# Development of 2.5MeV Neutron Spectrometer for Helical Deuterium Plasma Experiment

H. Iwai, T. Iguchi, H. Tomita, J. Kawarabayashi, M. Isobe, and C. Konno

***ABSTRACT*- A neutron spectrometer with associated particles coincident time-of-flight technique is being developed for deuterium plasma experiments in a large helical fusion device. In this experiment, the energy resolution less than 7% and the detection efficiency larger than $10^{-6}$ counts/neutron is required for the plasma diagnostics based on neutron spectrometry. The prototype spectrometer was partly assembled and the detector performance was experimentally checked at Fusion Neutron Source of Japan Atomic Energy Agency. By selecting the events with low energy loss from all coincident events in the radiator, the experimental results showed that the neutron spectrometer could achieve an energy resolution around 6.7% under a detection efficiency of $3.3\times10^{-7}$ counts/neutron for DD neutrons. To improve the detection efficiency, the configuraion of the neutron spectrometer system was designed toward the DD plasma experiment at an existent large helical fusion device.**

## I. Introduction

NUCLEAR fusion reactions in deuterium plasmas mainly consist of the following two reactions.

$$D + D \rightarrow {}^3He(0.8MeV)+n(2.5MeV) \quad 50\,\% \quad ...(1)$$

$$\rightarrow T(1.0MeV)+p(3.0MeV) \quad 50\,\% \quad ...(2)$$

Neutrons around energy of 2.5 MeV (DD neutron) are emitted from a deuterium plasma as a result of the reaction. process (1). It is well known that the neutron energy reflects the ion velocity distribution in high-temperature plasma. In early days of the nuclear fusion research, the neutron spectrometry was proposed as a fuel ion temperature diagnostic through the measurement of Doppler broadening of Maxwellian neutron energy spectrum[1]. It should be noted that the energy distribution of DD neutrons is distorted from Maxwellian distribution in current DD plasama experiments since a target plasma is commonly heated by NBI and/or ion cyclotron resonance heating that produce a substantial amount of suprathermal ions. Therefore, the detailed studies on the neutron spectra can serve as a useful diagnostic tool for dynamics of suprathermal ions. In Joint European Torus, neutron spectrometers, i.e. TOFOR and MPR are employed as a plasma diagnostic tool[2] for suprathermal ion behavior. In Japan, deuterium plasma experiments are now being planned in the world largest heliotron device of National Institute for Fusion Science (NIFS)[3]. In this device, the energy resolution less than 7% and the detection efficiency larger than $10^{-6}$ counts/neutron is required for the plasma diagnostics based on neutron spectrometry. For the measurement of neutron energy spectra in helical deuterium plasmas, we have been developing a neutron spectrometer[4] based on coincident detections of a scattered neutron and a recoiled proton from a thin plastic scintillator as the incident neutron. In this study, we designed and constructed a prototype of the DD neutron spectrometer toward the deuterium experiment planned in NIFS and evaluated the detector response experimentally by using the accelerator DD neutron source at FNS. We have so far obtained a DD neutron spectrum with the energy resolution of 14.7 % in full width at half maximum (FWHM). It is not good enough to discuss about energetic-ion dynamics through the ion velocity distribution measurement. To achieve higher energy resolution, we have proposed a new method which selects only events with low energy loss from all coincident events in the thin plastic scintillator as a radiator [5]. In this paper, we have verified the improvement on the energy resolution by applying the above event selection method to experimental results.

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## II. Detection Principle

Figure 1 shows the schematic diagram of the proposed spectrometer. The spectrometer consists of a thin plastic scintillator as a radiator in which incident neutrons are scattered by hydrogen atoms, a silicon surface barrier detector (Si SBD) for measuring energy deposition of recoiled protons and a plastic scintillator for measuring the time information of scattered neutrons. Energy of recoiled proton $E_{\mathrm{rp}}$ is given by sum of the energy deposition in the thin plastic scintillator (ΔE detector) and in the Si SBD (E detector), which is based on a recoil proton telescope (Eq. 3). On the contrary, energy of scattered neutron $E_{\mathrm{sn}}$ is measured with a time of flight of neutron (Eq. 4) between the radiator and the scattered neutron detector. The energy of the incident neutron $E_{\mathrm{in}}$ is, therefore, derived as follows:

$$E_{\mathrm{rp}} = E_{\mathrm{rad}} + E_{\mathrm{pd}} \qquad \ldots(3)$$

$$E_{\mathrm{sn}} = \frac{1}{2}mv^2 = \frac{1}{2}m\left(\frac{d}{t}\right)^2 \qquad \ldots(4)$$

$$E_{\mathrm{in}} = E_{\mathrm{rp}} + E_{\mathrm{sn}} = (E_{\mathrm{rad}} + E_{\mathrm{pd}}) + E_{\mathrm{sn}} \qquad \ldots(5)$$

where $E_{\mathrm{rad}}$ and $E_{\mathrm{pd}}$ are the energy deposition of the recoiled proton in the radiator and the Si SBD, respectively, $d$ is the distance from the radiator to the scattered neutron detector, $t$ is the flight time of neutron.

Coincident detections of a scattered neutron and a recoiled proton associated with one event of neutron elastic scattering in the radiator enable to measure $E_{\mathrm{in}}$ without the scattered angles (Eq. 5) between associated particles due to geometrical arrangement of the detectors. In addition, the high signal to noise ratio can be obtained because the event due to gamma rays can be removed by coincident counting.

## III. Experiments set up

To measure the detector response of for DD neutron, we partly assembled the prototype neutron spectrometer and experimented at the accelerator DD neutrons at Fusion Neutron Source (FNS), Japan Atomic Energy Agency. Figure 2 shows the experimental setup, and Table 1 summarizes the parameter of the detector configuration and electronic circuit modules. The DD neutron beam in a diameter of 2 cm was incident on the radiator. The distance from the radiator to the scattered neutron detector was set to 30 cm, and the distance from the radiator to the proton detector was 10 cm. Also, $\theta$ was set to 20 degrees which is the angle of the proton detector. We employed a thin plastic scintillator (BC-400 22 × 28 × 0.1 mm) for the radiator, and a plastic scintillator (BC-400 $\phi$12 cm × 5 cm) for the scattered neutron detector and a Si-SBD (ORTEC BR-018-450-500) for the proton detector. For a depositing energy of recoiled proton only to the radiator and the proton detector, the radiator with the photomultiplier tube (HAMAMATSU R7600U) and the Si-SBD were arranged in a stainless-steel vacuum vessel, in which internal pressure was kept under $10^{-4}$ Pa. The flight time information of scattered neutron between the radiator and the scattered neutron detector was converted to a pulse height by a module of Time to Amplitude Converter (TAC). The deposited energy of the recoiled proton corresponds to the pulse heights from the radiator and the proton detector. The pulse heights from the radiator, the proton detector and TAC were recorded with a Multi-parameter multi-channel analyzer (MCA) system.

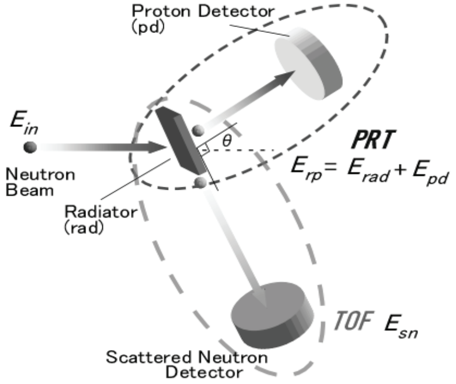

Fig. 1. Schematic diagram of the neutron spectrometer

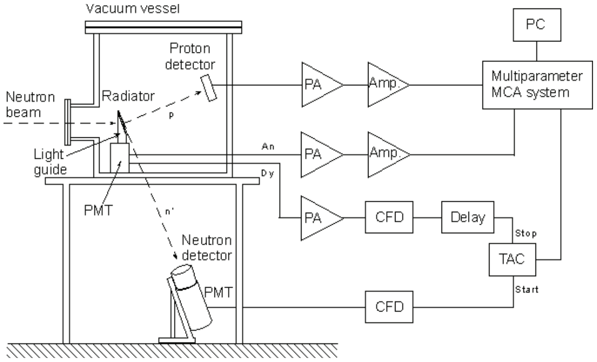

Fig. 2. Experimental setup at FNS.

Table 1 Experimental set-up of detector configuration and electronic circuit modules

| Set-up parameters | |
|---|---|
| Radiator<br>(Plastic scintillator , Bicron BC-400) | 100 μm |
| Proton detector(Si-SBD,<br>ORTEC BR-018-450-1000) | Sensitive area<br>:450 $mm^2$<br>Depletion layer<br>thickness:1000 μm |
| Scattered neutron detector<br>(Plastic scintillator , Bicron BC-408) | ϕ12 cm×5 cm |
| Tilted angle<br>of proton detector ($\theta$) | 20° |
| Tilted angle<br>of scattered neutron detector (90°-$\theta$) | 70° |
| Tilted angle of radiator ($\theta$) | 20° |
| Distance radiator<br>–proton detector | 10 cm |
| Distance radiator<br>– scattered neutron detector | 30 cm |

## IV. Results and Discussion

Figure 3 shows the result of measured neutron energy spectrum. The energy resolution for DD neutron was 14.7% in FWHM and the detection efficiency was estimated to be $1.3\times10^{-6}$ counts/neutron, which showed good agreement with the result predicted by Monte Carlo simulation[6]. But this energy resolution is not good enough to discuss the energetic-ion behavior in DD plasmas through the measured ion velocity distribution. The expected neutron energy with deuterium NBI heating with injection energy of 180 keV in a deuterium plasma planned at NIFS has a spread of about 7% in FWHM. Therefore, the energy resolution less than 7% at least is requiered for meaningful measurement of the ion velocity distribution .

To achieve this energy resolution for DD neutron, the deposited energy in the radiator should be reduced as much as possible because the energy resolution of the plastic scintillator is much poorer than that of the Si-SBD. We therefore calculated thickness of the radiator for achieving the energy resolution less than 7% by Monte Carlo simulation. The calculation results indicated that the radiator thickness should be less than several μm. But it is not easy to fabricate and to collect the scintillation lights from such a thin scintillator.

To avoid this difficulty, we adopted a new method to select only a part of measured data corresponding to low pulse height events from the radiator by setting to an appropriate upper discrimination level. As the result, only events of low pulse height due to recoiled protons generated in the vicinity of the radiator surface are picked up. Therefore, this method restricts the effective thickness of the radiator. At present, we call this method as "Virtual Thin Foil Method (VTFM)". The application of VTFM is effective to improve the energy resolution because $E_{rad}$ measured with poor resolution decreases whereas $E_{pd}$ measured with good resolution increases.

Figure 4 shows the experimental results of deposited energy of recoiled proton in the radiator and the proton detector. The horizontal axis and the vertical axis shows the deposited energy of the radiator ($E_{\mathrm{rad}}$) and the proton detector ($E_{\mathrm{pd}}$), respectively. The energy of the recoiled proton is derived from the sum of the $E_{\mathrm{rad}}$ and $E_{\mathrm{pd}}$.

We applied the VTFM to the experimental results. The discrimination level to $E_{\mathrm{rad}}$ was set to 1.0 MeV, 0.5 MeV, and 0.25 MeV, respectively. The dependence of the energy resolution and the detection efficiency on each discrimination level is shown in Table 2. By setting the

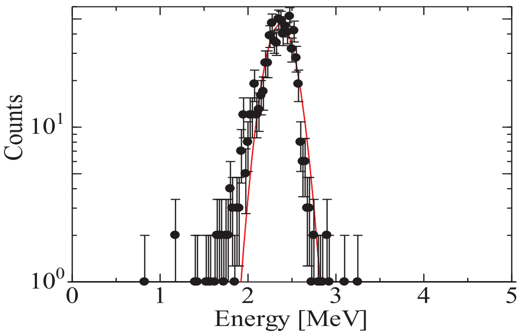

Fig. 3. Measured DD Neutron Spectrum

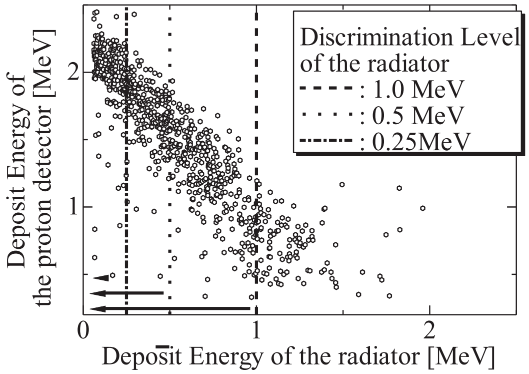

Fig. 4. Correlation of energy deposition between the radiator and Si-SBD

upper discrimination level of the deposited energy of radiator to 0.25 MeV, we obtained the energy resolution of 6.3% for DD neutron and the detection efficiency of $3.3\times10^{-7}$ counts/neutron. It is found that setting the upper discrimination level to 0.25 MeV is equivalent to thinning the thickness of the radiator about 25 μm. The improvement of the energy resolution was confirmed by changing the discrimination level, and the effectiveness of VTFM was confirmed experimentally by these results.

Table 2. Dependence of the energy resolution and detection efficiency on the discrimination level of VTFM

| Discrimination Level [MeV]* | Energy Resolution [%] | Detection Efficiency [Counts/Neutron] |
|---|---|---|
| 0.0 | 14.7 | $(1.3\pm0.1)\times10^{-6}$ |
| 1.0 | 12.9 | $(1.2\pm0.1)\times10^{-6}$ |
| 0.5 | 8.9 | $(6.7\pm0.3)\times10^{-7}$ |
| 0.25 | 6.3 | $(3.3\pm0.2)\times10^{-7}$ |

*Discrimination level of the pulse height energy of the radiator scintillator

To compensate the decrease of this detection efficiency, we have designed eight pairs of the scattered neutron detector and the proton detector centering on the beam axis as shown in Figure 5. Therefore, the detection efficiency is improved to 8 times that of one system, that is, up to $2.6\times10^{-6}$ counts/neutron under keeping the energy resolution of 6.3 %. If the radiator diameter is doubled, the detection efficiency will become about $\sim10^{-5}$ counts/ neutron.

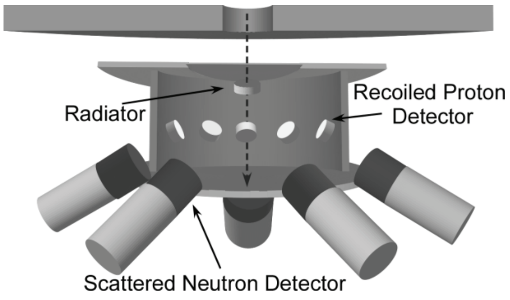

Fig. 5. Schematic drawing of DD neutron spectrometer system proposed for an existent large helical fusion device
(The detector pair is five in figure for simplification)

## V. Conclusion

We have developed a prototype of the proposed DD neutron spectrometer and measured the detector response to monoenergetic DD neutron at the FNS. The energy resolution of 6.3% for DD neutron and the detection efficiency of $3.3\times10^{-7}$ counts/neutron was demonstrated by selecting the events with the radiator deposit energy of less than 0.25 MeV. This system performance corresponds to the events occurred within 25 μm from the surface of the radiator. To compensate the decrease of this detection efficiency, we propose the neutron spectrometer system, and estimates that the detection efficiecny of this spectrometer improves to $\sim10^{-5}$ counts/neutron.

For the measurements of DD neutron in large magnetically confined fusion plasmas, an event rate in the radiator should be reduced because of high flux of neutrons and gamma-rays along the beam axis. Efforts will be made to optimize further the design of the neutron spectrometer system toward the deuterium plasma experiment planned in NIFS.

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