EUROPEAN FUSION DEVELOPMENT AGREEMENT

EFDA-JET-PR(04)07

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

New Developments in JET Neutron, γ-ray and Particle Diagnostics with Relevance to ITER

New Developments in JET Neutron, γ-ray and Particle Diagnostics with Relevance to ITER

A. Murari[1], L. Bertalot[2], S. Conroy[3], G. Ericsson[3], V. Kiptily[4], S. Popovichev[4],
H.Schuhmacher[5], J.M. Adams[4], V. Afanasyiev[6], M. Angelone[2], G. Bonheure[7],
B. Esposito[2], J. Källne[3], M. Mironov[5], M. Pillon[2], M. Reginatto[5], D.Stork[4],
A. Zimbal[5] and JET-EFDA Contributors*

[1] *Associazione EURATOM-ENEA sulla Fusione, Consorzio RFX, 4-35127 Padova, Italy*
[2] *Associazione EURATOM-ENEA sulla Fusione, CR ENEA Frascati, Roma, Italy*
[3] *INF, Uppsala University, EURATOM-VR Association, Uppsala, Sweden*
[4] *EURATOM/UKAEA Fusion Association, Culham Science Centre, Abingdon, UK*
[5] *Physikalisch-Technische Bundesanstalt, D-38116 Braunschweig, Germany*
[6] *Ioffe Physical-Technical Institute, Russian Academy of Sciences, St. Petersburg, Russia*
[7] *LPP-ERM/KMS, "Euratom-Belgian State" Association, TEC, B-1000 Brussels, Belgium*
** See annex of J. Pamela et al, "Overview of JET Results ",*
(Proc.20th IAEA Fusion Energy Conference, Vilamoura, Portugal (2004).

Preprint of Paper to be submitted for publication in
Nuclear Fusion

ABSTRACT.

Some recent JET campaigns, with the introduction of trace amount ($n_T/n_D<5\%$) of tritium into D plasmas and third harmonic ICRH acceleration of ^{4}He, provided unique opportunities to test “burning plasma” diagnostics. In particular new approaches and techniques were investigated for the detection of neutrons, a particles and the fuel mixture. With regard to neutron detection, the recent activity covered aspects such as calibration and cross validation of the diagnostics, measurement of the spatial distribution of the neutrons, particle transport and neutron spectrometry. The first tests of some new neutron detection technologies were also undertaken during the Trace Tritium Experiment (TTE) campaign. To improve JET’s diagnostic capability in the field of α particles, a significant development program was devoted to the measurement of their confinement and imaging with γ-ray spectroscopy. A new approach for the fusion community to measure the fast ion losses, based on the activation technique, was also attempted for the first time on JET. An assessment of the Neutral Particle Analyser’s potential to determine the fuel mixture and the particle transport coefficients is under way.

1. INTRODUCTION

JET’s recent experimental programme, with its high power and Trace Tritium Experimental (TTE) campaigns, was focused on producing plasmas of reactor relevance. Major achievements were made in several measurement techniques, in particular in the fields of neutron, α 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 further assessment. Some of the issues, which would benefit from more experimental data, are certainly those related to the calibration of neutron diagnostics, the design of the neutron cameras, the choice of detectors for neutron spectrometry and the assessment of γ-ray diagnostics. Also the qualification of new technologies, like diamond detectors, compact spectrometers and fast electronics require additional efforts.

With regard to *14 MeV neutrons* (Section 2), significant progress was achieved in the field of spectrometry with the absolute calibration of the Magnetic Proton Recoil spectrometer and the tests and cross validation of compact spectrometers (NE213 liquid and Stilbene scintillators). The reliable performance of the neutron cameras supported JET’s 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 for fast ion detection (Section 3), the first measurements of γ-ray emission from fusion-born a particles were successfully carried out, providing essential information on their confinement. Simultaneous imaging of the α and fast D-ions spatial distributions was obtained with the CsI detector arrays of the neutron cameras. 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). The upgrades being implemented to improve JET diagnostic capability in the field of “burning plasma” measurements are briefly described in section 5, before the summary and conclusions.

2. NEUTRON DIAGNOSTICS

The Magnetic Proton Recoil (MPR) spectrometer is a unique JET diagnostic [1]. Neutrons emitted from the plasma are collimated on a CH_2 target, where elastic collisions on H-nuclei (protons) create recoil protons of practically the same energy as the incident neutrons (see Fig.1). The recoil protons are momentum analysed in a suitably shaped magnetic field and imaged on a 37-element scintillator array (hodoscope), where they are detected. The information in these time resolved proton position histograms is then used to deduce the spectra of the neutrons emitted by the plasma.

The neutron spectra are a superposition of several contributions related to different velocity components of the fuel ions [2]. The kinetic parameters of the fuel ion populations, such as temperature and relative fraction of thermal and supra-thermal components, were routinely measured during the DTE1 campaign in 1997. In addition, collective states of the fuel ions, such as toroidal rotation, were also determined. Moreover, during the TTE campaign in 2003, the diagnostic was upgraded to provide the absolute total yield rate [3]. This absolute calibration is based on first principle calculations that take into account all the relevant physical and geometrical characteristics of the diagnostic, from the neutron collimator to the proton detection array. As a result, during TTE the MPR provided for the first time an almost independent (except for a profile factor derived from the neutron cameras) absolute measurement of the total 14MeV neutron yield, which was compared with the measurements of the other neutron systems, e.g. the Silicon diodes as shown in fig.2. The Silicon diodes were calibrated by cross-comparison with activation samples sent to the plasma edge using a specific pneumatic system. This method constitutes the reference measurement of the total neutron yield since the beginning of JET operations. Nowadays the neutron cameras (see below) can also determine the total neutron yield, using an independent calibration based on reference pulses used in the past. Therefore JET is the only device with three almost 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 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. With this configuration of the chords, the spatial resolution of the system in the centre is better than 10 cm. On each line of sight three different detectors are installed [4]:

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 $E\gamma < 10$MeV, for the measurement of 14MeV neutrons only;

3) a CsI(Tl) detector for measuring the Hard X-Ray and γ emission, in the energy range between 0.2 - 6 MeV (the γ-rays are induced by fast plasma ions interacting with C and Be impurities([5]).

With the neutron cameras the transport of tritium was investigated in different plasma scenarios and using different heating schemes [6]. The measurements of the neutron spatial distribution during ICRH Tritium fundamental heating showed clearly that the neutron emission centre was significantly shifted toward the high field side with respect to the magnetic axis [4]. Similar decoupling of the magnetic axis and the neutron emission peak was evident in off-axis neutral beam heated discharges [7]. 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.4 [7,8]. For the two reported discharges, whose main difference resides in the current profile in the core, the difference in the neutron profile is attributed to the effect of the current hole on the trajectories of the injected fast tritium atoms. This result was also simulated with TRANSP reproducing the experimental features quite satisfactorily.

Another very important line of research, particularly in the perspective of ITER, involves the improvement of compact spectrometers. Particular attention was devoted to organic scintillators, of which a typical example is the NE213 liquid scintillator, whose principle of operation is described in figure 5. Neutron and gamma rays produce pulses of different shape in the scintillating material and therefore, once the light has been collected and detected by a photomultiplier, the two events can be separated by using appropriate pulse shape discrimination techniques. The most important step is then the determination of the original spectrum of the neutrons impinging on the detector, which is achieved with sophisticated unfolding procedures.

During the campaign NE213 liquid scintillators provided good spectra of both 2.5MeV and 14MeV neutrons (see Fig.6), using unfolding methods based on Bayesian estimates and Maximum Entropy algorithms [9]. Positive results were also obtained with another organic scintillator, Stilbene and also natural diamond detectors were used for the first time at JET for the purpose of neutron spectrometry [10]. Since the advent of analog to digital 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.‘These measurements proved the validity of the approach since total count rates up to MHz level were detected as well as neutron and gamma pulse height spectra were acquired [11].

The technology of Carbon Vapour Deposited diamond detectors was tested for the first time in a Tokamak environment during TTE for the detection of 14MeV neutrons [12]. A simplified scheme of the detector is reported in figure 7, which shows how incident neutrons create charged particles, mainly α particles, in the bulk of the device, which in turn produce an electron current detectable with commercial current amplifiers. The fact that the useful charge is created in the bulk of the detector, which unlike Si diodes does not rely on the junction for its operation, is a key element in determining the robustness of the component. Since these detectors 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. The results obtained at JET are very positive, as reported in figure 8 where the CVD detector signal is compared with that of a Si diode, showing the excellent agreement between the two sensors.

3. FAST ION AND α PARTICLE DIAGNOSTICS

Since a new technique to simulate fusion generated α particles (using 3rd harmonic heating NBI injected ^{4}He) became available [13], more attention has been devoted to the confinement and slowing down of the α particles, which only JET has the current and the geometry to confine. The diagnostic method based on γ-rays detection from the ^{9}Be(α,n γ)^{12}C nuclear reaction is now commonly used to determine the spatial distribution of α particles in the plasma. The γ line at 4.44MeV emitted by the reaction allows the identification of the particles with energy in excess of about 2MeV and it is clearly detected by both JET cameras and high-resolution spectrometers. During TTE, the slowing down of fusion born αs 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 [14,15]. Classical estimates of α confinement were confirmed but some advanced scenarios with a “current hole” show significant losses of the fusion αs. These 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. The γ-ray spectroscopy therefore confirms the evidence of enhanced losses implying a reduction in the fast particle confinement, pointed out with the neutron camera (section 2), for magnetic configurations with a “current hole”. 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 αs and the fast deuterons (the D isotope is identified using the gamma ray emission from the ^{12}C(d,pγ)^{13}C nuclear reaction) is now routinely derived [14,16]. As an example, Fig.9 shows the γ-ray images of α particles and D-ions accelerated with ICRH heating. This technique can therefore be useful also in studying the effects on the fast ions of the various heating schemes. Moreover the detectors used are also quite sensitive in the hard X-ray region of the spectrum and therefore can be used to study the evolution of the runaway electrons during disruptions. This new diagnostic approach, developed at JET, is therefore of extreme relevance in the perspective of ITER.

An original technique for lost αs 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 [17]. The main advantage of the approach is that, unlike other more common detectors for lost ions (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, highlighting the potential of the technique even if, due to limited accessibility, 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 [18]. The Tritium content was also measured for the first time during TTE using JET ISEP Neutral Particle Analyser (see Fig.10) explicitly designed to operate under high neutron and gamma emission rates [19]. 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.11 for tritium), which can be linked to different radial positions. The neutrals escaping from the plasma are stripped with a carbon foil, accelerated and then analysed in both energy and mass by the combination of parallel electric and magnetic fields. The diagnostic is particularly effective for neutrals born in the external part of the plasma, where it can complement the results of the neutron cameras and in principle also provides an estimate of the transport coefficients. For experiments like those of TTE, with the minority species at the percentage level, the synergy between the NPA and the neutron cameras appears very interesting. The NPA is particularly suited to diagnose the edge, where neutron emission is low, whereas neutron cameras can provide better data for the core.

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. On the other hand, the on going analysis presents some difficulties, due to the low level of tritium and possibly the proximity of the NPA to the injection line of the heating neutral beam. A higher percentage of tritium would be of course easier to detect with satisfactory accuracy. On the other hand the shielding should be improved to cope with a higher 14MeV neutron background, which is at present strongly affecting the measurements. Therefore the prospects for an estimation of the transport coefficients with the present configuration of the diagnostic are still uncertain.

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 α particles detection. An array of Faraday cups and a scintillator detector are being installed to resolve the fluxes of lost αs both in time and space. These two methods are more consolidated but their applicability in ITER is questionable, due to their sensitivity to the neutron background. More efforts are therefore under way to improve the activation techniques for the lost fast particles, mainly investigating the potential of different materials for the samples. More sophisticated detection techniques, including ultra low background measurements to be performed in underground specific laboratories, have also already been undertaken. Neutron spectrometry is also being significantly upgraded, with the installation of a new time of flight diagnostic, capable of detecting the 2.45MeV neutrons. This system, reported in Fig.12, has been designed, using CERN GEANT4 Monte Carlo code, to optimise the count rate and therefore the time resolution. The existing MPR spectrometer will be upgraded with pulse-shape distinguishing detectors and associated transient-recorder electronics. This will allow measurements of 2.45MeV neutrons also with this diagnostic and provide a good platform to cross validate the TOFOR results. In the perspective of ITER, the refinement of the compact spectrometers is also progressing, with particular attention to the calibration and the unfolding methods. To detect the α-particles in the energy range between 200 and 400keV, which is considered the most relevant for plasma wave interactions, a new approach based on XUV spectroscopy is being actively pursued. It consists of measuring the intensity ratio of suitable lines, one of which sensitive to energetic particles. The approach implies the injection of extrinsic impurities, like krypton, and the calculation of the relevant cross section with sophisticated quantum mechanical codes. All neutron and γ-ray diagnostics would strongly benefit from further developments of Digital Pulse Shape Discriminators. This new electronic technology, in addition to improving the quality of the data obtainable from JET present diagnostics, is also indispensable for the next step. Alot of attention is also being devoted to the potential of He beams to measure the He ash through double charge exchange, at present an unresolved issue for ITER. Additional and for JET completely new burning plasma diagnostics of potential relevance for the next step, like Collective Thomson Scattering or Fast Wave Reflectometry, are also being considered for the long term program.

SUMMARY AND CONCLUSIONS

In the last years significant achievements have been obtained at JET in the field of burning plasma diagnostics. Particularly relevant are the results of the neutron diagnostics and the new technique, based on α-ray spectroscopy, for the detection of the α-particles. These diagnostics supported the experimental program more than adequately. Major progress was also achieved in the calibration of neutron diagnostics, an issue particularly delicate. Cross validation using three different systems was of great benefit, proving the advantage of synergies between different measurements.

Significant attention was also devoted to providing information for the development of ITER diagnostics, with particular emphasis on neutron spectroscopy and tomography. More problematic, in the perspective of the next step, remain the determination of the fuel mixture and the He ash. For these two quantities, very important from an operational point of view, no established method has been validated in reactor relevant conditions yet.

All the mentioned diagnostics also promoted significant technological developments. The fields of detectors and fast transient recorders are among the most active and they are likely to drive important spin-offs.

In any case, in the perspective of ITER, substantial additional work is required on all “burning plasma” diagnostics and technologies. This is the main reason why practically all the main JET diagnostics in the field are being upgraded and new ones are being installed, in the context of JET-EP, in order to alleviate present weaknesses. Even if a valuable information can be derived in normal operation, these systems can be fully exploited, deriving final information on the measurement methods and the relevant technologies, only in future D/T operation, which remains one of the main unique potentials of JET.

ACKNOWLEDGEMENTS

The work was performed under the European Fusion Development Agreement, and partly funded by the UK Engineering and Physical Sciences Research Council and EURATOM.

REFERENCES

[1]. G. Ericsson et al., Rev. Sci. Instrum **72** (2001) 759

[2]. Giacomelli, L., et al, “Neutron emission spectroscopy of fuel ion rotation and fusion power components demonstrated in the trace tritium experiments at JET” , (Proc. 31st EPS Conference on Plasma Phys, London, 2004), ECA, Vol. 28G, P-5.171 (2004) and http://130.246.71.128/pdf/P5_171.pdf.

[3]. Sjotrand, H., et al, ”Measurement of the fusion power with the MPR neutron spectrometer in the TTE and DTE1 experiments at JET” , (Proc. 31st EPS Conference on Plasma Phys, London, 2004), ECA, Vol. 28G, P-5.176 (2004) and http://130.246.71.128/pdf/P5_176.pdf.

[4]. Bertalot, L., et al, “ ITER relevant developments in neutron diagnostics during the JET Trace Tritium campaign” , 23rd Symposium on Fusion Technology, Venice, Italy, 2004 submitted for publication in Fusion Engineering Design.

[5]. Kiptily, V., et al, Rev. Sci. Instruments **74** (2003) 1753.

[6]. Zastrow, K.-D., et al Plasma Phys. Control. Fusion, **46** (2004) B255.

[7]. Popovichev, S., et al, “ Performance of Neutron Measurements during Trace Tritium Experiments on JET” , (Proc. 31st EPS Conference on Plasma Phys, London, 2004), ECA, Vol. 28G, P-5.173 (2004) and http://130.246.71.128/pdf/P5_173.pdf

[8]. Yavorskij, V. et al, “Confinement of Fats Tritum beam Ions in Current Hole Plasmas in JET” (Proc. 31st EPS Conference on Plasma Phys, London, 2004), P 1-157

[9]. Zimbal, Z., et al, Rev. Sci. Instrum **75** (2004) 3553

[10]. Kaschuck, Yu.A., et al, “Neutron Measurements during Trace Tritium Experiments at JET Using a Stilbene Detector” , (Proc. 31st EPS Conference on Plasma Phys, London, 2004), ECA, Vol. 28G, P-5.174 (2004) and http://130.246.71.128/pdf/P5_174.pdf.

[11]. Esposito, B., et al, Rev. Sci. Instrum **75** (2004) 3550

[12]. Angelone, M., et al, Rev. Sci. Instruments, **76**, (2005), 013506.

[13]. Mantsinen, M., et al, Phys. Rev. Letters **88** (2002) 105002-1.

[14]. Kiptily, V., et al, “Gamma Ray Measurements of Fusion Alpha Particles in JET Trace Tritium Experiments” , (Proc. 31st EPS Conference on Plasma Phys, London, 2004), ECA, Vol. 28G, O-1.06 (2004) and http://eps2004.clf.rl.ac.uk/pdf/O1_06.pdf

[15]. Kiptily, V., et al, Phys. Rev. Letters **93** (2004) 115001.

[16]. Kiptily, V. et al., “Gamma-Ray Imaging of D and 4He Ions accelerated by Ion- Cyclotron-Resonance Heating in JET Plasmas” submitted for publication on Physics review Letters

[17]. Bonheure, G., et al, “ First MeV ion losses measurements using activation technique in reversed B experiments at JET” , Rev. Sci. Instrum **75** (2004) 3540.

[18]. Gatu Johnson, M., “Determination of the tritium concentration in deuterium-tritium fusion plasmas from JET TTE campaign” , Master Thesis, Uppsala University, Department of Neutron Research, Uppsala, Sweden (2003)

[19]. Mironov M., et al, “ Tritium Transport Studies with JET ISEP NPA During Tritium Experimental Campaign” , (Proc. 31st EPS Conference on Plasma Phys, 2004), ECA, Vol. 28G, P-5.174 (2004) and http://130.246.71.128/pdf/P1_149.pdf

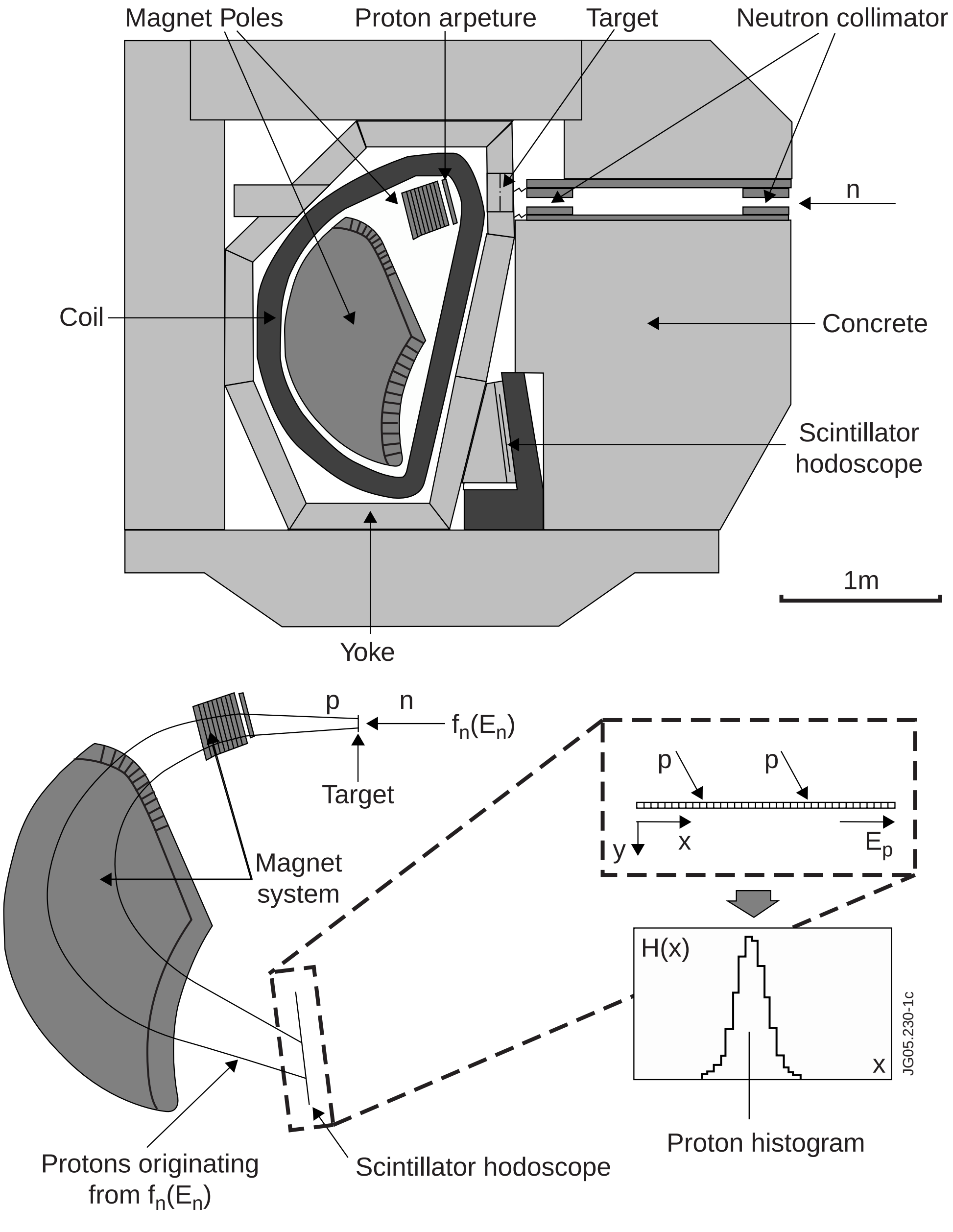


Figure 1: MPR overview. The neutrons coming from the plasma are collimated on the CH_2 *target. The resulting recoil protons are imaged on a scintillator hodoscope, creating the desired histogram.*

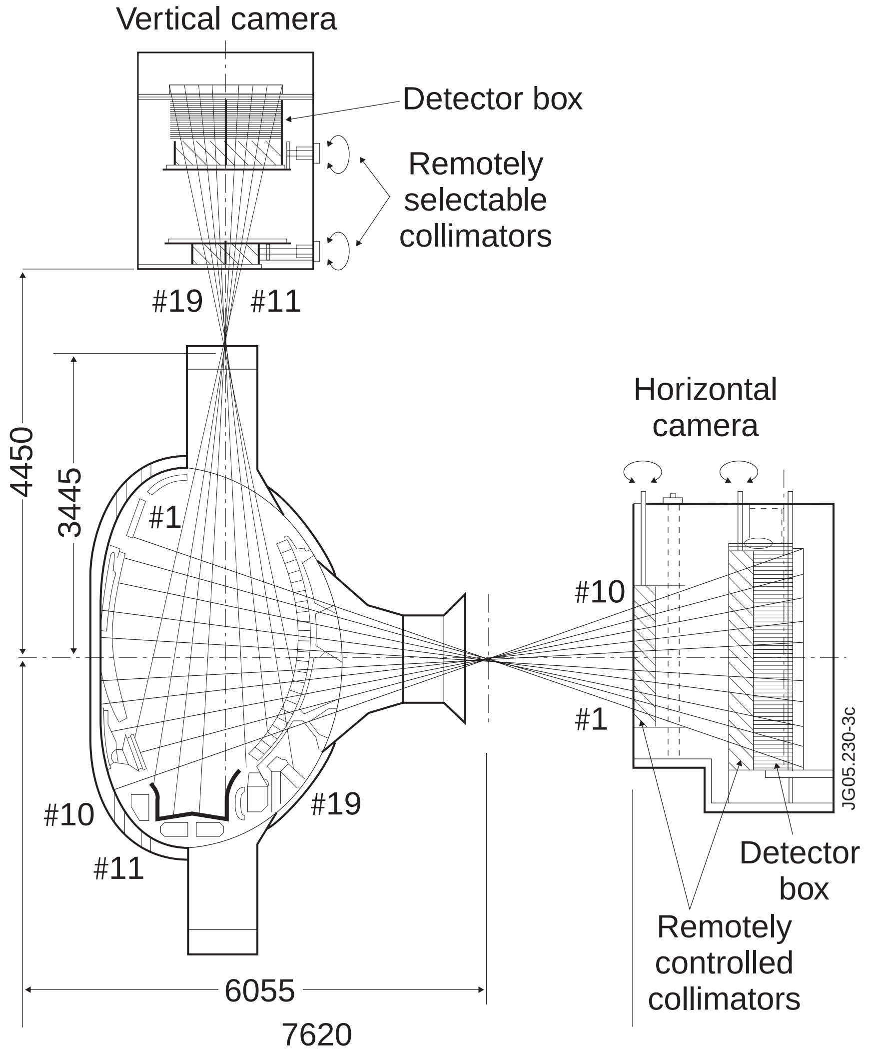


Figure 3: JET neutron cameras, with 10 horizontal and 9 vertical lines of sight. The spatial resolution in the centre is about 10cm

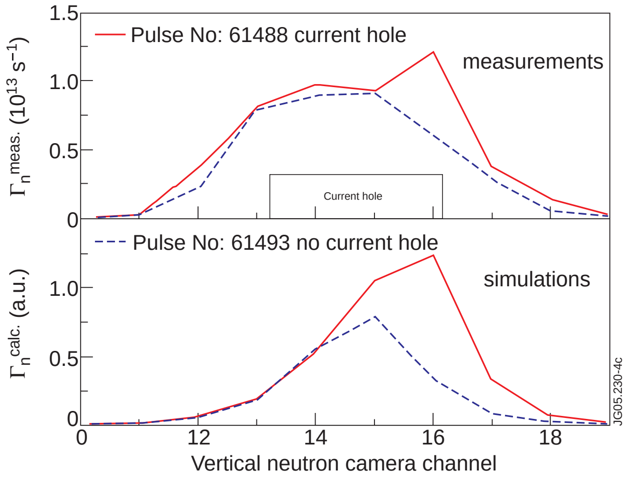


Figure 4: Comparison of 14MeV neutron for on-axis tritium beams (measured at the top calculated at he bottom). An outward displacement of the neutron emission is clearly detectable for plasmas with a current hole. Chord 15 corresponds to the plasma centre.

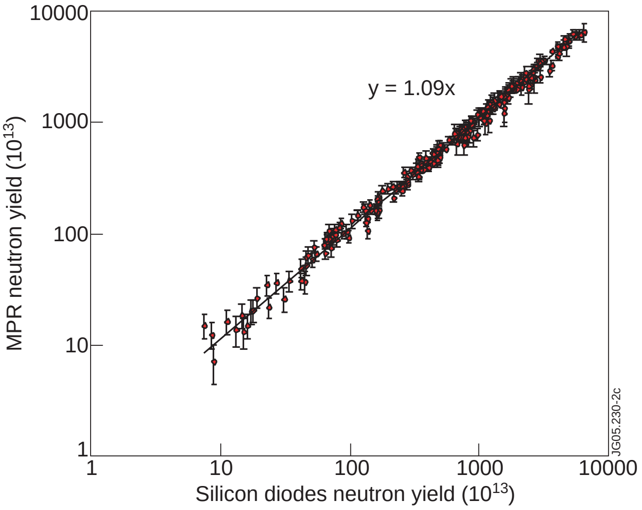
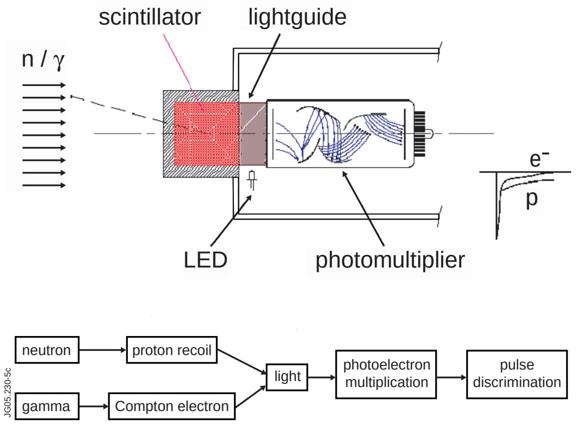


Figure 2: Cross validation of the 14MeV neutron yield measurements for the TTE campaign. The deviation from a 1:1 proportionality is within the error bars of the two diagnostics.



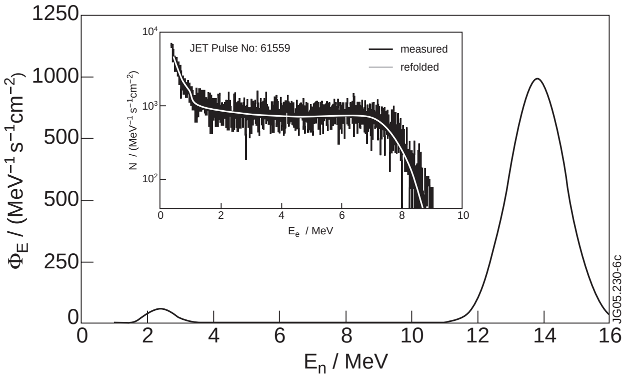
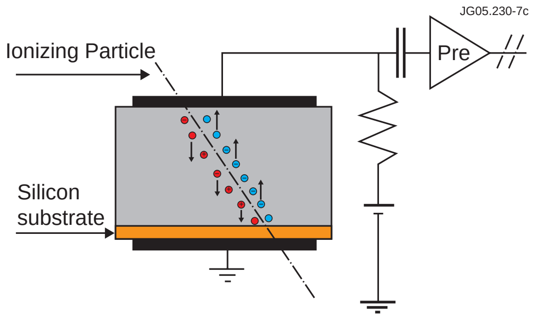


Figure 5: Schematic view and principle of operation of the NE213 liquid scintillator.

Figure 6: Neutron spectrum determined experimentally with the PTBNE213 system (JET Pulse No: 61559, ICRH fundamental Tritium heating). The insert shows the measured Pulse Height Spectrum and the folding of the neutron spectrum with the response functions.



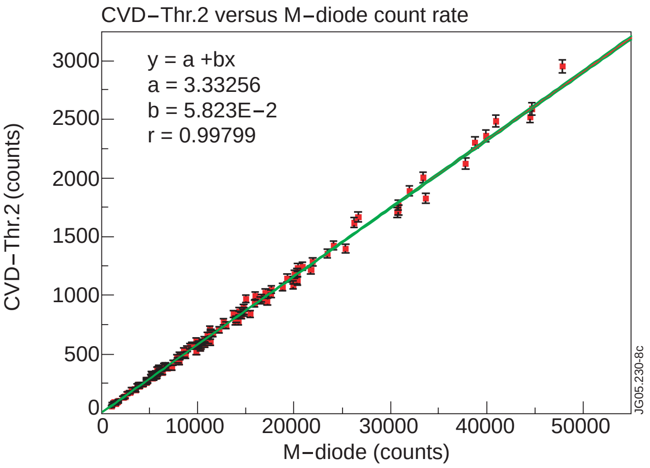


Figure 7: Schematic view and principle of operation of a CVD detector.

Figure 8: Comparison of the counts obtained with a CVD detector and a Si diode.

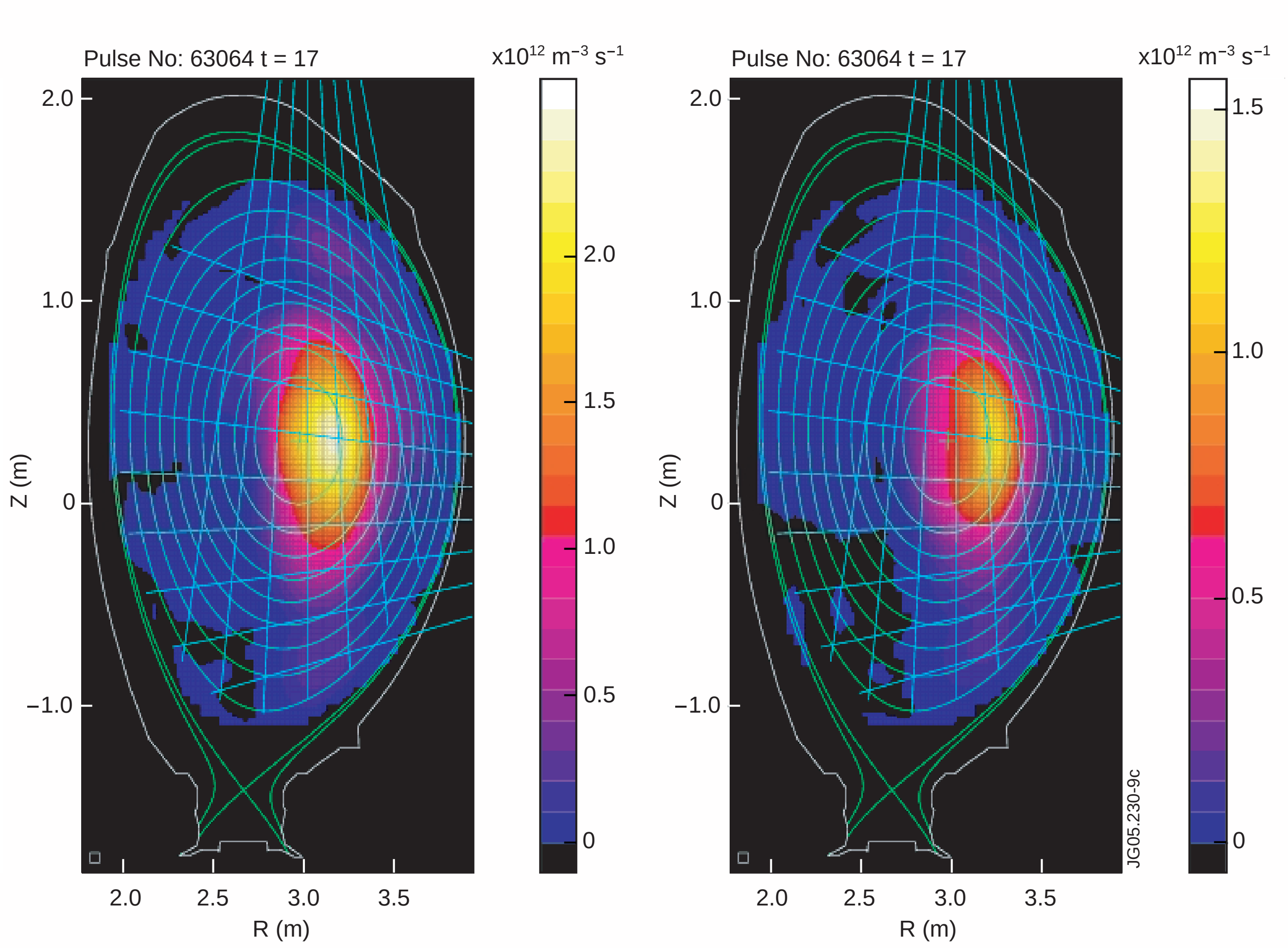
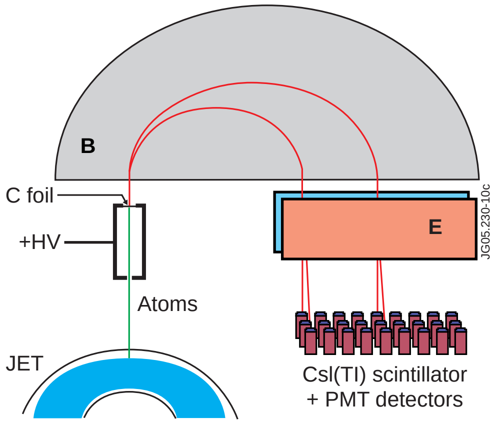


Figure 9: Gamma-ray images of alpha particles and D-ions measured simultaneously during a 2.2 T/2.0MA JET discharge with ICRH heating within plasmas: (a) D-image (ED > 0.8MeV); (b) alpha-image (Ea > 1.7MeV).



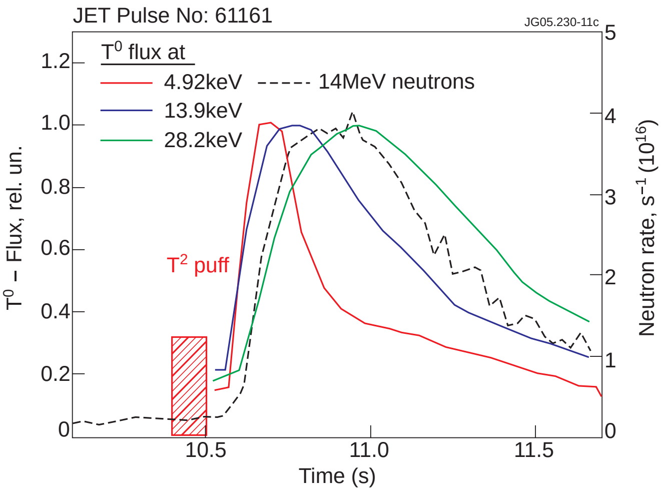


Figure 10: JET Neutral Particle Analyser for the determination of the fuel mixture.

Figure 11: Escaping neutral tritium fluxes measured by the NP after a T_2 puff. The signals at various energies, therefore emitted by different radial positions inside the plasma, are clearly discriminated.

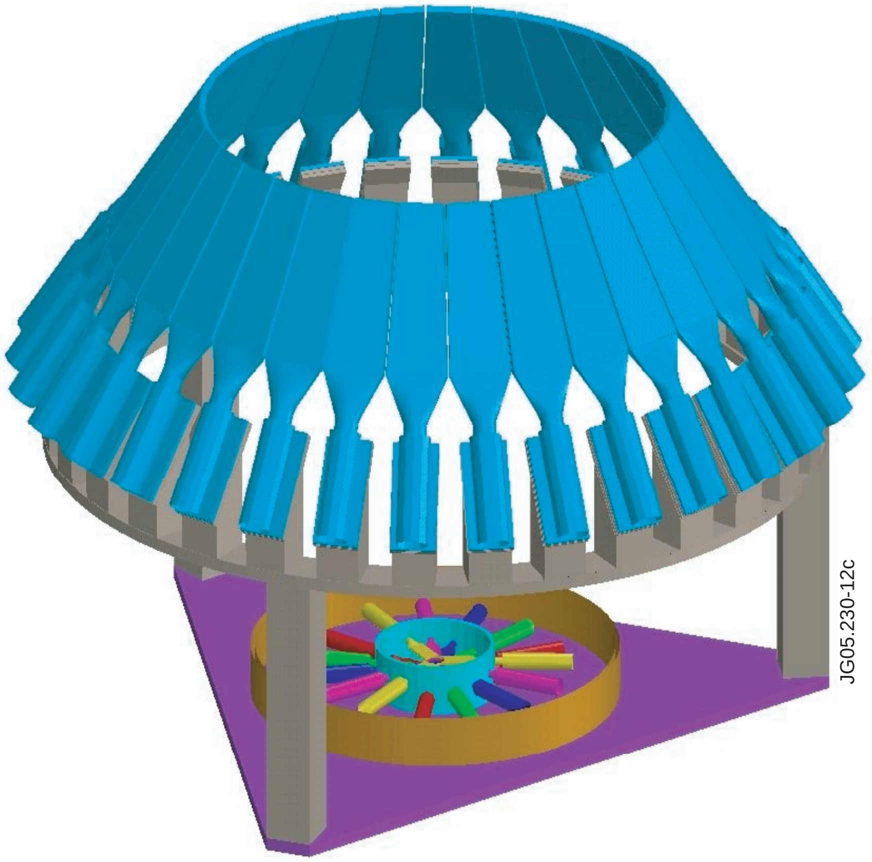


Figure 12: The new time of flight neutron spectrometer (TOFOR), optimized for high count rates. Neutrons enter the diagnostic from below.