Magnetic-Flux-Compression Experiments on OMEGA

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Summary

Tens of MG have been generated in laser-driven magnetic-flux-compression experiments on OMEGA

- A compact device generates up to 150-kG magnetic seed fields
- Cylindrical targets have been embedded with a 10- to 60-kG seed magnetic field and have been imploded with 14 kJ of laser energy
- Proton deflectometry used to map the hot-spot magnetic field confirms field compression up to tens of MG
- Recent experiments using spherical targets have been performed successfully on OMEGA—data is being analyzed
Collaborators

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Performance of ICF targets can be improved with MG magnetic fields

- Adding magnetic fields in a compressed ICF target can increase the thermal insulation of the hot spot
  - reduced electron thermal conductivity if \( \omega_{ce} \tau_e > 1 \)
  - enhanced \( \alpha \)-particle confinement to within the hot spot if \( r_\alpha/R_{HS} \leq 1 \)

- NIF 1.5-MJ, polar-drive point design
  - \( \rho_{HS} \approx 30 \text{ g/cm}^3, T_{HS} \approx 7 \text{ keV}, R_{HS} \approx 50 \mu\text{m} \)
  - \( B \geq 100 \text{ MG} \)
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

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

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

- B-field diffusion reduces the magnetic field trapped in the post-shock region.
- Strong compressed B-field requires $\text{Re}_m = \nu_i/\nu_f = \tau_i/\tau_f > 1$.
The maximum magnetic amplification is determined by the target convergence and magnetic Reynolds number.

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

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

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

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

$$Re_m \approx 50$$

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

*J. P. Knauer et al., Phys. Plasmas 71, 056318 (2010).*
Magnetic inertial fusion electrical discharge system (MIFEDS) provides in-target seed fields in a compact geometry

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

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

Geant4 simulations are used for an accurate interpretation of the data.

\[ \Delta \approx v_\perp \tau \sim v_\perp \frac{L}{v} \]

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

\[ \langle B \rangle D \sim \frac{m_p v \Delta}{eL} \]
The proton’s deflection and energy loss depend on the propagation path through the compressed target.
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 than the protons that travel only through the dense shell.
Measured proton deflections are well reproduced by Geant4 with a \( \langle B \rangle \) of \(~30\) MG over a 34-\(\mu\)m hot spot.

The peak from protons with maximum deflection gives \( \langle B \rangle \sim 30\) MG in simulations.
Cylindrical implosions have hot-spot conditions where the ion mean-free-path and Larmor radius $\sim$ hot-spot radius.

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

<table>
<thead>
<tr>
<th></th>
<th>$\rho_{HS} , (g/cm^3)$</th>
<th>mfp$_{ie} , (\mu m)$</th>
<th>mfp$_{ii} , (\mu m)$</th>
<th>r$_{iL} , (\mu m)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cylinder</td>
<td>0.5</td>
<td>151</td>
<td>5.6</td>
<td>5.7</td>
</tr>
<tr>
<td>Sphere</td>
<td>5.0</td>
<td>27</td>
<td>0.52</td>
<td>7.7</td>
</tr>
</tbody>
</table>

Spherical implosions are needed to measure the effect of magnetic fields on hot-spot yields.
2-D simulations of spherical implosions show very high magnetic fields and enhanced ion temperatures.

- Target hydrodynamics are strongly affected by compressed magnetic field.
- Thermal heat-flux inhibition leads to 30% enhanced ion heating.
- n-yield is enhanced by 20%.
Simulated proton deflectometry exhibits large deflection peak for slow, narrow-energy-band particles.

Protons affected by the central hot spot are strongly deflected and populate a narrow energy band from slowing down in the compressed target shell.
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