Laser-Driven Magnetic Flux Compression on the OMEGA Laser

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Summary

Tests of multi-megagauss field generation via laser-driven magnetic-flux compression are underway on OMEGA

- Magnetic-flux compression with lasers can potentially outperform flux compression via chemical detonation by orders of magnitude.
- A series of experiments has been designed to test the concept.
- Numerical simulations show 100-fold field amplification, accompanied by cross-field, heat-transport inhibition.
- This is used in a new, magneto-inertial approach to ICF, where significantly higher gains are expected from massive targets.
- A compact seed-field generator (9 to 15 T) has been integrated in OMEGA.
- Proton deflectometry was validated as the diagnostic method for upcoming experiments (December 2007).

Next field-compression implosion experiments scheduled for 5 December 2007 on the OMEGA laser.

E16184

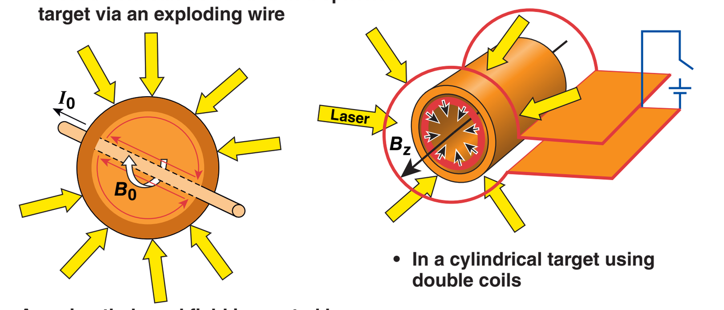
Magnetized plasma experiments are important for basic ICF research and HEDP applications

- ICF studies
  - magnetic (thermal) insulation of the forming hot spot in ICF implosions (MIF campaign)
  - electron thermal transport in target-generated magnetic fields
  - fast-electron transport in compressed plasmas; magnetic-field guiding
- Laboratory astrophysics studies of magnetized plasmas
- Charged-particle confinement and collimation; electron–positron plasma production in the laboratory
- Material properties in high magnetic fields

E16180

High magnetic fields can be generated via compression of a seed field by laser-generated plasmas

- A seed field can be seeded in a spherical target via an exploding wire



- In a cylindrical target using double coils

An azimuthal seed field is created by the current in an exploding lithium or carbon wire. Red lines show current path after gas ionization.

The axial seed field is created in a Helmholtz-type coil outside the target.

E15685a

Proposed laser-driven flux-compression experiments on OMEGA are initially focused on MIF[1]

- Cylindrical implosions
  - magnetic-field compression and measurement
  - effects on the implosion dynamics and stagnation parameters
- Spherical implosions
  - development of optimal field geometry and target configuration
  - measurement of the effect of magnetic insulation on the hot-spot temperature
  - thermal transport in the axial magnetic field; effect on the hydro-efficiency and implosion symmetry

[1] Magneto-Inertial Fusion. Particularly high-gain MIF as defined in Y. C. F. Thio, IFSA 2007, to be published in *J. Phys; Conf. Series* (IOP).

E16181

In the MIF approach, massive ICF targets imploded with low velocity provide higher gains*

- Assuming ignition, $G = \frac{E_{\text{fusion}}}{E_{\text{laser}}} \sim \frac{1}{V_i^{1.3}}$
- Low-implosion velocities V_i result in a "cold" hot spot: $T_{hs} \sim V_i^{1.3}$
- Conventional ICF designs fail to ignite at low-implosion velocities due to the cold hot spot
- Ignition can be triggered at low V_i and *the gain increased* by using MGauss magnetic field to reduce the thermal-conduction losses and increase the temperature in the hot spot

*R. Betti and C. Zhou, Phys. Plasmas 12, 110702 (2005).

E15683a

Effective reduction of the hot-spot thermal losses via magnetic insulation requires fields of hundreds of MGauss

- Considering NIF 1.5-MJ, direct-drive point design*
  - $\rho_{hs} \approx 30$ g/cc
  - $T_{hs} \approx 7$ keV (before ignition)
  - $r_{hs} \approx 50\ \mu m$
- Braginskii conductivity used; anomalous effects not considered.

At 10-MG compressed field		At 100-MG compressed field	
$\beta \approx 4 \times 10^4$	$\kappa_\perp \approx 0.2\ \kappa_\parallel$ for $\omega_{ce}\tau_e \approx 1.2$	$\beta \approx 4 \times 10^2$	$\kappa_\perp \approx 0.01\ \kappa_\parallel$ for $\omega_{ce}\tau_e \approx 12$
$\rho_\alpha = 270\ \mu m$	$\rho_\alpha/\rho_{hs} > 5$	$\rho_\alpha = 27\ \mu m$	α-particles magnetically trapped: $\rho_\alpha/\rho_{hs} \approx 0.5$

$$\beta = \frac{2\mu P}{B^2}$$

*P. W. McKenty *et al.*, Phys. Plasmas 8, 2315 (2001).

E15684a

Effective flux compression requires low resistivity of the compressing conductive layer

- Magnetic-flux ratio in an imploding cylindrical liner: $B = B_0\left(\frac{R_0}{R}\right)^2 \frac{\Phi}{\Phi_0}$

$$\frac{1}{B}\frac{dB}{dt} = \frac{2(v_i - v_f)}{R(t)} = \frac{2\,v_i}{R(t)}\left(1 - \frac{1}{\mathrm{Re}_m}\right),$$

where Re_m is defined through the time constant of exponential diffusion of the enclosed flux

$$\begin{cases} \tau = -\left(\frac{d\ln\Phi}{dt}\right)^{-1} = \frac{L_{sh}}{R_{sh}} = \frac{\mu_0 \pi R^2 L}{2\pi R\eta} = \frac{R}{2v_f}, \\ \mathrm{Re}_m = \frac{v_i}{v_f} = \frac{v_i L \mu_0}{\eta} \end{cases}$$

$v_f = \left(\frac{\eta}{\mu_0 L}\right)$ – diffusion speed

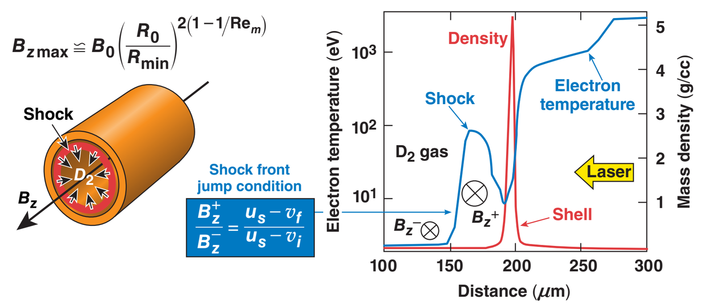
$v_i = \frac{dR}{dt}$ – implosion speed

- $B_{max} = B_0\left(\frac{R_0}{R_{min}}\right)^{2(1-1/\mathrm{Re}_m)}$ – effective flux compression for $\mathrm{Re}_m >> 1$

E16182

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

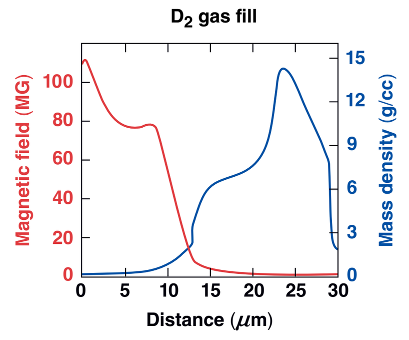
$$B_{z\,max} \cong B_0\left(\frac{R_0}{R_{min}}\right)^{2(1-1/\mathrm{Re}_m)}$$



- Re_m in OMEGA cylindrical implosions is high, due to the high-implosion velocity ($x \times 10^7$ cm/s) and high plasma conductivity $\sigma_\perp \sim 10^{18}\ s^{-1}$ in the ionized gas fill.
- An average value of $\mathrm{Re}_m \sim 50$ is obtained from simulations.

E14146c

According to 1-D simulations, a magnetic field of 100 MG is reached in the D_2 hot spot at peak compression

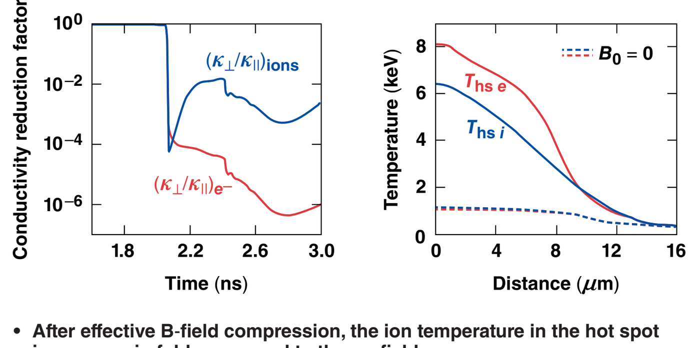


Particle gyroradii

	E (MeV)	$\rho_{100\ MG}$ (μm)
e^- (Thermal)	0.03	0.056
e^- (Hot)	1	0.16
p (D+D)	3.02	25.1
p (D+^{3}He)	14.7	54.8
T (D+D)	1.01	25.1
^{3}He (D+D)	0.82	11.3
^{4}He (D+T)	3.5	26.9
^{4}He (D+^{3}He)	3.6	27.3

E16183

The reduction of thermal conductivity leads to a significant increase of the hot-spot temperature in D_2



- After effective B-field compression, the ion temperature in the hot spot increases six-fold, compared to the no-field case.

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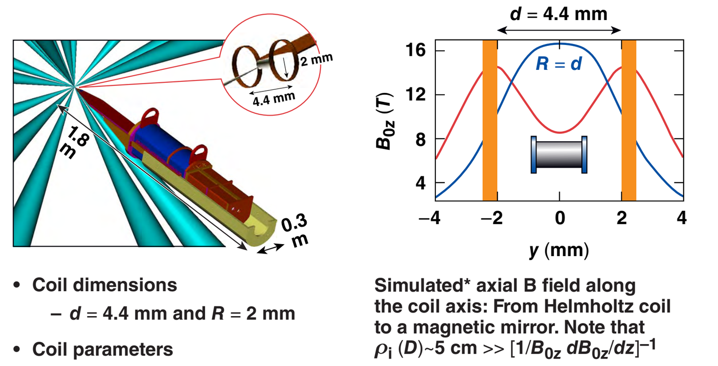
The seed magnetic field is generated in a double-coil configuration suitable for OMEGA implosions



- Coil dimensions
  - d = 4.4 mm and R = 2 mm
- Coil parameters
  - L = 14 to 25 nH and R ~ 0.1 Ω

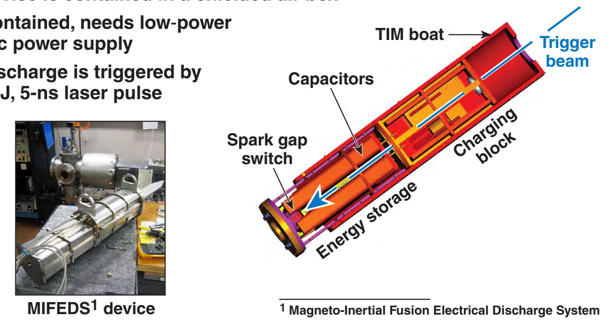
Simulated* axial B field along the coil axis: From Helmholtz coil to a magnetic mirror. Note that ρ_i (D)~5 cm >> $[1/B_{0z}\ dB_{0z}/dz]^{-1}$

*Radia simulation [O. Chubar *et al.*, J. Synchrotron Radiat. 5, 481 (1998)].

E15665a

A TIM-based, fast discharge delivers energy efficiently, while reducing the transmission distance and EMI issues

- Capacitive discharge system that can safely store up to 130 J of energy (at 36 kV)
- Low-impedance (<1 Ω) transmission line delivers the energy to the low-inductance coil
- The device is contained in a shielded air box
- Self-contained, needs low-power 24-V dc power supply
- The discharge is triggered by a 50-mJ, 5-ns laser pulse

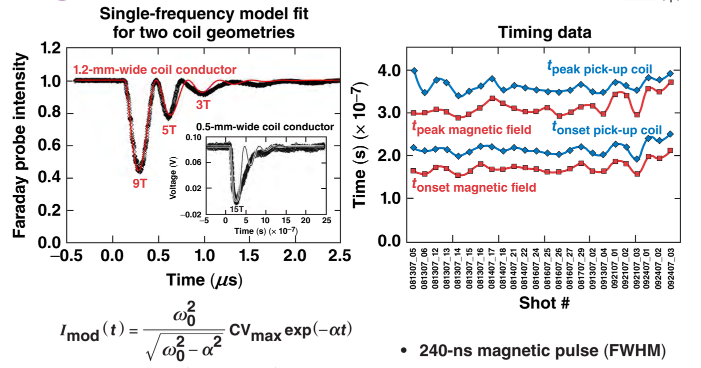


MIFEDS[1] device

[1] Magneto-Inertial Fusion Electrical Discharge System

E15143b

A seed magnetic field of 0.09 to 0.15 MG is measured with MIFEDS charged to 25 to 30 kV



$$I_{mod}(t) = \frac{\omega_0^2}{\sqrt{\omega_0^2 - \alpha^2}} CV_{max} \exp(-\alpha t) \times \sin\left(\sqrt{\omega_0^2 - \alpha^2}\,t\right)$$

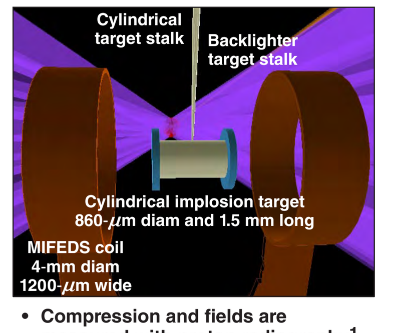
$\omega_0 = 9.20 \times 10^6$ rad/s

$\alpha = 1.60 \times 10^6$ rad/s

- 240-ns magnetic pulse (FWHM)
- 140-ns rise time
- 80-ns window at 90% of peak
- Total timing jitter of pulse ~14 ns.

E16185

The target will be compressed by 40 OMEGA beams (~16 kJ) while 20 (8 kJ) are used for proton radiography

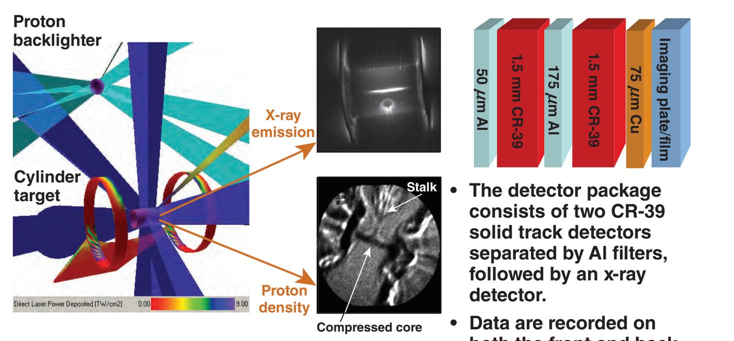


- Distance from backlighter to target is 9 mm
- Distance to the CR-39 detector is ~10.5 cm
- About 1% of the laser energy is intercepted by the coils
- 14.7-MeV fusion protons are produced by imploding a D^3He-filled glass micro-balloon
- Compression and fields are measured with proton radiography[1] (view from detector plane)

[1] Based on C. K. Li *et al.*, Phys. Rev. Lett. 97, 135003 (2006) and references therein.

E15146b

Deflection of the 15-MeV protons is used to measure both the seed and compressed fields

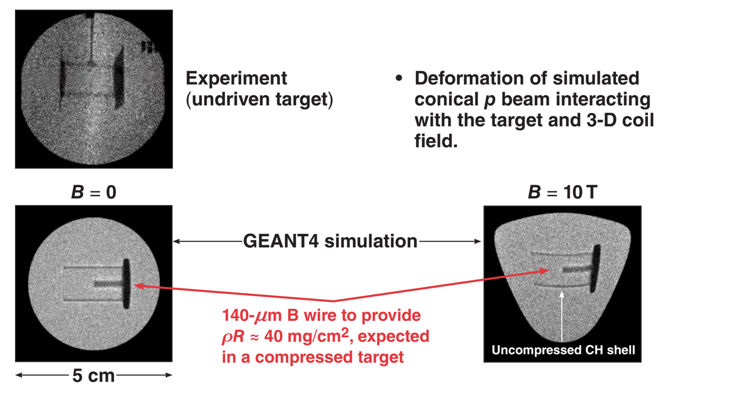


- The detector package consists of two CR-39 solid track detectors separated by Al filters, followed by an x-ray detector.
- Data are recorded on both the front and back surface layers of the two CR-39 slabs.

E16186

Deflection due to flux compression is superimposed on the seed-field deflection of the whole field of view

- Proton density maps at the detector plane



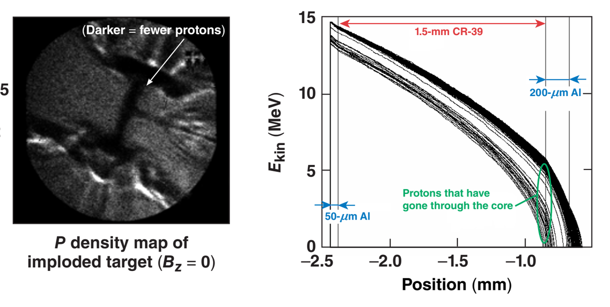
- Deformation of simulated conical p beam interacting with the target and 3-D coil field.

E16187

The protons that have traversed the core were completely slowed down in initial experiments

Shot 45425

CR-39 #2 (front)



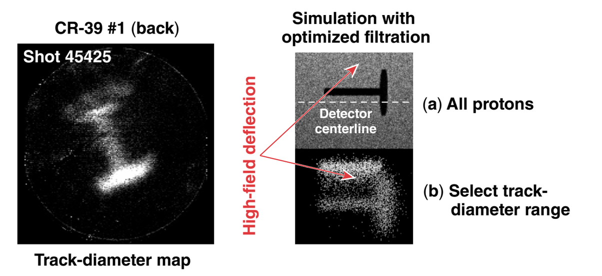
P density map of imploded target ($B_z = 0$)

- Kinetic energy versus depth curves show that the core-traversing particles are ranged down in the standard configuration.
- *LILAC* 1-D simulation results for the compressed target ρR were used in the simulation.

E16188

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

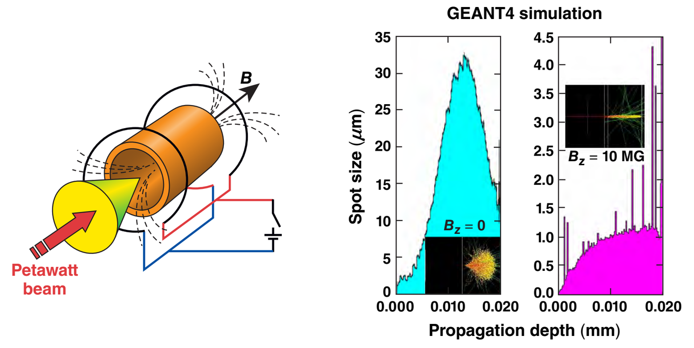
- Data from the back of the first CR-39 slab shows the presence of slowed down protons that have traversed the core.



- 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.

E16189

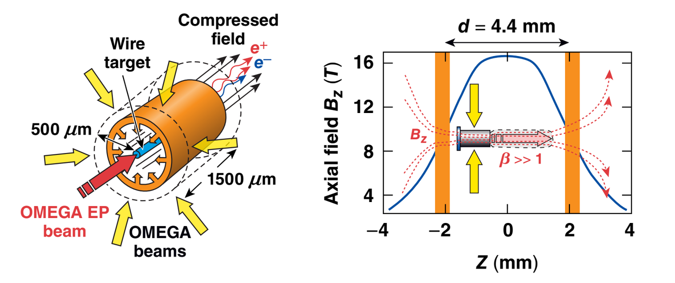
Low-adiabat, low-velocity implosions of magnetized ICF targets can be pursued in the context of fast ignition



- Parallel guiding fields for hot electrons in fast ignition.
- Lateral blooming of 1-MeV electron beam in 250-g/cc DT mix is greatly reduced in a 10-MG axial field (right side).

E16190

Applications outside of fusion are being actively considered



Possible magnetized-jet experimental geometry using the MIFEDS seed field

- Generation of positron–electron plasma in the laboratory.[1]
- Formation and propagation of magnetized plasma jets.

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

E16191

Summary/Conclusions

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E16184