Neutron Diagnostics in the Large Helical Device

M. Isobe[1,2], K. Ogawa[1,2], T. Nishitani[1], H. Miyake[1], T. Kobuchi[1], N. Pu[2], H. Kawase[2], E. Takada[3],
T. Tanaka[4], S. Li[4], S. Yoshihashi[4], A. Urinitai[4], J. Jo[5], S. Murakami[6], M. Osakabe[1,2],
and LHD Experiment Group[1]
[1]*National Institute for Fusion Science, Natural Institutes of Natural Sciences, Toki 509-5292, Japan*
[2]*SOKENDAI(The Graduate University for Advanced Studies), Toki 509-5292, Japan*
[3]*National Institute of Technology, Toyama College, Toyama 939-8630, Japan*
[4]*Nagoya University, Nagoya 464-8603, Japan*
[5]*Seoul National University, Seoul 151-744, Republic of Korea*
[6]*Kyoto University, Kyoto 615-8540, Japan*

Abstract—**The deuterium operation of the Large Helical Device(LHD) began in March 7, 2017, after long-term preparation and commissioning of apparatuses necessary for execution of the deuterium experiment. A comprehensive set of neutron diagnostics was developed and installed onto LHD through numerous efforts in preparation. Neutron diagnostics play an essential role in both neutron yield management for the radiation safety and extension of energetic-particle physics study in LHD. Neutron flux monitor characterized by fast-response and wide dynamic range capabilities is successfully working. Total neutron emission rate reached 3.3×10^{15} (n/s) in the first deuterium campaign of LHD. The highest neutron emission rate was recorded in inward shifted configuration. Neutron yield evaluated by neutron activation system agrees with neutron yield measured with neutron flux monitor. Performance of vertical neutron camera was demonstrated. Neutron emission profile was inwardly shifted in the inwardly shifted configuration whereas it was outwardly shifted in the outwardly configuration. Secondary DT neutrons produced by triton burnup in LHD deuterium plasmas were detected for the first time in stellarator/heliotron devices in the world. Similar to total neutron emission rate, the inward shifted configuration provided highest triton burnup ratio.**

Index Terms—**LHD, deuterium plasma, neutron, fission chamber, neutron activation system, neutron camera, triton burnup**

I. INTRODUCTION

The deuterium plasma experiment began in the Large Helical Device (LHD) on March 7, 2017, in order to explore higher-performance helical plasmas and to gain a positive prospect toward an LHD-type fusion reactor. This is the first deuterium operation in a large-scale helical device in the world [1]. Neutron yield measurement is essentially required in the deuterium operation of LHD since total neutron yield must be managed in compliance with weekly, three months, and annual neutron budgets approved by the Nuclear Regulation Authority of Japan. In a magnetic confinement fusion experiment currently being undertaken, a target fusion plasma is auxiliarily heated by intense neutral beam injection (NBI) to achieve high beta and/or to explore higher-confinement regime. In this case, neutrons generated in a fusion plasma are dominated by neutrons resulting from so-called beam-plasma reactions. In other words, neutron emission rate and/or yield is inseparably linked to the beam ion's slowing-down or confinement in existing magnetic confinement fusion experiments.

A study on energetic particles has been one of the primary subjects in fusion because energetic alpha particles produced in a future deuterium-tritium plasma will play an essential role in sustaining an ignited condition. Examining energetic particles will continue to be important at least until good confinement of alpha particle and/or sustainment of alpha particle-driven plasma are demonstrated in ITER. In stellarator/heliotron devices, confinement property of energetic particles has been a great concern rather than tokamaks because of intrinsic symmetry breaking of the system. In a hydrogen operation phase of LHD, charge-exchange neutral particle analyzer (NPA) and scintillator-based fast-ion loss detector (FILD) have played a primary role in measurement of energetic particles [2]. However, physics information obtained by using these diagnostics is fairly limited. Although NPA is beneficial in a particular physics purpose [3], it can detect energetic particles having a limited pitch-angle along the line of sight. Also, complicated analysis coming from neutral density profile lies between actual confinement of energetic particle in a plasma and experimental observation in understanding of NPA signals. FILD on LHD has contributed to physics understanding of interaction between energetic particles and energetic-particle-driven magnetohydrodynamics (MHD) instabilities [4]. However, there is room for argument for toroidally non-uniformed loss of energetic particles caused by an externally applied resonant magnetic perturbed field since it is a point measurement.

One of the primary research subjects in the LHD deuterium project is to demonstrate that the confinement capability of energetic ions is relevant to the future burning plasmas in helical systems. Because fusion neutron signals are newly available in LHD, the deuterium experiment can provide an important opportunity to extend energetic-particle physics study in a helical plasma. To execute this mission, LHD has been equipped with a comprehensive set of neutron diagnostics i.e., neutron flux monitor, neutron activation system, vertical neutron camera, scintillating-fiber (Sci-Fi) detectors, and neutron fluctuation diagnostic following our original plan [5]. In this paper, neutron diagnostics prepared for the LHD deuterium experiment, commissioning of these diagnostics, and representative results in the early stage of the first deuterium campaign are described.

II. LARGE HELICAL DEVICE AND EXPECTED NEUTRON EMISSION RATE

The LHD is one of the largest superconducting helical devices in the world, having a major radius of 3.9 m and an averaged plasma minor radius of ~0.6 m, offering high-beta and steady-state operation capabilities [6]. The toroidal magnetic field strength can be increased up to ~ 3 T. The first plasma was initiated on March 31, 1998. Hydrogen plasma experiments have been conducted in LHD to date. NBI facilities and its performance have been steadily enhanced year by year. As a result, LHD is now equipped with five neutral beam (NB) injectors consisting of three tangential negative-ion-source-based NB injectors with acceleration voltage E_b of 180 kV, and two perpendicular positive-ion-source based NB injectors with E_b of 60 kV [7]. NB injectors on LHD can deliver total port-through power of ~30 MW. High-energy beam ions are responsible in generating D-D fusion neutrons in LHD. Prior to the deuterium operation, the expected neutron emission rate was calculated by using the steady-state solution of Fokker-Planck equation. The calculation suggests that maximum neutron emission rate in LHD will exceed 1×10^{16} n/s when full power NB heating is performed [1, 8]. The neutron emission rate expected in LHD will be comparable to that in deuterium discharges of large tokamaks [9, 10].

III. NEUTRON DIAGNOSTICS ON LHD

A. Ex-vessel Neutron Flux Monitor

Because neutron emission rate and/or yield is one of the important parameters to assess plasma performance, it has been measured in many tokamaks by means of thermal neutron counters, neutron activation foil technique, and other methods [9-12]. In order to manage neutron yield and enhance energetic-particle physics study, ex-vessel neutron flux monitor (NFM) [13] characterized by a fast-response and wide dynamic range capabilities has been employed in LHD. In magnetic confinement fusion, total neutron emission rate varies according to injection pattern of NBI and/or experiment scenario. Also, neutron emission rate can change rapidly due to unusual events such as MHD instabilities. Therefore, fast-response and wide dynamic range capabilities are essentially required. The NFM on LHD consists of three thermal detector sets as shown in Figure 1. One set is installed on the axis of the device center above the device. The other two sets are placed near the device on the equatorial plane. Each set has two thermal neutron detectors different in sensitivity, i.e., a ^{235}U fission chamber (FC) (Toshiba Electron Tubes and Devices (TETD) Co., LTD/KSA-01), and a ^{10}B counter (TETD Co., LTD/E6863-558) or an ^{3}He proportional counter (TETD Co., LTD/E6862-500). Sensitivities to thermal neutrons of FC, ^{10}B and ^{3}He counters are 0.1, 6.5, and 39 (cps/nv), respectively. To avoid neutron irradiation effects onto electronics such as preamplifiers, signal processing units, and optical transducer used for NFM, the electronic devices are placed outside the LHD torus hall. Because Q-value in a nuclear reaction of ^{235}U is extremely high compared with that of ^{10}B and ^{3}He, FC can offer wide dynamic range capability by adopting combination use of pulse-counting and Campbelling modes [14, 15]. The combined system of pulse-counting and Campbelling modes was used in Tokamak Fusion Test Reactor (TFTR) and JAERI Tokamak-60 Upgrade (JT-60U). However, those electronics are based on traditional analogue techniques and are no longer available at this moment. Therefore, we newly developed a leading edge digital signal processing unit for the FC lines having both functions of pulse-counting and Campbelling modes. Our FC line system was designed so as to realize a very wide dynamic range up to 5×10^{9} cps. If we consider the dynamic range of ^{10}B and ^{3}He counters, the NFM on LHD can cover total neutron emission rate from ~10^{8} to ~10^{18} n/s. Time response of our system is minimized to be 0.5 ms until the statistical error of pulse counts in the Cambelling mode can be still negligible. The FC line is responsible for middle-

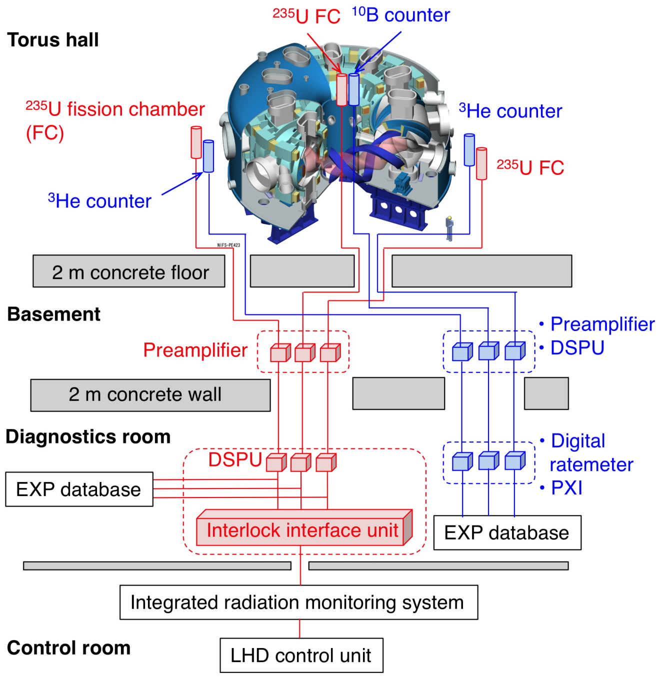

Fig. 1 Arrangement of ex-vessel neutron flux monitor on LHD.

and high-neutron yield shots and plays an essential role in neutron yield management and energetic-particle physics study. The ^{10}B and ^{3}He lines are used for a low-neutron yield shot, e.g., electron cyclotron resonance heating (ECRH) plasma without NBI. Since velocity distribution of fuel deuteron can be supposed to be Maxwellian, those detectors can provide fuel deuteron temperature in ECRH plasmas. Data on total neutron emission rate and yield from FC lines are fed into both experiment database and interlock system for radiation safety.

In situ calibration of NFM is indispensable to assess total neutron emission rate from a fusion plasma. Thus, the calibration of NFM has been carried out in many tokamak and stellarator/heliotron devices where the deuterium operation is performed [16-19]. In LHD, it was performed likewise in November, 2016 by using an intense ^{252}Cf spontaneous fission neutron source along the guideline standardized in the workshop on neutron calibration technique for comparison of tokamak results [20]. The birth neutron emission rate from the ^{252}Cf source used in LHD was $(1.34\pm0.014)\times10^{8}$ n/s at 12:00 GMT on 27 April 2015, which was calibrated at the National Physics Laboratory, United Kingdom. To simulate a ring-shaped neutron source, we installed a railway track designated as O-gauge at R_{ax} of 3.744 m along the magnetic axis position where the neutron production density is expected to be the highest in a confinement domain, and run a train loaded with ^{252}Cf source continuously on the track. The railway track used in the calibration of LHD NFM is shown in Figure 2. Relation between total neutron emission rate S_n from a plasma and neutron pulse-counting rate C_{rate} measured with each neutron detector is expressed as S_n (n/s)$=\alpha\times C_{rate}$ (cps). The in situ calibration with continuously travelling source were performed seven times with seven different discrimination voltages of FCs. In each run, we accumulated neutron pulse counts over 10,000 to ensure good statistics coming from numbers of pulse counts. Point-by-point measurements were also carried out at ten points for the purpose of comparison between the calibration result and that predicted by the three-dimensional general-purpose Monte Carlo N-Particle (MCNP) code.

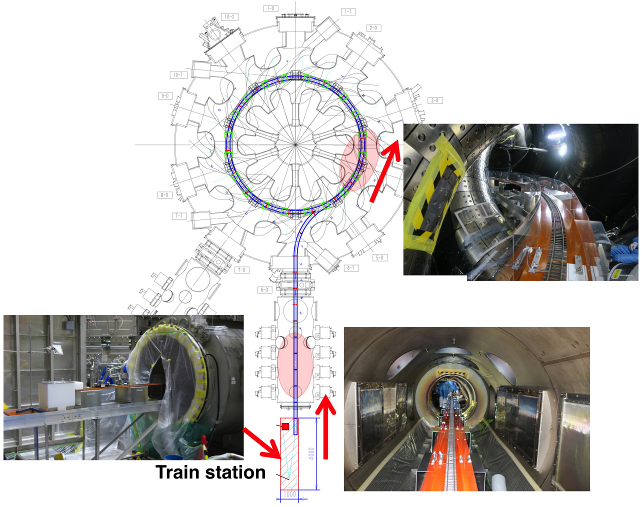

Fig. 2 Apparatus of in situ calibration of LHD neutron flux monitor by using ^{252}Cf neutron source of ~800 MBq. A railway is installed inside the vacuum vessel at major radius of 3.744 m and a train loaded with ^{252}Cf neutron source is run on the rail to simulate a toroidal neutron source.

Figure 3 shows dependence of detection efficiencies of three FCs on source toroidal angles. It is clearly seen that the efficiency of FC placed on the device axis above the device is almost constant and is not sensitive to the source toroidal angles as expected because there is a symmetry to the toroidal neutron source in the field of view of the FC on the top. The other two FCs installed on the equatorial plane show periodic increase and decrease of the detection efficiency according to the source toroidal angles. As a result of this work, the calibration factors α for six neutron counters were obtained. The FC on the top plays a primary role in evaluating total neutron emission rate. Coefficient α for the primary FC is evaluated to be 1.46×10^{8}. There are several differences between in situ calibration and actual deuterium plasma, e.g., neutron source spectrum, presence or absence of apparatus inside the vacuum vessel used in the calibration, liquid helium, and others. Prior to the in situ calibration of NFM, influence of those differences on the coefficient α was investigated by using the MCNP code [21]. The calculation tells us those differences give uncertainty of about 10% on the calibration factor.

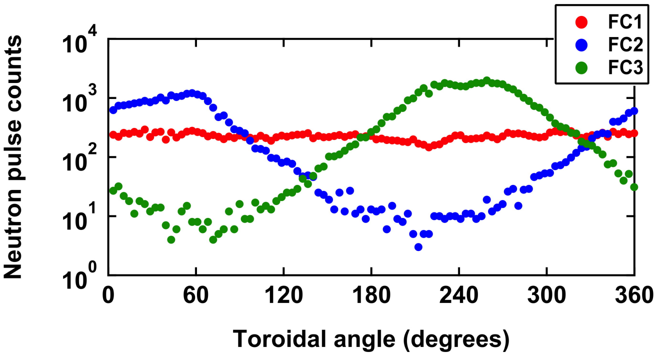

Fig. 3 Dependence of detection efficiencies of ^{235}U fission chambers on source toroidal angle. The discrimination voltage was set to be -180 mV in this case. The total accumulation time was about 15 hours. FC1 denotes FC placed above the device. FC2 and FC3 represents FCs installed on the equatorial plane near the 10-O port and 4-O port, respectively. The toroidal angle of 0 deg. corresponds to the center of 1-O port.

In the early phase of the deuterium operation, in order to confirm whether time evolution of neutron emission rate measured with NFM matches expected behavior, short pulse perpendicular NBs of which pulse width was much shorter than slowing-down time on beam ions were repeatedly injected into an ECRH plasma. This method is often called “beam blip” and provides a sort of “test particles” in a plasma [22]. Pulse duration of NB was ~20 ms in this shot.

To change beam deposition and slowing-down time on beam ions, the electron density was gradually ramped up during the discharge. Discharge waveforms in this particular shot are shown in Figure 4. Peak value of S_n increases as n_e increases as expected according to increase of beam deposition. Also, neutron decay rate immediately after NB turn-off tends to be faster as n_e increases as expected because slowing-down time is proportional to $T_e^{1.5}/n_e$. This tendency is consistent with that predicted by classical slowing-down theory on energetic ions. So far, total neutron emission rate has reached 3.3×10^{15} n/s when five NBs with total power of ~25 MW were injected at the same time.

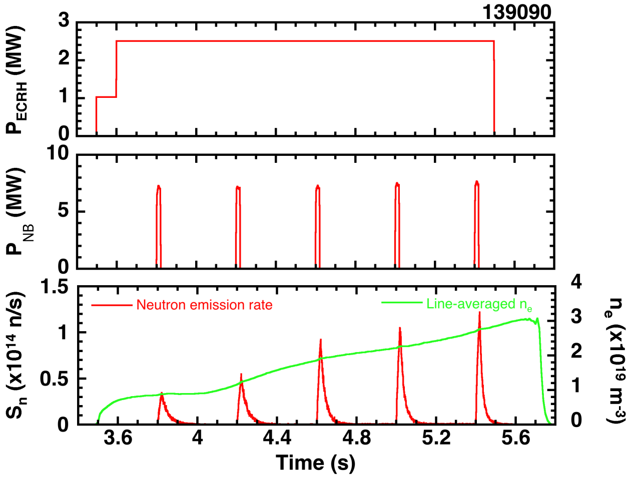

Fig. 4 Time evolution of total neutron emission rate when perpendicular NB#4 blips are repeatedly injected into an ECRH deuterium plasma at R_{ax}/B_t of 3.6 m/2.75 T. Electron density is ramped up to investigate neutron emission rate and its decay time right after NB turn-off.

To characterize neutron emission from LHD plasmas, density scanning experiments were carried out in three different magnetic field configurations, i.e., R_{ax} of 3.6 m, 3.75 m, and 3.9 m in high-B_t operation. The maximum neutron emission rates in each shot as a function of electron density are plotted in Figure 5. As can be seen, the total neutron emission rate observed in the plasma with R_{ax} of 3.6 m, i.e., inwardly shifted configuration is the highest, and it tends to decrease as R_{ax} is shifted outwardly. In LHD, the inwardly shifted configuration has provided the highest performance through good-confinement capability for helically trapped energetic ions. In LHD, because most of the neutrons are generated by beam-plasma interaction, the high neutron emission rates observed in R_{ax} of 3.6 m is supposed to be due to the highest T_e, in other words, the longest slowing-down time and good confinement property for helically trapped energetic ions among the three magnetic configurations.

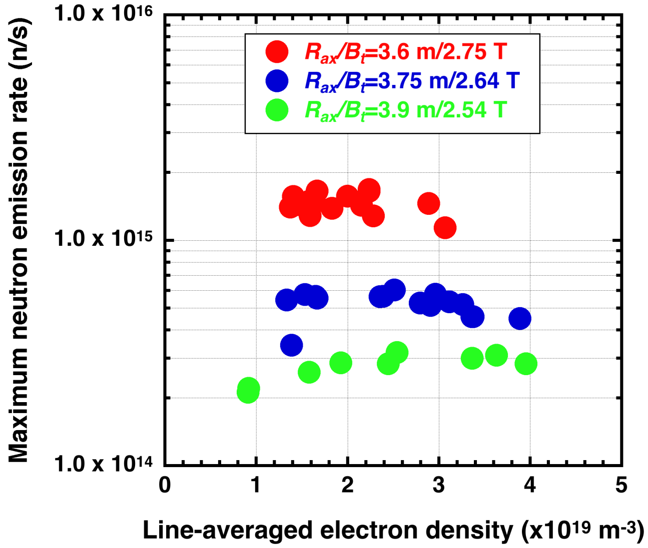

Fig. 5 Maximum neutron emission rate in three different magnetic configurations as a function of line-averaged electron density. Total neutron emission rate is the highest in an inwardly shifted configuration (R_{ax}=3.6 m) as expected. Plotted data were taken in May 23, 2017 when all five NBIs are deuterated.

B. *Neutron Activation System*

The neutron activation system (NAS) is one of the fundamental neutron flux measurement tools in neutron generation facilities. The NAS has been employed in deuterium operations of large tokamaks, as well [23, 24]. It is essentially insensitive to gamma-rays. Also, the NAS can measure both DD and DT neutron yield at the same time by choosing appropriate activation foil in accordance to the purpose. There are two primary roles of NAS in LHD. One is to manage total neutron yield. The NAS and NFM are complementary in evaluating neutron yield. The NAS can perform an important role in cross-checking neutron yield evaluated by the NFM. The other is to measure a triton burnup DT neutron fluence by choosing an activation foil of which threshold energy in reaction is higher than DD neutron energy.

Overview of the LHD NAS system is shown in Figure 6. The NAS on LHD has two irradiation ends at the vertically elongated and the horizontally elongated poloidal cross sections. In LHD, we prepared three different activation foils, i.e., indium, aluminum, and silicon. Each foil has the size of 10 mm ϕ and 1 mm thick and the purity is 99.999%. As for DD neutron measurement, we have used ^{115}In(n,n')^{115m}In nuclear reaction. Aluminum and silicon foils are used for 14 MeV neutron flux measurements. The activation foil is mounted inside a polyethylene capsule (18.5 mm ϕ and 40 mm long). A photograph of the capsule can be seen in Figure 6. The capsule is launched from the station before a shot and travels inside a pneumatic tube to the irradiation end. After the neutron irradiation is finished, it returns to the station, and then gamma-ray emitted from the activated foil is measured with a high-purity germanium (HPGe) semiconductor detector (Mirion Technologies(Canberra) KK, Model:GX3018/CP5-PLUS-U). In situ calibration of indium foil for the ring-shaped neutron source was carried out in November, 2016 during the NFM calibration [25].

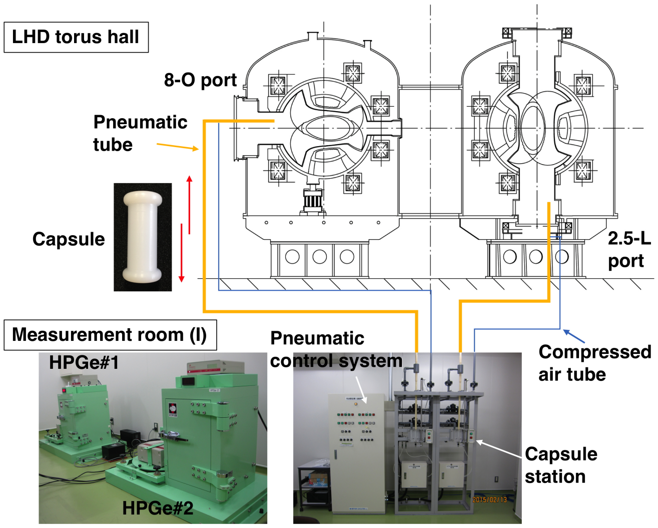

Fig. 6 Overview of neutron activation system on LHD. Two irradiation points are available at the horizontally and vertically elongated cross sections.

Shot-integrated neutron yields were evaluated for deuterium plasmas heated by perpendicular deuterium NBIs by using NAS, and were compared with those measured with NFM. The reaction of ^{115}In(n,n')^{115m}In was used in this analysis. The comparison result in neutron yield is shown in Figure 7. As can be seen, shot-integrated neutron yields measured with NAS agree well with those evaluated by NFM.

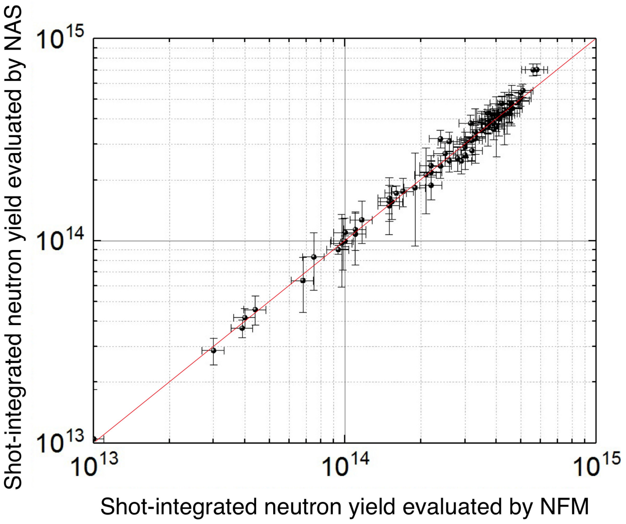

Fig. 7 Shot-integrated neutron yield evaluated by the neutron activation system as a function of that evaluated by the neutron flux monitor. Neutrons were produced by perpendicularly injected deuterium NBs. ^{115}In(n,n')^{115m}In reaction was used in this analysis.

C. *Vertical Neutron Camera*

Neutron profile diagnostic has been a powerful tool to diagnose spatial distribution of energetic ions in a fusion plasma [26-32]. It can play a practical role in studying radial beam ion transport induced by intrinsic magnetic field ripple and/or magnetic field perturbation leading to radiation transport of energetic ions [33, 34]. In LHD, a vertical neutron camera (VNC) was chosen for neutron profile diagnostic in terms of less effect of unfavorable radiation onto fast-neutron detector and construction cost. The overview of the LHD VNC is schematically depicted in Figure 8. A neutron collimator is essential in VNC. The neutron collimator in LHD is made of heavy concrete having the thickness of 1.5 m, and is embedded in the 2 m concrete floor of the LHD torus hall [35]. The heavy concrete having a high mass density (3.5 g/cm^2) was chosen in expectation of self-shielding effects against secondary gamma-rays produced by neutrons. Radially aligned eleven stainless steel cylinders of 3 cm ϕ and 150 cm long are embedded in a heavy concrete collimator as a path of unscattered fast neutrons. The spatial resolution of the LHD VNC was assessed by using the MCNP code. The analysis suggests that the spatial resolution is about 70 mm in full width at half

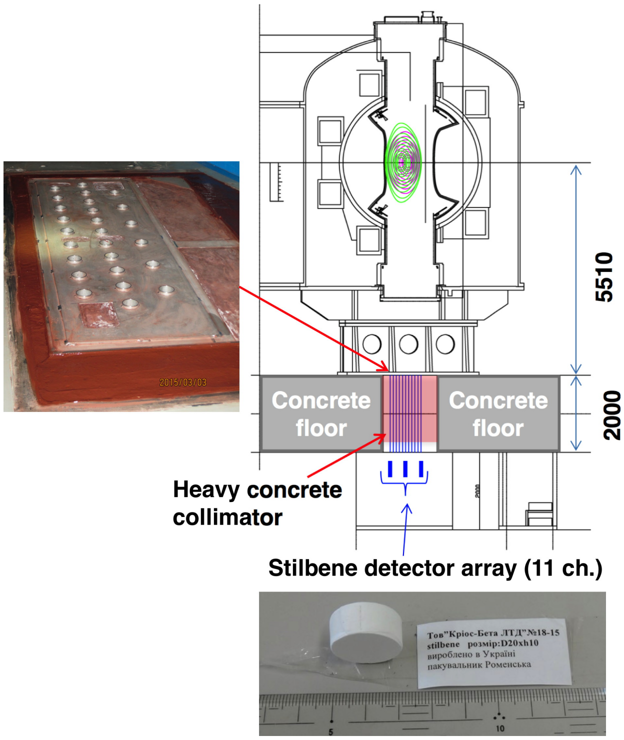

Fig. 8 Vertical neutron camera on LHD. Neutron collimator made of heavy concrete is embedded in the concrete floor of the LHD torus hall. The stilbene scintillation detector is chosen as a fast-neutron detector.

maximum, which is smaller than the collimator pitch [36]. As for a detector used in VNC, the stilbene scintillation detector was chosen in terms of brightness and good n-γ discrimination capability. Our fast-neutron detector system is characterized by multifunction. The whole system was designed so as to realize a wide dynamic range capability over 10^6 cps, having automated n-γ discrimination capability based on the leading edge fast digitizer equipped with a field-programmable gate array through numerous tests in accelerator-type monoenergetic neutron generation facilities. The system also can provide a raw shape of each pulse with a high-speed sampling frequency of 1 GHz at the same time. To demonstrate fundamental performance of the LHD VNC, spatial distributions of DD neutrons were measured in two different magnetic field configurations by using this system. As an initial result, line-integrated DD neutron pulse counts measured in deuterium NB-injected plasmas at inwardly shifted (R_{ax}=3.6 m) and outwardly shifted (R_{ax}=3.9 m) configurations are shown in Figure 9. The electron density was fixed to be ~ 2×10^{19} m^3 in both shots. The neutron emission profile is outwardly shifted in the plasma in R_{ax} of 3.9 m whereas it is inwardly shifted in R_{ax} of 3.6 m according to the magnetic axis positions as expected. We also performed a comparison of two neutron emission profiles between co- and counter-injected NB phases. VNC indicated that neutron emission profile is outwardly shifted in tangentially co-injected phase whereas it is inwardly shifted when NB is counter-injected according to characteristic difference of drift surfaces between co- and counter-going beam ions.

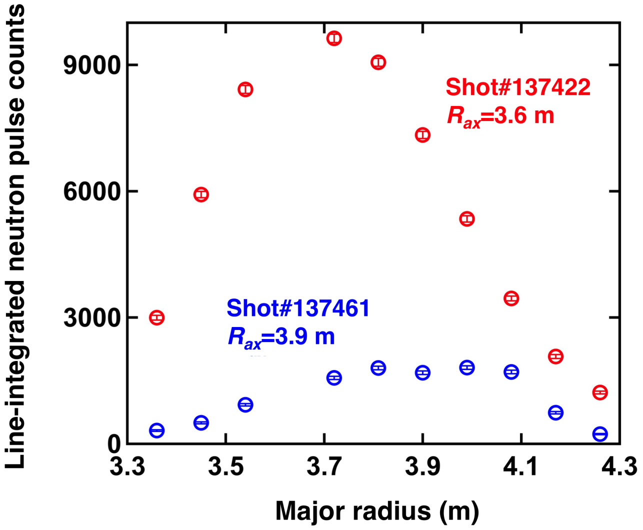

Fig. 9 Line-integrated DD neutron pulse counts in deuterium NB-injected plasmas at inwardly shifted (R_{ax}/B_t=3.6 m/2.75 T) and outwardly shifted (R_{ax}/B_t=3.9 m/2.538 T) configurations. The electron density was fixed to be ~2×10^{19} m^{-3}. Data accumulated from t=3.5 s to 4.5 s are plotted.

D. *Scintillating-fiber Detector*

A triton burnup study is one of the key subjects in the LHD deuterium phase to demonstrate that confinement capability of energetic ions is relevant to the future burning plasmas in a helical system. In a deuterium plasma, triton with birth energy of 1 MeV is produced due to d(d,p)t reaction and will undergo secondary d(t,n)α reaction with background deuterons while they slow down in a plasma. Kinetic parameters such as gyroradius and precessional drift frequency of trapped tritons are almost the same as those of DT alpha particles. Another important point to stress is that tritons born in a deuterium plasma are isotropic in velocity space unlike beam ions or fast ions accelerated by ion cyclotron resonance of frequency. It can be therefore mentioned that triton burnup study is equivalent to the study on DT born alpha particles. To investigate confinement property of 1 MeV tritons, DT neutron detectors based on Sci-Fi and NAS have been employed in LHD. The Sci-Fi detector was originally developed for time-resolved DT neutron flux measurement in TFTR [37, 38]. After TFTR, the Sci-Fi detector was adopted onto JT-60U to diagnose triton burnup DT neutron behaviors in deuterium plasmas [39, 40]. Secondary DT neutron measurement began in LHD by using three different Sci-Fi detectors and NAS. Head sections of two detectors are shown in Figure 10. Since forwardly recoiled proton gives maximum energy deposition onto scintillating fiber, we pick up pulses having high pulse-height generated by protons forwardly scattered by incident of DT neutrons.

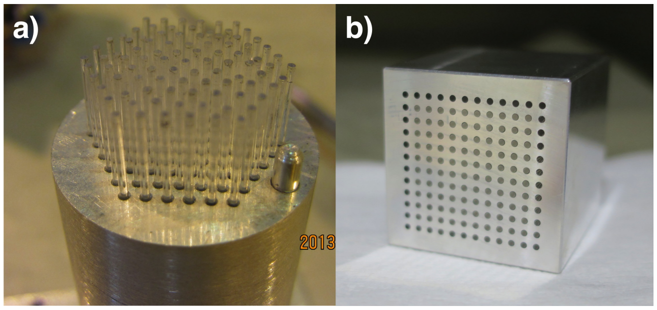

Fig. 10 Sci-Fi detectors installed onto LHD. a) Detector transferred from the JT-60U tokamak, b) Detector developed in National Institute of Technology, Toyama College.

Triton burnup ratio was evaluated in stellarator/heliotron devices for the first time. It is defined as a ratio of secondary DT neutron yield to total neutron yield. The Sci-Fi detector is calibrated by using results measured with calibrated NAS. Therefore, triton burnup ratio can be evaluated in every discharge in LHD. Confinement property of helically trapped energetic ions largely depends on magnetic field configurations. Collisionless orbits of helically trapped energetic ions in R_{ax} of 3.6 m, 3.75 m, and 3.9 m are shown in Figure 11(a), (b), and (c), respectively. Drift surface of trapped energetic ion in R_{ax} of 3.6 m matches with magnetic flux surfaces relatively. The drift surface tends to deviate largely from magnetic flux surfaces as magnetic axis position is shifted outwardly. The triton burnup ratios in R_{ax} of 3.6 m, 3.75m, and 3.9 m are plotted in Figure 11(d). The triton burnup ratio tends to decrease as the plasma column is shifted outwardly as expected from orbit calculations. So far, the highest triton burnup ratio was obtained in the inward shifted configuration (R_{ax}/B_t=3.55 m/2.89 T) and was evaluated to be 0.45 %.

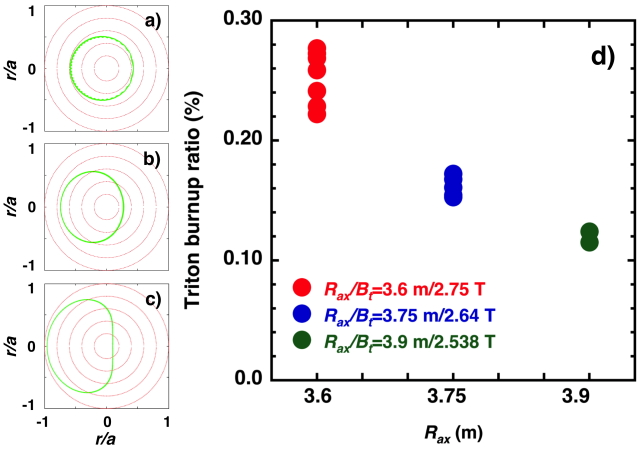

Fig. 11a) Collisionless orbit of helically trapped energetic ion in R_{ax} of 3.6 m, b) Trapped orbit in R_{ax} of 3.75 m, c) Trapped orbit in R_{ax} of 3.9 m, and d) Triton burnup ratio evaluated by the scintillating-fiber detector calibrated by the calibrated neutron activation system. Electron density ranges from 2×10^{19} m^{-3} to 3×10^{19} m^{-3} in these shots. Triton burnup ratio decreases as the magnetic axis position is shifted outwardly.

IV. SUMMARY

The LHD project has entered a new stage. The deuterium experiment began on March 7, 2017. A comprehensive set of neutron diagnostics has been installed onto LHD. NB-driven neutrons are dominant in LHD. Prior to the start of deuterium operation, in situ calibration of NFM were performed by using an intense ^{252}Cf neutron source in November 2016. Total neutron emission rate and yield have been measured with NFM characterized by fast response and wide dynamic range capabilities. The perpendicular beam blip injection experiment showed reasonable time evolution of neutron rate. Peak value of neutron rate increases and neutron decay time after NB-turn off tends to be shorter as electron density increases. So far, the total neutron emission rate has reached 3.3×10^{15} n/s. Neutron emission rate in inwardly shifted configuration was higher than that in outwardly shifted configuration as expected. The neutron yield was also assessed by using NAS in the early phase of deuterium operation when deuterium NBs were perpendicularly injected. Neutron yield evaluated by NAS agrees with that measured with NFM. Commissioning of VNC is steadily in progress. Neutron emission profile measured in R_{ax} of 3.9 m was outwardly shifted, compared with that in R_{ax} of 3.6 m as expected. In addition to NFM, NAS, and VNC, measurement of secondary DT neutron flux has begun by using Sci-Fi detectors to investigate confinement property of 1 MeV tritons. The triton burnup ratio was measured in LHD for the first time among heliotron/stellarators in the world. So far, the ratio has reached about 0.3% in the inwardly shifted configuration, decreasing as a plasma column is shifted outwardly as expected according to confinement property of helically trapped energetic-ion orbit.

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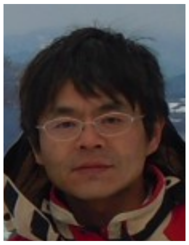

Mitsutaka Isobe was born in Nagoya city, Aichi, Japan in 1967. He received the B.S. and the M.S. degrees in applied physics from Fukui University, Fukui, Japan, in 1991 and 1993, respectively, and Ph.D. degrees in fusion science from SOKENDAI (The Graduate University for Advanced Studies), Hayama, Japan, in 1996. He has been working on helical devices, i.e., CHS and LHD. He is currently a Professor with the National Institute for Fusion Science since 2015. His current research interest is the confinement study of energetic ions by means of neutron diagnostics in the LHD plasma.

Kunihiro Ogawa was born in Mino city, Gifu, Japan in 1984. He entered Ritsumeikan University, Shiga, Japan and majored in electrical and electronic engineering. He skipped the B.S. degree and entered Nagoya University in 2006. He completed his M.S. and Ph.D. degrees in department of energy science and engineering of Nagoya University, Nagoya, Japan, in 2008 and 2011, respectively. He worked on National Institute for Fusion Science from 2012. He is currently an Assistant Professor with the National Institute for Fusion Science since 2013. His current research interest is the energetic-ion confinement in the LHD plasma.

Takeo Nishitani was born in Otawara city, Tochigi, Japan in 1954. He received the B.S. degree in nuclear engineering from Tohoku University, Sendai, Japan, in 1978, the M.S. degree in nuclear engineering from the University of Toyo, Tokyo, Japan, in 1980, and the Ph.D. degree in nuclear engineering from the University of Tokyo. He worked on the neutron diagnostics of the JT-60 tokamak in the Japan Atomic Energy Research Institute (JAERI) from 1980 to 2001. He was a Principal Scientist with Japan Atomic Energy Agency (JAEA) and worked on the fusion neutronics. He is currently a Specially Appointed Professor with the Institute for Fusion Science since 2015. His current research interest is the neutron diagnostics development and the energetic particle behavior study in the LHD plasma.

Hitoshi Miyake was born in Mizunami city, Gifu, Japan in 1957. He received the B.S. degree in physical chemistry from Toyama University, Toyama, Japan, in 1981. He worked on the tritium diagnostics and the tritium safety handlings in the Tritium Research Center of Toyama University from 1981 to 1993. He worked on the radiation safety and the development of environmental radiation diagnostics around the LHD from 1994 to 2018 in the National Institute for Fusion Science. He is now a senior adviser for radiation safety in the National Institute for Fusion Science.

Takashi Kobuchi received the Ph.D. degrees in fusion science from SOKENDAI (The Graduate University for Advanced Studies), Hayama, Japan, in 2001. He is currently a technical staff of diagnostics technology division on National Institute for Fusion Science. He has been developing the plasma diagnostics of the LHD, and supporting the operation and maintenance.

Neng Pu was born in Chengjiang, Yunan province, China in 1985. He received the B.S. and M.S. degrees in Heilongjiang University, Haerbin, Heilongjiang, China in 2008, and Yunnan University, Kunming, Yunnan, China in 2012. He worked at Institute of Plasma Physics, Chinese Academy of Sciences (ASIPP), Hefei, Anhui, China from 2012 to 2016. He is currently a Ph.D. student of SOKENDAI (The Graduate University for Advanced Studies) since October 2016.

Hiroki Kawase was born in Nagoya city, Aichi, Japan in 1993. He received the B.S. degree in physics from Ehime University, Matsuyama, Japan, in 2016. He is currently a Ph.D. student in SOKENDAI (The Graduate University for Advanced Studies) since 2016. His current research interest is the confinement study of energetic ions with neutron diagnostics in the LHD plasmas.

Eiji Takada was born in Toyama city, Toyama, Japan in 1964. He received the B.S. and M.S. degrees in nuclear engineering from University of Tokyo, Tokyo, Japan, in 1986 and 1988, and the Ph.D. degree in nuclear engineering from the University of Tokyo. From 1988 to 1994, he engaged in researches on global environmental change in Mitsubishi Research Institute, Inc. He worked on the radiation measurement with optical fibers in University of Tokyo from 1994 to 1999. Since 1999, he has been working in National Institute of Technology, Toyama College. His current interest is neutron diagnostics especially with scintillating optical fibers in the fusion experimental devices. He is also working on new types of radiation detectors as those with organic semiconductor materials.

Tomoyo Tanaka was born in was born in Nagoya city, Aichi, Japan. She received the B.S. degrees in physical engineering from Nagoya University, Nagoya, Japan, in 2017. She is currently a graduate student with Nagoya University since 2017. Her current research interest is the study of neutron spectrum measurement using neutron activation method on LHD.

Siyuan Li was born in Yangzhou city, Jiangsu, China in 1992. He received the B.S. degree in Department of Applied Nuclear Technology from Fukui University of Technology, Fukui, Japan, in 2017. He is currently a graduate student with Nagoya University since 2017. His current research interest is the measurement of neutron from accelerator for boron neutron capture therapy.

Sachiko Yoshihashi was born in Toyota city, Aichi, Japan. She received the B.S. degrees in electronic information engineering from Gifu University, Gifu, Japan, in 1996, M.D. and Ph.D. degrees in electrical engineering from Osaka University, in 1998 and 2001, respectively. She was an Assistant Professor at Graduate School of Engineering, Osaka University from 2001 to 2014. On 2015, she was employed an Associate Professor at Fukui University of Technology. She is currently an Associate Professor with the Nagoya University since 2016. Her current research interest is the neutron measurement.

Akira Uritani was born in Tanabe city, Wakayama, Japan in 1961. He received the B.S., M.S. and Ph.D. degrees in nuclear engineering from Nagoya University, Nagoya, Japan, in 1984, 1986, and 1992, respectively. He had worked on radiation measurements at Nagoya University from 1990 to 2001. He had worked on neutron standards at the National Institute of Advanced Industrial Science and Technology from 2001 to 2005. He has been a professor of Nagoya University since 2005. His current research interests are industrial and medical applications of radiations, especially neutrons.

Jungmin Jo was born in GwangMyeong-city, Gyeonggi-Do, South Korea in 1986. He received the B.S. degree in physics from Hanyang University, Seoul, Korea, in 2012 and M.S. degree in nuclear engineering from Seoul National University, Seoul, Korea, in 2014. He is currently a Ph.D. student of Seoul National University since 2014. His current research interest is the confinement study of energetic particle with neutron diagnostics in magnetic confinement fusion plasma.

Sadayoshi Murakami was born in Mihara town of Awaji Island, Hyogo, Japan. He received the B.S., M.S. and Ph.D. degrees in material science from Hiroshima University, Hiroshima, Japan. He has been working on the simulation of fusion plasmas. He is currently a Professor of Department of Nuclear Engineering, Kyoto University since 2016. His current research interest is the kinetic physics related to the plasma heating and the neoclassical transport in toroidal plasmas.

Masaki Osakabe was born in Souka city, Saitama, Japan in 1965. He received the B.S. degree in nuclear engineering from Nagoya University, Nagoya, Japan, in 1988, the M.S. degree in nuclear engineering from the Nagoya University, Nagoya, Japan, in 1991, and the Ph.D. degree in fusion science from SOKENDAI (The Graduate University for Advanced Studies). He worked for the neutral beam injection heating for the Large Helical Device (LHD) at National Institute for Fusion Science and also worked on energetic-particle confinement studies in toroidal plasmas from 1995. He is currently a Professor and the executive director for machine of LHD project. His current research interest is the energetic-particle behavior study in the toroidal plasmas, the plasma heating by energetic particles and ion source development for plasma heating.