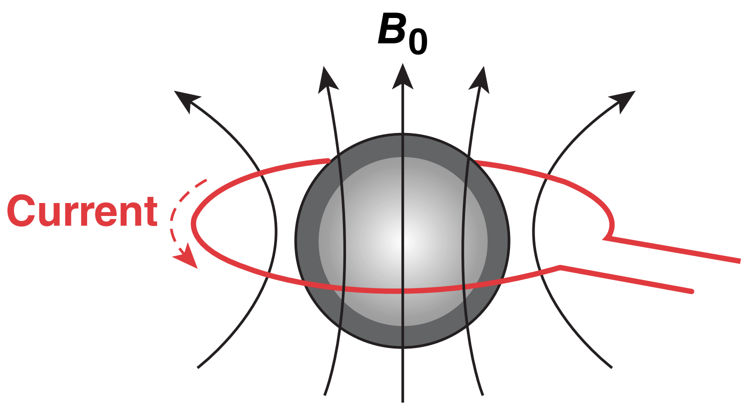
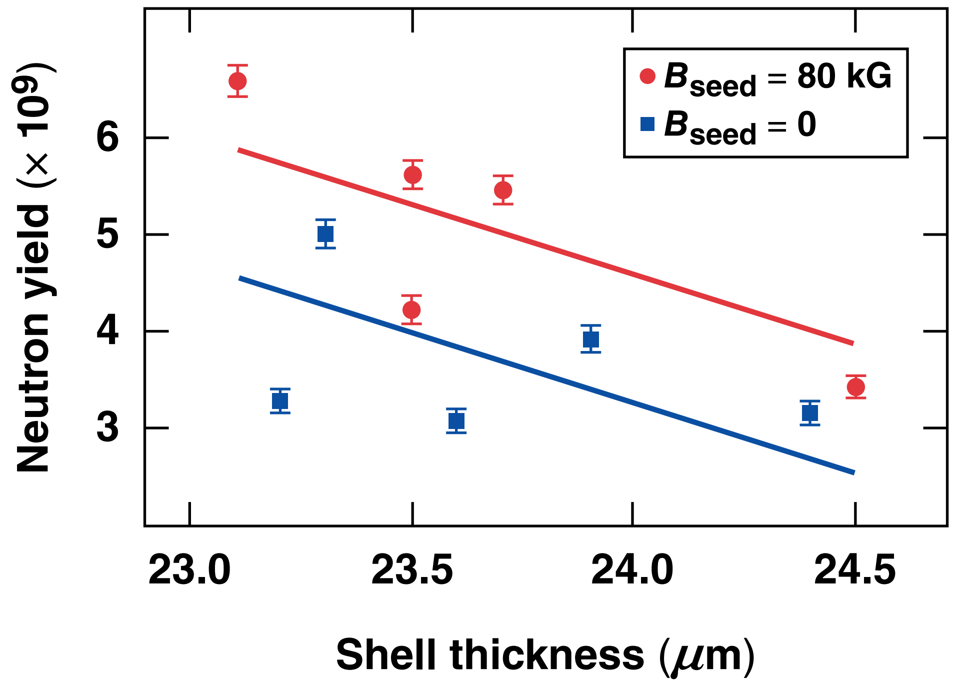
Inertial Confinement Fusion Implosions with Seeded Magnetic Fields on OMEGA





M. Hohenberger
University of Rochester
Laboratory for Laser Energetics

53rd Annual Meeting of the
American Physical Society
Division of Plasma Physics
Salt Lake City, UT
14–18 November 2011

Summary

Laser-driven flux-compression experiments on OMEGA show fusion performance enhancement for magnetized hot spots

- A seed magnetic-field generator has been developed
- Laser-driven magnetic-field compression to tens of MG has been demonstrated in cylindrical and spherical geometry
- Ion-temperature enhancement of 15% and fusion-yield increase of 30% have been observed

Magnetization of the hot spot of an ICF implosion has been achieved for the first time.

Collaborators

P.-Y. Chang, G. Fiksel, J. P. Knauer,
D. D. Meyerhofer, and R. Betti

Laboratory for Laser Energetics
and Fusion Science Center
University of Rochester

F. J. Marshall

Laboratory for Laser Energetics
University of Rochester

F. H. Séguin and R. D. Petrasso

Plasma Science and Fusion Center
Massachusetts Institute of Technology

Outline

- Introduction
  - magnetic-flux compression applied to ICF
  - MIFEDS
- Cylindrical targets
  - demonstration of laser-driven magnetic-flux compression
- Spherical targets
  - fusion performance enhancement
  - simulations
- Outlook

Magnetic confinement and magnetization of plasma electrons can be used to inhibit heat-conduction losses

- Basis for magnetic-confinement fusion and magnetized target fusion
- Long history of work considering adding magnetic fields to ICF*

The fusion performance of an ICF target can be improved through the magnetization of the fuel assembly.*

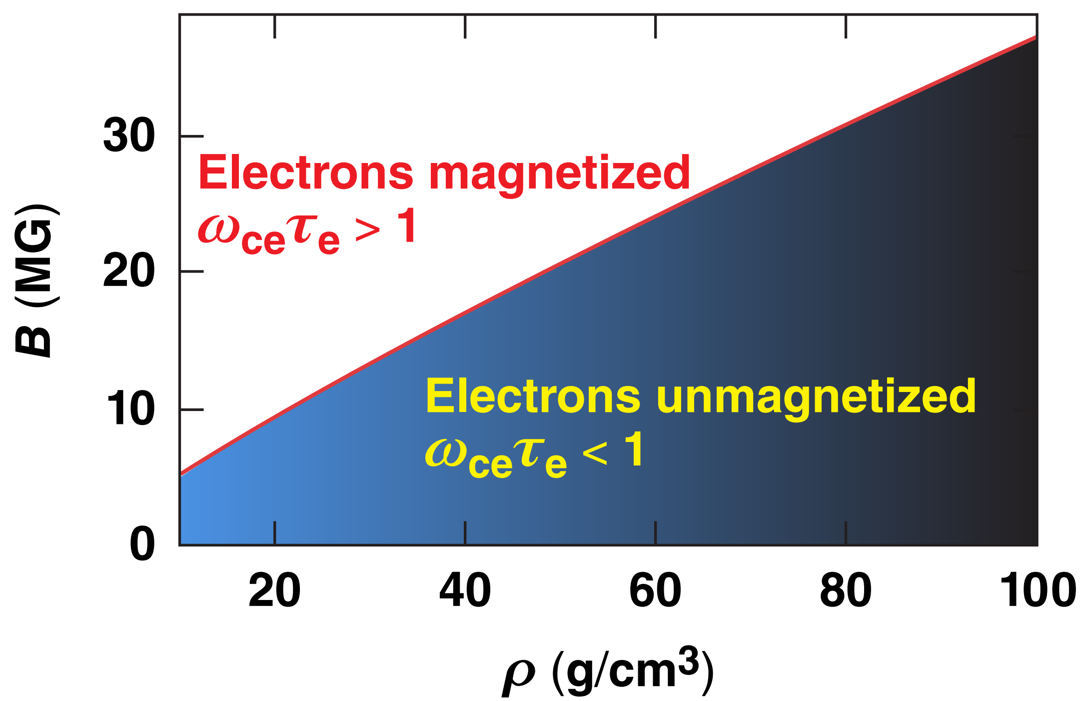
*M. M. Widner *et al*., Bull. Am. Phys. Soc. 22, 1139 (1977).
I. R. Lindemuth and R. C. Kirkpatrick, Nucl. Fusion 23, 263 (1983).
A. Hasegawa *et al*., Phys. Rev. Lett. 56, 139 (1986).

Magnetization of an ICF fuel assembly requires MG-strength magnetic fields

- Adding magnetic fields in a compressed ICF target can increase the thermal insulation of the hot spot
  - reduced electron thermal conductivity if

$$\omega_{ce}\,\tau_e > 1 \longrightarrow B > 10\ \mathrm{MG}$$

Magnetization parameter for fully ionized DT plasma at 5 keV

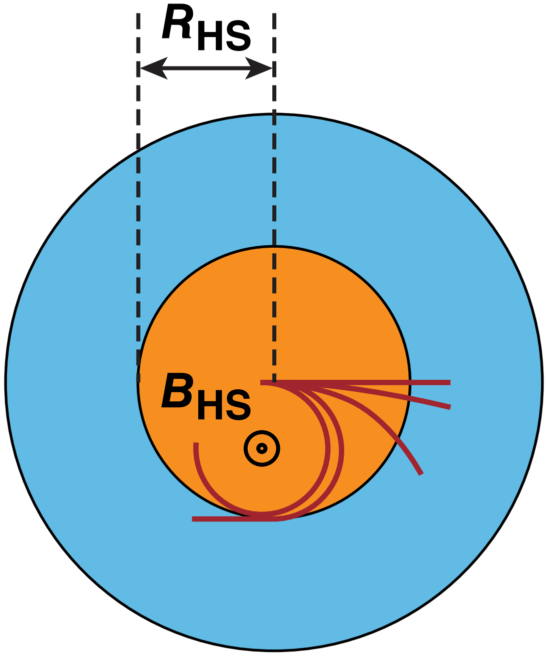


TC9746

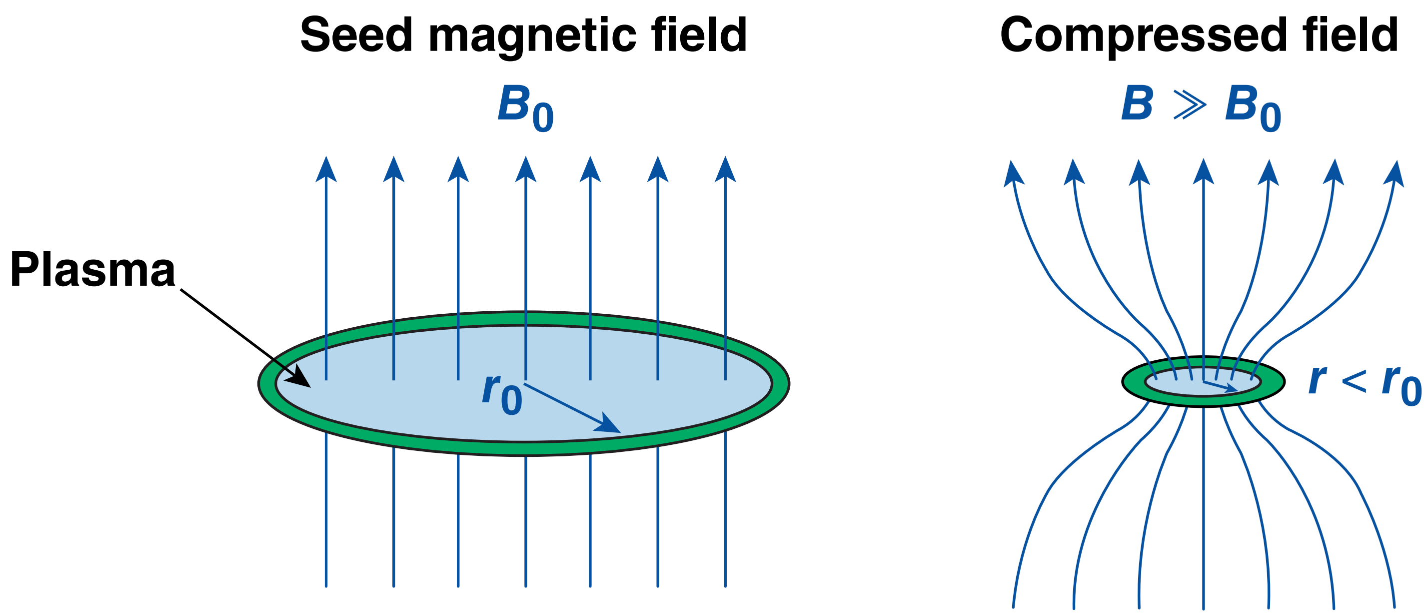
Alpha particles could be confined in the hot spot with ~100 MG field

- Confining α-particles to the hot spot further reduces energy losses
  - α-particles are confined if $r_{L\alpha} < R_{HS}$

    $r_{L\alpha}/R_{HS} \leq 1 \longrightarrow B > 100$ MG



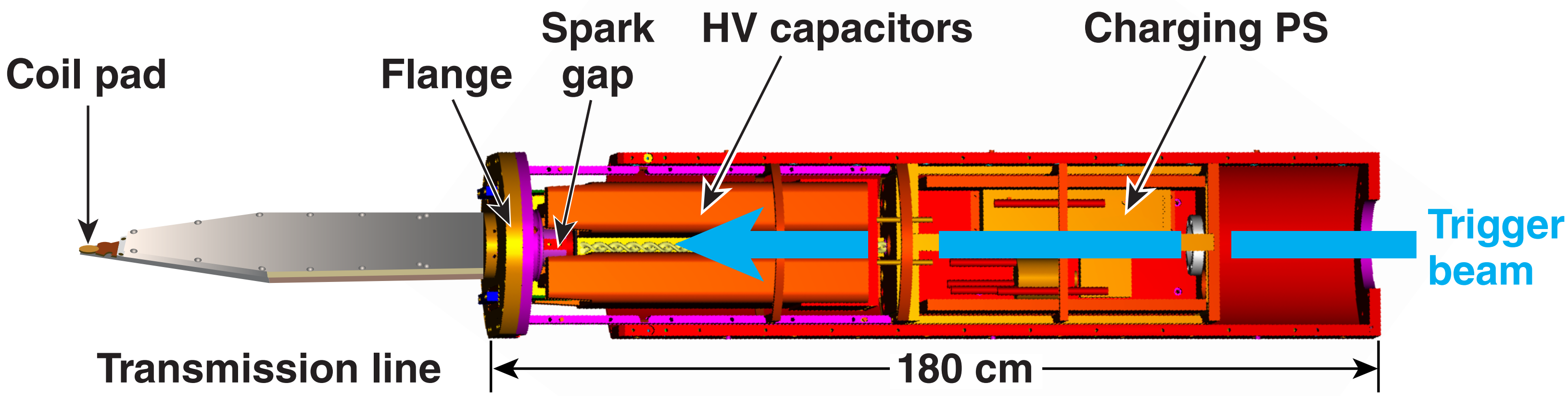
Very strong magnetic fields can be generated by compressing a seed field



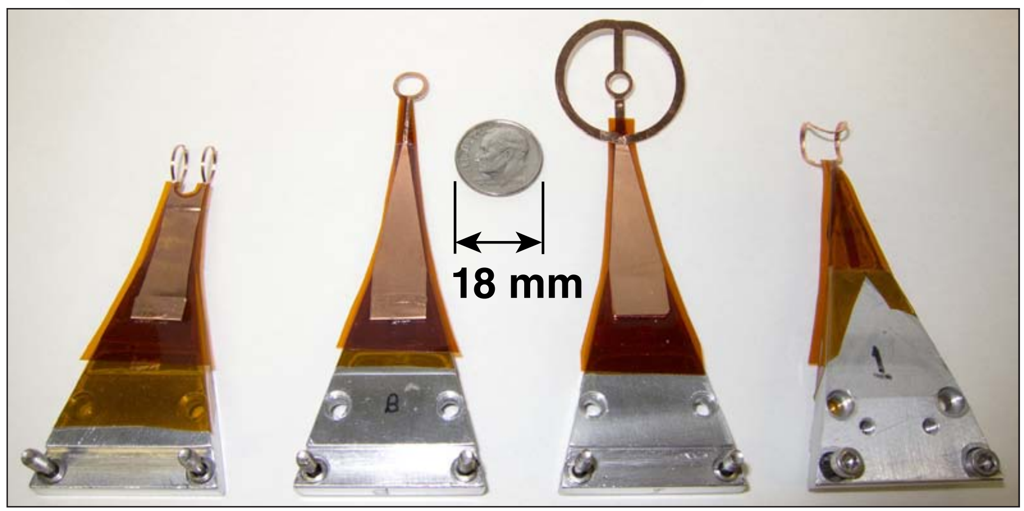
- If compression time is faster than diffusion time, then magnetic flux is conserved:

$$\boxed{B_0 \pi r_0^2 = B \pi r^2 \longrightarrow B \propto 1/r^2}$$

The seed field is created by a compact, self-contained magnetic-field generator



- MIFEDS – magneto-inertial fusion energy delivery system
- Various coils allow for different field strengths and topologies
- Seed fields up to 150 kG can be obtained



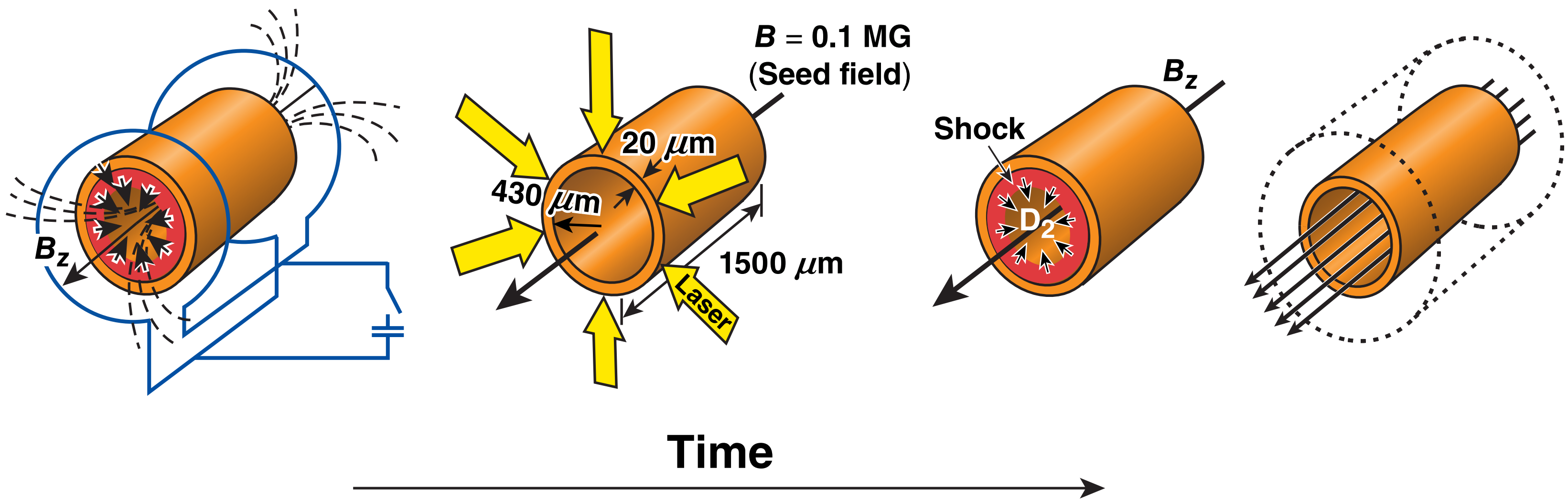
Helmholtz Single OMEGA Baseball

O. V. Gotchev *et al.*, Rev. Sci. Instrum. 80, 043504 (2009).

Outline

- Introduction
  - magnetic-flux compression applied to ICF
  - MIFEDS
- **Cylindrical targets**
  - demonstration of laser-driven magnetic-flux compression
- Spherical targets
  - fusion performance enhancement
  - simulations
- Outlook

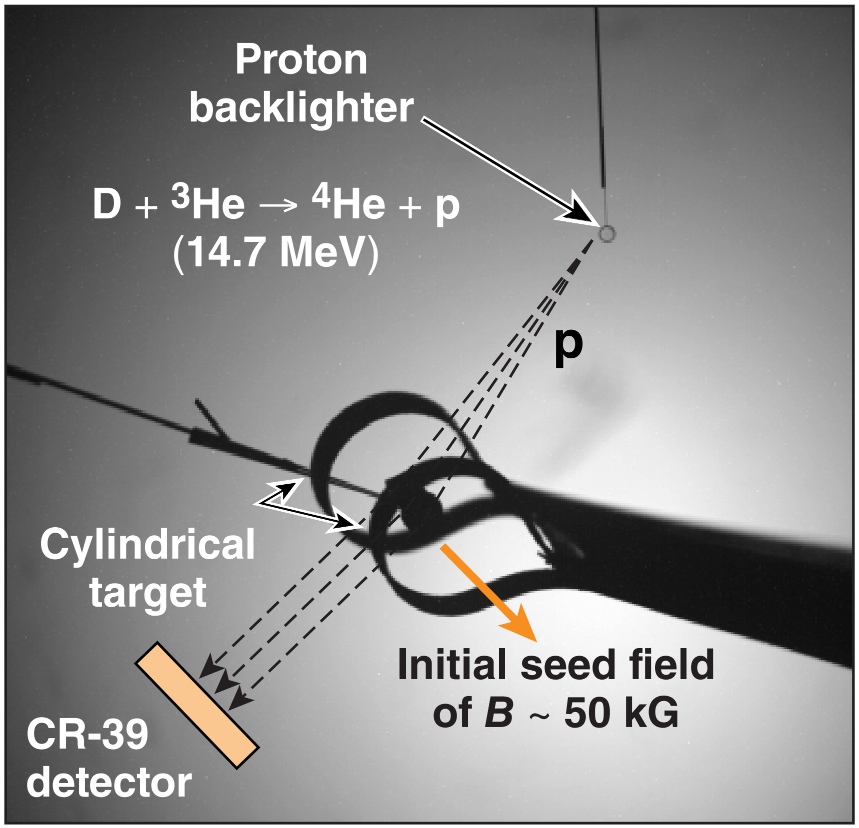
Laser-driven magnetic-flux compression was first demonstrated for cylindrical implosions*



- Axial field in cylindrical target is generated using a Helmholtz-like coil
- Laser-driven implosion creates a highly conductive plasma that traps and compresses the magnetic field together with the target

*O. V. Gotchev *et al.*, Phys. Rev. Lett. 103, 215004 (2009).

Proton deflectometry was used to infer the compressed magnetic field*

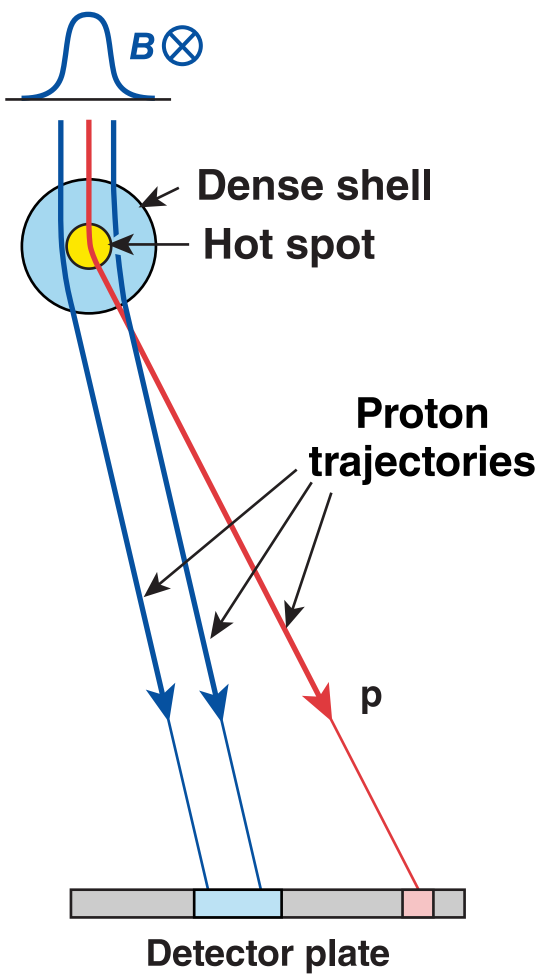


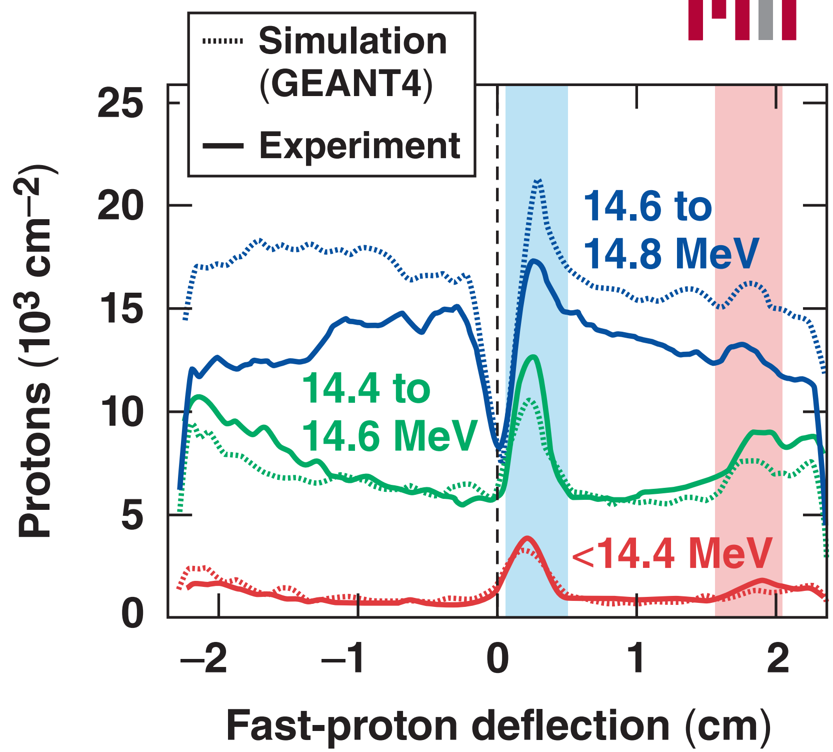
- 20-μm-thick CH cylinder filled with 3-atm D_2 gas
- 40 beams to implode main target, 20 beams to drive backlighter source

E18382b

*O. V. Gotchev *et al.*, Phys. Rev. Lett. 103, 215004 (2009).

In cylindrical implosions, hot-spot-averaged compressed magnetic fields of up to 36 MG were measured*



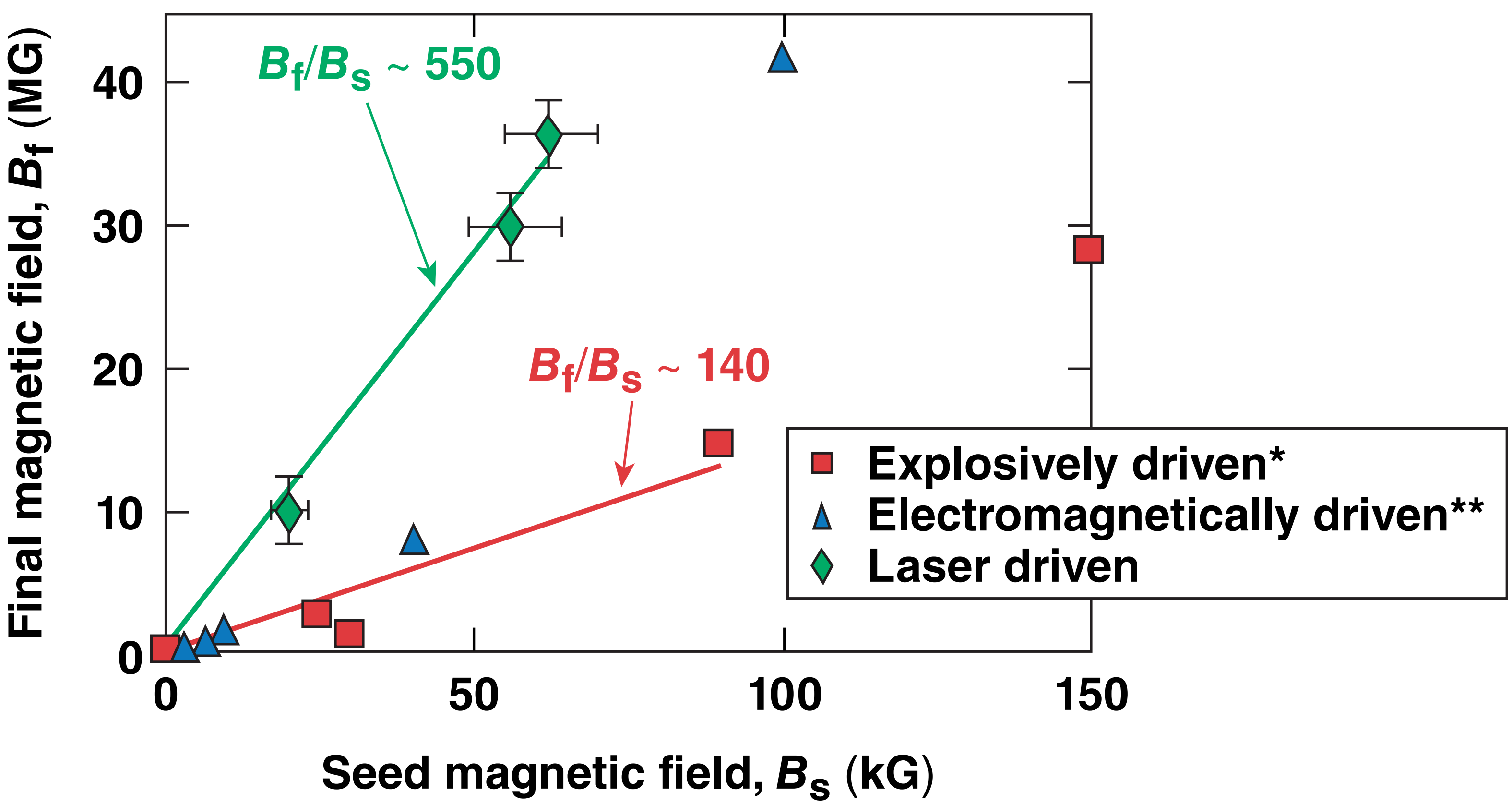


- Field topology and density distribution causes characteristic two-peak deflection pattern
- No fusion performance enhancement was observed with cylindrical targets

E19780e

*J. P. Knauer *et al.*, Phys. Plasmas 17, 056318 (2010).

Laser-driven magnetic-flux compression achieves an amplification factor of ~550



TC9796

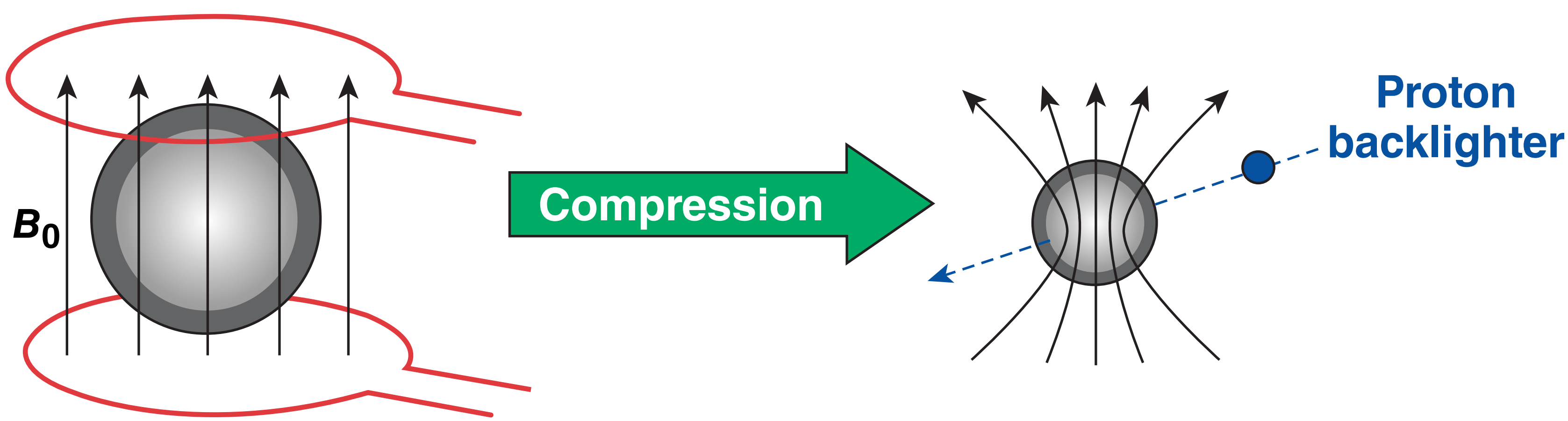
*A. D. Sakharov, Sov. Phys. Usp. 9, 294 (1966).
**F. S. Felber *et al*., Phys. Fluids 31, 2053 (1988).

Outline

- Introduction
  - magnetic-flux compression applied to ICF
  - MIFEDS
- Cylindrical targets
  - demonstration of laser-driven magnetic-flux compression
- **Spherical targets**
  - fusion performance enhancement
  - simulations
- Outlook

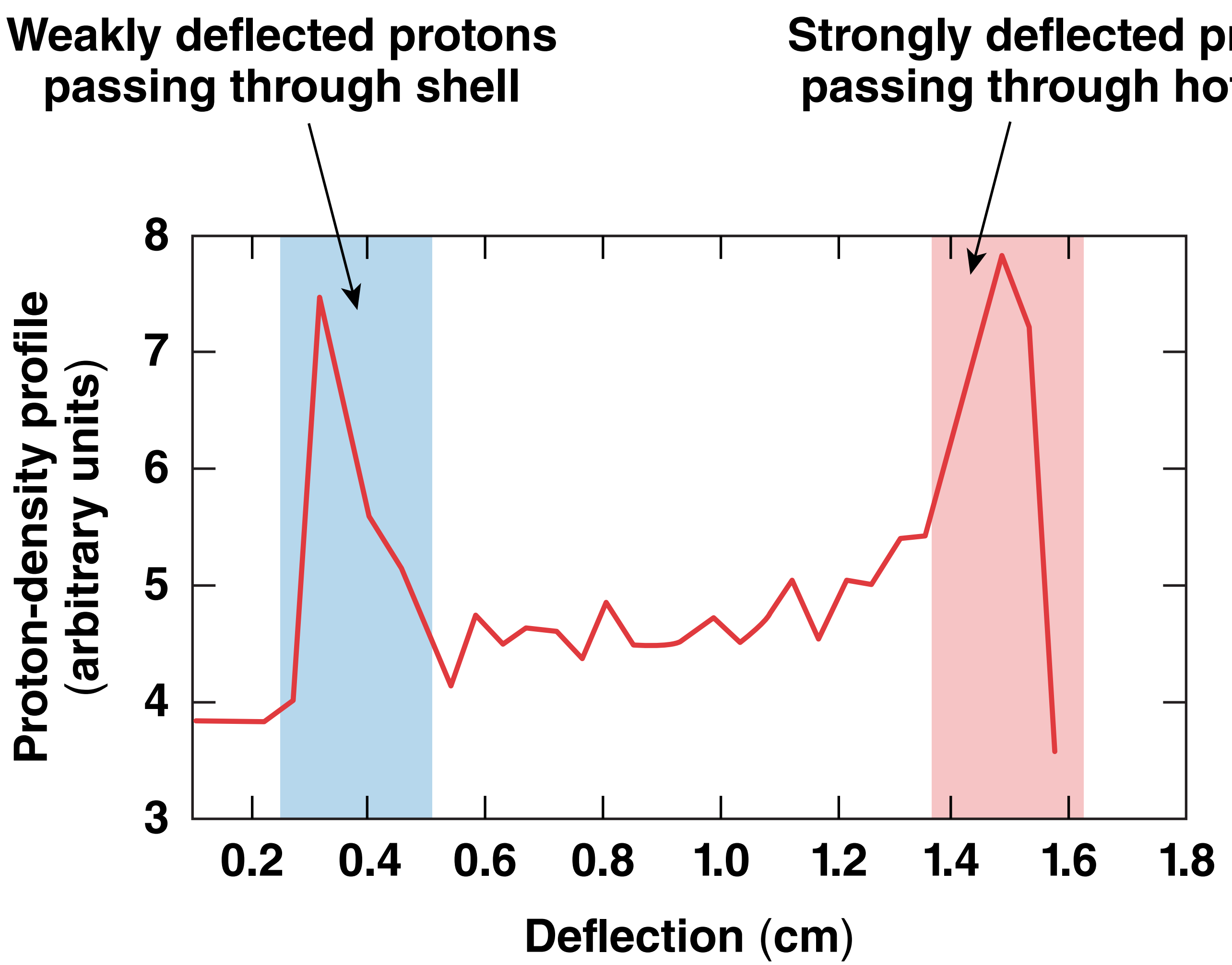
Measuring the compressed field in spherical geometry is challenging

- Spherical compression of straight field lines results in a radial component of the compressed field
- The proton-deflection pattern becomes more complicated than the cylindrical case
- A small cross section of the compressed core results in reduced signal-to-noise



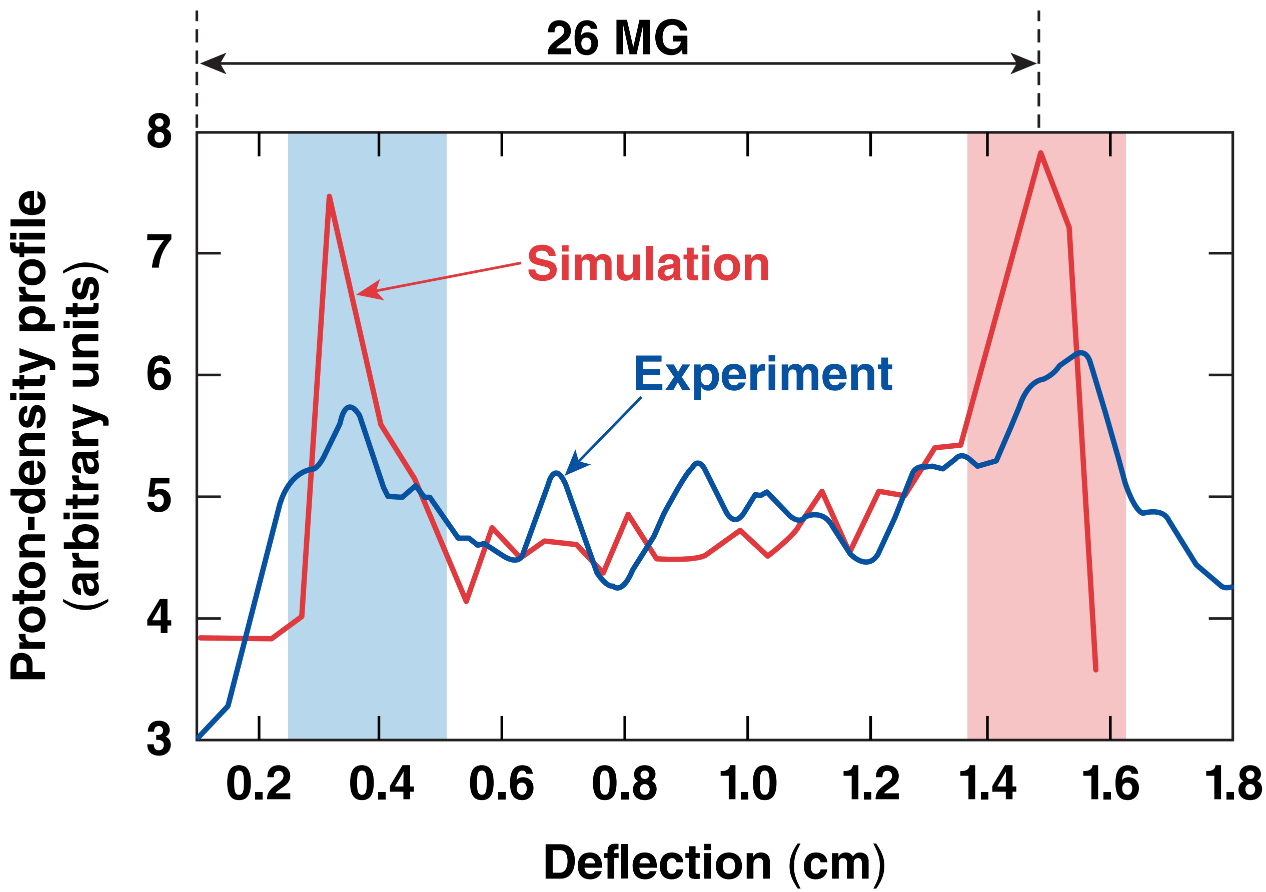
TC9784

A simulated proton-deflection pattern for spherical compression reproduces the two-peak signature seen in cylindrical implosions



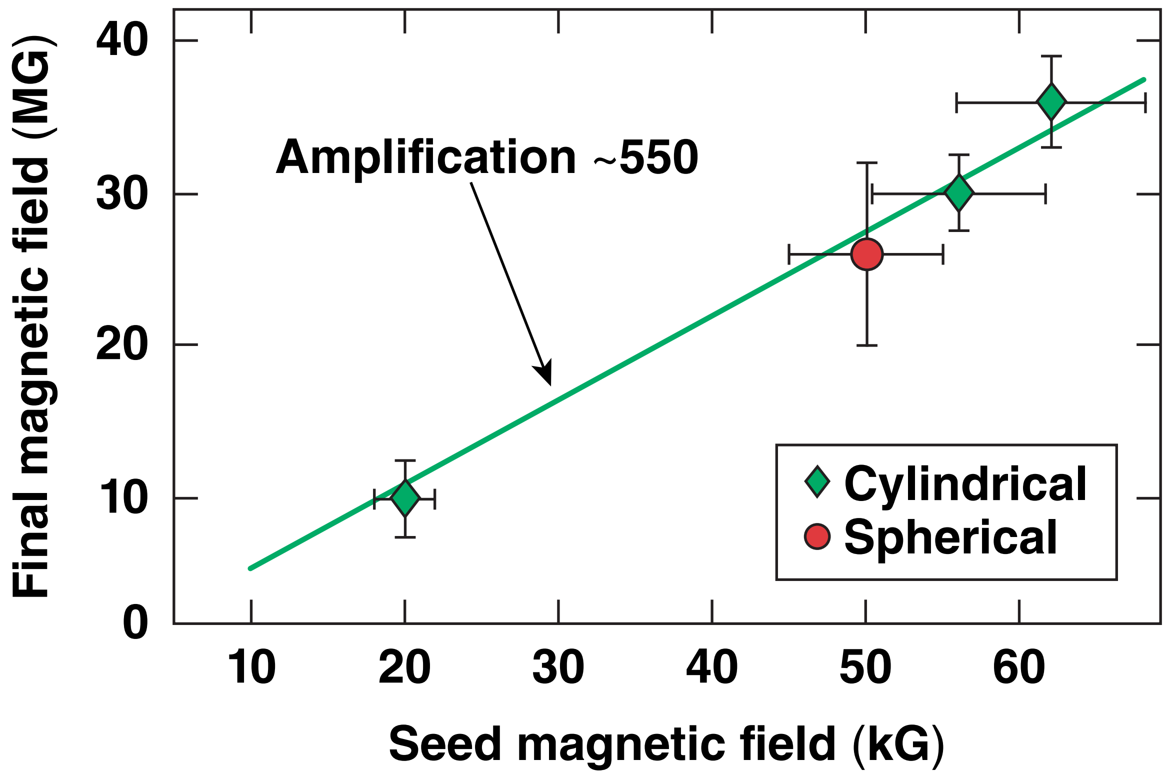
TC9785

The experimental data with a 50-kG seed field is consistent with the simulated deflection in a 26-MG hot-spot–averaged field



TC9785a

The measured field from the spherical experiment matches the compression ratio observed for cylindrical implosions

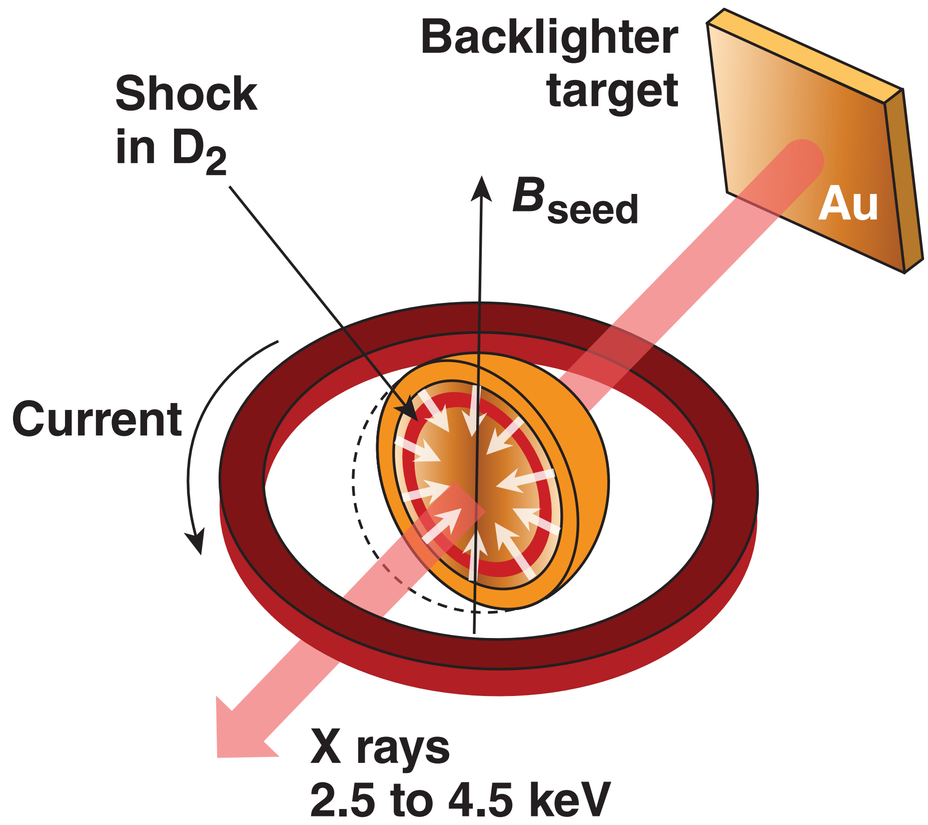


Additional experiments to measure the field were performed this week.

E19782b

A single-coil setup was used for compressing a spherical target in polar-drive* geometry on OMEGA

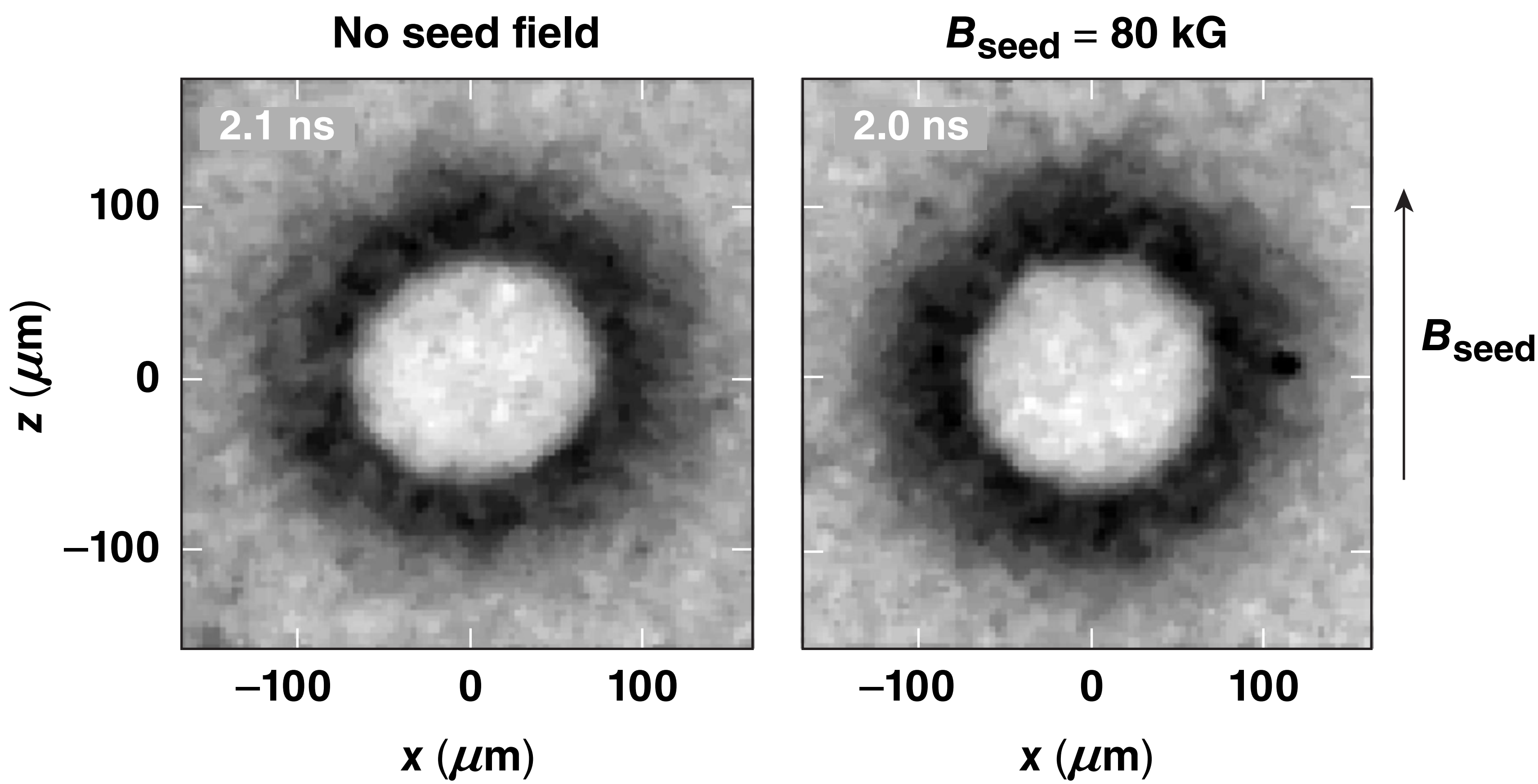
- A single coil provides less interference with laser paths (seed field 80 kG)
- Spherical CH target filled with 10 atm of D_2
- 40 beams in a polar-drive geometry were used for compression*
- Implosion uniformity is diagnosed using x-ray radiography
- Neutron yield and T_i are inferred from nTOF diagnostics



E19783c

*F. J. Marshall *et al*., Phys. Rev. Lett. 102, 185004 (2009).

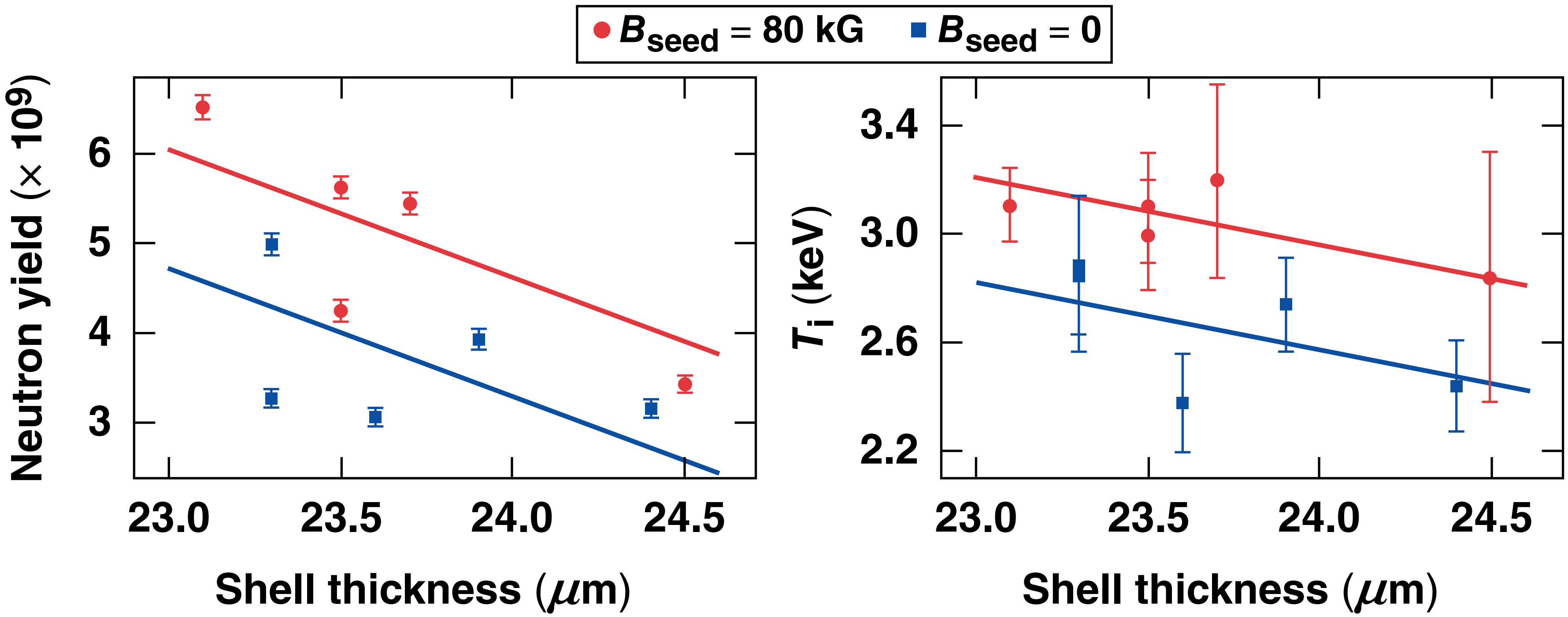
X-ray backlit images show no difference in implosion uniformity



- Implosion is very uniform
- MIFEDS coil was present in all measurements

E19784a

A 15% ion-temperature increase and 30% fusion yield enhancement for magnetized targets* was observed



A linear-regression fit reveals clear enhancement of magnetized hot-spot performance.

E19785b

*P. Y. Chang *et al.*, Phys. Rev. Lett. 107, 035006 (2011).

1-D *LILAC*-MHD* is used to simulate the equatorial plane in a spherical implosion

- ***B*-field effects are included by solving the induction equation**

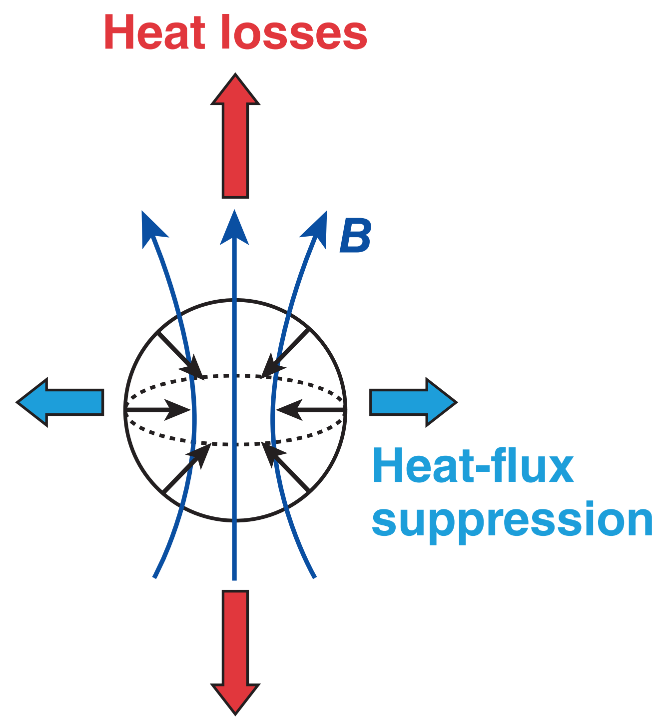
$$\frac{\partial B}{\partial t} = \hat{z}\left[\underbrace{-\frac{1}{r}\frac{\partial}{\partial r}\left(r\nu_{r}B_{z}\right)}_{\text{Convection}} + \underbrace{\frac{1}{r}\frac{\partial}{\partial r}\left(r\,D_{m}\frac{\partial B_{z}}{\partial r}\right)}_{\text{Diffusion}}\right]$$

- **Heat conductivities calculated based on Braginskii coefficients**

$$\kappa_{\text{tot}} = \frac{\kappa_{\parallel}A_{\parallel} + \kappa_{\perp}A_{\perp}}{A_{\parallel} + A_{\perp}}$$

- **Ratio of area with open field lines to target surface area for perfect sphere**

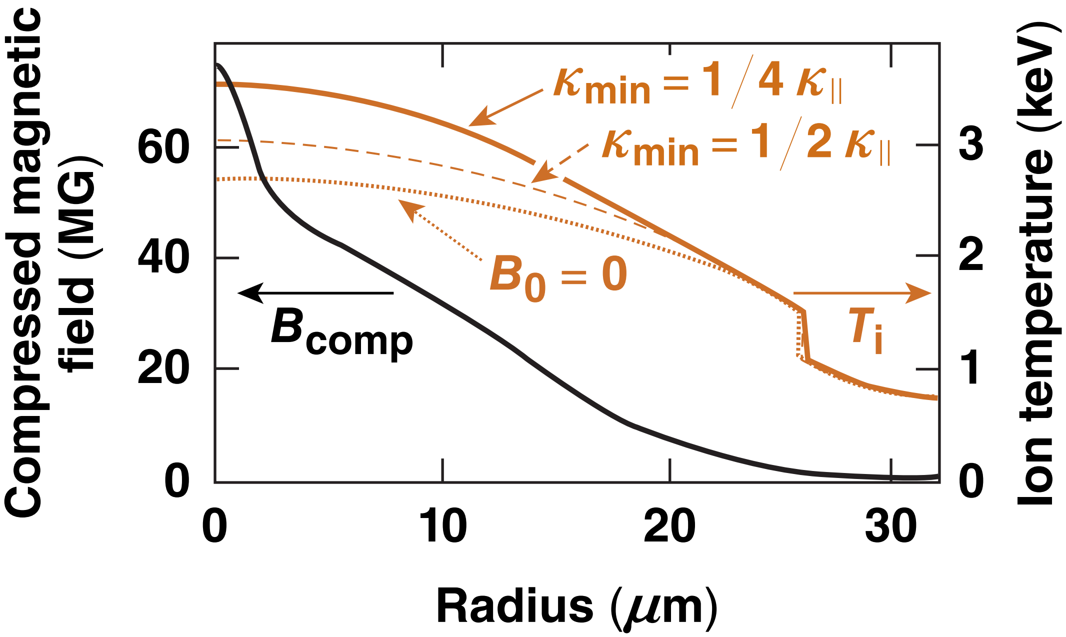
$$\frac{A_{\parallel}}{A_{\parallel} + A_{\perp}} = 1/2 \longrightarrow \kappa_{\min} = \frac{1}{2}\kappa_{\parallel}$$



E19786a

*N. W. Jang *et al*., Bull. Am. Phys. Soc. 51, 144 (2006).

1-D simulations predict 8% ion temperature and 15% neutron-yield enhancements in implosions of magnetized spherical targets



- 1-D simulations underestimate the experimentally observed enhancement
- Experimental result could be recovered by assuming

$$\kappa_{min} = 1/4\ \kappa_{||}$$

1-D simulations are simplified and do not capture topology of the compressed field; need 2-D or 3-D calculations.

Outline

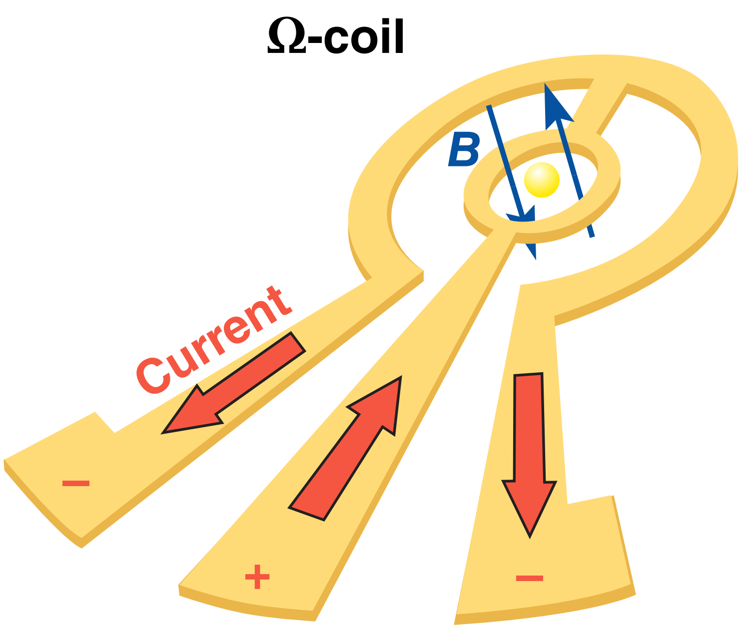
FSC

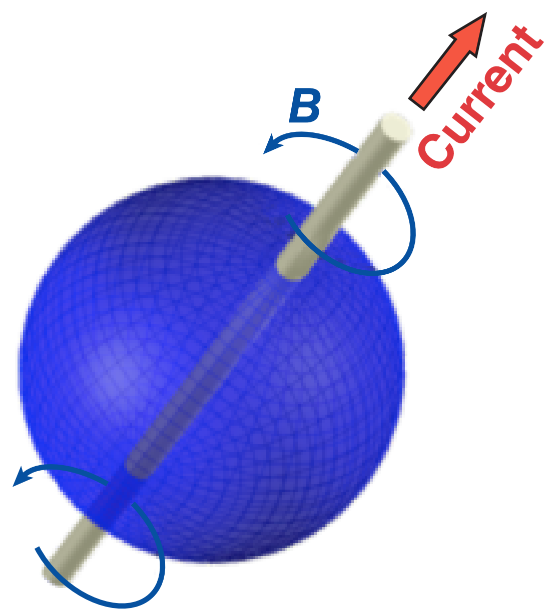
UR LLE

- Introduction
  - magnetic-flux compression applied to ICF
  - MIFEDS
- Cylindrical targets
  - demonstration of laser-driven magnetic-flux compression
- Spherical targets
  - fusion performance enhancement
  - simulations
- **Outlook**

Further numerical and experimental investigation of magnetic-flux compression is planned

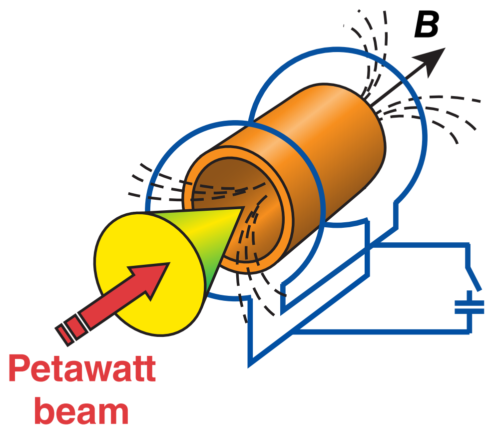
- Perform high-quality measurement of the magnetic field in a spherically compressed target
- Simulate spherical magnetic-field compression in 2-D
- Upgrade MIFEDS to achieve higher seed fields
- Investigate paths to closed-field-line geometries

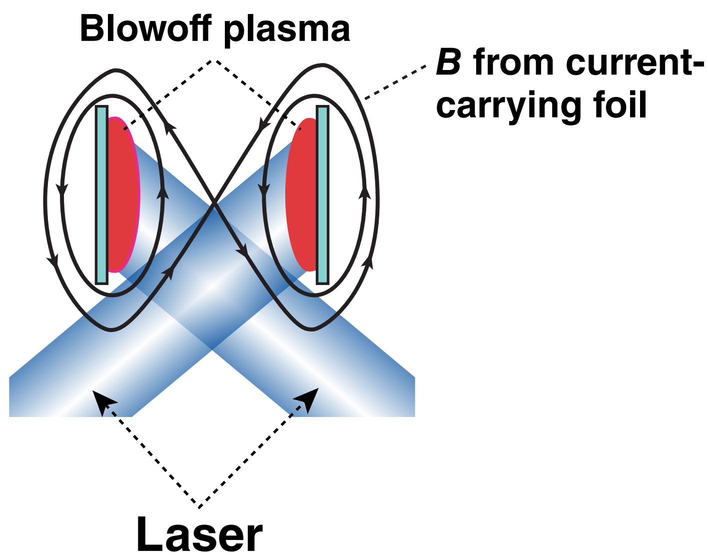


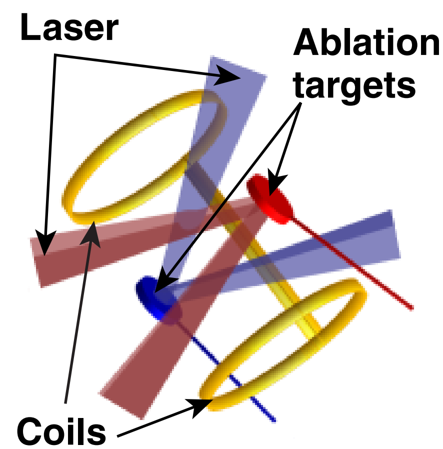


E19788a

MIFEDS is a versatile platform with exciting applications beyond magnetized ICF







- Use compressed magnetic fields to guide electrons in a fast-ignition scheme
- Study magnetic reconnection in laser-driven plasma*
- Investigate collisionless shock formation in the presence of a strong magnetic field**

*see talk by W. Fox, YI3.00004
**see poster by N. L. Kugland *et al.*, BP9.00035

E20246a

Summary/Conclusions

Laser-driven flux-compression experiments on OMEGA show fusion performance enhancement for magnetized hot spots

- A seed magnetic-field generator has been developed
- Laser-driven magnetic-field compression to tens of MG has been demonstrated in cylindrical and spherical geometry
- Ion-temperature enhancement of 15% and fusion-yield increase of 30% have been observed

Magnetization of the hot spot of an ICF implosion has been achieved for the first time.