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Neutron Spectroscopy as a Fuel Ion Ratio Diagnostic – Lessons from JET and Prospects for ITER

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ABSTRACT.

Determination of the fuel ion ratio n_T/n_D in ITER is required a precision of 20%, time resolution of 100ms, spatial resolution $a/10$ and over a range $0.1 < n_T/n_D < 10$. We use simplified but realistic MCNP models of ITER to assess the possibility to use neutron emission spectroscopy, NES, for such measurements. We show that NES meets the requirements for ion temperatures $T_i > 6\text{keV}$, and for $n_T/n_D < 0.6$. A crucial issue is the signal-to-background situation in the measurement of the weak 2.5MeV emission from DD reactions in the presence of a background of scattered 14MeV DT neutrons. Important experimental input and corroboration for this assessment is presented from the TOFOR neutron spectrometer at JET where the presence of a strong component of backscattered neutrons is observed. Neutron emission components on ITER due to beam-thermal and tritium-tritium reactions can further enhance the prospects for this technique.

I. INTRODUCTION

ITER requires the measurement of the Tritium (T) and Deuterium (D) fuel ion ratio, n_T/n_D , with a precision of 20% over the parameter range $0.1 < n_T/n_D < 10$ with a time resolution of 100 ms and a spatial resolution of $a/10$. Pre-vious work has shown that Neutron Emission Spectroscopy (NES) is potentially capable of contributing to this meas-urement [1-6]. In plasmas of mixed deuterium and tritium fuel, the following neutron-producing reactions are possible (energies in MeV are given):



It should be noted, that the TT reaction proceeds through several different branches [7], the most important one for this work being the two-body reaction $t + t \rightarrow {}^5\text{He} + n$, with a branching ratio of 20% and giving a neutron of $E_n = 8.6\text{MeV}$. The other major reaction channel is the $t + t \rightarrow {}^4\text{He} + n + n$, where the energy distribution of the resulting particles is determined by 3-body kinematics. Traditionally, NES as a fuel ion diagnostic is based on the fact that the intensity of the 14MeV neutron emission from DT reactions (I_{14}) and the 2.45MeV emission from DD reactions ($I_{2.5}$) is proportional to the fuel densities [1]:

$$I_{2.5} = 0.5 \cdot n_D^2 \cdot \rho_{DD}(T_i) \cdot V_1 \cdot C_1 \quad (4)$$

$$I_{14} = n_D \cdot n_T \cdot \rho_{DT}(T_i) \cdot V_2 \cdot C_2 \quad (5)$$

where the reactivities ρ_{DD} and ρ_{DT} are functions of the ion tem-perature, T_i . C_1 and C_2 are calibration coefficients, V_1 and V_2 are the effective plasma volumes viewed by the 2.5 and 14MeV spectrometers,

respectively. T_i can be measured by the neutron spectrometer from the width of the thermal emission or by an independent diagnostic. A single broad-band neutron spectrometer or two specialized instruments are used to measure the two emission components. The fuel ion ratio is then given by:

$$n_T/n_D = 0.5 \cdot (I_{14}/I_{2.5}) \cdot (\rho_{DT}/\rho_{DD}) \cdot (V_2/V_1) \cdot (C_2/C_1) \quad (6)$$

Assuming that the instrumental factors, C_1 , C_2 , V_1 and V_2 , can be determined to the required accuracy, the determination of the fuel ion ratio depends only on the neutron spectroscopic measurements of $I_{2.5}$, I_{14} and T_i . The expected direct (unscattered) neutron spectrum from a DT plasma is shown in Figure 1, where the DD, DT and TT reactions are included. In most of the relevant ITER operating scenarios, the DT reactivity is about a factor 100 greater than the DD (and TT) one. The reactivity for the TT reaction is only about a factor 2 lower than for DD [8] and this can be used for diagnostic purposes in fusion plasmas of high n_T ⁴. It is also important to note the relatively high cross section for DD reactions at the ITER Neutral Beam (NB) injection energy of 1MeV, where the DD and DT cross sections are of similar magnitudes. Let it also be clear that we here discuss line-integrated measurements with a single line-of-sight high-performance neutron spectrometer. Profile effects will affect the measurements and this can to some extent be taken into account in a combined analysis with neutron camera data.

2. SIMULATION STUDY

Important aspects for NES as a fuel ion ratio diagnostic are i) the choice of instrument, ii) interfacing to the fusion device and iii) the possible performance based on the signal and background situation in the measurement of the relevant emission components. In this paper we focus on point iii) where the adverse effect of scattered neutrons has been identified as a major contribution to the background. We make the simplified assumption, when necessary, of a spectrometer with a Gaussian shaped response function and 2.5 and 14MeV detection properties corresponding to a Magnetic Proton Recoil type instrument⁹, a technique which has shown great potential for high-resolution neutron spectroscopy on ITER [10, 11]. For the interfacing we assume an instrument placed in the ITER reference position in port cell 1, just outside of the biological shield about 12m from the plasma center with a close to radial Line-Of-Sight (LOS) (8 degrees to the radius at the plasma centre) in the horizontal plane. Discrepant estimates of the flux of scattered neutrons seen at the ITER neutron spectrometer position (or radial neutron camera in-cell channels in a similar location) have been reported [3,4,12,13], and we here present new results from two simple 3D MCNP models. The first model uses point detectors and a full 3D representation while the second model uses volume detectors and reflecting planes. No significant differences were observed between the two models, and in what follows we only report results for the point detector case. In this model, the ITER vessel and blanket are approximated by a rectangular shell with 2m thick walls. The cross section of the plasma source is also rectangular, centered at $R=6.2$ m with uniform temperature and density and isotropic neutron emission. The plasma volume was adjusted to give a total neutron yield corresponding to 350MW fusion power for a reference, purely thermal plasma of $T_i = 20$ keV, $n_{TOT} = 10^{20} \text{ m}^{-3}$, and $n_T/n_D = 1$. A cylindrical aperture (10 or

30cm diameter) is cut out along the reference LOS in the outer wall and two detection points are placed along this LOS, one close to the collimator and a second further out, at the reference spectrometer position. The MCNP model was used to determine the shape of the neutron spectrum at the detector locations. Figure 2 shows the emission spectrum at the far position for the reference plasma case, except $n_T/n_D = 0.5$, using a wall materials mix appropriate for the ITER First

The figure shows the direct and scattered neutron energy spectrum from the main 14MeV DT emission together with the corresponding DD (2.5MeV) emission. We find that at $E_n = 2.5\text{MeV}$, the (peak) intensity of the DD emission is about 50% of the scattered DT intensity. This result is consistent with what is reported in Refs 3,4 but in disagreement with Refs 12, 13. For the close detector, the shape of the spectrum is quite similar, only increased in intensity as expected from the inverse square of the distance to the source. In the main part of this study, we used a purely thermal scenario and varied T_i and n_T/n_D over a large range to determine the emissivity of the DD and DT components, both direct and scattered. We made the simplifying assumption that the strong DT emission allows an accurate determination of the DT component and T_i . The ideal number of counts seen by the spectrometer in the thermal DD peak and the background in the stipulated 100ms time interval were determined. For each set of T_i and n_T/n_D parameter values we produced 2000 different neutron spectra of synthetic data, using the method described in Refs 10,11. For each synthetic spectrum, we extracted the best-fit estimates of the DD intensity in a forward type analysis and calculated n_T/n_D from Eq. 6. The 2000 n_T/n_D estimates for each parameter set were analyzed statistically to find the mathematical accuracy (deviation from the known true value) and precision (spread around the mean). It was found that the accuracy was in all cases consistent with the known true value within statistics. In Figure 3 we therefore present only the results for the precision as a representative indication of the uncertainty in this synthetic measurement; results for first wall diameters of 10 and 30cm are shown. The results indicate that NES can provide an estimate of the n_T/n_D within the ITER requirements over a large part of the required parameter space. Specifically, for a 10cm first wall aperture we find the requirements met for $T_i > 6\text{keV}$ and $n_T/n_D < 0.6$. For the 30 cm aperture, the range is expanded to about $T_i > 3\text{keV}$ and $n_T/n_D < 1$. The 20% precision limit is indicated by the red line.

3. TOFOR EXPERIMENTS AND MODELING

Experimental results from the TOFOR neutron time-of-flight spectrometer [14,15] at JET show that such measurements are possible. This is exemplified in Figure 4, where the background-subtracted raw data t_{TOF} spectrum is shown together with the estimated energy spectrum obtained from an analysis of the data. TOFOR views the JET plasma from a position about 20m from the plasma centre with a long, narrow collimator, similar to the ITER case. The TOFOR LOS is directed towards the divertor region, where the wall is composed mainly of carbon composites and Inconel (a Ni rich alloy). JET was operated in D plasmas but as in all such cases, a weak component of 14MeV DT neutrons is present due to the breeding of tritium in the reaction $D + D \rightarrow T + p$; some of the produced tritons undergo a subsequent DT fusion reaction producing so called Triton Burn-up Neutrons (TBN).

Figure 4 shows the broad-band capability of TOFOR, with simultaneous measurements of the 14MeV TBN emission peaked at $t_{\text{TOF}} = 27\text{ns}$ and the 2.5MeV DD emission at 65ns; a neutron component due to DD NBI-thermal reactions is also included. The figure shows that a substantial component of scattered neutrons is present. The scattered intensity is about 18% of the total neutron emission for $E_n > 1\text{MeV}$, consistently and independently estimated from measurements and MCNP modeling using the same principles as in the ITER model above. It is interesting to note that both the Ni and C elastic scattering peaks are visible in the data, and even the first excited state of ^{12}C is resolved at about 42ns, induced by the high-energy DT emission. The data in Figure 4 were obtained in a situation where the tritium content is about $n_{\text{T}}/n_{\text{D}} = 10^{-4}$ and a very rough scaling of these results indicates that a NES instrument (of the TOFOR type) could be used to measure the DT and DD neutron emission up to about $n_{\text{T}}/n_{\text{D}} = 0.25$ (provided the count rate is low to avoid too high levels of the unavoidable random coincidence back-ground that accompanies this technique). At that point the high- t_{TOF} tail of TOFOR's response to the DT emission will be of the same magnitude as the 2.5MeV DD peak and the possibility to determine the 2.5MeV peak intensity will quickly deteriorate. The modeling and experiments with TOFOR highlight the possibilities to further enhance the use of NES as a fuel ion'

In Figure 5 we show the experimentally verified TOFOR model for scattered neutrons applied to a simulation of the neutron emission from a future DT plasma at JET, one with $n_{\text{T}}/n_{\text{D}} = 0.5$, another with $n_{\text{T}}/n_{\text{D}} = 9$. (Profile effects could account for the different proportions of direct and scattered flux between JET and ITER models.) In addition to the thermal emission, components due to beam-thermal and TT reactions have been added. For the main DT emission, the beam-thermal emission is only about 10% or less of the thermal DT intensity while the high cross section for 1MeV D on thermal D boosts the contribution in the 2.5MeV energy region to be on a par with the thermal DD emission. This enhanced DD emission thus offers a possibility to determine the fuel ratio in beam heated ITER plasmas of lower T_i , in particular for low $n_{\text{T}}/n_{\text{D}}$. Similarly, the presence of the TT emission, and in particular the peak at $E_n = 8.6\text{MeV}$, gives an additional emission signature to use in the analysis of plasmas with higher $n_{\text{T}}/n_{\text{D}}$. Even with a carbon dominated wall as in the JET case, the TT neutron peak at 8.6MeV is clearly discernable between the two carbon scattering peaks at about $E_n = 7$ and 11MeV, even for quite modest values of $n_{\text{T}}/n_{\text{D}}$. At higher $n_{\text{T}}/n_{\text{D}}$ the TT emission can replace role of the the DD in the derivation of the fuel ion ratio. A metal dominated ITER wall can be expected to give a slightly lower scattered intensity and with less structure and thus enhance this possibility even further.

CONCLUSIONS

A simulation study indicates that neutron emission spectroscopy can be used as a fuel ion diagnostic on ITER and provide line-integrated results on $n_{\text{T}}/n_{\text{D}}$ within the required time resolution for a large part of the parameter space; with a 10cm first wall diameter requirements are met for $T_i > 6\text{keV}$ and $n_{\text{T}}/n_{\text{D}} < 0.6$. The limiting factor for reaching higher in $n_{\text{T}}/n_{\text{D}}$ is the high level of scattered DT neutrons, disturbing the 2.5MeV measurement. For Ti the limit is set by the lack of statistics as the reactivity decreases with lower temperatures. Corroborating evidence for this assessment comes

from the TOFOR spectrometer at JET. Taking into account the neutron emission due to the 1MeV ITER neutral beam and the weak emission of tritium-tritium neutrons could expand the method to higher n_T/n_D and lower T_i values.

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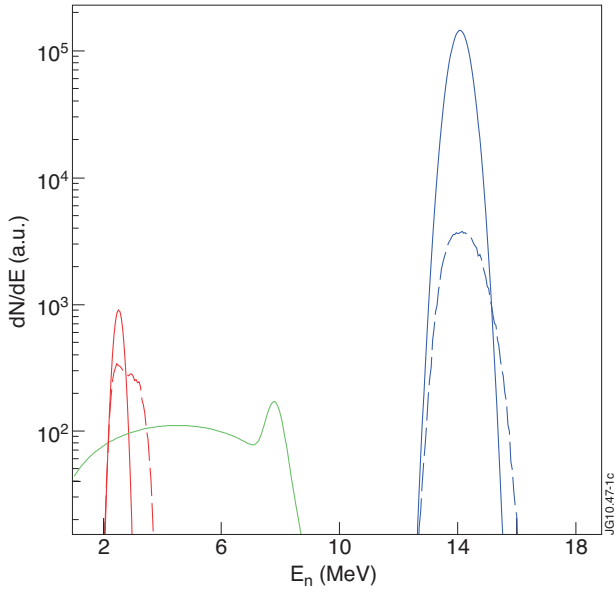


Figure 1: Direct neutron emission spectrum from DT plasma with NB heating. Emission components from thermal DT (blue solid), NB D on thermal T (blue dashed), TT (broad green solid) for $E_n = 0-8\text{MeV}$, thermal DD (red solid), is NB D on thermal D (red dashed). DT plasma with $T_i = 20\text{keV}$, $n_{TOT} = 10^{20}\text{m}^{-3}$, $n_T/n_D = 1$.

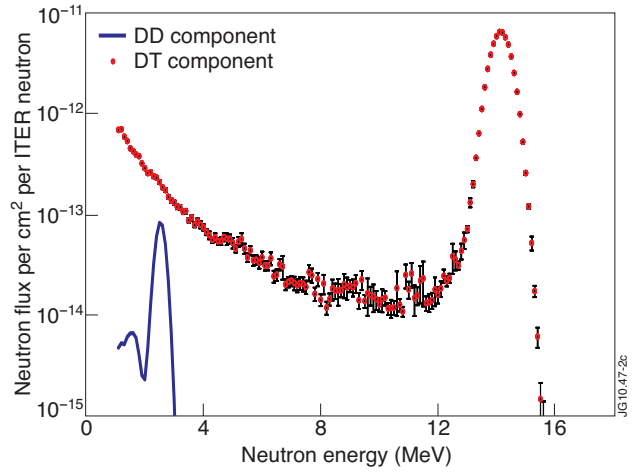


Figure 2: Simulated neutron emission spectrum from a thermal DT plasma with $T_i = 20\text{keV}$, $n_{TOT} = 10^{20}\text{m}^{-3}$, $n_T/n_D = 0.5$. An ITER First Wall/Blanket Module material composition is used.

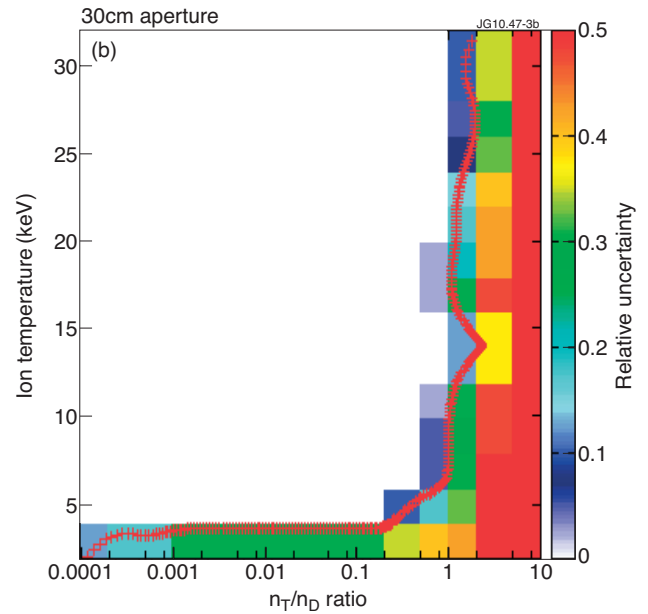
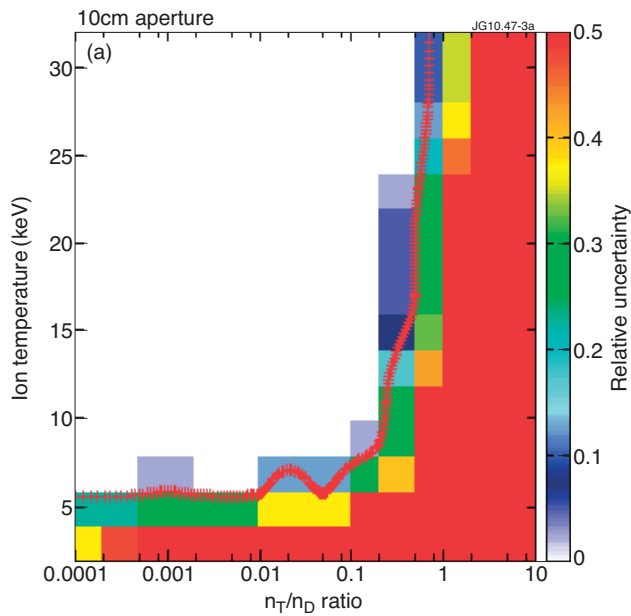


Figure 3: (Left) 2D plot of the estimated precision in the determination of n_T/n_D as a function of T_i and n_T/n_D for a time resolution of 100ms. For plasma and experimental conditions, see text. The series of crosses denotes the 20% precision boundary as required by ITER (requirement fulfilled above and to the left). (Right) Same as top panel but for a 30cm diameter first wall aperture.

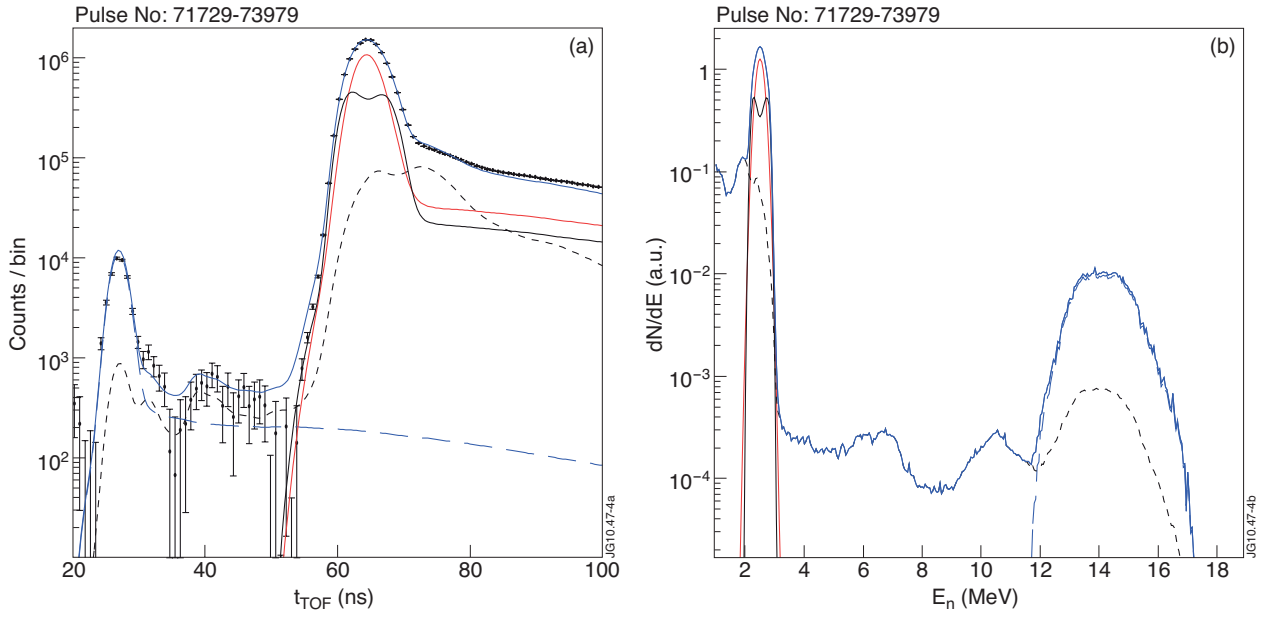


Figure 4: (Left) TOFOR time of flight spectrum from a selection of NB heated JET plasmas with the best-fit analysis result shown as lines. (Right) The estimated energy spectrum from the data in a). Emission components due 14MeV TBN (long dashed, blue), 2.5MeV thermal (solid, red), beam-thermal (solid black) besides scattered (short dashed, black) were used in the analysis.

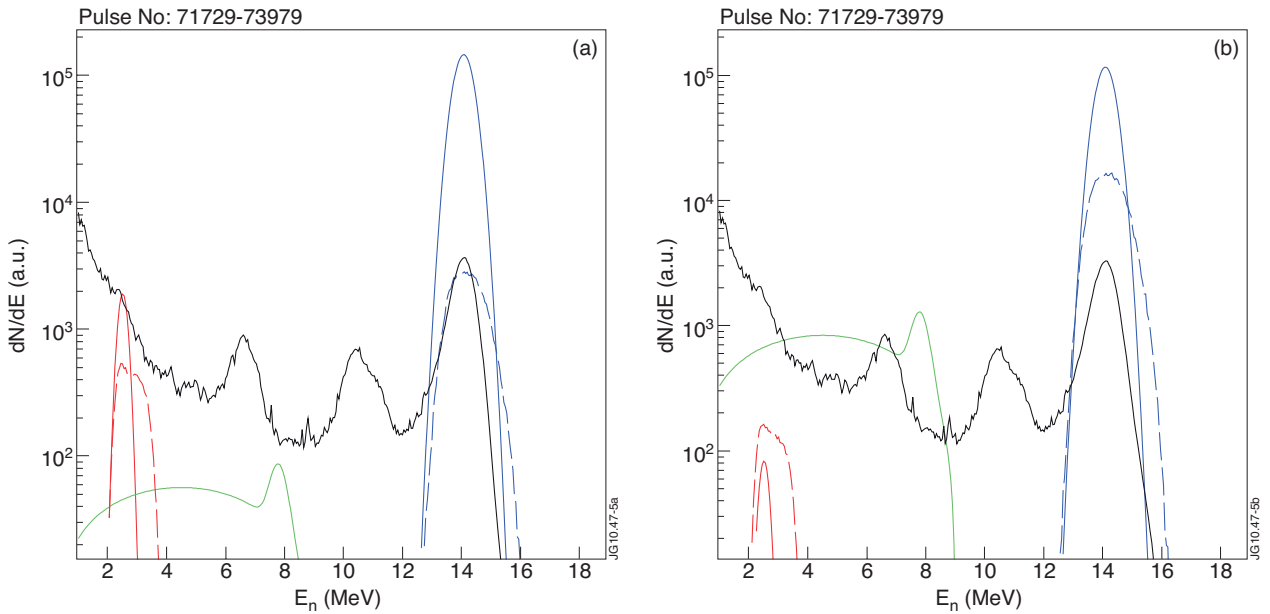


Figure 5: Simulated neutron emission from DT operations on JET. Included components are DD and DT thermal (red and blue solid) and beam-thermal (red and blue dashed), TT thermal (green) and scattered neutrons (black). Scattered flux based on the TOFOR experimentally verified MCNP model. DT plasma with $T_i = 20\text{keV}$, $n_{TOT} = 10^{20}\text{ m}^{-3}$ and (top) $n_T/n_D = 0.5$, (bottom) $n_T/n_D = 9$.