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Pulsed Megagauss Fields Produced by Laser-Driven Coils

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Abstract. The generation of pulsed magnetic fields in the range 20 kG to 2 MG by laser-driven coils is analyzed. Previous experimental results are modeled using a time-dependent circuit equation. By varying the circuit parameters and the coil geometry, it is shown that a field of 30 kG and a rate of change of 4 kG/ns can be generated by a small single-turn solenoid driven by a 1 J, 20 ns laser pulse. Using a more energetic laser pulse, a rate of 600 kG/ns is achievable. This value of dB/dt greatly exceeds that available from the more conventional field generation devices and is important for the observation of transient magnetic phenomena.

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When a plasma is created by focusing an intense laser beam onto a solid target, density and temperature gradients occur which generate large electron currents and magnetic fields [1]. The field strength in the plasma near the surface of the target is believed to be as high as 10 MG. This is greater than the magnetic fields that are available from the more conventional field generation devices such as capacitor-driven coils [2], and it is interesting to consider the conditions under which a laser-driven field would be useful for high-field material studies. One requirement is that the laser-driven electron current must be diverted into an external coil so that a material sample in the bore of the coil is isolated from the laser-target interaction region.

A portion of the electron current from a laser-produced plasma has been diverted into a small loop of wire embedded in a copper target [3–6]. The time dependence of the current in the wire is closely correlated with the occurrence of an intense magnetic field near the focus of the laser beam.

Korobkin and Motylev [7] have generated a 2 kA current in a small loop of wire by focusing a laser beam onto one tip of the wire. The laser-produced plasma, which is located in the narrow gap between the two ends of the wire that forms the loop, represents a low-inductance voltage source that drives the current in the circuit. The magnetic field at the center of the loop of wire is 20 kG.

In this paper, laser-driven coils are analyzed using a time-dependent circuit equation. The experimental results of [7] are simulated, and the possibility of scaling to higher magnetic fields is investigated. It is shown that when the time dependence of the exciting laser pulse is taken into account, the maximum field that is achievable using the parameters of [7] is approximately 1 MG. In this case, the current in the loop of wire is extremely high, and the coil is destroyed by resistive heating. It is shown that the use of the multi-turn solenoid geometry reduces the current in the coil and results in a nondestructive megagauss field that is potentially useful for the study of the effects of the field on a material sample in the bore of the solenoid. By using a single-turn solenoid, a rate of change of 600 kG/ns is achievable.

Pulsed megagauss fields are useful for a variety of interesting studies, particularly if the coil is not destroyed on every shot [8]. Even if destruction does occur, the disposable nature of the small coils that are considered here is an attractive feature.

The rate of change of the magnetic field is important for the observation of transient magnetic phenomena. The rate that was achieved by Korobkin and Motylev [7], which is estimated to be approximately 1.3 kG/ns,

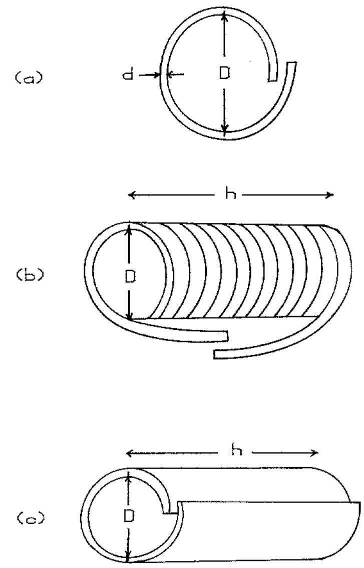

Fig. 1. (a) Single-turn loop of wire, (b) multi-turn solenoid, and (c) single-turn solenoid

is comparable to that available from capacitor-driven coils. The rate of 600 kG/ns that is possible using a small laser-driven coil greatly exceeds the capabilities of the more conventional devices.

1. Calculation of the Magnetic Field

The purpose of this analysis, which is an extension of the work of [7], is to realistically model the time dependence of the magnetic field generated by a laser-driven coil and to vary the coil parameters in order to produce pulsed megagauss fields. Shown in Fig. 1 are the following three coil geometries: a single turn of wire, a multi-turn solenoid, and a single-turn solenoid. The coil material is copper, as was the case for the previous experimental studies of laser-driven currents, and the initial temperature of the coil is set equal to 300 K.

In general, the current in a coil is found by solving the equation for an LR circuit with time-dependent coefficients:

$$I(t)\frac{dL}{dt}+L(t)\frac{dI}{dt}+R(t)I(t)=V(t). \tag{1}$$

The time dependence of the inductance would be due to the deformation of the coil and its leads by the laser pulse and by the magnetic field. Since this deformation occurs with a velocity [9, 10] of order 10^3 m/s, the deformation is small during a nanosecond laser pulse and will be neglected.

The resistance of the plasma in the electrode gap varies during the laser pulse. In addition, the current flows along the inner surface of the coil, and the resistance in this surface layer is a function of the temperature of the coil. A variable resistance means that the circuit equation (1) must be solved numerically.

By setting the resistance equal to a constant, the effect of the time dependence of the voltage on the current generated in the circuit can be isolated from the effect of a variable resistance. Let us now consider the analytical solution of the equation

$$L\frac{dI}{dt}+RI(t)=V(t), \tag{2}$$

where L and R are independent of time.

The voltage between the two electrodes, due to the presence of the laser-produced plasma, is approximately equal to

$$V(t)=T_e(t)\ln n_b/n_a[\mathrm{V}], \tag{3}$$

where $T_e(t)$ is the electron temperature in units of eV and n_a and n_b are the electron densities near the two electrodes. As in [7], we shall set $\ln n_b/n_a=5$. For a laser pulse with a duration of order 10 ns, the plasma density profile is nearly stationary [11] and the temperature follows the rise and fall of the laser intensity [12]. The time dependence of the voltage is therefore the same as that of the laser intensity.

The circuit equation (2) has been solved analytically for several different time-dependent voltage pulses $V(t)$. The maximum current does not depend strongly on the details of the time dependence of the voltage pulse, but only on the maximum value of the voltage. A realistic voltage pulse is given by

$$V(t)=V_m\frac{2t}{\tau}e^{1-2t/\tau} \tag{4}$$

and is illustrated in Fig. 2a. The voltage rises to the maximum value V_m at time $\tau/2$ and then decays more slowly for later time.

The solution to (2), found by the method of Laplace transforms [13], is

$$I(t)=\frac{2V_m}{L\tau(R/L-2/\tau)^2}\cdot\left[e^{-(R/L-2/\tau)t}-1+(R/L-2/\tau)t\right]e^{1-2t/\tau} \tag{5}$$

and is illustrated in Fig. 2b. The maximum current I_m, found by taking the time deviative of (5), is a function of the tuning parameter $\tau R/2L$. As shown in Fig. 3, the largest value, $I_m=V_m/R$, occurs when the circuit response time is much less than the laser pulse duration ($2L/R\ll\tau$). In this case, the maximum current occurs at the peak of the voltage pulse ($t_m=\tau/2$). For larger circuit response times $2L/R\gtrsim\tau$, the maximum current is less than V_m/R and occurs near the end of the voltage pulse. In order to produce the highest possible current and magnetic field, the circuit response time $2L/R$ should be smaller than the laser pulse duration τ.

The resistance due to the presence of the laser-produced plasma between the electrodes of the coil is [14]

$$R_p = 0.5 Zl/f^2 T_e^{3/2} [\Omega], \tag{6}$$

where the length l and diameter f of the plasma are in units of mm. The electron temperature T_e is nearly spatially uniform for a nanosecond laser pulse [11].

Due to the transient nature of the current pulse, the current is confined to the inner surface of the copper coil. For example, the thickness of the surface layer is 10 µm for a 20 ns pulse. The resistance in the surface layer is equal to

$$R_c = 8.2 \times 10^{-3} F(T_c) s/w\tau^{1/2} [\Omega], \tag{7}$$

where s is the length and w is the width of the conducting layer and $F(T_c)$ is a function of the temperature T_c of the coil material in the current layer [15]. At a temperature of 300 K, $F(T_c) = 1$. The thickness of the conducting layer is determined by the risetime of the current, and this thickness is assumed to be constant during the current pulse.

The temperature T_c is determined by the resistive heating of the surface layer and the heat capacity of copper. The diffusion of heat from the surface layer into the center of the wire is negligible during the transient current pulse.

The inductance of the coil depends on the geometry of the coil and its leads [15]. For the circular loop of wire shown in Fig. 1a,

$$L = 0.5 \mu_0 D (\ln 4\pi D/d - 2.45), \tag{8}$$

where D is the diameter of the loop and d is the diameter of the wire ($d \ll D$). For the long thin solenoids shown in Fig. 1b and c,

$$L = \pi \mu_0 N^2 D^2 / 4h, \tag{9}$$

where D is the diameter of the solenoid and h is its length. The leads contribute a small additional inductance.

The magnetic field produced by a current I in a coil with N turns is

$$B = \mu_0 NI/\alpha, \tag{10}$$

where α is the largest dimension of the coil (the diameter of the loop of wire or the length of the solenoid). Since the optimal current is equal to V_m/R, in order to produce the highest possible magnetic field with a given voltage, it is necessary that the size and resistance of the coil be small while maintaining the optimal condition $2L/R \ll \tau$. Since the voltage pulse duration τ must be small to prevent the deformation of

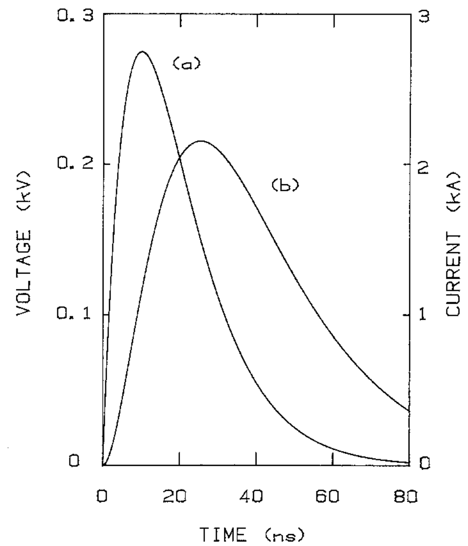

Fig. 2. (a) The 20 ns voltage pulse and (b) the current in a loop of wire with parameters given in Case A of Table 1 and with a constant resistance equal to 70.1 mΩ

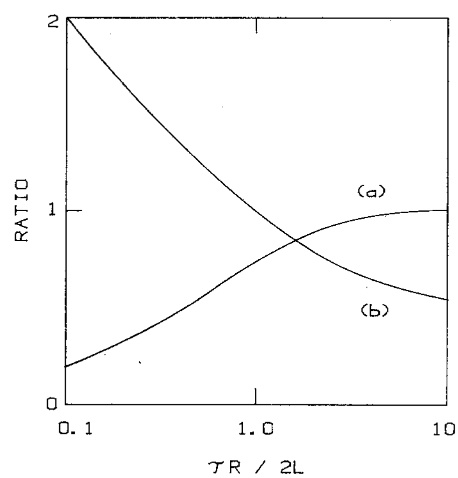

Fig. 3a and b. The dimensionless parameters (a) $I_m R/V_m$ for the maximum current I_m and (b) t_m/τ for the time t_m at which the maximum current occurs

the coil before the maximum possible field is achieved, the inductance of the coil must also be low.

As an example, consider a single turn of wire with the parameters shown in Case A of Table 1. Since the circuit response time ($2L/R = 41$ ns) is greater than the 20 ns duration of the laser pulse, Fig. 3 indicates that the maximum current is smaller than the optimal value V_m/R by a factor of 1.9 and is equal to 2.1 kA (Fig. 2). Using (10), the maximum field at the center of the loop is 19 kG.

The circuit equation (1) has been solved numerically for the case of a constant inductance and a time-

Table 1. Parameters for the calculation of the magnetic field of a single-turn loop of wire

	A[a]	B[b]	C[b]
τ [ns]	20	30	30
T_e [eV][d]	55[c]	500	500
Z	5[c]	10	10
D [mm]	1.4	1.0	1.0
d [mm]	0.3	0.3	0.3
l [mm]	0.1	0.1	0.1
f [mm]	0.1	0.1	0.1
M [gaps]	1	1	7
V [kV][d]	0.275	2.5	17.5
L [nH]	1.43	0.81	0.81
R_p [mΩ][e]	61.3	4.5	31.3
R_c [mΩ][f]	8.8	5.1	5.1
I [kA][d]	1.89	42.8	94.0
B [kG][d]	17.0	538	1181
dB/dt [kG/ns][d]	1.32	34.2	170
E_c [J][d]	0.001	1.88	24.6
T_c [K][d,f]	304	2987	35660

[a] Experimental parameters of [7]
[b] Computational example of [7] with 1 and 7 gaps
[c] Estimated for the 1 J Nd:glass laser of [7]
[d] Maximum value
[e] Minimum value
[f] For an initial wire temperature of 300 K

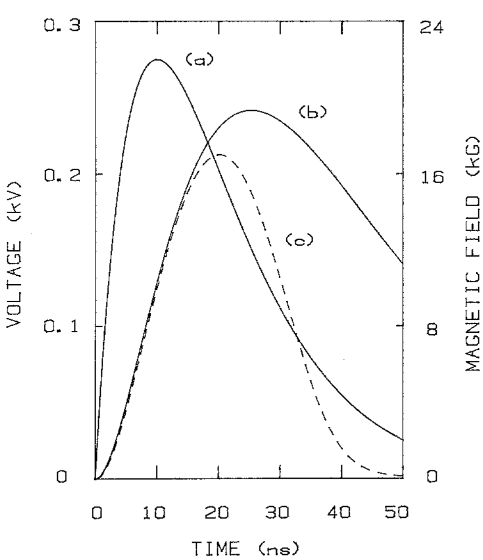

Fig. 4a–c. The calculated results for the loop of wire with parameters given in Case A of Table 1: (a) applied voltage, (b) magnetic field for a constant resistance equal to 70.1 mΩ, and (c) magnetic field for a variable resistance

dependent resistance given by (6) and (7). Typical results for the single-turn loop of wire just considered are illustrated by the dashed curves in Figs. 4 and 5. The solid curves in Figs. 4 and 5 are the results calculated from (5), where R is set equal to the value of

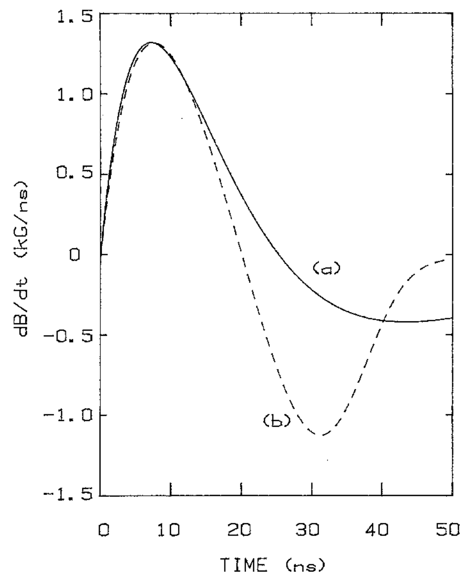

Fig. 5a and b. The rate of change dB/dt of the magnetic field of the loop of wire with parameters given in Case A of Table 1 for the two cases of (a) a constant resistance equal to 70.1 mΩ and (b) a variable resistence

the resistance at the peak of the laser pulse. It is apparent from Fig. 4 that the leading edge of the field is the same for the two cases of constant and variable resistance. This is because the initial increase in the current in an LR circuit is independent of the resistance. However, the decay of the current does depend on the resistance. In the case of the variable resistance, the high resistance of the cold plasma during the trailing edge of the laser pulse limits the maximum value of the current and also results in the rapid decay of the magnetic field and increased values of dB/dt (Fig. 5).

As a first approximation, an upper bound on the peak values of the current and the magnetic field may be estimated using the constant-resistance results of Fig. 3. More accurate values for the peak field and the detailed simulation of the time dependence of the magnetic field require the numerical solution of the circuit equation.

2. Variation of the Circuit Parameters

The magnetic fields that result from using various circuit parameters and coil geometries are now presented. In all cases, the current and the magnetic field are determined from the numerical solution of the circuit equation (1) with a constant inductance, a variable resistance given by (6) and (7), and a voltage pulse shape given by (4).

The circuit parameters that are used in the calculation of the magnetic field of a single turn of wire are listed in

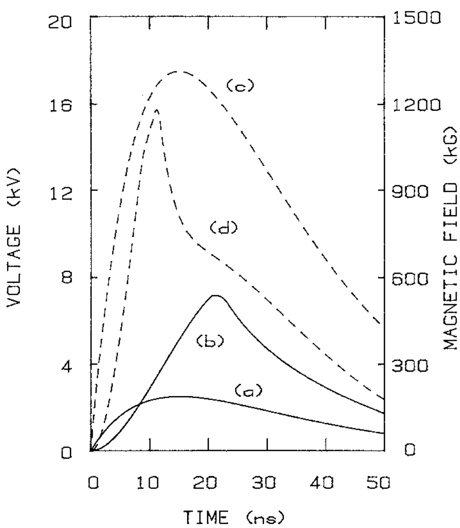

Fig. 6. (a) The applied voltage and (b) the magnetic field for the 1-gap loop of wire (Case B of Table 1). (c) The applied voltage and (d) the magnetic field for the 7-gap loop of wire (Case C of Table 1)

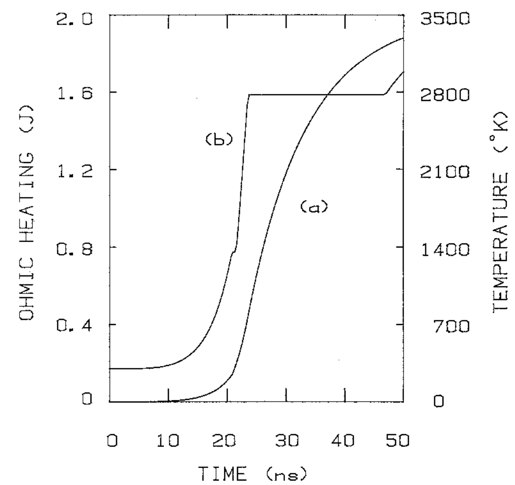

Fig. 7. (a) The resistive heating and (b) the temperature of the current layer for the 1-gap loop of wire (Case B of Table 1)

Table 1. Case A, which corresponds to the experiment of [7], is a 1.4 mm loop of wire with a plasma temperature of 55 eV resulting in an applied voltage of 275 V. The calculated magnetic field that is shown in Fig. 4c is in reasonable agreement with the measured peak field of 20 kG, and the time dependence of dB/dt shown in Fig. 5b is consistent with the magnetic probe measurements.

In Case B of Table 1, the loop diameter is reduced to 1.0 mm and the plasma temperature is increased to 500 eV (resulting in an applied voltage of 2.5 kV). As shown by the solid curves in Fig. 6, a peak field of 540 kG is achieved. The current and the magnetic field are limited by the increase in the resistance in the current layer caused by ohmic heating. As shown in Fig. 7, an energy of 1.88 J is deposited in the current layer by resistive heating, and this raises the final temperature of the coil material in the current layer beyond the boiling point of copper (2773 K) to a temperature of 2987 K.

As suggested in [7], the effective applied voltage can be increased by using multiple electrode gaps and irradiating each gap with a laser beam. As shown in Case C of Table 1, the use of seven electrode gaps results in a peak magnetic field of 1.2 MG (dashed curves in Fig. 6). A resistive heating of 24.6 J raises the temperature of the current layer to 35,660 K. Due to the increase in the resistivity of copper with temperature, the peak current and magnetic field for the case of seven electrode gaps are only about twice as large as for one electrode gap. It is concluded that the maximum magnetic field that can be generated using the single-turn loop geometry of [7] is of order 1 MG and the coil is destroyed by resistive heating.

Table 2. Parameters for the calculation of the magnetic field of a multi-turn solenoid

	A	B	C
τ [ns]	20	30	30
T_e [eV][a]	55	500	500
Z	5	10	10
h [mm]	2.0	1.0	1.0
D [mm]	0.5	0.2	0.2
N [turns]	20	20	10
d [mm]	0.1	0.1	0.1
l [mm]	0.1	0.1	0.1
f [mm]	0.1	0.1	0.1
V [kV][a]	0.275	2.5	2.5
L [nH]	49.3	15.8	3.95
R_p [mΩ][b]	61.3	4.5	4.5
R_c [mΩ][c]	187.9	61.4	30.7
I [kA][a]	0.11	4.67	11.3
B [kG][a]	14.3	1174	1420
dB/dt [kG/ns][a]	0.73	38.1	103.3
E_c [J][a]	0.0001	0.160	0.534
T_c [K][a, c]	300.3	1220	2773

[a] Maximum value
[b] Minimum value
[c] For an initial solenoid temperature of 300 K

The current in a laser-driven coil can be reduced by using the multi-turn solenoid geometry. A 20-turn solenoid that is 2 mm long and 0.5 mm in diameter is given by Case A in Table 2. The laser parameters and the electrode gap are the same as for the single-turn loop experiment of [7] (cf. Case A in Table 1). As shown in Fig. 8, a maximum field of 14 kG is generated. The peak current is 0.11 kA which is much smaller

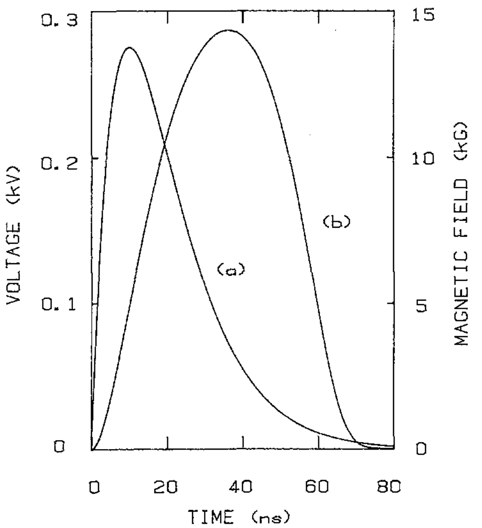

Fig. 8. (a) The applied voltage and (b) the magnetic field for the 20-turn solenoid with parameters given in Case A of Table 2

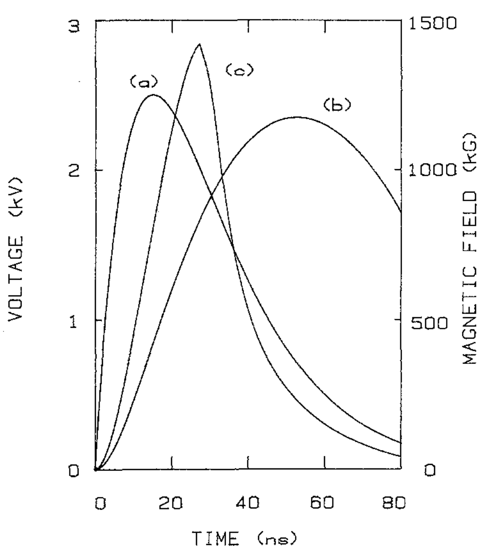

Fig. 9. (a) The applied voltage, (b) the magnetic field for the 20-turn solenoid (Case B of Table 2), and (c) the magnetic field for the 10-turn solenoid (Case C of Table 2)

than the 1.9 kA current of the single-turn loop that generates a comparable magnetic field (17 kG, Case A in Table 1).

By reducing the length of the solenoid to 1 mm and increasing the applied voltage to 2.5 kV (Case B in Table 2), a field of 1.2 MG is generated, and the final temperature in the current layer is below the melting point (1356 K) of copper. As shown by Case C in Table 2, a 10-turn solenoid with the same length and diameter (1 mm × 0.2 mm) generates a field of 1.4 MG. This increase in field is a result of the smaller response time $2L/R$ of the 10-turn solenoid. The time dependences of the magnetic fields are shown in Fig. 9. It

Table 3. Parameters for the calculation of the magnetic field of a single-turn solenoid

	A	B	C
τ [ns]	20	20	3
T_e [eV][a]	55	500	500
Z	5	10	10
h [mm]	2.0	2.0	2.0
D [mm]	0.2	0.2	0.2
d [mm]	0.1	0.1	0.1
l [mm]	0.1	0.1	0.1
f [mm]	0.1	0.1	0.1
V [kV][a]	0.275	2.5	2.5
L [nH]	0.02	0.02	0.02
R_p [mΩ][b]	61.3	4.5	4.5
R_c [mΩ][c]	3.8	3.8	9.7
I [kA][a]	4.2	37.4	26.7
B [kG][a]	26.3	235	168
dB/dt [kG/ns][a]	4.36	254	617
E_c [J][a]	0.0009	0.48	0.061
T_c [K][a,c]	432	18820	6836

[a] Maximum value
[b] Minimum value
[c] For an initial solenoid temperature of 300 K

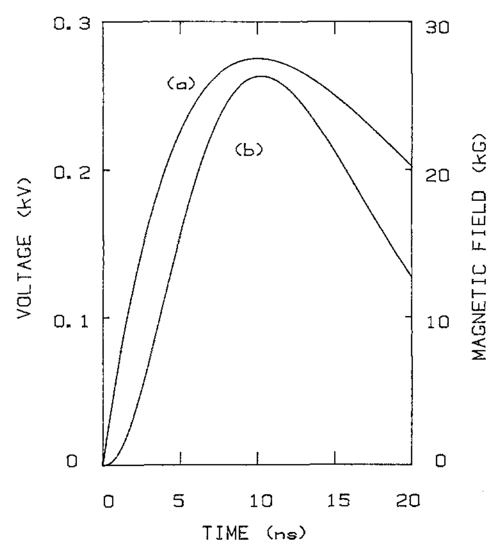

Fig. 10. (a) The applied voltage and (b) the magnetic field generated by the single-turn solenoid given in Case A of Table 3

is concluded that a megagauss magnetic field can be produced by using the multi-turn solenoid geometry and that the solenoid is not destroyed by the thermal stresses resulting from resistive heating. Due to the inertia of the coil and the transient nature of the magnetic field, the destruction of the coil by the Maxwell stress is expected to occur after the peak field is achieved.

The single-turn loop of wire and the multi-turn solenoid typically have response times that are greater than the laser pulse duration ($2L/R > \tau$ in Tables 1 and 2). We now consider single-turn solenoids with response times that are less than the laser pulse duration ($2L/R < \tau$). The rapid increase in the current during the leading edge of the laser pulse results in large values of dB/dt.

Case A in Table 3 represents a single-turn solenoid that is 2 mm long and 0.2 mm in diameter and has the same laser pulse and electrode gap parameters as the experiment of [7] (cf. Case A in Table 1). As shown in Fig. 10, a peak field of 26 kG is generated at a time of 10 ns. The peak field occurs at the mid-point of the voltage pulse and is consistent with the predictions of Fig. 3 for a fast coil ($2L/R \ll \tau$). As shown in Fig. 11, the field increases at a rate of 4.4 kG/ns during the leading edge of the voltage pulse. This value of dB/dt exceeds that which is available from capacitor-driven single-turn solenoids of comparable size [9, 10]. By using a more energetic laser pulse (Case B in Table 3) and a shorter duration laser pulse (Case C in Table 3), rates of change in the range 200–600 kG/ns are produced. In these latter two cases, the coil is heated to a temperature beyond the boiling point of copper and is destroyed.

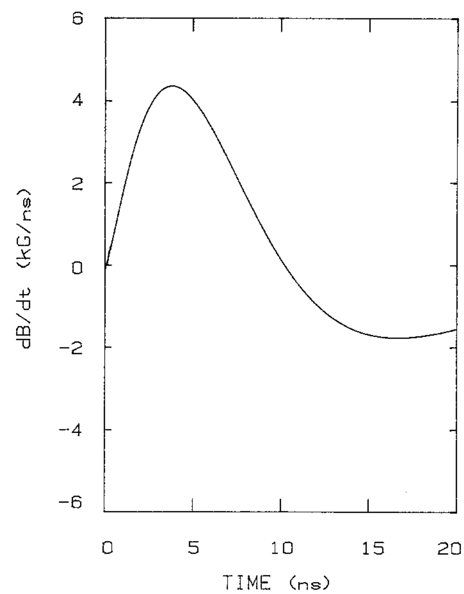

Fig. 11. The rate of change of the magnetic field for the single-turn solenoid given in case A of Table 3

3. Conclusions

Numerical modeling indicates that pulsed magnetic fields as high as 1–2 MG can be generated using small laser-driven coils. It is also shown that values of dB/dt as high as 600 kG/ns can be achieved.

A characteristic of the laser-driven coil is its small size and rapid response to the laser pulse. Although the coil is subjected to tremendous forces from the magnetic field and resistive heating, the deformation of the coil during the laser pulse is negligible due to the inertia of the coil material. In contrast to capacitor-driven coils, where the coil is destroyed during the slow capacitor discharge and before the maximum possible magnetic field is achieved, the destruction of the laser-driven coil is expected to occur after the peak field is produced.

The maximum magnetic field that can be generated by a laser-driven coil is determined primarily by the applied voltage and the resistance of the circuit. The voltage increases with the laser intensity and plasma temperature, and the plasma resistance decreases with plasma temperature. The use of a more energetic laser beam results in higher magnetic fields. The precooling of the coil and the use of superconducting coil materials would reduce the destructive effects of resistive heating in the early phase of the current pulse before the high field quenches the superconductivity.

The small sizes of the coils that are analyzed, in the range 1–2 mm, are compatible with optical excitation and detection techniques that require no electrical connections to the coil. The exciting laser beam that generates the plasma must be focused to a diameter of approximately 100 μm. High-field phenomena, such as the Zeeman and Faraday effects, can be studied using passive spectroscopic techniques or by actively probing the bore region with a secondary laser beam.

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