Chapter 4

Multi-Scattered Time-of-Flight Neutron Spectrometer for Fuel Ratio Monitoring

This chapter describes a new approach to fuel ratio monitoring in the ITER high-power DT phase. A neutron spectrometer based on a Double Crystal Time-Of-Flight (DC-TOF) method is a candidate for fuel ratio (n_D/n_T) monitoring at the plasma core in International Thermonuclear Experimental Reactor (ITER). A new neutron spectrometer was proposed for monitoring the fuel ratio at the plasma core of ITER. This system is based on a conventional DC-TOF method and composed of a water cell and several pairs of scintillators. The water cell is inserted before the first scintillator of the TOF system and serves as a neutron scattering material. The system characteristics that have been evaluated in the preliminary experiment are presented.

4.1 Neutron spectrometer based on time-of-flight method for the fuel ratio monitoring

As described in Chapter **1**, the fuel ratio (density ratio of deuterium and tritium, n_D/n_T) in the plasma is associated directly with the reaction ratio DD/DT and can be derived from the intensity ratio of DD/DT neutron coming from the plasma. Neutron spectroscopy can provide intensity ratio of DD/DT neutron and is superior to other methods in monitoring of the plasma core. The details of the measuring principles and their feasibilities in fusion reactors were reported in references 1-3. The requirements for the fuel ratio monitoring at the plasma core in the International Thermonuclear Experimental Reactor (ITER) are a/10 spatial resolution (a = minor radius of the torus) and 20% measurement accuracy. These are tabulated in Table 4.1.

A Time-Of-Flight (TOF) neutron spectrometer with double crystals is a candidate for a measurement system of fuel ratio in ITER. As mentioned in section **1.5**, the main difficulty in the fuel ratio monitoring with a neutron spectroscopy is high background due to "Wall Emission" neutrons from reactor materials [1-3]. In the ITER experiments, radiation intensity changes as the reactor power increases. Thicknesses of the scintillator pair and/or the aperture of the neutron collimator for the TOF neutron spectrometer must be adjusted as the reactor power increases, otherwise the first scintillator of the TOF system, which produces the timing signal for measuring time-of-flight, would suffer from accidental counts due to high event rate [4], which can be another background source in neutron spectrum measurement. The fuel ratio at the plasma core has been predicted to change from 0.1 to 3 [5], which corresponds to 0.05% to 1.5% of the DD/DT neutron intensity ratio; the typical value is 0.5% assuming that $\langle \sigma v \rangle_{DD}/\langle \sigma v \rangle_{DT}$ equals to 0.010. Here, $\langle \sigma v \rangle_{DD}$ and $\langle \sigma v \rangle_{DT}$ represent the averaged cross sections of the DD and DT fusion reactions, respectively. Since the relative intensity of the DD neutrons is very small compared to the rest of the entire spectrum, the accidental counts due to the high event rate of the first scintillator will be another difficulty in the detection of the DD neutrons and lead to a poor measurement accuracy. Thus, having an active detector in the neutron beam is undesirable in the high power operation region.

4.2 Multi-scattered time-of-flight neutron spectrometer

A Multi-Scattered Time-Of-Flight (MS-TOF) neutron spectrometer has been proposed to measure the fuel ratio in the high power operation region of the ITER experiment. Figure 4.1 shows the schematic diagram of this system. It is based on a conventional Double Crystal Time-Of-Flight (DC-TOF) method and composed of a radiator and a few tens of scintillator pairs distributed around the first scintillator in the corn shape with the apex angle θ_2. The radiator acts as a neutron scattering material and the energy of neutron scattered by it into the direction of θ_1 is measured by a DC-TOF method using one of the scintillator pairs. The energy of the incident neutron is identified by the following equation.

$$E_i = \frac{E_s}{\cos^2\theta_1 \cos^2\theta_2} \quad , \tag{4.1}$$

where E_i is the incident neutron energy and E_s is the double-scattered neutron energy, which is measured by DC-TOF technique. A larger cross section of elastic scattering for the DD neutron than that of the DT neutron is a necessary characteristic as the radiator in order to enhance the intensity ratio of DD/DT neutron in the scattered neutrons. Since TOF method is basically a coincidence counting, the enhancement of the relative intensity of DD neutron allows its detection easier. This system has no active detector in the incident beam line. It is, therefore, possible to reduce the event rate of the scintillator pairs without preparation of a special collimator and adjustment of a scintillator volume. The accidental counts of the TOF measurement and irradiation damage of the scintillators can be alleviated. For neutron spectroscopy and the neutron emission profile monitor in the ITER, a Radial Neutron Camera (RNC) with horizontal views and vertical views is mounted outside the Vacuum vessel of the ITER machine [6]. The RNC consists of fan-shaped arrays of neutron collimators. The radiator is placed in the center chord, which means the line of sight that views the plasma core.

4.3 Neutron scattering material and enhancement effect on the intensity ratio of DD/DT neutron

A larger cross section of elastic scattering of DD neutron than of DT neutron is required for the radiator. Radiation hardness and relatively high density are also important characteristics for the radiator. Elastic scattering with low-atomic-number materials is useful for this purpose, because neutron behaviors can be easily predicted according to simple kinematics. High-atomic-number materials are not appropriate, because they are likely to generate neutron-induced γ-rays. Hydrogen and helium have larger cross sections of elastic scattering for DD neutron than DT neutron. The candidates for the radiator are general plastic, water, liquid hydrogen and liquid helium as shown in Table 4.2. Radiation damage does not matter for liquid, and water is easier to use than the other liquid materials. Figure 4.2 shows the calculated energy spectra of neutrons that enter the first scintillator after the scattering with hydrogen nuclei in a water cell (2.0 cm$\phi \times$ 2.0 cmt). The first scintillator (3.5 cm$\phi \times$ 5.0 cmt) is placed 15 cm behind the water cell in the direction of θ_1. The incident neutron beam consists of two-component neutrons, DD/DT intensity ratio of which is 0.5%. The elastic scattering with the hydrogen nuclei in the water enhances the DD/DT intensity ratio of the scattered neutrons that enter the scintillator by approximately three times. It is expected that the enhancement of the relative intensity of DD neutron would reduce the counts of no interest in the first scintillator.

4.4 Basic experiment with a DT neutron beam

4.4.1 Experimental setup

The experimental setup is shown in Fig. 4.3. A plastic capsule (2.0 cmϕ × 5.0 cmt) is filled with water and placed in the incident neutron beam line as the radiator. The scattering angles θ_1 and θ_2 have been decided through the Monte Carlo simulation shown in Fig. 4.2. The first scattering angles θ_1 larger than 60 degree are not appropriate for the present purpose, because discrimination of the DD/DT neutrons is difficult and the scattering probability in this region is poor. To avoid direct incident of a neutron into the first scintillator, a scattering angle larger than 30 degree is preferable. A scattering angle of 30-50 degree is appropriate. Similar results of considerations on the scattering probability and the energy resolution were reported for the simple DC-TOF method [7, 8]. Neutrons that are elastically scattered in the 40-degree direction by the hydrogen nuclei in the radiator enter the first scintillator (3.5 cmϕ × 5.0 cmt, BC 400, Bicron), which is placed 15 cm behind the radiator. The first scintillator is optically coupled with the Photo-Multiplier Tube (PMT, R329-02, HAMAMATSU PHOTONICS). The scattered neutrons undergo another elastic scattering inside the first scintillator again in the 40-degree direction, and then enter the second scintillator (NE-213, S-2477, active volume 5.0 cmϕ × 5.0 cmt, OKEN) after a 50-cm flight. A conventional electric circuit for TOF method has been employed. The neutron incident signal in the both detectors are fed to the Time-Amplitude Converter (TAC, ORTEC 566) through the Constant Fraction units (CFD, ORTEC 584) generating standard timing signal. The TAC converts the time interval of the neutron signals from each detector or the flight time of the scattered neutron into a positive electrical pulse. The preliminary experiment with this configuration has been made using a DT neutron beam (2.0 cmϕ) at the Fusion Neutronics Source (FNS), Japan Atomic Energy Agency (JAEA) shown in Fig. 4.4.

4.4.2 Results and discussion

Figure 4.5 presents the experimental result. The DT neutron spectrum has been observed clearly and agrees with the results of Monte Carlo calculation. It has been confirmed that this system is feasible as a neutron spectrometer. The detection efficiency for the DT neutrons of the prototype system is $(4.20 \pm 0.17)\times10^{-7}$ cm^2, which agrees well with the calculated value of $(4.11 \pm 0.10)\times10^{-7}$ cm^2, and the measured energy resolution for DT neutrons is 43.1% in Full Width at Half Maximum (FWHM), whereas the calculated resolution is 35.6%. The intrinsic time resolution of this system is 2.2 ns, which has been tested with annihilation photons from ^{22}Na γ-ray source placed at the middle of the two detectors. A pair of 511 keV photon is emitted in the opposite direction each other from the positron annihilation event, and enters the two detectors simultaneously. The Monte Carlo calculation has also predicted that the energy resolution for DD neutron is 21.9% (FWHM), which is better than that of DT neutrons, because the averaged flight time of DD neutrons 41.9 ns is larger than that of DT neutrons (17.3 ns).

4.5 Experimental demonstration of DD neutron detection

The FNS accelerator irradiates a tritium-storage target with a deuterium beam and generates DT neutrons by DT fusion reactions. At the same time, a fraction of DD neutrons are produced following the DD reactions at the target as well as the DT reactions. The generation ratio of DD neutron around 1% can be predicted for the FNS neutron generator according to the cross section of DD reaction. The DT neutron beam in the FNS facility that involves DD neutrons of around 1% is helpful for a demonstration of DD neutron detection for this system.

An experimental demonstration of DD neutron detection needs a better energy resolution than that of the basic experiment described in the previous section. The prototype system was modified on the sizes of the radiator and both the detectors as well as the flight pass FL_2 according to the Monte Carlo simulations. The experimental setup is described in Fig. 4.6. The first scintillator is a plastic scintillator (BC 408, Bicron), the size of which is 2.5 cmϕ × 2.5 cmt, smaller than the basic experiment, and is placed 15 cm behind the radiator. The scintillation light in the first detector is detected with the PMT (H6612, HAMAMATSU PHOTONICS). The second scintillator is also the plastic scintillator (BC 408, 12 cmϕ × 5.0 cmt, Bicron) coupled with the PMT (H6527, HAMAMATSU PHOTONICS). The flight pass FL_2 has been extended to 150 cm to make the energy resolution better. The intrinsic time resolution is 1.0 ns, which has been improved compared to that of the basic experiment described above.

The measured neutron spectrum is shown in Fig. 4.7 and a DD neutron peak has been observed successfully. The detection efficiencies of the present system with the above-described specification is $(9.56 \pm 0.36) \times 10^{-8}$ cm^2 for DD neutron, $(1.36 \pm 0.04) \times 10^{-8}$ cm^2 for DT neutron. Although the efficiency for DT neutron has been estimated in this experiment, an experimental evaluation of the efficiency for DD neutron is not possible, because there are not any reliable reference data on the intensity of the DD neutrons that are generated accidentally from the accelerator with the tritium-storage target. Therefore the efficiency for the DD neutrons was estimated by the Monte Carlo simulation. The ratio of the peak counts of DD and DT neutron in this experiment is 1 : 7.6±0.6, which corresponds to the original generation rate of DD/DT neutron 1.9±0.2%. This result would be reasonable considering a higher rate of DD reaction than the original specification in this experiment, because the tritium-storage target that has considerably poor tritium retention after its excessively prolonged operation.

4.6 Summary

A new type of neutron spectrometer has been proposed to measure the fuel ratio in the plasma core for the ITER high-power operation region. This system is based on the conventional DC-TOF method and consists of a water cell and a few tens of scintillator pairs. A water cell is inserted before the first scintillator of the TOF system as a radiator or neutron scattering material. Elastic scattering in the radiator enhances the intensity ratio of DD/DT neutron by approximately three times before entering the TOF system. The enhancement of the relative intensity of the DD neutrons reduces accidental counts due to a high DT neutron flux of no interest.

Through the basic experiment using a DT neutron beam from an accelerator neutron source, it has been confirmed that this system can be operated as a neutron spectrometer. The detection efficiency for DT neutrons of the prototype system is $(4.20 \pm 0.17) \times 10^{-7}$ cm^2 and energy resolution for DT neutrons is 43.1% (FWHM).

The DT neutron beam comes with a fraction of DD neutrons due to DD reaction that occurs at the accelerator target accidentally, and can be used for demonstration of DD neutron detection. The experimental demonstration of DD neutron detection has been conducted with the improved system that has a better time resolution than that of the basic experiment. The improved system has the better intrinsic time resolution than the prototype system, which has been realized by having a longer flight distance and a relatively smaller-size water cell. The DD neutron peak has been successfully observed and the count ratio of DD and DT neutron was 1 : 7.6±0.6, which corresponds to the original DD neutron generation rate of 1.9±0.2%. It has been experimentally confirmed that this system is able to detect trace DD neutron in a DT neutron beam.

References

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