

NEUTRON SPECTROMETRY STUDY OF RF HEATED DT PLASMAS

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1. INTRODUCTION

The plasma response to the injection of radio frequency (RF) power in deuterium-tritium (DT) plasmas at JET has been studied as it can be observed in the energy distribution of emitted neutrons. The measurement was performed with a new type of neutron spectrometer based on the magnetic proton recoil (MPR) technique [1]. MPR data are available for most RF discharges from the DTE1 campaign of 1997 which include ion cyclotron resonance heating (ICRH) on D-minority, T-minority and second harmonic, and ³He minority (the same as second harmonic T) [2]. Some of these RF heated DT plasmas produced high neutron yield rates (up to 1/10 of the JET record of $Y_n \approx 6 \cdot 10^{18}$ n/s). This was exploited with the MPR which was installed at JET in 1996 for the DTE1 experiment to measure the spectrum of the $d+t \rightarrow \alpha+n$ emission at high count rates, approaching $C_n = 10^5$ n/s for the best RF discharges. This paper concerns ICRH coupling to deuterium, being a minority ion in a plasma of DT, denoted (D)T, with a relative density in the range $n_d/n_i = 10$ to 20 %.

The neutron emission reflects the fusion reactivity which is a product function of the velocity distribution of the deuterons and thermal tritons. Neutron spectrometry is a sensitive probe of the up-shift in the energy distribution of fuel ions, i.e., the RF power action on the deuteron population in (D)T plasmas. With the MPR it was possible to measure the principal features of the energy spectrum with a time resolution of 100 ms in powerful discharges and weaker details in the high energy tail could be observed with longer time integration periods. This tail of the neutron emission is particularly interesting as it carries direct information on the RF action on the deuterons and the formation of the high energy (HE) part of the deuteron population (specified by the temperature, T_{HE}).

The neutron spectrum for (D)T RF discharges is described in three parts, namely, those characterized by the thermal (TH) and supra-thermal (ST) energy distributions of the deuteron population, besides the HE tail distribution. The HE distribution is a direct reflection of the RF acceleration of the resonance ions in the direction perpendicular to the magnetic field. The interaction of the deuterons of this anisotropic velocity distribution with the tritons of the bulk gives an neutron emission of a characteristically different energy distribution from those involving thermal and supra-thermal ions which are isotropic; the latter ones are distinguished by the difference in the spectral Doppler broadening only. This approach of describing the ICRH action on (D)T plasmas is an adaptation of the conventional model description of ion velocity distributions specified by parallel and perpendicular temperatures. As the neutron emission spectrum includes a weighting of the ion velocity distribution with the reactivity it turns out that the TH, ST and HE components are characteristically different so this representation works well for describing the neutron emission and simplifies the fitting procedure used in the data analysis.

The simulated neutron emission is composed of TH, ST and HE distributions parameterized through a real or effective temperature (T_J where $J=TH, ST$ or HE and determined by the measured spectral width) and amplitude (A_J) from which the measured one is predicted by also including the accurately known instrumental response function. We show in this contribution that the measured spectra can be well described providing detailed information on the RF action on the plasma fuel ions of the plasma. The energy shifts of the neutron emission is also measured and can be attributed to plasma toroidal rotation (V_T).

2. EXPERIMENTAL

The MPR spectrometer, enclosed in a concrete shielding including a collimator, was set up in the torus hall at JET as close as possible to the plasma to receive maximum flux. The sight line makes a double pass through the plasma at an averaged angle of about 47 degrees to the toroidal direction, lying nearly in the mid but at a slightly elevated angle of 5°. This viewing position gives a neutron flux of $F_n = k \cdot Y_n$ where $k \approx 2 \cdot 10^{-9} \text{ cm}^{-2}$. Spectrometer principles and procedures for data acquisition and processing including background handling are described in the accompanying paper [3]. For mono energetic (E_{ni}) incident neutrons, the response is a position distribution which is well known for each E_{ni} . This response function is based on an energy calibration at the absolute accuracy, at present, of $2 \cdot 10^{-3}$, and better than 10^{-5} relative. These are relevant values for measuring neutron energy distributions and energy shifts (ΔE_n) from which one can determine ion kinetic properties and plasma rotation effects, respectively.

The discharges discussed here are RF heated (D)T with short (0.2 s) neutral beam blips of low power ($\leq 2 \text{ MW}$) applied to perform charge exchange spectroscopic (CXRS) measurements of the (carbon) ion temperature radial profile, $T_i(\rho)$ where $\rho = r/a$ and a is the minor radius; the line averaged measurement of MPR corresponds to $T_i(\rho)$ at $\rho \approx 0.3$. With the MPR, we performed time resolved measurements of the neutron emission spectrum where the practical resolution limited is set by counting statistics. The Ohmic heating (OH) periods with thermal plasma conditions were also observed although with poor statistics.

3. SPECTRAL ANALYSIS AND PLASMA INFORMATION

The neutron spectrum for the $d+t \rightarrow \alpha+n$ reaction was calculated as a superposition of three components formed by deuterons of the three distributions with tritons of a Maxwellian distribution specified by $T_{TH} = T_i$. The deuterons characterized the resulting neutron spectrum. The TH component is taken as a Gaussian whose width is specified by T_i while the ST and HE components are calculated as sums of spectra where the neutron emission for each is for deuterons of a certain energy and carrying the weight in the summation according to deuteron energy distribution; the ST and HE deuteron distributions are here taken to be Maxwellian specified by the temperatures T_{ST} and T_{HE} ; T_{HE} can be identified as a 'perpendicular' temperature while the others are normal isotropic ones. Calculated spectra are presented as function of neutron energy and have an intrinsic energy shift that varies with the relative d-t energy and is predicted with an absolute accuracy of better than 10^{-5} . The measured spectrum is the neutron source function folded with the spectrometer response function which provides the relationship between the measured functional variable (position) and the absolute neutron energy. The neutron source function is predicted and specified by 7 parameters, the temperatures T_J and amplitudes A_J ($J = TH, ST$ and HE) besides the common energy shift ΔE_n . These were varied and determined through fitting of the predicted folded spectrum to the measured one and determined through a χ^2 minimization procedure. For discharge periods of limited statistics, or for weak spectral components, some parameters had to be frozen based on external input information, or the number of components were reduced. The energy is measured absolute in keV but to use the high relative accuracy, the energy shift for the RF discharges is given relative to that of Ohmic discharges (average value $\Delta E_n = 33 \pm 3 \text{ keV}$) and similarly expressed as relative toroidal rotation V_T where $\Delta E_n = +1 \text{ keV}$ is $V_T = 2.65 \text{ km/s}$ in the plasma current direction. From the measured A_J and T_J values, adopting the well known temperature dependence of the thermal ion reactivity, the relative kinetic energy density for the three components (W_J) was also deduced. Time resolved as well as discharge integrated values were determined depending on the count rate of the discharge.

4. RESULTS

The neutron spectrum was recorded in time bins of 10 ms over individual discharges consisting of start-up and ending periods with Ohmic heating, and the intermediate RF pulse period with short (200 ms) NB blip periods, which were separated out. An example is shown in Fig. 1 demonstrating the dramatic difference of auxiliary heating on the neutron emission. The count rate increases a factor of about 10^3 and T_i increases from $1.9 \pm 1.6 \text{ keV}$ to about 5 keV (bulk

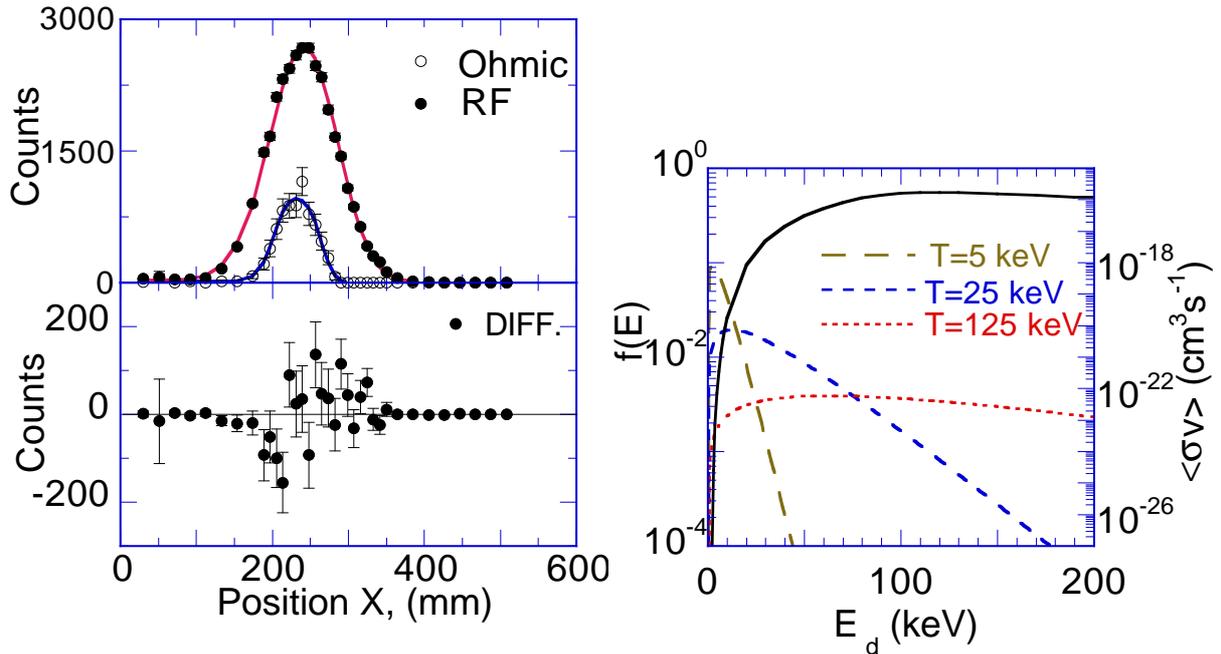


Fig. 1 (left). Comparison of measured histograms for neutron emission from JET discharge #42988 during periods without (Ohmic only, data multiplied by 20) and with auxiliary (RF) heating, and the difference spectrum for RF minus RF+NB; the integration time was 0.9 s for RF and RF+NB, and 14 s for the Ohmic part. E_n increases with x and the dispersion is 11.1 keV/mm.

Fig. 2 (right). Calculated Maxwellian ion distributions for $T_i=5, 25$ and 125 keV compared with the $d+t \rightarrow \alpha+n$ reactivity (cross section times velocity) as function of deuteron energy.

only) and falls back. Moreover, there is an energy up-shift from $\Delta E_n = -4 \pm 19$ keV (using the average value for Ohmic plasmas as off-set) to $\Delta E_n \approx +77 \pm 3$ keV corresponding to toroidal rotation of 117 ± 11 km/s .

The effect of the NB blips is small. It is best displayed by inspecting the difference between spectra recorded during RF+NB and RF (Fig. 1 lower panel). The 2-MW of NB (compared to 6 MW of RF) increases the count rate by 4 %. It also gives a systematic shape change in the range $x=150$ to 220 mm that can be interpreted as due to energy up-shift of the neutron emission due to rotation; the excess in the difference for $x > 200$ mm is due to rotation plus ion kinetic effects. Spectral analysis of the data show significant difference between the RF and NB+RF periods only with respect to the energy shift. It is found that $\Delta E_n = \Delta E_n(\text{RF+NB}) - \Delta E_n(\text{RF}) = [91 \pm 3] - [77 \pm 3] = 14 \pm 4$ keV which would translate into an average increase in toroidal rotation of 37 ± 11 km/s during NB blips.

The Maxwellian energy distributions probed in this study has a large temperature span and the neutron emission is weighted to the high energy end of these up to $T_i \approx 120$ keV where the dt fusion cross section peaks (Fig. 2). As the effect of the ICRH is often to create a supra-thermal distribution with $T_{ST} \gg T_{TH} = T_i$ and a high energy tail with $T_{HE} \gg T_{ST}$, it is possible to distinguish these contributions in the neutron emission spectrum. The HE part has the added feature of anisotropy manifesting itself in the form of a double humped neutron spectrum.

An example of a measured spectrum with a fitted calculated distribution is shown in Fig. 3. The low energy region ($x < 70$ mm) is dominated by scattered neutrons (e.g., inescapable contributions from the far side plasma facing wall) while the remainder is made up of the direct emission from the plasma which here is measured over an intensity range of nearly four orders of magnitude. The data are well described by the calculation giving a reduced χ^2 of 2.6, some of the contribution coming from last few high energy points which may indicate that some of HE features are not accounted for with a single HE-component model.

The best fit was obtained with the TH, ST and HE neutron emission components shown in Fig. 4 specified by the temperatures $T_{TH} = 4.5$, $T_{ST} = 18 \pm 1$ keV and $T_{HE} = 122 \pm 2$ keV and the relative amplitudes 6.7 ± 0.1 , 30.3 ± 0.3 and 63 ± 1 %; the value T_i was frozen in the fitting. We

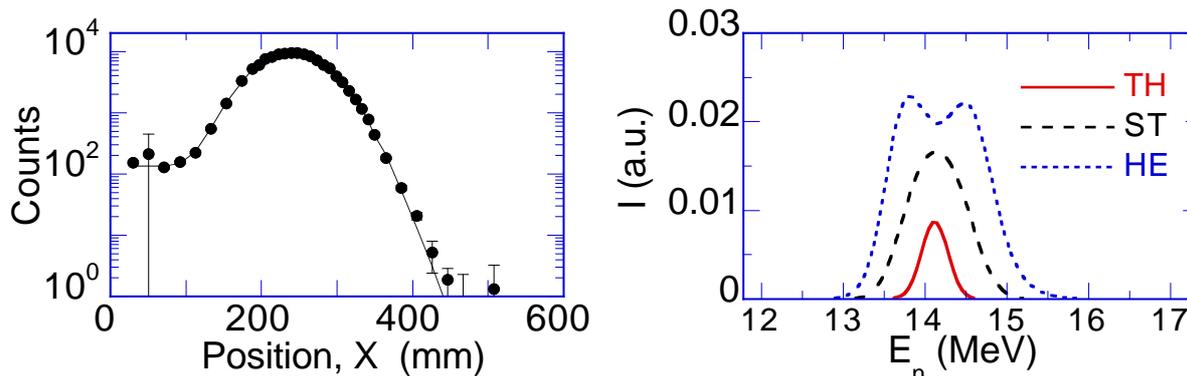


Fig. 3 (left). Measured position histogram for the neutron emission from JET discharge #42988 during the 5-s long RF pulse compared with the calculation including neutron source functions folded with the response function. The low energy ($x < 70$ mm) is dominated by scattered neutrons fitted in an approximate way.

Fig. 4 (right). The TH, ST and HE reaction components used to calculate the composite distribution giving the fit (reduced $\chi^2 = 2.6$) shown in Fig. 3.

derive relative deuteron energy densities of 22, 19 and 59 % (for an estimated total value of $w_d = 16.5$ kJ/m³). These results represent line averaged values typically centered at a radius of about 30 % of the minor radius. The analysis of the data obtained with the MPR neutron spectrometer is continuing and is expected to give information on the time evolution on the plasma during RF heating for the most favorable measurement conditions, i.e., essentially high Y_n -values.

5. CONCLUSION

This contribution has reported on measurement, performed with a new type of spectrometer, and analysis of the spectrum of the neutron emission from RF heated DT plasmas at JET. Results were presented showing the plasma response to the RF action on the deuteron population divided in thermal, supra thermal and high energy tail components; the ion kinetic parameters of (effective) temperature and amplitude, and derived energy densities; the neutron energy shift was also measured and attributed to a toroidal rotation. These results demonstrate that neutron spectrometry is a powerful diagnostic of the fuel ion kinetics of plasmas and its response to RF injection. The quality of the diagnostic results improves with statistics, i.e., count rate approaching the 100 kHz in the JET measurements up till now. Continued success RF heating of plasmas in future would be proportionally better diagnosed using MPR type of neutron spectrometers as these have no intrinsic count rate capability limitation.

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