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Neutron Spectroscopy at JET (1983 – 1999)

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Neutron Spectroscopy at JET (1983 – 1999)

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ABSTRACT

An account is given of the neutron spectrometric measurements on tokamak plasmas that have been performed at the JET Joint Undertaking. The original restrictions for physical access to the tokamak and the performance projections are described. The actual characteristics of JET plasmas as intense but highly transient sources of neutrons are then presented. Next, the various neutron spectrometers that have been deployed at JET are listed and their success in meeting the demands of the JET experiment is appraised. Finally, there is a discussion of the plasma physics considerations that determine the detailed shapes of the d-d and d-t spectral lines under the various plasma conditions and spectrometer viewing directions and of the results obtained.

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INTRODUCTION

In the present paper we are exclusively concerned with the application of neutron spectrometers for diagnostic purposes in the Joint European Torus (JET), during the lifetime of the JET Joint Undertaking. An early account of neutron spectrometry at JET is included in the review article [1]. The design, construction, installation and operation of the range of spectrometers deployed at JET have involved the efforts of a very large number of people over many years. The analysis of the measurements obtained is still not complete. This paper will attempt to indicate the extent to which these efforts have been worthwhile.

It might be thought that the main purpose of neutron spectrometry is to determine the ion temperature of the plasma [2]. However, whether this is possible or not depends on the means employed for heating the plasma. Nevertheless, even when a temperature determination is not possible, the measurements can still be very informative for other purposes

ACCESS TO JET FOR DIAGNOSTIC MEASUREMENTS

At the diagnostic design stage (1979 - 1985), the diagnostics were required to be located outside the biological shielding walls whenever possible. This was because the intention was to run a two-year programme of full d-t plasma operation, starting around 1990, during which time a total of about 10^{24} neutrons would be produced. Obviously, close-coupled diagnostics (those inside the Torus Hall) would experience very high neutron fields and significant repairs would only be carried out the most essential items of hardware, using remote handling techniques. Thus, whereas the neutron spectrometers for the early period of d-d operation could be installed inside the Torus Hall, the d-t spectrometers were expected to go outside. In the event, the anticipated major campaign of d-t operation has not taken place and neutron spectrometers for both d-d and d-t operation have been fielded in all three locations: the Roof Laboratory, the Diagnostic Hall and also close-coupled in the Torus Hall.

Because the magnetic field in the tokamak provides a preferred direction in space about which the charged particles in the plasma must gyrate, then the energy spectra of the fusion reaction neutrons will vary with the viewing angle (except when the fast ion velocity distribution is isotropic). It should, therefore, be possible to extract more information from two different lines-of-sight than from just one alone. Consequently, two very different viewing directions have been employed: one radial to the toroidal magnetic field lines and one tangential to them. Radial (or 90-degree) lines-of-sight were available only from the Roof Laboratory, with a vertical view into the plasma. The “tangential” lines-of sight (viewed from within the Torus Hall or from the Diagnostic Hall) are actually inclined at about 52 degrees at the major radius of the plasma because of the need to view between the closely-spaced toroidal field coils.

Ideally, the two lines-of-sight would have been equipped with identical spectrometers. However, for practical reasons, this was possible only for the smallest spectrometers (He^3 ionization chambers [3] for d-d discharges and diamond detectors [4] for d-t discharges), whereas the main spectrometers had to be designed specifically for their chosen locations.

DISCHARGE CHARACTERISTICS FOR JET

The arrangements for neutron spectrometry were mostly specified prior to the tokamak commencing operation, so it is understandable that the envisaged discharge characteristics were somewhat optimistic. Specifically, for d-t operation, it was anticipated that a fusion power of 20 MW could be maintained for 10 seconds. In the event, the best d-t discharge reached 16 MW fusion power, but exceeded 10 MW for no more than 0.6 s. Fig. 1 shows the neutron emission signals for some of the best d-t discharges, taken from different operating scenarios from the Preliminary Tritium Experiment (PTE, [5]) and the subsequent Deuterium-Tritium Experiment (DTE1, [6]). Due to a variety of circumstances, the neutron fluxes at those neutron spectrometers outside the Torus Hall are about one order of magnitude lower than originally anticipated. Neutron yields for d-d operation are scaled down according to the fusion reaction cross-sections (by two orders of magnitude).

Good statistical accuracy is obviously a requirement for any neutron spectrum to be

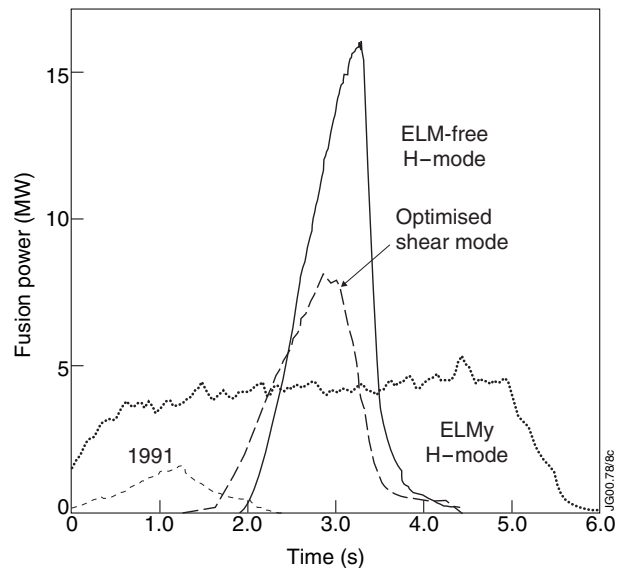


Fig.1: Neutron yields for some record tokamak d-t discharges. The JET 1991 Preliminary Tritium Experiment discharges [5] were the first in which d-t fuel was used. The three major plasma scenarios illustrated (an ELM-free H-mode, an optimized shear discharge and an ELMy H-mode discharge) were run in 1997 [6].

subjected to detailed analysis. Experience shows that a minimum of 1000 events is required in the full-energy part of the spectrum, which we refer to as the *useful* part of the spectrum. The time interval available depends on the discharge duration but should be short enough that the plasma conditions can be considered constant; for JET, 0.25 s is barely adequate but rarely achieved. The energy resolution must be no more than a few percent. The spectrometers must be capable of operating satisfactorily under highly transient conditions, with the data-taking count-rate moving from negligible to near saturation in about one second, and back to a negligible level in another second. Control of the neutron fluxes at the more rate-critical spectrometers is necessary, e.g. the ^3He ionization chambers, and massive pre-collimators with moveable jaws were provided for this purpose.

The neutron emission varies in both intensity and spectrum shape as the plasma heating conditions are changed. With ohmic heating, the ions are in thermal equilibrium and the spectrum shape will be almost precisely gaussian and the effective ion temperature, T_i , can be deduced simply from the *fwhm* of the measured spectrum, $fwhm = 82.5 \sqrt{T_i}$ for d-d plasmas and $178 \sqrt{T_i}$ for d-t plasmas (keV units). This temperature is actually an average along the line-of-sight through the plasma but, as the neutron emission is strongly localized near the plasma centre, the line-averaged temperature is typically only about 10% lower than the central temperature (an easily calculated correction). The thermal neutron emission is isotropic, of course.

With deuterium Neutral Beam Heating, the beam-plasma interactions and thermal-thermal interactions are generally of comparable intensity, with beam-beam reactions being sufficiently weak that they can be neglected. The number and energy of the injected ions, the direction of injection, the direction of observation, the thermal properties of the plasma and its rotation rate together determine the spectrum shape. A typical breakdown of reaction mechanisms is shown for a deuterium beam-heated d-d discharge in fig. 2 (see [7]). The broken curves show the yield predictions of a transport code [8] that attempts to reconcile the information obtained from the complete set of plasma diagnostics.

To complicate matters, the neutral beams have three energy components, full, one-half and one-third, although usually the neutron generation from the two lower energy components can be neglected in relation to that from the full-energy component. Moreover,

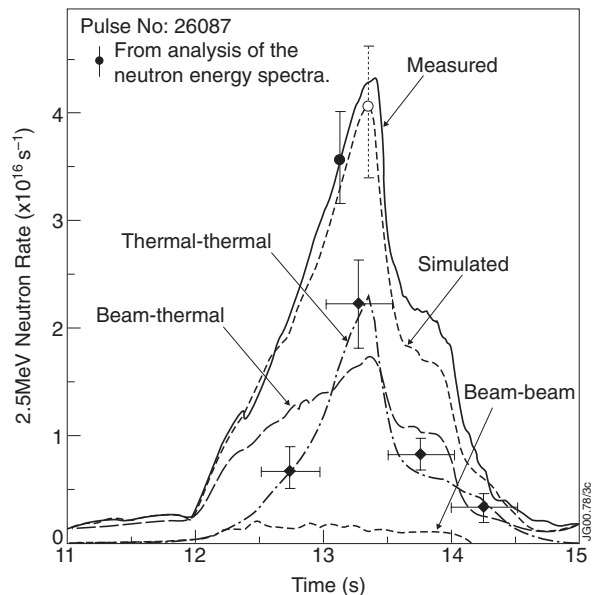


Fig.2: Illustrating the three contributions (*thermal-thermal*, *beam-thermal* and *beam-beam*) to the total neutron yield for a d-d discharge with a single beam injection energy. The lines are the predictions of a transport code. The four measurements [7] indicated on the *thermal-thermal* curve are obtained from an analysis of neutron energy spectra.

there are two beam boxes, usually operated at different potentials (e.g. 80 kV and 140 kV), with 8 positive-ion neutral injectors installed in each box; in d-t operation, the lower voltage box injected deuterium and the other tritium. In addition, power is also deposited in the plasma by means of Ion Cyclotron Radio-Frequency Heating; this may be used on its own or in conjunction with NBI heating. Ideally, the RF will heat the bulk ions and electrons only. More frequently, it accelerates the light particles in the plasma to high energies. These ions could be deuterium or tritium fuel ions, or other minority ions such as protons and ^3He that are present as impurities or by intent. Sometimes, these ions are particularly energetic (several MeV) and interact not only with the bulk fuel ions but also with not-so-light impurity ions, ^9Be and ^{12}C , derived from the plasma-facing components. The $^3\text{He} - ^9\text{Be}$ reaction can be a prolific source of neutrons. These light ion reactions are only of concern during d-d operation, since the higher yield from d-t reactions almost always will dominate. In general, the neutron emission from additionally-heated plasmas is not quite isotropic.

Apart from distinguishing d-d from d-t neutrons, it is not always possible to make useful statements about the nature of the fusion reactions responsible for the neutron emission on the basis of a simplistic analysis of the measured spectra alone. This is because the spectral components are relatively broad and overlapping, so that it is, at best, difficult to separate the contributing reactions from an unfolding of the neutron spectrum [9,10]. Instead, it far more profitable to start with the known or assumed plasma conditions and compute an expected spectrum shape for comparison with the measured spectrum; a least-squares optimization over one or more parameters can then be used to refine the starting conditions.

The kinematics of the d-d and d-t reactions are well known and it would be superfluous to rehearse them here. What may not be so familiar, however, is the 3-dimensional nature of the problem when the target is a plasma within an applied magnetic field. Most of our discharges involve NBI heating. The injected neutral particles ionize and then slow down and thermalize quite slowly, typically taking 100 ms. Depending on their ionization position, the ions may enter trapped particle orbits (banana orbits) that slosh back and forth or instead move straight into passing orbits that circulate the machine. As they slow down, they are subject to pitch-angle scattering and may cross from trapped to passing orbits, or vice-versa. The neutron energy spectra reflect the relative motions of the interacting ions, under the influence of the magnetic field, and - to a lesser extent - the bulk movement of the thermal plasma, which may rotate at very high speeds. Usually, the pitch-angle scattering and resultant diffusion are ignored. Monte-Carlo kinematics calculations [11] are performed to sample the 6-dimensional velocity space. A further problem is the variation of plasma conditions (ion and electron densities and temperatures) with minor radius. In principle, this involves a summation over a number of plasma volumes, although just one or two volumes appear sufficient.

TYPES OF NEUTRON SPECTROMETER THAT HAVE BEEN USED AT JET

Table I lists the various types of neutron spectrometer that have been employed on JET. Some of the requirements for operation on a tokamak are discussed in ref. [12].

Table I

2.5-MeV neutron spectrometers		
Spectrometer type and location RL - Roof Laboratory; TH - Torus Hall; DH - Diagnostic Hall	Energy resolution (fwhm, $\delta E/E$ %)	Efficiency (c/n.cm⁻²)
Nuclear emulsions; RL [13]	4	1×10^{-3}
NE213 liquid scint.; RL, TH, DH [14]	8	1
Spherical hydrogen prop. chmbr.; RL [15]	3	1×10^{-2}
Forward recoil proton; TH [3]	7	1×10^{-5}
³ He ionization chamber; RL, TH [16]	~ 2	1×10^{-2}
Time-of-flight RL; [9]	4.9	5×10^{-2}
14-MeV neutron spectrometers		
Nuclear emulsions; RL	3	1×10^{-4}
NE213 liquid scintillator; RL, TH	4	1
Silicon detectors [17]	0.8	1.3×10^{-4}
Diamond detectors; RL, DH [4]	2 - 3	
Associated-particle time-of-flight; RL [18]	1.1	1.4×10^{-5}
Annular radiator proton recoil; DH [19]	2.2	8×10^{-5}
Magnetic proton recoil analysis; TH [20]	2.5	5×10^{-5}

To design or specify a neutron spectrometry measurement such that the *useful* count-rate is at least 1 kHz can be a major challenge. Spectrometers that employ n-p scattering events without means for including directional information for the recoiling protons essentially provide flat energy spectra, and for nearly mono-energetic neutrons the useful information is contained in the slope of the high-energy edge. This information is extracted by unfolding the response function (in this case, effectively differentiation) so that the useful count-rate is only a few percent of the total count-rate. Such spectrometers do not provide good quality spectra under tokamak conditions, although they are valuable for simple purposes of energy discrimination. To be truly useful for high-resolution spectrometry, it is essential that the spectrometer provides a response that directly reflects the incoming neutron spectrum, i.e. it must have a very pronounced full-energy peak and little or no low-energy tail. In practice, depending on their design, spectrometers will have both low and high-energy tails of some magnitude, associated with

background events, neutron down-scattering in collimators, random background coincidences, pulse pile-up due to excessive count-rates and incomplete charge collection due to charged-particle escape from active regions (wall effects).

Unfortunately, when - as is usual - a spectrometer response function has a weak but non-negligible low-energy tail, it is often not appreciated that an otherwise apparently excellent energy resolution is only of value when studying almost mono-energetic neutron spectra. As the neutron spectrum broadens (with additional heating, the tokamak spectra may have *fwhm* values of up to 10%) then the low-energy tail becomes increasingly important. This is particularly serious for the ^3He ionization chamber (fig. 3), and for silicon and diamond solid-state detectors, when applied to beam-heated discharges.

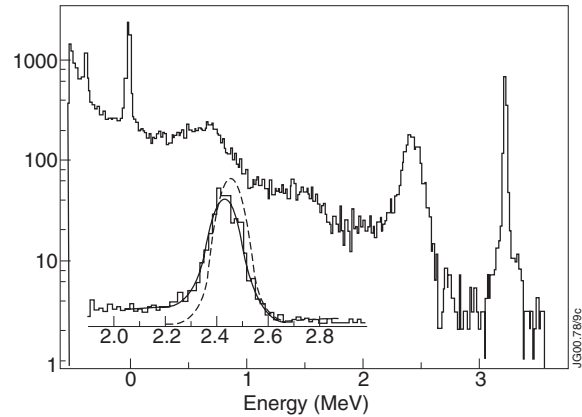


Fig.3: Showing the full energy spectrum recorded with a ^3He ionization chamber for four (aggregated) ohmic discharges in deuterium (12 seconds of data-taking). The insert shows the fitted energy spectrum and the unfolded spectrum for the incident neutrons. The ion temperature is 3.4 ± 0.2 keV, in good agreement with the averaged result obtained from Ni^{26+} X-ray spectroscopy.

Summarizing our experience at JET in the search for practical high-resolution neutron spectrometers, I draw the following conclusions:-

- (1) Nuclear emulsions are not competitive with active spectrometry techniques, where these are available.
- (2) The spherical hydrogen recoil spectrometer and the liquid scintillators that provide flat pulse-height responses are unsuitable for high-resolution spectrometry. (An easily overlooked problem is that photo-multipliers tend to exhibit rate-dependent gain shifts that can be troublesome under transient conditions).
- (3) Forward scattering of protons by 2.5-MeV neutrons results in energy resolution and efficiency that are wholly inadequate for use as a routine plasma diagnostic.
- (4) The ^3He ionization chambers have seriously limited count-rate capabilities, very good peak energy resolution but a strong low-energy tail that makes them unsuitable for examining broad energy spectra. Their usefulness is restricted to thermal d-d plasmas.
- (5) The 2.5-MeV time-of-flight neutron spectrometer in the Roof Laboratory provided proof-of-principle and, after its major upgrade, performed very well with additionally heated plasmas.
- (6) The silicon detector was never seriously investigated in high-resolution d-t spectrometry applications because of its rather strong low-energy tail. However, such detectors are routinely used in low-resolution applications [21].

- (7) Diamond detectors have been used for d-t plasma studies. They are low-efficiency devices, but offer excellent energy resolution in the full energy peak and have high count-rate ability. Unfortunately, they also exhibit large low-energy tails.
- (8) The associated-particle time-of-flight spectrometer offers good energy resolution and a well-defined full-energy peak. However, its efficiency was poor and it proved subject to severe random count-rate problems for the highest fusion power discharges, showing that the Roof Laboratory floor was not sufficiently thick.
- (9) The annular-radiator spectrometer performed acceptably. Its major difficulty is that of procuring the desired large area silicon detectors capable of stopping 18 MeV protons.
- (10) The magnetic analysis spectrometer was very successful. Its energy resolution was adequate and, because it is close-coupled with the tokamak, it has provided exceptionally good statistical accuracy.

RESULTS FROM STUDIES OF DEUTERIUM DISCHARGES

The earliest work at JET involved the ^3He neutron spectrometers. Detailed response characteristics to mono-energetic neutrons were obtained from extensive accelerator laboratory studies. This is an activity that has proven impossible for the major, physically large, spectrometers subsequently fielded at JET. The most important ^3He - spectrometer contribution came from early studies of ohmic discharges, for which they provided accurate and reliable core plasma ion temperatures. Taken together with an absolute measurement of the total neutron emissivity and electron density data, it was clear that in the early years of JET operation the plasmas were very dirty [22], the deuteron to electron density ratio being typically 0.5, i.e. a factor of 4 loss of neutron yield.

With the advent of deuterium neutral beam heating, it was found that the ^3He spectrometer performed very poorly, due primarily to the enhanced contribution from the low-energy tail when attempting to study 20 keV effective temperatures, as opposed to 2 to 3 keV. For such discharges, the 2.5-MeV time-of-flight spectrometer was much better. Fig. 4 shows an early example of a neutron spectrum from a beam-heated discharge obtained with the prototype 2.5 MeV time-of-flight spectrometer. It was found possible to obtain an acceptable understanding of the results using

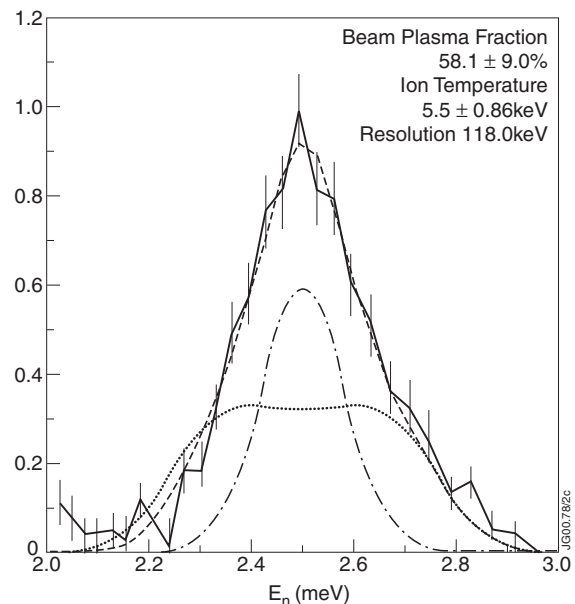


Fig.4: Showing a neutron spectrum obtained with the prototype time-of-flight spectrometer [9] for a deuterium beam-heated discharge. The viewing direction is vertical. The beam-plasma fraction and the ion temperature are deduced from the single-volume analysis of the spectrum. Thermal fractions from similar measurements are shown in fig. 2.

a simple single-volume model of the neutron emission from the plasma, in conjunction with just two contributions to the neutron emission, i.e. thermal and beam-thermal reactions. At this time the two beam boxes injected deuterium neutral particles at the same energy. A further useful simplification arose from the fact that the time-of-flight spectrometers (the prototype [9] and its upgrade successor [7]) were located in the Roof Laboratory and were therefore insensitive to plasma toroidal rotation

The introduction of NBI heating permitted a new diagnostic to be brought to bear. This is the charge-exchange recombination spectrometry diagnostic (CXRS, [23]) that depends on NBI to provide the penetrating neutrals for charge-exchange processes with the thermal carbon ions in the plasma. It produces radial profiles of ion temperature and rotation rate. This diagnostic immediately removed any remaining doubt on the impurity issue and the design of an internal divertor to lower the impurity levels in the plasma was promptly started. The charge-exchange technique also removed the necessity from neutron spectrometry to provide ion temperature information during NBI-heating. This was fortunate, because it is very often difficult, if not impossible, to distinguish the thermal-thermal and beam-thermal features in the neutron spectra and hence any resulting ion temperature estimates were not very reliable. Neutron spectrometry efforts were thereafter devoted to demonstrating that the spectrum shape was understood and that, under favourable circumstances, ion temperature data could be indeed derived - but with the expenditure of much effort. Fig 2 showed the thermal-thermal contributions deduced from spectra obtained with the time-of-flight spectrometer.

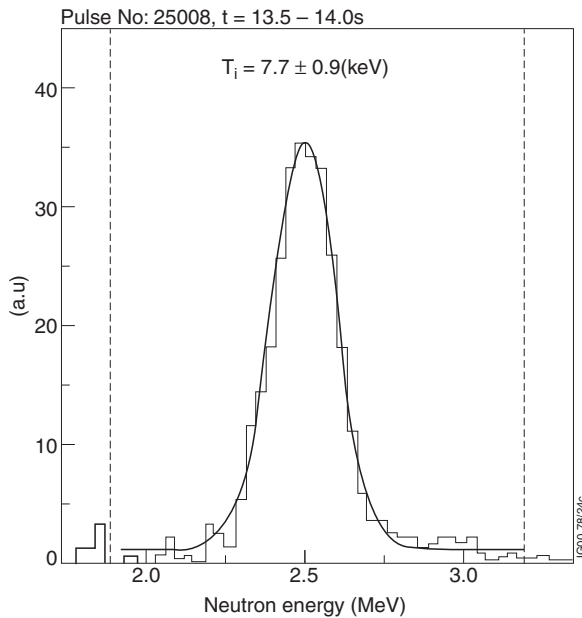


Fig.5: A neutron spectrum obtained with the upgraded time-of-flight spectrometer [7] for a discharge with ICRF heating of ^3He minority ions. The curve is well fitted with a gaussian corresponding to a temperature of 7.7 ± 0.9 keV, consistent with other ion temperature data indicating the lack of neutron emission associated with supra-thermal particles.

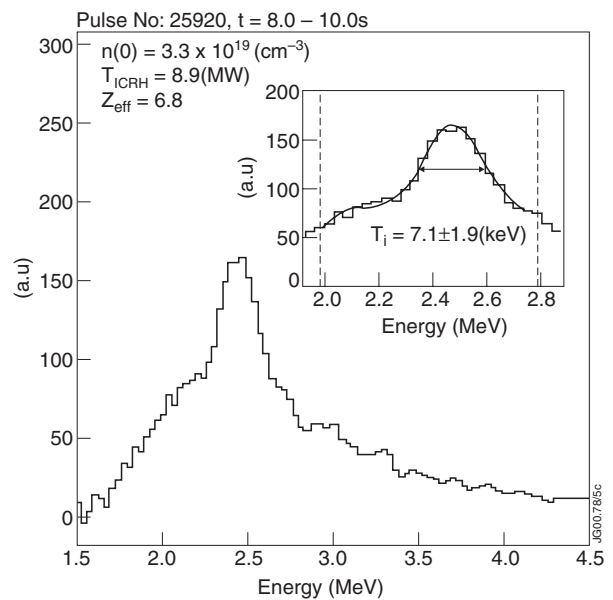


Fig.6: An example of a neutron spectrum obtained with the time-of-flight neutron spectrometer [7] for ICRF heating of hydrogen minority ions in deuterium plasma. In this example, there is strong second-harmonic acceleration of deuterons, resulting in the generation of neutrons with energies extending well above 4.5 MeV.

Of particular interest was the application of the time-of-flight spectrometer to ICRF heated discharges [7]. Ideally, the RF heats the plasma without significantly distorting the Maxwellian energy distribution of the ions. Fig. 5 shows an example of such a discharge. However, as mentioned earlier, the RF can accelerate light ions to high energies, with occasionally dramatic effects on the resulting neutron spectra, as shown in fig.6. Clearly, the spectrometer provides immediate warning of the presence of these high-energy ions and can give a good indication of the effective temperature of the high-energy tail. Usually, the acceleration of ions to these energies is to be avoided as it represents an inefficient use of RF heating power. The ability to measure the neutron spectrum under such conditions was also of great importance for the interpretation of results from the other neutron diagnostics that exhibit response functions that rise rapidly with neutron energy.

RESULTS FROM STUDIES OF DEUTERIUM-TRITIUM DISCHARGES

With deuterium-tritium discharges, the situation became more interesting but also potentially far more complicated. Fortunately, the quality of the spectra improved, because it is far easier to work with 14-MeV neutrons than 2.5-MeV neutrons and we have more and better spectrometers. In particular, we were also - for the first time - able to make accurate comparisons between spectra obtained from the radial and tangential lines-of-sight. At the most general level, the relation between the two lines-of-sight is easily understood. For isotropic fast ion distributions, the spectra are independent of viewing direction. The fast ion distributions are usually anisotropic, e.g. for ICRF heating where the ions have most of their energy in motion perpendicular to the magnetic field. In such a case, the vertical-viewing spectrum will have the maximum possible spectrum width. The spectra obtained with tangential-viewing spectrometers (the annular radiator proton recoil spectrometer or the magnetic proton-recoil spectrometer) would see a spectrum width reduced by $\sin^2\theta$, where θ is the viewing angle to the field lines (about 52 degrees). With beam heating, the beams are injected at about 57 degrees so the energy is predominantly in the perpendicular motion. Thus, in general, the tangential spectra will have widths of between 1.0 and $\sin^2 52$ times those for the vertical view. This is demonstrated in fig. 7, which compares effective temperatures obtained from vertical and tangential-viewing spectrometers for a variety of discharge scenarios.

A good example of vertically-viewed spectra for RF-heated discharges taken with the associated-particle time-of-flight spectrometer is shown in fig. 8, where the minority deuterium concentration determines the prominence of the fast-ion component (strength inversely proportional to relative density).

As discussed before, the tangential and vertical views differ in that only the tangential spectrum reflects the toroidal rotation rate of the plasma, with the thermal contribution being "Doppler shifted" in the appropriate direction. This shift is a significant fraction of the line broadening. Of course, the plasma rotation rate is well known for charge-exchange spectroscopic

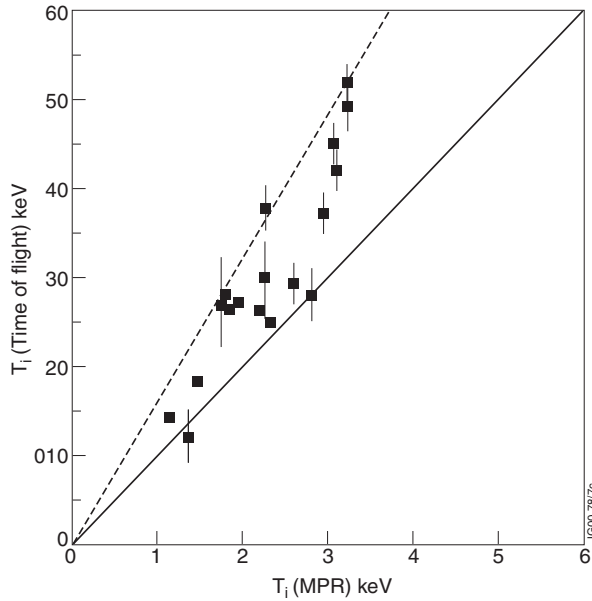


Fig.7: Comparing effective ion temperatures obtained with the associated-particle time-of-flight spectrometer (vertical view) with corresponding temperatures obtained with the magnetic analysis proton recoil spectrometer (tangential view). Results from an assortment range of high-performance d-t discharges are presented. The measurements should fall between the two lines, the upper corresponding to fast ions having most of their energy in perpendicular motion, the lower corresponding to isotropic motion.

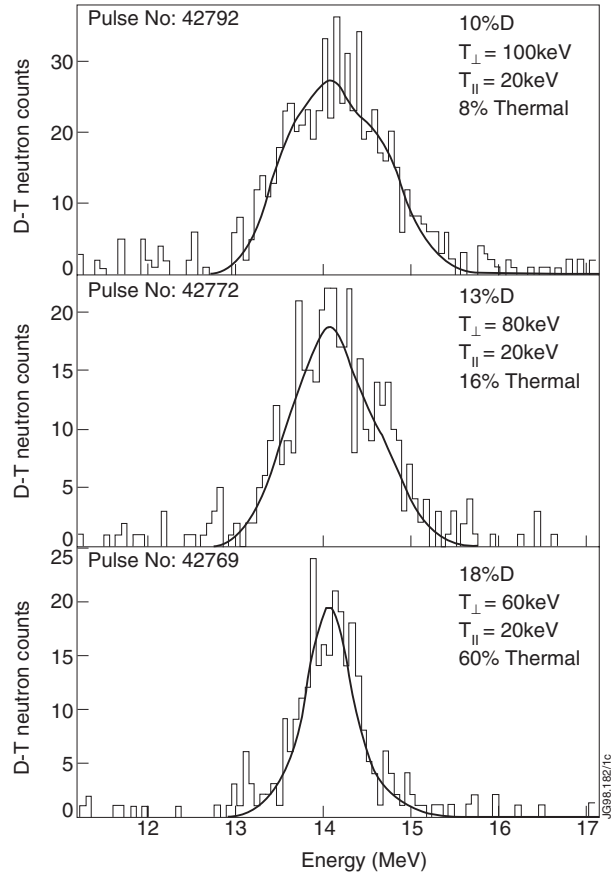


Fig.8: Neutron spectra obtained with associated-particle time-of-flight spectrometer for an ICRF-heated tritium discharge with minority deuterium [26]. The broadening due to the deuteron velocity distribution is shown clearly. The solid curves are best fits to the data of a combination of suprathermal and thermal components.

measurements. Fig. 9 shows a spectrum measured with the tangentially-viewing annular proton-recoil spectrometer for the relatively simple case of tritium beam injection into a 70:30 T:D plasma, where only two components have to be taken into account, the thermal and tritium beam-deuterium plasma contributions, including the effects of rotation. The plasma density is unusually high. The detailed spectrum analysis indicates that the beam ion distribution has become almost isotropic before significant energy has been lost, possibly due to pitch-angle scattering and diffusion while slowing down.

The most common d-t discharge scenario involves combined deuterium and tritium beams injected into a nearly 50:50 d:t plasma. Under such circumstances, the neutron yield is optimized and is insensitive to the precise d:t mix. To understand the transport of fuel ions, however, it is necessary to investigate discharges in which the fuel and beam mixes are far from optimal; specifically, plasmas with minimal quantity of either D or T. The main problem that then arises

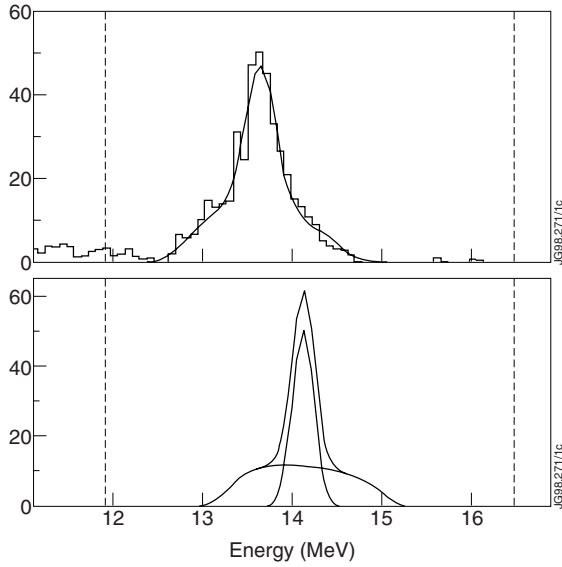


Fig.9: A spectrum obtained with the annular radiator spectrometer [19] (tangential view). Lower: the thermal and beam-plasma (t onto D only) components. Upper: total calculated spectrum, folded with response function and fitted to the data. The plasma has unusually high density and the fit demands a nearly isotropic fast triton distribution.

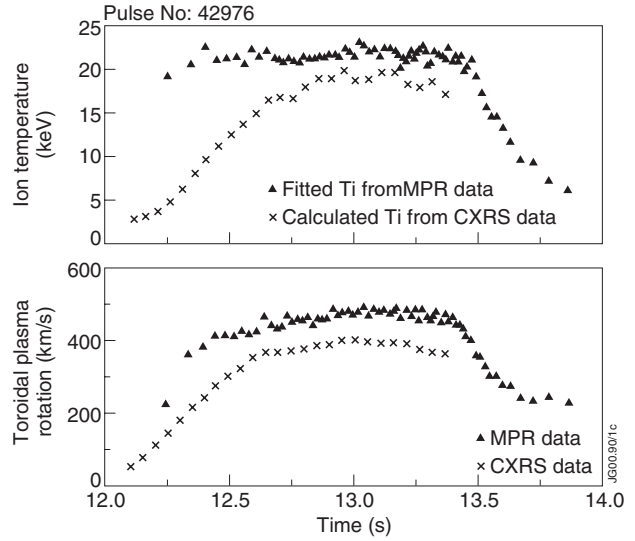


Fig.10: Effective ion temperature and plasma rotation rate deduced from fitting a single gaussian to the MPR data [25], compared with appropriately line-averaged CXRS data. The time resolution is excellent. Much improved agreement with the CXRS data is obtained after decomposing the neutron spectrum into pre-calculated beam-plasma and fitted thermal-thermal components.

is that there is no conventional diagnostic that provides a measure of the $d:t$ proportions in the centre of the plasma. However, under some circumstances the shape of the neutron spectrum is quite sensitive to the assumed plasma mix and its study can therefore provide the missing information. This exploits the fact that we inject tritium at an appreciably higher energy than deuterium (160 and 80 keV, respectively). Thus, the t - D spectrum component is far broader than the d - T component. By definition, the thermal contribution is negligible under these circumstances. See [24] for further results of d - t spectrum analysis using the annular radiator spectrometer.

Since the d - t neutron spectra from high performance discharges with 50:50 beam and plasma mixes are approximately gaussian-shaped, the spectra are most easily represented as usual by fitting a gaussian and extracting the mean energy, $fwhm$ and effective plasma rotation rates. It then becomes of interest to compare these *effective* temperatures and rotation rates with those derived from CXRS measurements. This comparison is most beautifully displayed in fig. 10 (from ref. 25), obtained from the magnetic proton recoil spectrometer [20] for which the statistical precision is excellent. The neutron and CXRS results tend to merge as the temperature (and the thermal-thermal contribution) rises. To proceed one stage further, the beam-plasma to thermal neutron production fractions are derived from plasma-physics calculations and the beam-plasma spectrum shape is approximated by a 22 keV gaussian (compatible with detailed kinematics calculations); the thermal neutron temperatures extracted by fitting to the measured spectra are then found to be in excellent agreement with the CXRS ion temperatures over the full duration of the discharge. This demonstrates a satisfactory understanding of the neutron emission for this discharge.

CONCLUSIONS

Neutron spectrometry on tokamak plasmas is a non-trivial undertaking. A wide variety of spectrometer types have been fielded at JET, with varying degrees of success. We have developed a quantitative understanding of the particle dynamics in plasmas that permits us to predict the form of the neutron energy spectra for all discharge scenarios so far encountered. This impacts most directly on the study of the effectiveness of different ICRF heating schemes. Information on the neutron spectrum is important for d-d discharges in that this has a direct bearing on the interpretation of results from other neutron diagnostics. Finally, the ability to determine reliably the d:t mix in situations where one or other is a weak minority presence will assist the analyses of such plasmas. For the future, with ignited plasmas, neutron spectrometry will hopefully meet the original intention of providing simple, credible, measurements of fuel ion temperature.

REFERENCES

- [1] O.N.Jarvis, Plasma Phys. Control. Fusion 36 (1994) 209- 244.
- [2] H.Brysk, Plasma Physics 15 (1973) 611.
- [3] N.P.Hawkes, P. van Belle, P.Dixon, M.A.Hone, O.N.Jarvis, M.J.Loughlin, M.T.Swinhoe, Nuclear Instrum. and Methods Phys. Res. A335 (1993) 533.
- [4] A.Krasilnikov, S.S. Medley, N.N.Gorelenko, R.V.Budny, O.V.Ignyatuk, Yu. A. Kaschik, M.P.Petrov, A.L.Roquemore, Rev. Sci. Instrum. 70 (1999) 1107, and *this meeting*.
- [5] P-H Rebut, A.Gibson, M.Huguet and the JET Team, Nuclear Fusion 32 (1992) 187.
- [6] M.Keilhacker, A.Gibson, C.Gormezano et al., and the JET Team, Nuclear Fusion 39 (1999) 209.
- [7] T.Elevant, P. Van Belle, O.N.Jarvis, G.Sadler, Nuclear Instruments and Methods, A364 (1995) 333-341.
- [8] R. V. Budny et al., Nuclear Fusion 32 (1992) 429.
- [9] T. Elevant, D.Aronsson, P. van Belle et al., Nucl Instrum and Methods in Phys. Res. A306 (1991) 331.
- [10] M. Olsson, P. van Belle, S.Conroy, T.Elevant and G.Sadler, Plasma Phys. Control. Fusion 35 (1993) 179.
- [11] P. van Belle and G.J.Sadler, in: *Basic and Advanced Diagnostic techniques for fusion Plasmas* (Varenna, 1986) vol. III (EUR 10797 EN) (Brussels: CEC) p. 767.
- [12] O.N.Jarvis, in: *Diagnostics for Fusion Reactor Conditions*, (Varenna, 1982) vol. I (EUR 8351-I EN) (Brussels CEC) p.353.
- [13] K.Huebner et al, Proc. 12th European Conf. on Controlled fusion and plasma Physics (Budapest 1985) (Europhysics Conference Abstracts 9F) p.231.
- [14] G.F.Knoll, Radiation Detection and Measurement, (New York, Wiley, 1989).
- [15] F.Hoenen and W.Bieger, Nucl. Instrum and Methods A259 (1987) 529.

- [16] Model FNS-1, manufactured by Jordan Valley Radiation Ltd (Migdal Hamaek), P.O. Box 103, Israel 10550.
- [17] T.Elevant, H.W.Hendel, E.B.Nieschmidt and L.E.Samuelson, *Rev. Sci. Instrum.* 57 (1986) 1763.
- [18] G.Grosshoeg et al. *Nucl. Instrum. and Methods Phys. Res. A* **249** (1986) 468.
- [19] N.P.Hawkes, P. van Belle, D.S.Bond, S.Croft and O.N.Jarvis, *Rev. Sci. Instrum.* 70 (1999) 1134.
- [20] J.Kallne et al., *Rev. Sci. Instrum.* 70 (1999) 181.
- [21] S.Conroy et al., *Nucl. Fusion* 28 (1988) 2127.
- [22] O.N.Jarvis, J.M.Adams, B.Balet, S.Conroy et al, *Nuclear Fusion* 30 (1990) 307.
- [23] W.Mandl, R.Wolf, M. von Hellermann, H.P.Summers, *Plasma Phys. Contr. Fusion.* 35 (1993) 1373.
- [24] N.P.Hawkes, D.S.Bond, O.N.Jarvis, V.Kiptily, S.W.Conroy, *this meeting*.
- [25] H.Henricksson, Diploma Thesis, Uppsala University, Sweden, 1999.
- [26] D.F.H.Start et al., *Nuclear Fusion* 39 (1999) 321.