EUROPEAN FUSION DEVELOPMENT AGREEMENT
JET

EFDA–JET–CP(04)07-30

A. Murari, L. Bertalot, G. Ericsson, V. Kiptily, S. Popovichev, J.M. Adams,
V. Afanasyiev, M. Angelone, G. Bonheure, S. Conroy, J. Källne, M. Mironov,
M. Pillon, D. Stork and JET EFDA Contributors

New Developments in JET Neutron, Alpha Particle and Fuel Mixture Diagnostics with Potential Relevance to ITER.

New Developments in JET Neutron, Alpha Particle and Fuel Mixture Diagnostics with Potential Relevance to ITER.

A. Murari[1], L. Bertalot[2], G. Ericsson[3], V. Kiptily[4], S. Popovichev[4], J.M. Adams[4],
V. Afanasyiev[5], M. Angelone[2], G. Bonheure[6], S. Conroy[3], J. Källne[3], M. Mironov[5],
M. Pillon[2], D. Stork[4] and JET EFDA Contributors*

[1] Consorzio RFX Assoc. EURATOM ENEA sulla Fusione, Corso Stati Uniti, 4, I-35127 Padova Italy
[2] Associazione EURATOM-ENEA sulla Fusione ENEA Frascati, Roma Italy
[3] Department of Neutron Research, Uppsala University, BOX 525, SE-75120 Uppsala, Sweden
[4] EURATOM/UKAEA Fusion Association, Culham Science Centre, Abingdon Oxon OX14 3DB, UK
[5] A.F.Ioffe Physical-Technical Institute, Russian Academy of Sciences, St.Petersburg, Russia
[6] Partners in the TEC, "Euratom-Belgian state" Association LPP-ERM/KMS, B 1000 Brussels, Belgium
** See annex of J. Pamela et al, "Overview of JET Results ",*
(Proc.20 th IAEA Fusion Energy Conference, Vilamoura, Portugal (2004).

Preprint of Paper to be submitted for publication in Proceedings of the
20th IAEA Conference,
(Vilamoura, Portugal 1-6 November 2004)

ABSTRACT

Some recent JET campaigns, with the introduction of trace amount ($n_T/n_D<5\%$) of tritium into DD plasma and third harmonic ICRH acceleration of ^{4}He, provided unique opportunities to test new diagnostic approaches and technologies for the detection of neutrons, alpha particles and fuel mixture. With regard to neutron detection, the recent activity covered all the most essential aspects: calibration and cross validation of the diagnostics, measurement of the spatial distribution of the neutrons, particle transport and finally neutron spectrometry. The first tests of some new neutron detection technologies were also undertaken successfully during the TTE campaign. To improve JET diagnostic capability in the field of alpha particles, a strong development program was devoted to the measurement of their slowing down and imaging with gamma ray spectroscopy. A new approach for the fusion community to measure the fast ion losses, based on the activation technique, was also successfully attempted for the first time on JET. A careful assessment of the NPA potential to determine the fuel mixture is under way and, for the data of the TTE campaign, the transport coefficients derived from this diagnostic will be compared with the results of the neutron cameras.

1. INTRODUCTION

JET recent experimental programme, with its high power and Trace Tritium Experimental (TTE) campaigns, was focused on producing plasmas of reactor relevance. Major progress was made in several measurement techniques, in particular in the fields of neutron, alpha particle and isotopic composition diagnostics. These developments provide not only essential new physical information but will also contribute to the design of ITER systems. In the prospect of the next step, the set of potential "burning plasma" diagnostics is indeed very limited and in many cases both experimental techniques and/or technologies require a final assessment. Some of the issues which would benefit from more experimental data are certainly those related to the design of the neutron cameras, the choice of detectors for neutron spectrometry, the assessment of γ-ray diagnostics and in general the qualification of new technologies, like diamond detectors, compact spectrometers and fast electronics.

With regard to *14 MeV neutrons* (section 2), spectrometry witnessed significant progress with the absolute calibration of the Magnetic Proton Recoil spectrometer and the first tests and cross validation of compact spectrometers (NE213 liquid scintillators, stilbene and Natural Diamond detectors). The reliable performance of the neutron cameras supported a very interesting scientific program, allowing detailed transport studies and imaging of the spatial distribution of the neutron emission. ITER relevant technologies were also investigated, with the use of Carbon Vapour Deposited detectors and the first acquisitions with Digital Pulse Shape recording electronics. In the context of testing new diagnostic solutions in the field of fast ion measurements (section 3), the first measurements of γ-ray emission from fusion-born a particles were successfully carried out, providing essential information on the slowing down and confinement of these fast particles. Imaging of the α spatial distribution was obtained with the CsI detector arrays of the neutron cameras, discriminating them from the D-ions. A new approach for the detection of fast ion losses, based on the activation of suitable samples located close to the plasma, was also successfully implemented and tested. Various experiments were also performed to investigate the potential of Neutral Particle Analysis to determine the plasma isotopic composition and particle transport (section 4) in an attempt to complement the results of the neutron systems, which have inherent limitations in diagnosing the cold edge.

2. NEUTRON DIAGNOSTICS

The Magnetic Proton Recoil spectrometer (MPR) is a unique JET diagnostic. Neutrons emitted from the plasma generate recoil protons in a thin plastic foil and these are energy analysed in a magnetic field and subsequently detected in an array of fast plastic scintillators. The neutron spectra recorded during TTE are a superposition of several contributions related to different velocity components of the fuel ions [1]. The kinetic parameters of the fuel ion populations, such as temperature and relative fraction of thermal and supra-thermal components, were routinely measured. In addition, collective states of the fuel ions, such as toroidal rotation, were also determined. Moreover the diagnostic was recently refined with particular attention to the absolute yield calibration. As a result, during TTE the MPR provided for the first time an almost independent (except a profile factor derived from the neutron cameras) absolute measurement of the total 14 MeV neutron yield, which is in very good agreement with the JET 14 MeV neutron yield monitors (fig.1) [2]. Since the neutron cameras (fig.2) can also determine the total neutron yield, JET is the only device with three independent absolute estimates of this essential parameter. The synergy between the three different approaches could also be of great relevance for ITER, in which the calibration of the neutron diagnostics remains an unresolved issue.

The availability of two cameras, with 19 lines of sight of which ten covering the horizontal and nine the vertical plasma cross section, is essential to interpret the spatial neutron emissivity in many JET experiments. On each line of sight three different detectors are installed [3]: 1) a NE213 liquid organic scintillator with Pulse Shape Discrimination (PSD) electronics for simultaneous recording of the 2.5MeV, 14MeV neutron and gamma emission; 2) a BC418 plastic scintillator, quite insensitive to γ-rays with E_γ<10MeV, for the measurement of 14MeV neutrons only; 3) a CsI(Tl) detector for measuring the HXR and γ emission, in the energy range between 0.2 - 6MeV, induced by fast plasma ions interacting with the C and Be impurities [4]. With this diagnostic the transport of tritium was investigated in different plasma scenarios and using different heating schemes [5]. The measurements of these cameras during ICRH Tritium fundamental heating showed clearly that the emission centre was significantly shifted toward the high field side with respect to the magnetic axis [3]. Similar decoupling of the magnetic axis and the neutron emission peak was evident in off-axis neutral beam heated discharges [6]. The effect of the magnetic topology, in particular the safety factor, on the neutron emission profiles was also investigated, showing, for example, that in the configurations with a substantial current hole the emission is significantly shifted towards the low field side, as shown in fig.2 [6]. Another very important line of research, particularly in the perspective of ITER, involves the improvement of compact spectrometers. NE213 liquid scintillators provided good spectra of both 2.5 MeV and 14 MeV neutrons, using sophisticated unfolding methods based on Bayesian estimates and Maximum Entropy algorithms [7] and the first positive results were also obtained with Stilbene and natural diamond detectors [8]. Since the advent of A/D fast transient recorders, the direct digitization of detector signals at high sampling rate and the storage of vast amount of data has become feasible. This gives unique possibility for post-experiment data reprocessing. A Digital Pulse Shape Discrimination (DPSD) system based on this technology was tested at high count rate operation in conjunction with organic scintillators during the TTE campaign. The obtained measurements proved the validity of the approach since total count rates up to MHz level were detected as well neutron and gamma pulse height spectra were acquired [9].

The technology of Carbon Vapour Deposited diamond detectors was successfully tested for the first time in a Tokamak environment during TTE for the detection of 14MeV neutrons [10]. Since these diodes have a radiation hardness, which is between two and three orders of magnitude higher than Silicon, they have to be considered very good candidates as 14MeV neutron counters for ITER.

3. FAST ION AND ALPHA PARTICLE DIAGNOSTICS

Since a new technique to simulate fusion generated α particles (using 3rd harmonic heating NBI injected ^{4}He) became available [11], more attention has been devoted to the confinement and slowing down of the alphas, which only JET has the current and the geometry to confine. The diagnostic method based on γ-rays from the ^{9}Be $(\alpha,n\gamma)^{12}$C nuclear reaction is now commonly used to determine the spatial distribution of energetic ions in the plasma. During TTE the slowing down of fusion born alphas was measured for the first time with this approach, using a well shielded high-efficiency γ ray spectrometer based on a bismuth germanate (*BGO*) scintillation detector [12]. Classical estimates of α confinement were confirmed but some advanced scenarios with a “current hole” show significant losses of the fusion α’s. The experimental results can be reconciled with the theory of classical collisions if the region of almost zero current, and therefore negligible poloidal field, is properly taken into account. From the 2-D γ-imaging, obtained with the CsI(Tl) detector arrays of the neutron cameras previously described, the spatial distribution of both the alphas and the fast deuterons (from the ^{12}C$(d,p\gamma)^{13}$C nuclear reaction) is now routinely derived [12]. As an example, fig.3 shows the γ-ray images of alpha particles and D-ions accelerated with ICRH heating. Furthermore the evolution of the runaway electrons during disruptions can also be obtained. Both measurements provide very important pieces of information in the ITER perspective.

An original technique for lost α’s detection was also tested during these campaigns. It consists of installing suitable samples, which are mounted on a probe and inserted close to the plasma, where they are exposed to the lost fast particles and get activated. Once removed from the machine, the flux and nature of the particles fallen on them can be determined by γ-ray spectrometry [13]. The main advantage of the approach is that, unlike other more common detectors (Faraday cups, scintillators), the measurement is based on nuclear reactions. As a consequence, with this method the various species of the fast particles can be discriminated, even those that have the same q/m ratio. The first results obtained at JET were very positive, hilighting the potential of the technique even if, due to accessibility problems, the samples had to be exposed in the upper part of the machine, which is very unfavourable, since the particle drifts tend to push the fast ions toward the lower part of the vacuum vessel.

4. DIAGNOSTICS FOR THE DETERMINATION OF THE FUEL MIXTURE

The measurement of the plasma isotopic composition is a major issue in the perspective of ITER. The TTE campaign was an ideal situation to test various approaches for experiments in which the minority species is maintained at a percentage level. As mentioned in section 2, the main diagnostics used for this purpose were the neutron cameras, which provided also the main information on the particle transport. The absolutely calibrated MPR was also able to provide a independent evaluation of the isotopic composition, averaged over the line of sight and therefore indicative of the core of the plasma [14]. The Tritium content was also measured for the first time during TTE using JET ISEP Neutral Particle Analyser explicitly designed to operate under high neutron and gamma emission rates [15]. This diagnostic determines the isotopic composition by detecting simultaneously the neutral fluxes of all hydrogen isotopes (H_0,D_0,T_0) leaving the plasma at various energies (see fig.4 for tritium), which can be linked to different radial positions. It is particularly effective for neutrals born in the external part of the plasma, where it can complement the results of the neutron cameras and also provide an estimate of the transport coefficients. A coherent strategy is emerging at JET for the measurement of the isotopic composition profile, in the case of the minority species in the percentage range, which consists of combining the NPA data for the edge with the neutron measurements in the centre of the plasma. One of the most advanced and ambitious applications of neutral particle analysis consists of studying the transport of the main fuel ion components of the plasma. The TTE campaign was a very good opportunity to test this approach since a very small fraction of tritium was introduced by gas puffing, not altering the main plasma parameters, an indispensable prerequisite for perturbative transport studies. Special features of the experiment such as the low tritium background in plasma, the small tritium influxes from the wall and the purity of deuterium neutral beam injection all contributed to obtaining a good signal to noise ratio. The on going analysis still presents some difficulties but the prospects for at least an average radial estimation of the transport coefficients are positive.

5. FUTURE PROSPECTS

JET's future programme will concentrate not only on the consolidation of the methods described in this paper but also on the development of techniques for measuring other burning plasma quantities. The new systems to be installed in the context of JET-EP (Enhanced Performance) will significantly increase JET diagnostic capability in the fields of neutron and lost alpha detection, as well as tritium retention. In particular various upgrades of the Quartz Microbalance are meant to substantially improve the time-resolved data-base on erosion. Neutron spectrometry is also being significantly upgraded, with the installation of a new time of flight diagnostic, capable of detecting the 2.45MeV neutrons, and an upgrade of the existing MPR spectrometer. These efforts involve further developments of the Digital Pulse Shape discrimination technique. This new electronic technology, in addition to improving the quality of the data obtainable from JET present neutron cameras, is also indispensable for the next step. A lot of attention is also being devoted to the potential of He beams to measure the He ash through double charge exchange. Additional and for JET completely new burning plasma diagnostics of potential relevance for ITER, like coherent TS or fast wave reflectometry, are also being considered.

REFERENCES

[1]. L. Giacomelli et al, “Neutron emission spectroscopy of fuel ion rotation and fusion power components demonstrated in the trace tritium experiments at JET”, EPS 2004

[2]. Henrik Sjˆstrand1 et al,”Measurement of the fusion power with the MPR neutron spectrometer in the TTE and DTE1 experiments at JET”, EPS 2004

[3]. L.Bertalot et al, “ITER relevant developments in neutron diagnostics during the JET Trace Tritium campaign” SOFT 2004

[4]. V.Kiptily et al, Nuclear Fusion **42** (2002)999, RSI 74(2003)1753

[5]. K.D.Zastrow et al, “Tritium transport experiments on the JET tokamak” EPS 2004

[6]. S.Popovichev et al, “Performance of Neutron Measurements during Trace Tritium Experiments on JET”, EPS 2004

[7]. A.Zimbal et al, “A compact NE213 neutron spectrometer with high energy resolution for fusion applications” to be published in Rev.Scien. Instruments

[8]. Yu.A.Kaschuck et al, “Measurements during Trace Tritium Experiments at JET Using a Stilbene Detector” EPS 2004

[9]. B.Esposito et al, “Neutron measurements on JET using an NE213 scintillator with digital pulse shape discrimination” to be published in Rev.Scien. Instruments

[10]. M.Angelone et al, “Time dependent 14MeV neutrons measurement using a polycrystalline CVD diamond detector at JET tokamak”, to be published in Rev.Scien. Instruments

[11]. M.Mantsinen et al, PRL 88(2002)105002-1

[12]. V.Kiptily at al, 31EPS Conference, London 2004;V.Kiptily et al. Phys.Rev.Letters (to be pulished in September 2004)

[13]. G.Bonheure et al, “First MeV ion losses measurements using activation technique inreversed B experiments at JET”, to be published in Rev.Scien. Instruments, October 2004

[14]. M.Gatu Johnson, PhD Thesis, Uppsala University, department of Neutron Research

[15]. M. Mironov et al,“Tritium Transport Studies with JET ISEP NPA During the Trace Tritium Experimental Campaign”, EPS 2004

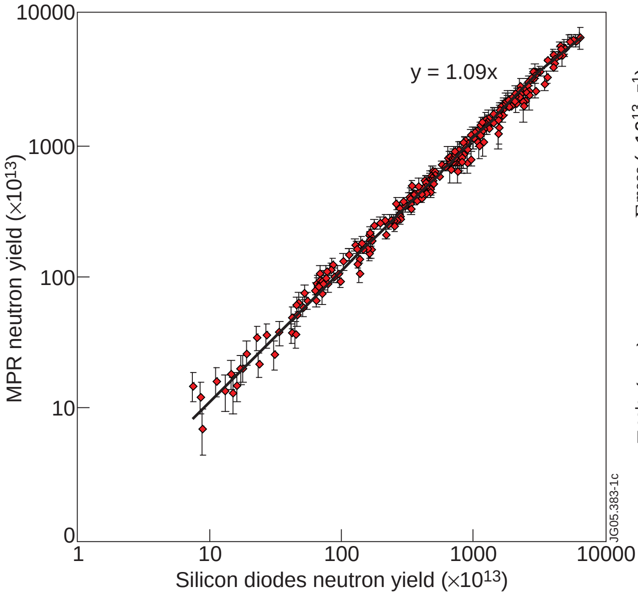

Figure 1: Cross validation of the 14MeV neutron yield measurements for the TTE campaign. The deviation from a 1:1 proportionality is within the errors of the two diagnostics.

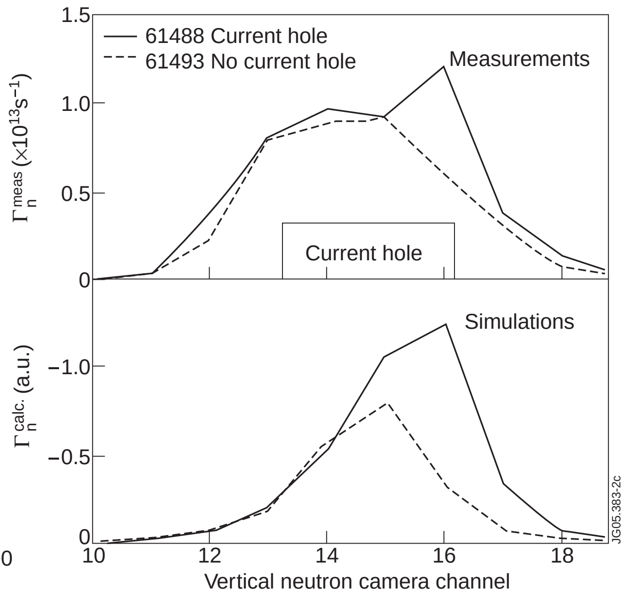

Figure 2: Comparison of 14MeV neutron profiles for on-axis tritium beams (measured at the top, calculated at the bottom). An outward displacement of neutron emission is clearly seen for plasmas with a current hole.

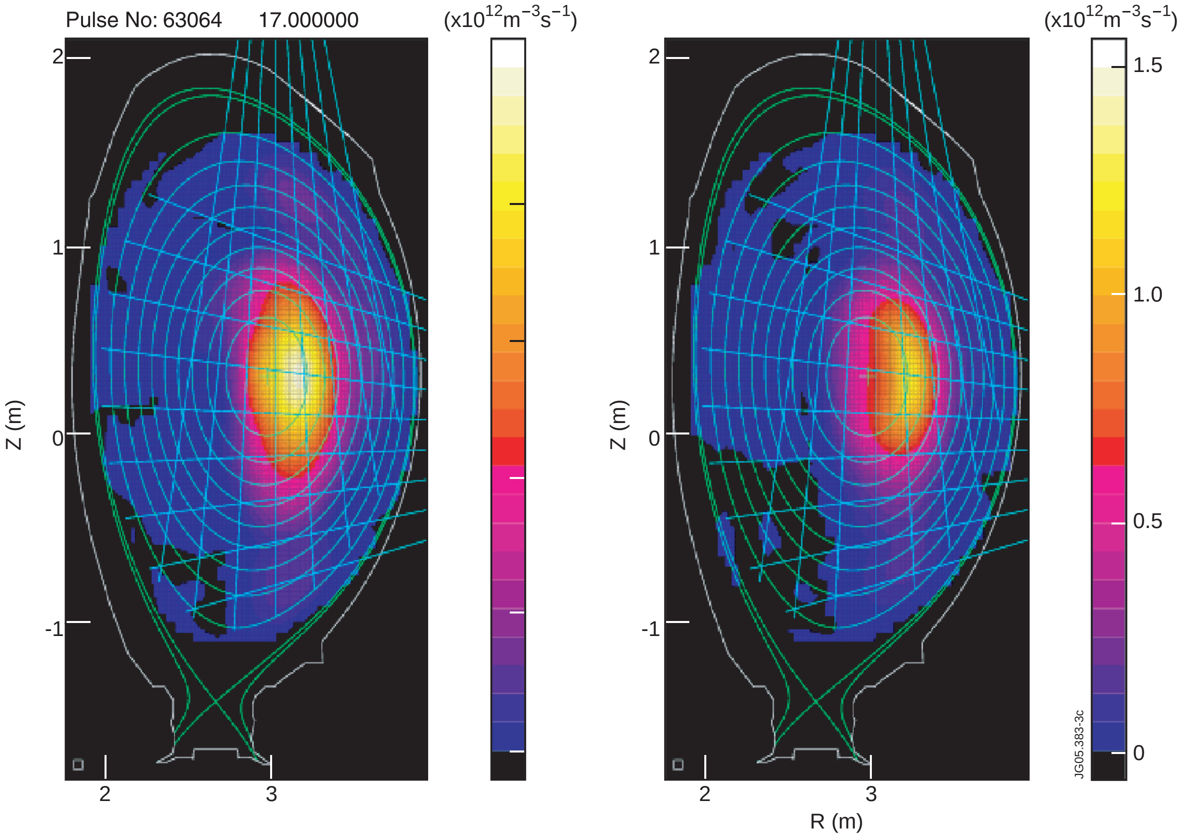

Figure 3: Gamma-ray images of α particles and D-ions measured simultaneously during a 2.2T/2.0MA JET discharge with ICRH heating: with in plasmas: left D-image(E_D> 0.8MeV) ; right alpha-image (E_α> 1.7 MeV).

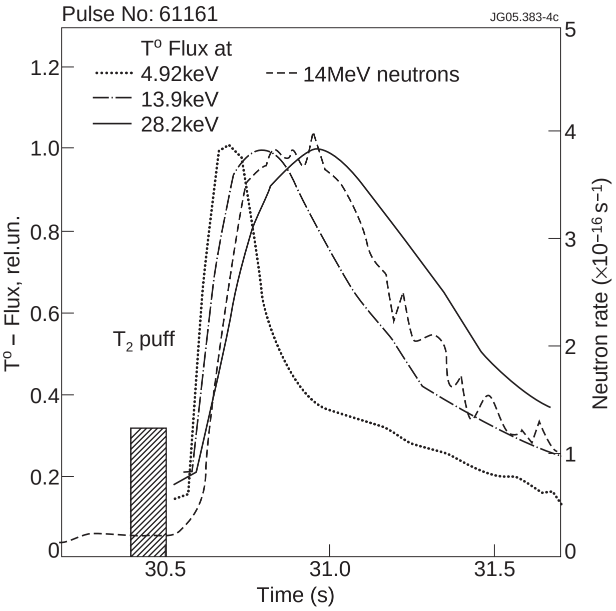

Figure 4: Escaping neutral tritium fluxes measured by the NPA.