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ABSTRACT.
The effect of ICRH on (^{3}He)D plasmas at JET was studied with the TOFOR spectrometer dedicated to 2.5MeV dd neutron measurements. In Internal Transport Barrier (ITB) plasma experiments with large ^{3}He concentrations (X(^{3}He)>15%) an increase in neutron yield was observed after the ITB disappeared but with the auxiliary NBI and ICRH power still applied. The analysis of the TOFOR data revealed the formation of a high energy (fast) D population in this regime. The results were compared to other mode conversion experiments with similar X(^{3}He) but slightly different heating conditions. In this study we report on the high energy neutron tails originating from the fast D ions and their correlation with X(^{3}He) and discuss the light it can shed on ICRH-plasma power coupling mechanisms.

Neutron emission spectroscopy is a plasma diagnostic technique that allows one to extract information from the measured neutron spectrum on temperatures and densities of the plasma ion populations involved in the fusion process and on their collective motion [1]. In February 2005 a brand new Time Of Flight Optimized Rate (TOFOR) spectrometer was installed in the JET roof laboratory viewing the plasma vertically with respect to the plasma toroidal magnetic axis [2]. TOFOR is dedicated to the measurement of neutrons emitted in D plasma fusion reactions, $d+d \rightarrow {}^{3}He+n$. The main neutron emission is peaked at about 2.5MeV if the deuterons (d) are in thermal equilibrium (i.e. characterized by - isotropic - Maxwellian distribution functions) resulting in a Gaussian shaped neutron spectrum. Due to losses there is a constant need for particle and energy fuelling, however, and thus this ideal situation is not commonly obtained. JET is equipped both with Neutral Beam Injection (NBI) and Radio Frequency (RF) heating to allow reaching a steady state - but non-thermalized - regime compensating the power losses. The auxiliary heating perturbs the plasma equilibrium state generating various ion populations characterized by non-isotropic velocity and pitch angle distributions, which give rise to complex spectra in phase-space. The shape of the neutron spectrum measured along the line of sight thus differs significantly from a Gaussian as it is a result of the intricate kinematics of the fusing ion populations. Since the fusion reactivity increases with the energy of the reactants, the creation of fast ion populations in the plasma due to the auxiliary heating can be observed in the neutron spectrum as high energy tails at neutron energy E_n>2.5MeV. As TOFOR measures the time of flight (t_{tof}) of the incoming neutrons interacting in the detectors, the high energy tail corresponds to t_{tof}<65 ns which is the reference t_{tof} for 2.5MeV neutrons. The diagnostic information is then interpreted by fitting the measured spectrum with a calculated neutron spectrum generated by ion populations of which the velocity distributions are assumed known. Modifying the free parameters of the adopted distribution functions allows scanning for the values giving the best fit to the experimental data. Accounting for the response function of the TOFOR diagnostic, the raw experimental data are thus fitted to the model [3].

TOFOR was operational and intensively exploited during the last campaigns run at JET in 2006-07 measuring neutrons emission from plasmas subjected to various auxiliary heating schemes and observing their effects [4][5]. This paper presents the observation of a fast deuteron population generated during experiments where RF heating was applied as ion cyclotron resonance heating (ICRH) together with NBI(D) to (^{3}He)D plasmas. The concentration of the ^{3}He minority species was varied between X(^{3}He)~5-18%.

Two experimental sessions are considered here [6]. The first aimed at the study of the transport effects induced by the ICRH power injection in ITB plasmas. The second session concerned mode conversion experiments and focused on the optimal ICRH-plasma conditions for the creation of a well localized electron heating source. The formation of D tail was only observed in two shots of ITB experiments when the ITB plasma configuration disappeared and X(^{3}He) grew above 15% (mode conversion regime).

In the ITB session, the toroidal magnetic field was around B_0 = 3.35-3.45T and the plasma current varied within I_p = 1.7-2.6MA. The auxiliary power applied was 2-6MW ICRH with dipole antenna phasing. The location at which ICRH resonance takes place is a sensitive function of f/B_t, where f is the generator frequency. Hence, in order to position the ion resonance on the low field side, in the centre or on the high field side of the plasma, different frequencies were adopted.

Approximately 8-20MW NBI power with mixed 80/130 kV D injection was used in these discharges. The heating schemes of the two experimental sessions were similar with overlapping ICRH and NBI power for the full duration of the shot. Only the Pulse No's: 69393, 69388 from the ITB experiment and 66421 of mode conversion will be considered here. Fig. 1 shows the heating scheme of Pulse No: 69393 together with the total neutron rate of the shots examined. Pulse No's: 69393 and 69388 featured 4.4 and 3.8MW ICRH power at 33MHz which placed the ion cyclotron resonance of the ^{3}He ions near the plasma centre (R≈3.1m) and the D resonance located around R≈2.3m. The NBI power was 16 and 17.8MW, respectively.

The total neutron yield of Pulse No's: 69393 was found to be suddenly increasing after the ITB plasma state disappeared (shot time t_{shot}>7s, see Fig.1) while the electron temperature remained constant at an average value of about 8keV at the magnetic axis and 3keV volume averaged. The evolution of the shots was studied using the TOFOR data. The 1s time integrated neutron t_{tof} spectra obtained in various phases of Pulse No's: 69393 (left) and 69388 (right) are presented in Fig.2.

In Pulse No: 69393 a high energy neutron tail ($t_{tof} \leq 50$ns → $E_n \leq 4$MeV) starts to develop for t_{shot} > 7s, reaching a maximum intensity around t_{shot} = 9-10s. The high energy neutron tail due to fast D ions disappears at the end of the pulse when the auxiliary power is switched off. A similar behaviour was observed in Pulse No: 69392 (not presented here), where only 8.5MW of NBI power was applied. On the other hand, Pulse No's:69388 shows very similar neutron spectra throughout the discharge, indicating that practically no fast deuterons are driven in the plasma. Both Pulse No's: 69392 and 69393 featured plasmas with X(^{3}He)~15-18% while in Pulse No's: 69388 the ^{3}He concentration was around X(^{3}He)~8-10% (see Fig.4). From the RF point of view, these pulses are in two different heating regimes. Pulse No's: 69388 exhibits a typical minority heating scenario, where most of the power is absorbed by the ^{3}He minority ions. For larger ^{3}He concentrations (Pulse No's: 69392 and

69393), the discharge enters the mode-conversion regime, where the RF power is typically mostly absorbed by the electrons via the mode-converted Bernstein wave [7].

The very different neutron spectra obtained in these two heating regimes may be interpreted as follows: In Pulse No's: 69392 and 69393, the ^{3}He concentration is such that neither minority heating nor mode-conversion heating is very efficient, and a considerable amount of ICRH power is available for the D beam ions, which have their Doppler-shifted ion cyclotron resonance extending up to R≈2.8-2.9m. In Pulse No's: 69388, the ^{3}He minority absorption is very efficient and much less power is left available (at the high-field side of the plasma) to accelerate the D-beam ions.

The TOFOR results of the ITB session were further corroborated by other diagnostics at JET. For Pulse No's: 69392 and 69393, γ-ray spectroscopy measured the evolution of 3.09MeV γ line from ^{12}C(d,pγ)^{13}C reaction within t_{shot} = 7.5-9.5s as for TOFOR. The reaction is induced by fast deuterons which temperature is assessed about 300keV. Also the neutral particle analyzer (NPA) diagnostic measured evidence of the fast D population for these two shots. For Pulse No:69388, γ-ray spectroscopy and NPA provided ^{3}He temperature about 100keV [6].

Furthermore, the analysis of the TOFOR data collected during the mode conversion experiments were considered since (^{3}He)D plasmas with high X(^{3}He) were produced with similar conditions to the ones of the ITB experiment. Here the results on Pulse No: 66421 only are presented. This featured B_0 = 3.35T, I_p = 2.1MA, ~5MW of modulated ICRH with the antenna set to -90^o and ~20MW NBI power. The X(^{3}He) was about 18% (as in Pulse No: 69393) but with an ICRH wave frequency of 37MHz, shifting the resonance of the ^{3}He and D ions to high field side. The 1-s time integrated neutron t_{tof} spectra are similar to the ones of Pulse No: 69388, with no fast D population observed (see Fig.2). The absence of fast deuterons in these conditions may be explained by the fact that at 37MHz and -90^o antenna phasing, the Doppler-shifted ion cyclotron resonance of the beam ions only extends up to R≈2.5-2.6m, where the density of the beam deuterons is rather low. Moreover, the neutron emission from this plasma region should have a lower contribution in the TOFOR spectra since it falls outside the spectrometer line of side which covers about 40cm across the plasma centre in radial direction [2]. Anyway, both g-ray spectroscopy and NPA diagnostic confirm the TOFOR results.

To extract the diagnostic information, i.e. temperature and density fraction of the plasma ion populations, the analysis of the neutron t_{tof} spectra was carried out [3][5]. The distribution function of the deuterons that gives rise to the fusion-produced neutrons registered by TOFOR was assumed to be the sum of 3 sub-populations: a subpopulation of particles with energies exceeding that of the beam source (E>130keV), a subpopulation of particles with energies lower than that of the beam source but higher than the thermal energy (slowing-down ions) and, finally, a thermalized (Maxwellian) distribution comprised of background bulk deuterons as well as beam particles that managed to finalize their slowing down and joined the thermal population. The former particles are interpreted as ICRH heated beam particles and their distribution is assumed to be proportional to an exponential exp(-E/T) of temperature T. The slowing down particles' distribution is modeled as a half-box extending up to the beam injection energy and referred to as NB. The thermal subpopulation (bulk) has a characteristic temperature higher than the temperature reached in absence of the supplementary heating. Free parameters in the fit were the density of the NB component and the temperature and density of the ICRH and bulk components. The neutron t_{tof} and energy spectra of the shots of interest are compared in Fig.3. They refer to the time interval t_{shot} = 9-10s for the ITB shots and to t_{shot} = 13-14s for Pulse No: 66421. The total number of neutrons in the t_{tof} spectra is respectively 21279, 28431 and 1615. The corresponding maximum number of peak counts is 1123, 2268 and 163.

The ICRH component was considered only in the analysis of shot 69393 to model the fast D ions. The fit was performed for $t_{tof} \leq 72$ns. The scatter determined with Cash statistics has a chi-square of χ^2 = 1.2, 1.7 and 0.63 for the three cases. The analysis of Pulse No: 69393 yields an estimate of the effective temperature of the fast ICRH deuterons higher than 240 ± 20keV.
The interaction of this fast deuteron population with bulk deuterons at temperatures of 30 ± 1keV is held responsible for the observed high energy neutrons. The density fraction of the three components results in 22% for the NB, 45% for the ICRH and 33% for the bulk. This concerns the maximum intensity reached by the neutron tail shown in Fig.3. The t_{tof} spectra for t_{shot} = 6-7s and 10-11s feature a bulk temperature of 18 ± 1keV and 28 ± 1keV, respectively.

In Pulse No's: 69388 and 66421 the temperature of the bulk populations was found to be 16 ± 1 and 22 ± 1keV, respectively, with density fraction ratio bulk/NB of 1.8 and 0.7. The variation of these parameters along the shots is small.

The high count rate capability (up to 0.4MHz for 10^{17} n/s JET total neutron rate) and energy resolution (7.4% FWHM) of TOFOR spectrometer [2] allows thus the detailed analysis of the evolution of the plasma conditions which can be further developed by using distribution functions that better represent the high energy plasma ions, which is in progress [8].

The evolution of X(^{3}He) in these shots is presented in Fig.4 together with the calculated slowing time (τ_s) of the NBI deuterons as average trends. In Pulse No: 69393, X(^{3}He)>15% is reached within t_{shot} = 5.5-6.5s and for t_{shot} > 7s. Though the high value, no sign of energetic neutrons is observed in the first time interval where an ITB was present in the plasma. The high energy tail instead develops for t_{shot} > 7s after the ITB has disappeared. The neutron tail intensity evolves to its maximum at t_{shot} = 9-10s when X(^{3}He) ~18%. As mentioned before, despite the similar value of X(^{3}He) in pulse 66421, the fast D population is not created due to the different ICRH resonance conditions.

Concerning the slowing down time t_s in general, the following aspects have to be taken into account. Both the ICRH and NBI power injection allow increasing the electron temperature and thus modify τ_s and the fast particle density. Long τ_s is beneficial for cranking up the number of reactions between the energetic NBI(D) and bulk deuterons due to the favorable cross section. The RF acceleration is more efficient for higher energy than for lower energy populations since the collisional drag opposing the RF heating is weaker for the faster particles. In the study discussed here, τ_s provides information on the effect of the plasma density on the ICRH coupling to the ions since the electron temperature was similar in the two experimental sessions.

At low densities (i.e. long τ_s), the beam may benefit more from the ICRH wave injection and a subpopulation of the beam particles can be accelerated to very high temperatures. For Pulse No's: 69393 and 66421 τ_s is comparable for $t_{shot} > 7s$ but only in Pulse No: 69393 fast D ions are observed. The results of this analysis indicate that although the ICRH scenario was tuned to the minority ^{3}He species (and to the electrons) in the experiments analyzed, at 33MHz with dipole phasing and X(^{3}He)>15% a substantial part of the RF power applied is absorbed by the NBI ions. Because of the antenna dipole phasing and their high energy, the injected beam deuterons have the ion cyclotron resonance strongly Doppler-shifted towards the plasma centre and therefore can efficiently absorb part of the RF power [9]. This Doppler-shifted D-beam absorption is believed to be the cause for the creation of the fast deuteron population responsible for the high energy neutron tail observed in the TOFOR spectra of Pulse No's: 69392 and 69393 independently on the NBI power.

Moreover the comparison with the other shots revealed a delicate dependence of this ICRH wave absorption mechanism on the wave frequency and on the minority ^{3}He concentration. The synergy effect NBI(D)-ICRH was already observed for larger ^{3}He concentrations (above 25%) in the past [7]. In the experiments discussed here (X(^{3}He)<20%), mode conversion of the ICRH wave to the plasma electrons was expected to be the main absorption mechanism. The TOFOR measurements and results described in this paper instead suggest that NBI heated (^{3}He)D plasmas with minority ^{3}He concentrations of ~15% already allow efficient ICRH coupling resulting in the formation of a fast deuteron population when the ICRH wave is tuned to the fundamental ^{3}He absorption close to the plasma centre with the ICRH antenna set to dipole phasing.

New experiments at JET have been proposed to confirm these observations and systematically study the (^{3}He)D plasma conditions with respect to auxiliary power injection and minority concentration. The theoretical modeling of these plasma conditions is going to be implemented in the simulation codes to confirm the experimental observations presented in this paper.

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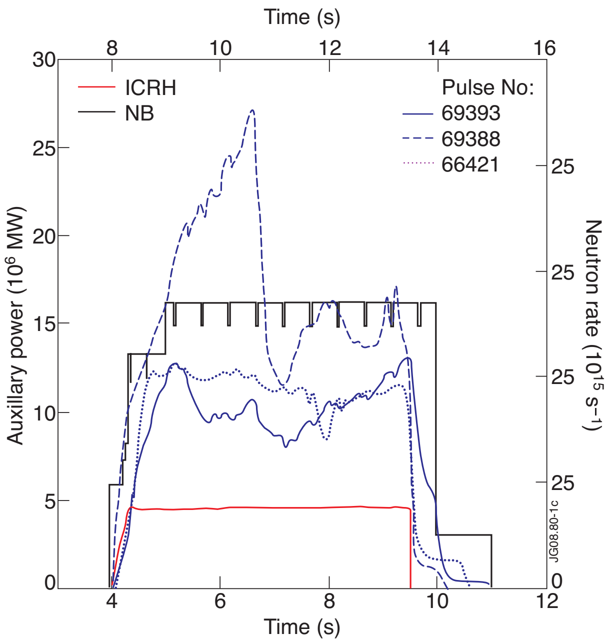

Figure 1: (Color on line) Time traces relative to the ICRH and NBI total power applied for Pulse No: 69393 plotted with the total neutron rate of Pulse No's: 69393 and 69388 within 3-12s and of 66421 within 7-16s.

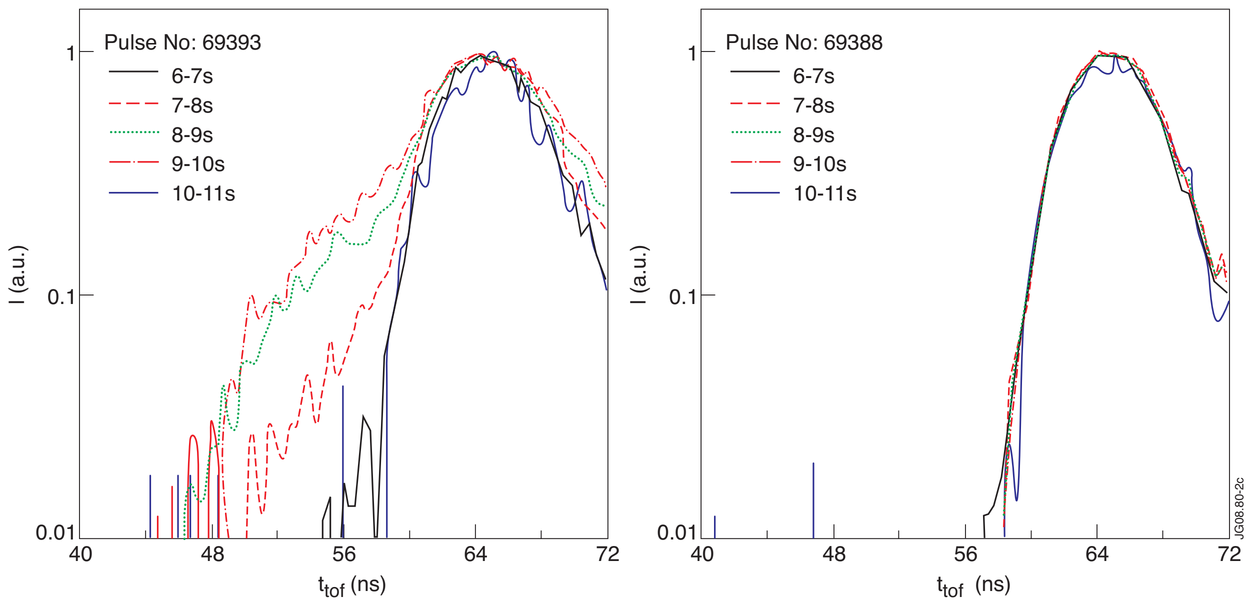

Figure 2: (Color on line) Comparison of the 1s time resolved neutron t_{tof} spectra TOFOR measured in Pulse No's: 69393 (left) and 69388 (right) normalized to their neutron peak. The data are background reduced.

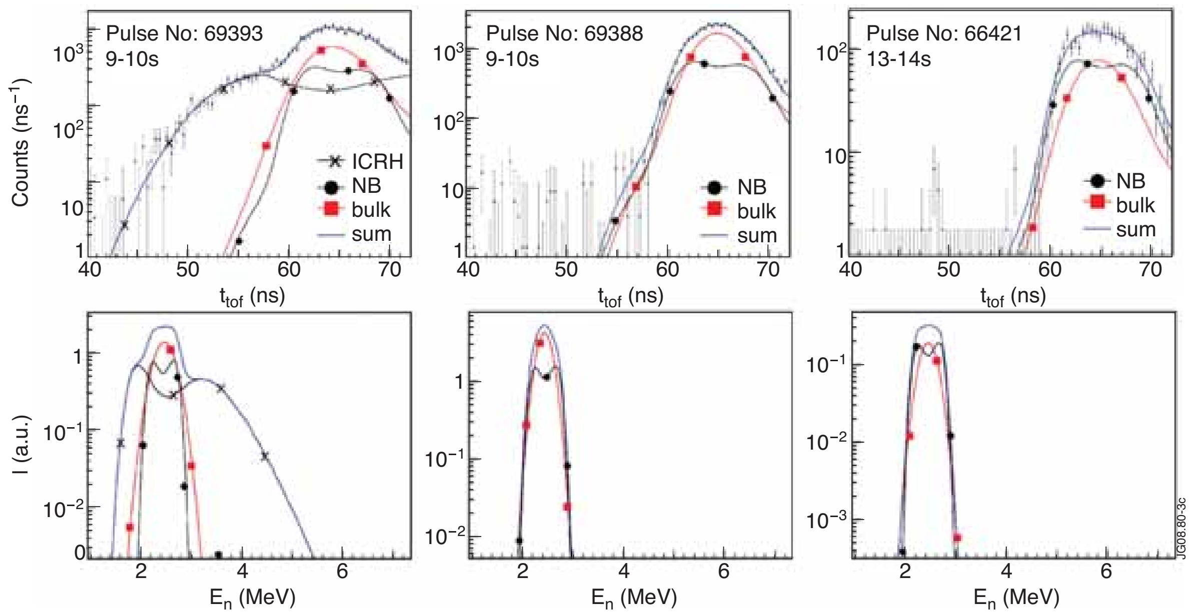

Figure 3: (Color on line) Neutron t_{tof} (top) and energy (bottom) spectra for t_{shot} = 9-10s of Pulse No's: 69393, 69388 and t_{shot} = 13-14s for Pulse No: 66421. The fit of the data (sum) is performed using a 3-component model-ICRH, NB and bulk ion populations-for Pulse No: 69393 while only NB and bulk components for Pulse No's: 69388 and 66421.

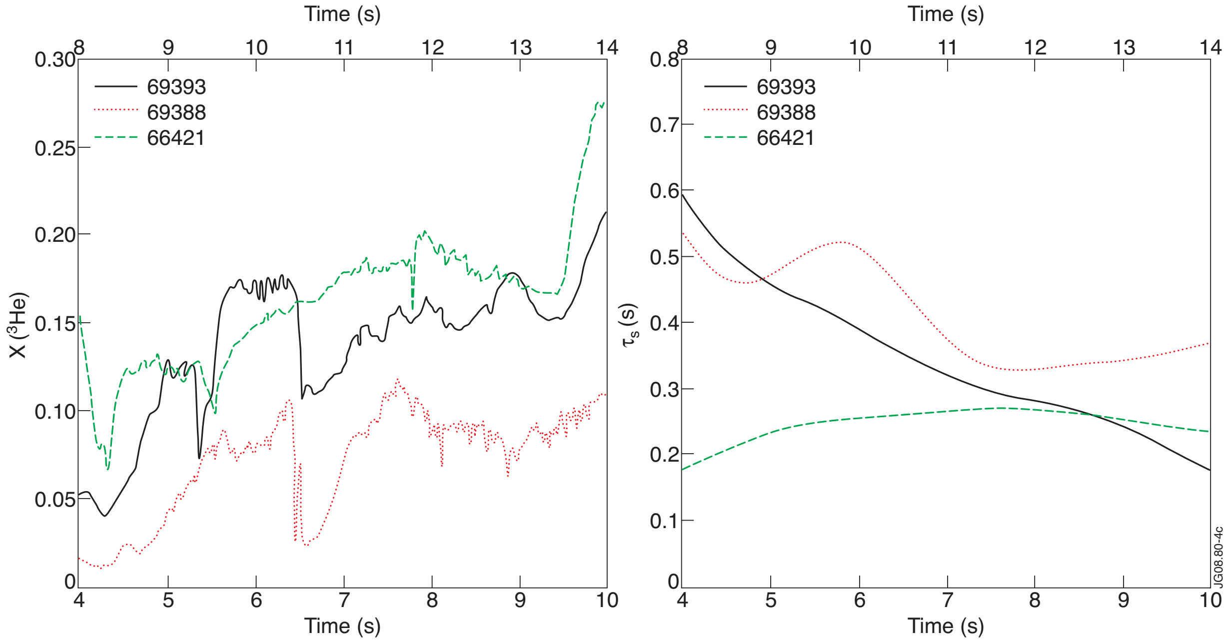

Figure 4: (Color on line) Evolution of the average ^3He concentration, $X(^3He)$, (left hand panel) and of the average NBI(D) slowing down time, τ_s, (right hand panel) calculated for the ITB and mode conversion shots of interest.