SPECTRUM OF CHARGE EXCHANGE NEUTRALS FROM ROTATING PLASMA

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In rotating plasma experiments (see, e.g., /1-3/) it often happens that the ions are produced in a device only due to ionization of neutral gas in the crossed electric and magnetic fields (and there are no other ion sources, say, external injection). Since the ions produced from cold neutral particles by the electron impact have a negligibly small energy at the initial moment, their further motion is described by the formulae:

$$V_r = \frac{cE(r)}{H}\sin\omega_L(t-t_0) \qquad (1)$$
$$V_\varphi = \frac{cE(r)}{H}\left[\cos\omega_L(t-t_0)-1\right]$$

where $E(r)$ is a radial electric field, H is a homogeneous magnetic field (directed along the z-axis, see Fig.1), ω_L is Larmor frequency of ions. It is assumed that the Larmor radius of ion equal to $cE/H\omega_L$ is negligible as compared to the scale-length of a radial electric field which is usually of the order of the plasma radius. Since the ionization moments t_0 are distributed randomly, the distribution of ions over the phase $\psi \equiv \omega_L(t-t_0)$ is also random.

As seen from eqs.(1), the absolute value of ion velocity $V(r) \equiv \sqrt{V_r^2(r)+V_\varphi^2(r)}$ lies within the limits from zero ($\psi = 0$, 2π) to $V_0(r) = 2c\,|E(r)/H|$ ($\psi = \pi$).

On the other hand, in off-axis measurements of charge exchange neutrals (Fig.1) the neutrals with maximum energy exceeding $\max_r W_0(r)$ (where $W_0(r) \equiv MV_0^2(r)/2$) are often detected, while at small energies the spectrum of neutrals is limited not by zero but by a finite quantity which is 1.5÷2 times smaller than $\max_r W_0$. In the present paper a simple explanation of these features of the neutral spectrum is given.

As is well known, in a resonant charge exchange event of a fast ion on a neutral the fast neutral arises, which has just the same momentum as the initial ion. In a sufficiently dense plasma, the fast neutral has some probability to be ionized again by electron impact or by charge exchange with plasma ion before reaching the plasma boundary (in both cases the initial momentum of the ion appeared is nearly the same as the neutral momentum). This leads to the formation of the ions with non-zero initial velocities. We call them "second generation" ions (in contrast to the "first generation" ions which are produced by electron impact ionization from cold neutrals and move according to eq.(1)).

Let us first consider the properties of charge exchange neutrals produced from the first generation ions. Using eq.(1), it is easy to show that the distribution function of fast neutrals registered by a detector will be the following:

$$\frac{dI}{dW} = A\,\frac{n_0(\rho)\,n(\rho)\,\sigma_0(W)}{r\,|d\Omega(\rho)/d\rho|\,\sqrt{\rho^2-r^2}} \qquad (2)$$

where $n_0(r)$ and $n(r)$ are the densities of neutrals and ions respectively, $\sigma_0(W)$ is the resonant charge exchange cross section, $\Omega(r) = cE(r)/rH$ is the angular drift frequency, and ρ in (2) is considered as a function of W, defined by the following relationship:

$$\Omega(\rho) = \frac{1}{2r}\sqrt{\frac{2W}{M}} \qquad (3)$$

From formulae (2) and (3) it follows an important for the experiment conclusion that in the case of "hard-body" rotation, when $\Omega(r) = \text{const}$, dI/dW is of the form of a delta-function: $dI/dW \sim \delta[W-W_0(r)]$; deviation of dI/dW from a delta-function is a measure of plasma motion deviation from hard-body rotation.

The form of the function dI/dW in the cases when $\Omega(r)$ monotonely increases and monotonely decreases with radius is shown qualitatively in Fig.2. The peculiarity of the case consists in the presence of the root singularity on the lower (in the first case) and upper (in the second case) ends of the interval where dI/dW differs from zero. This makes it possible to find readily the direction of variation of the function $\Omega(r)$ from experimental data.

Thus, consideration of the first generation ions allows us to explain the presence of a lower boundary of the energy spectrum of charge exchange neutrals. As to upper boundary, in this case it cannot of course lie above $\max\limits_r W_0(r)$.

For explanation of the fast neutrals formation we have to investigate the distribution function of the second generation ions. The number of these ions is determined by the ratio of ionization length λ_i to plasma radius R. Usually in experiments the condition $\lambda_i \gg R$ is fulfilled (the case when $\lambda_i \ll R$ is discussed in /4/).

Let the neutral, produced at radius r from the ion of first generation and moving at this moment at an angle α with respect to electric field, be ionized again at radius r^*. Then the velocity of thus produced second generation ion changes with time according to

$$V_r(r^*) = U\sin\psi \qquad (4)$$
$$V_\varphi(r^*) = \frac{V_0}{2} + U\cos\psi$$

where

$$U = \sqrt{\frac{V_0^2(r^*)}{4} + V_0^2(r)\left[1 - \frac{\Omega(r^*)}{\Omega(r)}\right]\sin^2\alpha} \qquad (5)$$
$$\psi = \omega_L t + \mathrm{const}$$

Using these formulae, one can find the distribution function of neutrals, produced by charge exchange from second generation ions. However, these calculations are too cumbersome, and we shall restrict ourselves only by revealing of the maximum value of the energy of the second generation ions. From expressions (4), one can see, that the maximum (over ψ) value of the ion velocity is

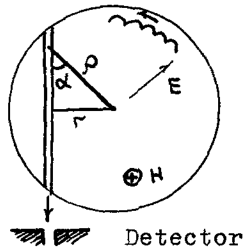

Fig.1

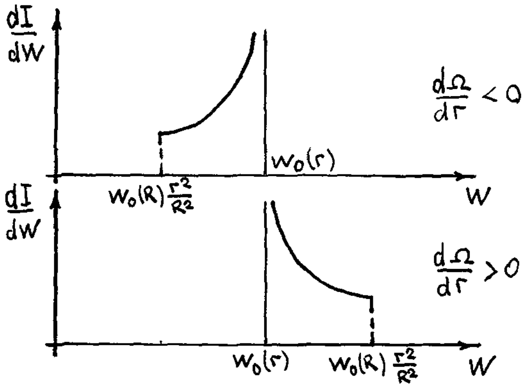

Fig.2

$$\frac{V_0(r^*)}{2} + \sqrt{\frac{V_0^2(r^*)}{4} + V_0^2(r)\sin^2\alpha\left[1 - \frac{\Omega(r^*)}{\Omega(r)}\right]} \qquad (6)$$

In the case of "hard-body" rotation the second generation ions have the same distribution function as the first generation ions, i.e. accelerated particles do not appear. The most obvious situation in which accelerated ions appear, is the following: $V_0(r)$ is the non-decreasing function of radius, $\Omega(r)$ is the decreasing one. Let, for example, $V_0(r)$ be independent of r (to judge by the results of the paper /3/, V_0 can be constant in a quite large region). Then, from eqs. (5)-(6) it is easy to obtain the maximum energy of the second generation ions, which is equal to $W_0(3+\sqrt{5})/2$, i.e. it is about 3 times higher than W_0. One can give some examples illustrating an even more noticeable gain.

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