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** See annex of M.L. Watkins et al, “Overview of JET Results ”,*
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ABSTRACT.

A method to generate synthetic neutron spectra from bulk and fast ion distributions simulated by TRANSP has been developed. In this paper, synthetic data generated from fuel ion distrubutions modeled with TRANSP is compared with measured data from two neutron spectrometers with different lines of sight; TOFOR with a radial one and the MPRu with a tangential one. The information obtained from the analysis of the measured neutron spectra such as the relative intensity of the emission from different ion populations puts additional constraints on the simulation and can be used to adjust the variables in the simulation.

1. INTRODUCTION

Neutron Emission Spectroscopy (NES) on fusion plasmas can provide important information on the motional state of the fuel ions through the d(d, n)^{3}He fusion reaction. The shape of the neutron emission is directly related to the velocity distribution of the fuel ions in the fusion plasma, where different parts of the fuel ion distribution, e.g., thermal or those due to auxiliary heating are revealed by characteristic signatures in the energy spectrum. This makes NES analysis well suited for benchmarking plasma-modeling codes such as TRANSP [1] that provide modeled ion distributions. These ion distributions can in turn be used to calculate the expected neutron energy spectra, which can subsequently be compared to measured data.

2. INSTRUMENTATION

At JET, two neutron spectrometers are being used in the analysis presented in this paper; The TOFOR [2] spectrometer, which is based on the time-of-flight principle and the MPRu [3] spectrometer based on the magnetic-proton-recoil principle.

In the MPRu, a collimated neutron beam from the plasma hits a thin plastic foil producing a recoil proton beam. The protons are subsequently momentum analyzed in a magnetic field (0.3T) and the energy spectrum is obtained as a proton position histogram over a 500mm wide detector hodoscope. This provides an energy bite of 2-3MeV, which permits studies of neutron spectra from d(d, n) ^{3}He fusion reactions in JET plasmas with Neutral Beam Injection (NBI) heating. The original MPR spectrometer was initially designed to measure 14MeV neutron emission from DT plasmas. An upgrade of the MPR (MPRu) allowed it to extend its use to 2.5MeV measurements in D plasmas, although with a lower efficiency compared to other designated 2.5MeV spectrometers. The MPRu views the plasma with a quasitangential line-of-sight in the counter current direction as is indicated in Fig.1.

With TOFOR, the time-of-flight (t_{TOF}) of neutrons is measured from the time difference of interactions between 5 primary and 32 secondary detectors. The flight path between the two detector sets is about 1.2m, which corresponds to a t_{TOF} of 65ns for 2.5MeV fusion neutrons. TOFOR is installed in the roof laboratory at JET and views the centre of the plasma from above (Fig.1) with a radial line-of-sight at a distance of about 19m. For both spectrometers, detailed

Monte Carlo (MC) simulations of the response functions have been made [4], which allows modeled neutron spectra to be directly compared with measured data.

3. MODELING

The shape of the energy spectrum of fusion born neutrons from d(d, n)^{3}He reactions is directly related to velocitiy components of the deuterium ions involved. In the analysis of NES data, a multi-component analysis can be used, where different velocity components are represented by their corresponding neutron emission spectra. The relative ion densities for the different distributions in the plasma can thus by obtained by folding the spectral components with the spectrometer's response functions and fitting the intensities of the components to the measured data [5]. In the analysis presented here, TRANSP simulations of the plasma were made. This provides modeled Maxwellian bulk ion distributions as well as fast ion distributions from auxiliary NBI heating. The bulk distribution was obtained as flux-surface averaged temperature and density profiles and the beam-ion slowing down-distribution in 4 dimensions (energy, pitch-angle, flux-surface and poloidal angle).

Spectral components representing THermo-Nuclear (THN) and Beam-Target (BTN) emission where calculated with the MC code ControlRoom [6], using the ion distributions obtained from TRANSP. A full 3D model of the sight-line of the two spectrometers MPRu and TOFOR is implemented in ControlRoom allowing for lineof- sight integrated spectra to be calculated. A second approach was also used to model the THN component; for reactor relevant temperatures (T < 40keV), the shape of the THN emission spectrum can to a high degree be considered as Gaussian. The width of the THN component (W) is proportional to the square root of the plasma temperature according to $W = 88.2 \cdot \sqrt{T_{EFF}}$ keV, where T_{EFF} is an effective temperature reflecting the line-integrated measurement. T_{EFF} is normally around 90% of the axial ion temperature [7] for typical emission profiles and can be determined by a fit to the measured data. Hence, NES analysis offers the possibility of deducing core ion temperature independently of other diagnostics.

The radial sight line of TOFOR makes the instrument insensitive to toroidal plasma rotation and only the velocity component perpendicular to the magnetic field affects the shape of the neutron spectrum. This simplifies the analysis of TOFOR data since one degree of freedom in the velocity distribution, namely the toroidal, can be neglected. On the other hand, the tangential sight line of the MPRu will result in a Doppler shift (ΔE) of the neutron emission spectrum proportional to the toroidal plasma rotation. This effect needs to be taken into account in the analysis of MPRu data [7] but also allows for rotational information of the plasma to be extracted from the MPRu data. For the thermal emission from d(d, n)^{3}He reactions, ΔE is given by the relation $\Delta E = C \cdot v \cos(\alpha)$ keV, where α is the plasma velocity in km/s, C is a constant at 0.23 keV/(km/s) and is the angle between the sight-line and the velocity, which for the MPRu is around 47^o in the plasma centre. For beam-target reactions, the slowing down distribution of the NBI is not affected by plasma rotation until it is thermalized. Consequently, to 1st order approximation, only one of the reactants is rotating and C is reduced to about 0.12 keV/(km/s) for the NBI component.

4. RESULTS AND DISCUSSION

Here we focus on JET Pulse No: 69992 that was mainly heated with 20MW of NBI power, which resulted in a peak neutron rate of $6\cdot10^{15}\ s^{-1}$ during a steady state period of 4s. The long steady state conditions are favorable for comparing spectroscopic data from the two spectrometers since the MPRu needs a rather long integration time to collect data with adequate statistics. In this period, the count rate of the MPRu was 320Hz giving a time-integrated spectrum with 1280 counts. The count rate of TOFOR reached 29.7kHz allowing spectral analysis with a 100 ms time resolution. Examples of data from TOFOR and the MPRu are shown in Fig.2 (points with error bars). The data are dominated by BTN and THN emission in the energy range 2–3MeV, which corresponds to the peak at 60–70ns for TOFOR (Fig.2a) and at 250mm for the MPRu (Fig.2b).

The spectral components calculated from the TRANSP distributions where folded with the spectrometers response functions and fitted to the measured data (Fig.2) with 2 red = 1.0 and 1.4 for TOFOR and the MPRu, respectively. The THN components are shown as red broken lines, the BTN components in black broken-dot and their sums in solid blue. In the analysis of the TOFOR data, only the intensities of the individual components were used as free parameters whereas for the MPRu, energy shifts of the thermal and NBI components with proportions as described above were also allowed. The TOFOR data show a tail at $t_{TOF} > 70$ ns, which is mainly due to multiple scattering in the spectrometer itself [4] as well as low energy neutrons from back-scattering inside the vacuum chamber [8]. Multiple scattering is included in the analysis as part of the response function while back-scattering is taken into account with the use of a separate spectral component (black dashed in Fig.2a and 3a). In principle, a back-scatter component should also be included in the MPRu analysis but due to the low number of counts it falls below the statistical limit and is disregarded here. The overall quality of the fits to the data is good and a consistent picture of the neutron emission spectrum from both TOFOR and the MPRu is obtained from the NES analysis. For both spectrometers, the ratio of THN/BTN is around 0.7, which is somewhat higher than predicted by TRANSP (around 0.4) although profile effects of THN and BTN emission play an important role. This is however outside the scope of study presented here, which is merely intended to demonstrate the potential of using NES to benchmark TRANSP analysis. Future work will adress the plasma physics interpretation of the results and the unique information on especially fast ions that can be obtained with NES.

The fitted temperature of the THN component as function of time is given in Fig. 4 together with core CXRS. The agreement is good, which is important and supports the analysis of fuel ion population using neutron emission spectroscopy. The energy shift for the MPRu was fitted to $\Delta E = 38 \pm 10$keV for the THN component, which corresponds to an effective bulk plasma rotation of about 240 ± 60km/s. This is a bit high compared to core CXRS rotation measurements at around 140km/s and the effect will be studied in more detail in future analysis of MPRu data.

CONCLUSION

A framework for detailed modeling of neutron emission spectra using ion distributions from a plasma-modeling code (TRANSP) was presented. It was shown that a consistent picture of the plasma could be given using two independent neutron spectrometers. While TOFOR with its higher efficiency can provide a more detailed and time resolved analysis, it is an important result that the two spectrometers, operating independently of each other, provide compatible results. In future DT operations at JET, the MPRu will serve as main neutron spectrometer with TOFOR as a complementary system.

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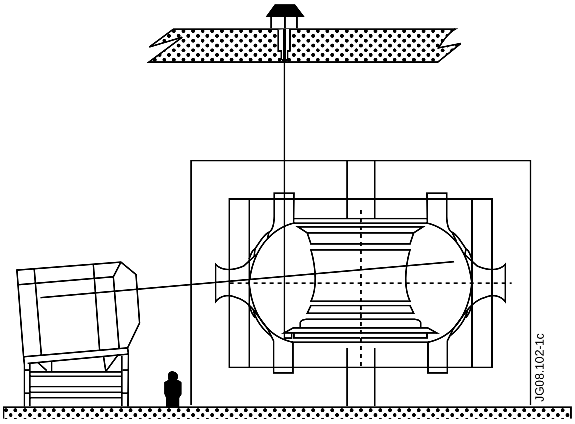

Figure 1: Illustration of the experimental setup at JET showing the sight-lines of TOFOR and the MPRu.

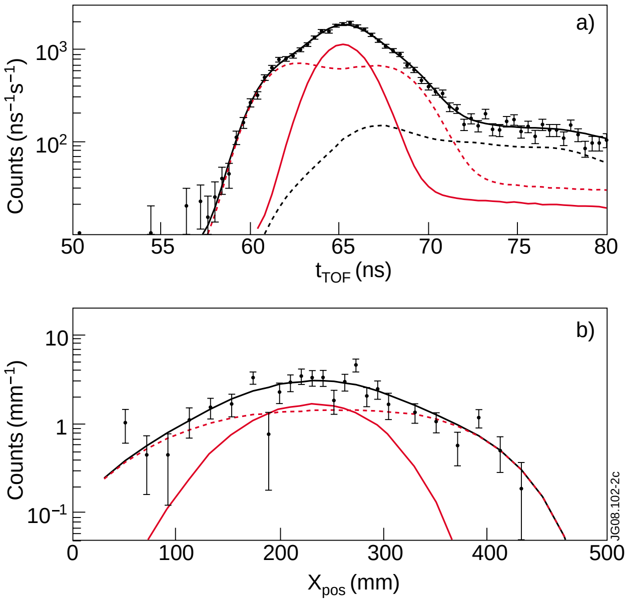

Figure 2: Measured data (points with error-bars) for TOFOR (a) and the MPRu (b) together with fitted TRANSP model with thermal (red broken), beam-target (black broken-dot), backscatter (black dash-dot) and the sum (blue solid).

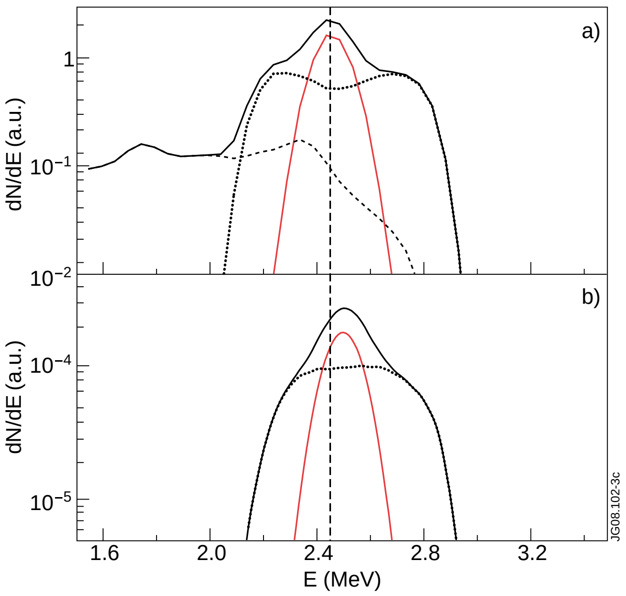

Figure 3: Neutron energy representation of the TRANSP modeled components with line coding as in Fig.2.

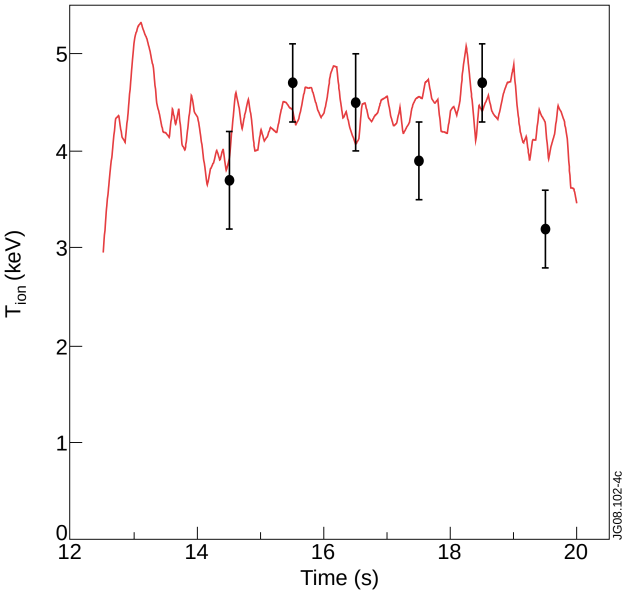

Figure 4: Measured central ion temperature from CXRS (red solid) compared with fitted temperature from TOFOR data.