Experimental Observation of the Hot-Electron Equilibrium in a Minimum-B Mirror Plasma

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Measurements of the hot-electron ($T=450$ keV, $n=2\times10^{11}$ cm^{-3}) equilibrium in the Constance B minimum-B magnetic mirror show that the pressure profile is peaked off the axis and is shaped like the seam on a baseball. This curve is the drift surface of the deeply trapped electrons and the location of the strongest microwave heating. The configuration is stable and decays quiescently on the hot-electron collisional time scale (1–2 s) after the microwave power is turned off. According to 1D pressure-weighted $\int dl/B$ analysis this plasma configuration is expected to be unstable.

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The equilibrium and stability of plasma configurations in magnetic fields is of fundamental importance in the development and understanding of plasma confinement devices. Experimental measurements of mirror equilibria have been made in electron cyclotron-resonance-heated (ECRH) maxima-B[1-3] and minimum-B[4] mirrors and bumpy tori.[5] The data show that, for maximum-B hot-electron plasmas, the plasma pressure is concentrated in a ring structure which is located near the second-harmonic ECRH resonance. From the previous measurements in a minimum-B mirror[4] it was not possible to infer the full three-dimensional structure of equilibrium. The measurements presented in this Letter indicate that the hot-electron pressure profile is peaked off axis and shaped like the stitched seam on a baseball.

In the Constance B mirror,[6] high-beta (beta is the ratio of plasma pressure to magnetic field pressure), hot-electron plasmas are created with use of up to 4 kW of fundamental electron cyclotron-resonance heating at 10.5 GHz. Typical plasma parameters are $T_{eh}=450$ keV, $n_{eh}=2\times10^{11}$ cm^{-3}, $\beta=30\%$, $n_{ec}=2\times10^{11}$ cm^{-3}, and $T_{ec}<100$ eV. The ECRH resonance zone is a closed ellipsoidal surface (Fig. 1). The typical operating hydrogen neutral pressure is 10^{-6} Torr although stable hot-electron plasmas can be formed over the pressure range from 5×10^{-8} to 10^{-4} Torr. Pulse lengths are typically 1–2 s. The hot-electron confinement is dominated by ECRH-induced diffusion when the rf is on, but when the ECRH is turned off the diamagnetic decay time of 1–2 s is consistent with collisional scattering loss of the hot electrons.

Insight into the spatial distribution of the hot electrons

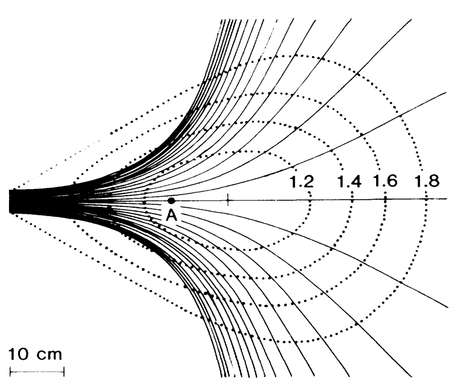

FIG. 1. Constance B magnetic field geometry. The solid lines are field lines and the dotted lines are surfaces of constant magnetic field.

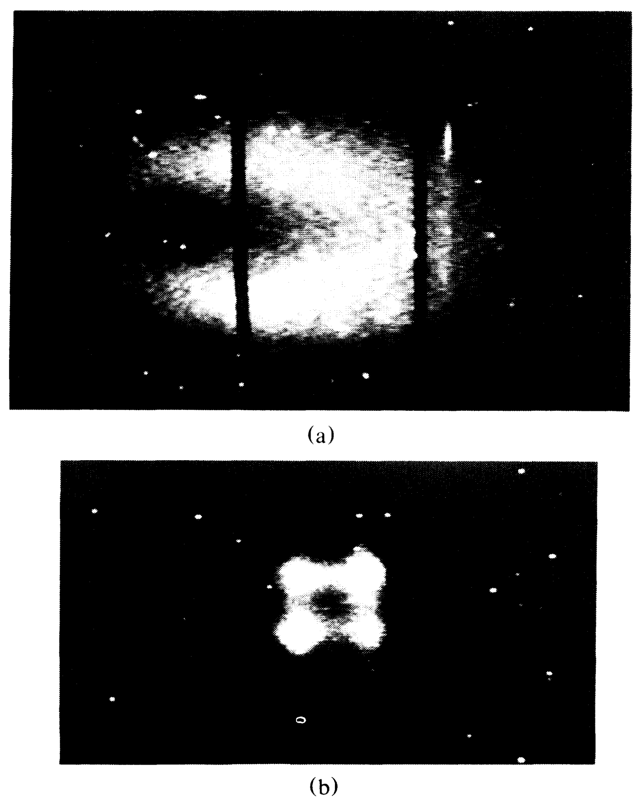

FIG. 2. Visible light photographs of the plasma 30 ms after ECRH turn-off. (a) Side view. The magnetic field is oriented as shown in Fig. 1. The vertical bars are an ion-heating antenna centered on the midplane. The bars are 7.6 cm apart. (b) End view.

is given by the visible light images of the plasma taken with a charged-coupled–device television camera. Figure 2 shows the photographs of the Constance plasma which are taken 30 ms after the ECRH is turned off. At this time, $>95\%$ of the cold electrons have scattered into the loss cone ($\tau_{scat}=50$ μs) and only the hot electrons are well confined. These pictures suggest that in three dimensions the hot electrons are concentrated along a baseball seam, i.e., the curve described by the stitched seam on a baseball. An x-ray pinhole photograph (Fig. 3) taken for the same plasma conditions verifies that the hot electrons are distributed as the visible-light photographs suggest. The plasma is contained within the resonant mod-B surface. Measurements of the H-α profiles, the hard x-ray flux, the hot-electron temperature profiles, and the hot- and cold-electron end-loss profiles also corroborate the hollow, and, in particular, the baseball-seam nature of the hot-electron profile. Another strong indication that the hot electrons are distributed along the baseball seam is the observation that it is possible to insert a $\frac{1}{4}$-in.-diam aluminum probe into the plasma axis at the opening of the "C" (point A on Fig. 1) with a resulting decrease in stored energy of less than 10%. Inserting the probe to the axis at other axial positions completely destroys the plasma.

This hot-electron equilibrium has been observed over a wide range of operating conditions. The baseball-seam shape is established within the first 30–60 ms of the discharge when beta is low ($\ll 1\%$). The plasma profile is initially peaked on axis and then changes to the baseball shape within 30 ms, which is the time resolution of the framing camera. When this transition occurs the hot-electron temperature is measured to be between 30 and 50 keV. In high–neutral-pressure discharges with no hot electrons, the baseball seam is not observed. The baseball equilibrium is seen in hydrogen, helium, and argon plasmas. Finally, the hollow plasma is seen over the range of midplane magnetic fields from 2.8 to 3.4 kG (resonant radial mirror ratio from 1.33 to 1.1).

Two plasma characteristics can be associated with the observed baseball-seam curve. First, this shape corresponds to the drift surface of the deeply trapped electrons at the resonance zone. Figure 4 shows the calculated drift orbit of a 340-keV electron with very little parallel energy which is started near the bottom of the well on a mod-B surface in the Constance magnetic field. This figure clearly shows the baseball-seam nature of the particle drift. Second, the ECRH absorption will be strongest along the baseball-seam curve. The largest heating rate occurs on field lines which are tangent to the resonant mod-B surface, since on these field lines the gradients in the field at the resonant surface vanish.[7] Mapping of this tangent point along the mod-B surface produces a baseball seam. It is the cold electrons, which are the source for the hot electrons, that are strongly heated on the baseball-seam curve. The relativistic hot electrons ($\gamma=1.7$) are resonant further out along the field line. Thus, the anisotropically heated hot electrons seek an equilibrium related to their drift motion and to the heating of their low-energy source electrons.

An interesting feature of this equilibrium is that it is very stable. Although the magnetic geometry is minimum B, plasma stability is not necessarily to be expected for pressure profiles which are peaked off axis. A detailed theoretical analysis is complicated by the geometry and by the wide parameter range of the ratio of the electron drift frequency to the magnetohydrodynamic (MHD) growth rates. This ratio varies from much less than unity at the beginning of the ECRH pulse to unity as the hot-electron temperature approaches 200–400 keV. Thus, we do not attempt in this Letter to give a detailed stability analysis but, instead, use the adiabatic fluid-energy principle of Rosenbluth and Longmire[8] to suggest why the stability of the observed configuration is surprising. If we apply the Rosenbluth and Longmire stability criterion, neglecting compressibility effects, to the plasma inside the pressure peak, we conclude that the plasma is unstable in this region because the magnetic field curvature is unfavorable

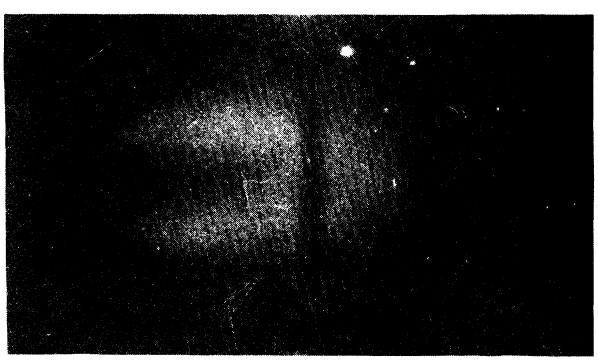

FIG. 3. X-ray pinhole photograph of the plasma. The dark vertical bar is the shadow of the diamagnetic loop.

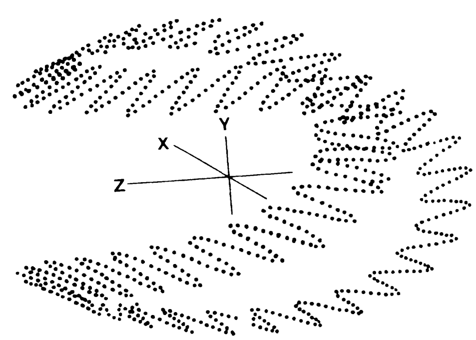

FIG. 4. Calculated drift orbit of a 340-keV electron which is started near the bottom of the well.

with respect to the pressure gradient. This is the familiar $\int dl/B$ criterion for ideal MHD stability. The plasma would thus be expected to flute radially inward and assume the most energetically favorable profile—one which is peaked on axis—on the time scale of the MHD growth rate. For Constance parameters, the MHD growth time is $\sim 0.1\ \mu s$. Experimentally, however, we observe that the plasma is stable and relaxes on the significantly longer hot-electron collisional time scale of seconds when the ECRH is turned off.

When compressional effects are taken into account, profiles which are peaked off the axis are theoretically stable provided that they are not too hollow. The marginally stable profile is given by $PV^\gamma = \text{const}$, where P is the pressure, V is the volume of a unit tube of flux ($V \sim \int dl/B$), and $\gamma = (N+2)/N$, where N is the number of degrees of freedom. For the Constance magnetic field, this profile is one which drops to 88% of its peak value on the axis. Figure 5 shows the midplane radial profile and line-integrated side and end views of two model pressure profiles which have the baseball-seam symmetry. Figure 5(a) is the theoretical compressibility-stabilized profile and 5(b) is a more hollow profile where the pressure drops to 45% on the axis. The line-integrated profiles can be directly compared to the visible-light photographs. Since the hot-electron temperature profile deduced from x rays is measured to be flat across the plasma the pressure profile is equivalent to the density profile. The light emission is proportional to the product of the hot-electron density and the neutral density and, since the neutrals are uniformly distributed in this low-density plasma, the light also reflects the hot-electron density profile. Better agreement is achieved with profile 5(b), a profile which is more hollow than the compressibility-stabilized pressure profile. Moreover, magnetic probe measurements of the diamagnetic fields outside the hot plasma[9] are in good agreement with the predictions of the profile which drops to 45% on the axis.

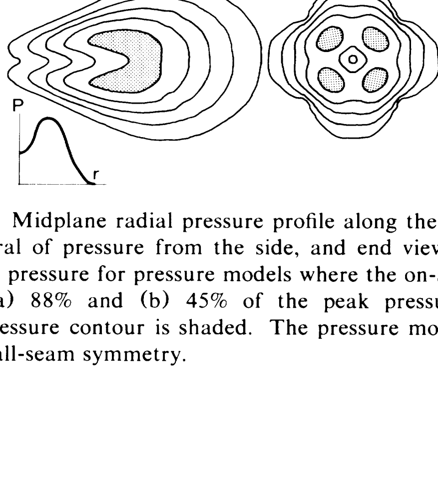

FIG. 5. Midplane radial pressure profile along the 45° line, line integral of pressure from the side, and end view of line-integrated pressure for pressure models where the on-axis pressure is (a) 88% and (b) 45% of the peak pressure. The highest-pressure contour is shaded. The pressure models have the baseball-seam symmetry.

Stabilization methods other than compressibility have been considered, but none yet provide a satisfactory explanation. First, stability is observed very early in the shot and for low-ECRH-power shots where the hot-electron beta is very low ($\ll 1\%$). In these cases the hot-electron diamagnetism is not sufficient to modify the vacuum magnetic field. Second, stability is observed in the absence of cold plasma. This contrasts with the experimentally observed lack of stability under similar conditions seen in the Elmo Bumpy Torus experiment.[10] Third, line tying is not thought to be the stabilization mechanism because the plasma density outside the mirror peaks is measured to be less than 1% of the peak density during ECRH and 100 times lower in the afterglow. The vacuum-chamber design causes plasma to hit the end walls at low density and magnetic field so that end-wall isolation can be achieved. Finally, the stability early in the shot when both beta and the hot-electron temperature are low suggests that decoupling due to fast particle drifts is not responsible. For electron energies of 50 keV the drift period is long compared to the MHD growth time. Although decoupling or stabilization due to effects of high plasma beta may be valid under some plasma conditions, they cannot be invoked in the early part of the shot or in low-β shots.

We have presented the observations of the hot-electron equilibrium in a quadrupole mirror. We have found that the pressure profile is shaped like the seam on a baseball, a curve which coincides with the drifts of the deeply trapped electrons at the ECRH resonance surface and the points where the heating of the cold-electron source is strongest. The data indicate that the pressure profile is more hollow than the profile which can be stabilized by compressibility. Stabilization by cold plasma, decoupling, line tying, and the digging of a diamagnetic well are unlikely. The extreme degree of stability which is experimentally observed is therefore not understood at this time.

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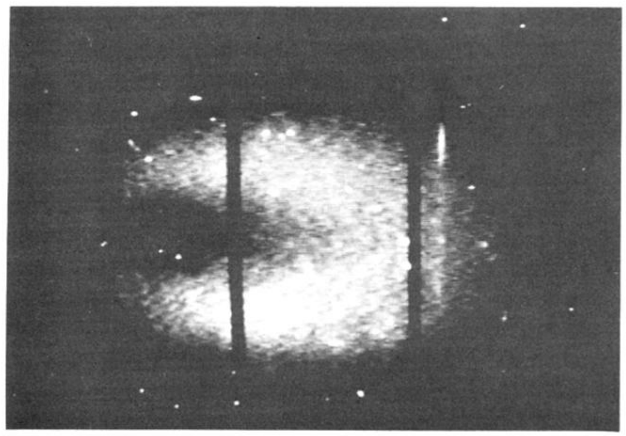
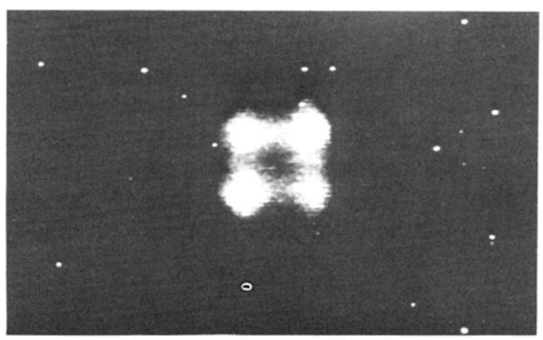


(a)



(b)

FIG. 2. Visible light photographs of the plasma 30 ms after ECRH turn-off. (a) Side view. The magnetic field is oriented as shown in Fig. 1. The vertical bars are an ion-heating antenna centered on the midplane. The bars are 7.6 cm apart. (b) End view.

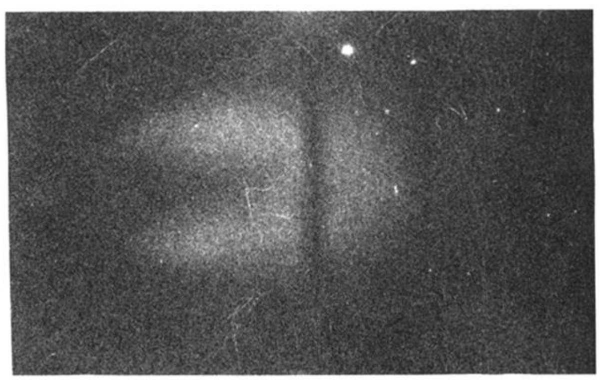


FIG. 3. X-ray pinhole photograph of the plasma. The dark vertical bar is the shadow of the diamagnetic loop.