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Comparison of neutron emission spectra for D and DT plasmas with auxiliary heating

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Abstract. The DT experimental campaign on JET (1997) represents a major step forward for neutron emission spectroscopy (NES) diagnostic through the high quality data collected by the Magnetic Proton Recoil (MPR) spectrometer. These data for different DT plasma heating scenarios were analyzed here to determine the underlying fuel ion populations which in turn were used to project the 2.5-MeV neutron emission spectra for deuterium plasmas. The results on neutron spectra for DT and D plasmas in the same conditions were compared in order to determine the plasma information that could be expected from NES diagnosis of D plasmas and the instrumental characteristics that would be required. Future NES experiments would make dual sight line observations possible and the added diagnostic value is also assessed based on the present results.

PACS. 52.55.Pi Fusion products effects (e.g., alpha-particles, etc.), fast particle effects – 52.70.Nc Particle measurements

1 Introduction

Neutron emission spectroscopy (NES) measurements have been successfully used to diagnose high power plasmas produced at JET during the first main deuterium-tritium experiment (DTE1) in 1997 [1,2]. Similar NES studies of D plasmas are being planned by the development of neutron spectrometers for measurements of the 2.5-MeV neutron emission [1,3] as part of the JET-EFDA enhanced performance program. The spectrometers, an upgrade of the MPR (MPRu) and a new 2.5-MeV TOF neutron spectrometer (TOFOR) will enhance the NES diagnostic capabilities for the future campaigns at JET viewing the plasma at 47 degrees in the horizontal plane with MPRu and from above (i.e., perpendicular sight line) with TOFOR.

As part of this development, a study has been conducted to compare similarities and differences of the neutron emission response to changes in D and DT plasma discharges. The results of this study are reported here as well as their implications for performing fusion diagnostic of D as compared to DT plasmas.

The measurements of the JET DTE1 plasmas were performed with the magnetic proton recoil (MPR) spectrometer [1] which can operate at high count rates (0.6 MHz was achieved at JET) to afford data of high statistical accuracy. This together with the absolute energy calibration of the MPR made it possible to obtain NES data of high overall quality that lend themselves to advanced analysis and subsequent interpretation. The interpretation means that features appearing in neutron emission spectra could be identified with certain velocity components of the deuteron and triton populations. Especially, one could register the changes arising as the result of applying auxiliary heating by means of neutral beam (NB) [4] and radio-frequency (RF) [5] wave power injection; in the latter case the power was absorbed through ion cyclotron resonance heating (ICRH).

With auxiliary power present, the ion populations consist of both thermal (TH) and supra-thermal (ST) velocity components so the neutron emission will show a multiple component spectrum. The deuteron and triton velocity distributions were approximated to allow suitable parameterization so that computed neutron spectra could be varied to seek best fitting to the data. The measured spectra could in this way be well described based on neutron emission due to reactions between thermal ions plus reactions involving supra-thermal ones.

The supra-thermal (ST) part of the ion populations can have several components. Those of the highest energy (HE) are the ones of greatest interest as these components

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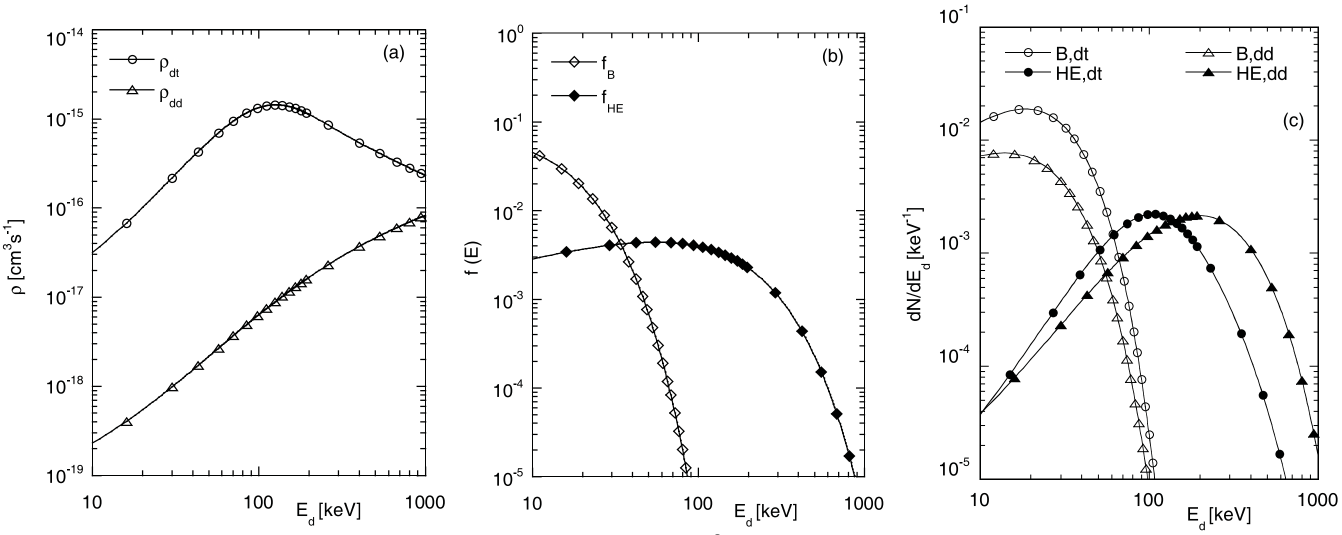

Fig. 1. The reactivity $\rho(E_d)$ for the $d + t \to \alpha + n$ and $d + d \to {}^3\mathrm{He} + n$ reactions (a). The deuteron population consists of Maxwellian energy distributions $f_B(E_d)$ and $f_{HE}(E_d)$ of the temperatures $T_B = 8$ keV and $T_{HE} = 110$ keV, respectively (b). The neutron emission probability as function of energy E_d (c).

carry the clearest signature of the heating that plasma is subjected to because of the anisotropy it causes. The low energy ions of the supra-thermal population, on the other hand, have lost their anisotropy because of large (pitch) angle scattering occurring during their slowing down in the plasma; these ions are referred to as epithermal (EP) as they show up in the neutron spectrum as the thermal (TH) component but with a greater Doppler broadening and hence a greater fictitious ion temperature (T_{EP}). Sometimes the TH and EP component are difficult to separate so that the neutron spectrum can be described with one component referred to as the bulk (B). Moreover, if one of the high energy components is dominant, it can be sufficient to use only two components to describe an ion population within the plasma [6]. In this study we have selected one each of the RF and NB heated of the JET DTE1 discharges that could be well described by using a deuteron population consisting of bulk and high energy components and single bulk component triton population. The ion populations of these discharges were derived from the model analysis of the measured proton spectra. This information was then used to project the spectrum of the neutron emission from a deuterium plasma of the same fractions of B and HE components as the DT plasma.

The projection of neutron emission from pure deuterium plasmas is motivated by the development of a new neutron spectrometer dedicated for this task. A Time-of-Flight neutron spectrometer designed for Optimized Rate, TOFOR [7], is being built for JET. TOFOR should permit advanced NES diagnosis of D plasmas which earlier has been limited to DT plasmas only.

NES diagnosis of D and DT plasmas presents certain differences because of the emission energies, 2.5 and 14-MeV, of $d+d \to^3$ He$+n$ and $d+t \to \alpha+n$ reactions and the deuteron energy dependence of the reactivities $\rho_{dd}(E_d)$ $\rho_{dt}(E_d)$. Moreover, in the coming JET D plasma experiments it will also be possible to observe the plasma from different lines of observation which will provide different spectra for the ions of anisotropic velocity distributions. In this paper we present results showing how the neutron emission from *dd* and *dt* reactions compare for plasma conditions subjected to auxiliary heating. It is also discussed how the anisotropy effects can allow spectra to be better analyzed with two sight lines forming different angles with the magnetic field in D plasmas as will be the case for upcoming D plasma studies at JET.

2 Spectral analysis

The relationship between spectra from *dd* and *dt* reactions for ions in thermal equilibrium is trivial as these spectra are of Gaussian shape where the width W (FWHM in keV) is given by the ion temperature (T_i in keV) through $W = C\sqrt{T_i}$ with C being 82.5 and 177, respectively, for *dd* and *dt* reactions [8]. This means that for a given temperature, the fractional spectral Doppler broadening is about 2.7 times greater for *dd* than for *dt*. Similar energy spreading effects can be expected for multiple-component neutron emission spectra but the situation is rather more complex, partly because of the difference in the energy dependence in the reactivity of the two reactions as, for instance, can be illustrated (Fig. 1a) as function of deuteron energy, i.e., $\rho_{dt}(E_d)$ and $\rho_{dd}(E_d)$. In this case, it is assumed that mono-energetic deuterons are interacting in a plasma of a temperature of 10 keV consisting of tritons or deuterons, respectively. The calculation is performed here by Monte Carlo methods using the cross-section parametrization of [9]. Both reactivities increase with E_d towards a maximum, which occurs already at $E_d = 100$ keV for *dt* compared to beyond 1 MeV for *dd* where $\rho_{dd}(E_d)$ and $\rho_{dt}(E_d)$ become similar. Moreover, $\rho_{dt}(E_d)$ is up to two orders of magnitude greater than $\rho_{dd}(E_d)$ with a ratio $\rho_{dt}(E_d)/\rho_{dd}(E_d)$ that varies in the

Table 1. Some principal characteristics of the studied discharges.

Discharge (#)	I_p [MA]	P_{AUX}	Y_n^{max} [10^{17} s^{-1}]	T_e [keV]	T_i [keV]	n_e [10^{13} cm^{-3}]	n_d/n_t	Z_{eff}
42769	3.3	ICRH	1.5	7.0	10.5	4.0	0.22	2.5
43134	1.7	NB	1.1	3.8	3.8	4.4	9.0	1.7

range 140 to 30 for E_d between 10 and 250 keV; this is the region of interest set by the deuteron velocity distributions of the supra-thermal components occurring in plasmas subjected to ICRH for a typical deuteron population. Such plasmas have typically a supra-thermal component of the ion populations that can be represented with a Maxwellian of temperature (T_{HE}) in the hundred keV range; the results in Figure 1b are based on a supra-thermal distribution determined by $T_{HE} = 110$ keV compared with a thermal (equilibrium) ion distribution of the bulk (f_B with $T_B \approx 10$ keV). The product of the reactivity and ion energy distributions gives the relative probability of neutron production as function of deuteron energy for ion reactions within the bulk or between high energy and bulk ions (Fig. 1c). This shows that neutrons are most likely to be produced at slightly lower deuteron energy in *dd* reactions compared to *dt* ($E_d \approx 15$ keV compared to $E_d \approx 20$ keV) within the bulk component. Moreover, the maximum is also about 3 times lower. For *dt* reactions involving high energy ions, the neutron production maximum occurs at $E_d \approx 100$ keV which is shifted to $E_d \approx 200$ keV for *dd* reactions.

The above differences, which derive from the energy dependence in the reactivities for *dt* and *dd* reactions, are in addition to those related to the emission energy noted in connection with the thermal Doppler broadening for given temperature. They will change the relative contribution of bulk and high energy components in the spectra of the neutron emission from *dt* and *dd* reactions. Another difference of importance is the relative magnitude of neutron production involving bulk ions only and high energy ones which are about 10:1 for *dt* and 3:1 for *dd*. This means that reactions between high energy ions are relatively less suppressed for *dd* than for *dt* and will actually not be an insignificant contribution in the spectra from D plasmas. The example above refers to plasmas with supra-thermal ion components due to RF heating.

In this study, the plasma was assumed to be homogeneous thus disregarding profile effects such as the RF and NB power deposition, particle diffusion, orbit size, etc. Since the neutron emission is normally strongest in the plasma core, it is the conditions of this region that are predominantly reflected in the NES measurements. The spectrum was measured with the MPR spectrometer that views the plasma in a direction of 47° to the tangent in the center of the torus (i.e., magnetic field direction) [1]. The viewing direction is "counter" the plasma current as well as to the injection direction of the neutral beams.

The analysis performed is phenomenological: The plasma ion populations are assumed to be generated in the discharge by the auxiliary heating method. For this study, the model neutron spectrum used for projections is the sum of two components. One of these (HE) is due to energetic deuterons. These are strongly anisotropic and have different distributions for ICRH and NB heating. In the ICRH case, a Maxwellian energy distribution is assumed but restricted to the pitch angle range $90° \pm 10°$ ("RF" model distribution); its temperature (T_{HE}) is a free parameter in the fit. In the NB case, a uniform energy distribution is assumed for 75 keV $< E_d <$ 150 keV in the pitch angle range $60° \pm 15°$ in the "counter" direction relative to the tangential NES view ("half box" model distribution). The other (bulk, B) component is due to thermal and epithermal deuterons. These are close to thermal, isotropic conditions, as is the case, for instance, for NB deuterons after they are slowed down to a fraction of their initial energy. A single Maxwellian (temperature T_B, free parameter) is assumed to model both thermal and epithermal deuterons. For a quantitative analysis, the instrument response function is convoluted with the parameterized neutron spectrum and the result is fitted to the measured proton spectrum: the goodness of the fit, i.e. the χ^2 test, confirms the phenomenological assumptions.

The MPR response function is well determined by a detailed characterization of the spectrometer and its contribution has been determined for mono-energetic incoming neutron fluxes in the range 10−18 MeV. The broadening of the simulated proton spectra is 2−4% depending on instrumental settings [1]. This broadening contribution is comparable to the broadening of the narrowest spectral component in the measured spectra (see below). Under these conditions good knowledge of the instrument response function is essential for a reliable determination of the spectral parameters.

All NES spectra are calculated using the Monte Carlo code APACHE [8]. This code has been developed specifically for simulation of neutron spectra. The velocity distributions of the reactants are provided as a numerical input to the code. In this way the neutron spectrum can be determined to the desired statistical accuracy.

3 Measured and fitted neutron spectra for DT plasmas

Two discharges are used for this study, namely, JET #42769 with RF heating (ICRH tuned to deuteron resonance frequency) in a plasma with a deuterium/tritium concentration of 0.22:1. The other discharge (JET #43134) was heated with a deuterium beam at $E_{beam} =$ 150 keV into a plasma with deuterium/tritium concentration of 9:1.

Some characteristics of the discharges such as plasma current I_p, auxiliary power P_{AUX} heating the plasma, neutron yield Y_n^{max} and electron temperature T_e and density n_e can be seen from the information given in Table 1.

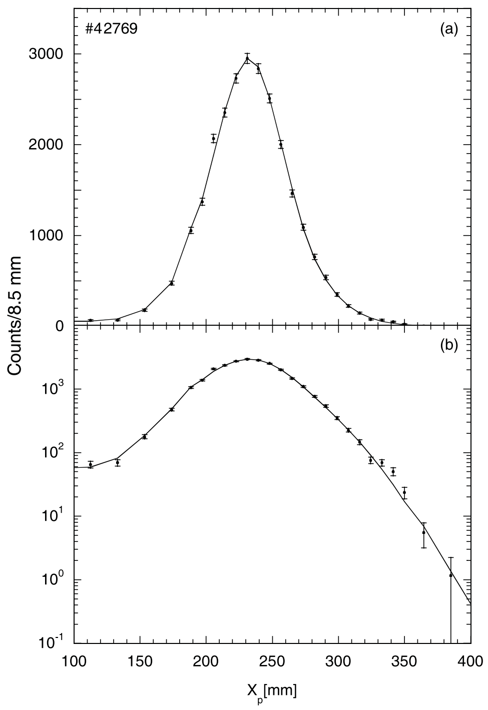

Fig. 2. Measured proton recoil histogram reflecting the spectrum of the neutron emission from the RF heated discharge JET #42769 plotted on (a) linear and (b) log scale; X_p is the position on the MPR focal plane detector having an energy dispersion of about 10 keV/mm. The full line is a fit to the data points using the model described in the text.

In the table are also shown the peak ion temperature measured by the CXRS diagnostic, the relative deuteron-triton density n_d/n_t and the plasma impurity index Z_{eff}.

The measured recoil proton histograms of the MPR spectrometer representing the spectra of the neutron emission from the RF and NB heated plasmas are presented in Figures 2 and 3. Here the flat region to the left (low energy) side is due to neutrons which have scattered in the plasma vessel or the neutron collimator before reaching the spectrometer. It is the peak and, especially, the high energy slope that is of direct diagnostic interest and reveals the differences that can be related to the ionic features of the RF and NB plasmas. The full line represents a fit to the data points using the model described and has a χ^2 value of 1.9 and 0.9 for discharges #42769 and #43134, respectively.

The measurement is well reproduced by the model with the neutron spectral components shown in Figures 4 and 5. In both cases the bulk component is dominant. It is a Gaussian whose amplitude and width are determined from the fit of the values given in Table 2; the width is expressed as a nominal ion temperature.

In the table, A_I and T_I represent the relative intensity and temperature of Ith component (I = B, HE), c_I^d the relative density of Ith deuteron component while ΔE is the energy shift of the peak of the neutron spectrum with respect its nominal value at 14.028 MeV.

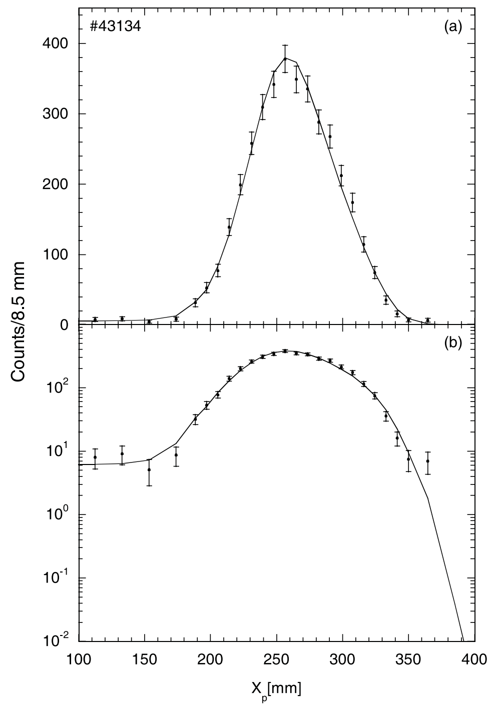

Fig. 3. Same as Figure 2 but for NB heated discharge JET #43134.

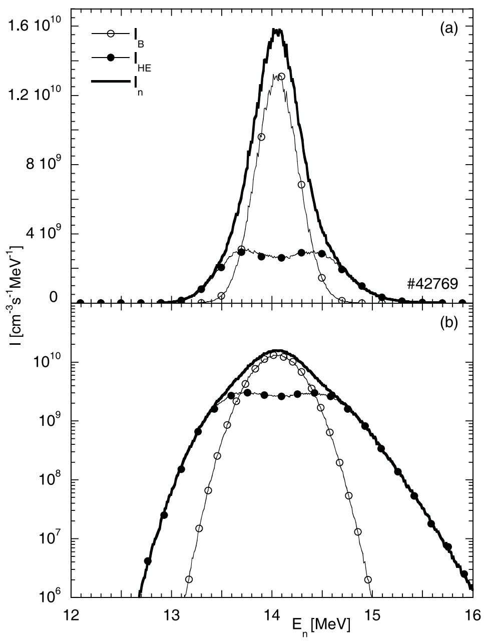

Fig. 4. The neutron spectrum and its B and HE components giving the best fit to measured spectrum of the neutron emission from the RF heated discharge JET #42769 in linear (a) and (b) log scale plots.

The spectral feature that is unique for the discharges is the HE component whose amplitude in the RF case is determined from the fit given the temperature of the high energy tail of the RF accelerated deuterons. The high energy deuteron distribution for NB plasma was fixed as

Table 2. NES spectral results for the selected JET DT plasma discharges.

Discharge (#)	P_{AUX}	A_B [%]	A_{HE} [%]	c_B^d [%]	c_{HE}^d [%]	T_B [keV]	T_{HE} [keV]	ΔE [keV]
42769	ICRH	63 ± 1	37 ± 1	17	1	8.0 ± 0.2	110 ± 4	59 ± 3
43134	NBI	73 ± 2	27 ± 2	84	6	15.4 ± 0.7		79 ± 7

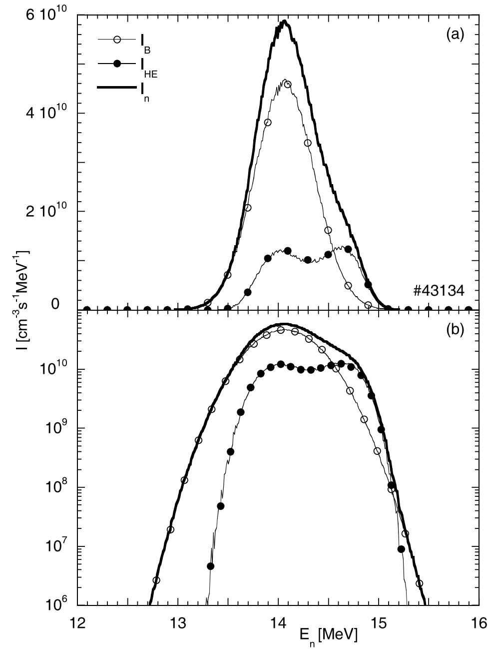

Fig. 5. Same as Figure 4 but for the NB heated discharge JET #43134.

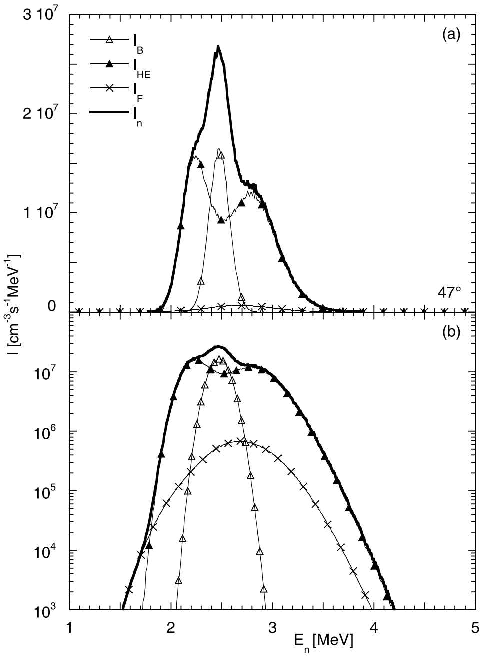

Fig. 6. The projected neutron spectrum for neutron emission from *dd* reactions in RF heated discharge of plasma conditions equivalent to those derived from neutron data for the DT discharge JET #42769 in (a) linear and (b) log scale plots; the bulk (I_B), high energy (I_{HE}) and fast (I_F) components are shown as well as the sum (I_n).

described above. Both spectra feature a HE component of double-humped shape which is Doppler shifted upwards in energy in the NB case due to the ion motion from the injection which is "counter" to the line of observation. In addition, the neutron emission from both the RF and NB plasmas required an overall energy shift (ΔE) as noted in Table 2 that is related to toroidal rotation. This is required to obtain good fit to the data.

From the intensity of the spectral components the relative density of the bulk and high energy deuterons is determined. The deuteron distribution is thus completely specified but for a global scale factor.

4 Projected neutron spectra for D plasmas

The spectra of the neutron emission from D plasmas were calculated on the assumption that the conditions were the same as for corresponding RF and NB plasmas of DT. We are not here concerned about how this would be achieved in practice. With the input of the relative concentrations of B and HE deuterons from Table 2, the B and HE components of *dd* reactions were calculated in the same way as for *dt*. However, an additional third fast (F) component was considered for *dd*, i.e., due to reactions between deuterons within the HE component of the deuteron population. Thus three components were used to project the 2.5-MeV neutron emission from D plasmas as being the equivalent of the 14-MeV spectrum from DT plasmas of the same conditions. The results on projected neutron spectra for the RF and NB cases are presented in Figures 6 and 7 while the numerical values for spectral amplitudes and temperatures are given in Table 3.

The main feature in the spectra of the *dd* reactions is the relatively greater importance of the supra-thermal component. It shows up more clearly than in the spectra of *dt* because it is relatively stronger, i.e., an increase from 37 to 73% for RF and from 27 to 41% for NB. In this context, the energy separation between the components is important for neutron emission from the plasma. On the scale of the thermal Doppler broadening, the energy separation of the components for *dd* is at least maintained relative to the situation for *dt*. These aspects together result in *dd* spectra with more distinct features then those of *dt* for similar plasma conditions. The spectra of the *dd* and *dt* neutron emission are very similarly related to each other independent of the heating applied. This suggests that the spectral differences noted are generic for *dd* and *dt* reactions. One feature that is unique to the neutron spectrum for the D plasmas is the finite fast component

Table 3. Spectral results for D plasma simulation.

Discharge (#)	θ_{view} [°]	P_{AUX}	A_B [%]	A_{HE} [%]	A_F [%]	c_B^d [%]	c_{HE}^d [%]
42 769	47	ICRH	24	73	3	96	4
42 769	90	ICRH	21	76	3	96	4
43 134	47	NBI	56	41	3	93	7
43 134	90	NBI	56	40	4	93	7

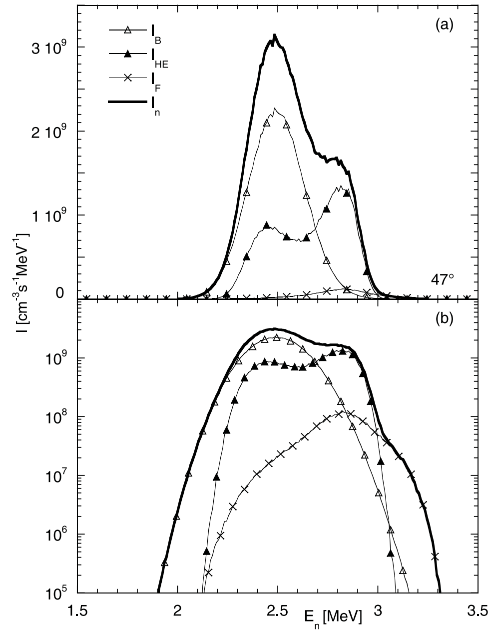

Fig. 7. The same as for Figure 6 but for an NB heated discharge.

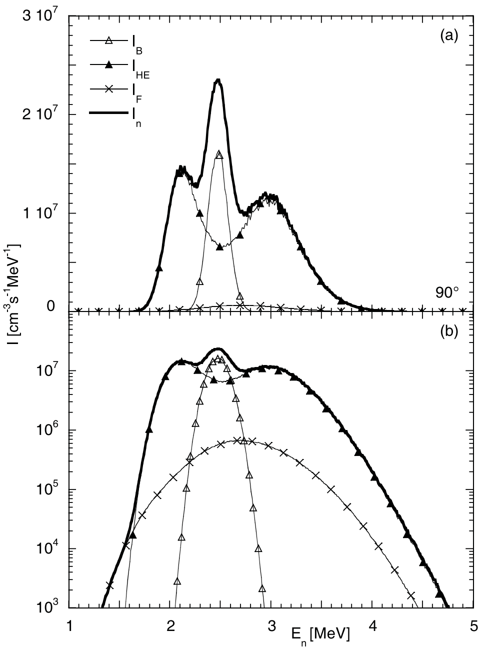

Fig. 8. Same as Figure 6 but for an angle of $\theta_{view} = 90°$ instead of $\theta_{view} = 47°$ (RF heated discharge).

at the few percent level. It leads to a slight modification of the total shape for RF plasma on the low energy side at the intensity level of 10^{-3} of the maximum. In the case of NB plasmas, the spectrum shape is affected by the fast component on the high energy side at the relative intensity level of 10^{-2}. This would be within reach of detectability, contrary to the situation for RF plasmas.

In future experiments at JET it will be possible to view the plasma at a viewing angle of $\theta_{view} = 90°$ to the magnetic field [10]. The differences between the 90° and 47° cases would derive from two factors. The Doppler shift in the neutron emission from reactions involving ions gyrating perpendicular to the magnetic field line will be greatest in the case of 90° viewing and decrease with decreasing angle as $\sin\theta_{view}$ so that it is reduced by a factor of 0.73 for $\theta_{view} = 47°$ [5] and nil for ion motion along the magnetic field line. The second factor derives from possible toroidal rotation.

These factors are indeed born out by the projections for *dd* neutron emission presented in Figures 8 and 9 for RF and NB heated plasmas, respectively. Specifically, the HE component stands out more clearly for the neutron emission from RF plasmas and the asymmetry of this component vanishes for NB plasmas. The conditions for detecting the fast component are much changed from the case of the 47° viewing.

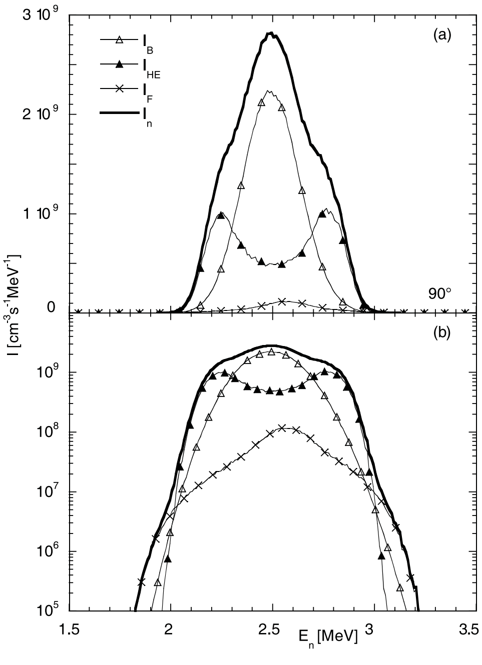

Fig. 9. Same as Figure 7 but for an angle of $\theta_{view} = 90°$ instead of $\theta_{view} = 47°$ (NB discharge).

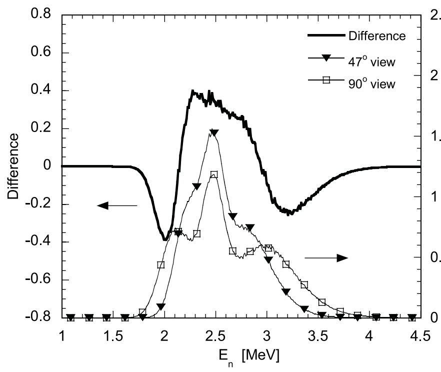

Fig. 10. Calculated difference spectrum for the 2.5-MeV neutron emission from D plasma subjected to ICRH derived from the results in Figures 6 and 8 representing observations at $\theta_{view} = 47°$ and $\theta_{view} = 90°$.

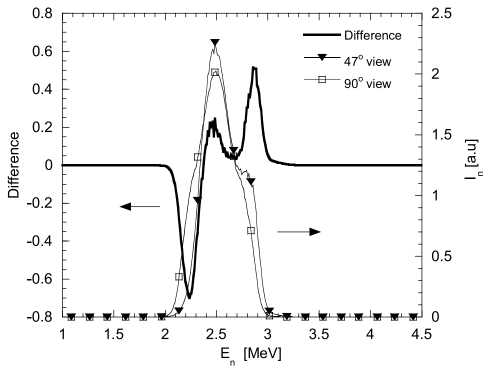

Fig. 11. Same as for Figure 10 but using the results in Figures 7 and 9 for a NB heated discharge.

In the future, vertical ($\theta_{view} = 90°$) measurement will be made with the new 2.5-MeV TOFOR neutron spectrometer [7]. The MPR viewing the plasma at $\theta_{view} = 47°$ will be upgraded (MPRu) [11] so it can be used to measure also 2.5-MeV neutrons. This opens up the capability to measure simultaneously the asymmetry effects in the neutron emission with respect the direction perpendicular (flux component $\phi_{\perp}$) and parallel ($\phi_{||}$) of the magnetic field besides the isotropic component (ϕ_o). From the planned measurements with the TOFOR and MPRu spectrometers at JET one can determine the measured spectral difference. The results on the projected measured difference for the RF and NB plasmas are shown in Figures 10 and 11.

5 Discussion and conclusion

The neutron emission spectra for the *dd* reactions for deuterium plasmas have been projected based on measured spectra for *dt* reactions in DT plasmas spectra. The comparison was based on the assumption that similar fuel ion velocity distributions are created with applied auxiliary heating in terms of neutral beam and radio frequency (ICRH) injection. The results show that energetic neutron spectral components are more easily separated from the bulk in *dd* reactions than in *dt*. This should make it somewhat easier to perform NES diagnoses of deuterium plasmas with regard to studying the creation of supra-thermal components in the fuel ion population due to auxiliary power injection. If the multiple sight line observation are available as will be the case at JET, this will render ever better possibilities of measuring supra-thermal fuel ion components in deuterium plasmas because of the unique signatures in the difference spectra connected with the anisotropy in the velocity components. The possibility for the advanced neutron emission spectrometry diagnosis of deuterium that will open up with the new Time-of-Flight spectrometer, can be expected to greatly promote the development in this diagnostic field and therefore important for the planning of the most central measurements in fusion burning plasmas.

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