rf Stabilization of an Axisymmetric Tandem Mirror

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Plasma with significant central-cell beta can be sustained in a tandem mirror composed of three axisymmetric simple mirror cells by the use of ion-cyclotron resonant heating. Radial ponderomotive force due to the rf electric field opposes the centrifugal force due to the field-line curvature to ensure interchange stability. This is indicated by the sensitive dependence of the plasma stability on the sign of the difference between the rf frequency and the ion-cyclotron frequency.

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Conventional tandem mirror designs combine an axisymmetric central cell with nonaxisymmetric, absolute minimum-$|B|$ anchor cells.[1-3] Weighting of the good field-line curvature in anchor cells with sufficient plasma pressure provides interchange stability.[4] Disadvantages of this design are the enhanced radial ion loss due to the nonaxisymmetric field regions associated with the minimum-$|B|$ cells[5] and the difficulty and expense in construction of the necessary coil sets. At present there is a significant effort directed toward the design of interchange-stable axisymmetric tandem mirrors.[6,7] In this Letter we report the first completely axisymmetric operation of a tandem mirror. Stability is maintained through the use of rf heating at the ion-cyclotron frequency (ICRH) in the central cell and the end-plugging cells. Radial ponderomotive force produced by a radial gradient in the applied rf electric field provides stability by opposing the centrifugal force due to the field-line curvature.[8] The net particle drift is then in the direction that would be due to good field-line curvature. This differs from the use of axial ponderomotive force in axial rf plugging experiments[9] in that the radial force only provides magnetohydrodynamic (MHD) stability while the plasma pressure is supported by the axial magnetic field. In addition we demonstrate that radial ponderomotive force is effective when the rf frequency is close to the ion-cyclotron frequency ($\omega/\Omega \lesssim 1.005$). In axial plugging experiments the most effective rf frequency was higher than the ion-cyclotron frequency.[9,10]

Stabilization of a single-cell mirror by radial ponderomotive force has been studied previously both experimentally and theoretically.[8,11,12] Here we extend this work to a three-cell tandem mirror and to significantly higher plasma beta and ion temperature. In addition, the use of a gun to produce the plasma continuously in previous experiments[11] resulted in some uncertainty as to the role of line tying[13] to the plasma source in the stabilization. In our experiments plasma guns are used only for 1 ms during startup. The plasma is sustained for the duration of the ICRH pulse of up to 15 ms which is more than 20 particle lifetimes. The plasma density outside the confinement region is low so that the confined plasma is decoupled from the end walls.

The axisymmetric coils of the Phaedrus tandem mirror[3] are used to produce a configuration with three simple mirror cells (Fig. 1). ICRH heats both ions and electrons in the plugs and the central cell. Fueling in the central cell is by ionization of hydrogen gas puffed into a gas box, and the plug plasma density is maintained by the trapping of a fraction of the central-cell ion-loss stream by the plug ICRH.[3] No neutral-beam injection is used. Plug and central-cell parameters are $n_p \simeq n_c \simeq 2\times10^{12}$ cm^{-3}, $T_{ic} \lesssim 160$ eV, $T_{ip} \simeq 700$ eV, $T_{ec} \lesssim 35$ eV, $T_{ep} \simeq 20$ eV, plug mirror ratio = 2.5, central-cell mirror ratio = 11,

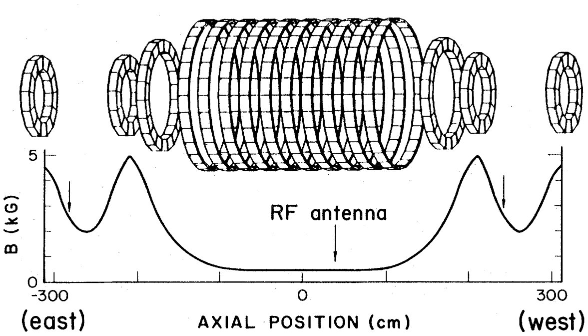

FIG. 1. The axisymmetric coil set and axial field strength profile. The locations of the rf heating antennas are indicated by the arrows. In the plugs the antenna is a straight copper rod (Ref. 3) 6 cm from the axis and in the central cell the antenna is a one-half-turn copper strap ($r = 22$ cm). No Faraday shielding is used here.

$B_c = 450$ G, and $B_p = 2$ kG.

The ponderomotive force can be written[10]

$$F_p = \frac{-e^2}{4m_i}\frac{\nabla_r E^2}{\omega^2-\Omega^2} \simeq \frac{-e^2}{4m_i}\frac{E^2}{l_r(\omega+\Omega)(\omega-\Omega)}, \quad (1)$$

where e and m_i are the ion charge and mass, E is the magnitude of the rf electric field, ω is the rf frequency, Ω is the local ion-cyclotron frequency, and l_r is the radial scale length of E^2. This force is apparently very large if $\omega = \Omega$. However, Eq. (1) is valid only under the condition that ion motion is adiabatic[10,14]:

$$v_i/l_z \lesssim \omega - \Omega. \quad (2)$$

Here v_i is the ion thermal velocity parallel to the magnetic field, l_z is the axial scale length of $\nabla_r E^2$, and v_i/l_z is the time an ion spends in the region of the radial E^2 gradient. Equation (2) specifies that the ion motion should be averaged over several periods of the oscillating electric field which has a frequency of $\omega - \Omega$ in the ion reference frame. If the axial electric-field scale length is large $\omega - \Omega$ can be very small. In this respect there is a considerable difference between the geometries of radial and axial ponderomotive force experiments. When axial force is used l_z is quite small because ions are reflected from the region of the axial E^2 gradient. In the case of a radial gradient of E^2 the axial magnetic field constrains the ions to remain in contact with the E^2 gradient so that with the proper antenna structure l_z can be comparable to the mirror-to-mirror length. We have made estimates of the electric field magnitude and scale lengths using the code XANTENA1[15] which can calculate the self-consistent plasma fields for the Phaedrus antenna configuration. For the central cell the code predicts that l_z is approximately 300 cm. If we use $T_{i\parallel} = 20$ eV Eq. (2) gives $\omega - \Omega \gtrsim 2\times10^4$ s^{-1}. This indicates that ion motion can remain adiabatic when ω is within 0.4% of Ω ($\Omega = 4.3\times10^6$ s^{-1}). The ponderomotive force must oppose the curvature force which is $F_c = mv_i^2/R_c$ where R_c is the field-line average radius of curvature. If we use $l_r = 5$ cm and $E = 0.5$ V/cm (also from the XANTENA1 code), and $R_c = 1000$ cm, the ratio of the ponderomotive force to the curvature force in the region where $\omega \approx \Omega$ is approximately 2. This region covers up to 50% of the length of the central cell depending on the field configuration. The ponderomotive force would be expected to have a significant influence on stability since it exceeds the curvature force over a large portion of the device.

We have produced stable plasmas both in a tandem-mirror configuration and by operating the central cell as a single-cell mirror. In both cases no loss of interchange stability is observed at low rf power. Instead the minimum power necessary to maintain a plasma ($\simeq 20$ kW) is determined by the need to maintain the electron temperature high enough to ionize the puffed gas ($\simeq 12$ eV). Both the ion and electron temperatures increase with coupled power with no saturation observable. Central-cell plasma beta as high as 8% is regularly observed.

Stabilization by ponderomotive force depends on the sign of $\omega - \Omega$ and the direction of the radial gradient of E^2 combining to produce a force in the proper direction to oppose the curvature force which is radially outward in a region of bad curvature. In our experiments $\omega > \Omega$ is necessary for stability and so the rf electric field must decrease from the plasma edge toward the axis of the device. Strong dependence of stability on $\omega - \Omega$ in the central cell is illustrated in Fig. 2 where the central-cell line density is used as a diagnostic for stability. For $\omega > \Omega$ the fluctuation level is reduced to the value due to instrumentation noise while for $\omega < \Omega$ 80% amplitude oscillations are observed. Note that only a 0.4% change in vacuum field strength produced the dramatic change in stability. This sharp change is consistent with a dependence on the sign of $\omega - \Omega$. The stability is sensitive to the

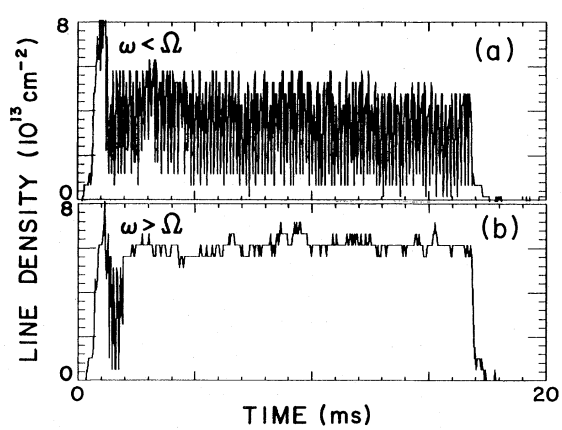

FIG. 2. The central-cell line density for single-cell operation measured with a 4-mm microwave interferometer. The vacuum field strength was varied between shots with the rf frequency fixed at $f = 680$ kHz. (a) $B = 444$ G, (b) $B = 442$ G. From the calibration and resolution of the coil current meters the absolute magnitude of the field is known $\pm 2\%$ but the change in field strength is known to be 2 ± 0.5 G.

changes in the beta-depressed magnetic field strength that result from small changes in the plasma diamagnetism. If the experiment is operated so that the diamagnetism decays slowly during a shot, the high-level oscillations begin abruptly at the critical field strength. Varying the vacuum field strength causes the time at which the oscillations begin to vary. The onset of instability occurs later in the shot when the vacuum field strength is lower because the plasma diamagnetism must decrease by a larger amount for the field strength to increase to the point where $\omega<\Omega$. The net, beta-depressed field strength at which the oscillations begin is independent of the vacuum field strength.

Plasma stability shows a much more gradual dependence on the plug field strength than the sharp dependence observed in the central cell. We believe that this is due to differences in the axial magnetic-field-strength profiles in the regions of strong rf electric field near the antennas. The magnetic field strength is uniform over a wide region near the central-cell rf antenna ($dB/dz \simeq 0.1$ G/cm) so that a small change in the vacuum field strength changes the sign of $\omega-\Omega$ over a large region where the rf electric field is strong and produces a sharp change in stability. The field strength has a stronger axial gradient (60 G/cm) near the plug antennas so that there are both stabilizing and destabilizing regions of ponderomotive force in the plugs. The ponderomotive force effect varies smoothly from net destabilizing to net stabilizing as the plug field strength is varied. This is illustrated in Fig. 3 in which the conditions are varied from unstable to stable in two shots by varying the plug rf and plug field strength. The central-cell field strength is adjusted so that operation of the central cell alone is stable. This is apparent during the period in each shot where only the central-cell rf is on. During the plug rf pulse some of the central-cell plasma stream is trapped resulting in a buildup of plug density and diamagnetism. When the $\omega=\Omega$ resonance is near the plug midplane [Fig. 3(a)], the plasma is unstable during the plug rf pulse. Although diamagnetism and density remain in both the plugs and central cell, the density oscillation level is very high in both cells. Both pressure weighting of bad curvature in the plugs and the plug ponderomotive force, which is destabilizing because $\omega<\Omega$ everywhere in the plugs, drive the system unstable. It is difficult to determine which is the most important destabilizing influence. However, gradually

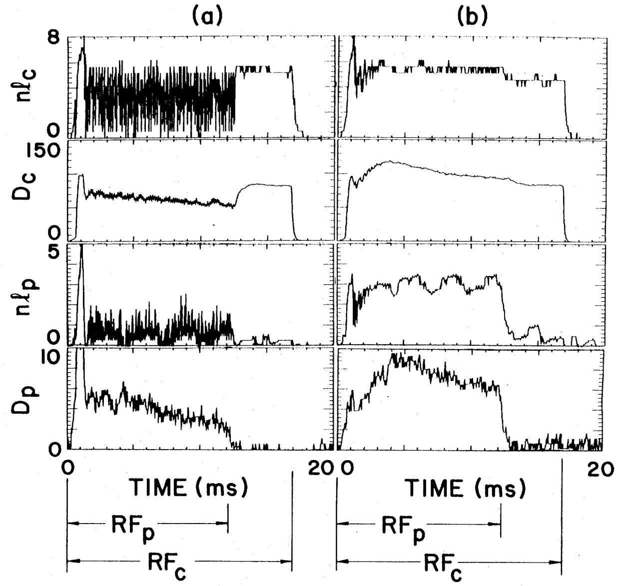

FIG. 3. East plug and central-cell line density (nl, 10^{13} cm^{-2}) and diamagnetism [$D=n(T_e+T_i)/B$, 10^{10} eV/cm^3 G] for two shots with different plug field strengths and fixed rf frequencies, $f_p=2.95$ MHz. (a) Plug midplane field is 1922 G, field at the plug antenna is 2458 G. (b) Plug midplane field is 1715 G, field at the plug antenna is 2179 G.

decreasing the plug field strength introduces regions of stabilizing ponderomotive force resulting in a gradual reduction of the oscillation amplitude during the period of the plug rf and increases in the plug diamagnetism. For $\omega/\Omega = 0.92$ near the plug antennas [Fig. 3(b)], the entire three-cell system is stable. Because the resonance is located between the plug midplane and the plug antenna, the net effect of ponderomotive force in the plugs should be destabilizing. This is evidence that average stability has been obtained for the three-cell system by strong stabilization in the central cell. The destabilizing influence of ponderomotive force in the plugs has been reduced to a level such that the overall system is stable. Although the rf is applied to both plugs in these experiments, the most significant buildup of density and diamagnetism has been observed in the east plug. We believe that this is due to the asymmetry in the plug antenna locations (Fig. 1). The diamagnetism and density observed in the west plug are typically one quarter of what is observed in the east plug so that the west plug has a relatively weak effect on the stability of the overall system.

Other possible stabilization mechanisms have been discounted as follows. Line tying[13] to the vacuum-chamber end walls is not expected because the plasma source is gas that is ionized in the central cell with no source in the end-wall region. This decouples the confined plasma from the end walls. The good-curvature regions near the mirror throats cannot provide stability because diamagnetic loop measurements show that the plasma pressure is peaked in the bad-curvature regions near the mirror midplanes. No evidence of a high-energy ion tail which might produce a magnetic well to stabilize the bulk plasma has been found from measurements of the ion distribution with a gridded electrostatic ion energy analyzer.

In summary, a plasma with significant beta can be sustained in an axisymmetric configuration with multiple mirror cells by the use of ion-cyclotron resonant heating. Interchange stability appears to be due to the effect of ponderomotive force which opposes the centrifugal force due to bad field-line curvature. The sensitive dependence of plasma stability on the sign of $\omega - \Omega$ provides strong evidence that stability is due to this ponderomotive effect.

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