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ABSTRACT

A 14 MeV neutron spectrometer, based on the principle of the proton recoil telescope, has been installed as a DT plasma diagnostic at JET. The device comprises three identical telescope modules arranged one behind the other, to increase efficiency without worsening resolution. It views the plasma along a horizontal line of sight. The total efficiency is 7.05×10^{-5} counts per [neutron per cm^2], and the calculated response function has a FWHM of 2.2% at an incident neutron energy of 14.1 MeV. The spectrometer was operational throughout the recent Deuterium-Tritium Experiment No.1, and selected neutron spectra have been analysed in terms of the contributions from the various neutron production mechanisms.

1. INTRODUCTION

Neutron spectrometers play an important role in plasma diagnostics, as they provide uniquely direct information on the velocity distribution of the reacting ions.

Good results have been obtained with time-of-flight spectrometers, for both DD (1) and DT plasmas. However, these devices are large, complex and manpower-intensive. Proton recoil telescopes offer a much simpler alternative. In such devices, neutrons irradiate a thin plastic film or 'proton radiator', and the energy distribution of the ejected protons is measured in a semiconductor detector. The neutron spectrum can then be deduced from the proton spectrum, given knowledge of the geometry of the instrument.

The inherently low efficiency of these devices, at a given resolution, has been a handicap up to now. With the high neutron fluxes produced by JET during the recent tritium experiments, however, a practical and useful DT plasma diagnostic based on this principle has become possible. This is the instrument described here.

2. GENERAL DESCRIPTION

The configuration of the spectrometer is shown in Figure 1. There are in fact three separate telescope modules, each with its own proton radiator and proton detector, arranged one behind the other. This increases the efficiency without degrading resolution, and also improves the maximum count rate capacity.

A fourth module, not shown in Figure 1, has a detector but no proton radiator, and allows the background inside the instrument to be measured.

The proton detectors are silicon surface barrier devices. They are protected from the neutron beam by a shadow bar, and this gives rise to the annular geometry shown. Metal masking discs (not shown in Figure 1) are carefully positioned within the shadow of the shadow bar, in such a way that each detector sees only the protons from its own proton radiator.

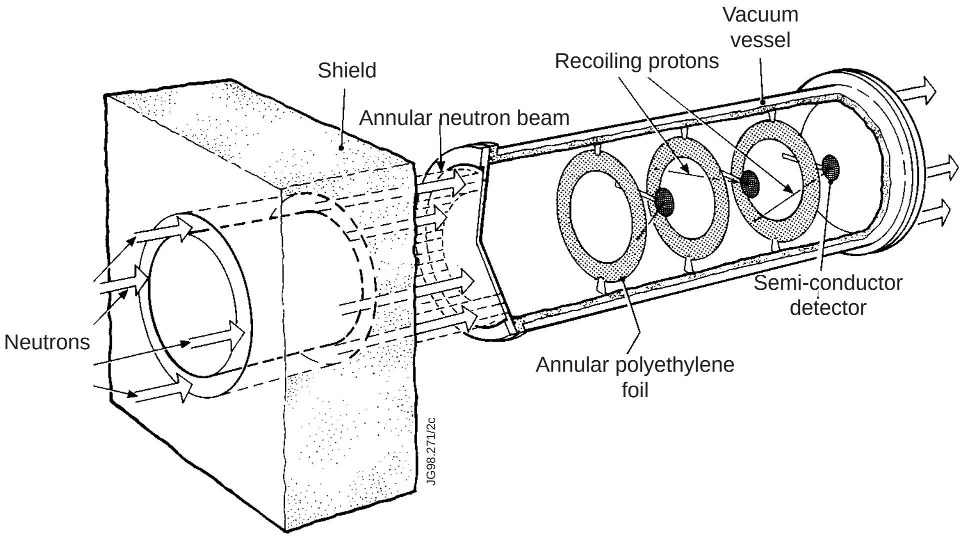

Fig.1: Spectrometer construction (schematic).

The vacuum vessel in which the telescope modules are housed is 2.3 m long and 0.325 m in diameter. The removable circular end plates have a thin window (0.4 mm thick and 230 mm diameter) to allow the neutron beam to enter and leave with minimal scattering. To minimise scattering within the spectrometer, the telescope modules are of low mass construction: the telescope elements are held in place by fine stainless steel rods 0.97 mm in diameter, and the rods are themselves supported by a light carbon fibre framework outside the neutron beam.

The telescope modules can be slid into position along rails in the vacuum vessel and then locked into place, allowing them to be removed and replaced without the need for re-alignment.

An ^{241}Am alpha source is mounted in front of each proton detector to provide an energy calibration and to enable the performance of the detector to be monitored.

The system employs conventional spectroscopic grade electronics. Each detector is connected to a pre-amplifier, which is in turn connected to an HT unit, a main amplifier, and a test pulse generator for monitoring the resolution. Each main amplifier is connected to a spectroscopy ADC with a memory module, and at the end of the JET discharge all ADCs return 128 spectra, each of 256 channels, covering 0.25 s each.

3. CONFIGURATION, EFFICIENCY AND RESOLUTION

Each proton radiator is of polyethylene 4.59 mg/cm^2 thick, with an inner radius of 60 mm and an outer radius of 78 mm. The proton detectors are 15 mm in radius and 1640 μm thick (sufficient to stop 16 MeV protons), and are mounted 410 mm behind the corresponding proton radiator.

FORTRAN programs (2) were written to calculate the efficiency and resolution of telescope configurations, and these programs were validated using data from a prototype spectrometer that was tested on the Harwell 500 keV Van de Graaff accelerator and also at JET during the Preliminary Tritium Experiment in 1991. In addition to calculating the kinematic energy spread due to the range of scattering angles, the programs also allow for the slowing down of the protons within the radiator, and for the intrinsic resolution of the proton detector.

The calculated response function of the spectrometer is closely gaussian, and has a FWHM of 293 keV and a mean proton energy of 13.610 MeV at incident neutron energy of 14.1 MeV. The efficiency is 7.05×10^{-5} counts per [neutron per cm^2] (measuring flux at the front of the vacuum vessel).

4. INSTALLATION AT JET

The spectrometer views the horizontal port of Octant 7 at an angle of 22.5° to the normal (see Figure 2). The line of sight lies in a horizontal plane 135 mm above the mid-plane of the machine (i.e. typically 165 mm below the centre of the plasma), and has a significant component tangential to the toroidal field lines.

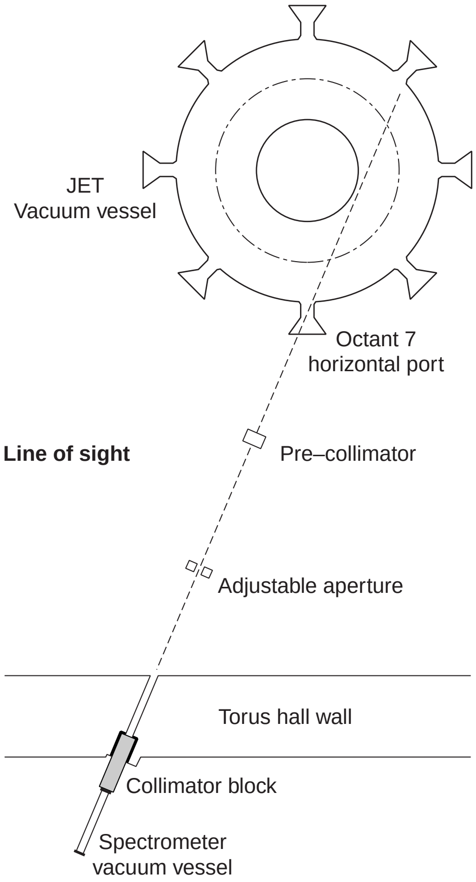

Fig.2: Line of Sight of the spectrometer as installed at JET.

The spectrometer occupies a blockhouse (not shown in Figure 2) which has concrete walls 0.48 m thick and abuts the Torus Hall. The steel shadow bar, 2 m long and 70 mm in diameter, is mounted in the collimator block immediately in front of the spectrometer, and the pre-collimator near the JET vessel ensures that the beam is sufficiently tightly defined as it passes through the spectrometer.

The final element in the beam line is a re-entrant beam dump, which is approximately 1.2 m on each side and made of alternate slices of iron and polyethylene.

5. ANALYSIS OF DATA

Total spectra are obtained by re-binning the spectra from the individual detectors onto a common energy axis, and summing the contributions from the three telescope modules. The spectrum from the background module is scaled according to the calculated neutron flux at the positions of the modules and then subtracted. In the energy region of the proton peak (12 - 16 MeV), the number of counts in the background spectrum is typically 1.5% of that from one telescope module.

The spectrometer was operational throughout the Deuterium-Tritium Experiment No.1 (DTE1) at JET, and the 71 discharges with yields above 10^{18} neutrons typically produced 2000 or more useful counts per discharge.

The measured spectra can be analysed to find the relative contribution from the principal neutron production mechanisms, namely plasma-plasma (thermal) interactions and beam-plasma interactions. In the latter case, because of the influence of trapped (oscillating) orbits, there will be a population of fast ions streaming in the opposite direction to the injected beams (counter-streaming), as well as one streaming in the same direction (co-streaming); intermediate directions may also have to be included. To date, only discharges with tritium beams alone have been considered. This allows the additional neutron production mechanisms introduced by the simultaneous presence of deuterium beams to be omitted.

The thermal contribution is assumed gaussian, with a FWHM equal to 177 $T^{1/2}$ keV(3), where T is the ion temperature in keV. The shapes of the beam-plasma spectra are calculated using the code FPS(4), which gives the energy spectrum of any fusion product under specified experimental conditions.

The calculated contributions are summed together, folded with the known response function of the spectrometer, and fitted to the measured spectrum. The plasma temperature and the relative sizes of the contributions are free parameters of the fit. The effect of plasma rotation can also be included in the calculation.

Many of the spectra measured during DTE1 are approximately gaussian, because the strong thermal emission at high temperatures gives spectral broadening comparable to the spread due to beam-plasma neutron production. However, some of the spectra, for lower temperature discharges, are noticeably different. Figure 3 illustrates such a discharge (number 42780, for which the additional heating was 10 MW of tritium beams). Making the reasonable assumption that the beam ions remain close to the flux surfaces on which they were deposited, with negligible pitch-angle scattering during slowing down, one would expect the co-streaming population to outnumber the counter-streaming population by about 3:1 (derived from the fact that beam ions are deposited into passing orbits in the core of the plasma, defined here as containing at least 70% of the total neutron emission, whereas in the periphery they are primarily deposited into trapped orbits). However, it was not found possible to obtain a reasonable fit to the neutron spectrum using this ratio.

Figure 3 shows a good fit obtained under the unusual assumption that the fast ions are equally likely to be streaming in any direction. The explanation offered for this is based on the fact that the beam injection angle at JET is such that the pitch angles of deposited ions are not far from the passing-trapped boundary, so that a modest amount of pitch-angle scattering and spatial diffusion can cause passing ions to cross the boundary and become trapped; after subsequent de-trapping, memory of the original injection direction is lost. The beams become nearly isotropic before a significant amount of energy is lost due to slowing down, even though this is very rapid.

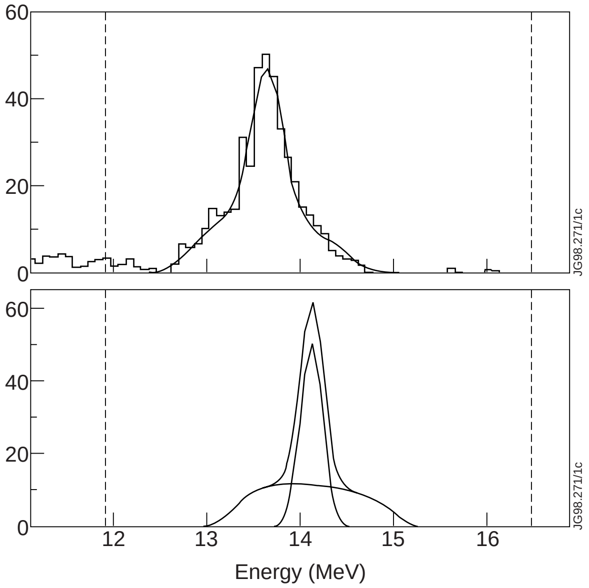

Fig.3: Fit to measured data for discharge 42780, 57.25 - 58.75 s. Lower picture: the gaussian thermal contribution, the broad contribution from the isotropic fast ions, and their sum. Upper picture: the total calculated spectrum, folded with the spectrometer response function and compared with the data. Vertical scale is in counts per 80 keV bin. The fitted temperature is 2.5±1.4 keV; this compares with a figure of 4.3 keV from Charge Exchange Recombination Spectroscopy (CXRS). The fitted proportions are: thermal (45±6)%, fast (55±6)%. Background has been neglected. A plasma rotation of 6.8×10^4 rad s^{-1} has been included in the calculation (cf the figure from CXRS of approximately $(8.6\pm0.6)\times10^4$ rad s^{-1}).

This mechanism (but restricted to equal populations of co- and counter streaming beam particles) has previously been suggested(5) to explain the observation that the beam-plasma neutron yield calculated when pitch-angle scattering is neglected falls some 30% short of the result from TRANSP(6) calculations which do not make this simplification. That suggestion is given strong support by observed neutron spectra such as that described here.

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