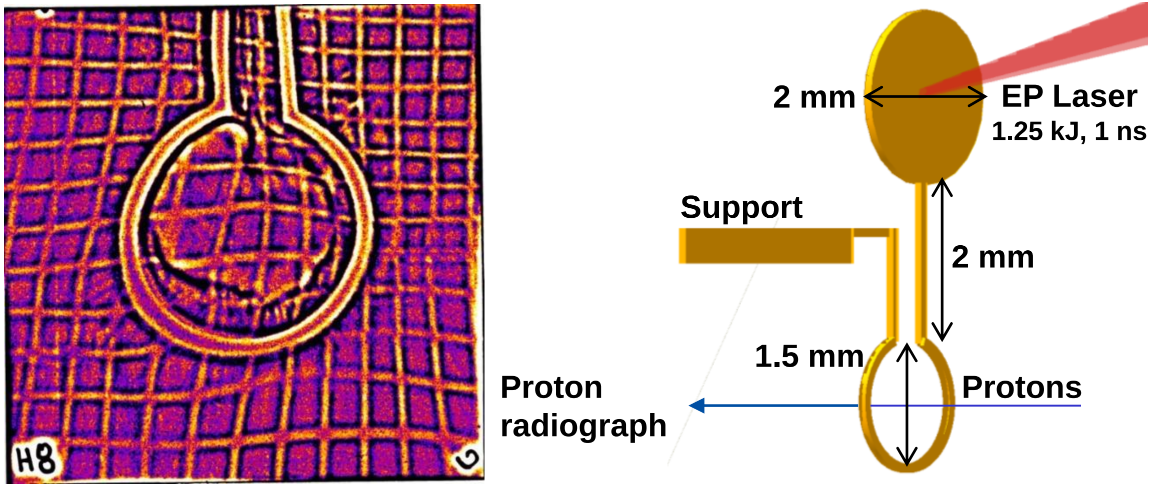
Current Transients in Laser-Driven Coils



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Summary

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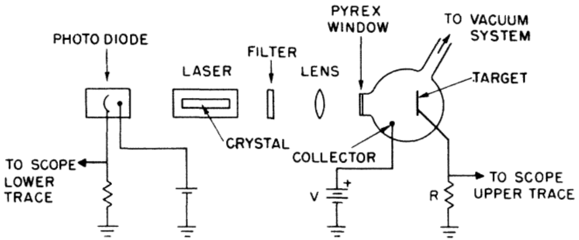
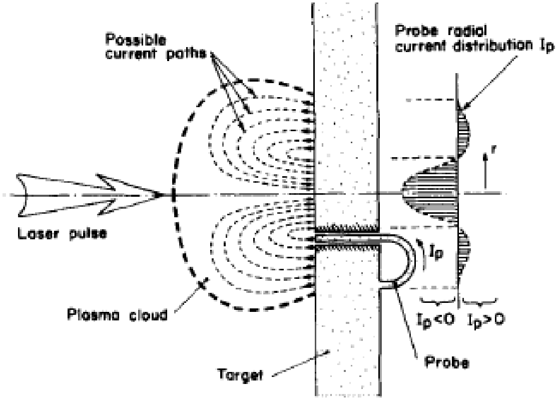
Lasers eject electrons from solids causing a return current to be drawn that can be used to generate a magnetic field

1960's
Currents measured in the target chamber



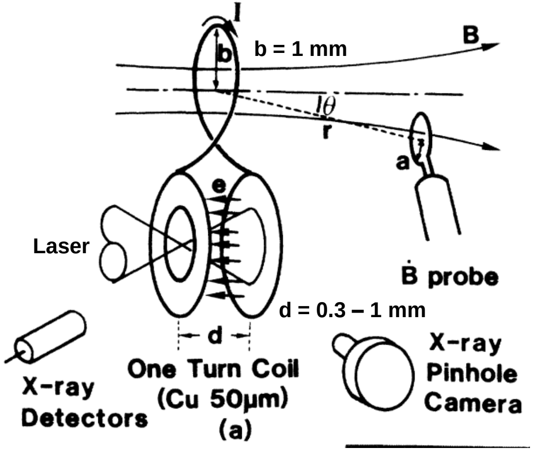
D. Lichtman and J. F. Ready
Phys. Rev. Lett. **10** 342 (1963)

1970's
Loop used to measure current in the target



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

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



H. Daido *et al*
Phys. Rev. Lett. **56** 846 (1986)

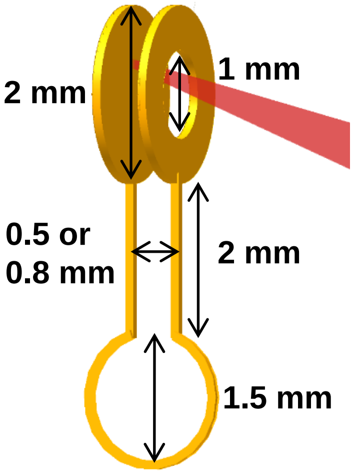
2010's
Double disk is back in fashion!
> 15 publications

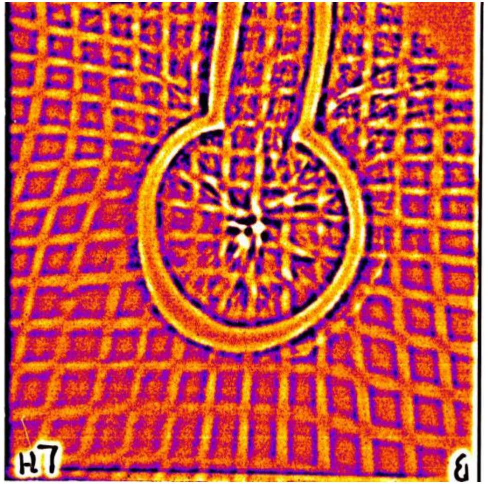
UNIVERSITY of ROCHESTER

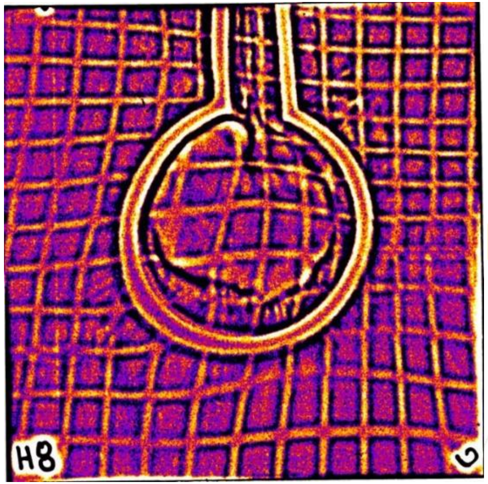
Experiments on EP showed no magnetic field in double plate coils and a non-uniform current of order 80 kA in single plate coils

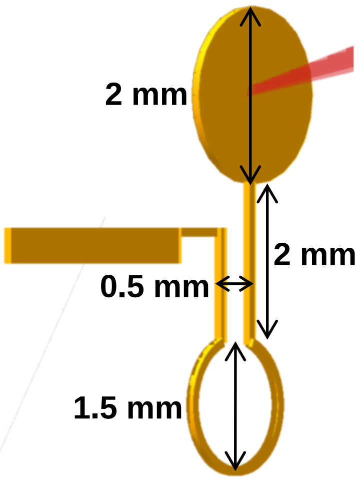
Double plate | **Single plate**

~ 20-MeV protons at 1.1 ns









1.25 kJ in 1 ns at 351 nm with a roughly Gaussian spot $R_{1/e}$ ~ 60 μm giving I_{max} ~ 1.1 $\times$ 10^{16} W cm^{-2}

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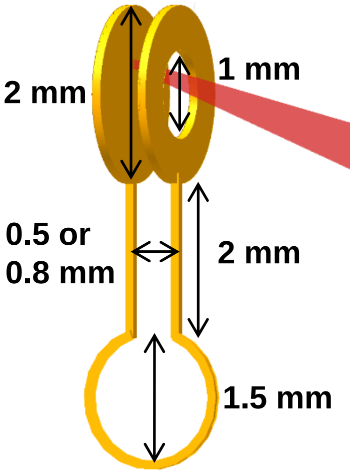
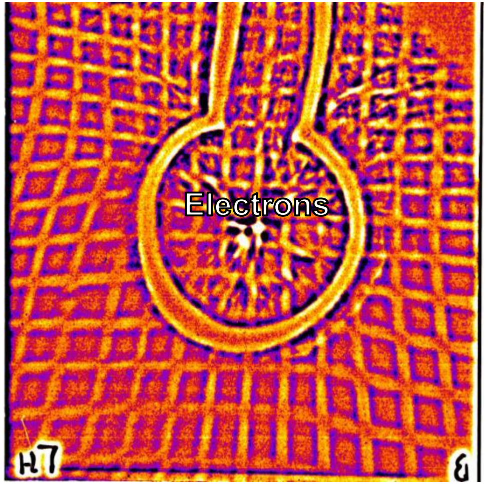
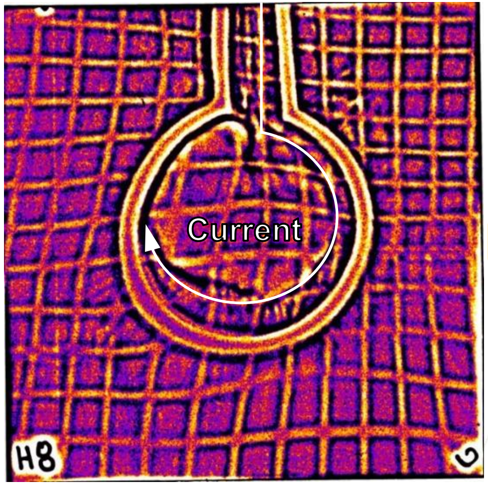
Double plate



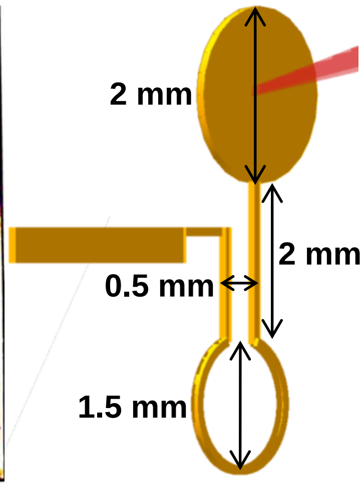
Grid pinching
Radial electric field



Grid pinching and rotation
Radial electric and magnetic fields



Single plate



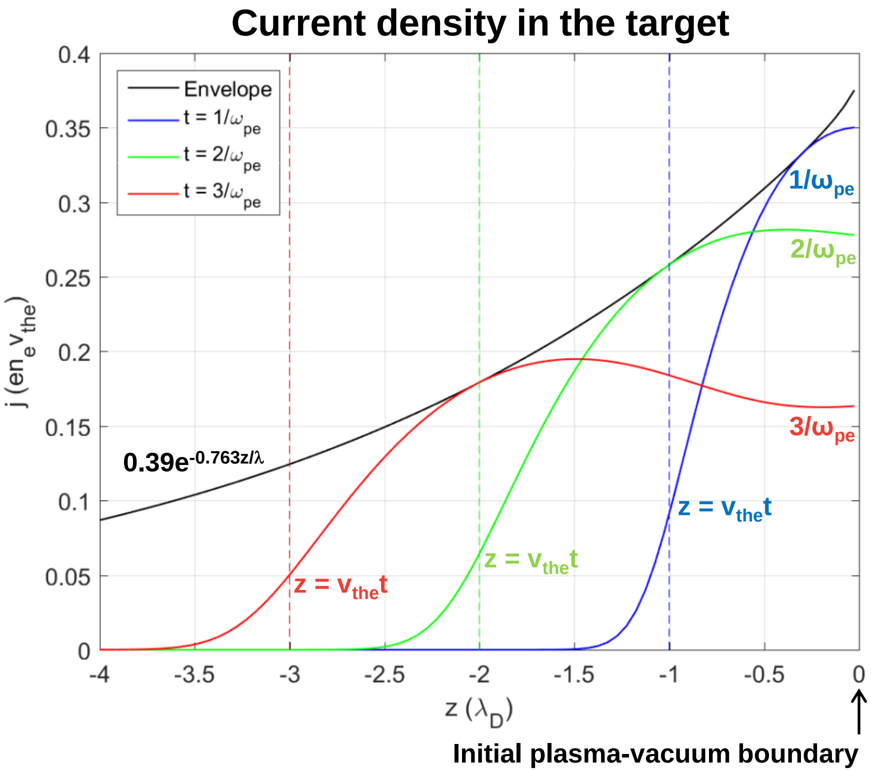
1.25 kJ in 1 ns at 351 nm with a roughly Gaussian spot $R_{1/e}$ ~ 60 μm giving I_{max} ~ 1.1 × 10^{16} W cm^{-2}

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



- **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 mm/ns requires kT_e > 140 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 μm 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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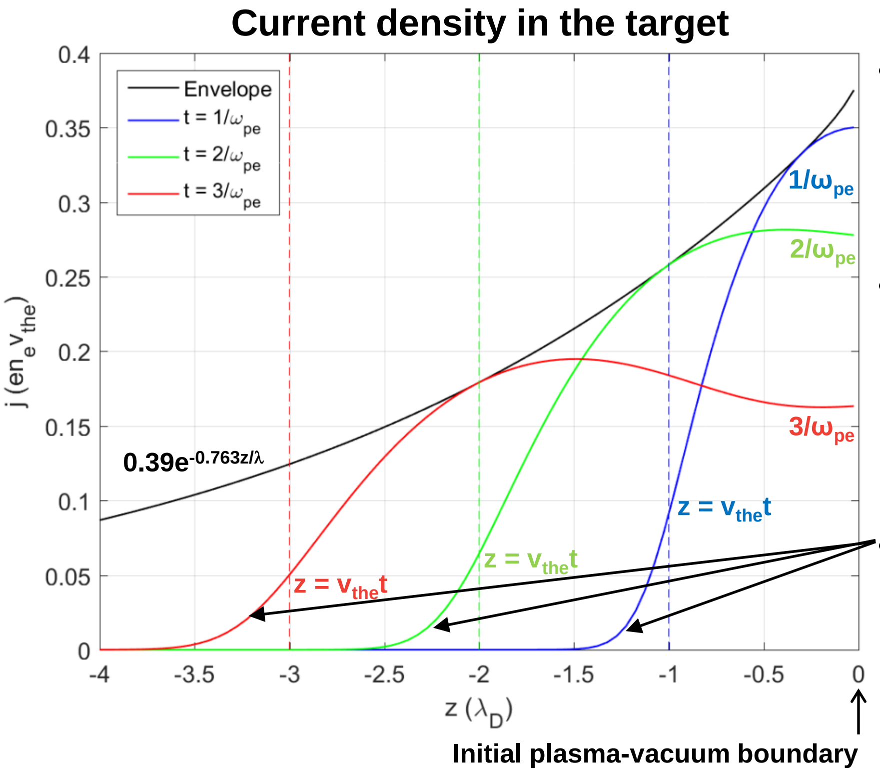

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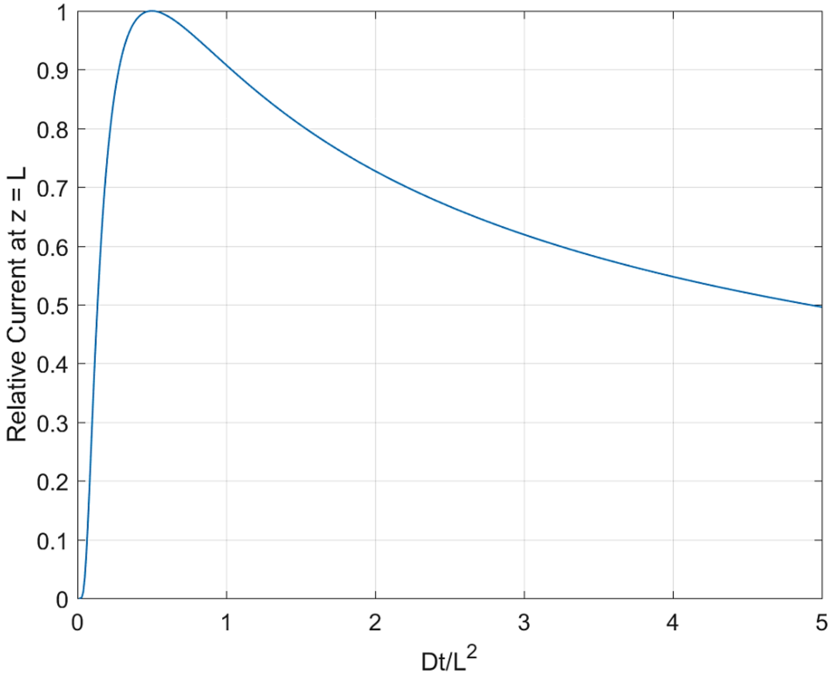
The self-similar solution for thermal diffusion in a semi-infinite slab with a fixed surface temperature T_s and constant thermal diffusivity D provides an estimate for the thermoelectric effect

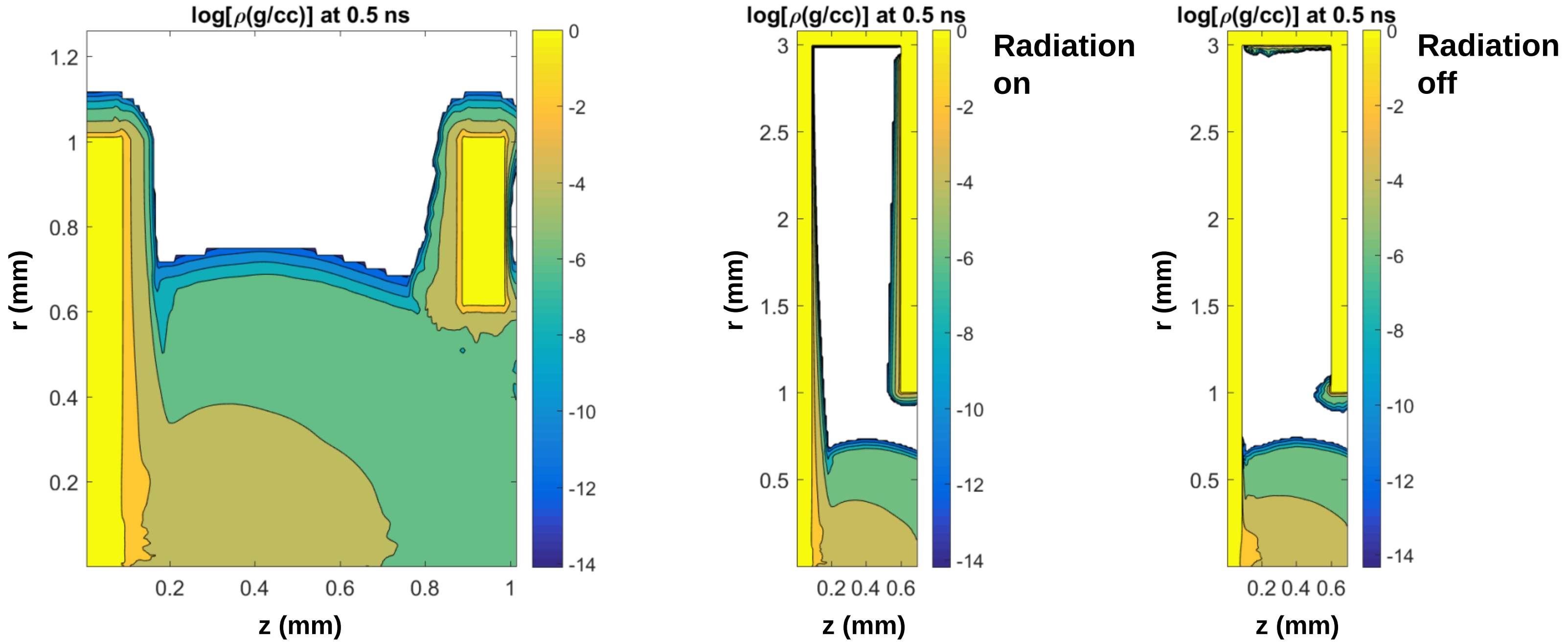


- **Thermal diffusivity of room temperature Cu is only 1.11×10^{-4} mm^2/ns**
- **To reach 25 mm^2/ns for a solid density plasma requires $kT_e \sim 4$ keV**
  - **Still require $kT_e \sim 200$ eV if density were to drop by a factor of 10^3**
- **Effective voltage is only $0.5\pi^{0.5}\beta kT_s/e \sim 10$ kV**
  - **β 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

Single disk with loop mock-up



Radiation rapidly formed plasma on all surfaces

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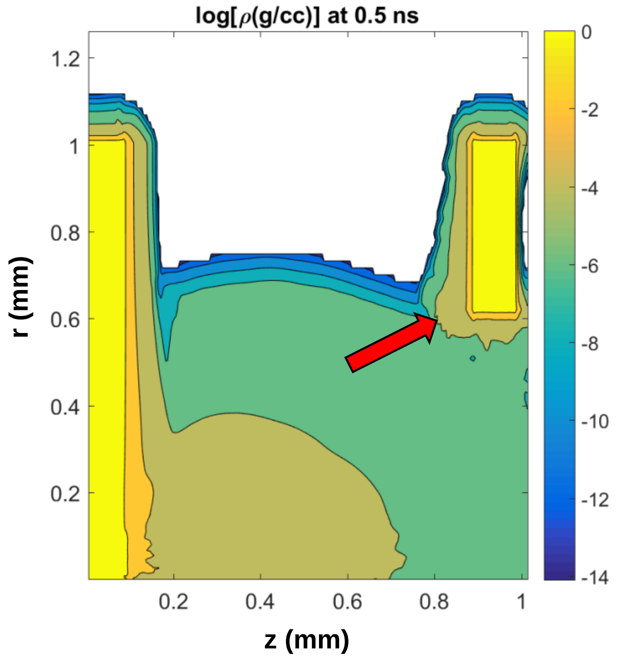
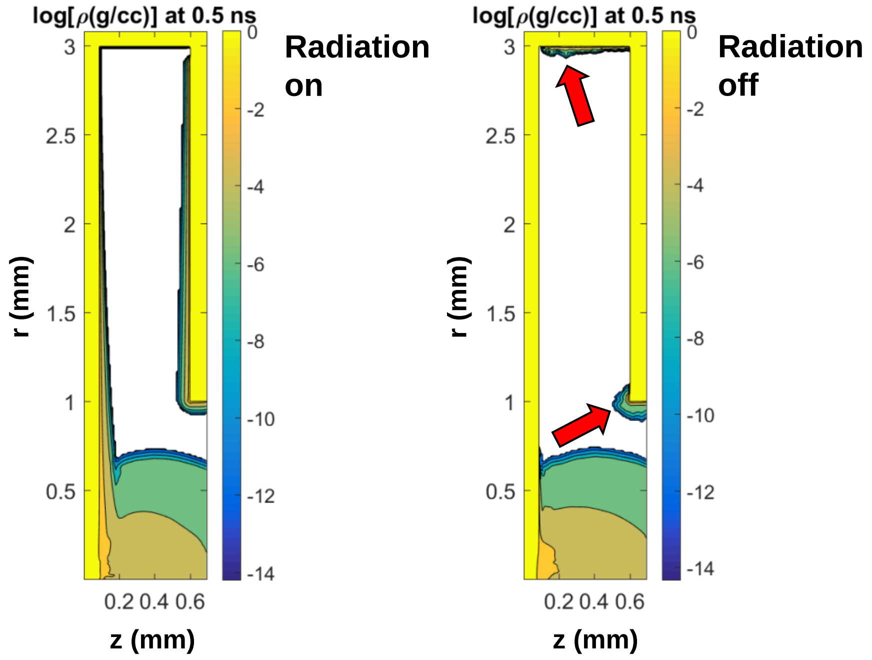


Single disk with loop mock-up



Refracted 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

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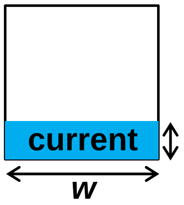
In both cases current propagation around the loop during the laser pulse requires the formation of plasma; how does this occur?

- **Thermal diffusion has already been ruled out**
- **Ohmic heating from the current itself**
- **Radiation from the laser-heated plasma**

Current will concentrate in a skin depth δ on the inner surface of the loop as this is the lowest inductance path



$\updownarrow$ $\delta = (\eta t/\mu)^{1/2}$

$$\Delta T = \frac{I^2 R t}{C \rho V} = \frac{I^2 \eta t}{C \rho \delta^2 w^2} = \frac{I^2 \mu}{C \rho w^2}$$

- **Skin heating is independent of resistivity η 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**