Theory and Simulation of Laser-Driven Magnetic-Field Compression

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Summary

Magnetic fields can be compressed to ultrahigh intensities through laser-driven implosions

• A seed axial magnetic field of 0.15 MG inside an imploding laser-driven cylindrical target can be compressed to ultrahigh intensities (≥10 MG).

• A high-intensity magnetic field has a variety of physical implications, including
  – improvement of the hot-spot energy confinement through magnetic insulation
  – improvement of collimation of fast electrons for fast ignition
  – study of magnetic collimation of plasma jets

• A compact Pulsed-Power System for Magnetized Target Experiments on OMEGA* is complete to conduct magnetic-field compression experiments scheduled for 9 November 2006.

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Collaborators

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A cylindrical target with a seed field is driven by 40 OMEGA laser beams.

- The targets were simulated with three different core materials: (1) DD gas at 3 atm, (2) vacuum, and (3) 10-mg/cc-density CH foam core.

Cylindrical plastic shell simulated with *LILAC-MHD*

Seed-field generator in the formation of two-turn coils

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The seed field is trapped by the inner layer of hot-shocked plasma with a high temperature ahead of the shell.

\[ \eta = 1.65 \times 10^{-5} Z_{\text{eff}} T_e^{-3/2} \]

The hot-halo layer prevents the diffusion of the magnetic field in the radial direction.
Resistive MHD equations were added to the 1-D hydrocode *LILAC*

• Use the existing program *LILAC* to simulate the target implosion.
  – *LILAC* is based purely on radiative hydrodynamics
  – modifications are required to build in the effects of the magnetic field. This code will be referred to as *LILAC-MHD*.

• Resistive *MHD* equations added to *LILAC* are
  – magnetic-field diffusion: \( \partial_t \mathbf{B} = \nabla \times (\mathbf{V} \times \mathbf{B}) + \nabla \cdot \eta \nabla \mathbf{B} \)
  – magnetic diffusivity calculated from temperature and density

• Contributions of magnetic field to existing hydrodynamics are
  – ohmic heating \( \eta J^2 \) is added as a source of heat
  – electron and ion thermal conductivity are reduced by the modification factor determined by gyrofrequencies and collision rates
  – magnetic pressure \( B^2/2\mu \) added to the hydrodynamic pressure
The magnetic field at peak compression reaches a magnitude greater than 10 MG.
Only a fraction of the initial magnetic flux is trapped and compressed.

- Assuming there is no diffusion, the hypothetical maximum field can be calculated by conservation of the magnetic flux.

<table>
<thead>
<tr>
<th></th>
<th>Peak compression radius (μm)</th>
<th>Without diffusion (MG)</th>
<th>Simulated maximum field (MG)</th>
<th>Fraction trapped</th>
</tr>
</thead>
<tbody>
<tr>
<td>DD gas</td>
<td>13</td>
<td>14.2</td>
<td>8.3</td>
<td>0.58</td>
</tr>
<tr>
<td>Vacuum</td>
<td>7</td>
<td>48.9</td>
<td>1.3</td>
<td>0.03</td>
</tr>
<tr>
<td>Foam</td>
<td>15</td>
<td>10.6</td>
<td>3.7</td>
<td>0.30</td>
</tr>
</tbody>
</table>
With the magnetic field, the thermal conductivities become highly anisotropic

\[
\frac{\kappa_\perp}{\kappa_\parallel} = \frac{1}{1 + \left(\frac{\omega_{ce,ci}}{\nu_{e,i}}\right)^2}
\]

\(\omega_{ce,ci}\): electron and ion gyrofrequencies
\(\nu_{e,i}\): electron and ion-collision rates

![Graph showing thermal conductivity reduction for DD gas and Foam](image)
Because of the thermal insulation, the hot-spot temperature increases significantly.

- The temperature over 1 keV in the hot spot is maintained for over 1.2 ns for DD gas.
With enhanced energy confinement, the 1-D neutron yield is one order of magnitude higher.

\[
\begin{array}{|c|c|}
\hline
\text{Without magnetic field} & 1.65 \times 10^8 \\
\hline
\text{With magnetic field} & 1.02 \times 10^6 \\
\hline
\end{array}
\]
Summary/Conclusions
Magnetic fields can be compressed to ultrahigh intensities through laser-driven implosions

• A seed axial magnetic field of 0.15 MG inside an imploding laser-driven cylindrical target can be compressed to ultrahigh intensities ($\geq 10$ MG).

• A magnetic field of high intensity reduces thermal conductivity and improves energy confinement.

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