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Measurement of DT and DD neutrons with a TOF spectrometer for determination of fuel ion density ratio in ITER

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Measurement of the fuel ion density ratio, n_D/n_T, is required for burning control in ITER. The measured n_D/n_T ratio must be fed back in real time. A neutron measurement system to measure n_D/n_T should be operable at high counting rate. The estimated number of emitted DT neutrons is 200 times higher than that of DD neutrons under the ITER standard operation conditions. A neutron measurement system was developed using an intense Cockcroft-Walton type DT neutron generator, where DT neutrons are dominant with slight DD neutron contamination in the neutron beam. The measurement instrument was a TOF spectrometer. Signals originating from each neutron must be distinguished to measure the fuel ratio. We have developed a circuit system with discrimination windows to distinguish each signal pulse, and this system was used to measured DT and DD neutrons separately and simultaneously. The experimental results suggested that this system is suitable for measurement of fuel ion density ratio in ITER.

Keywords: fusion, plasma diagnostics, neutron, time of flight spectrometer, fuel ion density ratio, ITER

1. Introduction

The fluctuation of fusion power in ITER is caused mostly by changes in plasma density, ion temperature, and fuel ion density ratio. Measurement of these parameters is necessary for maintenance of suitable operation of ITER and is required for burning control [1]. The fusion reactions assumed in ITER are as follows:

$$\mathrm{D} + \mathrm{T} \rightarrow {}^{4}\mathrm{He} + \mathrm{n}, \tag{1}$$

$$\mathrm{D} + \mathrm{D} \rightarrow {}^{3}\mathrm{He} + \mathrm{n}, \tag{2}$$

$$\mathrm{D} + \mathrm{D} \rightarrow \mathrm{T} + \mathrm{p} \tag{3}$$

where the reaction probabilities of two DD reactions are almost equivalent. The neutron energy of DT reaction is 14.06 MeV and that of DD reaction is 2.45 MeV. The neutron emission ratios are given by the following equations:

$$S_{\mathrm{DT}} = n_{\mathrm{D}} n_{\mathrm{T}} \langle \sigma v \rangle_{\mathrm{DT}}, \tag{4}$$

$$S_{\mathrm{DD}} = \frac{1}{2} n_{\mathrm{D}} n_{\mathrm{D}} \langle \sigma v \rangle_{\mathrm{DD}}, \tag{5}$$

where S_i is neutron emission rate, n_i is ion density, and $<\sigma v>_i$ is Maxwellian reactivity corresponding to each reaction. Maxwellian reactivity depends on ion temperature. The fuel ion density ratio is expressed by these two reactions (4) and (5),

$$\frac{n_D}{n_T} = 2\frac{S_{\mathrm{DD}}}{S_{\mathrm{DT}}}\frac{\langle \sigma v \rangle_{\mathrm{DT}}}{\langle \sigma v \rangle_{\mathrm{DD}}}, \tag{6}$$

and can be estimated if the DT /DD neutron emission ratio and ion temperature are measured. Maxwellian reactivity is shown in the following equations:

$$\langle \sigma v \rangle_{\mathrm{DT}} = 3.68 \times 10^{-18} T_{\mathrm{i}}^{-\frac{2}{3}} \exp\left(-19.84 T_{\mathrm{i}}^{-\frac{1}{3}}\right), \tag{7}$$

$$\langle \sigma v \rangle_{\mathrm{DD}} = 2.33 \times 10^{-20} T_{\mathrm{i}}^{-\frac{2}{3}} \exp\left(-18.76 T_{\mathrm{i}}^{-\frac{1}{3}}\right), \tag{8}$$

where T_i is ion temperature. Partial differential of equation (6) for S_{DD}/S_{DT} and T_i can be expressed by the following equations:

$$\frac{\partial\left(\frac{n_{\mathrm{D}}}{n_{\mathrm{T}}}\right)}{\partial\left(\frac{S_{\mathrm{DD}}}{S_{\mathrm{DT}}}\right)} = 316 \exp\left(-1.08 T_{\mathrm{i}}^{-\frac{1}{3}}\right), \tag{9}$$

$$\frac{\partial\left(\frac{n_{\mathrm{D}}}{n_{\mathrm{T}}}\right)}{\partial T_{\mathrm{i}}} = 114 \frac{S_{\mathrm{DD}}}{S_{\mathrm{DT}}} T_{\mathrm{i}}^{-\frac{4}{3}} \exp\left(-1.08 T_{\mathrm{i}}^{-\frac{1}{3}}\right), \tag{10}$$

The neutron emission ratio has a larger affect on the fuel ion density ratio than ion temperature because $S_{DD}/S_{DT} < 1$ and $T_i > 1$ keV, and neutron emission ratio is

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proportional to the neutron counting ratio. We have proposed a method for measurement of fuel ion density ratio with neutron measurement. The measured n_D/n_T data would be fed back in real time as part of the system for burning control. The requirements of neutron measurement for the fuel ratio measurement are a spatial resolution of $a/10$, where a is the plasma minor radius, time resolution of 100 ms, and accuracy of 20% in the fuel ion density ratio range of 0.1–10 [2]. The requirements for time resolution and accuracy mean a counting rate capability of 250 cps [3]. Under the standard operation in ITER, the fuel ion density ratio (n_D/n_T) is 1.0 and the ion temperature is 20 keV. The estimated number of emitted DT neutrons is 200 times higher than that of DD neutrons. Thus, a counting rate of 250 cps is required for DD neutrons, and the ratio of neutron emission rate (S_{DT}/S_{DD}) is 20–2000 in the range of fuel ion density ratio of 0.1–10. Measurement of fuel ion density can be divided into two parts. The first part is the choice of measurement location for neutrons from plasma. The DD neutron peak in the energy spectra is usually contaminated by the scattered/energy-degraded neutron background originating from DT neutrons [4]. Previous work indicates that the DD neutron peak can be separated from the scattered/energy-degraded background DT neutron s with a suitable collimator system [5]. The other part is the development of a neutron measurement method. The measurement of DD neutrons is not easy because the amount of emitted DT neutrons with energy about 6 times higher than that of DD neutrons is dominant.

2. Experimental setup

A measurement instrument must be located at the appropriate position for measurement in ITER. A double crystal time-of-flight (TOF) spectrometer was chosen as the measurement instrument [5]. The spectrometer provides real-time information, should not be affected by a magnetic field, and should be relatively compact. DT neutrons prevent the accurate measurement of DD neutrons due to accidental coincidence because DT neutron energy is 6 times higher than that of DD neutrons. To resolve this issue, a method of separate measurement of DT and DD neutron energy spectra with a TOF spectrometer is necessary.

A dedicated neutron TOF spectrometer and fast discrimination electronics were developed, and its performance was confirmed with the DT neutron beam at the Japan Atomic Energy Agency Fusion Neutronics Source (FNS) Facility. A schematic representation is shown in Fig. 1. At the facility, the energy of DT neutrons is 14.21 MeV and that of DD neutrons is 2.66 MeV. DT neutrons are dominant and the neutron source shows slight contamination with DD neutrons. The TOF spectrometer used in the experiment is shown in Fig. 2. A scintillator of the first detector (d1) was BC422Q with the luminous decay time of ~0.7 ns and 3×3×0.5 cm thick. That of the second detector (d2) was BC400 of 30×60×t2 cm in size. The incident neutron was well collimated to form a neutron beam. The scattering angle and distance between the first and second detectors were 45° and 120 cm, respectively. The geometrical arrangement of the first and second detectors is based on a TOF sphere [6].

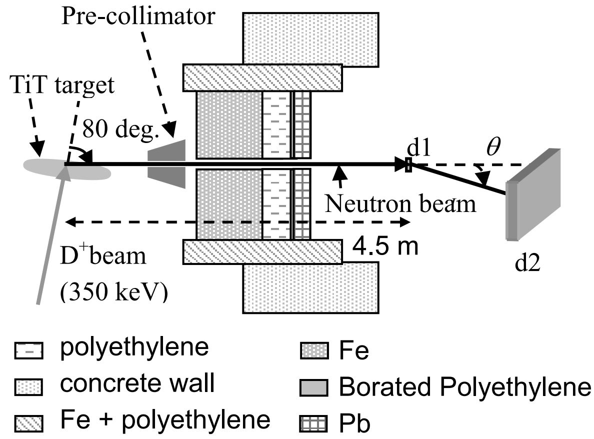


Fig. 1 Schematic drawing of the neutron beam source in the FNS facility. The DT neutron energy is 14.21 MeV and that of DD neutrons is 2.66 MeV. The collimator hole is 2.0 cm in diameter. The distance between the center of the target and the measurement instrument (TOF spectrometer) is 4.5 m.

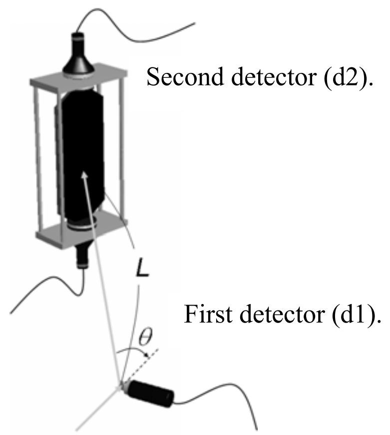


Fig. 2 Concept of the TOF spectrometer. The scattering angle (θ) and distance between the first and second detectors (L) were 45° and 120 cm, respectively. The geometric arrangement of the first and second detectors is based on a TOF sphere.

3. Results and Discussion

Signals originating from each neutron, especially DD neutrons the energy of which is much smaller than that of DT neutrons, were distinguished at an extremely early stage of the circuit without passing the amplifier with the discrimination window. The measurement system is shown in Fig. 3. High pulse-height signals obtained in both d1 and d2 are DT events. Low pulse-height signals obtained in both d1 and d2 are DD events. Thus, DT and DD neutrons were measured separately and simultaneously with one system. A discrimination window (ULD and LLD) was applied in the DD measurement system. Only a low discrimination level was used in the DT measurement system. The discriminator for the low discrimination level in the DT measurement system is the same as that for the high discrimination level in the DD measurement system. Pulse-height signals from d1 and d2 were monitored simultaneously to adjust the discrimination level.

The experimental results are shown in Fig. 4. The yield was obtained by dividing the counts by fluence entering d1. DD neutrons were clearly separated from DT neutrons. In the experiment, the incident DT neutrons were estimated with Nb activation foil. In addition, the incident DD neutrons were estimated with Nb and In activation foils. Incident DT neutron flux was $(3.65 \pm 0.20) \times 10^5$ $cm^{-2}s^{-1}$. Incident DD neutron flux was $(8.37 \pm 3.56) \times 10^3$ $cm^{-2}s^{-1}$. The ratio was 43.6 ± 18.1. The activation of In foil caused by DD neutron is estimated by the activation of Nb and the activation of In because the activation of In is caused by DD and DT neutrons. Therefore, the error margin of DD neutron flux is large. Where, systematic error was assumed 2.0 % and cross section error was assumed 5.0 %.

Incident neutron flux necessary to achieve the required statistic can be determined from the following equation.

$$n = \frac{c}{\phi}, \tag{11}$$

where n is the necessary incident neutron flux, c is the required counting rate of 250 cps, and ϕ is counting efficiency, which is equal to the counting yield defined in Fig. 4. n and ϕ are the necessary incident DD neutron n_{DD} and DD neutron counting efficiency ϕ_{DD}, respectively, because this requirement is for DD neutrons. The necessary incident DD neutron flux is 8.18×10^5 n/cm^2/s because c = 250 cps and $\phi_{DD} = 3.06 \times 10^{-4}$ count cm^2/DD neutron. The flux can be decreased to 9.21×10^4 n/cm^2/s with several d2 detectors located at the same scattering angle and the same distance from d1 as shown in Fig. 5. When the emission neutron ratio (S_{DT}/S_{DD}) is 200 under standard operation in ITER, the necessary incident DT neutron flux is 1.84×10^7 n/cm^2/s. When the emission neutron ratio is 2000 and the fuel ion density ratio is 0.1, the necessary incident DT neutron flux is 1.84×10^8 n/cm^2/s.

However, when the incident DT neutron flux is 1.84×10^8 n/cm^2/s and the first detector is the same in size as used in this experiment, pile-up may occur on it. The pulse width of the scintillation signal from the first detector is 6–10 ns. Thus, the incident neutron rate is less than 10^8/s even when neutrons enter constantly. To resolve this issue, some improvements are necessary. The first is improvement of counting efficiency. In general, counting efficiency becomes high as the length between detectors becomes short. The second is division of the d1. If the first detector is divided into 8 as in the current system, the neutron flux per detector is about 2.3×10^7 n/cm^2/s.

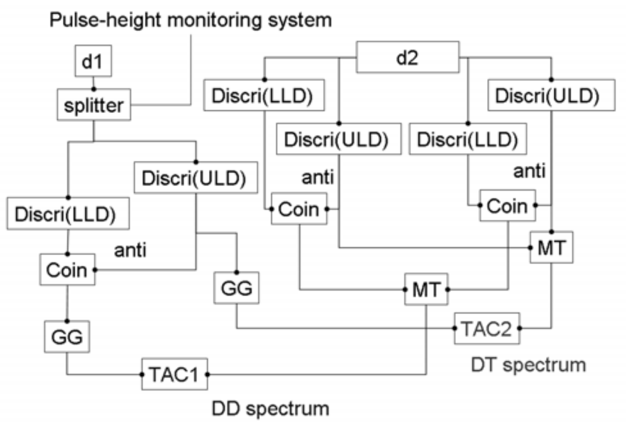
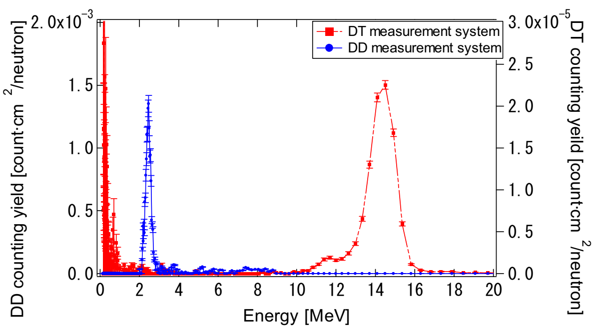


Fig. 3 A diagram of the measurement system. Discri is ELE discriminator, 17K19 (DEGITEX), Coin is 2-FOLD Coincidence, 1250 (OCTAL). GG is Dual Gate Generator, KN1500 (Kaizu Works). MT is Mean Timer, RPN-070 (REPIC). TAC1 is TAC/SCA, 567 (ORTEC). TAC2 is Biased Time to Pulse-height Converter, 457 (ORTEC).



Experimental results. The counting yield was obtained by dividing the counts by fluence entering d1. The DT neutron count yield is 3.49×10^{-5} counts cm^2/DT neutron. The DD neutron count yield is 3.06×10^{-4} counts cm^2/DD neutron. FWHM of the DT neutron peak is 1.54 MeV (10.6%) and that of DD neutron peak is 0.24 (8.95%).

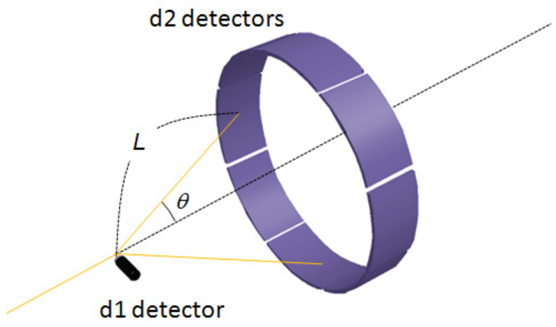


Fig. 5 Maximum counting efficiency setup. The d2 follows the shape of the TOF sphere. When θ is 45° and L is 120 cm, counting efficiency increases by about 9-fold.

4. Summary

The fuel ion density ratio, n_D/n_T, is an important parameter for burning control in ITER. The ratio can be obtained by measurement of the DD/DT neutron emission ratio. For feedback of the measured n_D/n_T ratio data in real time to the system for burning control, a DD counting rate capability of 250 cps is required. To achieve this measurement, the measurement geometry and collimation system should be selected so that the DD peak in the DD energy spectra is not covered with the scattered/energy-degraded neutron originating from DT neutrons.

A double crystal time-of-flight (TOF) spectrometer was chosen as the measurement instrument. A dedicate neutron TOF spectrometer and fast discrimination electronics were developed, and its performance was confirmed with the DT neutron beam at the FNS facility. In this experiment, DT neutrons were dominant with sight contamination by DD neutrons in the neutron source in the facility. The geometrical arrangement of the first and second detectors is based on a TOF sphere. Signals originating from each neutron were distinguished in the extremely early stage of the electronics with the discrimination window. Thus, DT and DD neutrons were measured separately and simultaneously with one system.

The experimental results indicated that DD neutrons were clearly separated from DT neutrons. The counting yield was obtained by dividing the counts by fluence entering the first detector. The DT counting efficiency was 3.49×10^{-5} counts cm^2/DT neutron, and DD neutron counting efficiency was 3.06×10^{-4} counts cm^2/DD neutron. FWHM of the DT neutron peak was 1.54 MeV (10.6%) and that of the DD neutron peak was 0.24 (8.95%).

By using the required counting rate of 250 cps and counting efficiency of this system, the necessary neutron flux can be estimated from the experimental results. This measurement system must be located at a position of at least this flux range in ITER. However, pile-up may occur on the first detector under the maximum incidence neutron flux. The smaller TOF sphere and division of the first detector may solve this problem. Then, the present experimental result indicates that this system may be suitable for measurement of fuel ion density ratio on ITER.

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Reference

[1] ITER physics Expert Groups on Diagnostics, Nucl. Fusion **39**, 2541 (1999).

[2] A. V. Krasilnikov, *et al.*, Nucl. Fusion **45**, 1503-1509 (2005).

[3] K. Okada, *et al.*, AIP Conference Proceedings **988**, 327 (2007)

[4] K. Okada, *et al.*, Proceedings of the 32nd EPS conference on plasma physics, P4.096 (2005)

[5] K. Okada, *et al.*, Rev. Sci. Instrum. **77** 10E726 (2006)

[6] M. Hoek, *et al.*, Fusion Eng. Design **45**, 437-453 (1999).