Fast Photography of a Laser Generated Plasma Expanding Across a Transverse Magnetic Field

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***Abstract*—The dynamics and confinement of laser generated Carbon plumes expanding across a transverse magnetic field have been investigated. 1.06-μm, 8-ns pulses from an Nd:YAG laser were used to create a plasma that was allowed to expand across a 0.64-T magnetic field. Fast photography employing an intensified charged–coupled device was used for two-dimensional imaging of the plume. Photographic studies showed the collapse of the ablation plume after the bubble lifetime, and formation of two lobes near the target surface at later times.**

***Index Terms*—Fast photography, laser produced plasma, magnetic field, plasma confinement.**

THE INTERACTION of a magnetic field and a laser-produced plasma during its expansion may lead to several interesting physical phenomena, including conversion of the plasma thermal energy into kinetic energy, plume confinement, ion acceleration, emission enhancement, plasma instabilities, etc. Recently, VanZeeland *et al.* [1] studied the expansion of a laser-produced plasma into ambient magnetized plasma capable of supporting Alfvén waves. Spectroscopic studies of dynamics of the plume species in the presence of a magnetic field showed that their spatial and temporal characteristics changed considerably with their charge state [2]. In this paper, the dynamics of laser ablated graphitic carbon plasmas expanding across a transverse magnetic field have been investigated using fast photography.

Details of the experimental setup are given in a recent publication [2]. Briefly, 1.06-μm pulses from a Q-switched Nd:YAG laser were used for creating the plume in a vacuum chamber. The base operating pressure and the laser irradiance were kept at $\sim 10^{-5}$ torr and 5 GW cm^{-2}, respectively, for all of the measurements. The transverse magnetic field is supplied by an assembly of two permanent magnets mounted in a steel core to create a maximum field of 0.64 T over a volume 5 cm × 2.5 cm × 1.5 cm. The target is placed at a distance of 1 cm from the pole edges creating a uniform magnetic field along the plume expansion direction. The plume imaging was accomplished using an intensified charged–coupled device (CCD) placed orthogonal to the plasma expansion direction. The visible radiation from the plasma was recorded integrally in the wavelength range 350–900 nm.

Typical images of the plume sequences in the absence and presence of the magnetic field recorded after the onset of plasma formation are given in Figs. 1 and 2. All of the images given in the figures are normalized to the maximum intensity in that image and each image is obtained from a single laser pulse. The gate of the intensifier was set at 20 ns. Ablation of carbon into a vacuum creates an intensely luminous plume that expands normal to the target surface. The plasma has an elliptical shape with contours along the propagation direction. The phenomenon is mainly due to the initial density gradient and pressure within the plasma plume, which are much larger in the direction perpendicular to the target surface than those in the lateral direction. The expansion velocity of the plume obtained from image analysis is $\sim 10^7 \text{cm/s}$.

When we introduce a magnetic field, the plume expansion dynamics change significantly. The behavior of the plume is not much affected at early times (< 50 ns), but it is slowed considerably with time. Comparing with the field free case, a relatively sharp boundary is formed between the field and the plasma. The plasma confinement caused by the field should increase the collision frequency of the charged species by confining them to a smaller volume. Hence, the constraint of the cross-field expansion by the magnetic field results in thermalization. The expansion of the plume will stop when the magnetic pressure is balanced by the plasma pressure or β (plasma pressure/magnetic pressure) $= 1$.

We estimated some important parameters of the plume's expansion into a transverse magnetic field. The density and temperature of the plasma are taken from [3]. Spectroscopic studies showed that most of the ions in the plume are contributed by C^{+}–C^{+++} whose Larmor radii varied from 0.9 to 0.5 cm, which is of the same order as the characteristic length of the plume. The estimated electron Larmor radius is very small (< 1 μm). Due to the highly transient nonequilibrium nature of the plume, assignment of dimensionless parameters like β to describe the behavior is somewhat limited in validity. Our analysis showed that the thermal beta (β_t) of the plasma approaches unity ~ 70 ns after formation of the plasma. Even though β_t approaches unity, imaging studies showed that the plume is not completely stopped by the magnetic field but is decelerated considerably. After the initial conversion of thermal energy to directed energy, the directed $\beta(\beta_d)$ becomes an important parameter. β_d is seen to vary by several orders of magnitude within the expansion duration of the plume. In the early phase of the plume expansion, β_d is on the order of a few thousand, indicating that the plume is in the regime of diamagnetic expansion. The diamagnetic currents exclude the magnetic field from the interior of the plume, and may interact with the steady state magnetic field through the $\mathbf{J} \times \mathbf{B}$ force, tending to decelerate the plume expansion. The laser produced plasma diamagnetic cavity (magnetic bubble) expands until

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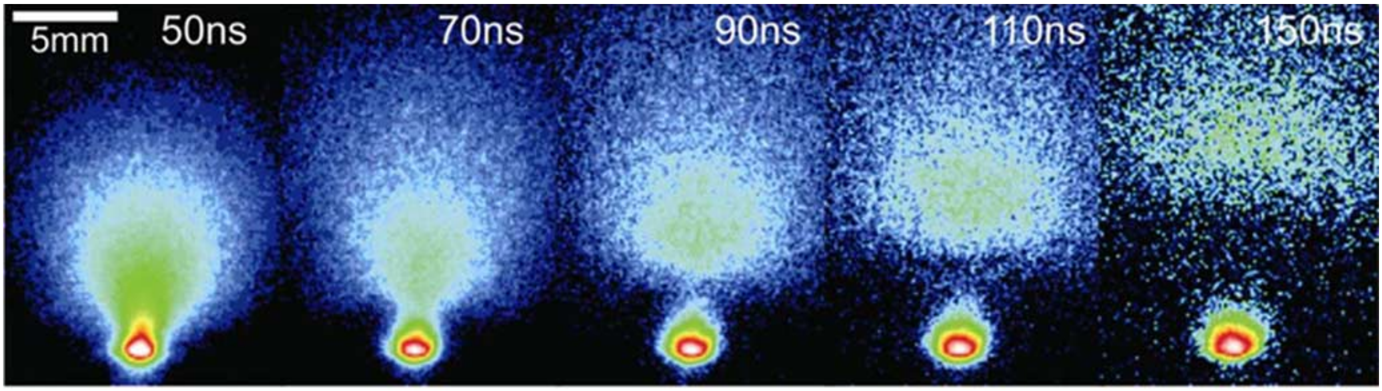

Fig. 1. Plume images recorded in the absence of the magnetic field.

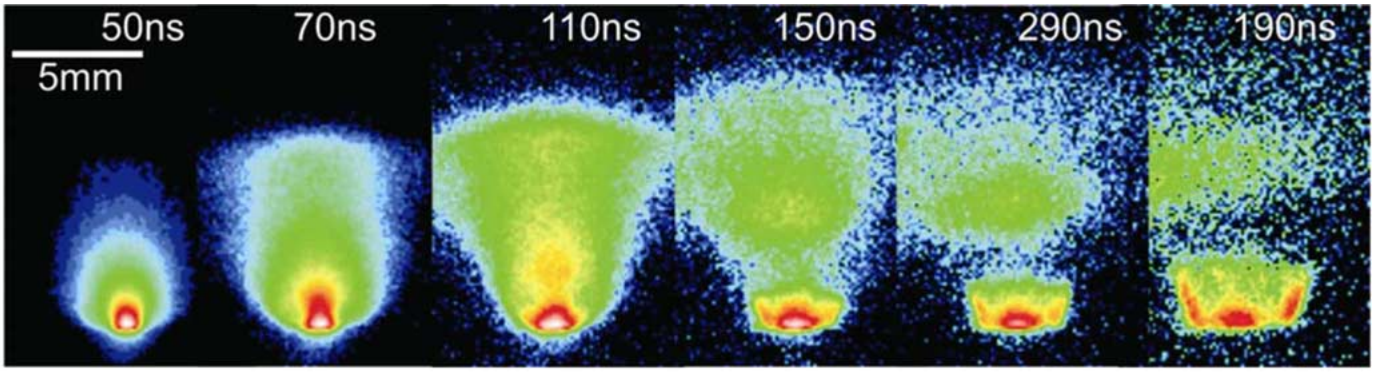

Fig. 2. Sequence of images recorded when the plume expands into a 0.64 T transverse magnetic field.

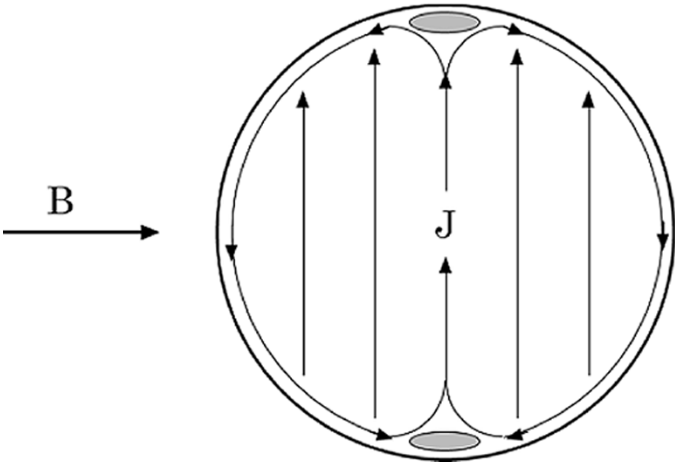

Fig. 3. Drawing of the induced current path after the collapse of the bubble.

the total excluded magnetic energy becomes comparable to the total plasma energy. By assuming spherical plume expansion from a planar target into 2π steradians, the estimated bouncing radius (R_b) or confinement radius is $\sim 0.7\ \mathrm{cm}$, which is in good agreement with the plume length obtained from the images. The values of deceleration and stagnation time (bubble lifetime) estimated by taking the plume velocity obtained from the images are $g = 7 \times 10^{13}\ \mathrm{cm/s^2}$ and $t_b = 140\ \mathrm{ns}$, respectively.

In the latter phase of the plume expansion, the plasma cools and the magnetic field is able to diffuse across the boundary relatively fast compared to the time scale of the experiment. The magnetic diffusion time is essentially the time required to convert the energy of the displaced magnetic field to Joule heat. At later times, $(\sim 150\ \mathrm{ns})$ after the collapse of the bubble, the emitting region close to the focal spot splits into two almost symmetrical lobes that propagate in the lateral direction. Neogi and Thareja [4] observed similar lobes at relatively later times $(\sim 1\ \mu\mathrm{s})$ and ascribed them to the $\mathbf{J} \times \mathbf{B}$ force. Depending on the direction of the diamagnetic current within the plume, this $\mathbf{J} \times \mathbf{B}$ interaction can simultaneously accelerate and decelerate different regions of the plume, giving rise to lobes that migrate toward the poles. In the present studies, however, the lobes or jets appeared just after the bubble lifetime. After the bubble lifetime, a backflow of plume species toward the target is expected because of the higher magnetic pressure relative to plasma pressure. Then the induced current caused by the interaction of the field with the plasma will flow in a modified direction, as shown in Fig. 3. Hence, the plasma will leak out laterally leading to jet formation as observed in the plume images at later times.

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