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A LOW ENERGY NEUTRAL SOURCE FOR FUELING THE CENTRAL CELL CORE PLASMA OF TMX-U

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INTRODUCTION AND SUMMARY

In this report we consider the performance of a low energy neutral source formed by negatively biased plates inserted in the edge plasma of the central cell of the Tandem Mirror Experiment-Upgrade (TMX-U). This technique promises to be capable of fueling the high density thermal barrier plasmas. We have found that annular ring electrodes mounted on the sides of the central cell gas box and inclined 45° to the plasma axis can produce about 80 A of inward-directed D^0 with an average energy $E_0 \approx 250$ eV (where the plate bias = -400 V). [Recall that the central cell gas box is located at $z = 325$ cm where $B = 5$ kG and the average plasma ellipticity is $\varepsilon = (1.16 + 1.38)/2 = 1.27$.]

This example was calculated for a peak plasma density $n_e(0) = 10^{13}$ cm^{-3} and an edge plasma density $n_L = 10^{12}$ cm^{-3} at the limiter edge defined by the biased plates. The energetic neutrals, attenuated by about an e-fold in reaching the plasma center, are thus much more efficient in fueling the core plasma than Frank-Condon atoms, which are attenuated by greater than a factor of 100. In addition, because their energy is greater than Frank-Condon atoms their initial collisional trapping rate in the thermal barrier is reduced by a factor of approximately $(100)^{3/2} = 1000$.

This technique will work as the sole source of fueling only if good confinement is achieved--roughly equal to that anticipated for thermal barrier operation. Specifically, if the plasma is sustained solely by the neutral source described, then the implied central cell confinement is $\tau_p \approx 20$ ms and the time for charge-exchange replacement of bulk ions by injected neutrals is $\tau_{cx} = 7.5$ ms. This constraint does not derive directly from the physics of confinement but follows from the observation that the edge plasma density

n_L in TMX-U scales linearly with the density on-axis [specifically $n_L = 0.1\ n_e(0)$]. The resulting formula is

$$\tau_p = \frac{2.5}{R_N} \frac{r_L L_c}{a_L \left(\frac{kT_e}{m_i}\right)^{1/2}} \left(\frac{\langle\sigma v\rangle_{cx} + \langle\sigma v\rangle_i}{\langle\sigma v\rangle_i}\right) \tag{1}$$

$$\approx 20\ \text{ms} \quad ,$$

where R_N = ion-neutral reflection coefficient = 0.37, r_L = limiter radius ≈ 20 cm, L_c = central cell plasma length ≈ 500 cm, a_L = e-fold length of edge plasma ≈ 6 cm, and T_e = edge plasma electron temperature = 10 eV. Obviously this constraint would be removed if the edge plasma density could be controlled independently of the core density. If we suppose, however, that $\tau_p \approx 20$ ms is achieved and the source works as described, then $n_e(0) \approx 10^{13}\ \text{cm}^{-3}$ and the 90° ion-ion scattering time is

$$\tau_{ii} = \frac{3.5 \times 10^{10}}{n_e(0)} T_{ic}^{3/2} \tag{2}$$

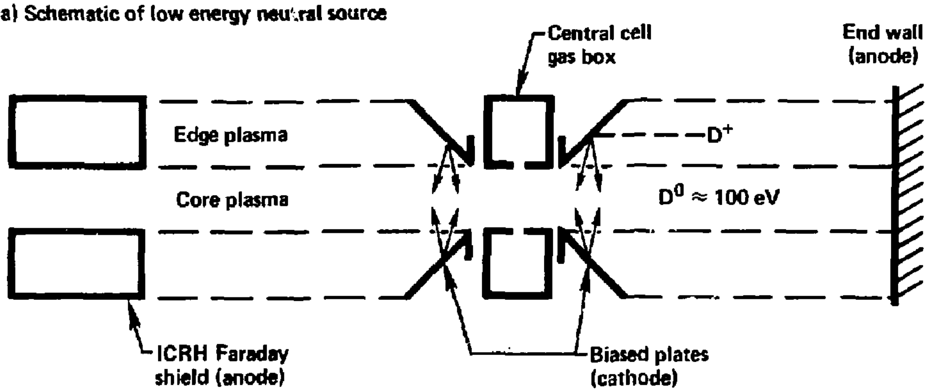
$$\approx 3.5\ \text{ms} \quad ,$$

for a central cell ion temperature T_{ic} = 1 keV. Therefore we would be in the desired regime where $\tau_{ii} < \tau_{cx}, \tau_p$. Then the ion-cyclotron resonant heating (ICRH) of the parallel ion temperature should be observed, and there is a good chance we can keep the barrier pumped at high density. These conditions would demonstrate thermal barrier confinement and not merely mirror confinement at high density.

A schematic of the low energy neutral source now being installed on TMX-U is shown in Fig. 1. The reflection coefficients for the copper cathodes are illustrated in Fig. 2. Figure 3 shows the neutral current expected from the biased plate on one side of the gas box as a function of the bias voltage V_b and the edge plasma density n_L. These and other details are described in the sections below.

It seems clear that there is much to be gained by fueling with a low energy neutral source compared with cold gas fueling at the edge. If the scheme described here fails, we should continue our search for alternate fueling as a high priority.

(a) Schematic of low energy neutral source



(b) Axial potential in the edge plasma

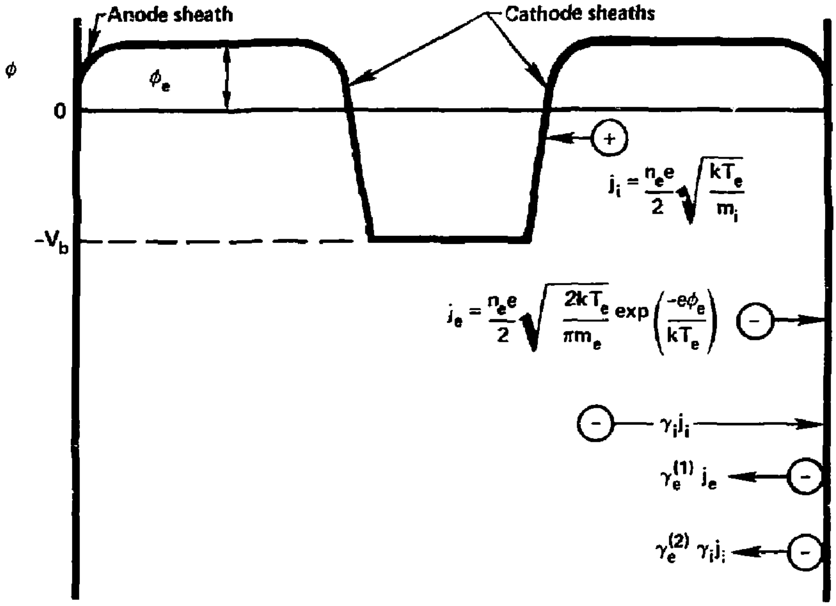


Fig. 1. Schematic of the low energy neutral source planned for fueling the core plasma in the central cell of TMX-U.

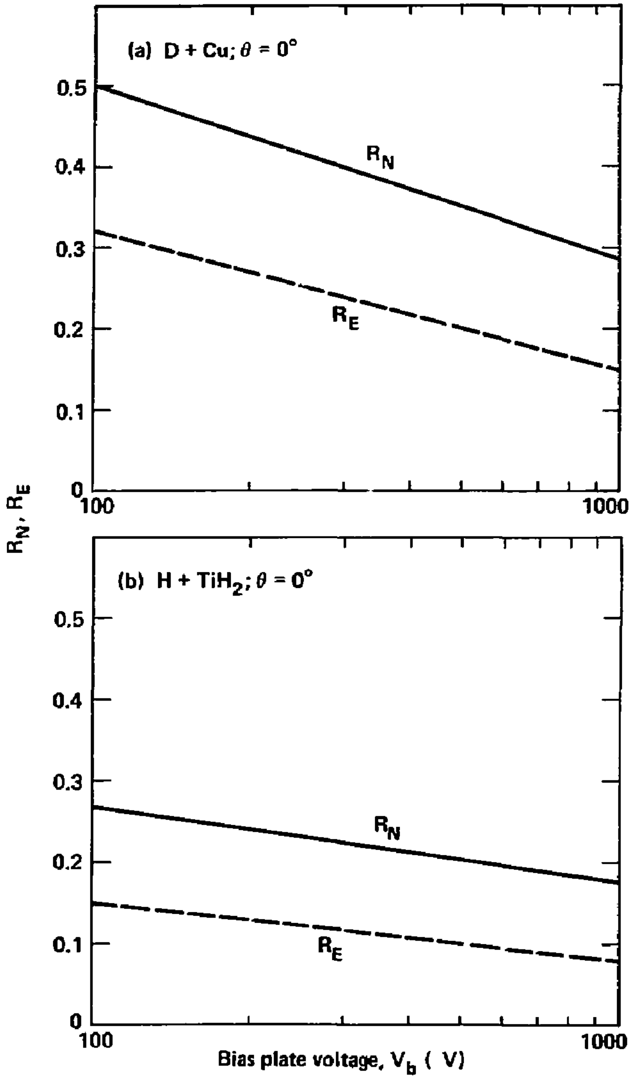


Fig. 2. Reflection coefficients using data from Ref. 2.

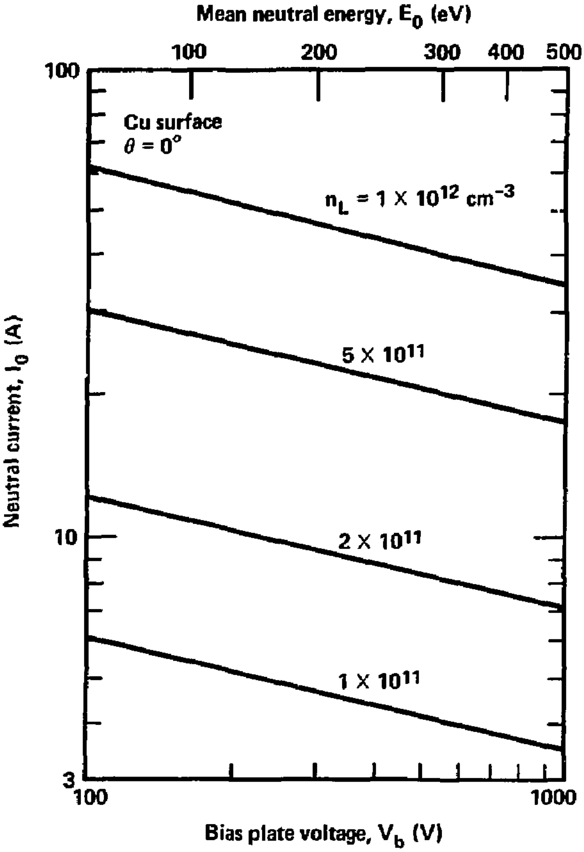


Fig. 3. Neutral current from a biased Cu plate in the TMX-U central cell. Note that for the Cu surface, $\theta = 0°$ and $T_e = 10$ eV. The term n_L refers to the limiter density.

SCHEMATIC OF THE LOW ENERGY NEUTRAL SOURCE

As depicted in Fig. 1, metallic plates are mounted on either side of the central cell gas box ($z = 225$ cm, $B = 5$ kG) and are biased negatively in the range of -500 to -1000 V to create a low energy neutral source. Ions from the edge plasma are accelerated across the cathode sheath and neutralized upon striking the plates, and a fraction are reflected inward toward the plasma core with an average kinetic energy in the range of 250 to 500 eV. Because the edge plasma in which the plates are immersed is already flow-confined between material boundaries, the insertion and biasing of the plates should not perturb n_e or T_e. The ion current density reaching the biased plates is simply the ion saturation current

$$j_i = \frac{n_e e}{2} \left(\frac{kT_e}{m_i} \right)^{1/2} \quad . \tag{3}$$

An axial profile of the potential in the edge plasma is sketched at the bottom of Fig. 1. A few Debye lengths ($\lambda_D \approx 0.002$ to 0.007 cm) away from the plates the potential rises from the plate bias $-V_b$ to a positive potential ϕ_e determined by quasi-neutrality. The current density of thermal electrons reaching the anode is then

$$j_e = \frac{n_e e}{2} \left(\frac{2kT_e}{\pi m_e} \right)^{1/2} \exp -(e\phi_e/kT_e) \quad . \tag{4}$$

Secondary electron emission modifies ϕ_e only slightly from its usual value of $\phi_e/kT_e = 3.9$. An electron current $\gamma_i j_i$ leaves the cathode. (Note that γ_i is the secondary electron emission coefficient for ions.) Because these electrons gain energy (500 to 1000 eV) as they are accelerated into the plasma, they pass freely through the anode sheath, yielding a secondary electron emission current $\gamma_e^{(2)} \gamma_i j_i$ leaving the anode. Similarly, thermal electrons reaching the anode release a secondary electron emission current $\gamma_e^{(1)} j_e$. Quasi-neutrality then requires that

$$[1 + \gamma_i \, \gamma_e^{(2)}] \, j_i = [1 - \gamma_e^{(1)}] \, j_e \quad ,$$

or

$$\frac{e\phi_e}{kT_e} = \ln \left\{ \left(\frac{2m_i}{\pi m_e}\right)^{1/2} \frac{1 - \gamma_e^{(1)}}{1 + \gamma_i \gamma_e^{(2)}} \right\} , \tag{5}$$

$$= 3.5$$

where $\gamma_e^{(1)} \simeq 0.1$ for $T_e = 10$ eV, $\gamma_e^{(2)} = 1.3$ for $E_e = 500$ to 1000 eV, and $\gamma_i \simeq 0.2$ for $E_i \simeq 500$ to 1000 eV. Photo-emission has been neglected.

NEUTRAL ENERGY REQUIRED TO FUEL THE PLASMA CORE

To fuel the plasma core, we want the incident neutral energy $E_0 = 1/2\ m_D v_0^2$ to satisfy

$$\sigma_{eff} \int_0^{r_L} n_e dr \approx \frac{1}{\sqrt{2}} \to 1 \quad , \tag{6}$$

where the core plasma density may be approximated by a parabola

$$n_e = \hat{n}_e \left(1 - \frac{r^2}{r_L^2}\right) \quad , \tag{7}$$

and the effective absorbtion cross section is

$$\sigma_{eff} = \frac{\langle\sigma v\rangle_{ei}}{v_0} + \frac{\langle\sigma v\rangle_{cx}}{v_0} \quad . \tag{8}$$

We choose $\hat{n}_e = 10^{13}$ cm^{-3}, so the core plasma can be fueled for high density operation. The limiter radius of $r_L \approx 20$ cm yields

$$\sigma_{eff} \approx 5.3 \to 7.5 \times 10^{-15}\ \text{cm}^2 \quad . \tag{9}$$

Inserting $\langle \sigma v \rangle_{ei} \simeq 3 \times 10^{-8}$ cm^3/s and $\langle \sigma v \rangle_{cx} \simeq 8 \times 10^{-8}$ cm^3/s then gives

$$E_0 \simeq 250 \rightarrow 500 \text{ eV} \quad . \tag{10}$$

PROPERTIES OF THE EDGE PLASMA

Langmuir probe data outside the limiter derived by W. Hsu[1] typically give an electron temperature $T_e \approx 10$ eV and a density

$$n_e = n_L \, e^{\frac{-(r - r_L)}{a_L}} \qquad \text{for } r \geq r_L \quad , \tag{11}$$

where $a_L \simeq 6$ cm and the density at the limiter edge scales linearly with n_e but is less by a factor of 10:

$$n_L \simeq \frac{n_e}{10} \quad . \tag{12}$$

NEUTRAL CURRENT

The ion saturation current collected by the cathode on one side of the gas box is

$$I_s = \int_{r_L}^{r_L+\Delta} \frac{en_L}{2} \left(\frac{kT_e}{m_i}\right)^{1/2} e^{\frac{-(r-r_L)}{a_L}} \, 2\pi r dr$$

$$= \frac{en_L}{2} \left(\frac{kT_e}{m_i}\right)^{1/2} 2\pi r_L a_L \left(1 - e^{\frac{-\Delta}{a_L}}\right) \left(1 + \frac{a_L}{r_L} - \frac{\Delta}{r_L} \frac{1}{e^{\frac{\Delta}{a_L}} + 1}\right) \quad ;$$

$$I_s \simeq \frac{en_L}{2} \left(\frac{kT_e}{m_i}\right)^{1/2} 2\pi r_L a_L \quad , \tag{13}$$

where r_L = 18.4 cm and a_L = 6 cm; Δ = 10 cm is the radial width of the plates. Because the Debye length is much less than the ion gyroradius, ions will strike the inclined cathode at near normal incidence. Certain fractions (R_N of the incident ions and R_E of the incident energy) are reflected from the cathode as neutrals. The fractions R_N and R_E depend on the incident ion energy or cathode bias voltage V_b. These fractions, taken from Oen and Robinson,[2] are given in Fig. 2 for the Cu cathodes. The angular distribution of reflected neutrals closely follows a cos θ dependence from the normal to the reflecting surface. The neutral current and the mean neutral energy are given by:

$$I_0 = I_s R_N V_b \quad ;$$

$$E_0 = \left[\frac{R_E(V_b)}{R_N(V_b)}\right] V_b \quad . \qquad (14)$$

The term I_0 is plotted in Fig. 3 as a function of V_b for the edge plasma density n_L = 1 x 10^{11}, 2 x 10^{11}, 5 x 10^{11}, and 1 x 10^{12} cm^{-3}. The average neutral energy is given on the horizontal axis at the top of the figure. Note that the current in Fig. 3 is from one side only, so a factor of 2 increase in fueling current may be obtained by using both sides.

If the cathodes are gettered on, pure Ti is about as effective as Cu for reflecting neutrals. However, if the Ti becomes significantly loaded with hydrogen, the effectiveness is reduced. Figure 4 shows the result for a completely hydrided surface of TiH_2; the neutral current is reduced by about a factor of 2 compared to Cu. Thus, it is desirable to test this scheme before gettering in the vicinity of the gas box.

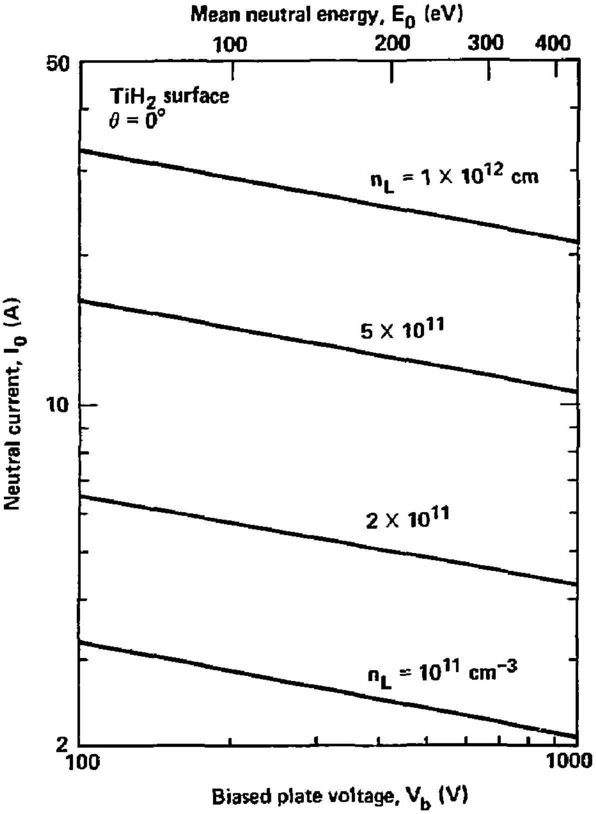


Fig. 4. Neutral current from a biased TiH_2 surface. Again, $\theta = 0°$ and $T_e = 10$ eV.

CONFINEMENT TIME

In general, for any plasma fueled by neutrals, the following relationship must be satisfied in steady state

$$\tau_{cx} = \left(\frac{\langle\sigma v\rangle_i}{\langle\sigma v\rangle_{cx}}\right) \tau_p \quad , \tag{15}$$

where τ_p is the particle confinement time and τ_{cx} is the time for replacement of the plasma ions by charge exchange on injected neutrals. If we also require that the plasma ions be isotropic so the passing central cell ions are heated by ICRH, then

$$\tau_{cx} > \tau_{ii} \quad ,$$

or

$$\tau_p > \frac{\langle\sigma v\rangle_{cx}}{\langle\sigma v\rangle_i} \tau_{ii} \approx 3\tau_{ii} \quad . \tag{16}$$

However, because of the linear relationship between the edge plasma and the on-axis densities, neutral fueling with a biased plate requires that an additional relationship for τ_p be satisfied.

Assuming that the sole source of plasma fueling is the technique described, the implied particle confinement time is

$$\tau_p = \frac{e}{2} \frac{n_e(0)\pi r_L^2 L_c}{I_0(1 - e^{-\mu})} \left[\frac{\langle\sigma v\rangle_{cx} + \langle\sigma v\rangle_i}{\langle\sigma v\rangle_i}\right] , \tag{17}$$

where μ is the beam absorbtion coefficient

$$\mu = \frac{4}{3} \sigma_{eff}\, n_e(0) r_L \quad . \tag{18}$$

Using Eqs. 12, 13, and 14, we find that

$$\tau_p = \frac{2.5}{R_N} \frac{r_L L_c}{a_L \left(\frac{kT_e}{m_i}\right)^{1/2}} \left[\frac{\langle\sigma v\rangle_{cx} + \langle\sigma v\rangle_i}{\langle\sigma v\rangle_i} \frac{1}{1 - e^{-\mu}} \right] , \tag{19}$$

where we have assumed fueling from both sides of the gas box. At high density $n_e(0) \approx 10^{13}$ cm^{-3}, $1 - e^{-\mu} \approx 1$, and τ_p is independent of density.

Inserting $R_N \approx 0.37$ for $E_0 \approx 250$ eV, $r_L = 30$ cm, $L_c = 500$ cm, $a_L = 6$ cm, $T_e = 10$ eV, $\langle\sigma v\rangle_{cx} = 8 \times 10^{-8}$ cm^3/s, and $\langle\sigma v\rangle_i = 3 \times 10^{-8}$ cm^3/s, thus yields $\tau_p \approx 20$ ms. The implication is that this technique will work only if the good confinement time anticipated for thermal barrier operation is achieved. This constraint arises because of the *linear relation observed in Eq. 12 between the core and edge density. The* time for charge-exchange replacement of bulk ions by injected neutrals is shorter than τ_p,

$$\tau_{cx} = \frac{\langle\sigma v\rangle_i}{\langle\sigma v\rangle_{cx}} \tau_p \tag{20}$$

$$\approx 7.5 \text{ ms} \quad .$$

At a density $n_e(0) = 10^{13}$ cm^{-3}, the ions will pitch-angle-scatter before being replaced by charge exchange on the source because

$$\tau_{ii} = \frac{3.5 \times 10^{10}}{n_e(o)} (T_{ic})^{3/2}$$

$$= 3.5 \text{ ms} \quad , \tag{21}$$

for $T_{ic} = 1$ keV. Therefore, appreciable ICRH heating of the ion parallel temperature should be observed.

The power lost from the charge exchange of bulk ions is

$$\frac{\langle\sigma v\rangle_{cx}}{\langle\sigma v\rangle_{cx} + \langle\sigma v\rangle_{i}} \quad I_0 \left(\frac{3}{2} T_{ic} - E_0\right) = 73 \text{ kW} \quad , \tag{22}$$

for $I_0 = 80$ A, $T_{ic} = 1$ keV, and $E_0 = 0.25$ keV. This power is roughly in the range of that which can be supplied by ICRH.

NEUTRAL DENSITY

Fueling the plasma with neutrals will always be limited because for each atom ionized, approximately three undergo charge exchange with a hot ion that is lost. There is a sizable gain (i.e., reduction in power lost by charge exchange), however, in fueling the core plasma with neutrals in the range of a few hundred electron volts rather than by Frank-Condon atoms with 2.5 eV. To estimate this gain, we have calculated the neutral density profiles required to achieve equal core fueling rates with both 250-eV and 2.5-eV neutrals.

For fueling with cold gas, Allen's gas code calculations[3] of the radial density of Frank-Condon neutrals $n_0(r)$ are reasonably well approximated by

$$n_0(r) = n_0(0) \quad , \qquad \text{for } \frac{r}{r_L} \leq 0.3 \quad ;$$

$$n_0(r) = n_0(0) \exp \sigma_{eff}\left(\int_{\frac{r}{r_L} = 0.3}^{\frac{r}{r_L}} n_e dr\right) , \quad \text{for } 0.3 \leq \frac{r}{r_L} \leq 1 \quad , \tag{23}$$

where $\sigma_{eff} = 7.0 \times 10^{-14}$ cm^2 is the effective cross section for absorbtion of 2.5-eV neutrals. The constant neutral density for $r/r_L < 0.3$ is caused by radial convergence in the cylindrical geometry. To estimate the radial neutral density profile for 250-eV atoms, we use the same formula with $\sigma_{eff} = 7 \times 10^{-15}$ cm^2. The neutral density profiles are shown in Fig. 5, normalized to the identical fueling rate [neutral density $n_0(0)$] in the core

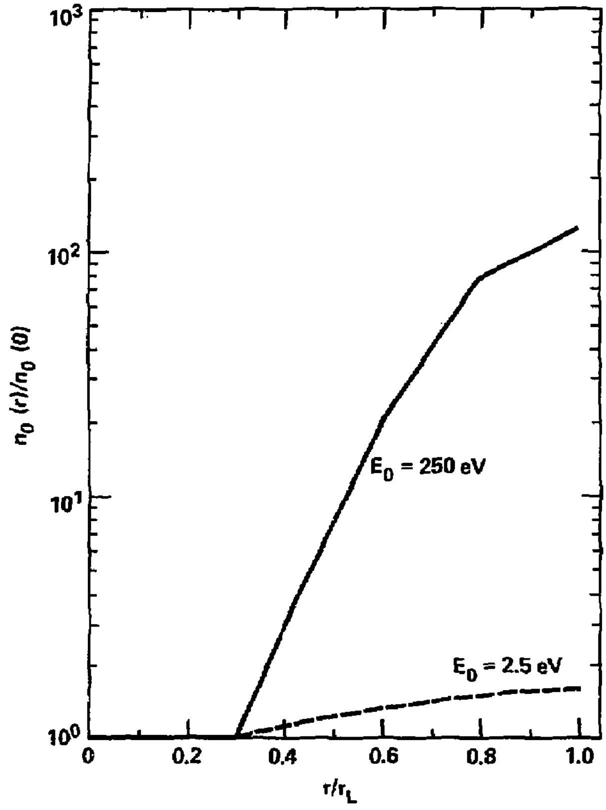


Fig. 5. Neutral density vs radius for neutral energies $E_0 = 250$ eV and $E_0 = 2.5$ eV. The calculations are normalized to an assumed constant neutral density inside a radius $r/r_L = 0.3$.

plasma $r/r_L < 0.3$. These calculations were performed for the high density case with $n_e(0) = 10^{13}$ cm^{-3}. We see that the neutral density profile is much flatter for the 250-eV atoms; at the plasma edge the neutral density is reduced by a factor of 80. This implies a much reduced volume-integrated loss of power from charge exchange. The volume-integrated charge exchange rate is

$$R_{cx} = \int_{r=0}^{r_L} 2\pi r dr \; n_0(r) n_e(r) \langle\sigma v\rangle_{cx} \quad . \tag{24}$$

For the plasma and neutral density profiles given in Eqs. 7 and 16, we obtain the reduction in charge-exchange rate for fueling with 250-eV atoms compared to 2.5-eV Frank-Condon atoms:

$$\frac{R_{cx}(E_0 = 250 \text{ eV})}{R_{cx}(E_0 = 2.5 \text{ eV})} \simeq \frac{1}{23.6} \approx 0.04 \quad . \tag{25}$$

The neutral current at the plasma edge is proportional to the product of the neutral density and velocity. The ratio of 250-eV fueling current to the current of the inward-moving Frank-Condon atoms required to achieve the same core neutral density is therefore reduced by

$$\frac{\dot{I}_0(250 \text{ eV})}{I_0(2.5 \text{ eV})} = \frac{1}{80} \times 10 \simeq \frac{1}{8} \quad . \tag{26}$$

REMAINING ISSUES

There are a number of uncertainties in the actual operation of the proposed device, including the four listed below:

Cathode spots

Cathode spots frequently are observed in high current discharges, giving rise to localized melting and emission of metallic vapor. Here the average current density is fairly low, typically 20 mA/cm^2. Also the occurrence of cathode spots can be reduced by conditioning.

Sputtering

Energetic neutrals can sputter metallic-surface atoms. Initially the cathode will be made of Cu because of its availability, but it is a poor choice for sputtering. Experimental data for 1-keV D^+ evident on Cu seems nonexistent, but the sputtering yield could be as high as 0.1 Cu atoms per incident D^+. It is unlikely that because of their slow velocity these atoms could reach the core plasma, but they could cool the edge plasma. The sputtering yield of molybdenum (Mo) is about 15 times less than Cu, and so we have ordered Mo to replace the Cu plates. During the next run, the 22-channel ultraviolet spectrometer will be placed to view axially through the central cell gas box; in this way we will be able to look for radial profiles of metallic as well as hydrogen emission lines.

Blistering

Thirty-to-fifty per cent of the ions striking the biased plates are reflected as energetic neutrals. The question is: what happens to the other 50 to 70%? Some of these may be trapped in the bulk material and eventually cause blistering and flaking of pieces, which can fall into the plasma.

Optimum Gas Box Fueling and Edge Plasma Parameters

Little is known about the fueling of the edge plasma and the extent to which it is fueled by radial transport or directly from cold gas. We may find that the intensity of the low energy neutral source is closely coupled to the gas fueling rate. The core density should be optimized with the gas fueling rate as an adjustable parameter. Also the biased plates work best at high density where there is sufficient edge-plasma density to provide 50 to 100 A of energetic neutrals. Early in time when the density is low ($\sim 10^{12}$ cm^{-3}), the energetic neutral current from the plates is also low and not efficiently absorbed by the plasma. Therefore, initial fueling will be by cold gas; then the gas fueling rate should be in the range of our earlier operation (20 to 30 Torr ℓ/s) and reduced as the density builds up. In addition, not too much is known about how the edge plasma is heated, although electron-cyclotron resonant heating (ECRH) undoubtedly plays an important role and perhaps so does ICRH. Finally, the edge plasmas on opposite sides of the gas box may be different because ECRH is on one side and the 2 x 170° ICRH antenna is on the other. We will be able to operate each side independently to see if there is any difference in the production of low energy neutrals.

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