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Distribution of Self-Generated Current in Laser-Produced Plasmas

M. G. Drouet and R. Bolton
Direction Sciences de Base, Institut de Recherche de l'Hydro-Québec, Varennes, Québec, Canada, J0L 2P0
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The current associated with the self-generated magnetic field has been measured in air and nitrogen at various pressures in a 4-J, 30-nsec-Nd-laser-produced plasma using a fast probe embedded in the copper target. The results reveal an active participation of the target in the current-flow process with anodic and cathodic regions, the source of the current (magnetic field) being at the plasma-target interface.

Although the existence of large self-generated magnetic fields in laser-produced plasmas has been well established experimentally[1-3] and their origin considered in a large number of theoretical papers,[4-6] the currents associated with these fields have only been determined by applying $\nabla \times \vec{B} = \mu_0 j$ to the magnetic field data.[2] We present here direct measurements, resolved in space and time, of the distribution of current flow to and from a target irradiated by a focused Nd-glass laser beam.

Our experiments were conducted in both air and nitrogen at various pressures. The beam from a Nd-glass laser ($\lambda = 1.06$ μm) was focused at normal incidence upon a flat copper target in an experimental chamber. The laser pulse was 4 J, 30 nsec (full width, half-energy). The focal-spot diameter at the target surface (in the absence of plasma), with a 10-cm lens, was 250 μm at half-energy, giving a power density of approximately 10^{11} W/cm^2.

The current flow through the plasma-target interface was monitored, as shown in Fig. 1, using a small wire probe (0.32 mm o.d.) embedded in the target and insulated from it except at its end where it is soldered to it. The wire probe is terminated in the form of a loop so as to inductively couple the element of current incident on the probe surface to a small secondary coil. The transfer impedance of this arrangement is a mutual inductance, the high-frequency response being limited by a pole because of the combination of the total output inductance and the 50-Ω termination. The experimental values are 4×10^{-9} H for the transfer inductance and 4 nsec (max) for the equivalent time constant of the pole. Therefore, by using this probe technique, direct oscilloscope display of dI/dt, the time rate of change of the net current flow I through the probe-plasma interface, is achieved. A notable advantage

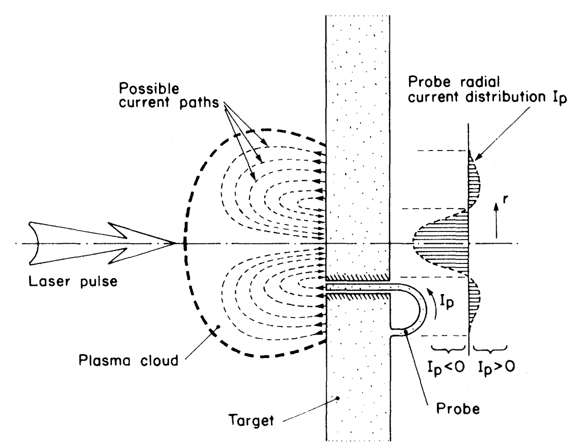

FIG. 1. Diagram showing the target with the wire probe sampling part of the current flow through the plasma-target interface.

of the use of this method of studying the laser-target interaction is that the angle of incidence of the laser beam is arbitrary, normal incidence being possible, whereas the use of magnetic probes requires oblique incidence for satisfactory coverage of the interaction region without having the probe intersect the incident laser beam.

If, from shot to shot, the position of the laser impact is moved on the target surface with respect to the probe, then the current distribution normal to the surface can be mapped out. For example, if as shown in Fig. 1 the probe is small with respect to the dimension of the current-carrying region, then each shot will give the local value of the current density for that position. The effective spatial resolution of the probe is of the order of the probe diameter; in the present instance this is 0.3 mm. If the current has a spatial distribution topologically similar to that deduced by McKee, Bird, and Schwirzke, and if in addition the assumption is made that the target itself participates in the conduction of current, then the measured probe distribution will be as illustrated in Fig. 1. This figure shows a central region centered on the laser-beam axis with conventional current flowing in, the "cathode," surrounded by an annular region with the current flowing out, the "anode."

A typical oscilloscope recording of the voltage pulse induced in the secondary coil during an experiment, the probe being located on the laser axis, is presented in Fig. 2 with, for reference, the intensity profile of the laser pulse as monitored by a photodiode. Comparing the time evolutions of both the laser pulse and the probe pulse dI/dt as shown in Fig. 2, we note that (a) the current flow appears simultaneously with the beginning of the laser irradiation of the target; (b) it changes direction during the laser-pulse buildup; (c) it reaches a maximum in absolute value near the end of the laser pulse; and then (d) it slowly decays. Except for the initial short-lived precursor the shape of the dI/dt pulse in Fig. 2 is comparable to that of the dB/dt variation published in the literature.[1,2] In addition, the direction of the current flow, on axis, is that of the laser-pulse propagation direction; this is in agreement with the direction of the azimuthal magnetic field reported previously.[1,2]

A typical distribution of the current collected by the probe, as a function of its position relative to the laser axis, is presented in Fig. 3. Here the probe dI/dt signal is integrated with a 1-μsec integrator to give a signal proportional to the current; eleven laser shots were used to obtain this distribution. For each shot, the position of the probe was varied with respect to the laser axis. The value of the probe current, corresponding to the same time during the evolution of the phenomenon shown as T on the oscillogram, is plotted here as a function of the position of the probe. The horizontal error bar shows the uncertainty in the radial position of the probe; the vertical error bar includes the uncertainties due to the measurement of current at time T and to the shot-to-shot variation. The distribution obtained is much larger than the size of the laser focal spot; it shows a central cathode surrounded by an annular anode as discussed earlier in relation to Fig. 1. This current distribution is topologically consistent

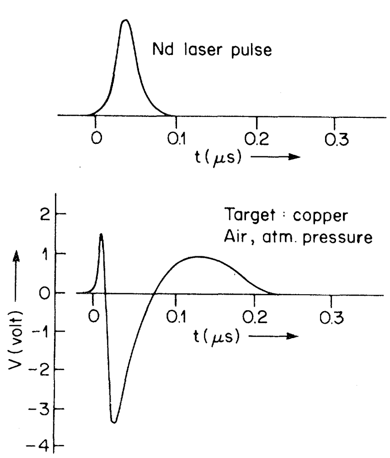

FIG. 2. Typical voltage pulse V corresponding to the probe dI/dt.

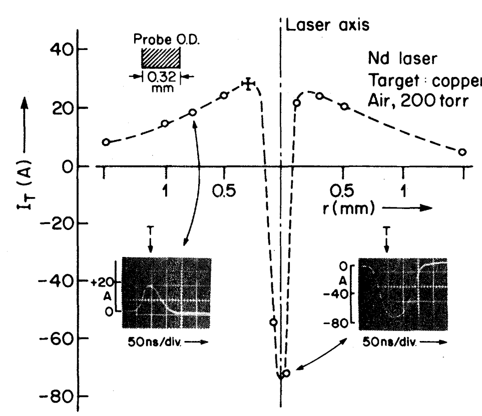

FIG. 3. Typical probe current distribution. A positive value implies conventional current flow across the target surface into the plasma.

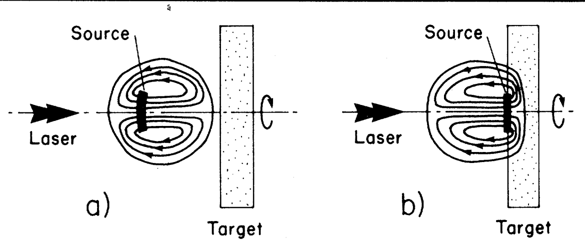

FIG. 4. Two different locations for the current flow paths. The sources are located (a) at the front of the expanding plasma or (b) at the plasma-target interface.

with that proposed by McKee, Bird, and Schwirzke[2] which they obtained by taking the curl of their measured magnetic field distribution. We therefore propose that the current measured here is the current associated with the magnetic field measured elsewhere. However, on the basis of our results, we confirm here for the first time the concept of the active participation of the target in the current-flow process.[7] This concept is illustrated schematically in Fig. 4(b) which can be contrasted to the previously suggested scheme of Fig. 4(a).

For the results of Fig. 3, the diameter of the probe used was relatively large with respect to the size of the distribution and therefore the profile shown does not correspond accurately to the current-density distribution. Futhermore, it is not possible to verify if there is conservation of current, i.e., if all the current paths are closed as illustrated in Fig. 1. In this respect, it is worth mentioning that, in our study, the grounding of the target did not make any noticeable difference to the results. Therefore, we do not expect a significant polarization of the insulated target and thus most of the current paths should be closed.

In general, the existence and polarity of the current precursor are functions of the operating conditions. For the situation corresponding to Fig. 3, the current precursor was of the same polarity as the main current pulse; furthermore it was measured both at the cathode and at the anode. This fact indicates that this early current component flows also on a closed path. Many different source mechanisms have been proposed in the literature; they include thermoelectric effect, polarization, radiation pressure, and resonance absorption. Our two components of current could correspond to two different source mechanisms, dominant at different times, or to different facets of the same mechanism. The reversal of polarity observed in some instances could be explained by the change of sign of a plasma parameter gradient in the interaction region as the plasma evolves in time.

The existence of a precursor azimuthal magnetic signal of small intensity has also been reported recently[8]; it was found to be temporally coincident with the 4-nsec ruby laser pulse used in the experiment. Its source was attributed[8] to electrons emitted during the time the laser impinges upon the solid copper target. Our measurements with a 30-nsec laser pulse length do not confirm this interpretation. It is the total buildup of current, rather than the duration of the short-lived precursor, which is coincident with the laser-pulse duration. This indicates that the conversion of the laser-pulse energy into the magnetic energy, $\frac{1}{2}LI^2$, associated with the current reaches a maximum at the end of the laser pulse. The subsequent decay of the current results from (a) the continuous expansion of the magnetic field contours well documented by others[1-3] which implies an increase of the equivalent L and (b) the energy dissipation in the plasma.

An important difference between most previous magnetic field measurements and our measurement of current is in the immediate response of the current variation to the laser pulse; in the case of the magnetic field measurements a delay was observed, which was interpreted[1] as the time taken for the magnetic field front to propagate from the source to the point of measurement. This interpretation is consistent with the image of the magnetic field contained within the expanding plasma since a symmetric current distribution, such as that illustrated in Fig. 1, produces a magnetic field which is entirely azimuthal and also entirely contained within the current-flow region. The absence of delay, in our case, suggests strongly that our measurements are performed at the source of current (magnetic field), i.e., the source is at the plasma-target interface. This observation is at variance with most of the published literature on the subject where it is proposed that the source at the front of the expanding plasma as illustrated in Fig. 4(a). If the current source is situated solely at the plasma-target interface then all the current can be expected to cross that interface as shown in Figs. 1 and 4(b) and thus be measured in the experiments. The existence of current paths flowing only in the plasma cloud and avoiding the target interface requires the existence of an important source region elsewhere in the plasma for which we have no experimental evidence.

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Circulation and Angular Momentum in the *A* Phase of Superfluid Helium-3*

N. D. Mermin and Tin-Lun Ho
Laboratory of Atomic and Solid State Physics, Cornell University, Ithaca, New York 14853
(Received 15 December 1975)

It is shown that the curl of the velocity field generally identified with $\vec{v}_s$ in the *A* phase of superfluid ^{3}He is entirely determined in the absence of singularities by the spatial gradients of the order-parameter symmetry axis $\vec{l}$. As a simple application of this relation it is argued that in a texture of cylindrical symmetry in a volume V, the liquid should have a nonvanishing thermal-equilibrium orbital angular momentum of order $\rho_s V\hbar/M$.

The broken symmetry associated with the ordering in superfluid ^{3}He-*A* gives rise to two new sets of hydrodynamic variables[1]: a velocity field $\vec{v}_s$ and the independent components of the gradient of the local symmetry axis $\vec{l}$ of the order parameter.[2] The development of a complete hydrodynamics based on these variables has been hampered by two related difficulties, of which only the first has received explicit attention:

(1) If $\vec{l}$ is not everywhere close to a fixed spatial direction then one cannot express $\vec{v}_s$ as the gradient of a global phase.[3] Perhaps as a result, hydrodynamic theories have been attempted only in the linear regime. Since it is likely that real samples of ^{3}He-*A* are characterized by textures in which, in the absence of aligning fields, the direction of $\vec{l}$ wanders slowly through large angles,[4] such linear hydrodynamics can be inadequate even when flow velocities are small. (2) It is often implicitly assumed that $\vec{l}$ and $\vec{v}_s$ are independent variables. We shall show that this too is only valid in linearized treatments. A theory of flow in the presence of finite spatial variations of $\vec{l}$ must take the constraint between $\vec{v}_s$ and $\vec{l}$ [Eq. (6) below] into account. The solution to a third problem[5] requires a resolution of the first two. (3) Does a specimen of ^{3}He-*A* in thermal equilibrium have a nonvanishing orbital angular momentum of order $\rho_s V\hbar/M$? From a macroscopic point of view this should indeed be the case, unless the terms in $\vec{v}_s$ in the equilibrium momentum density[3]

$$\vec{g} = \rho_s \vec{v}_s - \rho_0 \vec{l}\,\vec{l}\cdot\vec{v}_s + C\nabla\times\vec{l} - C_0\vec{l}(\vec{l}\cdot\nabla\times\vec{l}) \tag{1}$$

necessarily give rise to terms in $\vec{L} = \int d^3r\, \vec{r}\times\vec{g}$ which almost entirely cancel the contribution from the other terms (which will, in general, be of this order[6]).

In this Letter we wish to resolve the first two problems and, to illustrate the utility of this resolution, use it to argue in support of an equilibrium angular momentum of order $\rho_s V\hbar/M$. To do this we return to the more fundamental characterization of the broken symmetry in terms of the complex order parameter[2,7]

$$\psi(\vec{r}_1,\vec{r}_2) = [\vec{\varphi}^1(\vec{r}) + i\vec{\varphi}^2(\vec{r})]\cdot\vec{\rho}\,\chi(\rho), \quad \vec{r} = \tfrac{1}{2}(\vec{r}_1+\vec{r}_2),$$
$$\vec{\rho} = \vec{r}_1 - \vec{r}_2, \quad \vec{\varphi}^\alpha\cdot\vec{\varphi}^\beta = \delta_{\alpha\beta}, \quad \vec{l} = \vec{\varphi}^1\times\vec{\varphi}^2, \tag{2}$$

whose degeneracy is fully characterized by a set of two orthonormal axes (and no additional phase variable, the overall phase of ψ being entirely controlled by the orientation of the axes). From this point of view the additional hydrodynamic variables are a set of gradients sufficient to specify the linear spatial variation in orientation of the axes.[8] This information is carried by a tensor field, $\underline{\Omega}$, such that $\delta r_j \Omega_{ji}$ gives the infinitesimal rotation $\delta\omega_i$ necessary to produce the ax-

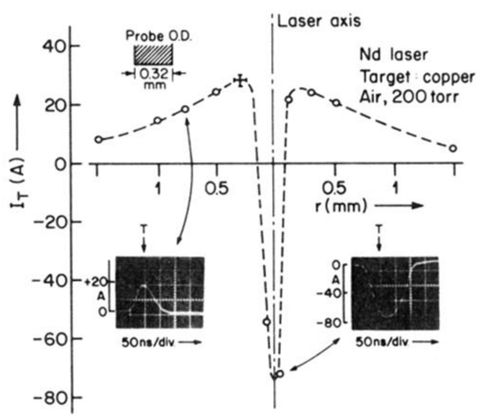

FIG. 3. Typical probe current distribution. A positive value implies conventional current flow across the target surface into the plasma.