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Neutron profile measurements for trace tritium experiments

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The JET neutron profile monitor was used to study the transport of tritium into a magnetically confined deuterium plasma. Trace amounts of tritium were introduced through a gas valve beyond the plasma edge into a variety of plasma confinement regimes. The $d(t,n)\alpha$ fusion cross section is two orders of magnitude greater than the $d(d,n)^3$He cross section and so a puff of tritium which has a negligible effect on the plasma nevertheless produces a large $d-t$ neutron signal. The profile monitor consists of two cameras each made up of a fan-shaped array of collimated lines of sight. It was used to measure the $d-d$ and $d-t$ neutron profiles simultaneously. This article describes the detection system, its operation and assesses the difficulties due to scattered neutrons. The profiles can be used to determine tritium density and transport coefficients. © *1999 American Institute of Physics.* [S0034-6748(99)58901-6]

I. INTRODUCTION

In 1997, experiments were conducted at the JET tokamak using deuterium and tritium fueling. The occasion provided an opportunity to study the transport of tritium into a magnetically confined plasma with well-defined boundary conditions since the experiment started with practically no tritium in the machine. A number of experiments were carried out in which the behavior of tritium was studied in a variety of confinement regimes but in all cases the tritium was introduced into a predominantly deuterium plasma through a gas valve beyond the plasma boundary as a short puff.

The two fusion reactions of interest are

$$\mathrm{D}+\mathrm{D}\rightarrow n+{}^3\mathrm{He} \tag{1}$$

and

$$\mathrm{D}+\mathrm{T}\rightarrow n+{}^4\mathrm{He}. \tag{2}$$

The energy of the neutron produced in each reaction is approximately 2.5 MeV from the $d-d$ reaction and 14 MeV from the $d-t$ reaction. The cross section for the $d-t$ reaction is almost two orders of magnitude larger than the $d-d$ reaction. In the case of deuterium neutral beam injection into a plasma of both deuterium and tritium, the ratio of the 2.5–14 MeV neutron yields provides a measure of the ratio of the densities of deuterium and tritium in the plasma for circumstances in which the neutron production is predominantly from beam-plasma reactions. The ratio of the reactivities is approximately independent of plasma ion temperature.[1] Using the JET neutron profile monitor it was possible to measure $d-d$ and $d-t$ neutron profiles simultaneously when the yields are comparable. The data can be used to determine transport coefficient profiles if adequate plasma coverage and time resolution are achieved.[2] This poses a severe technical challenge because of the need to measure the neutron signal at the plasma edge where the neutron yield is low but where a sufficiently high count rate is required to obtain a time resolution shorter than the transport times. At JET a new analysis technique has been employed in which the tritium transport is modeled and the neutron emission line integrals are calculated and compared to the measured line integrals which are used to constrain the parameters within the model using a least-squares fitting procedure.[3]

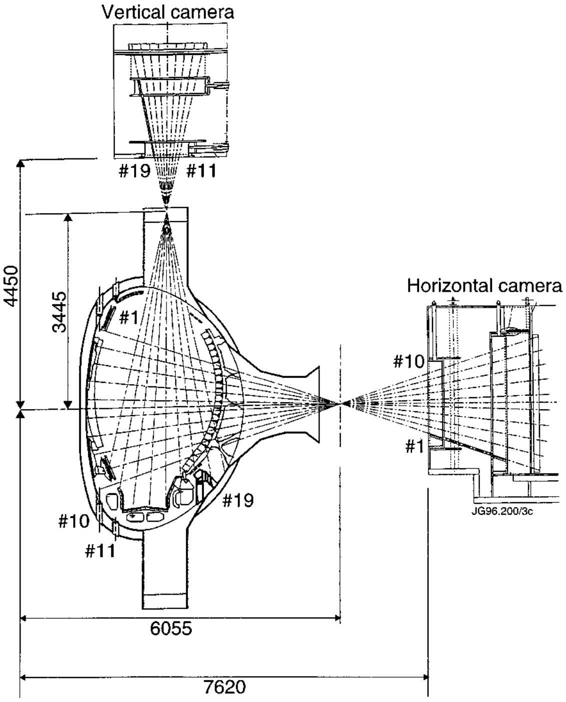

FIG. 1. JET neutron profile monitor.

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TABLE I. Maximum count rates in the detectors (in kHz) during tritium puff.

Channel	1	2	3	4	5	6	7	8	9	10
NE213 $d-d$	30.2	57.8	74.3	88.6	85.0	60.0	37.7	19.6	14.3	7.19
NE213 $d-t$	29.7	64.2	87.9	107.	102.	65.6	38.2	23.2	12.2	3.50
Bicron	19.9	32.5	54.1	57.3	49.8	42.2	20.4	12.3	6.9	2.0

II. NEUTRON DETECTION

The neutron profile monitor consists of two concrete shields which each provides a fan-shaped array of collimators (see Fig. 1). These collimators define the lines of sight for three different detectors. The collimation can be further refined by the use of two pairs of rotatable steel cylinders, one pair in each camera. These cylinders are penetrated by two sets of channels either 10 or 21 mm in diameter. The smaller channels lie at right angles to the larger so rotation through 90° alters the size of the collimation and can affect a factor of 20 reduction in the count rates in the detectors.

There are two neutron detectors, NE213 liquid scintillators and BC418 plastic scintillators. NE213 are sensitive to $d-d$ and $d-t$ neutrons and gamma rays but with electronic discrimination it is possible to distinguish them if the relative count rates are not excessive (<0.2 MHz). The detectors consist of the cell containing the liquid coupled to the window of a photomultiplier tube. A ^{22}Na source is mounted in the cell and is used in the setup and calibration of the processing electronics. The signal is taken from the base of the photomultiplier and split along two routes. On the first route, the signal is amplified by a factor of 2, then fed into a LINK[4] pulse shape discriminator (PSD) which eliminates gamma induced pulses; a high electronic threshold selects a signal which is only due to 14 MeV neutrons. The second route consists of amplification by a factor of 8 before input to PSDs. Upper and lower electronic thresholds select pulses which correspond to recoil protons of energies between 1.8 and 3.5 MeV. The signal in the low energy channel is the sum of the unscattered $d-d$ neutrons, a fraction of the unscattered $d-t$ neutrons and neutrons which have backscattered from the inner wall of the vacuum vessel.

The Bicron scintillators are positioned in front of the NE213 scintillators and are coupled to photomultiplier tubes via a light guide. Their signals are discriminated into four pulse heights. The lowest level is set at an energy corresponding to 8.5 MeV. The efficiency is the same as that for the NE213 detectors. The scintillators are sufficiently small that gamma rays cannot deposit sufficient energy to produce a pulse greater than that produced by a 8.5 MeV neutron.

III. THE RESPONSE OF THE HARDWARE

The response of the profile monitor will be examined using the data from one discharge. There were two tritium puffs one 16.5 s into the discharge and a second at 19.0 s. This discharge will be used to analyze the performance of the horizontal camera.

The peak 14 MeV neutron emission was 4.0×10^{16} n/s. The maximum count rates in each of the detectors are listed in Table I. To convert these figures to neutron brightnesses (i.e., the number of neutrons emitted per m^2 isotropically into 4π from a plane that completely fills the detector line of sight), account is taken of:

(1) Solid angle.
(2) Detector dead time (typically $<15\%$ for NE213).
(3) Intrinsic efficiency (counts/incident neutron) 3.7% for $d-d$, 1.08% for $d-t$.
(4) $d-t$ contamination in $d-d$ channel. The $d-d$ channel has a detection efficiency for $d-t$ neutrons of 0.49 times that of the $d-t$ channel.
(5) Neutron backscattering (typically 2×10^{-4} times the total neutron yield for $d-d$ and ten times less for $d-t$) and in-scattering in collimators (zero for $d-d$ neutrons and 10% for $d-t$ when 21 mm diameter collimators are used).
(6) The attenuation of magnetic shielding (50% for $d-d$, 25% for $d-t$).

The collimators were surveyed and do not introduce comparable errors ($<5\%$) and the dead time is actively monitored. The efficiency for $d-d$ neutron detection was measured to an accuracy of 5%. The gain of the NE213 detectors is monitored using gamma rays from an in-built ^{22}Na source and any change in efficiency as a result of a change in gain is taken into account in the data processing. However, there is some additional error ($\sim2\%$) which remains due to counting statistics in the gamma ray spectrum.

The efficiencies of both the NE213 and BC418 scintillators to $d-t$ have not been measured but instead are calculated and are not known to better than 10%. An error in this calculation will lead to a systematic error in the overall effi-

TABLE II. Errors in neutron brightness for the two DT neutron detectors in each channel of the horizontal camera.

Channel	1	2	3	4	5	6	7	8	9	10
NE213 $d-d$ err(%)	5.5	5.0	5.2	5.3	5.5	6.5	6.5	16.7	6.7	6.6
NE213 $d-t$ err(%)	3.1	2.0	1.7	1.5	1.6	2.0	2.7	3.9	5.3	19.5
Bicron error(%)	3.8	2.8	2.1	2.1	2.2	2.4	3.7	5.3	7.0	25.4

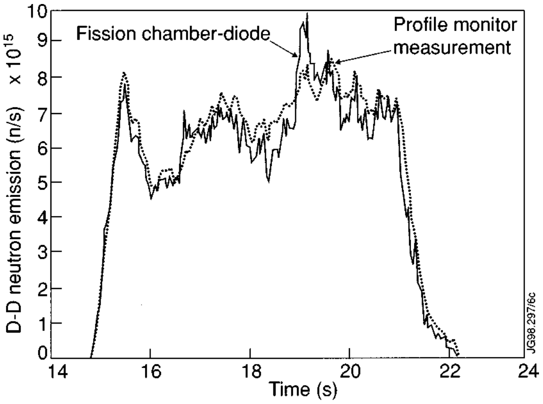

FIG. 2. Comparison of the $d-d$ neutron emission from a signal which is the subtraction of the diode 14 MeV signal from the total neutron emission measured by fission chambers (both calibrated against the JET neutron activation system) with measurements using the profile monitor NE213 scintillators. The calibration of the NE213 scintillators was independently derived.

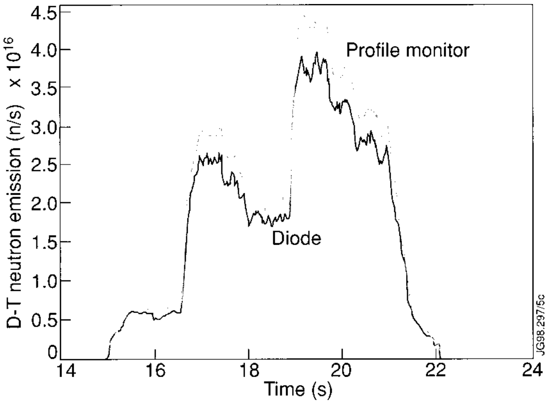

FIG. 3. Comparison of the $d-t$ neutron emission measurements using the profile monitor Bicron scintillators and a silicon diode, the latter being calibrated against the JET neutron activation system. The calibration of the profile monitor is independently derived.

ciency of the camera. There is also a random channel-to-channel error arising from the discriminator settings which should be set consistently. This error is estimated to be 6%.

The effect of neutron scattering, both backscattering and in-scattering as well as the attenuation of magnetic shielding is included (see Ref. 5 for more detail). The backscatter contribution is small for $d-t$ neutrons. Channel 10 sees only backscattered neutrons, but for the central channel the backscattered contribution is approximately 2%. These correction themselves are known to an accuracy of 6%; this includes contributions from cross-section data and Monte Carlo statistics. It should be noted that the backscatter is not constant because of the different material in the detectors' views.

The $d-t$ contamination of the $d-d$ channel is the largest correction and can be as large as 50%. The main source of error on this correction, and on the backscatter correction, is the error on the measurement of the global neutron yields. These are derived from independent instruments to an accuracy of 10%.

IV. ACCURACY

The size of the tritium puff must be set to give a sufficiently high count rate in the detectors to allow adequate time resolution and statistical precision while not being so large as to perturb the plasma. As criteria, a time resolution of 50 ms and error bars on the data $\leqslant 5\%$ were set. From Table I it is simple to calculate the variance on the data when a time resolution of 50 ms is used. However, after subtraction of the scattering contribution, etc., the fractional error is larger than $1/\sqrt{n}$. Table II summarizes the errors on the neutron profile as a function of channel number for a 50 ms time bin during the period of maximum $d-t$ emission for the NE213 and Bicron detectors.

V. RESULTS

Both the total $d-d$ and $d-t$ neutron yields can be measured simultaneously using the profile monitor. Independent measurements can also be obtained using silicon diodes which measure only the $d-t$ emission, and the fission chambers which measure the total neutron emission. The results are compared in Figs. 2 and 3. The profile monitor estimates the total $d-d$ yield to be 6% higher than the fission chamber/diode derived signal and the $d-t$ yield to be 12% higher than the diode.

The neutron measurements have been used to determine tritium transport coefficients.[3] The time-dependent neutron emission is well modeled in the plasma core. The steady state neutron emission (both $d-d$ and $d-t$) observed in the outer channels is, however, up to 40% lower than predicted. This discrepancy cannot be accounted for by instrumental effects and lies beyond the estimated error bars.

VI. SUMMARY

The JET neutron profile monitor was used to simultaneously measure the $d-d$ and $d-t$ neutron emission during discharges in which tritium was puffed in at the plasma edge. The measurements of the global neutron emission agree to within 15% with measurements from other independently calibrated instruments. The line-integrated neutron emission was determined across the entire plasma cross section with a time resolution of 50 ms and with sufficient precision that it was possible to determine tritium transport properties.

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