the appropriate time and space averages involved are such as to leave some doubt. It is hoped to resolve this by further computations.

Summarizing, we see that the computation described above exhibits similar features to those observed in tokamak experiments and also gives support to Kadomtsev's interpretation of these observations.

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Startup of a Neutral-Beam-Sustained Plasma in a Quasi-dc Magnetic Field*

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Warm plasma has been injected along field lines into a quasi-steady-state magnetic mirror in the 2XIIB experiment. This has provided a suitable target plasma for density buildup and heating with neutral-beam injection. With the injection of 310 A equivalent of 14-keV deuterium atoms, the density exponentiated to 3.7×10^{13} cm^{-3}, the average ion energy increased to 12 keV, and the β reached 0.4. A rate equation describing the density buildup is given.

The initial production and maintenance of a dense, energetic plasma in a steady-state magnetic mirror field has been a major experimental problem in the field of plasma physics. A number of possible solutions have been pursued, most of which involve the creation of a target plasma suitable for buildup and heating by neutral-beam injection. Only recently has neutral-beam current greatly exceeding the equivalent of 10 A become available[1] to test these methods. Previous experiments, which were limited to evaluating the major problems, are summarized below. Creation of plasmas by Lorentz ionization of energetic neutrals[2-6] has been limited by instabilities to densities up to 10^{10} cm^{-3}. Electron-cyclotron-resonance breakdown and heating of a background gas resulted in stable hot-electron plasmas with β's of 0.5.[7] (β is defined as the ratio of the plasma pressure to the vacuum magnetic field pressure.) However, the densities have been limited to less than 10^{12} cm^{-3}. Experiments in which plasmas are produced by laser irradiation of a pellet are in progress.[8,9] Other target plasmas that have been tried or suggested include arc discharges[10,11] and an injected plasma heated and trapped by electron-cyclotron resonance.[12]

Dense, high-energy and high-β, mirror-confined plasmas have been achieved in the 2*X* series of experiments.[13,14] These experiments used fast-pulsed magnetic mirrors for trapping and heating of an injected plasma. We have achieved densities $n_e \leqslant 10^{14}$, ion energies $E_i \leqslant 10$ keV, mean target diameters $10 \leqslant l \leqslant 19$ cm, and ratios of plasma density to external neutral density $n_e/n_0 \geqslant 100$. Calculations have shown that such plasmas can be sustained by trapping hot ions from neutral beams to balance losses, primarily charge exchange on cold gas and Franck-Condon neutrals.[15] In fact, this plasma was demonstrated to be a suitable target for buildup with neutral beams in 2XIIB if stabilized with streaming plasma.[16] The major disadvantage of this technique is the difficulty of combining pulsed trapping fields with dc magnetic field reactors.

This paper discusses experiments in 2XIIB which show that the streaming plasma used previously for stabilization forms a suitable target plasma for neutral-beam injection in a quasi-steady-state magnetic field. In fact, with neutral-beam injection, the plasma builds up to densities and energies equal to those achieved previously with pulsed magnetic fields.

The streaming plasma is created with a standard 5-cm-diam deuterium-loaded–titanium washer gun[17] operated with a 2.2-msec duration pulse line.[18] The gun current is normally 4 kA and the voltage across the terminals is ~250 V. Calorimetric measurements indicate that at least a third of the input power is transferred to the streaming plasma. Since the plasma is produced from gas occluded in the titanium-washer electrode, the gas efficiency of the discharge is high; no evidence has been found of an appreciable neutral-gas component due to the discharge.

We approximate a steady-state magnetic field by delaying the injection of the plasma stream and neutral beams until the pulsed magnetic field reaches its maximum value. During the 2-msec duration of the streaming plasma, the central magnetic field decays from 6.8 to 6.0 kG.

The streaming plasma has a measured 7.5-cm-diam circular cross section near the plasma gun. As shown in Fig. 1, the plasma fans out horizontally as it moves along the minimum-B magnetic field lines that map into a 0.7×23-cm ellipse in the containment region. The plasma evolves to a circular cross section in ~1 msec. Twelve neutral beams[1] are injected within 10° of parallel to the major diameter.

The streaming-plasma-line density, measured across the minor diameter in the containment region, is shown in Fig. 2. Without neutral-beam injection, the streaming plasma reaches a central line density $\int ndl = 5\times 10^{13}$ cm^{-2}. The average ion energy is less than 1 keV. The external plasma between the gun and the mirror increases with time, reaching $n_e \sim 10^{14}$ cm^{-3}. The external electron temperature, measured by Thomson scattering, is ~60 eV—high enough that these electrons do not greatly cool central electrons and cause excessive ion energy loss. The slow decay of the streaming-plasma density in Fig. 2, following the turnoff of the streaming-plasma gun at 3.4 msec, indicates that much of the central plasma is mirror trapped, perhaps by the low-level turbulence present. This conclusion is based on the much more rapid drop of external density at this time.

Injecting 310 A equivalent of deuterium atoms at 14 keV simultaneously with streaming-plasma injection results in a buildup of line density to $\int ndl = 4.8\times 10^{14}$ cm^{-2} within the 2-msec stream duration (Fig. 2). This line density is an order of magnitude greater than that with stream alone, and equals the best previously achieved with the aid of a target plasma trapped by pulsed magnetic fields.[16] As before, the plasma is stabilized by the stream. After the stream gun shuts off at 3.4 msec, turbulence increases the ion loss rate and neutral-beam injection no longer sustains in the plasma. The plasma-density profile is determined by measuring neutral-beam attenuation through chords of the plasma. This yields a mean diameter of 13 cm which, when combined with the microwave measurement of line density, gives a maximum central density of 3.7×10^{13} cm^{-3}. From the measured plasma density at the magnetic mirrors, we estimate an upper limit on the ratio of stream to total central plasma density of 10 to 15%. The central electron temperature is 100 eV, measured by Thomson scattering. A 12-keV average ion energy is measured with

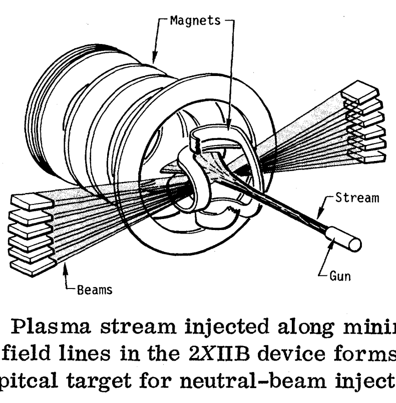

FIG. 1. Plasma stream injected along minimum-B magnetic field lines in the 2XIIB device forms an initially ellipitcal target for neutral-beam injection.

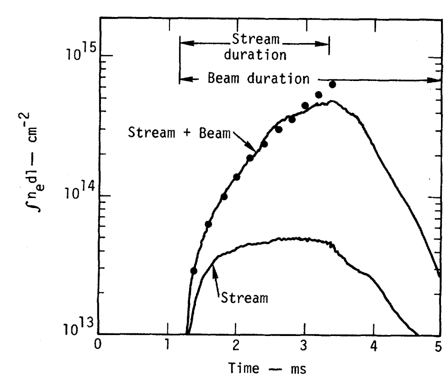

FIG. 2. Central plasma line density is plotted versus time with streaming plasma alone, and with the addition of the 310-A equivalent of 14-keV deuterium-atom beams. The dots show the density buildup calculated from Eq. (1).

an eleven-channel charge-exchange analyzer. This energy is in agreement with the D-D neutron production rate. We calculate a maximum β of 0.4, corrected for the estimated 15% warm-plasma density.

We interpret the trapped-density buildup (Fig. 2) with the injected neutral beam as buildup by ionization and charge exchange on the streaming plasma plus buildup by ionization on the already-trapped plasma. The trapped plasma includes a warm component from the stream and a hot component from the beam. These considerations lead to the following rate equation:

$$\frac{dn_t}{dt}=\frac{(\langle\sigma_i v\rangle+\langle\sigma_x v\rangle)l_s f_s I n_s}{v_b e V_t}+\frac{\langle\sigma_i v\rangle l_t f_t I n_t}{v_b e V_t}-\frac{n_t}{\tau}, \quad (1)$$

where σ_i and σ_x are the ionization and charge-exchange cross sections, and v_b and v are the neutral-beam and relative particle-beam velocities averaged over the measured ion distribution. The neutral-beam-trapping efficiency factor, f, is averaged over the profiles of plasma density, n, and beam current, I. The plasma volume is V, l is the plasma diameter, and τ is the lifetime due to all loss mechanisms. The subscripts s and t refer to the untrapped streaming plasma and to the trapped plasma, respectively.

Taking the loss rates to be small and treating the coefficients of n_t as adjustable parameters, we obtain the best fit to Eq. (1), shown by the dots in Fig. 2. Known values for the parameters in this model give calculated coefficients within a factor of 2 of the best-fit values. From the agreement with the data, we conclude that Eq. (1) furnishes a reasonable description of the observed buildup by neutral-beam injection on the streaming-plasma target.

Initially, with n_t small, the buildup proceeds linearly in time. Then, as n_t increases, the buildup becomes exponential and finally saturates. The saturation in density is due mainly to losses during bursts of ion-cyclotron fluctuations. The bursts are believed to occur when the plasma density exceeds a value for which the amount of streaming plasma can provide stability.[19] Such losses are not included in this model.

We check the assumption of small loss rates by evaluating the main particle-loss mechanisms of the stream-stabilized plasmas. In the absence of bursting, these are charge exchange on the background gas and ion losses from the lower-energy end of the ion-energy distribution due to electron cooling and low-level wave dissusion.[19] In the neutral-beam-injected plasma, losses due to electron drag and diffusion are reduced by charge exchange on the neutral beam which replaces a cooler ion by one at the injected energy. From Eq. (1), we obtain the condition for exponentiation:

$$I>\frac{v_b e V_t}{(\langle\sigma_i v\rangle)l_t f_t}\left(\frac{1}{\tau}\right). \quad (2)$$

Using measured values $V_t\approx 4.5$ l and $f_t=0.55$, we find the condition for exponentiation with 14-keV injection is $I(\mathrm{A})>210/\tau(\mathrm{msec})$. Initially, trapped ions are lost primarily by charge exchange on cold gas with a lifetime of 4 msec; therefore, $I>52$ A is required for exponential buildup. Thus, for the 310-A case of Fig. 2, we have neglected the loss term in the buildup calculations.

The advantages of using the stream plasma produced by a washer gun for startup of a neutral-beam-sustained plasma in a steady-state magnetic field include the following: (i) the equipment is relatively simple; (ii) target plasmas of large cross section can be produced with multiple guns; (iii) the gas efficiency of plasma production is high; (iv) the electron temperature is high, so electron drag times for ion energy loss exceed 1 msec; and (v) the same plasma that provides the target also stabilizes ion-cyclotron-frequency instabilities in a magnetic mirror field.[16]

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Quantum Mechanical Theory of Hydrogen Diffusion*

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A quantum mechanical description of low-concentration hydrogen diffusion is presented. Using the Kubo formula for the diffusion coefficent, harmonic wave functions for the hydrogen atoms, and polaronic wave functions for the lattice, an exact expression for the diffusion coefficent can be found. Two interesting predictions of the theory are (i) a decrease in the activation energy with mass for fcc metals, in agreement with experiment, and (ii) an activated form for diffusion between localized states even in the purely tunneling regime.

The diffusion of hydrogen in metals at room temperatures and above has been observed to display features which are not well described by simple classical diffusion theories.[1,2] In particular, the mass dependence of the diffusion constant is strongly dependent on lattice structure and is often found to be highly nonclassical both in the prefactor and in the activation energy.

There have been many attempts to improve the simple classical theory by including a variety of effects[3-5] (e.g., anharmonicity, zero-point motion, and a realistic description of the saddle-point dynamics). However, the applicability of these theories to hydrogen diffusion has not been established.[1,3] Indeed, in a system in which the energy between vibrational eigenstates of the hydrogen atom corresponds to 1370 K,[6] as for niobium, a basically quantum mechanical model is more appropriate. Until now all quantum mechanical treatments of the diffusion process have been restricted to simpler models than presented here: either neglecting the polaron effects[7,8] that