Novel concept of time-of-flight neutron spectrometer for measurement of the D/T burning ratio in the ITER

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A time-of-flight (TOF) neutron spectrometer is a candidate for the measurement of the D/T burning ratio in the International Thermonuclear Experimental Reactor (ITER). In ITER high-power experiments, the TOF system suffers from a high event rate or accidental counts due to high radiation intensities, which is one of several background sources in DD neutron measurement. We herein propose a new neutron spectrometer to apply to the measurement of the D/T burning ratio in the ITER high-power operation region. This system is based on the conventional double-crystal TOF method and consists of a water cell and several pairs of scintillators. A water cell is inserted before the first scintillator of the TOF system and acts as a radiator or neutron scattering material. Because DD neutrons have a larger cross section of elastic scattering with hydrogen than DT neutrons, the elastic scattering in the radiator enhances the relative ratio of DD/DT intensity by approximately three times before entering the TOF system. The enhancement of the relative intensity of DD neutrons makes the detection of DD neutrons easier. The feasibility of this method as a neutron spectrometer has been verified through a preliminary experiment using a DT neutron beam (20 mm ϕ) at the Fusion Neutronics Source, Japan Atomic Energy Agency. The present article describes the basic performance of the prototype system. © *2006 American Institute of Physics.*
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I. INTRODUCTION

The D/T burning ratio is related to fuel ion density and is derived from the DD/DT neutron intensity ratio, which can be monitored with a neutron spectrometer. Several types of neutron spectrometers have been proposed and developed for ion temperature measurements, including magnetic proton recoil spectrometers,[1,2] proton recoil telescopes,[3] and diamond detectors.[4] The requirements for measuring the ratio of the fuel ion density (n_t/n_d) in the plasma core at the International Thermonuclear Experimental Reactor (ITER) are $a/10$ spatial resolution (a=minor radius of the torus), 100 ms time resolution, and 20% measurement accuracy. The applicability of these neutron spectrometers for measuring the fuel ion density ratio (n_t/n_d) has yet to be confirmed. In addition, other systems, which are especially designed to measure the n_t/n_d, have also been proposed.[5,6] The details of the measurement principles and their feasibilities in fusion reactors have been reported.[7–9]

A time-of-flight (TOF) method with double crystals is a candidate for the measurement of the n_t/n_d in ITER. The main difficulty in the measurement of n_t/n_d with the TOF method is the high background due to the wall emission neutrons from the reactor materials and accidental counts under the intense radiation environment. In ITER experiments, the radiation intensities change as the reactor power increases. In the high reactor power region, the thickness of the first scintillator and/or the aperture of the neutron collimator must be adjusted; otherwise the first scintillator of the TOF system would suffer from a high event rate or accidental counts. The n_t/n_d at the plasma core has been predicted to change from 0.1 to 3, which corresponds to 5%–0.17% of the DD/DT neutron intensity ratio; the typical value is 0.5% assuming that $\langle\sigma v\rangle_{DD}/\langle\sigma v\rangle_{DT}=0.010$. Since the relative intensity of DD neutrons is very small with respect to the rest of the entire spectrum, the accidental counts due to the high event rate of the first scintillator would prevent the detection of DD neutrons. For this purpose, an active detector in the neutron beam is undesirable in this high-power operation region.

We herein propose a new neutron spectrometer to apply to the measurement of the D/T burning ratio in the ITER high-power operation region. This system is based on the conventional double-crystal TOF method and consists of a water cell and several pairs of scintillators. A water cell is inserted before the first scintillator and acts as a radiator or neutron scattering material. The elastic scattering with hydrogen nuclei enhances the DD/DT ratio of the neutrons before entering the TOF measurement system, because DD neutrons have a larger cross section of elastic scattering than DT neutrons. It is expected that enhancement of the relative DD neutron intensity would reduce the counts of no interest

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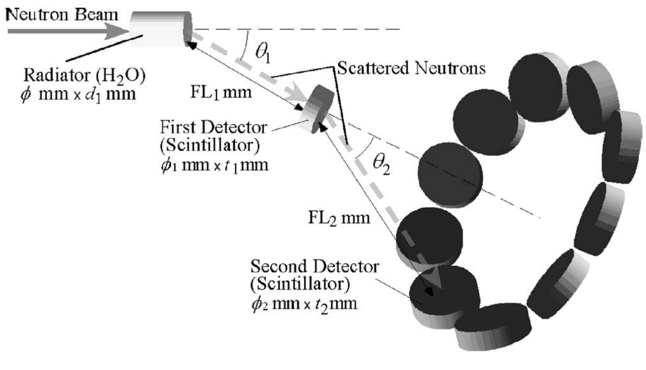

FIG. 1. Schematic diagram of the detector concept.

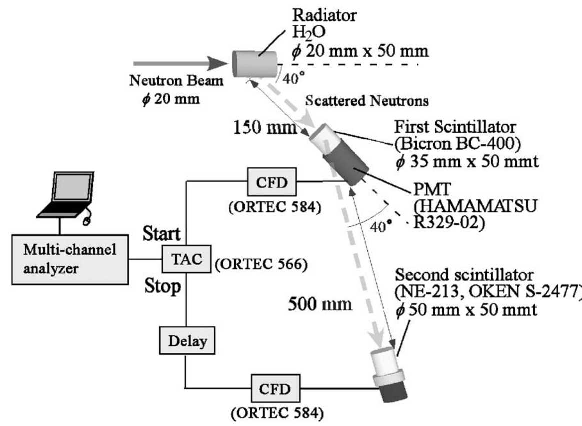

FIG. 3. Experimental setup at the Fusion Neutronics Source, JAEA.

in the first scintillator. We have demonstrated neutron spectrometry with this configuration and have assessed its basic performance through a preliminary experiment using a DT neutron beam.

II. DETECTOR CONCEPT

Figure 1 shows a conceptual diagram of this system. To monitor the neutron energy spectrum and the neutron emission profile in the ITER, a radial neutron camera (RNC) with horizontal views is mounted outside the vacuum vessel of the ITER.[10] The RNC consists of fan-shaped arrays of neutron collimators. The water cell, which acts as a radiator (neutron scattering material), is placed in the line of sight of the aperture of the RNC that views the plasma core. The energy of the neutron scattered in the direction of θ_1 is measured by a double-crystal TOF method using one of the scintillator pairs distributed in a cone shape with the apex angle of θ_2. The energy of the incident neutron is given by the following equation:

$$E_i = \frac{E_s}{\cos^2\theta_1 \cos^2\theta_2},$$

where E_i is the incident neutron energy and E_s is the double-scattered neutron energy.

Water has a macroscopic cross section of hydrogen that is approximately 30% larger than those of typical plastic scintillators, and DD neutrons have a larger cross section of elastic scattering with hydrogen nuclei than DT neutrons. Figure 2 shows the calculated energy spectrum of the scattered neutrons that enter the first scintillator (ϕ 3.5 cm $\times$ 5 cm thick), which is placed 15 cm behind the radiator. The source is a two-component neutron beam having a DD/DT intensity ratio of 0.5%. The elastic scattering with the hydrogen nuclei in the water enhances the DD/DT neutron ratio of the neutrons entering the scintillator pairs by approximately three times. This system has no active detector in the incident beam, and it is possible to simultaneously reduce the incident radiation flux to the scintillator pairs without special collimator preparation. In addition, alleviation of unfavorable accidental counts and irradiation damage of the scintillators is expected.

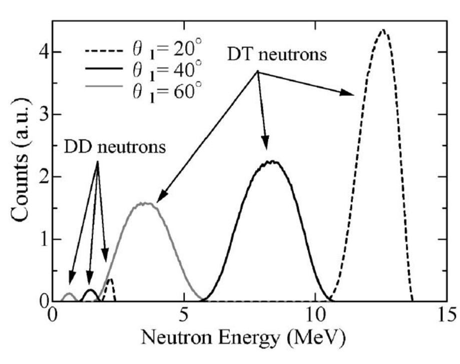

FIG. 2. Calculated energy spectra of neutrons entering the first detector. The energy of the source neutron beam (20 mm ϕ) has two component, Gaussian energy distribution (FWHM of 420 keV for 14.1 MeV and FWHM of 195 keV for 2.45 MeV).

III. PRELIMINARY EXPERIMENT

To experimentally confirm the basic performance of the prototype system, the system has been examined with a DT neutron beam (ϕ 20 mm) at the Fusion Neutronics Source (FNS), Japan Atomic Energy Agency (JAEA).

A. Experimental setup

From the Monte Carlo calculation results shown in Fig. 2, it has been confirmed that the first scattering angles (θ_1) larger than 60° are not appropriate for this purpose, because discrimination of DD/DT neutrons is difficult and the scattering probability in the 60°–90° region is poor. To avoid direct detection of neutron, a scattering angle larger than 30° is preferable. A scattering angle of approximately 30°–50° is appropriate. A similar finding has been reported for the simple double-crystal TOF method.[6,11] An angle of 40° has been chosen for this experiment. Figure 3 shows the experimental setup. A plastic shell is filled with water and placed in the neutron beamline as a radiator. Neutrons, which are elastically scattered in the 40° direction by the hydrogen nuclei in the radiator, enter the first scintillator (ϕ 3.5 cm $\times$ 5 cm thick, Bicron BC 400), which is 15 cm behind the radiator. The first scintillator is optically coupled with the photomultiplier tube (PMT) (Hamamatsu R329-02). The scattered neutrons undergo another elastic scattering inside the first scintillator, again in the 40° direction, and then enter the second scintillator (NE-213 ϕ 5 cm $\times$ 5 cm thick, OKEN S-2477) after a 50 cm flight. A conventional TOF electric circuit has been employed. A time-to-amplitude (TAC) con-

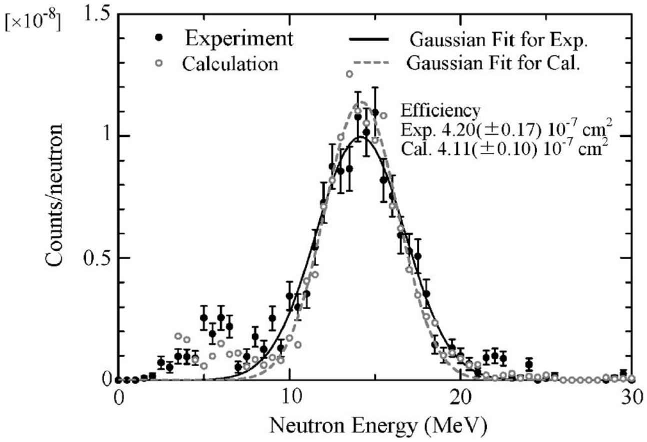

FIG. 4. Measured neutron energy spectrum for the DT neutron beam (20 mm ϕ) with the Monte Carlo calculation results. The neutron behavior due to the elastic scattering with a hydrogen nucleus in the radiator and the scintillators is simulated by the Monte Carlo method. The scattering with carbon is neglected.

verter (ORTEC 566) converts the time interval, or the flight time of the scattered neutron, into the pulse height.

B. Results and discussion

Figure 4 presents the experimental result. The neutron spectrum, in which the DT neutron peak is clearly observed, agrees with the Monte Carlo calculation result. The detection efficiency for DT neutrons of the prototype system is $(4.20\pm0.17)\times10^{-7}$ cm^2, which agrees well with the calculated value of $(4.11\pm0.10)\times10^{-7}$ cm^2, and the measured energy resolution for DT neutrons is 43.1% in full width at half maximum (FWHM), whereas the calculated value is 35.6% (FWHM). The intrinsic time resolution of this system is 2.23 ns, which has been tested with annihilation photons from ^{22}Na. The Monte Carlo calculation has also predicted that the energy resolution for DD neutrons is 21.9% (FWHM), which is better than that of DT neutrons, because the averaged flight time of DD neutrons is 41.9 ns, which is larger than that of DT neutrons (17.3 ns). Thus, this system is expected to discriminate DT and DD neutrons.

The proposed system has been confirmed to be applicable as a neutron spectrometer. In the future, experimental characterization with a DD neutron beam and demonstration of the discrimination of DT and DD neutrons are required. In addition, we will attempt to achieve pulse shape discrimination between neutrons and gamma rays using the NE-213 in order to decrease accidental counts in tokamak devices.

[1] J. Källne *et al.*, Rev. Sci. Instrum. **70**, 1181 (1999).
[2] G. Ericsson, L. Ballabio, S. Conroy, J. Frenje, H. Henriksson, A. Hjalmarsson, J. Källne, and M. Tardocchi, Rev. Sci. Instrum. **72**, 759 (2000).
[3] T. Iguchi, E. Takada, M. Nakazawa, J. Kaneko, T. Nishitani, T. Matoba, and Y. Ikeda, Fusion Eng. Des. **34–35**, 585 (1997).
[4] J. Kaneko, Y. Ikeda, T. Nishitani, and M. Katagiri, Rev. Sci. Instrum. **70**, 1100 (1999).
[5] T. Nishitani, M. Isobe, G. A. Wurden, R. E. Chrien, H. Harano, K. Tobita, and Y. Kusama, Fusion Eng. Des. **34–35**, 563 (1997).
[6] K. Okada, K. Kondo, S. Sato, T. Nishitani, K. Nomura, A. Okamoto, T. Iwasaki, S. Kitajima, and M. Sasao, Rev. Sci. Instrum. (these proceedings).
[7] J. Källne, G. Gorini, and L. Ballabio, Rev. Sci. Instrum. **68**, 581 (1997).
[8] J. Källne, P. Batistoni, and G. Gorini, Rev. Sci. Instrum. **62**, 2871 (1991).
[9] P. Antozzi, G. Gorini, J. Källne, N. Olson, E. Ramstrijm, and M. Campanella, Rev. Sci. Instrum. **66**, 939 (1995).
[10] L. C. Johnson *et al.*, Rev. Sci. Instrum. **70**, 1145 (1999).
[11] M. Hoek, T. Nishitani, H. Takahashi, M. Nakazawa, and T. Elevant, Fusion Eng. Des. **45**, 437 (1999).