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ARTICLE

Monte Carlo calculation of the neutron and gamma-ray distributions inside the LHD experimental building and shielding design for diagnostics

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On the Large Helical Device (LHD), deuterium plasma experiments began in March 2017. In the plasma control, plasma heating and diagnostic systems, radiation sensitive components such as a programmable logic controller (PLC) and CCD sensors are commonly used. Three-dimensional distributions of neutron and gamma-ray in the LHD experimental building have been calculated by Monte Carlo code MCNP6 with the nuclear data library of ENDF B-VII.1 to prove the precise information on the radiation field and to introduce a countermeasure to the radiation. The total neutron flux in the torus hall of LHD is ~10^9 n/cm^2•s for the maximum neutron yield shot. The total neutron and gamma-ray fluxes in the basement are 1-2 order smaller than those in the torus hall, which is due to the streaming through penetrations in the floor concrete slab. The shielding design for the compact neutral particle analyzer (CNPA) is also carried out. It is found that 10% borated polyethylene thicker than 15 cm is necessary for the shield in all directions.

Keywords: Monte Carlo calculation; MCNP6; LHD; neutron; gamma-ray; shielding design; plasma diagnostics; compact neutral particle analyzer

1. Introduction

The Large Helical Device (LHD) [1] is one of the largest superconducting fusion machine, with a major radius of R_{ax} = 3.42-4.1 m and a maximum toroidal magnetic field of B_t = 3T. In March 2017, LHD started deuterium plasma experiments [2]. The licensed annual neutron budget is 2.1 × 10^{19} neutrons/year. The maximum neutron production rate is expected to be 1.9 × 10^{16} n/s [2].

Highly integrated electronic components such as a programmable logic controller (PLC) and sensors such as a charge-coupled device (CCD) are indispensable in the control, plasma heating and diagnostic systems. Those components are considered to be very sensitive to neutrons and gamma-rays. Indeed, the neutron and gamma-ray irradiation tests on those components indicate the possibility of errors or damages even in the radiation field expected in LHD [3]. For the deuterium plasma experiments, relocation to the basement or the peripheral region of the torus hall, and shielding has been undertaken for control and diagnostic systems. Three-dimensional distributions of neutron and gamma-ray have been calculated by Monte Carlo code to prove the precise information on the radiation field and to introduce a countermeasure to the radiation.

Some diagnostic equipment has to remain in the torus hall, mainly because those have to face to the plasma directly. Radiation shielding is required for such diagnostics equipment to avoid radiation induced noises and errors. In this paper, shielding design for the compact neutral particle analyzer (CNPA) [4,5] is presented as one of the examples.

2. Calculation code and model

In this calculation, a General Monte Carlo N-Particle Transport Code version 6 (MCNP-6) [6] is used with the nuclear data library of ENDF/B-VII.1 [7].

The schematic view of the MCNP calculation model for LHD and the LHD experimental building is shown in **Figure 1**, which is drawn with SuperMC code [8,9]. In the previous work [10], 36° sector model of LHD including 36° sector cylindrical model of the concrete floor, wall and ceiling was used to estimate the radiation field arround the LHD machine, where the basement was not modeled. In this work, LHD and the LHD experimental building including the basement are modeled manually from the CAD drawings. Especially, penetrations in the floor concrete slab are carefully modeled, because the basement is the first candidate of the relocation place for electronic cubicles. In the torus hall, LHD itself and the interferometer support are modeled. The other apparatus such as neutral beam (NB) injectors and vacuum pumps are not included so far. NB injectors and vacuum pumps are not so large volume

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compared to LHD, however, may affect the radiation field in the torus hall. Therefore those components will be modeled in near future. MCNP could not treat helical surfaces, thus the helical coils and the case structures are divided by 6° toroidal angle pitch, and those components are assumed to be toroidally symmetric in a toroidal pitch angle [10]. The torus hall basement is separated by a mezzanine stage (Z = - 8 m from the floor level), made of stainless plates and frames to B1 and B2 levels, which is not modeled because the mass is not so large.

The helical and poloidal coils are modeled by homogenized materials, respectively, based on each composition such as superconductors of NbTi, electric insulators, copper stabilizing conductors, and liquid helium. The material of the vacuum vessel and the support structure is stainless steel (SS) 316L, and that of the cryostat is SS304. The LHD experimental building is built with normal concrete.

The LHD plasma, which is a volumetric neutron source, is modeled by the circular torus, and is divided into five regions in minor radius whose neutron emission rates are determined to be a neutron source profile expected by a plasma simulation. The source neutron energy is assumed to be 99.5% of 2.45 MeV and 0.5% of 14.1 MeV. The 14 MeV neutron is generated by reaction between the bulk deuteron and the energetic triton from the d(d,n)t reaction [11]. The source neutrons are assumed to be isotropic.

The calculations have been executed on a LINUX workstation with 36 cores of RC Viento 3600XB, Real Computing. Inc.

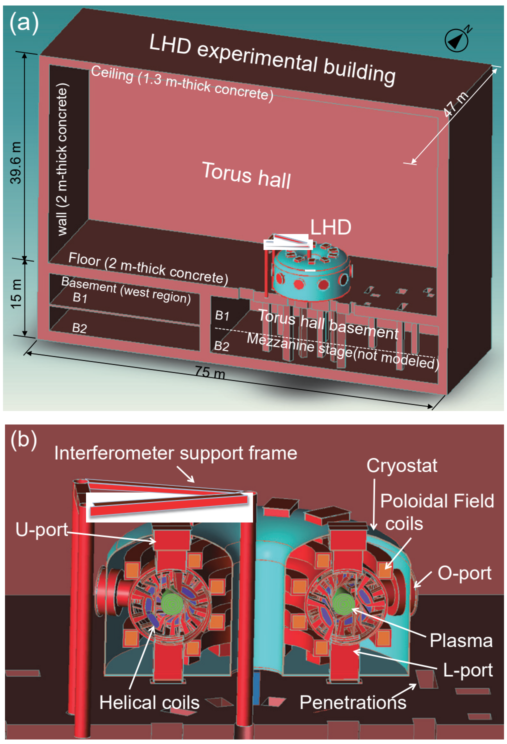

Figure 1. Schematic view of the MCNP calculation model for LHD and the experimental building. (a) overall view and (b) expanded cut view of LHD.

3. Calculation results

3.1. Neutron flux distributions

Three-dimensional neutron flux distributions have been calculated by using the mesh tally function of MCNP. **Figure 2** shows the contour plots of the neutron flux distribution on (a) the vertical plane at the center of LHD, (b) the horizontal plane at the equatorial level (Z = 5.5 m from the floor level), and (c) the horizontal plane at 1 m above the mezzanine stage level in the torus hall basement.

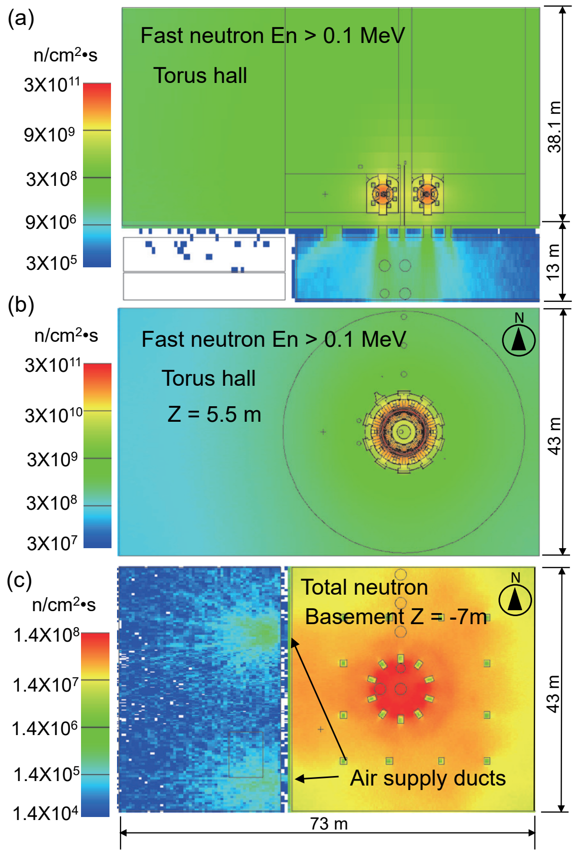

Figure 2. Contour plots of the neutron flux distribution at the neutron emission rate of 1.9 × 10^{16} n / s on (a) the vertical plane at the center of LHD, (b) the horizontal plane at the equatorial level (Z = 5.5 m), and (c) the horizontal plane (Z = -7 m) in the torus hall basement.

In the torus hall, neutron streaming from horizontal ports is not so clear, which is provably due to the thick port flange with 60 mm in thickness. Also there are not so large differences of the neutron flux in the direction of north, east and south from the center of LHD, which can be explained by the neutron reflection from the wall.

Neutron streaming from floor penetrations is clearly observed. In the torus hall basement, total neutron flux is rather high, typically ~1 × 10^8 n/cm^2•s, just under the LHD machine. That of other region is ~10^7 n/cm^2•s. Those neutron fluxes in the torus hall basement are much larger than we expected. Neutron streaming through air supply ducts in the wall between the torus hall basement and the basement west region is identified.

We have to consider the radiation effects on the equipment installed in the basement west region, where we expected that the neutron and gamma-ray flux would be very low.

Also three-dimensional gamma-ray flux distributions are calculated, which is similar to that of neutrons.

3.2. Neutron and gamma-ray spectra

Neutron and gamma-ray spectra in the LHD experimental building have been calculated by using a track length estimation tally, so-called cell tally. Those tally cells are spheres of 1 m diameter and 2 m diameter in the torus hall and the basement, respectively. Typical size of the electronics cubicle is $0.9 \times 0.9 \times 2$ m^3, therefore tally cells of spheres with 1 m diameter are adopted in the torus hall. In the basement, the diameter of tally cells is 2 m in order to obtain sufficient statistics.

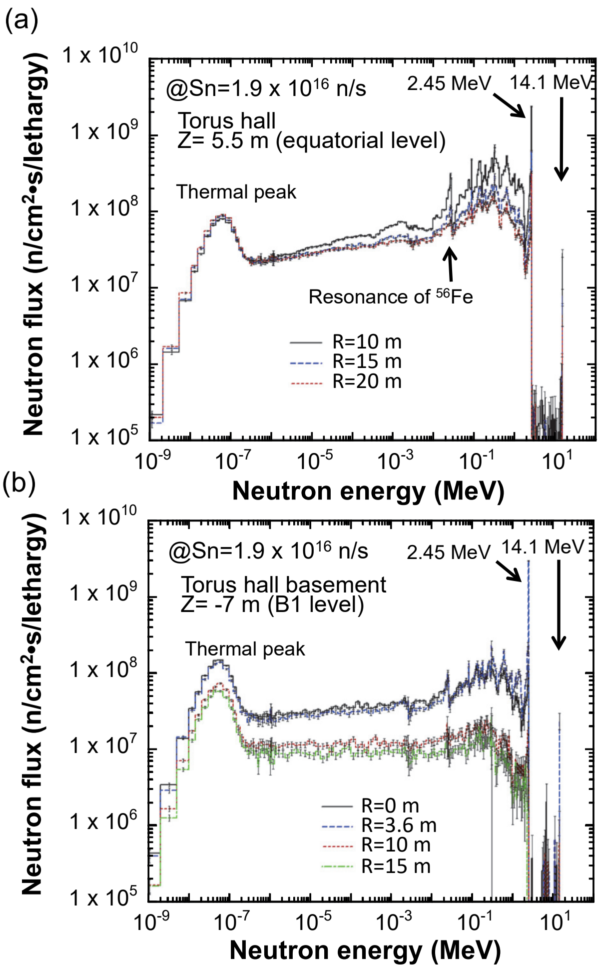

Figure 3. Neutron spectra at the neutron emission rate of 1.9×10^{16} n / s in (a) the torus hall on the equatorial level (Z = 5.5 m), and (b) the torus hall basement on the B1 level (Z = -7 m).

Figure 3 shows neutron spectra in the torus hall on the equatorial level, and the torus hall basement on the B1 level at the shot with the maximum neutron emission rate, where the number of energy bins is 199. Virgin neutrons of 2.45 MeV and 14 MeV are clearly seen not only in the torus hall but also in the torus hall basement, which indicates that those neutron in the torus hall basement come from the penetrations under the LHD machine. It can be considered that several peaks and gaps in keV region are corresponding to resonances of ^{56}Fe and other structural materials. The thermal neutron peak is formatted in all spectra. There is not so large difference of the neutron flux and spectrum among the major radius of 10,15 and 20 m in the torus hall. In the torus hall basement, neutron fluxes of the central region (R < 4 m) are about 1 order smaller than those of the peripheral region in the torus hall. On the other hand, neutron fluxes of the peripheral region are about 2 order smaller the those in the torus hall.

Also gamma-ray spectra in the torus hall and the torus hall basement are shown in **Figure 4**, where the number of energy bins is 80. Prompt gamma-rays from concrete components, such as H(n, γ), ^{56}Fe(n, n'), ^{29}Si(n, γ), and ^{56}Fe(n, γ) are identified. Spectrum shapes are almost same in the torus hall and the torus hall basement. Gamma-ray fluxes in the torus hall basement are 1-2 order smaller than those in the torus hall.

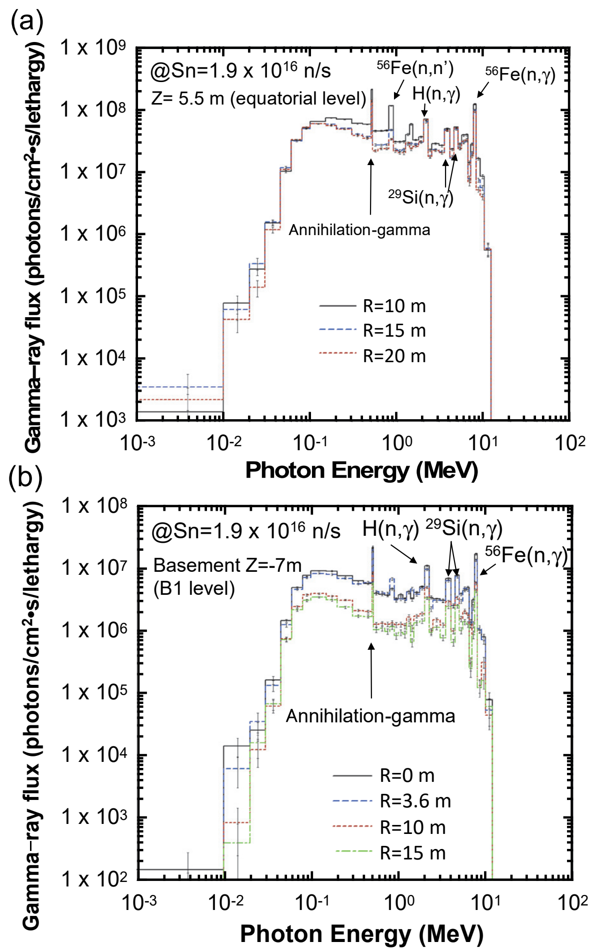

Figure 4. Gamma-ray spectra at the neutron emission rate of 1.9×10^{16} n / s in (a) the torus hall on the equatorial level (Z = 5.5 m), and (b) the torus hall basement on the B1 level (Z = -7 m).

4. Example of shielding design for diagnostic apparatus

The Compact Neutral Particle Analyzer (CNPA) is a E//B type neutral particle energy analyzer using permanent magnets as shown in **Figure 5**, which has been developed by the Ioffe Institute, Russia [5]. CNPA is installed on the diagnostic platform and connected to the outside horizontal port (O-port) via a flight tube.

The specification of CNPA indicates that the maximum allowed neutron flux at the NPA location is 1×10^7 n/cm^2•s [5], where the most sensitive component is the detector array. To meet this request, the neutron shield is designed within the weight limit of the diagnostic stage. Neutron fluxes are calculated for several cases with different shielding material (polyethylene or 10% borated polyethylene) and the thickness. Finally, 15 cm thick borated polyethylene (front side: 15+10 cm) is adopted as shown in Figure 5, where neutron flux inside CNPA is estimated to be 0.71×10^7 n/cm^2•s. The overall size of the shield is 1.05 m^w × 0.5 m^d × 0.85 m^h.

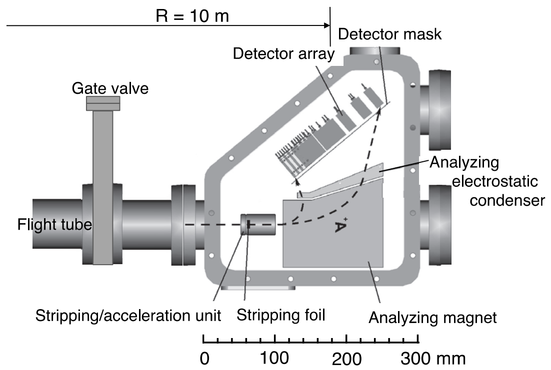

Figure 4. Schematic view of the Compact Neutral Particle Analyzer (CNPA) on LHD.

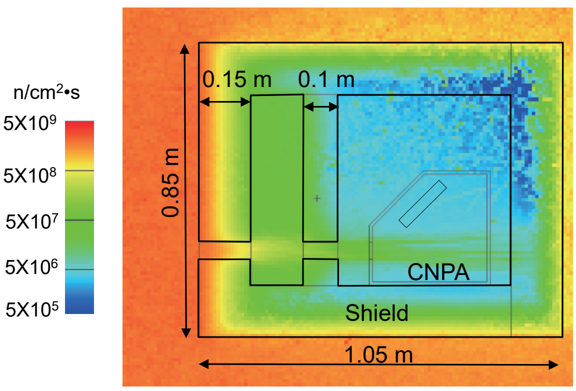

Figure 5. Neutron flux distribution around CNPA with the shield of 15 cm thick borated polyethylene (front side: 15+10 cm).

5. Summary

Three-dimensional distributions of neutron and gamma-ray in the LHD experimental building have been calculated by MCNP6 with the nuclear data library of ENDF B-VII.1 to prove the precise information on the radiation field for the shielding and/or the relocation of diagnostic and control equipment. The total neutron and gamma-ray fluxes in the basement are 10^{-2}-10^{-1} of those in the torus hall, which is larger than we expected previously. The shielding design for CNPA is also carried out. The shield of 15 cm thick borated polyethylene (front side: 15+10 cm) is adopted.

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