Design consideration for high-energy-resolution neutron spectrometer based on associated particle detection using proton recoil telescope and time-of-flight technique for ITER

N. Naoi,[a] K. Asai, T. Iguchi, K. Watanabe, and J. Kawarabayashi
Quantum Engineering, Nagoya University, Furo-chou, Chikusa-ku, Nagoya, Aichi 464-8603, Japan

T. Nishitani
Japan Atomic Energy Agency, Tokai-mura, Naka, Ibaraki 319-1195, Japan

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For ion temperature measurement in the ITER high power operation phase, we propose a promising high-energy-resolution neutron spectrometer based on the associated particle detection using a proton recoil telescope and a time-of-flight spectrometer. To verify the operational principle and the basic performance of this system, we have set up a prototype system through Monte Carlo simulations and carried out a preliminary experiment with a deuterium-tritium (DT) neutron beam at the Fusion Neutronics Source, JAEA. The results have demonstrated that the energy resolution could be achieved around 3.3% (in full width at half maximum) for DT neutrons. In addition, the design consideration of this system for an application to ITER is given on the detection efficiency, the applicable range in the ITER operation, and the detector lifetime. © *2006 American Institute of Physics.* [DOI: 10.1063/1.2221691]

I. INTRODUCTION

The high-energy-resolution neutron spectrometry is a useful method to obtain the ion temperature and velocity distribution in nuclear fusion and/or burn plasmas. The required performances of the neutron spectrometer for ion temperature measurement in the International Thermonuclear Experimental Reactor (ITER) are a measurement accuracy of 10% and a time resolution of 100 ms, which mean that an energy resolution of 3%–5% and a detection efficiency of $\sim 10^{-5}$ cm^2 for deuterium-tritium (DT) neutron are required in the high power operation of the DT phase. Although candidates for a neutron spectrometer are organic scintillators,[1,2] diamond detectors,[3,4] and Si detectors,[5] the energy resolutions of them deteriorate due to the pulse pileup at a high count rate (above 300 kHz). It is, therefore, difficult to apply the candidates above to the high power operation phase of ITER. To overcome this difficulty, we have been making design study on a promising concept of high-energy-resolution neutron spectrometry tolerable under the ITER high power DT operation phase, based on the associated particle detection using a proton recoil telescope (PRT) and a time-of-flight (TOF) spectrometer. In this article, we demonstrate the basic performance of this system through the preliminary experiments and the model calculations, including the design consideration to apply this system to ITER.

II. DETECTOR CONCEPT

Figure 1 schematically shows the present neutron spectrometer concept. We assume that this system will be installed on an aperture of a radial neutron camera (RNC) with a 35 mm diameter in the ITER. The spectrometer principle is based on integrating a PRT and a TOF spectrometer and consists of the radiator, which is placed on the aperture axis of the RNC, and the ring-shaped array of proton detectors (PDs) and scattered neutron detectors (SNDs). The radiator plays three roles: the proton emitter, the ΔE detector in the PRT system, and the trigger detector for the TOF measurement of the scattered neutrons. For application in a high radiation flux field, the radiator is divided into multichannel cells to suppress the event rate of each cell. The photons generated from each cell are supplied to a multianode photomultiplier tube (MAPMT), and the signals from each anode of the MAPMT are individually processed. The energy of the recoil protons E_{rp} is measured with the radiator as ΔE detector and a PD as E detector in the PRT, while the energy of the scattered neutrons E_{sn} is obtained from the flight time between the radiator and the SND. The PD and the SND are intersected at an angle of 90° ($=\theta+\phi$) in the geometrical arrangement because the incident neutrons are scattered in the direction of 90° from the direction in which the associated particles, or protons, are recoiled due to kinematics. The energy of the incident neutron E_{in} is, therefore, derived by the sum of the energies of the associated particles as follows:

$$E_{\mathrm{in}} = E_{\mathrm{rp}} + E_{\mathrm{sn}} = E_{\mathrm{rad}} + E_{\mathrm{pd}} + E_{\mathrm{sn}}, \tag{1}$$

where E_{rad} and E_{rp} are the energy deposition of the recoiled proton in the radiator and the PD, respectively. In a general PRT or TOF spectrometer, uncertainty of incident angles of recoiled protons or scattered neutrons incoming to PD or SND, respectively, is a cause of deterioration of their energy resolution. In this system, no angular information is required

[a]Author to whom correspondence should be addressed; FAX: +81-52-789-5127; electronic mail: naoi@avocet.nucl.nagoya-u.ac.jp

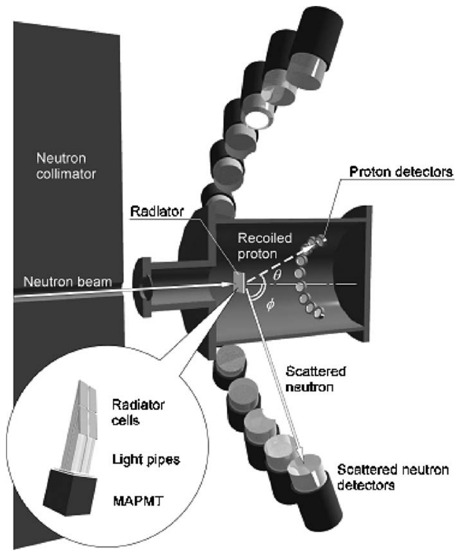

FIG. 1. The detector concept.

to obtain the incident neutron energy. It is possible to enlarge the solid angles of the PDs and the SNDs subtended by the radiator to increase the detection efficiency without deterioration of the energy resolution. In addition, a comparatively thick radiator can be employed for further improvement of the detection efficiency, because this system compensates for E_{rad}. The expected detection efficiency of this system is about one order higher compared to TANSY,[6] which is similar to this system in structure, securing the required energy resolution.

III. EXPERIMENTAL SETUP

To experimentally verify the operational principle and the basic performance, we made a prototype system and carried out a preliminary experiment with a DT neutron beam (ϕ20 mm) at the Fusion Neutronics Source (FNS), Japan Atomic Energy Agency (JAEA), Tokai. The prototype system has a simple configuration, consisting of an undivided radiator and a single pair of a PD and a SND. The performance of this system strongly depends on the geometry, including the mounting angle of the PD to the incident direction of the neutron beam, the radiator thickness, the distance between the radiator and the SND, and so on. We set up a prototype system based on the parametric survey using the simple Monte Carlo simulation. We used a 500 μm thick plastic scintillator (Bicron BC 400) as the radiator. Except for the surface coupled to the PMT, all of the radiator surfaces were covered by a 100 nm thick aluminum film to improve the collection efficiency of the scintillation light. The energy deposited in the Al film by a recoiled proton is less than 1 keV, which is negligible compared to the energy of incident neutrons. The radiator was optically coupled with the PMT (HAMAMATSU R7600U) through a glass light pipe to prevent the neutron beam from directly entering the PMT. The PD was a silicon surface barrier detector (Si-SBD) (ORTEC BR-018-450-1000) with a 450 mm^2 sensitive area and a 1000 μm thick depletion layer and tilted 20° ($=\theta$) to the direction of the incident neutron. To avoid energy loss of recoiled protons in the air, the radiator and the PD were mounted in a vacuum chamber, which had an internal pressure below 10^{-4} Torr. The SND was a 46 mm diameter $\times$50 mm thick plastic scintillator (Bicron BC-400), which is placed at a distance of 120 cm away from the radiator with a tilted angle ϕ of 70° to the direction of the incident neutron.

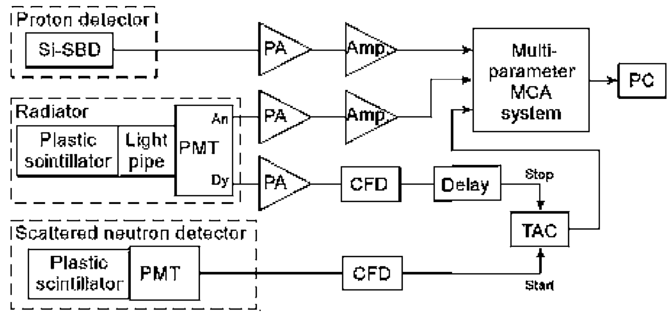

FIG. 2. The experimental system for Fusion Neutronics Source.

The signal processing electronics of this system is shown in Fig. 2. The information of energy deposition in the radiator was obtained from the PMT anode, while the dynode was used for the timing signal processing for the TOF measurement. The signals from the time-to-amplitude converter (TAC), the Si-SBD, and the anode of the PMT for the radiator were analyzed with a multiparameter multichannel analyzer (MCA) system. The intrinsic time resolution of TOF electronics which causes uncertainty of the scattered neutron energy E_{sn} in Eq. (1) was 2.9 ns. The energies of the radiator and the PD were calibrated using an ^{241}Am alpha source, and the energy resolution was estimated to be 17.7% and 0.4% for 5.48 MeV alpha rays, respectively.

IV. RESULTS AND DISCUSSION

Figure 3 shows the relation between the pulse heights obtained in coincidence between the radiator and the Si-SBD. The rectilinear distribution in Fig. 3 represents the expected events, because the energies of the protons recoiled to the Si-SBD are nearly constant. Because of their low scintillation efficiency, some kinds of nucleus recoiled in the light pipe do not contribute to the signals obtained in the radiator.

Figure 4 shows both the observed energy spectrum of DT neutrons in the preliminary experiment and the calculated spectrum. The observed energy resolution W_t includes the energy broadening W_n of the incident neutrons them-

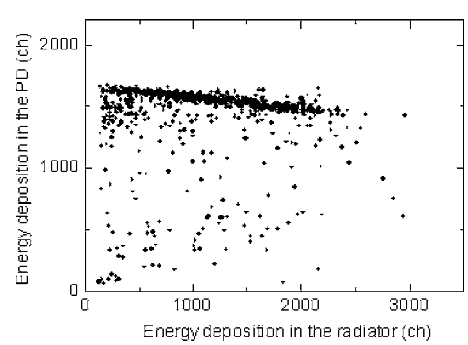

FIG. 3. The relation between the energy deposition of recoiled proton in the radiator and the PD.

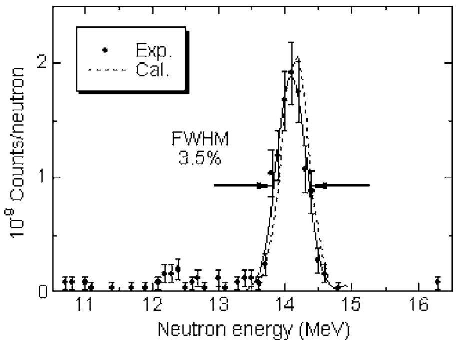

FIG. 4. DT neutron energy spectrum.

selves. W_n of 1.3% for the DT neutron beam in the FNS has been previously reported. The intrinsic energy resolution of this system R is, therefore, estimated to be 3.3% from the equation $R^2 = W_t^2 - W_n^2$. This result agrees well with the calculated energy resolution of 3.2% and almost satisfies the required energy resolution for the ITER neutron spectrometry. The measured detection efficiency of $(4.2 \pm 0.2) \times 10^{-8}$ cm^2 also agrees with the calculated result of 4.4×10^{-8} cm^2. It is, therefore, concluded that the operational principle and the basic performances of this system have been experimentally demonstrated.

V. DESIGN CONSIDERATION FOR AN APPLICATION TO ITER

We have tried the design study of this system for applicability to ITER. The main issues of the design consideration here are the detection efficiency, the applicable range, and detector lifetime.

A. System improvement

The detection efficiency of this system must be improved. The solid angle of the SND, in principle, is the only geometric parameter that can improve the detection efficiency without any deterioration of the energy resolution. The calculations indicate that a SND with a 20 cm diameter entrance window can realize a detection efficiency of 4.7 $\times 10^{-6}$ cm^2. Furthermore, the detection efficiency of this system is improved by increasing the number of the PDs and the SNDs. For example, a ring-shaped array with 30 PDs and 30 SNDs could lead to further improvement, where the expected detection efficiency reaches up to 9.7×10^{-5} cm^2.

The necessary number of the radiator cells depends on the event rate of each cell. The high count rate causes the deterioration of the energy resolution due to the pulse pileup. A rough estimate of the total count rate of the radiator cells at the full power operation in the ITER (2.0×10^{20} n/s in the neutron yield) is 1.2×10^6 counts/s. Dividing the radiator into 2×2 cells will decrease the count rate for each cell by around 3×10^5 counts/s, which does not cause the pulse pileup. Table I summarizes the design results.

TABLE I. The results of design. The expected performances for the DT neutron are the energy resolution of 3.2% and the detection efficiency of 9.7×10^{-5} cm^2.

Radiator	500 μm thick
(2×2 plastic scintillator cells)	
PD	Sensitive area: 450 mm^2
(30 Si-SBDs)	Depletion layer thickness: 1200 μm
SND	ϕ 200 mm $\times$ 50 mm thick
(30 plastic scintillators)	
Tilted angle of PD: θ	20°
Tilted angle of SND: ϕ	70°
Radiator-PD distance	160 mm
Radiator-SND distance	1200 mm

B. Applicable range in ITER operation

This system can be applied to the full operation phase of ITER by dividing the radiator. The lower limit of the applicable range depends on the measurement accuracy. Assuming that the incident neutron has a Gaussian energy distribution, the accuracy of ion temperature measurement is described by[7]

$$\Delta T_i / T_i = \sqrt{2/N}[1 + (R/F)^2],$$

where R is the intrinsic energy resolution of the spectrometer, F is the energy broadening of the DT neutrons, and N is the signal counts measured for the 100 ms sampling time, which is given as the product of the DT neutron flux at the detector position and the detection efficiency. The DT neutron flux at the detector position has been estimated under the assumption that it depends only on the ion temperature. It is expected that this system can be applied to the range over 2.7×10^{19} n/s in the neutron yield with a measurement accuracy better than a 10%.

C. Detector lifetime

The radiation resistance of this system is determined by that of the plastic scintillator used as the radiator exposed to the incident neutron beam. It has been reported that a plastic scintillator begins to decrease its scintillation efficiency over a fast neutron fluence of $\sim 4 \times 10^{14}$ n/cm^2. Assuming that the incident neutron flux is $\sim 10^8$ n/cm^2 s in the full power operation, the estimated lifetime of the radiator is 4×10^6 s.

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