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First measurements of thermal neutron distribution in the LHD torus hall generated by deuterium experiments

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ABSTRACT

For the estimation of the neutron field generated by deuterium plasma operation in the Large Helical Device (LHD), the first measurement of the thermal neutron distribution on the floor level of the LHD torus hall was carried out. For the thermal neutron detection, indium was used as activation foils. The radioactivity of these foils were evaluated by a high-purity germanium detector (HPGe) and an imaging plate (IP). The major components of radioactive isotope of indium was ^{116m}In. The mapping of thermal neutron distribution in the torus hall was performed. The interactions between neutron and components around LHD were observed in the thermal neutron distribution. Also, the borated polyethylene blocks effectively absorbed the thermal neutron. The thermal neutron distribution evaluated in this work can be helpful to predict the amount of radioactive waste in the torus hall proceeding with deuterium experiment in LHD.

1. Introduction

In the Large Helical Device (LHD), which is one of the largest superconducting fusion plasma experimental machines, experiments using deuterium plasma (deuterium experiment) began in March 2017. In the commissioning of deuterium experiments, the control of radiation such as tritium and neutrons generated by deuterium fusion reaction is remarkably important. The annual neutron yield is permitted up to 2.1×10^{19} [1]. It is also predicted that the maximum neutron yield is 1.9×10^{16} n s^{-1}. It is well known that neutron easily penetrates almost any kind of materials and activates materials mainly by the neutron capture reaction. The activated materials emit gamma/beta rays, and this results in a radiation dose for workers. Also, those interactions of neutron occasionally produce a malfunction in highly integrated electric components such as programmable logic controller (PLC) [2,3]. For the steady operation and the maintenance of LHD, neutron transport and subsequent activation should be precisely predicted.

The activation process of neutron depends not only on the materials but also on the neutron energy. In the deuterium plasma, most of the neutrons should be generated by the fusion reaction between deuterium with the energy of 2.45 MeV. Otherwise, tritons generated by a deuteron-deuteron fusion reaction subsequently react with other deuterons, resulting in the deuteron-triton fusion reactions, which produce the 14.1 MeV neutrons. These neutrons move from LHD plasma and lose their energy by collisions with the LHD machine itself as well as with the surrounding components and the concrete walls of the experimental building. The species of radioactive isotopes in the torus hall have specific decay processes and decay rates. Some radioactive isotopes have long half-lives, and will still survive even after a long time has passed following the shutdown of LHD. The prediction of radioactivity in the torus hall proceeding with deuterium experiments is required for the future decommissioning of LHD.

Three-dimensional Monte Carlo simulation is typically used to predict the neutron behavior and the activation in system. In particular, a General Monte Carlo N-Particle Transport Code version 6 (MCNP6) has been applied for the neutronics of LHD [4,5]. The distribution and energy spectrum of neutron as well as gamma-ray in the torus hall and the basement of the LHD experimental building have been calculated and reported elsewhere [5]. For the further development of neutronics calculation, the actual measurement of neutron distribution is quite important as it provides the answer of neutron transport and guarantees the validity of calculation.

Therefore, as the first actual measurements, the neutron distribution

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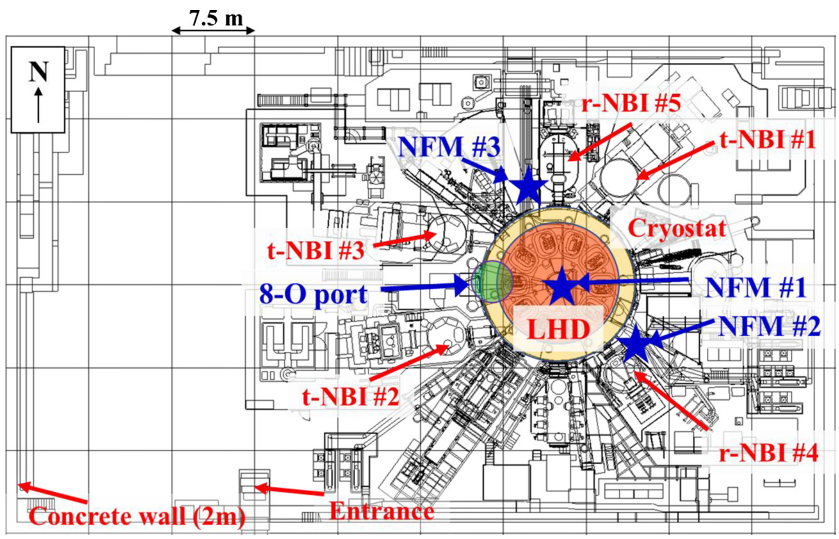

Fig. 1. Component layout of the LHD torus hall.

on the floor level of the LHD torus hall was evaluated in this work. Activation foils of indium were applied. The radioactivity of indium foils, which correlates with the neutron fluence across the foil, was evaluated by means of a high-purity germanium detector (HPGe) and an imaging plate (IP). This is the first measurement of neutron distribution in the torus hall of a large helical type fusion device, and will be an important benchmark for safety evaluation for the deuterium experiment in LHD.

2. Experiments and analyses

2.1. The component layout of the LHD torus hall

The torus hall of LHD is on the first floor of the LHD experimental building. The torus hall has the size of W75, L45, and H40 m^3, and is made of concrete wall with the thickness of 2 m to sufficiently shield radiation. The details of the component layout in the torus hall can be found in Fig. 1. LHD is placed slightly to the east side of the torus hall. The vacuum vessel of LHD is surrounded by the 2 helical coils and 6 poloidal field coils, and they are covered by the cryostat. The space between the vacuum vessel and the cryostat is evacuated to an ultra-high vacuum to prevent the air exposure to the surface of coils because the temperature of coils must be maintained in low temperature around 4 K.

Many systems are equipped to LHD and serve for heating plasma, diagnostics of plasma, and other purposes. One of the large heating systems in LHD is NBI. There are 5 NBIs for LHD. Three of them are tangential NBI (#1, #2, #3) and the two others are radial NBI (#4, #5).

The borated polyethylene blocks working as neutron shielding materials were widely used in LHD. Polyethylene can effectively decelerate fast neutron from LHD to thermal neutron due to its light constituent atoms. Then, boron inside the polyethylene blocks absorbs thermal neutrons by its large cross-section of $^{10}B(n,\alpha)^{7}Li$ reaction. The borated-polyethylene blocks contain 10% boron. Many electrical components in the torus hall were covered with borated polyethylene blocks. In addition, on the floor underneath LHD, the borated polyethylene blocks were placed like a disc with the inner radius of ~ 2.3 m, outer radius of ~ 6.9 m, and the thickness of 5 cm to reduce the radioactivity of the concrete floor underneath LHD. Exceptionally, unborated polyethylene blocks were used just below the 8-O port of LHD, which is the west side of LHD as seen in Fig. 1, and they occupied 36 ° of disc-shaped polyethylene blocks underneath LHD.

2.2. Neutron sources and diagnostics

The major source of neutron should be deuterium plasma in LHD. In the vacuum vessel of LHD, the deuterium plasma with the major radius of about 3.75 m will be generated. During this plasma operation (usually for 3 s), neutrons will be produced. Note that, neutron yields in each deuterium plasma operation are different because they depend on the many plasma parameters such as temperature, density, magnetic field, and others.

The other neutron source will be NBI. In NBI, the ions of hydrogen isotopes are accelerated and then neutralized in order to have hydrogen isotopes penetrate into plasma confined by the magnetic field. In this extraction process of neutral beam, not all hydrogen isotope ions are neutralized. These ions are guided by the magnetic force into the inner wall of the NBI system as a beam dump. In this time, deuterons in the ion beam collide with deuterium retained in the beam dump. Consequently, neutron will be generated. In the present study, hydrogen was used for tangential NBI. Deuterium was used in radial NBI. Therefore, the neutron generation was expected in NBI#4 and NBI#5.

Neutron yield was measured by the neutron flux monitors (NFM), which were placed at the top of the LHD center axis (#1) and around the vacuum port of LHD on the mid plane (#2, #3). The ^{235}U fission chambers, ^{10}B counters, and ^{3}He counters were adopted as NFM in LHD. The positions of NFM are also added into Fig. 1.

2.3. Activation foils

As the activation foil, indium (In) was selected in this work. The advantages of using indium foils are (i) high reaction cross-section with neutron, (ii) short half-life of radioactive isotopes and (iii) with selective reaction by neutron energy [6]. Indium was used in this work to measure fast and thermal neutrons individually at one time due to the third advantage above. The natural isotopes of indium are ^{113}In and ^{115}In. The natural abundances of these indium isotopes are 4.3% and 95.7%, respectively. Thermal neutrons react with ^{115}In as $^{115}In(n,\gamma)^{116m}In$. The cross-section of this reaction is 201.2 b for the 0.025 eV neutron. The minor isotope of indium as ^{113}In also reacts with thermal neutron as $^{113}In(n,\gamma)^{114m}In$. The cross-section is 12.1 b for the 0.025 eV neutron. Besides, fast neutrons can only react with ^{115}In as $^{115}In(n,n')^{115m}In$. The cross-section of this (n,n') reaction was about 2 b for 2.45 MeV neutron. This reaction requires higher neutron energy than the threshold energy of 0.3 MeV in order to occur. Therefore, the radioactivity of ^{115m}In presents only fast neutron fluence. The details of cross-sections for the above 3 reactions can be found in Ref. [7]. The