Calculation of the ICRF heated ion distribution function inside NPA viewing angle in ITER

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Introduction

Registration of the high energy neutral fluxes with neutral particle analyzer (NPA) in ITER shall contribute to studying the physics of energetic particles and provide unique opportunity to measure D/T ratio in the plasma core [1]. Line of sight of the NPA in ITER is directed along the major radius R at $Z \sim Z_{axis} \sim 0.6$ m. Then only deeply trapped ions with parallel velocity close to zero and barely trapped, i.e. close to the passing – trapped boundary, ones after charge exchange can contribute to NPA signal from low and high field side, respectively. The registered fluxes from isotropic energetic particles are sufficiently small [2,3]. While low $V_{||}$ domain of the phase space is effectively filled with energetic ions at the ICRF heating. Hereby it is necessary for diagnostic data processing to take into account the ICRF heating impact on the diagnostic signal.

Contribution of ICRF heated ions into the NPA diagnostic signal

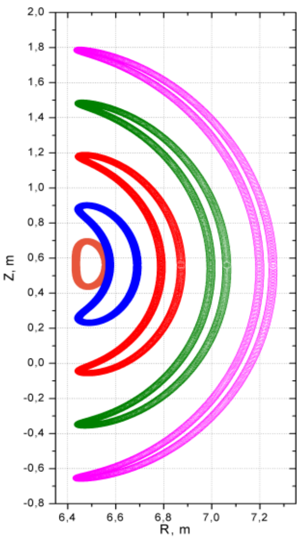

Fig. 1. "Banana" orbits.

Distribution function of the ICRF heated ions can be represented as a sum of two parts [4]. Namely it includes the isotropic one for the ions with energies below $E<E_c$, where E_c is the "critical" energy at which power transfer from the fast ion to the bulk plasma ions is equal to that of electrons. Approximately the same characteristic energy value determines the boundary in velocity space where pitch angle scattering of the energetic particle on the thermal ions effectively spreads velocity distribution of the fast ions. The second, but most interesting for our analysis, part is high energy "beam" of the particles moving along "banana" orbits with turning points in narrow vicinity of the IC resonance surface (Fig.1). Forming of the high energetic "beam" part of the distribution is most pronounced for the fundamental minority heating scenarios. In present paper two of the major scenarios of on-axis ICRF heating in ITER are considered: (1) fundamental harmonic heating of the He^3 minority ions in DT plasma and (2) fundamental

harmonic heating of the H minority ions in He^4 plasma. Parameters of heating are taken from [5]. Critical energy E_c for both cases is estimated as $E_c \approx 30 \cdot T_e$. Then for the DT plasma E_c is about 700 keV and for the He^4 plasma, E_c is about 300 keV. It means that contribution to the lower energy analyzer, LENPA, in both scenarios will come from the isotropic distribution, and thus should be calculated as described in [2,3]. Higher energy analyzer, HENPA, measures atomic fluxes with energies within the interval 200 keV < E < 4 MeV [1]. For such high energy particles finite orbit width, FOW, effect can not be neglected in calculations of the NPA signal.

Indeed, for zero banana width there are no particles from "beam" component of the distribution inside of the NPA viewing angle, $|Z\text{-}Z_{ax}| < \delta_Z$, $|\chi| < \delta_\chi$, except the "point" - like vicinity of the axis. While for the fat banana and, especially, for the "potato" orbits the parallel velocity remains close to zero on the inner leg of the orbit and, thus, can contribute to the registered signal. Therefore, FOW effect considerably widens the volume in configuration space for the minority ions contributing to NPA signal.

This is illustrated by the Figs. 2–5 (yellow region is a NPA coverage). One can see that for any vertical position of the turning point at the ICRF surface there is a minimum energy, $E_{min}(Z)$, above which "potato" orbit at the inner leg goes through NPA viewing angle. Then, the low energy particles are unseen by NPA (Fig.3), while for higher energies, as it follows from the Figs. 4–5, the contribution to NPA signal should be proportional to the ratio of the residual time within the NPA cone, τ_{NPA}, to the bounce period τ_b.

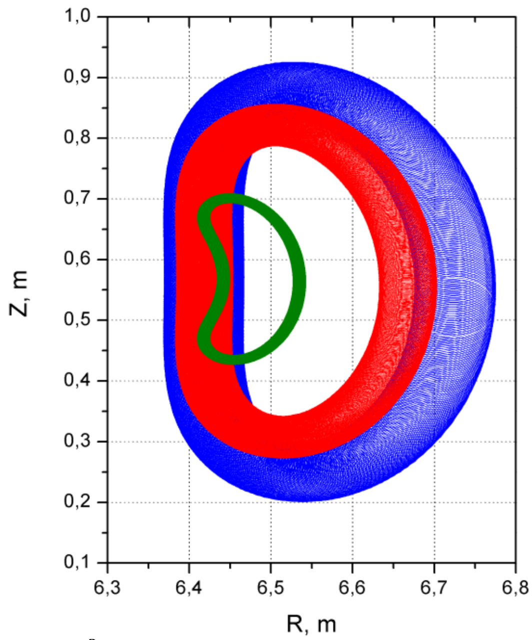

Fig. 2. He^3 minority ions orbits for energies 0,1 MeV (green line), 2 MeV (red line) and 4 MeV (blue line) in DT plasma.

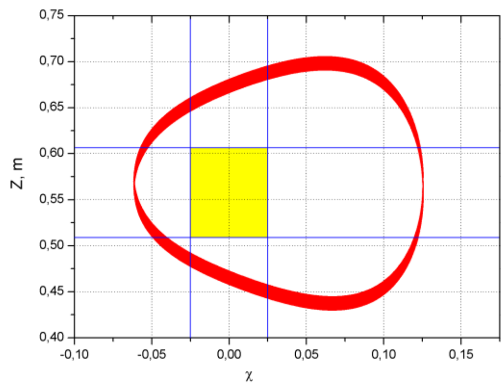

Fig. 3. Graph $Z(\chi=V_{\parallel}/V_0)$ for particle from fig. 1 with energy 0,1 MeV.

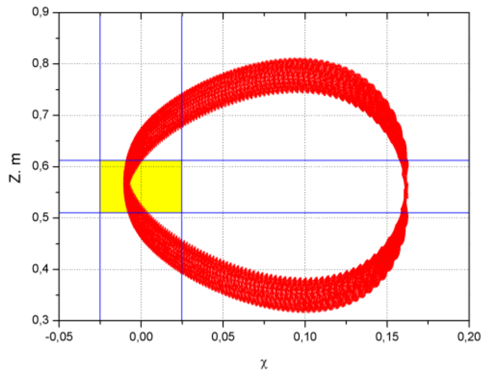

Fig. 4. Graph Z(χ) for particle from fig. 1 with energy 2,0 MeV.

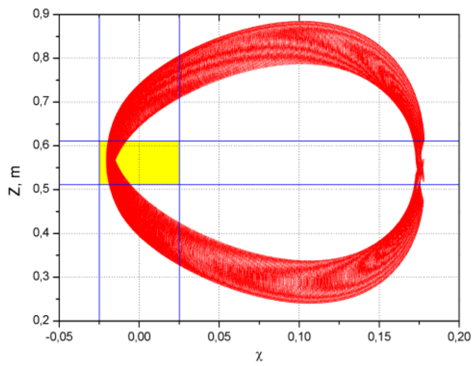

Fig. 5. Graph Z(χ) for particle from fig. 1 with energy 4,0 MeV.

Then the algorithm of calculation of the fast ("beam") minority contribution into NPA signal looks straightforward:

$$\Delta_{NPA} \sim \int_{Z_{ax}}^{\infty} \frac{\partial V}{\partial Z} dZ \int_{E(Z)_{min}}^{\infty} f_E \frac{\tau_{NPA}}{\tau_b} dE \,, \quad (1)$$

where $\partial V/\partial z$ is Z-derivative from plasma volume within the surface passing through current Z and f_E is the distribution function of the ICRF tail ions. Increase of the fast ion population within NPA viewing angle with rise of the particle energy is shown at the Fig.6. With rise of the energy E, particles with higher $Z_{reflection}$, and thus from larger plasma volume, contribute to the signal. In calculations the equilibrium of the 15 MA ITER reference scenario was used to evaluate particle orbits and plasma volume inside $\Psi(R_{ax},Z_{refl})$ surface. As in [5] we assumed uniform minority distribution with n_{He}~$0.02n_e$. Also, for these calculation parameters $E_{min}(Z)$ reaches NPA registration boundary of 4 MeV at $Z=Z_{ax}+17$ cm. This distance is sufficiently small to allow for variation of the temperature of ICRF heated ions.

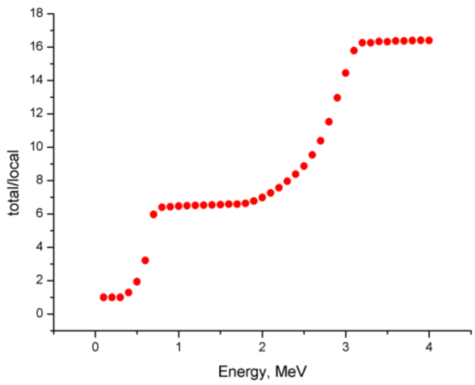

Fig.6 "Instrumental function" of the NPA registered ICRF tail ions at on-axis ICRF heating.

According to [5], central T_{icrf} ~150÷200 keV for both scenarios He^3 minority in DT plasma and H minority in He^4 plasma. Setting the distribution function, f_E, in Eq.(1) to be Maxwellian with T=150 keV we get the distortion of the fast ion spectrum inside of the NPA viewing angle due to the finite orbit width effect. Results are shown at Fig.7 (left). This figure corresponds to the He^3 minority case. For the H minority the picture is almost the same. One can see that distortion of the spectrum takes place for the energies below E_c≈700 keV. I.e. in the domain where isotropic component of the fast ion distribution function is dominant and thus FOW effect should be absent and the total signal effectively suppressed.

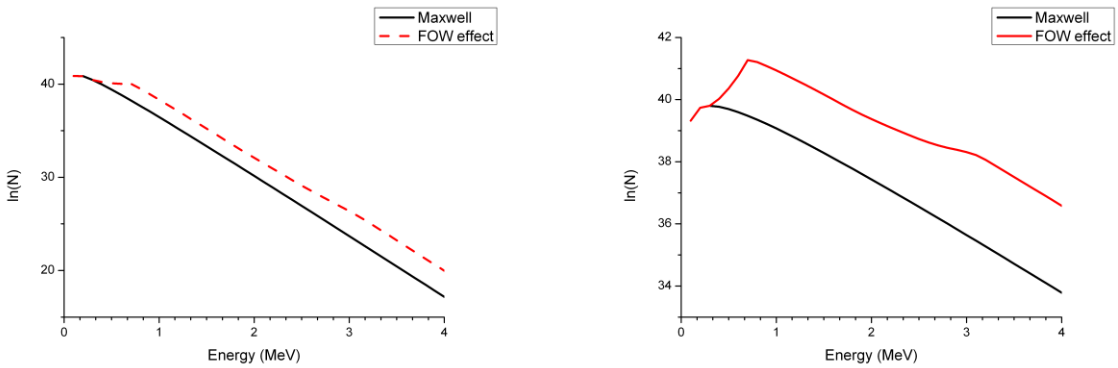

Fig.7 Distortion of Maxwell spectrum of the ICRF tail ions within NPA viewing angle due to the FOW effect. T_{icrf} =150 keV (left) and 500 keV (right).

Evidently, the distortion of the spectrum should be stronger for higher ICRF tail temperatures. For the model case of T_{He}=500 keV the spectrum of the particles inside the NPA aperture takes the form shown at the Fig.7 right. Then in interpretation of the data, the region with E<1MeV should be treated with care (or even skipped) in estimation of the ICRF heated ion distribution function.

It should be noted also, that finite orbit width effect influences ICRF tail spectra not only in the "registration" process considered here but also in the formation of the fast ion distribution as well [6]. The key idea of [6] was that for the potato orbits case, the residual time of a particle in the IC resonance becomes comparable to the bounce period, thus all analytical results obtained in the asymptotic limit $\tau_{icrf}/\tau_{bounce} \ll 1$ could not be applied, including widely employed quasilinear diffusion operator. Instead, the increments of the perpendicular velocity at the single resonance crossing were found to exceed the analytical estimate more than by the order of magnitude. Similarly should be changed the coefficients of the kinetic equation in description high energy domain of the phase space.

Finally, having in mind quite moderate ICRF power density projected for ITER operation, it is hardly probable to obtain ICRF tail temperatures much higher than predicted in [5]. Thus almost all population of the fast ICRF heated ions should form a distribution function close to the isotropic one. Therefore we should not expect strong influence of the ICRF heating on the NPA signal in ITER.

References

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