Neutron flux distributions in the Large Helical Device torus hall evaluated by an imaging plate technique in the first campaign of the deuterium plasma experiment

Makoto Kobayashi$^{1,2}$, Tomoyo Tanaka$^3$, Takeo Nishitani$^1$, Kunihiro Ogawa$^{1,2}$$^\circ$, Mitsutaka Isobe$^{1,2}$, Gen Motojima$^{1,2}$$^\circ$, Akemi Kato$^1$, Sachiko Yoshihashi$^3$, Masaki Osakabe$^{1,2}$ and LHD Experiment Group

1 National Institute for Fusion Science, National Institutes of Natural Sciences, Toki, Japan
2 SOKENDAI (The Graduate University for Advanced Studies), Toki, Japan
3 Nagoya University, Nagoya, Japan

E-mail: kobayashi.makoto@nifs.ac.jp

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Abstract

The global flux distributions for thermal, epithermal and fast neutrons in the torus hall of large fusion devices were experimentally evaluated for the first time in the Large Helical Device (LHD) using the activation foil method measured by the imaging plate and high-purity germanium detector. It turned out that the thermal neutrons were effectively absorbed by borated polyethylene blocks placed beneath the LHD. This should reduce the radioactivity of the floor and would be beneficial in maintaining a good environment for radiation workers. Uniform distributions of epithermal and fast neutrons were observed near the LHD. In particular, the significant decrease in fast neutron flux with increasing distance from the LHD, due to the fast energy loss of fast neutrons, was observed.

The neutron flux distribution measurement, with rough energy discrimination based on the threshold energy of the neutron activation foil, allows us to estimate the spatial radiation dose rate, as well as the radioactivity in components in the torus hall. The prediction of the radioactivity in the concrete floor indicated that radioactive isotope $^{55}$Fe will be a dominant source of radioactivity in the concrete after the nine-year deuterium experiment campaign finishes.

Keywords: neutron, LHD, imaging plate, high purity Germanium detector, MCNP

(Some figures may appear in colour only in the online journal)

1. Introduction

The experiments with deuterium plasma (deuterium plasma experiment) began in March 2017 in the Large Helical Device (LHD), one of the largest superconducting fusion plasma experimental machines in the world. The deuterium fusion reaction produces neutrons and tritium. Therefore, an appropriate radiation control for safe operation is of importance. The National Institute for Fusion Science (NIFS) has established the institutional radiation control regulations for the deuterium plasma experiment [1, 2]. This regulation limits the release of radiation into the environment in order to obtain public acceptance of the deuterium plasma experiment in the LHD.
For the safe operation of deuterium plasma in the LHD, the radiation control inside the torus hall is important too. Neutrons will be captured by many components in the torus hall, making them radioactive. The activated materials emit gamma/beta rays, producing a radiation dose for workers. Also, the radiation field in the torus hall occasionally causes malfunctions in highly integrated electronic components such as programmable logic controllers [3, 4]. Therefore, estimation of the radiation field produced by neutron transport is important for the steady operation of the LHD.

The other important purpose of radiation control is to plan the decommissioning of the LHD in the future. In the decommissioning of the LHD, the radioactivity of components such as the LHD body, heating system, diagnostics, and concrete walls should be evaluated precisely. The neutron distribution in the torus hall, which allows us to predict the radioactivity in the torus hall during the deuterium plasma experiment in the LHD, is required. The prediction of neutron transport and consequent radioactivity in materials during the deuterium experiment in the LHD has been estimated by using DORT 3.5, which is a 2D neutron transport code, combined with CINAC code [5]. In addition, the 3D neutron transport model, using a general Monte Carlo N-particle transport (MCNP) code, was developed for the LHD [6]. However, in both cases, many components around the LHD were absent in the calculation, although the neutron transport calculation relies on the precise input geometry data. As is the case with the LHD, the fusion devices, including ITER and DEMO, commercial reactors, and their torus halls, will have a large size with many components. As with the complex components of fusion devices, and the characteristics of neutrons by which neutrons can stream through a narrow pass, it is necessary to acquire the neutron flux distribution in the torus hall by actual measurements.

This paper reviews the experimental evaluation of the global flux distributions for fast, epithermal and thermal neutrons in the torus hall, measured in the first campaign of the deuterium plasma experiment in the LHD. The activation foil method, using indium (In), gold (Au) and nickel (Ni), was applied for neutron flux measurement. Although the activation foil method is a typical method to measure neutron flux, even in the field of fusion research [7, 8], this work is the first precise evaluation of neutron flux distribution discriminating the neutron energy, utilizing several tens of various activation foils placed in the torus hall of a large fusion device, which will be a benchmark not only for the LHD but also for other devices such as ITER and DEMO. The radioactivity of the foils was evaluated by the high-purity germanium detector (HPGe) for precise radioactivity determination and the imaging plate (IP) method for measuring many samples in a short time. In addition, according to the neutron flux distribution obtained in this work, the radioactivity in the plain concrete, which is the dominant component of the floors and walls of the LHD torus hall, during/after the deuterium experiment in the LHD, were evaluated.

2. The component layout in the LHD torus hall

The torus hall of the LHD is 75 m wide, 45 m long and 40 m high. The walls of the torus hall are made of plain concrete. The thicknesses of the walls and the floor of the torus hall are 2 m. The details of the component layout in the torus hall are shown in figure 1. The vacuum vessel of the LHD is equipped with two helical coils and six poloidal field coils. These coils are covered by the cryostat to prevent air exposure to the surface of coils for cooling. The deuterium plasma is generated by heating deuterium. The neutron is then generated by the fusion reaction. The components for heating plasma, plasma diagnostics, and other purposes are connected to the LHD [9, 10]. A major heating system in the LHD is the neutron beam injector (NBI) [11]. There are five NBIs for the LHD. Three of them can inject a neutral beam into the plasma tangentially and are...
called t-NBI (#1, #2, #3). The two others perpendicularly inject the neutral beam, and are described as p-NBI (#4, #5) in figure 1. In the NBI, part of the energetic deuterium collides with deuterium retained in the beam dump. Therefore, neutrons will be generated. In the present study, several combinations of hydrogen and deuterium were used as the source gas in the NBI. However, the neutron flux distribution in the torus hall should be independent of the source gas of each NBI because the neutron yield in the beam dump of the NBI is estimated to be three orders of magnitude lower than that in the LHD plasma [1].

The neutron yield during the deuterium plasma experiments were measured by the neutron flux monitors (NFM), which are located at the top of the LHD center axis (#1), near the large outside port on the mid plane (#2, #3), consisting of the 235U fission chamber, the 10B counter, and the 3He counter [12–14]. The neutron activation system (NAS) is also equipped in the LHD, which consists of pneumatic tubes to send the activation foils near the vacuum vessel, for the cross-check of the NFM. The details of the NAS are available in [15].

The borated polyethylene blocks were used as the neutron shield for components. Polyethylene effectively decelerates the kinetic energy of neutrons generated in the deuterium plasma. Then, boron contained in the polyethylene blocks captures thermal neutrons using the large cross section of the 10B(n,α)7Li reaction [17]. The borated polyethylene blocks contain 10% boron. On the floor underneath the LHD, the borated polyethylene blocks were placed in a disc shape with an inner radius of ~2.3 m, an outer radius of ~6.9 m, and a thickness of 5 cm. Exceptionally, unborated polyethylene blocks were used just below the 8.5-L port of the LHD, which is the west side of the LHD, as seen in figure 1, and they occupied 36° of the disc-shaped polyethylene blocks underneath the LHD.

3. Experimental

3.1. Activation foil

In, Au, and Ni were selected as the activation foil in this work. The radioactive isotopes of these activation foils emit a gamma ray with a specific energy. In and Au have large cross sections to capture thermal neutrons. In has two isotopes, 113In and 115In. The natural abundances of these indium isotopes are 4.3% and 95.7%, respectively. Thermal neutrons react with 115In as 115In(n,γ)116mIn. The minor isotope of indium, 113In, also reacts with thermal neutrons as 113In(n,γ)114mIn. The half-lives of 114mIn and 116mIn are 49.5 d and 54.3 min, respectively [18]. Au exists in nature as 197Au (100% abundance). Neutrons react with 197Au as 197Au(n,γ)198Au. The half-life of 198Au is 2.7 d [18]. In this study, Au foils were covered by cadmium (Cd) filters with a thickness of 1 mm. Cd is capable of absorbing thermal neutrons. Epithermal neutrons can penetrate the Cd filter to react with Au foil. It was assumed in this study that the radioactivity in the Au foil with Cd filters is only caused by epithermal neutrons. 58Ni is a major isotope of nickel (about 68% natural abundance). A threshold energy is required for the reaction of 58Ni(n,p)58Co to occur. Therefore, fast neutrons can produce 58Co in Ni. The half-life of 58Co is 70.8 d. Therefore, Ni foils were used as a fast-neutron detector in this study. In and Au foils were cut into squares of 0.5 × 0.5 mm². The thickness of the In foils was 0.5 mm, and that of the Au foils was 0.1 mm. The size of the Ni foils was 20 × 20 × 2 mm² to increase the radioactivity. Finally, these foils were put into plastic bags for neutron irradiation.

3.2. Neutron irradiation in the torus hall

In the weekly operation of the LHD, the first weekday is assigned for maintenance work. The other weekdays are for experiment. The samples were placed on the floor of the LHD torus hall on the maintenance day. The positions of the In, Au, and Ni foils are presented in figures 4–6, shown by the red circles, respectively. In foils were irradiated with neutrons in the the LHD torus hall for one day. Au foils with a Cd filter were irradiated with neutrons for one week. Ni foils were exposed to neutrons in the torus hall for two months in order to accumulate the radioactivity. However, the fast-neutron measurement by Ni foils placed far away from the LHD was not tried in this campaign because the radioactivity in Ni foils will be below the detection limit (~10⁻² Bq g⁻¹) of HPGe in that region. After their specific neutron irradiation durations, the samples were taken out of the torus hall for analysis. In particular, for In, because of the fast decay rate of 116mIn, all foils were salvaged from the torus hall within several hours after the daily experiment finished. For Au, foils were taken out of the torus hall after 2 d had passed since the last plasma operation.

3.3. Evaluation of the neutron flux distribution

One of the analysis systems used in this work was HPGe. HPGe has the capability to identify the radioactive isotopes by gamma-ray energy spectrometry. HPGe can also evaluate the precise quantity of radioactive isotopes. However, this method requires a longer time to measure one sample. The HPGe detector used in this work was supplied by Canberra Industries, Inc. (Model: GX3018/CP5-PLUS-U). Because the detector is in a lead shield with a thickness of 100 mm, the influence of external background radiation is sufficiently reduced. Output pulses from a preamplifier are fed into a multichannel analyzer, a DSA-LX by Canberra Industries.

The other method was IP. IP is a sheet-type detector which can store the energy transferred from radiation [19]. IP can release the integrated stored energy as photo-stimulated luminescence (PSL) by laser injection. IP is usually applied for 2D visualization of the radiation source as it has the capability to measure a large surface area. The IP sheet used in this work was BAS-SR 2040 manufactured by Fujifilm.

After salvaging, samples were mounted on a mylar file with a thickness of 100 μm, as shown in figure 2. The PSL values were measured by an image reader, Typhoon FLA 9500 by GE Healthcare. The average PSL values over the foil...
surface area were calculated using the software Image Quant TL, developed by GE Healthcare. The background PSL value was subtracted by measuring the PSL values for the region away from foils. In this work, the calibration of the PSL value to convert the radioactivity in the foils was carried out by measuring several foils by HPGe. The conversion factors from the PSL to radioactivity were obtained. The details of these analyses were described in our previous work [20]. For Ni, due to the low radioactivity and sufficiently long half-life, all samples were measured by HPGe.

The radioactivity in the foil measured by HPGe and IP correlates with the neutron fluence. The neutron flux at the position of the foil was evaluated by the following equation,

$$\frac{dN^{(A)}}{dt} = N^{(S)} \sigma \phi - \frac{\ln 2}{T_{1/2}} N^{(A)}.$$  

Here, $N^{(A)}$ and $N^{(S)}$ are the amounts of radioactive and stable isotopes, respectively, $\phi$ presents the neutron flux ($\text{cm}^{-2}\text{s}^{-1}$) and $T_{1/2}$ is the half-life (s). The reaction cross section, $\sigma$($\text{cm}^2$), is dependent on the neutron energy. The value of $\sigma$ is different for each activation foil and for each different place where the activation foils were set. In this study, $\sigma$ was evaluated by MCNP6 calculation based on our previous work [21]. The $N^{(A)}$ is zero before the neutron irradiation. Note that neutron flux is different for each activation foil and for each different place where the activation foils were set. In this study, $\sigma$ was different in each deuterium plasma operation, and $N^{(A)}$ is determined by the integration of these different neutron fields. On the other hand, the source and the energy of neutrons are almost the same in every deuterium plasma operation. Therefore, only $\phi$ is different in every plasma, and $\phi$ is proportional to neutron yield, which was measured by NFM.

4. Prediction of radioactivity in the concrete floor during the deuterium experiment

The prediction of the radioactivity in the concrete floor during the deuterium experiment was evaluated using the neutron flux distribution estimated in this work. The DCHAIN-SP code bundled in the PHITS code was used for the activation calculation [22]. DCHAIN-SP requires the composition of the concrete, the irradiation time, the cooling time, the neutron energy spectrum and the neutron flux to estimate the radioactivity.

The composition of plain concrete adopted in this study is the same as that used in our previous study [5]. The weight percent of hydrogen, oxygen, silicon, aluminum, calcium, sulfur, iron, magnesium, sodium, and potassium are 0.54, 47.98, 30.41, 4.40, 7.95, 0.12, 4.88, 0.23, 1.64, and 1.85, respectively. Note that the minor elements in concrete such as cesium, cobalt and europium were not considered in this study [23].

For the irradiation time and cooling time, the plasma operation period of four months and the maintenance period of eight months, were assumed to be an annual operation according to the previous experimental campaigns. The deuterium experiment in the LHD is planned to take nine years. The maximum annual neutron yield in the first six years is $2.1 \times 10^{19}$, and in the last three years is $3.2 \times 10^{19}$.

The neutron flux and neutron energy spectrum were tentatively evaluated by the MCNP6 code and corrected by the results of actual neutron flux measurement by activation foils in this study. The model for MCNP6 calculation used in this work includes the LHD body, the cryostat, the torus hall, and the basement of the torus hall. Pipes and ducts between the torus hall and the basement were also taken into account. The polyethylene blocks underneath the LHD were also considered. This model for MCNP6 calculation has already been applied to the calibration of NFM in the LHD, and the details of this model can be found in [20]. With this model, the nuclear data library of ENDF/B-VII.1 was used [24]. The calculation was performed until the statistical error became less than 0.1.

In this study, the neutron was separated by its kinetic energy into the thermal neutron, epithermal neutron, and fast neutron, which are defined as neutrons with energy ranged below 0.55 eV, 0.55 eV–100 keV, and above 100 keV, respectively. The fluences for the thermal neutron, epithermal neutron and fast neutron estimated by MCNP6 calculation were corrected by the neutron flux evaluated by In foils, Au foils with Cd filter, and Ni foils, respectively.
5. Results and discussion

5.1. Neutron flux distribution

The typical gamma-ray spectra obtained by HPGe measurements for In, Au, and Ni foils are shown in figure 3. For In, there were many peaks at 417, 819, 1097, and 1294 keV, which are caused by $^{116m}$In. For Au, a major gamma-ray peak at 411 keV was observed. This peak was attributed to gamma-rays from $^{198}$Au. In the measurement for Ni foils, there were two major peaks. One of them was located at 811 keV, and this gamma-ray was emitted by $^{58}$Co. The other peak at 511 keV should be generated by the electron-positron annihilation. Because $^{58}$Co decays with electron capture and $\beta^+ \text{ decay}$ mode, the positron emitted in the $\beta^+$ decay process reacted with the electron in the HPGe system and was detected. The peak areas in these spectra corresponded to the radioactive isotopes in the foils.

The thermal neutron distribution on the floor level of the LHD torus hall measured by In foils is shown in figure 4. In this figure, the local thermal neutron flux, $\varepsilon_{th}$, is defined as the local thermal neutron flux for a single neutron source. The mapping of flux distribution was done using GMT (Generic Mapping Tool), ver. 5. The thermal neutron flux distribution was concentrated within about 15 m from the center of the LHD. The relatively high thermal neutron flux was observed at the position underneath the 8.5-L port and the center of the LHD. As described in section 2, polyethylene blocks were placed in a disc shape underneath the 8.5-L port of the LHD. Most of the blocks contain 10% boron to absorb thermal neutrons. However, the polyethylene blocks were absent in the center part of the LHD. Fast neutrons from the LHD were thermalized effectively in the concrete floor as it contains a large amount of water, resulting in the relatively high thermal neutron flux there. Besides, the unborated polyethylene blocks were placed underneath the LHD. The fast neutrons were effectively converted to thermal neutrons there. Consequently, the borated polyethylene blocks effectively worked to reduce the radioactivity underneath the LHD.

Figure 5 shows the flux distribution of epithermal neutrons in the torus hall experimentally evaluated by the Au foils with a Cd thermal neutron absorber [25]. Unlike the thermal neutron distribution shown in figure 4, the epithermal neutron distribution showed almost uniform flux underneath the LHD. The epithermal neutrons were generated by the deceleration processes of fast neutrons. As is the case with thermal neutrons, polyethylene blocks would effectively convert fast neutrons to epithermal neutrons. However, boron inside the polyethylene blocks would not largely capture epithermal neutrons because the cross section of the $^{10}$B$(n,\alpha)^7$Li reaction is almost proportional to the reciprocal of the square root of the neutron kinetic energy [16]. Consequently, the uniform distribution of epithermal neutrons underneath the LHD is reasonable.

Fast-neutron flux distribution around the LHD is described in figure 6. The fast-neutron flux distribution away from the LHD was not measured in this study, as explained in section 3.2. Therefore, fast-neutron distribution near the LHD was evaluated in figure 6. The almost uniform distribution of fast neutrons underneath the LHD was observed. The flux of fast neutrons near the LHD was about one order of magnitude higher than that of thermal neutrons. The fast-neutron flux decreased sharply as the distance from the LHD increased.
compared to those of thermal neutrons and epithermal neutrons, due to the quick energy loss process of fast neutrons with components.

5.2. Activation evaluation for the concrete floor

According to figures 4–6, the largest neutron flux was found underneath the 8.5-L port on the floor level. Therefore, the radioactivity in the top surface of the concrete floor at this position is valuable from a safety point of view. The predicted radioactivity of 55Fe should be controlled. It was predicted that a wait of more than ten years will be required after the end of the deuterium experiment campaign for 55Fe to be below 0.1 Bq g⁻¹. The major generation channel of 55Fe should be the 54Fe(n,γ)55Fe reaction, which mainly occurs by thermal neutron. Therefore, as is the case with other positions underneath the LHD, the installation of a thermal neutron absorber, such as borated polyethylene blocks, underneath the 8.5-L port is available to mitigate the cooling time for 55Fe in the concrete floor.

Also, the minor elements in the concrete such as cesium, cobalt and europium were not considered in this study, although these elements usually create radioactive isotopes with a longer half-life [23]. The validity check for the prediction in this study, by the actual gamma-ray spectroscopy measurement for concrete, will be carried out in the future.

6. Summary

The flux distributions of thermal, epithermal and fast neutrons on the floor level of the LHD torus hall in the first campaign of deuterium plasma experiments in the LHD were experimentally evaluated using activation foils and by applying the IP and HPGe measurements. The relatively high thermal neutron fluxes were observed around the 8.5-L port and the center of the LHD. The borated polyethylene blocks worked well to reduce thermal neutron flux and the subsequent activation of components. Unlike thermal neutrons, the fluxes of epithermal neutrons and fast neutrons underneath the LHD were almost uniform. Because the ratio of 2.45 MeV and 14.1 MeV neutrons generated in the deuterium plasma in the LHD would not largely change, the distribution obtained in this work will be available for the future campaigns of the deuterium plasma experiment. According to these results, the prediction of radioactivity in the concrete floor during deuterium experiments was carried out for the decommissioning of the torus hall. The radioactivity of 55Fe should be a major radioactive isotope in the concrete. A radioactivity of less than 0.1 Bq g⁻¹ will be achieved over 11 years after the nine-year deuterium experiment in the LHD has finished.

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ORCID iDs

Kunihiro Ogawa https://orcid.org/0000-0003-4555-1837
Gen Motojima https://orcid.org/0000-0001-5522-3082
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