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CALIBRATION ISSUES FOR NEUTRON DIAGNOSTICS

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1. INTRODUCTION

The performance of diagnostic systems are limited by their weakest constituents, including their calibration issues. Neutron diagnostics are notorious for problems encountered while determining their absolute calibrations, due mainly to the nature of the neutron transport problem. Although neutrons penetrate large amounts of material and are difficult to shield against, they lose essential information (energy and direction) whilst interacting with shielding materials or other machine components. Detectors, fully characterized in the laboratory, respond only to the local neutron field, which is determined by radiation transport in the tokamak and the diagnostic itself. In general, detectors will not distinguish between virgin (unscattered) neutrons coming directly from the plasma and neutrons that have undergone scattering events, although some discrimination is possible if energy-sensitive detectors are used. In order to facilitate the determination of an accurate and precise calibration, the diagnostic design should be such as to minimize the scattered neutron flux. In addition, the largest possible fraction of the neutron emitting volume has to be viewed so as to avoid errors caused by profile and collimation effects, which is best achieved by choosing a location as close to the plasma as possible. The general issue of obtaining accurate calibrations for the neutron diagnostics on present-day tokamaks were discussed at a specialist meeting in 1989[1].

ITER will use a comprehensive set of neutron diagnostics[2] - comprising radial and vertical neutron cameras, neutron spectrometers, a neutron activation system and internal and external fission chambers - to provide accurate measurements of fusion power and power densities as a function of time. The calibration of such an important diagnostic system merits careful consideration. Some thoughts have already been given to this subject during the conceptual design phase in relation to the time-integrated neutron activation[3] and time-dependent neutron yield monitors[4]. However, no overall calibration strategy has been worked out so far.

This paper represents a first attempt to address this vital issue. Experience gained from present large tokamaks (JET, TFTR and JT60U) and proposals for ITER are reviewed. The need to use a 14-MeV neutron generator as opposed to radioactive sources for in-situ calibration of D-T diagnostics will be stressed. It is clear that the overall absolute determination of fusion power will

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have to rely on a combination of nuclear measuring techniques, for which the provision of accurate and independent calibrations will constitute an ongoing process as ITER moves from one phase of operation to the next.

2. ITER REQUIREMENTS

The complexity of the calibration issue can be appreciated from a brief consideration of the range of ITER machine operations during which neutron diagnostics are required: starting with hydrogen (H) plasmas, pure deuterium (D) and trace tritium (D(T)) will next be employed before moving on to 50:50 deuterium-tritium (D-T) plasmas. Hydrogen plasmas will generate a small neutron yield due to the natural abundance of D in H and the usual photo-neutron contribution is expected. It will be important to have absolutely calibrated 14-MeV neutron monitors even during the D-D phase to study triton burn-up. The same monitors cannot not be used during the D-T phase as the 14-MeV neutron yield will then be more than 4 orders of magnitude higher. Calibration for the D-T phase probably presents the least difficulty.

The use of different fuels causes large variation in neutron yield and important changes in neutron energy spectra, as does the employment of different plasma heating techniques. Ideally, the instantaneous neutron yield diagnostic would be designed to have:

- a linear response to neutron yield over some seven orders of magnitude,
- no sensitivity to the neutron energy spectrum,
- no sensitivity to neutron emission position, shape, profile, and anisotropy,
- no sensitivity to gamma-rays,
- long-term intrinsic stability,
- no sensitivity to changes to the machine structure.

It may seem over-ambitious to specify all these factors but it should be borne in mind that if the main diagnostic is lacking in a particular attribute then it implies the need for a subsidiary diagnostic which does not. Our present understanding is to meet the mission of ITER the calibration issue *alone* implies the need for an activation system, a profile monitor and neutron spectrometers to complement the neutron yield monitors.

3. METHODS USED ON PRESENT DAY MACHINES.

Greatest emphasis will be placed in this article on experience obtained from JET since the material from this machine is most readily available to the authors, although it should be remarked that the exchange of information between the main fusion laboratories has always been excellent so that the experimental techniques have been developed in common; the main procedural differences can often be related to differences in construction of the different tokamaks and in their perceived missions.

3.1 JET

At JET, the instantaneous neutron yield is monitored with three sets of fission chambers arranged around the machine, each set comprising a ^{235}U chamber and a ^{238}U chamber to provide the required dynamic range. These chambers are operated in pulse-counting and current modes. The fission chambers are checked against each other on a discharge by discharge basis and an alarm is raised if the response of one of the detectors deviates by more than a preset value (~6%) from their average. Apart from being triggered occasionally by photo-neutrons, it allows early detection of drifts (not observed at JET, so far) and changes to the disposition of equipment around the machine which influence the detector calibration (this inevitably happens during long shut-downs).

The absolute calibration of JET neutron yield monitors was first obtained in 1984, following the example of TFTR, from an extensive series of measurements[5] where the response of the fission chambers to a ^{252}Cf radioisotope source was mapped as a function of source location inside the vacuum vessel. At the same time, the insensitivity of the measurement to the neutron energy spectrum was demonstrated using additional sources (Am-Be and a pulsed 14 MeV neutron generator). The overall accuracy of the calibration was determined to be ± 10%. The calibration was checked at various occasions using the same ^{252}Cf source but never repeated in its entirety due to access limitations.

Later, foil activation measurements (see below) were used to derive the absolute calibration with an improved accuracy of around ± 7% [6]. Unfortunately, as time passed more and more bulky and heavy equipment was installed inside and outside the main access ports near to the fission chambers, inhibiting neutrons scattering from the access port windows from reaching the fission chambers but not affecting those arriving at the fission chambers after penetrating the concrete-filled mechanical shell. Consequently the fission chamber response changed considerably over the first 7 years of operation. It also transpired that their response had become dependent on the source energy spectrum[7] so the use of ^{252}Cf was renounced and, in the absence of convenient D-D and D-T generators, in-vessel calibrations were abandoned altogether. The causes of the neutron energy dependence and the associated changes in calibrations were investigated in a series of neutron transport simulations[8].

3.1.1 The activation method

At JET, the preferred method of calibrating the neutron yield monitors involves determining the induced activation of small samples of carefully selected materials exposed to the neutron field close to the vacuum vessel. Although a total of 8 irradiation stations were originally provided, the most accurate results were obtained with the two irradiation stations mounted inside the vacuum vessel (the others are outside but close to the vacuum vessel wall). The neutron transport calculations, required to relate the measured activation to the source, are most reliably performed for the inside locations. The resulting calibration is insensitive to hardware outside the vacuum vessel but it does depend on the position of the plasma within the vessel and it is only weakly dependent on internal machine components. Transport calculations are performed with two codes based on contrasting methods: FURNACE[9], a ray tracing code using double differential albedos, and the standard 3D Monte Carlo Code, MCNP. After extended investigations and iterations, agreement between the two codes was achieved and accuracies of ±7% obtained[6]. The inside of the machine has subsequently been changed by the installation of a divertor, the up-down symmetry of plasma position in the vacuum vessel has been lost and only one of the previous two inside irradiation ends is now available. The computer models have been updated and the profile monitor is needed to measure the up-shift (~30 cm) in the plasma position. The present (DTE1) calibration from the neutron activation system provides an accuracy ~ ± 10%.

The choice of material for irradiation and the operational aspects of the activation technique are standard practice and will not be elaborated here, other than to note that a very considerable dynamic range is readily achievable. The induced activity can usually be determined to an accuracy of about 3%, comparable with the uncertainty in activation cross-sections for dosimetry standard materials. The greatest uncertainty derives from the neutron transport calculations. Of special relevance for JET (but possibly not for ITER) is the use of delayed neutron counting using thorium or uranium samples for D-D discharges and silicon for D-T discharges (or for triton burn-up measurements in D-D discharges) because their associated decay half-lives are suitable for repeated use of the same samples in successive discharges. The delayed neutron measurement technique was calibrated very accurately at a research (fission) reactor installation. The silicon activation cross-sections are not well known so this material had to be cross-calibrated against dosimetry standard materials.

3.1.2 The neutron profile monitor

The new, upgraded, neutron profile monitor presently in use at JET is very similar to the one under design for ITER. It consists of two fan-shaped arrays ("cameras"), one viewing the plasma radially and the other viewing the plasma vertically. Absolute calibrations are provided for the two cameras, as described below.

First, a short description of the neutron detection system used in the profile monitor is presented. The JET neutron detectors operate in the pulse height mode and are energy sensitive.

The photo-multiplier pulses are amplified in a fast linear amplifier after having traveled over 60-m-long cables between the torus hall and the signal processing cubicles. For the BC418 scintillators used for operation in D-T, the amplified pulses are fed to a fan-out unit, from which five of the outputs are fed to pulse height discriminator units - 4 for measuring neutrons, the fifth for checking long term stability from in-built radioactive sources. A sixth output is fed to a 'charge' integrating preamplifier followed by a pulse shaping amplifier, so that fully shaped pulses can be presented to the input of an multi-channel analyzer (after having passed through a linear gate). Pulse height spectra can thus be accumulated in order to determine end-points and thresholds by gating the linear gate with the outputs from the various pulse height discriminators. Pulses from the NE213 detectors (used for D-D and trace tritium plasmas) can be treated in a similar way with the difference that we have to consider 2 branches: a D-D branch and a D-T branch. Fortunately, each branch is handled by one single, double-width, NIM pulse shape discriminator unit providing properly shaped output pulses for neutrons and gamma-rays already suitable for multi-channel analysis.

Setting up the low-energy branch of the NE213 detectors using the 1275-keV γ-rays from the in-built ^{22}Na sources posed few difficulties. Initially, the same procedure was used in setting up of the NE213 high energy (D-T) branch but, due to the large extrapolations involved, significant energy discrimination variations resulted and the measured profiles were not smooth. A subsequent attempt, using an Am/Be neutron source, proved very helpful while setting up the n/γ discrimination for the low energy branch but was of no assistance for the high energy branch due to the lack of neutrons with energies above 9 MeV.

Real progress was made with both types of 14-MeV neutron detector when a D-T generator was borrowed from PPPL. As the output of the generator (~1-2 10^7n/s) was too low to be of use when placed at the focal point of the camera, the rear camera shields were removed and all detectors units irradiated simultaneously from a short distance. Spectra for all detectors of a given type from one camera at a time were obtained in parallel by multiplexing the shaped pulses to a fast ADC of a Canberra PC-based multi-channel analyzer. Proceeding this way allowed statistically meaningful data to be obtained on an hourly basis for all detectors simultaneously. The high voltages and discriminator thresholds were adjusted until 'identical' spectra were observed. Only approximate settings could be obtained by proceeding as described above due to neutron scattering in the rather bulky components of the detector box.

The final adjustments were made using dedicated plasma discharges containing some trace tritium at the beginning of the DTE1 campaign. ELMy H-mode plasma discharges yielding relatively flat neutron profiles were used so as to obtain acceptable statistics in the wing channels within a single discharge. The relative efficiencies for all channels lie within less than 5% of the mean value.

Applying absolute, solid-angle-corrected detector efficiencies should lead to an absolutely calibrated system. However, a thorough accelerator characterization of the BC418 scintillator-detector units, as required here, has yet to be undertaken and the light output functions used for the NE213 detectors had to be utilized. A concern here is the inherent non-linearity of light output functions coupled with the fact that the experimentally determined NE213 light response functions do not agree well with published data.

Finally, corrections for back-scattering from the vacuum vessel wall regions viewed by the camera, attenuation, in-scatter and out-scatter all have to be made. The absolute magnitude of the backscatter correction is only weakly channel dependent. For D-T neutrons, the fractional backscatter contribution to the line-of-sight data is ~10% for a wing channel whereas, for D-D neutrons, this correction is ~10% for a central channel, despite the order of magnitude higher unscattered fluxes in central channels. Corrections for attenuation and scattering of neutrons directed towards the detectors, as determined by Monte Carlo calculations, are typically about 30% for D-T neutrons and 50% for D-D neutrons.

Our first D-T results are encouraging as the instantaneous 14-MeV neutron yields from the profile monitor agree to within 8 % with those obtained using silicon diodes calibrated using the activation system (when the discharges are analyzed using both camera simultaneously). However, the imbalance of ~12% between vertical and horizontal camera remains a concern. The calibration provided by the horizontal camera on its own is preferred because of the fortunate circumstance of the radial position of the focus of the fan-shaped arrangement of the lines-of-sight being almost exactly twice the radius of the major plasma axis. This means that the line-of-sight density of the viewing arrangement on the inboard side of the machine is significantly lower than on the outboard side. The good match between the radial dependence of the line-of-sight density and radial dependence of toroidal volume means that the radial-viewing neutron camera is, in principle, able to measure accurately the total volume integrated neutron emission strength without recourse to information regarding the spatial distribution of the neutron source profile along the camera's lines-of-sight (i.e. information from the vertical camera is not required). A weighted summation of the lines-of-sight data can therefore be used for deducing the total neutron yields. The viewing extent of the horizontal camera is such that at maximum an error of 5% is introduced for extreme, almost unrealistic, profiles. Unfortunately the location of the focus of the radial camera proposed for ITER does not have the property described here and information on the spatial distribution along the lines-of-sight (from a vertical camera and/or model calculations) will be required in order to deduce the total neutron yield.

3.2 TFTR

The early D-D neutron production measurements with fission chambers at TFTR relied on direct calibrations performed in-situ with radioisotope sources, as at JET. The sensitivity of the TFTR fission chamber responses to source energy spectra is less than at JET since the TFTR support structure is considerably less massive. Nevertheless, in later work particular emphasis was laid on the use of neutron generators as these possess the great advantage of providing the correct neutron source energy spectrum. Despite careful characterization of the directional emission from the D-D generator, only moderately accurate results (> 15%) were obtained from the first attempt[10]. Calibration for D-T operation involved a D-T neutron generator; however, such key issues as the number of spatial points that were necessary and the effects of anisotropic sources were addressed with ^{252}Cf sources[11]. Activation techniques were used to determine the output of the D-T neutron generator used for in-situ calibrations; the $^{27}Al(n,\alpha)^{24}Na$ reaction was chosen and a NIST-traceable gamma-ray source was used for calibrating the efficiency of the HPGe detectors.

In order to cover the required range of neutron intensities from TFTR, a variety of neutron detectors with differing sensitivities was employed. The absolute calibrations using portable neutron sources were performed for the highest sensitivity detectors; transfer of the calibrations to the low-sensitivity detectors used at high fusion powers required considerable care to deal with issues of non-linearity and detector drift over time. With proper attention to detail and the demonstrated stability of key detectors, the uncertainties from this process were reduced to a few percent at most[12, 13].

The use of the neutron activation technique for calibrating the fission chambers was given lower priority at TFTR than at JET and, indeed, as at JET, some initial inconsistencies were experienced while employing an irradiation position outside the vacuum vessel of the tokamak. Subsequent work with an irradiation position well inside the vessel led to reliable results being obtained. The internal consistency of the activation technique was demonstrated using materials with a range of threshold energies, those with low reaction thresholds being most sensitive to details of the neutronics modeling.

The TFTR neutron profile monitor provides only a vertical view through the plasma, considered sufficient as the flux surfaces are nearly circular (there being no divertor). The radiation detectors in the collimated sight-lines were calibrated[14] using neutron sources positioned inside the tokamak. A special feature of TFTR is the possibility of translating the plasma column radially through substantial distances without substantially altering the discharge characteristics; this was used[15] to test the relative efficiencies of the different collimation channels and to determine experimentally the magnitude of the backscatter corrections.

The fission chamber calibrations obtained from (i) activation measurements performed on high yield discharges coupled with neutron transport calculations[16], (ii) extrapolations using the absolute efficiencies of the most sensitive detectors determined with in-situ neutron generators[17], (iii) the profile monitor[18] and also (iv) from a "wide-angle collimated view" of a NE213 liquid scintillator spectrometer[19], were all very similar. The final "official" TFTR D-T fusion powers were derived from an independent-uncertainty-weighted average[20] of all these methods, giving a 1 s.d. uncertainty of $\pm$ 7%.

3.3 JT60U

The calibration of the fission chambers at JT60U was first derived from an extensive and carefully planned calibration[21] in which an in-situ ^{252}Cf neutron source was moved to 92 different toroidal locations using a purpose-built automated source carrier. Spectrum effects were examined using MCNP neutron transport calculations, showing no difference within statistical errors in the detection efficiency for ^{252}Cf or D-D neutrons. After integrating over the plasma volume, a final error bar of about ± 10% was deduced.

JT60U, as at TFTR, suffered problems with a "noisy" detector which created a problem during their calibration studies which was overcome by careful analysis. The need for redundant and complementary systems is emphasized by such experiences.

Calibrations of the fission chambers using foil activation measurements coupled with neutron transport calculations have recently been performed[22], providing an overall accuracy of ± 15-20% for D-D discharges, in good agreement with the in-situ source calibrations. The estimated error for 14 MeV neutron measurements (for triton burn-up studies since it is not proposed to employ tritium fueling) is ~ ± 20%.

4. ITER

4.1 Yield monitors

The US proposal for instantaneous neutron yield monitoring is to provide two arrays of 6 neutron detectors operating in the count rate mode with varying sensitivities (defined by the mass of ^{235}U in the fission chambers, location and extent of shielding) to measure over 7 orders of magnitude in neutron intensity. These detectors are to be located at two positions within the remote handling ports: two detectors will be embedded in the inboard shielding block in a chamber re-entrant into the primary vacuum (but actually in the bioshield) to measure primarily D-D and trace tritium yields while three less sensitive detectors devoted to D-T plasmas will be located in a re-entrant chamber at the outside wall of the cryostat vacuum (but actually at atmospheric pressure). This system will be duplicated in a second RH port for redundancy as well as to provide discrimination against local events such as photo-neutrons from runaway electrons and RF pickup. For calibration purposes, a sixth detector per array, will be located up against, and possibly embedded in the inner shield wall/blanket module of the vessel. These detectors will be considered "sacrificial" as no provisions will be made for maintenance unless there is a major vessel reconfiguration. Their primary function is to facilitate calibration using an "in-vessel" neutron source. They will be placed close to the plasma to provide the widest possible solid angle of view so that the calibration source best represents a plasma. The remaining detectors can be cross-calibrated to this detector using the plasma as a neutron source. One criticism of this proposal is the inconvenience of merging the count-rate signals provided by 6 detectors of differing sensitivities and limited ranges when, by using them in current mode, far fewer detectors are required. However, current and Campbelling modes have been observed to exhibit non-linearities on TFTR. Thus, a conservative approach would be to use count-mode over the entire dynamic range, backed by the other electronic modes for operational simplicity and to achieve better time resolution.

4.2 Proposed neutron yield monitor calibration techniques for ITER

The calibration issue for ITER has already been considered briefly[23] and is elaborated below.

4.2.1 In-situ calibration using in vessel neutron generators

Performing this task is evidently a non-trivial problem, since a very strong source of neutrons is required. A serious limitation is the fact that any extensive in-situ calibration can only be performed before start-up and/or during major interventions before the machine becomes radio-active; thereafter, the use of a neutron generator requires remote handling access and will occur infrequently. Only the most sensitive of the neutron yield monitors and the most sensitive detectors in the profile monitor can be calibrated in this manner. Because conventional neutron generators are bulky, a non-negligible fraction of the emitted neutrons interact with components of the generator itself, leading to spectrum degradation and anisotropic emission. The main source of error thus lies with the characterization of the neutron output of the generator. Careful monitoring with activation foils as demonstrated at TFTR and JET provides a measure of the neutron emission strength from the generator. The directionality of the neutrons emission and the energy spectrum, which also may be a directional property, need to be established.

The U.S. and Japanese proposals are that ITER should be provided with a robust, high-intensity D-T neutron generator capable of operation at the end of a remote handling arm inside the torus. The optimum generator would have an isotropic neutron output of over 10^{10} neutrons/s with a "fusion" (~14-MeV) energy and the capability of accurate "associated particle" detection (that is ability to measure 100% of the charged fusion products in some known solid angle) for direct absolute calibration of the emission strength. A comparable scheme (without the remote handling involvement) using a small Van de Graaff generator was briefly considered for JET but was rejected as being too complicated. The Inertial Electrostatic Confinement devices that are currently under development would be far more practicable.

4.2.2 Calibration using a pneumatic transport activation system

This is the preferred method in use at JET, where all other techniques are relegated to a supporting role. Its advantages are clear: it is intrinsically linear and can therefore be used for detecting possible non-linearities in neutron yield monitor responses. It is also stable in time, provided the necessary care is taken to maintain the calibration of the decay radiation detectors with standard radio-isotope sources. Reactor dosimetry materials, i.e. well chosen materials with evaluated cross sections yields, should be employed. Suitably high threshold reactions add energy discrimination, thereby reducing the importance of low energy, scattered neutrons. Its main weakness lies in the essential neutron transport calculations that involve a detailed modeling of the machine, especially the region close to the irradiation ends. The closer the irradiation station is to the plasma, the less difficult and time consuming is the modeling. At JET and TFTR, the irradiation ends protruding into the main vacuum vessel proved the most useful and are used to inter-calibrate supplementary ex-vessel stations.

At ITER, the irradiation stations would have to be protected from excessive heat flux and cannot be located too close to the first wall. Establishing a precise location is fraught with difficulty. Confidence in the transport calculations can be gained by using activation materials offering a range of threshold energies.

As a learning exercise at TFTR, a foil placed in an irradiation end was activated using an in-situ neutron source. Agreement between predicted and measured activities was obtained to about ± 20% accuracy, the limitation being the low strength of the source. On ITER, even with the planned source strength of 10^{10} neutrons/s, it is not clear that this direct in-situ approach would be possible due to the low of sensitivity of foils, even those with high cross-sections such as copper. Alternatively, a small well-characterized scintillator/photomultiplier tube could be placed in the irradiation end during the calibration period. This might even have the sensitivity to provide a full line-of-sight calibration of the irradiation end as a well-characterized generator is moved through a full transit around the vessel, thus providing a meaningful benchmark for the neutronics codes.

A variant of the activation technique would be to replace the pneumatic transport of small solid samples by the use of a fluid flow loop, where the active material is either the fluid itself or dispersed within it. This type of activation system has been used in fission reactor applications but has not yet been employed at a fusion device. It may have advantages for ITER and should be elaborated further. The calibration of such a system would be performed in a manner comparable to that for the pneumatic transfer system.

Instead of measuring the induced activation in a flowing fluid, it would be feasible simply to measure the temperature rise of the fluid due to nuclear heating between entry and exit from the machine as this should be related linearly to the fusion power production. However, it would be necessary for the pipework to be thermally insulated from the machine components, otherwise the calculation of temperature rise would have to include a consideration of the effects of all cooling systems, cryogenic as well as main coolant flows. Also, the full calculation would involve a careful assessment of deep penetration of neutrons and gamma-rays to *all* regions crossed by the pipework. To provide an accurate independent calibration this measuring system would be very difficult and the temporal response would be very poor. It has recently been suggested[24] that the temperature rise in the main coolant could also be used as a measure of the fusion power production. The task of providing an independent absolute calibration would be daunting indeed, due to the need to compute the nuclear heating in all machine components traversed by the pipework (no longer thermally insulated). The accuracy of such a calibration could never be competitive with that provided by activation techniques using high threshold reactions.

4.2.3 Profile monitors

A diagnostic comprising a pair of properly designed neutron profile monitors offering orthogonal full coverage views across the ITER plasma would provide a wealth of important information concerning plasma performance. The degree of compromise needed to achieve a practicable solution will be discussed elsewhere. We address here only the issue of providing an absolute calibration for the detectors. There are two alternative approaches that can be followed, although perhaps both should be pursued:

(i) In-situ calibration of cameras with generators:

The disadvantages of using neutron generators inside a tokamak were considered above, although for calibrating the profile monitor some of the constraints may be relaxed. Specifically, the neutron generator does not have to be exceptionally strong since the detectors view mostly uncollided neutrons and the angular emission is not an issue provided the foil for the activation calibration is placed at the same orientation as the collimated sight-line. This approach was used successfully at TFTR[25].

(ii) Calibration of the profile monitor from first principles:

As explained earlier, the practice at JET is to determine the detector using a first principles approach. The detectors are characterized at an accelerator laboratory, which actually means determining their light responses as a function of energy of incident monoenergetic neutrons. (Light response functions are available in the literature but are specific to the type of detector and, we suspect, production batch). A series of neutron transport calculations are then performed to determine the effective solid angles of the collimators, any attenuation and in-scattering effects and, separately, the neutron back-scattering from the vacuum vessel wall that intercepts the lines-of-sight.

The main problem with the JET D-D neutron detectors has always been the need to discriminate gamma-rays from neutrons, an essential requirement since the lines-of-sight unavoidably intercept the vacuum vessel walls and supporting structures. This is achieved through pulse-shape analysis, a conventional but inconvenient procedure. The pulse-shape discrimination electronics need careful setting up and are not very stable. Accordingly, gamma-ray spectra from in-built sources are acquired between discharges for monitoring purposes. This is not sufficient, however, and a new system is currently being assembled that will permit Am-Be neutron sources to be moved into position behind each detector in turn, also between discharges. For D-T measurements, on the other hand, it is possible to reduce the detection of gamma-rays to a negligible level by good detector design. Nevertheless, determining the neutron energy discrimination level remains a problem. Accordingly, it is strongly recommended for ITER that a set of small (switchable) 2.5 and 14-MeV neutron generators be installed behind each detector for between-discharge monitoring.

5. CONCLUSIONS

In order to fulfill the parameter ranges, target measurements resolutions and accuracies as laid down by ITER[26], particular attention has to be given to calibrating the neutron diagnostics. This could be the largest source of error in the total fusion power and power density measurements. Previous experience from present-day large tokamaks dictates that several different methods should be used. The use of a neutron generator for direct calibration of the total yield monitors and of profile monitor detectors is practical only before start-up and on the rare occasion of a major intervention. An activation system for routine calibration checks of the yield monitors is strongly recommended; apart from yielding an independent calibration, it is the only way of proving the linearity and stability of the various systems. In addition, a neutron profile monitor is required for neutron emissivity measurements and this can be calibrated (from first principles, if necessary) and should constitute a second independent calibration method available at all times. Experience with existing large machines indicates that the activation method is more accurate than the first-principles calibration of the profile monitor but the problems anticipated for ITER could result in this situation becoming reversed .

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