Stabilization of a Neutral-Beam–Sustained, Mirror-Confined Plasma*

F. H. Coensgen, W. F. Cummins, B. G. Logan, A. W. Molvik, W. E. Nexsen, T. C. Simonen, B. W. Stallard, and W. C. Turner
Lawrence Livermore Laboratory, University of California, Livermore, California 94550
(Received 22 September 1975)

We report results of plasma confinement experiments with an auxiliary warm-plasma component flowing along magnetic field lines to suppress ion-cyclotron instabilities. The reduced plasma losses, with the lower fluctuation amplitude, permits neutral-beam buildup of a 13-keV deuterium plasma to densities as high as 4×10^{13} cm^{-3} corresponding to peak beta values of 0.4. Variation of the beam energy demonstrates that longer confinement times are achieved at higher ion energies.

With the demonstration of high-β magnetohydrodynamic confinement in minimum-B magnetic wells,[1-3] the subject of plasma loss due to microinstabilities in mirror-confinement systems became an even more central issue. Microinstabilities[4,5] driven by velocity-space and spatial density gradients are theoretically predicted to be stable in large machines but unstable for present-size plasmas. However, in 2XII experiments,[1] quiescent plasmas were observed without fresh titanium gettering of vacuum-chamber walls. Quiescent plasmas with poorer vacuum conditions were attributed to plasma production, both exterior and interior to the mirrors, from ionization of recycled gas. These quiescent conditions contrasted with higher vacuum operation in which ion-cyclotron fluctuations were observed.[1,6,7] A recent quasilinear theory[8] shows that observed fluctuation amplitudes can generate sufficient warm plasma to fill the mirror-loss cone to provide marginal stability.

The 2XIIB magnet is similar to that of 2XII.[1] 2XIIB magnet parameters are 6.7-kG central field, 2:1 mirror ratio, and 150 cm between mirrors. In this minimum-B magnet system, a plasma with the following parameters is produced: $\leq 5\times10^{13}$ cm^{-3} density, 14 cm mean diameter, 2 to 5 keV mean ion energy, 80- to 150-eV electron temperatures, and 0.2- to 0.4-msec plasma confinement times. This plasma forms a target for ionization of atoms from an array of twelve neutral-beam injectors.[9] In these experiments, up to 260 A of equivalent atom current were injected at extraction energies of 15 to 19 keV, with approximately 50% being trapped by the plasma. The current was divided approximately 0.5, 0.4, and 0.1 between full-, half-, and third-energy components, respectively.

In 2XIIB, neutral-beam injection increased mean ion energies from 3 to 13 keV. Neutral-beam injection, without streaming plasma, increased the fluctuation level with no net improvement in particle confinement.

Plasma confinement was improved by injecting warm plasma[10] along magnetic field lines to reduce fluctuation levels, similar to experiments in the PR6 and PR7 devices.[7] Our streaming plasma is supplied from a standard 5-cm-diam, deuterium-loaded-titanium, washer gun[11] operated with a 1.1-msec-duration pulse line.[12]

Vacuum-chamber-wall conditions play a critical role in achieving the results described here. Before each shot, a titanium film several monolayers thick was deposited over the 60-m^2 surface area of the primary vacuum chamber and over an equal area in the beam injection tanks. Without neutral-beam injection, this reduced the background gas flux below 5×10^{15} atoms cm^{-2} sec^{-1} at the plasma surface. Neutral-beam injection produced intense charge-exchange wall bombardment, increasing the background gas flux to approximately 1×10^{16} atoms cm^{-2} sec^{-1}, resulting in charge-exchange lifetimes of about 4 msec.

Figure 1(a) shows line-density measurements with neutral-beam injection with plasma stream on and off. For comparison, we show in Fig. 1(b) the peak potential fluctuation amplitude $\tilde{\varphi}$ (in the frequency range $0.8 < \omega/\omega_{ci} < 1.2$) measured with an electrostatic probe beyond the mirrors.[6] Since turbulent scattering rates depend on $\tilde{\varphi}^2$, these reductions in fluctuation amplitudes, with streaming plasma, correspond to order-of-magnitude reductions in scattering loss rates. As seen in Fig. 1(b), with streaming plasma, noise bursts appear during stabilized operation with high beam currents at high densities. Without the stream the plasma becomes quiescent

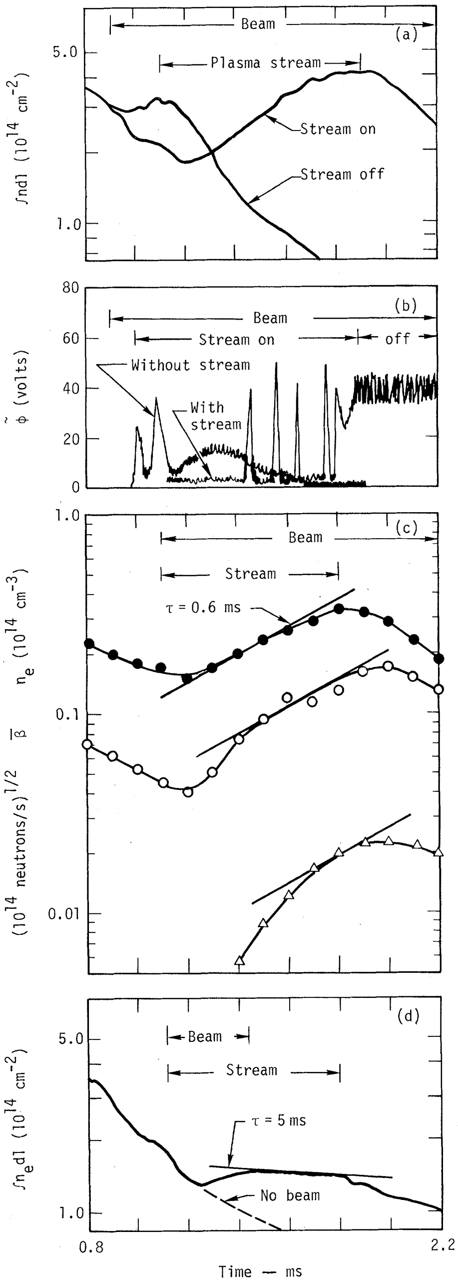

FIG. 1. (a) Line density with and without plasma stream; (b) ion-cyclotron instability amplitude with and without plasma stream; (c) density, diamagnetic-loop, and neutron measurements with plasma stream; (d) line density decay after neutral-beam turnoff with plasma stream.

late in time when the neutral background density rises relative to the plasma density; stabilization results from plasma produced by ionization.

The buildup of plasma line density [Fig. 1(a)] is due predominantly to buildup of a hot-ion plasma, rather than that of a warm component. This conclusion is based on the agreement, shown in Fig. 1(c), between magnitudes and buildup rates of density, plasma diamagnetism, and the square root of neutron production. We define plasma beta as $\beta = n_e \overline{W}_i/(B_0^2/8\pi)$, $\hat{\beta}$ as the peak value determined from the measured central density and energy, and $\bar{\beta}$ as the average value determined by diamagnetic loop.

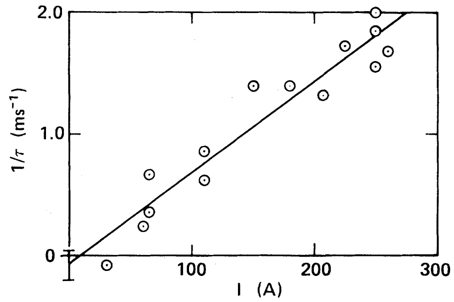

FIG. 2. Density buildup rate versus neutral beam current.

The buildup of density n is described by

$$\frac{1}{\tau}=\frac{1}{n}\frac{dn}{dt}=\frac{1}{n_h+n_W}\left[\frac{dn_h}{dt}+\frac{dn_W}{dt}\right],$$

where n_h and n_W are the hot- and warm-plasma densities. Assuming a constant warm-plasma density, n_W, the density buildup rate is

$$\frac{1}{\tau}=\frac{1}{n_h+n_W}\frac{dn_h}{dt}=\frac{Il}{eV}[\sigma_i+\alpha\sigma_x]-\frac{1-\alpha}{\tau_L}. \qquad (1)$$

Here l and V are the plasma diameter and volume, while σ_i and σ_x are ionization and charge-exchange cross sections. An upper limit to the fraction of warm plasma $\alpha = n_W/(n_h+n_W)$ is estimated from line-density measurements to be ~0.2. Equation (1) includes inputs due to ionization on both hot and warm components as well as charge exchange on the streaming component. The loss time, τ_L, includes Coulomb scattering, electron drag, charge exchange on background gas, instabilities, and any residual particle input due to trapping of the streaming plasma by processes other than charge exchange with the neutral beam, such as trapping by rf electric fields. As discussed above, for the data shown in Fig. 1 such trapping is small compared to the neutral-beam trapping rate. Charge-exchange losses from background gas, and wave-scattering losses, though strongly suppressed by gettering and streaming plasma, are not negligible on the long confinement-time scales of the present

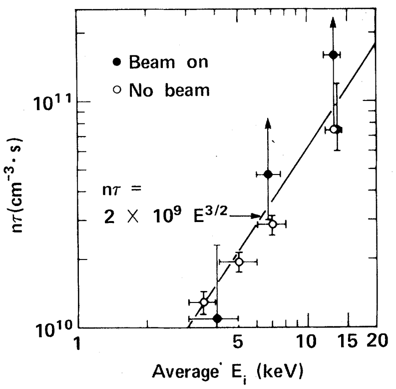

FIG. 3. Measured $n\tau$ versus average ion energy.

experiments.

Figure 2 shows, as a function of injected beam current, experimental τ^{-1} values obtained from microwave interferometer measurements during periods when fluctuations are suppressed. The zero-current intercept of Fig. 2 determines a lifetime τ_L of about 10 msec for $\alpha = 0.2$ with a 5-msec lower standard-deviation limit. The upper limit is indeterminate, since statistically the τ^{-1} intercept could be positive.

Of particular importance are measurements of τ_L versus average ion energy for stabilized plasma. Figure 3 shows solid circles for τ_L values determined from the intercept of curves such as in Fig. 2 and open circles for measurements obtained by switching off the neutral beam input and measuring the plasma density decay rate as in Fig. 1(d). These data, taken at a density of 1.5 $\times 10^{13}$ cm^{-3}, show confinement time increasing with ion energy. For comparison, a curve is shown, $n\tau = 2\times 10^9 E_i^{3/2}$. The coefficient of this curve is about a third of that found in Fokker-Planck calculations[13] without the streaming plasma. Since our measurements were obtained in the presence of residual charge-exchange and fluctuation losses and during periods of a few hundred microseconds when the stabilizing plasma stream was on, agreement with steady-state Fokker-Planck calculations is not to be expected. Rather, this comparison demonstrates that other loss processes have been significantly reduced.

To summarize, the experiments reported here demonstrate a means of suppressing microinstability amplitudes such that losses associated with these waves are reduced. Filling the loss cone is a plausible theoretical explanation[8] for the observed stability although there are no direct measurements to identify this specific mechanism. This plasma stabilization method has permitted us to obtain the following significant results with neutral-beam injection: (a) increase of ion energy from 3 to 13 keV, (b) density build-up to 4×10^{13} cm^{-3}, (c) achievement of peak plasma betas up to 0.4, and (d) increased $n\tau$ with increased mean ion energy.

We wish to thank A. S. Derheimer, C. Gormezano, and E. J. Powers for helping with diagnostic measurements; T. K. Fowler, R. F. Post, D. E. Baldwin, H. L. Berk, and L. D. Pearlstein for theoretical discussions; and our Livermore colleagues and the Berkeley neutral-beam group for technical assistance.

*Work performed under the auspices of the U. S. Energy Research and Development Administration.

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