Generation of a Strong Magnetic Field by an Intense CO_2 Laser Pulse

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A strong magnetic field of 600 kG (60 T) is generated at the center of a 2-mm-diam one-turn coil in which the current is driven by a CO_2 laser. The magnetic field, current, and voltage are measured as functions of the separation distance of the gap where the high voltage is induced by the laser irradiation in the coil loop at a fixed intensity of 1.3×10^{14} W/cm^2. These results are analyzed on the basis of hot-electron $\mathbf{E}\times\mathbf{B}$ drift and plasma expansion inside the gap. The analysis indicates how to design the target and the laser pulse for generation of a magnetic field of a few megagauss.

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Several papers have reported that high voltage and intense electric current are generated by laser-target interactions[1] and the self-generated magnetic field has been measured by Faraday rotation techniques.[2] In the works of Ref. 1, the light intensity was below 10^{12} W/cm^2. At that laser intensity, the laser light is mainly absorbed by inverse bremsstrahlung and heats thermal electrons. Since the laser plasma temperature is not high, the observed current and voltage are not high, say, 10^3 A and 10^2 V, respectively. At higher irradiances, i.e., higher than 10^{14} W/cm^2 at 10.6 μm laser wavelength, the target voltage can be several hundreds of kilovolts,[3] because hot electrons whose temperature is more than 10 keV are generated by resonance absorption. That laser-induced high voltage has been applied to induce high currents and strong magnetic fields. For example, a strong magnetic field was observed in the augmented-return-current target which was used for liner compression.[4]

Recently, various applications of strong magnetic fields to nuclear fusion devices have been proposed by several authors.[4-7] Magnetically insulated inertially confined fusion is one of these and the experimental and theoretical results have been published.[7,8] Another possible application is to the material sciences, since the laser-induced magnetic field can be larger than a few megagauss.

In this paper, we report the experimental evidence for the generation of magnetic fields which are greater than several hundred kilogauss at the center of a one-turn coil connected to a double-disk target. By the experiment, it was clarified that the magnetic field is proportional to the distance between the two disks when the laser pulse width is longer than the characteristic time in which the gap is filled with plasma. However, when the gap is too large, the magnetic field is found to decrease. From those results, we got a scaling law for the self-induced magnetic field and found a method to increase the magnetic field up to a few megagauss, which is strong enough for various applications of the high magnetic field.

A target and an observation system are shown schematically in Fig. 1(a). The target is composed of two disks, 50 μm thick by 2 mm in diameter, made of copper. The front disk has a 1-mm-diam hole at center for laser injection. These two disks are connected with a 2-mm-diam, one-turn coil which is made of 80-μm-diam copper wire. The relative direction of the gap to the coil is set so that the gap current can flow perpendicular to the current in the one-turn coil. The magnetic field is measured by use of a 1-mm-diam search coil linked to a Tektronix 7104 oscilloscope whose band width is 1 GHz. The response time of the

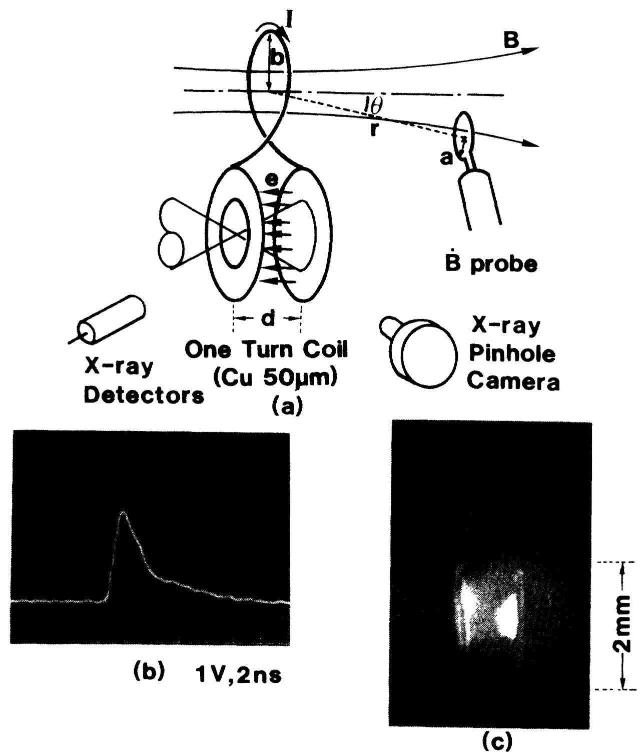

FIG. 1. (a) Schematic diagram of one-turn coil with the gap and the observation system. (b) Typical soft x-ray signal (0.1–1.0 keV) and (c) x-ray image (white regions) of the gap. The laser irradiates from the left. $a=500$ μm and $b=1$ mm.

observation system is less than 0.3 ns. The magnetic field, $B(t)$, at the center of the one-turn coil and the current $I(t)$ along the coil are calculated from the voltage $v(t)$ of the probe signal by use of the following equations:

$$B(t)=r^3\int_0^t \frac{v(t)\,dt}{\pi a^2 b^3(\cos^2\theta-\frac{1}{2}\sin^2\theta)} \tag{1}$$

and

$$I(t)=2r^3\int_0^t \frac{v(t)\,dt}{\pi a^2 b^2\mu_0(\cos^2\theta-\frac{1}{2}\sin^2\theta)}, \tag{2}$$

where r and θ are the distance and the angle between the center of the search coil and that of the one-turn coil. The two coils are parallel to each other. a and b are the radii of the search coil and the one-turn coil, respectively. μ_0 is the magnetic permeability in the vacuum. The voltage at the gap is estimated by the equivalent lumped-constant circuit model as follows:

$$V(t)=L\,dI(t)/dt+RI(t), \tag{3}$$

where $V(t)$, L, and R are the time-dependent voltage, the inductance, and the resistance of the one-turn coil, respectively. It is noted that the second term in the right-hand side of Eq. (3) is negligibly small compared with the first one in the present experimental condition. In Figs. 1(b) and 1(c), a typical x-ray signal (0.1 keV $\lesssim h\nu \lesssim$ 1 keV) and image (white regions) of the gap are shown. The laser light is injected from the left and is focused at the center of the 1-mm-diam hole on the front disk and hits the rear disk. The absorbed laser energy is converted into hot-electron energy via resonance absorption. The hot electrons are accelerated preferentially toward the underdense region[9] and some of them hit the front disk which generates a high voltage between the two disks. Then the return current flows in the one-turn coil, although some current is returned in the plasma particularly for larger gaps.

One arm of the LEKKO VIII CO_2 laser system, which delivers 100 J in 1 nsec, was used. The laser light is focused by an off-axis parabolic mirror with $f/1.5$. The focusing diameter and the depth of the focus are 250 (70% of laser energy contained) and 500 μm, respectively.[10] The average intensity at the focal point is $(1.3\pm0.2)\times10^{14}$ W/cm^2 and the hot-electron temperature is estimated to be 15 keV.[11]

Figure 2(a) shows a search-coil signal which corresponds to the time derivative of the magnetic field. In this experiment, the gap separation d is 500 μm and the other parameters of the coil are shown in Fig. 1. Figure 2(b) shows the magnetic field and the corresponding current which are derived from Eqs. (1) and (2) by use of the measured search-coil signal. Figure 2(c) shows the voltage at the gap derived from Eq. (3). To check the search-coil signal, we changed the arrangement of the one-turn coil so that the current flowed in the opposite direction in the one-turn coil. The signals indicated the opposite orientation of the magnetic field in comparison with the previous case.

Figure 3 shows the maximum magnetic field and the current as a function of the gap separation d. The solid circles and the triangle denote the data of a one-turn coil made of wire and that of cylinder type, respectively. Note that the schematic of the cylinder-type target is shown in the top of Fig. 3. The error bars show the reading uncertainty of the signals. The magnetic field is proportional to d when it is smaller than 700 μm. When d is 1 mm, the field strength is reduced drastically. It is noted that the magnitude of the magnetic field of the cylinder-type coil is two times larger than that of the wire-type coil because of the larger current due to smaller inductance and resistance in the coil.

Figure 4 shows the dependence of the voltage on the gap separation d. When d is less than 700 μm, the voltages scatter around 220 keV. When d is 1 mm, the voltage drops drastically.

Figures 3 and 4 show that the magnetic field and the

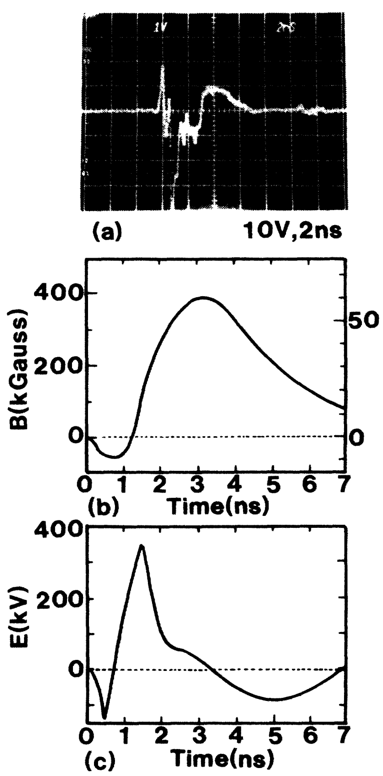

FIG. 2. (a) Typical search-coil signal which corresponds to the time derivative of the magnetic field. The vertical and the horizontal scales are 10 V/div. and 2 ns/div., respectively. The gap separation is 500 μm and the other parameters of the coil are shown in Fig. 1. (b) The magnetic field and the current as a function of time. (c) The voltage at the gap as a function of time.

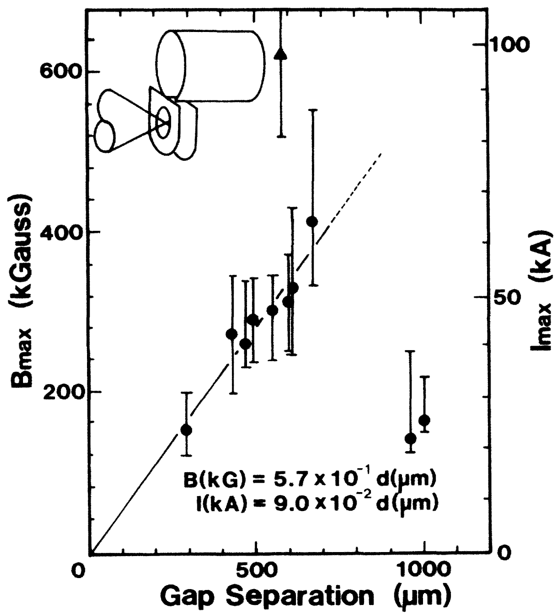

FIG. 3. Maximum magnetic field and the current as a function of the gap separation. The solid circles and the triangle denote the data of the one-turn coil made of 80-μm-diam wire and that of a cylinder-type one-turn coil whose diameter and width are 2 mm and 3 mm, respectively. The targets are made of copper. The solid line is the best fit to the experimental data.

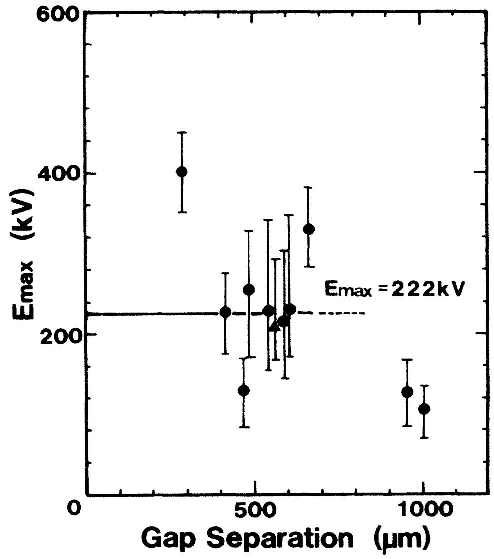

FIG. 4. Maximum voltage generated at the gap as a function of the gap separation.

voltage start to decrease when d exceeds 700 μm. The physical mechanism of this phenomenon is interpreted as the lateral spreading of the hot electrons due to $\mathbf{E}\times\mathbf{B}$ drift.[12] The schematic diagram of the gap and corresponding self-generated magnetic and electric fields are shown in Fig. 5. The equations of motion of the guiding center for an electron are written as

$$dZ/dt = v_Z = CE_r/B_\theta, \tag{4}$$

$$dr/dt = v_r = -CE_Z/B_\theta, \tag{5}$$

and thus

$$dZ/dr = E_0^{-1}\,\partial\phi/\partial r, \tag{6}$$

where the electric field E_Z perpendicular to the disk is assumed to be a constant, E_0, since the potential is constant on both disk surfaces. Therefore, the critical gap separation distance Z_c is[13]

$$Z_c = E_0^{-1}(\phi - \phi_0) = T_h/eE_0. \tag{7}$$

According to the isothermal expansion model,

$$eE_0 = T_h/C_{sh}\tau_L; \tag{8}$$

then

$$Z_c = C_{sh}\tau_L, \tag{9}$$

where E_i $(i = 0, \theta)$, B_θ, and ϕ are electric and magnetic fields and voltage as shown in Fig. 5. Note that the electrical potential is assumed to drop radially from the center to the edge, since the central part of the plasma is strongly heated and the electrons are ejected from that region in the form of hot electrons. T_h, C_{sh}, and τ_L are the hot-electron temperature, the hot-electron sound velocity, and the laser pulse duration, respectively. If d is larger than Z_c, a significant fraction of the hot electrons never reach the front disk because of the $\mathbf{E}\times\mathbf{B}$ drift and the voltage at the gap drops drastically. For $C_{sh} = 6.0\times10^7$ cm/s and $\tau_L = 1$ ns, Z_c is 600 μm. The critical gap distance Z_c reasonably agrees with the experimental results, namely, $Z_c(\text{exp.}) \simeq 700$ μm.

The linear dependence of the maximum magnetic field on d leads to the constant voltage at the gap as follows. We integrate Eq. (3) over the shorting time

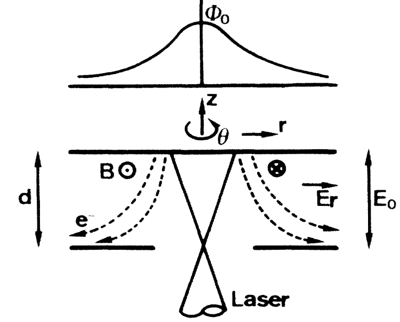

FIG. 5. Schematic diagram of the gap and corresponding self-generated magnetic and electric fields.

of the gap $t = d/C_{sh}$ which is much smaller than L/R. Then

$$V = LIC_{sh}/d. \quad (10)$$

In our experiment, L is 4.5 nH, $I = (9.0\times10^{-2}$ kA/μm$)d$, $C_{sh} = 6.0\times10^7$ cm/s, and thus $V = 222$ kV. This value also agrees with the experimental results as shown in Fig. 4. The maximum magnetic field and the current are determined and limited by the filling time of the gap with critical-density plasma. In our experiment, the ratio between the magnetic energy and the absorbed laser energy is roughly estimated to be 0.1. The above discussion indicates that the magnetic field can increase by the lengthening of the shorting time which can become longer by removing the plasma inside the gap or by increasing the gap separation without loss of hot electrons. This second alternative will be possible by adding appropriate hot-electron collectors at the edge of the front disk. The third method useful in increasing the field is to reduce the inductance and the resistance in the coil and to use a cylinder-type one-turn coil shown in Fig. 3. By optimization of the target configuration, the magnetic field will be more than a few megagauss at a CO_2 laser intensity of 1.3×10^{14} W/cm^2 and a few nanoseconds pulse width.

In summary, we have demonstrated that strong magnetic fields of 600 kG are generated at the center of a 2-mm-diam one-turn coil by use of a laser induced high-voltage source. The magnetic field (600 kG), current (100 kA), and voltage (220 kV) at the gap were measured as a function of gap separation at a fixed laser intensity of 1.3×10^{14} W/cm^2. These results are explained on the basis of lateral transport by hot-electron $\mathbf{E}\times\mathbf{B}$ motion and the expansion of the critical density plasma in the gap.

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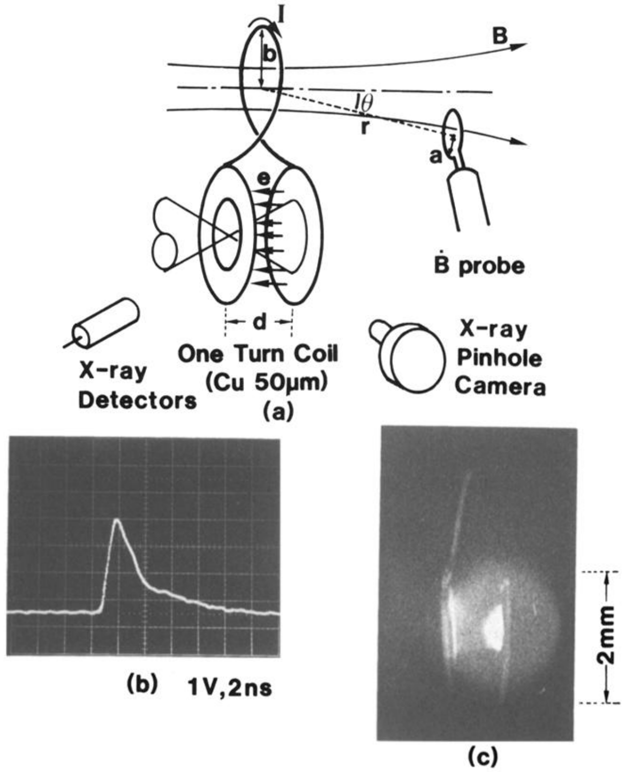

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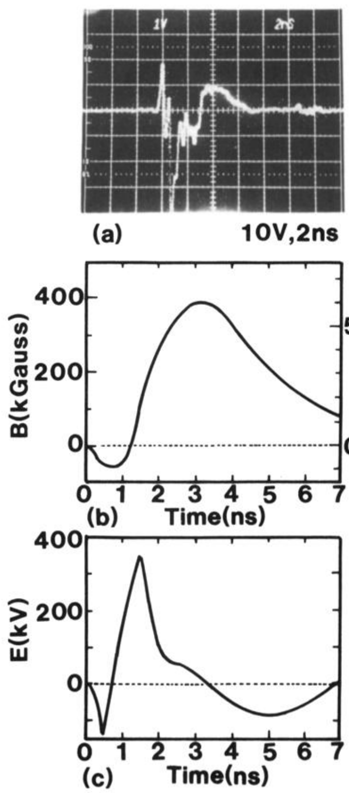

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