FAST-ION ORBIT EFFECTS DURING ION-CYCLOTRON

RANGE OF FREQUENCY EXPERIMENTS ON THE

PRINCETON LARGE TORUS

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ABSTRACT

The angular dependence of the flux of fast neutrals was measured in conjunction with Ion Cyclotron Range of Frequency (ICRF) experiments on the Princeton Large Torus (PLT). We found a regime where the energetic tail of the charge-exchange neutral flux was strongly anisotropic. Unexpectedly, however, the flux from co-moving ions was peaked at an angle intermediate between perpendicular and parallel. This could be the consequence of a preferential filling of that class of banana orbits whose tips are localized within the ion cyclotron resonance layer.

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I. INTRODUCTION

Plasma heating using ICRF waves has shown much promise, particularly in large toroidal magnetic confinement devices.¹ In some regimes the mechanism involves the creation of highly energetic "tail" ions, which slow down and thermalize with the bulk plasma ions. Consequently, a means of measuring the fast ion distribution directly, as a function of energy and angle, provides information about the particle confinement and the efficiency of the thermalization process. We have the unique capability to pursue such studies on PLT with the horizontally-scanning tangential charge-exchange analyzer.² During ICRF experiments on PLT, we have routinely observed the energetic fast ion "tail" created during ICRF heating. The analyzer is oriented to scan from viewing perpendicular to parallel counter-going ions, and we observed the expected peaking in the energetic flux as we scanned to look along near perpendicular sightlines. When the plasma current was reversed, however, and we detected co-going ions, the maximum flux occurred at a position between perpendicular and parallel. We present these data, and their scaling with toroidal field strength, and suggest a means of interpreting them in terms of the interaction between the ICRF resonance layer in the plasma and the fast ions whose banana tips reside in that layer.

II. EXPERIMENTAL RESULTS

The horizontally-scanning charge-exchange analyzer was used to measure the flux of energetic neutrals during ICRF experiments on PLT. The analyzer is capable of viewing the plasma along four separate sightlines simultaneously (Fig. 1). The fast neutrals emerging from

PLT were first ionized in a helium-filled stripping cell, and energy analyzed as they passed between cylindrical deflection plates. The ions were detected by four microchannel plates located immediately outside the deflection region. Figure 2 shows the angular distribution of 30 keV, 60 keV, and 89 keV residual hydrogen minority atoms as a function of analyzer tangency radius (defined in Fig. 1) during ICRF heating of a deuterium plasma. The current is in the direction indicated on Fig. 1, and the distribution of counter-moving particles drops off as the analyzer is moved from its perpendicular to its parallel position. These observations are consistent with results from two-dimensional Fokker-Planck calculations, where the quasilinear diffusion tends to produce anisotropic tails in the ion energy distribution in the presence of ICRF heating. When the plasma current is reversed, however, and we look at co-moving particles, our results are radically different (Fig. 3). There were slightly dissimilar plasma conditions during the two different days on which the experiments were conducted, and the fluxes at near perpendicular angles agreed to within a factor of two. With the analyzer set at the same three energies as in the "normal" field case, the maxima occurred at an intermediate position, and a sharp "cutoff" is observed at a tangency radius of about 100 cm in the 89 keV distribution. The "cutoffs" are not as dramatic for the distributions at lower energies, but there is still a change in their functional form at the same tangency radius.

III. DISCUSSION

Calculations indicate that at the angle where the flux peaks, we are observing about the largest orbits which both fit inside the PLT

limiter system, and whose banana tips coincide with the ion cyclotron resonance layer. We show here a collisionless orbit calculation for 89 keV H^+ ions in a 400 kA PLT plasma with a 29 kG toroidal field. We assumed a current profile of the form $J = [1-(r/a)^2]^{\alpha}$, where $\alpha = q(a)/q(0)-1$, to determine the poloidal magnetic field.³ We started the orbit at the outermost point on the midplane where there are no limiters or other material objects to block particles, and used the pitch-angle viewed by the charge-exchange analyzer at this location when it is aimed at a tangency radius of 100 cm. We obtained the orbit shown in Fig. 4; of the class of 89 keV orbits whose banana tips touch the resonant zone, this orbit is the one with the largest radial excursion into the region outside the plasma, but not touching the outer limiter. From the conservation of the magnetic moment μ , it is easy to show that the viewing angle for that orbit which connects the outermost midplane location to the resonant surface is independent of particle energy. As explained in the Appendix, if the major radius of the resonance where the banana tip is assumed to be located is R_{res} , and the detection radius is R_{det} , $v_{\parallel}/v$ at the detection point is given by

$$\frac{v_{\parallel}}{v} = (1 - R_{res}/R_{det})^{1/2} . \quad (1)$$

We varied the toroidal field to see if there was systematic agreement with this model, since for fixed ICRF frequency the location of the ion cyclotron resonance layer has a simple, linear dependence on the toroidal field strength. Figure 5 shows the "cutoff" points in the flux of 89 keV charge-exchange neutrals at five different toroidal

fields, and the locus of "cutoffs" predicted by the simple orbit calculations, also plotted on the figure as a solid line, agree with our observations. Changing other parameters affected the magnitudes of the fluxes we detected, but not where the "cutoffs" occurred. The plasma current was varied from 180 kA to 600 kA, and we saw no change in the "cutoff" tangency radius at a fixed toroidal field. Our model supports this hypothesis, since $v_{\perp}/v$ for the relevant loss orbits depends only on R_{res}/R_{det} , and not on I_p . We also increased the hydrogen minority concentration, which had the effect of changing the peak plasma density from $3.6 \times 10^{13} \text{ cm}^{-3}$ to $4.5 \times 10^{13} \text{ cm}^{-3}$. The flux of fast neutrals decreased by an order of magnitude, but the location of the "cutoff" was unaffected. The six ICRF antennas on PLT are grouped into two systems (see Fig.1), and as a final test, we tried each system individually to see if the proximity of our analyzer to any of the antennas could be responsible for our observations. This dropped the power from 850 kW to about half that level in each case, and although the fast neutral flux was correspondingly lowered by a factor of two, there was no difference in the "cutoff" location. Our measurements thus indicate that a population of energetic ions on loss orbits is formed during hydrogen minority ICRF heating. However, both the magnitude of this loss process and how to control it are still open questions, and more experiments at higher power levels and with different antenna configurations are planned. Together with better Monte-Carlo orbit calculations now in progress, we hope to improve our understanding of how these orbits are populated by the ICRF interaction.

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APPENDIX

The ion magnetic moment is conserved, so that

$$\mu = \frac{v_{\perp}^2}{B} = \text{constant} ,$$

where

$$B = B_0 \frac{R_0}{R} ,$$

B_0 being the toroidal magnetic field at the tokamak major radius R_0 . This means that

$$\frac{v_{\perp, \text{res}}^2 R_{\text{res}}}{B_0 R_0} = \frac{v_{\perp, \text{det}}^2 R_{\text{det}}}{B_0 R_0} .$$

Since

$$v^2 = v_{\perp, \text{res}}^2 = v_{\perp, \text{det}}^2 + v_{\parallel, \text{det}}^2 ,$$

we have

$$v^2 R_{\text{res}} = (v^2 - v_{\parallel, \text{det}}^2) R_{\text{det}} .$$

Solving for $v_{\parallel}/v$,

$$\frac{v_{\parallel}}{v} = (1 - R_{\text{res}}/R_{\text{det}})^{1/2} .$$

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FIGURE CAPTIONS

FIG. 1. Layout of PLT, showing the sightlines of the horizontally-scanning charge-exchange analyzer relative to the ICRF antennas. System #1 consists of antennas 4, 9, and 10, and System #2 consists of antennas 1, 13, and 18. (PPPL - 83X0105)

FIG. 2. Fast neutral flux, as a function of detector tangency radius, at three energies during ICRF. The plasma current (470 kA) was in the direction shown in Fig. 1, and the toroidal field was 29.6 kG. (PPPL - 83X0096)

FIG. 3. Fast neutral flux, as a function of detector tangency radius, at three energies during ICRF. The plasma current (450 kA) was opposite the direction shown in Fig. 1, and the toroidal field was 29 kG. (PPPL - 83X0097)

FIG. 4. Largest banana orbit in PLT whose tips touch the ICRF resonant zone. In a 400 kA plasma, the 89 keV ion illustrated here makes a maximum excursion of 50 cm in minor radius. This corresponds to a detector viewing point at a tangency radius of 100 cm, the location of the "cutoff" point in Fig. 3. (PPPL - 82X0264)

FIG. 5. Tangency radii of the "cutoff" points in the fast neutral flux as a function of toroidal field. The discrete points are the experimental measurements, and the solid line is from an orbit calculation. (PPPL - 82X1167)

Fig. 1

Fig. 2

83X0097

Fig. 3

#82X0264

Fig. 4

Fig. 5

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