Production of High Magnetic Fields by Using High Power Lasers and Scaling to Medium Power Lasers

Ariel Tarifeño¹,², Cristian Pavez² and Leopoldo Soto²

¹Universidad de Concepción, Chile
²Departamento de Plasmas Termonucleares, Comisión Chilena de Energía Nuclear, Chile

E-mail: atarisal@gmail.com

Abstract. Generation of intense currents through the emission of hot electrons beams from laser-plasma interactions has demonstrated to be an alternative for producing pulsed high magnetic fields. In the past, it was reported the generation of fields as high as 4 MGs in experiments with lasers for which the product between the intensity and the square wavelength is $I/\lambda^2 \approx 10^{16}$ W/cm² μm². In this work, we review and discuss the possibility to scale this kind of experiments for producing high magnetic fields by using medium power lasers where $I/\lambda^2 < 10^{14}$ W/cm² μm². We report results of preliminary experiments in which we used a Nd: YAG laser (6-8 ns FWMH, 1.3 J Maximal pulse energy, $\lambda=1.064$ μm, $I/\lambda^2 \approx 10^{11-13}$ W/cm² μm²).

1. Introduction
Currently there is a strong demand for high magnetic fields generators around the world. This demand has been generated due to the necessity of extreme conditions under which different kinds of experiments or diagnostics could be performed.

In the 1970's, by the way of the early research in inertial confinement, it was observed in laser-driven plasmas that hot electrons beams -expelled from the plasma preferentially in the laser beam direction- and high magnetic fields are generated in the plasma as a result of laser-plasma interactions [2]. This phenomenon is called self-generated currents or return currents. The physical mechanism involving the emission of hot electrons is given as follow: when a intense laser beam interact with a plasma, if the laser intensity is high enough (> $10^{13}$ W/cm²), the mainly process of energy transference from the laser beam to the plasma is via resonant absorption. It results in the generation of a two temperature electron plasma. The temperature of the hot electron plasma depends on the product of the laser intensity $I$ and the laser wavelength $\lambda$ like $T_H \approx (I/\lambda^2)^{4}$. This fact has been explained by Forslund et al [3] and has been experimentally confirmed by several authors [1, 4, 5, 6]. It has been also pointed out that when the laser intensities are less than $10^{12}$ W/cm², the laser energy is mainly absorbed via inverse Bremsstrahlung. Consequently, the background plasma is heated and, as a result, low return currents are expected.

By collecting and passing around the high currents generated in laser-plasma interactions through a single turn coil, high magnetic fields could be generated [1, 7]. Daido et al have reported the generation of magnetic fields as high as 4 MGs in a cylinder type one-turn coil driven by laser pulses where $I/\lambda^2 \approx 10^{16}$ W/cm² μm² at the focal point [8]. Recently, Courtois et al have reported the generation of a pulsed uniform high magnetic field environment of 7 T at the peak pulse. In this experiment, the
authors have used a helmholtz coil driven by a laser pulse where $I_0^2 \approx 10^{16}$ W/cm$^2$. In both experiments, the observed hot electron temperature was of the order of 15 keV.

In the present work, we report a preliminary experiment on magnetic field generation by a laser-driven single turn coil. We aim to study the scaling rules by which the experiments reported by Daido et al. and Courtois et al. could be performed at slower regimes of laser intensity. Particularly, we intend to explore the regime for which $I_0^2 \approx 10^{11-13}$ W/cm$^2$.

2. Experimental Setup

The preliminary experiments were performed in air under ambient conditions of pressure and temperature. The coil and plates design was based in the design proposed by Daido et al. [1]. In our case, the plates were made using copper strips of 110 $\mu$m thick. The back plate has 8 mm · 6 mm area, while the front one has 8 mm · 4 mm area. The front plate has a 1 mm diameter hole which is center at the medium horizontal point of the plate and 1.5 mm below the top vertical edge. The gap between the plates was set with a dielectric foil which is placed in the bottom part of the plates.

In this experiment, we use a single turn coil. The coil was made with a 150 $\mu$m copper wire. The inner diameter of the coil was set to 2 mm. The loop was made so that the current direction in the gap is perpendicular to the current direction in the coil. The gap was set to 1.3 mm. A Nd:YAG laser (6-8 ns FWMH, $\lambda = 1.064$ $\mu$m) was focused into the back plate by using a 200 mm focus lens. The energy of the laser pulse was estimated to 0.5 J. In this conditions, the intensity at the focal point was estimated to $6.1 \cdot 10^{11}$ W/cm$^2$ so that $I_0^2 \approx 7 \cdot 10^{11}$ W/cm$^2$ $\mu$m$^2$. A diagram and a real image of the experimental montage is shown in figure 1.

![Figure 1](image)

Figure 1. Diagram and real image of the experimental montage.

We used a magnetic probe to measure the magnetic field generated in the coil. The magnetic probe was made with a single turn coil (250 $\mu$m copper wire, 1 mm inner diameter) connected to rigid coaxial cable (fig. 1). The terminal of the coaxial cable is connected to the oscilloscope (Tektronix TDS684A). By getting a trace with the probe in the oscilloscope, the magnetic field on the axis of the coil could be measured by integrating the trace as follow:

$$B(t) = k \frac{1}{\pi a^2 b^3} \int_0^t v(t') \, dt'$$

Where $k$ is a calibration constant, $v(t')$ the trace and $a$, $b$, $r$ geometrical parameters in the experiment. The probe was calibrated using a RLC circuit (4.7 nF, 0.7 $\Omega$, 75 nH, 10 ns risetime, 10 V charge voltage) supplying a coil with similar characteristics of the one in our experiment. The RLC circuit delivers 1 A at the peak of the first pulse. We got an experimental value for $k$ of $k = 0.243$. 


3. Results
In the figure 2, we show the best shot that we got (SHOT # 5). The SHOT # 11 corresponds to the trace gotten when we turned over the probe. We make it to test if we really were measuring a magnetic field generated by the coil. The SHOT # 13 corresponds to the case when we cut the coil. There is no doubt about no magnetic field has been measured in this case.

![Figure 2. B-dot Traces.](image)

![Figure 3. Magnetic field generated for shot #5 (best shot).](image)

In general, the magnetic field pulse measured in our experiments has a peak in the range of 1-10 Gs. The magnetic field generated in the coil for the best shot is shown in the figure 3. For this shot, we see that the pulse have a risetime close to 2 ns, 9.5 Gs at the peak and the magnetic pulse width is similar to the laser pulse width (8 ns). In addition, the current peak in the coil is estimated to be 1.6 A.

The results reported above agree with the expected results for our working laser intensity. Now, we plan to improve the experimental conditions in order to get higher magnetic fields. By using the maximum available energy for the first harmonic of our Nd:YAG laser (close to 1.3 J/pulse) and reducing the focal length of the lens, we expect to increase the laser intensity at the focal point. We also plan to perform the experiments in a vacuum chamber (by this, we increase the mean free path of the hot electrons) and to reduce the dimensions of the plates so that we reduce the capacitance and then increasing the voltage between the plates. A Cylinder type coil should increase also the magnetic field due to the smaller equivalent circuit impedance.

The means advantages of this kind of magnetic field generators are the high risetime and the electromagnetic noiseless. They could be use to calibrate or test a magnetic field diagnostic method.
or, when the magnetic field is high enough, to perform laboratory plasma astrophysical simulations [9] or for generating higher fields by magnetic flux compression [10].

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