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1. INTRODUCTION

Neutron Emission Spectroscopy (NES) measurements in plasmas subjected to ion cyclotron resonance heating (ICRH) were performed during the DT experimental campaign on JET (1997). A magnetic proton recoil (MPR) neutron spectrometer was used for the measurements, which provided high quality data for a broad range of plasma conditions [1]. This paper presents NES results from plasmas with fundamental minority heating schemes, (D)T and (T)D, as well as ICRH tuned to the second harmonic of tritons ($2\omega_{CT}$), see Table 1. The results illustrate the type of diagnostic information on energetic fuel ions that NES can provide.

The neutron emission spectrum arising from ICRH driven energetic ions is strongly anisotropic. Its shape depends on the viewing line angle (α) relative to the magnetic field. This is shown in a NES simulation of fusion reactions of monoenergetic deuterons with cold tritons (Fig. 1) where a pitch angle range 90°±10° was assumed for the deuterons. The spectral width is largest in the radial direction where the spectrum has a characteristic double-hump shape; this feature disappears for a tangential view. For an oblique view the spectral width scales roughly as $\sin\alpha$ [2]. The anisotropicity provides a distinct signature of the plasma response to ICRH power injection and can be measured with a neutron spectrometer of suitable measurement capabilities.

The NES analysis [2-3] is based on a model describing the neutron emission spectrum in terms of up to three components. These represent contributions from fuel ions of different velocity distributions for the species to which the ICRH is coupled; a thermal distribution is assumed for the other fuel ion species. The first NES component is due to reactions between thermal fuel ions (TH); the second component represents the interaction between anisotropic (pitch angle range 90°±10°) high-energy (HE) ions, driven by ICRH, and thermal ions. In some cases the data analysis showed that a third component is needed. This component, called epithermal (ET), represents the interaction between thermal ions and those fast ions which, having slowed down below their critical energy, have an average energy (effective temperature) that is higher than the bulk plasma. These ions are essentially isotropic, unlike the HE ones, which are strongly anisotropic. Often the TH and ET components are not distinguishable, in which case they have been lumped into a single component denoted as bulk (B). In the analysis, each NES component was assigned two free parameters, i.e amplitude and temperature (A_j and T_j for J = TH, ET, HE) which were determined from a best fit to the NES data. The results on A_j and T_j were taken one step further to derive the kinetic ion energy densities for each velocity distribution. Information on the toroidal rotation related to ICRH was also determined from the overall shift of the neutron spectrum.

This paper presents NES results from JET plasmas with fundamental minority heating schemes, (D)T and (T)D, as well as ICRH tuned to the second harmonic of tritons ($2\omega_{CT}$).

OBSERVATIONS OF ENERGETIC FUEL IONS

Four discharges have been selected here for illustration of NES results under different ICRH conditions (Table 1). The data were time integrated over the period when only ICRH was on, thus excluding any Neutral Beam (NB) effect. NES analysis of (D)T discharges benefits from the highest neutron yield rates (Y_n up to $5{\cdot}10^{17}$ s^{-1}) produced with ICRH [4]. The MPR count rate reached about 75kHz under those conditions hence ensuring good data quality (see Fig. 2). A detailed NES study [2], including some time resolved analysis [5], has been carried out for eight (D)T selected discharges. The main observation was that the discharges separate in two groups, depending on the deuterium concentration being high (c_d = 16-20%) or low (c_d = 9-13%); here $c_d = n_d/(n_H+n_d+n_t)$. These plasmas have a strong supra thermal neutron emission, which for the low c_d cases is dominant (A_{HE} = 40-60%); the corresponding deuteron tail temperature is in the range T_{HE} = 100-140keV where the highest T_{EH} and A_{HE} values were observed for the low-c_d plasmas. Bulk ion heating, on the other hand, is stronger for high c_d values, where T_{TH} reaches 8keV; this is a significant increase over the T_{TH} = 5keV observed for low c_d. The reason for this ion heating mechanism has not been completely understood yet, although NES results indicate that the transfer of power into the bulk ions is not via energetic deuterons [2, 6]. A further observation is the need for a three component NES model in the low c_d cases, an example of which is shown in Fig. 2b. In this particular example, T_{TH} was locked to the value obtained from Charge Exchange Recombination Spectroscopy diagnostic (CXRS). Note that T_{TH} is a line averaged value; comparison with CXRS has shown that the ion temperature value at the plasma centre is usually $T_i(0) \approx 1.2\text{-}1.3T_{TH}$ [2].

Examples of NES spectra for discharges with second harmonic tritium heating ($2w_{CT}$) in DT plasmas are shown in Fig. 3 and 4; in the latter case, ^{3}He was added to the plasma at the 10% level so that the main heating mechanism is fundamental ^{3}He minority heating, (^{3}He)DT. Both spectra allow for a two component NES analysis. In Fig. 3, T_{TH} is estimated to increase from T_{TH} = 2.3±1.1keV in the Ohmic phase of the discharge to T_{TH} = 4.70, 3keV when ICRH is applied; a HE component driven by ICRH is also observed. The latter has a high T_{HE} value, T_{HE} = 2.3±1.1keV, but relatively low intensity (A_{HE} = 9.5±0.7%). This is typical of heating at 2nd or higher harmonics, which is a Finite Larmor Radius (FLR) effect and hence accelerates a small number of particles to very high energies. As few as 1% of the tritons are responsible for the 10% HE component in Fig.3 thanks to the high T_{HE} value; even higher T_{HE} values (up to 400keV) have been observed with this type of heating. At these temperatures the triton slowing down is dominated by electron collisions, resulting in strong electron heating (central electron temperature up to T_e = 10keV have been measured). The example of Fig. 3 illustrates how NES can successfully diagnose energetic fuel ions of intensity at the percent level. This is mainly due to the favourable energy dependence of the fusion reactivity. For instance, the reactivity between a 200keV triton beam in a deuteron plasma of T_d = 5keV is about 65 times higher than the reactivity of equal temperature tritons and deuterons of $T_d = T_t$ = 5keV. In order to fully exploit the potential of NES as a diagnostic of energetic fuel ions, suitable neutron spectrometry systems are required of which the MPR is a prototypical example [1].

The main effect of ^{3}He added to the plasma (Fig. 4) is a T_{TH} increase. The fitted value of T_{TH} = 7.5±0.2keV is representative of a time averaged value over the ICRH period. Time resolved analysis provides values up to T_{TH} = 10.9±0.5keV. This can be explained by the ion heating effect of minority ^{3}He ions as they slow down below their critical energy. More surprising is the relatively strong high-energy tail of the neutron spectrum. This is tentatively attributed here to a population of energetic tritons with T_{HE} = 136±10keV. Previous analyses based on of data from a low count rate spectrometer [7] did not take this observation into account. With low count rate statistics it is impossible to discern the high energy tail of Fig. 4; hence the neutron emission was assumed to be thermal which led to the erroneous determination of T_{TH} illustrated by the TH' fit in Fig. 4.

As a final example, Fig. 5 shows a neutron spectrum recorded with (T)D heating. These plasmas have a low ion temperature value (T_i<3keV [4]). Most of the neutron yield is due to energetic tritons reacting with thermal deuterons. The available data, despite the modest statistics typical of these low neutron yield discharges, can be interpreted in terms of a triton HE component of T_{HE} = 76±7keV and a bulk component of TB = 5.9±1.0keV. The bulk temperature is higher than T_i, indicating that some epithermal tritons must be present that have slowed down below their critical energy (E_c = 45keV).

CONCLUSIONS

Neutron emission spectroscopy (NES) as a diagnostic of energetic fuel ions is illustrated here by the observations made with the MPR neutron spectrometer on JET DT plasmas with powerful ion cyclotron resonance heating. The results presented include NES measurements in plasmas with fundamental minority heating schemes, (D)T and (T)D, as well as ICRH tuned to the second harmonic frequency of tritons ($2\omega_{CT}$). These provided energetic fuel components of different intensity and temperature. A simple NES model has been used for the analysis with up to three spectral components from thermal (TH), epithermal (ET) and high-energy (HE) fuel ion populations. The model provides an adequate description of the data. Among the fitted parameters, of particular interest here are the intensity and temperature of the high-energy components. The examples provided in this paper illustrate the kind of information on energetic ion populations in the plasma that can be obtained with high accuracy NES measurements.

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Symbol	Heating Scheme	JET Discharge Number
(D)T	1st Harmonic Resonance on Minority Deuterium in a Tritium Plasma	42792
(T)D	1st Harmonic Resonance on Minority Tritium in a Deuterium Plasma	43057
$2\omega_{CT}$	2nd Harmonic Resonance on Tritium in a DT Plasma	42753
(^{3}He)DT	1st Harmonic Resonance on Minority ^{3}He in a DT Plasma	42755

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Table 1: Summary of the JET discharges studied

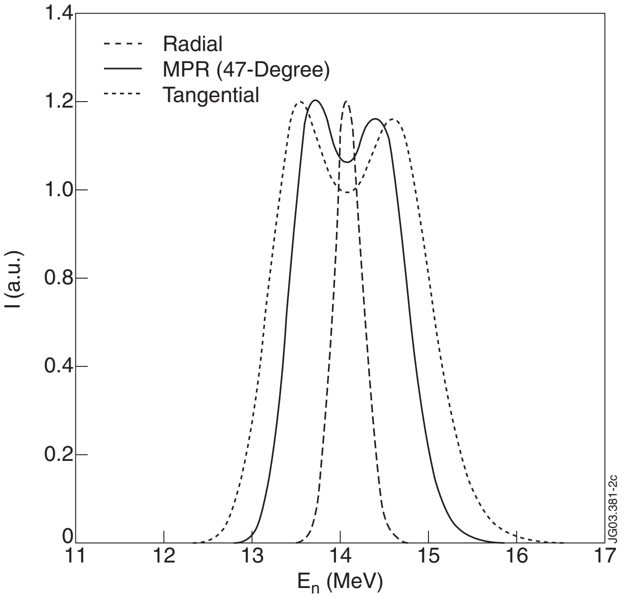

Figure 1: Simulated neutron energy spectra from, anisotropic deuterons of T_{HE} = 140keV reacting with bulk tritons of T_B = 5keV for radial, oblique and tangential viewing lines. The peak intensities of the spectra are normalised to unit

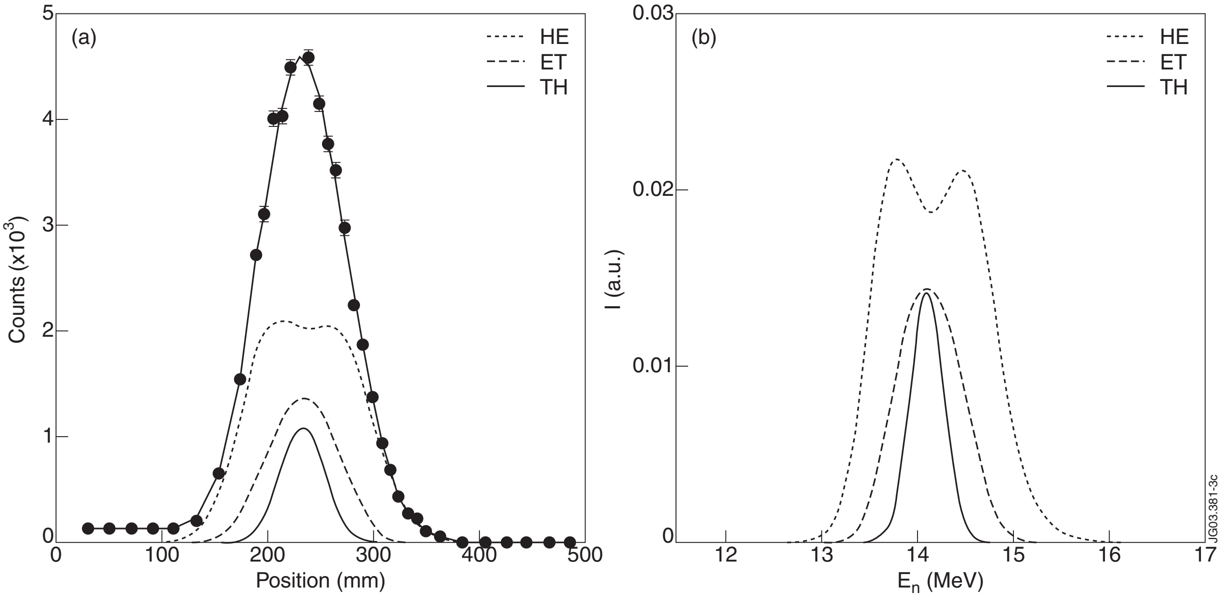

Figure 2: (a) Measured proton recoil spectrum for JET Pulse No: 42792, time integrated with exclusion of the periods when NB blips were applied. The position along the hodoscope (x axis) is approximately proportional to the neutron energy. The solid line is the best fit to the data using a model with three components (TH, ET and HE, see text). (b) NES components for the fit in (a). The fitted parameters are T_{TH} = 5.5keV (locked), T_{ET} = 24 ±1keV, T_{HE} = 140 ±2keV, A_{TH} = 10 ±1%, A_{TH} = 32 ±1% and A_{HE} = 58 ±0.3%.

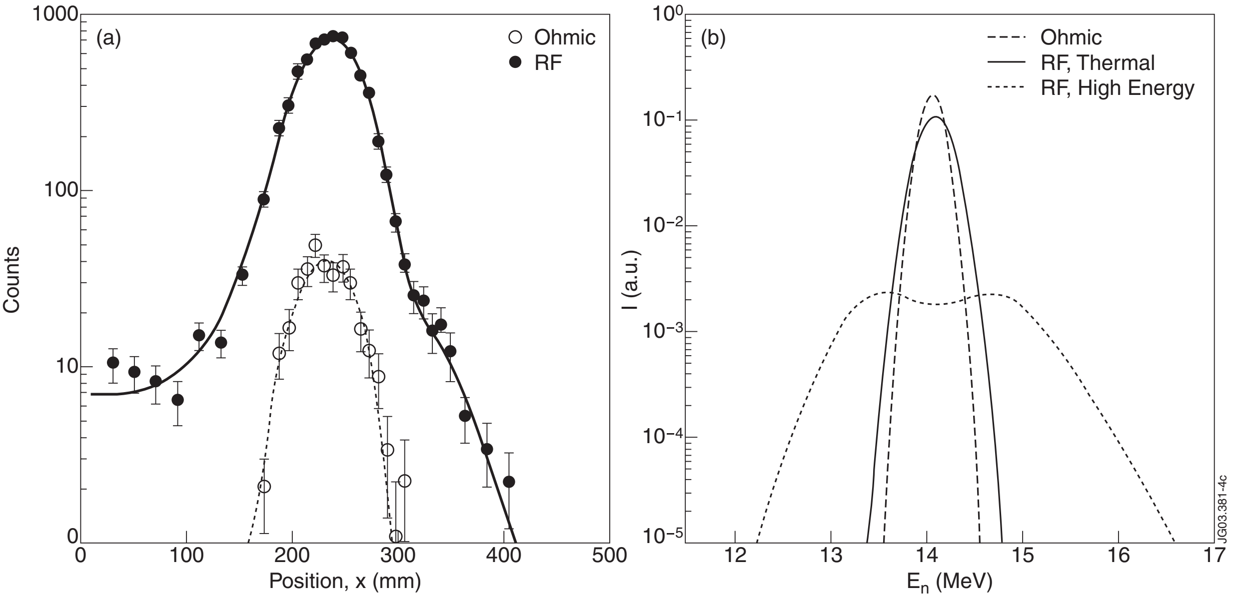

Figure 3: (a) Measured proton recoil spectra for JET Pulse No: 42753 collected during the Ohmic period and when ICRH was applied. Also shown are best fits to the data using a model with two (TH and HE) and one component (TH). (b) NES components for the fit in (a). The fitted parameters are $T_{TH} = 2.3 \pm 1.1$keV for the Ohmic spectrum, and $T_{TH} = 4.7 \pm 0.3$keV, $T_{HE} = 218 \pm 37$keV, $A_{TH} = 90.5 \pm 1.8$ and $A_{HE} = 9.5 \pm 0.7$% for the ICRH spectrum.

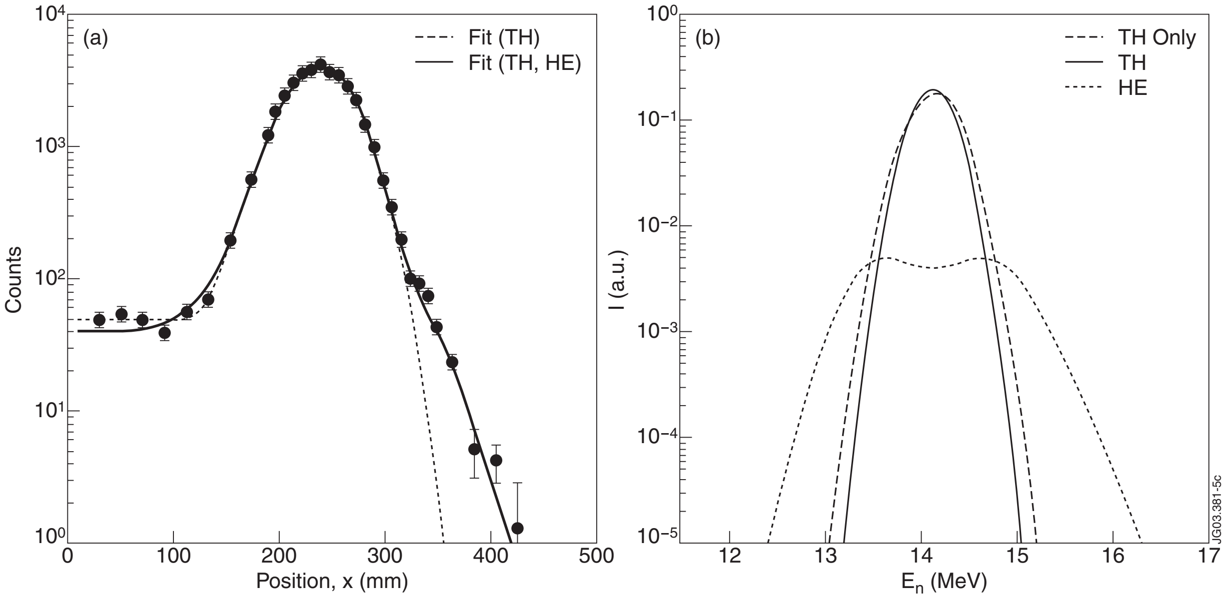

Figure 4: (a) Measured proton recoil spectrum for the ICRH phase of JET discharge #42755. The solid and dashed lines are best fits to the data using a model with two (TH and HE) and one (TH') component, respectively. (b) NES components for the fit in (a). The fitted parameters are $T_{TH} = 7.5 \pm 0.2$keV, $T_{HE} = 136 \pm 10$keV, $A_{HE} = 8.2 \pm 0.3$%, and $T_{TH'} = 10.4 \pm 0.2$keV.

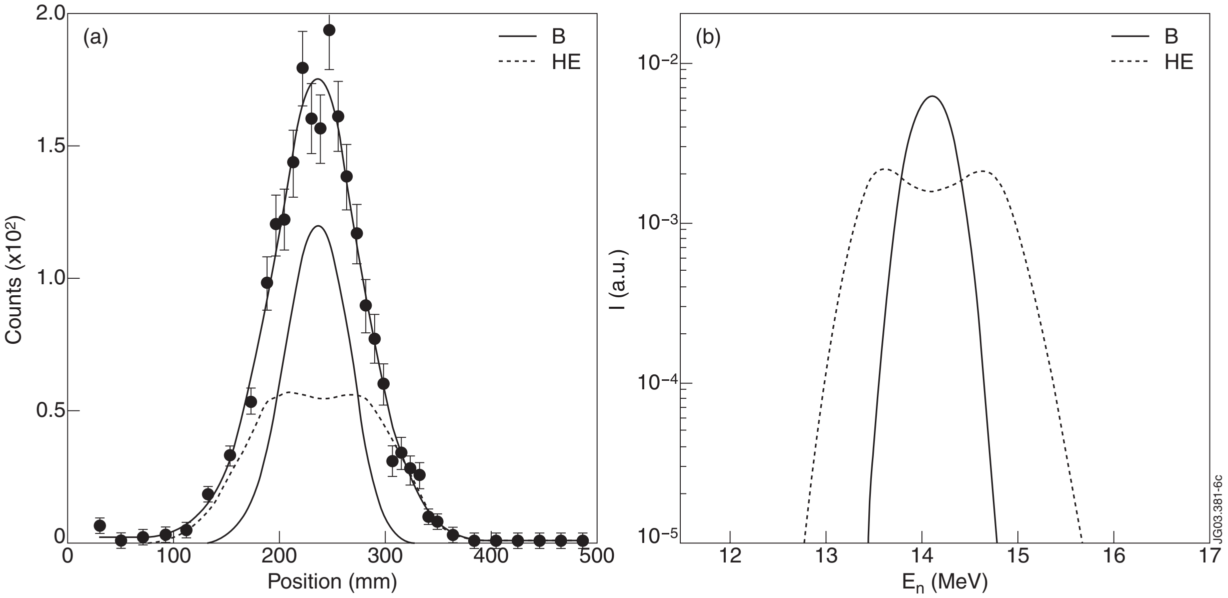

Figure 5: (a) Measured proton recoil spectrum for JET (T)D Pulse No: 43057, time integrated with exclusion of the periods when NB blips were applied. The solid line is the best fit to the data using a model with two components (B and HE). (b) NES components for the fit in (a). The fitted parameters are T_B = 5.9±1.0keV, T_{HE} = 76±7keùV, A_B = 45±2% and A_{HE} = 55±3%.