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ABSTRACT
The neutron emission spectrum from $d + t \rightarrow \alpha + n$ reactions has been measured as a means to study the plasma response to radio frequency (RF) power coupled to hydrogen and deuteron minority components (through fundamental and second harmonic, respectively) in a tritium discharge at JET. The spectrum was measured with the magnetic proton recoil (MPR) spectrometer and was analysed in terms of two spectral components due to thermal (TH) and high-energy (HE) deuterons interacting with the bulk ion population of thermal tritons. The results were used to derive information on the deuteron population in terms of temperatures (T_{TH} and T_{HE}) as well as corresponding particle and kinetic energy densities of the plasma; the bulk ion temperature ($T_i = T_{TH}$) was determined both before (with Ohmic heating only) and during the RF pulse. Similar information on protons was derived from other measurements in order to estimate the different RF effects on protons and deuterons. The present study illustrates qualitatively the type of empirical ion kinetic information that can be obtained from neutron emission spectroscopy; the data serves as a basis for comparison with results of predictive and interpretative models on RF effects in plasmas.

1. INTRODUCTION
The purpose of auxiliary power (P_{AUX}) injection in fusion plasmas is primarily to raise the fuel ion temperature so as to enhance the fusion reactivity (ρ), ultimately, to the point of ignition. The power injection has often the effect of perturbing the thermal equilibrium of the ion populations. This is especially true with respect to the creation of supra-thermal components such as those caused by radio frequency (RF) power (P_{RF}) absorbed at certain ion cyclotron resonance frequencies (ω_c). Neutron emission spectroscopy (NES) is a sensitive probe of such changes in the ion velocity distributions. This is exemplified by the tritium (T) discharges produced at JET using RF tuned to hydrogen (H) as a minority species together with deuterium (D) heated through fundamental (ω_{cp}) and second harmonic (ω_{cd}) resonances which can be studied through measurement of the neutron emission spectra of the $d + t \rightarrow \alpha + n$ and $p + t \rightarrow {}^3He + n$ reactions.

The dt reaction is exothermic and gives a neutron spectrum centred around $E_n = 14$ MeV whose shape contains information on the fuel ion velocity distribution, specially, that of deuterons in this case. In the present study, the detailed shape of the 14-MeV neutron spectrum was measured and analysed in terms of thermal and supra-thermal deuteron velocity components. Concerning the proton velocity distribution, only the supra-thermal protons can be detected, as the protons are not fuel ions in contrast to the other hydrogen isotopes. In other words, the pt reaction is endothermic which requires proton energies of $E_p = 1.0$ MeV or higher to produce a neutron emission spectrum that would be expected to peak at $E_n \rightarrow \approx 0$ MeV for the conditions at hand. This neutron spectrum can not be measured directly but its intensity increases as the proton energy is pushed beyond the threshold so that increasing neutron yield of the pt reaction reflects, say the temperature of the supra-thermal protons, which can be observed as an extra-ordinary contribution to the total neutron yield as compared to the normal one from the exothermic fuel ion reactions $d + t \rightarrow \alpha + n$ and $d + d \rightarrow {}^3He + n$. This paper presents new results from measurement of the dt neutron spectrum performed with the magnetic proton recoil (MPR) spectrometer for the (HD)T discharge at JET Pulse No: 41759. This discharge has recently been the subject to a study [1] of the RF effects based mainly on the measured presence of supra-thermal protons and model calculations of the plasma response to the injected ion cyclotron radio frequency power. With the detailed NES data of the present study, new empirical information is provided on the PRF heating and acceleration of the fuel ion population and its corresponding velocity distributions and reactivities. From the measured partial reactivities and derived temperatures, qualitative results are derived on corresponding particle energy densities.

2. EXPERIMENTAL

The MPR spectrometer has been used since the beginning of the DT campaign at JET in 1997. High quality data have thus been obtained for several important DT and D plasmas as already reported [2,3]. The spectrometer works on the principle of converting a fraction of the flux of dt fusion neutrons from the plasma to nearly the same energy recoil protons. The conversion takes place in a thin polyethylene target placed at the end of a neutron collimator that defines the neutron flux and the plasma source volume. The protons are magnetically momentum analysed over a certain energy range (normally about 11-17 MeV) and focused onto a hodoscope consisting of a plastic scintillator array, which records a proton position histogram, $H_p(x)$. The histogram reflects the spectrum of the incident neutron flux, S(En), where the relationship between $H_p(x)$ and $S(E_n)$ is specified by the well known functions defining the MPR response to mono-energetic neutrons over the energy range of detection; i.e., $H_p(x)$ is the 4 convolution of $S(E_n)$ and the response functions [3]. The proton histogram is also predicted based on an assumed form for $S(E_n)$. This prediction is used for comparison with data and selection of the model spectrum that provides the best fit.

As the MPR sight line is quasi-tangential to the central plasma, the neutron spectrum is Doppler shifted (ΔE_S) for toroidally rotating plasmas [2]. The thermal Doppler broadening of the neutron spectrum scales with the square root of the ion temperature, T_i, of the plasma, i.e., $\Delta E_n = 177 \cdot T_i^{1/2}$; for instance, $\Delta E_n / E_n = 2.5$ % (FWHM) for $T_i = 4$ keV assuming a dt-reaction. The MPR count rate, C_n, is proportional to the neutron yield rate $Y_n(dt) \equiv Y_{dt}$ in the energy range E_n = 11-17 MeV from dt-reactions [4]. This can be compared (Fig. 1) with the total yield rate (Y_n) measured with the fission chambers [5]; the flat energy response and yield calibration of these detectors make them suitable to measure the summed partial yields of the pt, dd and dt reactions.

The composite spectrum of the neutron emission from the (HD)T discharge for the plasma conditions during the RF pulse is shown in Fig. 2; it is based on the calculated ion velocity distributions described below. The present study is mainly concerned with the plasma periods affected by RF as compared to Ohmic heating while those affected by blips of neutral beam (NB) heating will be considered in a separate study. The RF power was applied to a (HD)T plasma with the minority concentrations of $c_p = n_p/(n_p+n_d+n_t) = 4$ % and $c_d = 5$ %; these values represent averages during the period of P_{RF}^{MAX} and were taken from the JET database [1]. The presence of impurities was neglected; the overestimation of the ion concentrations would be at the 5 % level corresponding to Z_{eff} = 2.5 if caused by carbon. The RF power was tuned for absorption at the fundamental resonance frequency of hydrogen ($\omega = 1\ \omega_{cp}$ = 51 MHz with $P_{RF} \leq 8$ MW), which takes up most of P_{RF} through the creation of a supra thermal component in the proton population ($p^{\prime}$).

The reactivity of the fast protons interacting with tritons, $\rho_{p^{\prime}t}$, increases strongly with temperature for $T_{p^{\prime}} > 100$ keV (Fig.3) so that $\rho_{p^{\prime}t}$ at $T_{p^{\prime}}$ = 300 keV would be comparable to that of thermal dt-reactions ($\rho_{p^{\circ}t}$) at, say, T_i = 10 keV [6]. Although hydrogen would dominate the P_{RF} absorption, a weak supra-thermal deuteron ($d^{\prime}$) component can also be created whose corresponding reactivity, $\rho_{p^{\circ}t}$, can be almost an order of magnitude higher than $\rho_{p^{\circ}t}$ at $T_{p^{\circ}}$ = 10 keV (Fig. 3). As we shall see below, $T_{d^{\prime}}$ does not exceed 500 keV, which means that $\rho_{d^{\prime}t}$ always dominates $\rho_{d^{\prime}d}$, as does ρ_{dt} compared to ρ_{dd}. Therefore, the total neutron yield rate is made up of the sum $Y_n = Y_{p^{\prime}t} + Y_{p^{\circ}t} + Y_{d^{\prime}t}$; the contribution from t + t $\rightarrow \alpha$ + 2n reactions is insignificant at $T_t = T_i$ = 10 keV.

3. ANALYSIS AND INTERPRETATION MODELS

The spectrum of the neutron emission from dt-reactions in the plasma was determined based on the $H_p(x)$ data of the MPR spectrometer. The amplitude (A) and the width (assumed to correspond to thermal Doppler broadening) of the calculated spectral components were varied to obtain the best fit to the data. These fits resulted in a certain neutron spectrum in terms of the underlying deuteron and triton velocity distributions, which could thus be determined. Examples of data for the Ohmic and RF periods of the discharge are shown in Fig. 4 together with the computed fits. The fits were based on the neutron spectra shown in Fig. 5. Two spectral components are needed to describe the neutron emission from the RF heated plasma period and this is also sufficient to provide an excellent fit (Fig. 4).

The MPR measurement resulted in the determination of the absolute energy distribution of the incoming neutron flux. These data were used to infer information on the fuel ion populations such as the ion temperature (T_i) for the Ohmic phase of the 6 discharge, and the thermal (TH) and high-energy (HE) tail temperatures for the deuteron population ($T_{TH} = T_{d^{\circ}}$ and $T_{HE} = T_{d^{\prime}}$) for the RF periods. In the latter case, TTH was taken as the common ion temperature for p, d and t during the RF part of the discharge. Moreover, the absolute energy of the calculated neutron spectrum was used to predict the corresponding histogram $H_p(x)$ apart for the general energy shift, ΔES, which was used as a free parameter in the fitting procedure. The thus obtained ΔES value was taken to reflect toroidal rotation and expressed relative to the typical value found for Ohmic discharges. For more details about the analysis model and interpretation, the reader is referred to ref. [2].

The neutron yield rate of dt-reactions is given by

$$Y_{dt} \propto n_d\, n_t\, \rho_{dt}\, (T) \tag{1}$$

where T is the temperature assuming a plasma in thermal equilibrium. The density ratio of fast and bulk deuterons in the plasma, disregarding profile differences, can be estimated from the relative yield rates and reactivities for the different reactions

$$\frac{n_{d'}}{n_d} = \frac{Y_{d't}}{Y_{dt}} \, \frac{\rho_{dt}}{\rho_{d't}} \tag{2a}$$

which is (for low $n_{d'}$ values) approximated to

$$\frac{n_{d'}}{n_d} = \frac{n_{d'}}{n_{d^\circ} + n_{d'}} \approx \frac{n_{d'}}{n_d} \approx \frac{A_{HE}}{A_{TH}} \, \frac{\rho_{d^\circ t} + (T_{d^\circ})}{\rho_{d't} + (T_{d'})} \tag{2b}$$

Here, A is the measured neutron intensity of each component and the $\rho(T)$-values are those shown in Fig. 3; the d't-reaction is specified by a single temperature value, $T_{d'}$. Similarly, one can determine the density ratio for the fast components of the proton and deuteron populations

$$\frac{n_{p'}}{n_d} = \frac{Y_{p't}}{Y_{dt}} \, \frac{\rho_{d't}}{\rho_{d't}} \tag{3}$$

By making use of the experimentally measured ratio

$$\frac{Y_{p't}}{n_{dt}} \equiv k = \frac{Y_n - [Y_{d^\circ t} + Y_{d't}]}{Y_{d^\circ t} + Y_{d't}} \tag{4}$$

one can determine the yield ratio

$$\frac{Y_{p't}}{Y_{d't}} = k\left(\frac{Y_{d^\circ t}}{Y_{d't}} + 1\right) \tag{5}$$

for p't and d't. The fast component of the proton population has thus a relative density of

$$\frac{n_{p'}}{n_p} = \frac{n_{p'}}{n_{p^\circ} + n_{p'}} = k\,\frac{c_d}{c_p} = \frac{\frac{n_{d'}}{n_{d'}}}{\left(1 + \frac{n_{d^\circ}}{n_{p'}}\right)} \, \frac{\rho_{d't}}{\rho_{d^\circ t}} = k\,\frac{c_d}{c_p} \, \frac{\frac{A_{TH}}{A_{HE}}}{\left(\frac{\rho_{d't}}{\rho_{d^\circ t}} \, \frac{A_{TH}}{A_{HE}} + 1\right)} \, \frac{\rho_{d't}}{\rho_{d^\circ t}} \tag{6}$$

where the relationship between the deuteron and proton concentrations (c_d and c_p) is given by the particle number densities through

$$\frac{c_p}{c_d} = \frac{n_{p^\circ} + n_{p'}}{n_{d^\circ} + n_{d'}} = \frac{n_{p^\circ} + n_{p'}}{\left(\frac{n_{d^\circ}}{n_{d'}} + 1\right) n_d}, \tag{7}$$

The relative ion energy densities in the plasma, w_j, can be determined from the temperatures and the concentrations (relative densities) of the ion populations

$$w_j = c_j \cdot T_j \tag{8}$$

where the index j represents the ion species p, d and t; the electron energy density, we, is expressed similarly.

4. RESULTS AND DISCUSSION

The NES results for the Ohmic and RF periods of the discharge are shown in Fig. 4 in the form of measured $H_p(x)$ histograms together with calculated fits. The fits were obtained by folding the known MPR response functions with neutron spectral functions of prescribed shapes. The spectral components that gave the best fits are shown in Fig. 5. These are represented by a Gaussian spectrum for the thermal plasma conditions and a two-component spectrum for the RF period. The latter is made up of contributions for reactions between thermal ions of temperature ($T_{TH} = T_i$), and between RF-accelerated supra-thermal ($T_{HE} = T_{d'}$) deuterons and thermal tritons (see Ref. 2 for details). Thus, the Ohmic period was determined to have $T_i = 1.1 \pm 1.6$ keV for an 8 average count rate of $C_n = 0.03$ kHz; the large error in T_i is due to the combination of modest statistics and a small Doppler broadening (1.3 %, FWHM) relative to the instrumental resolution of $\Delta E_n / E_n = 4.0$ % (FWHM). The RF plasma is found to have a bulk component of ions with $T_i = 8.4 \pm 0.5$ keV and a high-energy tail component due to ions with $T_{d'} = 300 \pm 50$ keV. The average MPR count rate at $P_{RF}{}^{MAX}$ is $C_n = 1.8$ kHz with a split on spectral components according to the measured relative spectral intensities, $A_{TH} = 91 \pm 2$ % and $A_{HE} = 9 \pm 1$ %. Information was also obtained on the plasma toroidal rotation which was found to be 70 ± 16 km/s (relative to the Ohmic heating conditions [2]) based on a measured energy shift of $\Delta E_S = 59 \pm 5$ keV. The errors on the derived plasma parameters are calculated in such a way that they reflect a change of the minimisation parameter (χ^2) with one unit.

The above results are based on measurements of the average neutron emission along the MPR sight line through the plasma, which represents the local conditions at some distance from the plasma centre ($r/a \approx 0.25$ where a is the minor radius [7]). The plasma was also diagnosed with other methods such as x-ray emission crystal spectroscopy (XCS) performed on Ni^{26+} impurities. The XCS diagnostic showed an increase in T_i from 1.5keV (representing the Ohmic phase) to 4 keV due to P_{RF}, which would reflect the plasma conditions at a radius of $r/a \approx 0.4$ [1]. The NES result for the Ohmic phase is not inconsistent with the XCS result considering the large uncertainties and is also close to the electron temperature measured to be about 2keV in the plasma centre. For the RF heated period, however, the bulk fuel ion temperature obtained with the MPR is significantly higher than what was extracted from the XCS diagnostic for impurity ions (T_i = 8.4keV compared to 4 keV). The measured effective ion temperature of 8.4keV with the MPR would correspond to T_i = 11keV in the plasma centre (assuming a typical plasma profile). This is close to the measured central electron 9 temperature thus suggesting that the d and t bulk ions are heated by RF to about the same temperature as electrons [1]. What concerns toroidal rotation, there are no other measurements to compare with for this discharge.

Information on the fast component of the proton population during the RF pulse was obtained by other diagnostics. The velocity distribution was measured with the neutral particle analyser (NPA) diagnostic [8] from which $T_{p'} = 380$ keV was derived representing the plasma conditions off centre. Information on the amplitude of the velocity distribution was not available from this measurement but was derived from the ratio of the energy integrated neutron yield rate (measured with the fission chambers) and that for high energy neutrons; the latter yield rate of dt reactions was recorded by the MPR (see Fig. 1), and also by the JET neutron camera [5]. It was found that $Y_n/Y_{dt} = 1+Y_{pt}/Y_{dt}$ showed an increase of about 50 % during the RF pulse thus reflecting the relative fast proton density as shown in Eqs. 4 and 6.

From knowledge about the reactivity, and the measured bulk and tail temperatures of the plasma, besides the neutron yield ratio for neutrons in the energy range $E_n < 2$ MeV and $E_n > 10$ MeV, several aspects of the ionic state of the plasma can be derived. One such aspect concerns plasma ion densities. The relative densities of fast and thermal deuterons and protons were determined using Eqs. 2 and 6, resulting in the ratios $n_{d^{\prime}} / n_{d^{\circ}} = 1.4\%$ and $n_{p^{\prime}} / n_{p^{\circ}} = 22\%$. This means that the RF power is about 16 times more efficient in populating a high-energy state of protons than deuterons. The proton and deuteron tail temperatures are found to show a small difference (380 keV compared to 300 keV), which is not a significant difference considering the uncertainties.

Estimates for the particle kinetic energy density for ions (w) was determined relative to that for electrons (we) and differentiated with respect to species and velocity component, viz. $w = w_p + w_d + w_t$, and $w_p = w_{p^{\circ}} + w_{p^{\prime}}$ and $w_d = w_{d^{\circ}} + w_{d^{\prime}}$; the triton population is assumed to have no fast component so $w_t = w_{t^{\circ}}$. Using Eqs. (2), (5) and (6), w is found to be a factor of 1.25 higher than we with the division on species being $w_p = 34$, $w_d = 5$ and $w_t = 61$ %. The division between fast and thermal ions is determined to $w^{\prime}/ w^{\circ} = 34 / 66$ and within each species the ratios are 94 / 6 for protons, 33 / 67 for deuterons and 0 / 100 for tritons.

Assuming that the RF power absorption is reflected in the high-energy component of the proton and deuteron populations, one can make the following observations. The proton and deuteron tail temperatures are found to be similar within the uncertainties ($T_{p^{\prime}}$ = 380keV and $t_{d^{\prime}}$ •300keV) so there is no significant difference in the • c and 2 • c couplings in this regard. However, the relative density of the fast protons (about 20 %) is much higher than that of fast deuterons (1.4 %) for about the same population concentrations ($c_p = 4$ and $c_d = 5\%$). This suggests that the RF power absorption on protons and deuterons is divided in the ratio 10 to 1. There is, as far as we know, no theoretical prediction of the fundamental and 2nd harmonic RF couplings to compare with. However, this exists for the total energy content of ions and electrons ($w_{tot} = w + w_e$) in the plasmas as well the split between thermal and supra thermal ions (w^{o} and $w^{\prime}$). The calculations give an overestimation of 30% in total energy compared to experiment. Moreover, the supra-thermal component is predicted to be much stronger ($w^{\prime} / w = 0.6$) than the experimental estimate of $w^{\prime} / w = 0.2$. This difference could actually account for the 30% overestimation in the predicted w. Considering just the $w^{\prime}$ ratio, the noted difference could indicate an incongruence between the theoretical definition of how the supra-thermal component ion populations are divided in an ion 11 population and how the division is made based on experimental observations. In the latter case, there is an ambiguity in the separation of the low-energy part of the supra-thermal component from the thermal component where it might enter as an undetected perturbation. In the case of the NES data, this would lead to an underestimation of $w^{\prime}$ but not at the level of the observed difference of a factor 3 at hand.

The temperature dependencies of the neutron yield rates of different ion reactions can be compared by approximating the reactivity values (Fig. 3) with exponential functions T^{α}. This would apply to local changes in plasma conditions around the values measured, neglecting, of course, any plasma profile effects. The results are $Y_{d't} \propto T^{2.2}$, $Y_{d^{\circ}t} \propto T^{2.4}$ and $Y_{d't} \propto T^{-0.54}$ for the temperatures used here. It is then found that the fast ions produce a yield ratio $Y_{p't} / Y_{d't}$ with a strong temperature dependence, proportional to $T^{2.7}$. The ratio $Y_{p't} / Y_{dt}$ (from the data on $[Y_{p't} + Y_{dt}]/Y_{dt}$), however, is essentially temperature independent. This means that the two ratios reflect, respectively, the fast ion amplitude and temperature effects of the RF power, assuming that the temperature changes are concurrent. In summary, RF is found to promote a fast component in both proton and deuteron populations up to about the same temperatures, but the proton amplitude is about 16 times higher than that for deuterons.

5. CONCLUSION

Spectra have been measured for the neutron emission from tritium plasmas heated with RF power coupled to the hydrogen and deuterium minorities through their fundamental and second harmonic resonances. From data on the $d + t \rightarrow \alpha + n$ reaction for a JET discharge, results were obtained on the temperature and amplitude of the bulk and fast components of the deuteron population besides plasma toroidal rotation. The results were used in conjunction with other neutron yield data and the temperature of the fast proton component to gain insight on the plasma response to the applied RF heating compared to the thermal equilibrium state during Ohmic heating only. It is found that RF excites the proton population a factor of 16 more strongly than that of deuterons while the tail temperatures are both in the 300keV range (compared to 8.4keV for the bulk). This study is a demonstration of the use of neutron emission spectroscopy measurements in plasma experiments on RF heating and their information capability. The studied (HD)T discharge illustrates the anomalous increase in neutron yield rate from endothermic $p + t \rightarrow {}^{3}He + n$ reactions which have no corresponding effect on the fusion power being dominated by fuel ion reactions $d + t \rightarrow \alpha + n$.

6. ACKNOWLEDGEMENTS

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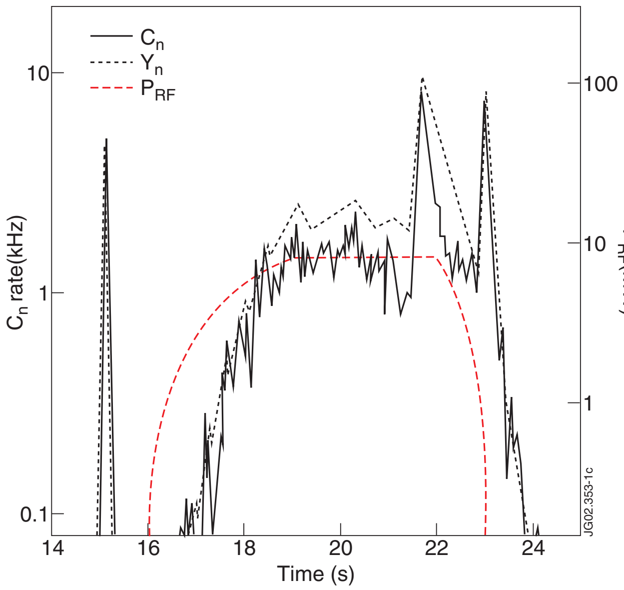


Figure 1: The count rate (C_n) of the MPR spectrometer for JET Pulse No: 41759 as function of time during the extended radio frequency (RF) power pulse (shown) where the spikes indicate the injection of short (200 ms) neutral beam (NB) pulses. Comparison is made with the time evolution of total neutron yield rate (Y_n) measured by the fission chambers, here normalised to C_n during Ohmic and (NB) heating.

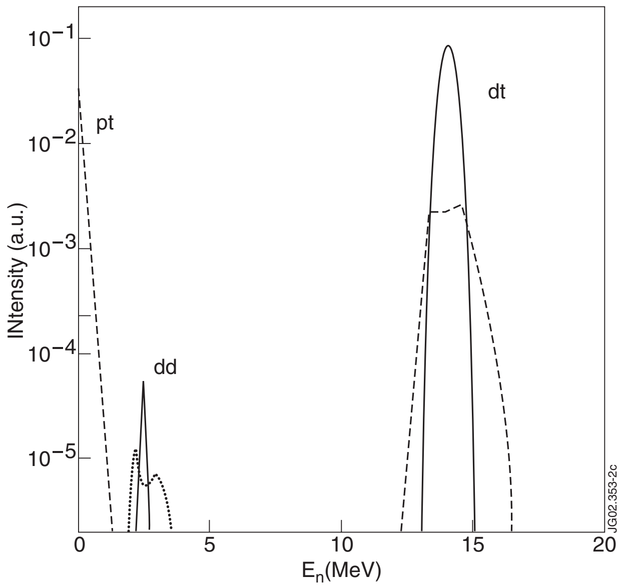
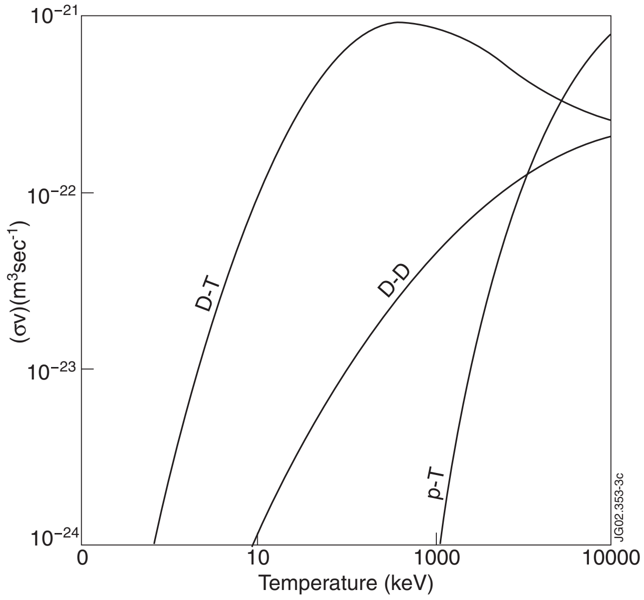


Figure 2: Illustration of the spectral contributions of the neutron emission spectrum from the RF heated (HD)T discharge as based on the calculations of thermal ion reactions (dd and dt solid curves) and fast-thermal ion reactions (p't, d'd and d't dashed curves); see text for details.



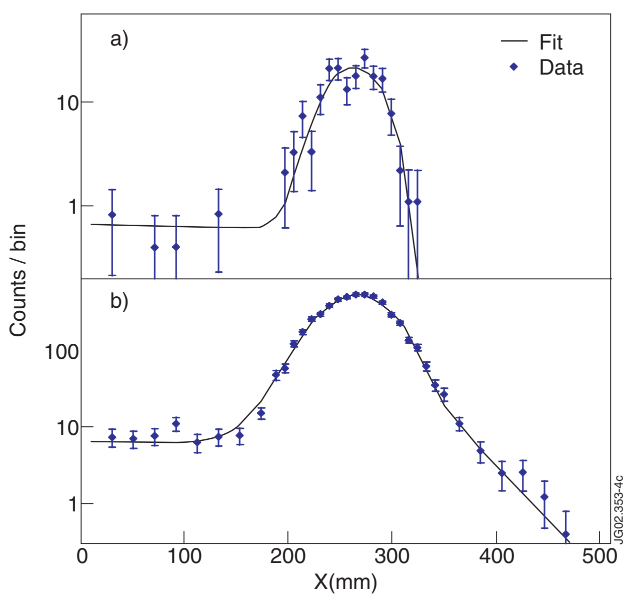


Figure 3: Reactivity as function of ion temperature, T_i, for the dt, dd and pt reactions(adapted from ref. [6]).

Figure 4: The measured spectrum of the neutron emission from the Ohmic (a) and RF heated (b) periods of JET (HD)T Pulse No: 41759 obtained with the MPR spectrometer. The data in the form of proton recoil histograms as function of position (x) represent the energy distribution of the received neutron flux folded with the known instrumental response functions for each neutron energy; proton recoil energy, and hence neutron energy, increase with x, the dispersion being about $dE / dX \approx +11keV/mm$ in the centre. Error bars indicate statistical errors in data.

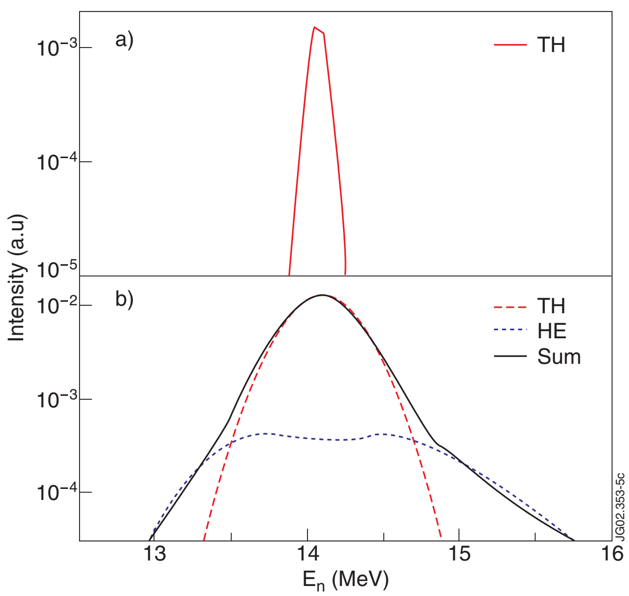


Figure 5: Results on the energy distribution of the neutron emission during Ohmic (a) and RF (b) heated plasma periods; also shown in (b) are the components due to thermal ion reactions (TH), and reactions with thermal tritons and supra-thermal deuterons (HE).