TABLE II. Optimum stable plasma parameters obtained in this series of experiments.

Max. I_p	100 kA
Max. average β	7.4% ($q=1.3$, $\beta_p=0.85$)
Max. energy density	5 J/cm^3 ($=10^{17}$ eV/cm^3)
Plasma temperature	< 500 eV
Max. average β_p	~ 1
Min. surface q	1.3
Plasma density	10^{14}–10^{15} cm^{-3}
Energy confinement time τ_E	~ 28 μsec
Ideal energy confinement time τ_{E0}	> 100 μsec

by impurities also appears in the compression phase. In the case of a bad vacuum condition, the capacitor charging voltage needed to induce the same plasma current is reduced by 20%. Therefore, to observe the stability window, clean vacuum conditions are apparently necessary.

The optimum plasma parameters obtained in this series of experiments are listed in Table II. It is concluded that stable confinement of high-β plasma is possible where the value of q is between 1.3 and 1.5. Stable operation is also possible if q is larger than 2. In order to discuss longer energy confinement times, a power crowbar system would be necessary.

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High-β Plasma Containment in the 2XII Mirror Device*

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High-β confinement of a hot-ion plasma has been observed in the 2XII magnetic mirror experiment. The maximum measured β values of 0.3 to 0.4 were near the limit predicted for mirror equilibrium in the 2XII mirror ratio of 1.8 to 2.3.

An attribute of mirror confinement systems is the ability to operate at high β, which allows high energy density and reduces the size of a fixed-output thermonuclear system. High-β mirror confinement has been observed in hot electron plasmas.[1] We report here containment of high-β hot-ion deuterium plasmas at measured values of β approximately 0.3 to 0.4.

The 2XII plasma is formed by injecting an energetic ($\overline{E}_i \simeq 2.5$ keV) deuterium plasma along a magnetic guide field. Ions that reflect off of a magnetic mirror are trapped between it and a 15-μsec-risetime gate mirror. Timing of this fast gate relative to plasma injection allows control of the trapped plasma energy. A pulsed 4.6-kG magnetic field then compresses the trapped plasma in 400 μsec and contains it in a minimum-B well. We define

$$\beta = \tfrac{2}{3}\beta_\perp + \tfrac{1}{3}\beta_\parallel = \tfrac{2}{3}nk\overline{E}/(B^2/8\pi) ,$$

as the ratio of plasma pressure to the vacuum magnetic field pressure in the absence of plasma. Here $\beta_\perp$ and $\beta_\parallel$ are the components perpendicular and parallel to the magnetic field, which are not equal for anisotropic, mirror-contained plasmas. For a collisional plasma contained in a field of mirror ratio 2, $\beta_\perp = 1.35\beta$. We determine β from measurements of the magnetic field strength and of the plasma density and energy as described below.

The central density was determined from the measured attenuation[2] of a 16-keV, 5-A equivalent, neutral hydrogen beam.[3] A pair of slits accepted particles that had traversed a 1.5-cm-high path through the plasma diameter. Below the 4-mm microwave interferometer[4] cutoff density ($n \simeq 6\times10^{13}$ cm^{-3}), line densities determined by beam attenuation and by the interferometer agreed to within 10%. Central densities were derived from line densities using adiabatic compression ($nr^2 \propto Br^2 = \text{const}$, where r = plasma radius) of measured injected radial plasma profiles. These radial profiles were confirmed (during compression) by measuring beam attenuation across nine chords of the plasma. The central density following compression was verified by Thomson scattering of ruby-laser light. Three independent measurements of density are shown in Fig. 1.

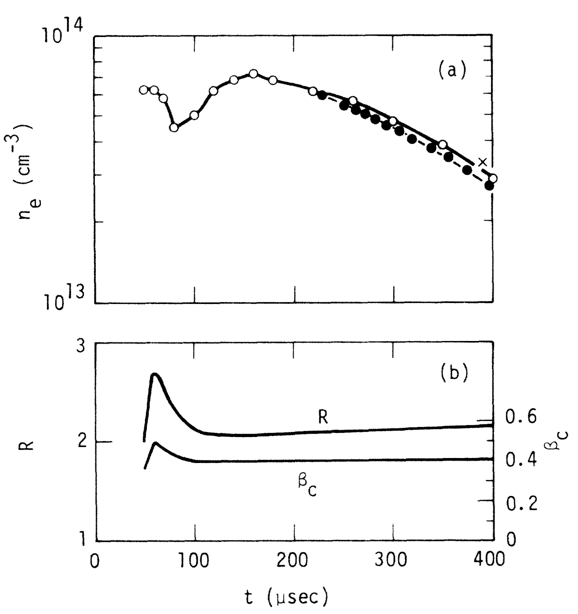

FIG. 1. 2XII parameters versus time. (a) Open circles, plasma density measured by neutral beam attenuation; closed circles, microwave interferometer; and crosses, Thomson scattering, for a high-β shot that exhibited a density decrease between 60 and 80 μsec. (b) 2XII mirror ratio R and mirror instability β limit β_c for 1000-G magnetic guide field. The β limit decreased during the same time that the density was observed to decrease.

The mean plasma energy $\overline{E}$ is the sum of the average electron and ion energies. The average electron energy was taken to be 5% of the average ion energy, consistent with T_e determined from Thomson scattering measurements.[5] The average ion energy was determined by a calibrated eleven-channel neutral analyzer,[6] that measured the energy of fast charge-exchange neutrals having nearly zero velocity parallel to the magnetic field. To calculate the average ion energy from the charge-exchange spectrum we assumed that (1) the angular distribution was separable from the energy distribution, (2) the charge-exchange spectrum was representative of the plasma center, and (3) the distribution was cut off below the lowest energy channel at 500 eV. If the first two assumptions were not satisfied we underestimated the plasma energy while the third overestimated the energy by less than 15%. That no substantial error existed in calculating ion energy distributions has been confirmed by agreement between Thomson-scattering measurements[5] and Fokker-Planck calculations of electron temperatures for ion energy distributions determined on the basis of the above assumptions. Nevertheless the major uncertainties in determining β were from the mean ion energy, since the magnetic field and density were each known within 10%.

We select the highest energy-density shots from 2XII with each guide field (0.5, 1.0, and 2.0 kG) and plot the plasma energy density $n\overline{E}$ versus the magnetic field energy B^2 in Fig. 2. Further variation of B^2 comes from the time dependence of the pulsed field. Data before 100 μsec were excluded to allow time for the plasma to relax collisionally from the injected distribution. The slope of $n\overline{E}$ versus B^2 is proportional to β. After 100 μsec, β is observed to decrease as plasma is lost through the mirrors. We draw two conclusions from these data: (1) The initial β was high, 0.3 to 0.4, for all guide fields; and (2) the initial energy density was higher for higher guide fields. This indicates that at lower fields, the plasma was β limited, rather than limited by injector output.

As hydromagnetic instabilities are predicted to limit β we have evaluated the theoretical stability boundaries for the interchange, firehose, and mirror instabilities using 2XII parameters.

After 100 μsec, the radial magnetic well is deep enough[7] (10^{-3} at the edge of the plasma) to stabilize the interchange instability for $\beta_\perp \leq 1$. Before this time, low-β interchange stability is

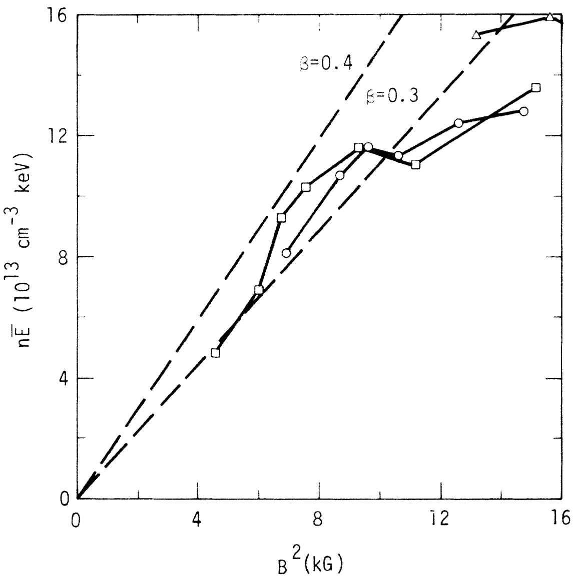

FIG. 2. Energy density of plasma versus energy density of the magnetic field for guide fields of 0.5 kG (squares), 1.0 kG (circles), and 2.0 kG (triangles). Constant-β lines are shown for comparison.

expected, but high-β instability cannot be ruled out.

The firehose and mirror instabilities arise from anisotropies in the plasma pressure. The firehose instability is caused by an excess parallel pressure such that[8]

$$B - 4\pi\, dp_{\parallel}/dB < 0.$$

The centrifugal force of streaming plasma then unstably increases the curvature of field lines. A collisional mirror-contained angular distribution[9] is prediced to be stable to the firehose mode for all β. This instability is unlikely to occur after 100 μsec in 2*X*II, when the distribution is well randomized, but cannot be ruled out at earlier times, i.e., during plasma trapping.

The mirror instability[10] arises from an excess of perpendicular pressure if[8,11]

$$B + 4\pi\, dp_{\perp}/dB < 0.$$

This results in the magnetic field expanding perpendicularly which increases the mirror ratio and traps more particles causing further ballooning.

We compare the measured β with the maximum β (β_c) allowed by the mirror instability in a collisional,[9] needle-shaped plasma in Table I. The theoretical β limit and the maximum experimental β are seen to be equal within 20%. This comparison is made for a collisional angular distribution since the ion-ion scattering time from the loss cone to 90° is about 100 μsec. After 400 μsec the angular distribution has been measured to be nearly collisional.[12] If the plasma were not yet fully collisional, the energy measured at 90° would be underestimated, since higher energy ions scatter more slowly, and the negative region of $dp_{\perp}/dB$ would occur at larger values of B; hence both the experimental values and theoretical limits of β would be underestimated.

TABLE I. Comparison of the maximum experimental β with the β limit for the mirror instability, β_c, for various magnetic guide fields B_{dc} and mirror ratios R all measured at time t. (Data are from Fig. 2.)

B_{dc} (kG)	t (μsec)	B^2 (kG)	R	β_c	β
0.5	130	6.8	2.26	0.43	0.37
1.0	120	8.7	2.08	0.40	0.33
2.0	100	13.2	1.80	0.32	0.32

Further experimental evidence of a β limit came from several shots in which the density was observed to decrease, beginning at 60 μsec and continuing for 20 to 40 μsec, then to resume increasing as expected for adiabatic compression. Figure 1 shows the density versus time for one such shot (1.0-kG case in Fig. 2). β was high in every such shot (averaging 0.29 ± 0.06 at 100 μsec) leading us to interpret the density decrease as a manifestation of a β limit.

We ascribe the time dependence of the density decrease to that of the theoretically derived maximum β (β_c) for equilibrium with the mirror instability. The critical β depends on mirror ratio, and is thus time dependent as the 2*X*II mirror ratio peaks at 60 μsec (when the fast gate peaks). The mirror ratio then decreases until 100 μsec, as the 400-μsec risetime minimum B field becomes dominant, as shown in Fig. 1. Thus, if β were near β_c at 60 μsec, a decrease in plasma density or energy would be required to maintain β at or below β_c between 60 and 100 μsec. Comparing β_c with β from every shot that exhibited such a density decrease, we find that $\langle\beta/\beta_c\rangle$ at 100 μsec was 0.69 ± 0.15. Therefore, both the time behavior of the density of these high-β shots and the magnitude of the maximum observed β were consistent with β limited by the mirror instability.

In conclusion, we have measured the containment of high-β plasmas ($\beta \simeq 0.3$ to 0.4) in the 2XII magnetic mirror device and have observed evidence of a β limit. The magnitude and time dependence of this limit were consistent with those predicted for the mirror instability.

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Dynamics of Charged Macromolecules in Solution*

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Analysis of the scattered intensity and photocount correlation function of light scattered from charged R17 virus indicates incipient macromolecular ordering.

If a coherent light source is focused on a macromolecular solution, fluctuations are observed in the scattered light intensity. Fluctuations result since motion of the particles produces a constantly changing interference condition at the detector.[1] If the positions of the particles are uncorrelated, it is well established that the decay rate of intensity fluctuations is directly proportional to macromolecular diffusion constant.[2]

In the case of solutions in which the range of interparticle interaction is comparable to the interparticle distance d, macromolecular dynamics have remained quite obscure. This is the case, not only because of the theoretical difficulties associated with many-body systems, but also because of limited experimental data. In order to elucidate this problem we present data on both the magnitude and time dependence of light scattered from solutions of charged macromolecules (R17 virus) in which the range of the electrostatic interaction σ is comparable to d. Both the scattered intensity and the decay rate Γ of the field correlation function depend strongly on scattering angle indicating incipient translational ordering. These data are interpreted by the Zwanzig-Mori projection-operator formalism,[3-5] through which we demonstrate that the dependence of Γ on scattering angle is largely