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Title: # CALIBRATION ISSUES FOR NEUTRON DIAGNOSTICS

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OVERVIEW OF FUSION PRODUCT DIAGNOSTICS FOR ITER

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INTRODUCTION

In order for ITER to meet its operational and programmatic goals, it will be necessary to measure a wide range of plasma parameters.[1-3] Some of the required parameters – e.g., neutron yield, fusion power and power density, ion temperature profile in the core plasma, and characteristics of confined and escaping alpha particle populations – are best measured by fusion product diagnostic techniques. To make these measurements, ITER will have dedicated diagnostic systems,[4] including radial and vertical neutron cameras, neutron and gamma-ray spectrometers, internal and external fission chambers, a neutron activation system, and diagnostics for confined and escaping alpha particles. Engineering integration of many of these systems is in progress,[5-11] and other systems are under investigation.

This paper summarizes the present state of design of fusion product diagnostic systems for ITER and discusses expected measurement capability. Details are given in other papers in these proceedings.

MEASUREMENT REQUIREMENTS AND SYSTEMS

An extensive list of plasma parameters required for ITER, together with target measurement accuracies and resolutions, has been presented.[2,3] Measurement specifications for parameters associated with fusion reactions are shown in Table 1. Most of the listed parameters can be measured by fusion product diagnostic techniques, and nine systems based on these techniques are currently included in the ITER EDA Work Breakdown Structure

(WBS) in the fusion product diagnostic group, as shown in Table 2. The table also lists the parameters for which each system can provide measurements and indicates the Home Team primarily responsible for leading the system definition and design activity. For some systems, other Home Teams provide support for the lead party.

Note that there is not a one-to-one correspondence between systems and parameters. This is generally true for all ITER diagnostic systems. For some of the parameters, more than one system is needed to fulfill measurement requirements. In some cases, requirements can not yet be met.

Table 1. Target measurement specifications for parameters related to fusion products.

Parameter	Parameter range	Spatial resolution	Time resolution	Accuracy
1. Total neutron source strength	10^{14}–10^{21} n s^{-1}	integral	1 ms	10%
2. Neutron/a source profile	10^{14}–4¥10^{18} s^{-1} m^{-3}	30 cm	1 ms	10%
3. Fusion power	≤2 GW	integral	1 ms	10%
4. Fusion power density	≤10 MW m^{-3}	30 cm	1 ms	10%
5. Ion temperature profile	0.2–50 keV	30 cm	100 ms	10%
6. n_T/n_D in plasma core	0.1–3	30 cm	100 ms	20%
7. Confined a energy spectrum	0.1–3.5 MeV	30 cm	100 ms	20%
8. Confined a density profile	10^{16}–2¥10^{17} m^{-3}	30 cm	100 ms	20%
9. Escaping a flux (steady state)	≤2 MW m^{-2}	30 cm	100 ms	10%
10. Escaping a flux (transients)	≤20 MW m^{-2}	...	10 ms	30%
11. Neutron fluence on first wall	0–3 MW a m^{-2}	~10 locations	10 s	10%

Table 2. Fusion product diagnostic systems for ITER.

WBS #	Name of system	Parameters[1]	Lead party	Support party
5.5.B.01	Radial Neutron Camera	1,2,3,4,11	EU, JCT	...
5.5.B.02	Vertical Neutron Camera	1,2,3,4,11	US, JCT	...
5.5.B.03	Microfission Chambers[2]	1,3,11	JA	...
5.5.B.04	Neutron Flux Monitors	1,3,11	US	...
5.5.B.05	Radial Neutron Spectrometer	5	EU	RF
5.5.B.07	Gamma-ray Spectrometers	2,8	RF	...
5.5.B.08	Neutron Activation System	1,3,11	US	EU, RF
5.5.B.09	Lost Alpha Detectors[2]	9,10	US	...
5.5.B.10	Knock-on Tail Neutron Spectrometer[2]	7,8	US	...

[1]Parameter numbers refer to item numbers in Table 1.

[2]Requires new concept development.

Most of the fusion product diagnostic systems presently planned for ITER are based upon methods commonly used in contemporary large tokamaks. However, the systems must be tailored to a much more severe nuclear environment than that encountered in present-day experiments. Although central fusion power densities in ITER will be comparable to those observed in high power D-T operation on JET[12] and TFTR,[13] neutron flux on the first wall will be ten times higher, fusion power will be 100 times higher, and the neutron yield per pulse will be more than 10^5 times as large. Design of the fusion product diagnostic systems must not only account for the higher fluxes and fluences but also adjust to constraints imposed by the attendant massive radiation shielding. For example, radiation shielding around the flight tubes for systems which require line-of-sight diagnostic access to the plasma must be sufficient not only to prevent unacceptable heating of the superconducting magnetic field coils but also to limit nuclear activation of other components inside the bioshield. In addition, the aspect ratio of the vacuum vessel port nozzles and their extension ducts to the cryostat boundary will restrict the angular field of view of neutron cameras and spectrometers. This affects the accuracy of the fusion power calibration as well as the achievable resolution of spatial profile measurements. The thick blanket and vacuum vessel also complicate the design of material activation systems and limit the applicability of conventional calibration techniques for neutron source strength monitors. These issues will be addressed below in discussions of individual systems.

NEUTRON CAMERAS

Neutron cameras for ITER are intended to fulfill a number of measurement requirements. In an ideal implementation, at least two fan-shaped arrays of sight lines view the entire plasma, and absolutely calibrated detectors measure the uncollided flux and spectrum of neutrons emitted along those sight lines. Summation of the chordal signals from either array, together with knowledge of the plasma position, gives the global neutron source strength, hence the total fusion power. This provides a secondary standard for calibration of other neutron flux and fusion power monitors. Combining data from all the measurements allows tomographic reconstruction of the spatial distribution of neutron emissivity, $n_D n_T \langle sv \rangle$, which determines the alpha particle source profile and fusion power density and constrains inferred values of fuel concentrations and effective ion temperature. Analysis of high-resolution neutron spectra provides chord-averaged ion temperature profiles in an ignited plasma.

As mentioned above, however, the ITER environment imposes limitations which prevent us from achieving an ideal configuration. In particular, only two arrays can be installed, and neither array can view the entire plasma. The neutron cameras are patterned after systems used on JET[8] and TFTR.[13] The principal challenges in implementing the cameras on ITER are (a) the design of satisfactory interfaces with the blanket, backplate, vacuum vessel, cryostat, and bioshield; (b) the selection of detector/collimator combinations which enable coverage of a very wide range of neutron fluxes with adequate accuracy and energy resolution; and (c) the development of suitable calibration methods.

Interfaces between the neutron cameras and major tokamak components must provide unencumbered diagnostic access to the neutron emitting region of the plasma while preserving the heat load handling capability of the first wall, the radiation shielding properties of the blanket, backplate, vacuum vessel, and bioshield, and the tritium containment characteristics of the vacuum vessel and cryostat. Figure 1 shows an exploded view of the present configuration of the Radial Neutron Camera[9] and illustrates design approaches for resolving interface issues. The arrangement provides three separate collimated flight tubes and detector housings for each poloidal angle, thus offering a variety of choices of collimator/detector combinations. A massive diagnostic shield plug in the vacuum vessel port, with an integrated first wall and shield blanket, surrounds the sight lines and reduces neutron streaming. A re-entrant cryostat door allows the collimator assembly to extend inward from the biological shield while remaining outside the secondary vacuum volume of the nozzle extension. Additional shielding blocks in the secondary containment volume surround the neutron beams emerging from the diagnostic shield plug and prevent unacceptable heating of the superconducting coils and unnecessary nuclear activation of neighboring components.

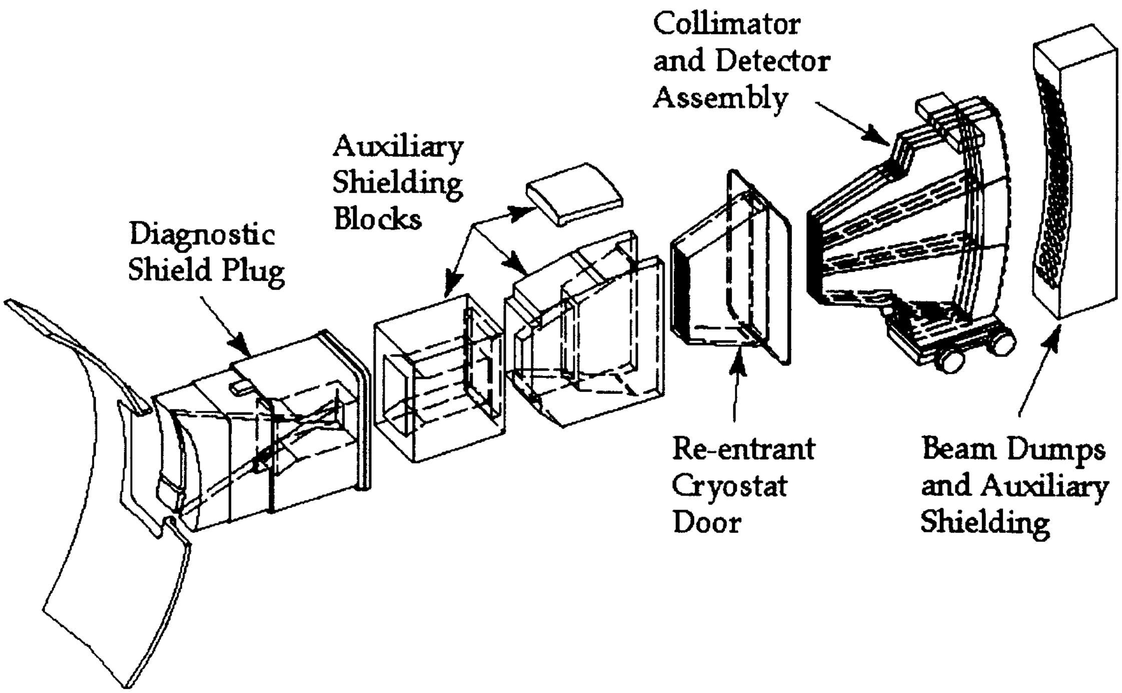

Figure 1. Exploded isometric view of the Radial Neutron Camera.

Design of the Vertical Neutron Camera is particularly challenging because of difficult interfaces with the blanket and backplate at the top port and with the cryostat lid. Unlike the situation at equatorial ports, ITER will not be equipped with large-diameter secondary vacuum extensions between the top port nozzles and the cryostat boundary. Shielding around flight tubes for the vertical camera must be either inside the primary vacuum region of the port or inside the cryostat vacuum. In addition, the width and length of the viewing slot through the blanket and backplate will be restricted, although precise limits have not yet been established, and the design must accommodate relative displacements between the upper port nozzle and the cryostat lid.

Figure 2 shows the present arrangement of the Vertical Neutron Camera. In this configuration, the front collimators are integrated into the design of the vacuum vessel port plug in order to make maximum use of the permissible aperture through the blanket and backplate and to maintain system alignment during thermal and operational excursions of the nozzle position. As a result, the diameters of the front collimators can not be changed after initial installation. In order to span the required range of flux with fixed front collimators, multiple detectors with different sensitivities will sample each sight line, as was the case in the TFTR neutron camera.[13] The detectors and rear collimators are in the space between the cryostat lid and the top bioshield. Additional shielding on the cryostat lid and around the detectors and rear collimators is not shown in the figure. A passive auxiliary shielding assembly encloses the sight lines inside the cryostat between the primary vacuum boundary and the cryostat lid. The height and angular position of this assembly can be adjusted from outside the cryostat vacuum space in order to account for displacement of the upper support structure under vacuum and static weight loads. Except for the support frame, the entire assembly can be installed and removed through a standard port in the cryostat lid.

Figure 3 shows expected line-integral power density profiles for the present designs of both neutron cameras. The profiles were computed from a simple model which approximates the magnetic flux surfaces with concentric ellipses. Two cases are shown, corresponding to a flat emissivity profile and one more peaked on axis. The dashed-line portions of the curves will not be observable because of limitations on the angular fields of view. Clearly, analysis of data from the neutron cameras will be subject to errors arising from the inability to observe the entire emission profiles. Measurements with the vertical camera, extending almost to the outer edge of the plasma, should be useful in constraining the profiles in the unobserved areas. The situation may be further ameliorated by invoking other information (e.g., knowledge of the position of the separatrix), but some errors will persist. The problem will be most severe for detectors which require corrections to the raw data because of their inability to completely distinguish uncollided neutrons from the background of gammas and scattered neutrons. A proper estimate of the expected errors under various operational conditions has not yet been made.

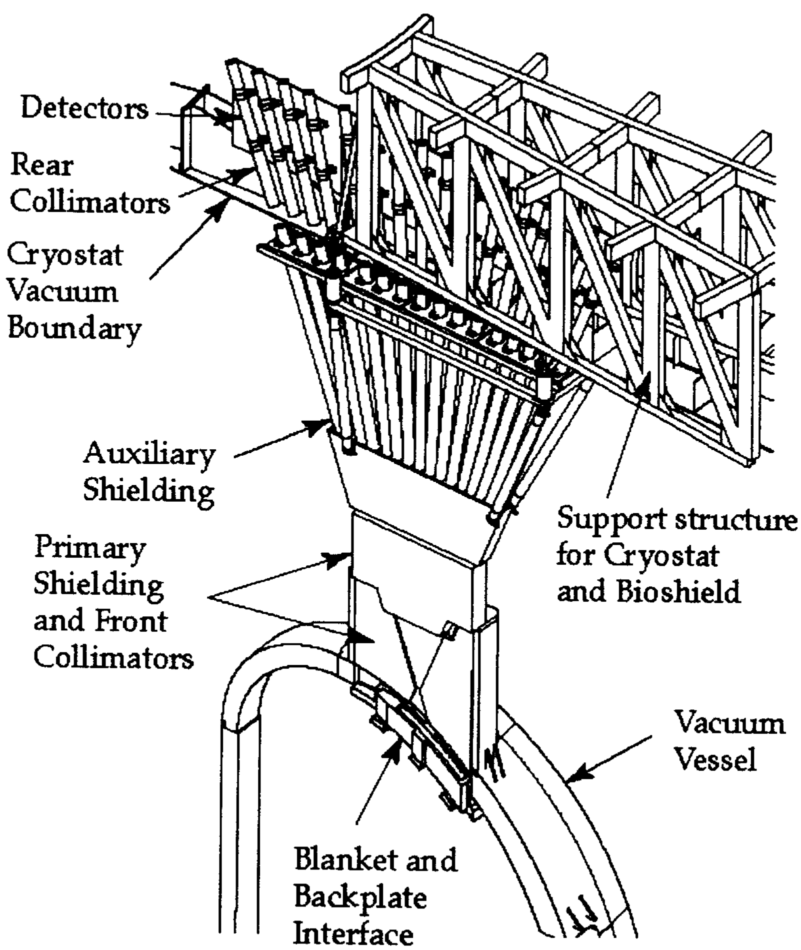

Figure 2. Isometric view of the Vertical Neutron Camera. For clarity, shielding on top of the cryostat lid and surrounding detectors and rear collimators is not shown.

NEUTRON SPECTROMETERS

The Radial Neutron Spectrometer is an adjunct to the Radial Neutron Camera, namely, a set of high resolution neutron spectrometers fitted to some of the camera flight tubes. In order to measure ion temperatures from the Doppler width of the 14.1 MeV emission over a reasonable fraction of the required parameter range, an energy resolution of less than 3% is needed. Among systems which may have sufficient resolution are natural diamond detectors[14] and various types of proton recoil and time-of-flight spectrometers.[15] Some of the spectrometers are quite bulky and not suitable for deployment around ITER except in small numbers. It is therefore not feasible to install enough large, high resolution spectrometers to measure the ion temperature profile with 30 cm spatial resolution. The natural diamond detectors are very compact and may serve as general purpose spectrometers in conjunction with flux detectors in the neutron cameras.

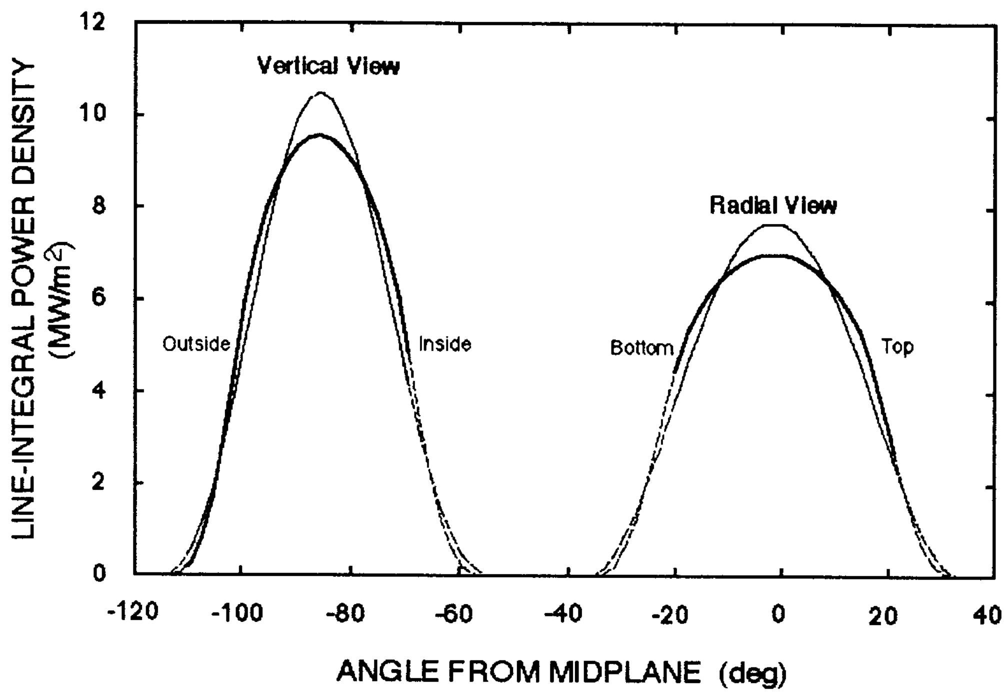

Figure 3. Computed line-integral power density profiles for the Radial Neutron Camera (right) and the Vertical Neutron Camera (left). The thick lines correspond to a flat emissivity profile, and the thin lines represent a profile more peaked on axis. The dashed portions of the profiles will not be observable because of limitations on angular fields of view.

Gamma-ray spectrometers[16] may be installed on some of the flight tubes of the Radial Neutron Camera. The purpose is to detect and analyze high energy gamma rays produced by fusion reactions and by interactions of fast ions with impurities such as Be. In order for the technique to be successful, the spectrometers must be able to distinguish the fusion gammas from a large background of prompt gammas produced in the first wall and blanket. The measurement capability of such spectrometers in the ITER environment is under study.

FISSION DETECTORS

The Neutron Flux Monitor System[5,7] will provide time-resolved measurements of neutron source strength. The proposed system for ITER will consist of a set of conventional ^{235}U fission chambers, similar to those used on JET, JT-60U, and TFTR. Each counter will be housed inside a moderator, to give flat energy response, and will be shielded against gamma rays.

As indicated in Table 1, the system is required to have a dynamic range of seven orders of magnitude with 1 ms time resolution and absolute accuracy of 10%. Since no single detector can satisfy these requirements, counters containing different amounts of fissionable material, and therefore having different sensitivities, will be chosen in order to span the necessary parameter range. The sensitivity may also be varied by locating some detectors near the plasma, e.g., in the pre-shield of the Radial Neutron Camera, while others will be situated in shielded locations outside the vacuum vessel. One complete set of detectors will consist of six fission chambers, with effective sensitivities decreasing in factors of no more than 25 to allow adequate overlap of linear operational ranges. This overlap is essential so that the six detectors of a set may be cross calibrated to one another.[18] In addition, "blank" proportional counters, containing no fissionable material but otherwise identical to the fission chambers, will be used to identify and correct for spurious signals generated by noise, etc. At least two complete sets of detectors will be needed to provide redundancy and protect against single-point failures.

The shielding effects of the blanket and vacuum vessel will make *in situ* calibration of flux monitors more difficult in ITER than in present large tokamaks. An important design goal is to situate the most sensitive detectors such that (a) they are close enough to the plasma so that they may be directly calibrated and (b) they view enough of the plasma volume so that their sensitivity is not strongly dependent on plasma position or shape. The calibration source will be a neutron generator mounted on an articulated arm attached to the standard remote handling transport system inside the vacuum vessel. Therefore, the most sensitive fission chambers and all machine components that affect their detection efficiency must be fully installed before the transporter is removed. Several possible detector locations are under study.[7]

The least sensitive detectors will be designed for operation in count rate mode during ignited D-T conditions. Instrumentation for all the fission chambers will operate in different electronic modes (count, Campbell, current) to extend the dynamic ranges of individual detectors and to allow temporal resolution of 1 ms. Provisions will be made for periodic insertion or permanent installation of standard calibration sources near the fission chambers to verify long term stability of the detectors and electronics.

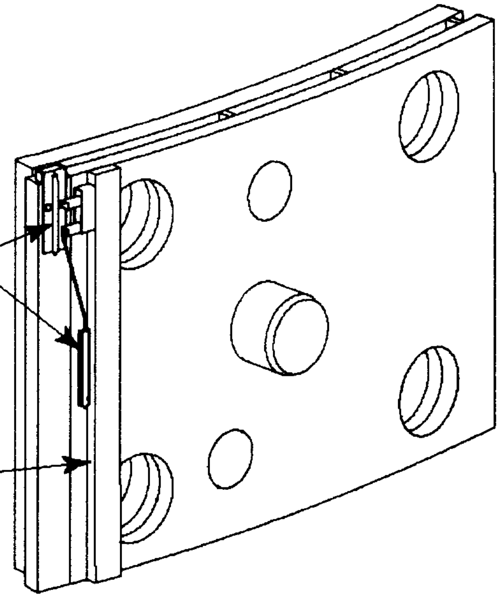

Figure 4. Possible locations of a pair of microfission chambers. The figure shows a portion of the backplate on the inboard side of the plasma. Signal cables are routed through a diagnostic conduit integrated into the backplate.

A set of Microfission Chambers[10] will augment the Neutron Flux Monitor System. These are small fission chambers, similar to those used for flux measurements inside fission power reactors. They will be installed in poloidal arrays at two toroidal locations inside the ITER vacuum vessel. Figure 4 shows possible locations for a pair of detectors on a portion of the backplate on the inboard side of the plasma. One detector is positioned behind a blanket module, and the other is in the gap between adjacent modules. Signal cables for the detectors are routed through diagnostic conduits integrated into the backplate.

Microfission chambers can use either ^{235}U or ^{238}U for the fissionable material, although they will differ in detector sensitivity, spectral response, and burn-up characteristics. The counters appear to be insensitive to gamma radiation and magnetic field effects. Extensive two-dimensional Monte Carlo calculations show that the detection efficiency is only modestly dependent on changes in plasma position and shape, and these profile effects may be further reduced by combining signals from opposite detectors in a poloidal array. The toroidal field of view will be limited for detectors located in the gap between modules, but *in situ* calibration should be possible.

NEUTRON ACTIVATION SYSTEM

A traditional and fundamental technique for determining neutron fluence is the measurement of radioactivity induced in some materials by neutron interactions. If the mean-free-paths of activating neutrons and decay radiation in the material are large compared with the sample size, the process is intrinsically linear and may be applied over a range of many orders of magnitude in neutron flux. Activation cross sections are accurately characterized for a number of materials whose nuclear and physical properties make them suitable for dosimetry. By choosing materials with reactions such as *(n,p)*, *(n,a)*, and *(n,2n)*, which usually require a minimum or threshold energy, thermal neutrons may be rejected and some degree of energy discrimination is possible. The method is insensitive to gamma flux at the sampling station, and decay radiation measuring equipment and analysis software are well developed. The principal problem in applying the technique to the measurement of neutron yield in fusion plasmas is in establishing the relationship between the plasma neutron source strength and the flux and spectrum at the sample irradiation station. This usually requires detailed Monte Carlo neutron transport calculations, and the resulting uncertainties depend critically upon the types and amounts of materials separating the exposed sample from the plasma and on the accuracy of the geometrical modeling of those materials in the vicinity of the sample.

The Neutron Activation System[6,7] for ITER will be similar to those used successfully on JET and TFTR. Encapsulated foils will be transferred pneumatically to an array of irradiation stations, deployed poloidally at two toroidal locations. After irradiation for about 100 s, the samples will be retrieved to remote counting stations, where gamma rays from the induced radioactivity will be measured.

Because of the high neutron and heat fluxes on the first wall and the long pulse lengths expected in ITER, special care will be required in the design of irradiation stations and re-entrant transfer tubes and in the handling of the extremely radioactive exposed samples. The samples should have wide-angle views of the neutron emitting region of the plasma with as little intervening material as possible, but the irradiation stations and foil capsules must be protected from excessive nuclear heating, and there can be no sharp bends in the transfer tubes. It does not appear to be feasible to embed the irradiation stations in the removable blanket modules. The present design approach is to locate irradiation stations in some of the permanent filler modules and view the plasma through the natural gaps between neighboring removable blanket modules. Routing of transfer tubes will make use of standard diagnostic conduits in the blanket backplate. Uncertainties in measurements of neutron yield arising from transport calculations can not be evaluated until the irradiation stations are designed in detail, but it is unlikely that the activation system for ITER can achieve the degree of accuracy demonstrated on JET and TFTR because of the less favorable local geometry.

CALIBRATION OF NEUTRON SYSTEMS

Calibration methods for neutron systems on ITER will be similar to those used on JET[17] and TFTR.[18] A variety of techniques will be utilized, including *in situ* calibration of flux monitors and neutron cameras with a neutron generator, activation measurements coupled with neutron transport calculations, and laboratory calibration of individual detectors. As discussed above, the thick blanket and vacuum vessel will impose limitations on some of the traditional methods. A comprehensive calibration program, which uses the advantages of some of the techniques to offset the limitations of others, is under development.[19]

ALPHA PARTICLES

A consideration of alpha particle physics issues in ITER indicates the need for measurements of alpha heat losses, alpha instabilities, confined alphas, and lost alphas and suggests measurement requirements and possible techniques.[20] The alpha birth profile should be well characterized by the neutron diagnostic systems. Under the assumption of classical confinement, this and other basic plasma parameters may be used to calculate the alpha heating profile, the confined alpha density and energy spectrum, and losses to the walls. Alpha heat losses and instabilities manifest themselves indirectly by giving rise to local hot spots on the first wall, observable with infrared cameras and thermocouples, and to plasma fluctuations, observable by magnetic loops, reflectometry, etc. A new detector using thin foil Faraday collectors to measure escaping alphas is being tested on JET[21] and may be suitable for installation on ITER. The direct measurement of confined alphas would be of great interest, but the present status of confined alpha diagnostics only allows a discussion of possible candidates and requires further R&D. Among the candidate techniques for monitoring the steady state alpha population are measurements of neutron and triton knock-on tails.[22] Measurements of the redistribution of alphas due to MHD events might be performed in the range r/a>0.4 - 0.5 through the use of neutral particle analyzers (NPA) with a helium diagnostic beam (200-400 keV, ~3 MW)[23] or by means of Pellet Charge Exchange (PCX),[24] but such systems are not presently planned for ITER.

CONCLUSIONS

The fusion product diagnostic systems required for the ITER device have been identified, and the principal characteristics of most of them have been established. Engineering of a number of the systems is well advanced, and solutions to many of the integration problems have been found. It appears that target measurement requirements for fusion power and emission profile can be met. The ion temperature profile can be measured, but it will be difficult to satisfy requirements on spatial resolution and parameter range. Methods for measuring properties of confined alpha particles are under study, but no technique is yet available that can satisfy requirements.

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