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1. INTRODUCTION

In spite of the negligible effect of Toroidal Field (TF) ripples on beam ion confinement in the standard N=32 TF coil configuration of JET, we expect a significant degradation of NBI ion confinement in JET experiments with enhanced TF ripples envisaged for investigating the ripple-effect on the performance of ELMy H-mode plasmas [1]. The ripple enhancement will be accomplished by current reduction in every 2nd coil, whereby an additional N=16 harmonic is introduced in the TF ripple perturbation. Note that, in earlier experiments, an increased ripple induced loss of injected ions has been observed in JET [2,3] and in TFTR [4,5] in the energy range $T<E<E_b$, where T is the plasma temperature and E_b the initial energy of injected ions. A substantial ripple transport mechanism believed to be responsible for this loss is the collisional superbanana diffusion resulting from resonant interaction of toroidally trapped fast ions with ripple perturbations [6,7]. Here we present results of predictive Fokker-Planck modelling of NBI ion loss in enhanced TF ripples experiments on JET and also interpret the enhanced ripple loss of beam deuterons in previous JET experiments [2-4].

2. SUPERBANANA ORBITS INDUCED BY ENHANCED TF RIPPLES

Variation of the current in every second coil, i_2, of the standard N=32 configuration from minimum $i_2=0$ to maximum $i_2=i_1$ produces the N=16 ripple harmonic with the magnitude $(i_2-i_1)/(i_2+i_1)\delta_{16} \equiv F\delta_{16}$, which essentially exceeds the magnitude of the standard N=32 ripple harmonic δ_{32}, even at small differences $i_2-i_1<<i_1$, as is shown in Fig.1. To avoid a large loss of ripple trapped particles the ripple magnitude should satisfy the condition

$$\delta < \delta_M = 1/(NqA), \tag{1}$$

where A is the aspect ratio and q the safety factor at the plasma edge. The upper limit of ripple magnitude, δ_M, guarantees the absence of ripple wells in the main part of the plasma cross section except the narrow outboard area and in mid-plane vicinity, and supposes the current modulation to be rather weak, $(i_2-i_1)/i_1 < 0.3\text{-}0.4$. On the other hand, only high ripple magnitudes [7, 8]

$$\delta < \delta_M \le A^{-1}/(Nq)^{3/2}, \tag{2}$$

may noticeably affect the radial transport of toroidally trapped particles, both in collisional and collisionless regimes. Therefore, under conditions (1) only trapped particles from the outer periphery of the plasma cross-section are expected to undergo the ripple effects (see Fig.1). The main contribution to ripple induced transport of beam ions with intermediate energies up to 100-200keV is anticipated from those trapped particles that are in resonance with the ripples, i.e. for which

$$l\omega_b - N\,\omega_d = 0, \mathrm{l} = 0, \pm1, \pm2, \dots\ , \tag{3}$$

where ω_b and ω_d are the ion bounce and precession frequencies, respectively. Figure 2 demonstrates the typical resonant banana orbit or superbanana [7], executed by an 80keV deuteron in an I/B=2.5MA/2.4T plasma. Notwithstanding the small radial excursions of super-banana particles, $\Delta r_{sb} \sim r/(Nq)$, the latter can substantially contribute to pitch-angle scattering induced transport of toroidally trapped ions [7, 8]. The reason for that is the strong localization of superbananas in longitudinal energy [8]. According to [8] an essential ripple effect may be expected on the neoclassical diffusion coefficients of trapped fast ions with moderate energies from tens to hundreds of keV even for small ripple magnitudes $\delta \sim \delta_1 \cong \varepsilon/(Nq)^{3/2}$. This is confirmed by the numerical modelling results of radial diffusion coefficients of 20keV<E<110keV deuterons in a typical JET plasma, displayed in Fig.3. Apparently, TF ripples affect the neoclassical diffusion of toroidally trapped particles only slightly in the presence of a single N=32 harmonic. However, 30% of an additional N=16 ripple harmonic can significantly enhance the radial diffusion of toroidally trapped ions.

3. MODELLING RESULTS OF THE TF RIPPLE INDUCED LOSS OF NBI DEUTERONS IN JET

Our modelling is based on a 3D Fokker-Planck simulation in the constant-of-motion space and accounts for axisymmetric neoclassical diffusion as well as for ripple induced collisional and collisionless transport of toroidally trapped ions [7-9]. Here we investigate the dependence of the NBI deuteron loss due to collisional superbanana transport on the N=16 ripple harmonic and on the magnetic shear in the plasma core. Table 1 summarizes the modelling results for the loss of E>40keV deuterons produced by off- and on-axis injection at E_b = 130keV into monotonic current (Pulse No:61493) and current hole (Pulse No: 61488) plasmas for weak and enhanced ripples. It is seen that enhanced TF ripples in JET may result in 6-8 times increased loss of E > 40keV NBI deuterons in monotonic current (MC) plasmas and in a 14-15 times loss enlargement in current hole (CH) plasmas. The modelling demonstrates a synergistic effect of TF ripples and CH on the beam ion loss, approximately doubling the simple superposition of losses induced separately by TF ripples and by the current hole. The reason of this synergism is the overlapping of regions of core localized CH transport and the peripheric TF ripple induced loss mechanism. Therefore the effectiveness of the joint TF ripple + CH influence on ion transport significantly exceeds the total of separate ripple and separate CH effects. Note that the partly thermalized deuterons are the major contributors to the ripple induced loss. This is confirmed by Fig.4 where the energy dependent loss fraction of deuterium beam ions is plotted for MC and CH plasmas in JET as a function of the direction of injection and the magnitude of the N=16 ripple harmonic. Due to the predominant contribution of banana particles to the ripple loss of partly thermalized ions, a significant reduction of the number of toroidally trapped deuterons may be expected in plasmas with enhanced ripples. We note that the ripple-induced reduction of neutral deuteron fluxes observed in 1994/1995 JET experiments [3] was obviously also caused by the dominant loss of toroidally trapped slowed down beam deuterons. This conclusion is confirmed by Fig.5 where we display the modelled energy dependence of the ratio of the number of toroidally trapped beam deuterons in the plasma with enhanced ripples to that in the standard low ripple case. From this figure we clearly see a substantial reduction of the population of toroidally trapped deuterons due to enhanced TF ripple loss. For 30keV deuterons this reduction is of the order of 40% in MC plasmas and exceeds 60% in the CH case. Taking into account that the trapped ion population determines the neutral particle flux measured at mid-plane, we suggest the transport mechanism considered here to be possibly responsible for the reduction of neutral deuterium fluxes observed in previous JET ripple experiments. On the other hand, the synergistic enhancement of beam ion loss caused by TF ripples in the presence of a current hole may help to interpret the significant decrease of the neutron rate detected in the case of strong reversed shear in TFTR. For a quantitative comparison with TFTR measurements, however, additional modelling is required. We note that, due to the high efficiency in the moderate energy range, the TF ripple collision transport can be of interest to the problem of ash removal in future tokamak reactors.

SUMMARY

The modelling of the confinement of NBI deuterons in JET demonstrated a substantial effect of enhanced TF ripples on beam ion loss. Thus the introduction of a 50% additional N=16 TF ripple harmonic in JET leads to a 6-8 times increased loss of $E > 40$keV NBI deuterons in monotonic current plasmas and enlarges the beam ion loss in current hole plasmas by a factor 14-15. The overlapping of regions of TF ripple and CH transport and hence their combined efficacy is found to result in an essential synergistic enhancement of beam ion loss. Partly thermalized deuterons are found to constitute the main contribution to the ripple induced loss of beam ions. Therefore the effect of enhanced TF ripples on the DD neutron yield is weaker when compared with the ripple induced reduction of the population of partly thermalized beam ions and especially, when compared to the reduction of trapped ion population which determines the neutral particle flux at mid-plane. The modelling results are in qualitative agreement with previous JET and TFTR observations. In the presence of current holes, the ripple effect on beam deuterons is predicted to be detectable by ~10-20% reduction of the beam-target DD neutron yield due to ripple loss of beam ions in envisaged JET experiments with enhanced ripples. However, the most pronounced effect of ripples may be observed in measurements of the ripple induced reduction of mid-plane neutral particle fluxes at energies in the tens keV range (neutral flux reduction expected to exceed that in the standard ripple case by 40-50%).

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Current profile	Monotonic Current (MC)		Current Hole (CH)	
Injection direction	off - axis	on - axis	off - axis	on – axis
Weak ripple, $\delta=\delta_{32}$, $i_2=i_1$	2.2%	2.3%	2.2%	3.0%
Strong ripple, $\delta=\delta_{16}/2+\delta_{32}$, $i_2=i_1/2$	13.4%	18.6%	31.0%	40.9%

*Table 1: Total calculated loss of E > 40*keV *NBI deuterons (FP modelling)*

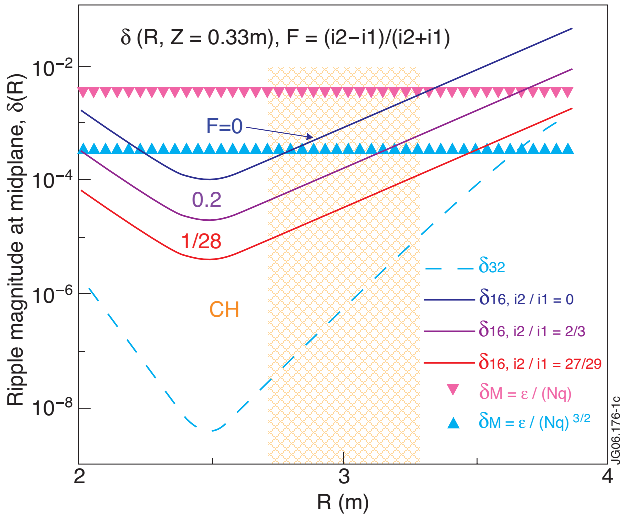

Figure 1: Profiles of the magnitudes of N=16 and N=32 ripple harmonics in the JET mid-plane.

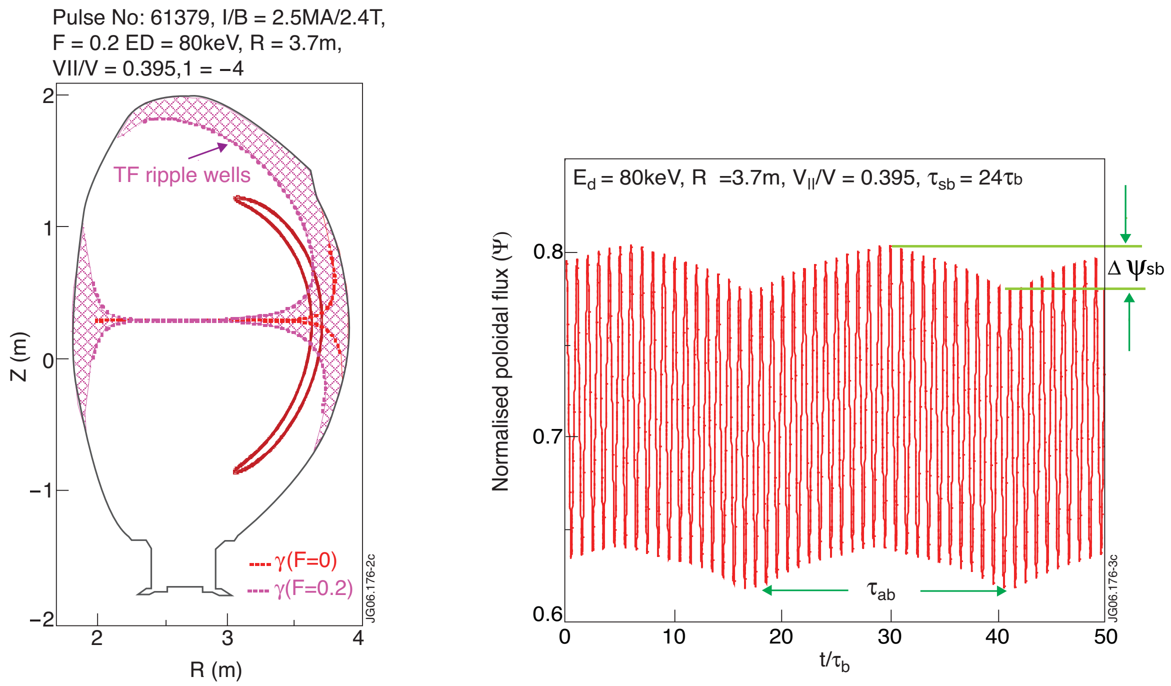

Figure 2: l=4 superbanana orbit of 80keV deuteron in I/B=2.5MA/2.4T JET plasma (Pulse No: 61379) in the presence of 20% of N=16 ripple harmonic.

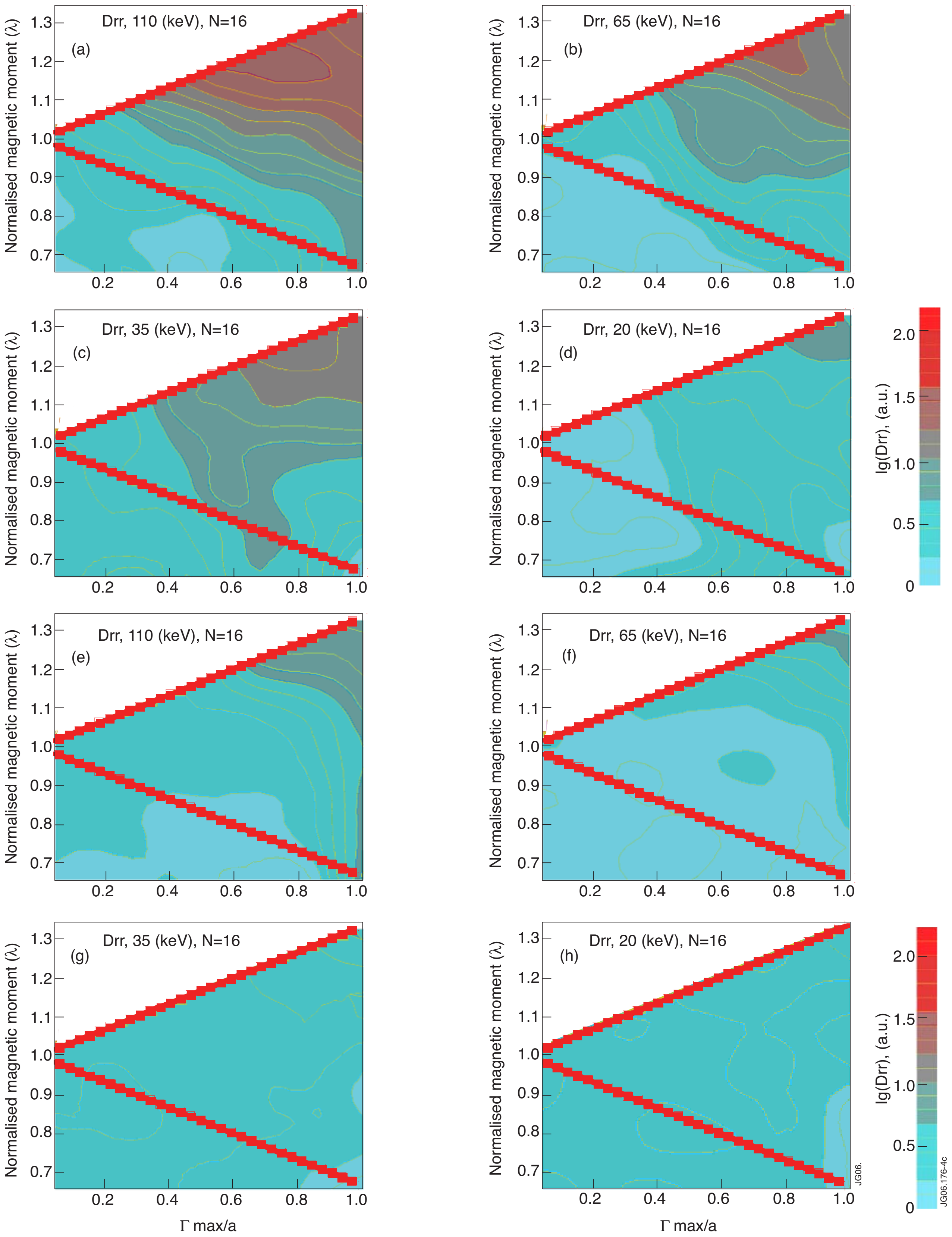

Figure 3: (λ, r_{max}/a)-distributions of radial diffusion coefficients of 20keV < E < 110keV deuterons in a JET plasma with I/B = 3MA/2.8T in the standard N=32 (bottom) coil configuration and in the presence of 30% additional N=16 (top) ripple harmonic. Here the normalised magnetic moment is $\lambda \equiv \mu B/E$.

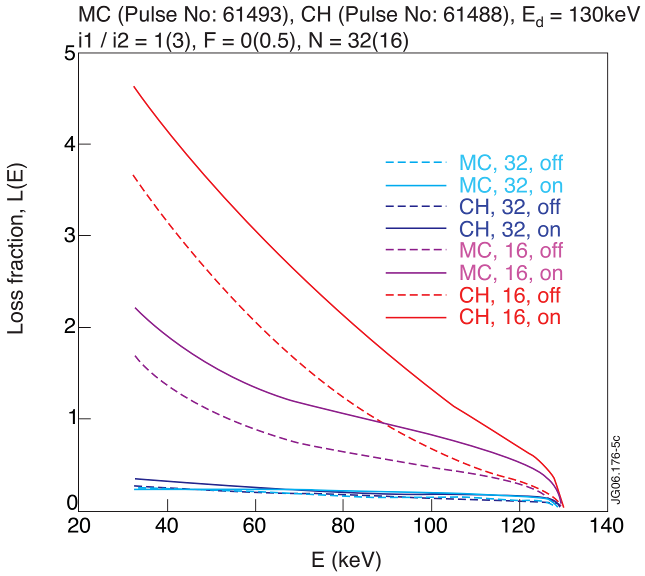

Figure 4: Loss fraction of deuterium beam ions versus energy for MC and CH plasmas in JET depending on the injection direction and the N=16 ripple harmonic.

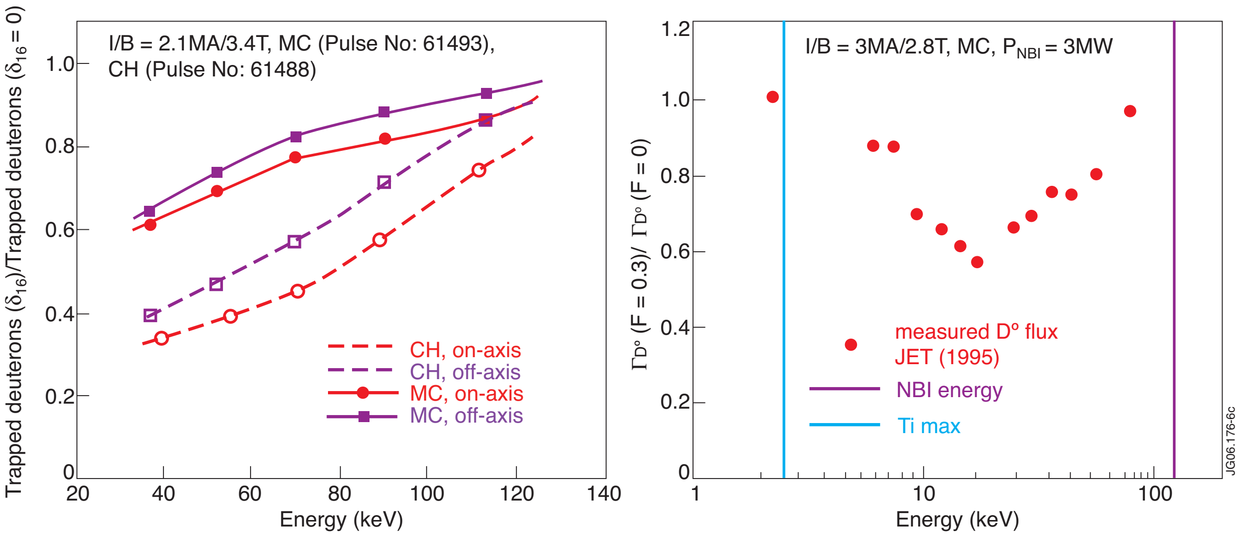

Figure 5: Modelled ratio of the number of toroidally trapped beam deuterons in an I/B=3MA/2.8T JET plasma with enhanced ripples to that in the standard low ripple case as a function of energy (left). The right figure shows the ripple effect on the measured [3] neutral particle flux $\Gamma_{D}o$.