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Neutron diagnostics for reactor scale fusion experiments: a review of JET systems

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Fusion is preparing for and moving towards reactor scale plasma experiments. The ITER project requires stepping up the capabilities of neutron measurement systems because in a fusion reactor, measurements of neutron yield and of fusion power and power density are essential. Fast neutron measurement systems for fusion applications include neutron flux measurement systems, neutron imaging systems and neutron spectrometers. The JET tokamak is the most suitable test bed for the development of these systems due to its plasma parameters and unique tritium operation capability. Existing systems include 2 neutron cameras composed of multi-collimator arrays and which allow the development of more advanced applications such as 2-D neutron imaging for the study of critical physical phenomena. The spectral width of the neutron emission should be a reliable indicator of ion temperature in a reactor grade plasma. Therefore, three types of neutron spectrometers are currently being developed. The different approaches, methods and calibration techniques are summarised. Finally, since the needs for development of robust and proved neutron measurement systems for ITER are increasingly recognised, JET has now started a series of interesting technological developments in various fields including new radiation hard detectors, new electronics and data acquisition.

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1. Introduction

The present article reviews some neutron measurement techniques and detectors in use or under development at the JET tokamak[1, 2], which is the world largest fusion research machine currently in operation. Various reviews of all neutron diagnostic systems available at JET can be found in the literature[3]. What the reader will find in this paper is a list of neutron measurement techniques and detectors which are applied in fusion research and are relevant for potential applications in the next step fusion device ITER. The paper's scope is to give a brief description of the different systems and current work areas.

The ITER project (International Thermonuclear Experimental Reactor) is a worldwide project aimed at testing the physics and technologies that will be essential for ultimately developing a fusion power plant (See www.iter.org). The main challenge for neutron diagnostic systems is to step up the current systems capabilities and performances or develop new ones in order to meet the ITER requirements. Synergy between the different systems will be essential in order to exploit the full potential of neutron measurements. The definition, development, testing and mechanical integration of neutron diagnostic systems into ITER is already under way to a large extent. In that process, the JET tokamak provides a major contribution as a test facility for neutron measurements techniques and detectors which are still at a development stage but hold promises for applications into ITER.

1.1 A reactor scale fusion experiment as a neutron source

The principal objective of neutron diagnostics is to characterise the fusion plasma under study as a neutron source. In magnetic fusion experiments, neutrons are emitted by a high temperature plasma. The fusion plasma consists of a low density and fully ionised gas (usually deuterium or a deuterium-tritium mixture) whose pressure is balanced by a strong magnetic field. In the fusion reactor core, the fuel is in 'plasma state'. Therefore an essential part of nuclear fusion research is devoted to plasma physics research. The neutrons produced in fusion reactions do escape promptly without being stopped by the plasma and without being retained by the magnetic field. In the reactor walls, neutrons transfer their kinetic energy to the reactor coolant and they are used for tritium breeding which is a fuel regeneration process.

In a deuterium plasma or a deuterium-tritium mixture plasma, ideally, only fusion reactions between ions of deuterium and tritium are involved, generating 2.5 and 14 MeV neutrons from the two reactions D(d,n)^3He and T(d,n)^{4}He. However, some neutron generation from other channels occur in some particular plasma operation modes[4, 5]:

- Nuclear reactions between light ions (p,d,^3He) and plasma impurities : light plasma ions accelerated to high energies (> 1MeV) produce neutrons over a broad energy range
- Photonuclear reactions : plasma electrons accelerated at very high energies (>10 MeV) generate further (γ,n) reactions.

1.2 Scales and numbers

The volume of JET plasmas extend up to about 100 m^3 with an effective neutron source volume ranging usually from a few up to 40 m^3 depending on the mode of plasma operation[6]. In ITER, the plasma volume will be of the order of 850 m^3.

The neutron source strength in JET has an extremely wide range from $10^{10}s^{-1}$ to about $10^{18}s^{-1}$. A world record value of $5.710^{18}s^{-1}$ for the fusion neutron source strength was attained in JET. In ITER, the neutron source strength is expected to range from $10^{14}s^{-1}$ up to $5.10^{20}s^{-1}$, that is up to 2 orders of magnitude higher than the maximum value in JET.

The range of primary energies of interest is limited to a narrow band around to 2.5 and 14 MeV. The fusion reactions of principal interest and producing neutrons are the following:

$$
\begin{array}{lcr}
D+D \rightarrow & {}^{3}He(0.82MeV)+n(2.45MeV) & Q=4.03MeV \\
D+T \rightarrow & {}^{4}He(3.56MeV)+n(14.03MeV) & Q=17.59MeV \\
T+T \rightarrow & {}^{4}He+2n & Q=11.33MeV
\end{array}
$$

In the above equations the hydrogen species are represented by upper case letters for reacting thermal ions and by lower case letters for energetic fusion products. The particle energies for zero-energy reactants are given within parentheses and the Q-values are provided.

The necessary time resolution for the neutron instrumentation is generally determined by the need to investigate rapid phenomena. In ITER, it is required to measure the total neutron emission with 1ms time resolution[7]. There will be also the need to control fusion power in real time. In JET, it is sometimes desirable to measure neutrons with a faster time resolution when plasma magnetohydrodynamic activity induces rapid fluctuations in plasma parameters and neutron emission. However measurements with sub-millisecond time resolution become difficult due to worsening of the counting statistic.

1.3 The jump to ITER

Compare to the present fusion experiments in JET, the total neutron emission in ITER will increase by about 2 orders of magnitude. As the tokamak size increases, the detectors are located further away and the resulting increase in neutron fluxes is about one order of magnitude at maximum. The big jump in parameter space is happening with neutron fluences which increase by 4 orders of magnitude typically per plasma pulse. Radiation hardness issues will therefore be critical for neutron diagnostics systems in ITER. Another important aspect which will be a major computational task in ITER is the neutron scattering which can considerably affect neutron diagnostic systems and their calibration. Numerical simulations of the neutron transport require a great deal of effort and considerable care in the modelling of the complex tokamak environment and the detectors.

1.4 Neutron diagnostic systems

In a reactor scale fusion experiment, the variety of measurements that are possible is rather restricted. The main constraints are 1) Practical difficulties such as access to the plasma 2) the harsh radiation environment (X, γ), the presence of strong magnetic fields and currents, the vicinity of powerful high frequency wave generators and power supply, heat loads and finally 3) the time resolution required for the measurements. Given these constraints, neutron measurements are limited to the list in table 1.

Systems	JET	ITER[7]
Time-resolved total emission (non-collimated flux)	Fission counters Silicon diodes (14 MeV)	Fission counters Diamond detectors
Time-integrated emission (non-collimated fluence)	Foil activation	Foil activation Water flow activation
2D cameras (collimated flux along camera viewing lines)	Liquid scintillators NE213 Plastic scintillators BC418 (14 MeV)	Diamond detectors Stilbene, NE213 U238 fission counter ZnS, fast plastic
Spectrometers (collimated flux along radial and tangential viewing lines)	Time of flight Proton recoil systems: 1)NE213 and Stilbene 2)Magnetic proton recoil	To be defined

Table 1: List of neutron diagnostic systems

The paper is organised as follows. In the first section, time-resolved total neutron emission measurements are described. The time-integrated neutron emission is covered in the second section as well as the calibration of the time-resolved neutron emission measurements. Neutron emission profiles and 2-D neutron imaging are covered in the third section while the last section is dedicated to neutron spectrometry.

2. Time-resolved neutron emission

The solution adopted in JET for the measurement of the time-resolved total neutron emission is based on fission counters containing ^{238}U and ^{235}U. The counters are embedded in polyethylene moderators and lead shield[8]. This system covers a large dynamical range of 10 orders of magnitude in the neutron flux. It has a rather flat energy response in the energy band of interest and it is fairly insensitive to X and γ radiation. To ensure good reliability, redundancy is provided with three pairs of fission counters installed at three different positions with non-collimated view to the plasma . The system was originally absolutely calibrated to 10% in situ using a Californium ^{252}Cf neutron source. It is periodically re-calibrated using the activation technique (see in the next section). Fission counters are sensitive to the moderated neutron flux and have a time response of 100 microseconds. They are not suitable to follow rapid excursions in the neutron emission and therefore other detectors must be employed for that purpose[9].

ITER neutron diagnostics will include a number of fission counters to monitor the total neutron flux and the fusion power. Several internal neutron flux monitors are foreseen to be installed in 20 mm gaps between the shielding blanket and the vacuum vessel. For this purpose, pencil-size, micro-fission chambers (MFC) are currently developed, mainly in Japan. Operational conditions are severe: Neutron flux of $1.10^{12} - 1.10^{13} cm^{-2}s^{-1}$, neutron fluence of $3.10^{19} - 3.10^{20} cm^{-2}$, a strong magnetic field of about 10 Teslas and a temperature of about 350C and the MFC must be operated under vacuum[10, 11].

Fission counters do not discriminate between 2.5 and 14 MeV neutron emission. For studies of mixed 14 MeV and 2.5 MeV neutron fields it is essential to use a detector that permits a clear separation of 14 MeV from 2.5 MeV neutrons and γ radiation. The Silicon diode detector is employed for that purpose in JET[12]. The (n,α) and (n,p) threshold reactions induced by high energy neutrons in Silicon provide large signals and the threshold energy of about 7 MeV ensures rejection of events due to 2.5 MeV neutrons. There are two difficulties: 1) radiation damage is a serious concern with a fluence limit of $10^{12} ncm^{-2}$; as a consequence, they are repeatedly replaced at JET. 2) As they are operated in counting mode the dynamic range is restricted. A possible solution is to increase radiation hardness of silicon detectors[13]. Another solution presently pursued at JET is to look at alternative materials that could substitute silicon as detecting medium in harsh environments.

Diamond has a large band gap energy of 5.5 eV, a high breakdown voltage of $10^7 Vcm^{-1}$, a high radiation hardness $> 3.10^{15} ncm^{-2}$ and low atomic number. Because of these properties, fast and low noise detectors can be obtained. Two different types of diamond detectors are investigated at JET:

1) The natural diamond detectors (NDD): Several NDDs of high energy resolution (1.2-3%) have been tested at JET and used for monitoring the time-resolved 14 MeV neutron emission[14]. These detectors did not show degradation of performance despite the accumulated fluences (2.4 $10^{13} ncm^{-2}$ and $1.210^{13} \gamma cm^{-2}$).

2) Chemical vapour deposited (CVD) diamond: A limitation with NDD is their availability , the small size and high cost. An emerging technology allows to produce high quality polycrystalline CVD diamond films at low cost with large surfaces and thickness ranging from a few microns up to more than 1mm. The production of high quality polycrystalline CVD diamond films with low defect concentration represent the goal of present research in this field. Recently, the first tests of polycrystalline CVD diamond detectors (see figure 1) at JET to monitor the time-resolved 14 MeV neutron emission demonstrated the capability of this new class of detectors to withstand the tokamak environment and operate reliably for sufficiently long time[15]. Recent developments in this activity include new tests of a polycrystalline CVD covered with ^6LiF film to monitor the time-resolved 2.5 MeV neutron emission, a single crystal CVD and a higher efficiency polycrystalline CVD. Both NDD and CVD diamond detectors are candidate for applications in ITER.

3. Time-integrated neutron emission

The use of neutron activation methods for determining the neutron fluence at the measuring points has a long history in the neutron metrology and methods have been developed that permit the full energy spectrum to be deduced for neutron energies ranging from thermal up to 20 MeV. Tokamak applications of the neutron activation method are well developed [16, 17, 18, 19, 20, 21, 22] and are concentrated in the interesting neutron energies band at 2.5 and 14 MeV. The activation technique was also used to measure time-integrated neutron spectra[23]. Pneumatically operated sample transfer systems using polythene capsules are employed in order to position and remove the activation samples automatically. The sample activity is measured with two different absolutely calibrated techniques. 1) γ-ray spectroscopy measurements using High purity germanium and NaI detectors. 2) The delayed neutron technique using ^3He detectors.

As there is a significant amount of material between the sample and the plasma, neutron transport calculations are performed to obtain the response coefficient for the materials of interest. At JET, the time-integrated neutron emission is measured at up to 8 irradiation positions around the plasma. These measurements coupled with the neutron transport calculations provide the basis for the absolute calibration of the fission counters[24, 25]. The uncertainty for the total yield amounts to about 7% at best[26]. An activation sample system is planned for ITER.

4. Neutron emission profiles

4.1 Neutron profile monitor

The JET neutron profile monitor (figure 2) is a unique instrument among neutron diagnostics available at large fusion research facilities. The instrument was well described in several papers[27, 28]. In short, the system consists of 2 concrete shields of which each includes a fan-shaped array of collimators. These collimators define a total of 19 lines of sight, grouped in two cameras. The larger one contains 10 collimated channels with a horizontal view through the plasma while the smaller one has 9 channels with a vertical view. The collimation can be adjusted by use of 2 pairs of rotatable steel cylinders. The size of the collimation can modify the count rates in the detectors by a factor 20[29]. The plasma coverage is adequate for neutron tomography, although the spatial resolution is rough. Neighbour channels are 15-20cm apart and have a 7 cm width as they pass near the plasma centre. Each line of sight is equipped with a set of three different detectors:

- a NE213 liquid organic scintillator with pulse shape discrimination (PSD) electronics for simultaneous measurements of the 2.5 MeV D-D neutrons, 14 MeV D-T neutrons and γ-rays
- a BC418 plastic scintillator, insensitive to γ-rays with $E_\gamma < 10 MeV$ for the measurements of 14 MeV D-T neutrons
- a CsI(Tl) scintillation detector for measuring the Hard X rays and γ emission in the range between 0.2 and 6 MeV.

Each NE213 detector-photomultiplier unit sends output pulses to pairs of pulse shape discriminators (PSD), one tuned for D-D neutrons and the other one for D-T neutrons, to distinguish neutrons from γ ray induced events. These PSD have upper and lower energy detection biases set to detect preferentially unscattered neutrons and to reject scattered neutrons. The detector efficiencies depend on the scintillator geometry and the energy bias setting of the PSD electronics. The setting is controlled by recording the count-rates from a ^{22}Na γ ray source which is mounted with the scintillator. The Bicron scintillators are located in front of the NE213 scintillators and are coupled to photomultiplier tubes via a light guide. They are sufficiently small that energetic γ rays cannot deposit sufficient energy to produce a pulse greater than that produced by a neutron of 10 MeV. Each Bicron detector has several lower energy detection thresholds to be set for the proton recoil energy providing several neutron signals with different sensitivity.

The PSD is an essential component of the neutron profile monitor due to mixed neutron-γ radiation fields at JET. An important upgrade foreseen for this instrument is to replace the conventional analog pulse shape discriminator[30] with new state-of-the art digital electronics. With the new Digital Pulse Shape Discrimination (DPSD) acquisition systems, the pulse shape discrimination between neutrons and γ-rays is no longer a hardware operation but it becomes a much more flexible software operation with significant advantages:1) a higher amount of information from the detector is collected, 2) events data are always available for various types of post-processing and evaluation analysis, 3) a larger acquisition dynamic range up to MHz level. This latter property is highly relevant for fusion applications. With the current analog electronic discrimination, the count rates are limited to typically < 200 kHz. Recently, excellent timing properties, good pulse amplitude resolution and n/γ discrimination have been demonstrated with several DPSD systems with typical parameters: 8 bit- 1 Gigasample/s[31], 12 bit- 200 Megasample/s[32, 33] and 8 bit - 500 Megasample/s [34]. Another benefit of these systems will be the possibility to transmit rapidly measurements information to a real time control system. Work will start in future on systems where the front-end detector data will be elaborated with a pulse shape discrimination software and then transmitted to the real time control system.

4.2 Neutron 2D-imaging

The solution adopted in JET and ITER for imaging the extended neutron source is to use a multi-collimator detector array. The desirable properties of such a system are: 1) the plasma must be viewed through a thin vacuum window, typically no more than 2-3 mm stainless steel, to avoid an image blurred by neutron scattering in the vacuum vessel window. 2) the detector energy resolution must be sufficient to discriminate the neutrons emitted from the plasma against scattered neutrons 3) the detector must discriminate against γ-ray 4) the shielding must be well designed to reduce the background and cross-talk event rates. The JET profile monitor allows to obtain 2-D images from the plasma neutron emission. The minimum fisher regularisation method (MFR) is a suitable tomography technique for the sparse projections as given by the JET neutron profile monitor. Other tomography techniques used in JET include constrained optimisation[35]. The MFR technique is being developed presently at JET and its potential is being assessed as a new tool to study both the 2-D spatial distribution of the neutron emission[36] and the neutron spectral unfolding[37]. Being fully based on matrix operations, it is fast and a single matrix can be applied on a time evolution of neutron data[38]. As an application, pixel-based images of deuterium plasmas with tritium gas puffs were computed. This new approach is extremely helpful for observing dynamic processes such as tritium diffusion (figure 3) into the plasma[39].

5. Neutron spectrometry

The original motivation for measuring the energy spectra of neutrons and fusion products emitted from fusion plasmas was the determination of the plasma ion temperature[40]. This determination is straightforward when the plasma ion energy distribution is Maxwellian. In practise, the prevalent plasma operations at JET and other present generation tokamaks do not lead to such simple neutron energy spectra. Instead, neutron spectra are frequently complex, involve composite neutron emission and line of sight effects. Their interpretation depend upon sophisticated modelling[41, 42]. In order to measure the neutron energy spectrum broadening, a neutron spectrometer with sufficiently high energy resolution must be employed. The neutron spectrometer energy resolution needs to be rather less than the spectrum broadening. In general, a difficult

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compromise has to be made between energy resolution and detection efficiency. Higher energy resolution is gained at the expense of detection efficiency. Many neutron detector types have been used for neutron spectrometry of tokamak plasmas[43, 44, 45, 46, 47, 48, 49, 50]. There have been also several attempts to use solid state detectors, like Silicon diodes or more recently diamond detectors, to measure neutron spectra, with a resolution in the range of 0.8% and an efficiency of about $10^{-4}cm^2$. One disadvantage is their rather complex response function. Presently, the activity in neutron spectrometry at JET is mainly concentrated in the development of three different spectrometers: A time of flight spectrometer and two proton-recoil spectrometers.

5.1 Time of flight spectrometer

In the time of flight spectrometer (figure 4), neutrons pass through a scintillator which intercepts a line of sight. Some neutrons scatter towards a large bank of neutron detectors placed at a distance of about 2 meters and the flight times of neutrons are measured. There have been several instruments and upgrade in the course of the years. The first instrument installed at JET [46] had an energy resolution for DD neutrons of about 4.6% and and an efficiency of about $5.10^{-2}cm^2$. The major disadvantage of the time-of-flight approach is the need for a large experimental area that is well screened from background neutron and γ radiation. At JET, this is resolved by placing the instrument in the Roof laboratory, directly above the tokamak, with a 2m thick concrete floor. The last generation of these instruments is the TOFOR spectrometer [51, 52] which has been optimised to provide high count rates, up to 300 kHz (at 1% signal-to-random level). To achieve this, the TOFOR instrument combines a high detection efficiency of about 1.2 $10^{-1}cm^2$ with a data acquisition system based on free-running digital time recorders. The energy resolution is about 6%.

5.2 Proton recoil spectrometers

The n-p scattering reaction can be used for neutron spectrometry in a wide range of devices. The simplest approach is to provide a sufficiently thick hydrogen rich target such as the whole of the energy of any recoiling proton is deposited. The first solution currently adopted in JET is based on scintillator detectors NE213 or Stilbene which combine high efficiency, high light output and good pulse shape discrimination properties. The energy spectrum of the recoil protons is recorded with no information on the recoil angle. Therefore, the neutron energy spectrum is recovered by an unfolding or differentiation process to restrict attention to forward scattering events. Its size facilitated transportability, permitting its detailed characterisation at an accelerator laboratory. Recently, measurements of neutron spectra with a spectrometer based on a well characterised NE213 detector[53, 54, 55, 56] demonstrated an energy resolution of 4% with DD 2.5 MeV neutrons and 2% with 14 MeV neutrons. Neutron energy spectra are obtained using several unfolding techniques including the Maximum Entropy unfolding procedure[57] and the newly developed Minimum fisher regularisation technique. Good agreement between the two unfolding procedures has been found for spectral measurements of fusion neutrons emitted from JET plasmas[37].

Another approach is to use a thin hydrogen rich target or proton radiator. However, the thin target proton recoil devices are not ideal for 2.5 MeV neutron spectroscopy because of the unrecorded energy loss by the recoil protons in the thin target. This energy loss can be reduced by using a thinner target at the cost of a reduced efficiency. For 14 MeV neutrons, the energy loss becomes less significant. The second solution currently applied in JET uses a Magnetic proton recoil spectrometer MPR [50], which is a dedicated instrument based on proton scattering in a thin target and combined with the magnetic analysis of recoil protons (figure 6). It has a typical efficiency of $5.10^{-5} cm^2$ and a resolution of 2.5% for 14 MeV neutrons. The last generation of this instrument is the MPR upgrade (MPRu) with the capability to measure neutron spectra in the energy range of $E_n \pm 20\%$ with a peak energy that can be set within $1.5 < E_n < 18 MeV$. This is achieved by setting the required magnetic field. A new focal plane detector array has been installed, based on phoswich scintillators which, in combination with DPSD electronics, will improve the immunity to background, thereby enhancing the signal-to-background ratio[58]. This instrument can be absolutely calibrated from first principles.

Conclusions

With the move towards the next step reactor scale fusion experiments, neutron measurement systems will play an increasingly important role in fusion plasma diagnostics. Capabilities and performances of the neutron measurement systems will have to be stepped up to cope with increased neutron fluxes of about one order of magnitude. The main significant change is the increase in neutron fluences due to longer plasma pulse which introduce new constraints and radiation hardness issues. The design of ITER neutron diagnostics is presently and will also in the future draw on the R&D work done at the JET tokamak which has a unique set of neutron measurements systems and many years of accumulated experience. Current major topics of research at JET in this field include new radiation hard detectors, new electronics and data acquisition, neutron spectrometers, tomography and unfolding techniques. The scientific fusion work programme at JET is driven by the need to support the future ITER operation and explore new physics that will occur in ITER plasmas such as burning plasma physics[59]. In this respect, neutron diagnostics contribute significantly to the scientific fusion work programme with advanced studies such as tritium diffusion studies and fast particle physics.

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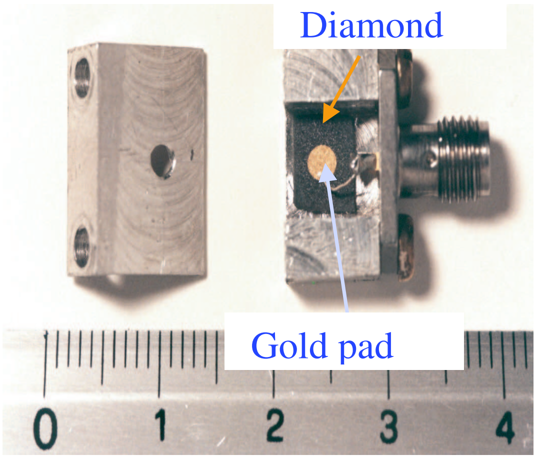

Figure 1: Photograph of one chemical vapour deposited (CVD) diamond detector prototype (scale in cm)

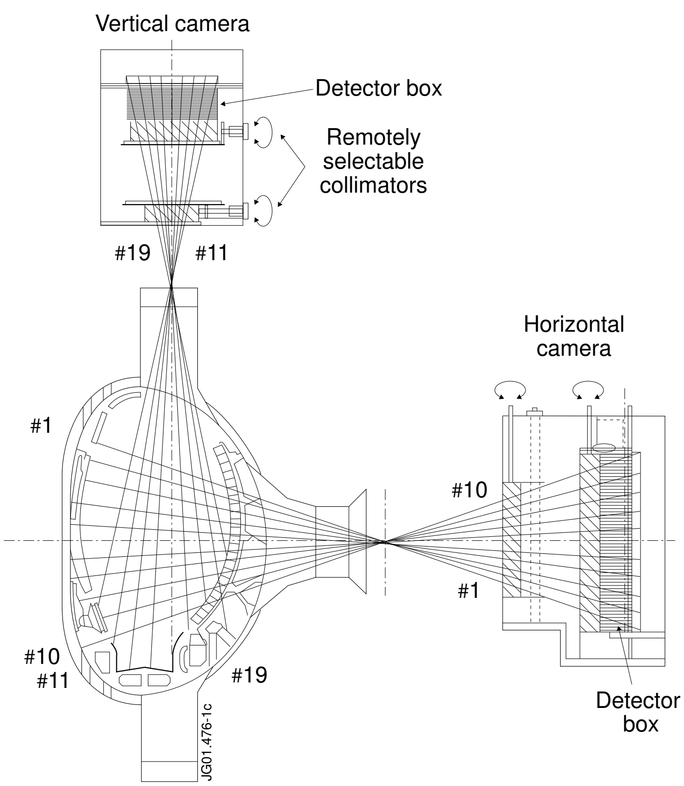

Figure 2: The JET neutron profile monitor with its 19 lines-of-sight

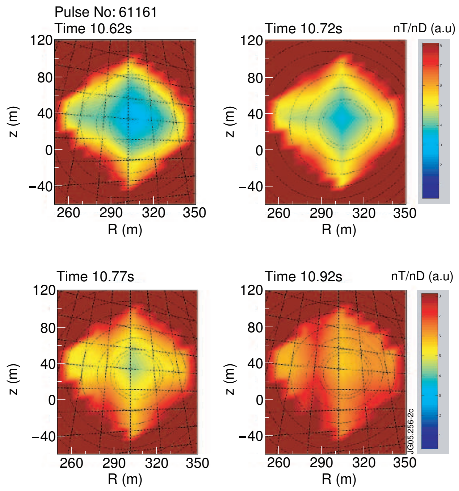

Figure 3: Time evolution of two-dimensional tritium concentration $\frac{n_T}{n_D}$ spatial distribution obtained with the ratio method[39] and using tomographic reconstructions of the 2-D camera measurements of 14 MeV and 2.5 MeV neutron emission. The progressive diffusion of the tritium inside the plasma is clearly detected and visualized (spurious structures along some lines of sight are artifacts)

Figure 4: Photograph of the TOFOR 2.5 MeV neutron time-of-flight spectrometer. The neutron beam is defined by a vertical collimator set into the floor, and passes through the scintillator placed close to the floor, on the axis of the array of secondary detectors

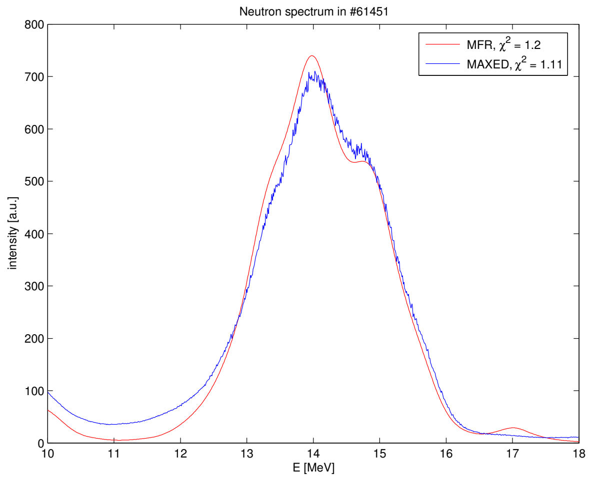

Figure 5: Unfolded spectrum of neutrons for pulse 61451 obtained with a well-characterised NE213 spectrometer. A comparison between MFR method and MAXED method is shown

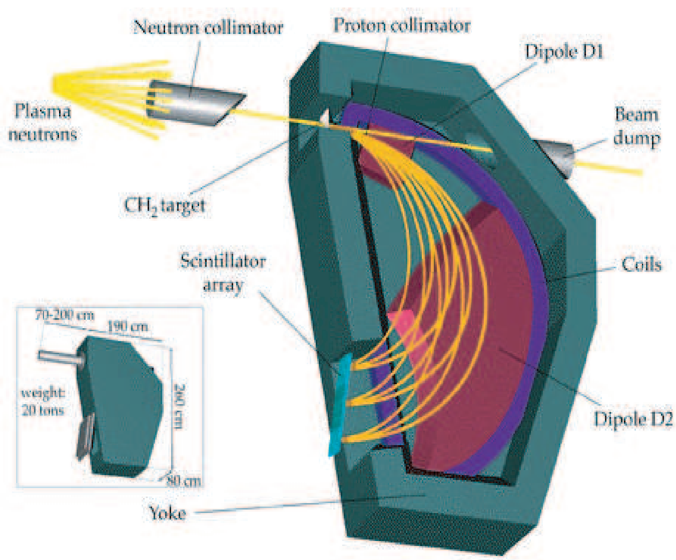

Figure 6: A sketch showing the principle of the magnetic proton recoil spectrometer (MPR)

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