Monte Carlo calculations of the fast ion distribution function for needs of NPA diagnostics in ITER

P.B. Aleynikov[1,2], S.V. Konovalov[1], V.M. Leonov[1], V.I. Afanasyev[3], M.I. Mironov[3],
A.A. Teplukhina[1,2]

[1]*Russian Research Center Kurchatov Institute, Moscow, Russia*

[2]*Moscow Institute of Physics and Technology, Moscow, Russia*

[3]*Ioffe Physical-Technical Institute, St.Petersburg, Russia*

Introduction

The main objective of the neutral particle analysis (NPA) diagnostics in ITER is to measure the DT fuel composition of the fusion plasma [1]. It can be done on the basis of measurement of the fluxes of the H, D and T neutrals in the thermal (10-200 keV, LENPA) and D and T neutrals in the suprathermal (0.1-4 MeV, HENPA) energy ranges. Both HENPA and LENPA are viewing plasma along the major radius close to the equatorial plane of the torus. Then the registered neutral fluxes originate due to charge exchange of the fast ions with almost perpendicular (to the magnetic field) velocity on the neutralization target. Therefore, the fluxes should be sensitive to the ripple perturbations. Experimental and modelled NPA signals on JET revealed significant reduction of the neutral fluxes due to fast ion ripple losses [2]. In case of the ITER, due to the compensation of ripple perturbations by ferromagnetic inserts, the associated losses of fast ions are almost absent. However, the local magnetic wells near the midplane still can, in principle, affect the ion behaviour inside the NPA line of sight (LoS). The trapping into the local wells changes the residual time of the fast ion in the detector solid angle. On the other hand, the ripple wells extend the pitch angle domain in the velocity space for the particles contributing to the diagnostic signal. Then the principal goal of the present study is to clarify to which extent ripple perturbation can affect fast ion distribution and, therefore, NPA signal in ITER.

Calculation algorithm and parameters

In ITER the NPA line of sight is horizontal $Z_{NPA}=Z_{ax}=0.5$m and strictly perpendicular to the major axis of the torus. Viewing angle of the NPA is formed by the aperture of 20 cm diameter at the port in the first wall, FW, and by the window of 2 cm diameter at the analyser entrance 12m away of the FW. Then from the whole fast ion distribution, only extremely narrow cone centered around zero parallel velocity can contribute to NPA signal.

We employ orbit following Monte-Carlo code DRIFT for direct evaluation of the fast ion distribution inside the NPA viewing angle. Every time, when a test particle orbit passes the vertical interval Z_{NPA}-15cm<Z<Z_{NPA}+15cm the time, $\Delta t_{i,j,k,l}$ spent by the particle inside the grid cell $R_i<R<R_{i+1}$, $Z_j<Z<Z_{j+1}$, $V_k<V<V_{k+1}$, $\chi_l<\chi<\chi_{l+1}$ is recorded. Every orbit is calculated from the "birth" point, at which birth velocity $V=V_0$, until the particle is collisionally slowed down to $V<0.25V_0$ or $E<1.5\,T_i$. Then the stationary number of the fast ion in the specified grid cell $N_f(R,Z,V,\chi)$ is given by $N_f(R,Z,V,\chi) = Q_f/N_{tot} \sum\limits_{test\ particles} \sum\limits_{orbit\ crossing} \Delta t$, where $Q_f \sim \delta(V-V_0)$ is the fast ion source rate, N_{tot} is the total number of the test particles, and summation is taken over all particle ensemble and includes all time spent by an individual particle orbit within the $[i,j,k,l]$ cell boundaries. For N_f grid we used [40,12,40,40] dimension with 4m<R<8.5m, Z_{NPA}-15cm<Z<Z_{NPA}+15cm, $0<V/V_0<1$, $-1<\chi<1$.

Ripple effect on the fast ion orbits is stronger for higher q (lower plasma current) values. Thus, for our simulations we chose equilibrium and plasma parameters for relatively low plasma current (Ip=9MA) steady state ITER reference scenario (#4). It is also well known from previous studies [3 and references therein] that ferromagnetic inserts, FI, compensating ripple perturbation in ITER, almost cancelled out fast ion ripple losses. Then, to make ripple effect on NPA signal more visible we considered maximum possible ripple amplitude case (ripple produced by TFC only) along with the ripple distribution calculated according to the latest (2009) FI design. The boundaries of the area, where local ripple wells exist for TFC and TFC+FI cases are shown at the Fig.1. All input data were taken from ITER data base [4].

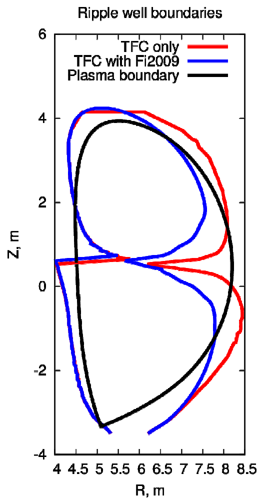

Fig.1 Local magnetic well domains for ripple due to TFC and TFC+FI in Scenario #4.

We consider 3 species of fast ions: heating and diagnostic beams and fusion alphas. Sources for the beam ions were calculated according to accurate injection geometries [5]. For the heating beam vertical inclination of the central line of injection was set providing most possible off-axis injection. For the DNB small deviation from strictly perpendicular injection (R_{targ}=0.14m) direction was taken into account. Such rotation of the diagnostic beam excludes the possibility for the beam ions to be trapped into the local magnetic well right near the ionization point and instantly being lost to the FW. For the fusion alphas with isotropic velocity distribution at birth energy we have chosen volume uniform instead of real fusion burn profile. This artificial spreading of the source profile was necessary to provide sufficient statistics in calculation of the alpha distributions at the plasma periphery, where ripple effect is strongest. For all simulations the same number of 10^5 test particles was used.

Calculation results

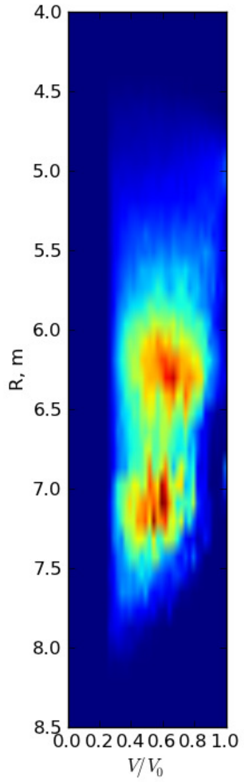

Fig.2 Stationary (R,χ) distribution of the heating beam ions.

Stationary distribution of the **HNBI** fast ions along the NPA line of sight (along R) and spectra are shown at the Fig.2. Here calculated values of $N_f(R,Z,V,\chi)$ has been integrated over all Z and for pitch angle distribution integration was done for the smallest (according to chosen grid step size) possible interval around zero parallel velocity $-0.05<\chi<0.05$. It is seen that zero pitch angle component of the beam ions distribution appears after slowing down to the velocity of about $0.8V_0$, firstly in the inner plasma region (due to separatrix orbits separating originally passing from toroidally trapped orbits) and then also at the outer side due to continuous pitch angle scattering. Further integration of such distributions over V results in profiles of total number of beam ions with $-0.05<\chi<0.05$ inside the toroidal "ring" of radius Ri<R<Ri+1 with 30cm height for the different ripple perturbation cases, Fig.3. Significant depletion of the fast ion population at the outer plasma region is seen for the strong ripple case (TFC only). While in the presence of FI, no ripple effect on HNBI ion remains. It should be also noted that for the strong ripple case total loss of HNBI ions was found to be of 3.3%. While the difference between number of fast ion with almost zero parallel velocity (see Fig.3) exceeds 10%. Therefore strong ripple results in both anomalous loss and deformation of distribution function of the fast ions.

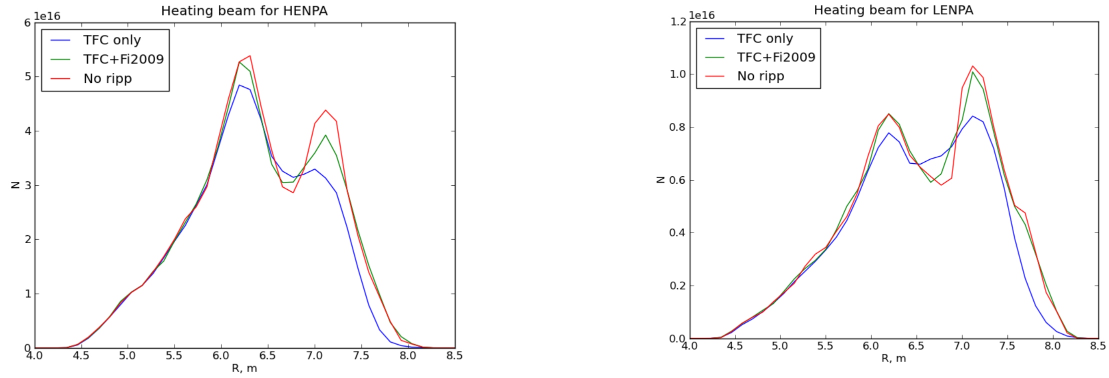

Fig.3 HNBI distribution along NPA LoS for high (>100keV) and low (<200keV) energy range

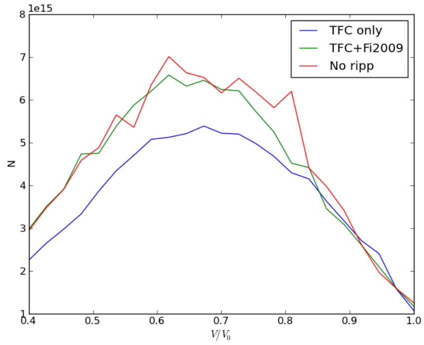

Fig.4 Fast neutral from HNBI spectrum

Estimated spectra of the neutrals from HNBI in the NPA are shown at the Fig.4. In their evaluation we assumed radiative neutralization (uniform) only, and plasma transparency $T(R,V)$ according to [6]. Ripple effect, seen for TFC only case, appears at the lower energy part as initially passing HNBI ions scattered to banana orbits contributing to NPA signal after significant slowing down (see Fig.2). Ripple effect is most visible for **DNB** (Fig.5) distribution due to high losses (of 15.5% for TFC only). While for TFC+FI case the distribution is equal to the axisymmetric one.

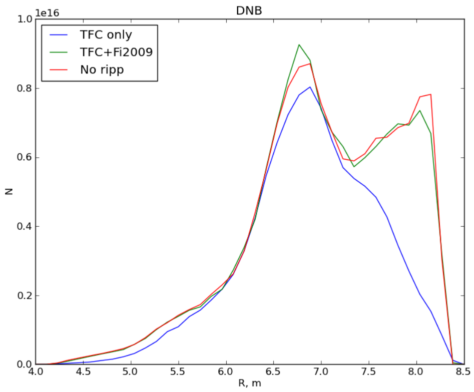

Fig.5 DNB distribution along NPA LoS

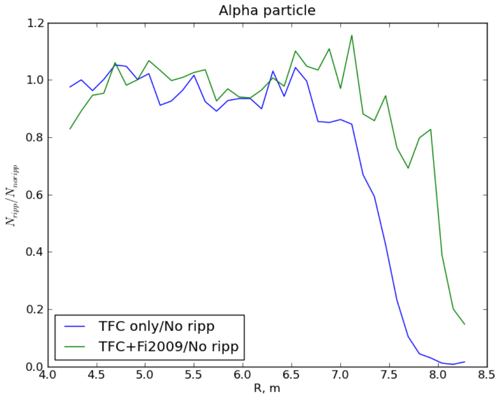

Fig.6 α-distribution normalised by no-ripple case

The ratio of the fast **α particles** inside the NPA viewing angle for the 2 ripple/no-ripple cases is shown at the Fig.6. Deviation from unity is still seen at the plasma periphery even for the compensated ripples. However, if realistic highly peaked to plasma axis fusion birth profile is taken into account, no change of NPA signal in the compensated ripple case is found.

Summary

Our simulations have shown that moderate change in NPA signal amplitude and in registered neutral spectra can be seen for sufficiently strong (non-compensated) ripples only. DNB ions undergo most serious influence of ripple perturbation due to almost perpendicular injection. HNBI ions and fusion alphas along the NPA LoS are weakly affected by ripples. For the TFC+FI ripple no detectable effect on NPA signal is expected.

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