EFDA–JET–CP(07)04/03

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** See annex of M.L. Watkins et al, "Overview of JET Results ",*
(Proc. 21st IAEA Fusion Energy Conference, Chengdu, China (2006)).

Preprint of Paper to be submitted for publication in Proceedings of the
Inernational Workshop on Burning Plasma Diagnostics, Villa Monastero,Varenna, Italy.
(24th September 2007 - 28th September 2007)

ABSTRACT.

In large tokamak devices, such as JET, TFTR, JT-60U and ITER, a neutron emission profile monitor is considered as one of the principal diagnostic tools, firstly in providing information to characterize the fusion source in terms of its location, shape, intensity and secondly in developing an understanding of fast ion physics in tokamak plasmas. The JET neutron profile monitor is one of the most advanced such instruments currently operating. It enables 2-D imaging of the non-circular plasma neutron source through a tomographic deconvolution of line-integrated measurements. Historically it was usually assumed that the fusion neutron source is a function of the Magnetic Flux Surfaces (MFS), but recent JET results have clearly demonstrated the influence of non-uniform fast particle populations on the neutron emission profile.

Neutron energy spectroscopy also carries valuable information about fast ion behaviour and the fusion and nuclear reactions taking place in the plasma. Spectrum measurements of neutrons will be particularly important for the up-coming JET experiments with a Be wall. The neutron spectroscopy capabilities at JET were recently enhanced by several instruments: a new Time-Of-Flight spectrometer Optimized for high count Rates (TOFOR), compact neutron spectrometers based on organic scintillator (NE213) and an upgrade of the Magnetic Proton Recoil system (MPRu). In recent JET campaigns, a prototype Digital Pulse Shape Discriminator (DPSD) has been successfully tested on one central chord of the JET neutron profile monitor and spectral information has also been obtained. Neutron spectrometry results obtained during the last JET experimental campaigns illustrate the measurement capabilities and indicate their potential use on ITER. Several projects are in progress to further develop such diagnostic capabilities and these are briefly summarized.

1. INTRODUCTION

Diagnosis of the plasma neutron source is of major importance for characterization of the fusion burning process and for determination of the performance of next step burning plasma devices, such as ITER. JET is the machine closest to the ITER parameters and it provides a unique tritium operation capability making it a good test bed for development of the ITER-relevant plasma diagnostics. The neutron emission from the JET tokamak is investigated using an extensive set of diagnostics, permitting the instantaneous neutron yield, the radial profile of the neutron emission and neutron energy spectra to be studied.

The JET neutron profile monitor is a unique instrument among the diagnostic systems available at large fusion devices. Section 1 of this paper briefly reviews the design of this device and presents some recent results. The necessity of 2-D neutron emission measurements arises from the fact that in the presence of fast ion component, contours of equal neutron emissivity are not necessarily coincident with Magnetic Flux Surfaces (MFS). At JET, this disconjunction has been observed in recent DD and trace tritium experiments during periods of ion cyclotron resonance heating, neutral beam injection, sawtooth oscillations and other MHD instabilities. To improve the performance capabilities of the neutron profile measurements, the replacement of analogue pulse shape discrimination electronics with new digital systems has been started under a JET enhancement programme.

Significant attention is also paid on JET to developing new diagnostics for energetic particle studies. Neutron energy spectroscopy carries valuable information about fast ion behaviour and the fusion and other nuclear reactions taking place in the plasma. Recently, the major neutron spectroscopy development efforts at JET have been focused on the time-of-flight spectrometer TOFOR and on two different kinds of proton-recoil spectrometers: the Magnetic proton recoil (MPR) spectrometer and the organic liquid scintillator NE213. Neutron spectrometry results obtained lately at JET are provided in Section 2 to illustrate the measurement capabilities and indicate their potential use on ITER. Several projects are in progress to further develop such diagnostic capabilities and these are briefly summarized in Section 3.

1. NEUTRON EMISSION PROFILE MEASUREMENTS AT JET.

The primary function of a neutron profile monitor is to measure the neutron emissivity profile over a poloidal plasma cross-section using line-integrated measurements along a number of chords (lines-of-sight). Knowledge of the absolute detection efficiency of the system enables one to obtain the total instantaneous neutron yield from the tokamak, and this can independently supplement the results derived from primary methods of yield measurement, such as neutron activation or neutron flux monitors. Therefore a well-designed neutron profile monitor is potentially the most important among the other neutron diagnostics. The JET neutron emission profile monitor is one of the most advanced such instruments currently operating.

1. THE JET NEUTRON PROFILE MONITOR.

The upgraded neutron profile monitor was installed in the mid 90's and since then has been used routinely, often playing a vital role in the physics understanding of fast ion population effects in the plasma and of the impact of different heating scenarios. The instrument was well described in several papers [1, 2], therefore only a short description will be given here.

The JET neutron emission profile monitor consists of two concrete shields (“cameras”) which each providing a fan-shaped array of collimators. One camera views the plasma horizontally (10 channels), and the other vertically (9 channels). In each camera, the collimation can be remotely set up by the use of two pairs of rotatable steel cylinders with a choice of two aperture sizes. This permits one to tune the count rates in the detectors by a factor of 20 [3], so the detectors are able to cope with a neutron emission rate up to 10^{19} s^{-1}, making the instrument equally suitable for both DD and DT regimes of operation. The plasma coverage by neutron profile arrays is adequate for 2D tomography, although the spatial resolution is rather poor (~8cm at the plasma centre for a collimator aperture of 10mm by 10mm when neighboring channels are 15–20cm apart). Each channel is equipped with a set of three different detectors: i) a NE213 liquid scintillator with

Pulse Shape Discrimination (PSD) electronics to measure 2.5MeV, 14MeV neutrons and gamma-rays simultaneously; ii) a Bicron BC418 plastic scintillator for 14MeV neutron detection only with very low sensitivity to gamma radiation; iii) CsI(Tl) photodiodes known as the ‘Fast Electron Bremsstrahlung (FEB)’ detectors, for spatial measurements of Hard X rays and gamma emission with energies from 0.2 up to 6MeV.

As mentioned above, each NE213 detector channel is equipped with quite complex analogue signal processing electronics with pulse shape discrimination capabilities to allow neutrons to be separated from gamma-rays and to provide the necessary energy discrimination, so that DD neutrons and DT neutrons within set energy windows can be recorded separately. The Bicron scintillators are positioned in front of the NE213 scintillators and record neutrons with energy above 8.5MeV, i.e. DT neutrons only. Because of their small size they are relatively insensitive to γ-rays with $E\gamma < 10$MeV and the PSD complications are not required. The CsI(Tl) gamma detectors allow the JET neutron profile monitor to also act as a gamma-ray profile monitor as is illustrated in [4].

The absolute efficiencies and light outputs response of the two neutron detectors were measured using the Harwell Van de Graaff accelerator [1]. Since all of the detectors view the inner vessel wall of the JET vacuum vessel, extensive Monte Carlo neutron transport calculations are required to evaluate scattering and attenuation effects. This has been done and the profile monitor provides an independent, absolute measurement of the instantaneous neutron yield that agrees with measurements obtained from the neutron activation system to well within the estimated combined errors of about 10-15% [2, 5].

1.2. NEUTRON PROFILE MEASUREMENTS AT JET.

The JET neutron profile monitor was the key diagnostic for the Trace Tritium Experimental (TTE) campaign (with the introduction of trace amount (<5%) of tritium into D plasmas) in 2003, with over 80% of the experiments relying on its profiles of 14 MeV neutrons. The power of this instrument is demonstrated below by reference to some results recently obtained.

Many JET discharges employ auxiliary ICRH and NBI heating which can lead to anisotropy of fast ion velocity distributions. In such cases, the magnetic flux surfaces can no longer be assumed to be contours of constant neutron emissivity. For example, neutron emission spatial asymmetries have been clearly observed by the vertical camera in the TTE ICRH experiment with fundamental heating of tritium [6]. In this case, the high-energy tritons reacting with the deuterium bulk plasma induce a neutron emission profile which peaks off axis, close to the T cyclotron resonance layer [5, 6].

The effect of the current-hole, a region of negligible current in the core of the plasma with strong reverse shear, on the fast particles distribution was investigated in experiments using NB injected tritons as test particles and monitoring their spatial and temporal evolution via their 14MeV neutron emission, as observed by the neutron cameras [7]. In the case of on-axis injection into a monotonic current profile, the emission was peaked on the plasma axis. For injection into a current-hole plasma, there was a clear shift in the emission in the radial outward direction [6, 8].

The radial distribution of NB-injected fast ions can be assessed using the neutron emission profile in cases where the thermal neutron yield is negligible. Dedicated experiments were carried out in the 2003 TTE campaign using short tritium beam blips (~300ms) with both on-axis and off-axis trajectories injected into deuterium plasmas to provide a basis for the validation of NB fast ion models. The measured 14MeV-neutron emission showed peaked or flat profiles corresponding to on-axis or off-axis beam injection respectively, in good agreement with TRANSP Monte Carlo simulations for both cases [8].

During 2003 TTE campaign, the neutron profile monitor was an indispensable tool for studies of tritium transport [10], fuel ratio [11], and different heating scenario [7,8,9]. As mentioned above, it also complements the activation system and neutron flux monitors providing an independent estimate of the absolute neutron yield from the plasma. The total 14 MeV neutron yields derived from the silicon diodes and the neutron profile measurements during TTE in 2003 were in an agreement with the profile monitor estimate to within ~8% [5].

Tomographic inversion of the line-integrated measurements has been also carried out to obtain a 2D mapping of the neutron emission strength. It should be noted that the number of lines of sight in the JET neutron profile is well short of what usually is considered needed for reliable tomography reconstruction. Several tomography techniques, including those used successfully for X-ray imaging, have been tested and used at JET for the purpose of neutron and gamma tomography giving clear indications of asymmetries in the poloidal neutron profiles [12, 13].

2. NEUTRON SPECTRUM MEASUREMENTS AT JET.

At JET, neutron spectrometry has been used since its early days and always rated as an essential tool for obtaining valuable information on the fuel ion temperature and composition and, in the case the plasma is subjected to auxiliary heating, the intensity and velocity distribution of the fuel ion populations for both DD and DT plasmas. JET plasma operating conditions can vary considerably in ion temperature and density, resulting in a large range of variation in both the rate and the energy distribution of the neutron emission. Since individual spectrometers have characteristic efficiencies and energy resolutions and operate within a more limited dynamic range, it is almost impossible to design a single neutron spectrometer which can satisfy all the JET operational demands. The result has been that a range of neutron spectrometers have been deployed at JET, for operation both in DD and DT plasmas. An early account of JET neutron spectrometry is given in the review article [14]. Developments of neutron spectrometers have continued at JET and three systems will be described below: a new time-of-flight spectrometer optimized for high count rates (TOFOR), an upgrade of the Magnetic Proton Recoil system (MPRu) and compact neutron spectrometers based on an organic scintillator (NE213).

2.1. THE JET TOFOR NEUTRON SPECTROMETER.

The Time-of-Flight (TOF) technique for neutron spectrum measurements in fusion plasma studies is among those that can offer high energy and good time resolution. It is based on the measurements of the times of correlated neutron scattering events in a ‘start’ and a ‘stop’ detector, placed on a constant TOF sphere. In this configuration the flight time recorded is independent of the scattering angle and defines the energy of the incident neutron. The first such instrument for 2.5MeV neutrons was installed at JET in the early 90s and had an energy resolution of about 5% and an efficiency ~5.10^{-2} cm^2 [15]. It performed satisfactory with count rates of up to a few kHz only requiring data integration times of several hundreds ms to provide good statistics. Such time resolution is not sufficient to study rapid plasma phenomena. Therefore the recent efforts at JET were aimed at improving the time and spectral characteristics of the neutron measurements at JET.

A new Time-Of-Flight (TOFOR) neutron spectrometer was designed and installed at JET presently as part of the JET Enhancement programme. It has been optimized for high count rate measurements of 2.45MeV neutrons. It is able to cope with the DD neutron rates from 10^{17} n/s (expected JET maximum) to below 10^{14} n/s (subject to minimum statistical accuracy required and hence time resolution). The instrument’s design is described in [16, 17]. In short, it consists of a “start” detector, segmented in five layers to increase its rate capabilities, and 32 “stop” detectors forming a ring around the instrumental axis along the defining neutron collimator. Each of the “start” scintillators in the stack of five is equipped with 3 PM tubes to improve light collection. For the first time in fusion neutron TOF spectrometry, an innovative digital Data AcQuisition (DAQ), based on time digitizing PC boards, has been especially developed, which contributes to raising the count rate capability limit of TOFOR to a projected level of 0.5 MHz [17]. The control and monitoring system, containing laser and LED test pulses and radioactive sources, has been implemented to allow setting of working points. Finally, the response of TOFOR to neutrons has been described with the help of detailed geometrical modelling and neutron transport calculations.

The TOFOR is now fully incorporated into the JET diagnostic and data acquisition systems and provides data to the present experimental campaigns. The maximum count rate achieved was 39kHz at a neutron rate of 1.1016 n/s, where the observed “random-to-true” signal level was determined to 4.2% in the peak channel. From this one can project that TOFOR could be operated up to 400kHz for a maximum DD neutron rate at JET of 1×10^{17} n/s with an expected value of accidental events of ~43%. The attained energy resolution ($\Delta E_n/E_n$) is 7.4% only while it has very good flux efficiency of $0.12cm^2$. This allows DD spectral measurements to be performed with high statistical accuracy. The TOFOR capabilities and the quality of the neutron energy spectra that can be obtained are reported in [18, 19] where a discussion of neutron spectrum analysis for NBI and RF heated plasmas can also be found. An assessment of the impact of the scattered flux on the neutron spectrum has been recently carried out leading to improvement of the methods for studying TOFOR data [20]. It was also stressed that this has strong implications for the possibility of measuring 2.5-MeV neutrons on ITER.

The Magnetic Proton Recoil (MPR) Neutron Spectrometer. The original Magnetic Proton Recoil (MPR) spectrometer was designed for diagnosis of the 14-MeV neutron emission in high-power DT fusion experiments. The principle and components of the MPR technique are described in detail in [21]. It works on the principle of converting the incoming neutron flux from the plasma into recoil protons which are further momentum analyzed in the magnetic field. It was installed at JET in 1996 and successfully used in the first deuterium-tritium (DTE1) campaign in 1997 and in the TTE campaign in 2003 [22]. It has a flexible setting for energy resolution within a range from 2.5% up to 10% with a flux efficiency of ~10-4 cm2. The MPR design also permits an accurate absolute calibration in both energy and flux efficiency, except for a profile shape factor derived from neutron profile monitor, making the instru-ment capable of providing an almost independent measurement of the neutron yield.

To explore its full potential, this device has been recently upgraded (MPRu JET enhancement project), permitting measurements for a wide range of plasma conditions, from relatively low-power DD plasmas (giving count rates of kHz for 10^{16} DD n/s) to DT plasmas of the highest power (10MHz for 10^{19} DT n/s). The emphasis of the upgrade work has been to achieve a high level of background immunity in all measurement scenarios. New possibilities have been added by the combined use of phoswich detectors and state-of-the-art digital data acquisi-tion elec-tronics, making measurements of 14MeV neu-trons from DT plasmas virtually background-free, i.e. only the counting statistics will set the limit for the instru-mental sensitivity. For DD plasma operations, the MPRu will deliver data of high absolute accuracy but moderate time resolution which will be complementary to the TOFOR data of high time resolution. In addition, with its narrow line width and high immunity to background, the MPRu can efficiently separate the scattered and direct neutron flux, thereby providing important data in the “interme-diate” energy region 4–11MeV, useful for benchmarking of neutron transport codes. These properties make the MPRu technique an interesting option for the next step fusion devices, such as ITER.

2.2. JET COMPACT NEUTRON SPECTROMETERS.

From the ITER engineering demands it is highly desirable to minimize the interfaces of any diagnostic. In particular, so called “compact” neutron spectrometers are considered as possible candidates for neutron flux and spectra measurements. In response to this, several candidate detectors have been subjected to tests at JET, with the focus mainly on spectrometers based on the NE213 organic proton recoil scintillator. Measurements with NE213 scintillators (5cm by 5cm) have been carried out at JET during the 2002 DD and 2003 TTE campaigns [23]. An energy resolution of 2% at 14MeV and 4% at 2.5MeV neutron energy has been achieved. Neutron spectra measurements have been performed for different plasma scenarios and the contribution of various neutron production mechanisms have been evaluated using unfolding techniques based on the Bayesian method. Simultaneous measurements of both 2.5 and 14MeV neutron spectra have been conducted for the ohmic plasma with trace tritium gas puff. The unfolding analysis requires a detailed knowledge of the detector response function. In this respect the JET NE213 scintillator was fully characterized at the Physikalisch-Technische Bundesanstalt accelerator facility. Different methods can be used for unfolding of neutron spectra from measured pulse height spectra. Therefore particular attention was paid to validation of several unfolding codes (summary is given in [24]).

3. NEUTRON DIAGNOSTICS DEVELOPMENT AND TESTS AT JET.

The development and improvement of neutron measuring techniques are among the main objectives of the EFDA JET programme. Several important upgrades are foreseen in the near future. With respect to the neutron profile monitor it is planned to replace the conventional analog pulse shape discriminators with a state-of-the-art Digital Pulse Shape Discrimination acquisition system [25]. Preliminary tests of such an approach have been conducted during the TTE campaign with a NE213 spectrometer and recently with a NE213 detector of the one central channel of the JET neutron profile monitor. It has been shown that such an upgrade, together with the pile-up resolving procedure proposed recently [26], will significantly improve the dynamic range in energy and count rate for both diagnostics. In addition, a new digital data collection system will allow a deconvolution of spectrum information from all neutron profile NE213 detectors since in fact they are acting as low-resolution spectrometers. No doubt it will be a tremendous step forward in establishing of key phenomena of fusion fast particles.

Essential upgrades are under consideration for TOFOR and MPRu neutron spectrometers as well. For TOFOR it is proposed, firstly, to install a new “start” detector to improve light collection, and secondly, to upgrade its data acquisition system to use electronics modules with simultaneous capability to measure time and pulse height. The combined effect of these upgrades would lead to significant improvement in the ability to reject random (false) coincidences and also give the possibility to correct for timing walk on an event-by-event basis. As was mentioned above, MPRu could provide an independent method to determine the total neutron flux, and thereby the fusion power, based on a neutron detection system com-bining a high-performance spectrometer with the neutron emission profile monitor. The method has been successfully tested in full power DT plas-mas and trace T conditions at JET [27]. The installation of a high count-rate neutron flux detector in the collimated MPRu neu-tron “beam line” shall provide an increase in the time-resolution of the system in both full and trace T fusion power measurements and, furthermore, provide an opportu-nity to study the applicability of the method in D operations.

It is worthwhile to mention here that some other neutron diagnostic developments and R&D, with strong relevance to ITER, are now in progress at JET. There is current work on improving of flux spectral characteristics of the natural and CVD diamond detectors, Stilbene scintillators and an upgrade of the JET γ-ray cameras.

SUMMARY

In the last years a significant achievements have been made at JET in respect of development of burning plasma diagnostics. The data obtained by means of JET neutron profile monitor provide essential information for investigating fast particle physics. In particular, the vertical camera played a key role to perform these studies and the importance of this diagnostic tool for ITER is confirmed. Significant progress was also achieved on neutron spectroscopy and tomography. In addition, the upgraded Magnetic Proton Recoil (MPRu) spectrometer, together with the new Time-Of-Flight at Optimized Rate (TOFOR) spectrometer, represents a significant step forward of the JET neutron emission spectroscopy capability permitting detailed studies of neutron energy spectra. Considerable attention at JET was also devoted to developing and testing of some other ITER-relevant neutron detectors, such as compact neutron spectrometers and radiation hard detectors, along with new electronic technology.

ACKNOWLEDGMENTS

This work was funded partly by the United Kingdom Engineering and Physical Sciences Research Council and by the European Communities under the contract of Association between EURATOM and UKAEA. The views and opinions expressed herein do not necessarily reflect those of the European Commission. This work was carried out within the framework of the European Fusion Development Agreement.

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