Radiation Field Estimation for the Diagnostic and Control Components by Monte Carlo Neutronics Calculations with LHD 3-Dimensional Modeling[*)]

Takeo NISHITANI[1)], Kunihiro Ogawa[1,2)], Kiyohiko Nishimura[1)] and Mitsutaka Isobe[1,2)]

[1)]*National Institute for Fusion Science, 322-6 Oroshi-cho, Toki 509-5292, Japan*

[2)]*The Graduate University for Advanced Studies, 322-6 Oroshi-cho, Toki 509-5292, Japan*

(Received 24 November 2015 / Accepted 9 March 2016)

The precise estimation of the radiation field is required to evaluate the soundness of the diagnostic and control components for the LHD deuterium experiment. Monte Carlo neutron calculations are carried out with three-dimensional modeling of LHD using MCNP-6 code with the cross-section library of ENDF B-VI. Three-dimensional map of the total neutron flux, neutron and gamma-ray spectra, and the dose rate profile are obtained. Neutron and gamma fluxes by MCNP-6 code are about 2/3 of those by DORT code, which is probably due to the two-dimensional modeling of the DORT calculation. The gamma-ray absorbed dose for Si is 20 - 70 Gy during nine years operation, where high integrated electric devices such as the programmable logic controller (PLC) may survive if we consider the gamma-ray effect only.

Keywords: LHD, deuterium experiment, radiation field, neutronics, MCNP-6, three-dimensional modeling, neutron spectrum, gamma-ray spectrum, dose rate

DOI: 10.1585/pfr.11.2405057

1. Introduction

LHD plans to start the deuterium experiment in the spring of 2017. The deuterium experiment is nine-years campaign, in which the total neutron budget is 2.1×10^{19} neutrons for the first six years, and 3.2×10^{16} neutrons for the next three years. One of the most important issues of the deuterium experiment is irradiation effect on diagnostics components and control devices. The precise estimation of the radiation (neutron and gamma) field is necessary for responding to the influence of irradiation effects on those components. Previously, the radiation field in the LHD torus hall was calculated by two-dimensional neutron transport cord DORT [1] mainly for the radiation safety analysis and the licensing of the deuterium experiment. However, LHD has a structure too complicated to be treated by the two-dimensional model. Here, we evaluated the radiation field in the LHD torus hall by Monte Carlo neutrons calculation with three-dimensional modeling of LHD.

2. Calculation Method

In this calculation, the MCNP Monte Carlo neutronics code (MCNP-6) [2] is used with the cross-section library of ENDF B-VI [3]. The model is divided by cells in the MCNP calculation, where all surfaces of cells are defined by quadratic (or less) equations or torus. However, the helical surface could not be represented. In the MCNP calculation geometry, the LHD components within the support structure are divided by small toroidal angle pitch, and the components are assumed to be toroidally symmetric in a toroidal pitch angle. The geometry in one toroidal pitch angle is modeled based on the CAD drawing with some simplification. As the first step, the toroidal pitch angle is selected to be six degrees. Figure 1 shows the poloidal cross sections of the LHD calculation model, where the toroidal angle of $\phi = 0$ is defined by the center of the U/L port. A poloidal angle θ of a center of one helical coil is presented by $\theta = \phi\,(m/l) + \alpha \sin\{\phi\,(m/l)\}$, where $m = 10$, $l = 2$, and $\alpha = 7.8$ degrees. Surface equations of the helical structure are automatically generated by EXCEL based on this formula for each toroidal pitch angle. The LHD plasma is modeled by a simple torus with the major radius of 3.9 m and the minor radius of 0.5 m. The neutron source is isotropic and homogeneous in the torus with the energy of 2.45 MeV. The secondarily-generated 14 MeV neutron by the triton burn-up process is ignored. The helical and poloidal coils are modeled by homogenized materials respectively, based on each composition such as superconducting coils, electric insulators and liquid helium. The material of the vacuum vessel and the support structure is stainless steel (SS) 316L, and the cryostat is SS304. This model includes the concrete torus hall wall, the floor, and the ceiling, with cylindrical geometry. This 36-degrees model consists of approximately 150 cells.

author's e-mail: nishitani.takeo@nifs.ac.jp

[*)] This article is based on the presentation at the 25th International Toki Conference (ITC25).

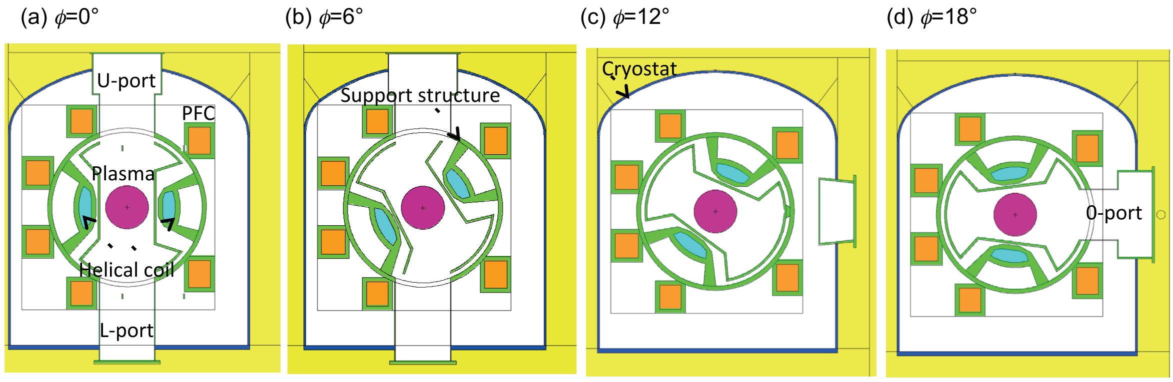

Fig. 1 Poloidal cross sections of the LHD calculation model at $\phi = 0°$, 6° 12°, and 18°, where the toroidal angle $\phi = 0°$ is defined by the center of the U/L port. Also poloidal cross sections at $\phi = -6°$, $-12°$, and $-18°$ are similar.

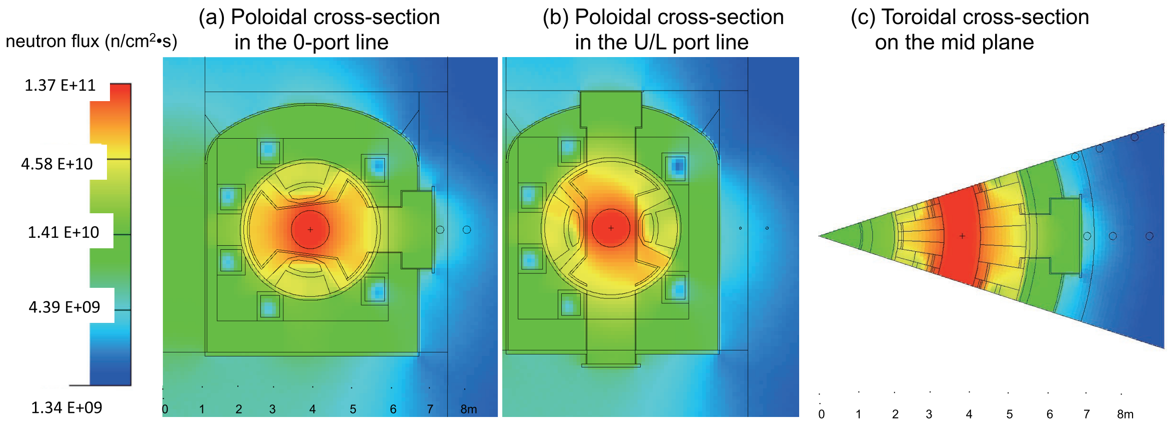

Fig. 2 Detailed neutron flux distributions in the poloidal cross-sections on the O-port and the U/L port radial directions, and in the toroidal cross-section on the mid plane for the plasma with the total neutron yield of 1.9×10^{16} neutrons/s.

3. Results

3.1 Neutron and gamma-ray flux distributions

Three-dimensional maps of neutron and gamma-ray fluxes in the LHD torus hall were obtained. Figure 2 shows the detailed neutron distributions in the poloidal cross-sections on the O-port and U/L port radial directions, and in the horizontal cross-section on the mid plane for the plasma with the total neutron yield of 5.7×10^{16} neutrons/3s (1.9×10^{16} neutrons/s), which is the expected maximum neutron yield. The neutron flux decreased dramatically outside the cryostat. The neutron streaming from O-port or U/L ports is not as distinguished as we expected, which is probably due to the shielding effect of rather thick port flanges. The neutron flux in the center column is as large as that in the cryostat.

Figure 3 shows the neutron and gamma-ray flux profiles in the torus hall for the same neutron yield plasma as Fig. 2 compared with the DORT calculation [4]. Neutron and gamma fluxes by MCNP are about 2/3 of those by the DORT calculation where the neutron and gamma fluxes are derived by averaging those fluxes by two cylinder models based on the O-port and the U/L port cross-section without port flanges, as shown in Fig. 4. Even though averaging two models, the effective port area is excessive, which may cause overestimation of the neutron and gamma fluxes in the torus hall. However, this DORT calculation is adequate for the radiation safety analysis, because it provides safety side estimation of the radiation field.

The neutron flux in the O-port line at $R = 7.3$ m is about 40% larger than that in the U/L-port line, which is due to the neutron streaming effect from the O-port. However, the neutron fluxes in the O-port and U/L-port lines are almost identical for $R > 9$ m.

The gamma-ray flux profile by MCNP is rather flat for $R > 9$ m compared with that by DORT. The reason is under discussion at present.

3.2 Neutron and gamma-ray energy spectra

Figure 5 shows neutron and gamma-ray spectra in the torus hall in front of the O-port outlet ($R = 8$ m). In the neutron spectrum, 2.45 MeV neutrons from D-D reactions are identified, however, scattered neutrons lower than 2 MeV are dominant. The averaged neutron energy is derived to be 0.54 MeV from this spectrum, which is important for the shielding design of the equipments in the torus hall and

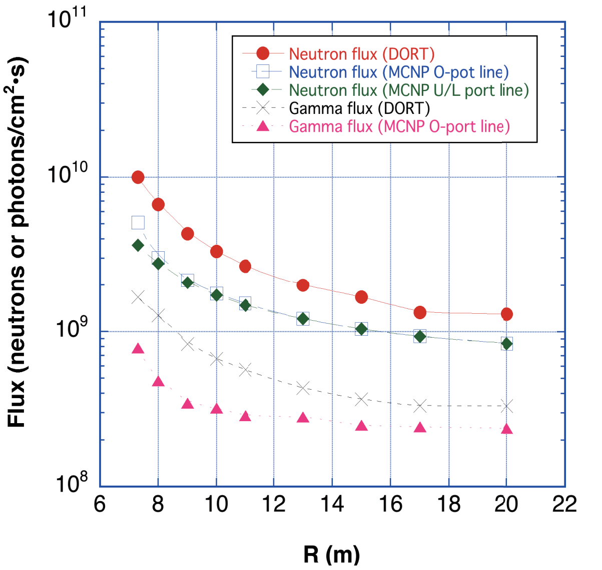

Fig. 3 Neutron and gamma-ray flux profiles in the torus hall for the plasma with the total neutron yield of 1.9×10^{16} neutrons/s compared with the DORT calculation [4].

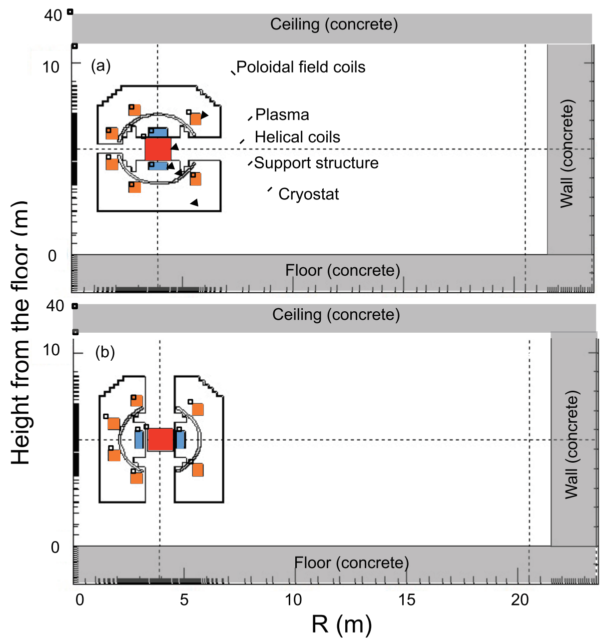

Fig. 4 Cylindrical models of LHD for DORT calculation based on (a) the O-port line and (b) the U/L-port line cross-sections.

also for the sky shine dose estimation.

On the gamma-ray spectrum, a peak of 7.8 MeV is the prompt gamma-ray from ^{56}Fe which is a major component of stainless steels. The averaged gamma-ray energy is 1.4 MeV. This gamma-ray spectrum does not include delayed gamma-rays from activated materials of LHD and the torus hall concrete, which are considered to be much smaller than prompt gamma-rays.

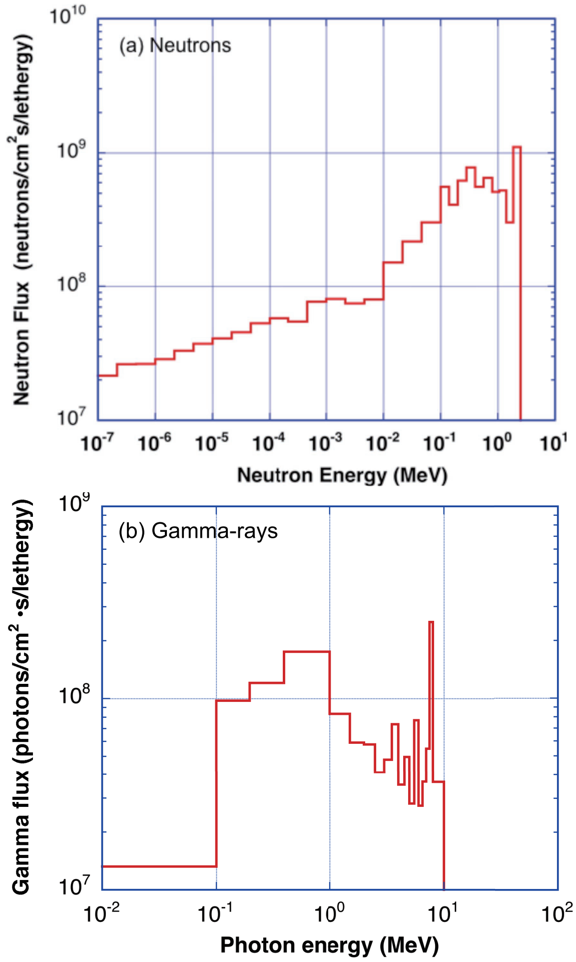

Fig. 5 Neutron and gamma-ray spectra in the torus hall in front of the O-port outlet ($R = 8$ m).

3.3 Dose rate and dose distributions

From the engineering point of view such as the irradiation effect on the components for diagnostics and control systems, not only neutron and gamma-ray fluxes but also dose rate and/or total dose are important. Organic materials for electric insulator and highly integrated electronic devices are considered to be rather irradiation sensitive. Figure 6 shows the dose profiles for organic material in the torus hall on the mid plane during nine years of the LHD deuterium experiment. Here polyethylene, (CH_2)n, is assumed as a typical organic material. It is very clear that the neutron contribution is about 10 times larger than that of gamma-rays.

The radiation damage on the electronic devices with high integrated circuits, such as a PLC (Programmable Logic Controller) for diagnostics, and control systems is one of the most urgent issues for the LHD deuterium experiment. Figure 7 shows the profiles of the dose on Silicon, which is a major composition of the electronics devices during nine years of the LHD deuterium experiment. Contrasting with Fig. 6, the gamma-ray contribution is dominant. The gamma-ray dose is almost insensitive to the

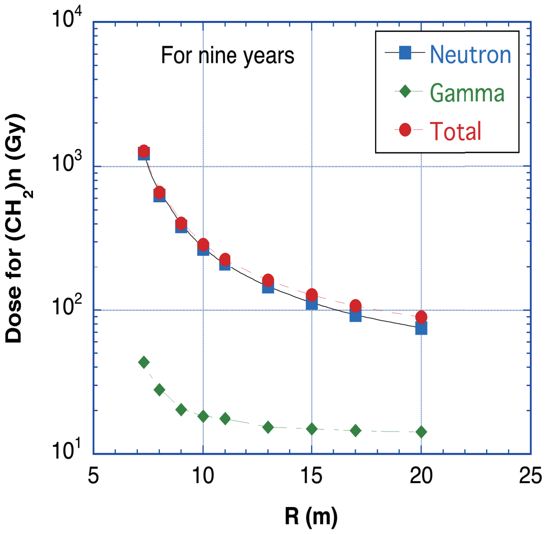

Fig. 6 Equivalent dose rate profiles for polyethylene, $(CH_2)n$, in the torus hall on the mid plane.

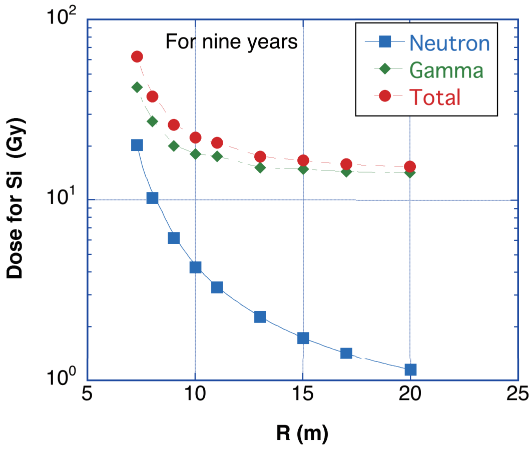

Fig. 7 Dose profiles for Si in the torus hall on the mid plane during nine years of the LHD deuterium experiment.

target material, however, the neutron dose depends on the target material. If we consider the energy deposition by elastic collisions, the neutron dose decreases with the mass number of the target material. The energy transfer to Si is much smaller than polyethylene which contains much hydrogen. Thus, the differences between Figs. 6 and 7 are reasonable.

Recently we performed the gamma-ray irradiation tests on the electronic devices with high integrated circuits such as a PLC at the ^{60}Co irradiation facility of Nagoya University. There, some devices broke down around 100 Gy [5]. If we consider the dose only, such electronic devices may survive nine years. However, the neutron irradiation provides not only energy deposition but also atomic replacements on the material and single event errors in the electronic devices. Thus, the soundness of such electronic devices should be considered more carefully taking account of the neutron irradiation effect, which will be investigated in the near future.

4. Summary

Monte Carlo neutron calculations are carried out with three-dimensional modeling of LHD using MCNP-6 code by dividing six degrees toroidal angle pitch for the LHD deuterium operation. Three-dimensional map of the total neutron flux, neutron and gamma-ray spectra, and the dose rate profile were obtained. Neutron and gamma fluxes by MCNP-6 code are about 2/3 of those by DORT code, which is probably due to the two-dimensional modeling of the DORT calculation. Outside the cryostat, scattered neutrons are dominant. The total equivalent dose rate reaches to about 1 Sv/s near the cryostat, where the neutron contribution is about 100 times larger than that of gamma-rays. The gamma-ray absorbed dose for Si is 20 - 70 Gy during nine years of operation, indicating that high integrated electric devices such as the PLC may survive if we consider the gamma-ray effect only.

[1] M.B. Emmett *et al.*, the DORT section of *A User's Manual for MASH 1.0 - A Monte Carlo Adjoint Shielding Code System*, ORNL/TM-11778 (Oak Ridge National Laboratory, Oak Ridge, 1992).
[2] X-5 Monte Carlo Team, *MCNP User's Guide - Code Version 6.1.1beta*, LA-CP-14-00745 (Los Alamos National Laboratory, Los Alamos, 2014).
[3] H.D. Lemmel, *et al.*, *ENDF/B-VI Release 8 (Last release of ENDF/B-VI) The U.S. Evaluated Nuclear Data Library for Neutron Reaction Data*, IAEA-NDS-100, Rev. 11 (IAEA, Vienna, 2001).
[4] *Safety management plan of the deuterium experiment at the Large Helical Device* (National Institute for Fusion Science, Toki, 2012) in Japanese.
[5] K. Ogawa *et al.*, *Effects of gamma-ray irradiation on electronic and non-electronic equipment of the Large Helical Device*, presented at the 25th Int. Toki Conf., 3-6 November, 2015, Toki-city, Japan.