Estimation of the fast ion anisotropy effect on the neutron source intensity measurement and the experimental observation

Takeo Nishitani, Hideaki Matsuura, Neng Pu, Kunihiro Ogawa, Hiroki Kawase, Mitsutaka Isobe, and the LHD Experiment Group

***Abstract*—In the Large Helical Device (LHD) deuterium plasma experiment, the neutron emission rate and the shot-integrated neutron yield are measured with the neutron flux monitor (NFM) and the neutron activation system (NAS), respectively, where the neutron emission is assumed to be isotropic in the plasma. The differential cross-section of the D(d,n)^{3}He reaction has a large anisotropy for the forward direction of the incident deuteron direction. LHD has intensive tangential neutral beam injectors (NBIs), which may cause an anisotropic neutron emission in the plasma. The angular distribution of the neutron emission is calculated from the fast ion distribution function evaluated by a code which solves Fokker-Plank equations for the 180 keV tangential NBI. The effect of the anisotropic neutron emission on the NFM and NAS measurements is estimated by MCNP calculations. Also the effect is confirmed experimentally. The neutron emission rate measured with the NFM near the equatorial port is about 10% larger than that with the NFM at the top of the LHD center axis. The shot integrated neutron yield measured with NAS is 25% larger than that with NFM at the top of the LHD center axis in the case of the tangential NB injection, which is consistent with the MCNP calculation.**

***Index Terms*—LHD, neutron anisotropy, fast ion anisotropy, neutron flux monitor, neutron activation system, Fokker-Plank calculation, MCNP.**

I. Introduction

THE Large Helical Device (LHD) started deuterium plasma experiments in March 2017 [1]. The neutron measurement is one of the most important diagnostics on the deuterium experiment, not only for the plasma performance understanding but also the radiation safety. In the LHD deuterium plasma experiment, the neutron emission rate and the shot-integrated neutron yield are measured with the neutron flux monitor (NFM)[2, 3] and the neutron activation system (NAS)[4], respectively. The detection efficiencies of the NFM detectors and the reaction rate of an Indium foil for NAS were calibrated by ^{252}Cf neutron source rotating inside the LHD vacuum vessel [4, 5], where the neutron emission is assumed to be isotropic. LHD has two perpendicular neutral beam injectors (NBIs) with the typical energy of 60-80 keV and three tangential NBIs with the typical energy of 180 keV. The differential cross-section of the T(d,n)^{3}He reaction is almost isotropic. On the other hand, the differential cross-section of the D(d,n)^{3}He reaction has a large anisotropy for the forward direction of the incident deuteron direction as shown Fig.1 In particular, the anisotropy is enhanced for the incident deuteron energy larger than 100 keV. Therefore, the intensive tangential NBI may cause an anisotropic neutron emission in the plasma on LHD.

The effect of the neutron emission on the NAS measurement was evaluated by the MCNP calculation for the TEXTOR tokamak previously [6]. In the present work, the effect of the anisotropic neutron emission not only on the NAS measurements and but also NFM is investigated by the MCNP-6 [7] calculation. Also, the anisotropic neutron emission effects have been confirmed on the LHD deuterium plasma experiment.

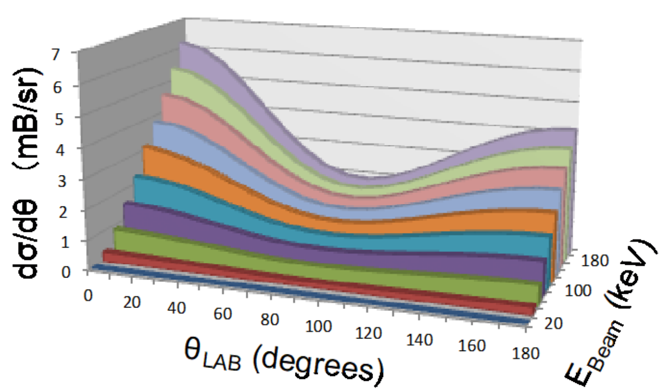

Fig. 1. Differential cross-section of the D(d,n)^{3}He reaction for the different deuteron beam energy.

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II. Neutral Beam Injectors and Neutron Diagnostics

A. Neutral beam injectors

Fig. 2 shows the schematic view of NBIs [8], NFM, and irradiation ends of NAS on LHD. NBI#1, #2, and #3 are tangential direction injectors with negative-ion sources whose typical energy is 180 keV. NBI#4 and #5 are perpendicular direction injectors with positive-ion sources whose typical energies are 60 keV and 80 keV, respectively. The normal direction of the toroidal magnetic field is counterclockwise viewed from above. Therefore, NBI#1 and #3 are counter-direction injection to the toroidal magnetic field, and NBI#2 is a co-direction injection to the toroidal magnetic field direction.

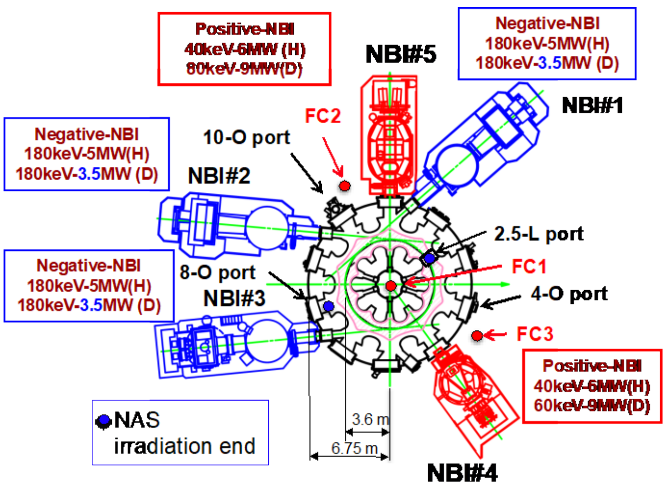

Fig. 2. Arrangement of NBIs, NFM, and irradiation ends of NAS on LHD.

B. Neutron flux monitors

The absolute neutron emission rate has been measured with NFM, which consists of ^{235}U fission chambers and additional highly sensitive neutron detectors of a ^{10}B proportional counter or a ^{3}He proportional counter. For plasmas with NB injection, ^{235}U fission chambers only are available, because highly sensitive neutron detectors are saturated. The locations of three ^{235}U fission chambers, FC1-FC3, are shown in Fig. 2. FC1 is on the top of the center axis. FC2 and FC3 are near two large outside ports called O-port. In this study, precise position of the detectors is important. Therefore, the center positions of three ^{235}U fission chambers are listed in TABLE I.

TABLE I
Center Positions of ^{235}U Fission Chambers

Detector	Height from the LHD magnetic axis	Toroidal position (+:Counter CW)
FC1	5.48 m	Center of LHD axis
FC2	0 m	-14.5° from 10-0 axis
FC3	0m	-15.0° from 4-0 axis

The ^{235}U fission chamber is surrounded by a 50-mm-thick polyethylene moderator and a 1-mm-thick cadmium thermal neutron absorber. The fission event of ^{235}U has large cross-section for thermal neutrons, which are generated in the concrete wall and surrounding equipment through slowing down process. In order to prevent the contribution of those thermal neutrons to the fission chamber signal, the cadmium thermal neutron absorber is employed. The detector has rather flat response for the neutron energy of 0.1 – 2 MeV as shown in Fig. 3 [3], which is suitable to the total neutron yield measurement not only for 2.45 MeV neutrons but also neutrons scattered by the LHD structure.

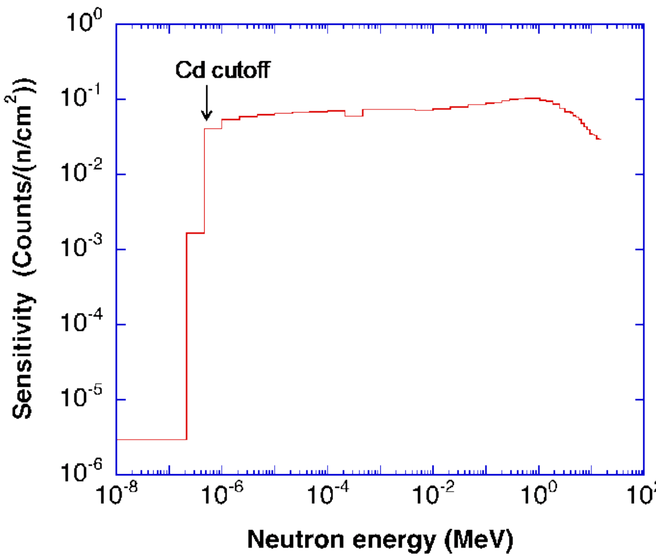

Fig. 3. Response function of the ^{235}U fission chamber with a 50-mm-thick polyethylene moderator and a 1-mm-thick cadmium thermal neutron absorber.

C. Neutron activation system

A neutron activation system is widely used in fusion experimental devices [9-11] for the shot-integrated neutron yield measurement. A piece (or pieces) of metal called activation foil is transferred to an irradiation end near the plasma by a pneumatic tube before the plasma shot. After the shot, the activation foil will return to the counting station, where gamma-rays from the activation foil is measured with a gamma-ray spectrometer such as a high-purity germanium detector. If the irradiation end is close to the plasma, the activation foil can measure direct neutrons from the plasma mainly.

LHD has a neutron activation system with two irradiation ends [4]. One is in an O-port, and another is in a lower vertical port called L-port as shown in Fig. 4. Those locations of the irradiation ends are not so close to the plasma due to the complicated helical plasma configuration and the mechanical structure issue of the irradiation end such as the vibration of the cantilever type transfer tube. The distances between the irradiation ends and the typical plasma center, where the major radius of the plasma axis is 3.6 m, are 1.7 m and 2.7 m for the irradiation end in the 8-0 port and the 2.5-L port, respectively. Thus, the activation foil in the 2.5-L port is less sensitive to the total neutron yield than that in the 8-O port.

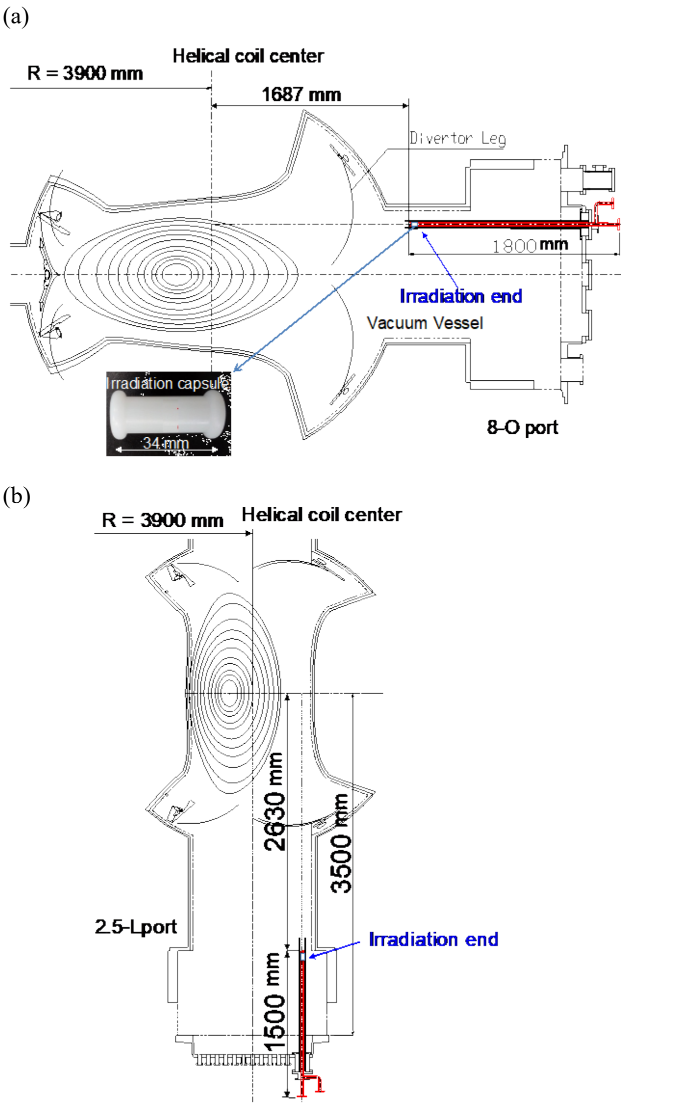

Fig. 4. Schematic view of the irradiation ends in LHD. (a) is in the 8-O port and (b) is in the 2.5-L port.

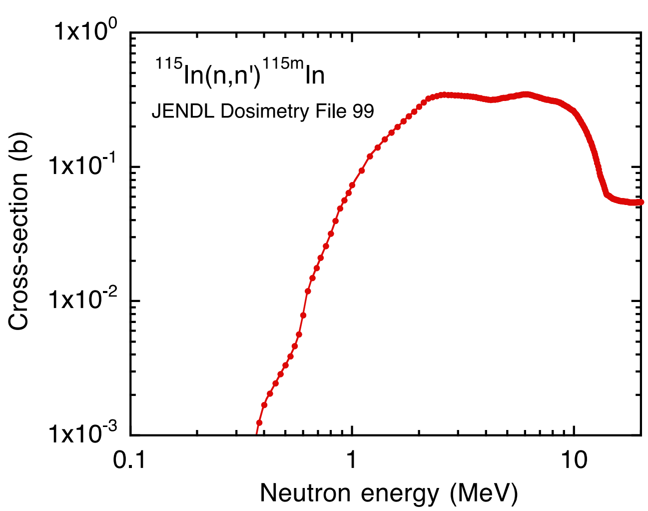

Fig. 5. Cross-section of ^{115}In(n,n')^{115m}In reaction as a function of neutron energy from the JENDL Dosimetry File 99 [12].

By selecting the kind of foil material and the nuclear reaction, neutrons with certain energy range can be measured with NAS. The nuclear reaction of ^{115}In(n,n')^{115m}In is employed for the measurement of the total neutron yield from the deuterium plasma in LHD. Figure 5 shows the cross-section of ^{115}In(n,n')^{115m}In as a function of neutron energy, which has a threshold energy of 0.336 MeV and rather flat response in the energy range of 1.5-10 MeV [12]. The activated nucleus of ^{115m}In has a half-life of 4.486 h, which is suitable for the shot-integrated neutron yield measurement even at one hour shot of LHD.

III. Estimation of Fast Ion Velocity Distribution Function and the Angular Distribution of the Neutron Emission

At first, the fast ion velocity distribution function is evaluated by the Fokker-Plank calculation [13] for the tangential NBI with the beam energy of 180 keV and the beam power of 1 MW, where bulk plasma parameters are assumed to be electron temperature T_e of 2 keV, electron density n_e of 2×10^{19} m^{-3}, the particle confinement time τ_p of 0.2 s, and the energy confinement time τ_E of 0.2 s. Fig. 6 shows calculated fast ion velocity distribution function, where average velocity of deuterons v_0 is assumed to be the velocity for 60 keV deuteron. It is found that fast ion velocity distribution function has an intensive anisotropy toward the $v_{//}$ direction (tangential direction).

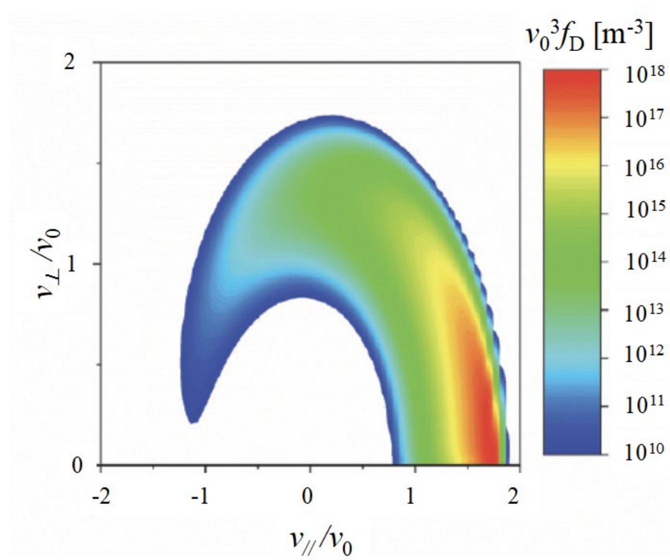

Fig. 6. Calculated velocity distribution function for the tangential NBI with the beam energy of 180 keV and the beam power of 1 MW.

The angular distribution of neutrons from reactions between fast ions and bulk ions is calculated by using the fast ion velocity distribution shown in Fig. 6 and the differential cross-section of D(d,n)^{3}He reaction shown in Fig. 1. As shown in Fig. 7, neutrons from fast ions and bulk ions have large anisotropy. The relative intensity is approximately 0.35 and 0.55 at the emission angle of 90 degrees and 180 degrees against that of 0 degree, respectively.

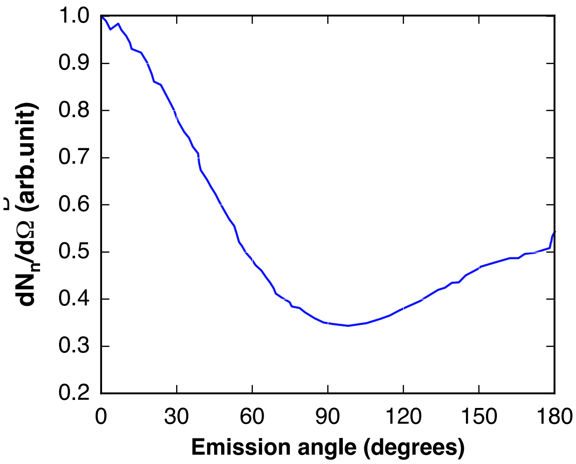

Fig. 7. Calculated angular distribution of the neutron emission from reactions between fast ions and bulk ions. The values are normalized to that at 0 degree.

IV. Effect of Anisotropic Neutron Emission on Neutron Source Intensity Measurement Estimated by Neutronics Calculation

The detection efficiencies of the ^{235}U fission chambers of NFM and the reaction rate of an Indium foil for NAS are calculated by the MCNP-6 code [7] with the nuclear data library of FENDL-3.0 [14]. The three-dimensional calculation model includes not only LHD but also the torus hall building in order to take account of the neutrons scattered by the torus hall walls. The helical coils and the casing for the coils are divided by 6° toroidal angle pitch, and those components are assumed to be toroidally symmetric in a toroidal pitch angle [3]. Fig. 8 shows the schematic view of the MCNP calculation model, which is drawn with SuperMC/MCAM code [15].

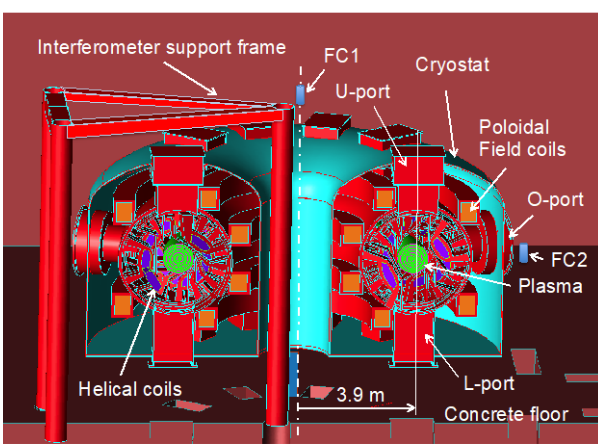

Fig. 8. Three-dimensional model of LHD including the torus hall building.

The LHD plasma is modeled by a simple torus, which is divided 60 toroidal sectors with the toroidal pitch angle of 6 degrees. The angular distribution of the neutron emission is defined at each plasma sector according to the angular distribution of neutrons shown in Fig.7. The source neutron energy is assumed to be mono-energetic of 2.45 MeV.

The detection efficiencies of the ^{235}U fission chambers are derived from the product of the response function shown in Fig.3 and the calculated neutron spectra at the detector location. The result is summarized in TABLE II. FC1 is almost insensitive to the anisotropy, however, FC2 and FC3 has small sensitivity to the anisotropy.

TABLE II
Detection Efficiencies of ^{235}U Fission Chambers

Detector	Detection efficiency (× 10^{-8} /source neutron)		Anisotropic / Isotropic
	Isotropic source	Anisotropic source	
FC1	0.583 ± 0.006	0.582 ± 0.006	0.998 ± 0.014
FC2	1.08 ± 0.01	1.11 ± 0.01	1.03 ± 0.01
FC3	0.689 ± 0.008	0.694 ± 0.008	1.01 ± 0.02

Also, the reaction rate of $^{115}In(n,n')^{115m}In$ is calculated by MCNP using the nuclear data library for two irradiation ends. The reaction rate *R* is defined as follows,

$$R = \int \sigma(E)\phi(E)dE \ , \quad (1)$$

where *σ(E)* is the cross-section and *ϕ(E)* is the neutron energy spectrum. Here, the nuclear data library of JENDL 99 Dosimetry file [12] is used for the *R* calculation, which is specially compiled for the activation measurement. The result is summarized in TABLE III. The reaction rate at the irradiation end in the 8-0 port for the anisotropic source is 25% larger than that for isotropic source. The statistical error of the reaction rate is still large in the case of the 2.5-L port, because the position is far from the plasma and the volume of the irradiation capsule is very tiny. However, it seems that the reaction for the anisotropic source is 10-20% smaller that that for the isotropic source.

TABLE III
Reaction rates of $^{115}In(n,n')^{115m}In$ at the Irradiation Ends

Position	Reaction rate (× 10^{-31} /source neutron)		Anisotropic / Isotropic
	Isotropic source	Anisotropic source	
8-O	1.77 ± 0.006	2.22 ± 0.17	1.25 ± 0.17
2.5-L	0.622 ± 0.116	0.484 ± 0.101	0.778 ± 0.217

V. Experimental Observation

The fast ion anisotropy effect on NFM is investigated in the shot shown in Fig.9, where tangential NBIs were injected from 3.3 s to 7.3 s and perpendicular NBIs were injected from 7.3 s to 9.3 s. The total neutron yields *Sn* measured with FC2 and FC3 are almost identical, and larger than that with FC1 in the phase of the tangential NB injections. We employed FC1 as the reference detector, because the detector is considered to be the most insensitive to the anisotropy of the neutron emission by the result of the neutronics analyses in Section IV. The ratios of FC2/FC1 and FC3/FC1 are approximately 1.1 in the phase of the tangential NB injections, which indicates that anisotropy of fast ions injected by tangential NBIs are confirmed experimentally through the anisotropy in the neutron mission. However, those ratios are much larger that the MCNP simulation. Further discussion is required.

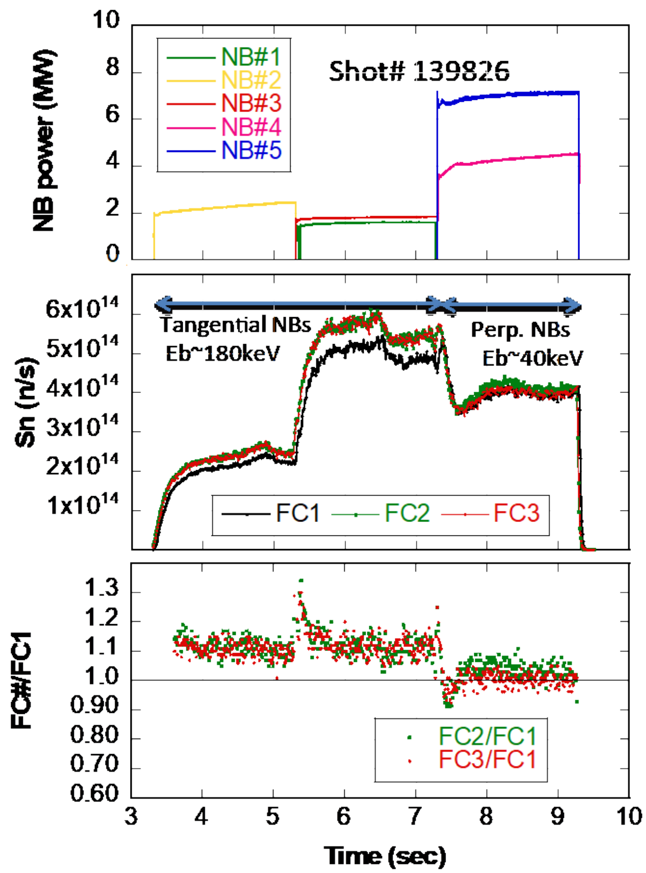

Fig. 9. Time evolution of the neutron emission rate measured with FC1,2, and 3, and the ratios of FC2/FC1 and FC3/FC2 for different NB injections.

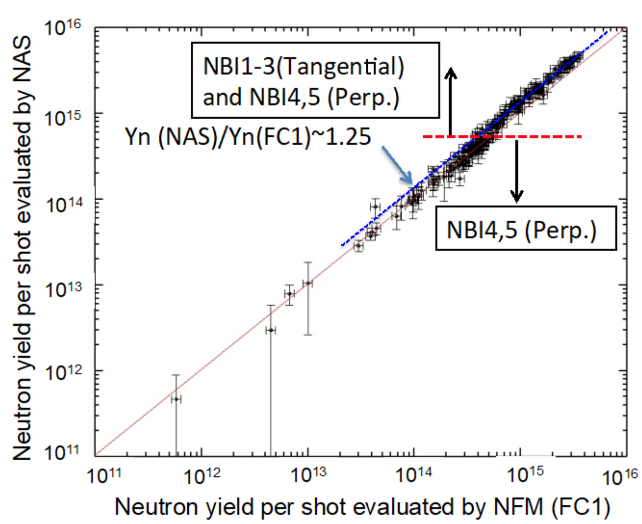

Fig. 10. Shot integrated neutron yield measured with NAS at 8-O port as a function of that with FC1 of NFM.

Fig. 10 shows the shot integrated neutron yield measured with the NAS measurement in the 8-O port as a function of that with FC1 of NFM. For the perpendicular NBI, the shot integrated neutron yield measured with NAS is coincide with that by NFM, however, is 25% larger than that by NFM for the plasma with tangential NBIs, which is consistent with the MCNP calculation. Unfortunately, we did not have sufficient data in the 2.5-L port until now. In the next LHD campaign, we will accumulate the data of the NAS measurement in the 2.5-L port.

VI. Experimental Observation

The angular distribution of the neuron emission is calculated from the fast ion distribution function evaluated by the Fokker-Plank code for the 180 keV tangential NBI. The effects of the neutron emission anisotropy on the neutron yield measurement are estimated by the MCNP calculation. The neutron emission rate measured FC2 and FC3 are about 10% larger than that with FC1, which are much larger that the MCNP simulation. The shot integrated neutron yield measured with NAS is 25% larger that by NFM (FC1) for the plasma with tangential NBIs, which is consistent with the MCNP calculation. Thus, we confirmed the effect of the fast ion anisotropy effect on the neutron source intensity measurement experimentally. Previously, we consider that NAS is the most accurate direct measurement of the shot-integrated neutron yield. However, we should consider the fast ion anisotropy effect on NAS. Also, we should take account of the fast ion anisotropy effect in the interpretation of the NFM data.

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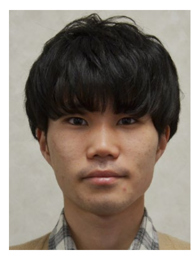

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