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PLASMA WALL CHARGE EXCHANGE INTERACTIONS IN THE 2X118 MAGNETIC MIRROR EXPERIMENT

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ABSTRACT

Plasma-wall interactions by charge-exchange wall bombardment in the 2X118 magnetic mirror experiment are discussed. Experimental measurements are modeled with a time-dependent, radial density build-up calculation. A low-density plasma sufficient to help shield the hot interior plasma from cold-gas erosion, as required by the model, is measured.

This paper discusses wall bombardment by energetic charge-exchange atoms from the 2X118 mirror-confined plasma.^[1-4] Figure 1a illustrates the basic process. Neutral beam injection into the plasma results in energetic charge-exchange products bombarding the wall. Backscatter of primary atoms or gas released from the walls can cause charge-exchange loss on the plasma surface if it is not pumped away. To reduce the amount of particle reflux and gas release, the walls in 2X118 are getterted prior to each shot with several monolayers of titanium. This produces a cleaner surface with the ability to adsorb energetic atoms. Calculations described below show that if hot ions are lost at a rate equal to the charge-exchange loss rate on background gas, then the experimental measurements of buildup of hot-plasma density cannot be explained. This suggests that the hot interior is shielded from the cold gas by a region of lower density and temperature plasma as schematically illustrated in Fig. 1b. The required particle confinement in this shield is $n_{s_0} \sim 10^{13} \text{ cm}^{-3}$.

Figure 2 shows the outline of the plasma and vacuum chamber. The plasma volume is 4.5-6.5 liters, whereas the central vacuum chamber volume is 3,400 liters. The plasma radius is 7-8 cm, while the average vacuum chamber wall radius is about 50 cm. Along magnetic field lines, the plasma length is 25 to 40 cm, in contrast to the vacuum chamber length of 700 cm. The untrapped neutral beam is dumped into the opposite beam tank 190 cm from the plasma. The large vacuum chamber dimensions, relative to the plasma dimensions, help minimize the effect of plasma-wall interaction.

The principal 2X118 plasma parameters^[1-3] are $n_0 \approx 1.5 \times 10^{14} \text{ cm}^{-3}$, $\bar{v}_i = 3-13 \text{ keV}$, and

$T_0 \leq 65 \text{ eV}$. The plasma is sustained by a neutral beam system consisting of 12 neutral beam injectors operating with extraction energies as high as 20 keV. Up to 4.8 MW of deuterium atoms have been injected. The plasma is maintained in a condition of marginal stability, with respect to the drift-cyclotron loss-cone instability, by means of a low-energy plasma stream supplied either from a plasma gun or by ionization of gas supplied at the mirror throat.

The charge-exchange flux is peaked near 90° as indicated in Fig. 2 because ions are initially injected near 90° to the magnetic axis. The ions diffuse principally by electron drag and turbulent diffusion for waves with $k_\perp \ll k_\parallel$, which do not cause significant angular diffusion. For walls 50 cm from the plasma, the first-wall bombardment flux is $10^{17} \text{ atoms cm}^{-2} \text{ s}^{-1}$ at a peak power level of 200 W cm^{-2} for the 5-10 ms duration of the experiments.

The neutral charge exchange flux from the plasma surface is measured by an 11-channel analyzer in the range 0.5-39 keV. The measured increase of flux due to background gas is shown in Fig. 3 for 260 Amperes of injected neutral beam current. The background gas creating the charge exchange flux in the figure is produced by wall reflux of plasma ions which charge exchange on the neutral atom beam.

To a good approximation, the background gas density n_0 increases as

$$V \frac{dn_0}{dt} = r(1_{cx} + \frac{1}{4} n_0 v_0 A_p \alpha_x / \alpha_T) - \frac{1}{4} n_0 v_0 A_{\text{pump}} \quad (1)$$

where V is the volume filled by the gas with speed v_0 . The reflux coefficient r is the number of atoms from the wall per incident energetic charge-exchange atom. The first term in the parenthesis, 1_{cx} , is the charge-exchange current from the neutral beam on the hot plasma, while the second term is the charge-exchange current from background gas at the plasma surface. The effective pumping area for cold gas is $A_{\text{pump}} = A_p + s_w A_w + A_x$. Here A_p , A_w , and A_x are the areas of the plasma surface, wall, and external pumping opening, respectively, and s_w is the wall sticking coefficient. Charge-exchange and total ionization cross sections for cold gas are α_x and α_T , respectively. The source of cold gas is wall reflux of energetic charge-exchange neutrals, while pumping is by getterted walls, conducting apertures in the plasma chamber walls, and ionization by the plasma. The ionized gas is assumed to flow along field lines and out the mirrors into the end tanks.

The buildup of charge-exchange flux predicted by eq. (1) has been fitted to the data with the curve in Fig. 3 for two extreme limits. In the first limit, we assume a perfect beam dump, i.e. that untrapped beam current does not cause gas reflux. In the second

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limit, we assume that all the untrapped beam, as well as charge exchange current I_{cx} , causes gas reflux. In the first limit, we fit the measured data with $\tau = 1.5$ and v_0 corresponding to $E_0 = 14$ eV deuterium, whereas in the second limit we find $\tau = 0.5$ and $E_0 = 3$ eV.

The expected reflux coefficient has been estimated by averaging the backscattering coefficient, which is a function of energy, over the measured energy distribution of the particles bombarding the surface. For a typical 2XIB energy distribution bombarding a clean titanium surface at perpendicular incidence, this coefficient is estimated to be 0.15. The higher values needed to match the experiment are attributed to the angular dependence of backscatter coefficient and to release of gas from the surface.

A radial buildup code^[5] (BUILDUP III) computes time-dependent radial density profiles created by injection of neutral beams. This code balances the neutral beam input with particle losses due to Coulomb losses and erosion of the plasma boundary by background gas. The calculation is one-dimensional, assuming symmetry about the magnetic axis. Particle rate equations for plasma density are solved taking into account neutral beam attenuation and charge-exchange reactions between the injected beam atoms and the plasma ions. Finite Larmor radius effects are treated by simultaneously calculating the guiding center and plasma particle densities for the ions, assuming circular orbits.

In the calculation, three neutral beams are injected having a current profile similar to the experimental beams. To simulate buildup on a plasma stream, a time-independent, cylindrical plasma target is included in the code. The target density is adjusted to match the initial plasma buildup rates of the calculation and the experiment. To simulate the experimental measurements of plasma density buildup, several input parameters determined from experimental measurements are required. These include the particle confinement parameter n_1 , the plasma length measured from microwave interferometry, and the wall reflux coefficient obtained by the method already described.

The dashed curve in Fig. 4 shows a computed radial profile for $\lambda = 0$. The normalized profile is insensitive to charge-exchange losses since the plasma size is determined by beam geometry and plasma ion Larmor radius. Also plotted in Fig. 4 is a typical profile measured by neutral beam attenuation through several plasma chords for similar plasma conditions and a normalized Langmuir probe density measurement at 20 cm. The measured and computed profiles are in agreement.

Loss rates by charge exchange are comparable to beam trapping rates for the value of reflux coefficient inferred from the experiment. Consequently, the calculated time dependence of plasma buildup is strongly dependent on λ , as shown in Fig. 5. For these calculations, the computed buildup is insensitive to n_1 for $n_1 = 4 \times 10^{10} \text{ cm}^{-3}$. An important

result of the calculation is that good agreement between the experiment and calculation can be obtained only if charge-exchange losses on cold gas are neglected when beams are on during buildup. The calculated dashed curves are shown in Fig. 5 along with the line density measured by microwave interferometry (solid curve). However, if gas losses are included after beams are turned off, agreement is obtained for the plasma decay rate for values of f consistent with Fig. 3, as shown in Fig. 5. These calculations suggest that the plasma is shielded from cold-gas losses when beams are on.

Langmuir probe measurements indicate the presence of a plasma density in the 10^{11} cm^{-3} range with 16-eV electron temperature at a 20-cm radius. To attenuate several eV energy neutrals, a line density of 10^{13} cm^{-2} is sufficient. For a central density $n(0) = 5 \times 10^{13} \text{ cm}^{-3}$, the plasma is one mean free path thick to the gas at $r = 12 \text{ cm}$, as indicated schematically in Fig. 4.

The source of particles and energy for the shield are not clearly evident. However, the following picture is consistent with our present measurements. Particles are supplied to the shield from the cold gas and from the plasma stream. With beams on, the residual ion-cyclotron turbulence level is sufficiently high to heat and mirror trap some of these cold ions. Electrons are heated by these ions as well as by neutral-beam-injected ions trapped in the gas shield. When beams are turned off, the turbulence level decreases and the lifetime of cold ions in the shield is too short to maintain a sufficient density to attenuate the cold gas. Langmuir probe measurements indicate that the shield decays rapidly when the beams are turned off. The hot plasma then decays by charge-exchange erosion at the expected rate, as shown in Fig. 5.

In summary, the experimental plasma density measurements can be modeled by the buildup code if a plasma shield exists having sufficient density and energy to attenuate cold gas impinging on the plasma surface. Two important consequences of the plasma shield are: first, a reduction in the ion heat loss by cold-gas charge exchange since a relatively cool ion is lost rather than a hot ion; and second, that particle input to the plasma boundary need not be supplied by neutral beam trapping alone.

FIGURE CAPTIONS

Fig. 1

Plasma charge-exchange interaction with vacuum chamber wall. (a) cold gas penetrates directly to the interior and (b) cold gas is shielded from the interior by a boundary layer.

Fig. 2

To-scale schematic of 2X11B plasma and central vacuum chamber. Neutral beam injection is from two 23,000-liter tanks (not shown).

Fig. 3

Measured and calculated charge exchange flux versus time.

Fig. 4

Measured and calculated radial density profile normalized to central density.

Fig. 5

Measured and calculated line density buildup with 260-A, 14-keV neutral beam injection.

REFERENCES

- [1] COENSGEN, F.H., CUMMINS, W.F., LOGAN, B.G., MOLVIK, A.W., NEXSEN, W.E., SIMONEN, T.C., STALLARD, B.W., and TURNER, W.C., "Stabilization of a Neutral-Beam-Sustained, Mirror-Confined Plasma", Phys. Rev. Lett. 35, 1501, p. 1501-1503 (1975).
- [2] COENSGEN, F.H., CUMMINS, W.F., GORMEZANO, C., LOGAN, B.G., MOLVIK, A.W., NEXSEN, W.E., SIMONEN, T.C., STALLARD, B.W., and TURNER, W.C., "Startup of a Neutral-Beam-Sustained Plasma in a Quasi-dc Magnetic Field", Phys. Rev. Lett. 37, 143 p. 143-146, (1976).
- [3] COENSGEN, F.H., CUMMINS, W.F., GORMEZANO, C., LOGAN, B.G., MOLVIK, A.W., NEXSEN, W.E., SIMONEN, T.C., STALLARD, B.W., and TURNER, W.C., "2XIIB Plasma Confinement Experiments", Proc. Sixth Conf. Plasma Physics and Controlled Nuclear Fusion, Brechtsgarden, Oct. 1976.
- [4] SIMONEN, T.C., BULMER, R.H., COENSGEN, F.H., CUMMINS, W.F., GORMEZANO, C., LOGAN, B.G., MOLVIK, A.W., NEXSEN, W.E., TURNER, W.C., STALLARD, B.W., VOGTLIN, G.E., and VANDERVOORT, R.R., "Control of First-Wall Surface Conditions in the 2XIIB Magnetic Mirror Plasma Confinement Experiment", UCRL 77600 (1976) and to be published in J. of Nuclear Materials.
- [5] STALLARD, B.W., "Radial Plasma Buildup Code for Neutral Beam Injection into a Mirror Machine", Lawrence Livermore Laboratory, UCRL 51784 (1975).

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