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Neutron Spectrometry for D–T Plasmas in JET, using a Tandem Annular-Radiator Proton-Recoil Spectrometer

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ABSTRACT

A selection of the 14-MeV neutron spectra obtained at the JET Joint Undertaking tokamak during the deuterium-tritium operating campaign in 1997 are presented and analyzed. While several neutron spectrometers were operational during this campaign, the present paper is concerned solely with one: the tandem annular-radiator proton-recoil spectrometer (or proton recoil telescope, for brevity). During neutral beam heating with combined *d* and *t* beams, analysis of the spectra can define the core fuel composition (*D:T*) ratio. The spectra are sensitive to the population balance of the fast ions streaming in directions parallel and opposite to that of the injected beams. During ICRF heating of minority deuterium in bulk tritium plasmas, the spectra provide measurements of the effective temperature of the fast-deuteron energy tail and of its relative strength, which vary with the deuterium concentration. This information contributes to the overall understanding of the fusion performance of the various operating scenarios.

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INTRODUCTION

Neutron spectrometry can be used as a tool in fusion plasma research for obtaining important information on the fuel ion composition and velocity distributions. The different techniques used for plasma heating in tokamaks result in a complex superposition of plasma components and their velocity distributions that change during a discharge but which should be engineered for optimum performance. The present paper presents analyses of some specific 14-MeV neutron spectra that were recorded with a proton recoil telescope spectrometer during the 1997 deuterium-tritium campaign (DTE1) at the Joint European Torus (JET). Neutral beam and RF ion resonance plasma heating were employed for these discharges.

EXPERIMENT AND DATA ANALYSIS

The spectrometer consists of three independent modules, set one behind the other (i.e. in tandem). Each module has its own polyethylene radiator and silicon surface barrier detector to capture the recoil protons. The spectrometer views the plasma through an annular collimator having a geometry that permits the detectors to hide behind a central shadow bar. The spectrometer line-of-sight lies in a horizontal plane 135 mm above midplane of the JET vacuum vessel and subtends an angle of 52° to the toroidal field lines in the centre of the plasma column. (Because the d-t campaign was carried out with a divertor in place, the plasma axis was about 300 mm above the midplane of the vacuum vessel). The construction of the telescope is such as to provide neutron measurements at relatively high count-rates, with rather low backgrounds and without apparent degradation of the theoretical energy resolution of 2.2%. A general description of the spectrometer has been reported in [1] and some further details are presented in [2].

The data analysis is based on a comparison of experimental neutron spectra with theoretical spectra calculated by means of the Monte Carlo kinematics code FPS [3]. This code calculates fusion product spectra for specific plasma parameters and conditions.

There are two general mechanisms of neutron production in JET plasmas: thermonuclear fusion and beam-plasma interactions. A typical *D*-T neutron energy spectrum contains a number of discrete contributions, having broadly similar shapes. Except in particularly favourable circumstances, it is impossible to unfold these contributions without having recourse to prior knowledge. Consequently, the analysis approach adopted is to utilise all relevant diagnostic information in a calculation of the neutron emission. This calculation, described below, identifies the individual contributing processes and provides their absolute contributions to the total neutron emission strength. Next, using FPS, the necessary kinematics calculations to obtain the shapes of the contributions to the neutron spectrum are performed and these are then weighted according to the previous calculations and summed for comparison with experiment. The calculated spectrum should adequately fit the measured spectrum, with only the precise value of the overall normalisation factor to be determined empirically. However, improved representations can usually be obtained by adjusting the key quantities through a least-squares fitting procedure.

The calculation of the expected neutron emission from a plasma discharge is not a trivial matter. First, the data from the neutron profile monitor [4] were used to obtain the position of the centre of the neutron emission and the form of the neutron emissivity radial profile, using a simple geometry based on a system of nested ellipses. To reduce the spectrum analysis procedure to manageable proportions, the neutron emission is next re-modelled using just two volumes [5], consisting of core and peripheral regions, in which about two-thirds of the emission is generated within the core. A pre-processor code is then used to derive the appropriately averaged parameters (density, ion and electron temperature, rotation rate, impurity and fuel concentrations, etc) for these two volumes, ensuring conservation of particle numbers, energy and momentum. Finally, the neutron emission is calculated for both volumes. When needed, the calculation can be re-run to determine separately the $T(d,n)^4He$ and $D(t,n)^4He$ contributions, and to investigate the relative importance of the different energy components of each beam (full, half and 1/3 energy components). Because the fuel concentration ratio may vary with plasma radius, it is also necessary to perform a first-order transport calculation to determine the *D:*T fuel concentration in the plasma core, starting with measurements of the (recycling) gas fuelling ratio measured outside the plasma periphery. This involves a momentum conservation calculation that is required to reproduce precisely the measured rotation rates. Adjustment of two normalization constants (one for each volume) then permits the calculation to reproduce approximately the measured ion and electron temperatures, when the fuel transport calculation can be considered reliable. As a further check, the calculated and measured total neutron yields and the emission profiles should agree within experimental errors.

The above computational procedure predicts the relative proportions of co/counter passing fast beam ions from the beam injection geometry and the particle deposition profile, as is appropriate for the injected ions after the moment of ionization. However, as the ions slow down they may suffer pitch-angle scattering and cross-field diffusion and thus change from co-passing to counter-passing and vice versa. Of course, a particle that never becomes trapped is always co-passing. But once a particle becomes trapped, on average it will thereafter spend equal times in co- and counter-passing directions, even if it subsequently becomes de-trapped. For the total neutron yield to be interpreted accurately in the case of rapidly rotating plasmas, a knowledge of the co/counter-passing ratio is needed. This can be derived from examination of the neutron spectra.

The predictive approach is much more difficult for ICRF heating. However, the neutron measurements are sufficient to provide a general interpretation of the effectiveness of the RF heating and fast-particle acceleration if an iterative approach is pursued. The fast ion energy tail is assumed to take a Maxwellian form.

For the present work, the neutron spectra have been calculated as if the whole neutron emission is concentrated in the core, which is reasonable since the thermal emission from the peripheral volume is relatively weak and the beam-plasma spectrum shapes for core and periphery are very similar. Two-volume spectrum calculations have been performed but show little if any improvement over the single volume calculation. For beam-heated plasmas, the plasma rotation rates have to be taken into account.

RESULTS

Exceptional examples of the sensitivity of neutron spectra to fuel ion mixture are presented in figs 1 and 2. In both cases, tritium beams were used for plasma heating. The spectrum for discharge 41600 (a low-temperature H-mode discharge) shows that the 155-keV tritium beam produces the two differently directed components while slowing down in plasma, with a co- to counter-passing ratio of 3:1, as predicted. By way of contrast, shot 42780 is an example of the fast ion distribution in the core having become effectively isotropic, contrary to expectations. In this case, the plasma was exceptionally dense but with somewhat higher temperature than for shot 41600. These results, along with those for the other discharges, are summarized in Table I.

The spectrometer can define the core fuel composition ratio for combined d and *t* neutral beam heating because the spectrum width from d-beams is appreciably smaller than for t-beams. Fig.3 shows the best fit obtained for the neutron spectrum corresponding to discharge 43005, for which the plasma was 85% tritium. Accordingly, the spectrum shows the principal contribution to the neutron yield to be from the d-beams (67±17%). The yields from the *t* -beam and thermal fusion are 17±6% and 16±6%. The co/counter-passing ratio for the *d* - and *t* -beams are both 4:1, as expected.

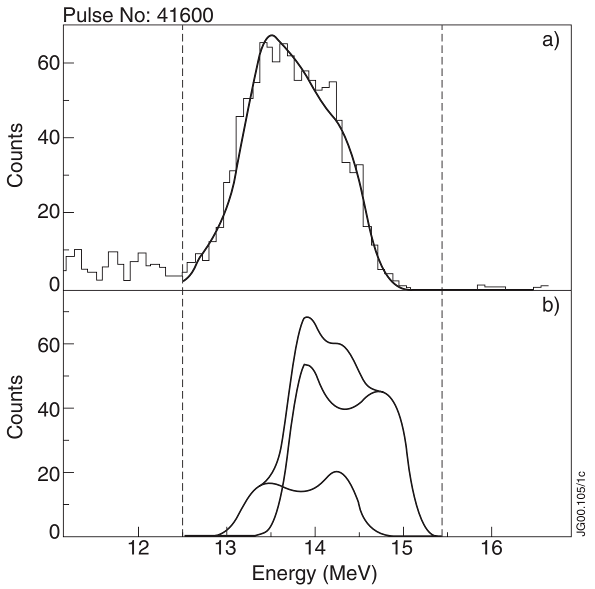

Fig.1: Fit to spectrum for discharge number 41600, recorded during interval 17.5-20.25 s. a): the calculated total neutron spectrum has been folded with the spectrometer response function for comparison with the recorded recoil proton data. Vertical axis is in counts per 80-keV bin. b): two calculated components of the beam-plasma neutron spectra and their sum. The 155-keV tritium beam produces co- and counter-passing components in the proportion 3:1. The thermal contribution is negligible.

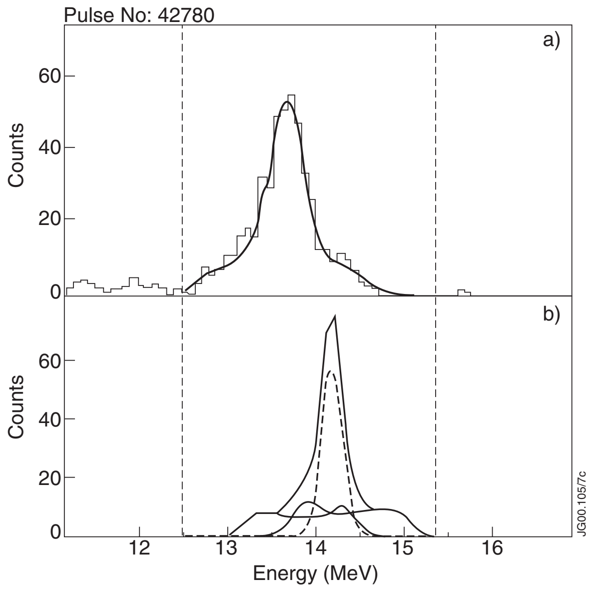

Fig.2: As in fig.1, but for discharge 42780, recorded during interval 16.5-18.25 s. The tritium beam produces nearly isotropic fast ion distributions (co:counter ratio of 1.3±0.3) while slowing down in dense plasma. The thermal contribution (dashed line) is 45±10%, at a temperature of about 4 keV.

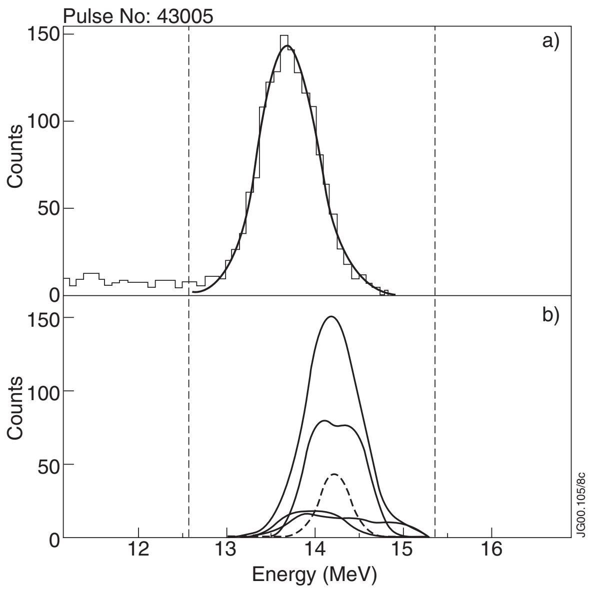

Fig.3: As in fig.1 , but for the almost pure tritium discharge 43005 with combined d and t *neutral beam heating, recorded during interval 17.75-21.50 s. The neutron spectra in (b) are the principal fusion contributions:* d *-beam (67%),* t *-beam (17%) and thermal (dashed line) 16% .*

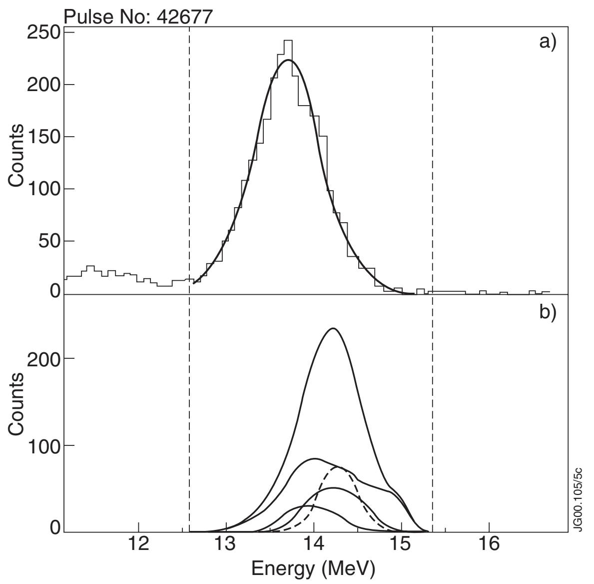

Fig.4:As in fig.1, but for the 35%-tritium discharge 42677 with combined d and t *neutral beam heating, recorded during interval 13.0-13.5 s. The neutron spectrum (b) shows the principal fusion contributions:* d *-beam (25±10%),* t *-beam (45±5%) and thermal (dashed line) (30±10%).*

In ordinary discharges with approximately equal *D:*T fuel concentration in the plasma core, the neutron spectra properly reflect both beam-plasma and thermal neutron emission but, understandably, the sensitivity to the plasma parameters can be poor. Fig.4 presents the best fit obtained for discharge 42677 for which the tritium concentration was about 40%. The analysis provides a thermal neutron yield contribution of 30±10%, while the yields produced by d- and t-beams are 25±10% and 45±5%, respectively. The co/counter-passing ratio obtained for the d-beam is 2.0 ± 0.4, rather smaller than the expected ratio of 3.2.

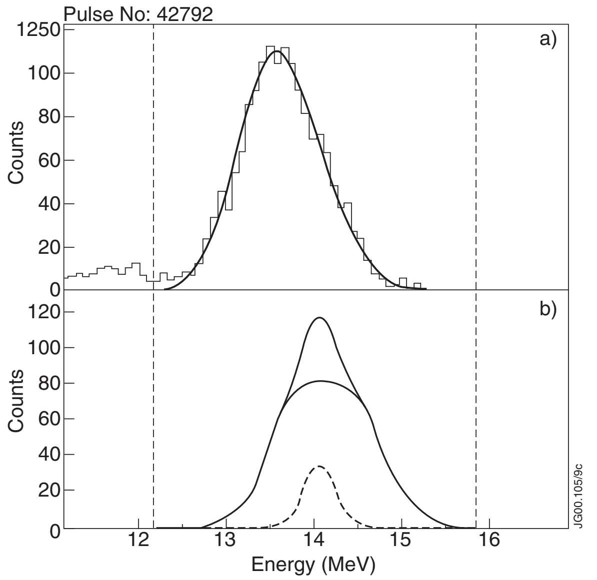

Fig.5: As in fig.1, but for tritium discharge 42792 with ICRH with 9% deuterium minority, recorded during interval 15.50-17.25 s. The perpendicular temperature component is $T_\perp$*=120±20 keV, while the thermal contribution (dashed line) is 10±5% at temperature 5 keV.*

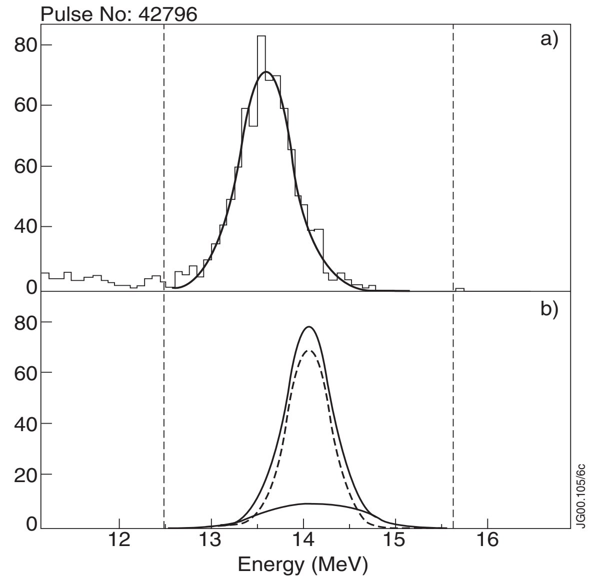

Fig.6: As in fig.1, but for tritium discharge 42769 with ICRH at 18% deuterium concentration, recorded during interval 15.75-17.75 s. The shot exhibited weaker coupling to deuterium ions with $T_\perp$*=80±20 keV and a high thermal contribution (dashed line) of 78±8% at temperature 10±2 keV.*

Interesting results were obtained from neutron spectra recorded in discharges with RF ion resonance heating of plasma, during a search for optimal fusion reactivity with the RF tuned to hydrogen (deuterium at second harmonic). Figures 5 and 6 show the spectra and best fits that permit an investigation of the heating effectiveness at different concentrations of the deuterium minority in the plasma. It can be seen that in shot 42792 (fig.5), performed at nominally 10% deuterium, the RF energy is strongly coupled to deuterium ions and the perpendicular temperature component, $T_\perp$, is about 120 keV, whereas the thermal contribution is around 5 keV. In contrast, discharge 42769 (fig. 6), with a higher deuterium minority concentration of about 20%, exhibited weaker coupling to deuterium ions with $T_\perp \approx 80$ keV, while the thermal temperature rose to 10 keV. The RF power fractions contributing to the high-energy tails are estimated to be 50% and 10%, respectively.

Table I: Deductions from neutron spectrum analysis

Shot number	Beam/ RF	Plasma mixtures	<Ti> keV	Thermal fraction %	Co/Counter Ratio		RF power fraction to fast tail & $T_{\perp}$ (keV)
					Spectrum	Prediction	
41600	t	95% D : 5% T	2	< 4	2.9 ± 0.2	3.2	-
42780	t	20% D: 80% T	4	45 ± 10	1.3 ± 0.3	2.5	-
43005	d + t	15% D: 85% T	5	16 ± 6	4.3 ± 0.7	4.1	-
42677	d + t	60% D: 40% T	14	30 ± 10	2.0 ± 0.4	3.2	-
42792	RF(d)	15% D: 85% T	5	10 ± 5	-	-	50% & 120 ± 20
42769	RF(d)	25% D: 75% T	10	70 ± 10	-	-	10% & 80 ± 20

CONCLUSIONS

Analyses of the neutron spectrometer results provide information concerning the ion velocity distributions in the plasma core. The fuel composition ratio is determined in the case of combined d and t neutral beam heating, as is the relative population of fast ions streaming in directions parallel and opposite to that of the injected beams. The neutron spectra also help define a suitable deuterium (minority) composition for optimal fusion reactivity using RF heating of tritium discharges.

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