changes very slowly with E/Z (line II) which also agrees with the theoretical calculations for this "plateau" region.[5]

More detailed information on impurity ion spectra is provided by Ref. 12 (power 0.5 TW; target diameter 55–80 m). In order to compare with theoretical predictions we note that the velocity of an impurity ion is determined by $(v_k - \tau)dv_k/d\tau = (Z_k/M_k)(M/Z)S \equiv P_k S$ assuming a Boltzmann distribution for the electrons. If $P_k < 1$ we obtain approximately[5,6] $v_k - \tau \simeq P_k$ and from the density equation we then derive the spectrum of the ion impurity as $n_k(v_k)/n_k(0) = \exp[-v_k/(P_k S)]$. Thus the slopes, α_k, of the different ion spectra in a logarithmic plot should be related to the slope of the main ion species, α, by $\alpha_k/\alpha = 1/P_k$. This yields $\alpha(\mathrm{C}^{5+})/\alpha(\mathrm{C}^{6+}) = \frac{6}{5} = 1.20$ and $\alpha(\mathrm{O}^{7+})/\alpha(\mathrm{C}^{6+}) = \frac{8}{7} = 1.14$ in very good agreement with the experimental slopes as indicated in Fig. 2. The original slope of the main ion spectrum ($\mathrm{O}^{8+}, \mathrm{C}^{6+}$) yields an electron temperature of 18 keV, again a factor 1.5–2 larger than stated. Finally, we point out that, as in the previous experiment, a "plateau" region[5] seems to be present in Fig. 2.

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Experimental Stabilization of Interchange Mode by Surface Line Tying

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Experiments are performed in an attempt to stabilize the magnetic-curvature–driven interchange instability (mirror flute mode) using a Q-machine plasma. The stabilization method consists of applying a tenuous plasma blanket, which is line tied to the end wall, around a flute-susceptible higher-density core plasma which has no electrical contact to the wall. By controlling the degree of line tying between the blanket and the wall, the stabilizing effect of surface line tying is demonstrated.

It is well known that a simple mirror with circular coils is susceptible to interchange instabilities (flutes) in which axially trapped plasma escapes by moving sideways across magnetic field lines.[1] When it was demonstrated that minimum-$|B|$-field configurations are stable against fluting,[2] the major efforts in magnetic mirror confinement used this approach, with many positive results.[3] However, because the coils necessary to generate minimum $|B|$ fields are very complicated to fabricate, and, therefore, extremely expensive,[4] there has been a continuing interest in stabilizing simple mirrors.

Among the proposed stabilization mechanisms are bulk line tying,[5] a passive procedure in which the potential in the plasma is tied to the end-wall potential by electrical conduction along the magnetic field lines, and axial feedback, an active procedure in which the end-wall conditions are externally modified in response to low-level fluctuations. A simple mirror reactor might be stabilized by feedback and numerous experimental and theoretical studies have been done on this subject.[6, 7] On the other hand, even though it has been demonstrated that bulk line tying can stabilize flutes,[8] this method is not practical for reactors. When the electrical conduction between the plasma and the end wall is sufficient to stabilize flutes, the thermal conduction to the wall is large enough to cause an unacceptable drain on the electron energy.[9]

A third type of stabilization mechanism, surface line tying, has been proposed[10] in which only the outer edge of an otherwise unstable plasma is line tied. Although the axial heat transport to the end wall would increase in an annulus around the core plasma, the axial transport in the bulk of the plasma remains unchanged. Further, when the annulus is sufficiently line tied, it becomes, effectively, a perfect conductor surrounding the main plasma, thus preventing surface charge separation. In this Letter, we present experimental evidence that a strongly line-tied low-density core does prevent the cross-field particle transport which is characteristic of flutes. It is observed that as the degree of line tying between the blanket and the end wall is reduced, there is a smooth transition from a stable to an unstable core plasma.

The experiment, shown schematically in Fig. 1, is performed in the University of California at Irvine Q Machine,[11] modified to provide a mirror ratio continuously variable from 1 to 5.4. The field in the mirror throat is maintained at 6 kG while the field in the central region is varied. The source of the core plasma is a high-density ($n \sim 8\times10^9$ cm^{-3}) contact-ionized potassium plasma, separated from the region of curved field lines by a negatively biased fine (100 lines/in.) grid. The grid acts as a "plasma shutter"[12]; i.e., it interrupts the flow of plasma on command.

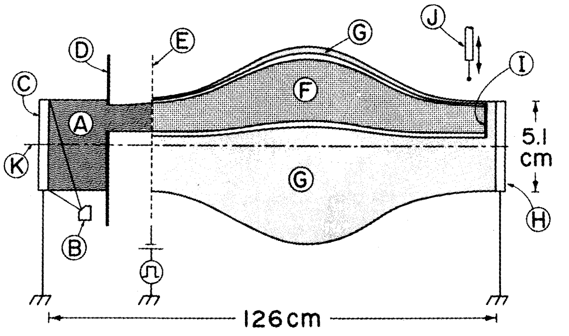

FIG. 1. Schematic of experiment: (A) Source plasma, (B) atomic beam oven, (C) source hot plate, (D) limiter with off-axis circular aperture, (E) electron-reflecting grid, (F) test plasma, (G) low-density blanket hot plate, (H) blanket hot plate, (I) limiter defining blanket position, (J) Langmuir probe, and (K) magnetic axis.

Initially, with the grid biased to large negative values, electrons are reflected from it and ions are prohibited from entering the region of field curvature by space charge effects. When the grid potential is raised to a value close to the source plasma potential, a small amount of plasma passes freely into the experiment region. When the grid bias is returned to its large negative value, electrons can no longer pass through the grid and the line tying between the source hot plate and the core plasma is interrupted. (Although ions can still pass freely through the grid, it was experimentally determined that the ion current from the source hot plate was not sufficient to inhibit the flute growth.) The core plasma has a density of the order of 10^9 cm^{-3}. This is low enough that the plasma remains collisionless; i.e., the ion mean free path is about 10 machine lengths yet high enough that $(\omega_{pi}/\omega_{ci})^2 \gg 1$, allowing the maximum flute growth.[13] The duration of the experiment is essentially the axial transit time of the plasma through the machine, approximately 400 μs.

Under our experimental conditions, an axisymmetric plasma is lost axially before the flute can grow. To ensure transverse plasma motion during the experiment time, it is necessary to give the plasma a large initial perturbation by starting it away from the magnetic axis, thus forcing an $m = 1$ mode. This is accomplished by inserting a limiter with an off-axis circular aperture of 1.9 cm diam between the source hot plate and the grid. Because the plasma is forced to move in a fixed direction, sampling techniques can be used; we pulse the experiment at 60 Hz and use a boxcar integrator to obtain temporal resolution of the order of 50 μs. Cross-field plasma motion is detected by a Langmuir probe in the zero curvature region on the other side of the machine. In this region, magnetic field lines originating at the aperture do not move as the central magnetic field is changed. Because bulk-line-tied plasmas follow field lines almost exactly,[12,14] the flute motion is detected as a radial displacement from the bulk-line-tied situation. A second electron-emitting hot plate forms a uniform line-tied blanket plasma, with the ions presumably supplied by contact ionization of background potassium vapor and/or potassium ions that have diffused radially on this hot plate. A 2.2-cm-diam insulating disk masks the part of the plate that is attached to the same field lines as the aperture, so that the core, decoupled from the source hot plate, is not line tied to the blanket hot plate. By varying the heating power to this plate, the electron emission and the degree of line tying between the blanket plasma and the end wall[5,7] can be controlled.

The effect of magnetic curvature on the plasma in the absence of surface line tying can be seen in Fig. 2. Radial profiles of ion saturation current are taken at successive times by changing the boxcar window position; the mirror ratio R is 5.4. It is seen that as time increases, there is an increasing displacement of the plasma center (as indicated by the arrows) away from the magnetic axis. Also shown is the profile of the bulk-line-tied plasma, in which the plasma shutter is left open. The radial profiles have different amplitudes because the length of the plasma column is less than that of the machine and it spreads axially as it moves along the machine. It is apparent that the plasma begins to move across the field lines before it drifts axially to the probe location. The magnetic field lines which touch the vacuum vessel wall at the midplane of the machine converge to a radial distance of 3.6 cm at the probe location; therefore, no flute motion is observed beyond this point. A probe located near the grid (before the field lines diverge) indicates that the whole plasma moves across field lines simultaneously, showing that the mode is flutelike ($k_z = 0$).

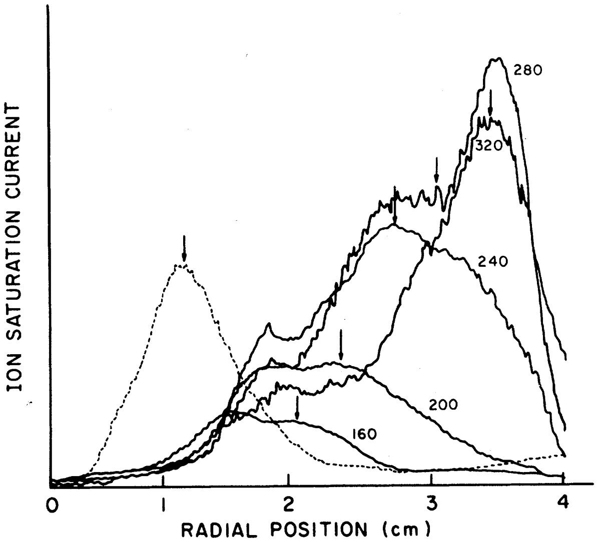

FIG. 2. Radial profiles of flute-unstable plasma taken for increasing delay times after the plasma enters the test region. The arrows indicate the center of the profile. Also shown is the profile of a stable plasma (dashed). Data taken at the maximum mirror ratio 5.4. The boxcar window width is 40 μs. The delay times are in microseconds.

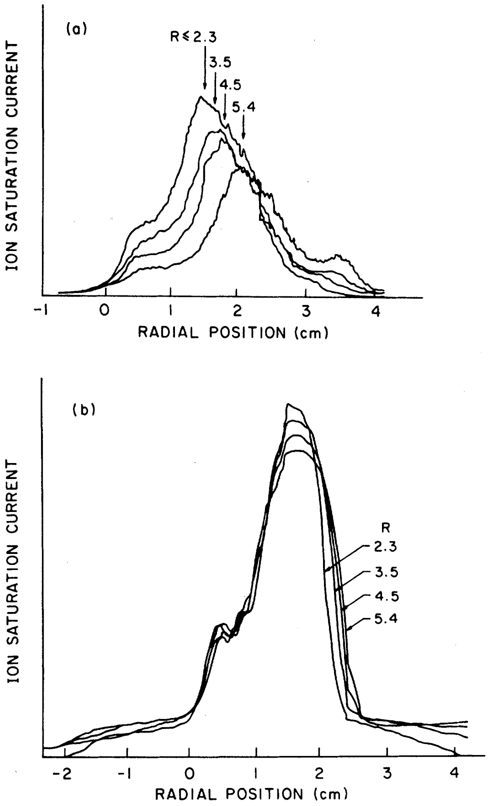

FIG. 3. Radial profiles vs mirror ratio for both (a) an unstable plasma and (b) a stable (bulk line tied) plasma. For the unstable case, the observation delay time is 400 μs and the boxcar window width is 60 μs.

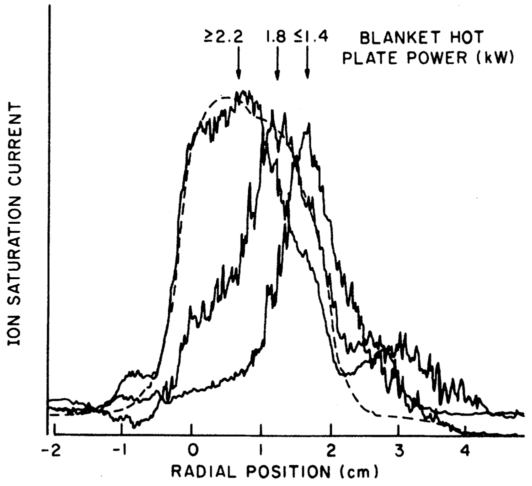

FIG. 4. Effect of blanket on unstable core. As the blanket–hot-plate heating power is increased, the core plasma displaces less from the stable position (dashed). The arrows above the peaks indicate the center of the profile. The observation time is 250 μs and the boxcar window width is 40 μs.

Plasma displacement as a function of mirror ratio is illustrated in Fig. 3(a). The plasma profile is recorded at the same boxcar window position for different mirror ratios. For a higher mirror ratio the plasma shifts farther in the same amount of time showing that magnetic field curvature is indeed the driving force. There is no shift seen for mirror ratios less than 2.3. The corresponding bulk-line-tied profiles are shown in Fig. 3(b).

To test the surface-line-tying scheme, the maximum mirror ratio is used (Fig. 4). Radial profiles of the bulk-line-tied core plasma are taken, both with and without the blanket. No difference can be seen between the profiles. This indicates a blanket density at least two orders of magnitude lower than that of the core plasma. As the heating power to the blanket hot plate is increased, the surface line tying is increased because electron emission decreases the impedance of the sheath in front of the plate.[5] For plate power less than 1.4 kW, the core plasma shifts the maximum amount, as shown in Fig. 4, showing that the surface line tying is not sufficient to stabilize the flute. However, as the plate power is increased, the displacement of the plasma from its bulk-line-tied position decreases, showing a reduction of the driving mechanism. Finally, at plate powers of 2.2 kW and above, the plasma core does not shift at all, showing that the blanket line tying was sufficient to completely stabilize the flute. Note that this 0.8-kW increase in plate power corresponds to an increase in temperature of less than 9%, from 2150 to 2350°K, while Richardson emission increases a factor of 9, from 14 to 130 mA/cm^2.

In summary, we have demonstrated that to stabilize our plasma against the curvature-driven flute instability, it is sufficient to line tie only the surface of the plasma rather than its entire bulk. An electron-emitting end wall is required to provide the amount of surface line tying necessary for stabilization; a nonemitting wall will not suffice.

Since the core plasma in these experiments is at the same temperature (very nearly) as the blanket, this still leaves open the question of whether or not, in the case of a hot core, the presence of a colder plasma blanket might result in unacceptable heat loss due to radial transport. Clearly this point must be the subject of future investigations, which we hope to be able to do. Nevertheless, we believe that we have demonstrated an important stabilization mechanism of interest in those cases where surface charge separation may exist.

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Debye-Length Discrimination of Nonlinear Laser Forces Acting on Electrons in Tenuous Plasmas

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Experimental results are presented which reveal the important role played by nonlinear radiation or ponderomotive forces in laser plasma interactions. The existence of these nonlinear forces are clearly revealed by the properties of tenuous helium plasmas generated by focusing of intense laser beams.

One of us (H. H.) has drawn attention to the potentially important role[1,2] that the well-known "ponderomotive force" could play in laser-plasma interactions. However, because other, more established, mechanisms could also account for the properties of laser-produced plasmas observed during recent years, some uncertainty has always existed regarding the true role of nonlinear radiation forces[1,2] in such plasmas.

The important role of the nonlinear radiation forces[1,2] in modifying the density profile of dense, laser-produced plasmas was recently reported by Enright and Richardson[3] and by Azechi *et al.*[4] in this journal. These observations have had a critical bearing on laser fusion studies based on CO$_2$-laser excitation due to the fact that the nonlinear radiation forces[1,2] modify the plasma density profile in such a manner that the laser energy can be deposited much nearer to the critical-density surface than was previously thought possible.

In an effort to further the understanding of the properties of nonlinear radiation forces,[1,2] we have initiated a research program aimed at studying the properties of these important forces[5,6] under conditions where other effects, considered in the past to be the dominant processes in laser-plasma interactions, cannot possibly be effective. We believe that tenuous plasmas irradiated with intense laser radiation provides the ideal environment for the detailed study of the nonlinear radiation forces.[1,2] In this Letter we present experimental results which clearly demonstrate the manner in which the importance of the nonlinear radiation forces[1,2] are revealed as the density of the tenuous plasma is decreased.

The experimental arrangement is shown in Fig. 1. A 4 GW (0.1 J in 25×10^{-12} sec) beam of Gaussian intensity profile, generated by a Quentron Model 100, high-power, shoft rod Nd:YAlG:glass (yttrium aluminum garnet) laser system, was focused, using a SORO *F*1.5 aspheric lens, inside a chamber filled with helium at pressures in the range 10^{-2} to 10^{-5} Torr after initial evacuation to less than 5×10^{-7} Torr.

A monodirectional, retarding-field electron energy analyzer placed along the direction of the electric field vector allowed any electrons emit-