetic field, and preheat only match closely with simulation predictions



TC13148

Improvements in target fabrication have increased yields of implosion-only shots

November 2015	July 2016	September 2016
		
Highest yields		
7.49×10^7	7.65×10^8	1.04×10^9

The MagLIF platform is continuing to develop and improve.

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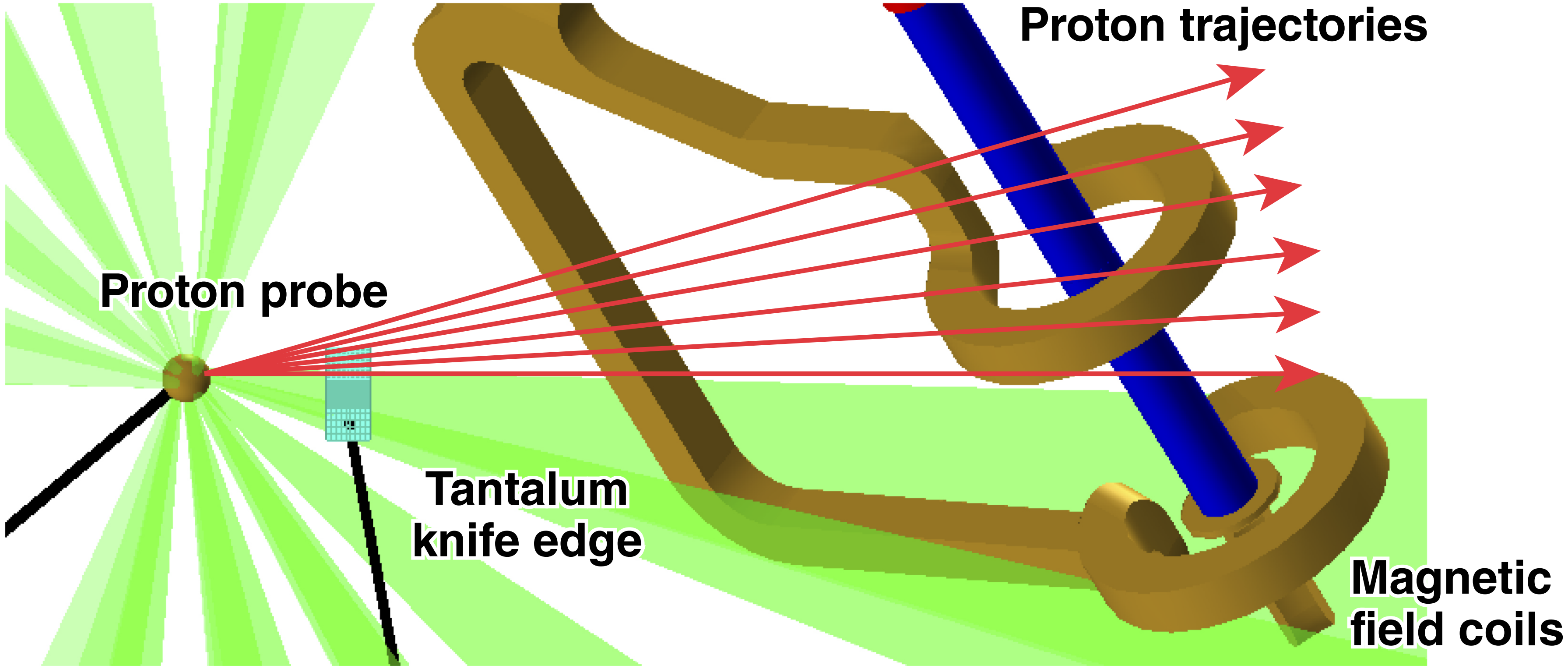
Measurements of axial magnetic-field compression will be made next week

- Probing magnetic-field advection within the hot spot will validate MHD simulations and the inclusion of the Nernst effect



The Nernst effect provides an additional advection velocity to the magnetic field proportional to the electron heat flow:*

$$\frac{\partial \vec{B}}{\partial t} = \nabla \times \left(\vec{v}_{\mathrm{eff}} \times \vec{B}\right) + \ldots$$

$$\vec{v}_{\mathrm{eff}} = \vec{v} - \frac{\vec{j}}{n_e e} + \frac{\vec{q}_e}{2.5\, P_e}$$

TC13150

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*M. G. Haines, Plasma Phys. Control. Fusion 28 1705 (1986).

Experiments to explore the MagLIF parameter space are scheduled over the next year

- **B-field scan**
  - – optimum B field is a key question for MagLIF
  - – scaling with B field to study Nernst effect
  - – experiment with new techniques to reach higher fields
- **Fill-density scan**
  - – determine highest achievable convergence ratio
- **Shell-thickness scan**
  - – determine minimum thickness possible
  - – laser-driven MagLIF has the ability to use thinner shells with higher implosion velocities because of ablative stabilization of the Rayleigh–Taylor instability

TC13151

Summary/Conclusions

Laser-driven magnetized liner inertial fusion (MagLIF) on OMEGA is providing the first experimental data on scaling

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TC13137