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EXPERIMENTAL OBSERVATION OF WALL STABILIZATION

OF AXISYMMETRIC MIRRORS AT HIGH BETA

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ELECTRONICS RESEARCH LABORATORY

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Abstract

A high β plasma is injected into an axisymmetric magnetic mirror. The β is varied principally by varying the midplane value of the magnetic field. The plasma fills most of the space inside of a conducting vacuum chamber. It is observed for a radially averaged $\langle\beta\rangle > 45$ percent that the plasma is initially stable, while for $\langle\beta\rangle < 35$ percent the plasma is initially unstable. The values of β required for stability are lower than those predicted from MHD theory.

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In tandem-mirror or multiple-mirror confined plasma configurations there would be considerable advantage if stability could be achieved in axisymmetric magnetic fields. The two most obvious advantages are a reduction of radial diffusion and magnet simplification, both of great importance in fusion reactor design. Berk and coworkers first pointed out, for axisymmetric plasmas in which a hot electron distribution and a cooler background plasma mutually stabilize each other (e.g. the EBT configuration), that the presence of a nearby wall could lead to a rugged stability criterion (1,2). The concept of wall stabilization was also applied to a tandem mirror in which all components acted together as an MHD (but anisotropic) fluid (3,4). In both of the above situations, the stability was significantly enhanced by the anisotropy of one or more species. It has also been shown that a rippled magnetic field in the central cell of a tandem mirror could considerably enhance the stability of the device (5). The values of β required for stability, obtained from these theories, are generally quite high. For example, with an isotropic pressure, with a uniform radial pressure profile out to the wall, and a low mirror ratio it was found that for an optimized ripple the minimum β for stabilization was $\beta = 0.5$ (5). This critical β rapidly increased toward unity if the gap between the plasma edge and the conducting wall was increased (5).

The MHD calculations were done in the limit in which finite Larmor radius (FLR) effects stabilized all azimuthal wave numbers except $m = 1$, which is taken to be unaffected by FLR. In fact, even for $m = 1$, the FLR terms can be significant near a wall. A study including this effect showed that if the plasma were considered to have a finite pressure at the wall, the FLR effect was strongly stabilizing (6). The boundary conditions at the wall are, however, poorly specified, as within one ion Larmor radius of the wall ions are lost directly to the wall and a sheath exists. There can, of course, also be colder ions confined in this sheath region.

The difficulty of characterizing the wall-sheath region increases the importance of performing an experiment to test wall stabilization. We have performed such an experiment as part of a general study of high β MHD stability (7,8,9). In the work reported here, plasma is injected into a single cell of a multiple-mirror device from a Marshall gun source. The streaming plasma is partly stopped by a magnetic mirror, and confined primarily to a single 75 cm long mirror cell by a second, fast-rising mirror field which is pulsed on while the plasma is traversing the trapping region. The strength of the mirror field is 4 kG. The background solenoidal field is varied between 0.7 and 2 kG to vary the plasma β, but also has the effect of varying the mirror ratio. The plasma is contained within a conducting vacuum chamber of radius r_w = 4.5 cm.

The plasma properties have been measured with diamagnetic loops and arrays of Langmuir probes. The electron temperature is measured both by biased Langmuir probes and by time of flight. These measurements indicate an initial electron (and probably ion) temperature above 20 eV. This temperature decays quite rapidly ($\tau_T \lesssim 5\ \mu$sec) to a much lower value, while the plasma density decays much more slowly (typically $\tau_n \gtrsim 20\ \mu$sec) indicating the rapid cooling of the plasma with some additional cooling provided by entry of additional cooler source plasma. The peak (in time) beta averaged over r, $\langle\beta\rangle$, is varied primarily by varying the solenoidal magnetic field, but also has shot-to-shot variation. It is generally in the range $0.15 \lesssim \langle\beta\rangle \lesssim 0.7$. The corresponding densities are upwards of $n = 10^{15}\ \mathrm{cm}^{-3}$. The plasma cross-section is fairly flat-topped, dropping rapidly within a centimeter of the walls.

The stability of the plasma was qualitatively determined by comparing the relative ion saturation current on three Langmuir probes positioned on a ring at a radius of 3 cm. A typical result for a stable and for an unstable plasma are shown in Figs. 1 and 2, respectively. In Fig. 1a the unnormalized (from probe to probe) signals are shown from the three Langmuir probes for B_{sol} = 0.7 kG and

$\langle\beta\rangle = .60$. The signals are smoothed to remove digitizing noise but not plasma fluctuations. In Fig. 1b a corresponding diamagnetic signal is shown, indicating the faster decay of the temperature. This shot is clearly qualitatively stable. In contrast, in Fig. 2a the ion saturation current on the three probes is shown (with a different gain) for $B_{sol} = 2$ kG and $\langle\beta\rangle = 0.12$. Here we qualitatively see unstable motion. The corresponding decay of the diamagnetic signal is shown in Fig. 2b. The similar decay time indicates that plasma is not lost precipitously due to the unstable motion.

The above experiments were repeated over a large number of shots. The β was changed from high to low value on alternate shots by changing B_{sol} from 0.7 kG to 2 kG. Natural source variation gave a further spread of β values. The results generally showed stable decay for $\langle\beta\rangle > 0.45$ as in Fig. 1, and initially unstable behavior for $\langle\beta\rangle < 0.35$. Sometimes the plasma remained unstable later in time, as in Fig. 2, and sometimes the plasma restabilized.

The experiment was compared with theory in which FLR effects force the mode to be rigid. For this approximation only the $m = 1$ mode is important. The equations are similar to those in Ref. 3, except that the radial pressure profile is taken to be diffuse. The equation can be written in Sturm-Liouville form

$$(sY')' + (q + rw^2)Y = 0,$$

with

$$s = \Lambda + \frac{\langle Q\rangle}{B_v^2},$$

$$q = -2\frac{\langle p\rangle}{B_v^2}\frac{R_v''}{R_v} - \frac{1}{8}\left\langle\frac{\beta'_\perp}{l-\beta_\perp}\right\rangle^2\left[-\frac{\langle p\rangle}{B_v^2}\right]$$

$$-\frac{1}{2}\left[\left\langle\frac{\beta'_\perp}{1-\beta_\perp}\right\rangle\left[-\frac{\langle p\rangle}{B_v^2}\right]\right]' .$$

$$r = \frac{\langle \rho \rangle}{B_v^2}\,.$$

and where Y is the eigenvalue related to the perturbed potential by

$$Y = \frac{B_v}{B}\varphi.$$

Here

$$p = \frac{1}{2}(p_\perp + p_\parallel),$$

$$Q = B_v^2 - 2p,$$

$$\Lambda = (R_w^2 - R_p^2)/(R_w^2 + R_p^2),$$

where p is the total pressure, ρ the mass density, B_v the vacuum field, R_w and R_p the wall radius and plasma radius respectively, $\beta_\perp$ the perpendicular beta, and the primes are derivatives with respect to axial position z. The equation reduces to the constant pressure profile equation if the radially averaged quantities, $\langle p \rangle$ etc., are replaced by constant values. A similar equation for a diffusive profile plasma has recently been reported (10).

The second order differential equations were solved numerically, together with floating boundary conditions, using a shooting method. The numerical results indicate that, relatively independent of radial profile, with the experimental magnetic field configuration, stability is obtained for $\langle \beta \rangle \gtrsim 0.9$. The theoretical $\langle \beta \rangle$ required for stability is thus considerably higher than that found experimentally. We attribute the improved experimentally observed stability at peak β to the effect of FLR, near the walls, as described in Ref. 6. However, source line-tying and/or other effects may also contribute. Because of ballooning, we would expect line-tying to be more effective at low, rather than high, β, and thus suspect that this is not a predominant effect.

The generally stable behavior after the β has decayed significantly may be due to a combination of rapidly decreasing temperature (increasing growth time) and increased line-tying due to cold plasma streaming from the source. An increased line-tying results because the ratio of stream density to confined plasma density increases in time.

In conclusion, we have seen evidence of a transition from instability to stability with increasing β when the plasma edge is near a conducting wall. The transition occurs at lower β than predicted from an MHD theory and may be due to an effective finite plasma pressure at the wall.

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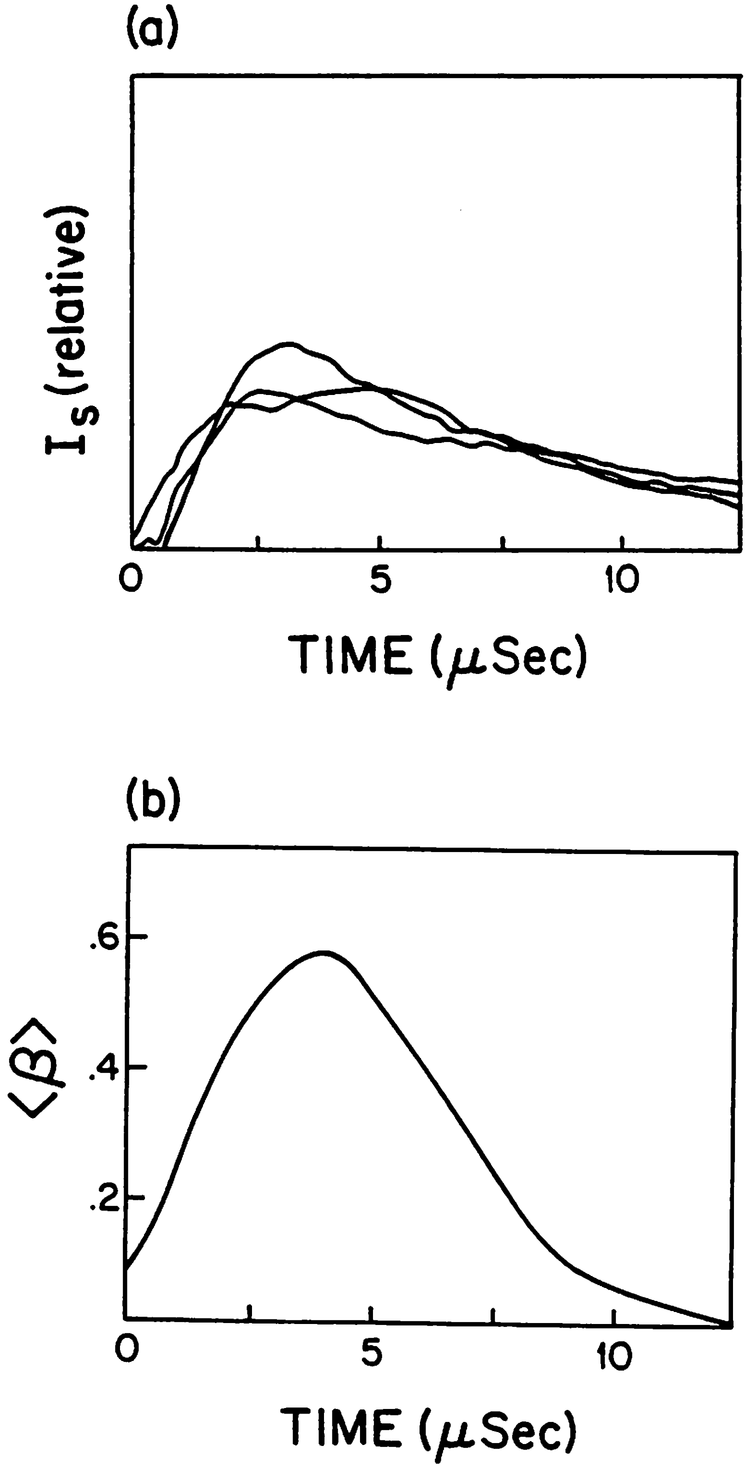
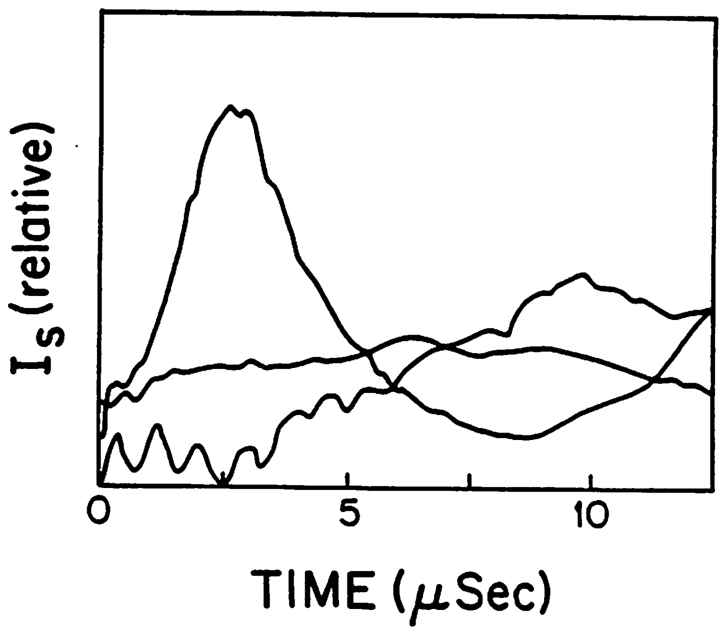
Figure Captions

Fig. 1 (a) The relative ion saturation current on three Langmuir probes for a high β stable case; (b) the corresponding radially averaged β.

Fig. 2 (a) The relative ion saturation current on three Langmuir probes for a lower β unstable case; (b) the corresponding radially averaged β.

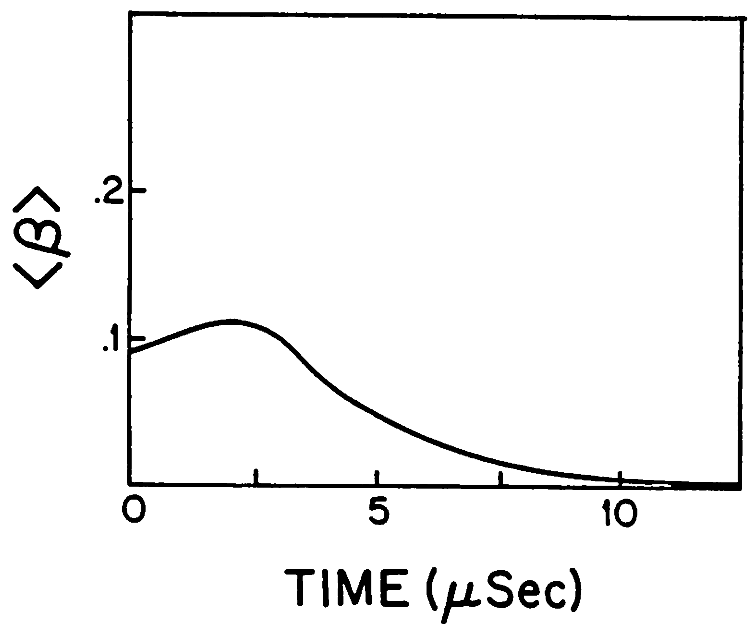

(a)
I_s (relative)
0
5
10
TIME (μSec)
(b)
$\langle\beta\rangle$
.6
.4
.2
0
5
10
TIME (μSec)

(a)



I_s (relative)
0
5
10
TIME (μSec)

(b)



$\langle\beta\rangle$
.2
.1
0
5
10
TIME (μSec)