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High rate neutron and gamma ray spectroscopy of magnetic confinement fusion plasmas

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Abstract: An important instrumental development work has been done in the last two decades in the field of neutron and gamma ray spectroscopic measurements of magnetic confinement plasmas. Starting from the present state of the art instrumentation installed at JET, this paper reviews the recent development that has been carried out within the EUROFUSION programme for the forthcoming high power JET D and DT campaign. This development was dedicated to the realization of new compact neutron and gamma-ray spectrometers which combine very high energy resolution (typically better than 5%) and MHz counting rate capabilities allowing for time resolution in the 10 ms time scale. One of the advantages offered by the compact dimensions of these spectrometers

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is to make possible their use in multiple sight-line camera configurations, such as for future burning plasma reactors (ITER and DEMO). New compact neutron spectrometers based on single crystal diamond detectors have been developed and installed at JET for measurements of the 14 MeV neutron spectrum. Measurements on a portable DT neutron generator have shown that neutron spectroscopy of the accelerated beam ions at unprecedented energy resolution ($\sim$ 1% at 14 MeV) is possible, which opens up new opportunities for diagnosing DT plasmas. For what concerns gamma ray measurements, the JET gamma ray camera has been recently upgraded with new compact spectrometers based on a LaBr3 scintillator coupled to Silicon Photomultiplier with the dual aim to improve the spectroscopic and rate capabilities of the detectors. The upgrade camera system will reconstruct the spatial gamma ray emissivity from the plasma in the MeV energy range at MHz counting rates and energy resolution in the 2–4% range. This will allow physics studies of gamma rays produced by the interaction of fast ions with impurities in the plasma and bremsstrahlung emission from runaway electrons.

Keywords: Diamond Detectors; Gamma detectors (scintillators, CZT, HPG, HgI etc); Neutron detectors (cold, thermal, fast neutrons); Nuclear instruments and methods for hot plasma diagnostics

Contents

1 Introduction

The worldwide effort on high power thermonuclear fusion experiments in magnetic confinement Deuterium (D) and Deuterium-Tritium (DT) plasma is finalized to the goal of producing a burning plasma based on the reaction D + T $\rightarrow \alpha$ (3.5 MeV) + n (14.1 MeV). The best condition to reach the so called self-sustaining plasma requires deuterons (d) and tritons (t) fuel ions with Maxwellian distribution of ion temperatures in the range 15–20 keV. In such conditions the heating to the plasma will be predominantly given by the fusion α particles, which by the slowing down can transfer a significant fraction of their energy to the fuel ions. A minority fraction of fuel ions as well of other non-fusion born energetic ions (such as for instance He-3 or He-4 ions) can be present due to the external heating in the form of Ion Cyclotron Resonance Heating (ICRH) or Neutral Beam (NB) injection. The diagnosis of the fuels ions and of the non-fusion born suprathermal particles distribution functions, together with the alpha particles, is crucial in a DT burning plasma as their confinement affects the plasma performance and their losses could cause serious damage to the tokamak first wall [1].

On present day machines operating in D plasmas, suprathermal ions can be created by ICRH and NB injection in the hundreds keV range and their energy distribution is diagnosed by dedicated diagnostics. A review of the fast ion diagnostics can be found in ref. [2]. In a DT burning plasma, many of the mentioned techniques present principle and technical limitations which strongly limit their applicability [3]. The hundred times 14 MeV larger neutron flux than 2.5 MeV flux in a D plasma and the harsh environment represented by a DT experiment on a tokamak requires the use of nuclear physics based diagnostics and interesting candidates are here represented by high resolution Neutron Emission Spectroscopy (NES) [4, 5] and Gamma Ray emission spectroscopy (GRS) [5, 6]. 14 MeV neutrons are produced directly by the DT reaction itself while gamma rays are emitted by reactions among alpha particles or other fast ions and light impurities (typically beryllium or carbon) which are present in the plasma. Both neutron and gamma rays, being uncharged, leave the plasma and can be used to infer information on fast ions in a burning plasma device. This requires the use of dedicated spectrometers that match the measurement requirements. Among the various instrument requirements, the most demanding ones and specific to the fusion applications are: i) good energy resolution in the range 1–5% which is needed in order to perform analysis of the spectral lines; ii) high counting rate capabilities (ideally above 1 MHz) for achieving time resolution in the tens of ms time scale [5]. Physical parameters such as the bulk ion temperature, the high energy tail temperature and energy density of the fast fuel ion population can be extracted from NES observations [7] as well as the study of the interactions between fast deuterons and MHD activity [8]. Similarly, in GRS measurements from the Doppler Broadening of gamma ray peaks from the reactions ^{12}C(^{3}He,pγ)^{14}N and ^{9}Be(α,nγ)^{12}C information on the fast ^{3}He and ^{4}He distribution function has been inferred in JET ICRH experiments [6, 9].

This paper focuses on the recent development that has been carried out within the EUROFUSION programme for the forthcoming high power JET D and DT campaign. This development was dedicated to the realization of new compact neutron and gamma-ray spectrometers which combine very high energy resolution (typically better than 5%) and MHz counting rate capabilities. One of the advantages of the compact dimensions of these spectrometers is to make the integration with a tokamak easier and to extend their use in multiple sight-line camera configuration. This opens up the possibility to perform space and energy resolved neutron and gamma tomography measurements in future burning plasma reactors (ITER and DEMO).

The paper is organized as follows. The principles behind high resolution NES and GRS in a fusion plasma are described in section 2, while section 3 and section 4 describe the recently developed compact neutron and gamma-ray spectrometers, respectively and illustrate their performances. Finally conclusions are drawn in section 5.

2 Neutron and gamma ray emission spectroscopy of fusion plasmas

NES and GRS measurements of fusion plasmas require advanced neutron and gamma ray spectrometers capable to operate in a tokamak environment at the required instrumental performances. In particular, energy resolution, count rate capability, detection efficiency and signal to background ratio are among the most important requirements for these spectrometers [10]. A high energy resolution is needed for measurements of the Doppler broadening of the neutron and gamma ray spectra. In fact, it is from measurements of the detailed spectral shape that information on the fuel and fast ion distribution can be inferred. The limit in the achievable energy resolution is mainly due to the detection principles on which the spectrometers are based. It is easier for instance to achieve very high energy resolution with gamma ray spectrometers (typically HPGe detectors have FWHM $< 0.2\%$ at 1.3 MeV) than with neutron spectrometers (FWHM in the range 1–3% for 14 MeV neutrons). On the other hand, the broadening of the gamma lines shape is significantly less than for the neutron spectrum and therefore a detailed line shape analysis requires higher energy resolution [6, 9]. The second crucial requirement of the spectrometers is the high count rate capability which implies the possibility to perform time resolved measurements of the neutron and gamma ray emission spectra, and thus studying the time evolution of the bulk and fast ion energy distribution. The limit here is mainly linked to the detection principles of the instruments and to the data acquisition chain. Custom designed spectrometers combined to the last generation of fast electronics and data acquisition allow counting rates capability of 1 MHz. It is important to note in this context to distinguish between the total load on the spectrometer and the fraction of the so called “good” events, since the latter are the one that set the lower limit to the achievable time resolution. If for instance one requires 10^4 “good” counts in the recorded spectrum, corresponding to a statistical accuracy of 1%, this implies that a time resolution of 10 ms or 100 ms can be achieved with recorded counting rates of 1 MHz or 100 kHz of good events, respectively.

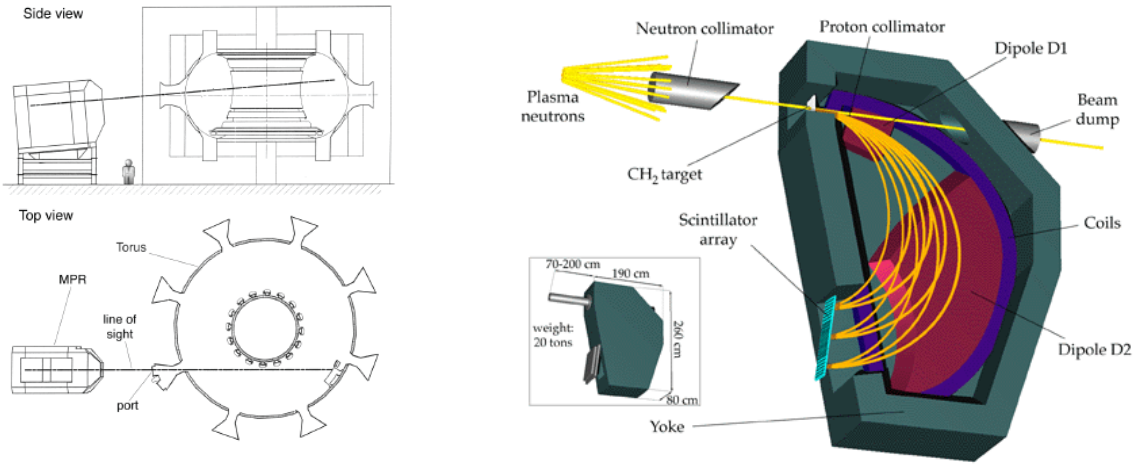

Figure 1. On the left it is shown the line of sight of the Magnetic Proton Recoil spectrometer Upgrade (MPRu) with a side and top view of the JET tokamak. A schematics of the MPRu is shown on the right [5]

Lower time resolution can be achieved by accepting a large statistical uncertainty. The detection efficiency (ε) of the spectrometer is also important to guarantee that the spectrometer can record the desired counting rates. However, what matters is the product $\Phi \cdot \varepsilon$ where Φ is the incoming neutron or gamma ray flux (measured in $s^{-1} \cdot cm^{-2}$). This means that low ε values can be accepted if the incoming flux is high. Signal to background is instead related to the spectrometers capability to resolve small features in the measured spectrum. It can vary significantly for the different spectrometer types, their collimations, shielding and installation position around the tokamak.

The state of the art of fusion neutron spectrometers is represented by the Magnetic Proton Recoil Upgrade (MPRu) and Time Of Flight Optimized for Rate (TOFOR) spectrometers, which are installed along a single line of sight at the JET tokamak. The MPRu neutron spectrometer [10, see figure 1] is optimized for 14 MeV measurements of DT plasmas and detects the incoming collimated neutrons via elastic scattering into recoil protons in a polyethylene target and measurement of the recoil protons dispersion in a known magnetic field. The MPRu features an excellent energy resolution (2.5% at 14 MeV), a detection efficiency of about 10^{-6} and a count rate capability $\gg$ 1 MHz. A thick 80 tons concrete shielding allows to reach signal to background values in excess of 10^4 which allows for observing weak features in the neutron spectrum [10]. Example of results achieved with the MPRu are described in ref [4, 10, 11].

Although the MPRu spectrometer can measure as well 2.5 MeV neutrons, due to the combined low detection efficiency and lower incoming neutron fluxes it is not the best spectrometer choice for D plasmas. The TOFOR neutron spectrometer is the state of the art instrument for high counting rates operation in D plasmas. TOFOR is installed in the JET roof laboratory in a shielded low-background area, at about 19 m from the plasma centre with a vertical view into the plasma (see

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figure 2). TOFOR [12], which detects neutrons via the time of flight techniques, has the unique feature that the stop detectors are placed on the so called constant time of flight sphere, which allows achieving the highest possible count rate in time of flight measurements (about 500 kHz [12]). Higher values are limited by the so called random coincidences. The energy resolution is about 7% at 2.5 MeV with a detection efficiency of 1%. An example of information provided by NES on D plasma is shown in figure 3 where the measured TOFOR spectrum for the JET discharge #86461 is shown with the spectral components analysis [13]. From analysis of the NES data it was possible to infer the D distribution function (see figure 3-right). A collection of results achieved with TOFOR can be found in ref [13].

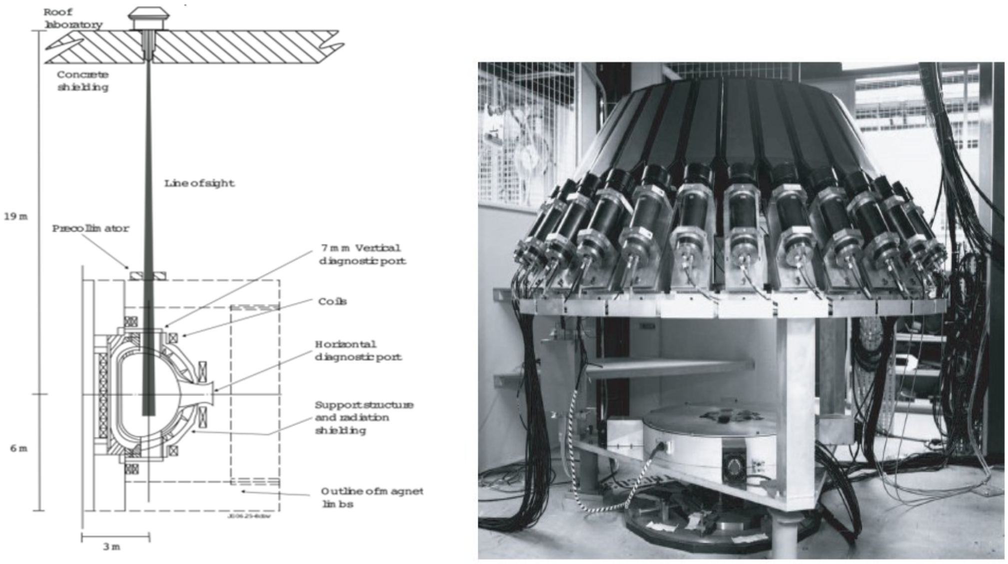

Figure 2. On the left it is shown the line of sight of the TOFOR neutron spectrometer with a side view of the JET tokamak. A picture of TOFOR is shown on the right [5].

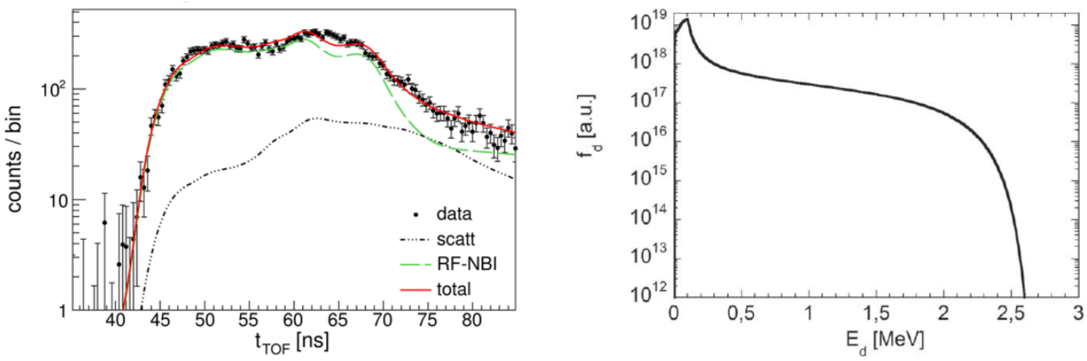

Figure 3. On the left, example of TOFOR time flight spectrum for the JET discharge #86461 with ICRH tuned on the third ion cyclotron harmonic. The line shown is a fit to the experimental data based on the deuterium distribution shown on the right (dashed line) and the effect of neutron energy scattering along the line of sight from the plasma to the detector (dashed-dotted line) [13].

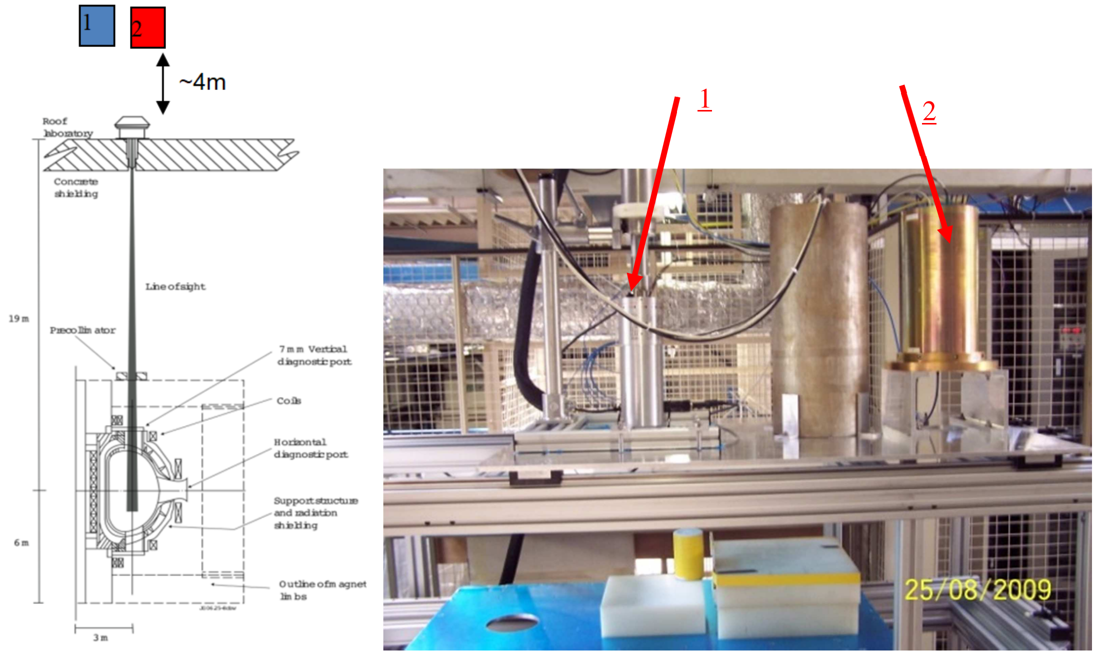

Figure 4. On the left it is shown the line of sight of the gamma ray spectrometers HPGe semiconductor (label 1) and $LaBr_3$ scintillator (label 2) installed at JET. A picture of the installation on a movable detector slider is shown on the right [5].

For what concerns GRS measurements at JET, determination of the Doppler broadening of characteristic gamma ray emission peaks from fusion plasmas are performed with a High Purity Germanium (HPGe) semiconductor (see figure 4-left). The detector features an energy resolution of 2.4 keV at $E_\gamma = 1.33$ MeV and a 100% relative full energy peak efficiency. Operation in high neutron flux environment is made possible by using a N-type germanium which is more resilient to neutron damage and by equipping the detector with an electromechanical cooling system rather than the traditional nitrogen cooling to facilitate operation in restricted areas. The HPGe spectrometer is placed on the same radial line of sight of the TOFOR neutron spectrometer, at a distance of 23 m from the plasma centre. In view of GRS measurements on next step tokamaks such as ITER it has been developed a large size $3'' \times 6''$ LaBr3 scintillator crystal which has been designed for high rate operation in large neutron background. The LaBr3, which shares the same line of sight of the HPGe spectrometer (see figure 4-right), features a lower energy resolution (about 30 keV at 1.3 MeV) than the HPGe spectrometer but has higher full energy peak efficiency and can sustain higher count rates. By combining the detector with a fast digital data acquisition, for the first time it has been shown that gamma ray spectroscopy measurements can be sustained at rates in excess of 2 MHz without a significant degradation of the energy resolution [14]. An identical LaBr3 detector is installed on oblique line of sight equipped with a LiH neutron attenuator. These gamma ray spectrometers are routinely used at JET for fast ion physics studies and for determination of the effectiveness of the ICRH schemes [6, 15]. An example of Doppler Broadening analysis of a GRS spectrum is shown in figure 5 for the reaction $^{12}C(^{3}He,p)^{14}N$. From the data analysis of both the Doppler broadening and the recorded intensity gamma ray emission it was possible to infer a tail temperature of 400 keV

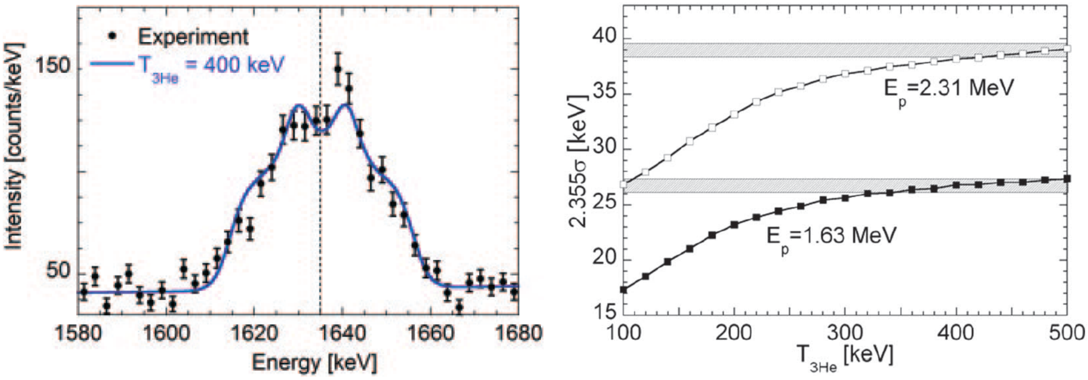

Figure 5. On the left, GRS measurement of the 1635 keV lines from the reaction $^{12}C(^{3}He,p)^{14}N$ measured at JET with the HPGe spectrometer and shown with a fit to the data. On the right it is shown the relation between the Doppler Broadening of the 1635 keV and 2310 keV lines and the tail temperature of the fast ^{3}He population [15].

for the fast He3 population [6, 15]. A collection of gamma ray results on fast ions can be found in references [16].

3 Diamond 14 MeV neutron spectrometers for DT

Since a few years artificial diamonds grown with the Compact Vapour Deposition technique have reached a high quality in terms of impurities that allows for realizing detector for radiation spectroscopic measurements [27]. Single crystal Diamonds (SD) are being exploited as compact high resolution 14 MeV neutron spectrometers for DT plasmas. Neutron detection in SD is based on the collection of electron-hole pairs produced by charged particles generated by neutron interaction with ^{12}C nuclei. Neutron interacts via elastic and inelastic scattering besides nuclear reaction channels that open up at energies above about 6 MeV. For energies below 6 MeV, the SD response features a characteristic flat broad response up to the elastic scattering edge corresponding to the maximum energy that a neutron can transfer to the recoil ^{12}C. In this case, such as for 2.5 MeV neutrons, the detector can be exploited as counter/flux monitor and moderate energy resolution neutron spectrometer. For neutron energies above about 6 MeV high resolution neutron spectroscopy is possible by measuring the deposited energies of the charge products of the reaction $^{12}C(n,\alpha)^{9}Be$ which can fully deposit their energy in the SD. In this case the SD response features a peak than can be exploited for neutron spectroscopy.

The first CVD diamond detectors were installed at JET in the year 2005 and featured dimensions of 5–10 mm^2 area and 20–30 μm thickness [17]. Both diamonds were covered with 2 μm of Lithium Fluoride (LiF) 95% enriched in ^{6}Li to provide a neutron-to-charged particle converter in order to be sensitive to thermalized neutron. These diamonds have been successfully used as 2.5 MeV and 14 MeV neutron monitors [17].

A SD neutron spectrometer prototype based on a single pixel 4.5×4.5×0.5 mm^3 was installed at JET in 2011 [18] and the achieved results have successfully shown for the first time its spectroscopic capability of measuring 2.5 MeV neutrons from deuterium plasmas. Following this first exploratory measurements a matrix of 12 independent pixels was developed in 2015 as part of the enhancement program for the high power JET DT campaign. The CVD matrix (see figure 6-left) is installed at JET in a fixed position above the TOFOR spectrometer and being very light and of low Z material it does not interfere with the gamma ray beams, and can thus coexists with the gamma ray spectrometers located above it [19]. The electronic chain consists of fast charge preamplifiers and a 500 Ms/14bit digitizer which provides in list mode information on the time and deposited energy of each neutron event. For each pixel, the overall total detection efficiency is about 1% at 14 MeV and 0.05% for the spectroscopic channel ^{12}C(n,α)^{9}Be alone.

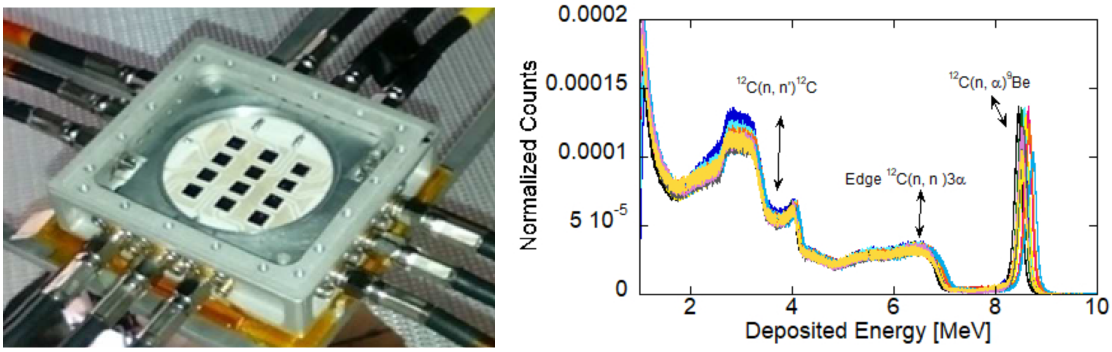

Figure 6. On the left, picture of the 12-pixels diamond matrix installed at JET. On the right, calibration of the 12 pixels with quasi monoenergetic 14 MeV neutrons carried out at Frascati Neutron Generator. The labels indicate the main features in the pulse height spectrum [19].

Operations at 1 MHz counting rates have been demonstrated thanks to the fast acquisition chain and the energy resolution is $<$ 1% FWHM at 14 MeV [20]. The matrix has been subject of extensive calibration dedicated to the measurement of the detector response function to quasi-monoenergetic neutrons in the energy range 1–20 MeV. Reports of the calibration performed at the Heavy Ion Physics department at the Peking University (China) and at the CN facility at the INFN-LNL (Laboratori Nazionali di Legnaro) in Legnaro (Padua, Italy) are given in References [20, 21]. Here we summarize the response of the 12 pixels to quasi mono energetic 14 MeV neutrons which was found to be uniform as shown in figure 6-Right. The pulse height spectrum features several structures due to the different reaction channels, among which the so called (n,α) peak located at 8.5 MeV is the one that deposit most energy and that is used for spectroscopy. The diamond matrix is in operation at JET and will be used in the forthcoming high power D and DT campaign.

The enhanced energy resolution at 14 MeV of the CVD diamond opens up to new opportunity for neutron spectroscopy of DT plasmas. While no DT plasma experiment have been yet performed at JET at the time of the writing of this manuscript, a CVD diamond neutron spectrometer was used to measure the neutron spectrum of a portable DT neutron generator. The results (see figure 7) indicated that it was possible to resolve for the first time the complex features of the neutron energy spectra resulting from the mixed D/T beam ions reacting with the T/D nuclei present in the target [22]. Similarly, in JET and ITER DT plasmas it is expected that the diamond detectors would provide good separation of the different 14 MeV neutron components and that information on the NB slowing down can be achieved [22].

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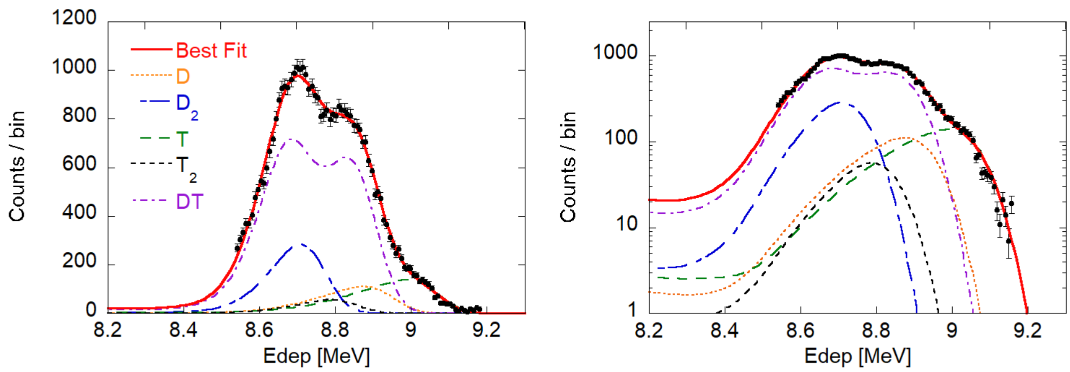

Figure 7. SD pulse height spectrum of a portable DT neutron generator shown in linear (left) and log (right) scale at 0 degrees with respect to the accelerated beam. The lines represent the different neutron components that have been identified and are due to acceleration of a mixture of D/T beam ions on a D/T target [22].

4 Compact $LaBr_3$ gamma ray spectrometer

Among other diagnostics, the JET gamma ray camera (GC) has been recently upgraded within the EUROFUSION enhancement program with the goal to achieve improvements in terms of energy resolution and counting rate capability and to allow high fusion power operation. The GC consists of 10 horizontal and 9 vertical fan shape line of sights, respectively [23]. The previous gamma ray detectors were based on CsI scintillators coupled to pin photodiodes and featured very limited spectral capabilities and were slow (decay time in the range 0.5–4 µs) which meant that they could not be used in high power operations. The upgrade consisted in replacing the detector with more performing ones, with the constraints of not modifying the shielding, frames and supports as well as insensitivity to magnetic fields. The developed solution is based on a $1'' \times 3/4''$ LaBr3 scintillator crystal coupled to a $12 \times 12\,\mathrm{mm}^2$ Hamamatsu Silicon PhotoMultiplier (SiPM) (see figure 8-left). SiPM have been chosen since they feature very compact size, high internal gain and insensibility to magnetic field. The SiPM is embedded in a readout electronic board implementing a CR differentiator circuit with pole zero compensation to shorten the output signal length and enable high rate capabilities by accepting a reduction of the pulse amplitude. The optimization provided a pulse signal length of about 150 ns [23]. The output signal of each detector goes to digital data acquisition system based on the Advanced Telecommunications Computing Architecture which features 200 MSamples/s and 13 bits [26]. The DAQ system offers the possibility to be operated in different modes depending on the needs and on the expected fluxes. Finally, the system is equipped with real-time temperature monitors and integrated power supplies which provide stabilized bias voltage and gain compensation for each SiPM [23].

The upgraded JET GC has been fully characterized through gamma-ray measurements calibrations carried in the laboratory and in situ. The latter are possible via the use of radioactive sources that are permanently located in the GC and can be moved near the detectors when needed. In situ calibrations are important in order to assess the noise pick up level that can arise due to the 80m long coaxial cables running from the GC to the data acquisition. Calibrations indicate that all the

19 spectrometers feature good energy resolution which is about 5% at 662 keV (see figure 8-right). These results extrapolate favourably for fast ion studies at JET through γ-ray spectroscopy. In particular, an energy resolution in the range 2–3% can be estimated at 4.44 MeV for γ-rays emitted from ^{9}Be(α,nγ)^{12}C reactions. This would allow spatially resolved measurements of fast ions, such as the fusion α particles in DT plasma, and for studying instabilities effects driven by fast ions. An added feature of the detectors is the intrinsic background due to the natural activity of ^{137}La present in the crystal. Due to the limited volume of the crystal this background load is low and does not perturb the measurement. Monitoring of the gain and of the working point of the spectrometer is an important issue and when possible is done with a control monitoring system based on LED system [24]. Due to space and interface constraints it was not possible to implement such a system on the GC. However the natural background provides a peak at 1.436 MeV which can be used to monitor gain changes of each individual detector in between JET discharges. Finally, tests performed at accelerator have shown that counting rates up to 2.9 MHz can be reached by accepting a change of the gain of the detector [25].

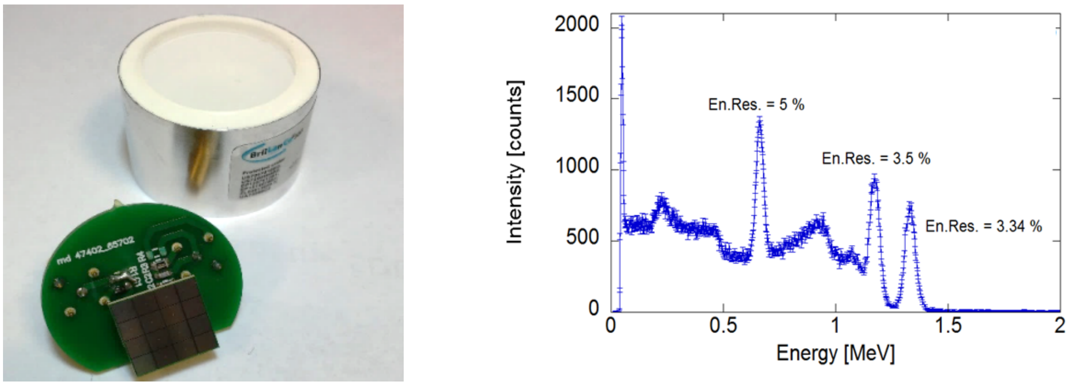

Figure 8. On the left, picture of the compact $1'' \times 3/4''$ LaBr3 and of the Silicon Photomultiplier developed for the JET gamma ray camera. On the right, example of calibration with Cs137 and Co60 sources collected in situ at JET [23].

The upgraded GC at the time of the writing of this paper is being commissioned with D plasma and will contribute to the scientific program of JET. In particular, it is expected to contribute to the studies of fast ions and runaway electrons [16], the latter being diagnosed by a measurement of the hard X-ray bremsstrahlung emission caused by collisions of the confined and unconfined runaway electrons with plasma impurities and tokamak materials.

5 Conclusions

In this paper the NES and GRS state of the art spectrometers installed at JET have been reviewed, with focus on the recent development that has been carried out within the EUROFUSION programme for the forthcoming high power JET D and DT campaign. This development was dedicated to the realization of new compact neutron and gamma-ray spectrometers which combine very high energy resolution (typically better than 5%) and MHz counting rate capabilities allowing for time resolution in the 10–100 ms time scale. New compact neutron spectrometers based on single crystal diamond detectors have been developed and installed at JET for measurements of the 14 MeV neutron spectrum. Measurements on a portable DT neutron generator have shown that neutron spectroscopy of the accelerated beam ions at unprecedented energy resolution (∼ 1% at 14 MeV) is possible, which opens up new opportunities for diagnosing DT plasmas. For what concerns gamma ray measurements, the JET gamma ray camera has been recently upgraded with new compact spectrometers based on a LaBr3 scintillator coupled to a Silicon Photomultiplier with the dual aim to improve the spectroscopic and rate capabilities of the detectors. The upgrade camera system will reconstruct the spatial gamma ray emissivity from the plasma in the MeV energy range at MHz counting rates and energy resolution in the 2–4% range. This will allow physics studies of gamma rays produced by the interaction of fast ions with impurities in the plasma and bremsstrahlung emission from runaway electrons.

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