Magnetic Field Generation by a Laser-Driven Capacitor-Coil Target

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Introduction

- A new method of generating high magnetic fields using laser-driven capacitor-coil targets, shown below, has been studied in a handful of experiments.

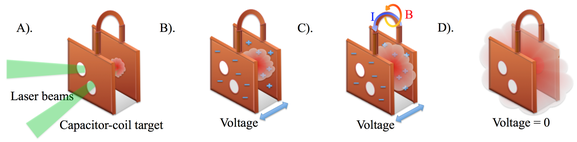


Figure 1: The process of magnetic field generation in the coil.

- Such magnetic fields have a wide range of applications in high-energy-density (HED) science, including laboratory magnetic reconnection experiments and magnetizing inertial confinement fusion (ICF) capsules for yield enhancement.
- The purpose of this project is to develop a theoretical lumped-circuit model to simulate the time-evolving current in the coil of the target based on recent experiments carried out with the OMEGA EP lasers.

Experiment

- The main target, comprised of two parallel Cu foils connected by a U-shaped Cu coil, was irradiated with two 1.25 kJ, 1-ns EP laser pulses at a focused laser intensity 3×10^{16} W/cm^2.

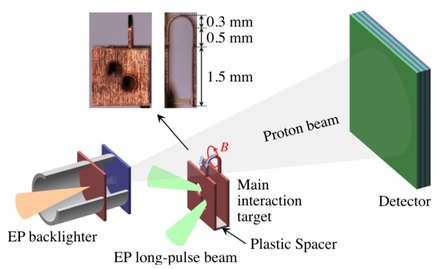


Figure 2: Experimental Set-up for the OMEGA EP experiments

- An energetic proton beam, generated by the 0.3-kJ, 1-ps EP backlighter irradiating a 20-μm-thick Cu foil, was used to measure the magnetic field generation around the coil.

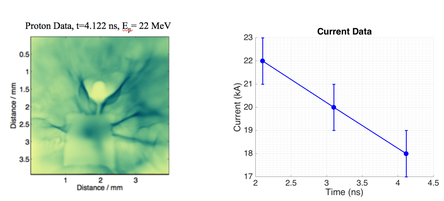
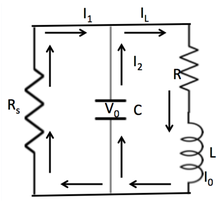


Figure 3: Experimental Results

L. Gao, H. Ji, G. Fiksel, W. Fox, M. Evans, N.Alfonso Phys. Plasmas, 23(043106) 2016

Building a Lumped Circuit Model



The parallel plate target can be thought of as a capacitor with an initial stored voltage that decays to zero by discharging through currents in the coil and plasma. The parameters for the model were calculated as follows:
Using Kirchoff's voltage law to analyze the circuit on the left, Current, $I_L(t)$ is:

$$I_L(t) = A_1 e^{s_1 t} + A_2 e^{s_2 t} \quad (1)$$

$$s = \frac{-L \pm \sqrt{C^2R^2R_s^2 - 2CLRR_s - 4CLR_s^2 + L^2 + CRR_s}}{2CLR_s} \quad (2)$$

Where s_1 and s_2 are the $\pm$ forms of s. R_s = source or plasma resistance, R = coil resistance, L = coil inductance, C = capacitance, which represents foils. L is a geometric constant and R_s, is calculated by the parallel Spitzer resistivity at $T_e = 2000eV$. R and C are calculated theoretically below:

$$\eta(T) = \eta_0(1 + 3.9 \times 10^{-3}(T - T_0)), R(T) = \frac{\eta(T) l_w}{\pi d_w \delta} \quad (3)$$

$$C(t) = \frac{A\epsilon_0}{d} + \frac{A_p l \epsilon_0}{3\lambda_d} \quad (4)$$

$$\frac{dT(t)}{dt} = \frac{I_L(t)^2 R}{C_{cop} l_w d_w \delta \pi} \quad (5)$$

Where δ = skin depth, η_0 = room temperature resistivity, l_w = coil length, d_w = coil diameter, A = foil area, and d = gap distance

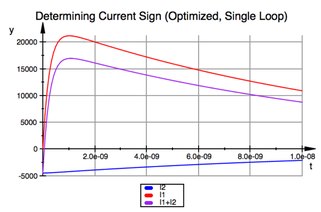
Temperature during the laser pulse, $T(t < 1ns)$, is calculated by equation 5. $T(t > 1ns)$ is determined by the rate of radiative heat transfer, where emissivity, $\epsilon = 0.6$

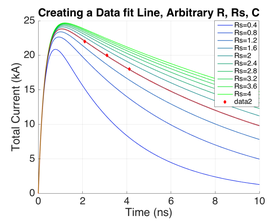
N.Sinenian et al, Plasma Phys. and Controlled Fusion, 55 (045001), 2013.

Simulation

The time-evolving current is simulated below using the lumped-circuit model:

A). Single Coil





The current direction in the inductor was first verified by summing the currents I_1 and I_2. Afterwards a fit line based on the experimental data was created using arbitrary values.

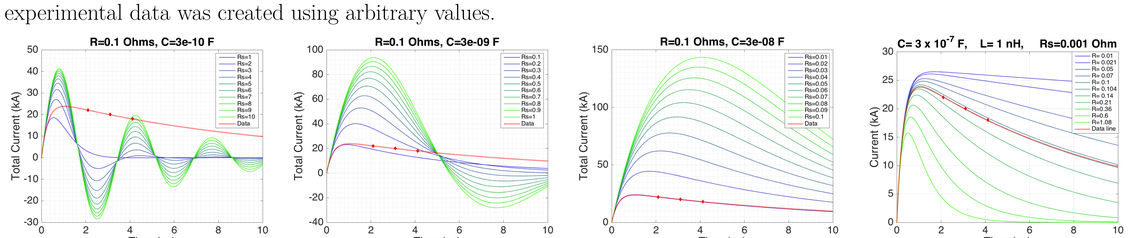
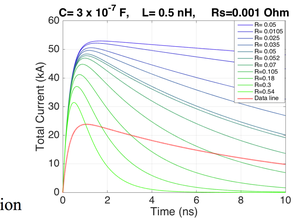


Figure 4: Current response for a representative simulation set.

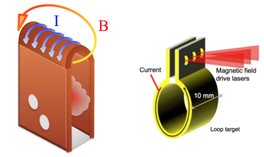
Current response was simulated for a sweep of R, R_s, and C values. The first three of the above plots shows sweeping at a given resistance, and the last compiles best fit sweeps over many resistances and a constant capacitance.

Applications

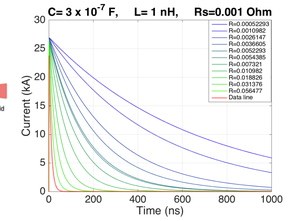
1). Double Coil: Magnetic Reconnection



The total time-evolving current response in both coils is twice the magnitude of that in the single coil, demonstrating that the hot electrons behave as a voltage source rather than a current source



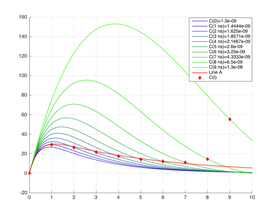
2). Cylinder: Magnetized ICF



The cylinder configuration is directly relevant to magnetized ICF. A magnetized hohlraum being studied at NIF for improved confinement is shown next to the target modeled. The current response plot shows a much longer decay time than single coil.

Conclusion and Future Work

- the target was successfully modeled as a lumped circuit and the current evolution was simulated for various geometries



- this plot shows a fitted current response using varying capacitance based on the the narrowing gap distance. In the simulation, R and C were fixed, whereas in reality, both are time varying
- the next step is to build a self-consistent model with time varying R and C.

Acknowledgements

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