Laser-Produced Plasma Jets: Collimation and Instability in Strong Transverse Magnetic Fields

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Highly collimated plasmas jets are produced with laser irradiation of solid barium targets. The plasma streams many Larmor radii across a strong transverse magnetic field (10 kG) with little inhibition. The plasma jet is observed to narrow or "focus" in the plane perpendicular to the field, while in the plane of the field the plasma expands along the field lines and displays flutelike striations. The narrowing of the plasma jet is understood in terms of the configuration of the plasma polarization fields, while the flute structure is identified as an electron-ion hybrid velocity-shear instability.

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The physics of plasma flow across magnetic field lines is important in many laboratory and space plasmas. The collimation and stability properties of such flows is of particular relevance to the propagation of charged particle beams, solar wind evolution, virtual anode formation, astrophysical jets, magnetotail physics, beam plasma heating, and cross-field injection fueling of tokamak plasmas.

In this Letter we present direct observations of laser-produced plasma flows which are collimated into two-dimensional jets, focused, and driven unstable by strong (5–10 kG) transverse magnetic fields. The jet instability takes the form of flutelike structure in the plane of the magnetic field, whereas focusing is observed in the plane perpendicular to the field. The plasma flow is not impeded by the field even though the background magnetic pressure is much larger than the thermal or kinetic pressure of the plasma, i.e., low β. Unimpeded plasma flows across B-field lines have been observed in some early work with laser-produced plasmas,[1-3] plasma guns,[4] and ion diodes;[5] however, the mechanism for collimation was not well understood and the flows were not observed to be unstable. By measuring the plasma density, density scale lengths, temperature, and ion velocity distributions we are able to isolate the mechanisms responsible for the plasma collimation and focusing as well as identify the most likely candidate for producing the flutelike structure we observe. This work agrees with recent predictions[6] of electron-ion hybrid instabilities driven by velocity shear.

The plasma jets are created with a low-energy [few mJ, $I \approx 10^8$ W/cm^2, 3-4-ns (FWHM)] Nd-glass laser beam focused onto a solid planar barium target. The laser-target interaction produces a plasma which expands into a vacuum with a uniform magnetic field formed by a pair of Helmholtz coils, Fig. 1. The 0- to 10-kG field is in steady state on the time scale of the experiment and the orientation of the field is adjustable by rotation of the coil assembly. The primary diagnostics for characterizing the plasma are resonant shadowgraphy, resonant absorption, resonant scattering,[7] and ion time-of-flight detectors. Resonant diagnostics are necessary because the plasma densities ($n_e \leq 5\times10^{14}$ cm^{-3}) in these experiments are too low to be detected by nonresonant optical techniques. For these measurements a tunable–dye-laser beam serves as a probe. The probe passes parallel to the target surface and perpendicular to the main laser axis. By tuning the probe wavelength to within 0.5 Å of the 4554-Å Ba II resonance line the index of refraction of the Ba plasma is enhanced by about 3 orders of magnitude over the electron contribution, while at line center the absorption by the barium ions is so strong that complete absorption of the probe occurs for $n_e l \approx 10^{14}$ cm^{-2}.

The expansion of the plasma from the Ba target is close to a simple 1D rarefaction caused by a sudden planar expansion of an isothermal gas.[8] In the experiment the plasma has asymptotic flow velocities normal to the target surface between 1×10^6 and 3×10^6 cm/sec. As the plasma jet flows away from the target it expands transversely with a velocity characteristic of its temperature. The $B=0$ transverse profiles of the plasma jet, measured by 90° resonant laser scattering,[7] are shown in Fig. 2. The barium-ion density is peaked at about 5×10^{14} cm^{-3} and the plasma temperature is about 1 to

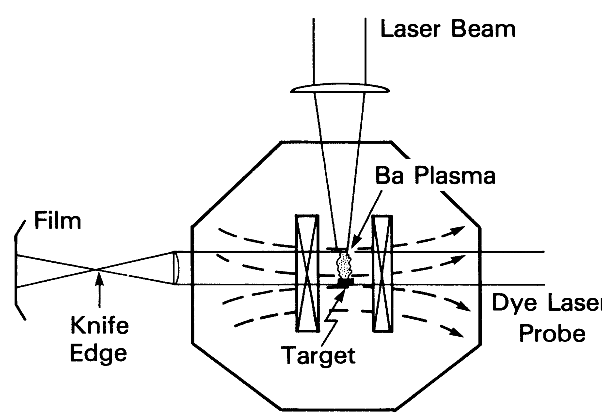

FIG. 1. Schematic of experimental setup.

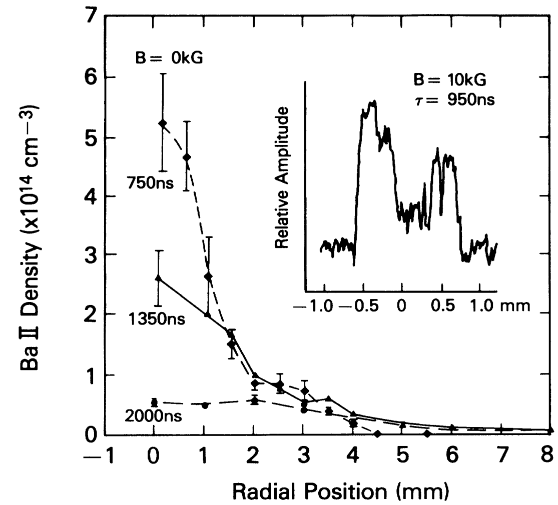

FIG. 2. Radial density profiles of the expanding plasma as measured by resonant Rayleigh scattering for the $B=0$ kG case. Inset: Radial profile for the $B=10$ kG case; obtained from a densitometer lineout of Fig. 3(b). Note the edge density gradient length of ≈ 30 μm. Both profiles are for $z=5$ mm.

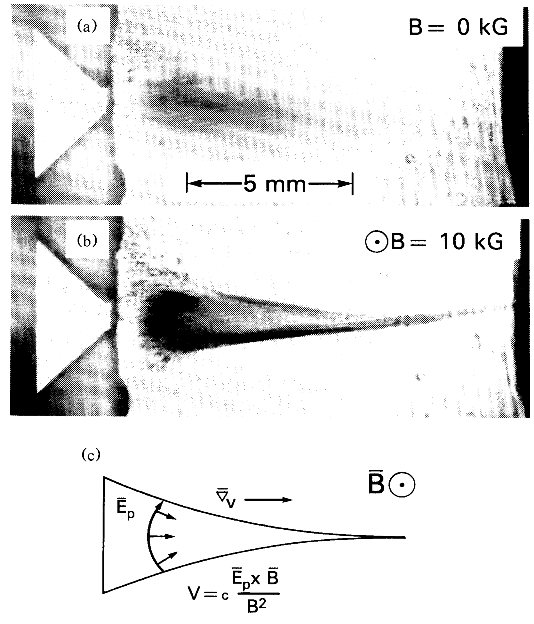

FIG. 3. (a) Typical resonant absorption image of a laser-produced Ba plasma expanding into a vacuum, $B=0$ kG. (b) Absorption image of the same plasma as in (a) except expanding into a 10-kG transverse B field (image in the plane perpendicular to B). (c) Configuration of polarization fields believed to be responsible for focusing of the plasma jet.

3 eV as inferred from the transverse expansion velocity. A typical absorption image of the $B=0$ plasma jet is shown in Fig. 3(a); the flow is well collimated normal to the target surface and its tip moves away from the target surface with a constant velocity. The tip position versus time is plotted in Fig. 4 and a typical ion velocity distribution as measured by ion time-of-flight detectors is displayed in the inset. The ion velocity distribution is very broad, consistent with the 1D expansion model.

With magnetic fields between 1 and 10 kG, the ion Larmor radius (20–2 cm) is always larger than the characteristic plasma dimensions, whereas for the electrons the reverse is true ($r_e < 0.01$ mm). The plasma ram pressure $P_r = nMV^2/2$ is much larger than the thermal pressure $P_t = nkT$ of the plasma, but is still small compared to the magnetic pressure $P_B = B^2/8\pi$. The plasma $\beta = (P_t + P_r)/P_B$ is about 0.05 for $B=10$ kG; thus the diamagnetic currents are weak and the background magnetic field is not strongly perturbed by the flowing plasma, i.e., $\nabla \times \mathbf{E} = 0$ and $B=$const. The jet's tip velocity is not reduced by the field—even for fields as large as 10 kG. On the other hand, the profile of the plasma jet in the plane normal to the field is profoundly modified, as can be seen in Fig. 3(b) and the inset in Fig. 2. The plasma jet becomes wedge shaped, develops regions of higher density at the edges and lower density in the center, and exhibits an asymptotically narrower and denser tip. The steepness of the jet boundary, characterized by the density scale length L_n, changes from a few mm at $B=0$ kG to about 30 μm with $B=10$ kG. The plasma retains its wedgelike character even after traversing several ion Larmor radii.

A Lorentz transformation to the frame of the plasma moving in a magnetic field shows that the moving plasma experiences an induced electric field $\mathbf{E} = (\mathbf{V} \times \mathbf{B})/c$.[9] If the plasma geometry permits the accumulation of charge at boundaries normal to $\mathbf{E}$, such as in a directed expansion, and the low-frequency plasma dielectric constant[10] is large, then the plasma polarizes readily to produce an

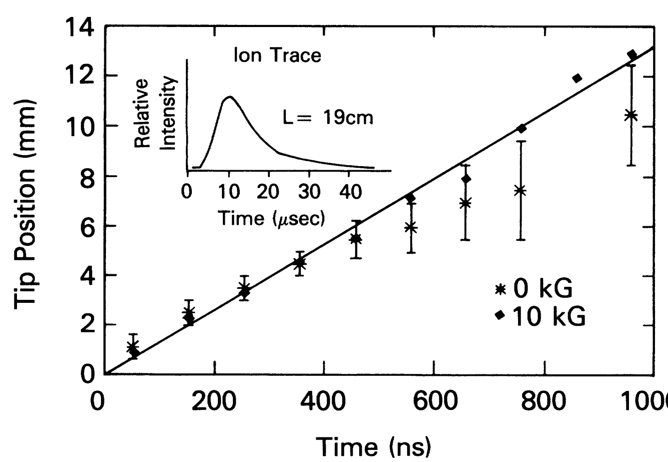

FIG. 4. Tip position of the plasma jet as a function of time for $B=0$ and 10 kG. The low density of the tip in the $B=0$ kG case results in a high uncertainty in its position and gives the impression of deceleration at late times. Inset: Typical ion time-of-flight detector trace.

equal and opposite electric field **E** inside the plasma. The polarization charges produce an electric field $\mathbf{E} = -(\mathbf{V}\times\mathbf{B})/c$ in the laboratory frame; thus, the bulk of the plasma can cross the magnetic field unimpeded via a $\mathbf{V} = c(\mathbf{E}\times\mathbf{B})/B^2$ drift.

At the boundary of the jet the polarization electric field loses strength due to the finite extent of the charge layers. As a result, the charge layers at the jet boundary are continuously left behind due to their lower drift velocities and must be replenished by charges from within the plasma. This mechanism[11] predicts a jet that narrows by attrition as it propagates. But, given our measured plasma density, the surface charge density $\sigma = (1/4\pi c)VB$, and a maximum relative charge layer velocity of V, we find that the amount of plasma lost by this process during the time of the experiment ($\tau < 2$ μsec) is negligibly small ($\Delta N/N < 10^{-6}$).

The mechanism responsible for the jet narrowing is believed to be due to focusing caused by the curvature of the polarization electric field. This occurs because the flow velocity is not constant, but instead has a distribution as shown by the ion time-of-flight measurements. For a plasma flow with a finite velocity distribution the polarizing surface charge density and the polarization electric field must increase in regions of higher flow velocity. Since $\nabla\times\mathbf{E} = 0$ for small β, an axial gradient in the transverse electric field implies that the polarization field must also have an axial component with a transverse gradient, i.e., $\nabla_x E_y = \nabla_y E_x$. This produces a polarization field as depicted in Fig. 3(c). The $\mathbf{E}\times\mathbf{B}$ drift will now have a velocity component pointing inward as well as in the direction of the jet. This $E_x\hat{\mathbf{x}}\times\mathbf{B}$ drift focuses the flow to produce an asymptotically narrow jet. Since the ions are effectively unmagnetized, a positive space charge will also develop at the front of the jet as the ions shoot ahead of the electrons. The resultant axial electric field should curve the jet in the electron gyrodirection ($-\mathbf{V}\times\mathbf{B}$ direction). The observed curvature of the jet tips at late times is consistent with this model. Reversal of the B-field direction produces a corresponding reversal of the jet curvature, as expected.

If the magnetic field is rotated by 90°, such that the plane parallel to the field is under observation, we observe very different behavior. As the plasma expands axially it simultaneously expands out along the field lines and is accelerated by the fringing polarization fields. This expansion, Fig. 5(a), is highly structured, taking the form of narrow flutelike striations aligned along the magnetic field. The striations appear almost periodic ($L \approx 0.015$ to 0.03 cm) and have widths less than the detection resolution ($\Delta x \leq 60$ μm). Observations of the projection width of the striations as a function of angle between the jet axis and the probing beam indicate that the striations do not extend down into the interior of the jet but instead appear to be localized in a very thin sheet (≤ 300 μm), presumably on one or both surfaces of the jet. On the other hand, variations of the angle between the jet axis and the direction of the ambient magnetic field, Fig. 5(b), show that the instability is flutelike ($\mathbf{k}\cdot\mathbf{B} = 0$) even for $\mathbf{V}\cdot\mathbf{B} \neq 0$. The B-field threshold for observing the flutelike structure is about 3 kG. Above threshold, the contrast of the structure increases with field strength, but the characteristic periodicity of the structure is approximately independent of the magnetic field strength. To our knowledge this is the first observation of such structure in a low-β laboratory plasma expanding across a magnetic field. It may, however, be related to observations of similar striations in barium-release space experiments[12] or in tokamak cross-field pellet-injection experiments.[13]

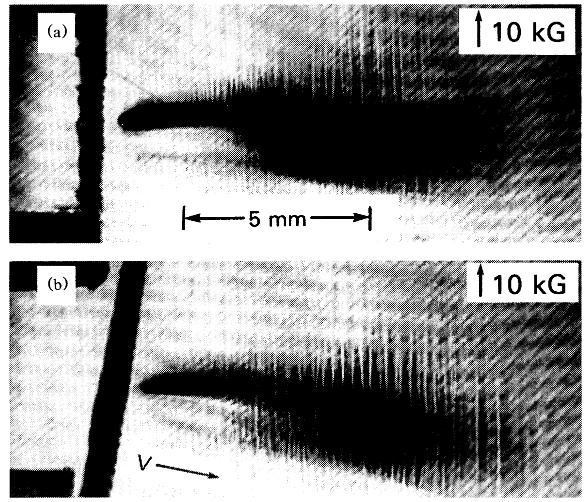

FIG. 5. Resonant absorption image in the plane of the B field. The plasma expands along the field lines and is highly structured. The periodicity of the striations is observed to relate to the density gradient along the field lines through $\lambda \approx \pi L_n$. (a) $\mathbf{V}\cdot\mathbf{B} = 0$. (b) Instability is flutelike ($\mathbf{k}\cdot\mathbf{B} = 0$) even for $\mathbf{V}\cdot\mathbf{B} \neq 0$.

The observed field-aligned nature ($\mathbf{k}\cdot\mathbf{B} = 0$) of the striations is characteristic of instabilities such as the Rayleigh-Taylor or interchange instabilities,[14] velocity-shear instabilities,[6] lower-hybrid drift-wave instability,[15] as well as other electron-ion cross-field instabilities[16] for which $0 < \Theta \leq (m_e/m_i)^{1/2}$, where Θ is the angle between k and normal to B in the k-B plane. In the early stages of the jet formation, i.e., when the polarization fields are set up, the jet could be Rayleigh-Taylor unstable as a result of the focusing forces on the jet. However, at times later than this startup phase the jet is not likely to be Rayleigh-Taylor unstable because the density gradient and acceleration vectors are pointed in opposite directions. A necessary condition for cross-field streaming instabilities is that there be a relative electron-ion drift, or, in the case of ion instabilities, an ion-ion drift. In our plasma relative ion-ion drifts are not present. But relative electron-ion drifts are possible in the boundary layers of the jet where the polarization field falls sharply and the electrons, unable to sustain an $\mathbf{E}\times\mathbf{B}$ drift, fall behind as the unmagnetized ions stream ahead.

Even though, in principle, relative electron-ion drifts are possible in the boundary layers, linear local cross-field streaming instability theory[15,16] cannot explain the observed structure. Space-charge effects limit the relative drift, the nonuniformities of the boundary region make the problem inherently nonlocal, and the observed periodicity of the structure has a much longer wavelength than that predicted $[kr_{Le}(T_i/T_e)^{1/2}\approx 1]$ by the cross-field streaming instabilities. Wavelengths comparable to experimental values would require unreasonably high ion temperatures (≈ 100 eV).

A more likely explanation of the striations are instabilities driven by the electron velocity shear in the boundary layers of the jet. In recent work,[6] it is shown that $\mathbf{E}\times\mathbf{B}$ drifts with localized polarization fields are unstable to electrostatic electron-ion hybrid modes in regions of transverse velocity shear. As in the experiment, this theory applies to the $r_{Le} < L_v \ll r_{Li}$ range of the velocity-shear scale length L_v. For the parameters of our experiment, the lower-hybrid velocity-shear instability has strong growth rates, on the order of the lower-hybrid frequency $\gamma\approx 0.3\omega_{lh}$. The most unstable wave number is given by $k_m L\approx 2$ and is very weakly dependent on the B field for $\omega_{pe}/\omega_{ce}\gtrsim 1$. Since the experiment is in the regime where $\omega_{pe}/\omega_{ce}\gtrsim 1$, the observed insensitivity of the striation periodicity on the B field is in agreement with this model. Assuming that the velocity-shear scale length is of the same order as the density scale length and using $L_n\approx 30$ μm, obtained from densitometer lineouts of the jet profile, $k_m L\approx 2$ ($\lambda\simeq 100$ μm) is in reasonable agreement with the experiment for $\lambda\simeq 150$–300 μm. With $\omega_{lh}\approx 10^8$ sec^{-1}, the time over which the striations are observed allows for about one hundred growth e foldings. Clearly, nonlinear effects are important. More complete understanding of this instability will require extension of this theory into the nonlinear regime and/or numerical simulations.

In conclusion, resonance detection techniques were used to observe and diagnose laser-produced barium plasma jets. The jets focus in the plane perpendicular to the B field due to curvature of the polarization fields, while in the plane of the field the plasma is structured into flutes along the B-field lines. The structuring is believed to be due to lower-hybrid velocity-shear instabilities[6] occurring in the boundary of the jet.

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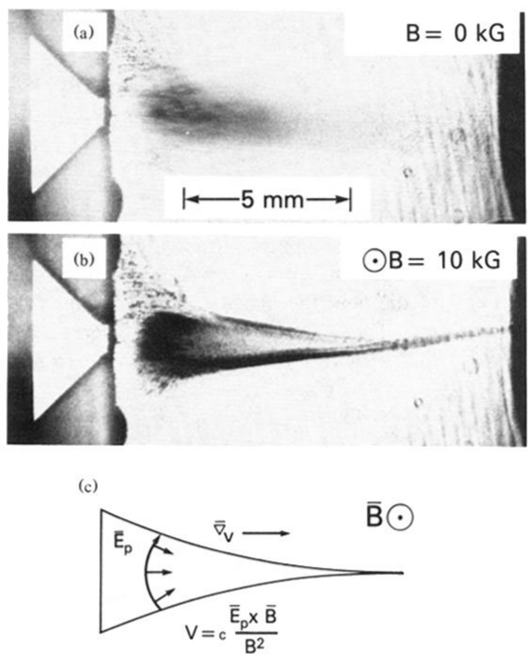

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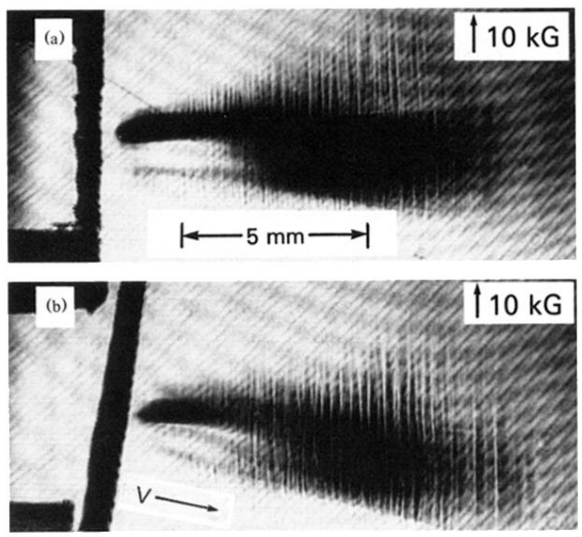

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