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Neutron Emission Spectroscopy Diagnosis of Fast Ions in RF D(^{3}He) Heated Plasmas at JET

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** See annex of M.L. Watkins et al, "Overview of JET Results ",*
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Neutron Emission Spectroscopy (NES) is a probe of High Energy (HE) components in the fuel ion populations in fusion plasmas. This is now exploited in experiments on D plasmas at JET with the new neutron Time-Of-Flight (TOF) spectrometer TOFOR (Fig.1), installed in 2005. It can be operated in 2.5MeV neutron yield rates from $Y_n \approx 10^{17}$ n/s (expected JET maximum) to below $Y_n \approx 10^{14}$ n/s set by required minimum statistical accuracy and time resolving power [1]. The focus in this paper is on the detection of a tail in the neutron energy spectra as a manifestation of HE deuterons (d') which during their slowing down suffer burn-up in the bulk population (d), i.e., d' + d → ^{3}He + n. The sensitivity of NES to the presence of d':s increases with their amplitude and energy (E_d) up to the maximum of the reactivity (Ed " 1 MeV). The dominant part of the spectrum is due to bulk dd reactions giving rise to a narrow peak centered at neutron energy $E_n \approx 2.5$MeV,i.e, $t_{tof} \approx 65$ns in the measured spectrum (see below). The present study concerns a series of D(^{3}He) plasmas (Pulse No's: 69419–69430) with up to 5MW ICRH coupled to the minority ions ($n_{^3He} \approx 1\%$); the electron density was low ($n_e \approx 2\times10^{19}$) to promote the creation of a HE tail in the ^{3}He population.

TOFOR views the plasma vertically from a JET roof laboratory position. The data consist of time-of-flight (t_{tof}) spectra reflecting the energies of neutrons in a collimated flux and detected at a count rate proportional to Y_n (say 200 Hz at $Y_n \approx 10^{14}$ n/s). Integration over the RF period of maximum intensity for a single discharge (t = 17.0–20.7 s in Fig.2) gave spectra with statistics of approximately 500 counts which together with TOFOR's sensitivity was sufficient to detect certain features in the ttof spectrum (Fig.3a). Eleven similar discharges in the series were summed (Fig.3b) to enhance the statistics and, hence, the analysis and interpretation of the measured spectrum. The analysis was performed with parameterized neutron spectral components in terms of amplitude (A) and shape (T). The spectral components were folded with the fixed response function to predict a ttof spectrum [1]. The A and T values are varied until a best fit and, hence, description of the measurement is obtained.

Three components were used in this case, namely, a Bulk (B) of Gaussian shape whose width is connected to the thermal Doppler Broadening (TB), besides a Super Thermal (ST) and a High Energy (HE) component due to deuterons of assumed Maxwellian states of temperature (TST and THE) which interact with bulk deuterons. The analysis was tried with a standard Maxwellian as has been found to work well in cases where the HE tail is directly caused by the RF power injection. As other possibilities exist here, also modified Maxwellians were attempted to describe the data, for instance, truncation to $E_{d'} < E_d^{MAX}$ with E_d^{MAX} as a seventh fitting parameter. The best result was obtained with E_d^{MAX} = 2.9MeV which gave THE = 1200keV and TST = 60keV compared to THE = 820keV and TST = 50keV with a standard Maxwellian. In any case, the HE temperature is extraordinarily high if it was due to direct ICRH acceleration of deuterons; this is unlikely as the coupling would be through 2nd harmonic resonance, whose position would be outside the plasma on the in-board side. Other explanations should be sought for the HE deuteron tail, such as knock-on effects.

In previous 14MeV spectra for d + t → + n reactions (E_α = 3.5MeV) in high power DT plasmas, a tail was identified as due to α-particle Knock-on Neutron' (AKN) emission at a level of about 10^{-3} of the main Deuteron-Tritium Neutron (DTN) emission [2]. The AKN component arises because of the creation of high energy fuel ion velocity components through the knock-on collisions $\alpha + d \rightarrow \alpha' + d_\alpha$ and $\alpha + t \rightarrow \alpha' + t_\alpha$. With energies up to 3MeV, d_α and t_α ions can suffer burn-up, especially, in the region of maximum dt fusion cross section at about $E_d = 100$keV (Fig.4). In the present case of neutron emission from D(^{3}He) plasmas, AKN contributions could also be present due to fast fusion α's from $^3He_{RF} + d \rightarrow \alpha' + p$ where $E_\alpha = 3.7$MeV and $E_p = 14.7$MeV. The reaction chains for AKN emission in DT and D($^3He_{RF}$) plasmas would share the α-particle knock-on and slowing down steps. However, the α-source term, for instance, would differ. While it is directly linked to the underlying neutron emission (DTN) in DT plasmas, for D plasmas it would depend on the external factors such as RF power injection and ^{3}He minority concentration, besides plasma conditions in general. In other words, the AKN tail in D($^3He_{RF}$) relative to the underlying neutron emission (DDN) is determined by the amplitude of the HE tail of the ^{3}He ions and its energy distribution relative to $^3He + d$ fusion cross section peaking at $E_d = 400$keV (Fig.4). Moreover, the burn-up steps differ, involving d_α and t_α in DT compared to d_α in D plasmas. As an order of magnitude estimate for the $d_\alpha/(d_\alpha + t_\alpha)$ burn-up ratio, one can use the fusion cross sections in Fig.4, i.e., about 1:4. With this information together with the presented result on the AKN/DDN ratio of 0.25 and AKN/DTN $\approx 10^{-3}$ from ref. [2], one would estimate that the HE densities of nd! generated by $^3He_{RF} + d \rightarrow \alpha + p$ in D($^3He_{RF}$) plasmas is at the level of a few percent of the $n_{d\alpha} \approx n_{t\alpha}$ for DT under the assumption of similar plasma conditions. This qualitative estimate is mentioned here just to illustrate that with proper calculations one can make comparison with RF and fusion driven AKN in D($^3He_{RF}$) and DT plasmas, respectively, and, hence, gain certain insight on fusion ! effects without using tritium.

It is interesting to note, that several knock-on reactions can take place in D plasmas with manifestation in the neutron emission spectra. There are several reaction channels giving rise to charge fusion products in the MeV range (p, t and ^{3}He) not to mention the 15MeV proton from ^{3}He + d. It is, therefore, possible that these could contribute to the ST and HE component that was included in the analysis of the measured t_{tof} spectra. The direct (2nd harmonic) acceleration on D is in principle possible but a more unlikely explanation as a super thermal ion source here because the resonace layer is ouside the plasma volume.

ACKNOWLEDGMENT

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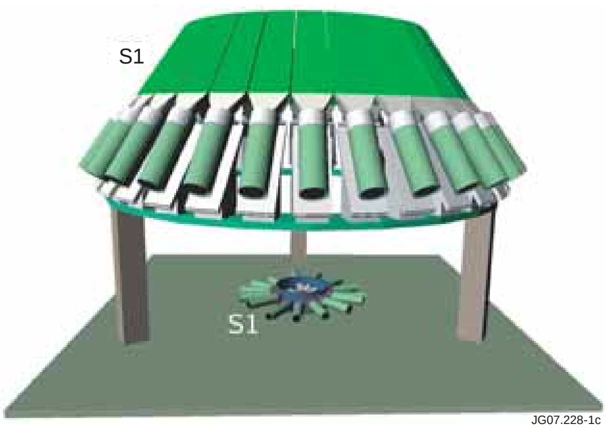

Figure 1: Schematics of TOFOR with detector S1 in the neutron flux from the plasma and S2 to detect the scattered fraction.

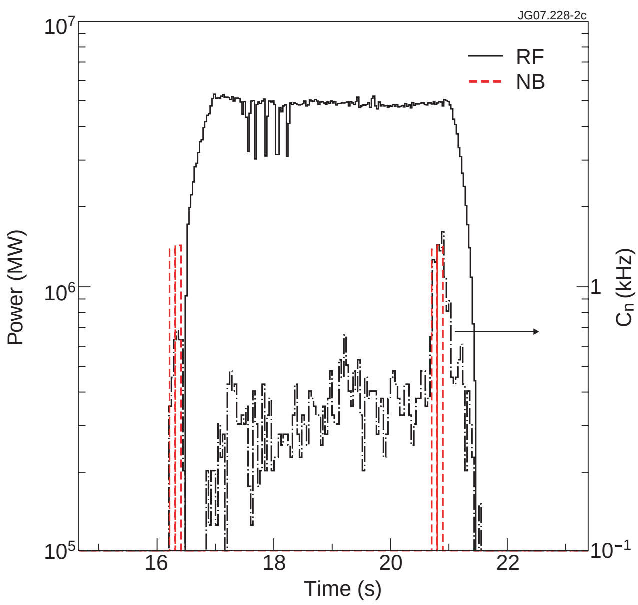

Figure 2: Time trace of PNB (blips) and PRF (extended pulse) for JET Pulse No: 69423. Also shown is the TOFOR count rate C_n.

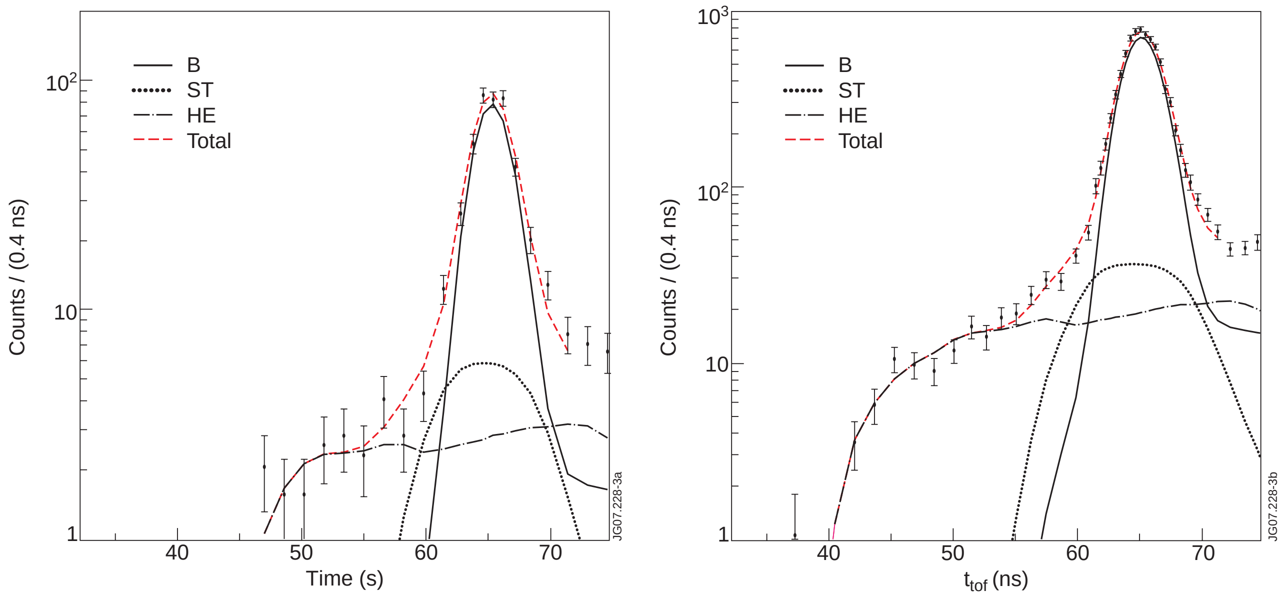

Figure 3: Measured t_{tof} spectra with TOFOR for an individual discharge (a) and summed ones (b) with best fit results (components and total).

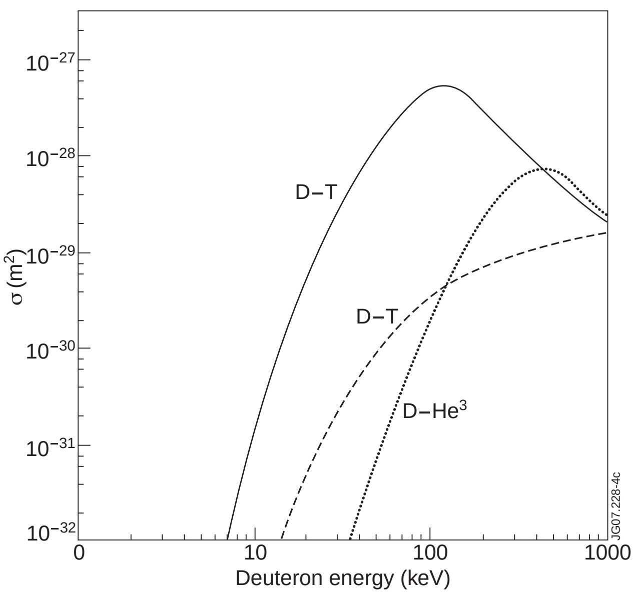

Figure 4: Cross sections of the fusion processes d + t, d + d and d + ^{3}He as function of deuteron energy adapted from ref. [3]. The d + ^{3}He maximum at E_d = 400 keV equals E^3He = 410keV.