Generation of magnetic fields and currents in an optical discharge in a recombining plasma

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Substantial magnetic fields and currents have been observed during the optical breakdown of preionized air at atmospheric pressure.

The magnetic fields and currents in a laser plasma have been the subjects of many studies, in particular, Refs. 1–5. Most of the experiments have been carried out on the plasma burst at a target at a low pressure (P) of the surrounding gas. The reason is that the amplitudes of the currents and fields which are measured have a resonant dependence on P (Refs. 3 and 4), peaking at $P_M = 0.01$–1 torr. At $P = 1$ atm, only an asymmetric focusing of a laser beam will give rise to a weak dipole moment, ~ 0.05 G/cm^3, of the plasma of the optical breakdown of the gas.[1]

In this letter we report the first demonstration that it is possible to generate in air at atmospheric pressure magnetic fields and currents of the same order of magnitude as at P_M by using a preliminary pulsed ionization of the medium. From the various possible methods for ionizing the medium we selected the breakdown of air by the first of two successive pulses from a TEA CO_2 laser. The second laser pulse, which arrived after a delay τ, ignited an optical discharge in the relaxing plasma; this optical discharge was accompanied by the generation of intense magnetic fields and currents. This experimental approach is of interest both for determining the mechanisms for the generation of currents in a laser plasma and for possible applications of the emf in a plasma, for example, for directly converting laser energy into electrical energy.[3]

The energy of each of the laser pulses was $E_{1,2} = 1.5$ J; their temporal profile is shown in Fig. 1a. The light was focused in air at atmospheric pressure into a spot $\simeq 2$ mm in diameter on the surface of a copper target by a lens with $F = 10$ cm. The maximum light intensity at the target was $I_{1,2} = 100$ MW/cm^2. The currents were detected by the method proposed in Ref. 4 (Fig. 2), involving the insertion of a copper probe 0.9 mm in diameter into an aperture 1 mm in diameter in the target. The current between the probe and the target was measured by a Rogowski loop. The derivative of the magnetic field was measured by a single turn (4 mm in diameter) of a thin conductor. The plane of the turn was covered by an insulator. In some control experiments we simultaneously used two such turns, oriented 180° apart. The signals detected in this arrangement were of opposite polarity, confirming their magnetic nature. The output signals from the detectors were fed to S8-14 and S8-2 dual-trace oscilloscopes. The dynamics of the development of the plasma along the direction of the laser beam was simultaneously photographed by an FÉR-7 "photochronograph."

Figure 1,b and c, shows oscilloscope traces of the derivative of the azimuthal

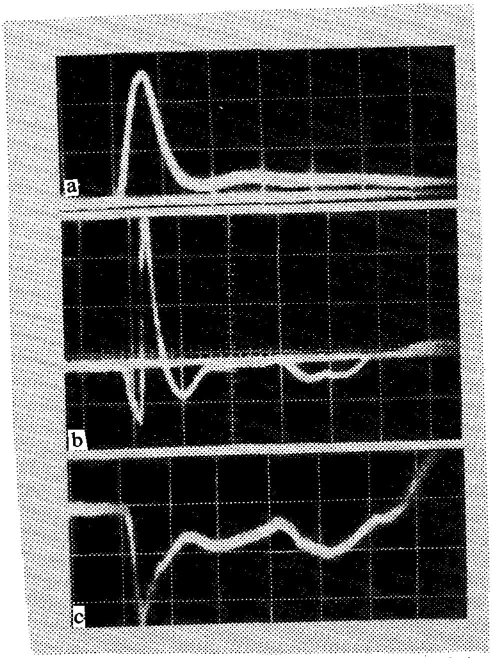

FIG. 1. a—The laser pulse; b—derivative of the azimuthal magnetic field (the center of the turn is at the point $r = 5$ mm, $z = 4$ mm); c—current signal from the probe. The sweep time is 200 ns/div.

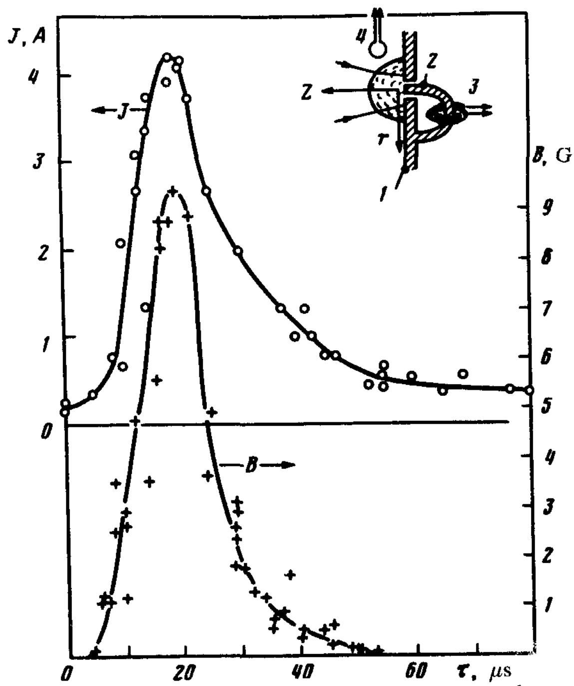

FIG. 2. Amplitude (J) of the current from a probe near the center of the focus and azimuthal magnetic field B (the center of the turn is at $r = 5$ mm, $z = 4$ mm) versus τ for $E_1 \simeq E_2 \simeq 1$ J. 1—Target; 2—wire probe; 3—Rogowski loop; 4—measuring turn.

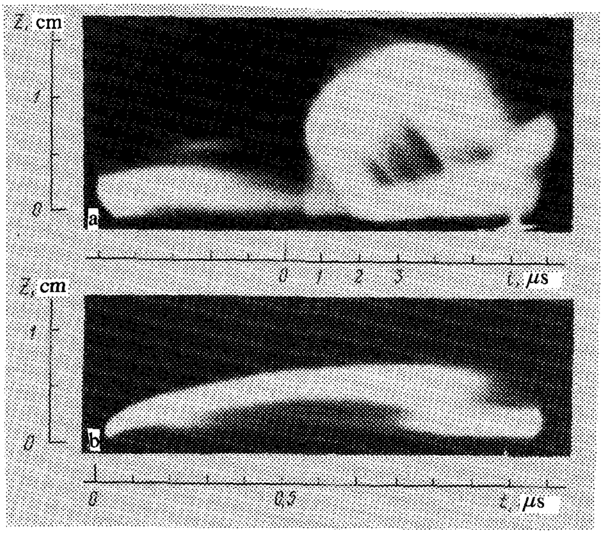

FIG. 3. Streak photographs of the development of the optical discharge during the second laser pulse. a—$\tau = 7\ \mu s$, $E_1 \simeq E_2 \simeq 1.4$ J; b—$\tau = 37\ \mu s$, $E_1 \simeq E_2 = 0.4$ J. The origin for the z scale is the plane of the target. The second pulse arrives at $t \simeq 0$.

magnetic field B and of the current (J) from a probe near the center of the focus for a delay $\tau = 20\ \mu s$ and for pulse energies $E_1 = E_2 = 1$ J. The curves of the amplitudes of B and J versus τ (Fig. 2) have clearly defined maxima at an optimum delay $\tau_M \sim 20\ \mu s$. At $\tau = 0$, there is no magnetic field during the initial stage of the laser pulse at the sensitivity level of these measurements (~ 0.01 G), while the current is 0.1–0.2 A, as in Ref. 5. We might note that the maximum current, $J(\tau_M)$, is approximately equal to the value ($\simeq 6$ A) measured during the evaporation of a target ($P_M \simeq 0.1$ torr) by a single pulse. A detailed comparison of these two cases is complicated by the different plasma compositions.

Photography of the plasma evolution during the second laser pulse revealed that the structure of the optical discharge depends on the value of τ at fixed values of $E_{1,2}$. Short delay times, $\tau \lesssim 3\ \mu s$, are equivalent in practice to increases in the energy and length of the first pulse. As τ is increased to $\sim 12\ \mu s$, the optical discharge, which is ignited near the boundary of a rather hot initial plasma, has a complicated structure because of the propagation of plasma fronts through the ionized medium. Figure 3a shows a representative streak photograph of a discharge of this type. Finally, at $\tau > 12\ \mu s$, the plasma is ignited at the target (Fig. 3b), but it propagates at much higher velocities than during the first laser pulse. At $\tau > 100\ \mu s$, the effect of the breakdown of the air by the first pulse becomes less important. In the case in Fig. 3a, a plasma front, which moves toward the target, is formed. When the plasmoid arrives at the probe, there is a spike in the current signal, which is 2–5 times higher than the current in the initial stage. The magnetic field has a complicated time dependence near the plasma in this discharge.

We turn now to an interpretation of the results. During the breakdown of the air by the first laser pulse, a fireball with dimensions (~ 1 cm) considerably greater than those of the initial plasma forms near the target. Shadow photographs of the fireball are shown in Ref. 6. Estimates show that ~ 10 μs after the breakdown the pressure of the gas heated in the fireball falls to ~ 1 atm, and its density is $\rho_{fb} \simeq (2–4) \times 10^{-2}$ ρ_0, where ρ_0 is the standard density of air. At $\tau \sim \tau_M$ the second laser pulse ignites an optical discharge precisely in this fireball. We might note that the magnitude and polarity of the emf, which arises in the plasma under these conditions, cannot be explained on the basis of radiation pressure in the ionized gas.[2] Furthermore, by itself a decrease in the density of the surrounding gas to ρ_{fb} cannot by itself explain the observed increase in the current due to the emf of the double layer at the plasma boundary. This conclusion was reached from experiments at $P \simeq 3 \times 10^{-2}$ atm, where the value $J \simeq 0.7$ A was found in a single pulse. A more important factor is in the ionization of the gas in the extended fireball, which gives rise to large currents and magnetic fields in the surrounding gas because of an increase in its conductivity, whereas during the breakdown of air by a single pulse the only substantial currents that flow are in the immediate vicinity of the plasma.[5] Consequently, by varying τ we can essentially optimize (for detection of J and B with probes) the ionization of the relaxing plasma in the fireball, in the manner in which the photoionization of the surrounding gas by ultraviolet emission from the plasma is optimized at P_M (Refs. 3 and 4). The initial parts of the curves of $J(\tau)$ and $B(\tau)$ in Fig. 2, at small values of τ, can be explained on the basis that an optical discharge is ignited only at the boundary of a rather hot fireball. The decreases in J and B at $\tau > 30$ μs indicate a recombination of the plasma in the fireball.

We wish to emphasize that the lower gas density in the fireball also promotes increases in J and B, because of an increase in the temperature of the plasma of the optical discharge during the second laser pulse (in comparison with that during the first pulse). This interpretation is supported by the behavior of the plasma resistance $R_{\rm pl}$, measured by the method proposed in Ref. 5. The resistance $R_{\rm pl}$ falls off from 2–5 Ω at $\tau = 0$ to ~ 0.1 Ω during the second pulse with $\tau = 20$ μs.

During preliminary experiments with $P = 1$ atm and $\tau = 20$ μs we obtained a conversion of 0.01% of E_2 into electrical energy in a load $R = 0.1$ Ω $(R \sim R_{\rm pl})$, in approximate agreement with the results of experiments[3,7] carried out in a vacuum at P_M. However, the ionization of air at atmospheric pressure, which we are proposing here, is considerably more convenient for converting the energy of lasers with high pulse repetition frequencies, since it does not require a vacuum system, evaporation of target material, etc.

There is another interesting fact to be noted. In a low-density atmosphere, at $P_M < P < 1$ atm, the magnetic fields and currents detected during the second laser pulse are also greater than during the first; the optimum delay τ_M depends on P. We note in conclusion that a study of optical discharges in a preionized medium is of independent interest in connection with the possible attainment of new plasma-front propagation regimes.

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