Development of a Time of Flight Spectrometer for n_d/n_t Fuel Ratio Measurement in Burning Plasma

K. OKADA, K. KONDO[1)], N. KUBOTA[2)], K. OCHIAI[2)], S. SATO[2)], T. NISHITANI[2)], C. KONNO[2)], A. OKAMOTO, S. KITAJIMA and M. SASAO

Tohoku University, Sendai 980-8579, Japan

[1)] *Osaka University, Suita 565-0871, Japan*

[2)] *Japan Atomic Energy Agency, Tokai, Naka, Ibaraki 319-1195, Japan*

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A neutron spectrometer system based on TOF (time of flight) measurement has been studied for determination of fuel density ratio in ITER. The effective collimator diameter was examined against both the saturation of the first detector and measurement efficiency as a spectrometer to achieve the sufficient statistics with required time resolution. Relation between collimator diameter and lower limit measurement efficiency was obtained. Measurement efficiency for every design of TOF spectrometer was calculated with MCNP. Those results indicate that two or three collimators of different size are needed to attain statistics errors within 10 %. An experiment to test the TOF spectrometer and to evaluate the system efficiency was conducted using accelerator neutron source. The result shows that both DD and DT neutrons are measured separately and simultaneously with a fast discrimination electronics system. The fast discrimination improves the counting capability by one order of magnitude.

Keywords: fusion, plasma diagnostic, neutron, time of flight, spectrometer

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1. Introduction

For burning control experiments in ITER, it is essential to measure the deuteron and triton density ratio in the core plasma. It can be achieved by measurement of DT/DD reaction ratio [1]. Neutron spectra would be measured for this ratio. However, the DT neutrons emission rate is 200 times higher than that of DD neutrons. Spectrum in the DD neutron energy region is usually contaminated by the scattered energy-degraded neutron background originating from DT. That makes it difficult to measure DD neutrons. There are two key issues which are mutually contradicted. One is the separation of two kinds of neutrons and the other is the sufficient statistics (typically within 10 % error) for the burning control in a short time. In order to meet these two issues, it is required to measure the each neutron separately and simultaneously under high neutron counting rate.

2. Measuring Efficiency for DD Neutron on Assumed Measurement Position of ITER

It is assumed that ITER will be operated in a wide range of fusion power. The power is determined by ion temperature, fuel density, the plasma confinement, etc. and consequently the neutron flux at the measurement position changes over more than several orders of magnitude. The arrangement position of the measuring instrument that we assume is 10 m distances from the center of plasma [1]. In order to evaluate the number of incident neutrons to this position, the model of Fig. 1 is considered, where l is the distance between the center of the plasma and the measuring instrument. N_{obs} is neutron emission from observation volume, that is the volume in viewed by the collimator and S_d is the effective cross-section area that is detector area viewed in direction of collimator. Considering the solid angle from the center of the plasma, $S_d/4\pi l^2$, the number of incident neutrons to the measuring instrument can be estimated by the following equation.

$$n_{DT} = N_{obs}\frac{S_d}{4\pi l^2} \quad \text{[n/sec]} \tag{1}$$

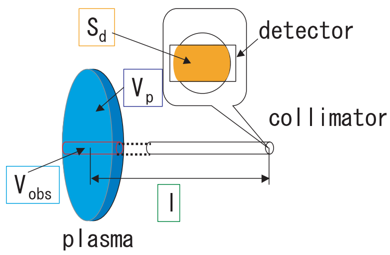
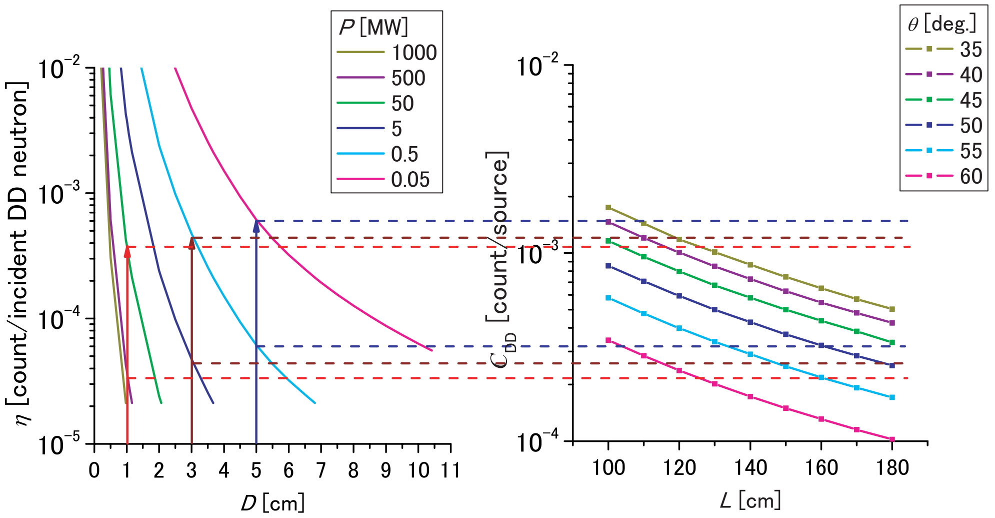


Fig. 1 The calculated ITER model. l is the distance between the center of the plasma and the measuring instrument. V_{obs} is plasma observation volume. S_d is the effective cross-section area

author's e-mail: kouichi.okada@ppl2.qse.tohoku.ac.jp



(a) (b)

Fig. 2 (a) The tolerable lower limit of measurement efficiency against collimator diameter for every fusion power. (b) The measurement efficiency of TOF spectrometer desined using MCNP calculation. Some TOF spectrometer meet s the requirement in the dynamic range from 0.05 to 1000 MW in fusion power by three collimators of 1 cm, 3 cm and 5 cm diameter, as indicated by arrows.

Here n_{DT} is the number of incident DT neutrons to the measuring instrument. N_{obs} is determined by fusion power. S_d is determined by collimator diameter.

A double crystal time-of-flight (TOF) spectrometer [2] was chosen as the measuring instrument. Because the aim of this measuring instrument is burning control support, this measurement results have to be analyzed in a short time. Thus, the measuring instrument should be capable to the high counting rate. The saturation that is concerned is in the first detector (named d1). The counting rate can be estimated using Eq. 1. In the present work, a d1 detector is assumed to be bicron 400(BC400) plastic scintillator of 5 mm thickness. The saturation limit of the counting rate is 4.17×10^8 cps because the scintillation decay time of BC400 is 2.4 ns. Since neutrons enter the detector randomly, we here assumed that the limit of the counting rate is 1.0×10^8 cps. The number of incident neutrons is controlled by collimator diameter. When the counting rate is 1.0×10^8 cps, the typical relation between collimator diameter (D) and fusion power (P) is $D = 1.10$ cm in case of $P = 1000$ MW, $D = 1.31$ cm in case of $P = 500$ MW, $D = 2.33$ cm in case of $P = 50$ MW and $D = 4.14$ cm in case of $P = 5$ MW.

Next, the measurement efficiency for DD neutron is examined. The number of incident DD neutrons, n_{DD}, is about 1/200 of the number of incident DT neutrons, n_{DT}. The number of incident DD neutrons (n_{DD}) per sec can be calculated by Eq. 1 ($n_{DD} = n_{DT}/200$), while the maximum acceptable level is limited by the saturation in d1. The typical dwell time of this measurement, i.e., time resolution is 1 second and 100 DD events are needed in this time because it is required to attain the statistics errors within 10 %. The requirement on the measurement efficiency (η) can be represented as the number of DD event recorded in the d2 per incident DD neutrons to the d1. It is calculable by the following equation.

$$\eta = \frac{C_r}{n_{DD}} \quad \text{[count/incident DD neutron]} \qquad (2)$$

Here C_r is the DD event rate, and it should be attain acceptable statistics, that is over 10 cps per one d2 detector if ten detectors are installed. The lower limit of measurement efficiency can be evaluated by Eq. 2. Fig. 2a shows a relation between collimator diameter and the lower limit of measurement efficiency required from the d1 saturation and sufficient statistics in DD event number. These curves are corresponding the lower limit of measurement efficiency for each collimator diameter. The result indicates that it is necessary to use 1 cm diameter collimator to adjust the some hundreds MW. Especially, in 500 MW, which is assumed maximum fusion power of ITER, it is required that collimator diameter is 1 cm and the measurement efficiency is over 3×10^{-5} [count/incident DD neutron] for DD neutron.

3. Restriction to the Collimator Diameter and the Design of TOF Spectrometer

Here we calculate measurement efficiency for a realistic TOF spectrometer with Monte Carlo calculation (MCNP: Monte Carlo N-Particle code system [3]). The TOF spectrometer considered in this section has assumed two fast plastic scintillators (see Fig. 3). The incident neutron beam is 2 cm diameter. The thickness of d1 is 0.5 cm

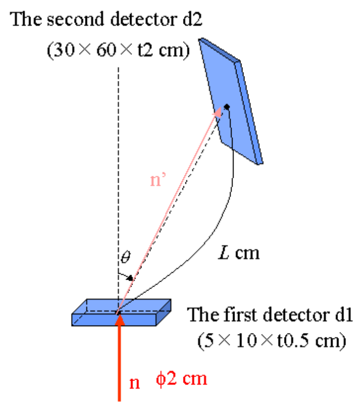


Fig. 3 MCNP calculation model for TOF spectrometer. This spectrometer has two plastic scintillators. The size of the fast detector is $5 \times 10 \times 0.5$ cm, and that of the second detector is $30 \times 60 \times 2$ cm. The considered parameter is θ, and L.

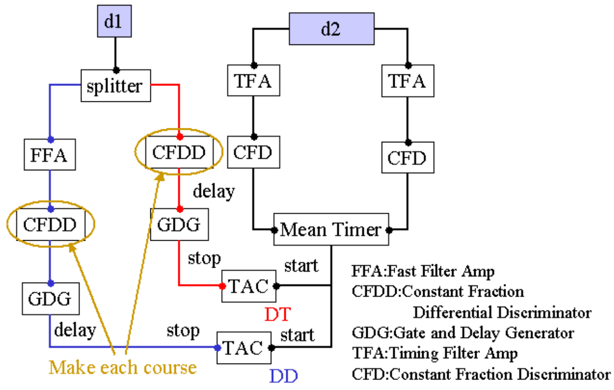


Fig. 4 The measurement system for neutron separation. The signal from d1 is divided into two routes using the splitter. The red line is DT neutron measurement route, and the blue line is DD neutron measurement route. Each route is made by CFDD.

and the size of d2 is $30 \times 60 \times 2$ cm. The examined parameters are the angle and distance between d1 and d2 for 54 patterns, ranging from 35 to 60 degrees for angle (θ) and from 100 to 180 cm for distance (L). The calculated output is converted to counting efficiency (count/ns/source) from neutron efficiency (neutron/ns/source), and the DD count, C_{DD} (count/source), are shown in Fig. 2b against L every θ. Comparing the graph between (a) and (b), it can be noticed that some TOF spectrometer designed in this study meets the requirement in the dynamic range from 0.05 to 1000 MW in fusion power by three collimators of 1 cm, 3 cm and 5 cm diameter, as indicated by arrows.

4. Test Experiment Using DT and DD Neutrons From an Accelerator

In section 2, the capable counting rate in d1 is discussed. Here we discuss the capable counting rate of the TOF electronics. The flight time of DT neutron for 100 cm in L and 35 degrees in θ, is 23.5 ns and that of DD neutrons is 54.2 ns. If the electronics system is waiting for the DD event during this flight time, the maximum tolerable event rate would be 10^7 cps. Here we propose to select DD events and DT events as fast as possible in d1 detector by discriminating their pulse height corresponding the recoil proton energy in d1. The recoil proton energy can be defined for each DD and DT neutrons because the detection angle of scattered neutron is defined by the geometry. If these events are selected, the electronics becomes active during 10 nsec after the time delay corresponding to each neutron flight time. Then the maximum counting rate would be improved to 10^8 cps.

In order to examine this concept, an experiment was conducted for a proto-type TOF spectrometer at the Japan Atomic Energy Agency, Fusion Neutron Source facility. A deuteron beam is accelerated and DT fusion reaction causes between the deuteron beam and tritium target. DD reactions occur as well because accelerated deuterons are implanted into the target. By constructing a shield with the collimator of 2 cm in diameter between the target and the measuring instrument, beam-like neutrons can enter to the measuring point.

The TOF spectrometer has tested parameters of 100 cm in L and 35 degrees in θ. Other parameters of detectors are same as in MCNP calculation. Fig. 4 shows the electronics system for neutron separation measurement. The signal from d1 is divided into two routes using the splitter. Each route is characterized by a module CFDD (constant fraction differential discriminator). CFDD makes discrimination window for pulse height spectrum. The route for DD neutron measurement has set up the discrimination window corresponding to the energy of a recoil proton when DD neutrons are scattered on 35 degrees. Similarly, the route for DT neutron measurement has set up the discrimination window corresponding to the energy of a recoil proton when DT neutrons are scattered on 35 degrees. The signal from d2 is the start signal because of delaying the signal from d1.

Fig. 5a and 5b show time spectrum of each neutron separated by fast discriminations of pulse heights in the d1 detector. The energy of DT neutron scattered on the direction 35 degrees are 9.54 MeV. That of DD neutron is 1.78 MeV. The flight time of DT neutron in this case is 23.5 ns in theoretical calculation. And that of DD neutrons is 54.2 ns. The experimental result indicated flight time almost equal to theoretical calculation. The cause of the small difference between theoretical calculation and the experiment result is because the detector has volume in the experiment but detector is point in the calculation.

A peak exists in 3.34 ns for both spectra. The peak is the γ-ray peak originating in the inelastic scattering between ^{12}C and DT neutron (^{12}C(n, n′ γ)^{12}C) in d1. Since the velocity of a γ-ray is constant, it was used as a standard

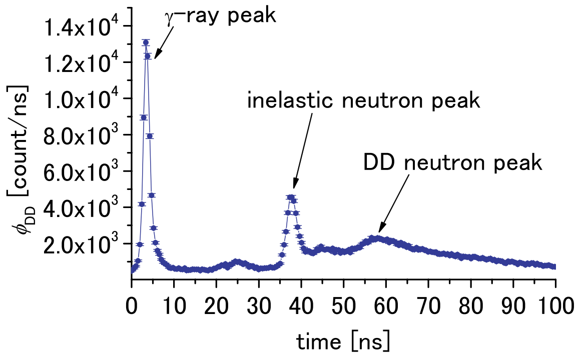


Fig. 5a The experimental result of neutron TOF spectrum separated from DT neutrons by fast discriminations of pulse heights in the d1 detector. The peak around 5 ns is γ-ray peak. The γ-ray peak originates in the inelastic scattering between ^{12}C and DT neutron in d1. The peak around 38 ns is inelastic scattering neutron peak. The peak around 55 ns is DD neutron peak.

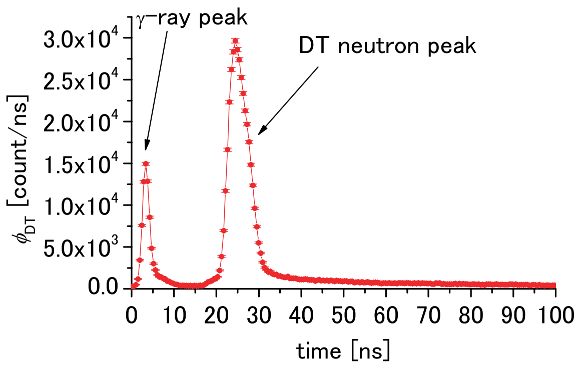


Fig. 5b The experimental result of neutron TOF spectrum separated from DD neutrons by fast discriminations of pulse heights in the d1 detector. The peak around 5 ns is γ-ray peak. The peak around 25 ns is DT neutron peak.

of a time-axis. Moreover, the inelastic neutron peak exists near the 40 ns in DD spectrum.

The DT spectrum is clearly separated from the DD spectrum and DT neutron peak hardly exists in the DD spectrum, indicating that DD neutrons was separated from DT neutrons. However, there exist backgrounds signals in the DD peak region. The main cause is accidental coincidence with low pulse hight signals in d1. In order to reduce this influence, it is necessary to improve the d1 detector and/or the TOF geometry.

5. Summary

For measurement of DD/DT neutron ratios in ITER, the collimator diameter was examined from viewpoints of saturation in the first detector and the detection efficiency We assumed that the saturation-counting rate for BC400 is 1×10^8 cps. In addition, we estimated lower limit measurement efficiency to attain statistics errors within 10 %. The measurement efficiency of DD neutrons for present designs is raging from 1×10^4 to 2×10^3 count/source. Two or three collimators of different diameters are needed. the dynamic range from 5 MW to 500 MW. Finally, an experiment was conducted using an accelerator to test a proto type TOF spectrometer of considered design. DT and DD neutrons were separated simultaneously. As a next R&D stage, we will raise separation accuracy by improvement of a measurement system.

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