
EFDA–JET–CP(07)03/69

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TF Ripple Effects on the NBI Deuteron Confinement in JET

V. Yavorskij^{1,2}, M. Cecconello^{3,4}, V. Goloborod'ko^{1,2}, M. Brix³, C. Challis³,
S. Gerasimov³, V. Kiptily³, A. Korotkov³, V. Parail³, S. Reznik^{1,2}, M. Santala⁵,
K. Schoepf¹, S.E. Sharapov³, E. Surrey³, P. de Vries³
and JET EFDA contributors*

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

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

³EURATOM /UKAEA Fusion Association, Culham Science Centre, Abingdon, OX14 3DB, UK

⁴Fusion Plasma Physics, Alfvén Laboratory, School of Electrical Engineering,

Royal Institute of Technology (KTH), Stockholm, Sweden, EURATOM-VR Association

⁵Helsinki University of Technology, Association Euratom-Tekes, FI-02015 TKK, Finland

* See annex of M.L. Watkins et al, "Overview of JET Results",
(Proc. 21st IAEA Fusion Energy Conference, Chengdu, China (2006)).

Preprint of Paper to be submitted for publication in Proceedings of the
34th EPS Conference on Plasma Physics,
(Warsaw, Poland 2nd - 6th July 2007)

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 $5 - 40keV$ 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. Figure 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 $E \sim 40keV$ 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 ($E > 20keV$), while the bulk plasma deuterons, responsible for the D^0 fluxes observed at low energy ($E < 10-20keV$) are practically unaffected. The magnitude of the $N = 16$ ripple harmonic for the last closed flux surface at the outboard midplane ($R \approx 3.8m, Z \approx 0.3m$), d_{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 $\delta_{16}^0 \approx 3.4\%$ 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 ($n_{\text{NBI}} \propto \tau_s$). However, relative reduction of the D^0 fluxes with TF ripple both for $\tau_s = 0.35\text{s}$ and for $\tau_s = 0.6\text{s}$ is close to 50% for $E > 30\text{keV}$. 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 $E > 20\text{keV}$ 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 $1.8\text{--}1.9\text{MA}/2.2\text{T}$ with $P_{\text{NBI}} = 8.8\text{--}12.7\text{MW}$ and $P_{\text{ICRH}} = 3.2\text{--}3.8\text{MW}$ and with the core values of deuterium slowing down time $\tau_s = (1.2\text{--}1.3)\text{s}$. In contrast to the PS plasma without ICRH, these NPA measurements indicate an increased flux of low energy neutrals ($E < 20\text{keV}$) 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]. Figure 4 shows the ripple effect on the D^0 fluxes detected from RS plasmas at $1.8\text{MA}/2.2\text{T}$ with $P_{\text{NBI}} = 8.7\text{--}11.7\text{MW}$ and $P_{\text{ICRH}} = 3.2\text{--}3.8\text{MW}$ for $\tau_s = (1\text{--}1.5)\text{s}$. Similarly to the low shear plasmas with moderate ICRH in RS plasma the TF ripple reduces the D^0 flux at high energy ($E > 30\text{keV}$) in accordance with the expected ripple induced loss of NBI fast ions, but increased fluxes are observed at lower energies ($E < 10\text{keV}$) 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 ($E < 50\text{keV}$) 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 $5\text{--}40\text{keV}$ 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].

Figure 5 demonstrates the calculated emissivity profiles of deuterium neutrals emitted along the LoS of the NPA for Pulse No: 69710 (time averaged between 20 and 22s) 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. Figure 6 shows the contours of the calculated distribution of beam ions with $V_{\parallel}/V = 0$ along the LoS of the NPA ($Z=0.28\text{m}$) in the plane spanned by major radius R and ion energy E for PS plasma (Pulse No: 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_{\parallel}/V along the LoS of the NPA. At $E \sim 30\text{--}40\text{keV}$ the ripple reduction of f_{NBI} exceeds 50%.

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 5–40keV 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 30keV. In positive shear plasmas without ICRH ripple reduction of D^0 fluxes vanishes at energies below 10keV. 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 $\delta \sim 0.5\%$.

ACKNOWLEDGEMENT

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

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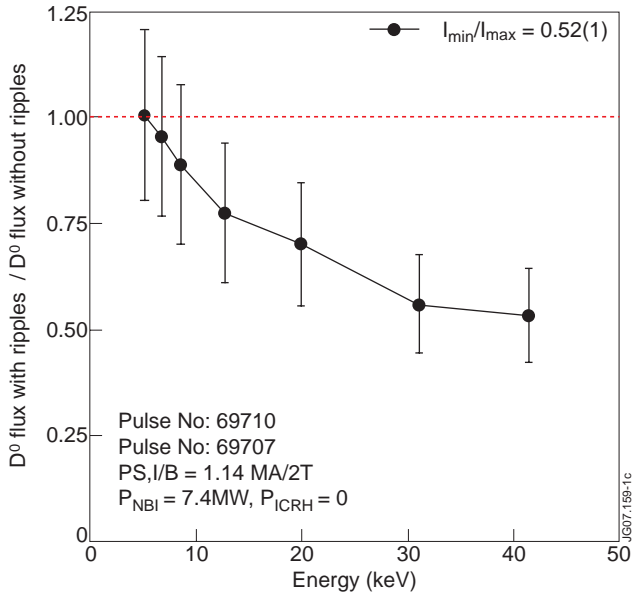


Figure 1: TF ripple reduction of D^0 fluxes in PS plasma without ICRH.

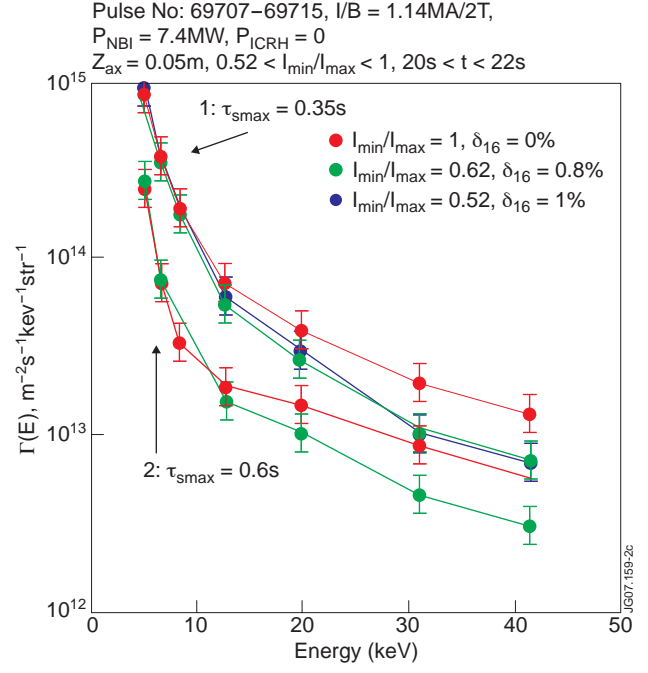


Figure 2: Effect of $N=16$ TF ripple harmonic on the neutral deuterium fluxes in PS plasma without ICRH in the case of predominant normal NBI.

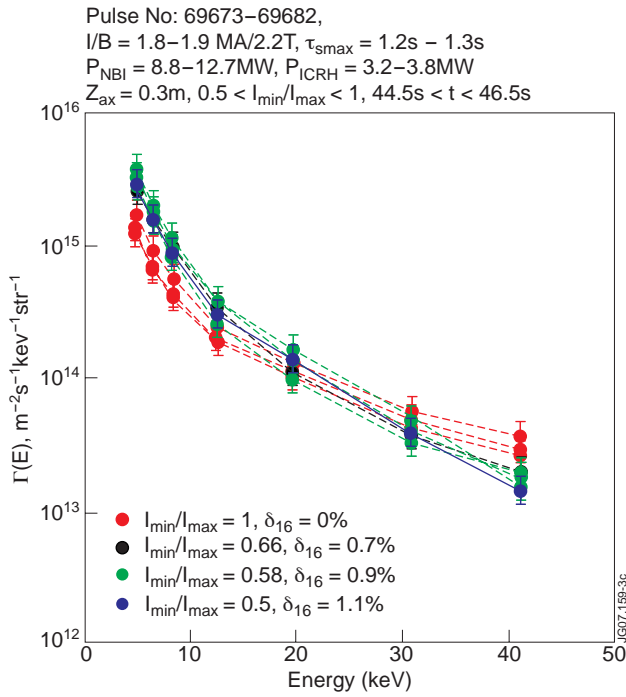


Figure 3: Effect of $N=16$ TF ripple harmonic on the D^0 fluxes detected from OS plasma with moderate ICRH.

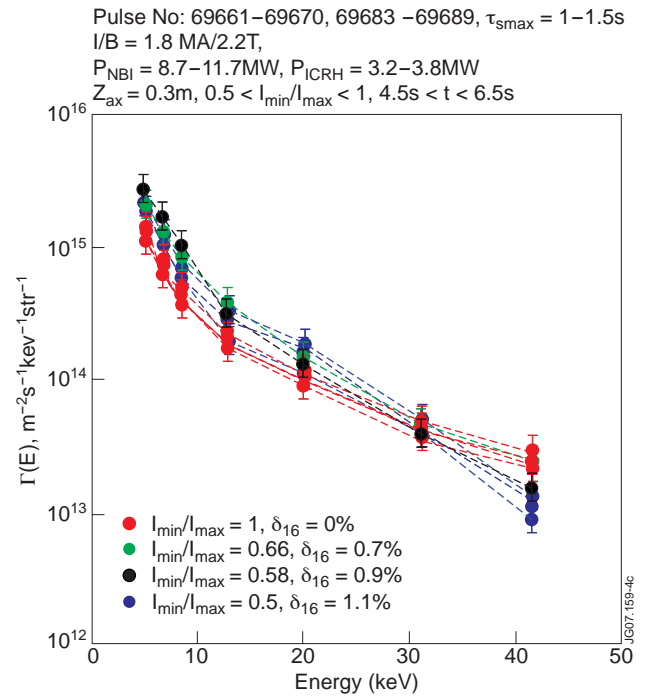


Figure 4: Effect of $N=16$ TF ripple harmonic on the D^0 fluxes detected from RS plasma with moderate ICRH.

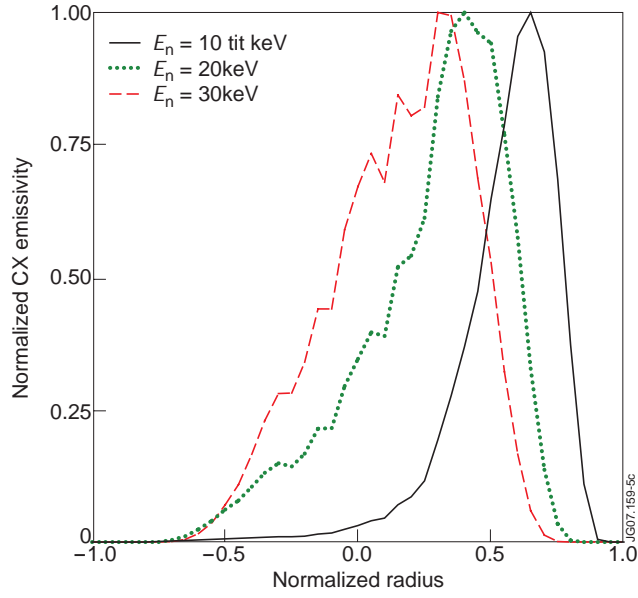


Figure 5: Calculated profiles of D^0 emission induced by bulk plasma deuterons in Pulse No: 69710 as dependent on the neutrals energy.

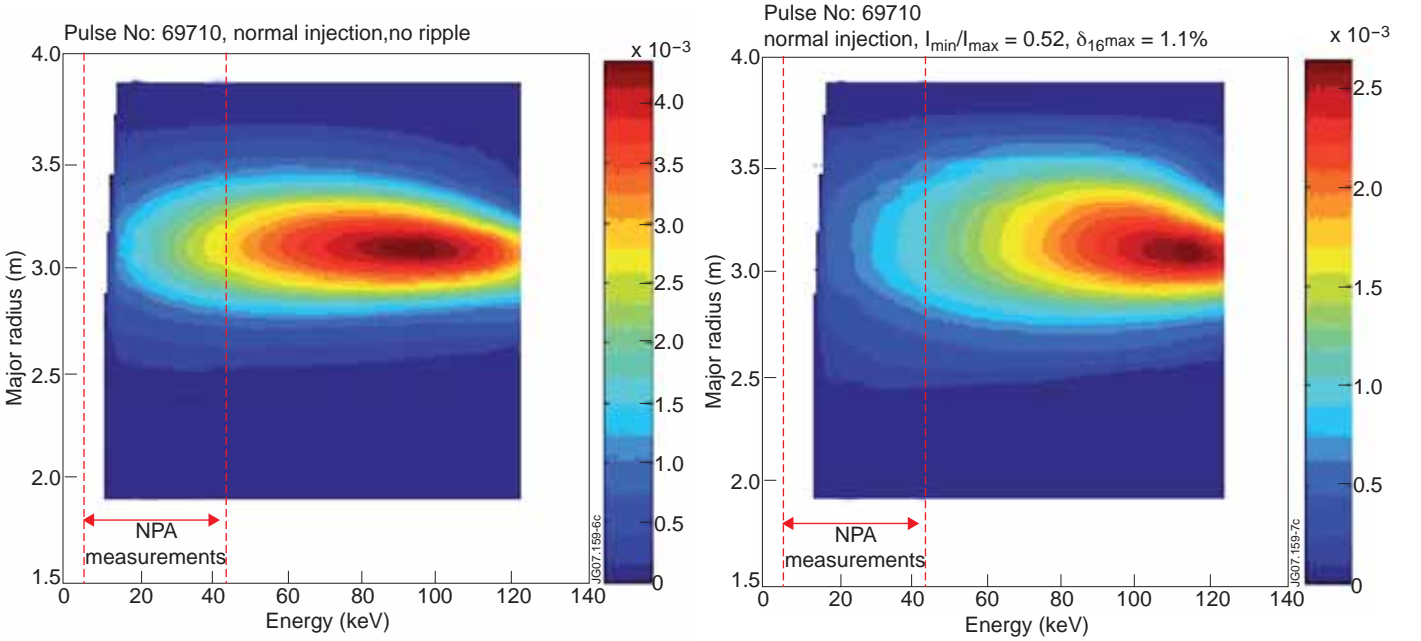


Figure 6: Contours of calculated distribution of beam ions $f_{NBI}(R, E, V_{||}/V = 0, Z = 0.28m)$ for PS plasmas (Pulse No: 69710) in the case of normally injected 130keV deuterons in the absence of TF ripples (left) and in the case of $N=16$ TF ripple harmonic (right) induced by $I_{min}/I_{max} = 0.52, \delta_{16max} = 1.1\%$.

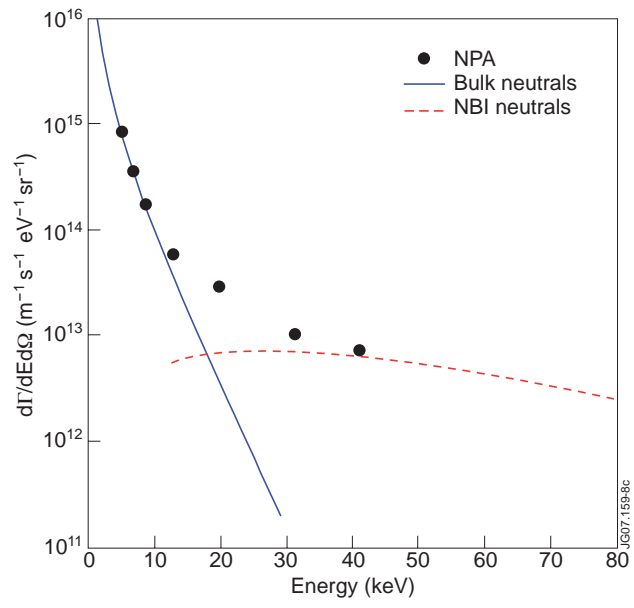


Figure 7: Modelled D^0 fluxes for Pulse No: 69710 as a function of energy.