Impurity Pumping by Beam Injection

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(49年4月15日受理)

The presence of a beam in a toroidal plasma will affect the flow of impurity ions. By choosing an appropriate energy and direction of the beam, the impurity may be pumped out.

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It has been known that the impurity ions with a larger ionic charge than the background ions would migrate towards the center of plasma due to collisions.¹ There are some indications that this phenomenon is occurring in Tokamak plasma.² The purpose of this note is to point out that the direction of migration may be reversed; thus, the accumulation of impurities may be avoided by injecting a beam into the plasma.

An impurity ion placed in a collisional hydrogen plasma receives a frictional force due to collision with protons. This force causes the ion to drift across the magnetic field. The collisions with electrons may be neglected for the time scale of this process. The drift velocity is given by

$$u = F_{\perp} / ZeB \quad (1)$$

where $F_{\perp}$ is the frictional force perpendicular to the magnetic field B and Z is the charge number. The frictional force is given by approximately

$$F_{\perp} = m_i \int \nu f v_{\perp} dv^3 \quad (2)$$

where ν is the collision frequency, f is the ion distribution function and $v_{\perp}$ is the velocity perpendicular to the magnetic field. For a

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Maxwellian distribution with density gradient, Eq. (2) becomes

$$F_1 = m_1 v n v_c, \quad (3)$$

where n is the density, v_c is the diamagnetic drift velocity and is given by

$$v_c = \frac{T}{eB} \frac{\nabla n}{n}. \quad (4)$$

By combining Eqs. (1), (3) and (4), we obtain

$$u = \frac{T}{Ze^2 B^2} m_1 v \nabla n, \quad (5)$$

the impurity ion drift toward the higher plasma density.

If there are two temperature components of hydrogen ions, the drift velocity is given by

$$u = \frac{m_1}{Ze^2 B^2} [T_1 v_1 \nabla n_1 + T_2 v_2 \nabla n_2]. \quad (6)$$

Since the collision frequency is proportional to $T^{-3/2}$, the impurity ions

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move toward the higher density side of the cold component, if $(T^{-\frac{1}{2}}vn^2)_{\text{cold}} > (T^{-\frac{1}{2}}vn^2)_{\text{hot}}$. Thus a large amount of hydrogen recycling near the wall tends to inhibit the impurity migration towards the center of the plasma.

In the neo-classical regime, where the mean free path of ions is longer than the trapped region, the banana orbits of the trapped impurity ion will become asymmetric due to the frictional force and drift at the velocity given by

$$u = F_{\parallel}/eB_p, \quad (7)$$

when B_p is the poloidal magnetic field, $F_{\parallel}$ is the frictional force parallel to the magnetic field and is given by

$$F_{\parallel} = m_i \int v f v_{\parallel} dv^3, \quad (8)$$

Whether the total frictional force is parallel or antiparallel to the ohmic current determines whether the drift velocity is inward or outward. Since the parallel velocity of a beam can be large, the presence of a beam may affect the direction of the drift.

If the background hydrogen plasma has zero momentum in the parallel direction, the parallel velocity is given by

$$\langle v_{\parallel} \rangle \approx \frac{j m_e}{en m_i} \quad (9)$$

where j is the ohmic current density and m_e is the electron mass. In

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the present day tokamaks, the current density is roughly

$$j \cong en\sqrt{T_e/m_i} \quad (10)$$

If a proton beam is injected antiparallel to the ohmic current, the total frictional force is given by

$$F_{\parallel} = m_i [vn\langle v_{\parallel} \rangle - v_b n_b v_b] \quad , \quad (11)$$

where the suffices b denote the beam quantities. By assuming $T_e \approx T_i$, we obtain

$$F_{\parallel} = m_i vn\langle v_{\parallel} \rangle \left[1 - \frac{n_b}{n} \frac{T_i}{W_b} \frac{m_i}{m_e} \right] \quad , \quad (12)$$

where W_b is the beam energy. Thus, the frictional force is reversed, if the beam energy density $n_b W_b$ is larger than the limit given by

$$n_b W_b > n T_i \left(\frac{W_b}{T_i} \right)^2 \left(\frac{m_e}{m_i} \right) \quad . \quad (13)$$

For a typical example, $W_b/T_i \approx 10$, $m_i/m_e \approx 2000$, a beam of 5% energy density is sufficient to reverse the drift velocity. The trapped protons of the background plasma also receive the frictional force and drift in the same direction as the impurity ions. The relative velocity of the impurity ion to the background plasma is then given by

$$u = \frac{m_i vn\langle v_{\parallel} \rangle}{ZeB_p} \left[1 - \frac{n_b}{n} \left(\frac{T_i}{W_b} \right) \left(\frac{m_i}{m_e} \right) (1 - 1/Z) \right] \quad . \quad (14)$$

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Thus it appears that the impurity flows may be reversed by the presence of a beam with a moderate energy density. In the wet wood burner concept proposed by Dawson, Furth, and Tenney,³ a beam energy density comparable to the plasma energy density is considered. It would certainly affect the flow of impurity ions. The beam could be used to pump the impurity out in addition to increasing the thermonuclear yield. The more elaborate calculations of the Fooker-Planck type is needed to obtain accurate estimates.

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REFERENCES

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