TF Ripple effects on the NBI Deuteron Confinement in JET

V. Yavorskij[1,2], M. Cecconello[3,4], V. Goloborod'ko[1,2], M. Brix[3], C. Challis[3], S. Gerasimov[3], V. Kiptily[3], A. Korotkov[3], V. Parail[3], S. Reznik[1,2], M. Santala[5], K. Schoepf [1], S.E. Sharapov[3], E. Surrey[3], P. de Vries[3] and JET-EFDA contributors[§]

[1]*Association EURATOM-OEAW, Institute for Theoretical Physics, University of Innsbruck, Austria*
[2]*Institute for Nuclear Research, Ukrainian Academy of Sciences, Kiev, Ukraine*
[3]*EURATOM /UKAEA Fusion Association, Culham Science Centre, Abingdon, OX14 3DB, UK*
[4]*Fusion Plasma Physics, Alfvén Laboratory, School of Electrical Engineering, Royal Institute of Technology (KTH), Stockholm, Sweden, EURATOM-VR Association*
[5]*Helsinki University of Technology, Association Euratom-Tekes, FI-02015 TKK, Finland*

1. Introduction

This paper reports the effects of toroidal magnetic field (TF) ripple on the confinement of NBI-produced deuterons in recent JET experiments where an N=16 TF ripple harmonic was induced [1]. The influence of an enhanced TF ripple on NBI deuterons is examined with a neutral particle analyzer (NPA) in the 5 – 40 *keV* energy range by analyzing the neutral deuterium fluxes formed by Charge eXchange (CX) and recombination of deuterium ions with energies well above the temperature of plasma deuterons [2]. Due to the NPA line of sight, the observed flux is induced mainly by the charge exchange between neutrals and deuterium ions with $V_{||} \approx 0$ at the plasma mid-plane: the measured fluxes characterize therefore the ions mostly affected by ripples. Such a reduction in the deuterium neutrals emitted from plasmas with an N=16 ripple harmonic was observed in previous ripple experiments at JET [2, 3]. The main purpose of this paper to report on an experimental study of the reduction in neutral deuterium (D^0) flux and its dependency on the magnetic shear in the plasma core (as well as other plasma parameters) and on the magnitude of the N=16 TF ripple harmonic. Interpretive 3D Fokker-Planck modeling of the effect of TF ripple on the partly thermalized NBI deuterons contributing to measured D^0 fluxes is in reasonable agreement with measurements.

2. Experimental results

We analyze ripple effects on NBI ions for three groups of plasmas: 1) Positive Shear (PS) plasmas without ICRH; 2) ITB plasmas with low Optimised Shear (OS) in the core and moderate ICRH heating; 3) ITB plasmas with Reversed Shear (RS) in the core and moderate ICRH heating. Fig. 1 illustrates the reduction of the D^0 flux emitted from a positive shear I/B=1.14MA/2T plasma with predominantly on-axis injected ions (P_{NBI}=7.4MW with 'normal' beams at $R_{tangency}/R_{axis}\approx 0.44$) in the absence of ICRH (P_{ICRH}=0) and at relatively mild ELM activity. In this paper the measured data are averaged over the 2s time interval during the quasi steady-state phase of NBI. It is seen that the ripple induced reduction of D^0 flux is maximum at energy $E \sim 40$ *keV* and vanishes at energies <10 *keV*, in agreement with previous observations [2, 3]. This observation indicates that the main effect of TF ripple in this case is on the beam ions (E>20 *keV*), while the bulk plasma deuterons, responsible for the D^0 fluxes observed at low energy (E<10-20 *keV*) are practically unaffected. The magnitude of the N=16 ripple harmonic for the last closed flux surface at the outboard midplane ($R \cong 3.8$m,

[§] See the Appendix of M.L.Watkins et al., Fusion Energy 2006 (Proc. 21st Int. Conf. Chengdu, 2006) IAEA, Vienna (2006)

$Z \cong 0.3$m), δ_{16}, is characterized by the ratio of the currents in neighbouring TF coils (I_{min}/I_{max}) such that $\delta_{16} = F\delta_{16}^0$ with $F = (I_{max} - I_{min})/(I_{max} + I_{min})$ and δ_{16}^0 being the magnitude of pure N=16 ripple harmonic (I_{min} =0). Note that in the JET plasma cross section the maximum δ_{16}^0

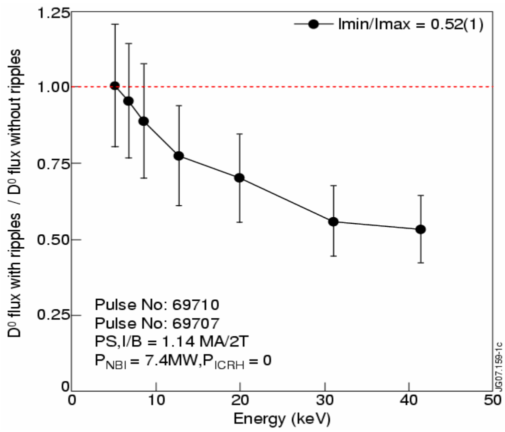

Fig. 1 TF ripple reduction of D^0 fluxes in PS plasma without ICRH

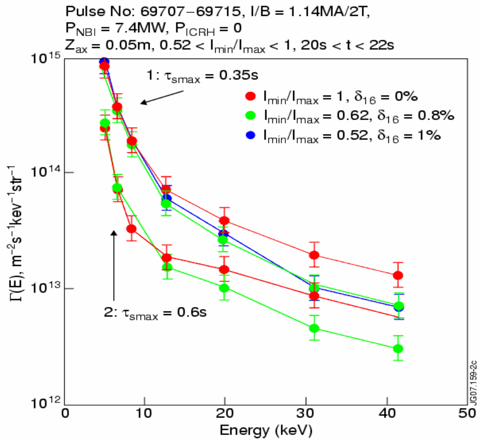

Fig. 2 Effect of N=16 TF ripple harmonic on the neutral deuterium fluxes in PS plasma without ICRH in the case of predominant normal NBI.

$\cong$ 3.4% is reached at the low-B. Figure 2 shows the neutral deuterium fluxes in PS plasma without ICRH in the case of predominantly ‘normal’ NBI as the function of energy for different ripple magnitudes and different plasma parameters. The red curves correspond to the plasmas without additional TF ripple (I_{min}/I_{max}=1) and blue curves are for plasmas with $\delta_{16max} \approx 0.8$% and 1% ($I_{min}/I_{max}$=0.62 and 0.52 respectively). As expected plasmas with longer slowing-down times for beam deuterons, $\tau_s^{-1} \propto n/T_e^{3/2}$, produce higher fluxes of energetic neutrals due to higher steady-state density of beam ions ($n_{NBI} \propto \tau_s$). However, relative reduction of the D^0 fluxes with TF ripple both for τ_s=0.35s and for τ_s=0.6s is close to 50% for

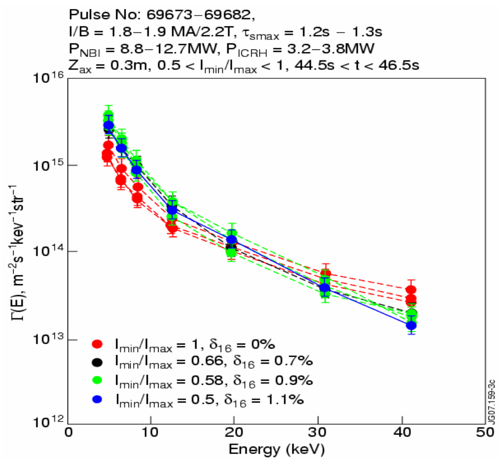

Fig. 3 Effect of N=16 TF ripple harmonic on the D^0 fluxes detected from OS plasma with moderate ICRH.

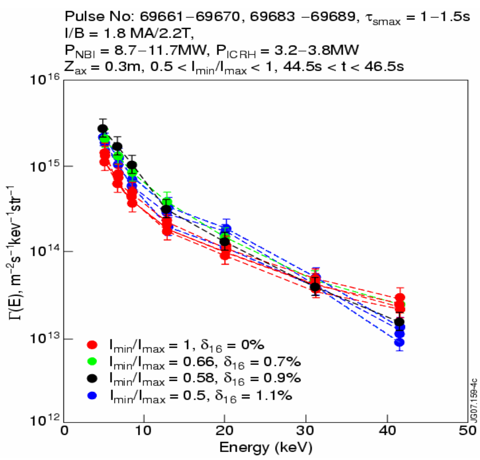

Fig. 4 Effect of N=16 TF ripple harmonic on the D^0 fluxes detected from RS plasma with moderate ICRH.

E>30keV. It is clearly seen that TF ripple essentially decreases the fluxes of energetic neutrals in all pulses shown thus indicating that TF ripple produced a reduction in the population of beam ions with low longitudinal velocities.

Similar ripple reduction of the D^0 emission at E>20keV is observed for plasmas with low shear in the core and moderate ICRH power as seen in Fig. 3. The figure shows the energy dependence of the D^0 fluxes detected from LS plasmas at 1.8-1.9MA/2.2T with P_{NBI}=8.8-12.7MW and P_{ICRH}=3.2-3.8MW and with the core values of deuterium slowing down time τ_s= (1.2-1.3)s. In contrast to the PS plasma without ICRH, these NPA measurements indicate an increased flux of low energy neutrals (E<20keV) from plasmas with TF ripple. One possible explanation for this might be the decreased ELM induced deuteron loss from the plasma periphery due to the reduction of ELM amplitude in discharges with TF ripple [4]. Fig. 4 shows the ripple effect on the D^0 fluxes detected from RS plasmas at 1.8MA/2.2T with P_{NBI}=8.7-11.7MW and P_{ICRH}=3.2-3.8MW for τ_s=(1-1.5)s. Similarly to the low shear plasmas with moderate ICRH in RS plasma the TF ripple reduces the D^0 flux at high energy ($E>30keV$) in accordance with the expected ripple induced loss of NBI fast ions, but increased fluxes are observed at lower energies ($E<10keV$) in the presence of additional ripple.

3. Modelling results

According to 3D Fokker-Planck modeling carried out in [5] the N=16 TF ripple harmonic can affect the confinement of toroidally trapped NBI deuterons in JET plasmas. Super-banana diffusion of toroidally trapped ions induced by enhanced TF ripple was shown to reduced the density of partly thermalised beam deuterons ($E<50keV$) in typical JET plasmas by up to 30 - 50% compared with cases without ripple. In this paper we present Monte-Carlo modelling of the flux of neutral deuterons in the 5 - 40 keV energy range emitted from the positive shear plasmas without ICRH. Simulation accounts for charge exchange and recombination of Maxwellian deuterium ions of the bulk plasma and of beam deuterons with a distribution function calculated using the 3D COM Fokker-Planck code [5].

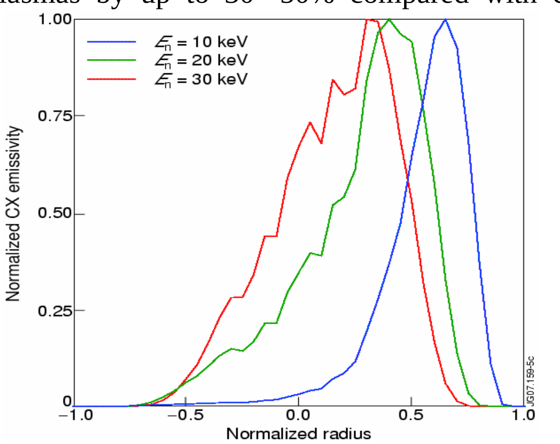

Fig. 5 Calculated profiles of D^0 emission induced by bulk plasma deuterons in shot #69710 as dependent on the neutrals energy

Fig. 5 demonstrates the calculated emissivity profiles of deuterium neutrals emitted along the LoS of the NPA for pulse #69710 (time averaged between 60 and 62 s) as a result of charge exchange and recombination of bulk plasma deuterons. The modeling illustrates the outward shift of the emission region as the energy of neutrals is increased [6]. To evaluate the contribution of NBI deuterons to the observed D^0 emission we use the distribution function of partly thermalised beam deuterons obtained with the 3D COM Fokker-Planck calculation. Fig. 6 shows the contours of the calculated distribution of beam ions with $V_{||}/V=0$ along the LoS of the NPA (Z=0.28m) in the plane spanned by major radius R and ion energy E for PS plasma (pulse #69710) in the case of 'normally' injected 130keV deuterons. The TF ripple is seen to substantially reduce the population of NBI deuterons with small $V_{||}/V$ along the LoS of the NPA. At E ~ 30-40keV the ripple reduction of f_{NBI} exceeds 50%.

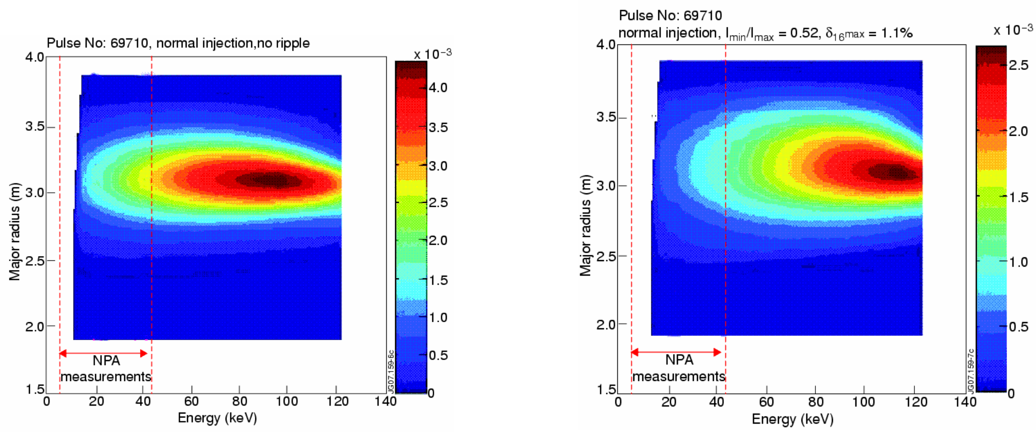

Fig. 6 Contours of calculated distribution of beam ions $f_{NBI}(R,E,V_{//}/V=0, Z=0.28m)$ for PS plasmas (shot #69710) in the case of normally injected 130keV deuterons in the absence of TF ripples (left) and in the case of N=16 TF ripple harmonic (right) induced by $I_{min}/I_{max}=0.52$, $\delta_{16max}=1.1\%$

Finally, figure 7 shows the modeled D^0 fluxes for pulse 69710 as a function of energy taking into account the NBI distribution function shown in figure 6: it can be seen that the interpretive modeling of ripple effects on NBI ions is in reasonable agreement with the measurements.

4. Summary

Ripple induced reduction of the fluxes of deuterium neutrals in the 5 – 40 keV energy range from the plasma mid-plane was observed in recent JET experiments. The maximum observed reduction of D^0 fluxes due to ripple is approximately 50 % and occurs at energies above 30 keV. In positive shear plasmas without ICRH ripple reduction of D^0 fluxes vanishes at energies below 10 keV. However, in the case of plasmas with low or reversed shear core, increased D^0 fluxes were observed for energies below 10 – 20 keV in the presence of additional ripple and ICRH heating. Interpretive modeling of the deuterium neutral emission that accounts for the superbanana ripple diffusion of NBI ions is in reasonable agreement with measurements at least for the scenarios without ICRH. Note that ripples may essentially effect the fast ion confinement in ITER where TF ripple magnitude at the outer separatrix is expected to be δ ~ 0.5%.

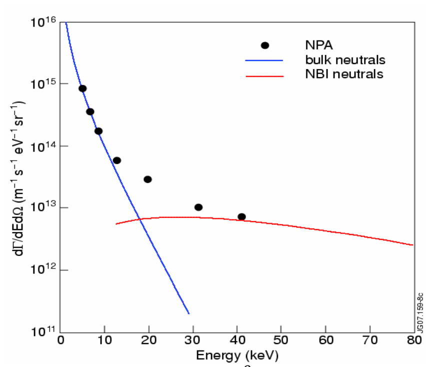

Fig. 7 Modelled D^0 fluxes for shot #69710 as a function of energy

Acknowledgement

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