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ABSTRACT
Using a 3D Fokker-Planck code we examine the Toroidal Field (TF) ripple induced transport of NBI generated deuterons for the purposes of Neutral Particle Analyzer (NPA) diagnostics. The neutral loss fluxes measured in recent JET ripple experiments are compared with modeling results. The observed reduction of deuterium fluxes in the case of enhanced ripples might be quantitatively explained by ripple-induced diffusion of trapped NBI deuterons.

1. INTRODUCTION

Here we model the effects of Toroidal magnetic Field (TF) ripples on the neutral deuterium (D^0) fluxes produced by charge exchange and recombination of NBI deuterium ions in recent JET experiments where an additional N=16 TF ripple harmonic was induced [1]. In spite of the negligible effect of TF ripples on beam ion confinement in the standard N=32 JET TF coil configuration, a significant degradation of NBI ion confinement in previous JET experiments with enhanced TF ripples was observed in the energy range $T<E<E_b$, where T is the plasma temperature and E_b the energy of injected ions [2,3]. One of the most important ripple transport mechanisms responsible for these losses is collisional superbanana diffusion arising as a result of resonant interaction of toroidally trapped fast ions with ripple perturbations [4, 5]. The influence of enhanced TF ripples on NBI deuterons was examined with NPA by analyzing the neutral deuterium fluxes formed by charge exchange and recombination of deuterium ions with energies well above the temperature of bulk plasma deuterons [6]. In ICRH free plasmas the TF ripples induced a reduction of the D^0-flux in the energy range $5keV<E<40keV$. The D^0-maximum flux decrease was detected at $E \sim 40keV$, while the diminution vanishes for energies E <10keV, which agrees with previous observations [2]. A Fokker-Planck code in constants-of-motion space (FPCOM) was used to model the distribution function of NBI generated deuterons in discharges with and without an additional N=16 TF ripple harmonic. This distribution function was employed in a Monte-Carlo code for calculation of the neutral deuterium fluxes to the NPA detector. Numerical simulations of JET discharges demonstrate a reasonable agreement of the calculated neutral fluxes to the NPA with the measurements [6], at least in plasmas without ICRH.

2. JET NPA FLUXES SIMULATION

To evaluate the NBI ion induced emission of neutrals that contribute to the NPA signal, we determine first the neutral-emission rate per volume, per energy and per pitch-angle. This quantity may be expressed as

$$\frac{dR_{cx}(R, E, Z = Z_{eq}, \xi = 0)}{dVdEd\xi}$$
$$2\pi\sqrt{2E}\, f_d(R, E, Z = Z_{eq}, \xi = 0)\, n_n(R, Z = Z_{eq}) \left[\sigma_{cx}(u)\, u\right]_{E,R} \quad (1)$$

$$\left[\sigma_{cx}(u)\, u\right]_{E,R} = \frac{1}{2\pi n_n} \int d\vartheta_d\, d\mathbf{V}_n f_n(\mathbf{r}, \mathbf{V}_n) \sigma_{cx}(|\mathbf{V}_d - \mathbf{V}_n|)|\mathbf{V}_d - \mathbf{V}_n| \quad (2)$$

where *fn* and *fd* are the neutral and deuteron distribution functions respectively, $[\sigma_{cx}(u)]_{E,R}$ is the rate coefficient of charge exchange of deuterons in interactions with neutrals, Z_{eq} is the vertical coordinate of the NPA line of sight (Z_{eq} = 0.28cm on JET) and x the deuteron pitch-angle cosine along the NPA line of sight ($x = 0$ on JET). Using Eqs. (1) and (2) the neutral deuterium flux to the NPA can be calculated to be

$$\Gamma_n(E) = \int dR d\Omega \frac{dR_{cx}\,(R,\,E,\,Z = Z_{eq},\,\xi = 0)}{dVdEd\xi}$$
$$2\pi\Delta\Omega \int dR \sqrt{2E}\, f_d\,(R,\,E,\,Z = Z_{eq}, \xi = 0)\; n_n\,(R, Z = Z_{eq}) \left[\sigma_{cx}\,(u)\; u\right]_{E,R} \eta, \tag{3}$$

$$\eta = \exp\left(-\int \frac{dR}{\lambda}\right). \tag{4}$$

Here Ω is the solid angle and $\Delta\Omega$ the value determined mainly by NPA geometry, n_n denotes the deuterium density, and h is the attenuation factor defined in Eq.(4), wherein λ is the "ionization" length calculated by use of the total cross-section for electron loss by ionization. Evidently, the neutral flux measured by the NPA in JET is directly determined by the deuteron distribution function in the mid-plane as well as by the distribution function of neutral deuterium. The D^0-distribution function for present simulations of NPA signals was obtained by a Monte-Carlo code. For JET Pulse No's: 69707 (no TF ripple) and 69710 (1% TF ripple) this code delivers a Maxwellian distribution for D^0 (*T(0)=3.5keV*) and radial density profiles as shown in Fig.1. The attenuation factor calculated for Pulse No: 69707 is plotted in Fig.2. Figs.1, 2 indicate the important role of NBI deuteron transport not only in the plasma central region but also at the periphery.

3. NBI DEUTERON DISTRIBUTION FUNCTION

The distribution functions of energetic deuterons was calculated with a 3D (in constants-of-motion space) Fokker-Planck code (3D COM FP) for JET Pulse No's: 69707 (no TF ripple) and 69710 (1% TF ripple at the edge), where NBI PINIs 1, 4, 5, 6 and 8 were applied. Enhanced radial transport as caused by ripples in the intermediate energy range was described by the "superbanana" diffusion coefficient [5]

$$D_{sb} = v_{eff}\,\frac{F\Delta r_{sb}^2}{1 + (v_{eff}/\,\omega_{sb})^2},$$
$$v_{eff} = v_{\perp}\,(Nq(1 + \kappa^{-1}))^2 R\,/\,r\,,\;\; F = \kappa(1 + \kappa)\frac{\Delta r_b}{r}, \tag{5}$$
$$\kappa = g\sqrt{\delta\,/\,\delta_1}\,,\;\; \delta_1 = r(Nq)^{-3/2}\,/\,R$$

where $\nu_\perp$ is the pitch-angle scattering rate, q is the safety factor, δ and N are TF ripple amplitude and number of coils respectively, Δr_{sb} and w_{sb} are superbanana width and frequency respectively, Δr_b denotes the banana width and g an empirical coefficient. As an example, we show in Fig.3 the calculated NBI deuteron distribution function along the NPA line of sight (in Pulse No: 69707). Further, to specify the difference of fast deuteron distributions in discharges with and without ripples, Fig.4 displays the calculated decrease of fast ion density along the NPA line of sight as induced by TF ripples. The main reductions take place at the outboard plasma periphery (maximum ripple amplitude) and in the region of steepest gradient of the distribution function.

4. COMPARISON WITH JET NPA MEASUREMENTS

Both the 3D COM FP modeled distribution functions of NBI deuterons and the Maxwellian background deuteron distributions were used for calculation (Eq.(3)) of the neutral deuterium fluxes to the NPA in Pulse No's: 69707 and 69710. In Fig.5 we present the comparison of simulation results with experimental data obtained on JET in these shots. For Pulse No: 69707 with no TF ripples a reasonable quantitative agreement becomes apparent. For cases with TF ripples, e.g. Pulse No: 69710, an empiric coefficient g is introduced and set to unity in Eq. (5) in order to fit the measured neutral fluxes.

SUMMARY

The numerical simulation of D_0-fluxes to the NPA with positive shear plasmas without ICRH demonstrates that the 3D Fokker-Planck model describes reasonably the TF ripple effect on NBI generated deuterons in JET ripple experiments. The comparison of experimentally measured and calculated deuterium fluxes allows for validation of the 3D COM FP code for NBI ions in tokamaks. The deuterium flux reduction observed in JET ripple experiments may be quantitatively explained by ripple-induced diffusion of trapped NBI deuterons and provides the scale for the ripple induced "super-banana" radial diffusion coefficient of fast deuterons. This benchmarking essentially improves the accuracy of the 3D FP COM code for fast ion transport calculations. Concludingly, we inject to note that ripples may substantially affect the fast ion confinement in ITER where the TF ripple magnitude at the separatrix is expected to be about 0.5%.

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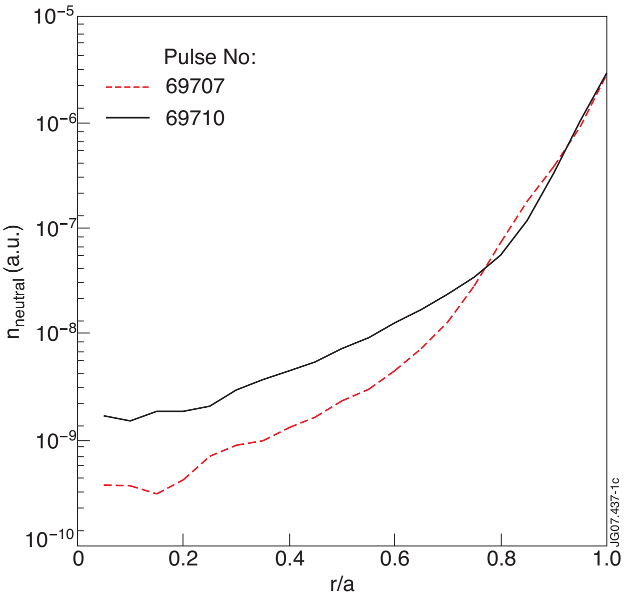

Figure 1: Radial distribution of neutral deuterium in JET Pulse No's: 69707 and 69710 calculated with MC code.

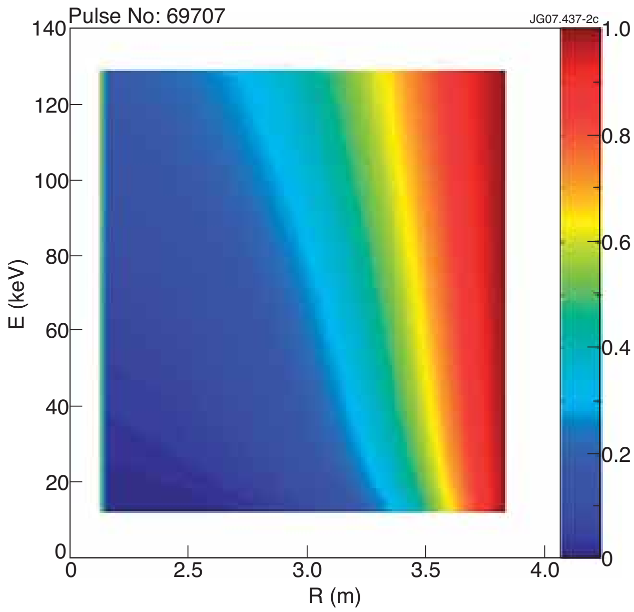

Figure 2: Attenuation factor η versus energy of neutrals along NPA line of sight calculated for JET Pulse No: 69707 plasma parameters.

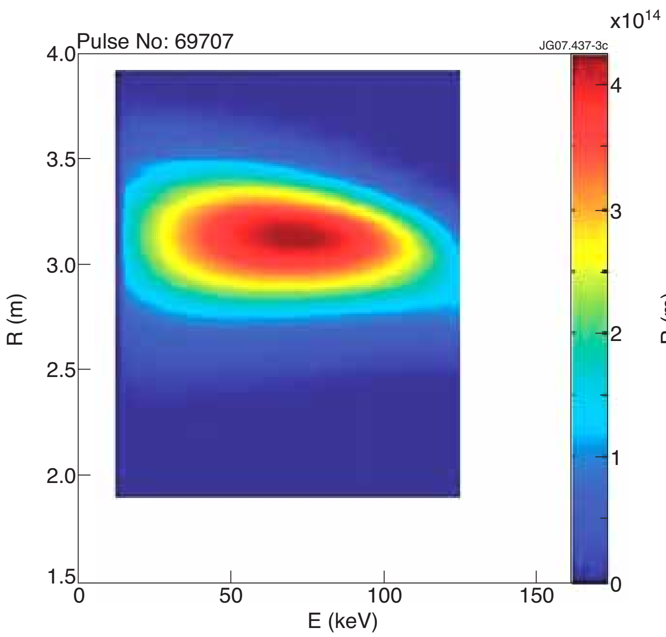

Figure 3: NBI deuteron density per energy (N_{69707}) in JET Pulse No: 69707(no ripple) calculated along the NPA line of sight.

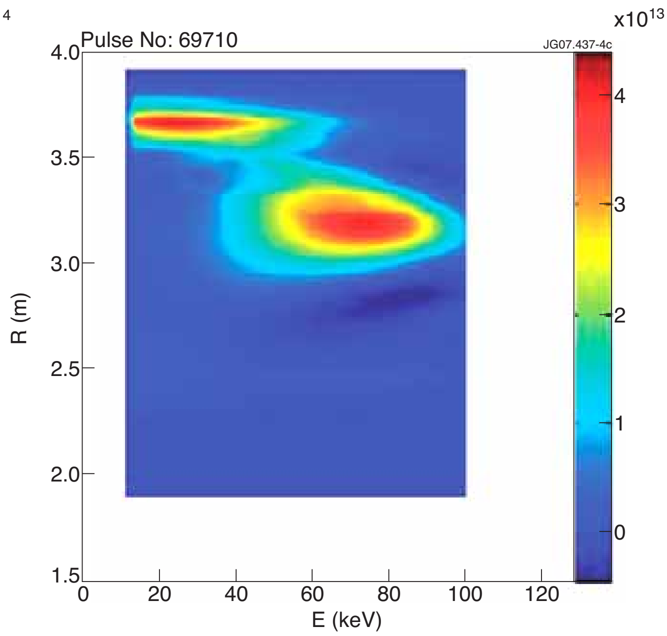

Figure 4: Ripple induced decrease of NBI deuteron density per energy (N_{69707}–N_{69710}) in JET Pulse No: 69710 in comparison to Pulse No: 69710 calculated along the NPA line of sight.

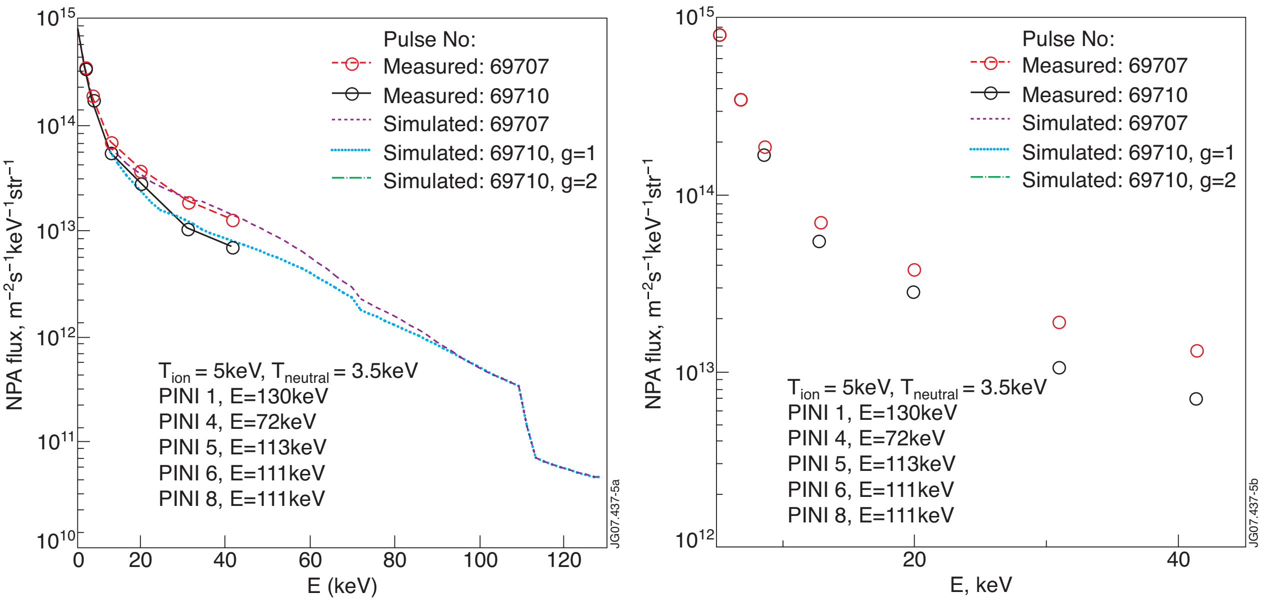

Figure 5: Measured and simulated deuterium fluxes to NPA in JET Pulse No's: 69707 (no TF ripple) and 69710 (1% TF ripple). (a) shows calculated fluxes in the NBI deuteron energy range E<130keV and (b) in the measured energy range 5keV<E<40keV.