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Impurity Ions in a Rotating Tokamak

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Abstract

It is pointed out that the impurity ions in rotating toroidal plasmas tend to behave like trapped particles. That may explain the observed fact.

1. Introduction

Tokamak plasmas are subject to rotation in the toroidal direction (i.e., in the $\hat{\phi}$ direction). The equilibrium of plasma under that circumstance could be obtained from the equation

$$\vec{J} \times \vec{B} = \vec{v}_p - \frac{(1/2) M v_r^2 n_i}{\rho} \hat{e}_0 \quad (1)$$

where cylindrical coordinates (ρ, ϕ, z) are used. v_r signifies the rotational velocity of ions and n_i is the ion density. The equilibrium of Eq. (1) no longer satisfies the condition $p = p(\psi)$ but the technique to solve the above equilibrium exists¹ and we do not repeat it here.

We assume the plasma is composed of protons and electrons with few impurity ions with mass M_i and ionized charge of z' . Thus $n_i \approx n_e$.

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2. Equilibrium of Main Plasmas on a Given Magnetic Surface

From Eq. (1) we notice

$$\frac{\partial p}{\partial \rho} = \frac{1}{2} \frac{M v_r^2 n}{\rho} . \quad (2)$$

We let

$$v_r^2 = \alpha v_{th}^2 , \quad (3)$$

hence

$$\frac{1}{2} M v_r^2 = \alpha k T_i . \quad (4)$$

Assuming temperatures are constant parallel to $\vec{B}$, we obtain in small ϵ ($= r/R$; where r is the minor radius) expansion

$$(n_+ - n_-) (k T_i + k T_e) = 2 \alpha k T_i \epsilon \frac{n_+ + n_-}{2} \approx 2 \alpha k T_i \epsilon n_0$$

or

$$n_+ - n_- = \Delta n = \frac{2 \alpha k T_i \epsilon}{k T_e + k T_i} n_0 . \quad (5)$$

Here n_+ is the density at the maximum major radius in ψ and n_- is the density at the minimum major radius.

Since electrons could be treated as mass less, electric field exists. The potential difference is given by (ϕ represents potential)

$$\frac{e\Delta\phi}{kT_e} = \frac{\Delta n}{n_0}, \quad \Delta\phi = \phi_+ - \phi_- \quad (6)$$

3. Orbit of Impurity Ions

Impurity ions are dragged by rotating ions and gain the same rotational velocity v_r . These ions therefore feel the centrifugal force

$$\frac{(1/2)M_I v_r^2}{\rho} \quad (\rho \approx R).$$

Hence the particle must have the parallel energy $W_{||}$ to circulate at the maximum major radius point $\rho \approx R + r$, such that

$$\begin{aligned} W_{||} &> 2e\alpha \frac{M_I}{M} kT_i - ez'\Delta\psi + 2W_{||}\epsilon \\ &\approx 2e\alpha kT_i \left(\frac{M_I}{M} - \frac{z'kT_e}{kT_e + kT_i} \right) + 2\epsilon W_{||} \quad (7) \end{aligned}$$

The factor in parenthesis is always positive except when kT_i is negligibly small. Thus impurity ions are usually impossible to circulate along the magnetic field line, if toroidal rotation is present. Correspondingly the poloidal orbit size of heavy ions becomes large not unlike the banana orbit. Hence impurity diffusion is enhanced.

The banana size is approximately

$$\frac{q}{e} \frac{M_I}{M} \frac{M_I v_I}{z' e B} \left(\frac{M_I}{M} - \frac{z' k T_e}{k T_i + k T_e} \right)^{-1} .$$

Recent ISX-B experiment shows that impurities are purged by neutral beam injection. It is quite probable that the mechanism discussed here is responsible for this phenomena.

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References

- ¹S. Yoshikawa, Toroidal Plasma Equilibrium with Gravity, PPPL-1704, Princeton Plasma Physics Laboratory (August 1980); submitted to Physics of Fluids.