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Measurements of the Burn-Up of Fast ^{3}He and ^{3}H Ions in Deuterium Plasmas

J. Källne, G. Gorini*, O. N. Jarvis, G. Martin†, V. Merlo, G. Sadler and P. van Belle

JET Joint Undertaking, Abingdon OX14 3EA, England

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Abstract

Study of fusion reaction products emitted from deuterium plasmas provides information on the confinement and slowing down of fast charged particles. The information gained through these studies has a bearing on the confinement of α-particles and may contribute to predictions concerning the α-particle heating in deuterium–tritium plasmas.

Proton spectra have recently been measured at JET from the reaction $d + {}^3He \rightarrow p + \alpha$ at energies around $E_p = 14.6$ MeV. ^{3}He was introduced by gas puff (for ICRF minority heating) but is otherwise always present as a product of the reaction $d + d \rightarrow {}^3He + n$. The instrument and some of the results obtained are described.

Neutrons of about 14.0 MeV from the reaction $t' + d \rightarrow \alpha + n$ (where the 1.0 MeV tritons t′ come from $d + d \rightarrow p + t'$) can be studied given a spectrometer of high efficiency ($\varepsilon \gtrsim 0.2\,cm^2$) and low sensitivity to 2.5 MeV neutrons. A proposed spectrometer design and its envisaged diagnostic capabilities are discussed.

Besides studying the fast ions in the plasma through their fusion burn up products, atomic "burn up" is suggested as another possibility; i.e. the radiative recombination $e + t \rightarrow \gamma + t^0$ of fast tritons and measurement of their velocity distribution as represented in the neutral t^0 emission.

A comparison is made of limitations and capabilities between charged particle, neutron and neutral t^0 measurements for purpose of studying the fast ion physics and of diagnosing the plasma.

1. Introduction

Deuterium plasmas can be studied through the d–d reactions by observing their reaction products, generally the 2.5 MeV neutron and 3.0 MeV proton emission. While neutron measurements are routine diagnostics on tokamaks, proton measurements have only recently been used for special purpose investigations [1, 2]. In addition, protons and neutrons with energies of 14 to 15 MeV can be obtained from $^3He + d$ and $t + d$ reactions in deuterium plasmas in two different ways. ^{3}He can be injected for the purpose of ^{3}He ICRF heating while another source is the $d + d \rightarrow {}^3He + n$ reaction. Tritium, for obvious reasons, is not normally used, so only reaction product tritons are present in a deuterium plasma. The reaction ^{3}He particles and tritons are produced at energies of 0.8 and 1.0 MeV, respectively, and are slowed down to thermal energies over a time span of 0.1 to one second. During this slowing down time, a small fraction will undergo fusion reactions (burn up) and study of the burn up proton and neutron spectra can tell us something about the slowing down features and the confinement of these fast particles. Moreover, it is noted that fast tritons will undergo "atomic burn up" through the radiative recombination reaction $e + t^+ \rightarrow \gamma$ $e + t^0$ at similar rates to those of nuclear burn up. Measurement of escaping neutral tritons is proposed as a third possibility for investigating the plasma containment of fast tritons.

* Scuola Normale Superiore, Pisa, Italy.

† Association EURATOM-CEA-DRFC/TS, CEN, F-13108, Cadarache, France.

A motivation for the study of fast ^{3}He and triton ions in deuterium plasmas is the comparison that can be made with the slowing down of fast α particles. Of course, from the ^{3}He/t studies we can not expect to learn much about the dynamic or collective aspects of α-particle/plasma interactions when α-particle heating becomes significant in the power balance of $d + t$ plasmas. On the other hand, there are diagnostic techniques at hand for studying the behaviour of ^{3}He ions and tritons in deuterium plasmas whereas it has been found to be hard even to conceive credible measurements of α-particles in deuterium–tritium plasmas.

This paper begins in Section 2 with a short description of fast ion burn-up in high temperature plasmas. In Section 3 we discuss a proton experiment performed recently at JET and present some of the results. The aim is to demonstrate the scope of such data and the information that can be obtained on thermal and fast ^{3}He reactions in a deuterium plasma. The quantitative analysis of proton spectra requires modelling of $d + {}^3He$ reactions and proton trajectory effects which will be addressed in an accompanying paper [3]. The possibility of performing neutron measurements will be discussed in Section 4 together with an evaluation of the design limits for a dedicated spectrometer for 14 MeV minority neutrons; expected performance values in terms of efficiency, energy resolution and dynamic range will be given in comparison with the neutron fluxes for deuterium plasma operation at JET. The possibility of measuring the emission of neutral tritons from the plasma will be considered in Section 5; such measurements would give the most direct information on the slowing down velocity distribution of fast tritons and their confinement. Finally in Section 6 a comparison is made of the three approaches to the study of the behaviour of fast ^{3}He/t ions in laboratory type of experiments and for diagnostic applications under conditions of fusion plasma optimization.

2. Fast ion deuterium plasma

The fusion reactions in a deuterium plasma which produce fast ^{3}He ions and tritons are

$$d + d \rightarrow t + p \qquad (E_t = 1.01\,\text{MeV},\ E_p = 3.02\,\text{MeV})$$

$$d + d \rightarrow {}^3He + n \qquad (E_\tau = 0.82\,\text{MeV},\ E_n = 2.45\,\text{MeV})$$

where for the ^{3}He ions we use τ as subscript symbol, and t′, ^{3}He′ and τ' will be used when necessary to distinguish fast ions from thermal ions. They describe orbiting trajectories with a Larmor radius (L_R) determined by

$$L_R = 3.3p/(qB)$$

where L_R is in centimetres, the momentum p in MeV/c, the magnetic field in kG and q is the charge number; for ^{3}He and ^{3}H of maximum energy, the Larmor radius is 3.3 and 7.2 cm, respectively, assuming a field of 3.4 T.

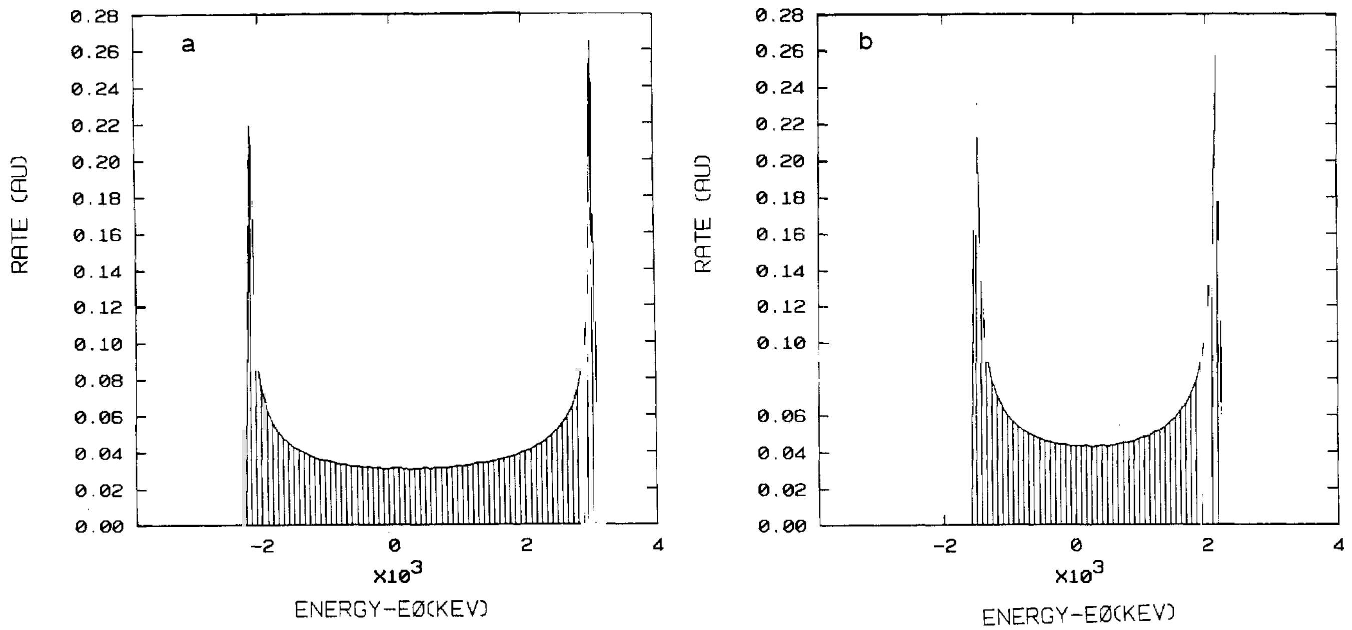
After their birth, the fast ions are slowed down to thermal velocities in the plasma on the time scale of 0.1 to 1 s for typical plasma conditions. During this time, some of the fast ions are lost from the plasma which becomes significant if the energy confinement time is short relative to the slowing down time or if there are sudden extraordinary particle losses. A small fraction of the fast ^{3}He ions and tritons undergo the fusion reactions:

$$\mathrm{t} + \mathrm{d} \rightarrow \alpha + \mathrm{n} \quad (E_\alpha = 3.6\,\mathrm{MeV},\ E_\mathrm{n} = 14.0\,\mathrm{MeV})$$

$$^3\mathrm{He} + \mathrm{d} \rightarrow \alpha + \mathrm{p} \quad (E_\alpha = 3.7\,\mathrm{MeV},\ E_\mathrm{p} = 14.6\,\mathrm{MeV})$$

This "burn up" of the fast ions can be used to study the behaviour of fast ions in the plasma by measurements of the neutron and proton emission spectra [4–6]. The protons are, of course affected by the magnetic field and only protons on escape trajectories are detectable. This limits the usefulness of proton measurements on larger machines which provide effective trapping of 15 MeV protons at high plasma currents (say $I_\mathrm{p} \gtrsim 3$ MA for JET). Proton measurements, however, have the advantage over neutron measurements in that ^{3}He can readily be introduced into a deuterium plasma whereas tritium cannot. The study of the neutron measurements, on the other hand, are of particular interest since the fast tritons and α-particles have almost the same Larmor radii.

For a definite energy of the fast tritons or ^{3}He ions, the neutron or proton energy distribution will reflect the fast ion angle distribution relative to the line of observation (in the case of neutrons) or the trajectory of observation (in the case of protons). Two examples of neutron spectra are shown in Fig. 1 for neutrons observed vertically at 90° to the toroidal axis. The triton has an energy of $E_\mathrm{t} = 1.0$ MeV. The cases shown are (Fig. 1a) for a stationary orbit in the poloidal plane ($v_\perp = v$ and $v_\parallel = 0$) and (Fig. 1b) for a spiralling trajectory ($v_\perp = v_\parallel = v/2$); the effect of thermal deuterium motion is demonstrated in Fig. 1c. These figures show a neutron energy centred slightly above the zero reaction energy of 14.0 MeV and a width of the order of an MeV, reflecting the $v_\perp$ velocity



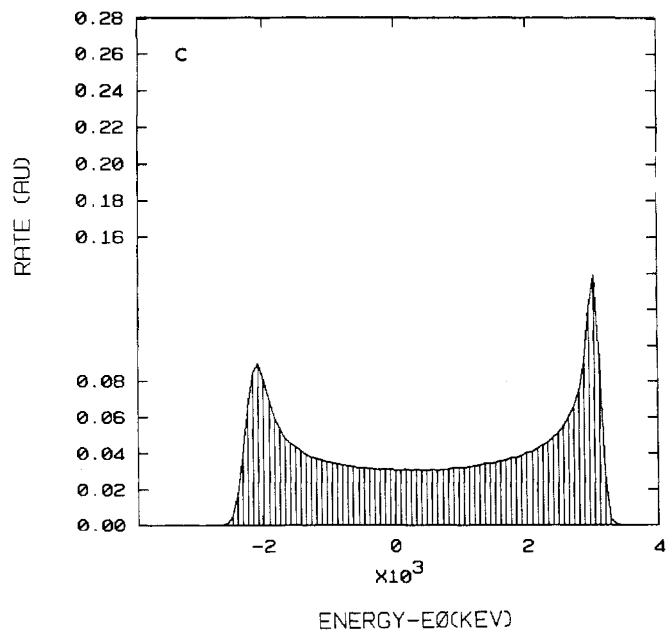


Fig. 1. The neutron energy distribution of $\mathrm{t} + \mathrm{d} \rightarrow \alpha + \mathrm{n}$ for $E_\mathrm{t} = 1.0$ MeV viewed along a perpendicular line of sight to the toroidal plasma axis. The triton trajectory is assumed to be in the plane (a) perpendicular to the toroidal axis ($v_\perp = v$ and $v_\parallel = 0$), (b) at 45° ($v_\perp = v_\parallel = v/2$); the effect of the deuterium thermal motion ($T_\mathrm{d} = 5$ keV) is also shown for $v_\perp = v$ and $v_\parallel = 0$ (c).

component of the tritons. The neutron spectrum observable in practice will be the sum of fast triton interactions for the actual range of energies and pitch angles in the plasma [5]. The shape and width of the proton and neutron spectra from ^{3}He and t burn up in deuterium plasma will therefore reflect the fast particle velocity distributions. These distributions can be determined through computer modelling and the comparison with measured spectra can be used as a test for the occurrence of anisotropic particle loss mechanisms [6].

3. Proton measurements

3.1. *Instrument*

Measurements have been made at JET using a surface barrier silicon detector which was placed close to the plasma in one of the vertical ports on the machine (Fig. 2); earlier reports on the measurements have appeared in Refs. [7–10]. The detector was separated from the JET vacuum by a 20 μm stainless steel window corresponding to a proton stopping range of about 1 MeV, for which the energy loss and the straggling are 350 keV and $\geq$ 10 keV at E_p = 14.6 MeV; the detector thickness was 2 mm (area 1 cm^2) corresponding to a proton stopping range of about 19 MeV. Water cooling was used to keep the detector at an operating temperature of about 15°C in a several hundred degree environment. The detector was shielded from direct proton and neutral radiation although the shielding was insubstantial in terms of neutrons and hard γ's. In order to minimize electrical noise, the preamplifier was placed in vacuum close to the detector and was powered with batteries. The whole assembly was housed in a 6 cm diameter tube as shown in Fig. 2. The detector was collimated so as to accept proton orbits in the poloidal plane and hence protons with velocities mostly perpendicular (pitch angles of 90°) to the magnetic field lines ($v_\perp \simeq v$ and $v_\parallel \simeq 0$).

The trajectories along which protons can reach the detector depend on both the toroidal magnetic field and the plasma current. Examples of backtrack calculations of trajectories are shown in Fig. 3 for high field and high current (B_T = 3.1 T and I_p = 2.7 MA) and for low field and low current (B_T = 2.0 T and I_p = 2 MA). In the former case, with high current, particle confinement is so effective that normally only protons born outside the plasma core (defined by the q = 1 surface) can escape from the plasma and reach the detector. For low currents, no such exclusion zone exists so the detector receives protons from the plasma core where generally the temperature and fusion reaction rate are the highest. It should be noted that the size of the exclusion zone is determined mostly by the plasma current but it is also affected by the B_T field to the extent of proton Larmor radius effects (for instance, r_L = 18 cm for B_T = 3.1 T and E_p = 14.6 MeV).

The probability for detecting protons produced in the plasma depends on several factors. The solid angle subtended by the detector for each source volume element varies with position and with proton momentum p; it is also constrained by the collimator angular acceptance at the detector. The detected fraction has been calculated and is shown in Fig. 4 as a function of minor radius and pitch angle. The detection efficiency is an important consideration in the interpretation of the measured proton emission, discussed in detail in the accompanying paper [3].

The present instrument was in operation in JET during the period April to June 1985. It has since been dismounted and will be replaced with an instrument of modified design which

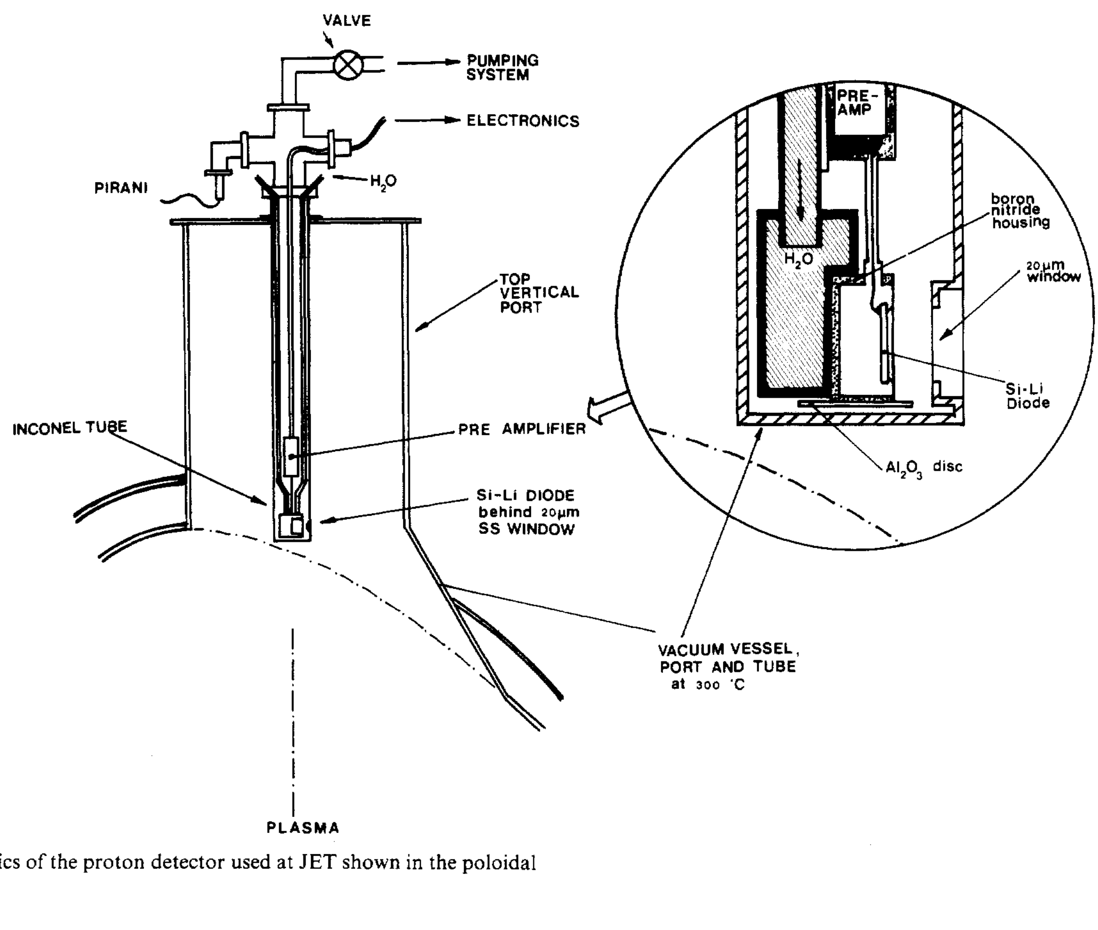
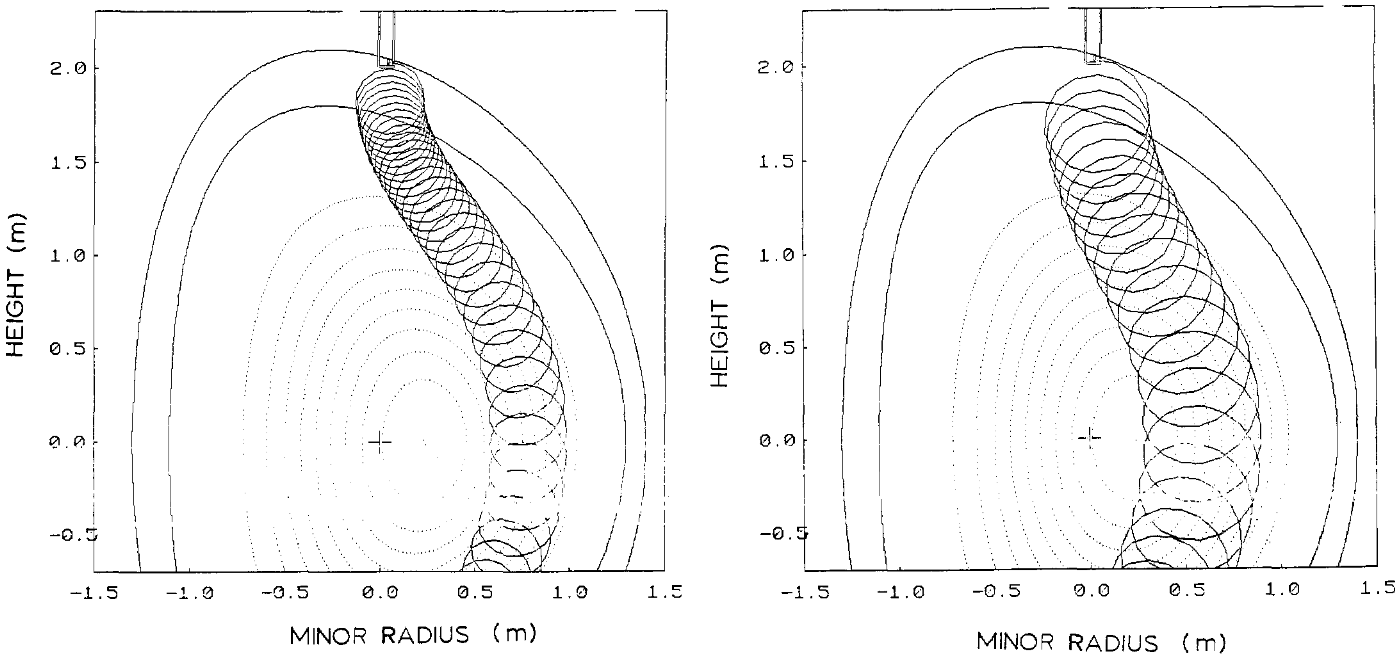


Fig. 2. Schematics of the proton detector used at JET shown in the poloidal plan projection.



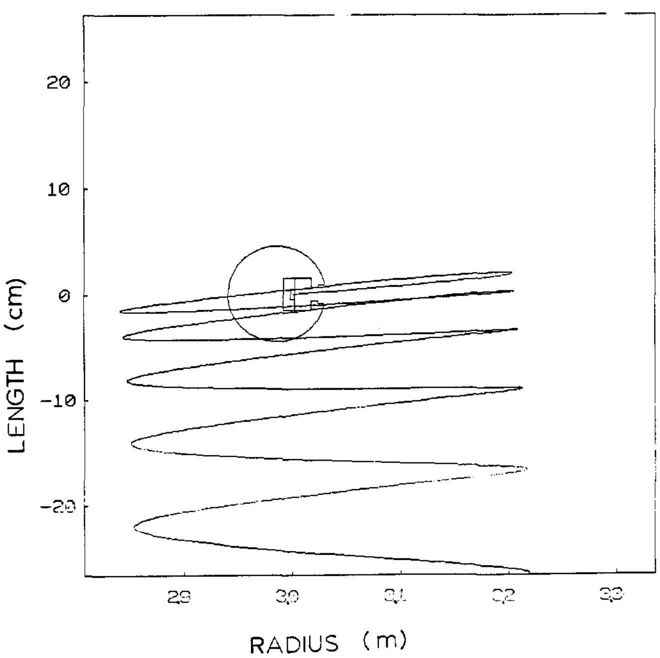


Fig. 3. Examples of proton orbits in the poloidal projection for trajectories of pitch angles close to 90° as accepted by the detector; the detector at the top of the torus is also shown. Two cases of different toroidal fields (B_T) and plasma currents (I_p) are shown: (a) I_p = 2.7 MA and B_T = 3.1 T; (b) I_p = 2.0 MA and B_T = 2.0 T. A detail of the proton trajectories close to the detector seen vertically is shown in (c).

will consist of two detectors of the same type, positioned one behind the other. The front detector will stop protons of $E_p \leqq 20$ MeV so the back detector will not respond to protons but both will essentially see the same background of neutrons and high energy γ-radiation. This measurement will therefore allow background subtraction from the measured spectrum and hence result in cleaner proton spectra. The instrument will also have a rotatable collimator for proton pitch angle selection.

3.2. *Measurements*

The experiments consisted of measuring the proton count rate and, when possible, the proton energy spectrum. The count rate was reported with a single channel analyzer ($10 \leqq E_p \leqq 16$ MeV) coupled to a latching scaler and memory. This gave the count rate as function of time over a period of some 20 s in time bins of 5 ms. The pulse height spectrum was recorded with a CAMAC analogue to digital converter (ADC) and a histogramming memory module which was incremented each 1 s for the duration of the discharge (up to 20 s). The detector energy resolution was better than about 40 keV including the energy straggling in the foil, while the system resolution was ultimately limited by electrical noise pickup which was measured to be at the level of $\Delta E/E \simeq 1\%$.

Measurements were made during three types of discharges: (i) Low field and low current were studied during the current decay phase of deuterium discharges with a small ^{3}He component ($n_\tau/n_d \simeq 0.1$ or $n_\tau/n_e \simeq 0.05$); (ii) Moderate current (2 MA), low field (B_T = 2.1 T) discharges were studied in deuterium in which H (about 10%) was added for the purpose of ICRF heating; (iii) High field (B_T = 3.1 T) and high current discharges were studied during ^{3}He minority ICRF heating.

Below we present typical examples of data on the proton count rates and energy spectra from the JET plasma.

Fig. 5 shows a spectrum from a deuterium discharge with 10% ^{3}He at low field and current so that there are no completely forbidden zones for the detector. This spectrum shows

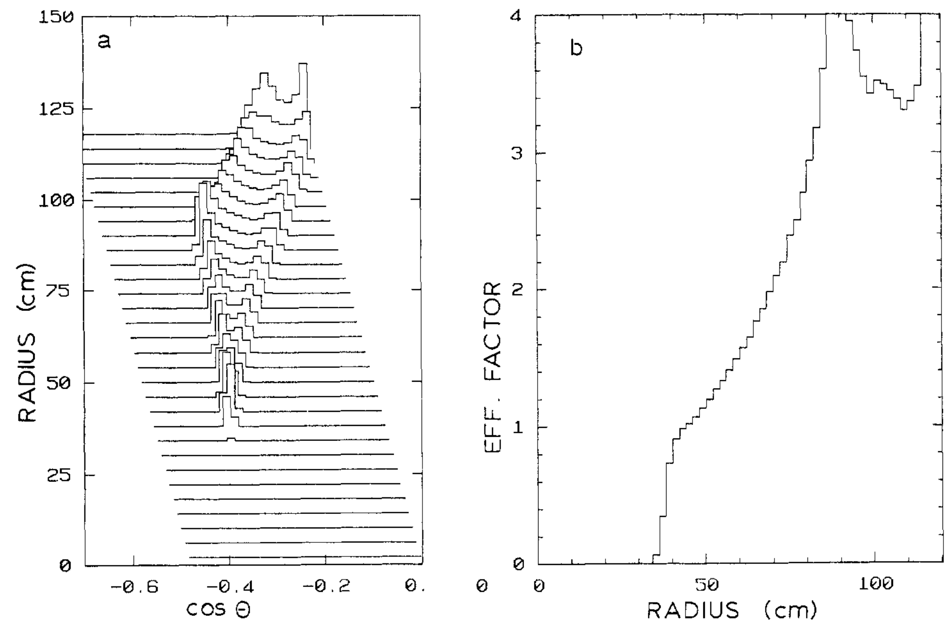


Fig. 4. The detector acceptance region in the source radius and pitch angle space (a) and variation of detector efficiency versus minor radius position of the source (b); the conditions are $B_T = 3.1$ T and $I_p = 2.7$ MA.

a narrow peak (corresponding to protons of 14.6 MeV energy) whose width can be accounted for by the instrumental resolution of 130 keV (taken as the electronic noise determined by the pulser peak) and a Doppler broadening of $\Delta E_D = 250$ keV (FWHM). The equivalent ion temperature is $T_i = [\Delta E_D/181]^2 = 1.9$ keV which should mostly reflect conditions in the plasma centre because this is the region of highest reactivity. The deduced temperature is found to be consistent with other ion temperature measurements lending support to the interpretation that the sharp proton peak stems mostly from thermal d + ^{3}He reactions. The presence of the broad proton distribution also at 14.6 MeV is attributable to interactions between fast (reaction product) ^{3}He′ ions and thermal deuterons; this is discussed below.

The proton emission due to ^{3}He′ + d was studied in deuterium discharges with minority H ICRF heating [11] for which no ^{3}He was added to the plasma. The measured proton count rate (in the energy interval 12–18 MeV) as function of time is shown in Fig. 6 and compared with the results of measurements of neutron yield and electron temperature. The proton rate shows a time lag and moderation in rate of change relative to the neutron rate, both with regard to the initial rise and the time of sawtooth crashes. These observations are consistent with the picture of proton production which is stretched in time over a period corresponding to the slowing down time of the fast ^{3}He′ from their initial energy of 0.8 MeV to thermal energies.

The proton energy spectrum was measured for similar plasma conditions (Fig. 6b). This shows a peak centred at 14.6 MeV and a width of 2.5 MeV (FWHM). The maximum

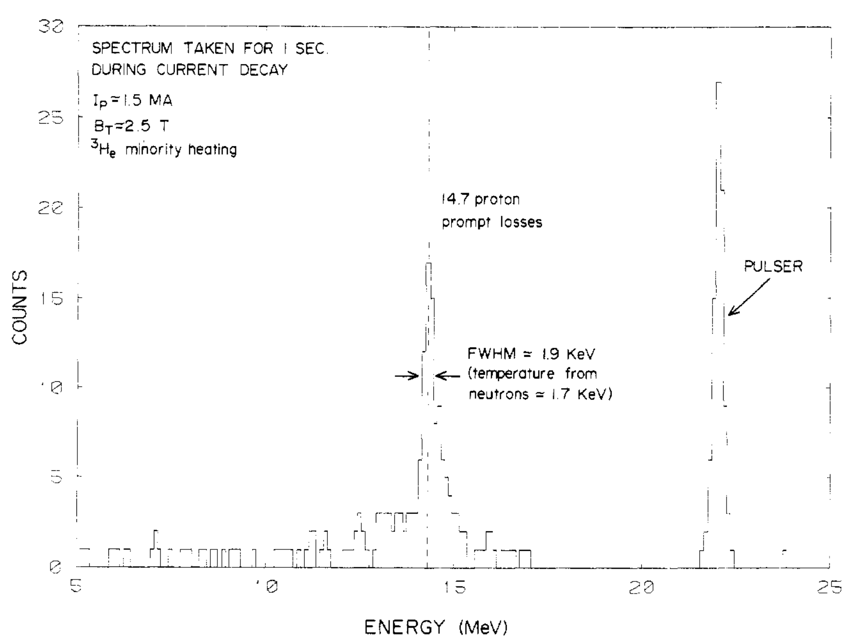


Fig. 5. Example of proton spectrum recorded during 1 s of the current ramp down phase ($I_p = 1.5$ MA) for a deuterium plasma with 10% ^{3}He at a field of $B_T = 2.5$ T. The spectrum shows a narrow and a broad peak due to d + ^{3}He → a + p reaction of thermal and fast ^{3}He ions, respectively, apart from some low pulse height background; the instrumental resolution was determined by the width of the pulser peak appearing to the right.

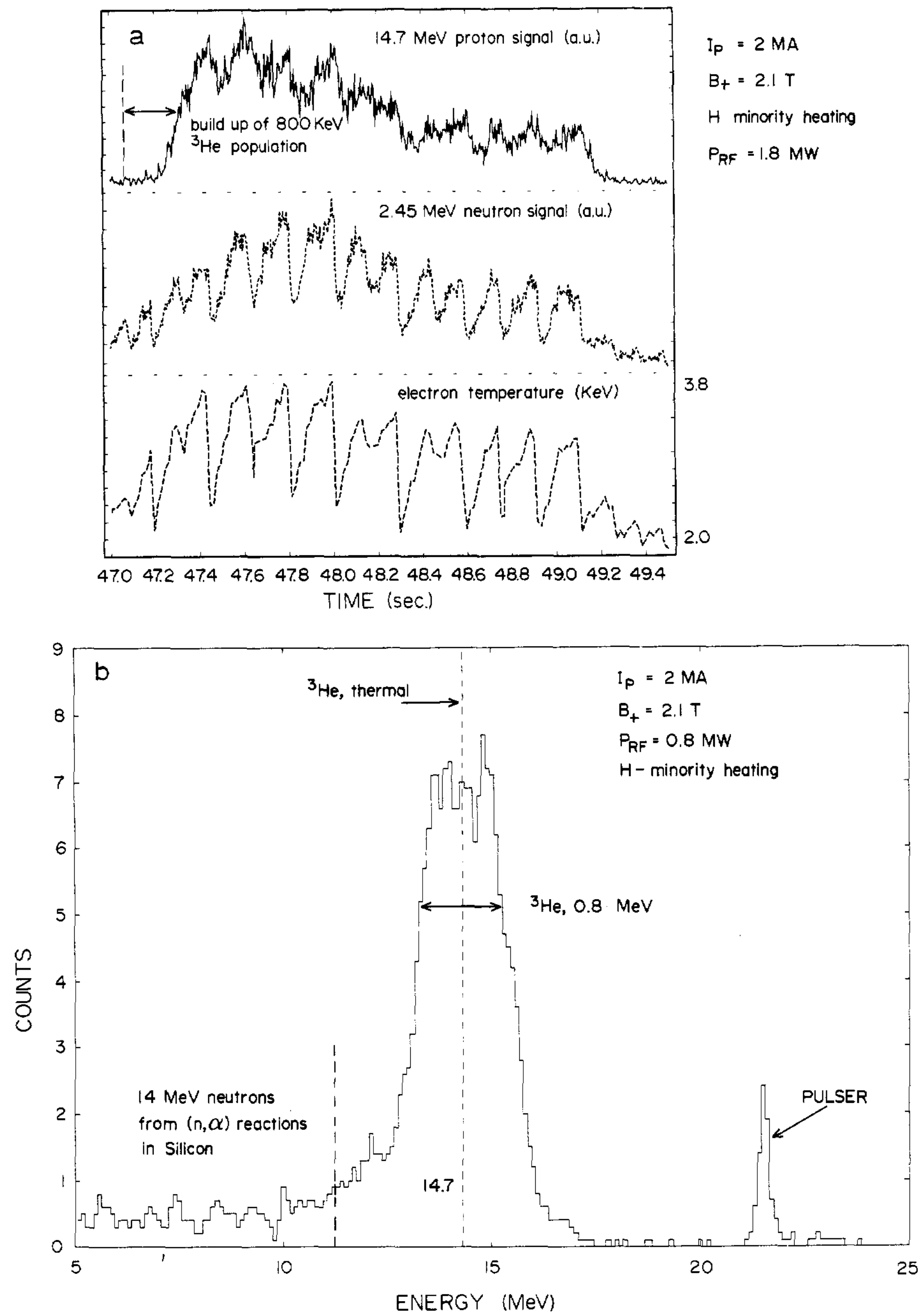


Fig. 6. Proton data typical for discharges in deuterium with H ICRF heating of around 1 MW (B_T = 2.1 T and I_p = 2 MA), (a) proton count rate as function of time compared with the neutron production rate and the electron temperature, and (b) an example of a measured proton spectrum accumulated over 1 s.

proton energy variation for the reaction $^3He' + d \rightarrow \alpha + p$ is $12.5 \leqq E_p \leqq 17.5$ MeV if the interactions take place at the initial energy $E_\tau = 0.8$ MeV while the limits are narrower if the fusion reaction (or the ^3He burn up) occurs in the course of the slowing down to thermal energies. The observed spectrum can be ascribed to protons from ^3He burn-up; as no ^3He was added to the plasma, no thermal reactions are seen in the spectra.

4. Neutron measurements

The neutrons from the $d + t \rightarrow \alpha + n$ reactions are a minority component of the neutron flux for a deuterium plasma. In order to measure the 14.0 MeV minority neutrons, the spectrometer to be used must be rather insensitive to the 2.5 MeV neutrons. In addition, the efficiency for detecting 14 MeV neutrons must be high in order to accumulate sufficient counting statistics over a time scale of 1 s. Even at the high neutron levels reached in large machines liked JET and TFTR a dedicated instrument needs to be developed for this task.

4.1. *Principle of TOF Spectrometer*

The spectrometer described here uses the time-of-flight (TOF) technique which is a standard approach for measuring neutron energy spectra over a wide energy range. The principle of TOF spectrometers is to allow the neutrons to scatter in a scintillator so that the recoiling particle creates a pulse (start time signal) with the neutron flying off towards another scintillator at known distance and determinable angle; neutron scatters in the latter scintillator give rise to the stop timing signals for the TOF measurement. Various scattering

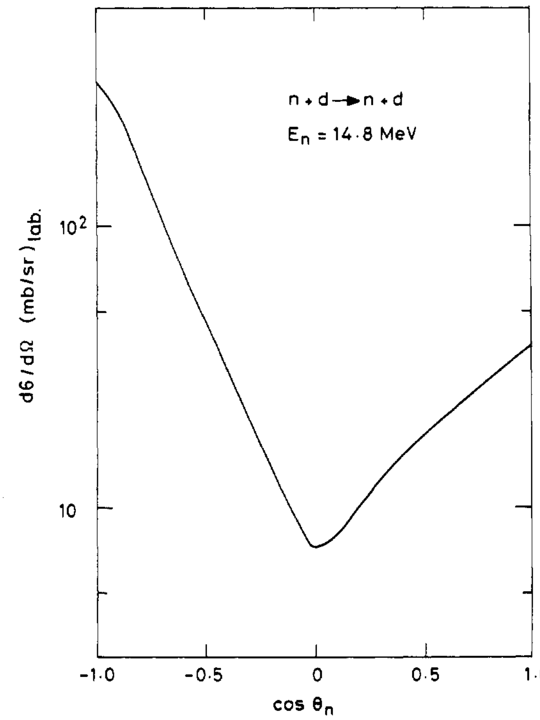


Fig. 7. The differential cross section of n + d → n + d elastic scattering in the laboratory system based on the data of Ref. [14].

geometries can be considered but it is standard to use hydrogenous material in the first scintillator so the n + p scattering limits the choice to forward neutron scattering angles. In a previous study [13] it was shown that backscattering geometry presents significant advantages to the conventional n + p TOF spectrometers; the cross section for n + d elastic scattering in the backward direction is smaller than that for forward scattering although it has a second maximum at $\theta = 180^\circ$ (Fig. 9). The n + d scattering takes place in a deuterated plastic scintillator positioned in a collimated neutron beam and the scattered neutrons are detected in a large volume scintillator system (Fig. 8). While this spectrometer is not suitable for very low neutron energies it is nearly ideal for neutrons around 14 MeV.

The backscattering geometry allows one to obtain a high efficiency ε (defined as the number of detected neutrons per unit flux of incident neutrons given as neutrons/cm^2); for instance, a design study of Ref. [7] has given the value $\varepsilon = 8 \times 10^{-3}\,\text{cm}^2$ at a resolution of $\Delta E/E = 2.6\%$ (i.e. 360 keV FWHM) at $E_n = 14.0$ MeV, with a practical dynamical range of about a factor of five hundred. For this type of spectrometer one can define a figure of merit $\varepsilon(E/\Delta E)^2$ which is of the order 10 cm^2. ε and $\Delta E/E$ can be reciprocally varied within this relationship by simply changing the flight path length L. Efficiencies $\varepsilon < 10^{-2}\,\text{cm}^2$ are adequate for measuring time resolved 14 MeV neutron spectra for the projected range of fluxes for the d + t operation of JET.

A particular feature of this technique is its relative insensitivity to 2.5 MeV neutrons so that 14 MeV neutrons can be measured even in a relatively higher flux of 2.5 MeV neutrons. The 14 to 2.5 MeV neutron intensity ratio in JET with deuterium plasmas is of the order of 10^{-2}; this intensity of 14 MeV minority neutrons is some 10^4 times lower than the 14 MeV neutron intensity from a d–t plasma under equivalent conditions. The spectrometer of the design described in Ref. [13] can in principle be used to study 14 MeV minority neutrons from a deuterium plasma if its efficiency is increased as discussed below.

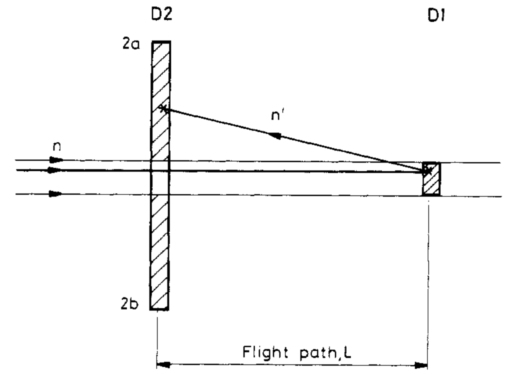


Fig. 8. The principle of the 14 MeV neutron time-of-flight (TOF) spectrometer. Dector D1 is placed in the collimated neutron flux and scattered neutrons (n′) are detected in the large area detector D2. TOF is obtained from the timing signals through TOF $= \frac{1}{2}[(T_{2.a} - T_1) + (T_{2.b} - T_1)]$ where a and b refer to different ends of the elongated scintillators of which D2 is composed. The time difference $T_{2.a} - T_{2.b}$ gives position information.

4.2. *Optimized efficiency*

An outline of the nd TOF spectrometer is shown in Fig. 9. A well collimated neutron flux from the plasma is made to hit the detector system D1 consisting of several deuterated plastic scintillators (16 in the basic design of Ref. [13] as shown in Fig. 10). The neutrons scattered through n + d → n′ + d′ reaction in D1 are detected with a large area (A) neutron detector D2 consisting of elongated plastic scintillators (for

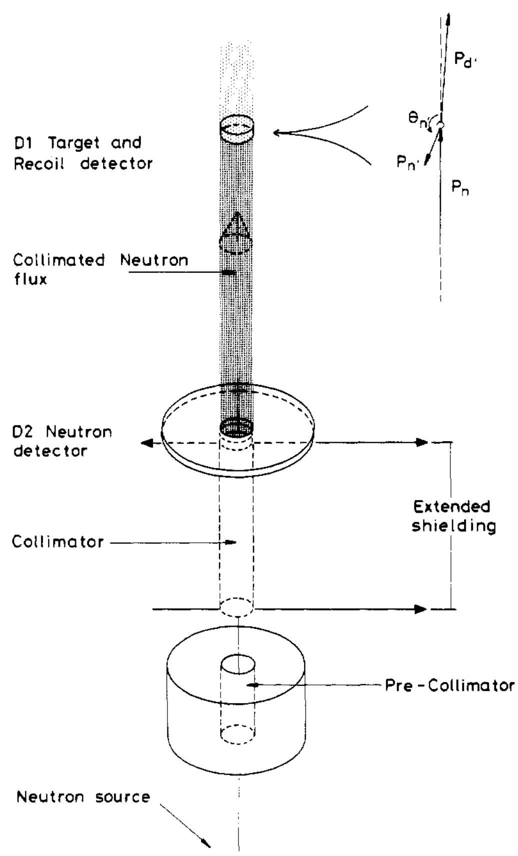


Fig. 9. Outline of the nd TOF spectrometer showing the detection area of the deuteron recoil detector (D1) and the scattered neutron detector (D2) as well as the collimated neutron beam. The kinematical diagram of n + d → d′ + n′ reactions in D1 is also indicated.

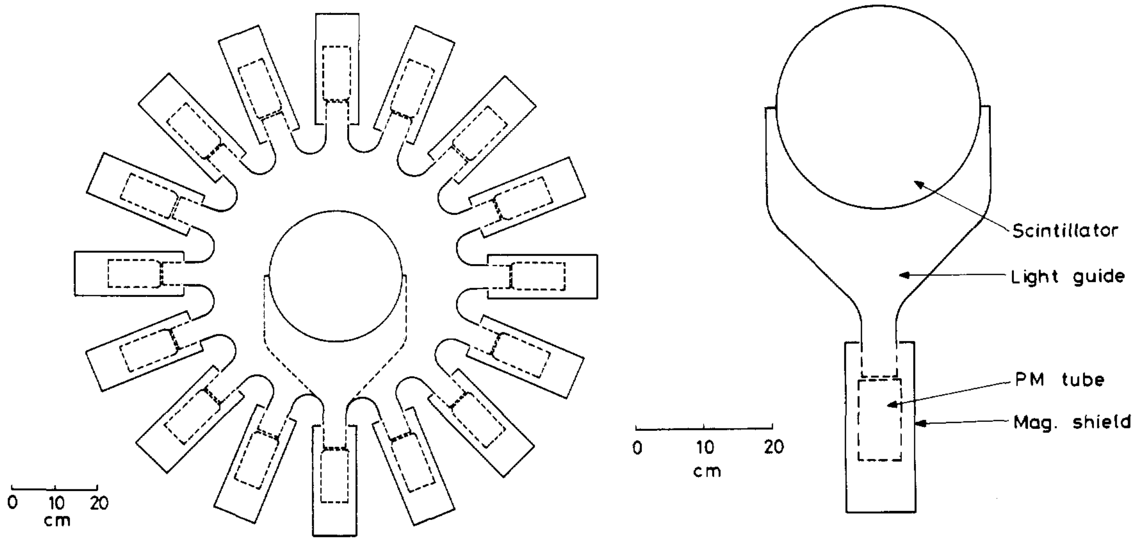


Fig. 10. (a) The D1 detector system consisting of 16 assemblies of deuteriated scintillators, light guides (shown for only one detector) and photomultipliers; (b) detail of one detector unit.

instance, A = $2900\,\text{cm}^2$ using 12 scintillators $1.5 \times 6 \times l\,\text{cm}^2$ where $l = 38 - 66\,\text{cm}$; see Fig. 11). This gives a figure of merit of $\varepsilon(E/\Delta E)^2 = 13\,\text{cm}^2$, and within this reciprocity, ε and $\Delta E/E$ can be changed as desired by using the TOF path L defined as the distance between D1 and D2. This, however, is strictly valid only for neutron scattering angles in the extreme backward direction where the variation in $\Delta E/E$ is proportional to $1/L$. For $\theta_{n'} < 170°$ (corresponding to $L = 200\,\text{cm}$ for a D2 detector within an extension radius of 30 cm) the deviation from proportionally becomes of practical significance. At this point the apparent increase of L with θ_n using a flat D2 detector is not sufficient compensation for the kinematic angular variation in the neutron energy, $E_{n'} = E_n/9[\sqrt{3 + \cos\theta} + \cos\theta]^2$.

In order to remedy the degradation in resolution due to kinematics, but retaining the flexibility offered by operation with variable L, spatial information is needed from the D2 detector [17]. The elongated scintillator with one PM tube attached to each end (a and b) can provide this information. First, the timing for the TOF measurement is obtained from the sum $\frac{1}{2}[(T_{2,a} - T_1) + (T_{2,b} - T_1)]$, which is independent of event position while the time difference $T_{2,a} - T_{2,b}$ can give information on the position along an elongated detector with an estimated accuracy of about 10 cm. The detector timing measurement together with identification of which detector was hit give the neutron coordinate in the D2 detector. With this information, corrections can be made for the kinematical energy shift in the region $\theta \geqq 150°$ in order to keep its contribution to the TOF energy resolution to less than 5%.

Besides the above mentioned constraint on the angular range, there are practical limits on the size of the detector to be used. The upper limit for the D1 detector volume is about $500\,\text{cm}^3$ as dictated by the multiple interaction probability (total thickness) and resolution degradation (area) but also partially because of cost. The D2 scintillator must be limited in length to about 1 m (to keep the light attenuation to a manageable level), with a total thickness of no more than about 3 cm. In this way we can increase the spectrometer

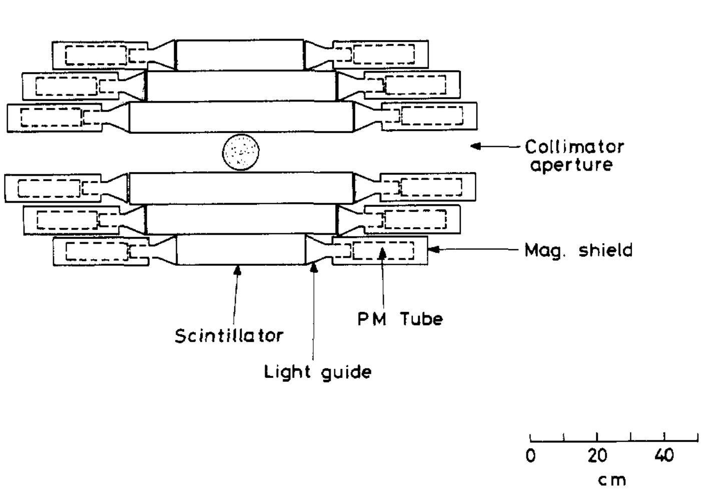


Fig. 11. One of the two detector planes of the neutron system (D2) consisting of elongated scintillators with light guides and multiplier tubes attached at each end.

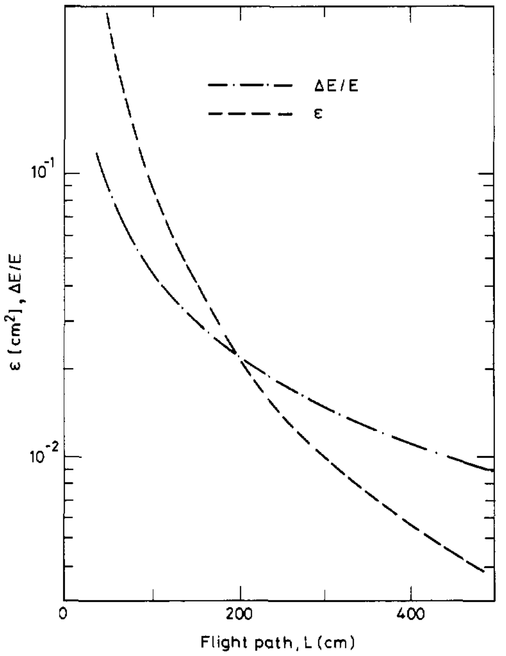


Fig. 12. The spectrometer efficiency (ε) as function of flight path length L_1 and the energy resolution ($\Delta E/E$) assuming a timing resolution of 1 ns and no kinematical effects.

figure of merit by about a factor of three. With this type of spectrometer one can achieve an efficiency of $\varepsilon = 0.2\,\text{cm}^2$ and a resolution of $\Delta E/E = 0.05$ using a flight path length of $L = 80\,\text{cm}$. Larger L values can be chosen to improve the resolution ($\Delta E/E \propto L$) with corresponding loss of efficiency ($\varepsilon \propto 1/L^2$) as indicated in Fig. 14. The efficiency can be increased up to a maximum of about $2\,\text{cm}^2$ if the flight path is decreased to $L \simeq 0.3\,\text{m}$ but the instrumental resolution is then increased by kinematics effects to about 30%; this is therefore the efficiency in the counting mode limit.

Even at high efficiency for 14 MeV neutrons the majority flux of 2.4 MeV neutrons should cause no interference problems. The 2.4 MeV pulses in D1 are 10 times smaller than those of 14.0 MeV neutrons while in the D2 detector they are 50 times smaller. This means that with the additional separation by means of TOF, all 14 MeV neutrons can be clearly identified and counted at rates in excess of 10 kHz. The presence of the 2.4 MeV neutrons can therefore be considered as noise causing a jitter in the timing signals at the level of 1/10 of the rise time, or less than 0.5 ns; this is an insignificant contribution to the instrumental energy resolution.

4.3. *Possible measurements*

The instrument described above would allow measurements of the 14 MeV neutrons from deuterium plasmas. If we assume the conditions for the JET machine providing a deuterium discharge with a 2.4 MeV neutron production rate in the range 10^{16} n/s and $I_{14.0}/I_{2.4}$ of about 10^{-2}, the spectrometer count rate would be at the level of 1 kHz with 5% energy resolution or 10 kHz in the counting mode operation with energy resolution only sufficient for event identification.

5. Measurements of neutral tritium emission

Instead of measuring the reaction products of the ^{3}He + d and t + d reactions one might consider measuring the fast ^{3}He or tritons directly. This is, of course, rather difficult in practice and it is basically also not the lost ions one is primarily interested in but those contained in the plasma. However, a small fraction of these ions undergo electron capture in the plasma; while the probability for double electron capture (as required for ^{3}He) is practically nil there is some probability for forming neutral tritons by radiative recombination, i.e. $e^- + t^+ \to t^0 + \gamma$ in the energy range of interest from 1 MeV and down. At $E_t = 1\,\text{MeV}$ the triton velocity is $v_t = 8 \times 10^8\,\text{cm}\,\text{s}^{-1}$ which is small compared to the electron velocity of $v_e = 6 \times 10^9\,\text{cm}\,\text{s}^{-1}$ (at $T_e = 10\,\text{keV}$) so the recombination rate R_{rr} is determined by the electron temperature. It is known to be $4 \times 10^{-17}\,\text{cm}^3\,\text{s}^{-1}$ at $T_e = 7\,\text{keV}$ [16] so that at an electron density of $3 \times 10^{13}\,\text{cm}^{-3}$, an assumed 2.5 MeV neutron production rate of 10^{15} n/s (a representative source rate of tritons for JET) and with a triton slowing down and containment time of 1 s, the production rate of fast neutral tritons would be in the $10^{12}\,t^0$/s range. These are mostly produced within the hot core of the plasma which for JET is of the order of cubic meters, so the central neutral triton production rate density is $10^6\,\text{s}^{-1}\,\text{cm}^{-3}$. These neutral tritons would leave the plasma with energies and trajectories as at the moment of neutralization, apart from those ionized through electron or ion collisions along the escape path. Both these processes will attenuate the fast t^0 flux while ion collisions can also change the initial momentum; the latter effect, however, should be rather small.

Instead of attempting to estimate the attenuation factor from the recombination/ionization balance, comparison is made with the situation for thermal neutral deuterons which are routinely measured in the neutral particle analyzer diagnostic [18]. For the conditions mentioned above, the d^0 production rate can be estimated to be $10^{10}\,d^0\,\text{cm}^3\,\text{s}^{-1}$. (The ionization/recombination equilibrium occurs in this case at the n_{d0} level of 10^{-6} to 10^{-4} times n_e, i.e., the density range 10^7 to $10^9\,d^0\,\text{cm}^{-3}$). While the difference in production rate is a factor of 10^4 between thermal d^0 and fast t^0 the outward flux ratio of escaping d^0 and t^0 should be smaller for two reasons. First, the attenuation due to electron impact ionization decreases with increasing particle velocity; for instance, the difference between thermal deuterons and 1 MeV tritons is a factor of 10. Second, the thermal neutral measurements usually extend to the high energy tail of the Maxwellian distribution; this means a reduction of $\exp(-E_d/4kT)$ or a factor of 10^3 assuming $kT = T = 7\,\text{keV}$ for deuterons measured at $E_{d0} \simeq 40\,\text{keV}$. It therefore would seem that the flux of fast neutral tritons under the conditions mentioned could be comparable to that of thermal deuterons at an energy of 7 times the ion temperature.

Spectra of neutrals from the bulk plasma are routinely measured at tokamaks with neutral particle analyzers (NPA) in energy bins of 1 to 10 keV over the 1 to 100 keV energy range with sufficient sensitivity to permit mass separation to distinguish hydrogen and deuterium. The thermal neutrals (or rather the high energy tail of the Maxwellian distribution) are usually found to give adequate flux for diagnostic measurements. For instance, NPA measurements at JET have been made under the conditions of the above example for deuterons out to about 40 keV with a tolerable neutron background; this instrument is presently being upgraded to withstand higher neutron fluxes and to detect higher neutral energies [17, 18]. In the proposed application of NPA measurements one would be interested in tritons from 1 MeV and down. This would be the dominant source of high energy neutrals in the plasma while in some intermediate energy range these $t^{0\prime}$ particles and the thermal d^0 particles of the bulk plasma would be of comparable intensity. However, with a dedicated instrument one should be able to obtain sufficient separation between mass 2 and 3 particles so as to measure the triton energy spectrum over the region of 0.1 to 1 MeV and obtain simultaneous measurement of neutral deuterons and tritons over some energy bands.

A measurement of the emitted neutral triton spectrum should give a very direct representation of the triton slowing down spectrum since the recombination rate is not sensitive to the triton energy. However, correction for the attenuation of the neutral emission as a function of energy will be the largest uncertainty especially towards lower energy. Since the triton momentum is frozen at a point in space and time by the recombination, one could actually scan the triton emission in the horizontal plane and thereby directly obtain the pitch angle distribution. One could also hope to obtain rather good time resolution compared to the slowing down times of about 1 s or even at shorter time scales which might be of interest for monitoring sudden loss of particle confinement. Simultaneous measurement of deuteron and triton spectra and their ratio could provide useful additional information.

6. Comparison of fast ion measurements

The measuring capabilities and limitations of the three techniques discussed are rather different and in certain respects they can be seen to be complementary. They can all provide information on fast ion behaviour in plasmas but the scope of the data are different and so are the analyses needed. Below we compare the three techniques and make some comments on their utilization under different plasma conditions.

6.1. *Proton measurements*

Silicon proton detectors are commercially available and provide good detection efficiency and energy resolution. They can, with special care for electrical interference, be placed close to the torus. The proton flux can easily be collimated so as to define the angular acceptance which can be changed for measurement of proton pitch angle distributions. However, Si(Li) detectors are sensitive to neutron radiation and massive shielding cannot be used. The neutrons cause background in the spectra which is not disturbing at low count rates (see Section 3.1) but will be a burden on the proton count rate capability at higher neutron rates and eventually the detector will suffer radiation damage. Because of the high detection efficiency and the neutron flux limitations, this is a technique for low fusion rate deuterium discharges.

The proton spectrum measured from $^3\mathrm{He}' + \mathrm{d} \rightarrow \alpha + \mathrm{p}$ reactions is not only a function of the burn up but also of the proton confinement in the plasma. This is therefore an inclusive measurement of two effects which can be separated by model analysis of the data (cf. Ref. [3]). Moreover, the determination of the detection efficiency for different source volume elements in the plasma is a non-trivial exercise. It is, therefore, rather difficult to obtain an accurate absolute value on the $^3\mathrm{He}' + \mathrm{d}$ fusion reactivity rate from measured proton rates. Proton spectrometry, however, is unique among the techniques in that ^{3}He can easily be introduced into a deuterium plasma making it an interesting probe of the ^{3}He ions in the 100 keV plus range created by ICRF heating.

6.2. *Neutron measurements*

There is no standard neutron spectrometer available but we have shown that an instrument could be developed for 14 MeV minority neutron measurements. The spectrometer would work with a collimated neutron flux and can preferably be placed in a well shielded position at a distance from the plasma. Even after efficiency optimization the count rate will be low so that time resolved data on the time scale of 100 ms can only be hoped for γ with the highest neutron production rates in deuterium for the present big machines. In this respect, neutron and proton measurements would complement each other. In contrast to the proton measurements, the neutron spectra of $\mathrm{t}' + \mathrm{d} \rightarrow \alpha + \mathrm{n}$ would only depend on the burn up factor and the effective source volume as defined by the line of sight and plasma depth. Neutron data can therefore be used to determine the $\mathrm{t}' + \mathrm{d}$ reactivity rate density with rather good accuracy. The intensity ratio of 14 MeV to 2.5 MeV neutron production can be determined (using 2.5 MeV data from standard diagnostics) and is largely independent of plasma conditions other than through their effect on the burn up [5]. Data on the intensity ratio (without the spectral information) are most informative if high count rates can be achieved, i.e. good statistical time resolution which, however, is difficult to accomplish. Finally, it should be pointed out that the proposed TOF spectrometer would also readily measure the much higher 14 MeV neutron rates that are obtained if tritium is admixed with deuterium; but that is, of course, tritium phase operation when α-particles should be studied directly for their dynamic effects on the plasma.

6.3. *Neutral triton measurements*

The neutral triton emission for a deuterium plasma is the most direct source of information on the velocity distribution of fast triton ions in the plasma. Since the source volume is defined by the line of sight, the triton pitch angle can be obtained by scanning the instruments in the toroidal mid plane. The estimated emission rates appear to be sufficient to allow measurements on plasmas with high triton production rates, which means high neutron production rates. Therefore, in order to be able to detect the emission of neutral tritons, the t^0 detector efficiency and neutron background sensitivity need to be improved to a level where the signal to background is better than say 10 to 1. The measurability of the spectrum will then depend both on the triton production rate in the plasma and on the t^0 count rates that can be achieved for the desired time resolution. Some preliminary experimental information on these questions might be obtained from the existing NPA instruments on JET now under modification [17] and further design studies should be made to establish if time resolved measurements of the velocity distribution of fast tritons in the plasma can be realised.

6.4. *Experimental conditions*

The interpretation of burn up spectra from fast ion interactions in deuterium plasmas depends on the bulk plasma conditions. It is clear that the plasma of Ohmic discharges, with thermal particle velocity distributions, are most easily characterized and present the most stable plasma conditions. These plasmas are therefore most amenable to data reduction and analysis. They also offer the best opportunity for predicting the confinement and slowing down of fast tritons and ^{3}He ions in terms of specific physics assumptions. In this case it can be hoped that by comparing burn up data and plasma model predictions one will learn something about the basic behaviour of fast ions in the plasma. This approach to fast ion study would be closest to what one can call the laboratory approach where one tries to control the influencing factors as much as possible. Unfortunately, these well characterized Ohmic discharges are usually not the ones which provide the strongest burn-up signal so a trade off must be made between experimental and interpretational needs.

The other application for burn-up measurements would be to provide diagnostic information on discharges when attempts are made to optimize the parameters of fusion plasmas. In these one usually employs powerful additional heating (neutral beams and RF waves) which leads to complex states of plasma with non-thermal particle velocity distributions and plasma rotation accompanied by a high level of internal disruptions and instabilities. These conditions are difficult to model theoretically and the objective of the diagnostic measurements becomes largely to monitor the occurrence of adverse phenomena such as loss of confinement of fast ions. In these discharges one would expect to reach the highest fusion reactivity levels leading to enhanced fast ion densities in the plasma which would benefit the neutron and t^0 measurements.

7. Conclusions

We have discussed different approaches for studying the slowing down and confinement of fast ^{3}He ion and tritons in deuterium plasmas. Measurement of proton spectra for $^3He + d \rightarrow \alpha + n$ have already been made and some recent results from JET were presented to exemplify some experimental and interpretational aspects. A spectrometer design was proposed for 14 MeV minority neutron measurements of the $t + d \rightarrow \alpha + n$ reaction. Besides these fusion burn up reactions, "the atomic burn up" reactions was proposed as a third possibility for fast ion studies. Measurements of proton, neutron and neutral tritium spectra were compared from the experimental as well as the interpretational viewpoints with the identification of two main areas of applications: Fast ion studies in deuterium plasmas should be performed (a) in laboratory type measurements using Ohmic plasma discharges to gain insight into the physics of the confinement and slowing down of such particles and (b) in discharges set up for fusion parameter optimization to provide fast ion diagnostic information.

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