ROLE OF COLLISIONAL RIPPLE TRANSPORT FOR FAST ION CONFINEMENT IN TOKAMAKS

V. Yavorskij[1], K. Schoepf[2], V. Goloborod'ko[1], S. Reznik[1]

[1]*Institute for Nuclear Research, Ukrainian Academy of Sciences, Kiev, Ukraine*
[2]*Institute for Theoretical Physics, University of Innsbruck, Austria*
Association EURATOM-OEAW

INTRODUCTION

Toroidal field ripples are known to strongly enhance the radial transport of fast ions. In the periphery of a tokamak plasma, where the ripple magnitude exceeds the Goldston-White-Boozer stochasticity threshold, they result in stochastic transport of toroidally trapped high-energetic ions with a diffusion coefficient $D \propto$ 10-100 m^2s^{-1} and hence in fast loss as compared to slowing down processes [1-7]. In the central region of plasma, usually the stochasticity criterion of Goldston-White-Boozer is not fulfilled even for *MeV* ions; nevertheless the toroidal field ripples can cause there an enhanced collisional radial transport of toroidally trapped fast ions that resonate with the ripple perturbations.

Here we investigate the ripple induced loss mechanism of charged fusion products and NBI ions in tokamaks with weak TF ripples accounting the collisional ripple transport processes of fast ions, both in the moderate and in the high energy range. The results of corresponding 3D time dependent Fokker-Planck modeling of the ripple induced loss of NBI ions and fusion alpha particles in JET-like tokamak-reactor are presented.

SIMULATION APPROACH AND METHOD

Our energetic ion confinement modeling was based on the numerical solution of the non-stationary drift 3D Fokker-Planck equation for the distribution function in the constants-of-motion space (COM). This equation was solved applying a 6-steps integration method, 3 implicit and 3 explicit steps, in order to account for the diffusion cross terms. Using this method the FP equation was solved simultaneously in the confinement domains of co- and counter-moving particles (σ_m=1 and σ_m=-1) taking into account the matching conditions on the separatrix. Bounce averaging of the convection and diffusion coefficients as well as of the energetic ion source term in COM space was performed by numerical integration of the drift equations of motion using a JET-like axisymmetric analytical magnetic model field [8] with noncircular flux surfaces (matched with JET shot #45341). The problem was solved in the

COM space grid 20×20×20 to achieve a reasonable PC computing time. The ripple induced radial diffusion coefficient has been chosen in the form $D=D_B+D_{st}+D_{sb}$, where D_B represents the ripple induced Boozer radial diffusion coefficient [1], D_{st} describes the stochastic ripple transport [2] and D_{sb} is the superbanana collisional ripple coefficient [9]. For our calculations we used the following parameters: $n_e(0) = 0.75\cdot10^{14}\ cm^{-3}$, $T_e(0) = 15\ keV$, $T_i(0) = 35\ keV$ (50% - *d*, 50% - *t*), $Z_{eff} = 3$; three types of fast ion sources: 1 – 100 *keV* co-NBI deuterons, 2 – 100 *keV* co- and counter-NBI deuterons of equal amount, 3 – 3.5 *MeV* alphas with thermal source broadening taken into account. The ripple magnitude δ_{max} was varied in the range 0.1% - 2%. The above calculational scheme may, of course, be adopted also for simulations purely based on the EFIT plasma equilibrium data.

REULTS OF 3D TIME DEPENDENT FOKKER-PLANCK MODELING

Energy spectra of NBI ion loss for different values of the TF ripple magnitude are displayed in Fig. 1. It is seen that an increase of the ripple amplitude results enhances the ion loss in the moderate and the high-energy range $E/E_0 > 0.2$-0.3. As shown in Fig. 2, the time required to reach the steady state loss distribution is about a slowing down time τ_s. To estimate the effect of anisotropy of the NBI ion sources we compared the loss of co- and compensated (as many co- as counter-injected) ions. The corresponding results are given in Fig. 3 where only a moderate sensitivity of the loss spectra to the ions source anisotropy is observed both in the case of weak (δ_{max}= 0.3%) and in the case of strong (δ_{max}= 1%) TF ripples.

Due the weak dependence of the collisional ripple induced radial diffusion of fast ions on the ripple magnitude, the loss of NBI ions is also not significantly varied by δ as demonstrated in Fig. 4. Increasing δ_{max} from 0.1% to 2% results in an approximately 3-fold increase of the ion loss during the initial phase t << τ_s ~ 0.1s. The loss variation with δ becomes even weaker for t > τ_s, as is shown in Fig.4 by the light brown curve. The weakening of the loss dependence on the ripple magnitude with time is evident from Fig. 5 where the time dependent ripple loss is demonstrated for different values of δ_{max}. This weakening indicates that the ripple-induced losses of fast ions take place mainly in the moderate and low energy range. Finally, Fig. 6 displays the time evolution of the energy spectra of fusion alpha particle loss in a JET-like tokamak. For times t ~ 0.03s << τ_s~ 0.1s the maximum alpha loss occurs around $E/E_0 < 0.4$. We note that this corresponds with alpha particle loss measurements in JET [10].

SUMMARY

The ripple induced loss of fast ions in tokamaks obtained via time-dependent Fokker-Planck calculation is shown to exhibit only a weak dependence on the ripple magnitude, which is in qualitative agreement with ripple reduction experiments carried out at JFT-2M [11]. The calculated fast ion losses reach a maximum in the energy range from a few tens of *keV* to a few hundreds of *keV* well below the birth energy. This has been experimentally detected not only on JET [11] and TFTR [12,13], but also on the stellarator device LHD [14].

The ripple transport mechanism investigated is supposed to be responsible for the enhanced loss of NBI ions observed in the intermediate energy range in JET and TFTR and, hence, should be essentially embodied into any modelling of charged fusion products in tokamak-reactors for energies $E < 1$ *MeV*.

Acknowledgement

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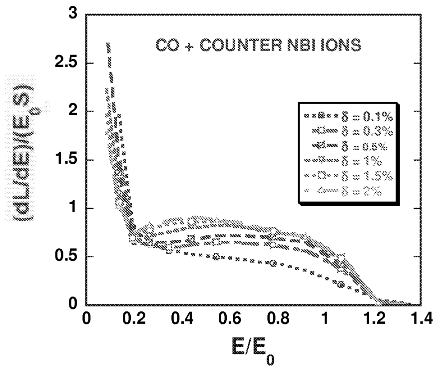

Fig. 1 Ripple induced loss of NBI ions for different δ_{max}

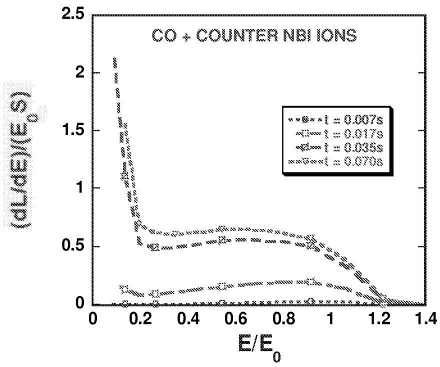

Fig. 2 Time evolution of the energy spectrum of NBI ion loss

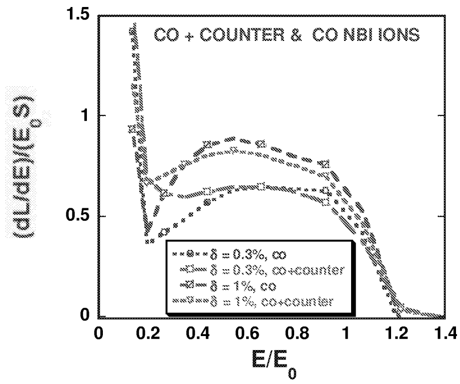

Fig. 3 Effect of anisotropy of the NBI ion source for ripple loss

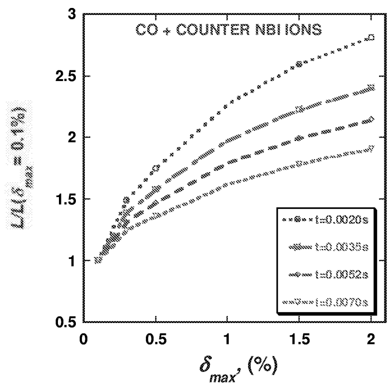

Fig. 4 Ripple induced loss of NBI ions *vs* ripple magnitude

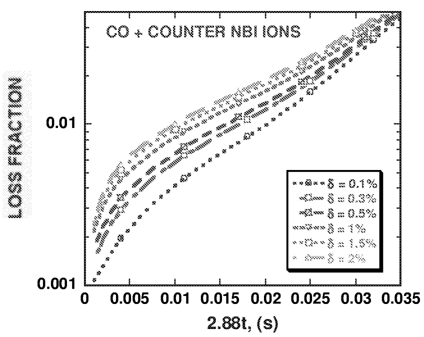

Fig. 5 Time dependence of ripple loss for different values of δ_{max}

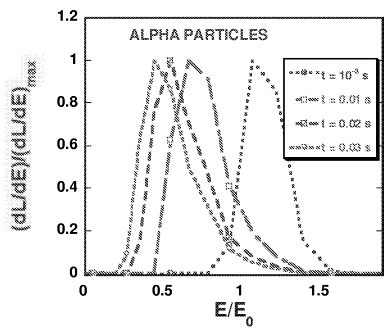

Fig. 6 Time evolution of the energy spectrum of alpha particle loss