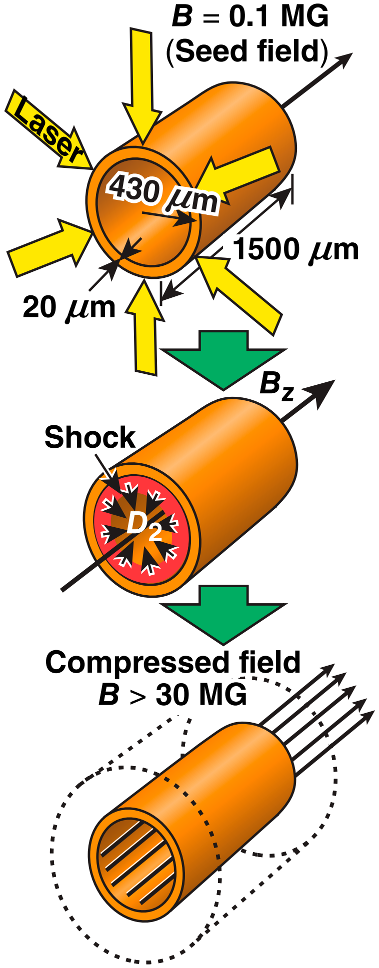
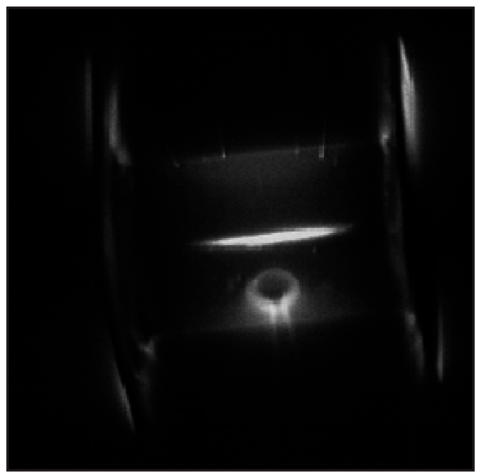
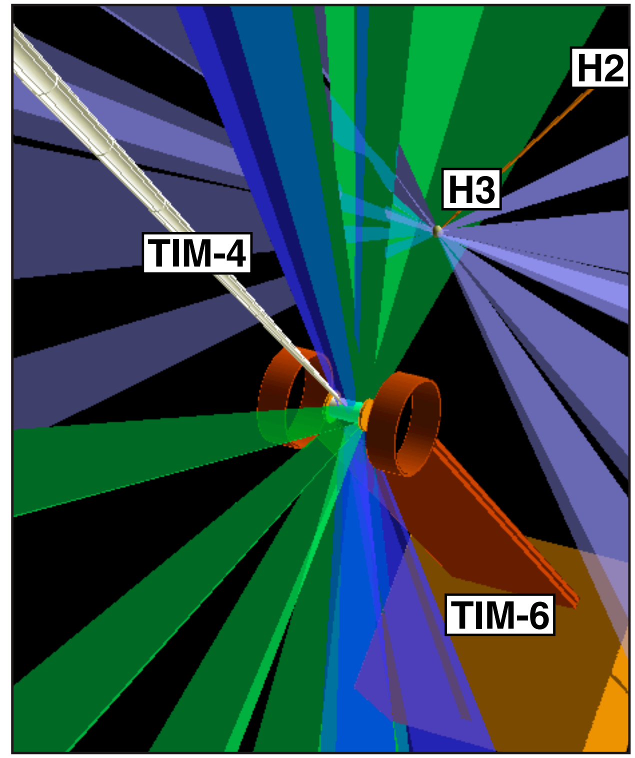
Magnetized Hot-Spot Implosions Via Laser-Driven Flux Compression







O. V. Gotchev
University of Rochester
Laboratory for Laser Energetics

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Summary

Experiments indicate the feasibility of laser-driven flux compression in HED plasmas

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- Magnetized cylindrical targets were imploded on OMEGA to compress a pre-seeded magnetic flux to high values.
- An ~100-kG seed magnetic field was generated with a double coil driven by a portable capacitive discharge system (MIFEDS).
- Proton deflectometry along with data interpretation tools was developed and used to detect the compressed magnetic fields.
- There is compelling evidence that the magnetic field is compressed to multi-megagauss values.
- Spherical implosions in axial fields are planned to study the heat transport in the conduction zone in the presence of the seed field.

Collaborators

**R. Betti, P. Chang, J. P. Knauer,
and D. D. Meyerhofer**

University of Rochester
Laboratory for Laser Energetics

**J. A. Frenje, C. K. Li, M. Manuel, R. D. Petrasso,
and F. H. Séguin**

Plasma Science and Fusion Center
Massachusetts Institute of Technology

A megagauss field can expand the ICF gain window or alternatively, reduce the energy required for ignition

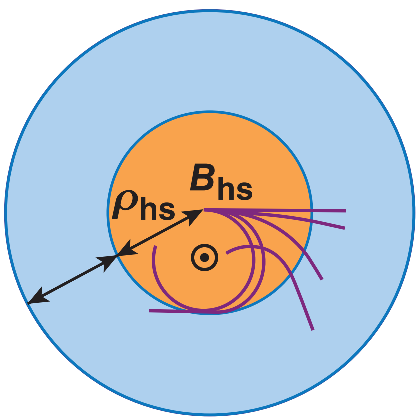
- An igniting targets' gain scales inversely with implosion velocity υ_i,*

$$G = \frac{E_{\text{fusion}}}{E_{\text{Laser}}} = \sim \frac{1}{\upsilon_i^{1.25}}, \text{ but } T_{hs} \sim \upsilon_i^{1.25}.$$

- A megagauss magnetic field should reduce thermal conduction losses in the forming hot spot.

$$\kappa \sim T_e \tau_e \sim T_e^{5/2} \rightarrow \kappa_\perp \sim \frac{T_e \tau_e}{(\omega_{ce}\tau_e)^2} \sim \frac{1}{B^2 T_e^{1/2}}$$

- Considering the NIF 1.5-MJ, direct-drive point design,** $\rho_{hs} \approx 30$ g/cc, $T_{hs} \approx 7$ keV (before ignition), $r_{hs} \approx 50$ μm.

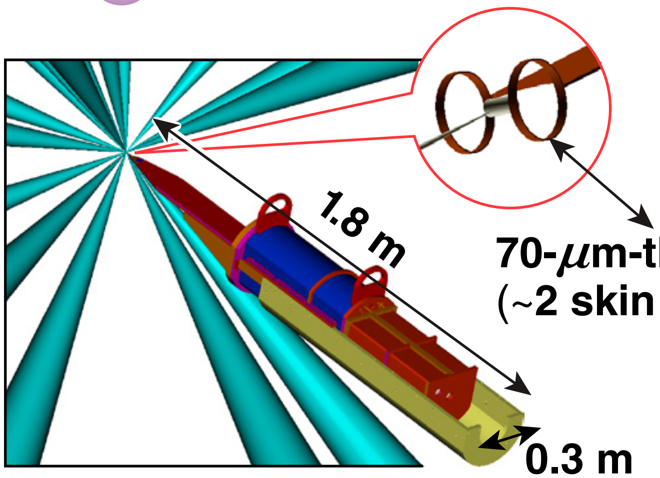


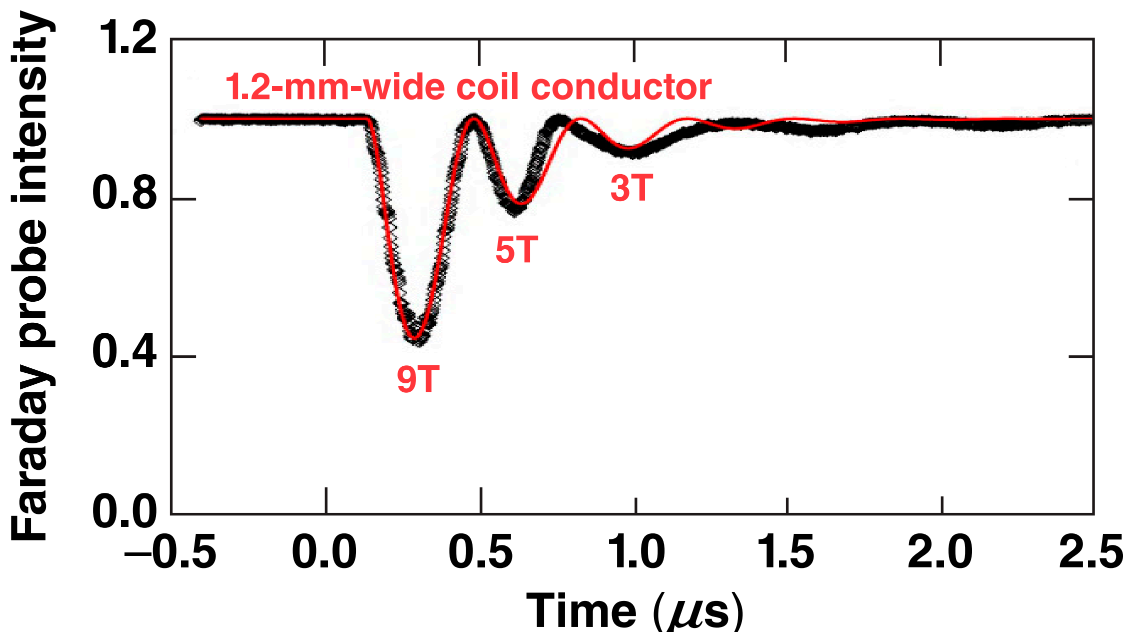
$B_{hs} \sim 10$ MG		$B_{hs} \sim 100$ MG	
$\beta \approx 4 \times 10^4$	$\kappa_\perp \approx 0.2\ \kappa_{\parallel}$ for $\omega_{ce}\tau_e \approx 1.2$	$\beta \approx 4 \times 10^2$	$\kappa_\perp \approx 0.01\ \kappa_{\parallel}$ for $\omega_{ce}\tau_e \approx 12$
$\rho_\alpha = 270$ μm	$\rho_\alpha/\rho_{hs} > 5$	$\rho_\alpha = 27$ μm	α-particles magnetically trapped: $\rho_\alpha/\rho_{hs} \approx 0.5$, $\omega_{c\alpha}\tau_\alpha \approx 0.1$

E17121a

* R. Betti and C. Zhou, Phys. Plasmas 12, 110702 (2005).
** P. W. McKenty *et al.*, Phys. Plasmas 8, 2315 (2001).

The seed magnetic field is generated in a double-coil geometry optimized for OMEGA implosions





MIFEDS seed-field generator

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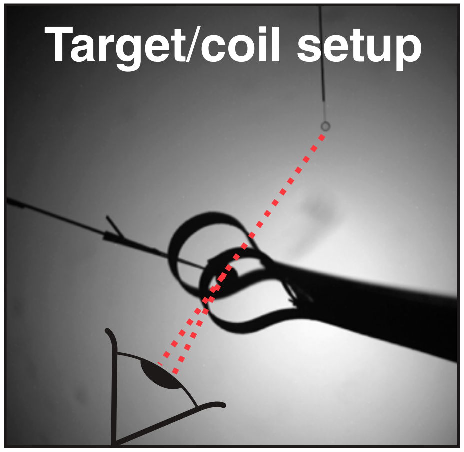
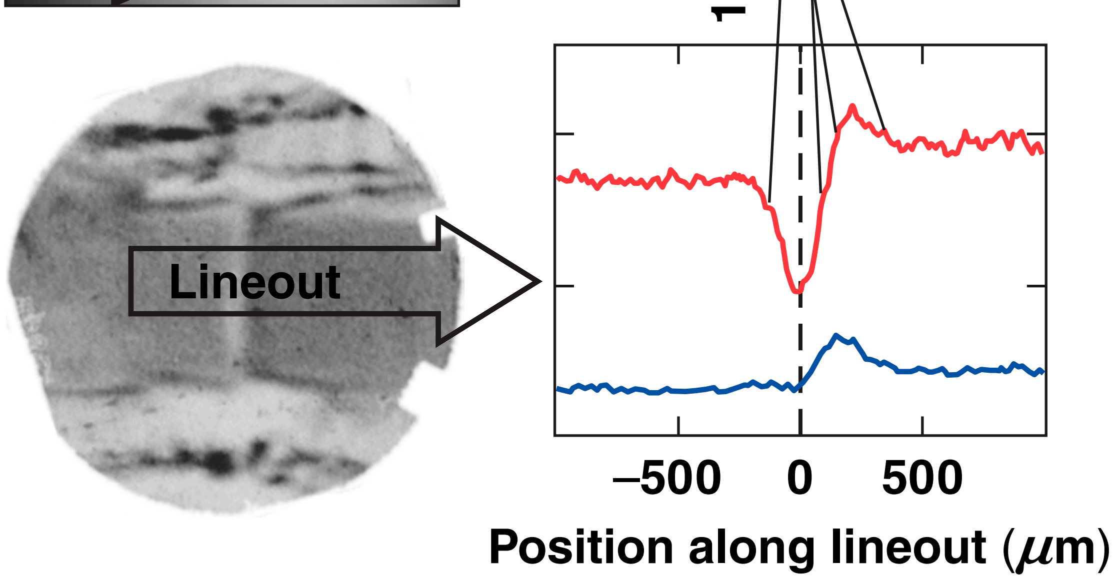
The field in the compressed core is probed by 15-MeV protons from the implosion of a D^3He-filled target





- Selection of tracks by diameter (energy) is used to expose the particles deflected in the amplified field.
- A powerful method that can help infer the core density and field profiles and promote particles deflected by the field peak above the background.

*See for example C.K.Li *et al.* (BI1.00005) and M. Manuel *et al.* (YP6.00011).

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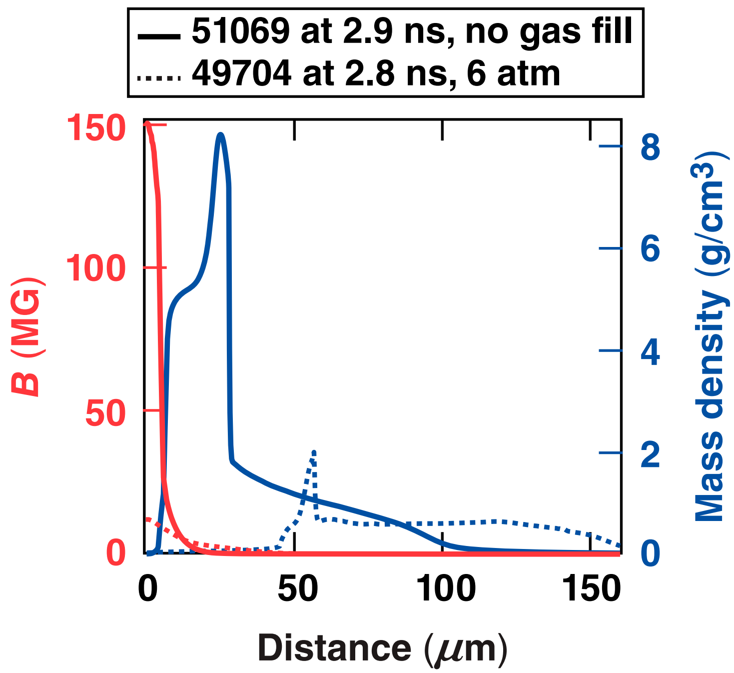
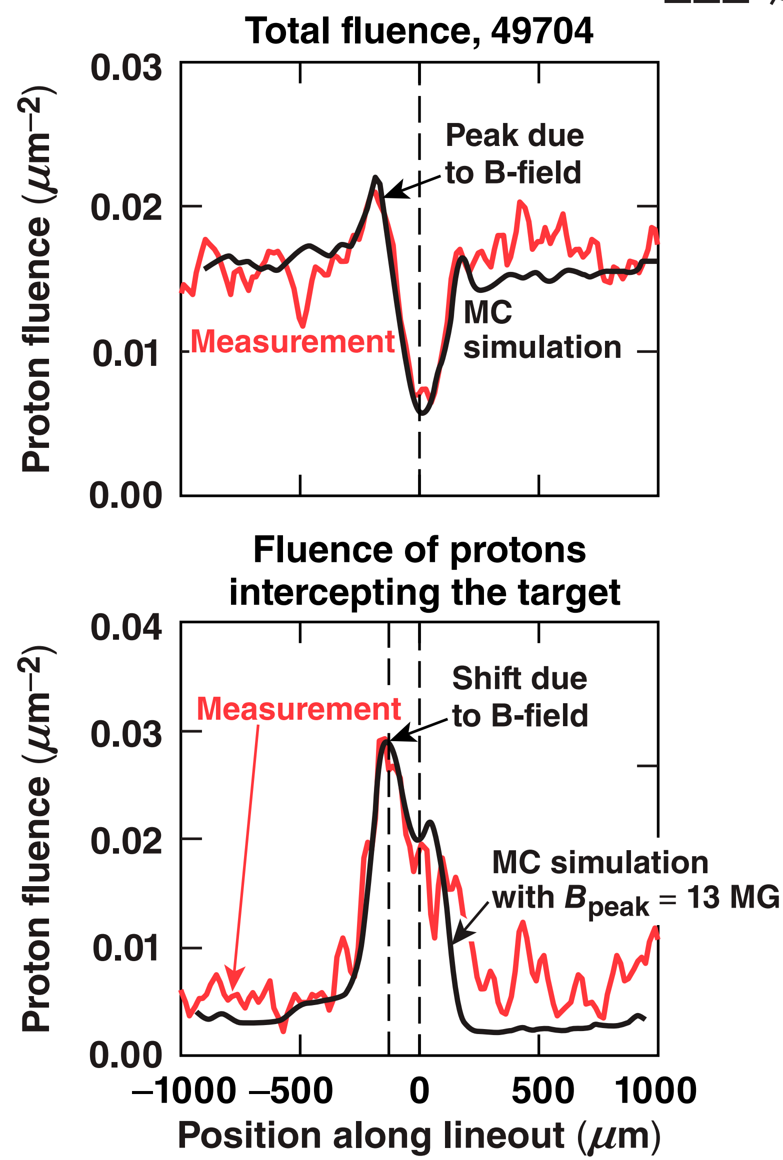
Field amplification has been observed in all the magnetized implosions probed by protons

Density and field profiles from *LILAC*-MHD
(~60% of the initial flux retained)

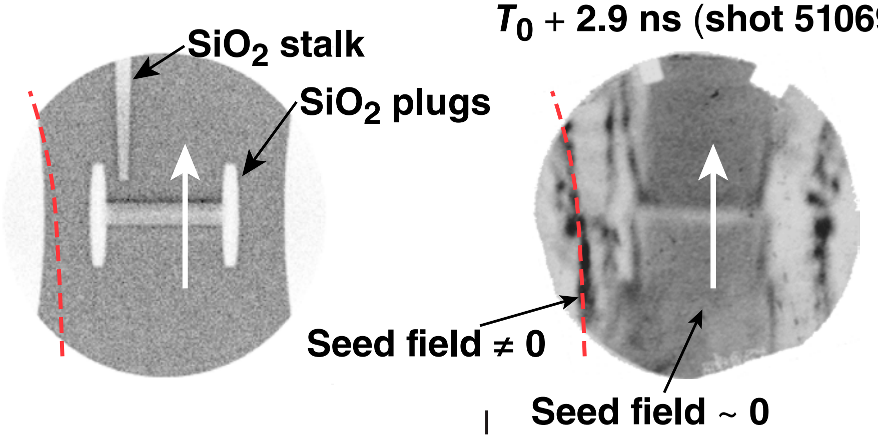


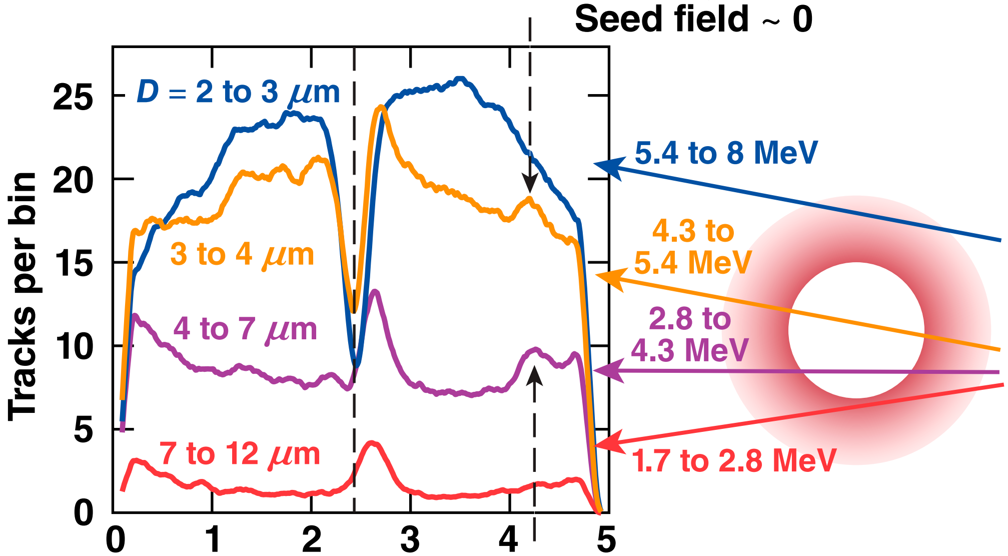


The particle transport code GEANT4 uses the hydro simulation profiles to match the experiment under the constraint of flux and mass conservation

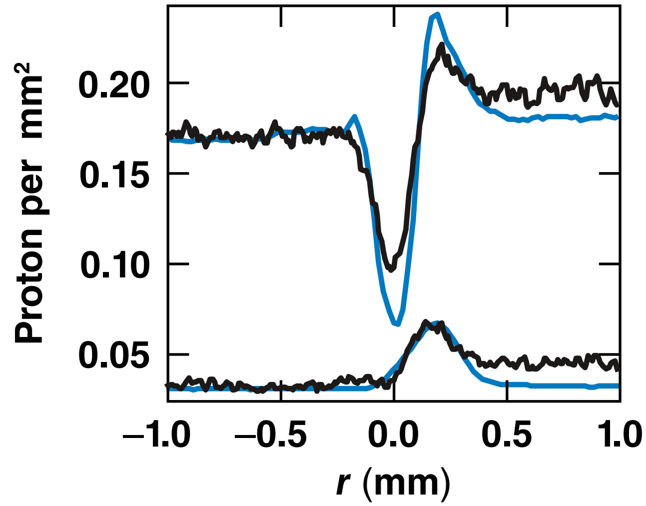
Strong magnetic field (B > 30 MG) is present in the compressed core in low-fill-pressure shot 51069

Proton maps at
T_0 + 2.9 ns (shot 51069)





Experimental data at various energy bands
(paths through the target)



Experimental and simulated
proton maps
(total and core-traversing)

- The sharp field peak results in strong deflection.
- 30-MG average core field is the lowest value that can match this deflection.

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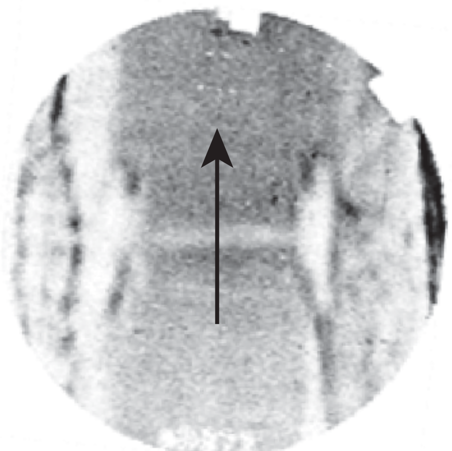
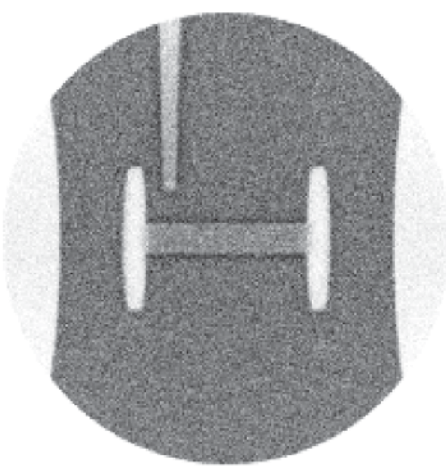
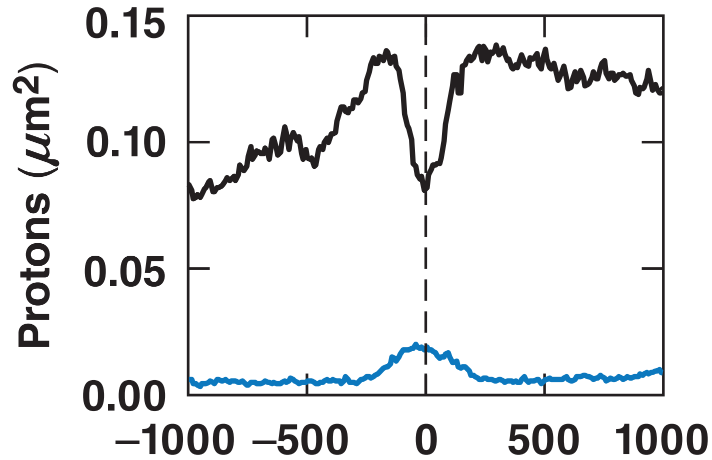
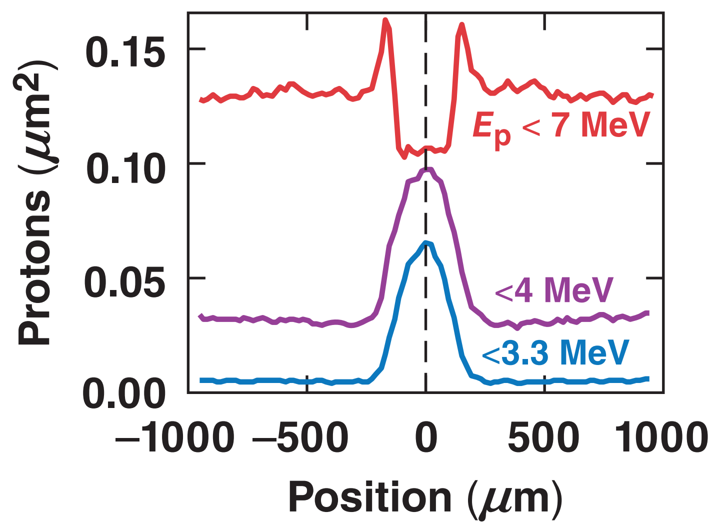
Null (no field) experiments were also performed showing no deflection of the core-traversing protons

Proton map at $T_0 + 2.9$ ns
(shot 51073, 2-h etch)









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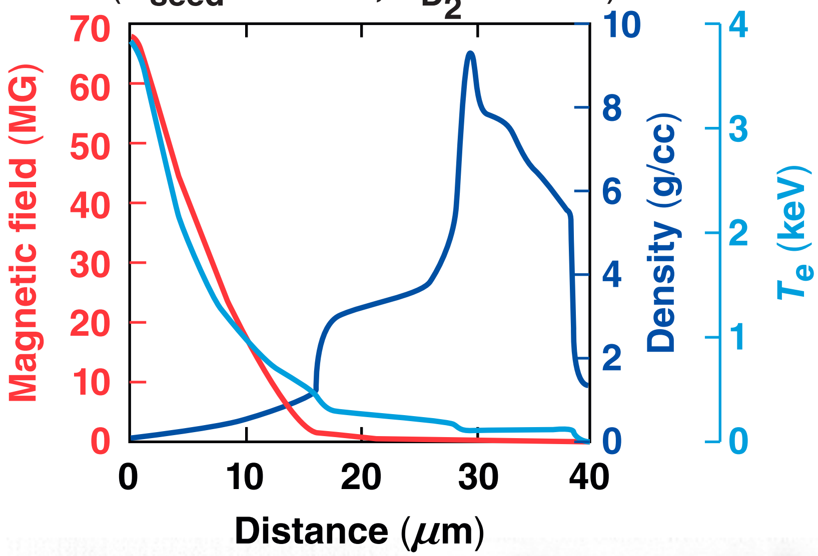
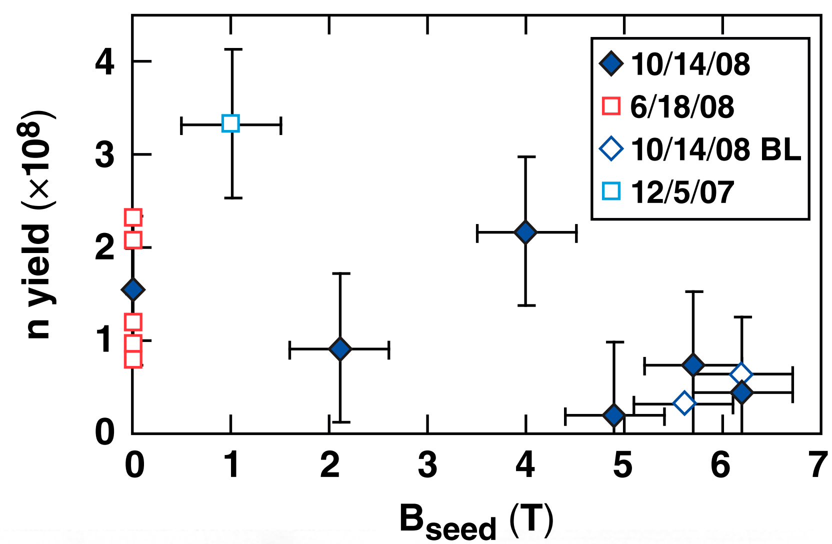
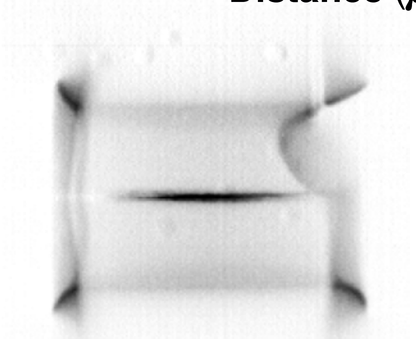
LILAC-MHD simulations (1-D) predict a 3 to 4× increase in the neutron yield of magnetized targets

Profiles at stagnation (B_{seed} = 80 kG, P_{D_2} = 8 atm)

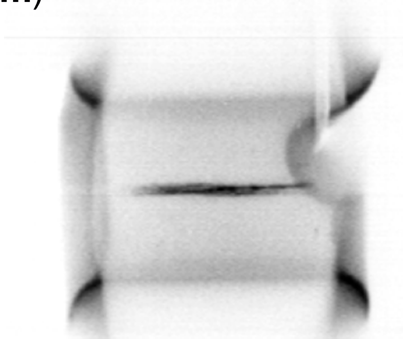


Yield versus seed field for magnetized target shots



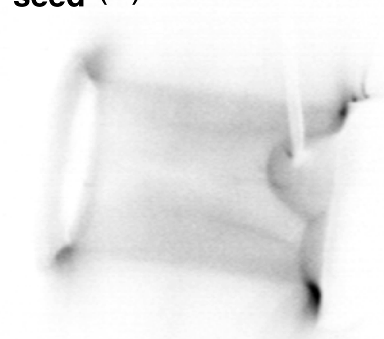


52527
4T seed field
$Y_n = 2.2 \times 10^8$



52538
no seed field
$Y_n = 1.54 \times 10^8$

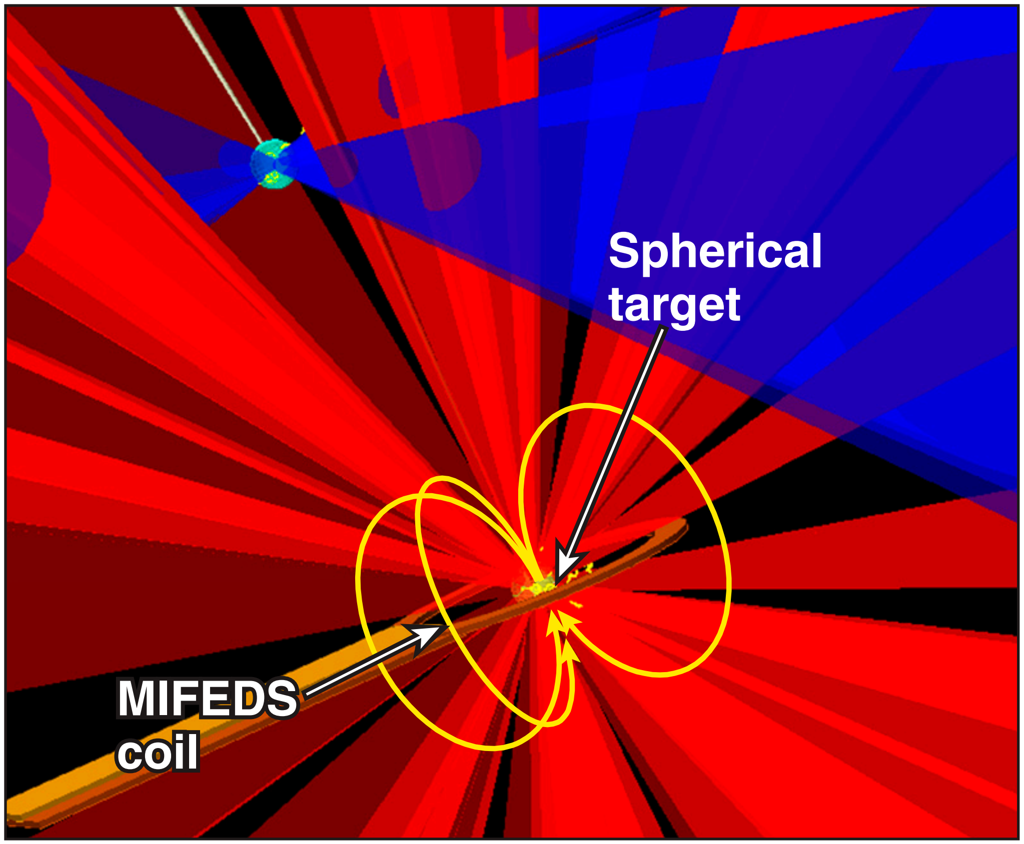
52537
5T seed field
$Y_n = 2 \times 10^7$



52536
5.6T seed field
Y_n undetectable

E16183c

Spherical implosions in an axial field can shed light on possible heat transport inhibition in the ablation region



- Shots with and without an embedded dipole field can be compared.
- A significant field-induced thermal-transport inhibition should manifest itself in an asymmetric drive.
- Shot-to-shot variation is expected to be under better control for spherical targets.
- Core temperature, magnetic field, and neutron yields will also be measured.

Summary/Conclusions

Experiments indicate the feasibility of laser-driven flux compression in HED plasmas

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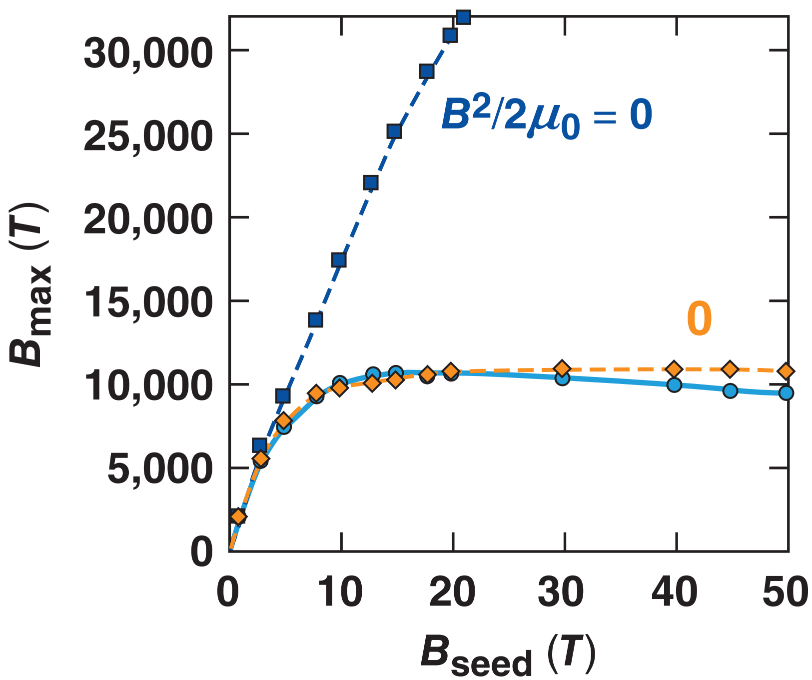
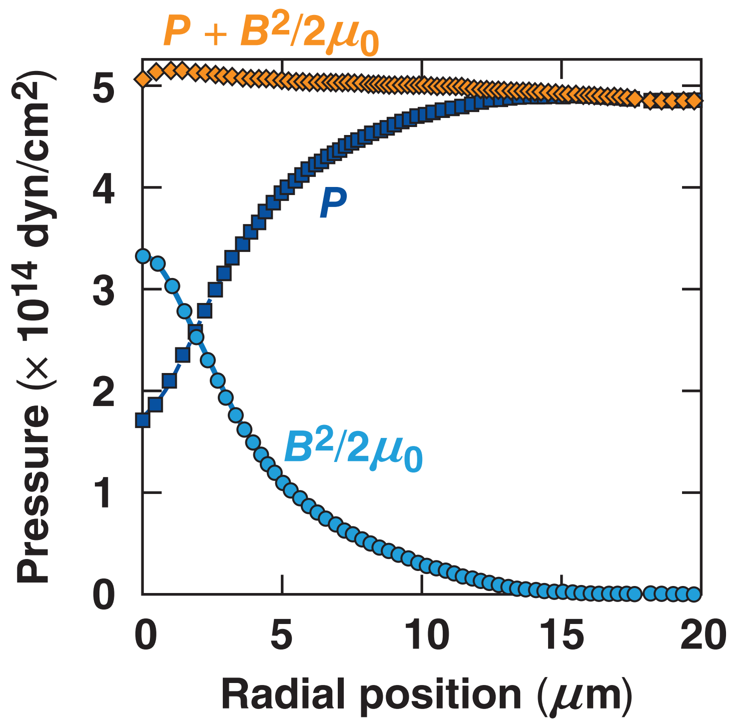
- Magnetized cylindrical targets were imploded on OMEGA to compress a pre-seeded magnetic flux to high values.
- An ~100-kG seed magnetic field was generated with a double coil driven by a portable capacitive discharge system (MIFEDS).
- Proton deflectometry along with data interpretation tools was developed and used to detect the compressed magnetic fields.
- There is compelling evidence that the magnetic field is compressed to multi-megagauss values.
- Spherical implosions in axial fields are planned to study the heat transport in the conduction zone in the presence of the seed field.

The hot-spot beta affects the implosion dynamics, setting an optimum of the seed field

- The maximum compressed field on OMEGA is limited by the driver energy to ~10,000 *T* (at ~12 *T* seed field).



LILAC-MHD simulations show that the magnetic pressure in the hot spot affects peak compression.

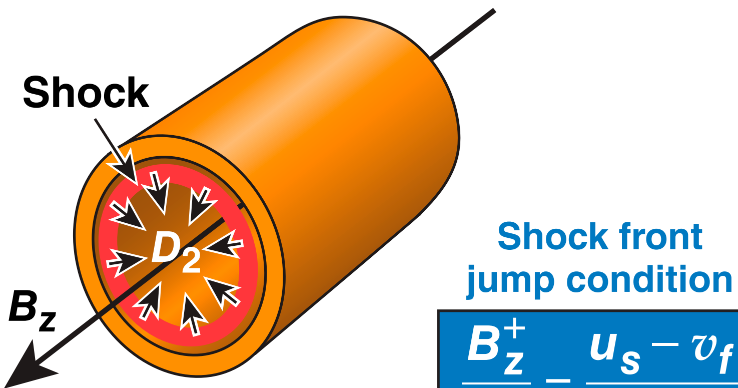


There is a balance between $B^2/2\mu_0$ and the hot-spot pressure that sets the pressure profile (plotted for B_{seed} = 8 *T*).

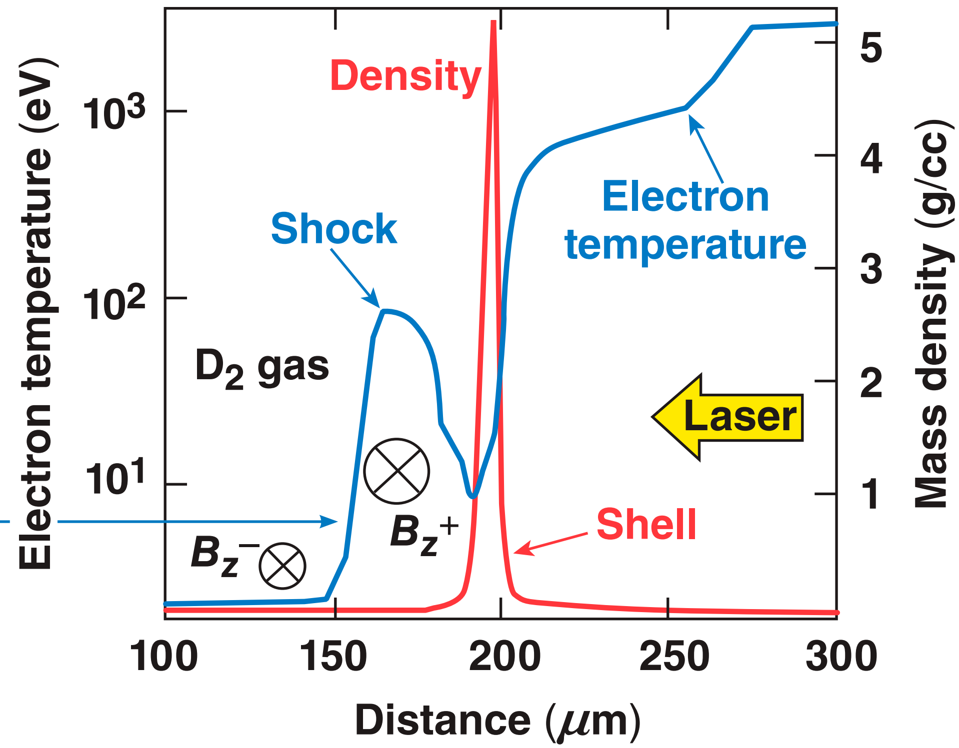
E16911

The magnetic field is first trapped in the shock-ionized gas fill and then compressed by the imploding shell

$$B_{z\,max} \cong B_0 \left(\frac{R_0}{R_{min}}\right)^{2(1-1/Re_m)}$$



$$\frac{B_z^+}{B_z^-} = \frac{u_s - v_f}{u_s - v_i}$$



- In OMEGA cylindrical implosions, Re_m is high (>50) due to the high-implosion velocity (>10^7 cm/s) and plasma conductivity ($\sigma \sim 10^{18}$ s^{-1}) in the ionized gas fill.

E14146d