Current Transients in Laser-Driven Coils

Protons
EP Laser
1.25 kJ, 1 ns

Support
2 mm

Proton radiograph

1.5 mm

Protons

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Experiments and basic theoretical considerations indicate that the current in laser-driven coils has significant transient components.

- An electron fluid model indicates that current propagation into a target driven by electron expansion into vacuum occurs at the electron thermal velocity.
- A thermal diffusion model indicates that current propagation due to the thermoelectric effect is not significant.
- Radiation-hydrodynamic simulations of EP experiments show rapid plasma formation on the loop due to radiation that will carry the current.
Collaborators

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Lasers eject electrons from solids causing a return current to be drawn that can be used to generate a magnetic field.

1960’s
Currents measured in the target chamber

1970’s
Loop used to measure current in the target

1980’s
Double disk to generate magnetic field in a loop

D. Lichtman and J. F. Ready
Phys. Rev. Lett. 10 342 (1963)

M. G. Drouet and H. Pépin
Appl. Phys. Lett. 28 426 (1976)

H. Daido et al

2010’s
Double disk is back in fashion!
> 15 publications
Experiments on EP showed no magnetic field in double plate coils and a non-uniform current of order 80 kA in single plate coils.

Double plate:

- 2 mm
- 0.5 or 0.8 mm
- 1.5 mm

Single plate:

- 2 mm
- 0.5 mm
- 1.5 mm

1.25 kJ in 1 ns at 351 nm with a roughly Gaussian spot $R_{1/e} \sim 60 \mu m$ giving $I_{max} \sim 1.1 \times 10^{16} \text{ W cm}^{-2}$
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Grid pinching and rotation
Radial electric and magnetic fields

1.25 kJ in 1 ns at 351 nm with a roughly Gaussian spot $R_{1/e} \sim 60 \, \mu\text{m}$ giving $I_{\text{max}} \sim 1.1 \times 10^{16} \, \text{W cm}^{-2}$
Non-uniform current means a steady state was not achieved

Is there a simple model that can describe transient currents?

• Electron inertia
  – Electrons in the loop take a finite time to respond to the expulsion of electrons from the laser spot
  – Simplest possible model is an electron fluid and fixed ions

• Thermoelectric effect*
  – Heat front propagates through the loop → current pulse propagates through the loop
  – Simplest possible model is the analytic solution for thermal diffusion

*V. V. Korobkin and S. L. Motylev Pis'ma Zh. Tekh. Fiz. 5 1135 (1979)
Lagrangian and Eulerian electron fluid codes in 1D planar geometry with isothermal electrons were used to obtain the current in the target due to electron expansion into vacuum

Current density in the target

- A decaying electron plasma wave propagates into the target at the electron thermal velocity
  - In cold Cu the Fermi velocity is 1.6 mm/ns
  - \((kT_e/m_e)^{1/2} > 5 \text{ mm/ns requires } kT_e > 140 \text{ eV}\)
- Hot electrons ejected from the laser spot cannot travel far enough through the Cu to provide the return current from the target
  - 100 keV electron has a 25 \(\mu\text{m}\) range
  - A 10 mm range requires 17 MeV
- Expect the field around the laser spot to be closer to a dipole giving a \(1/r^3\) decay
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The self-similar solution for thermal diffusion in a semi-infinite slab with a fixed surface temperature $T_s$ and constant thermal diffusivity $D$ provides an estimate for the thermoelectric effect.

- Thermal diffusivity of room temperature Cu is only $1.11 \times 10^{-4}$ mm$^2$/ns.
- To reach 25 mm$^2$/ns for a solid density plasma requires $kT_e \sim 4$ keV.
  - Still require $kT_e \sim 200$ eV if density were to drop by a factor of $10^3$.
- Effective voltage is only $0.5 \pi^{0.5} \beta kT_s/e \sim 10$ kV.
  - $\beta$ effective thermoelectric coefficient.
- The loop is not going to be heated by thermal conduction during the laser pulse.
  - Need another mechanism to form the plasma required to propagate current around the loop.
Radiation-hydrodynamic simulations in 2D cylindrical geometry were used to study plasma formation in the EP experiments.

**Double disk without loop**

Radiation rapidly formed plasma on all surfaces.

**Single disk with loop mock-up**

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Double disk without loop

Single disk with loop mock-up

Radiated laser light also formed plasma
The simulations provide a qualitative explanation of our EP results

• Double plate
  – Photo-electrons from the second plate provided the initial return current so no current was drawn through the loop
  – Photo-electrons in the loop expanded inwards

• Single plate
  – Photo-electrons were eventually drawn from the loop
  – 1 ns is insufficient to establish a steady-state electron flow so the current is non-uniform
  – The magnetic field prevented the electrons from expanding into the loop

• Electron-ion separation, electrostatic fields and electron flow, not included in single fluid models or MHD, are required to give a more detailed description
  – Working on an electron fluid model for the wires with an applied dipole electric field to represent the laser-driven plasma
Conclusions

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- A thermal diffusion model indicates that current propagation due to the thermoelectric effect is not significant.
- Radiation-hydrodynamic simulations of EP experiments show rapid plasma formation on the loop due to radiation that will carry the current.
In both cases current propagation around the loop during the laser pulse requires the formation of plasma; how does this occur?

- Thermal diffusion has already been ruled out
- Ohmic heating from the current itself
- Radiation from the laser-heated plasma
Skin heating is independent of resistivity $\eta$ and current rise time $t$

- Temperature dependent resistivity will lead to the current moving to regions of lower resistivity that will change the heating

For a current $I$ of 80 kA, a width $w$ of 0.1 mm, a specific heat capacity $C$ based on 4 free electrons per atom at solid density gives $kT_e \sim 10$ eV

- Cu boils at 0.24 eV and it’s first ionization potential is 7.7 eV

Ohmic heating could create a plasma and the current would then switch to the lower resistivity plasma, completely changing the heating regime.