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ABSTRACT.

The diagnostics functions of neutron measurements are reviewed as well as the roles played by neutron yield monitors, cameras and spectrometers. The importance of recent developments in Neutron Emission Spectroscopy (NES) diagnostics is emphasized. Results are presented from NES diagnosis of Joint European Torus (JET) plasmas performed with the Magnetic Proton Recoil (MPR) spectrometer during the first Deuterium Tritium Experiment (DTE1) of 1997 and the recent Trace Tritium Experiment (TTE) of 2003. The NES diagnostic capabilities at JET are presently being enhanced by an upgrade of the MPR (MPRu) and a new 2.5MeV Time-of-Flight (ToF) neutron spectrometer (TOFOR). The principles of MPRu and TOFOR are described and illustrated with the diagnostic role they will play in the high performance fusion experiments in the forward program of JET largely aimed at supporting ITER. The importance for the JET NES effort for ITER is discussed.

1. INTRODUCTION

Neutron Diagnostics (ND) have been used since the early days of fusion research but became a topic for special development at Joint European Torus (JET) in the early 1980’s. Detectors were installed for measuring the total neutron yield as were neutron cameras which both have become routine diagnostics. The use of the neutron cameras have become more sophisticated with the build of operating and interpretation experience which has been boosted with an instrumental upgrade for the tritium operation in 1997. Spectrometers were also put on JET at an early stage and many different types have been tested following the increase in the fusion power produced in the plasma. The most drastic advances in ND over the last 10 years have taken place mainly through the development in the neutron emission spectrometry (NES) [1,2]. It has been brought about through putting into use a new type of neutron spectrometer of the magnetic proton recoil (MPR) type [3] with much increased measurement precision. Moreover, it can operate at high count rate (C_n), only limited by the flux received from the plasma, i.e., the fusion power produced; count rate is a fundamental figure of merit for high performance NES diagnostics.

The first MPR was installed at JET in 1996 and was tested during the main Deuterium Tritium Experiment (DTE1) of 1997 on discharges producing a fusion power up to 16MW [4]. The MPR has demonstrated that NES diagnostics can provide information far beyond what was projected [5,6]. The MPR is dedicated to measurement of 14MeV neutrons of $d+t\rightarrow\alpha+n$ reactions so the world’s NES data bank is limited to DTE1. This is what has been used to develop analysis and interpretation methods to extract diagnostic information contained in the data. The recent JET trace tritium experiment (TTE) of 2003 was the first time the full NES diagnostic machinery was at hand so that information from the MPR could be presented between shots making NES an online diagnostic in the control room [7].

Notwithstanding the above achievements, development of the NES diagnostics has been impeded by the fact that the MPR was practically effective only for measurement of the 14MeV emission from plasmas with tritium. Such discharges are only produced in JET of the present tokamaks and very rarely so. Clearly, the opportunities for learning by doing have been very limited. This will now drastically change through the decision to include two new neutron spectrometer projects as part of the JET-EFDA Enhancement Program (JET-EP) now under way with start of experiments in 2005.

The first project concerns an upgrade of MPR (MPRu) to permit measurements over the full fusion neutron energy spectrum (say 1.5 to 20MeV) [8]. This means that MPRu can be used for regular diagnosis of either D or DT plasmas besides for special diagnosis of high power DT plasmas where the extra high sensitivity can be exploited fully all the way down to the limit set by the statistics. The second project is a new Time-of-Flight (TOF) neutron spectrometer where optimal count rate has explicitly been included in the design criteria; it is dubbed TOFOR [9,10]. TOFOR is dedicated to measuring 2.5-MeV neutrons from d+d->^{3}He+n reactions [9,10] and should reach count rates of about half of what was demonstrated by the MPR during DTE1. These JET-EP neutron spectrometers are planned to come into operation in 2005 and will mean a drastically enhanced NES observational capability and corresponding contribution to high performance fusion experiments to be conducted to a large extent in support of the International Thermonuclear Experimental Reactor (ITER).

This paper reports on results obtained with the MPR neutron spectrometer at JET illustrating some diagnostic uses of NES. The principles of the two new instruments MPRu and TOFOR are described and the enhanced NES diagnostic capabilities presented. The envisaged role of the forward ND effort at JET as an input to developing ITER's ND complement is discussed.

2. NEUTRON MEASUREMENTS AND DIAGNOSTIC FUNCTIONS

The neutron spectrometer has a special role to play among the neutron diagnostics which is illustrated by introducing a classification of the ND systems based on their functions.

Detectors to monitor the Neutron Inclusive Flux (NIF) are installed on most fusion plasma devices [1]. These measure the uncollimated flux which can be related to the total neutron yield rate, $Y_n(t)$, given appropriate calibration [11]. The NIF monitors are unique among neutron diagnostics as they provide information on a single plasma parameter, namely, $Y_n(t)$ and, hence, also the fusion power P_f in most cases; the latter assumes that only one neutron producing fusion reaction dominates, normally, d+d->^{3}He+n or d+t->α+n.

Advanced Neutron Emission Tomography (NET) diagnostics are used only at JET [1]. NET diagnostics are based on measurements of the neutron flux in arrays of collimators (cameras) whose sight lines intersect the plasma in the poloidal plane. It is preferred to have two perpendicular cameras each with good radial coverage. From the measured radial brightness distributions of the neutron source, different types of plasma parameter information can be extracted.

JET is the only place with advanced Neutron Emission Spectrometry (NES) diagnostics in the fusion field of magnetic confinement. In NES, one measures the energy distribution of the collimated neutron flux along one or several sight lines, usually through the plasma core.

The measured spectrum is used to derive information on a number of plasma parameters which will be illustrated below. In addition, NES measurements can be used for calibration of the NIF and NET diagnostics as well as for the purpose of benchmarking simulations of the neutron flux field in a tokamak. Here, NES provides the crucial information on the spectrum of the scattered neutron flux coming into a detector which always appears admixed to the direct flux. For correct interpretation of ND results, the direct/scattered (D/S) ratio of measured data must be known either from measurements or validated calculations.

As indicated above, NES measurements are essential to make reliable use of neutron yield monitors and cameras so it is appropriate to ask: How can this information be obtained? Genuine spectrometers is the obvious answer. These are instruments whose data depict the neutron spectrum apart from a response function of finite neutron energy resolution. The most powerful spectrometers are always large so, of course, it is tempting to explore how to reduce the size. This has turned out to be very difficult as a smaller size is found to come at a compromise of the neutron spectrum information in the data recorded. In this situation, an interest has been developed to look into the use of detectors, such as liquid scintillators for use as ‘compact spectrometers’. However, the data of these do not depict the neutron spectrum but it is embedded in data. As this is an intrinsic characteristic of the detector, one has tried to compensate the neutron spectral information content in the data by the development of advanced data unfolding techniques and elaborate response calibration and stabilization. These compacts are not an alternative to genuine neutron spectrometers; this is further discussed in the next section ———[1].

3. NEUTRON EMISSION SPECTROSCOPY

NES diagnostics became a topic for special development at JET in the early 1980’s. A number of different neutron spectrometers and compacts have been built and tested over the years both for general NES diagnostic purposes and special studies [1]. The 2.5MeV neutron spectrometer type that has remained after these tests is based on the Time-Of-Flight (TOF) technique. There was also a large effort on instruments for studies high fusion performance with DT plasmas and of the three spectrometers it is the one that uses the Magnetic Proton Recoil (MPR) technique that remains.

The NES diagnostic experience has been built up successively over the years but was indeed accelerated with the high neutron yield of the DTE1 campaign of 1996. The progress made during the DTE1 has exceeded what had been expected possible in terms of NES contribution to fusion experiments in the 1980’s when this was outlined [5,6]. The TTE of 2003, represented a new mile stone as advanced NES was, for the first time, part of the active control room diagnostics.

Instrumentally, the progress is represented by the use of the MPR spectrometer (Fig.1) [4]. It is unique among fusion neutron spectrometers in that it involves no active element to measure energy and the neutrons are merely made to scatter in a passive hydrogenous target. A fraction (10^{-4}) of the neutrons is converted to a flux of proton recoils of (nearly) the same energy distribution apart from a broadening reflecting the finite instrumental energy resolution. The energy of the protons is determined in a momentum-dispersing magnet which results in a recoil spectrum in the form of a position histogram, i.e., protons counts per channel. In the MPR, the measurement of neutron energy is thus reduced to counting recoil protons in a detector array covering an energy range of typically ±20% around a central value. The MPR belongs to the class of magnetic spectrometers used for high accuracy measurement in nuclear physics under controlled laboratory conditions. However, the design was adapted for measurement of fusion neutrons for observations of varying plasma conditions. This meant special requirements on the proton detectors to cope with large variations in count rate with practically 100% efficiency to protons of energies up to about 20MeV while having high immunity to background radiation. The MPR was dedicated to measurement of 14MeV neutrons from d+t->α+n, i.e., for NES diagnosis of DT plasmas. The most successful spectrometer for measurement of 2.5MeV neutrons from d+d->^{3}He+n reactions, i.e., for D plasmas diagnostics, uses the time-of-flight technique (Fig.1). The first version dedicated to fusion applications stem from the beginning of JET and the design has gone through several stages of evolution over a 10 year period.

It reached a level of performance making it possible to detect interesting features in the spectrum caused by auxiliary heating but did not quite reach the status of a routine diagnostic mainly because of the count rate being limited to the range of a few kHz maximum [12].

Today, there are new versions developed of the above spectrometers. The MPR is being upgraded (MPRu). The MPRu contains a new proton detector which will improve the background immunity of the measurements by several orders of magnitude. This means that one can study the very weakest components in the spectrum diagnostic information which can be fully exploited for discharges of high fusion power. Moreover, the MPRu can also be used for measurements of 2.5MeV neutrons from dd reactions in D plasmas. Another important consequence is that MPRu will be able to measure the full extent of the scattered spectrum for 14MeV primary neutrons of dt reactions.

With regard to a dedicated NES diagnostic for D plasmas, a new design of the TOF techniques has been developed. The main limitation of the TOF technique is the count rate capability so the primary aim of the new design was to push this up to its intrinsic limit estimated to be just below 500kHz; it is dubbed TOFOR standing for TOF designed for optimized rate.

The MPR and TOFOR instruments are genuine spectrometers which means that the measured data depict the energy distribution of the incoming neutron flux. The MPRu shows the neutron spectrum as a proton energy distribution as function of the position parameter x (Fig.2(a)), and TOFOR as neutron time of flight (t) distribution as function c/t^2 (Fig.2(b)). The depicted spectrum is broadened with the neutron energy resolution assumed to be 2.5% (full width at half maximum) and 6.6%, respectively, for the two spectrometers intended for 14MeV dt neutrons and 2.5MeV dd neutrons (see below). As the purpose of NES diagnostic is to determine neutron spectra of unknown distribution they need to be able to resolve those of multiple components. In figure 2 is therefore illustrated how well a low (10^{-2}) intensity component can be resolved at an assumed energy separation of $2 \times 2.5 = 5\%$ and $2 \times 6.6 = 13.2\%$, respectively. In a compact detector, such as a NE213 liquid scintillator, mono-energetic neutron flux~~s~~ would give rise to data in the form of an extended pulse height distribution whose high-energy edge corresponds to the neutron energy. Clearly, these data do not depict the incoming neutron spectrum but information about it can be obtained by differentiating the high-energy slope when the spectrum is monolithic. For complex spectra, the unfolding procedure is not unambiguous and is not a tractable approach to separate superimposed extended distributions as would be case for the situation represented in Fig.2(c) and (d).

4. THE TOFOR AND MPRU INSTRUMENTS

The spectrometer requirements are different for measurements of 2.5MeV neutrons of dd reactions and 14MeV neutrons of dt. For instance, with regard to energy resolution ($\Delta E/E$), it should be set relative to the thermal Doppler broadening which is 2.6 times greater for dd than for dt neutron emission; this means $\Delta E/E = 6.6$ and 2.5% (FWHM), respectively, for $T= 4$keV. An energy resolution much beyond the Doppler broadening will not improve the overall resolving power of the measurement because of the reduced efficiency it leads to and subsequent reduced statistical accuracy in terms of lower count rate. Moreover, the detection efficiency (ε) must be a factor of 10^2 greater for 2.5MeV than for 14MeV neutrons to compensate for the lower dd reactivity; the values for TOFOR and MPRu are $\varepsilon = 8\times10^{-2}$ and $5x10^{-5}$ cm^2 and match quite well the requirements to reach comparable levels of performance at JET in terms of count rate for D and DT plasma operation at C_n<500kHz and <700kHz, respectively. However, the performance limitations have different intrinsic causes, namely, C_n capability for TOFOR and ε for MPRu; in case of TOFOR, the C_n-limit is treasonous as it leads to data degradation, i.e., paralysis of the diagnostic.

TOF spectrometers become paralyzed when the rate in the first detector D1 (Fig.1(b)) exceeds a certain limit. This limit can be increased by suitable filtering so as to accept only those D1 signals which correspond to neutrons being scattered into the angular range subtended by detectors D2. The D2 detector assembly should, therefore, be ring shaped to achieve maximum catching efficiency of the selected scattered neutrons coming from D1. The design for optimized count rate looks like the sketch of the TOFOR spectrometer shown in Fig.3. It consists of five D1 detectors at the bottom where the collimated neutron flux comes in from the plasma and a ring array of 32 D2 detectors. It will be placed in the roof lab with 2 m thick floor protecting the spectrometer from the environmental background radiation (see Fig.9(a)). The exact TOFOR design is derived from extensive simulations of the neutron response of the detectors and their light emission and transport characteristics. It is being readied for installation in JET early 2005.

The MPR spectrometer system is shown schematically in Figs.4 and 5. The system includes the spectrometer itself enclosed by shielding to protect the detector against extraneous radiation such as the direct neutron flux from the plasma as well as the ambient neutron flux in the torus hall of JET in which the MPR is placed. A large attenuation is needed in part to compensate for the fact that the plasma viewed through the collimator is small compared to the neutron emitting volume of the plasma that can give background in the detector. The shielding must reduce this flux by more than four orders of magnitude. Moreover, the collimated neutron flux on the target gives only one recoil proton per 10^4 neutrons. Therefore it is important that the detector has high immunity to background radiation and can separate~~d~~ such events from the signal events of interest, namely, proton recoils; the latter is helped by the fact that the proton energy is known from the momentum analysis afforded by the spectrometer magnet.

The present MPR detector uses an array of scintillators. It works well for 14MeV neutrons in which the signals stand out from background even for spectral features of low relative intensity. Indeed, by background subtraction of the data it is possible to measure details of low intensities down to the limit set by counting statistics of the recorded DT plasmas of JET.

The MPRu will be able to record practically background free data for much extended measurement conditions compared to those of the MPR. This is to be achieved by developing a new detector which will make it possible to use both range and pulse height to discriminate background radiation. It is based on laminated scintillators of the phoswich type with which one can perform 2-dimensional discrimination compared to the 1-dimensional used in MPR. The background immunity is estimated to increase by several orders of magnitude where the actual number can only be determined from operation at JET. MPRu will allow diagnostic utilization of the weakest neutron emission components set by the statistics of the measurement. Similarly, the MPRu operates over the entire energy range of fusion neutrons down to about 1.5MeV making it useful also as a D plasma diagnostic which was not possible with the MPR. It should be noted that the ultimate objective is to be able to measure 2.5MeV neutrons under the condition of very strong background radiation of DT plasmas. This will be exploited in the proposed uses of NES diagnostics to determine fuel ion densities in ITER.

Both the MPRu and TOFOR spectrometers will be fully calibrated before installation with reference to certain working points which later can be controlled and monitored also during operation. A rudimentary Control & Monitoring (C&M) system was used on the MPR and this has now been further developed [13]. Together with a state of the art communication, control and data acquisition system, the experiments with MPRu and TOFOR will be operated fully electronically and monitored for stability over short (transient) and long time periods allowing remote experimentation. With regard to data processing, time digitizers and transient recorders based on PC cards are being developed for the first time for NES diagnostic applications [14,15].

The MPRu and TOFOR spectrometers are~~s~~ the most advanced NES systems built to date for testing reliability, machine interface and diagnostic capabilities in fusion experiments on JET that mimics ITER as close as today’s generation of tokamaks permits. The demonstrations made refer to the DTE1 campaign of 1997 and the recent TTE of 2003, the latter being the first ever fusion experiment with an on-line advanced NES where absolute measurement of the fusion power was achieved [16].

5. RESULTS FROM JET

As an illustration of NES results obtained with the MPR during DTE1 at JET we choose discharge

Pulse No: 42982 which produced the record fusion energy (21.7MJ). Fourteen neutron spectra were measured of which one is shown with its 3-component fit in Fig.6a. The results deduced on the ion temperature and the thermal fusion power fraction as a function of time, T(t) and A(t) are shown Fig.6b.

Inspection of the results show that T(t), from 1 to 6keV, rises significantly starting at the onset of the auxiliary power (P_{aux}) with some possible variation at the high level, till the end of the heating. The excursion at t = 15s might reflect an instability in the fitting and is under study. The fusion power due to thermal reactivity rises also up to the 80% level following the rise in temperature but with some deviations. At the beginning of the heating pulse, the fusion power is dominated by supra-thermal ion reactions and one can also determine its composition from the NES data (not discussed here). Here it suffices to point out that NES provides information on the thermal part of the total power generated by the fuel and the temperature at which it burns.

In the analysis shown in Fig.6a there is also a~~he~~ fourth component, SC, shown. It represents the flux of scattered neutrons coming into the MPR data and dominates the measured spectrum for positions on the detector below about x = 100mm. Above x = 100 mm, the scattered flux is admixed to the direct flux at the level a few percent. The scattered flux spectrum can be modeled and determined by fitting to MPR data as indicated in Fig 6a.These results can be used to benchmark neutron transport calculations undertaken to make prediction for the analysis of data of other neutron diagnostics affected by the ratio of direct/scattered~~/direct~~ components in the neutron flux. Here we single out the role of information on SC as essential for determining the absolute neutron yield rate from flux measurements. As NES data is the best source of this information, they can also be used for absolute determination of Y_n given that the spectrometer is suitably calibrated.

The MPR is ab initio calibrated affording absolute measurement of both neutron flux and energy. We have taken advantage of the former to determine the absolute neutron yield from MPR data [16]. The model includes a detailed voxel based characterization of the neutron emissivity profile of the plasma, the MPR line of sight and accounts for all the losses in the neutron flux from the source voxels in the plasma to proton detection. The details of the method are going to be presented in a forthcoming paper.

The source extension is determined as the plasma volume defined by the solid angle of the MPR collimator with consideration to the above mentioned scattered neutron admixture. This is expressed by factors whose errors are quantified leading to the relationship between measured MPR count rate and total yield rate of neutrons of given energy (here 14MeV corresponding to dt-reactions), i.e., $Y_n(t) = k_{0||} \cdot C_n$. This relation-ship was determined for a specific 3-D neutron emissivity distribution which we take as reference. The neutron emission profile is measured with the neutron camera at JET and this information is used in the model to determine k in $Y_n(t) = k_{||} \cdot C_n$ which thus takes into account possible changes; comparison of results obtained with k_0 and k is used to illustrate the importance of profile changes.

The above new method to determine the neutron yield has been tried during the recent TTE campaign at JET but also on the data bank from DTE1. Some preliminary results from the analysis of DTE1 are shown in Fig.7. Here the results on Y_n from MPR are compared with those from the regular NIF based yield monitors at JET (referred to as KN1); $Y_n(t)$ from KN1 is equally sensitive to all fusion neutron energies but since the dt reaction is dominant it should scale with the result of the MPR. The comparison shows a linear correlation between the MPR and KN1 results over the dynamic range (about an order of magnitude) with some scatter at the level of 12 % in standard deviation (Fig.7(a)). These results were obtained assuming the reference profile for the radial distribution of the neutron emission, i.e., proportionality factor k_0. With the factor k which includes the profile dependence, the scatter from a linear fit is reduced to less than 3% which is consistent with the intrinsic statistical errors in these data (Fig.7(b)). With MPRu, it will be possible to make absolute measurement of the yield rates of either dd or dt reactions and, hence, also the fusion power even if both reactions contribute to the total neutron yield rate.

The absolute energy calibration of the MPR data is 2×10^{-3} besides much higher stability for relative measurements, which make it profitable to look for shifts in the measured relative to the predicted spectrum of neutron emission. As the neutron emission arises from the $d+t\text{->}\alpha+n$ reaction its energy distribution can be calculated, for given initial conditions such as with the fuel ions in thermal equilibrium at a certain temperature, to high accuracy on an~~he~~ absolute scale. When making a comparison between the result of such absolute measurement and calculations one finds that they differ with respect their peak position which is ascribed to a Doppler shift in the neutron emission from the plasma.

These shifts are interpreted to come from the collective motion of the ion populations as toroidal rotation and correlate normally with other observations based on Doppler shifts in the electromagnetic radiation. The toroidal rotation (V_r in km/s) was determined from the measured neutron energy Doppler shift ΔE (in units of keV) as $V_r = 2.70\ \Delta E$; the neutron emission was viewed at 47 deg relative to the toroidal direction which was taken into account [17]. It should be noted, though, that NES measures the rotation of the fuel ion component of the plasma while other diagnostics are based on radiation from impurity ions; fuel and impurity ions can show different rotations. A point in case is the response of fuel ions to subjecting the plasma to neutral beam injection but also to Radio Frequency (RF) of Ion Cyclotron Resonance Heating (ICRH).

A particularly clear energy shift observation was made during TTE of 2003 showing that the fuel ion rotation changed depending on the phasing of the ICRH antenna. The componential fit to such data is shown in Fig.8(a) and the total fit for the ±90 degree phasing cases is shown in Fig.8(b). These Doppler shifts in opposite direction correspond to toroidal rotation velocities of about 200 km/s. These results are of scientific significance~~t~~ as they represent a clean observation of the response of the plasma to a specific effect imparted on it. Moreover, they represent a mile-stone in that it was the first time NES data were analyzed between discharges so the information was able to produce input for the next to come. This is also an example where NES provides unique diagnostic information.

One feature of the neutron emission that has not been exploited is its anisotropy relative to the direction of the magnetic field. This can occur, for instance, when the fusion reactivity is affected by P_{aux} injection. This will change in 2005 at JET when the two spectrometers will view the plasma (Fig.9) from above with TOFOR (i.e., perpendicular sight line) and at 47 degrees in the horizontal plane with MPRu. The kind of spectra one would see have been simulated for a discharge with ICRH based on two main components, namely a bulk (B) of isotropic emission and an anisotropic High-Energy (HE) component due to reactions involving RF accelerated ions.

The spectra of the dd neutron emission into MPRu and TOFOR are shown in Figs.10(a) and (b) where one can see how the HE component is relatively enhanced or suppressed depending on angle of observation. As TOFOR and MPRu can be expected to provide data of high quality, it will also be meaningful to use the data to determine the difference spectrum (Fig.10(c)) to help in the analysis and interpretation of spectra of more complex structure than~~t~~ the clinical examples shown here~~ar~~. The difference technique will be a new tool in NES diagnostics.

6. IMPLICATIONS FOR ITER

MPRu experiments at JET are essential for the development of ITER neutron diagnostics; this includes the aspects of concepts and implementation of instrumentation as well as demonstration of possible diagnostic information output. Regarding NES diagnostics, specifically, the MPR should now beexploited because it is the technique offering the highest performance. It is thus the bellwether for testing already identified NES diagnostic functions and trying out new ones. To perform actual measurements is, of course, needed for assessing new functions while those already exploited ~~tried~~ need to be substantiated with respect to the extent of information can be extracted depending on quality of data and analyses.

The performance of NES diagnostics varies with count rate. In the case of the MPR it is a question of obtaining maximum flux in the MPR collimator for given neutron yield rate. This comes down to questions of the diagnostic-machine interface imposing sight line limitations and the spatial resolution limiting the plasma volume to be viewed. The performance impact of these aspects is illustrated below.

The MPR neutron collimator is circular with an area of $10cm^2$ with an opening angle of ±40mrad. The viewing aperture of the collimator (Ω) must be reduced if the MPR must be placed at so great a distance from the plasma that the spatial resolution (Δx) exceeds the desired value (Fig.11). This would lead to reduced flux and hence performance. The flux will also be reduced if the full MPR solid angle extends beyond the acceptable limit of the aperture one can have in the plasma facing wall (A in Fig.11).

An example of location for the MPR beside the NB injectors is shown in Fig.12. A viewing aperture of the order of 40cm at the first wall would give maximum count rates in the range of tens of MHz for an estimated flux of the order 10^{12} n/s entering the MPR. This is near the practical limits of any NES diagnostic systems that can be perceived today. From this level one can sustain some reduction in count rate, i.e., performance, which may come from interface restrictions. In any case, the performance of an MPR spectrometer at ITER would be an order of magnitude higher than achieved in the measurements conducted at JET during DTE1.

The mentioned example refers to a tangential sight line. For a radial sight line with the same geometrical assumptions, the count rate would be slightly lower (up to a factor of 2). With a tangential sight line one can measure neutron emission effects that show up relative to the direction of the magnetic field or the NB injection direction which do not show up in the radial view; the latter on the other hand, shows greater sensibility to fast ion cyclotron motion. The simultaneous NES measurements on ITER along two orthogonal sight lines would greatly enhance the capabilities to separate the different ion velocity components reflected in the neutron emission of the type illustrated above. Moreover, if two opposite tangential directions are used, one can also enhance the high-energy component due to NB injected ions or suppress it to favor observation of other features.

The NES diagnostic functions and the performance that can be achieved depend on the neutron emission conditions. We have above mentioned the importance of the neutron yield rate to give high count rate and, hence, performance. The plasma composition is also important, i.e. whether~~it~~ it consists of pure deuterium (D) or mixed D and T ranging from 50:50 to those with minority admixtures of T or D, i.e., D(T). Below we present a summary of demonstrated and/or potential NES diagnostic functions assuming a DT plasma viewed with 14-MeV spectrometers using radial and tangential sight lines in the horizontal mid plane; the spectrometer is assumed to be of the MPR type. Some functions such as the one to determine the fuel ion ratio n_d/n, requires simultaneous measurement of 2.5-MeV neutrons from dd and 14-MeV from dt. The parameters marked with an asterisk * have been noted as essential for measurement on ITER.

The NES diagnostic provides data that can be analyzed and used to derive information on a number of plasma parameters as displayed in Table 1. The information has been structured into the five groups: (A) fuel ion kinetics with the sub-headings of (a) purely thermal plasmas and (b) the added information that NES can provide when supra-thermal components are present due to the injection of additional heating (P_{aux}); (B) confined α-particle information is derived from the supra-thermal velocity component generated in the fuel ion population due to fast α-particle collisions; (C) collective motions of fuel ion population; (D) fusion parameters not mentioned under A; (E) other information includes especially determination of the extended spectrum of direct and scattered (D/S) neutrons from the plasma; the D/S information is essential input for analysis of camera data to determine neutron and α-particle source profiles [18].

As can be seen from the compilation, there is a wealth of information that can be extracted from NES data. At the core of it all is fuel ion kinetics which is difficult to obtain by other diagnostics and to some of its aspects unique for NES diagnostics. Regarding the fusion parameters, NES is the sole provider of the information. The information that NES can provide on confined α-particles adds up to a comprehensive set of observations regarding the d+t burn process when it is driven by the input of auxiliary heating until the α-particle self-heating has gained strength to be the dominant power source to sustain the temperature-. It is true that, NES measurement can only be performed along a few lines of sight so that spatial resolution can not be provided. Even without interface restrictions for installing arrays of spectrometers, measurements along peripheral sight lines would not be possible because the need for high fluxes to obtain data of sufficient quality to provide the information summarized in Table 1. Therefore, the NES measurements will use sight lines intersecting the plasma core and this is the region that will carry most weight in the NES observation as this has usually the strongest neutron emissivity. The information extracted from NES represents the conditions of the core and the effect on the measurements from other regions need to be assessed through model calculation of the neutron emission with important input from the neutron cameras on the neutron emission profile.

Neutron spectrometry is different from most other diagnostics in that it does not just provide information on one parameter but many with a focus on what can be referred to as the central fusion reaction parameters. On top of this comes information on the toroidal rotation as an extra bonus.

It should also be mentioned in this context that the TOFOR experiments at JET will play an important role in extending the experience of NES diagnostics for different plasma conditions. This experience will be put to use to plan NES diagnosis of fusion experiments on ITER. The TOF method is not deemed suitable for DT diagnosis at ITER, but only at the start up phase with D plasmas.

We end this section by listing some of the diagnostic parameters which can be derived from NES measurements. NES provides information on the scattered and direct neutron flux from the plasma. It provides information the absolute fusion power (for D and DT plasmas) as well as the thermal and supra-thermal fractions. Information is provided on the fuel ion kinetics in terms of velocity components specified by temperatures (where it applies) and amplitudes as well the toroidal rotation of the fuel ion component of the plasma. The confined alpha particle population can be determined from NES measurements and specifically the alpha particle pressure in a burning plasma. Another essential parameter for ITER is the fuel ion density ratio n_d/n_t which can potentially be determined in ITER and JET can and will provide feasibility information with the MPRu, but actual tests can not be done on JET without mayor efforts.

CONCLUSION

We have described in this paper how the development in neutron diagnostics for fusion experiments over the last 10 years have been driven by what has happened in the sub field of Neutron Emission Spectroscopy (NES). This development will be given a new boost when two neutron spectrometers, MPRu and TOFOR, will be in operation at JET. These will by themselves enhance the capabilities at JET to perform fusion experiments besides strengthening the ND complement as a whole as exemplified in this paper. ND diagnostics are likely to benefit from developments in the field of fast data acquisition which for the first time is being exploited by both MPRu and TOFOR. This will next also be implemented for the neutron cameras. This is significant as the combined use of neutron cameras as illustrated in the paper can be expected to be an important line along which to advance neutron diagnostics. This leads to the conclusion that development in the ND of late combined with what can be envisaged to come from ND based fusion experiments at JET over the next few years is essential to the success of design and implementation of a complete neutron diagnostic complement on ITER. Knowing this complement and its capabilities must be judged as fundamental for the planning and conduction of future fusion experiments.

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REFERENCES

[1]. JARVIS, O.N., Plasma Phys. Control. Fusion **36** (1994) 209.

[2]. KÄLLNE, J., et al., Phys. Review Letters **85** (2000) 1246.

[3]. KÄLLNE, J., et al., Nucl. Instr. Meth. A311 (1991) 595.

[4]. ERICSSON, G., et al., Rev. Sci. Instr. **72** (2001) 759.

[5]. KÄLLNE, J., et al., Com Plasma Phys. Control. Fusion **12** (1989) 235.

[6]. KÄLLNE, J., et al., Com Plasma Phys. Control. Fusion **15** (1993) 193.

[7]. LAMALLE, P.U., et al., in Fusion Energy 2004 (Proc. 20th Iint. Conf. Vilamoura, 2004) (Vienna: IAEA) CD-ROM (EX/P4-26) and http://www-naweb.iaea.org/napc/physics/fec/fec2004/datasets/index.html.

[8]. ERICSSON, G., et al., in “Advanced Diagnostics for Magnetic and Inertial Fusion”, Kluwer Academic/Plenum publishers, ed. Scott et al., pg. 121, New York 2002.

[9]. GORINI, G., et al., Rev. Sci. Instr. **63** (1992) 4545.

[10]. HJALMARSSON, A., et al., Rev. Sci. Instr. **74** (2003) 1750.

[11]. ANGELONE, M., et al., Rev. Sci. Instr. **61** (1990) 3536.

[12]. ELEVANT, T., Nucl. Instr. Meth. A476 (2002) 485.

[13]. TARDOCCHI, M., et al., Rev. Sci. Instr. **75** (2004) 3543.

[14]. COMBO, A., et al., “A PCI transient recorder for the magnetic proton recoil neutron spectrometer at JET”, Fusion Engineering and Design **71** (2004) 151-157.

[15]. SOUSA, J., et al., “A PCI time digitizer for the new JET time-of-flight neutron spectrometer”, Fusion Engineering and Design **71** (2004) 101-106.

[16]. SJÖSTRAND, H., et al., “Absolute measurement of the fusion power in the Trace Tritium Experiments at JET”, Proceedings of 31st EPS Conf., London, England (2004).

[17]. TARDOCCHI, M., PhD Thesis, Uppsala University, Uppsala, Sweden, 2000, “Neutron emission spectroscopy studies of fusion plasmas of deuterium-tritium in tokamaks”, unpublished.

[18]. DONNÉ, T., in Fusion Energy 2004 (Proc. 20th Iint. Conf. Vilamoura, 2004) (Vienna: IAEA)

CD-ROM (IT/P3-19) and http://www-naweb.iaea.org/napc/physics/fec/fec2004/datasets/index.html.

Table 1: Compilation of potential plasma parameter information derivable from Neutron Emission Spectroscopy (NES) measurements in high power DT plasmas.

A. Fuel ion kinetics

(a) Thermal (T) population

(1) Reaction rate (R_T)
(2) Density product $n_d n_t$
(3) Temperature T_T*

(b) Population with significant supra-thermal (ST) velocity components; as above but

(1) Up to 4 ST reaction rate components (R_{ST}) besides R_T
(2) Relative densities of S_T velocity components
(3) T_T and T_{ST} temperatures (if Maxwellian, otherwise slowing down)

B. Confined α-particles

(1) Amplitude of slowing down distribution*
(2) Pressure

C. Collective motion of fuel ion populations

(1) Toroidal rotation*

D. Fusion parameters

(1) Power P_f*; will provide values for dd and dt reactions separately
(2) Division of P_f into thermal and supra-thermal components
(3) Fuel ion densities in the core (n_d, n_t and n_d/n_t*)$^{+)}$

E. Other information

(1) The extended spectrum of direct and scattered neutrons from the plasma

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** Denotes diagnostic functions listed as essential for measurement on ITER*

$^{+)}$ *Requires simultaneous measurement of 2.5MeV neutrons from dd and 14MeV from dt.*

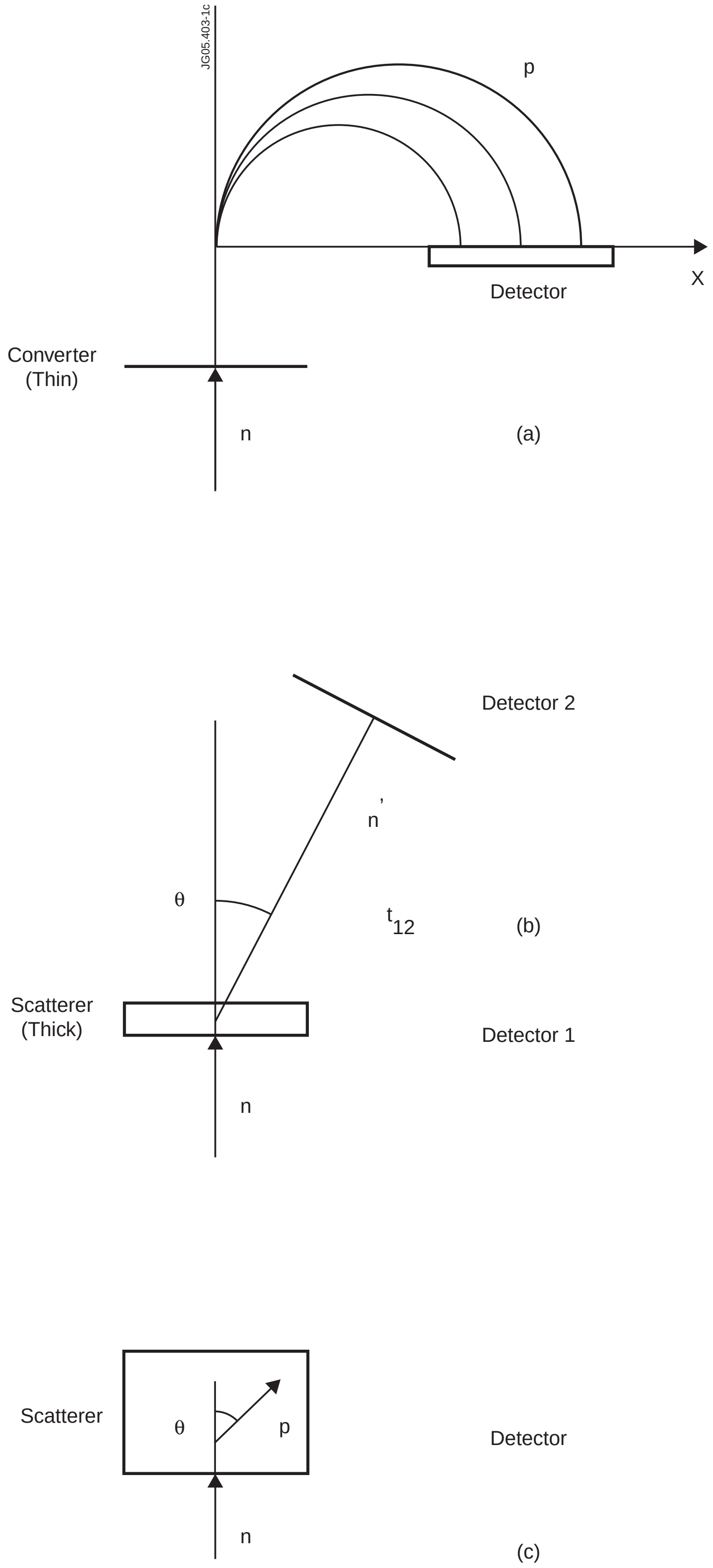


Figure 1: The principles for measuring neutron energy based on counting of momentum analyzed recoil protons in a space sensitive detector of the MPR (a) and using the recorded time delay t12 of signals from two detectors for scattered neutrons of TOF (b) techniques. Comparison is made with the principle of compact detectors in which the neutron energy is derived from recoil pulse height distribution measured by a scintillation converter (c)

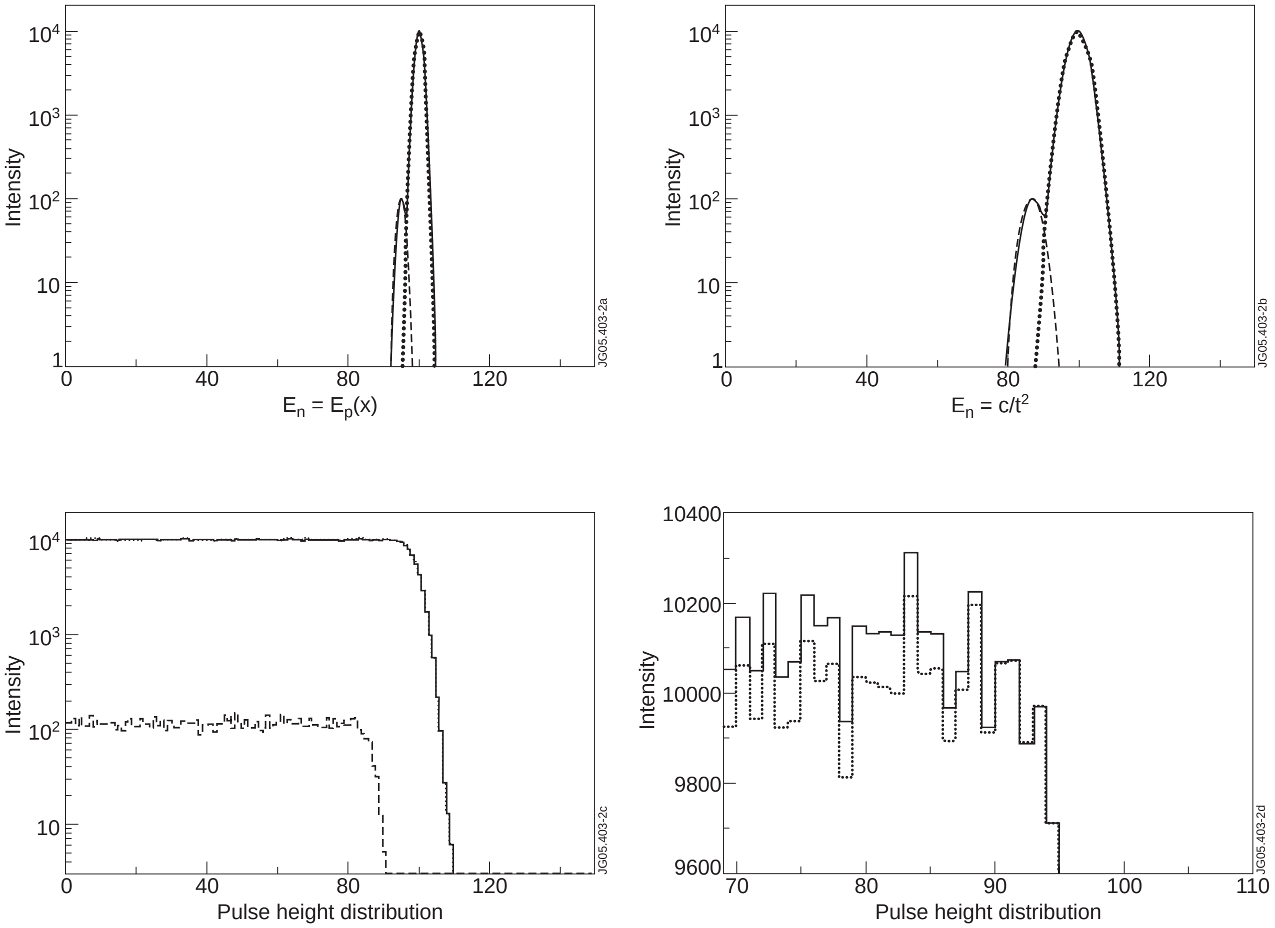


Figure 2: Illustration of the principle response of different types of spectrometers and detectors to a neutron flux consisting of a principal mono-energetic component and minor of 1/100 intensity on the low energy side and the superposition of the two. The response parameter is arbitrarily set to 100 for the main component and the minor at 100-2W where W is the assumed instrumental resolution (FWHM in %). (a) The MPR neutron spectrometer with W= 2.5% (as appropriate for 14MeV dt neutrons) and response parameter $E_n \approx E_p(x)$ where x is position. (b) The TOF neutron spectrometer with W= 6.6% (as appropriate for 2.5MeV dd neutrons) and response parameter $E_n = c/t^2$ where c is a constant and t the time-of-flight. For the latter conditions, comparison is made with a liquid scintillation detector used as a compact spectrometer whose individual response to the two neutron components would be the pulse height distributions shown in (c) and the superposition of the two compared with that of the minor component in the enlargement (d); the pulse height distributions were generated with 10^6 events so the scatter represents statistics. The figure shows idealized response distributions meant to illustrate principal features of different measurement techniques.

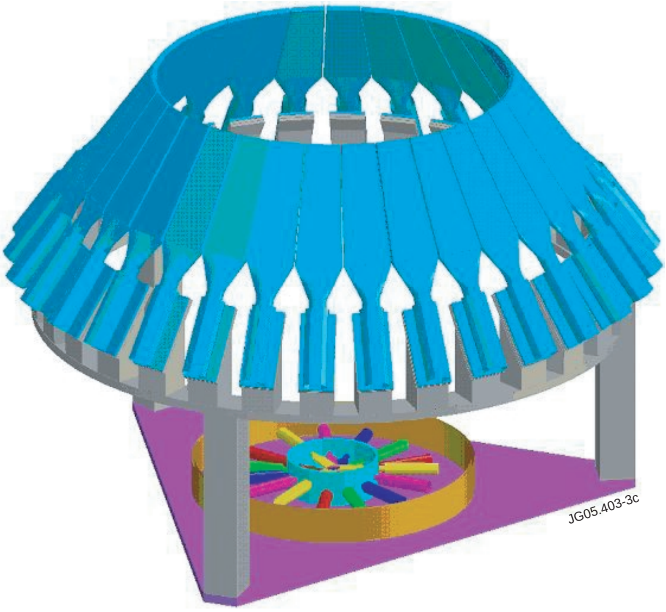


Figure 3: Sketch of the TOFOR neutron spectrometer showing the 5-element detector at the bottom where the collimated neutron flux comes in and the upper ring of 32 detectors at the top. The instrument is about 1 m tall.

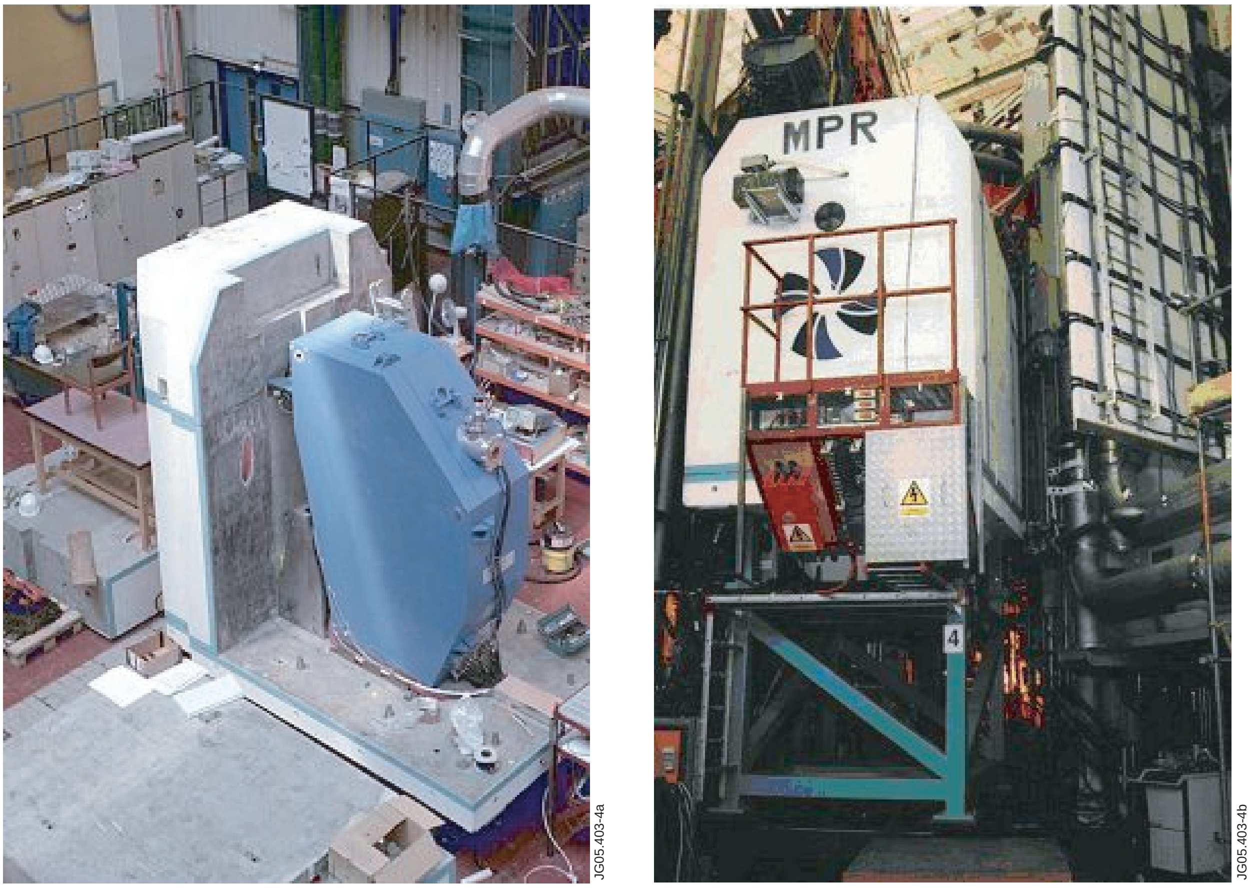


Figure 4: (a) The MPR neutron spectrometer (20 tons) under assembly of concrete blocks (66 tons) to protect the detector from extraneous background radiation. An extra local 2-ton lead shielding is enclosing the detector (bottom left). (b) The MPR installed in the Torus Hall. The overall size of the spectrometer is $1.9 \times 2.6 \times 0.8\ m^3$ $(l \times h \times w)$ *that becomes* $4.3 \times 3.9 \times 2.3\ m^3$ *including the shielding.*

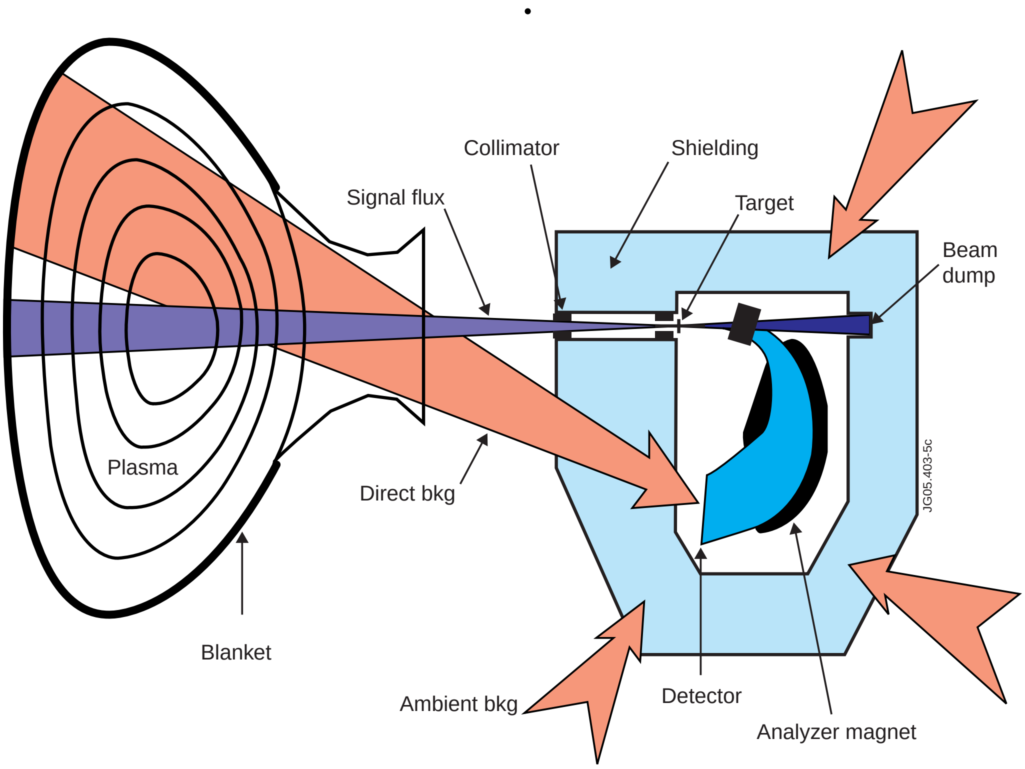


Figure 5: Schematic of the MPR spectrometer system showing the collimated neutron flux received from limited volume of the plasma and the exposure to a direct neutron background flux from a much larger volume and the ambient background of the torus hall. The concrete shielding attenuates the background before it reaches the detector which is near 100 % effective in recording protons and with an ability to reject background radiation events. The MPRu will be equipped with new detectors with significantly higher background rejection efficiency.

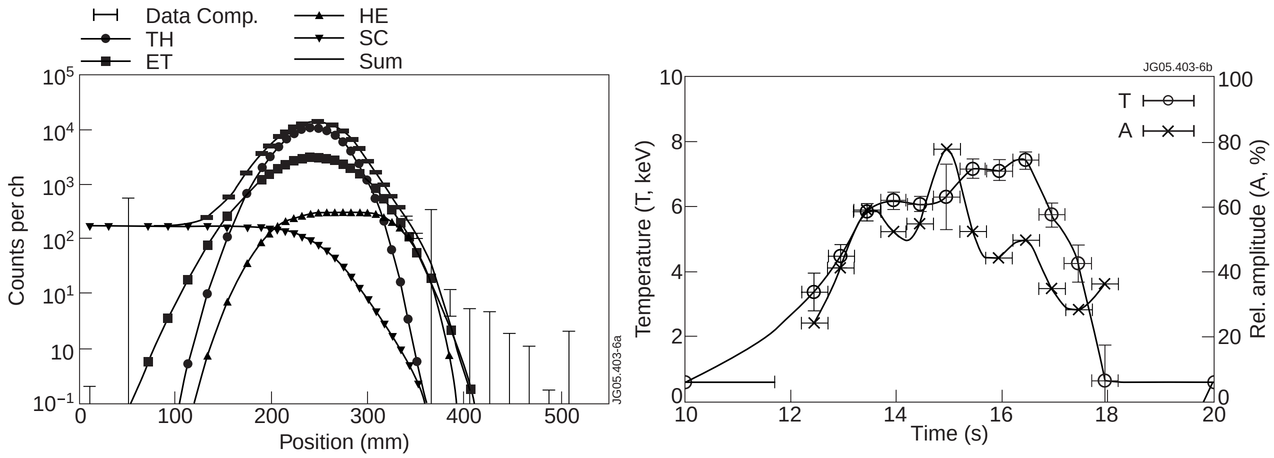


Figure 6: Example of an MPR recorded spectrum for the 14-MeV neutron emission from JET discharge #42982 representing record high fusion energy produced (a). The spectrum is fitted with three spectral components representing a thermal reaction component (TH) and two supra thermal (epithermal ET and high energy HE); a fourth component represents contribution from scattered (SC) neutrons. Deduced results are shown in (b) consisting of temperature, T, and relative thermal amplitude, A, as function of t; P_{aux} *in the form of a neutral beam (NB) pulse was used during the period 11.6 to 17.3s.*

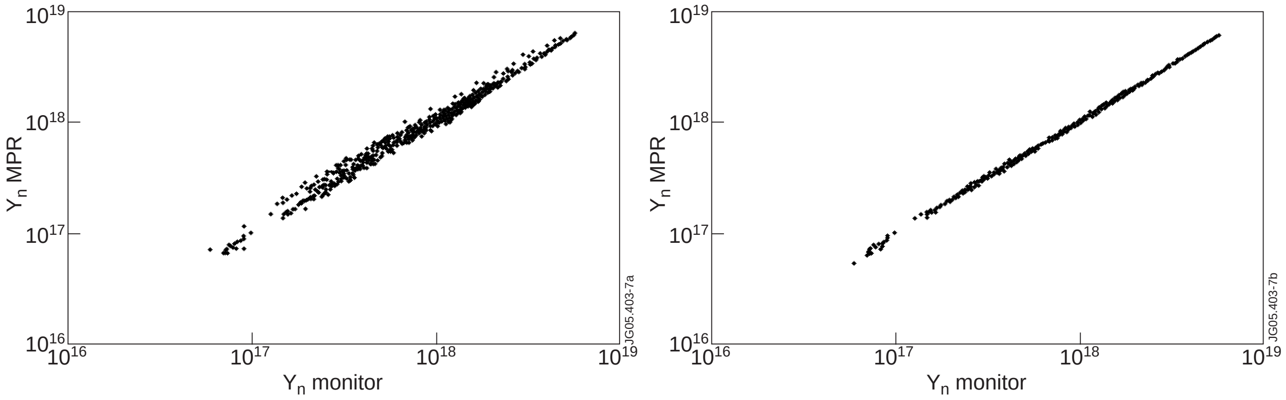


Figure 7: Example of results on the absolute neutron yield rate, $Y_n(t)$, derived from the MPR measured neutron flux for DT plasmas compared with the results of the neutron flux monitors calibrated to provide $Y_n(t)$; the results shown were obtained (a) with fixed (reference) neutron emission profile and (b) variable as obtained from the neutron cameras

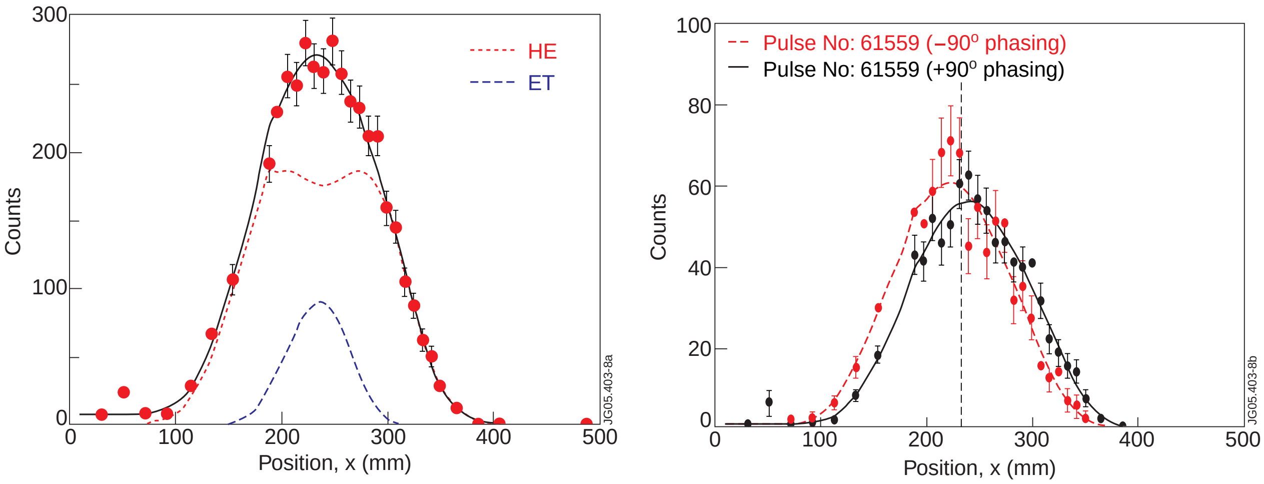


Figure 8: Example of MPR results obtained during the TTE campaign for discharge with ICRH heating. (a) Spectrum for JET Pulse No: 61280 fitted with bulk (ET) and high-energy (HE) components. (b) The measured spectra for ±90^o phasing of the antenna with an observable energy shift.

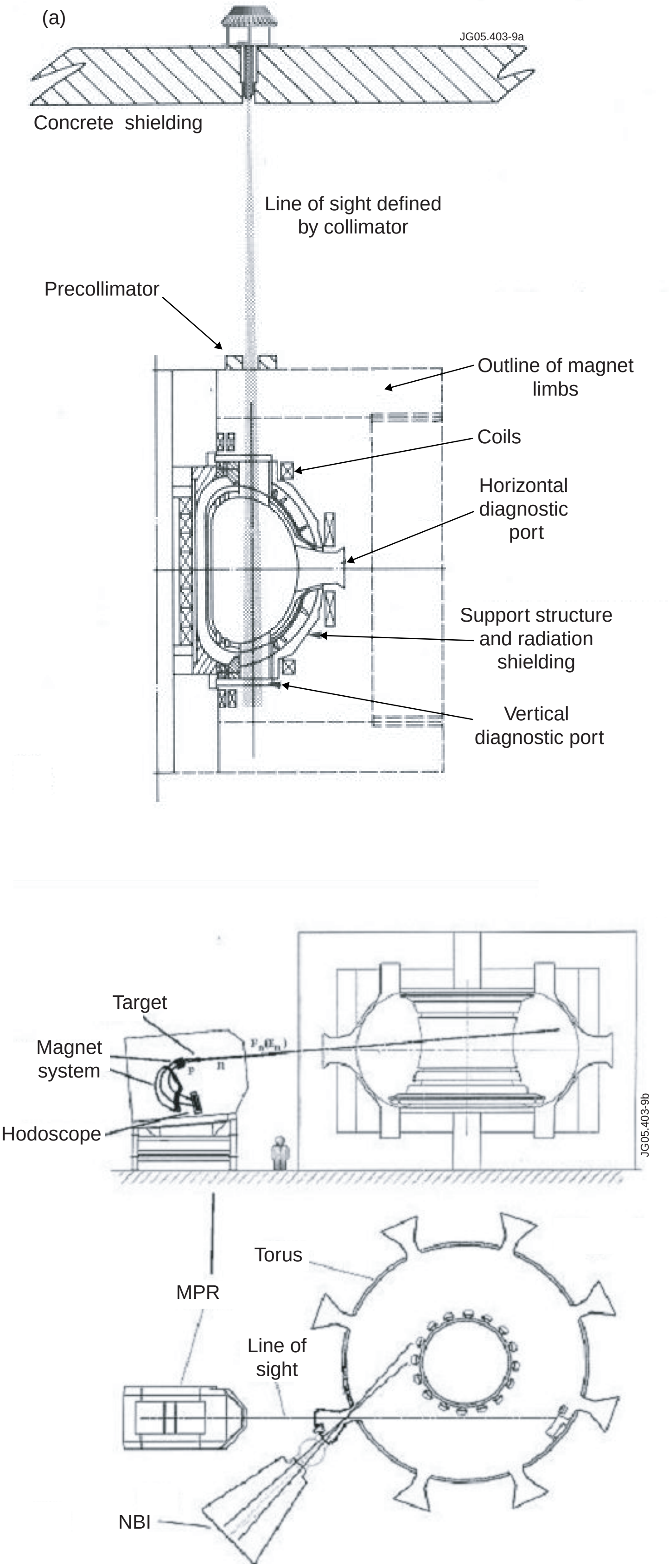


Figure 9: Sketch of sight lines for the TOFOR spectrometer located in the roof laboratory of JET (a) and for the MPRu in the torus hall (b).

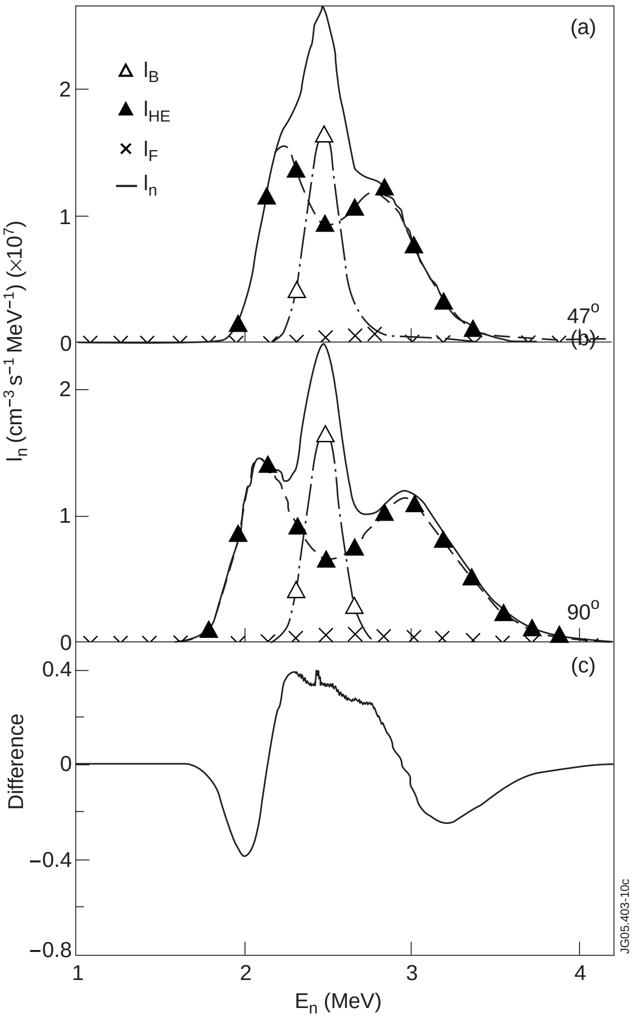


Figure 10: Simulation of sight line effects on spectrum of the neutron emission from discharges in deuterium subjected to ICRH power injection based on projections from fits to measured spectra for DT plasmas. The spectra are those that (a) the MPRu with 47 deg viewing direction and (b) the TOFOR with 90 deg viewing would record besides (c) the difference between the two.

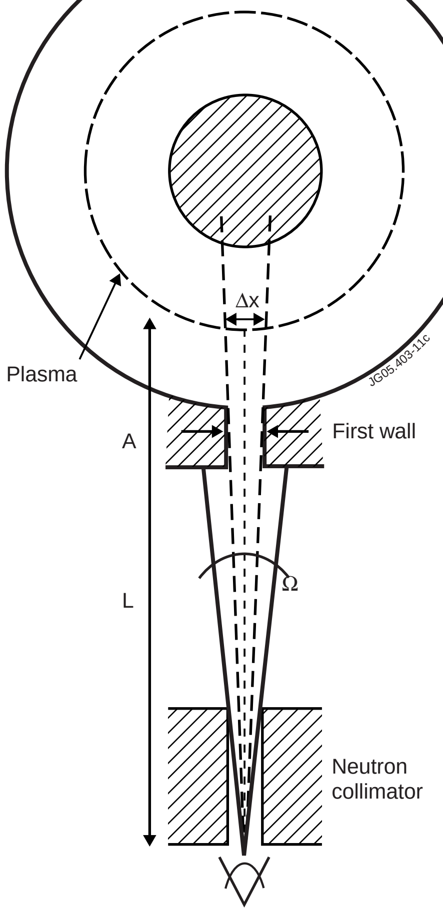
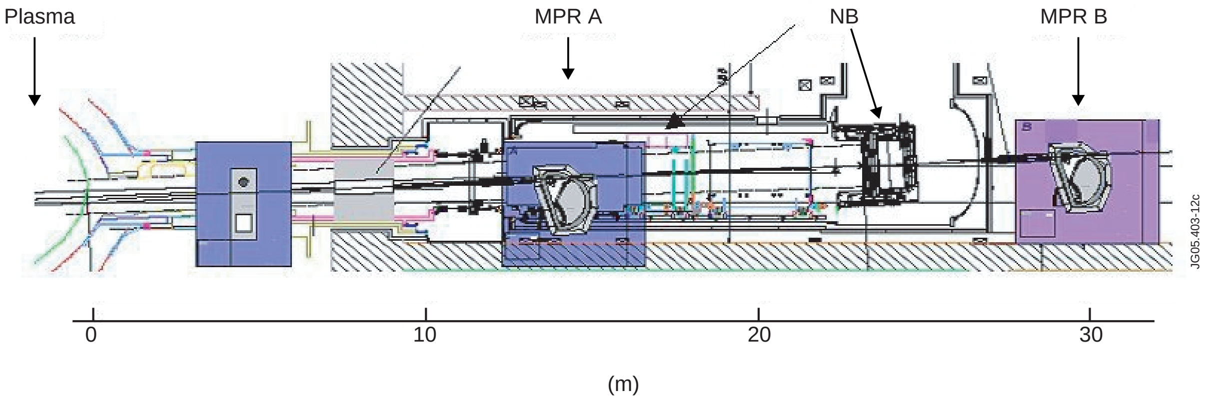


Figure 11: Sketch of the neutron collimator solid angle (Ω) relative to the critical interface limitations in terms of the maximum aperture penetration in the neutron collimator solid angle and first wall aperture for maximum MPR performance.



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by a Neutral Beam (NB) injector looking into the plasma at tangential sight line; inserted to left is the projection of the front of the MPR facing the plasma.