Progress in neutron diagnostics at JET

J. Mlynář

Association EURATOM–IPP.CR, Institute of Plasma Physics
Za Slovankou 3, 182 00 Prague, Czech Republic
e-mail: jan.mlynar@jet.efda.org

G. Bonheure

Association EURATOM–Belgian state, LPP–ERM/KMS
TEC, B–1000 Brussels, Belgium

A. Murari

Association EURATOM–ENEA sulla Fusione
Consorzio RFX, 4–35127 Padova, Italy

L. Bertalot, M. Angelone, M. Pillon

Association EURATOM–ENEA sulla Fusione
CR ENEA Frascati, Rome, Italy

S. Conroy, G. Ericsson, J. Källne

Association EURATOM–VR
Uppsala University, Uppsala, Sweden

S. Popovichev

Association EURATOM–UKAEA Fusion
Culham Science Centre, Abingdon OX143DB, UK

and EFDA JET contributors *)

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In the ITER tokamak, diagnosing the plasma neutron emission will be essential to characterise fusion burning process and determine the performance of the machine. JET, currently the world largest tokamak, is the most suitable test bed for development of the fusion–relevant neutron diagnostics due to its plasma parameters and unique tritium operation capability. Current works aim at improving the spatial and spectral characteristics of the neutron measurements at JET, as well as on technological tasks. The present enhancements of neutron diagnostics and data analyses at JET make – together with new fast particle measuring techniques and tritium retention studies – part of the "burning plasma" diagnostic developments towards reactor–grade fusion facilities.

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1 JET and the role of the neutron diagnostics

The Joint European Torus JET [1], [2] is currently the world largest magnetic fusion research facility. Its technical capabilities (major radius $\sim$ 3 m, divertor configuration with ITER–like plasma shape, plasma current up to 5 MA, toroidal magnetic field up to 4 T, tritium and beryllium handling facilities) allow for research and technological development directly linked to future fusion reactors. Indeed, JET recent experimental programme has been clearly focussed on studies of ITER–relevant subjects. Such a programme involves the detection techniques for "burning plasmas" (plasmas with fusion power exceeding the heating power) and requires their further development [3]. Neutron diagnostic systems are the key component in these efforts [4].

The total neutron rates at JET have a wide range, with typical values for deuterium (D–D) fusion about 10^{15} s^{-1}. In the record deuterium–tritium (D–T) discharges the neutron rates well above 10^{18} s^{-1} were achieved. In the future experiments on ITER, up to two orders of magnitude increase in neutron rate is expected, nevertheless the major challenge for diagnostics will be posed by increase of neutron fluence by approx. four orders of magnitude due to longer discharge duration. Diagnostics of fusion neutrons provide a direct indicator of plasma properties, like the fusion power, ion temperature, incidence of fast particles etc. In particular, neutron data will be instrumental for the real–time control of fusion power in future reactors.

2 Neutron rate measurements at JET

At JET, fission counters [5] are the standard diagnostics for the time–resolved neutron emission measurements. However, the fission counters do not discriminate between 2.5 MeV and 14 MeV neutron emission, corresponding to neutrons produced in D–D fusion and D–T fusion, respectively. Silicon diodes based on (n, α), (n, p) threshold reactions have been used for neutron rate measurements limited to higher energies (i. e. D–T fusion only) [6], but these detectors are not reactor–relevant as they suffer radiation damage even in relatively low neutron fluence $> 10^{12}$ cm^{-3}. Therefore, JET presently fosters development of diamond detectors as a substitute of silicon detectors that should be suitable for radiation harsh environment.

Several natural diamond detectors have been used at JET for monitoring the time–resolved 14 MeV neutron emission [7]. Due to the small size and high cost of natural diamonds, a chemical vapor deposited polycrystalline diamond films have been also tested at JET [8]. Both options have recently proved to cope well with the tokamak environment and operate reliably over long periods.

Spatial distribution of neutron emission from fusion plasmas has often proved to be asymmetric and difficult to predict, in particular when asymmetric heating is applied. Therefore, the JET neutron profile monitor [9] is an instrument of unique importance among fusion neutron diagnostics. The monitor consist of two cameras, one with ten collimated channels providing a fan–shaped horizontal view, and

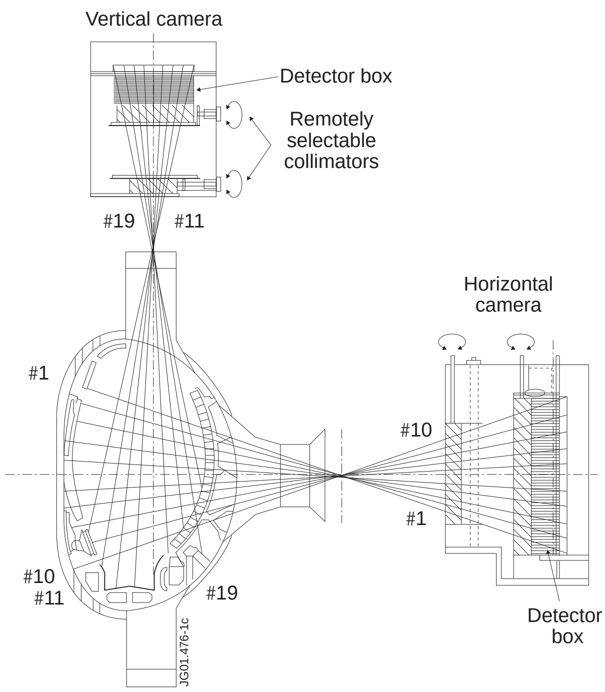

Fig. 1. Scheme of the JET Neutron and Gamma rays Monitor.

another with nine collimated channels providing a fan–shaped vertical view, see Fig. 1. Each channel is equipped with a remotely selectable collimator and a set of three detectors differing in the scintillator: the liquid organic NE213 (for wide range of neutron and γ–ray energies, with integrated pulse shape discrimination), the plastic bicron BC418 (for higher energy neutrons only), and the CsI(Tl) (for γ rays only).

An important upgrade foreseen for the neutron profile monitor is to replace the conventional analog pulse shape discriminator with the state–of–the–art Digital Pulse Shape Discrimination acquisition system [10]. This upgrade is highly reactor–relevant as it will significantly increase dynamic range of the acquisition rate. The neutron profile monitor is subsequently expected to be integrated into the real time control of the JET facility.

The spatial plasma coverage provided by the neutron profile monitor is adequate for 2D tomography – i. e. for the inverse reconstruction of the neutron emissivity cross–section – albeit with a rather scarce spatial resolution. Minimum Fisher Regularisation algorithm [11] has been recently adapted for the neutron tomography [12]. Based on the first encouraging results, the technique will be further developed e.g. to allow for constraints given by the magnetic field geometry. Spatially resolved measurement of the neutron emissivity dynamics could significantly contribute to the studies of tritium transport.

3 Neutron spectrometry at JET

In fusion plasmas, spectrometry of fusion neutrons is instrumental for determining the plasma core ion temperature from the peak broadening. Moreover, the neutron spectra often reflect composite effects as well as geometric dependencies due to complex trajectories of fast ions in high power plasmas.

Trade–offs between spectral resolution and detection efficiency, and between time resolution and statistical errors are characteristic for neutron spectrometry. Consequently, many neutron detectors have been tested and used for neutron spectroscopy in fusion experiments [4]. At JET, for example, neutron activation methods have been applied for time–integrated spectral measurements [13]. In this case, neutron transport calculations have to be performed in order to obtain the response coefficient for the materials between the sample and the plasma. There have been also attempts to use the above mentioned Silicon diodes and diamond detectors for spectrometry, however, their response function is complex and not yet sufficiently determined. The major development efforts are recently focussed on 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.

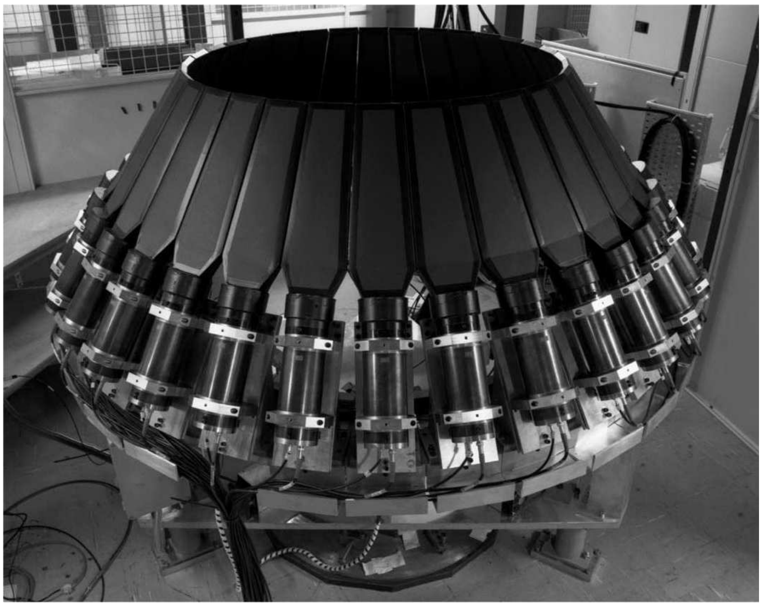

Fig. 2. Photo of TOFOR – Time Of Flight for Optimised Rate diagnostic.

The new time–of–flight spectrometer TOFOR [14] was installed in the JET Roof laboratory during past shutdown, see Fig. 2. In this detector, neutrons are recoiled within the primary (scattering) scintillators towards a large bank of secondary scintillators, so that the registered time of flight between the co–incident pulses correspond to neutron energy. Notice that the the time of flight is independent of the recoil angle as both the primary and the secondary detectors lie on an imaginary sphere. The main advantage of TOFOR is its high count rate capability ($> 10^5$ n/s) combined with a good calibration and an energy resolution of about 6 %, but somewhat limited efficiency and challenging discrimination of the co–incidences. The TOFOR detector is optimised for measurements of 2.5 MeV D–D fusion neutrons.

The Magnetic proton recoil spectrometer [15] was originally installed at JET to measure spectral properties of 14 MeV D–T fusion neutrons. The measurement is based on magnetic spectrometry of protons recoiled from a thin target in head–on collisions with collimated neutrons. This principle combines a good energy resolution (about 2.5 %) with properly defined absolute calibration, the downside is its low efficiency. Recently the system has been significantly upgraded so that it is capable of measuring spectral properties of the 2.5 MeV D–D fusion neutrons with approx. 6 % energy resolution. This extension was possible due to considerably improved signal–to–noise ratio, which was achieved in particular by installing a new scintillation unit for identification of recoil protons.

The organic liquid scintillators known as NE213 [16] combine high efficiency, high light output and good pulse shape discrimination properties. However, the pulse height spectrum correspond to protons that were recoiled in the scintillator's volume, so that there is no information on the recoil angle. The neutron spectrum can be unfolded from the measured pulse height spectrum using the detector's response function that describes the extended proton recoil distribution. The above mentioned Minimum Fisher Regularisation [11] was successfully adapted to run the unfolding process for the NE213 data [17]. The results are in good agreement with the standard MAXED unfolding code [18], which proves the promising potential of NE213 for neutron spectrometry in wide energy range and with good resolution of the peak width (up to 4 % and 2 % for D–D and D–T neutrons, respectively). The agreement also clarifies that minor artifacts in the unfolded spectra are most likely due to uncertainties in the available response function. Therefore, the response function requires more profound modelling efforts and (even more importantly) a detailed experimental calibration of the NE213 scintillator on a neutron source. The latter is now foreseen as an significant part of the future upgrades of the JET diagnostics.

4 Conclusion

With recent progress towards ITER, importance of neutron measurements for fusion plasma diagnostics has been clearly recognised. In this respect, the JET tokamak plays a key role in neutron diagnostics development due to both its unique parameters and its accumulated experience. Current topics of research and development at JET include new radiation hard detectors, digital data acquisition, new and upgraded neutron spectrometers, optimised tomography and unfolding techniques.

At the same time, the scientific programme at JET is derived from the ITER requirements, so that the programme is in particular focussed on the burning plasma physics. The contribution of neutron diagnostic to this research has been very important, and there is a large potential for further progress, for example, in tritium transport studies and/or in fast particle physics.

References

[1] J. Pamela, J. Ongena and JET EFDA contributors: *Overview of JET results*. Nuclear fusion **45** (2005) S63.

[2] J. Mlynar, J. Ongena et al.: *JET: Preparing the future in fusion*. Czechoslovak Journal of Physics **54** (2004) C28.

[3] A. Murari et al: *"Burning plasma" diagnostics for the physics of JET and ITER*. Plasma physics and controlled fusion **47** (2005) B249.

[4] G. Bonheure et al.: *Neutron diagnostics for reactor scale fusion experiments*. International Workshop on Fast Neutrons Detectors and Applications FNDA 2006, Cape Town, Proceedings of Science PoS(FNDA2006)RE02

[5] M. T. Swinhoe and O. N. Jarvis: *Calculation and measurement of* ^{235}U *and* ^{238}U *fission counter assembly detection efficiency*. Nuclear instruments and methods **221** (1981) 460.

[6] S. Conroy et al.: *Time resolved measurement of triton burnup in JET experiments*. Nuclear fusion **28** (1988) 2127.

[7] A. V. Krasilnikov et al.: *Study of D–T neutron energy spectra at JET using natural diamond detectors*. Nuclear instruments and methods **A476** (2002) 500.

[8] M. Angelone et al.: *Time dependent 14 MeV neutrons measurement using a polycrystalline chemical vapor deposited diamond detector at the JET tokamak*. Review of Scientific Instruments **76** (2005) 013506.

[9] O. N. Jarvis et al.: *Neutron profile measurements in the Joint European Torus*. Fusion Engineering and Design **34–35** (1997) 59.

[10] B. Esposito et al.: *Digital pulse shape discrimination in organic scintillators for fusion applications*. Nuclear Instruments and Methods **518** (2004) 626.

[11] M. Anton et al.: *X–ray tomography on the TCV tokamak*. Plasma physics and controlled fusion **38** (1996) 1849.

[12] G. Bonheure et al.: *2–D spatial distribution of D–D and D–T neutron emission in JET ELMy H–mode plasmas with Tritium puff*. 32nd EPS Conference on Controlled Fusion and Plasma Physics, Tarragona, Spain, Europhysics Conference Abstracts **29C** (2005) P–1.083.

[13] B. Esposito, L. Bertalot, M. Loughlin and A. L. Roquemore: *Neutron spectrum measurements in DT discharges using activation techniques*. Review of Scientific Instruments **70** (1999) 1130.

[14] A. Hjalmarsson et al.: *The TOFOR spectrometer for 2.5 MeV neutron measurements at JET*. Review of Scientific Instruments **74** (2003) 1750.

[15] J. Kallne and H. Enge: *Magnetic proton recoil spectrometer for fusion plasma neutrons*. Nuclear Instruments and Methods **311** (1992) 595.

[16] A. Zimbal et al.: *Compact NE213 neutron spectrometer with high energy resolution for fusion applications*. Review of Scientific Instruments **75** (2004) 3553.

[17] J. Mlynar, J. M. Adams, L. Bertalot, S. Conroy et al.: *First Results of Minimum Fisher Regularisation as Unfolding Method for JET NE213 Liquid Scintillator Neutron Spectrometry*. Fusion Engineering and Design **74** (2005) 781.

[18] M. Reginatto, P. Goldhagen and S. Neumann: *Spectrum unfolding, sensitivity analysis and propagation of uncertainties with the maximum entropy deconvolution code MAXED*. Nuclear Instruments and Methods **A476** (2002) 242.