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Advanced Neutron Diagnostics For ITER Fusion Experiments

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ABSTRACT.
Results are presented from the Neutron Emission Spectroscopy (NES) diagnosis of JET plasma performed with the MPR during the DTE1 campaign of 1997 and the recent TTE of 2003. The NES diagnostic capabilities at JET are presently being drastically enhanced by an upgrade of the MPR (MPRu) and a new 2.5-MeV 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

The advances in Neutron Diagnostics (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] which possesses very high measurement precision. Moreover, it can operate at high count rate, 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]. The MPR is dedicated to 14-MeV neutron measurements 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. 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 [6].

Notwithstanding the above success, development of the NES diagnostics has been severely impeded by the fact that the MPR was practically only effective for measurement of the 14-MEV emission from plasmas with tritium. Such discharges are only produced in JET of 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 enhanced performance program 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) [7]. 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 [8]. TOFOR is dedicated to measuring 2.5MeV neutrons from dd reactions [8] and should reach a NES figure of merit in terms of count rate 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 extend in support of ITER.

In this contribution we report on results obtained with the MPR illustrating some diagnosticuses of NES. The role of the new MPRu and TOFOR instruments in enhancing JETÕs NES capabilities is discussed and the envisaged importance of the forward ND effort at JET for developing ITERÕs ND complement.

2. NEUTRON MEASUREMENTS AND DIAGNOSTIC FUNCTIONS

To illustrate the role of NES among the ND systems, the following classification can be made considering 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 [9]. The NIF monitors are unique among neutron diagnostics as they provide information on a single plasma parameter, namely, $Y_n(t)$, i.e., also fusion power in most cases. 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 bright 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 magnetic confinement field. 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. In addition, NES measurements can be used for calibration purposes and for benchmarking simulations of the neutron field in a tokamak. Here, the information of interest is the spectrum of the scattered neutron flux which always admixes to the direct flux. For correct interpretation of ND results, the scattered/direct ratio must be known from measurements or validated calculations. With regard to NES diagnostics one should note that true spectrometers are instruments whose data depict the neutron spectrum apart from a response function of finite neutron energy resolution. These are the most powerful ones and are always large so it has been popular to substitute them for detectors referred to as ÔcompactsÕ. These have various intrinsic limitations and some of them do not even measure the neutron emission spectrum but some information about it can be derived under certain conditions [1]; these will not be discussed here.

3. NEUTRON EMISSION SPECTROSCOPY

NES diagnostics have been used since the early days of fusion research but became an important part of the ND development with JET in the early 1980’s. The ND complement of JET was planned for tritium operation including tests of a number of different neutron spectrometers and compacts over the years both for general NES diagnostic purposes and special studies [1]. The build up of experience and the increasing neutron yield has worked together leading to accelerating development of NES diagnostics over the last ten years. The progress made during the DTE1 has far exceeded what had been expected possible in terms of NES contribution to fusion experiments in the 1980Õs when this was outlined [5]. The TTE of 2003, represented a new mile stone as advanced NES was for the first time made 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 compared to earlier fusion neutron spectrometers in that it involves no active neutron measurement, but the neutrons do merely scattering a passive hydrogenous target. A fraction (10^{-5}) 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 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 reduced to counting recoil protons in a detector array covering an energy range of typically ±25% around a central value. The MPR belongs to the class of magnetic spectrometers are used for high accuracy measurement.

Its design is dedicate to the fusion neutron application and this includes the proton detectors that, of course, must be practically 100 % efficient 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., or NES diagnosis of DT plasmas. The most successful spectrometer for measurement of 2.5-MeV 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 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 [10].

Today, there are new versions developed of the above spectrometers. The MPR is being upgraded (MPRu). The MPRu embodies 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 with diagnostics 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. It can also be used for measuring the scattered neutron spectrum over the full energy range. With regard to developing a NES diagnostic for D plasmas, a new design of the TOF techniques has been developed to increase the count rate up to the estimated intrinsic limit for this type of just below 500kHz; this is dubbed TOFOR standing for TOF designed optimized rate.

4. THE TOFOR AND MPRU INSTRUMENTS

The spectrometer requirements are different for measurements of 2.5MeV neutrons of dd reactions and 140MeV of dt, for instance, with regard to energy resolution. It can be set relative to the thermal

Doppler broadening which is 2.6 times greater for dd than for dt with ΔE/E values of 6.6 and 2.5% (FWHM), respectively for T=4keV. Moreover, the detection efficiency (ε) must be a factor of 10^2 greater than that for 14MeV neutrons to compensate for the lower dd reactivity; the values are ε= 8×10^{-2} and 5×10^{-4} cm^2 for TPFOR and MPRu match quite well the requirements to reach comparable levels of performance in terms of count rate at JET for D and DT plasma operation C_n < 500kHz and > 700kHz. However, the performance lismitations have different intrinsic causes, namely, C_n capability for TOFOR and ε for MPRu.

TOF spectrometers become paralyzed when the rate in the first detector D1 (Fig. 1b) 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 should therefore be ring shaped to achieve maximum catching efficiency of the selected scattered neutrons coming from D1. The design of optimized count rate design looks like the sketch of the TOFOR spectrometer shown in Fig.2. 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 D1 detectors. 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 at JET early 2005.

The MPR uses an array of scintillators which works well for 14MeV neutrons while background subtraction is applied to see weak components at the statistical limit of the recorded DT plasmas of JET.

The MPRu will be able record background free data for the same conditions which is achieved by developing a new detector which will also make possible 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-dimensionl 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 actual 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 which will be exploited in the proposal to use NES diagnostics to determine fuel ion densities in ITER.

Both 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 [11].

This 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 [12]. This is the most advanced NES systems built 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 refer to the DTE1 campaign of 1997 and the recent TTE of 2003; the latter being the first ever fusion experiment with an (active) advanced NES where absolute measurement of the fusion power was achieved.

5. RESULTS FROM JET

As an illustration of NES results obtained with the MPR during DTE1 at JET we choose Pulse No: 42982 which produced the record fusion energy. Fourteen neutron spectra were measured of which one is shown with its 3-component fit in Fig. 3a and the deduced ion temperature and the thermal fusion power fraction as function of time, T(t) and A(t), in Fig.3b. T(t) rises significantly starting at the onset of the auxiliary power (P_{aux}) from 1 to 6keV with some possible variation at the high level, till the end of the heating. The excursion at t = 55s 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 differences. At the beginning of the heating pulse, the fusion power is dominated by supra-thermal ion reactions and one can also see its decomposition in the NES data (not discussed here). The fourth component, SC, is due to the scattered neutron flux which constitutes a few percent admixture of the measured neutron flux above say x = 100 mm. Information on SC is 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 Yn given that the spectrometer is suitably calibrated.

The MPR is *ab initio* calibrated affording absolute measurement of both neutron flux and energy. With we have taken advantage of the former to determine the absolute neutron yield from MPR data with detailed accounting of all flux losses from source to proton detection and the plasma volume defining solid angles besides the above mentioned scattered neutron admixture. Preliminary results of such an exercise are shown in Fig. 4 where the results on Y_n from MPR are compared with those from the regular NIF based yield monitor at JET (referred to as KN1). Here we can see a linaer correlation betwen the MPR and KN1 results over the dynamic range (about an order of magnitude) with some scatter of 12 % standard deviation (Fig. 4). These results were obtained assuming a reference profile for the radial distribution of the neutron emission.

If the profile factor obtained from the neutron camera data is included, the scatter from a linear fit is reduced to less than 3% which is consistent with the intrinsic statistical errors in these data.

The absolute energy calibration of the MPR data makes it fruitful to look for shifts in the measured relative to the predicted spectrum as the latter is also determined to high accuracy on the absolute scale. Such shifts are interpreted to come from toroidal rotation in the fuel ion component of the plasma which is not measured by other diagnostics. A finite toroidal rotation has been seen in many discharges, especially, those subjected to neutral beam injection but also for RF of ion cyclotron resonance heating.

A particularly clear case was found 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 are shown in Fig. 5(a) and the total fit for the ±90 degree phasing cases are shown in Fig.5(b) representing estimated rotation velocities of more than ± 200m/s. Besides the scientific significance, these results represent a mile stone in that it was the first time NES data were analyzed between discharges so the information was able for the next to come.

One NES feature that has not been exploited is the anisotropy of the neutron emission realtive to the direction of the magnetic field which can occur 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 from above, i.e., perpendicular, with TOFOR 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 of isotropic emission and a anistropic high-energy component due reactions involving RF accelerated ions.

The spectra of the dd neutron emission into MPRu and TOFOR are shown in Figs.6(a) and (b) where one can see how the HE component is relatively enhanced or suppressed depending on angle of observation. As the TOFOR and MPRu can be expected to provide data of high quality, it will also be meaningful to use the data to determine difference spectrum (Fig.6(c)) to help in the analysis and interpretation of spectra of more complex structure that the clinical examples shown hear. 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 which includes both concepts and implementation of instrumentation and diagnostic information output. Regarding NES diagnostics, specifically, the MPR should now be exploited because it is the technique offering the highest performance and is thus the bellwether for testing already identified NES diagnostic functions and trying out new ones. Here, the only option available is to do actual measurements which are needed for assessing new functions or defining the reach of identified ones. As there is no alternative technique to the MPR for high performance NES diagnostic, the diagnostic-machine interface is critical for the diagnostic tools that can be used for the conduction of fusion experiments.

The performance of NES diagnostics varies with count rate so in the case of the MPR it is a question of obtaining maximum flux in the MPR collimator for given neutron yield rate. The collimator is circular with an area of $10cm^2$ at the MPR with an opening angle of ±40mrad. The collimator must be reduced if the MPR must be placed at so great a distance from the plasma that the spatial resolution exceeds the desired value (Fig.7).To remedy 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 plasmas facing wall (A in Fig. 7).

It should also be mentioned in this context that 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 t 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 derive 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)s 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 fro ITER is the fuel ion density ratio nd/nt. 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 the contribution 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 be a new given a new boost when two neutron spectrometers, MPRu and TOFOR be operation ion 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 development in fast data acquisition field which for the first time is being exploited by both MPRu and TOFOR which now also be implemented for neutron cameras to better facilitate the combined use of neutron spectrometer and cameras as was also demonstrated in the paper. This leads to the conclusion that development in the ND of late combined 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 implantation 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]. Ericcson, G., et al., Rev. Sci. Instr. **72** (2001) 759.

[5]. Källne and Gorini, Com Plasm Phys Contr Fusion, **12** (1989)235, and Ibid 15(1993)193.
[6]. Lamalle, these procedings
[7]. Ericcson, G., et al in "Advanced Diagnostics for Magnetic and Inertial Fusion", Kluwer Academic/Plenum publishers, ed. Scott et al., pg. 121, New York 2002.
[8]. Gorini, G., et al., Rev. Sci. Instr. **63** (1992) 4545, and Hjalmarsson, A., et al, Rev.Sci.Instr. **74** (2003)1750.
[9]. Angelone, M., et al, Rev Sci Instr **61** (1990) 3536.
[10]. Elevant, T., Nucl Inst Meth **A476** (2002) 485.
[11]. Tardocchi, M., Rev Sci instr (2004)
[12]. Combo, A., et al, "A PCI transient recorder for the magnetic proton recoil neutron spectrometer at JET" In Proccedings of 4th IAEA TM on data acquisition, control etc. in fusion experiments. San Diego July 2003, and SOUSA, J., et al, "A PCI time digitizer for the new JET time-of-flight neutron spectrometer", Ibid.

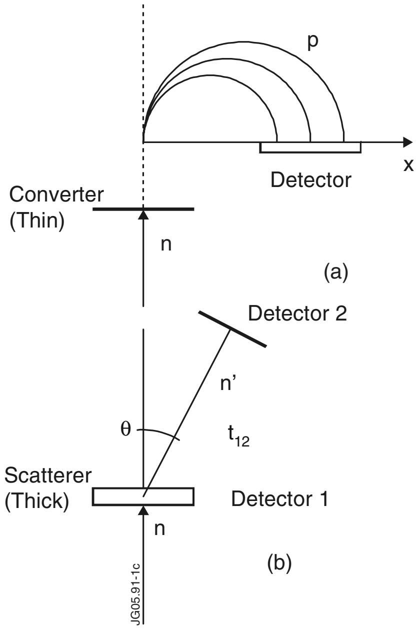

Figure 1. The principles for measuring neutron energy based on proton counting in a space sensitive detector of the MPR (a) using the recorded time delay t_{12} of signal from two detectors scattered neutrons of TOF techniques (b).

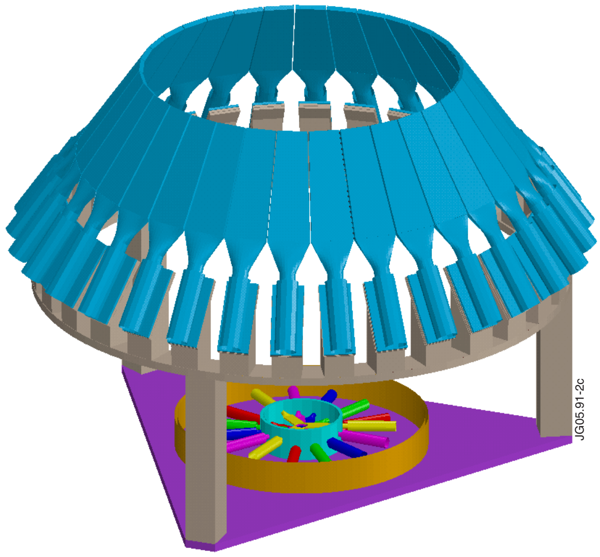

Figure 2. Sketch of the TOFOR neutron spectrometer show the 5-element detector at the bottom where the collimated neutron flux comes in and the upper ring of 32 detectors at the top. The instrument is about 1 m tall.

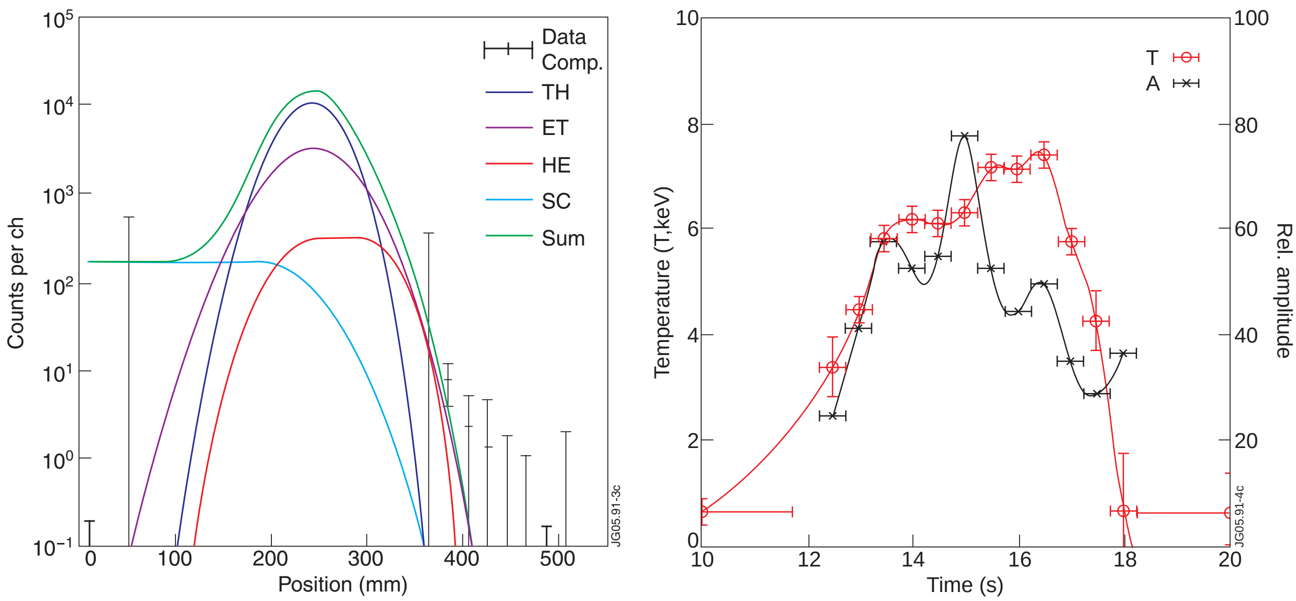

Figure 3. (a) Example of an MPR recorded spectrum for the 14MeV neutron emission from JET Pulse No: 42982 representing record high fusion energy produced. The spectrum is fitted with three spectral components representing a thermal reaction component /TH) and two supra thermal (epithermal ET and high energy HE). (b) deduced results on temperature T and thermal amplitude A as function of t; P_{aux} in the form of an NB pulse was used during the period 11.6 to 17.3s.

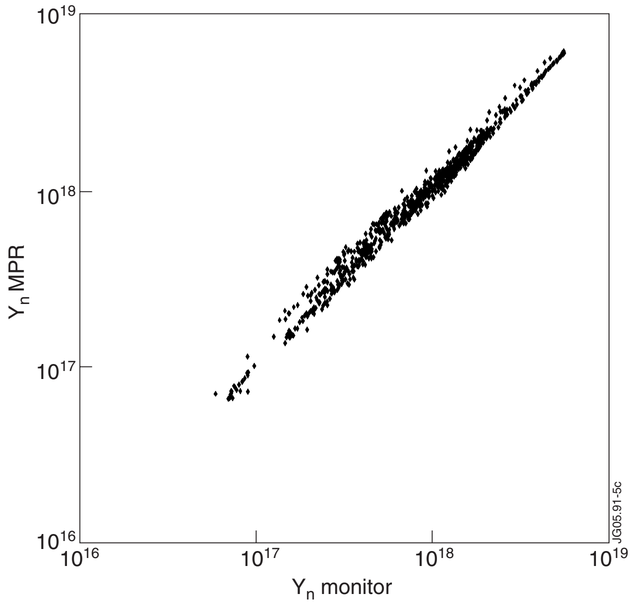

Figure 4. Example of deduced information on the absolute neutron yield rate, $Y_n(t)$, derived from the MPR measured neutron flux for DT plasmas compared with the results of the neutron flux monitors calibrated to provide $Y_n(t)$; the results shown were obtained (a) with fixed (reference) neutron emission profile and (b) variable as obtained from the neutron cameras.

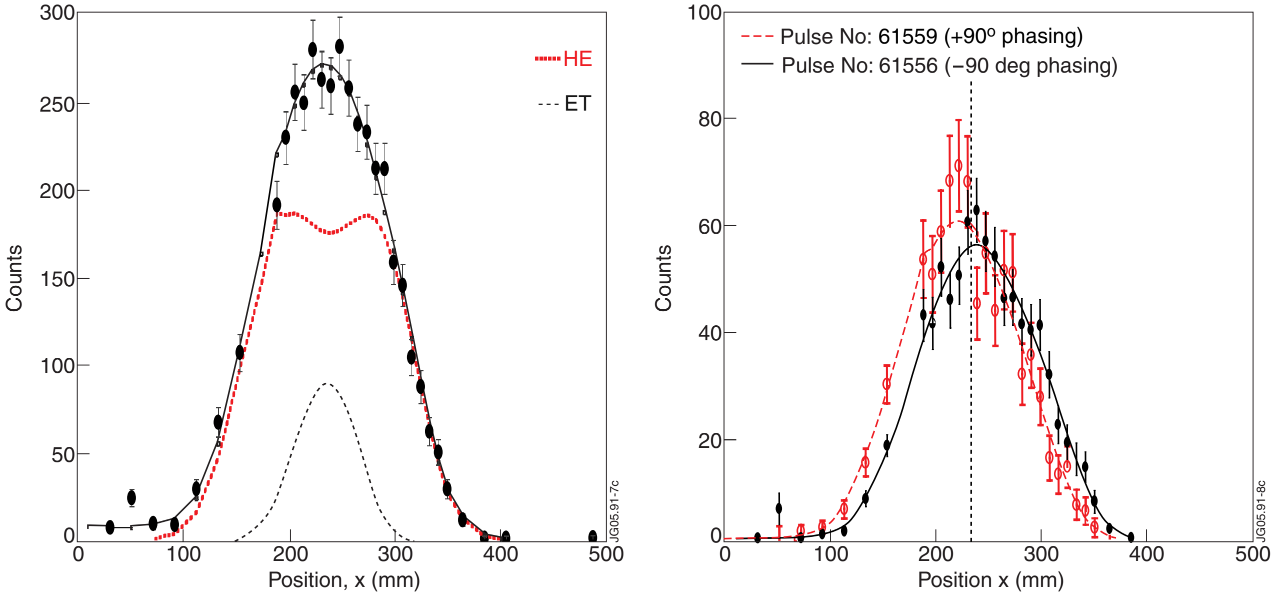

Figure 5. Example of MPR results obtained during the TTE campaign for discharge with ICRH heating. (a) spectrum for JET Pulse No: 61280 fitted with bulk (ET) and high energy (HE) components. (b) The measured spectra for ±90^o phasing of the antenna with an observable energy shift.

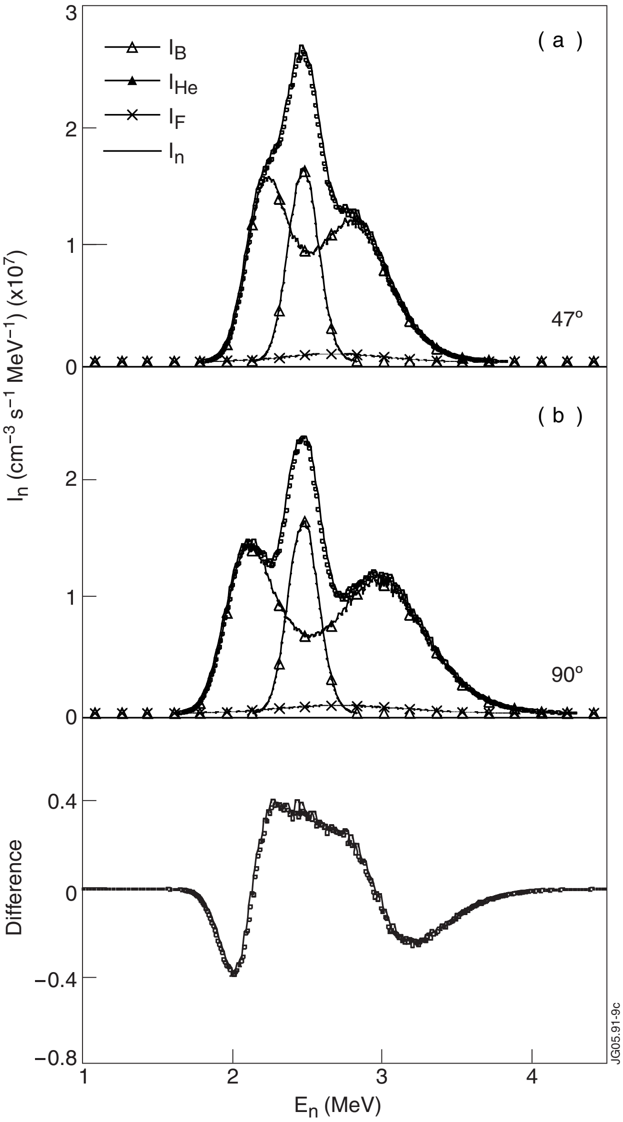

Figure 6. Simulation of sight line effects on spectrum of the neutron emission fromdischarges in deuterium subjected to ICRH power injection based on projections from fits to measured spectra for DT plasmas. The spectra are those that (a) the MPRu with 47^o viewing direction and (b) the TOFOR with 90^o viewing besides (c) the difference between the two.

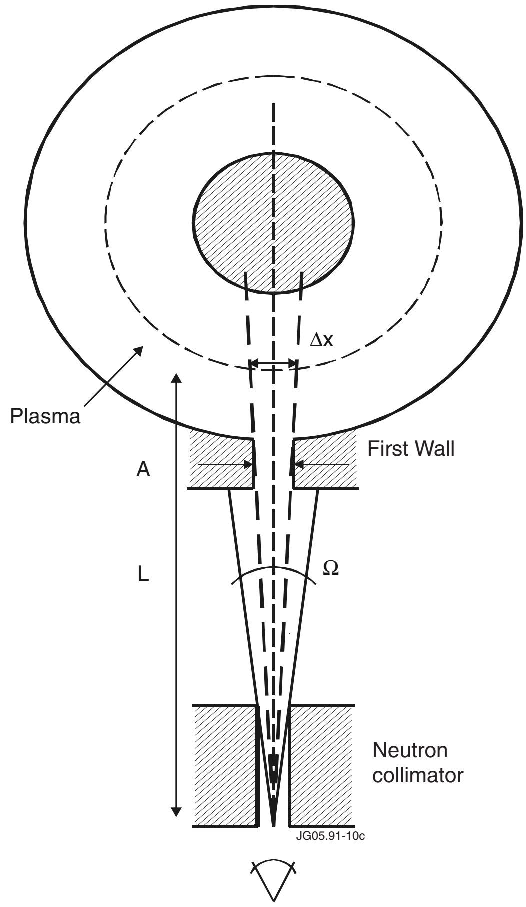

Figure 7. Sketch of the neutron collimator solid angle (Ω) relative to a critical interface limitation in terms of the maximum aperture penetration in the aperture Neutron collimator solid angle and first wall aperture limitations for maximum MPR performance.