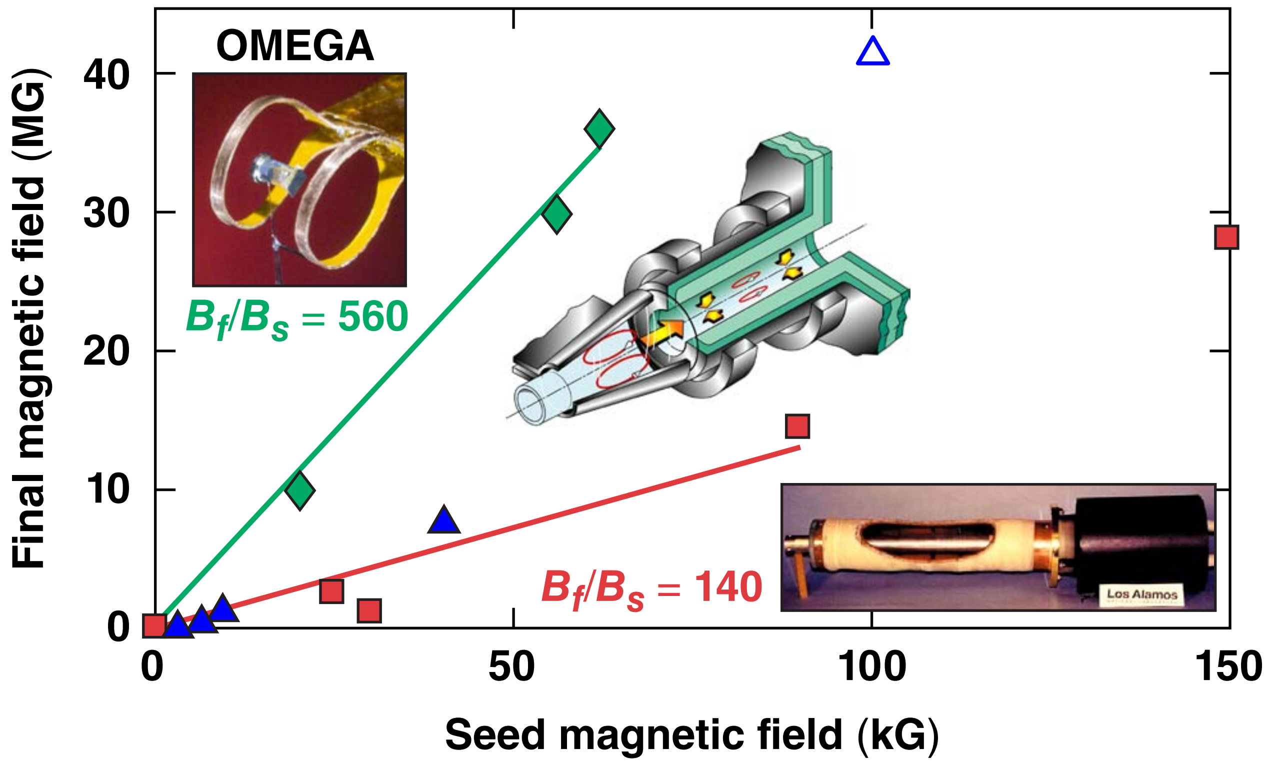
Compressing Magnetic Fields With High-Energy Lasers



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51st Annual Meeting of the
American Physical Society
Division of Plasma Physics
Atlanta, GA
2–6 November 2009

Summary

10- to 40-MG magnetic fields are produced on OMEGA by laser-driven flux compression

- A compact device to generate up to 150-kG magnetic seed fields has been assembled
- Cylindrical targets embedded in a 10- to 60-kG seed magnetic field have been imploded with 14 kJ of laser energy
- The compressed magnetic field in the target hot spot is measured by proton deflection
- Cylindrical targets have demonstrated magnetic amplification
- Spherical targets will be used to measure the effect of MG magnetic fields on ICF hot spots

Collaborators

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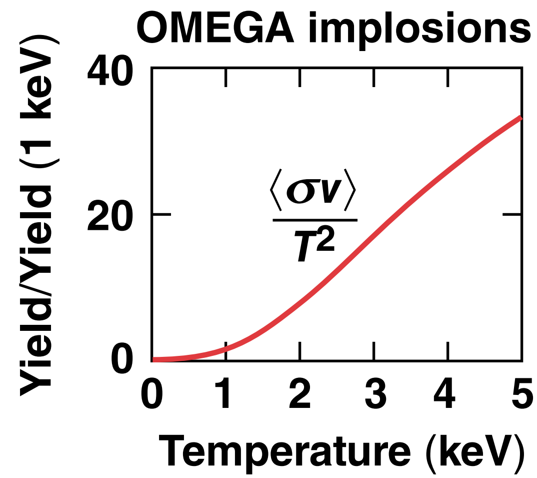
The performance of ICF targets can be improved with MG magnetic fields

- **Adding a magnetic field in a compressed ICF target increases the temperature and decreases the density for constant P_{HS}**

$Y_n \sim n^2 \langle \sigma v \rangle$

$\langle \sigma v \rangle \propto 1/T^{1/2}\, e^{-a/T}$

for constant P_{HS}, $n \propto 1/T$

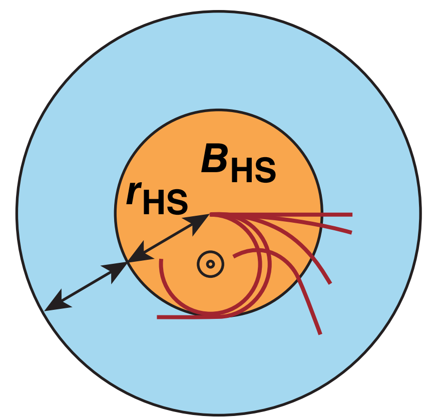


NIF 1.5-MJ, polar-drive point design

$\rho_{HS} \approx 30$ g/cm^3, $T_{HS} \approx 7$ keV (before ignition), $r_{HS} \approx 50\ \mu$m

$\kappa_\perp/\kappa_\parallel \sim 0.2$ for $B = 10$ MG

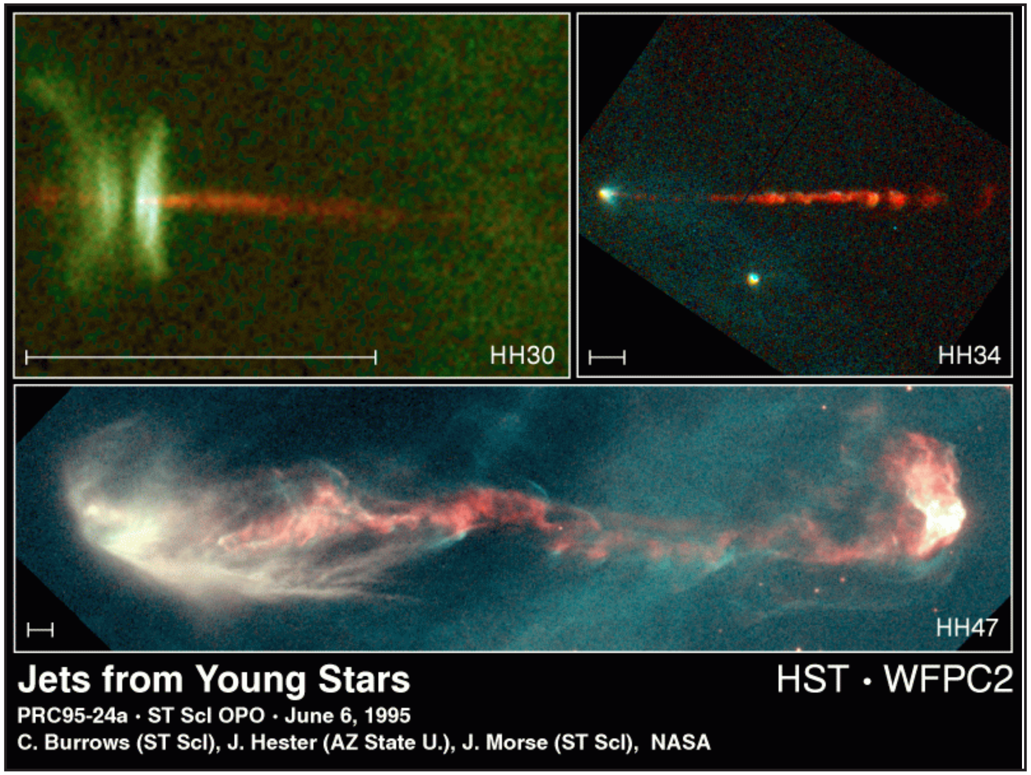
$r_{L\alpha} = 27\ \mu$m $\sim 1/2\ r_{HS}$ for $B = 100$ MG



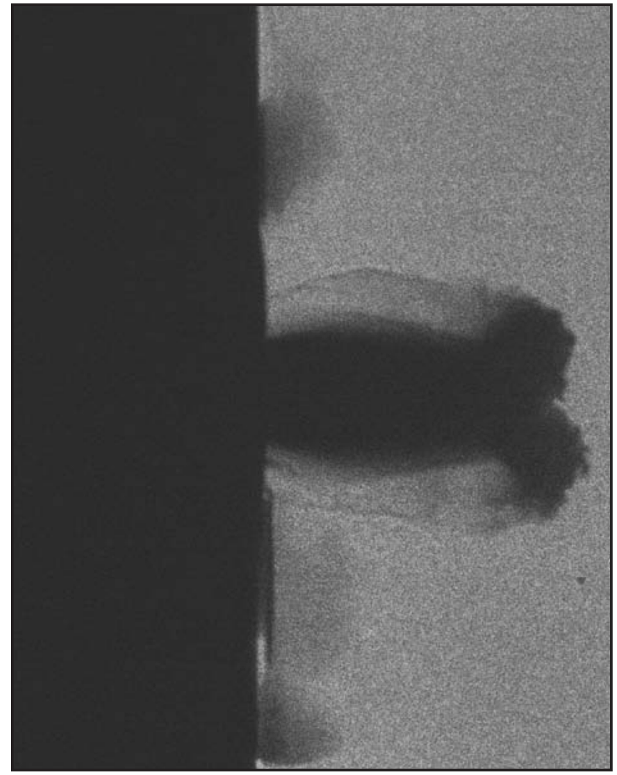
E18375

Magnetic fields may play a significant role in the collimation of astrophysical jets

Hubble Space Telescope images



OMEGA jet (no magnetic field)



A MG magnetic field would be required to significantly alter the laboratory jet performance.

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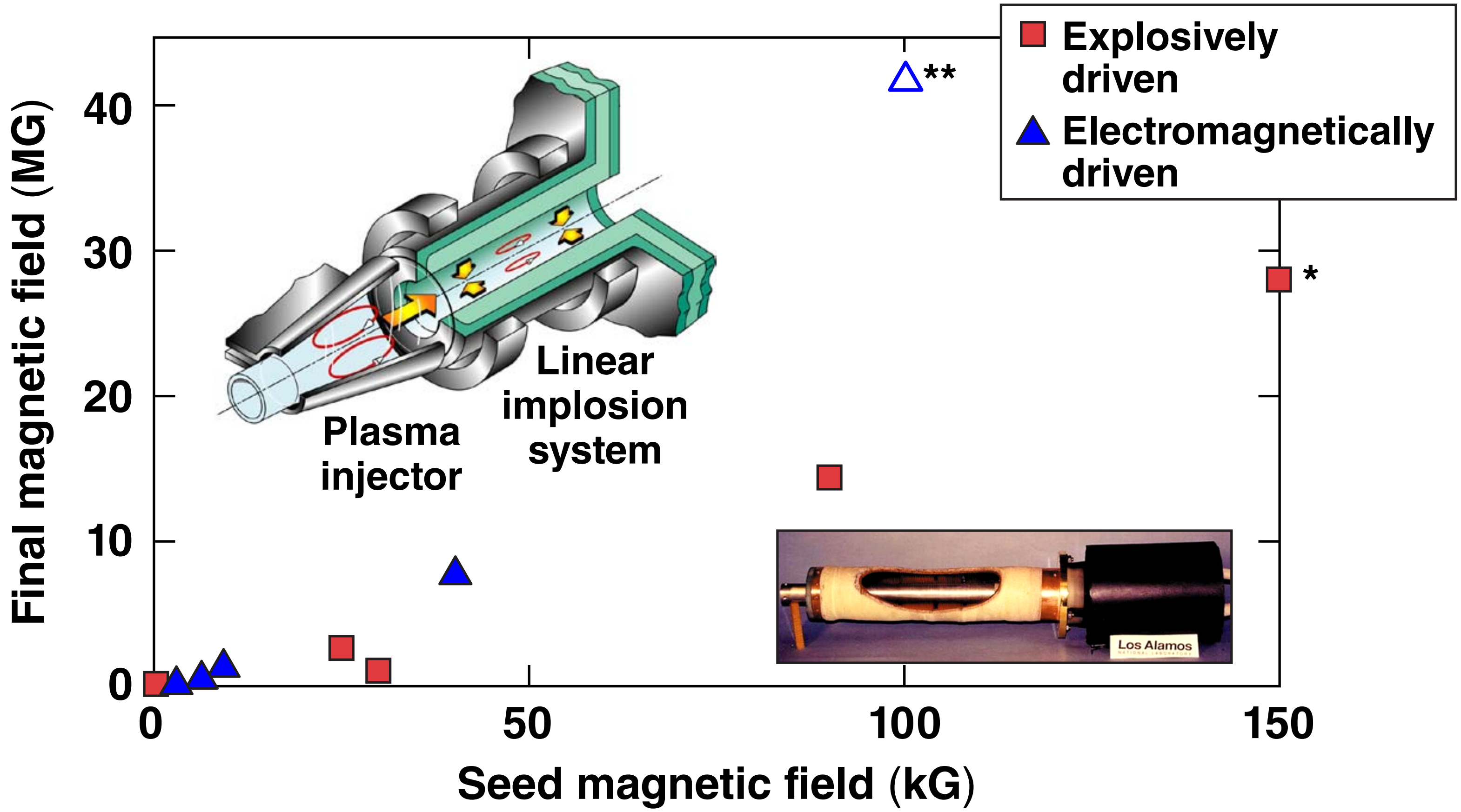
Magnetic fields have been achieved through flux compression of electromagnetically or explosively driven implosions



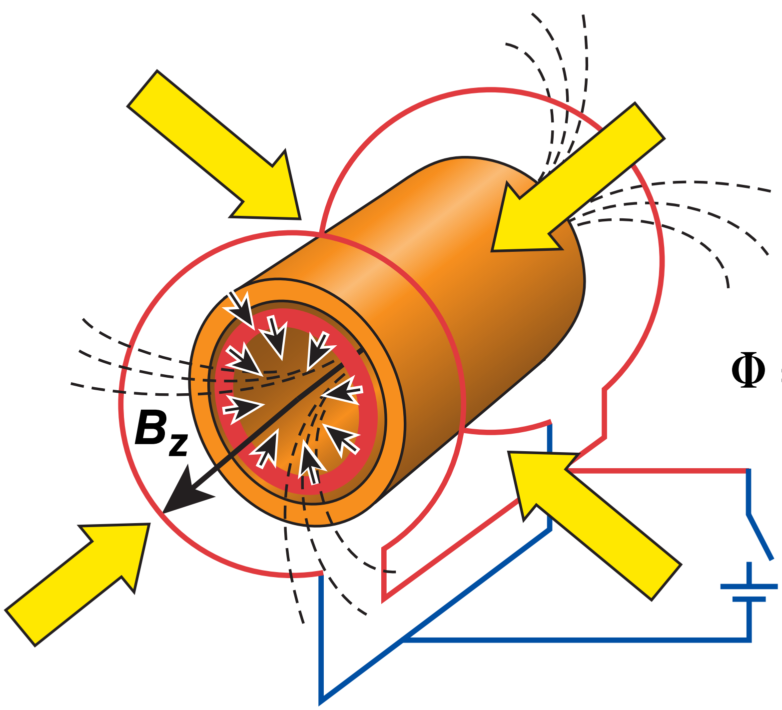
B field of 28 MG achieved with high explosives at VNIEF (Russia).

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

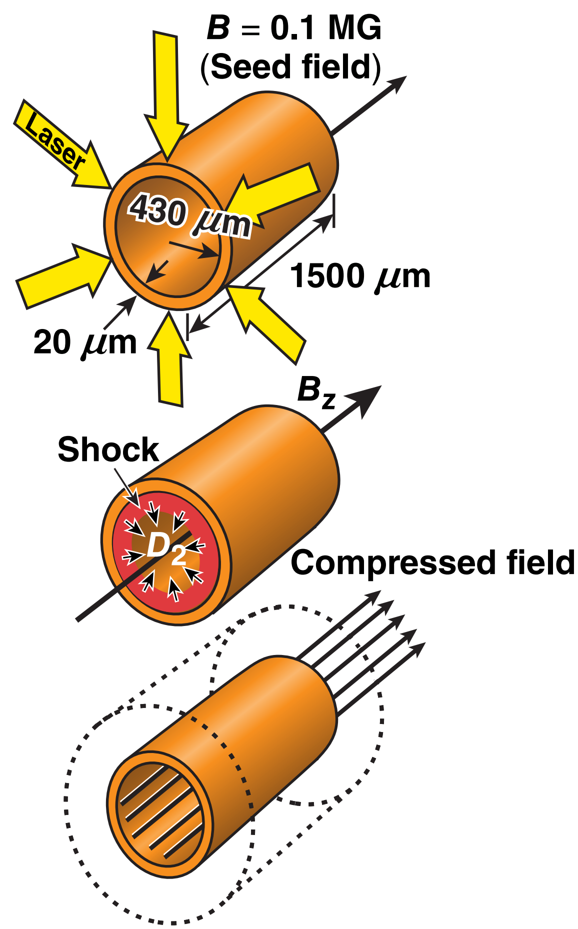
E18377

High magnetic fields are generated through laser compression of a seed field*

- In a cylindrical target, an axial field can be generated using two Helmholtz-like coils; the target is imploded by a laser to amplify the field

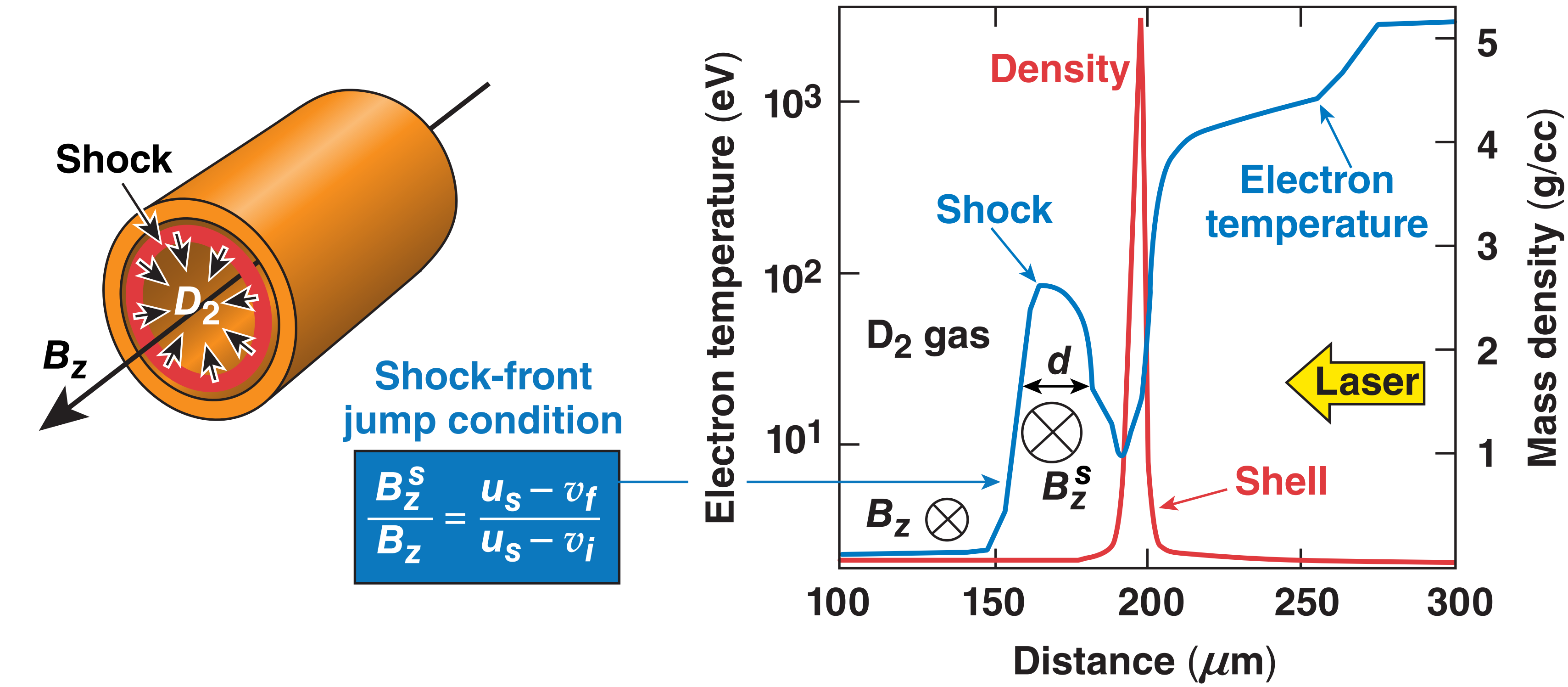


$$\Phi = \pi B_z R^2 \approx \text{const}$$



*O. V. Gotchev *et al.*, to be published in Phys. Rev. Lett.

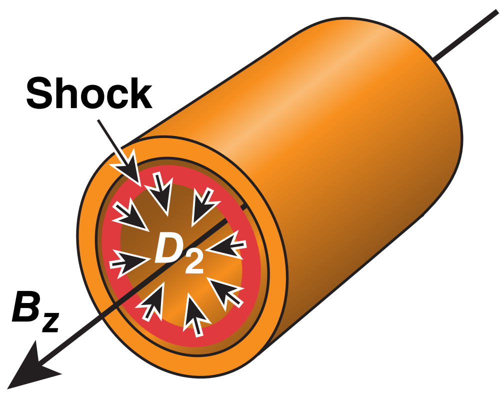
The magnetic field is trapped in the shock-ionized gas fill and then compressed by the imploding shell



Further compression by the shell amplifies the shock-compressed magnetic field.

E18378

The maximum magnetic amplification is determined by the target convergence and magnetic Reynolds number



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

$$Re_m = \frac{\tau_{diffusion}}{\tau_{implosion}}$$

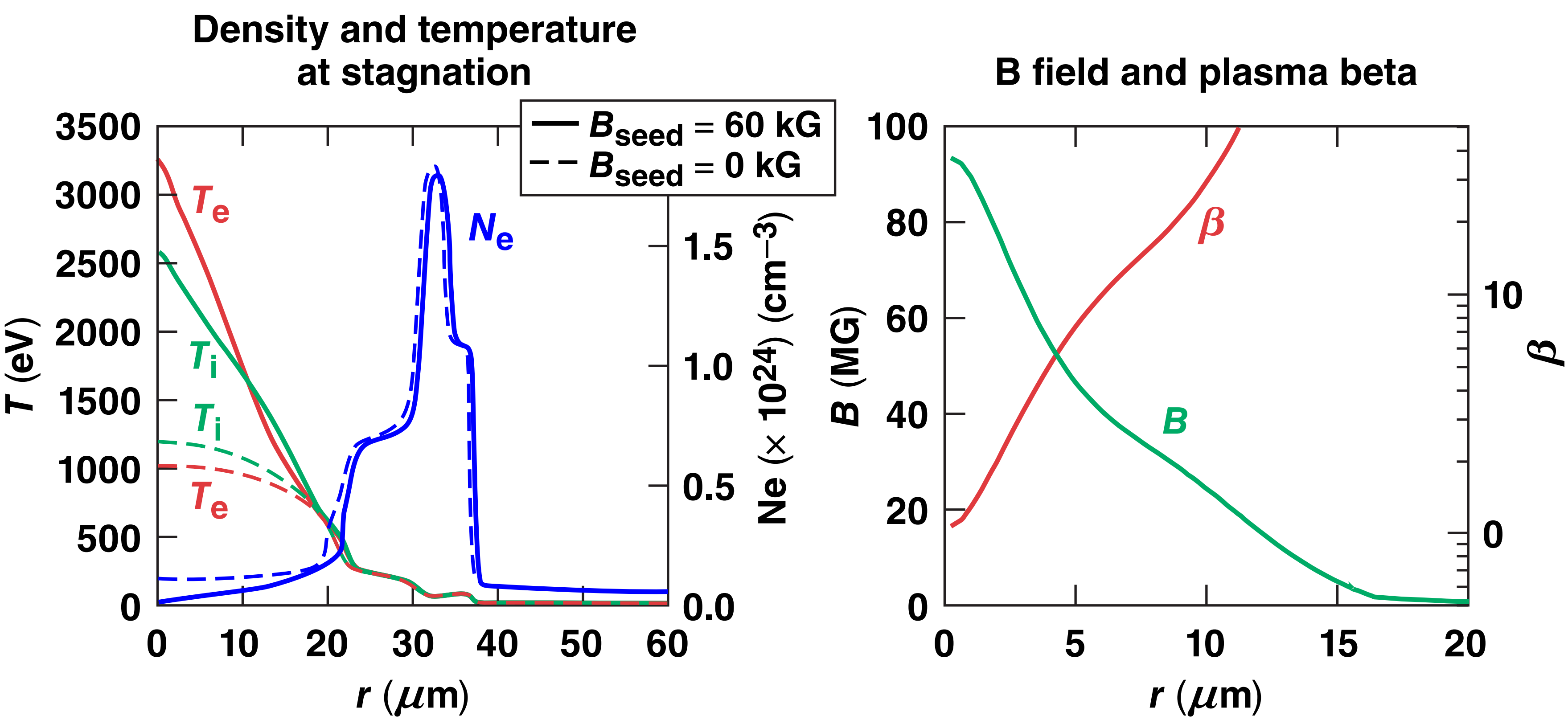
$$\tau_{diffusion} = \frac{4\pi\sigma_{shock} d^2_{shock}}{c^2} \sim 200 \text{ ns}$$

$$\tau_{implosion} = \frac{r_{ID} - r_{core}}{v_{implosion}} \sim 4 \text{ ns}$$

$$Re_m \sim 50$$

- In OMEGA cylindrical implosions, Re_m is ~ 50 because of the high implosion velocity ($>10^7$ cm/s) and plasma conductivity

1-D MHD simulations of cylindrical implosions show a T_{ion} with a magnetic field ~2 × T_{ion} without magnetic fields

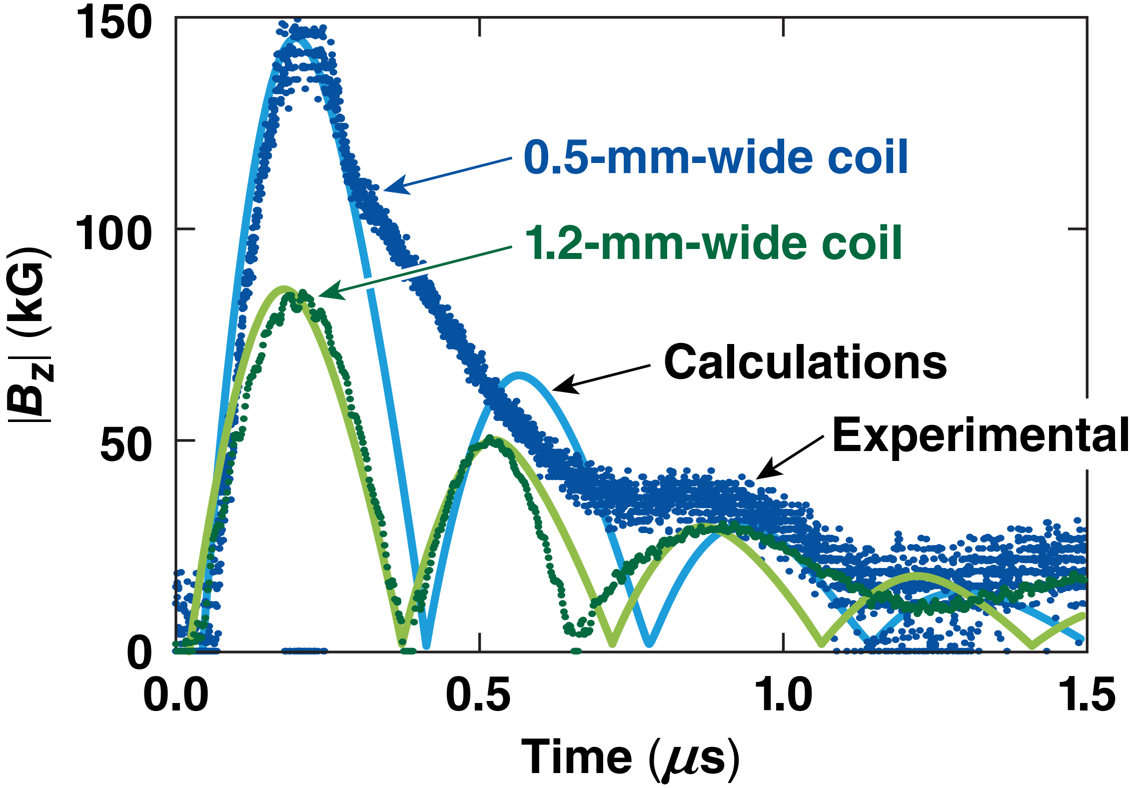


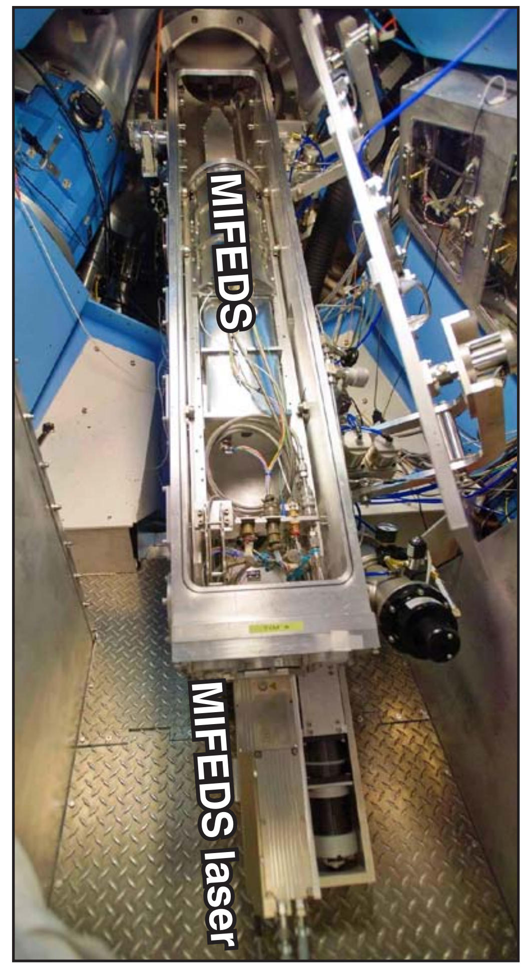
The B field is compressed to ~100 MG at the hot-spot center giving a plasma beta of ~1 at the peak magnetic field.

E18380

MIFEDS provides in-target seed fields between 10 and 150 kG, depending on coil geometry and energy settings

Faraday rotation measurements of seed field



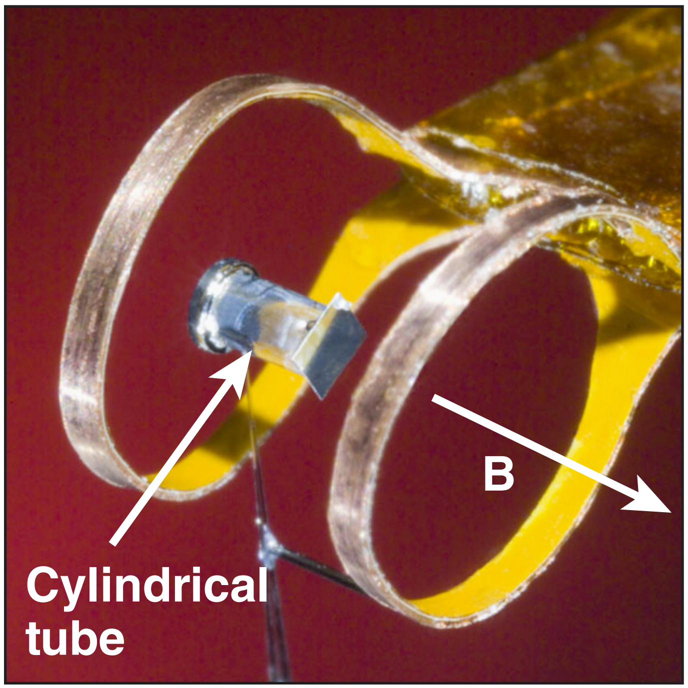


- MIFEDS is a compact, self-contained system that stores less than 100 J and is powered by 24 VDC
- It delivers ~110-kA peak current in a 350-ns pulse

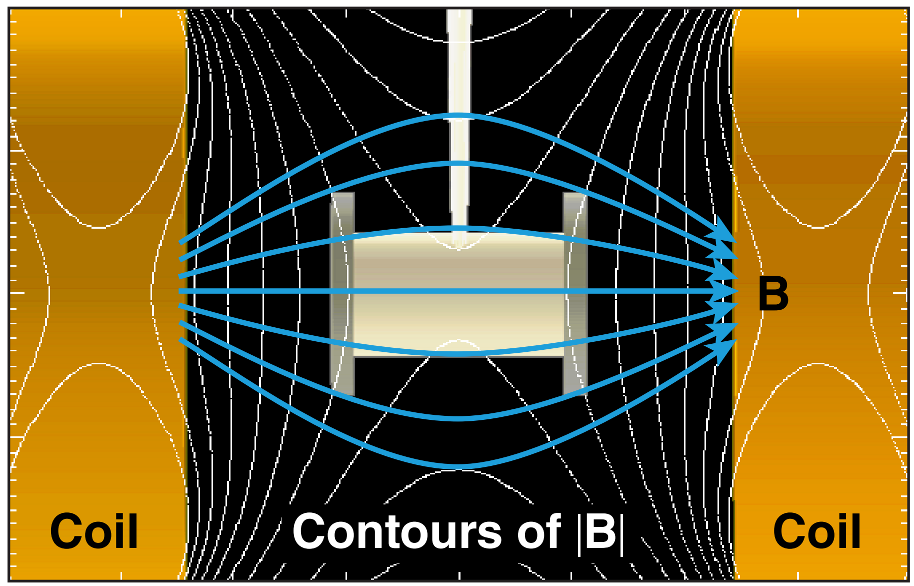
E18381

Coil geometry and placement of the cylindrical target have been optimized for OMEGA implosions

Coil geometry
Radius = 2 mm
Separation = 5.25 mm



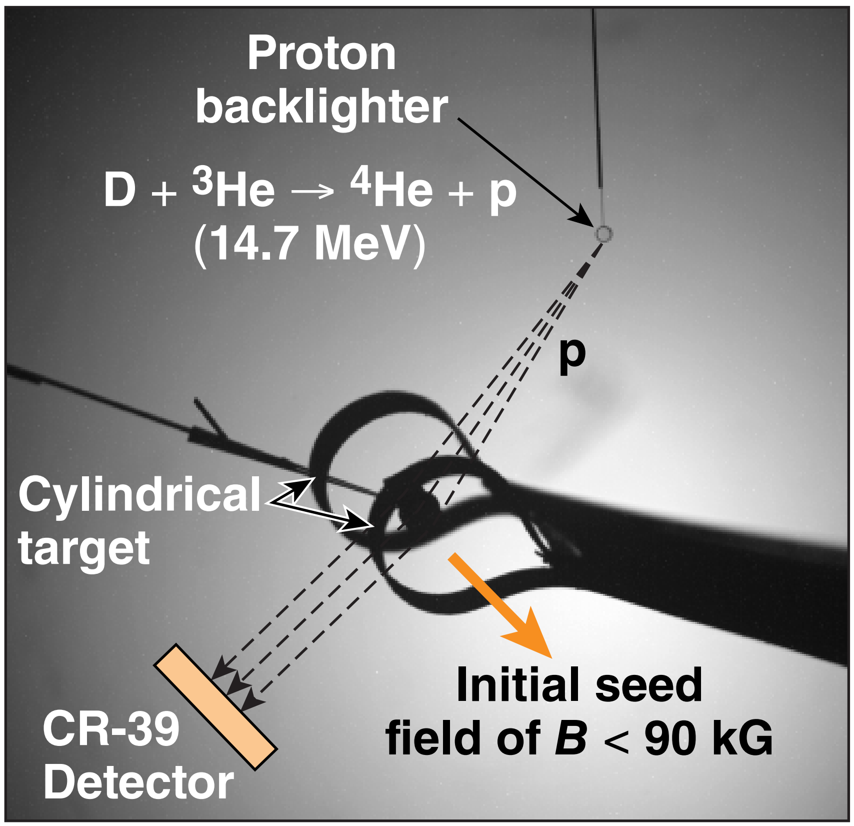
Cylindrical target
Radius = 430 μm
Length = 1.5 mm
Wall thickness = 20 μm
Fill = 9 atm D_2



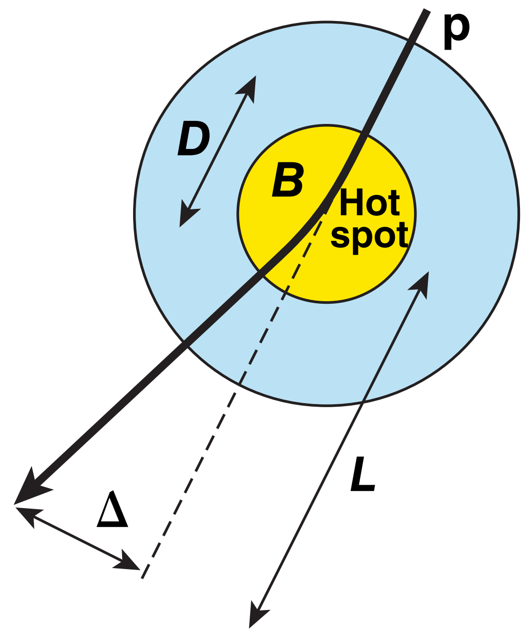
The cylindrical implosion target is positioned in a uniform-field region between the coils.

TC8512a

Proton deflectometry is used to measure the magnetic field in the compressed core



Geant4 simulations are used for an accurate interpretation of the data



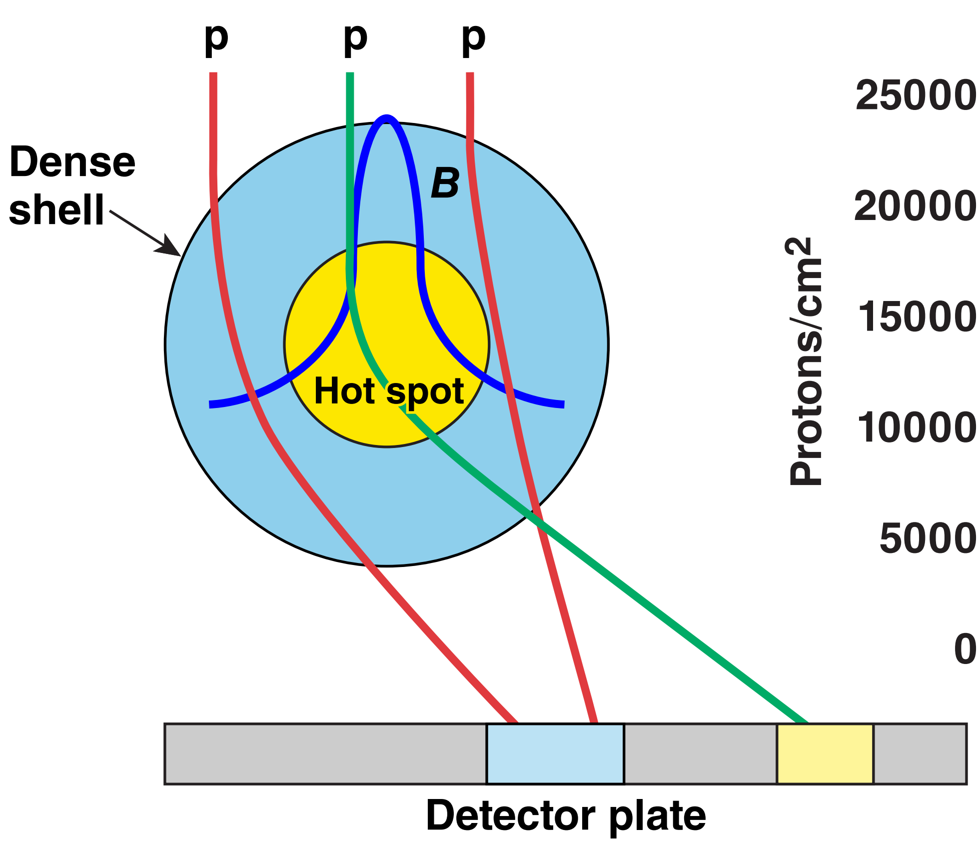
$$\Delta \approx v_{\perp}\tau \sim v_{\perp} L/v$$

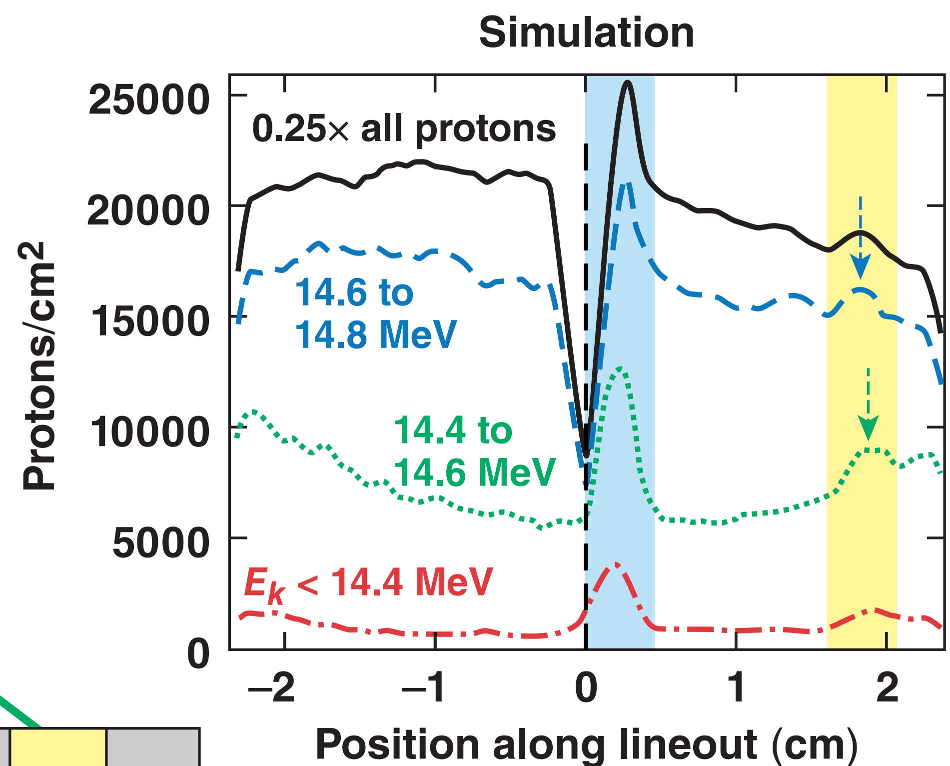
$$v_{\perp} = \frac{e}{m_p}\int B d\ell = \frac{e\langle B\rangle D}{m_p}$$

$$\langle B\rangle D \sim \frac{m_p v \Delta}{eL}$$

E18382

The protons with the largest deflection probe the highest B-field region in the target hot spot

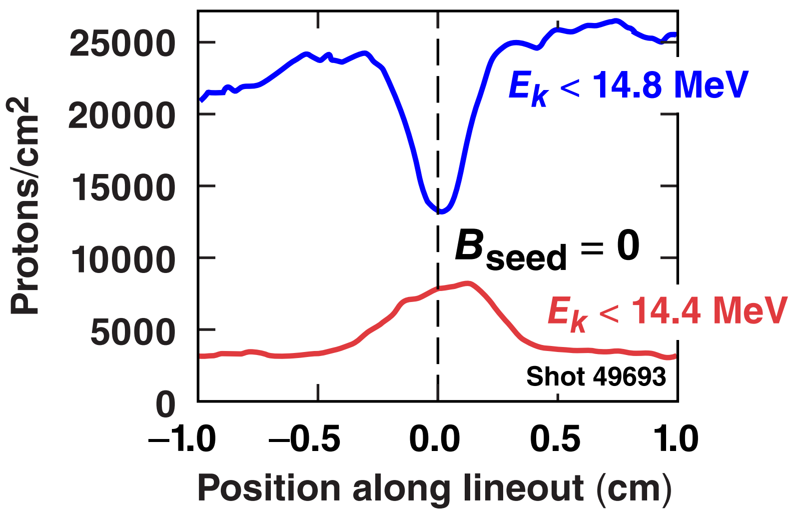




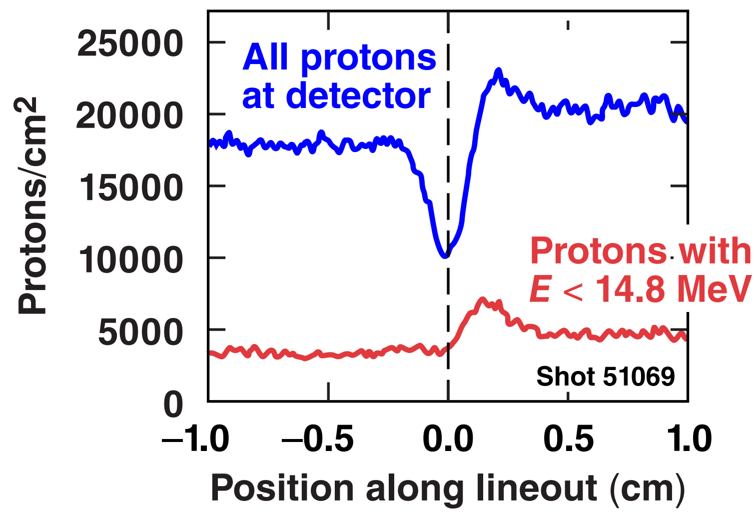
Protons that travel through the hot spot lose less energy that the protons that travel only through the dense shell.

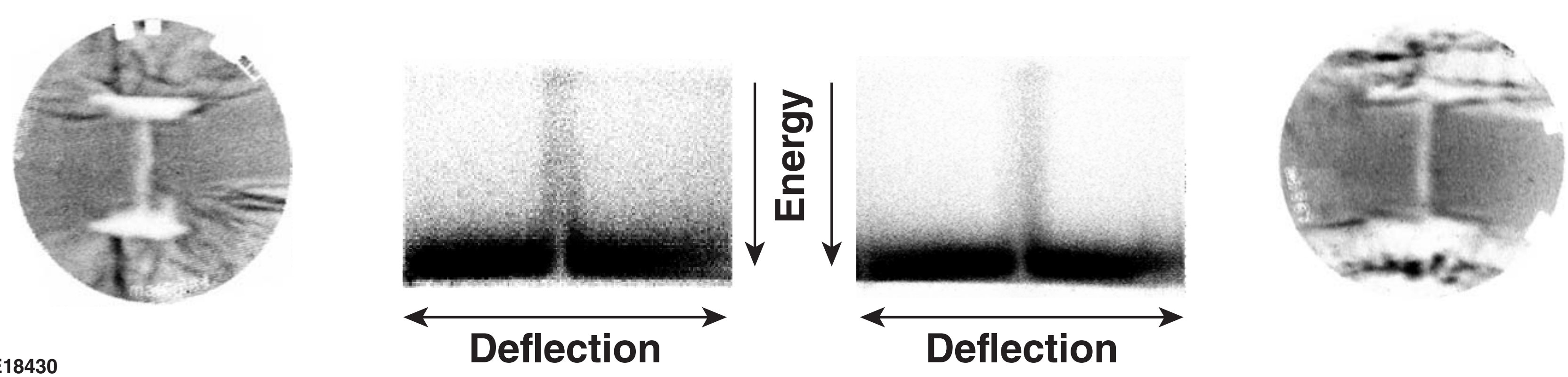
Experimental data from proton radiography clearly show deflection in a magnetic field

B_{seed} = 0
Peak and valley are aligned



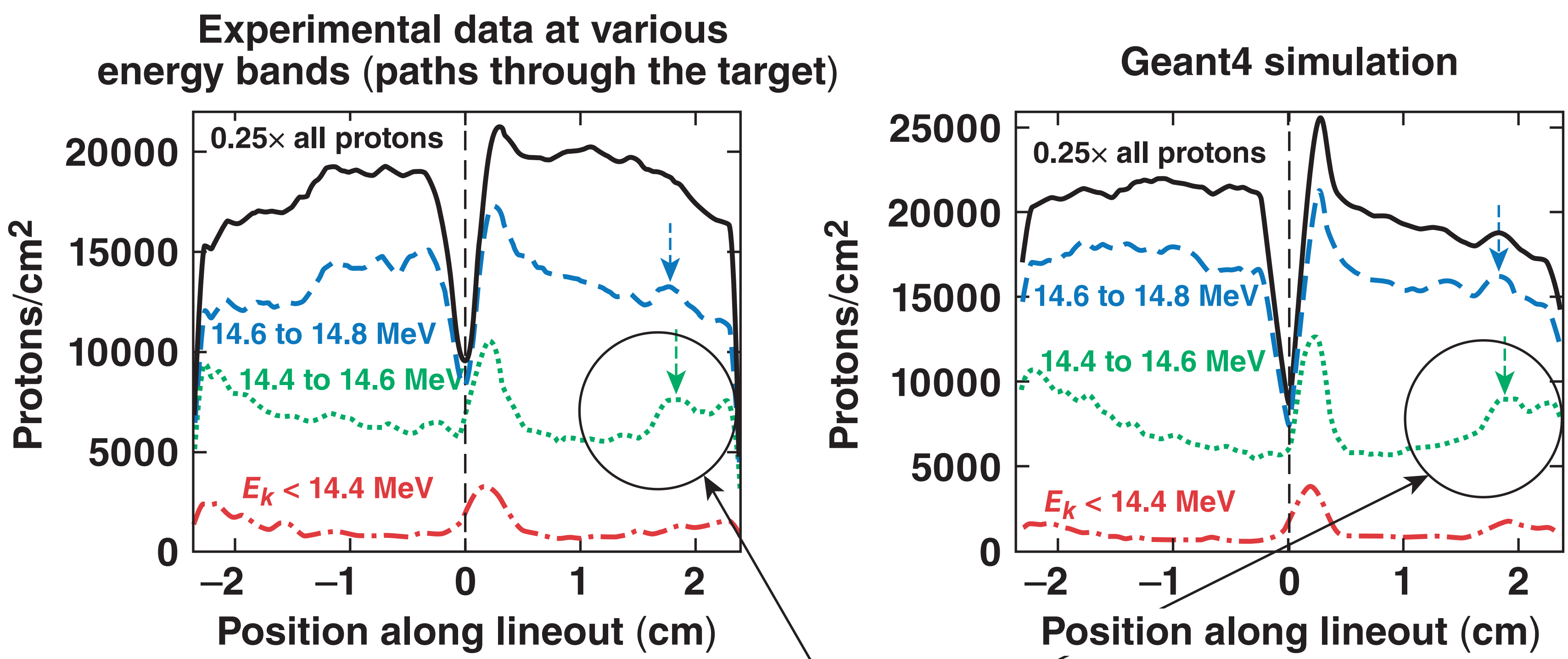
B_{seed} = 5.6 kG
Peak and valley are misaligned





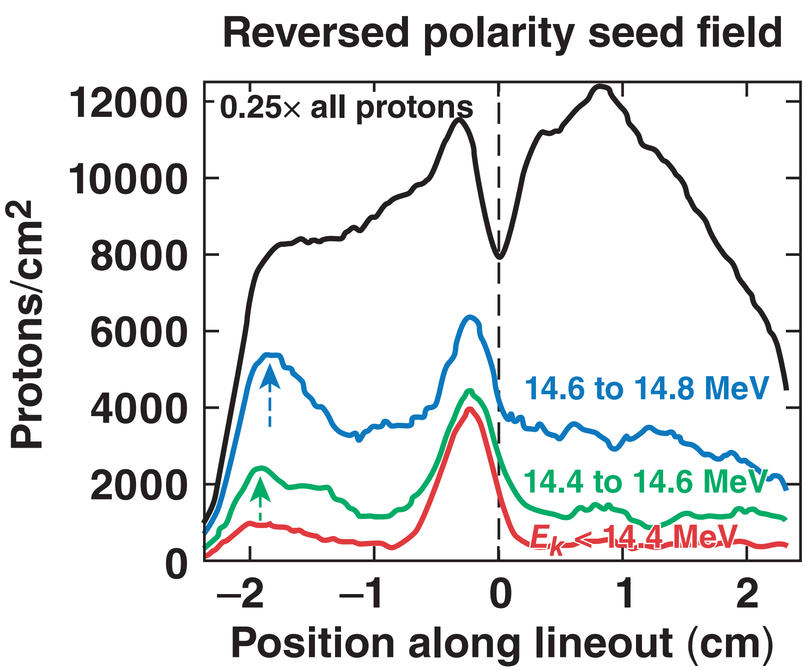
E18430

Measured proton deflections are well reproduced by Geant4 with an $\langle B \rangle$ of ~30 MG over a 34-μm hot spot

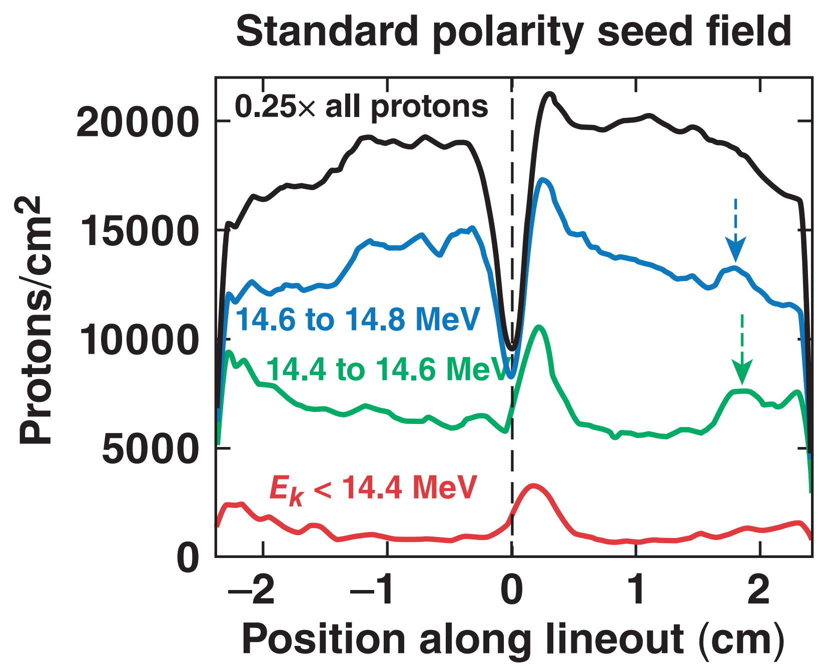


The peak from protons with maximum deflection gives $\langle B \rangle$~30 MG in simulations.

Reversing the polarity of the seed field reverses the deflection of the proton probe



The minimum average magnetic field matching this deflection is 40 MG.



The minimum average magnetic field matching this deflection is 30 MG.

E18431

Cylindrical implosions have hot-spot conditions where the ion mean-free-path and Larmor radius ~ hot-spot radius

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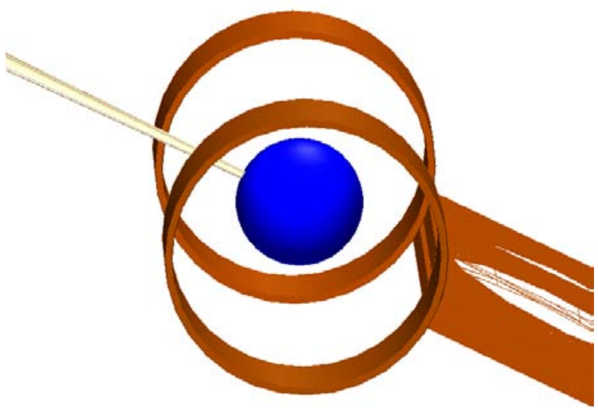
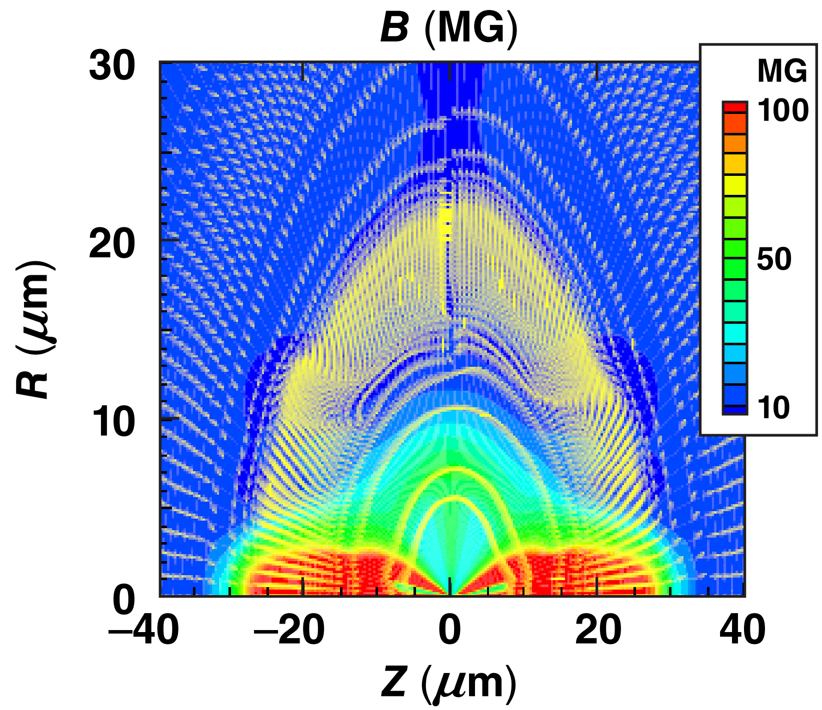
Collision mean-free-path and Larmor radii for a simulated magnetized hot spot (R = 20 μm) with a volume-averaged field of 30 MG.

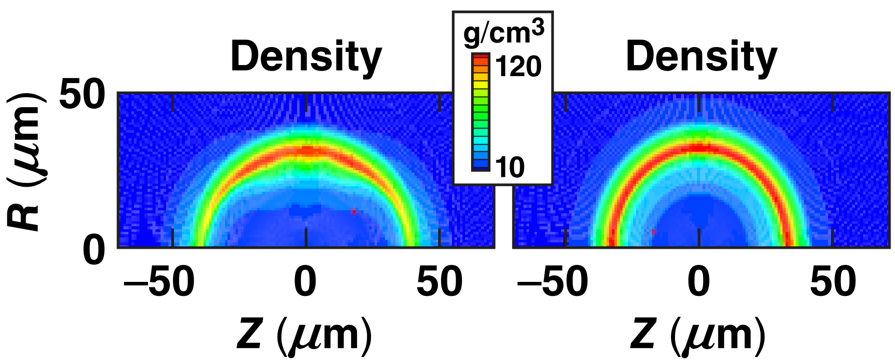
	ρ_{HS} (g/cm^3)	mfp$_{ie}$ (μm)	mfp$_{ii}$ (μm)	r_{iL} (μm)
Cylinder	0.5	151	5.6	5.7
Sphere	5.0	27	0.52	7.7

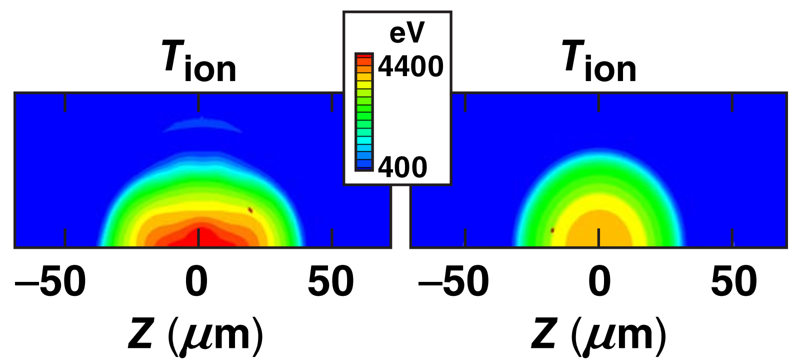
Spherical implosions are needed to measure the effect of magnetic fields on hot-spot yields.

2-D simulations of spherical implosions show higher-ion temperatures with a magnetic field





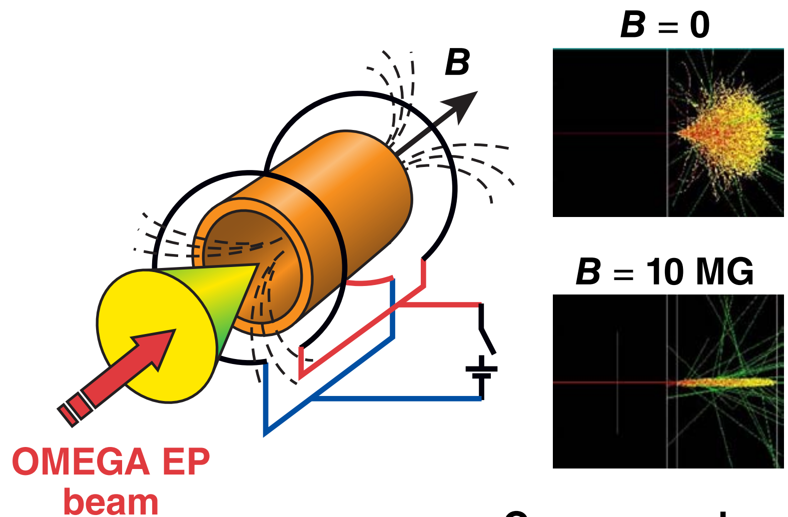


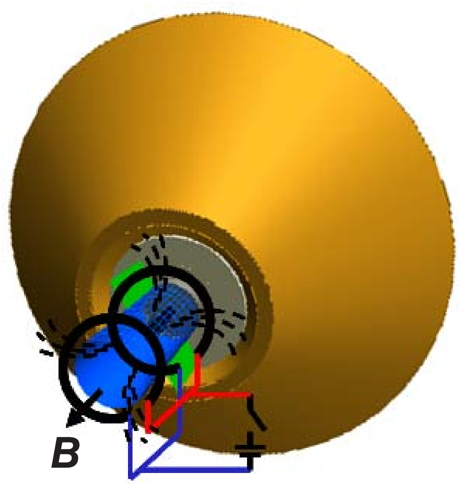


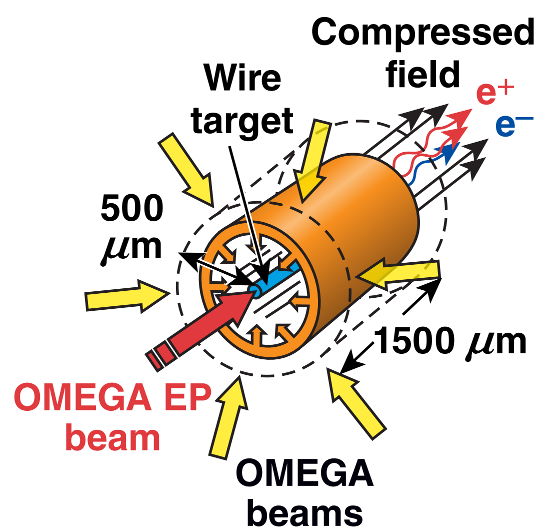
E18433

The applications of laser-driven flux compression go beyond ICF

- Guiding fields for hot electrons in fast ignition.
- Generation of positron–electron plasma in the laboratory.*
- Propagation of plasma jets in large-scale magnetic fields.







E15690b

*J. Myatt *et al.*, Bull. Am. Phys. Soc. 51 (7), 25 (2006).

Summary/Conclusions

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- A compact device to generate up to 150-kG magnetic seed fields has been assembled
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