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Fusion Power Measurement Using a Combined Neutron Spectrometer – Camera System at ITER

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ABSTRACT.

A central task for fusion plasma diagnostics is to measure the 2.5 and 14MeV neutron emission rate in order to determine the fusion power. A new method for determining the neutron yield has been developed at JET. It makes use of the magnetic proton recoil neutron spectrometer and a neutron camera and provides the neutron yield with small systematic errors. At ITER a similar system could operate if a high-resolution, high-performance neutron spectrometer similar to the MPR was installed. In this paper, we present how such system could be implemented and how well it would perform under different assumption of plasma scenarios and diagnostic capabilities. It is found that the systematic uncertainty for using such a system as an absolute calibration reference is as low as 3% and hence it would be an excellent candidate for the calibration of neutron monitors such as fission chambers. It is also shown that the system could provide a 1ms time resolved estimation of the neutron rate with a total uncertainty of 5%.

1. INTRODUCTION

The ultimate goal of fusion research is to produce fusion power and hence its determination will be an essential requirement at ITER. By separately measuring the 2.5 and 14MeV neutron yield (*Y*) and neutron rate (*R*) at ITER the fusion energy and power can be determined. The fusion power measurement requirement for ITER is set to 10% accuracy with 1 ms time resolution [1]. At JET a system consisting of a Magnetic Proton Recoil (MPR) High Resolution Neutron Spectrometer (HRNS) and a neutron camera has been used to measure the 14MeV neutron yield independent of other neutron diagnostics [2] and this paper describes how a similar system could be used at ITER. The paper will concentrate on the ability to measure *Y* and the magnitudes of the systematic relative uncertainties that are associated to such measurements. The measured *Y* provides an absolute calibration for time resolved diagnostics such as fission chambers. The paper also investigates the accuracy of which *R* can be determined directly with the spectrometer-camera-system.

2. METHOD

In order to measure *Y* the spectrometer's neutron flux *F* has to be determined and its relation (*p*) to *Y* has to be known. This is described in detail in Ref. [2], and simplified in Equation 1.

$$Y = \int_t R\delta t = \int_t F \cdot p^{-1}\ \delta t = \int_t \frac{C}{e} \cdot p^{-1}\ \delta t \qquad (1)$$

where *p* depends on the Neutron Emission Profile (NEP), *C* is the spectrometer count rate, *t* is the integration time and *e* is its efficiency. Besides the terms given in Equation 1, material effects, such as scattering, attenuation and transmission have to be taken into account.

The uncertainties in this paper are relative and divided into systematic (l), random (σ) and total (Δ), where $\Delta = \sqrt{\lambda^2 + \sigma^2}$. The uncertainty of *Y* and *R*, Δ*Y* and Δ*R*, is given by the uncertainty of the parameters in Equation 1 combined with the uncertainties in the material effects. To evaluate these uncertainties two different ITER Lines Of Sight (LOS) have been investigated. One is for the ITER HRNS reference position in equatorial port cell 1 and the other is for a hypothetical tangential LOS. C and e have to be known in order to determine the flux at the spectrometer. As reference an MPR type spectrometer with a 4% resolution setting was used. The systematic uncertainty of the efficiency, λ_e, for the MPR is 2.6 % [2] and similar or better performance is expected for a dedicated ITER spectrometer. DC is dominated by counting statistics, which gives σ_R.

In this work the NEP have a quasi-parabolic shape (see Equation 2) and is assumed to consist of 10 nested elliptical iso-emissivity contours (IECs)[1]. Each IEC has a centre in the poloidal plane and a Neutron Emission (NE).

$$\mathrm{NE}\,(r_n) = \mathrm{NE}_0 \left(1-(r_n)^2\right)^{\alpha}, \quad n = 1...10 \tag{2}$$

where n is the index of the IEC, r_n is the normalized distance to the plasma centre, NE_0 is the peak neutron emission and α is the peaking factor. In this work the radial position of the common centre has been fixed to 6.2m. The height above the mid-plane (Z) of the centre was varied between 0 and 1.2m and the peaking factor was varied between 0 and 10.

The λ_p depends on the NEP and its magnitude is determined by λ_{Z}, λ_{NE} and the uncertainty in the alignment of the LOS, where as σ_p depends on σ_{Z} and σ_{NE}. The propagation of the LOS and plasma position uncertainties was calculated by varying the centre of the NEP and evaluating how p changes with Z. The ITER requirement for the overall uncertainty in the determination of the NE in each IEC is 10% [1]. λ_{NE} has still to be evaluated and is dependent on the characteristics of the ITER neutron camera. For this work three different scenarios have been examined with ΔNE of 2%, 5% and 10%, where Δp was determined for a wide range of NEPs. This was done by reconstructing each IEC using ΔNE as the standard deviation and NE as the mean in a Gaussian random number generator and thereby producing a randomized NEP for which p was evaluated. This was repeated 1000 times with the spread in p giving Δp and hence ΔY.

In order to assess the material effects a MCNP [3] model of ITER and the MPR collimator have been set up to calculate the amount of scattered and transmitted[2] neutrons reaching the spectrometer. The amount of attenuation and scattering in the vacuum window has also been assessed. The model consists of a conical steel collimator with a radius of 17mm at the foil and a radius of 150mm at the first wall and a 5mm vacuum window 5m from the plasma edge. The neutron source in the model has full toroidal and poloidal coverage in order to correctly calculate the scattering contributions. MCNP point detectors (F5 tallies) were used [3].

3. RESULTS

The uncertainty for different parameters varies with changing plasma conditions. Figure 1a shows how ΔY varies as a function of α and ΔNE. The difference between using a radial and a tangential

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[1] *The ITER requirement for the spatial resolution is* a*/10, where* a *is the minor radius.*

[2] *Those neutrons penetrating the collimator*

LOS is also illustrated. Figure 1b shows the *Y* dispersion in Z, $\delta Y/\delta Z$, as a function of Z and α, giving $\Delta Y = \delta Y/\delta Z \cdot \Delta Z$

A well-designed collimator should minimize the scattered and transmitted flux. It was found that a conical collimator where the angle and the size of the cone increase towards the plasma fill these criteria. In addition, the flux at surfaces close to the spectrometer should be minimized in order to reduce the scattered flux at the foil. It was established that scatters in the vacuum window gives a very small contribution (0.05% of the direct flux), due to its distance from the plasma. This number would have to be re-evaluated if a vacuum window was placed close the plasma. Back-scattered neutrons (central column) is the only unavoidable scattering contribution.

A summary of the different contributions to λ_Y can be seen in Table 1 for a plasma (p1) with Z = 0.4, α = 2 and λ_{NE} = 5% and for an extreme plasma (p2) with Z = 0, = 5 and λ_{NE} = 10%.

If the system is used to measure *R* a significant contribution to the total uncertainty comes from σ_C and σ_{NE} [4], which both are time dependent.

DISCUSSION AND CONCLUSION

The results given in Table 1 supports the idea that a HRNS with a broad central LOS combined with a neutron camera can determine *Y* with an accuracy (3.0%) well below the ITER requirements. Consequently, the system could be used as an independent absolute calibration of the ITER neutron monitors. The uncertainty in the reconstructed NEP is an important contribution to λ_Y. Therefore, a research effort to evaluate the systematic uncertainties associated to the ITER camera should be pursued. λ_e is the dominating term for λ_Y and hence the choice of HRNS is very important. Thin foil HRNSs like the MPR have the advantage of *e* mainly depending on the well-known hydrogen cross section, which reduces the uncertainty.

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Contributor	**Magnitude**	**λ_Y (p1)**	**λ_Y (p2)**
Scattered neutrons	0.4%	0.04%	0.04%
Transmitted neutrons	0.25%	0.025%	0.025%
Attenuation (5mm port)	8%	0.4%	0.4%
λ_{NE} (see Fig.1a)	5% / 10 %	1.3%	3.2%
λ_Z (see Fig.1b)	1cm	0.3%	1.2%
LOS alignment uncertainty	0.5cm	0.1%	0.4%
Efficiency	1.44×10^{-5}	2.6%	2.6%
SUM (in quadrature)	–	3.0%	4.3%

Table 1: Parameter sizes and their contribution to $a\lambda_Y$

Time resolution	σ_{NE}	$\sigma_R(\sigma_{NE})$	$\sigma_R(\sigma_C)$	$\lambda_R = \lambda_Y$	$\Delta R = \sqrt{\sigma_R^2(\sigma_{NE})+\sigma_R^2(\sigma_C)+\lambda_R^2}$
1ms	5%	1.3%	3.5%	3.0%	4.8%
10ms	2%	0.5%	1.1%	3.0%	3.2%
100ms	2%	0.5%	0.4%	3.0%	3.1%

Table 2: Parameter sizes and their contribution to ΔR *for a 400MW plasma*

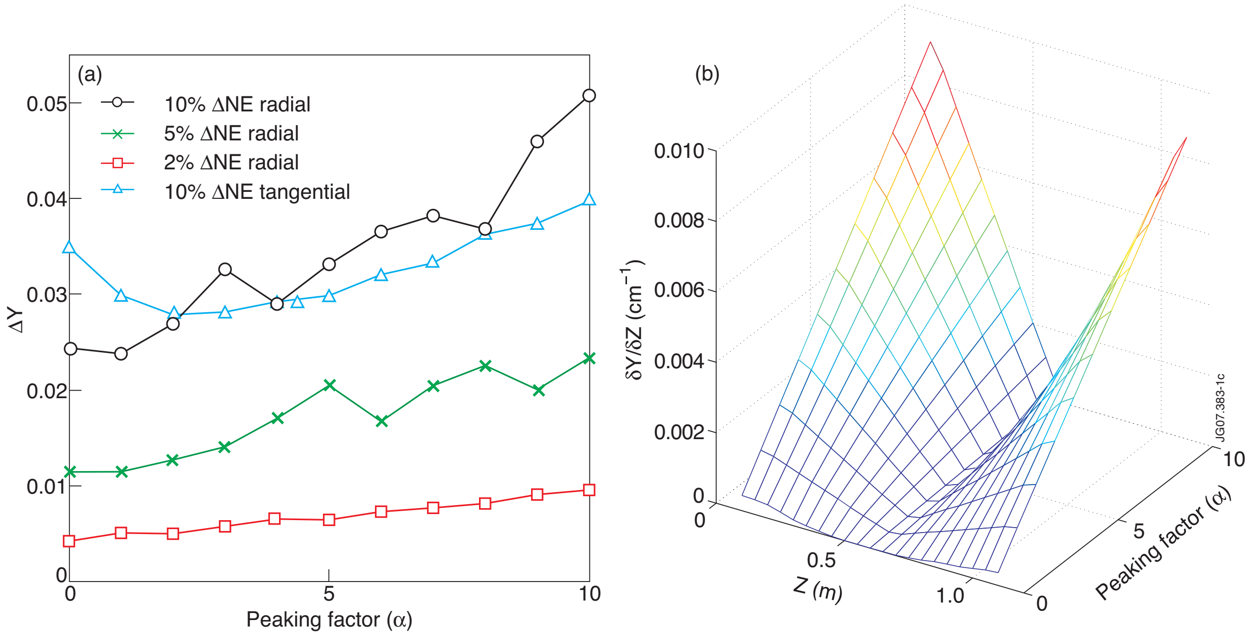

Figure 1: (a) ΔY as a function of α. (b) The $\delta Y_n/\delta Z$ *as a function of Z and α.*