Modelling of spatial and velocity distributions of diffusive fast ion loss in JET

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1. Introduction

Spatial and velocity distributions of charged fusion products (CFPs) escaping from tokamak fusion plasmas provide important information about the loss mechanisms involved [1-3] and the knowledge of these distributions is essential for predicting the heat loads associated with CFP's impinging on the tokamaks first wall [4].

The present study aims at modelling the poloidal, toroidal and pitch-angle distributions of high energy ions diffusively lost to the first wall. We consider an inevitable and hence most important loss mechanism due to pitch-angle scattering of fast ions on the bulk plasma particles [5]. Evidently, the diffusive loss of fast ions may be substantially enhanced by toroidal field (TF) ripples or MHD perturbations [1, 6]. We note that radial diffusion of fast ions is crucial for the CFP heat deposition on the first wall, since it results in a strong localization of the escaping ions in the vicinity of the mid-plane [5]. Lastly it should be pointed out that modelling of the poloidal, toroidal and pitch-angle distributions can help in the interpretation of anomalous loss of CFP's from D-D reactions observed on JET by a scintillator probe [2, 3].

2. Model of fast ion loss

Our simulation is based on a Monte-Carlo model of diffusive loss of marginally confined fast ions and accounts for pitch-angle scattering, TF ripples and radial electric fields, E_r, at the plasma edge. In this model the pitch-angle scattering is taken into account by a standard Monte-Carlo operator employing a continuous spectrum of random velocity changes [7, 8]. Particle orbits are considered in drift approximation with the loss condition, $r_{GC}=r_{FW}-\rho_L$, where r_{GC} and r_{FW} are the radial positions of the particle guiding center and the first wall and ρ_L is the gyroradius. We assume here axisymmetric 2D first wall coinciding with the wide poloidal limiter. The magnetic field $\mathbf{B}(\mathbf{r})$ is supposed to be a superposition of an axisymmetric component $\mathbf{B_{as}}(r,\chi)$ and of a TF ripple perturbation $\mathbf{B_{rip}}(r,\chi,\varphi) = \delta\mathbf{B_{16}}(r,\chi)\cos16\varphi + \delta\mathbf{B_{32}}(r,\chi)\cos32\varphi$, where $\delta\mathbf{B_{16}}(r,\chi)$ and $\delta\mathbf{B_{32}}(r,\chi)$ describe the poloidal shape of the 16th TF ripple harmonic (relevant for JET experiments with enhanced ripples) and of the 32nd TF ripple harmonic (relevant for JET standard configuration). Here r is the radial flux coordinate and χ, φ are the poloidal and toroidal angles.

3. Loss distributions induced by collisions and TF ripples

In Fig. 1 we display the calculated poloidal profile of 900 keV tritons with $\xi\equiv V_{\|}/V=0.37$ lost to the limiter in JET. Here $\xi=\cos\zeta$ is the pitch-angle cosine of lost ions at the first wall.

* See the Appendix of F. Romanelli et al., Proceedings of the 23rd IAEA Fusion Energy Conference 2010, Daejeon, Korea

Losses are localized in rather narrow range of poloidal angles (0>θ>-50°) below the midplane (θ=0). Clearly seen is the substantial effect of TF ripples, which shift the fast ion

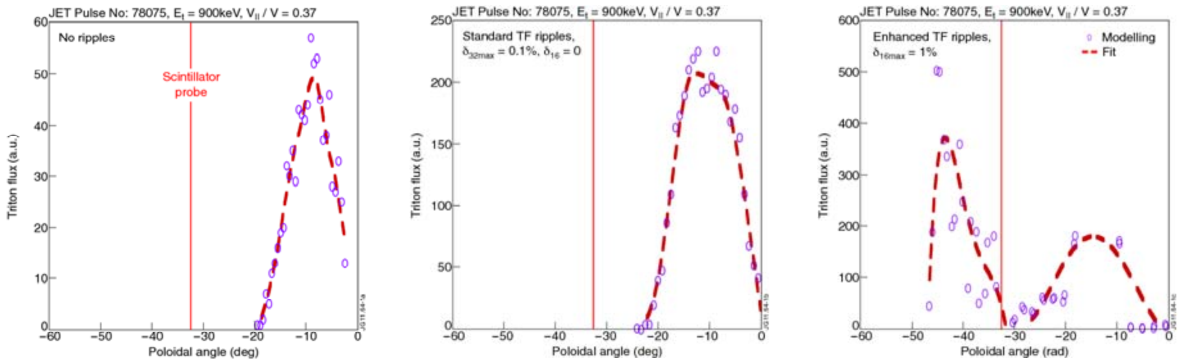

Fig.1 Modelled poloidal distributions of the diffusive loss of 900 keV tritons to the JET limiter (Pulse 78075) (a) neglecting the effect of TF ripples, (b) accounting for standard N=32 ripple harmonic and (c) incorporating the effect of both standard N=32 and additional N=16 TF ripple harmonics.

loss by about 5-10^0 in the poloidal angle in the case of standard TF ripples with toroidal harmonic *N*=32 (curve *b*). In both cases (a) and (b) the typical half width of the poloidal ion loss distribution is less than 15^0. Adding of *N*=16 TF ripple harmonic with the relative magnitude about 1% at the low-B area result in a strong modification of the loss distribution of fast tritons over the poloidal angle shown in Fig.1c. Enhanced ripples with *N*=16 seen to give rise to additional loss of 900keV tritons shifted in poloidal angle up to 50° below the

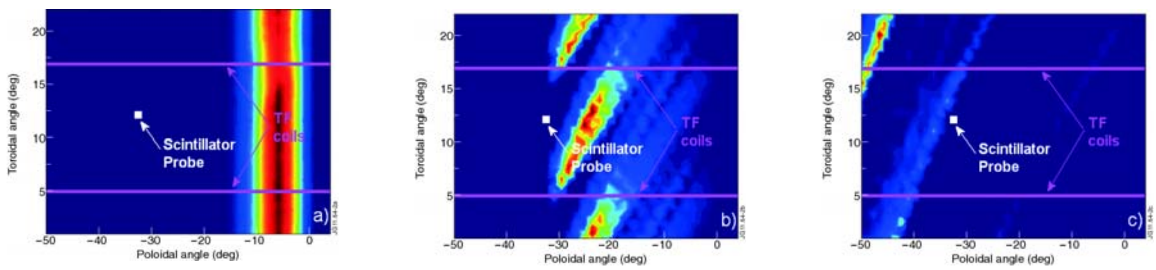

Fig.2 Modelled distributions of the diffusive loss of 900 keV tritons (0.20<$V_{||}$/V<0.24) to the JET limiter (Pulse 78075) over the poloidal and toroidal angles neglecting the effect of TF ripples (a), accounting for standard N=32 ripple harmonic (b) and incorporating the effect of both standard N=32 and additional N=16 TF ripple harmonics (c).

midplane. Note that TF ripples can substantially affect distribution of diffusive loss over the toroidal angle as well. That is clearly demonstrated by Fig. 2 where 2D angular distributions of diffusive loss of 900keV tritons with $0.20 < \xi < 0.24$ are displayed. It is seen that even standard ripples result in strong modulation of loss over the toroidal coordinate contrary to the toroidally homogeneous losses in the case of axisymmetric magnetic configuration, and that enhanced ripples make this modulation even more pronounced (see Fig. 2b,c). One important point for the interpretation the fast ion losses is to know how the distribution of diffusive loss varies with the pitch angle. Fig. 3 represents the poloidal distributions of the diffusive loss of 900 keV tritons to the JET limiter in axisymmetric magnetic field for the different values of ξ. It is seen that poloidal shape of neoclassical axisymmetric flux of fast ions is weakly dependent on ξ. However dependence of diffusive loss on pitch angle becomes significant in presence TF ripples. This is confirmed by poloidal distributions of 900 keV triton fluxes in JET standard magnetic configuration in Fig. 4a. Clearly seen is the strong variation of poloidal shape of diffusive flux, $\Gamma(\theta,\xi)$, with the variation of $V_{||}/V$. Thus the poloidal position of the flux maximum, $\theta_m(\xi)$, shifts from -26° at ξ =0.24 to θ_m=-30° at ξ =0.22. Important feature of poloidal distributions of diffusive loss is the non monotonic dependence θ_m on ξ. It is seen that minimum θ_m is reached at ξ=0.22 in pitch-angle range $V_{\|}/V$=0.20-0.24 and at ξ=0.25 in range $V_{\|}/V$=0.24-0.28. Accordingly the 900 keV tritons with ξ=0.22 (ζ~77°) can be lost at poloidal angles below θ = -32.5° corresponding to the poloidal position of Scitillator Probe (SP). Note that non monotonic dependence $\Gamma(\theta, \xi)$ on ξ is in agreement with the resonant nature of TF ripple effect on the fast ion behavior [6].

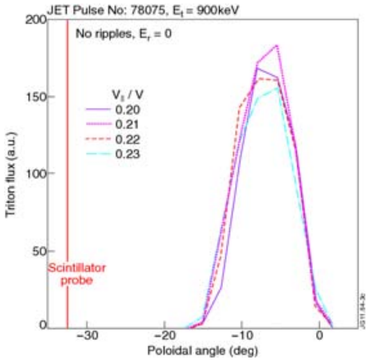

Fig.3 Modelled poloidal distributions of the diffusive loss of 900 keV tritons to the JET limiter neglecting the effect of TF ripples for different values of pitch-angle cosine.

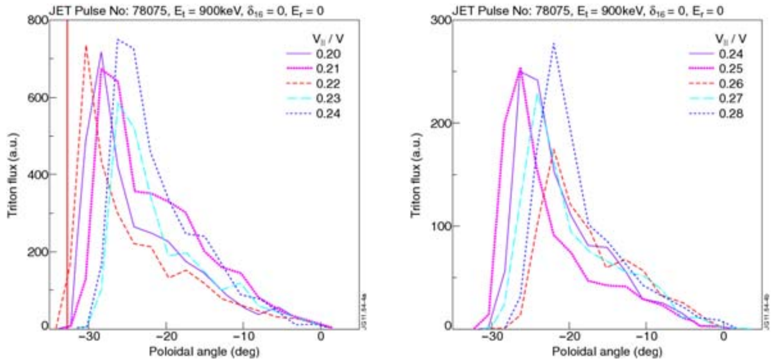

Fig.4 Modelled poloidal distributions of the diffusive loss of 900 keV tritons to the JET limiter (Pulse 78075) accounting for the effect of regular TF ripples for different values of pitch-angle cosine.

Really the 900 keV tritons with ξ = 0.22 are in resonance with N=32 ripple perturbation ($N\omega_p = 9\omega_b$, [3, 6] here ω_p and ω_b are toroidal precession and bounce frequencies) in JET conditions of Pulse 78075. Note that pitch-angles of these resonant tritons, ζ~77°, are in agreement with the pitch angles of anomalous loss of DD CFPs observed in JET [2, 3]. Nevertheless in case of standard TF ripples the resonant 900 keV tritons with ξ=0.22 can not be detected by the scintillator probe as these ions are lost at the toroidal angles different from the SP toroidal position φ =12° (Fig. 4b).

4. Effect of radial electric field

Radial electric fields, E_r, at the edge of JET plasma are known to be of order tens of kV/m [9]. These fields are characterized by large radial gradients and can noticeably affect the orbit shape even for *MeV* ions. Correspondingly they may modify the spatial and velocity distributions of diffusively lost fast ions. Fig. 5 displays the profiles of radial electric field used in our modelling. Note that profiles $E_1(r)$ and $E_2(r)$ are in qualitative agreement with those experimentally derived in [9]. Figs. 6, 7 demonstrate spreading of modelled poloidal distribution of

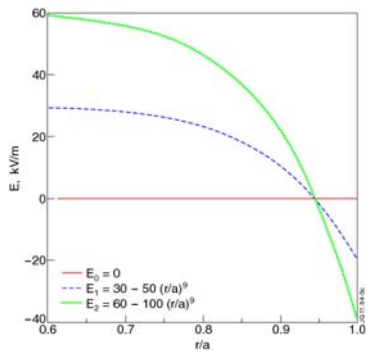

Fig. 5: Model profiles of radial electric field used in present paper.

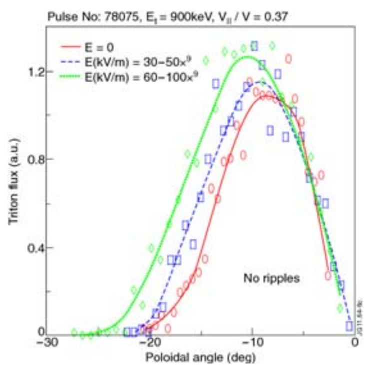

Fig. 6: Poloidal distribution of axisymmetric neoclassical loss of 900keV tritons for different electric fields at the plasma edge shown in Fig. 5.

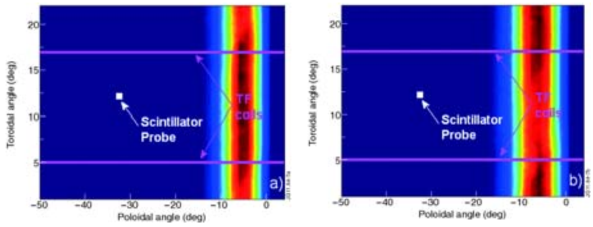

Fig.7 Modelled distributions of the diffusive loss of 1MeV tritons (0.20<$V_{||}$/V<0.24) to the JET limiter (Pulse 78075) over the poloidal and toroidal angles in case of $\delta B_{16}=\delta B_{32}=0$ neglecting the effect of electric field (a) and incorporating the effect of $E_r = E_2$ (b).

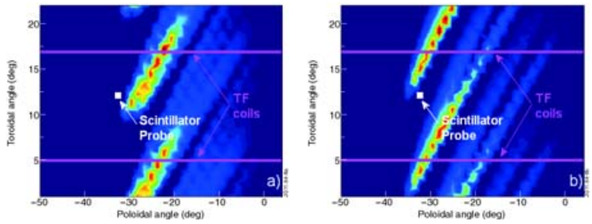

Fig.8 Modelled distributions of the diffusive loss of 1MeV tritons (0.20<$V_{||}$/V<0.24) to the JET limiter (Pulse 78075) over the poloidal and toroidal angles in case of $\delta B_{16}=0$ neglecting the effect of electric field (a) and incorporating the effect of $E_r = E_2$ (b).

axisymmetric neoclassical loss of fast ions caused by electric field. It is seen that the addition of an radial electric field E_r of order 50 *kV*/*m* can result in additional poloidal shift of loss about 3°. The reason of this shift is an increase of the curvature radius of the guiding centre trajectory of lost ions. In presence of standard TF ripples radial electric field results in about 5° additional poloidal shift of fast triton flux like shown in Fig. 8, moreover the presence of E_r makes the dependence of diffusive loss on the toroidal angle more prominent. Finally, comparing Figs. 8a done for 1 MeV tritons and Fig. 2b done for 900keV tritons allows concluding that a 10% reduction in the triton energy results in an additional poloidal shift of their diffusive fluxes of around 5°.

In the end we conclude that diffusive losses of 1MeV tritons with ξ~0.20-0.24 (ζ~76°-78.5°) can be detected by the scintillator probe located at θ=-32.5°, φ=12° (see Fig. 8). It should be mentioned that the pitch-angle range (76°<ζ<78.5°) used for the modelling is in agreement with the pitch angles of anomalous loss of DD CFPs observed in JET [2,3].

5. Summary

Diffusive losses of fast ions in tokamak are localized in rather narrow range of polidal angles below the midplane. Thus losses of DD charged fusion products in JET configuration with standard ripples are localized in the range of poloidal angles of order 30°. TF ripples result in the additional shift of diffusive loss in poloidal angle and in substantial modulation of the loss over the toroidal angle. Maximum poloidal shift takes place for ions resonating with TF ripple perturbation. Electric fields at the plasma edge can result in additional (as compared to *E*-free case) poloidal shift of loss about 5°.

Acknowledgement

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