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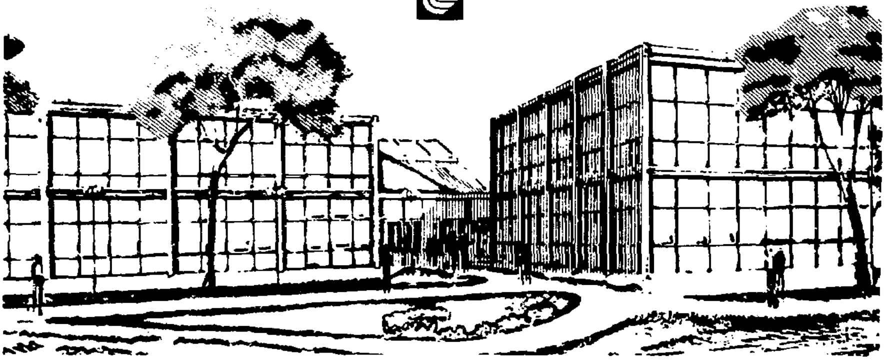

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ABSTRACT

This paper reports results of 2XIIB neutral-beam injection experiments with plasma-stream stabilization. The plasma stream is provided either by a pulsed plasma generator located on the field lines outside the plasma region or by ionization of neutral gas introduced at the mirror throat. In the latter case, the gas is ionized by the normal particle flux through the magnetic mirror. A method of plasma startup and sustenance in a steady-state magnetic field is reported in which the plasma stream from the pulsed plasma generator serves as the initial target for the neutral beams. After an energetic plasma of sufficient density is established, the plasma generator stream is replaced by the gas-fed stream. Lifetimes of the stabilized plasma increase with plasma temperature in agreement with the plasma stabilization of the drift-cyclotron loss-cone mode. The following plasma parameters are attained using the pulsed plasma generator for stabilization: $\hat{n} \approx 5 \times 10^{13}$ cm^{-3}, $\bar{W}_i \approx 13$ keV, $T_e = 140$ eV, and $n\tau_p \approx 7 \times 10^{10}$ cm$^{-3}\cdot$s. With the gas feed, the mean deuterium ion energy is 9 keV and the peak density $\hat{n} \approx 10^{14}$ cm^{-3}. In the latter case, the energy confinement parameter reaches $n\tau_E = 7 \times 10^{10}$ cm$^{-3}\cdot$s, and the particle confinement parameter reaches $n\tau_p = 1 \times 10^{11}$ cm$^{-3}\cdot$s.

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1. INTRODUCTION

Several results from the 2XIIB magnetic-mirror confinement experiment are reported in this paper. In these experiments using injected neutral beams, it is necessary to stream warm plasma along the magnetic field lines [1] to obtain improved ion confinement and to produce high plasma betas. The stream reduces the amplitude of ion-cyclotron fluctuations and, consequently, the turbulent diffusion loss of ions. The experimental results are described in considerable detail by the quasilinear theory [2,3] for the drift-cyclotron loss-cone (DCLC) mode [4]. Earlier experimental results [5,6] are also explained by this theory. According to this theory, the ion velocity distribution evolves to a marginally stable state as turbulent diffusion from either the hot-ion population or from an external stream fills in the ambipolar hole. In the latter case, the hot-ion confinement is improved.

The 2XIIB magnet is a minimum-B, Yin-Yang set with a 0.67-T central field, a 2:1 mirror ratio, and 150-cm mirror-to-mirror length. The size of the magnet is similar to that of the 2XII magnet but differs in that it has considerably larger openings for neutral-beam injection. The 2XIIB neutral-beam system consists of 12 injectors [7] operating with extraction energies between 15 and 20 keV. Up to 4.8 MW of neutral deuterium atoms with an equivalent current of 370 A have been injected. This current is divided between full-, half-, and one-third-energy components. The stream is supplied either by a deuterium-loaded-titanium washer gun [8] or by ionization of gas injected at the mirror throat as shown in Fig. 1.

We discuss two modes of operation of the 2XIIB device. In the first, described in Section 2, the target plasma is formed by trapping and adiabatically compressing a plasma injected along a magnetic field in the manner of the previous 2XII experiments [6]. In this mode, the target plasma has a density $n_e \approx 4 \times 10^{13}$ cm^3, mean ion energy $\bar{W}_i \approx 3$ keV, and electron temperature $T_e \approx 100$ eV. Approximately 50% of the neutral beam injected into this target is trapped by charge exchange and ionization; the mean ion energy of the contained plasma is raised to 13 keV within a few hundred microseconds. In the second mode of operation, described in Section 3, plasma and beam injection begin after the magnetic field has reached its maximum. In this mode, beam trapping and exponentiation are initiated on the colder and lower-density plasma stream in a quasisteady-state magnetic field.

2. STREAM STABILIZATION AND ENERGY SCALING

The data in Fig. 2, taken with a plasma target trapped and heated by magnetic compression, show the effect of the stabilizing plasma stream. Neutral-beam injection begins at the peak of compression (1.1 ms). With the plasma stream, the neutral-beam current and duration are 200 A and 1.6 ms; without the plasma stream, they are 200 A and 1.2 ms.

Figure 2(a) shows the central plasma electron density $\hat{n}_e$ versus time. These data were obtained by dividing microwave interferometer measurements of line density by the measured (14-cm) mean plasma diameter [9]. The plasma target densities are comparable with and without streaming plasma. With no stream, the neutral beam maintains the density for a brief 0.3 ms. Afterwards, the beam input rate cannot overcome the plasma losses due to the increasing amplitude of the ion-cyclotron fluctuations. By contrast, the density with a plasma stream continues to build up until the neutral beams are shut off.

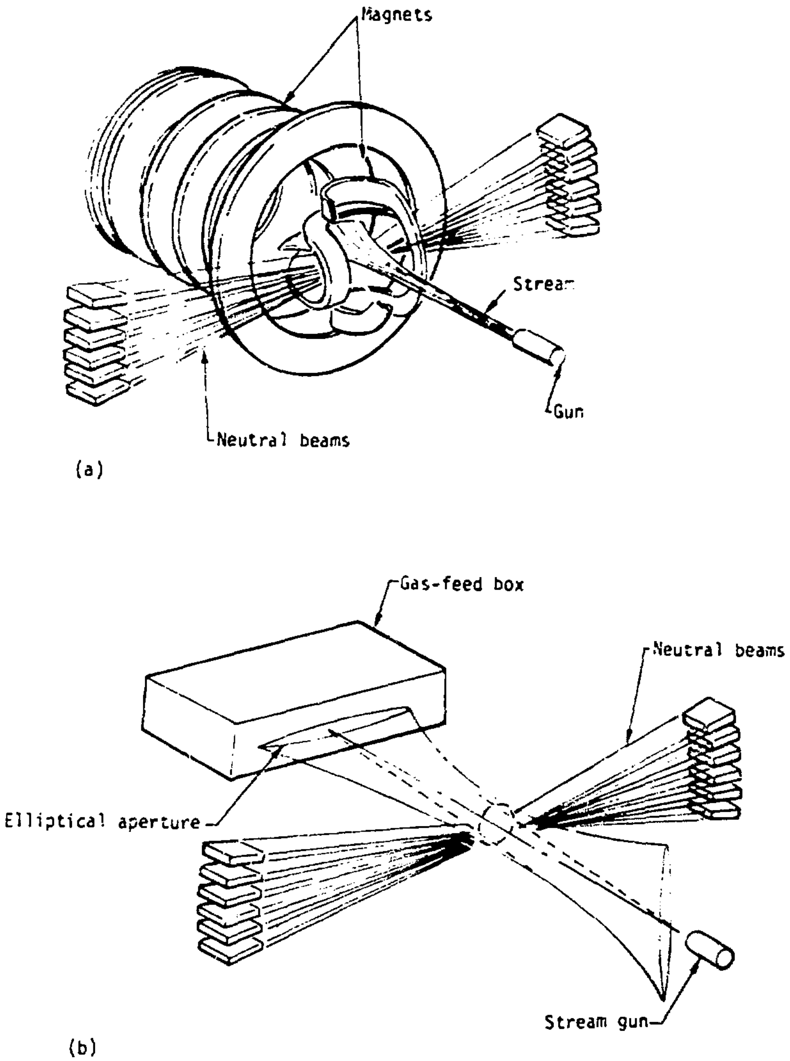


Fig. 1. Schematic diagrams illustrating (a) injection of plasma stream and (b) injection of gas at mirror throat.

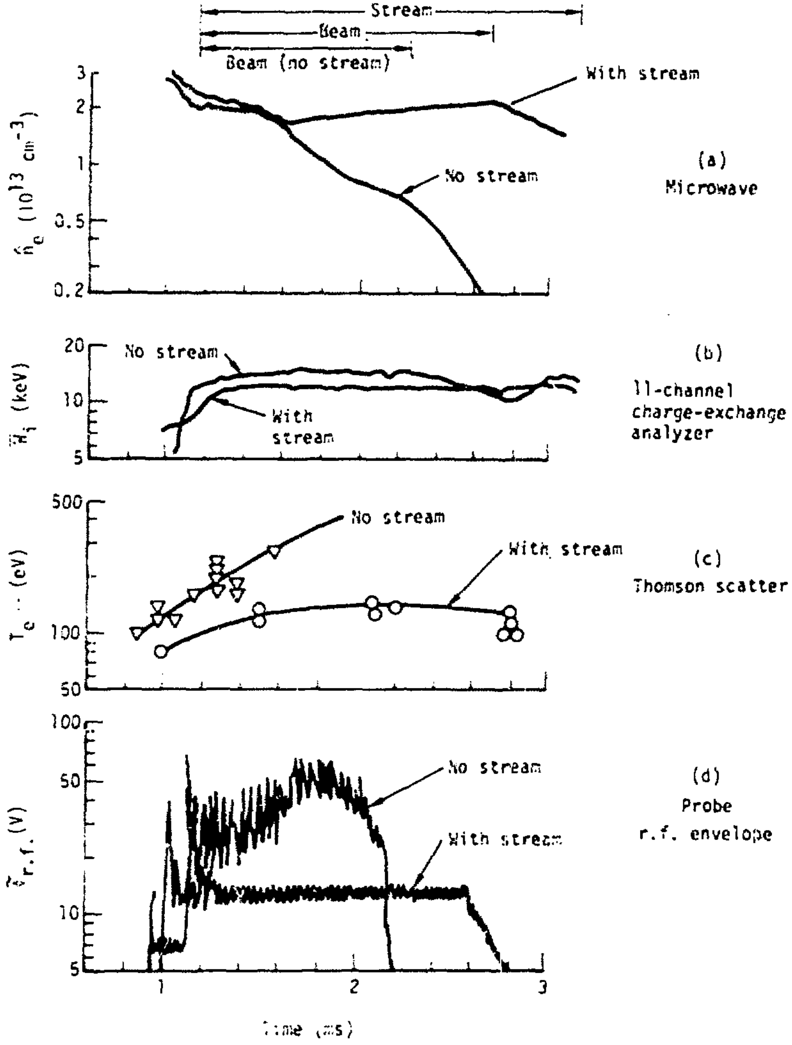


Fig. 2. Plasma parameters versus time, showing that the plasma stream (a) permits density buildup, (b) results in small decrease in average ion energy, (c) cools electrons, and (d) reduces ion-cyclotron fluctuations.

The mean deuteron ion energy is shown in Fig. 2(b). Without the stream, the mean ion energy increases rapidly. With the streaming plasma, the mean ion energy rises more slowly to 12 keV within 0.3 ms of beam turn-on. The 12-keV mean ion energy has been verified by absolute measurements of fast-atom charge-exchange flux, plasma diamagnetism, and absolute measurements of neutron production [10].

Electron temperature versus time measurements were made by Thomson scattering. In Fig. 2(c), the electron temperature with no stream rises rapidly to 250 eV. With the stream, the electron temperature increases from 75 eV to about 140 eV in 0.5 ms, and then remains relatively constant.

Ion-cyclotron fluctuations are detected with electrostatic probes [11] located beyond the mirrors and with microwave beams [12] at the center of the plasma. Figure 2(d) illustrates that the stream lowers the ion-cyclotron fluctuation amplitude by a factor between 2 and 4. Increasing the streaming-plasma input further reduces the fluctuation amplitude. The large decrease in fluctuation amplitude at 2.2 ms with no stream occurs when the hot-plasma density drops to a low enough level that the plasma is stabilized by background cold gas, much the same as in partially gettered operation [5,6]. The dominant fluctuation frequency is centered near the ion-cyclotron frequency [13], corrected for finite beta. Experimental observations of turbulent ion energy diffusion are obtained from measurements of charge-exchange flux at 12 discrete energies from 0.5 to 36.9 keV. The observed diffusion is reproduced theoretically by the quasilinear theory [14].

Longitudinal density measurements [9] with a movable microwave interferometer indicate that the axial plasma length is ~40 cm. Inverting this density profile [15] determines an ion-angular distribution peaked nearly perpendicular to magnetic field lines. This distribution indicates that the ions, injected near 90°, diffuse primarily in the perpendicular velocity direction by electron drag and wave turbulence, rather than in pitch angle, in agreement with the quasilinear theory.

The scaling of the plasma confinement parameter $n\tau_p$ with mean ion energy has been determined from 3 to 15 keV by varying the neutral-beam extraction voltage. Particle lifetime τ_p is obtained from the density decay rate after the neutral beams are turned off [1,16]. Such measurements indicate that particle confinement increases with ion energy, from $n\tau_p \approx 1.5$ to 2.0×10^{10} cm^{-3}·s at 3 keV up to $n\tau_p \approx 7 \times 10^{10}$ cm^{-3}·s at 15 keV. The beam current required to sustain the plasma at 10^{13} cm^{-3} density decreases with mean ion energy, indicating improved energy confinement at higher ion energies.

Energy confinement time τ_E is calculated from energy balance once steady state is achieved. Quantitative determination of τ_E is not available because the power input from the streaming gun is not well known. However, with gas-feed stabilization and with all power being supplied by the neutral beams, $n\tau_E = 7 \times 10^{10}$ cm^{-3}·s.

Electron temperature measurements using Thomson scattering are available for a limited number of shots and indicate a slow increase in electron temperature with ion energy. The hot-ion cooling rate depends on the electron temperature and follows the Spitzer [17] drag dependence $n\tau_d = 4.4 \times 10^7 \, T_e^{3/2}$ over a range of electron temperatures $30 < T_e < 140$ eV.

3. HIGH-BETA BUILDUP IN A STEADY MAGNETIC FIELD

We have found that the streaming plasma used for stabilization can be injected into a quasi steady-state magnetic field to form a suitable target plasma [18]. With an injected beam current of 260 A, the data in Fig. 3(a) show that the density of the hot plasma increases exponentially, reaching densities and energies similar to those achieved previously with target plasmas that were trapped by pulsed magnetic fields. The points are computed from a density buildup code [19]. This procedure offers a simple solution to the important technical problem of plasma startup in d.c. magnetic-mirror machines.

Using a single deuterium-loaded-titanium washer gun to provide startup and stabilizing plasma stream, a maximum beam-injected plasma beta of 0.4 is reached. Here beta is defined by $\beta \equiv 8\pi \hat{n}_i \bar{W}_i/B_{vac}^2$, where $\hat{n}_i$ is the central hot-ion density, $\bar{W}_i$ is the average ion energy, and B_{vac} is the applied central field. The beta is limited by end losses associated with periodic bursts of ion-cyclotron fluctuations and not by the available neutral-beam current. Increasing the amount of stabilizing plasma stream with three guns raises the beta to 0.6, but β is again limited by the same phenomenon.

To further increase the plasma stream, a gas-feed system [20] was installed as shown in Fig. 1(b). A ceramic box, with elliptical apertures conforming to the flux tube passing through a 12-cm-diam circle at the central midplane, is located just beyond one mirror throat of the minimum-B field. Hydrogen or deuterium gas is injected at a controlled rate into the box above and below the plasma fan by four pulsed gas valves. Gas neutrals are ionized in the box by electrons ($T_e \approx 100$ eV) conducted along the field from the central plasma. Because the mean free path of gas neutrals is short compared to the thickness of the plasma fan, few neutrals leak out of the box. Measurements of charge-exchange flux from the center of the machine indicate a charge-exchange lifetime on background gas greater than 5 ms. This loss rate was negligible compared to other losses of the hot ions.

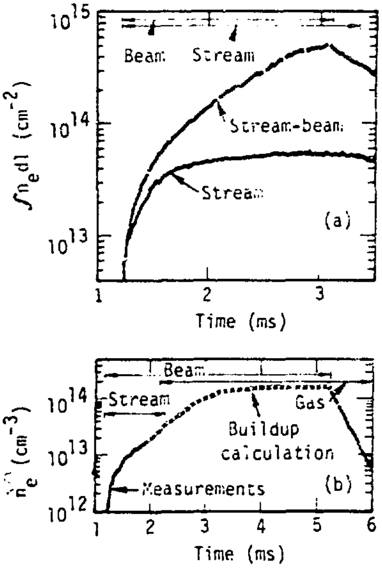


Fig. 3. Density buildup history on streaming plasma target, showing (a) $\int ndl$ without gas feed and (b) $\hat{n}_e$ with 8000-A hydrogen gas feed.

To start ionization of injected gas, a hot plasma is initially created as described above. Figure 3(b) shows buildup with 225-A of beam injection. The guns are turned off, and gas injection begins with 8000-A atom equivalent of hydrogen gas. The central density reaches 1.5×10^{14} cm^3 and is sustained for the duration of beam injection. No strong bursts of ion-cyclotron fluctuations are observed, indicating that the stabilizing plasma is not limited with the gas feed. Similar results were obtained with deuterium.

The dots shown in Fig. 3(b) are obtained by fitting the observed time dependence of the plasma density to the rate equation

$$\frac{dn}{dt} = a(1 - e^{-bn}) - \frac{n^2}{\langle n\tau_p \rangle} . \tag{1}$$

The coefficient a is the beam current trapped per unit volume calculated for Gaussian plasma and beam density profiles and taking into account reionization of charge-exchange neutrals. The parameter $b = \langle \sigma v \rangle (2\bar{r}_p)/v_b$ is an attenuation factor averaged over the energy components of the neutral beam. Here, $\langle n\tau \rangle$ is a density-independent loss parameter, appropriate for particle loss by ion-ion scattering and electron drag. For a constant 10% fraction of cold plasma, the best fit of Eq. (1) to the measured density buildup gives a plasma volume V = 4.5 litres (defined by $\hat{n}_e V$ = total number of particles), and $\langle n\tau_p \rangle = 1.2 \times 10^{11}$ $cm^{-3} \cdot s$.

Hydrogen was used in the gas feed with deuterium neutral-beam injection so that hot beam-injected ions could be distinguished from warm ions trapped from the streaming plasma by the mass-selective neutral analyzer. At the high-density saturation, after correcting for reionization of charge-exchange neutrals the mean ion energy was calculated to be 9 keV. The maximum fraction of cold ions, hydrogen, and impurities is estimated to be less than 20%.

The dashed line in Fig. 4 shows the average plasma diamagnetism $\overline{\Delta B}/B_{vac}$ measured by a compensated diamagnetic loop around the vacuum chamber. The excluded flux of the plasma is normalized to the total flux excluded by a field-free metal object ($\Delta B = B_{vac}$) of the same volume as the plasma, placed at the position of the plasma for calibration. For constant plasma dimensions, the measured diamagnetic flux will be proportional to the average field reduction $\overline{\Delta B}/B_{vac}$ within the plasma. Because of the substantial reduction in field, the mean ion gyroradius is comparable to the plasma radius. Accordingly, the frequency of ion-cyclotron fluctuations decreases with $\overline{\Delta B}/B_{vac}$, as indicated by the point labeled ($\Delta\omega_{ci}/\omega_{ci\ vac}$) in Fig. 4.

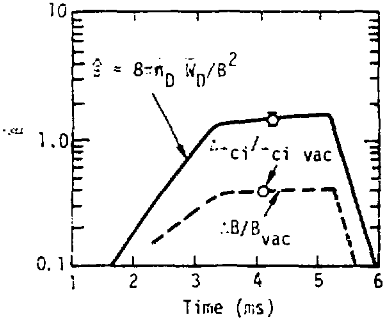
The solid line in Fig. 4 gives the peak value $\hat{\beta}$ obtained from the measured central density $\hat{n}_D$ and average ion energy $\bar{W}_D$. The central beta reaches a value well above unity. The error bar shows the uncertainty in peak density and cold plasma fraction. Because of the short axial length of the plasma ($L_p/r_p \approx 3$) and the high plasma pressure, the field lines are likely to have substantial curvature; therefore, a central beta value of roughly 2 is required to depress the on-axis field to zero.

Figure 5 shows how the energy confinement parameter $\hat{n}\tau_E$ scales with neutral-beam current I_b for constant average beam energy $\bar{E}_b$. The average plasma energy lifetime in steady state is calculated from

$$\tau_E = (\hat{n}_D V)\bar{W}_D/(f I_b \bar{E}_b) . \tag{2}$$

In Eq. (2), the numerator is the energy content of a total number of ions ($\hat{n}_D V$) at average energy $\bar{W}_D$ = 9 keV, and the denominator is the fraction f

Fig. 4. Central values of beta, diamagnetic flux, and ion-cyclotron frequency shift versus time.



of incident beam power that is absorbed in the plasma. This fraction varies with density, but it reaches typical values of 0.6. At I_b = 225 A, $\hat{n}\tau_E = 7 \times 10^{10}$ $cm^{-3}\cdot s$. Averaging over an ion orbit from the center of the plasma rather than taking the central density gives $n\tau_E \approx 5 \times 10^{10}$ $cm^{-3}\cdot s$. At I_b = 225 A, a Thomson scattering measurement of the central electron temperature T_e = 100 ± 20 eV gives a confinement parameter of $n\tau_d = 4.4 \times 10^{10}$ $cm^{-3}\cdot s$ ± 30% due to electron drag. Thus, ion losses are largely accounted for by classical electron drag, consistent with the quasilinear theory for marginal stability [2]. Figure 5 shows that the central beta increases with beam current (at constant beam energy), with no apparent saturation. No evidence is found of a beta limit due to the mirror mode, the Alfvén ion-cyclotron mode, or nonadiabatic effects. Comparison of diamagnetic measurements with density measurements indicates that the energy of the plasma ions remains approximately constant with increasing beta. The energy containment time τ_E is found to be nearly constant over the range of beam current shown in Fig. 5. The product $n\tau_E$ in Fig. 5

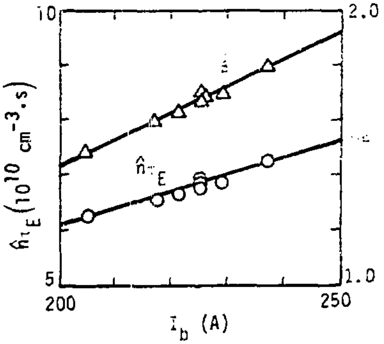


Fig. 5. Energy confinement $\hat{n}\tau_E$ and $\hat{\beta}$ increase with neutral-beam current I_b.

increases proportionally to beta (density) as the beam power is increased. Preparations are underway to pursue this favorable scaling of $\hat{n}\tau_E$ to higher neutral-beam power.

4. CONCLUSIONS

In summary, the principal results of the 2XIIB experiments are:

- Demonstration that stabilization is provided by a small fraction of warm plasma.
- Demonstration of plasma heating and sustenance by neutral-beam injection.
- Demonstration that the plasma confinement parameters $n\tau_p$ and $n\tau_E$ increase with ion energy.
- Achievement of startup in a steady-state magnetic field.
- Attainment of central plasma beta greater than unity.

Two fundamental properties of mirror systems are shown: the increase in $n\tau$ with ion energy and the ability to contain high-beta plasmas. The energy scaling and the satisfactory theoretical interpretation of these data establish a basis for the design of future open-geometry experiments. The high-beta result has particular significance for mirror fusion reactor design, since high-beta operation enhances the fusion energy balance.

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