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Neutron emission spectroscopy of fuel ion rotation and fusion power components demonstrated in the trace tritium experiments at JET

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Introduction

Neutron emission spectroscopy (NES) has been used to study JET plasmas produced with auxiliary power (P_{AUX}) during the recent trace tritium experiments (TTE of October 2003), as well as the main deuterium-tritium experiments (DTE1 of 1997). The spectrum of the neutron emission from d+t→α+n reactions was measured with the magnetic proton recoil (MPR) neutron spectrometer [1]. The recorded spectra were analysed as a superposition of several contributions related to different velocity components of the fuel ion populations perturbed by P_{AUX}. Information was derived on the kinetic states of the fuel ion populations, such as temperatures and relative fractions of thermal and supra-thermal reactions. In addition, the collective states of the fuel ions, such as toroidal rotation were also measured. Moreover, the MPR count rate was used to determine the total neutron rate, $Y_n(t)$, taking into account neutron emission effects as explained in an accompanying paper [2]. While the DTE1 data were subjected to post mortem analysis, the TTE data were analyzed between discharges during the on-going campaign so that direct input could be given to the evolving experimental program on a shot-by-shot basis.

Experimental

The MPR records the neutron spectrum as a spatially dispersed distribution of recoil protons, registered by an array of plastic scintillators as a position histogram, $H_p(X)$. $H_p(X)$ is related to the spectrum of the incoming neutron flux, $F_n(E_n)$, through the well known spectrometer response function of the MPR [1]. A calculated $F_n(E_n)$, folded with the response function, that leads to the best fit to the data is determined as representing the actual neutron emission spectrum. The measured proton histograms are determined with high accuracy on an absolute scale [3]. The uncertainty is mostly determined by measurement statistics, which preclude time dependent studies during TTE.

The TTE discharges studied here were those with ion cyclotron resonance heating (ICRH) and neutral beam (NB) heating of either deuteron or triton beams (NB_D and NB_T, respectively) or both. In JET discharge #61065, 5 mg of tritium gas was introduced during NB_D. The JET discharges, JET #61150 and #61151, were subject to NB_D heating, with NB_T injected on- and off axis, respectively. Two ICRH schemes at low tritium concentration have been investigated in the TTE, namely fundamental heating (ω_{CT}) and second harmonic ($2\omega_{CT}$) heating. For this study we have selected three ω_{CT} discharges with different phasing of the ICRH antennae. In ICRH scenarios, the key observable is the high-energy (HE) tail that can be found in the neutron spectrum as a direct evidence of the ICRH effects on fuel ions [3]. Other supra-thermal spectral components due to the involved reactions with NB injected ions can be seen in the neutron spectra; even reactions in different ion orbits can be distinguished [4].

Results

NB_D heated deuterium plasmas with puffing of tritium gas show a much slower response than for plasmas with short NB_T blips, as reflected in $Y_n(t)$ measured with the MPR [2] shown in Figure 1a and b; JET discharge #61065 (a) is compared with #61150 and #61151 (b). Here it can be seen how $Y_n(t)$ peaks about 0.5 s after the tritium gas puff (at t=22.5 s), while the time response is immediate for the NB_T blip (at t=8.5 s) and the decrease after 2 s is a factor of four in the first case, and almost two orders of magnitude for the NB_T discharges.

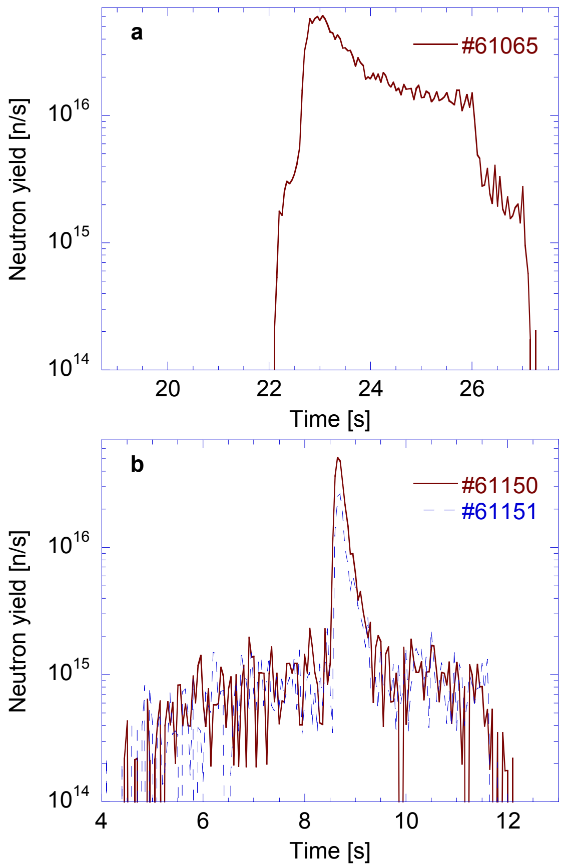

Figure 1. Neutron yields derived from MPR data for JET discharges #61065 (a), #61150 (b, solid line) and #61151 (b, dashed line).

Y_n is a factor of two lower for the NB_T off-axis case as compared to the on-axis one (Figure 1b), indicating better power coupling; it is not a neutron emission profile effect, as this has been factored in, in the yield calculation [2].

The spectral results for the above discharges are shown in Figure 2. The analysis of the gas-puff and NB_D discharge (#61065) shows that the temperature for the thermal (TH) component of the fuel ion populations is 2.9 keV (cf. Figure 2a) at the time of the gas puff, and increases to 5.1 keV at *t*≈24 s. The bulk temperature (spectral width) for the discharge is 10.3±0.5 keV. This could be compared with the bulk temperatures derived for the NB_T discharges, showing higher values for the on- and off-axis cases (cf. Figure 2b) with 16±1 keV and 13±1 keV, respectively during the period of peak emissivity (t≈8.6 s in Figure 1b).

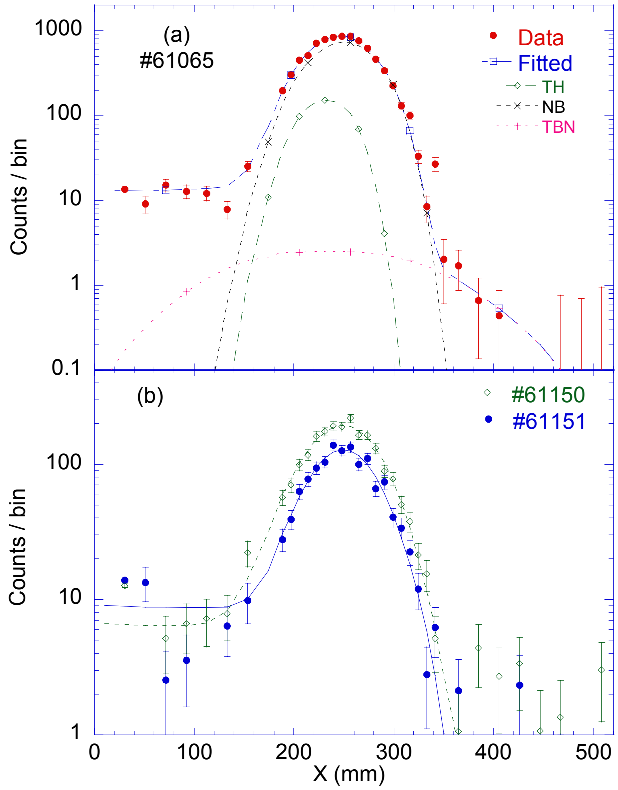

Figure 2. MPR proton position histograms (dots) of the NB_D discharge #61065 (top panel) and the NB_T discharges #61150 and #61151 (lower panel) together with best fits to data (dashed lines).

A component analysis describing the TH as well as NB heated ion populations indicates that the TH component contributes about 15±2 % of the total dt-fusion power at t≈23 s of the NB_D discharge, which increases to 40±2 % at t≈24 s; a weak component due to triton burn-up neutrons (TBN) can also be seen (Figure 2a). The two NB_T discharges differ in that the TH fraction is 3 times higher for the on-axis compared to the off-axis case, the latter being at the 10 % level. The toroidal rotation is found to be the same within the errors (v_{tor}=317±30 km/s compared to v_{tor}=350±30 km/s, respectively) for the NB_T discharges, while it is lower for the NB_D discharge, with an increase from 0±20 km/s to 95 ±17 km/s between t≈23 s and t≈24 s.

Among the studied ICRH discharges we focus on the NES results obtained on toroidal rotation of the fuel ion population receiving ICRH power under different phasings of the antenna, namely, dipole phasing (JET#61271), +90^o (JET#61451) and –90^o (JET#61557)

[5]. The results of the measured neutron spectra for these cases show a clear energy shift that is correlated with the antenna phase changes (Figure 3). When converting the observed energy shifts to toroidal rotations we find it to be 300 km/s for 90^o phasing with a change in direction from being co plasma current for +90^o, to counter for -90^o. With a dipole antenna, there was little or no indication of a plasma rotation. The actual values obtained were +309±8 km/s, -279±41 km/s and +57±41 km/s respectively. These results represent the first direct experimental observation of the correlation of the fuel ion toroidal velocity to the applied external momentum through ICRH. The relative fraction of the HE contribution due to ICRH [3] was 70-80 % with a temperature of about 110±10 keV for all three cases, indicating that a supra-thermal T ion population is created in the plasma as a consequence of the ICRH coupling, and reactions of those T ions with the bulk deuterium dominates the neutron emissivity.

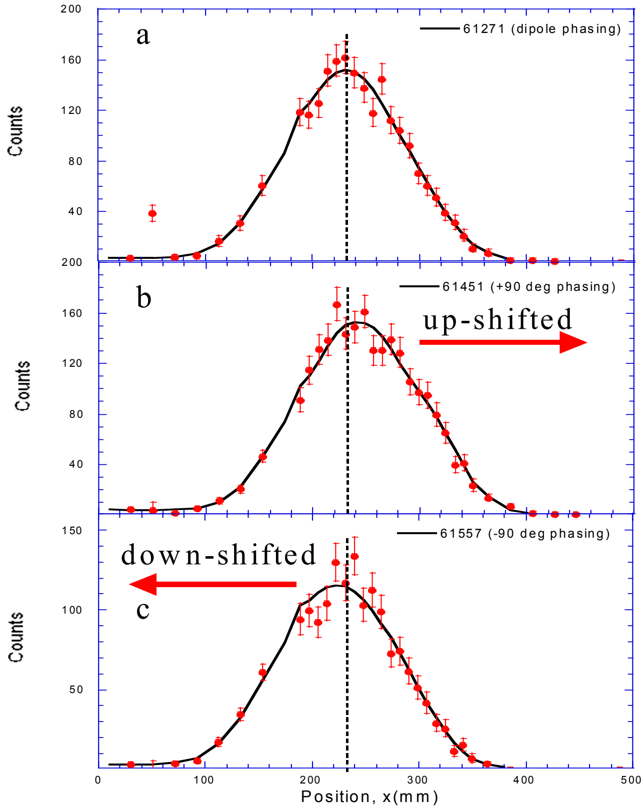

Figure 3. MPR proton position histograms for three ICRH discharges with different phasings of the antenna, namely, dipole (a), +90^o (b) and -90^o (c).

Conclusion

TTE discharges have been diagnosed with neutron emission spectroscopy where, for the first time, information could be provided on a shot-by-shot basis. Effects of D and T neutral beams were studied and the dependence on the type of fueling (gas-puffing or by NB_T) carefully investigated, as an extension to the DTE1 analysis. On-line data analysis provided for the first time the temperatures of the heated T population as well as the evidence of a clear correlation between antenna phasing and fuel ion rotation during ICRH reported here.

References

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