33rd EPS Conference on Plasma Phys. Rome, 19 - 23 June 2006 ECA Vol.**30I**, P-1.192 (2006)

The role of TF ripple and MHD-mode synergy in fast ion confinement

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

[1]*Association EURATOM-OEAW, Institute for Theoretical Physics, University of Innsbruck, Innsbruck, Austria*

[2]*Institute for Nuclear Research, Ukrainian Academy of Sciences, Kiev, Ukraine*

1. Introduction

Toroidal field (TF) ripples as well as MHD induced low frequency perturbations are known to lead to an enhanced loss of fast ions in tokamaks due to the break-down of toroidal momentum conservation [1,2]. Usually, theoretical investigations of the effects of ripple and MHD perturbations on fast particle confinement neglect the synergetic impact of these perturbations. According to Ref. [3], however, TF ripples co-acting with TAE modes may result in a significant enhancement of fast ion loss in magnetically confined toroidal plasmas. On TFTR it has been experimentally demonstrated [2] how MHD perturbations modulate the TF ripple loss of charged fusion products; both enhancement and reduction of fast ion loss was observed. Here we model the joint effect of TF ripples and MHD perturbations on the transport behaviour of fast ions in a tokamak magnetic configuration. We carry out our analysis in the single-harmonic approximation, in which each type of the perturbations is represented by a single harmonic. The combined effect of both perturbations on the stochastic domain in phase space is investigated by analysis of pair correlations of toroidal momentum variations [4] calculated with the simplectic integration method for Hamiltonian systems [5]. It is shown that MHD perturbations with low poloidal and toroidal numbers can degrade the ripple induced fast ion transport, whereas high toroidal numbers may enhance it.

2. Drift Hamiltonian in the presence of TF ripples and MHD perturbations

Assuming the MHD perturbations to affect only the magnetic field (similar to TF ripples), we start from the drift Hamiltonian of a fast ion,

$$H = \left(\frac{\psi(p_1) + p_2}{g} b(p_1, q_1, q_2) \right)^2 + \lambda b(p_1, q_1, q_2) \qquad ; \tag{1}$$

here the canonical variables are p_1 –toroidal flux on the trajectory, q_1 – conjugated poloidal angle, p_2 – toroidal angular momentum and q_2 – conjugated toroidal angular co-ordinate, ψ is the poloidal flux, $b=B/B_0$ with the magnetic field B and B_0 its value on the magnetic axis. $\lambda=\mu B_0/E$ represents the normalised magnetic moment, and $g=\rho_L/(aA)$ incorporates the particle gyro-radius ρ_L, the minor plasma radius a and the plasma aspect ratio A. In our modelling we use the following explicit expressions for the poloidal flux and magnetic field:

$$\begin{gathered}
\psi = \int_0^{p_1} dp_1'/q(p_1'), \quad q = q_0 / \left[1 + 2p_1 \left(\frac{q_0}{q_a} - 1 \right) \right], \\
b = \left[1 + \delta_{TF}(p_1, q_1) cos(Nq_2) + \delta_{MHD}(p_1) cos(nq_1 + mq_2) \right] / \left[1 + rcos(q_1)/A \right], \\
p_1 = 0.5r^2, \, \delta_{TF} = \delta_{TF0} exp\left\{ \alpha\sqrt{F} + \beta F \right\}, \, F = \left[rcosq_1 + \Delta(r) \right]^2 + \left[rsinq_1 \right]^2, \\
\Delta = \Delta_0 \left[1 - \left(A_c r / A \right)^2 \right], \, \delta_{MHD} = \delta_{MHD\max} exp\left\{ -\left[(r - r_c)/\Delta_c \right]^2 \right\}, \, p_2 = -\psi + g\chi / b, \\
\chi = \sigma\sqrt{1 - \lambda b}, \quad \sigma = \pm 1 .
\end{gathered} \tag{2}$$

Here q_0 and q_a are the safety factors at the magnetic axis and at the plasma boundary, respectively, δ_{TF} is the TF ripple magnitude [3] for a toroidal coil number of $N=32$ with a minimum value δ_{TF0} ($=5.0\times10^{-7}$) and the parameters $\alpha=8$, $\beta=1$, $A_c=2$; δ_{MHD} denotes the MHD perturbation [4] with poloidal and toroidal numbers n and m and a maximum value $\delta_{MHD\max}$($=1.0\times10^{-4}$), localized at $r=r_c$ with the localisation half-width $\Delta_c=0.1$. The radial profiles of TF ripple and MHD perturbations taken for the calculation are displayed in Fig.1.

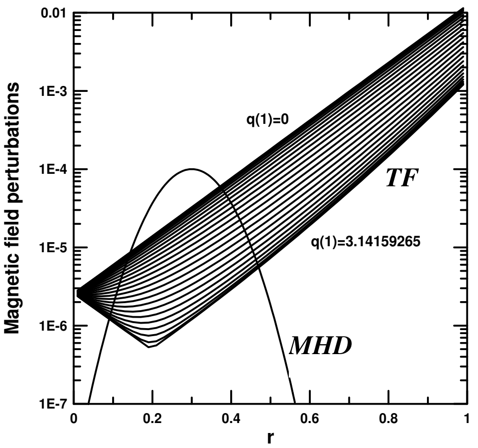

Fig. 1: Radial profiles of the magnitudes of magnetic field perturbations due to TF ripples and the MHD mode with poloidal and toroidal numbers n=5 and m=16, respectively, localised at $r_c=0.3a$ (here a is the plasma radius).

Using the simplectic integration method for Hamiltonian systems [5] to minimize error accumulation, we perform long-time-period (more then 10^3 bounce periods) computations achieving a relative accuracy of 10^{-4}. This enabled us to investigate the effect of the above field perturbations on the non-conservation of the toroidal momentum of fast ions and on their radial transport, both in the collisionless case and considering Coulomb collisions.

3. Modelling results of the combined effect of TF ripples and MHD modes on fusion alpha behaviour in tokamak plasmas

The radial diffusion coefficient of alphas is evaluated according to

$$D_{rr} = \frac{1}{N_t(N_t-1)} \sum_{i=1}^{N_t} \sum_{j=1}^{i-1} \frac{\left(\overline{p}_{2i} - \overline{p}_{2j}\right)^2}{\left| t_{(i-1)M_t+0.5(M_t+1)} - t_{(j-1)M_t+0.5(M_t+1)} \right|} \ , \tag{3}$$

where, in a time interval considered, N_t denotes the number of averaging subintervals and M_t the number of grid points in each subinterval. Thus N_tM_t is the total number of integration time steps in a considered time period. Fig.2 displays typical contours of the modelled collisionless diffusion coefficient of 1.7 MeV alphas in a plane spanned by λ and the maximum radial orbit excursion, r_{max}/a, for (a) a weakly rippled tokamak magnetic field ($\delta_{TF\max} < 1\%$, $N = 32$) without MHD perturbations and (b) in the presence of a core localised MHD mode ($r_c = 0.3a$, n=5, m=16) with a magnitude <0.05%. The green and yellow areas in Figs. 2a,b belong to the domain of toroidally trapped alphas which are more sensitive to TF ripples than circulating ones (blue areas). As expected, the maximum ripple induced transport, characterized by stochastic diffusion [1], is observed for well trapped ions in the orange regions at the plasma periphery, r_{max}/a>0.7-0.8. The yellow textures in the trapped particle domain represent the fine resonant structure typical for a rippled magnetic field [3]. Figure 2b illustrates the changes in the resonant structure as caused by an additional helical

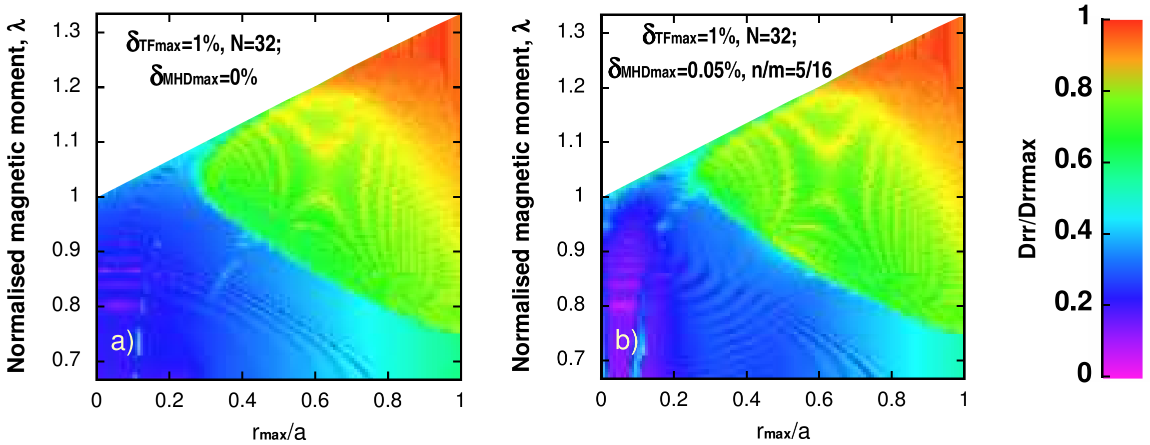

Fig.2. Resonant structure of the modelled radial collisionless diffusion coefficient of 1.7 MeV alphas in the (λ,ρ=r_{max}/a)-plane in the presence of TF ripples only (a), and in the case of both TF ripple and MHD perturbations of the magnetic field (b) .

perturbation of the toroidal magnetic field. Thorough inspection reveals the enhancement of collisionless diffusion in the vicinity of resonances near the boundary between the trapped and circulating ion domains ($\lambda \approx 1\text{-}r_{max}/(aA)$) as well as a reduction of this diffusion at greater λ. Though the effect of resonant interaction is weak for the collisionless transport of alphas, it becomes more pronounced, as shown in Fig.3, for the radial diffusion induced by collisions. For the modelling results presented here we used a Monte Carlo approach in combination with simplectic orbit following calculations. The pitch-angle scattering frequency was chosen as $\nu_{\perp} = 0.5n(r)/n(0)$ s^{-1} with a central plasma density $n(0)=0.5\cdot10^{14}$ cm^{-3}.

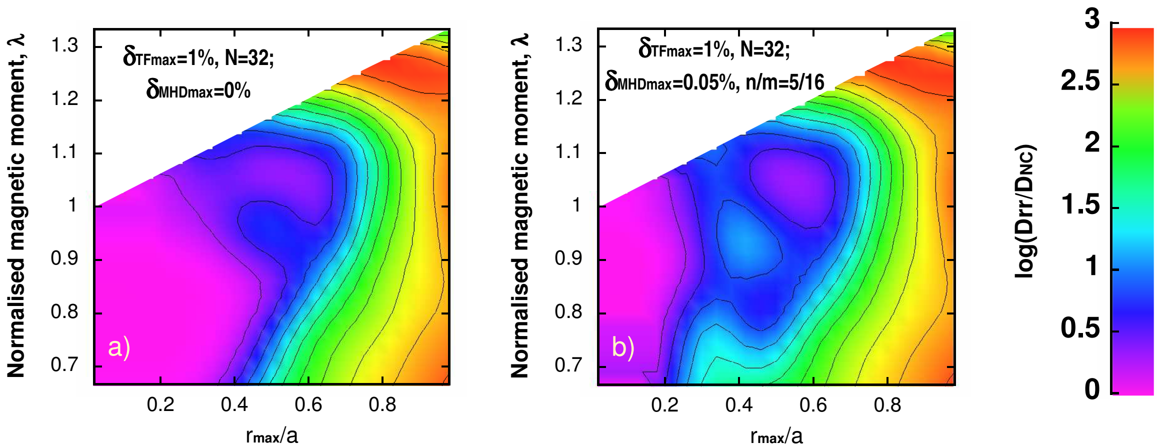

Fig.3. Modelled collisional diffusion coefficients of 1.7 MeV alphas in the (λ,ρ=r_m/a)-plane in the presence of TF ripples only (a), and in the case of both TF ripple and MHD perturbations of the magnetic field (b).

Finally, Fig.4 demonstrates the synergetic effect of MHD and ripple perturbations of the magnetic field on the collisional diffusion of 1.7 MeV alphas. To measure the pure synergistic contribution, neoclassical diffusion has been subtracted for the comparison of co-acting and separate TF ripple and MHD-mode diffusion. As becomes evident from Fig. 4, the considered MHD mode reduces the rates of ripple induced radial diffusion by ~ 70% at λ~1, r_{max}~0.5a and, on the other hand, can lead to a 2.5-fold enhancement of the radial diffusion of

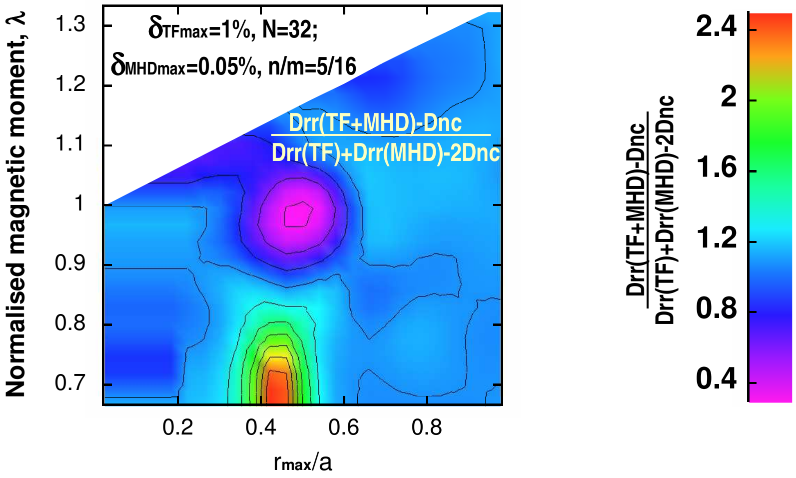

Fig.4. Synergetic effect of MHD and TF ripple induced perturbations of the magnetic field on the collisional radial diffusion of 1.7 MeV alphas.

marginally circulating alphas with λ~0.7, r_{max}~0.4a. Thus, MHD modes may result both in enlargement and in reduction of ripple induced radial diffusion of fast ions in tokamak plasmas.

4. Summary

The transport behaviour of fusion alphas in tokamak plasmas with TF ripples and MHD modes was modelled using the simplectic method for integration of Hamiltonian systems. An essential synergistic effect of the two specific perturbations on the radial transport of alphas could be demonstrated. MHD induced modes were seen to affect both enlargement and reduction of the rates of the ripple induced radial diffusion. We note that the modelling results are in qualitative agreement with observations of charged fusion products confinement in TFTR [1], where in the presence of MHD activity both degradation as well as improvement of fast ion confinement was detected.

Acknowledgement

This work has been partially carried out within the Association EURATOM-OEAW and under EFDA.

References

[1] GOLDSTON, R.J., et al., Phys. Rev. Lett. **47**, (1981) 647.
[2] ZWEBEN, S.J., et al., Nucl. Fusion **40**, (2000) 91.
[3] HLADSCHIK, T. and SCHOEPF, K., Proc. Int. Conference on Plasma Physics, Foz do Iguacu, Brazil, Oct/Nov 1994, Vol 1, pp. 29-32.
[4] CHIRIKOV, B.V., Sov. J. Plasma Phys. **4**(3), (1978) 289.
[5] CHANNELL, P.J. and SCOVEL, C., Nonlinearity **3**, (1990) 231.