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Multi-scattering time-of-flight neutron spectrometer for deuterium to tritium fuel ratio measurement in fusion experimental reactors

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ABSTRACT

A time-of-flight (TOF) neutron spectrometer has potential as a fuel ratio (n_D/n_T) measurement system in the International Thermonuclear Experimental Reactor (ITER). A new neutron spectrometer is proposed to monitor the fuel ratio in the core of the ITER plasma. This system is based on a conventional TOF method and is composed of a water cell and a few tens of scintillator pairs. The water cell is inserted before the first scintillator of the TOF system and serves as a neutron scattering material. A trial experiment demonstrates the feasibility of this system for detecting trace-DD neutrons within a DT neutron beam. The system responses to DT and DD neutrons are also presented.

1. Introduction

The DT burn control in the International Thermonuclear Experimental Reactor (ITER) requires real-time information on the fusion power and fuel ratio (the ratio of deuterium density n_D and tritium density n_T) in the plasma. For instance, fuel ratio monitoring in the plasma core is used to tailor the isotope ratio D/T of the fuel to be injected [1]. Several types of tools have been proposed to monitor the fuel ratio [2–7]. Monitoring of fuel ratio with neutron spectroscopy [8–12] is superior in the plasma core where fusion reactions most frequently occur. The fuel ratio in a burning plasma can be derived from the intensity ratio of DD/DT neutron where detecting trace amounts of DD neutrons that are due to the DT burning plasma is a key issue. Refs. [13–15] have reported feasibility considerations for this kind of measurement. A major concern is the down scattering of the overwhelming amount of DT neutrons inside the ITER machine structure and Radial Neutron Camera (RNC) [16], which is called "Wall Emission". This Wall Emission creates a background signal that prevents DD neutron detection.

Fuel ratio monitoring based on neutron spectroscopy is not yet practically applied to the actual Tokamaks. Although the applicability of the existing neutron spectrometers to monitor the fuel ratio has been discussed, specific techniques or designs for this purpose are not yet presented. A double crystal time-of-flight (DC-TOF) system is a potential neutron spectrometer for this purpose. The DC-TOF system is composed of a pair of scintillators used to measure the flight time of a neutron between them. This simple system can easily distinguish neutron energy without complicated processes such as the spectrum unfolding method, and typically has a higher detection efficiency than other methods based on recoil proton detection. On the other hand, the DC-TOF method where the first detector is placed in the beam line of the incident neutron is disadvantageous under a high radiation flux. In the ITER experiments, the radiation intensity such as neutrons and γ-rays changes as the reactor power increases. In a high reactor power region, the thickness of the first scintillator and/or the aperture of the neutron collimator must be adjusted. Otherwise an accidental count due to high radiation fluxes can be a major background source of the TOF system [17].

The fuel ratio in the plasma core has been predicted to change from 0.1 to 3 [18], which correspond to 0.05% to 1.5% of the DD/DT neutron intensity ratio. Because the relative intensity of the DD neutrons is very small, a typical value is 0.5% compared to the rest of the spectrum, accidental counts due to the high event rate of the first scintillator will be another background source when detecting DD neutrons, which will lead to poor measurement accuracy.

Hence, a new approach for a time-of-flight (TOF) neutron spectrometer to monitor the fuel ratio in a burning plasma core is proposed and discussed. The proposed system has a radiator or neutron scattering material in front of the TOF system. The radiator has a larger cross-section for DD neutrons than for DT neutrons, which enhances the relative intensity of the DD neutron after scattering. The feasibility of this new concept is successfully demonstrated

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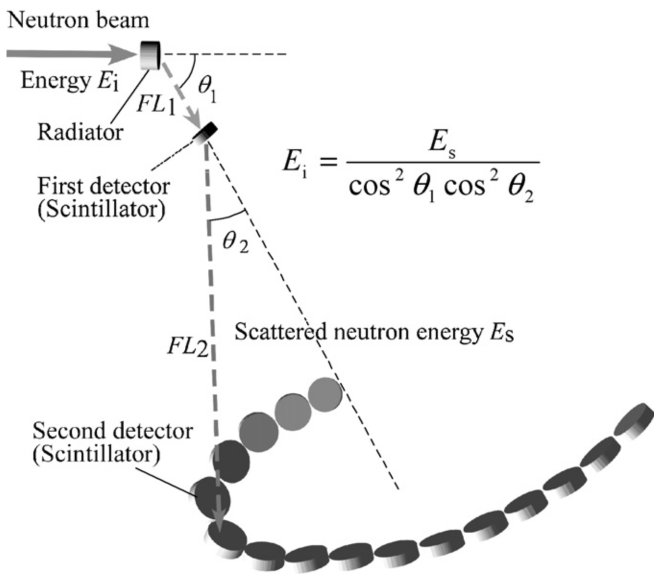

Fig. 1. Basic concept of a multi-scattered time-of-flight neutron spectrometer to monitor the fuel ratio in a DT burning plasma. Time-of-flight of neutrons scattered by the radiator is measured with a circularly distributed scintillator pairs.

with a DT neutron beam [19]. This paper experimentally demonstrates trace-DD neutron detection within a DT neutron beam.

2. System configuration

Fig. 1 shows the basic concept of this system, which is based on a conventional DC-TOF method. The system is composed of a radiator as a neutron scattering material and a few tens of scintillator pairs distributed around the first scintillator in a corn shape with the apex angle θ_2. The radiator is a water cell, hydrogen nuclei in it have about three times-larger cross-sections of elastic scattering for DD neutrons than DT neutrons. If a DT neutron beam including trace amount of DD neutrons enters the water cell and the incident neutrons are elastically scattered with hydrogen nuclei in it, the relative intensity of DD neutrons compared to DT neutrons is enhanced approximately three times before reaching the TOF crystals. Because the TOF method is basically coincidence counting, the enhanced relative intensity of DD neutrons allows them to be detected easier. This system does not have an active detector in the incident beam line. Consequently, it is possible to reduce the event rate of the scintillator pairs without preparing a special collimator and adjusting the scintillator volume. Therefore, the accidental counts of the TOF measurement and irradiation damage of the scintillators can be alleviated.

3. Experimental demonstration of trace-DD neutron detection

An experimental demonstration was conducted using a DT neutron beam (2.0 cm diameter) that included a trace amount of DD neutron at the Fusion Neutronics Source (FNS), Japan Atomic Energy Agency (JAEA). The FNS is an accelerator, which irradiates a tritium-storage target with a deuterium beam to generate DT neutrons by DT fusion reactions, but simultaneously produces a fraction of DD neutrons at the target.

The higher rate of the DD reaction than the original specification was predicted, because the tritium-storage target that was used in this experiment had much poorer tritium retention after an excessively prolonged operation. In other words, a large amount of deuterium ions was self-loaded in the target and the DD reaction rate was much higher than the original specification. Assuming that the self-loaded deuterium ions and the tritium retention were equivalent in this experiment, the cross-section of the DD reaction can predict that generation ratio of DD neutrons is around 1% for a FNS neutron generator in this experiment. It nearly equals to the typical value for burning plasma. The DT neutron beam generated by the FNS neutron generator is helpful to demonstrate trace-DD neutron detection in this system.

Quantitative measurements of DT and DD neutrons require detection efficiencies for both neutrons. Although the efficiency of DT neutrons can be provided by this experiment using a DT neutron beam with known characteristics, the efficiency of DD neutrons was impossible to evaluate because reliable reference data on the intensity of the DD neutrons accidentally generated from a tritium-storage target in the FNS accelerator was unavailable. Therefore, an additional experiment using a DD neutron beam was conducted to experimentally estimate the detection efficiency for DD neutrons.

4. Experimental setup

Fig. 2 describes the experimental setup. Neutrons elastically scattered in the θ_1 direction (40°) by the hydrogen nuclei in the radiator enter the first detector. The first detector is a plastic scintillator (BC 408, 2.5 cm diameter, 2.5 cm thickness, Bicron) placed 15 cm behind the radiator. The scintillation light in the first detector is detected with the PMT (H6612, HAMAMATSU PHOTONICS). Then the scattered neutrons in the 40° direction enter the second scintillator (BC 408, 12 cm diameter, 5.0 cm thickness, Bicron) coupled with the photomultiplier tube (H6527, HAMAMATSU PHOTONICS) after a 150-cm flight. A conventional electric circuit for the TOF method is employed. The neutron incident signal in both detectors are fed into the Time-Amplitude Converter (TAC, ORTEC 566) through the Constant Fraction units (CFD, ORTEC 584), which generates a standard timing signal. The TAC converts the time interval of the neutron signals from each detector into a positive electrical pulse. The intrinsic time resolution of this system is 1.0 ns, which was tested with annihilation photons from a ^{22}Na γ-ray source placed in the middle of the two detectors. A pair of 511 keV photons

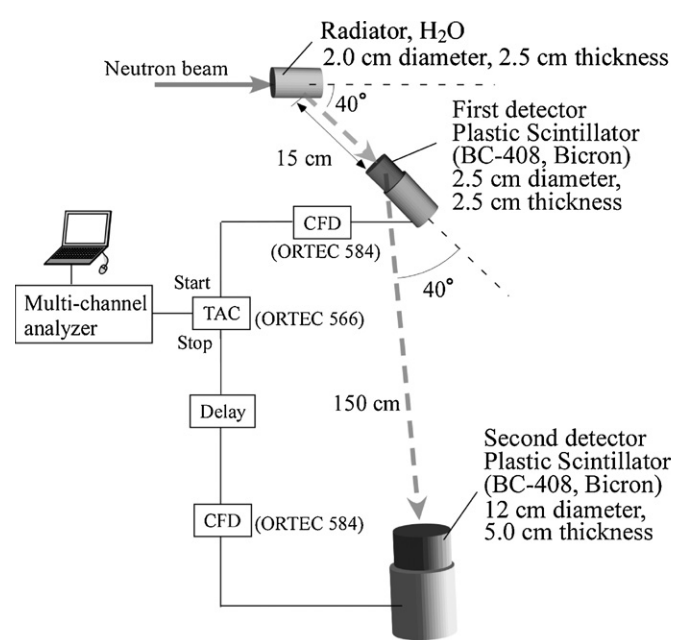

Fig. 2. Experimental setup to demonstrate trace-DD neutron detection.