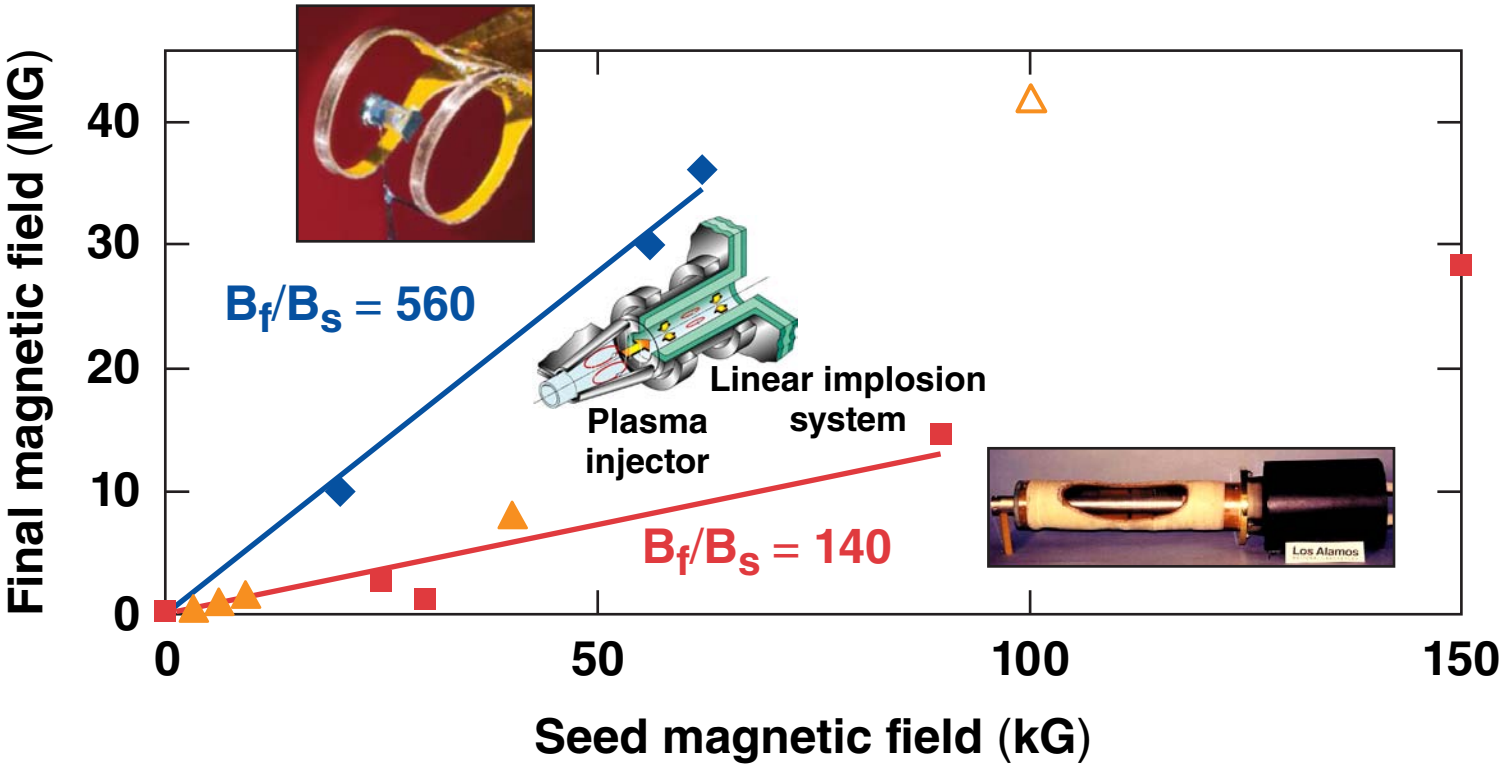
Compressing Magnetic Fields with High-Energy Lasers



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MAGLIF Workshop
Sandia National Laboratory
Albuquerque, NM
5–8 February 2012

Summary

Laser-driven flux compression produce 10- to 40-MG magnetic fields on OMEGA

- A compact device to generate up to ~150-kG magnetic seed fields has been assembled
- Magnetic-field compression with lasers has been demonstrated for cylindrical and spherical implosions
- Cylindrical targets have demonstrated magnetic amplification to 40 MG
- Plasma magnetization opens up new exciting opportunities in the areas of fusion, HEDP, and astrophysics

Collaborators

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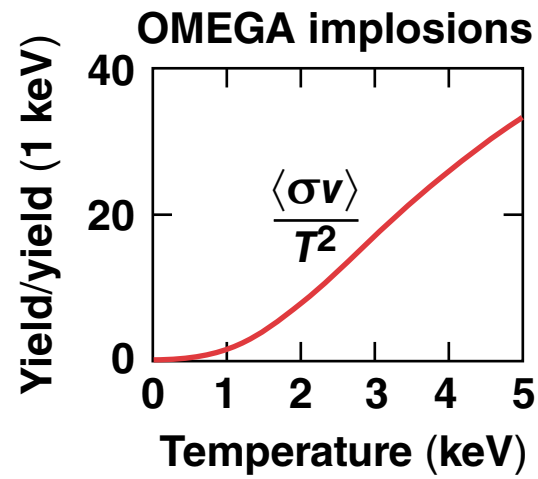
The performance of ICF targets can be improved with MG magnetic fields

- 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}, $n \propto 1/T$

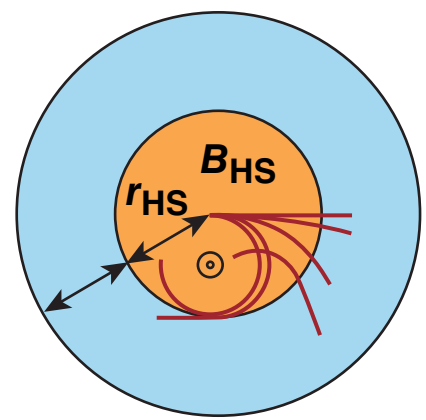


NIF 1.5-MJ, polar-drive point design

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

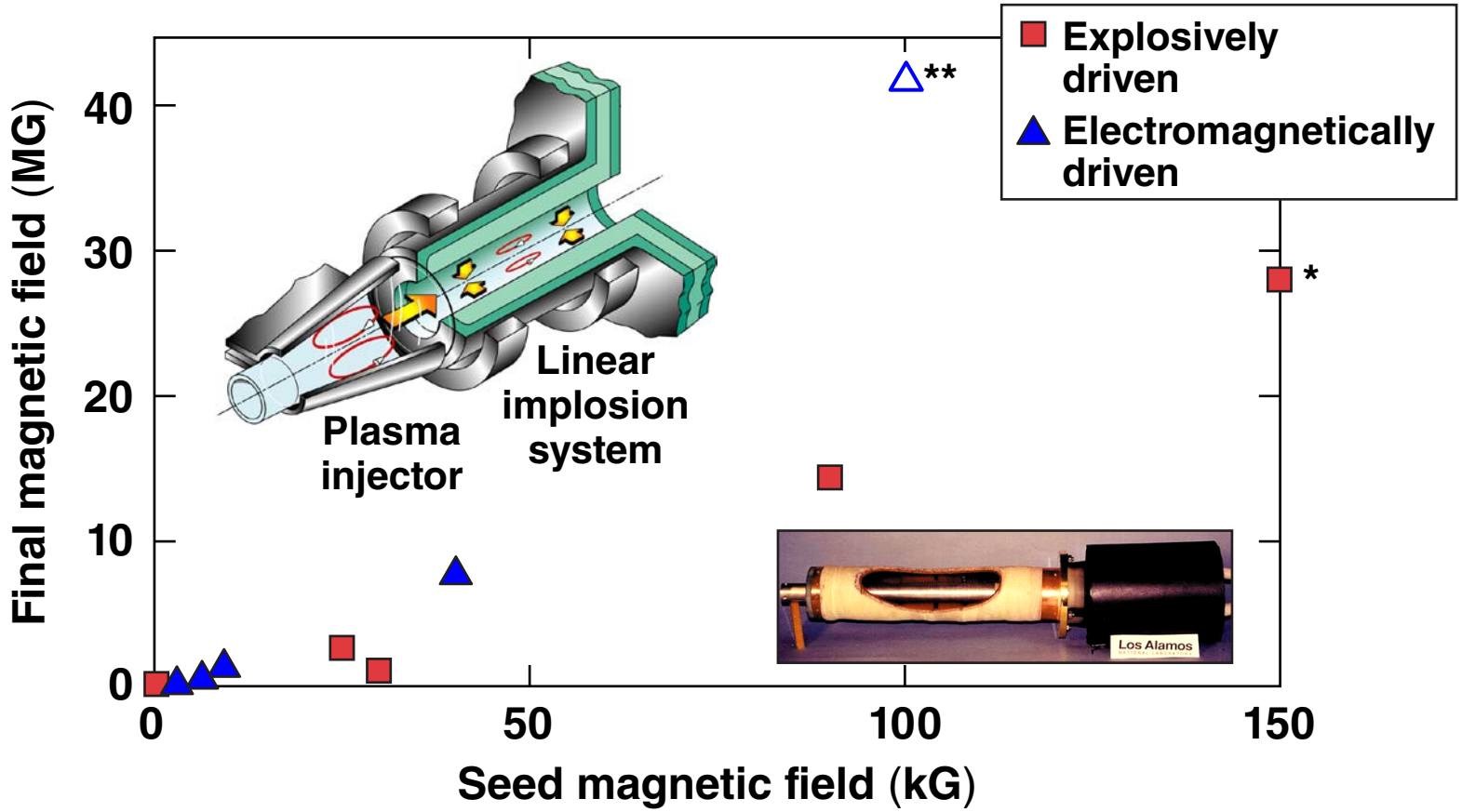
$\kappa_\perp/\kappa_\parallel \sim 0.2$ for $B = 10$ MG

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



E18375a

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

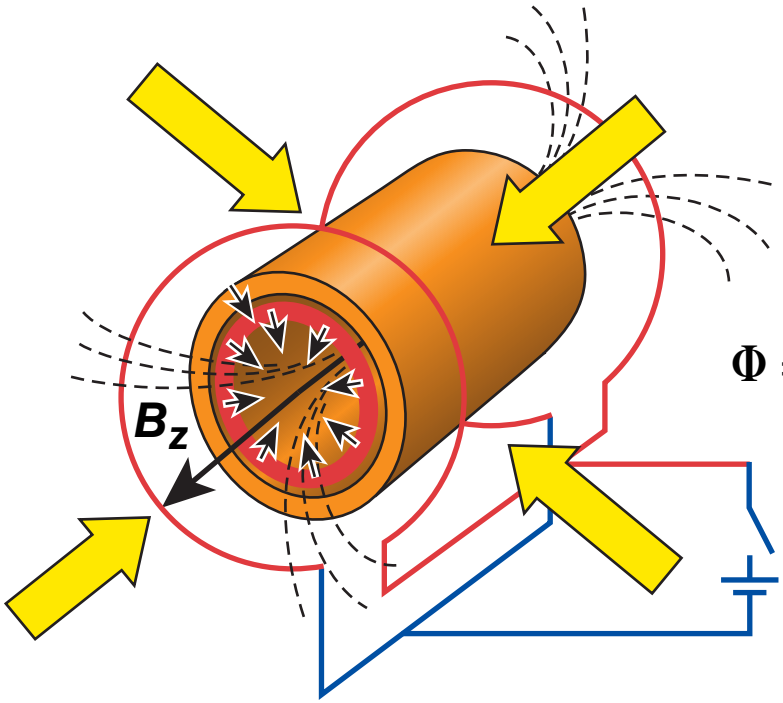


***B* field of 28 MG achieved with high explosives at VNIEF (Russia).**

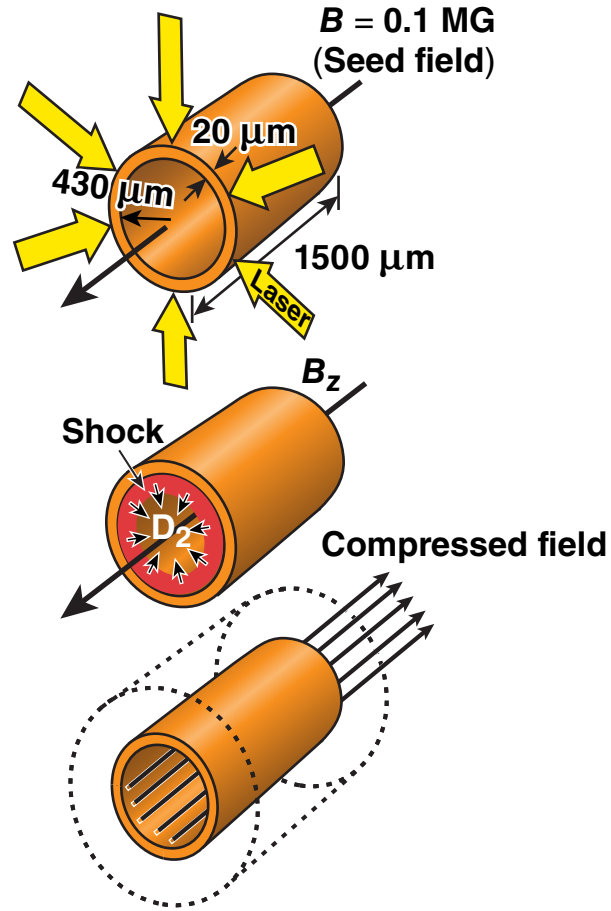
*A. D. Sakharov, Sov. Phys. Usp. 9, 294 (1966).
**F. S. Felber *et al.*, Phys. Fluids 31, 2053 (1988).

E18377a

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



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

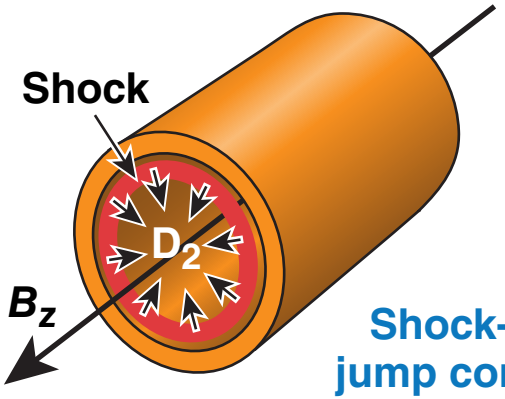


- In a cylindrical target, an axial field can be generated using two Helmholtz-like coils; the target is imploded by a laser to amplify the field

E17764c

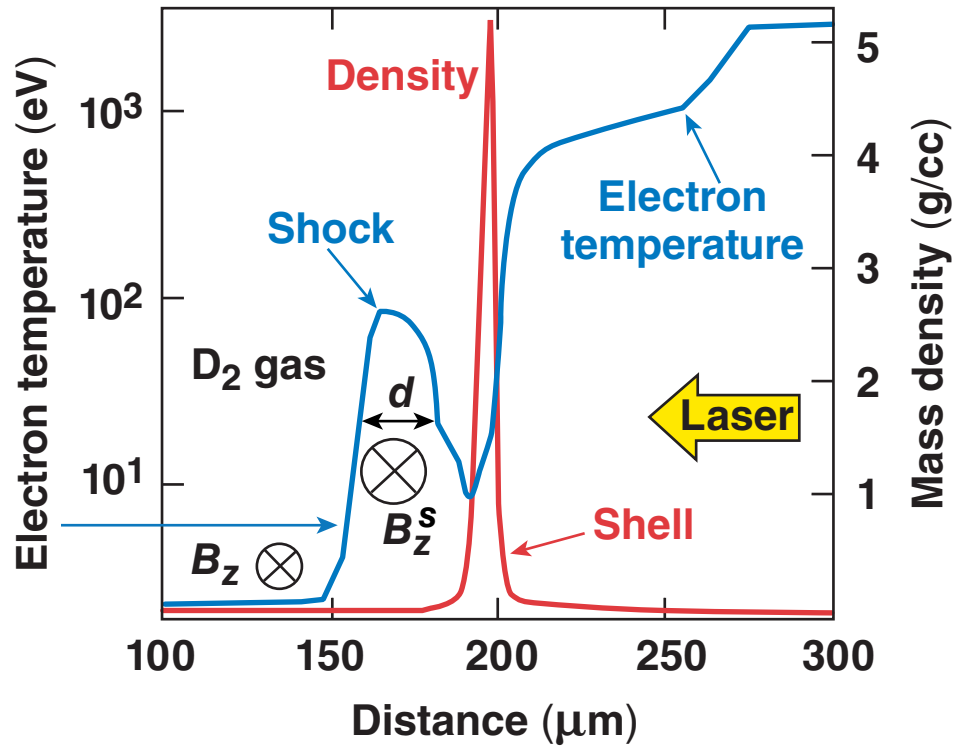
*O. V. Gotchev *et al.*, Phys. Rev. Lett. 103, 215004 (2009).

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



Shock-front jump condition

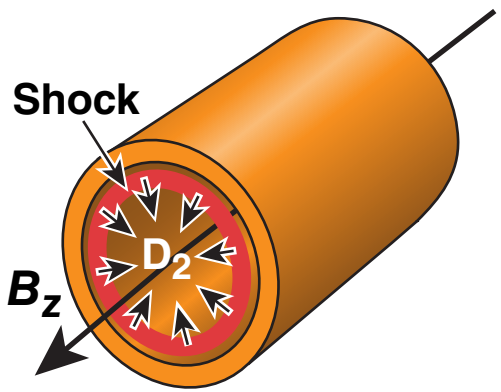
$$\frac{B_z^s}{B_z} = \frac{u_s - v_f}{u_s - v_i}$$



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

E18378b

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



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

$$\mathrm{Re}_m = \frac{\tau_{\text{diffusion}}}{\tau_{\text{implosion}}}$$

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

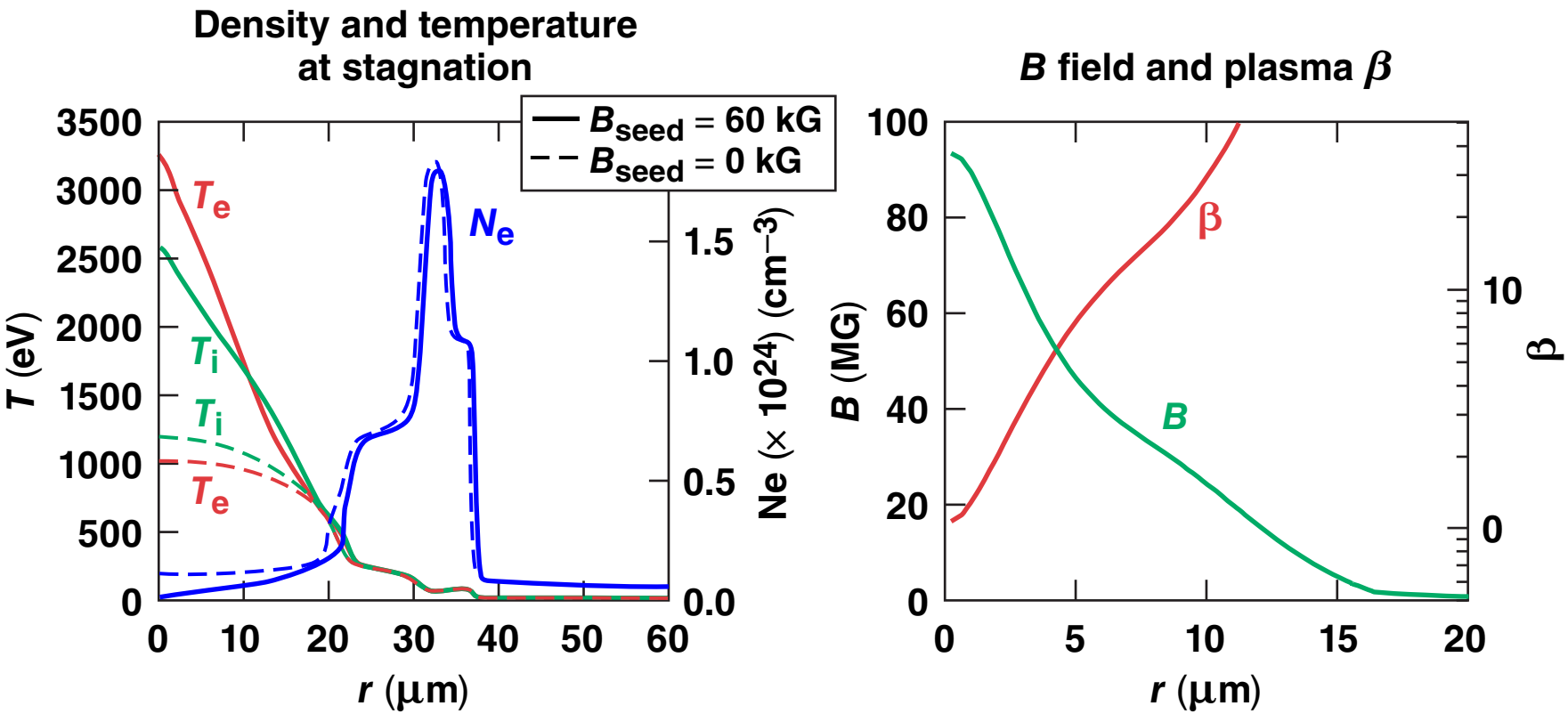
$$\tau_{\text{implosion}} = \frac{r_{\text{ID}} - r_{\text{core}}}{v_{\text{implosion}}} \sim 4\ \text{ns}$$

$$\mathrm{Re}_m \sim 50$$

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

E18379b

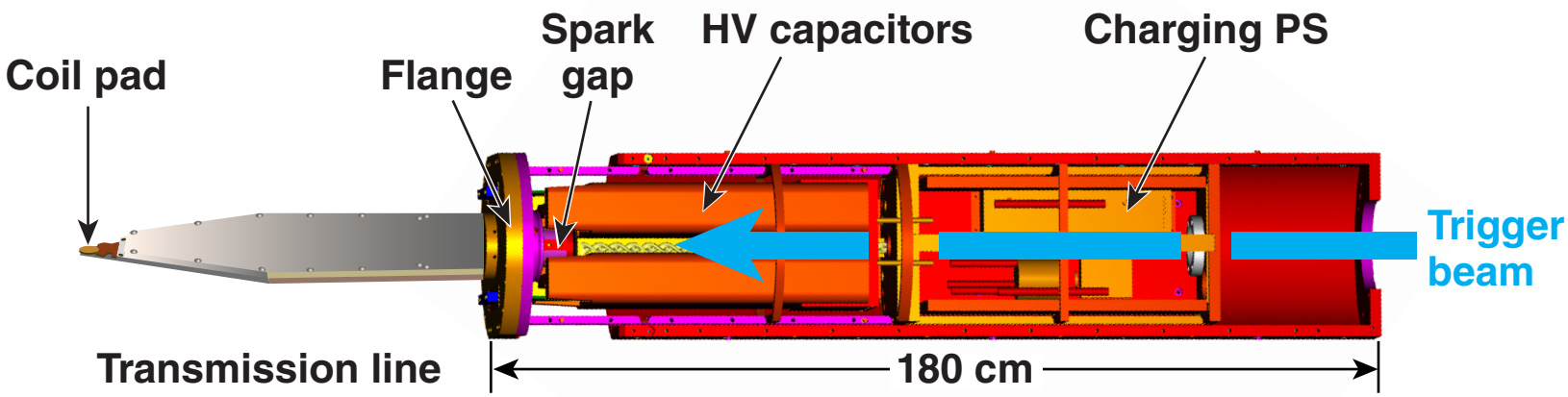
One-dimensional MHD simulations of cylindrical implosions show a T_i with a magnetic field ~2 × T_i without magnetic fields



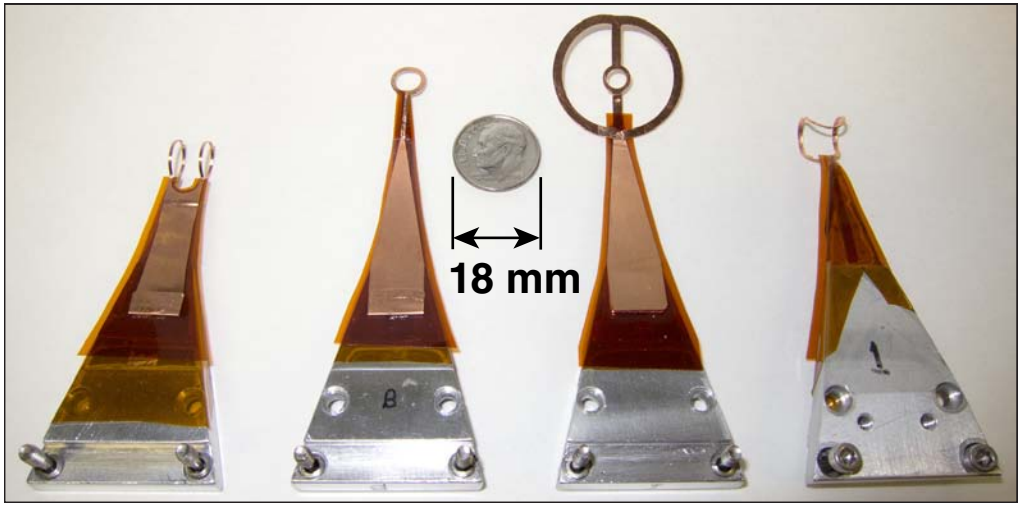
The B field is compressed to ~100 MG at the hot-spot center giving a plasma β of ~1 at the peak magnetic field.

E18380a

The seed *B* field is created by MIFEDS



- Various coils were tested
- Seed fields up to 150 kG can be obtained (depending on the coil geometry)



Helmholtz Single OMEGA Baseball

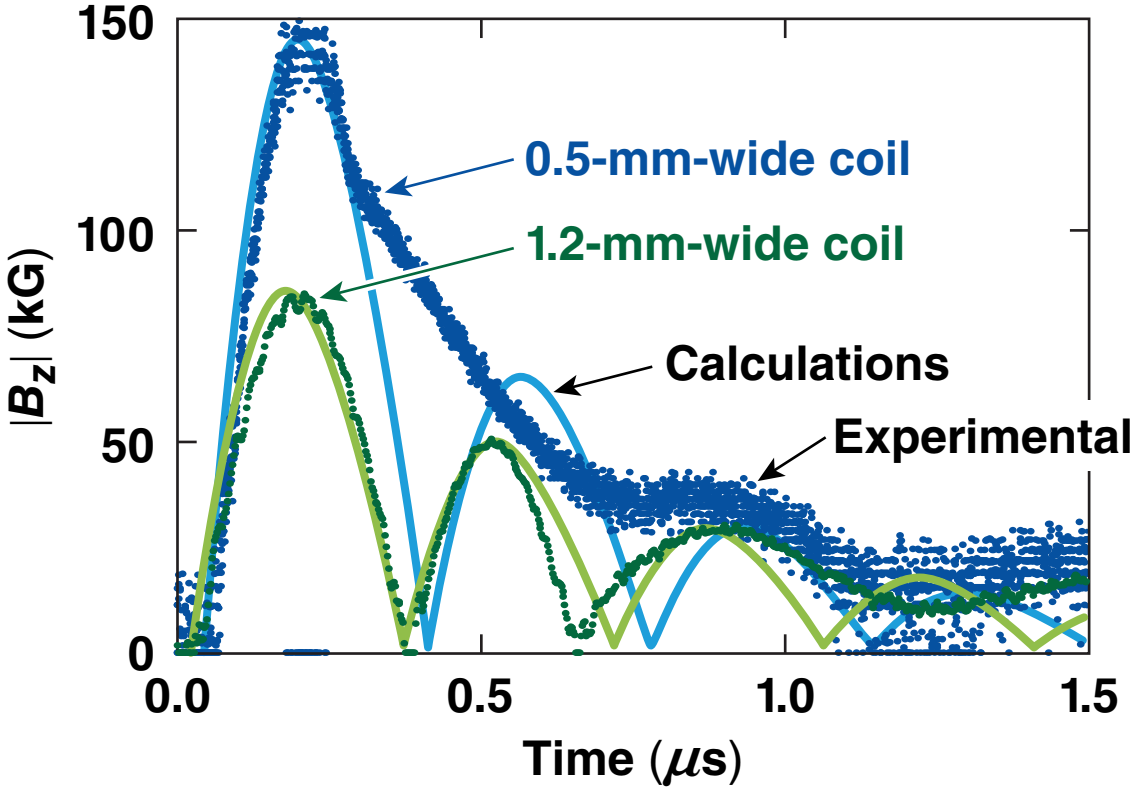
E19778c

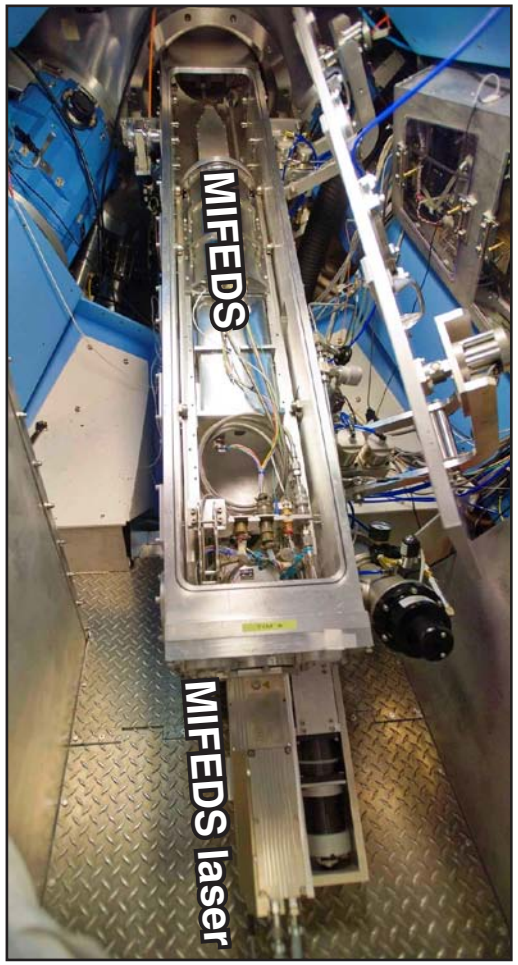
MIFEDS provides in-target seed fields between 10 and 150 kG, depending on coil geometry and energy settings

FSC

UR LLE

Faraday rotation measurements of seed field



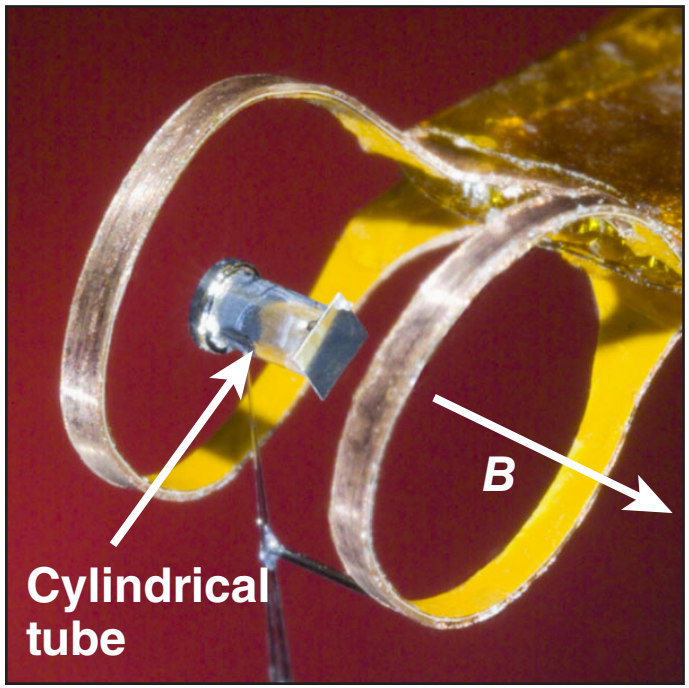


- MIFEDS is a compact, self-contained system that stores less than 100 J and is powered by 24 V dc
- It delivers ~110-kA peak current in a 350-ns pulse

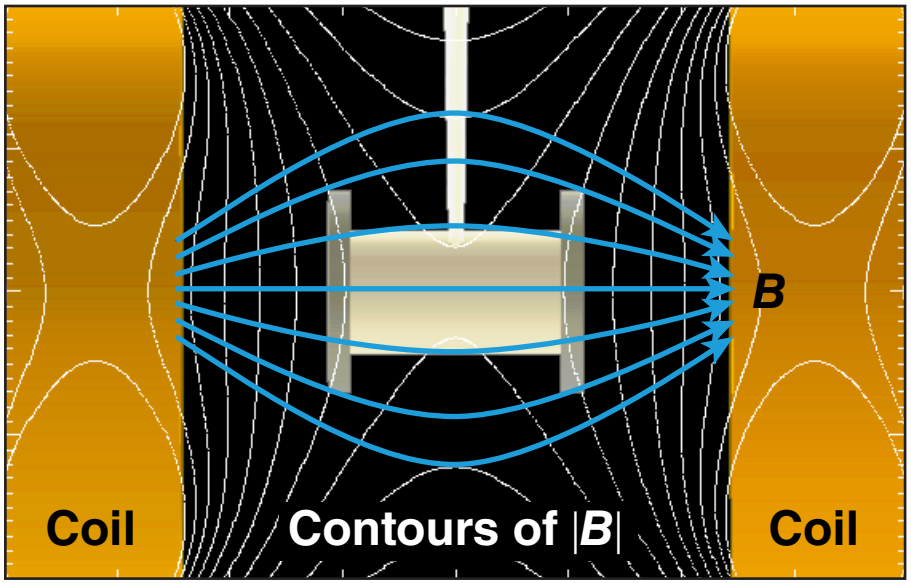
E18381a

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

Coil geometry
- Radius = 2 mm
- Separation = 5.25 mm



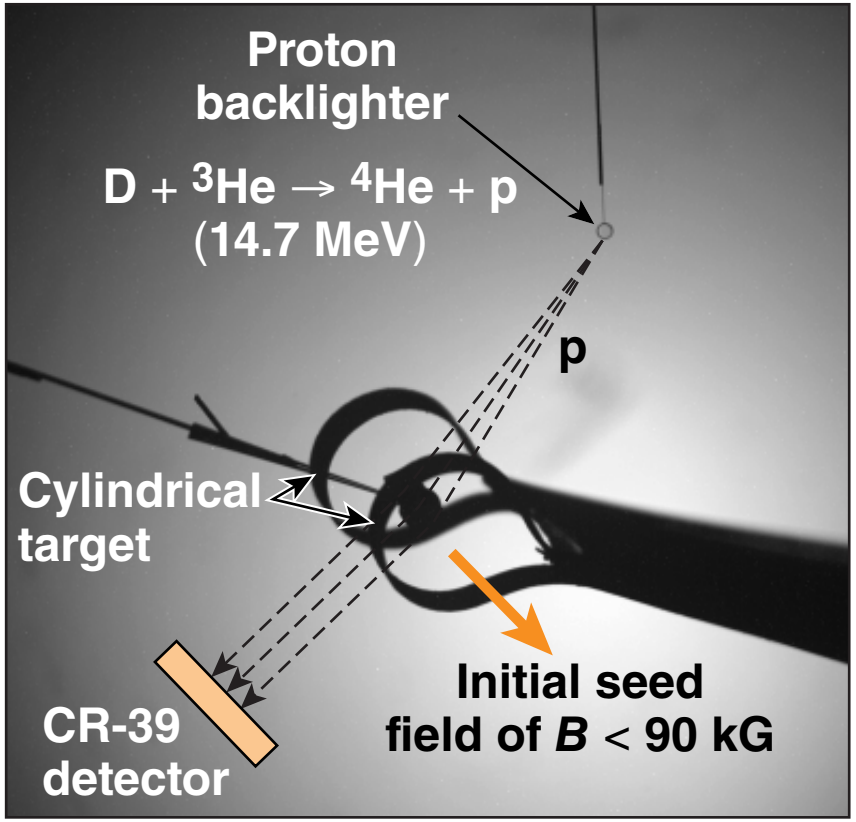
Cylindrical target
- Radius = 430 μm
- Length = 1.5 mm
- Wall thickness = 20 μm
- Fill = 9 atm D_2

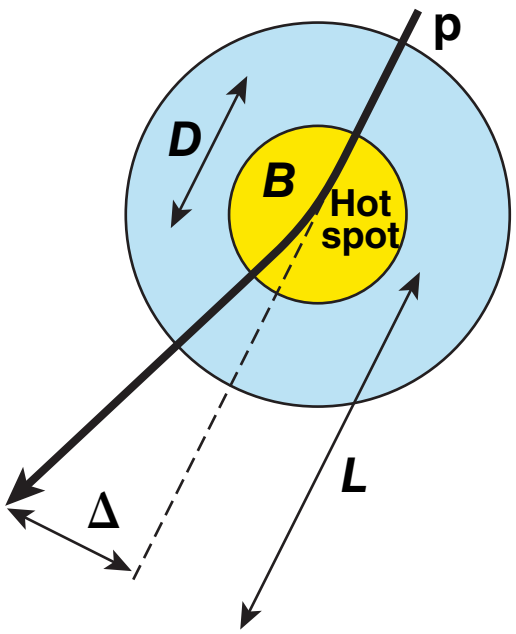


The cylindrical implosion target is positioned in a uniform field region between the coils.

TC8512b

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





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

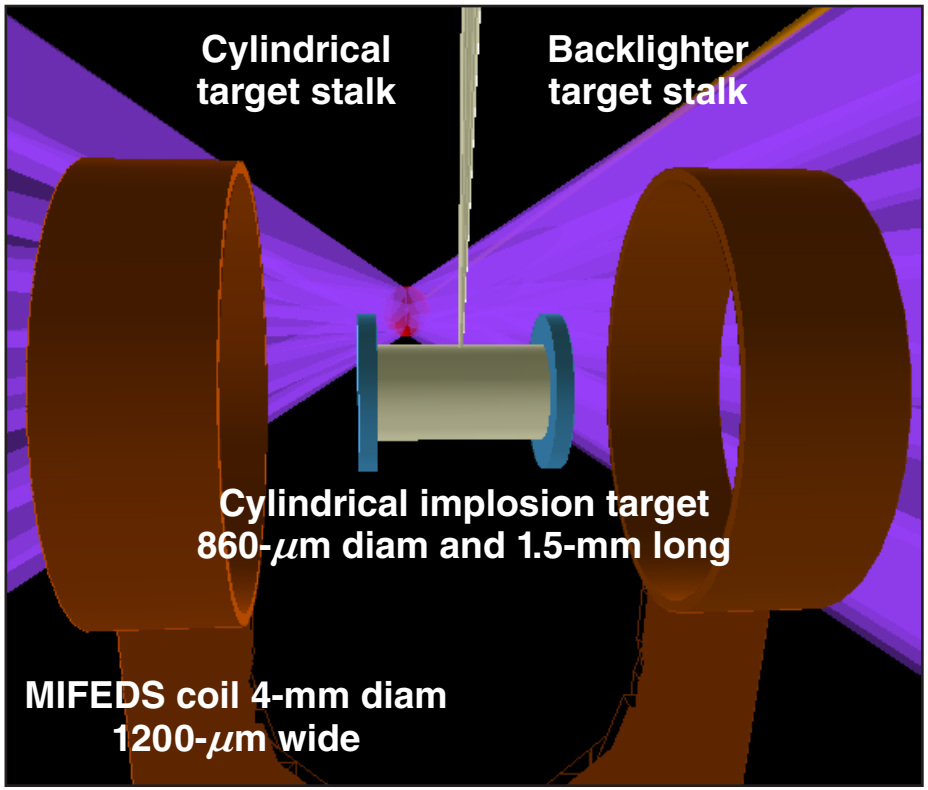
$$v_\perp = \frac{e}{m_p}\int B d\ell = \frac{e\langle B\rangle D}{m_p}$$

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

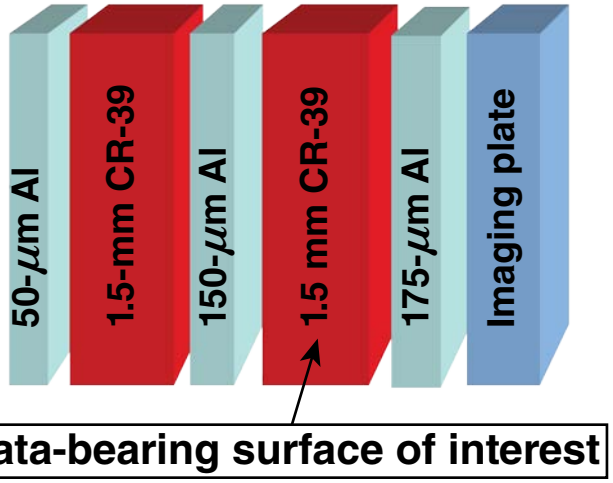
Geant4 simulations are used for an accurate interpretation of the data

E18382a

Magnetic fields are measured via deflection of the D^3He backlighter protons traversing the target area



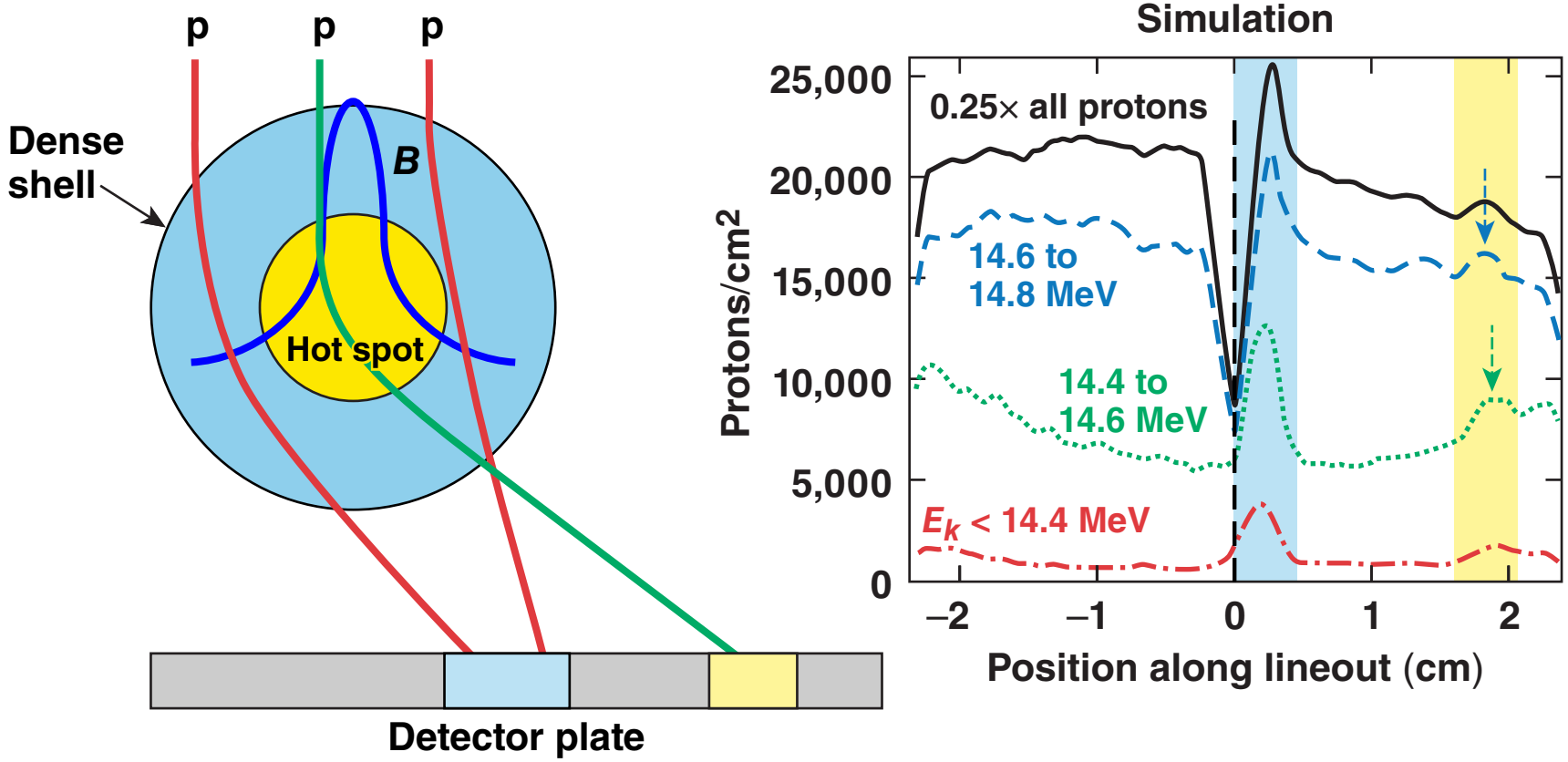
- D^3He (18 atm) backlighter target placed 9 mm from cylinder
- Distance to the CR-39 detector is ~10.5 cm, magnification ~12.7



- Setup for proton deflectometry of a cylindrical magnetic inertial fusion target as viewed from detector
- Detector package can be set to record both protons and x rays

E15146e

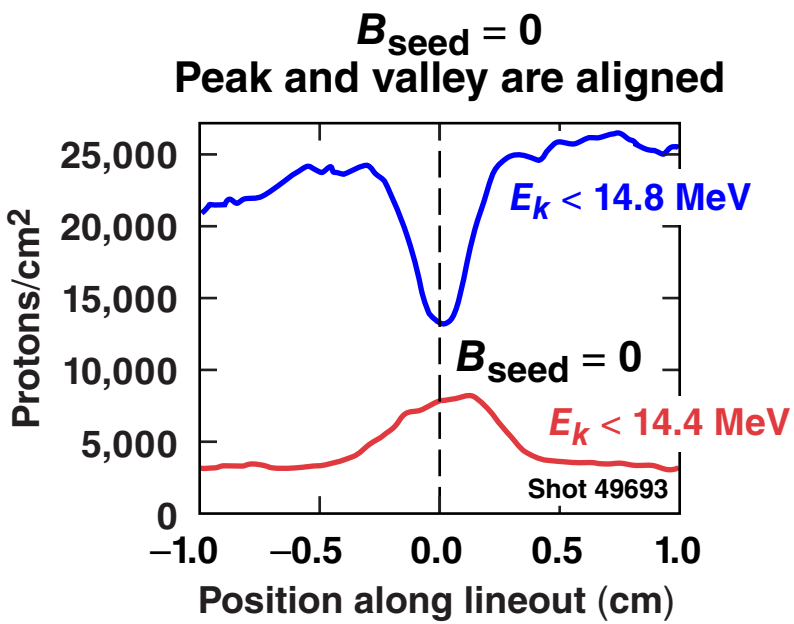
The protons with the largest deflection probe the highest *B*-field region in the target hot spot

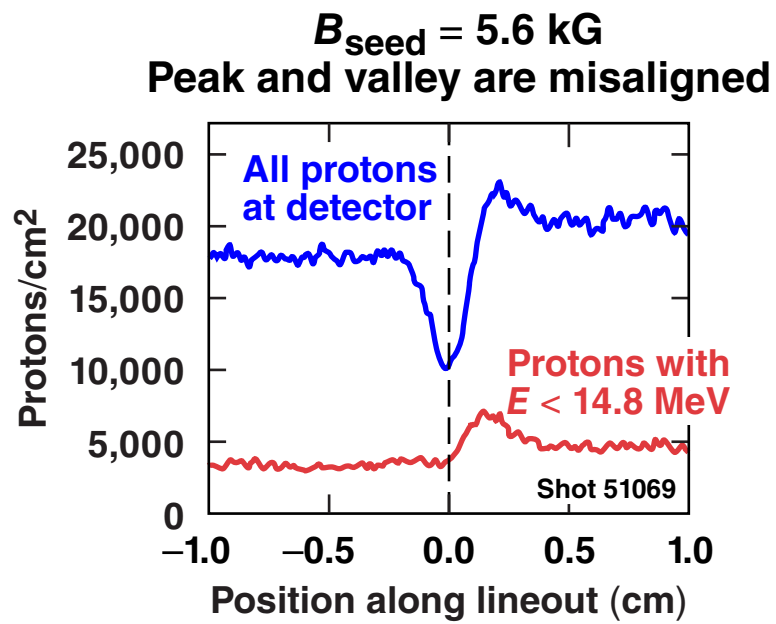


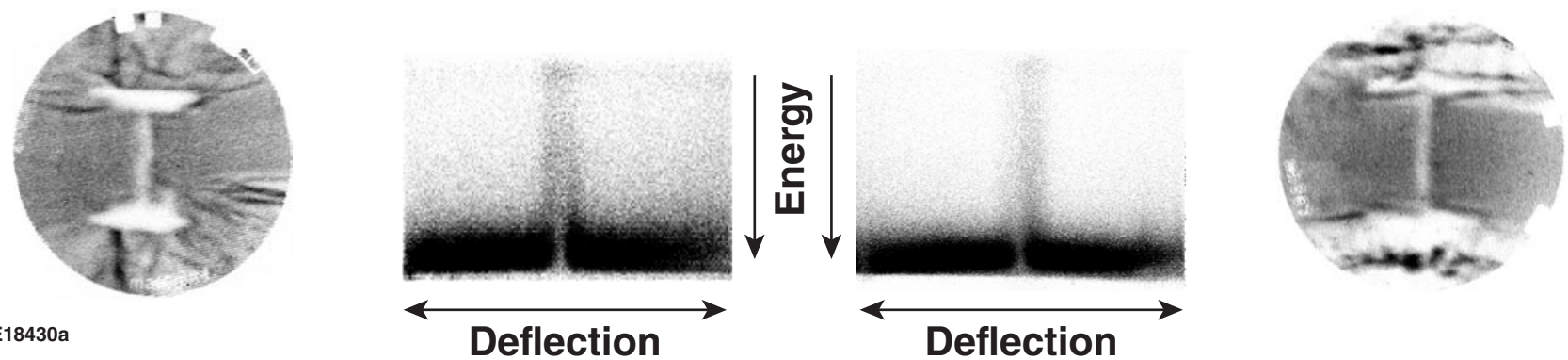
Protons that travel through the hot spot lose less energy that the protons that travel only through the dense shell.

E18383a

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

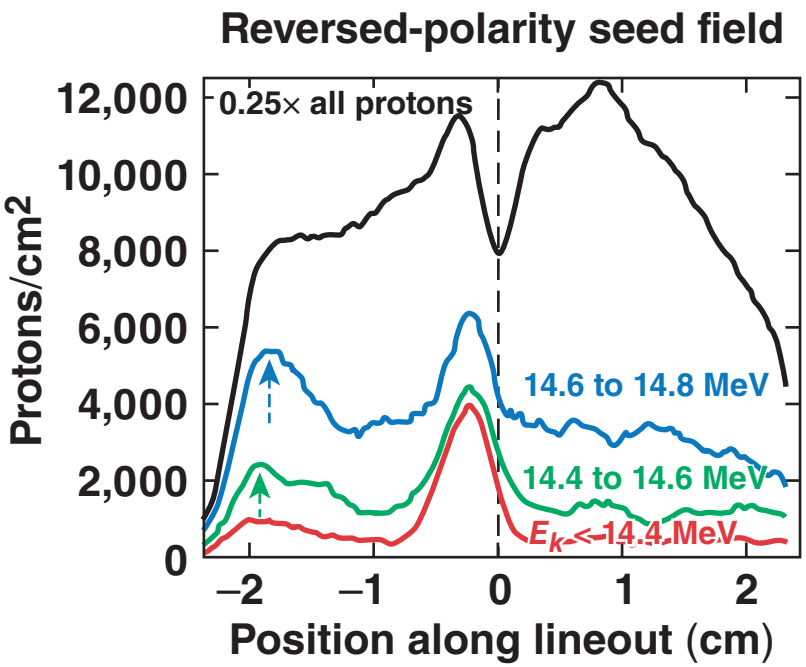




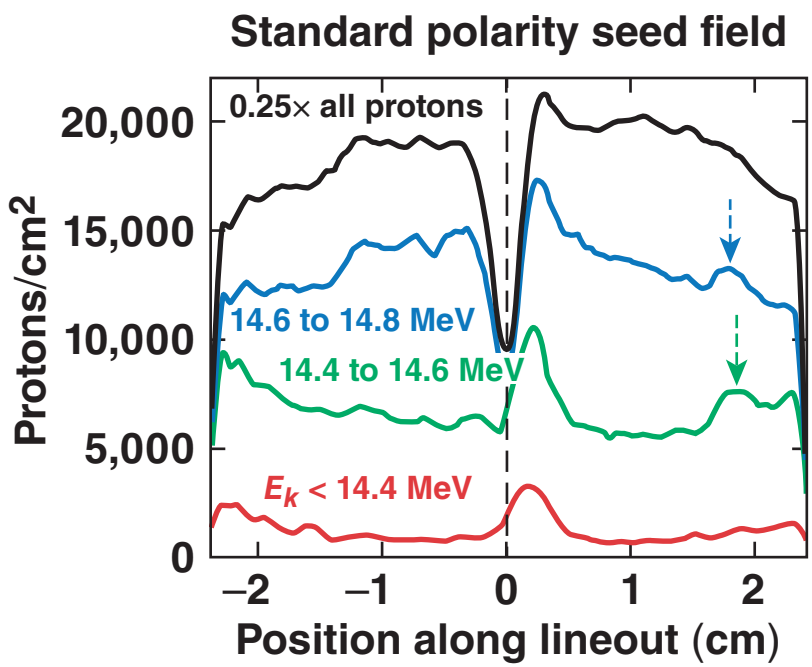


E18430a

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.



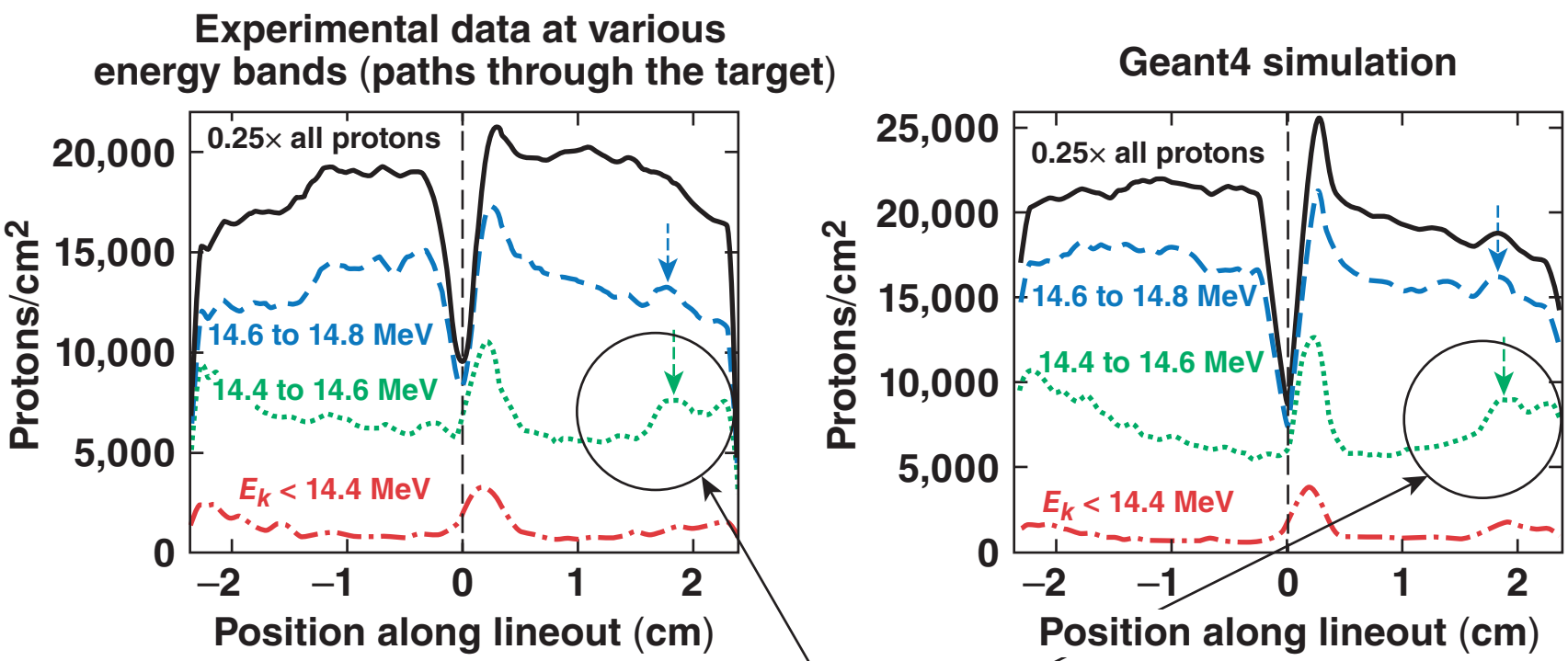
The minimum average magnetic field matching this deflection is 30 MG.

E18431a

Monte Carlo simulation framework was developed for predictive ability and data interpretation

- Built around the Geant4 particle-transport code base
- Proton trajectory in field, multiple scattering, and ionization modeled together
- The simulations were essential in establishing a successful setup and data analysis strategy
  - showed that we need to optimize the standard detector package for the core traversing protons
  - additional discrimination by energy (track diameter) was necessary to isolate the protons deflected by the compressed fields
  - helped in data interpretation to verify that the observed deflections are caused by localized compressed fields, not the seed field

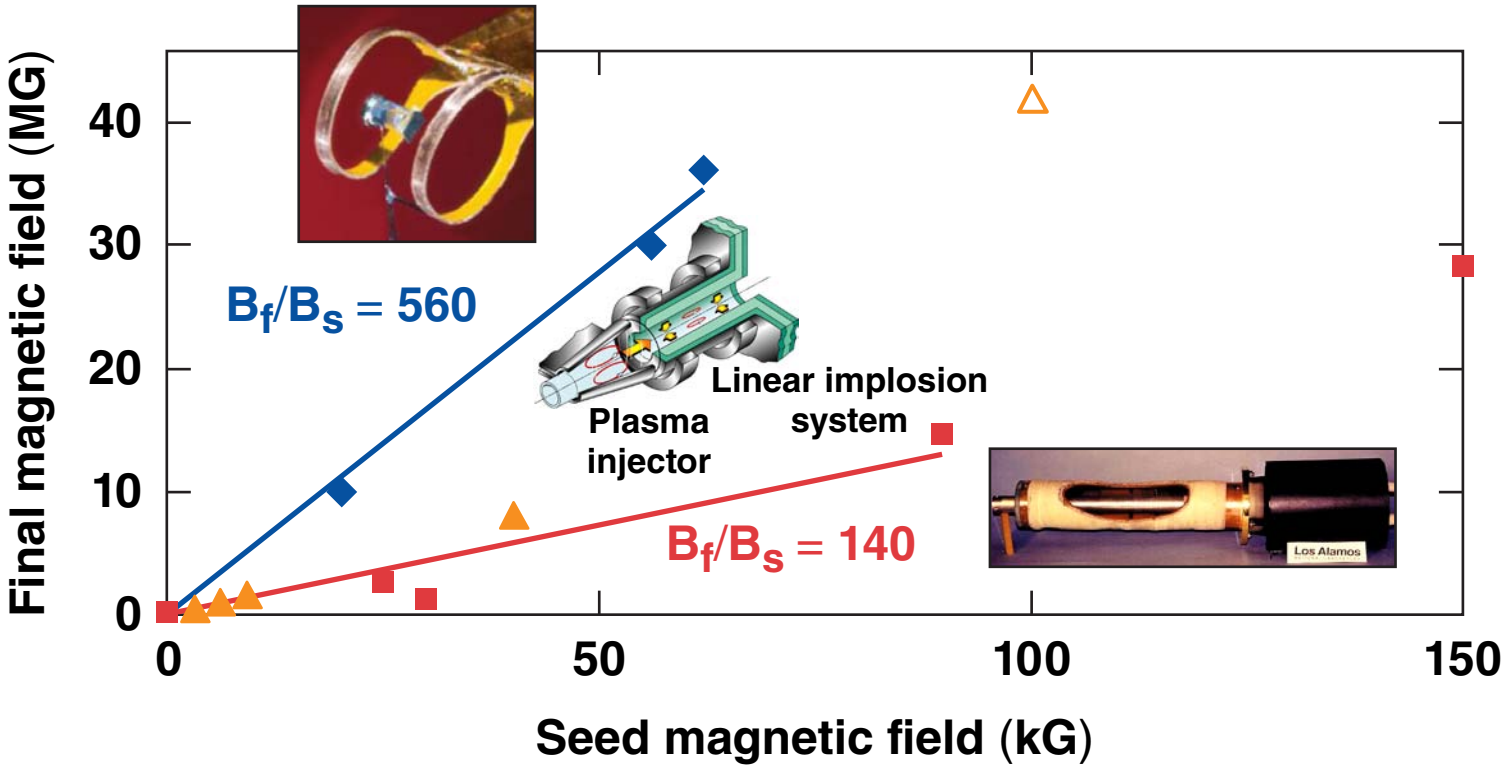
Measured proton deflections are well reproduced by Geant4 with a ⟨*B*⟩ of ~30 MG over a 34-μm hot spot



The peak from protons with maximum deflection gives ⟨*B*⟩ ~ 30 MG in simulations.

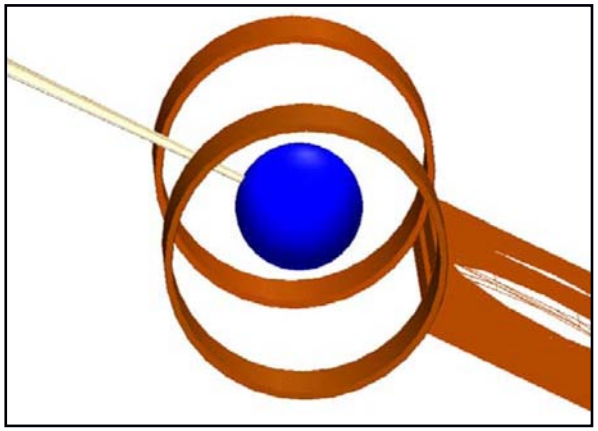
E17867b

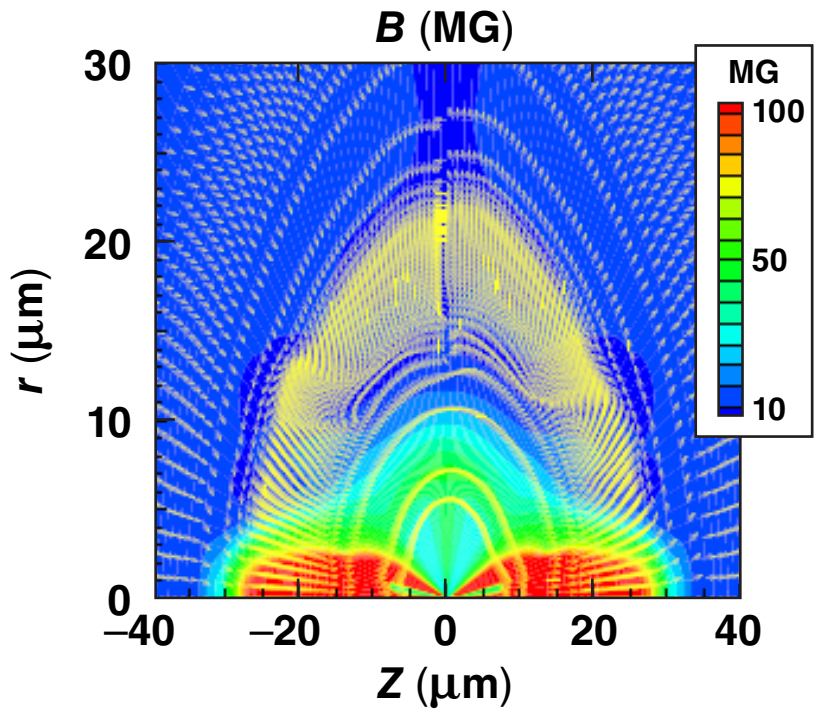
Laser flux compression has amplified magnetic fields to 40 MG

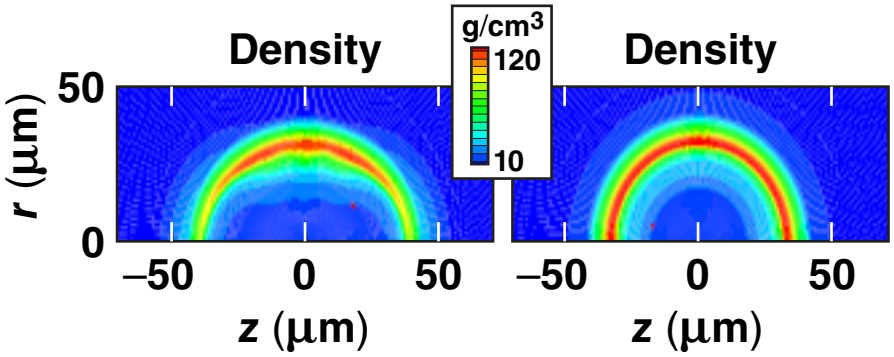


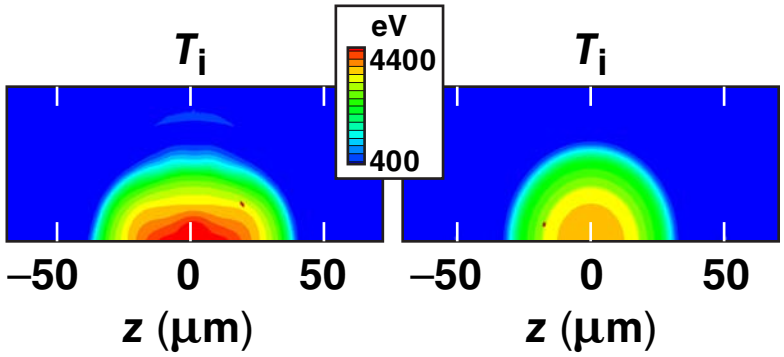
E20686

Higher ion temperatures with a magnetic field are shown in 2-D simulations of spherical implosions



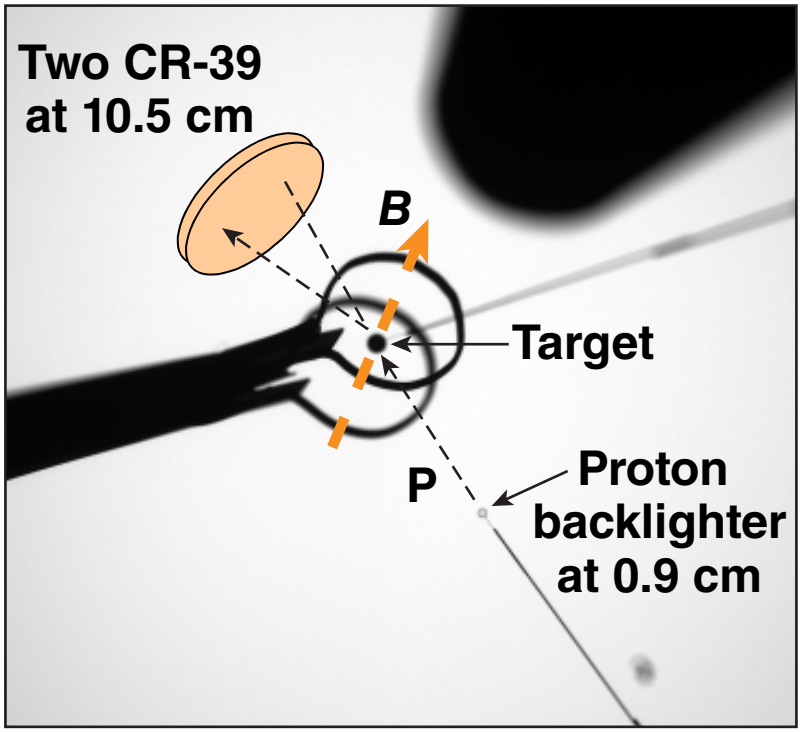






E18433b

Proton radiography was used for *B* measurements in spherical implosions

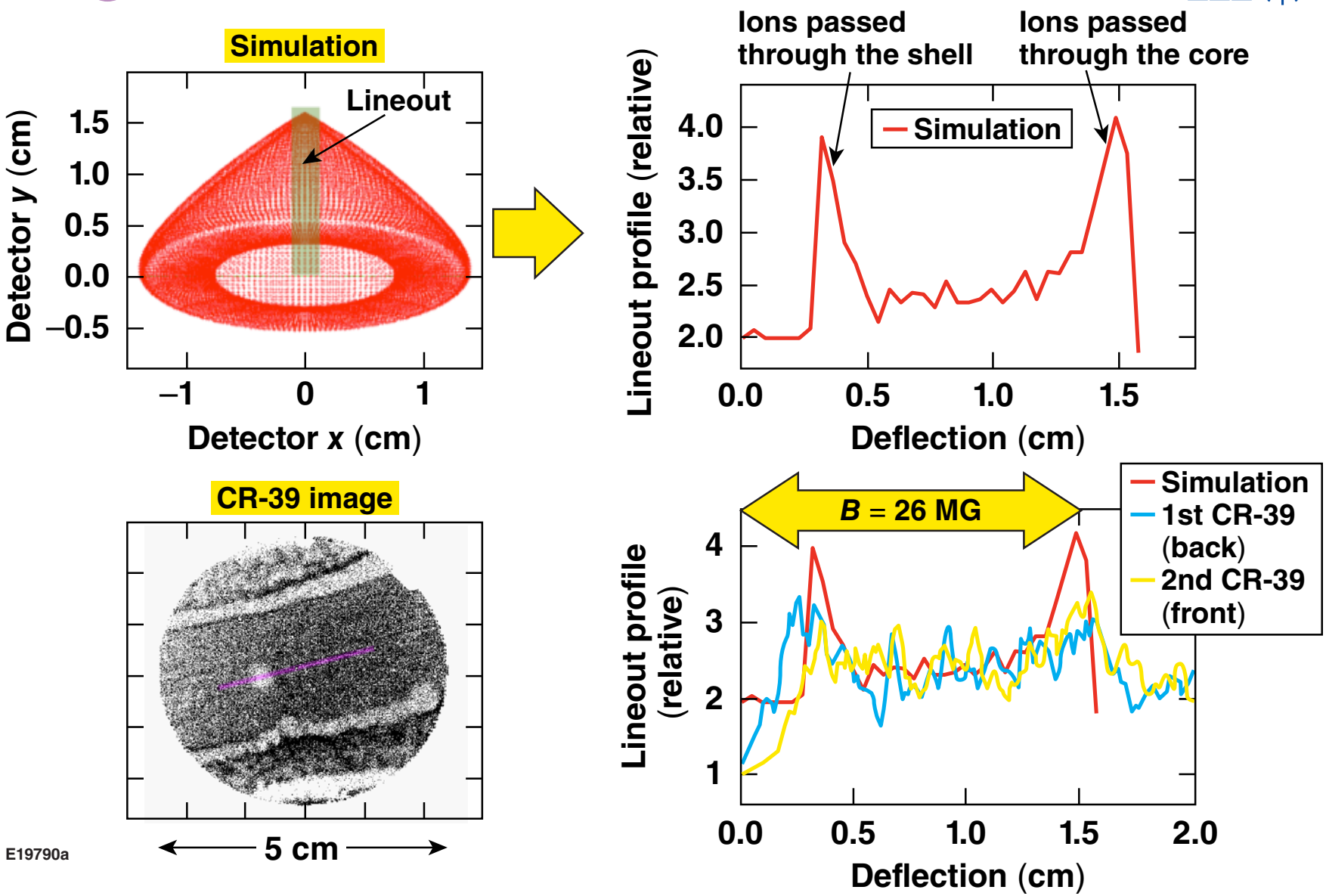


$D + {}^3He \rightarrow {}^4He + p$ (14.7 MeV)

- **Main target**
  - D_2-filled CH
  - P = 3/5/10 atm
  - r_{D_2} = 406 μm
  - d_{CH} = 24 μm
  - 18.9 kJ (42 beams)
- **Backlighter**
  - D^3He-filled SiO_2
  - 9 mm away from TCC
  - 5.4 kJ (12 beams)

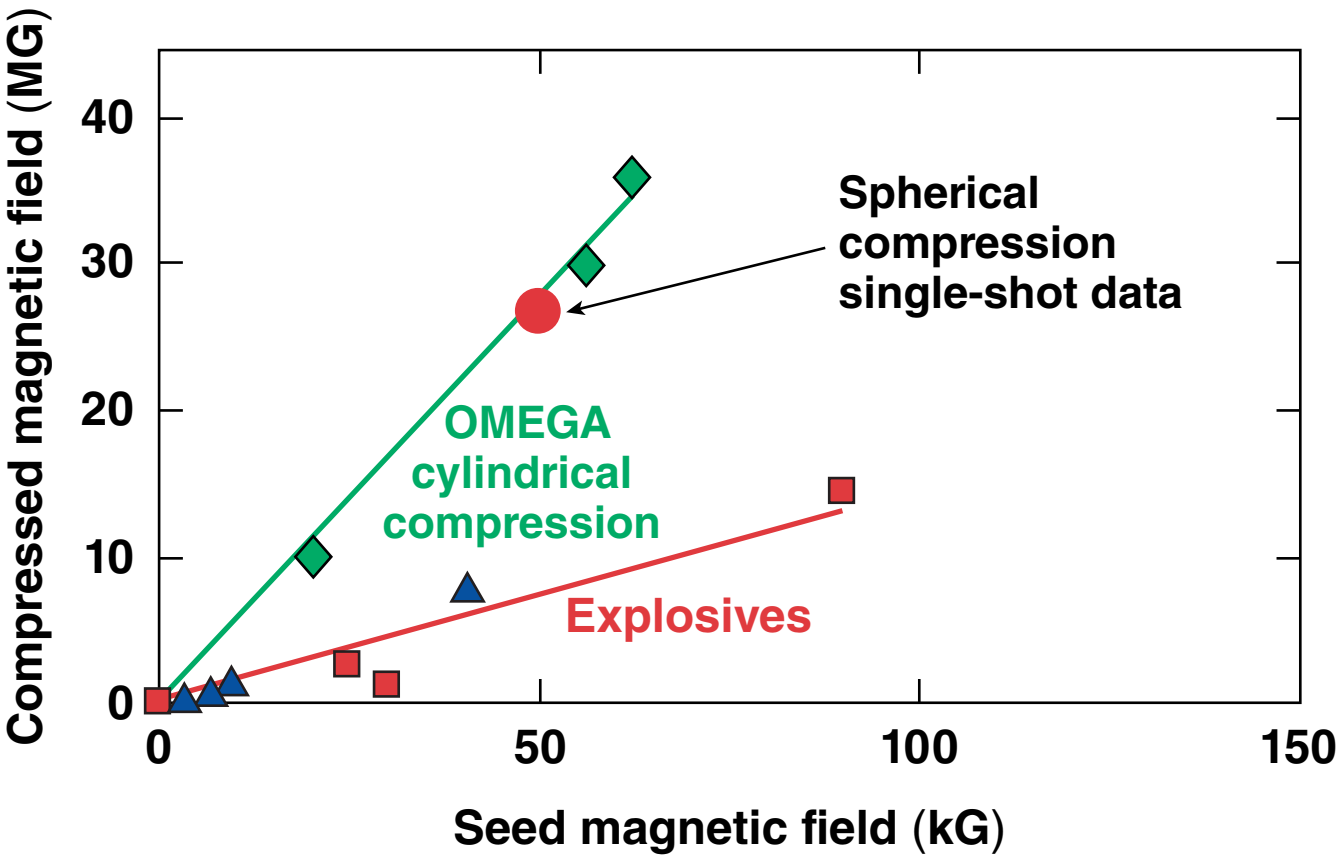
TC9002a

Which agrees with the measured lineouts on both front and rear CR-39 plates; inferred *B* = 26 MG



E19790a

Field compression of ~500 agrees with flux conservation

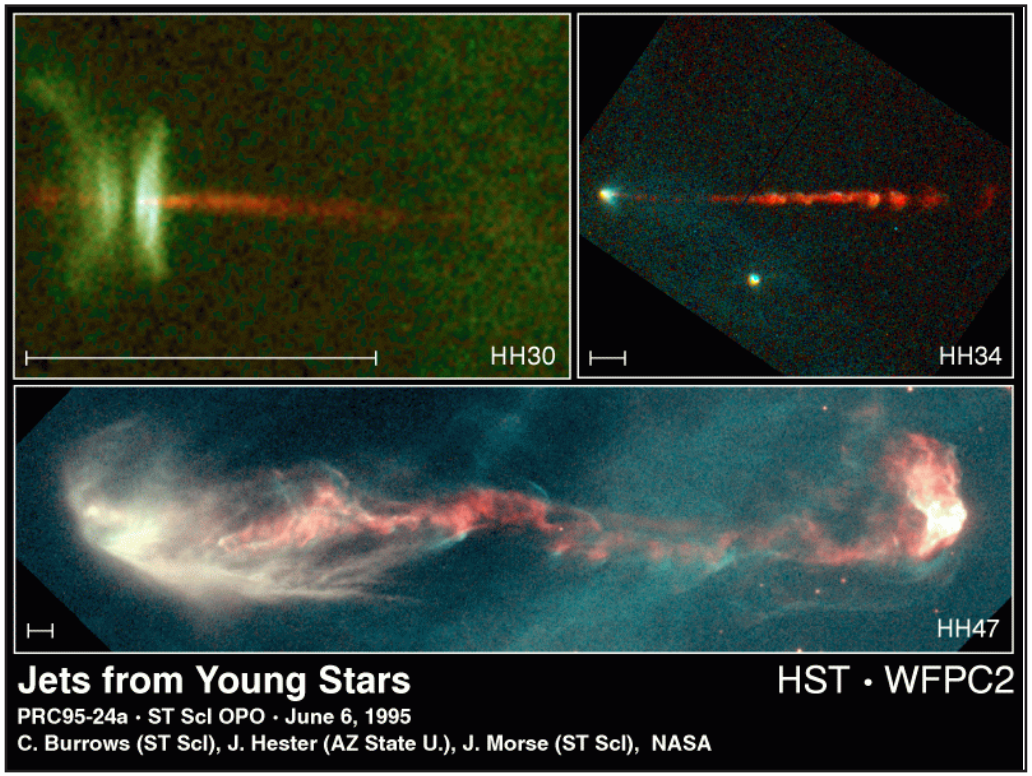


- Magnetic-field compression ~500
- Convergence^2 ~ 500
- Magnetic flux is conserved!

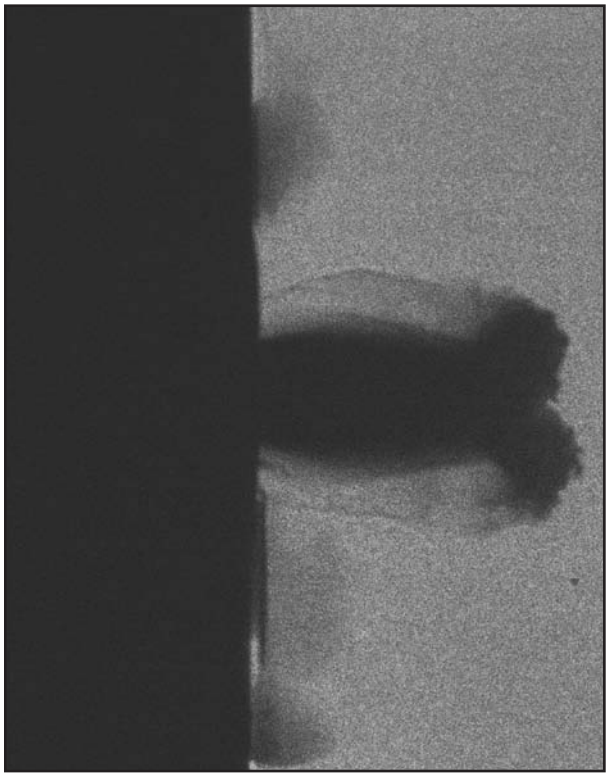
E19782b

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

Hubble Space Telescope images



OMEGA jet
(no magnetic field)

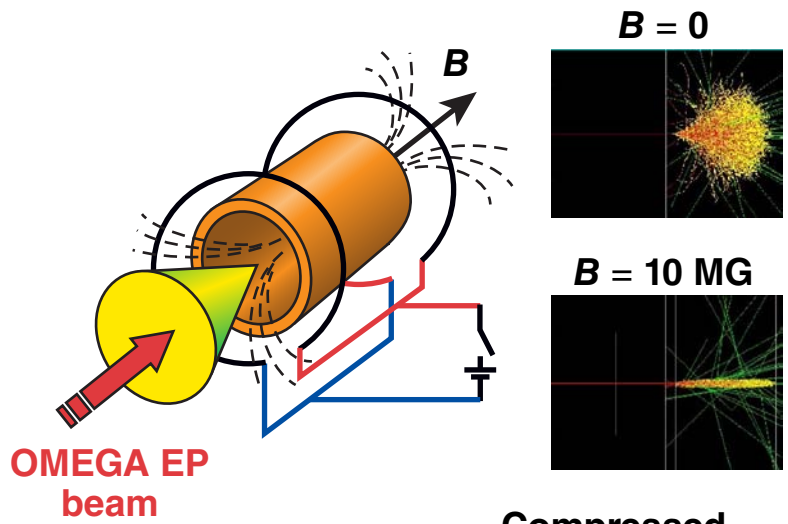


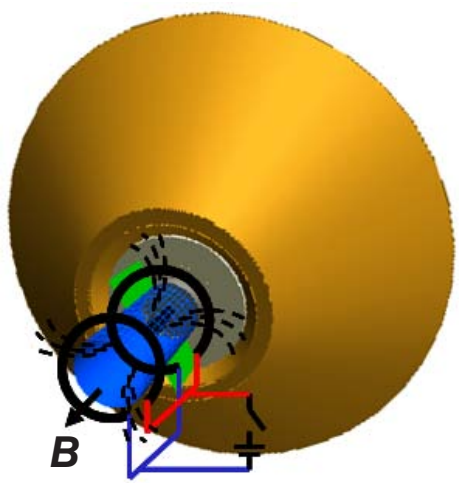
A MG magnetic field would be required to significantly alter the laboratory jet performance.

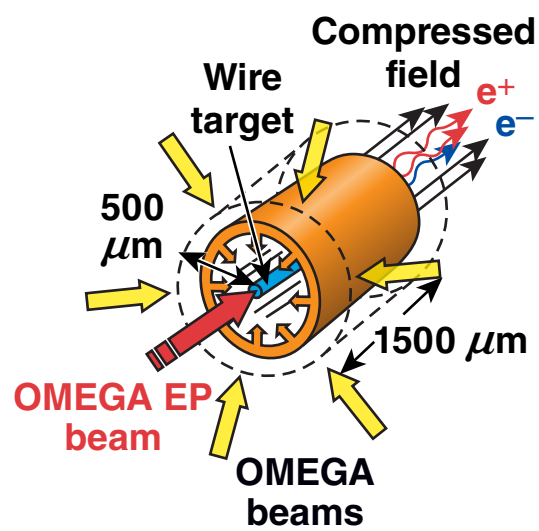
E18376a

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







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

E15690c

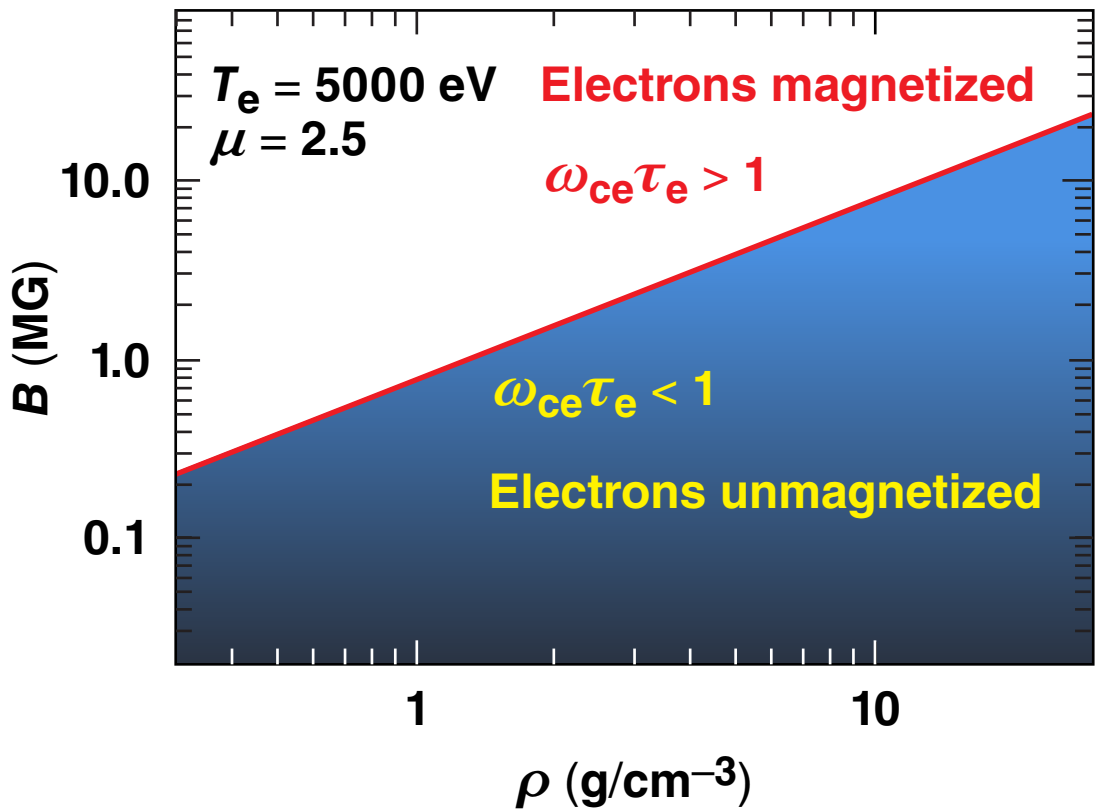
Summary/Conclusions

Laser-driven flux compression produce 10- to 40-MG magnetic fields on OMEGA

- A compact device to generate up to ~150-kG magnetic seed fields has been assembled
- Magnetic-field compression with lasers has been demonstrated for cylindrical and spherical implosions
- Cylindrical targets have demonstrated magnetic amplification to 40 MG
- Plasma magnetization opens up new exciting opportunities in the areas of fusion, HEDP, and astrophysics

Need 10's of megagauss to magnetize electrons

- Need 10's of megagauss to magnetize electrons
- Need 100's of megagauss to confine alphas



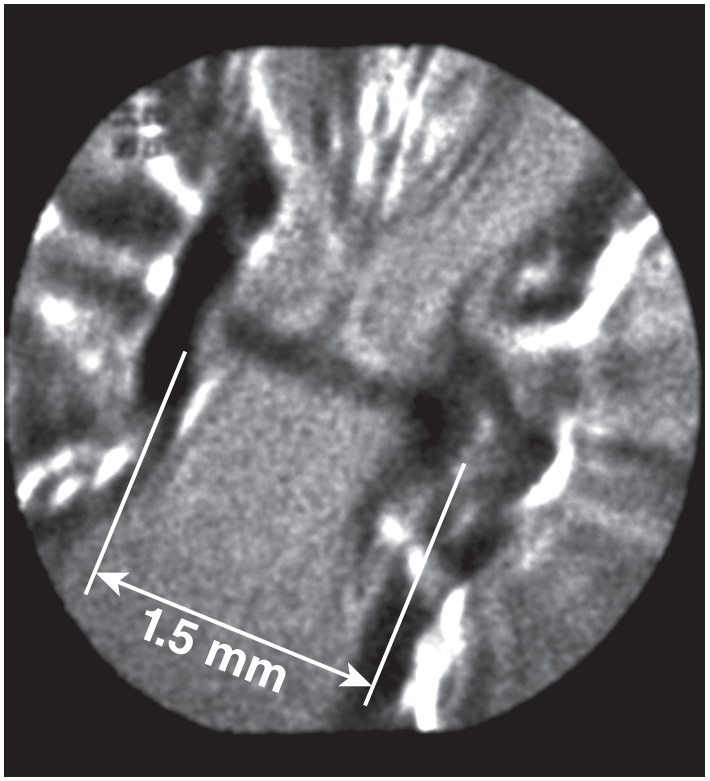
E19775c

MIFEDS was installed on OMEGA

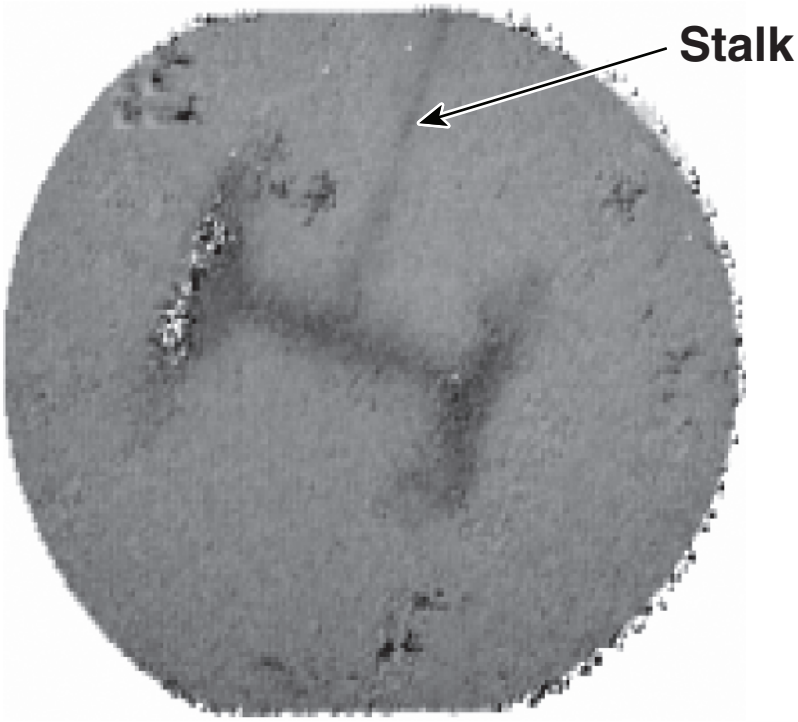
E19779a

Proton radiograph of an imploded cylindrical D_2-filled shell shows no implosion-generated fields near core

CR-39 track-density map



Track-diameter map



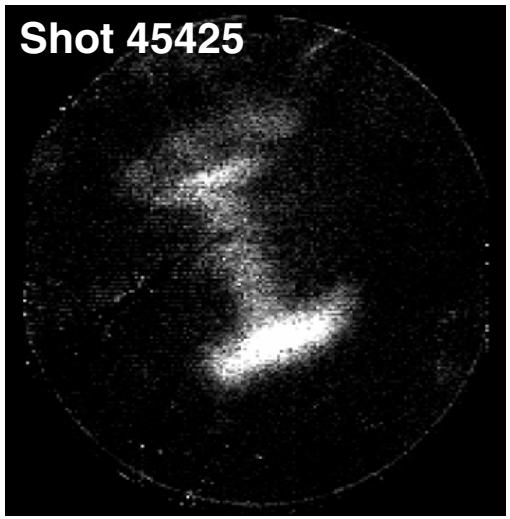
- No seed field present in this shot
- Field structure visible around stalk and end caps
- In this setup the core-traversing protons have been ranged out

E16186b

Selection of tracks by diameter (energy) is necessary to expose the particles deflected in the amplified field

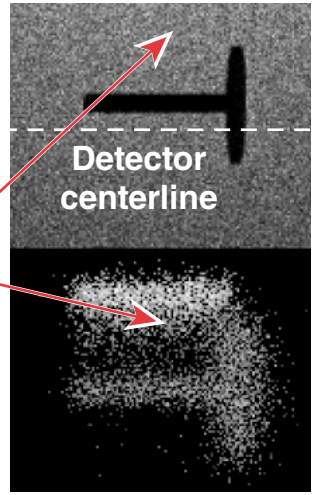
- Data from the back of the first CR-39 slab shows the presence of slowed down protons that have traversed the core

CR-39 #1 (back)



Track diameter map

Simulation with optimized filtration



High-field deflection

(a) All protons

(b) Select track-diameter range

- The filter thickness in front of the CR-39 was optimized for recording the core-traversing protons
- Geant4 Monte Carlo simulations show that the selection of proton tracks by diameter (energy) will help expose the ones traversing the core

E16189b

Supplemental

Gyroradii of fusion products in 100-MG magnetic fields are of the order of the core radius

Gyroradius in μm (the core radius is ~15 μm for a convergence ratio of 30)					
	Energy (MeV)	0.1 MG	1 MG	10 MG	100 MG
e (Thermal)	0.03	56	5.6	0.56	0.056
e (Hot)	1	160	16	1.6	0.16
p (DD)	3.02	25050	2505	251	25.1
p (DHe^3)	14.7	54760	5476	548	54.8
T (DD)	1.01	25122	2512	251	25.1
He^3 (DD)	0.82	11318	1132	113	11.3
He^4 (DT)	3.5	26925	2692	269	26.9
He^4 (DHe^3)	3.6	27306	2731	273	27.3

The gyroradius of 30-keV electrons is less than the core radius for magnetic fields as low as 0.2 MG (λ_{MFP} ~ 360 μm in the compressed core).

E16910a

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

FSC

UR LLE

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

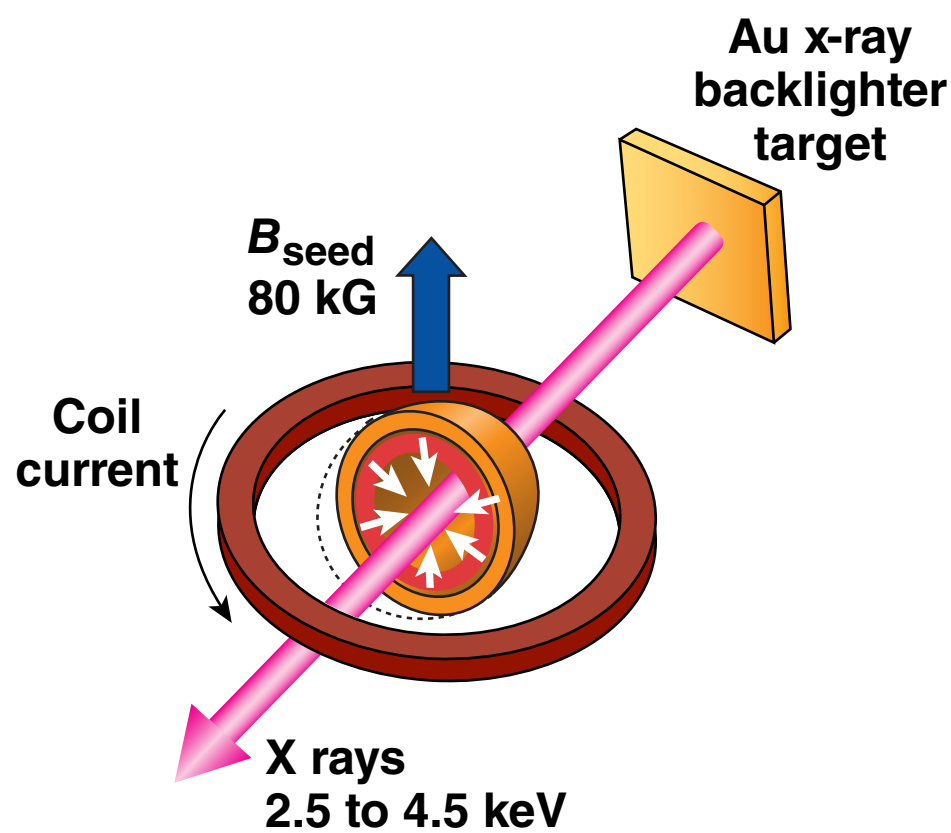
	ρ_{HS} (g/cm^3)	mfp$_{ie}$ (μm)	mfp$_{ii}$ (μm)	r_{iL} (μm)
Cylinder	0.5	151	5.6	5.7
Sphere	5.0	27	0.52	7.7

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

E18432a

Single-coil *B* field was used for fusion-enhancement measurements in spherical geometry

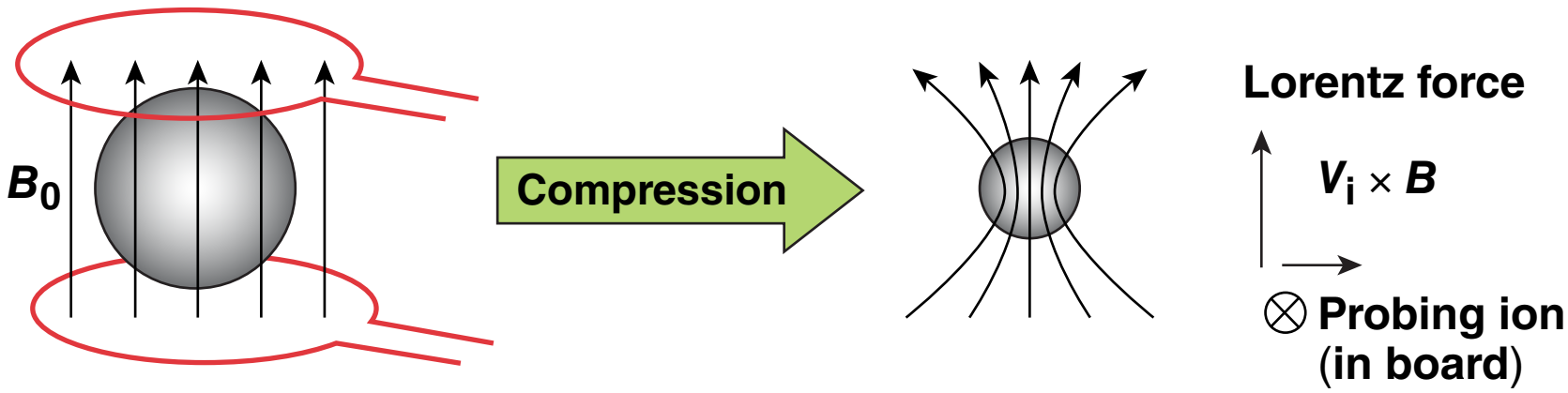
- Single coil provides stronger seed fields (80 kG) and less interference with laser beam
- 40 beams (450 kJ/1 ns) were used for compression
- Implosion uniformity is diagnosed using x-ray backlighter radiography
- nTOF diagnostic was used for T_i and neutron-yield measurements



E19783c

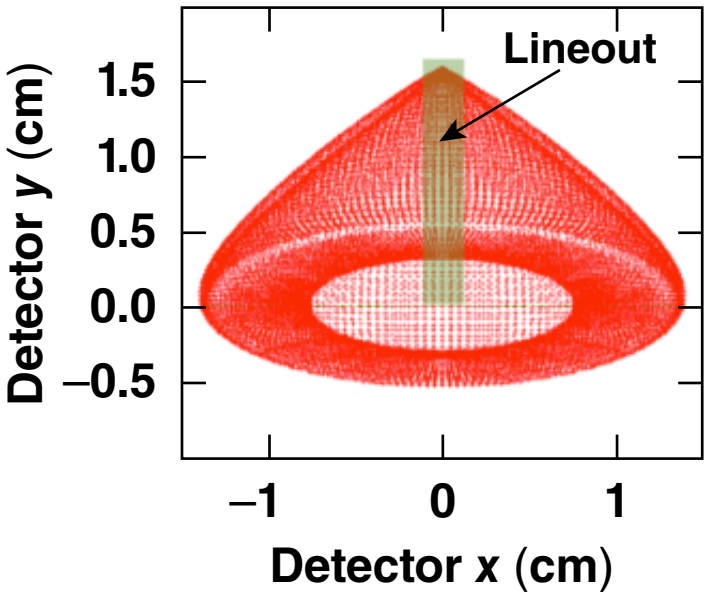
The magnetic field in spherical implosions is more complicated and more difficult to measure

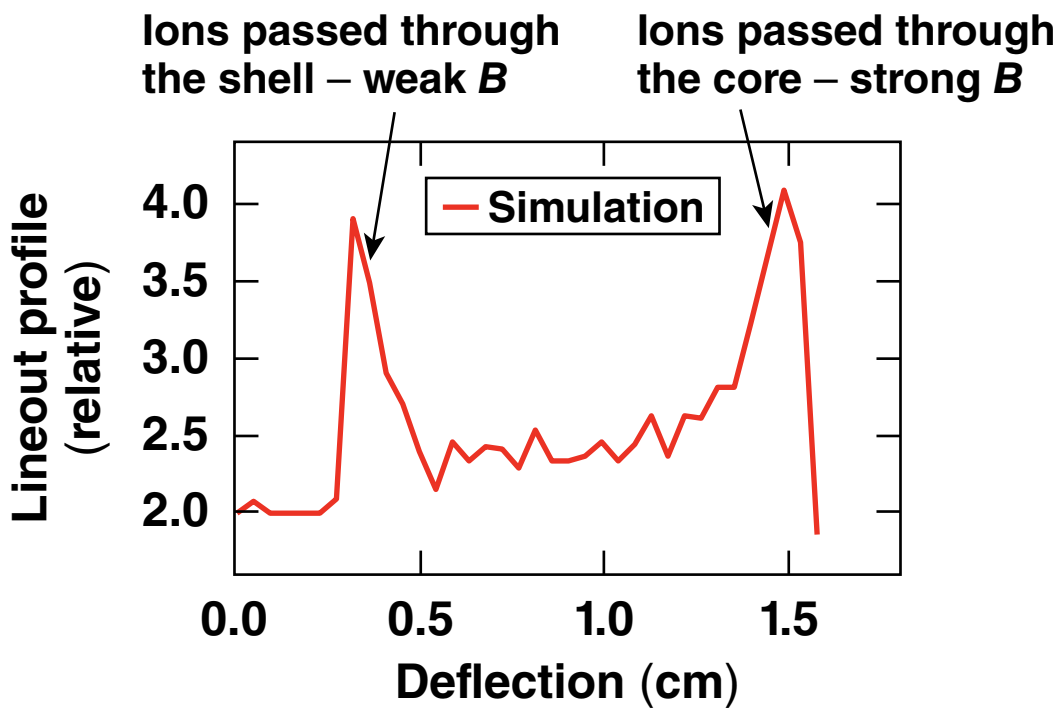
- Magnetic field has a radial component
- Probing ions deflect in two directions
- Small target results in a much lower signal to background
- Initial results are in agreement with cylindrical data; work in progress



E19781a

Simulation indicates two peaks for slowed down ions passed through the core and through the shell...





- Distance from backlighter to target 0.9 cm
- Distance from target to CR-39 10.5 cm
- Target radius 20 μm
- Magnetic field 26 MG

E19789a