Radiation control in LHD and radiation shielding capability of the torus hall during first campaign of deuterium experiment

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Abstract

The activities carried out to obtain public consent for deuterium experiments in LHD, which began in 2017, are reviewed in this paper. In addition, the upgrades and the safety management of LHD for deuterium experiments, including neutron yield measurement system, exhaust detritiation system, institutional regulation for radiation control, and other issues, are briefly presented.

During the first campaign of the deuterium experiments in LHD, the shielding of gamma-ray and neutron by the concrete wall of the LHD torus hall was evaluated. Also, the confinement of radioactive isotopes in air inside the torus hall was investigated. No increase of radiation dose was measured outside the torus hall, although the high radiation dose field inside the torus hall was found during deuterium experiments. Therefore, almost all gamma-rays and neutrons were shielded by the concrete wall of the torus hall due to its sufficient thickness of 2 m. The radioactive isotopes in air as well as in other components were well confined in the torus hall. In particular, the pressure control inside the torus hall being lower than outside the torus hall effectively prevented the radioactive isotopes in air from diffusing to the unprescribed area.

Keyword

LHD, deuterium experiment, neutron, gamma-ray, radiation control

1. Introduction

In the Large Helical Device (LHD), which is one of the world's largest superconducting fusion machines, plasma experiments using hydrogen (hydrogen experiments) have been carried out for about 20 years [1]. The goals of the LHD project are to achieve high temperature plasma, high density plasma and high beta plasma, and to reveal the physics in these high-performance plasmas [2]. For these goals, LHD has been upgraded so far with installing heating systems, higher power supply systems, and the components for improved plasma confinement [3-8]. On the other hand, it has been experimentally confirmed by the plasma experiments in other fusion devices that the use of deuterium plasma can improve the plasma performance [9-11]. Therefore, the plasma experiments using deuterium (deuterium experiments) were planned in LHD.

Unlike the hydrogen experiments, the issues of radiation control must be considered for deuterium experiments due to the fusion reaction of deuterons resulting in the generation of tritium and of neutron. The large fusion experimental devices using deuterium are regarded as the radiation generator in Japanese radiation protection regulation. Also, even very small amounts of neutron and tritium are generated in the plasma with using deuterium, it is necessary to obtain public consent for deuterium experiments with local government bodies. Therefore, the comprehensive safety management systems needed to be established for the public acceptance as well as for the requirement in radiation protection regulation before starting the deuterium experiments in LHD. However, due to the severe accident at Fukushima-Daiichi nuclear power plant in 2011, Japanese public were mistrustful on the nuclear technology. This was a difficult mission to obtain the public acceptance for the deuterium experiment in LHD.

The first experiment campaign of deuterium experiments in LHD began in March 2017, and was successfully completed in August 2017 [12, 13]. This paper reviews the efforts of the National Institute for Fusion Science (NIFS) for more than 10 years to obtain the public consent for deuterium experiments. Also, this paper presents the successful radiation control in this experimental campaign, especially, radiation shielding in the torus hall of LHD to prevent occupational exposure of workers, which is strictly required for radiation protection regulation. The evaluation of radiation shielding was carried out with the comparison of radiation monitoring data inside and outside the torus hall during deuterium experiments, and it was confirmed that the radiation inside the torus hall caused by deuterium experiments was effectively shielded by the concrete wall of the torus hall. Also, the shielding of radioactive isotopes generated by the nuclear reaction with neutrons in the torus hall was also discussed in this work.

2. Preparation for deuterium experiment in LHD

2.1 Public consent for deuterium experiments in LHD

The monitoring of environmental tritium concentration in the atmosphere, river water and pond water in the Toki region, where NIFS is located, has been conducted from the 1980s [14-25]. The field dose rate due to gamma(X)-ray has also been investigated [14-25]. These background radiation data for evaluating the impact of experiments on the environment were desired from the public confidence point of view. Although this radiation monitoring was first carried out for another project (R-project), it has been continued for more than 30 years, even after the R-project was aborted [26].

The construction of LHD started in 1990. The first plasma using hydrogen in LHD was achieved at 1998. The deuterium experiments in LHD were planned when the LHD project was proposed. With extending higher performance of hydrogen plasma in LHD, the implementation of deuterium experiments in LHD became further desired. For obtaining public acceptance to conduct deuterium experiments, NIFS established the deuterium experiment security evaluation committee (SE committee), which consists of journalists, local public people, and expert advisors on radiation, fusion plasma, risk communication, tritium, earthquakes from 2007. SE committee is a third party to evaluate the upgrade plan of LHD and the safety structure of NIFS for deuterium experiments, such as the exhaust detritiation system, neutron shielding, control of activated materials, radiation monitoring around NIFS and disaster prevention, and other issues. NIFS proposed the safety management plan to the SE committee. The details of the safety management plan for deuterium experiments are in Section 2.2.

After the review of the public comments, the SE committee published the final evaluation report in 2007. That report evaluated the upgrade plan and the safety management plan of LHD for deuterium experiments as appropriate. Then, NIFS revised the safety management plan in LHD after the accident in the Fukushima Daiichi nuclear power station. Thereafter, the SE committee reviewed the revised plan and authorized it in 2012 [27]. Finally, the agreement treaty among NIFS and the local government bodies for proceeding with the deuterium experiments in LHD was concluded in 2013. After the agreement with local government bodies, the SE committee was in charge of evaluating that the proposed safety management plan and the upgrades in LHD were adequately conducted. Also, the SE committee has evaluated the radiation control during deuterium experiments in LHD up to now.

After the agreement treaty for deuterium experiments, the local government bodies established the safety monitoring committee (SM committee) in 2015 which evaluates the monitoring and the measurement necessary for environmental protection, accident and disaster prevention in NIFS, the response system of NIFS to large-scale disasters that occurred around NIFS, the preparation of operational handbooks and the education and training of workers, and other issues. The SM committee also measures the environmental radiation, such as neutron and tritium at the same place as NIFS to check the validity of measurement by NIFS.

2.2 Safety management of LHD for deuterium experiments

2.2.1 Measurement of neutron and tritium yields

A major issue for deuterium experiments, as mentioned above, should be neutron and tritium. The yields of tritium and neutron generated in the plasma are almost equivalent because of almost the same cross-sections between D(d,p)T and D(d,n)^{3}He reactions. Therefore, the measurement of neutron yield in experiments can give us the amount of tritium generated in the vacuum vessel of LHD. For the measurement of neutron yield, the neutron flux monitors (NFM) with a wide dynamic range for neutron flux measurement were adopted. The details of these monitors are shown elsewhere [28, 29]. In-situ calibration of NFM was carried out with using ^{252}Cf spontaneous fission neutron source before starting deuterium experiments in LHD. The neutron source was rotated in the vacuum vessel of LHD along a toy train rail track to simulate a ring-shape plasma. This calibration method is based on the guideline standardized in the workshop on neutron calibration technique [30, 31]. The neutron activation system (NAS) is also employed in LHD to perform the cross-check of the neutron yield evaluated by the NFM. The details of NAS can be found in Ref. [32].

2.2.2 The exhaust detritiation system

For tritium, tritium generated in plasma will be evacuated through the vacuum pumps of LHD as an exhaust gas, which finally will be released to outside the LHD experimental building. Therefore, the exhaust detritiation system (EDS) was installed in LHD. In this system, hydrogen isotopes in the exhaust gas are oxidized to water vapor by catalysts. Then, the water vapor containing tritiated water will be eliminated from the exhaust gas stream by the molecular sieve packed bed. In the maintenance of LHD, maintenance purge gas processing is conducted by the combination of the catalyst and the polyimide hollow fiber membrane units. The water vapor separated from the gas stream is liquefied and stored for disposal. The details of EDS are found in Ref. [33]. The recovery rate of hydrogen isotopes in the exhaust gas stream was demonstrated by using hydrogen gas for the commissioning of deuterium experiment. The recovery rate of more than 95% was sufficiently achieved [34].

The tritium gas concentration monitoring in the stack gas was also carried out by the active tritium sampling system consisting of the catalyst bed and molecular sieve packed bed to secure the sufficient detritiation operation in the exhaust gas. The tritium concentration captured by the molecular sieves was quantified by the liquid scintillation counters. The details of this system is described elsewhere [35].

2.2.3 Radiation shielding performance by the concrete wall of the torus hall

Because LHD is not equipped with the blanket system which can work as neutron shielding as well as tritium and heat generation of fusion reactor, neutrons generated in the deuterium plasma can easily penetrate through vacuum vessel of LHD to the torus hall. In the experiment, no one can be in the torus hall of LHD for radiation safety. But, there is much work outside the torus hall during the deuterium experiments. Therefore, the concrete wall of the torus hall needed to be the boundary of the radiation control area. For this purpose, the performance of shielding for neutron and gamma-ray by the torus hall of LHD was carefully inspected with using neutral particle transport codes [28, 36, 37]. The flux distributions of neutron and gamma-ray in the equatorial plane of LHD in one deuterium plasma experiment calculated by the DOT-3.5/DORT is shown in Fig. 1 [27, 28]. In this figure, it was assumed that the neutron yield is 5.7×10^{16} n $shot^{-1}$. The distance of 0 in the abscissa of this figure indicates the center axis of LHD, and the concrete wall with the thickness of 2 m of the torus hall is placed between about 2150-2350 cm away from the center axis. Then, it was evaluated that the fluxes of neutron and gamma-ray can be decreased 7 orders of magnitude lower by the concrete wall of the torus hall. According to this result, the maximum of total neutron yield in an experimental campaign (annual neutron budget) was decided so that the fluxes of neutrons and gamma-ray outside the torus hall are below the institutional regulation level during the deuterium experiments [38]. The details of the annual neutron budget and the institutional regulation level are in Section 3.1.

2.2.4 Handling of activated materials

The activation of materials in the torus hall by the nuclear reaction with neutron is also an issue in deuterium experiments. The borated polyethylene blocks were widely used in LHD to reduce the activation. The borated polyethylene blocks effectively decelerate neutron by its light mass, and subsequently, capture thermal neutrons by boron due to its very high cross-section.

Also, all materials inside the torus hall and inside the basement of the torus hall during deuterium experiments are prohibited to be removed from the radiation control area. All work inside the radiation control area must be authorized in advance by a radiation control office.

All workers must wear work clothes in the radiation control area in order to prevent their personal clothes being contaminated. This also works to keep the contaminated clothes in the radiation control area. The radiation contamination on belongings such as clothes, phones, lap-tops, and other objects was appropriately surveyed by survey-meters such as NaI(Tl) scintillation counters, GM counters and hand-foot-cloth monitors.

2.2.5 Radiation monitoring system

The real-time monitoring system for radiation is also important for successful radiation control. In LHD, the radiation monitoring system called RMSAFE (Radiation Monitoring System Applicable to Fusion Experiments) has been developed [39-43]. In this system, the radiation monitors located inside and outside the torus hall, and at the site boundaries acquire the real-time radiation data continuously. The radiation data about gamma(X)-ray, neutron, radioactivity concentration in atmosphere, and other issues are integrated in this system.

2.2.6 Education and personal dose monitoring for radiation workers

The education for workers regarding radiation such as radiation physics and its biological effects on the human body are conducted according to the regulation (Act on prevention of radiation hazard due to radioisotopes). Additional radiological education and training were carried out for radiation workers who will do specific work such as work inside the vacuum vessel of LHD, vacuum port handling, and so on. The workers who enter the vacuum vessel must wear personal protective equipment such as a respiratory mask to reduce the risk for internal dose due to radioactive dust. The workers for vacuum port handling also need to learn tritium handling techniques. The personal radiation dosimeters were distributed to all radiation workers to monitor the personal radiation dose. The personal radiation doses were evaluated every month.

3. Regulations for radiation control

3.1 Institutional regulation

For the public acceptance of deuterium experiments, NIFS decided to set stricter regulation of radiation control for tritium concentration in stack gas, tritium concentration in drainage and the annual radiation dose at the site boundary, and other regulations, compared to Japanese radiation protection regulation. The regulation levels were determined by the ALARA (as low as reasonably achievable) based concept as far as they are precisely measureable with the practical technology so that the public and the SE committee can accept the deuterium experiment. The institutional regulation of radiation control referred in the safety management plan for LHD deuterium experiment is listed in the Table 1. For instance, the institutional regulation of radiation permits tritium concentration in stack gas (averaged in three months), tritium concentration in drainage (averaged in three months) and the annual radiation dose caused by deuterium experiments at site boundary to be 2×10^{-4} Bq/cm^3, 0.6 Bq/cm^3 and 50 μSv, respectively. These are 1/25, 1/100, and 1/20 lower than the Japanese radiation protection regulation, respectively. The maximum neutron yield in a deuterium plasma experiment was predicted as 1.9×10^{16} n s^{-1}. With this value and the radiation shielding property of the concrete wall of the torus hall, the annual neutron budget was determined as 2.1×10^{19} in the first to the sixth campaign and 3.2×10^{19} in the seventh to the ninth campaign, so that the radiation control described in the institutional regulation can be done sufficiently [38]. The increase of annual neutron yield in the last 3 years was set for the integrated high-performance operation on LHD and the development of steady state plasma operation scenarios.

3.2 Evaluation of radiation control area by the Japanese government's Nuclear Regulation Authority

As LHD in deuterium experiments will be the radiation generator, the radiation control area and the safety management in LHD were evaluated by the Japanese Nuclear Regulation Authority (NRA). In particular, the radiation shielding by the concrete wall of the torus hall was evaluated. The test operation of deuterium plasma in LHD was predominantly carried out for about 2 weeks to produce neutron with 1.5 times larger than the predicted maximum neutron yield in an experiment. The personal dosimeter placed outside the torus hall showed that the dose was less than the detection limit (0.01 mSv). By this process, the proper confinement of radiation in the torus hall was confirmed.

Also, the safety management plan, the handling capacity of radioactive materials and personal protective method in radiation control area, and other matters, were all evaluated by NRA. Finally, the radiation control area for LHD deuterium experiments were authorized by NRA.

4. Radiation monitors around the torus hall

4.1 Location of radiation monitors around the torus hall

A torus hall is placed on the first floor of the LHD experimental building, and neighbored with helium refrigerator room and the room for heating power equipment, access control room, and other purposes. The thickness of concrete walls separating the torus hall from these rooms is 2 m. The radiation monitors were placed in the torus hall and other rooms. Fig. 2 shows the component layout in the torus hall and the radiation monitors around LHD. The size of the torus hall is W75 × L45 × H40 m^3. As the main heating system, three tangential neutral beam injectors (t-NBI) and two radial neutral beam injectors (r-NBI) are connected to LHD [44, 45]. Neutron yield during deuterium plasma experiments were measured by the neutron flux monitors, located at the top of LHD center axis (#1), near the large outside port on the mid plane (#2, #3), consisting of ^{235}U fission chamber, ^{10}B counter and ^{3}He counter as found in Fig. 2 [46, 47]. The gamma(X)-ray monitors and neutron monitors were placed at the boundary between the access control room (Region A), the boundary between the room for heating power equipment (Region B), and the boundary between helium refrigerator room (Region C). The gamma(X)-ray monitor is made of the pressurized Ar-filled ion chamber. The neutron monitor is REM (Roentgen Equivalent Man) counter, except the neutron monitor inside the torus hall in Region A, where a ^{3}He counter is used. Both radiation monitors are of Fuji Electric Co. Almost all monitors were calibrated by the controlled dose field to evaluate the absorbed dose. However, the ^{3}He counter in Region A was not calibrated precisely. Therefore, the count data (count rate, integration of count, and other information) was used below for this monitor. These monitors were hung on the concrete wall at the height of about 3 m from the floor level of the torus hall. Fig. 3 shows the picture of these two radiation monitors inside and outside the torus hall in Region A. All radiation monitors in RMSAFE continuously acquire radiation monitoring data 24 h every day.

4.2 The evaluation method of radiation dose caused by deuterium experiments

A high-performance plasma experiment in large fusion devices usually consists of a short plasma operation (called a “shot”) and a long interval. The plasma is usually generated in the vacuum vessel just for several seconds. The intervals between shots in LHD during deuterium experiments was 3 min. Therefore, the evaluation of the radiation dose at site boundaries caused by the deuterium experiments requires data processing because the intervals between shots (3 min) are much longer than the time duration of the experiment (usually, 10 s in LHD). Also, the annual dose by the environmental radiation (~ 2.1 mSv average in Japan) is much higher than the site annual dose regulation (50 μSv). This means the radiation dose caused by the deuterium experiments needs to be appropriately evaluated by extracting the inspecting radiation dose from the relatively high environmental radiation dose field. For this process, the radiation dose for 10 seconds before the shot was regarded as a background radiation dose. Then, the radiation dose during the shot was subtracted from this background radiation dose to evaluate the net radiation dose caused by a deuterium experiment.

4.3 Operation of deuterium experiments in the first campaign

The atmospheric pressure in the torus hall was kept a bit lower than that in the other places to prevent radioactive isotopes in the torus hall diffusing out to an unprescribed location. In the weekly operation, the first weekday was for maintenance and the other weekdays were for experiment. In this campaign, more than 10000 experiments were carried out (shot number #133270 - #144104). About 3.6×10^{18} neurons were generated in this experimental campaign according to the measurement by NFM. The RMSAFE has continued working well during this experimental campaign without any failure or lack of data.

5. Evaluation of radiation monitoring data

5.1 Neutron yield in the first campaign of LHD deuterium experiment

Neutron yield measured by NFM in this experimental campaign is summarized in Fig. 4. The first regime of the experiment, which is between the shot number of 133270 to around 137500, showed relatively small neutron yield compared to the second regime of the experiment between the shot number of around 138000-141500. In the first regime, only radial NBIs served for deuterium injection and tangential NBIs served for hydrogen injection. In the second regime, all NBI were used for deuterium injection. Therefore, the neutron yield was high in this regime. Note that the neutron yield was different in each plasma shot because of the many parameters of the plasma. In the third regime after the shot number of about 142000, the neutron yield was slightly or hardly observed. As the hydrogen experiments were conducted for eliminating tritium in the vacuum vessel by the isotope exchange reaction in the third regime, the neutron yield was very small in this regime.

5.2 Radiation shielding in the torus hall

Fig. 5 shows the integration of radiation dose with the shot number measured by gamma(X)-ray monitors and neutron monitors in Region A. In this figure, the radiation dose caused by the deuterium experiments and the background radiation dose, which are explained in section 4.2, are displayed. Note that a neutron monitor inside the torus hall

in Region A, which adopted ^{3}He counter in this campaign, was not calibrated precisely. Therefore, the radiation dose by neutron measured by ^{3}He counter in Fig. 5 is just expressed as the integration of detection count (int-count). The radiation doses due to neutron and gamma(X)-ray inside the torus hall were significantly higher than those of the background radiation dose. This indicates that neutrons generated in the vacuum vessel of LHD released out to the torus hall. Subsequently, neutrons were captured by the components in the torus hall as well as by the concrete wall, and elsewhere, resulting in the emission of prompt gamma-ray. The integration of radiation dose increased with the shot number up to about #142000. Then, the radiation dose did not show a further increase. The trend of gamma(X)-ray dose was almost consistent with the integral neutron yield measured by the NFM as shown in Fig. 4. The same trend of radiation dose was also measured by the gamma(X)-ray monitor inside the torus hall in Region B as found in Fig. 6. On the other hand, the trend for the integral of neutron count measured in Region A showed difference compared to the NFM. Because of the neutron count by ^{3}He counter usually reached to the saturation level in the high neutron flux field, the neutron yield measured by ^{3}He was not precisely consistent with NFM.
The radiation doses during the deuterium experiments measured outside the torus hall in the Region A (Fig. 5), Region B (Fig. 6), and Region C (Fig. 7) showed little difference from the background radiation dose. The increase of background radiation dose with the shot number is only caused by the environmental radiation. Thus, the radiation dose by the shot measured outside the torus hall, which showed the same trend with background radiation dose, should be caused by the environmental radiation field. These results clearly indicate that the neutron and gamma-ray produced by the deuterium experiments were shielded, and the radiation dose caused by deuterium experiments outside the torus hall was below the detection limit of radiation monitors.
The net radiation dose outside the torus hall caused by the deuterium experiments, for example, in the Region A, was evaluated as found in Fig. 8. The net radiation dose was quite small or no-existent. The concrete wall of the torus hall worked with a prescribed performance to secure the worker’s safety in the LHD experimental building.

5.3 Confinement of radioactive isotopes in the torus hall

One of the concerns regarding the radiation control in the fusion experimental device is the leakage of radioactive isotopes generated by neutron to the uncontrolled area through the boundary, such as the entrance. After the emission of prompt gamma-ray caused by the neutron capture reaction, radioactive isotopes still remained in the torus hall. They decay with their half-life with emitting radiation. It is well known that the atoms

composing air are also activated by the neutron. In particular, ^{41}Ar is one of the radioactive isotopes to be considered in the radiation control because of its long half-life (109 min), sufficiently high concentration of argon in air (~ 1%), and high mobility in air [48-50]. Fig. 9 shows the time trend of the gamma(X)-ray radiation dose rates inside and outside the torus hall, and the neutron count rate inside the torus hall in the Region A during the weekly deuterium experiment. There are four regimes with high radiation dose rate in a week, corresponding to four daily deuterium experiments. The neutron count rate showed quick reduction to the background level after the daily experiment finished. On the other hand, the gamma(X)-ray radiation dose rate gradually decreased. Then, it did not reach to the background level before the weekly experiment began. The gamma-ray from radioactive isotopes generated by neutron must be a cause of this radiation dose. From the decrement of radiation dose rate, the apparent half-life for this radiation dose rate was deduced to be around 140 min. This is close to the half-life of ^{41}Ar (109 min). It is reasonably considered that complex radiation dose field induced by many kinds of radioactive nucleus with longer half-life as well as ^{41}Ar made the half-life of ^{41}Ar apparently longer. Consequently, it can be assumed that one of the major components of radiation in the torus hall after the experiment was ^{41}Ar.
On the other hand, the time trend of gamma(X)-ray monitor outside the torus hall in Fig. 9 showed no change in spite of the high radiation dose field inside the torus hall. This result means that the radioactive isotopes generated during deuterium plasma experiments were appropriately confined in the torus hall. Due to a slightly lower inner pressure in the torus hall compared to that in the access control room as well as other rooms in the experimental building, the radioactive isotopes in air could not diffuse to an unprescribed area.

6 Summary

The deuterium experiments in LHD could begin due to many efforts on achieving radiation safety. It took a long time to obtain public consent for the deuterium experiments. Although there was a large nuclear accident in Japan, the safety management plan in LHD was evaluated to be appropriate, and the agreements with local government bodies were achieved. This knowledge will be available to decide the construction site for DEMO reactor in future.
The radiation monitoring system in LHD, named as RMSAFE, worked well during the first campaign of deuterium experiments without any problems. From the comparison of radiation doses inside and outside the torus hall during deuterium experiments, it was fairly judged that almost all gamma-ray and neutrons were shielded by the concrete wall

of the torus hall due to its sufficient thickness of 2 m. The radioactive isotopes in air as well as in other components were well confined in the torus hall. In particular, the pressure control in the torus hall being lowered than other rooms in the LHD experimental building effectively prevented the radioactive isotopes in the air from diffusing to the unprescribed area. These evaluations of radiation shielding in the torus hall made clear that the design of radiation control in LHD was appropriate, providing the confidence in our radiation safety system.

The summary of the radiation control in the 1st campaign of deuterium experiment in LHD are open to the public as found in ref. [51]. Opening these data to the public is important to keep the public acceptance for experiments. Also, apparatuses such as portable high purity germanium detector to assess the radiation products in the torus hall, are installing for the 2nd campaign of deuterium experiment for enhancing our radiation monitoring system. The continuous improvement of radiation safety is ongoing for the successful future experiments in LHD.

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Figure captions

Table 1 The list of institutional regulation of radiation control referred in the safety management plan for LHD deuterium experiment.

Fig. 1 The flux distributions of neutron and gamma-ray in the equatorial plane of LHD in one deuterium plasma experiment calculated by the DOT-3.5/DORT[27,28]

Fig. 2 The component layout of the LHD torus hall. Blue stars indicate the NFM. Red circle and red triangle indicate the neutron monitor and gamma(X)-ray monitor placed at the boundary of the torus hall, respectively.

Fig. 3 Pictures of radiation monitor placed (a) inside the torus hall and (b) outside the torus hall in Region A.

Fig. 4 The summary of neutron yield measured by NFM in the first deuterium experiment campaign in LHD.

Fig. 5 The integration of radiation dose or count data during the deuterium plasma experiments and background radiation for (a) neutron and (b) gamma(X)-ray inside the torus hall and for (c) neutron and (d) gamma(X)-ray outside the torus hall in the region A. Note that the monitor for neutron inside the torus hall is not calibrated, therefore, the integration of count data (int-count) is used here.

Fig. 6 The integration of radiation dose during the deuterium plasma experiments and background radiation for (a) gamma(X)-ray inside the torus hall and for (b) neutron and (c) gamma(X)-ray outside the torus hall in the region B.

Fig. 7 The integration of radiation dose during the deuterium plasma experiments and background radiation for (a) neutron and (b) gamma(X)-ray outside the torus hall in the region C.

Fig. 8 The evaluation of (a) the net radiation dose by neutron and (b) the net radiation dose by gamma(X)-ray outside the torus hall in the region A by the deuterium plasma experiments. Green lines indicate the error.

Fig. 9 A typical radiation monitoring data in a weekly deuterium plasma experiment. Red and green lines indicate the gamma(X)-ray dose rate and the neutron count rate inside the torus hall, respectively. The blue line expresses the trend of gamma(X)-ray dose rate outside the torus hall. (shot number #139657 - #140207)

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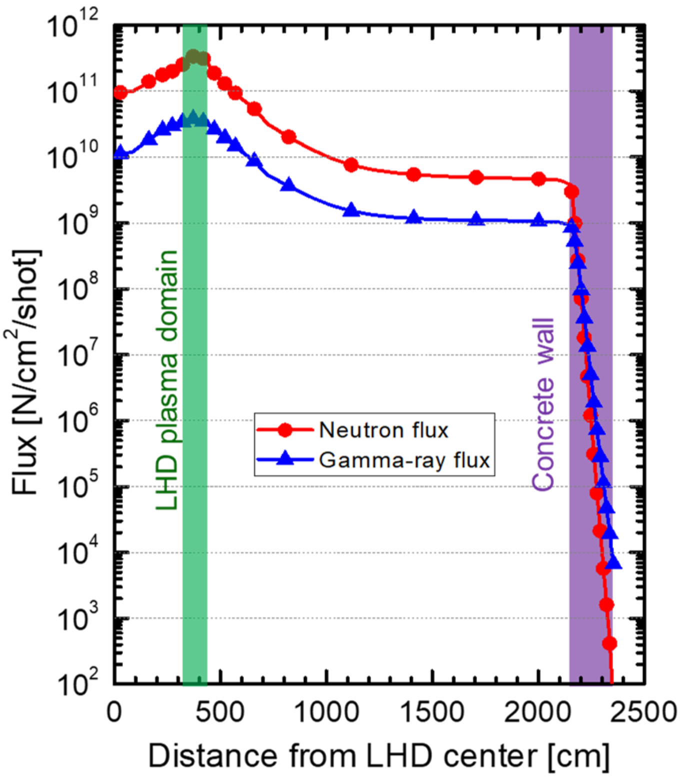
Institutional radiation control referred in the safety management plan for LHD deuterium experiment	First to sixth campaign	Seventh to ninth campaign
Maximum annual yield of tritium	3.7×10^{10} Bq	5.55×10^{10} Bq
Maximum annual yield of neutron	2.1×10^{19}	3.2×10^{19}
Annual radiation dose caused by deuterium experiment at site boundary	50 μSv (1/20 of Japanese radiation protection regulation)	
Annual tritium release in stack gas	3.7×10^{9} Bq	
Tritium concentration in stack gas averaged in three months	2×10^{-4} Bq/cm^3 (1/25 of Japanese radiation protection regulation)	
^{41}Ar concentration in stack gas averaged in three months	5×10^{-4} Bq/cm^3 (1/1 of Japanese radiation protection regulation)	
Tritium concentration in drainage averaged in three months	0.6 Bq/cm^3 (1/100 of Japanese radiation protection regulation)	



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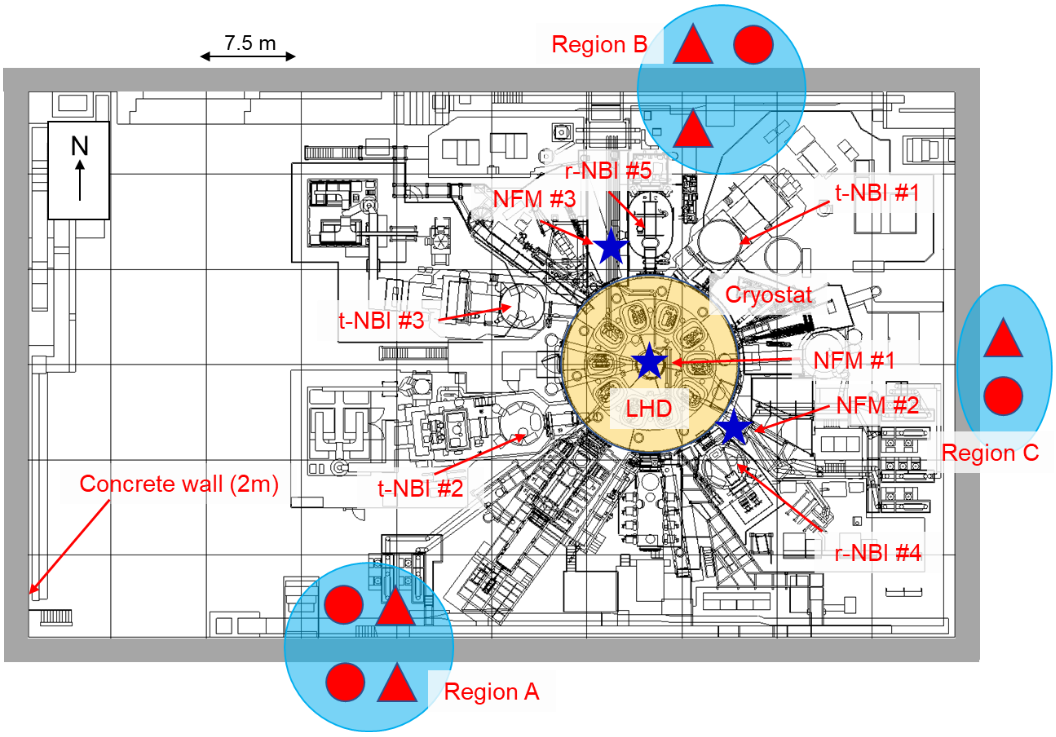

Fig. 2 Makoto Kobayashi et al

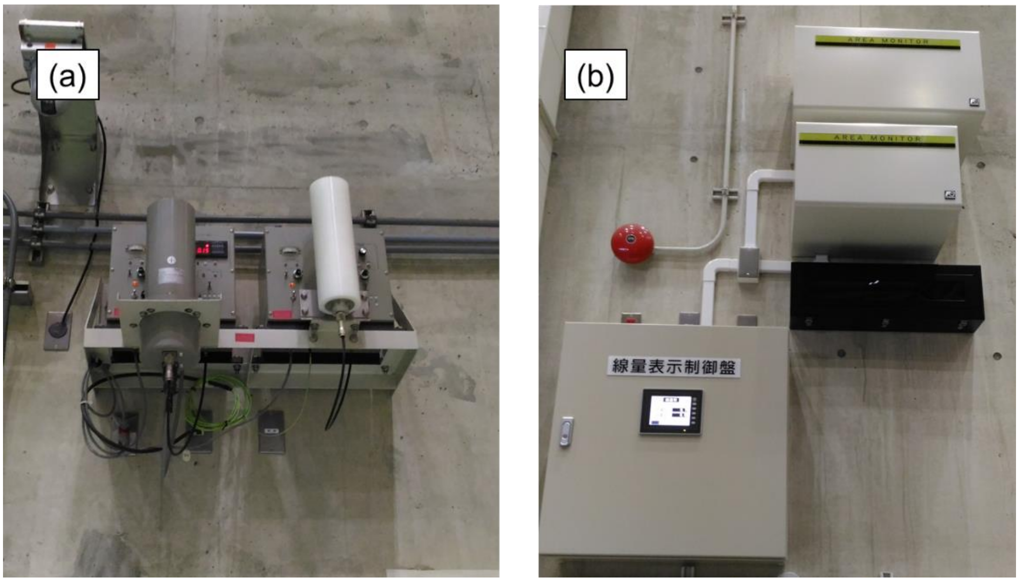

Fig. 3 Makoto Kobayashi et al.

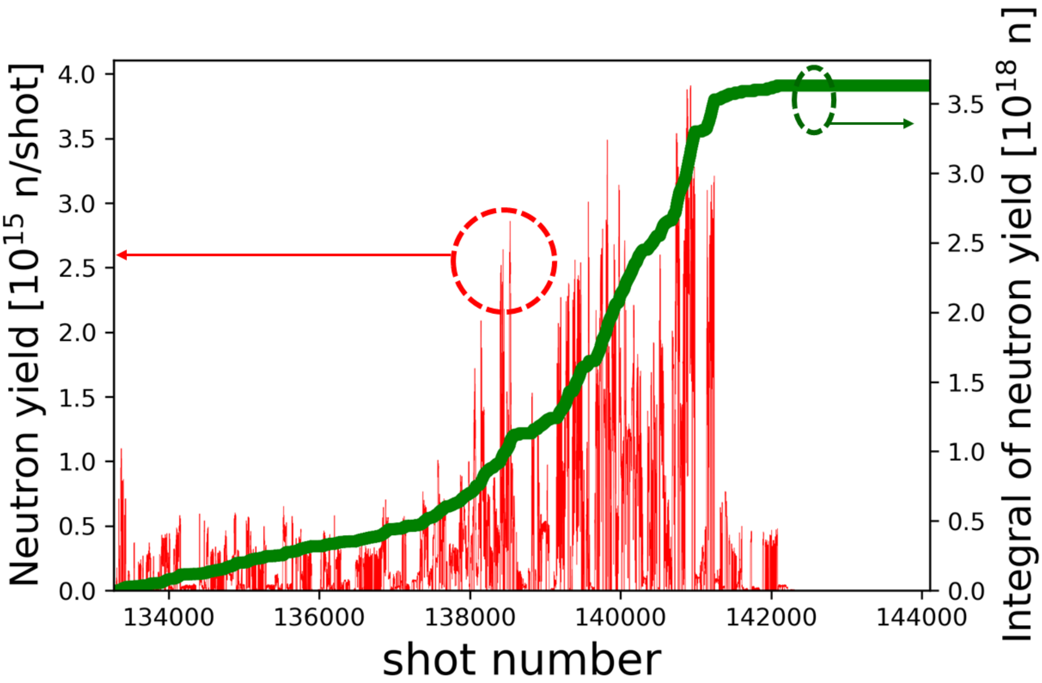

Fig. 4 Makoto Kobayashi et al.

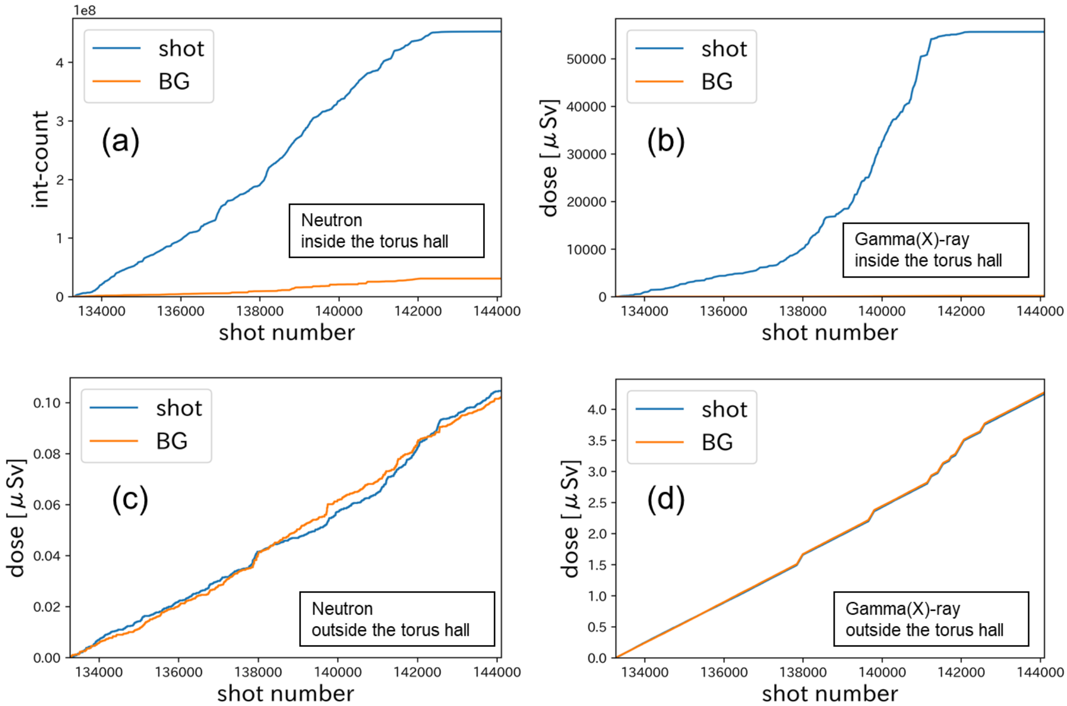

Fig. 5 Makoto Kobayashi et al.

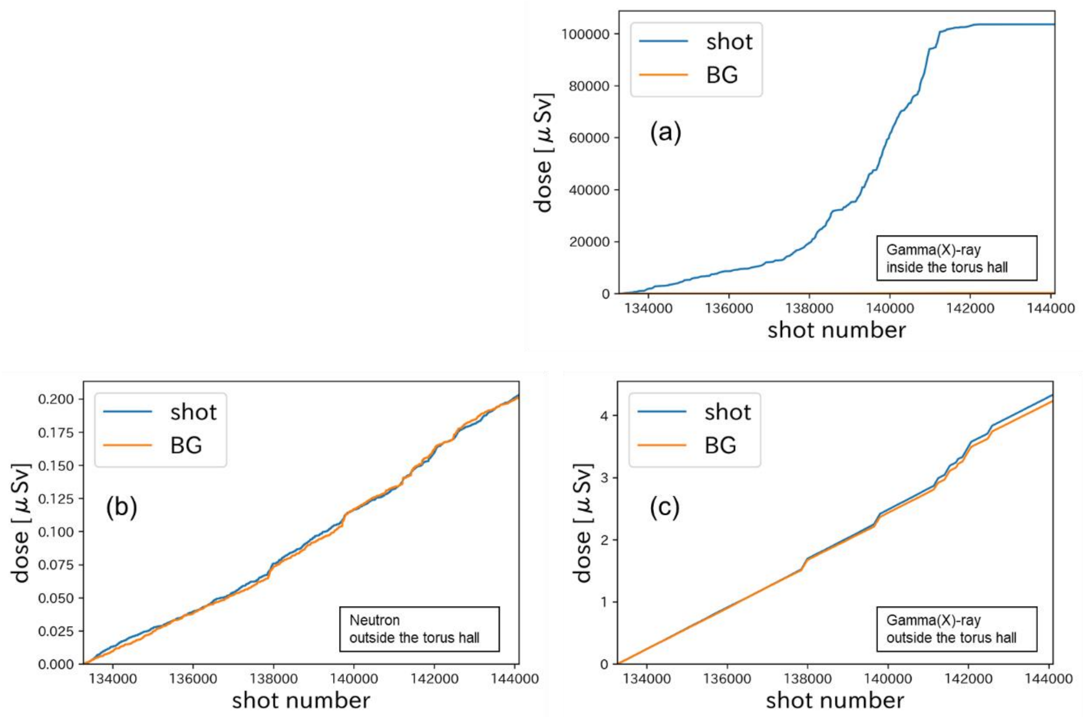

Fig. 6 Makoto Kobayashi et al.

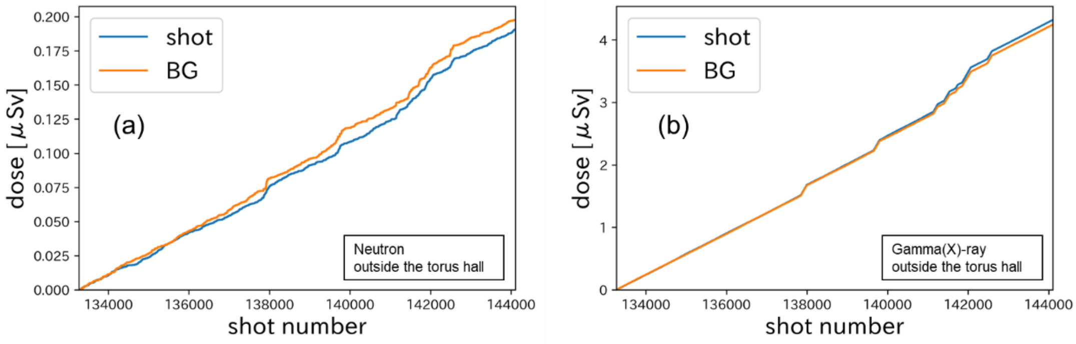

Fig. 7 Makoto Kobayashi et al.

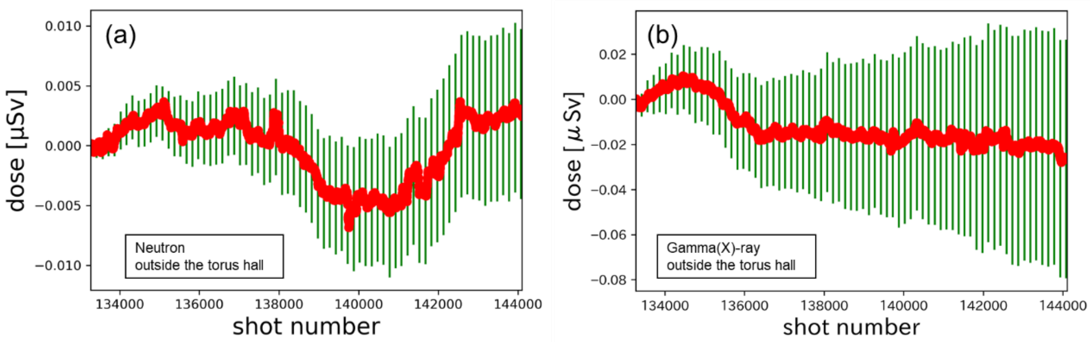

Fig. 8 Makoto Kobayashi et al.

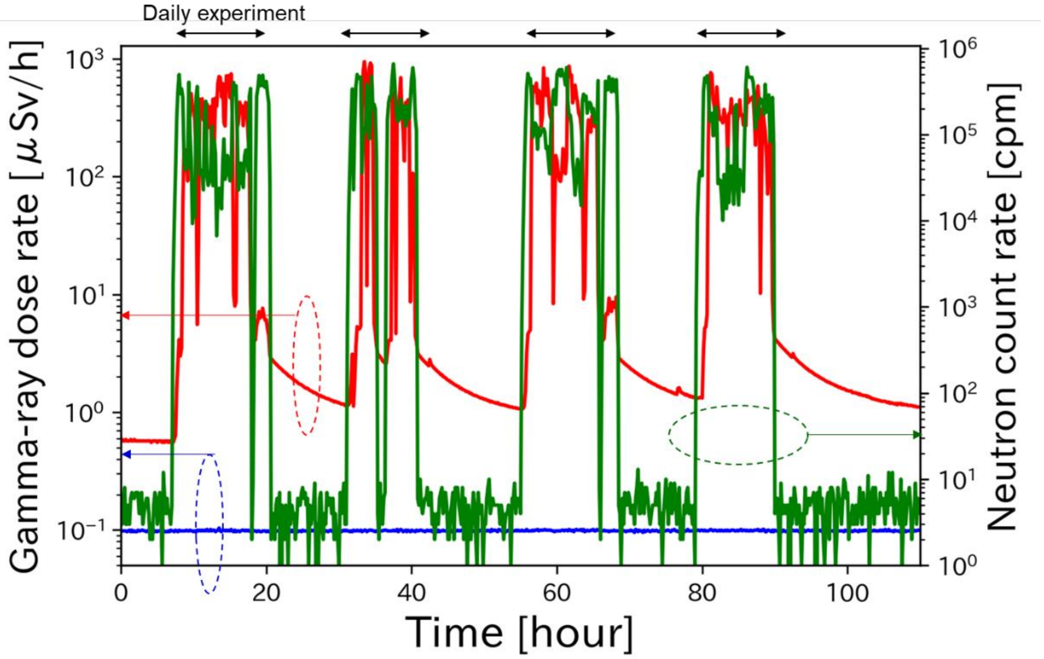

Fig. 9 Makoto Kobayashi et al.