Effects of Self-Generated Magnetic Fields in Rayleigh–Taylor Unstable Laser-Irradiated Plastic Foils

Results of 2-D magnetohydrodynamic simulations

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Summary

Megagauss magnetic fields are predicted in Rayleigh–Taylor (RT) unstable, laser-accelerated plasma

- Self-generated magnetic fields were measured in RT unstable accelerated plastic and metallic foils on the OMEGA EP Laser System
- The inferred fields were in good agreement with 2-D magnetohydrodynamic (MHD) simulations
- RT-generated magnetic fields are significantly subthermal ($\beta > 100$) and do not directly affect the plasma dynamics
- These fields moderately affect (reduce) the RT growth by altering electron-heat fluxes when the Hall parameter $\omega_e \tau_e > 0.1$
Collaborators

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Proton radiography of RT unstable laser-accelerated foils was used to detect self-generated magnetic fields

• Magnetic fields up to ~2 MG were inferred
• Cellular magnetic structures are related to nonlinear RT bubble and spikes

OMEGA EP experimental setup*

- Plastic tube 1 mm
- 4 kJ, 2.5 ns
- $4 \times 10^{14}$ W/cm$^2$
- 0.3 kJ, 1 ps
- $1.5 \times 10^{19}$ W/cm$^2$
- Cu foil foil
- Ta foil foil
- CH foil
- 8 mm
- 80 mm
- Proton beam
- Proton film pack

Proton radiograph of RT unstable target

15-μm-thick CH foil
$E_p = 13$ MeV
$t = 2.62$ ns

Self-generated magnetic fields in RT unstable plasma were studied using the Braginskii MHD model*

- The 2-D code DRACO** uses the induction equation with all Braginskii’s terms

\[
\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{V} \times \mathbf{B}) + \frac{c}{e} \left[ \nabla \times \frac{\nabla P_e}{n_e} - \nabla \times \frac{\left( \nabla \times \mathbf{B} \right) \times \mathbf{B}}{4\pi n_e} - \nabla \times \frac{R_T + R_u}{n_e} \right]
\]

- National Ignition Facility (NIF) related conditions
  - \( I = 6 \times 10^{14} \text{ W/cm}^2 \)
  - up to 20-ns pulse duration
  - 100-\( \mu \text{m} \) and thicker CH foils

- Main mechanisms
  - Biermann battery source
  - resistive dissipations
  - Nernst convection


Self-generated magnetic fields are sourced by thermoelectric currents developed near the tip of RT spikes.

Magnetic fields produced by electron currents

\[ \nabla T_e \]

The Biermann battery source*

\[ \frac{\partial B}{\partial t} \sim \nabla T_e \times \nabla n_e \]

The Nernst convection dominates the convection flow and compresses magnetic fields toward the ablation surface.

- Nernst effect: Convection of tangential magnetic fields by thermal electrons:

\[ \frac{\partial B_y}{\partial t} = \frac{\partial}{\partial x}(V_T B_y), \]

\[ V_T \propto -\frac{\partial T}{\partial x} \]

- \( \bar{V}_T \cdot \bar{V}_{abl} < 0 \) and \( V_T \gg V_{abl} \) in the conduction zone

Nernst convection increases the dissipation rate of self-generated fields.

*A. Nishiguchi, T. Yabe, and M. G. Haines, Phys. Fluids 28, 3683 (1985).*
Resistive dissipations are efficient and determine the magnitude of self-generated magnetic fields.

Main mechanisms diagram

- **RT instability**: $t_{\text{dyn}} \sim 5 \text{ ns}$
- **Biermann source**
- **Resistive dissipations** $\approx (\text{+Nernst convection})$
  - $t_{\text{dis}} \sim 100 \text{ ps}$
- $t_{\text{dyn}} \gg t_{\text{dis}}$
- **Field magnitude**: $B \sim MG$
Saturation of self-generated magnetic fields is predicted at highly nonlinear RT stages

- $I = 6 \times 10^{14}$ W/cm$^2$
- 100-$\mu$m-thick CH foil
- $t_{\text{RT}} \gg t_{\text{mag}} \sim 100$ ps $\Rightarrow$ Quasi-steady magnetic field
- Resistive dissipations limit the fields at small wavelength perturbations
Simulations predict complicated plasma flows resulting in sandwiched magnetic fields

- Self-generated fields are significantly subthermal, $\beta_{\text{min}} \sim 100$
- $\omega_e \tau_e > 0.1$ is achieved for long-wavelength perturbations ($\lambda > 100 \, \mu m$) and at highly nonlinear stages
The sandwiched fields focus the heat flux toward the tip of the RT spike

\[ \nabla T_e \]

\[ \omega_e T_e \geq 0.1 \]

- The ablation pressure near the tip increases
- Heat entering the RT bubble decreases

\[ T_e = T_e(z), \quad \vec{B} = (0, B_y, 0) \]

Spitzer flux
\[ \left( q^e_T \right)_z = -k^e_\perp \frac{\partial T_e}{\partial z}, \quad k^e_\perp = k^e_\perp (B_y) \]

Cross-gradient flux
\[ \left( \tilde{q}^e_T \right)_x = -k^e_\wedge \frac{\partial T_e}{\partial z}, \quad k^e_\wedge \propto B_y \]
Self-generated magnetic fields moderately reduce the RT growth

Growth of the axisymmetric RT spike

Without fields

With fields

\[ \lambda = 160 \, \mu m \]

(Peak-to-valley amplitude) / \lambda

Time (ns)

With fields

Without fields

\[ t = 6.2 \, ns \]

Flattened tip

\[ \rho(\text{g/cm}^3) \]

\[ 4 \]

\[ 3 \]

\[ 2 \]

\[ 1 \]

\[ 0 \]
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