Three-Dimensional Modeling of Laser–Plasma Confinement in a Strong Magnetic field

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Extended MHD is needed to simulate plasma disc formation and magnetic confinement observed in laser-wire interaction experiments on Zebra

- The plasma disc is pinched and magnetically confined by the azimuthal magnetic field from the wire.
- These simulations are in general agreement with the experiments at the Zebra facility using $\lambda = 1.06\mu m$ light and 1 MA of current.
- A simulation using an extended magnetohydrodynamic (MHD) model captures the azimuthal plasma expansion and the evolution of plasma perturbations seen in experiments.

Collaborators

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Studies of laser-generated magnetized plasmas have an important impact on magnetized inertial confinement fusion (ICF) and laboratory astrophysics

- Multiple magneto-inertial fusion concepts involve the interaction of magnetic fields and laser plasmas

- The coupling of laser-ablated plasmas in strong magnetic fields is also similar to magnetized astrophysical phenomena with the plasma $\beta$ parameter changing from $\beta < 1$ to $\beta \gg 1$

$$\beta = \frac{nkT}{B^2/2\mu}$$

MIFEDS (LLE) $\beta$ 4 to 60
MagLIF (SNL) $\beta$ 5 to 80
Magnetic NIF (LLNL) $\beta$ ~190

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D. J. Strozzi, et al., No. LLNL-CONF-672979. Lawrence Livermore National Lab. (LLNL), Livermore, CA (United States), 2015
The Zebra pulsed-power generator at UNR can be coupled with the Leopard laser for magnetized laser-plasma studies

- **Zebra generator**
  - load current 1 MA with LCM 1.7 MA*
  - current rise time 80 ns
  - storage energy 150 kJ
  - impedance 1.9 Ω

- **Leopard laser**
  - short pulse: 15 J, 0.35 ps
  - $I \sim 10^{19} \text{ W/cm}^2$, $K = 106$
  - long pulse: 35 J, 0.8 ns
  - $I \sim 6 \times 10^{15} \text{ W/cm}^2$


LCM: liquid-crystal modulator
UNR: University of Nevada, Reno
Disc-type plasma structures have been observed in recent experiments in megagauss magnetic fields

- The laser was focused to a spot of 30 μm with an intensity of $\sim 3 \times 10^{15} \text{ W/cm}^2$ for $\sim 1 \text{ ns}$
- UV shadowgraphs show no disc plasma without the current
- Laser probing and x-ray spectroscopy
  - measured electron density $n_e \sim 10^{19} \text{ cm}^{-3}$
  - density in the rings of $7 \times 10^{18} \text{ cm}^{-3}$
  - electron temperature $T_e = (200 \text{ to } 400) \text{ eV}$

Cylindrical \((r-z)\) simulations with azimuthal symmetry show axial collimation in the external magnetic field not seen without the magnetic field.

Electron density

Electron temperature (keV)

Magnetic \(\beta\) parameter

4 ns after laser pulse
The laser pulse ablates the plasma, pushing the external field and generating Biermann battery (BB) magnetic fields $B_{BB} \sim \nabla n_e \times \nabla T_e$.

- BB fields introduce asymmetry to the disc
- The magnetic field pinches down on the plasma
- As the plasma expands, the temperature drops, and magnetic fields diffuse into the disc
The extended MHD model leads to faster disc structure formation compared to the resistive MHD model.

Ohm’s Law

\[
\vec{E} = -\frac{1}{c} \vec{U} \times \vec{B} + \vec{\eta} \times \vec{J} + \frac{\vec{J} \times \vec{B}}{c\epsilon n_e} - \frac{\nabla \vec{P}_e}{\epsilon n_e} - \frac{k}{\epsilon} \vec{\beta} \times \nabla T_e
\]

\[
\vec{E} = -\frac{1}{c} \vec{U} \times \vec{B} + \vec{\eta} \times \vec{J}
\]
Plasma structures are similar in simulations and experiments and measured parameters are in general agreement.
Summary/Conclusions

Extended MHD is needed to simulate plasma disc formation and magnetic confinement observed in laser-wire interaction experiments on Zebra

- The plasma disc is pinched and magnetically confined by the azimuthal magnetic field from the wire
- These simulations are in general agreement with the experiments at the Zebra facility using $\lambda = 1.06$-$\mu$m light and 1 MA of current
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Backup
The plasma $\beta$ parameter transitions from larger than unity to less than unity around the disc, and the Hall parameter changes from small to large.

<table>
<thead>
<tr>
<th>Magnetic $\beta$ parameter</th>
<th>Hall parameter $\chi = \tau_e \omega_e$</th>
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<table>
<thead>
<tr>
<th>Blue laser</th>
<th>Red laser</th>
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<tbody>
<tr>
<td><img src="image1.png" alt="Blue laser" /></td>
<td><img src="image2.png" alt="Red laser" /></td>
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The field curvature of the disc and pressure gradient suggest the possibility of interchange instability.

\[ \kappa \times \nabla p > 0 \] allowing for possible interchange instability