Gamma ray diagnostics for high time resolution measurement in large helical device

Gamma Ray Diagnostics for High Time Resolution Measurement in Large Helical Device

K. Ogawa[a,b,1], S. Sangaroon[c], L. Y. Liao[b], H. Matsuura[d], K. Kimura[d], D. Umezaki[d], M. Naoi[d], T. Fukuda[d], S. Wakisaka[d], and M. Isobe[a,b]

[a] *National Institute for Fusion Science, National Institutes of Natural Sciences, Toki, 509-5292, Japan*
[b] *The Graduate University for Advanced Studies, SOKENDAI Toki, 509-5292, Japan*
[c] *Mahasarakham University Maha Sarakham 44150, Thailand*
[d] *Kyushu University, Fukuoka, Japan*

E-mail: ogawa.kunihiro@nifs.ac.jp

ABSTRACT: A 1-inch $LaBr_3$:Ce gamma ray scintillation detector, characterized by high time and energy resolution, was installed to advance energetic particle physics studies in Large Helical Device (LHD). We reduced the size of the scintillator from 3 inches to 1 inch to reinforce the radiation shielding to reduce the unwanted signal in the detector induced by fast neutrons and stray gamma rays according to the commissioning results. The radiation shielding composed of 10% borated polyethylene and lead was redesigned to suppress the gamma-ray induced signal based on the Monte Carlo three-dimensional neutron and gamma-ray transport code MCNP6. We increased the lead thickness from 50 mm to 77.5 mm to suppress the stray gamma ray effect. The gamma ray spectrum was measured in the hydrogen neutral beam heated deuterium plasma with ^{6}LiF pellet injection. We might obtain a gamma ray peak near 0.48 MeV due to the ^{6}Li(d,p'γ)^{7}Li reaction.

KEYWORDS: Large Helical Device; $LaBr_3$:Ce scintillator; Gamma ray detector; Nuclear fusion.

Contents

1. Introduction

In the measurement and control of a fusion-burning plasma, gamma ray diagnostics are one of the fundamental tools to measure energy production complementary to neutron flux measurement in deuterium-tritium (D-T) plasmas [1]. In the current study performed in D or D-T plasma experiments, gamma ray detectors were developed for fuel temperature or MeV ion diagnostics [2, 3]. Measurement of ion temperature was performed by the measurement of gamma-ray flux from the $^{10}B(d,n)^{11}C$ reaction in the CTR tokamak [4]. A two-dimensional spatial profile of 3.5 MeV alpha particles in D-T plasmas was measured in the Joint European Torus JET using 4.44 MeV gamma rays due to the $^{9}Be(\alpha,n\gamma)^{12}C$ reaction [5, 6]. Moreover, the gamma ray detector is proposed as the confined alpha particle diagnostics [7] using neutron attenuator [8, 9] as well as lost alpha particle diagnostics [10] in the ITER D-T phase. Gamma ray diagnostics are also important in so-called aneutronic fusion. Previously, a gamma ray detector was utilized to study the D-^{3}He discharge in the Tokamak Fusion Test Reactor using 16.7 MeV gamma rays created by the $^{3}He(d,\gamma)^{5}Li$ reaction [11, 12]. Recently, the study of fusion reactors based on the p-^{11}B reaction has again become popular, especially among startup companies [13]. In an aneutronic fusion study, a gamma ray monitor is a potential candidate for a fusion power monitor [14, 15].

Deuterium operation of the Large Helical Device (LHD) was performed from 2017 to 2022 [16]. Because the deuterium experiment is the first deuterium experiment in large stellarators/helical devices, one of the targets of the experiment was to enhance the energetic ion confinement study in helical systems toward helical-type fusion reactors [17-19]. The classical confinement of energetic ions [20-23] as well as energetic ion transport due to magnetohydrodynamics [24-29] have been studied using comprehensive neutron diagnostics [30-38]. The installation of gamma ray systems was planned [39] to understand the MeV ion confinement created by the ion cyclotron range of frequency wave heating experiments [40]. Additionally, gamma ray diagnostics played an important role in knock-on tail observation [41-43] through the $^{6}Li(d,p'\gamma)^{8}Be$ reaction [44, 45] and a study toward aneutronic p-^{11}B fusion [46]. In the commissioning of gamma ray diagnostics based on a large volume $LaBr_3$:Ce detector conducted in LHD [47], the gamma ray signal suffered from prompt gamma rays induced by neutrons. In this manuscript, improvement of gamma ray diagnostics and initial results of gamma ray spectrum measurements in ^{6}LiF pellet injection discharge were reported.

2. Installation of high-time resolution gamma ray diagnostic

2.1 Experimental Setups

A $LaBr_3$:Ce scintillation detector was installed on the outboard LHD diagnostic port, as shown on the left side of Figure 1. The detector was immersed in the thick radiation shielding (Figure 1 right). The size of the $LaBr_3$:Ce scintillator with 8% Ce dope had a cylindrical shape with a height of 1 inch and a diameter of 1 inch. The $LaBr_3$:Ce scintillator [48] is relatively sensitive to gamma rays compared with NaI:Tl due to its relatively heavy weight density of 5.2 g/cc [49]. The energy resolution of the detector was approximately 3% to the 662 keV gamma ray, and the pulse width is 100 ns. The scintillator was directly coupled with the conventional 1-inch photomultiplier tube (H10580-100, Hamamatsu K.K.), which could be operated in the relatively high pulse counting rate region i.e., 10^6 pulse per second. The shielding box was composed of three layers: steel SS400 for the magnetic shield, lead for the gamma ray shield, and 10% borated polyethylene for the fast neutron shield, as shown in Figure 1 right. The thickness of steel was 10 mm to avoid the magnetic field effect on the photomultiplier tube because the magnetic field at the detector position was up to 30 mT. The thickness of lead was 77.5 mm, which was 27.5 mm thicker than the previous design to reduce stray gamma rays.

The expected performance of shielding was evaluated using the Monte Carlo neutron transport calculation MCNP6 [50] based on a simplified LHD model [51]. The model has been utilized for evaluating neutron and gamma-ray distributions in the LHD torus hall and validated with experiments using activation foil methods [52, 53]. In this calculation, the plasma neutron source was assumed to be a simple torus with 99.5% deuterium-deuterium and 0.05% deuterium-tritium neutrons based on a so-called triton burnup experiment conducted in LHD [54], as performed in previous studies [55, 56]. Figure 2 shows the neutron and gamma ray flux map obtained by the transport calculation. The expected neutron and gamma ray fluxes at the detector at the total neutron emission rate of 1.9×10^{16} n/s are ~3×10^8 and ~2×10^9, respectively. Here, the expected total neutron emission rate of 1.9×10^{16} n/s predicted in advance of the LHD deuterium experiments [57] was selected as the reference. The gamma-ray flux from the side and rear was slightly reduced compared with the 3-inch $LaBr_3$:Ce detector case due to the increase in the thickness of lead.

The block diagram of the control and data acquisition of the $LaBr_3$:Ce detector is shown in Figure 3. The $LaBr_3$:Ce detector signal is directly fed into the fast data acquisition systems with a 60 m double shield coaxial cable (3D-FB). The fast data acquisition system is composed of a 14 bit 1 GHz digital-to-analog converter, field programmable gate array, and 1 GB dynamic random access memory (APV8102-14MWPSAGb, Techno AP) developed for a vertical neutron camera in LHD [58]. Note that the input impedance of the data acquisition system is 50 Ohm. The trigger time and 64 points of the waveform were simultaneously stored in the memory when the signal was over the threshold. The pulse height spectrum was obtained with postprocessing using the trigger time and waveform data. The high voltage of the $LaBr_3$:Ce detector was externally controlled by a 4 channel up to -3000 V high voltage module (APV3304, Techno AP) via the LHD LABCOM service [59].

2.2 In situ energy calibration and high voltage scan

We performed an in situ energy calibration using a ^{60}Co gamma ray source. We placed the gamma ray source in front of the $LaBr_3$:Ce detector separated by a radiation shield. We changed the high voltage from 800 V to 1200 V with 100 V steps. The two peaks corresponding to 1.173 MeV and 1.332 MeV were clearly obtained, as shown on the left side of Figure 4. Here, the energy resolution of the $LaBr_3$:Ce detector for 1.173 MeV was evaluated to be 6%. As expected, the corresponding pulse height nonlinearly increased as the voltage increased (Figure 4 right). By using both 1.173 MeV and 1.332 MeV peaks, the relationship between the gamma ray energy and pulse height at a high voltage of 800 V was obtained as [Gamma ray energy (MeV)] = 5.865 x [Pulse height (V)].

3. Initial result of gamma ray measurement

3.1 Operation limit of the detector

We performed the experiment to determine the operation limit of the $LaBr_3$:Ce detector under relatively low total neutron emission rate (S_n) experiments (Figure 5 top). Here, both fast neutrons and prompt gamma rays induced signals [60, 61]. The experiment was performed with extremely low density plasma in a relatively low magnetic field strength with an outward shifted configuration to achieve S_n on the order of 10^{12} to 10^{13} n/s. Here, a low-density plasma was used for less deposition of the neutral beam injection. The low magnetic field strength and outward shifted configuration were due to the relatively poor confinement of beam ions and relatively low electron temperature inducing a short slowing time of beam ions. Figure 5 bottom shows the pulse count rate of the $LaBr_3$:Ce detector as a function of S_n. The relationship is different in tangential negative ion source and perpendicular positive ion source phases. The difference could potentially cause by the difference in neutron energy or neutron anisotropy [62-65]. The limitation of the pulse count rate of the $LaBr_3$:Ce detector was approximately 200 kcps, where S_n was below 10^{13} n/s.

3.2 Gamma ray spectrum measurement

We measured the gamma ray spectrum in hydrogen-neutral-beam-heated deuterium plasma discharge with ^{6}LiF pellet injection (Figure 6 top). The plasma was initiated by electron cyclotron resonance heating (ECRH) [66] and sustained by negative ion based neutral beam injections (NB1, NB2 and NB3) [67]. Positive ion-based neutral beam injections (NB4 and NB5) were utilized to measure the ion temperature and Li density profile by charge exchange recombination spectroscopy [68]. Here, the Li in the ^{6}LiF pellet contained 95% enriched ^{6}Li to avoid the ^{7}Li(d,t)^{6}Li reaction. The significant increase in electron density measured by an interferometer [69] and significant decrease in the central electron temperature measured by Thomson scattering diagnostics [70] were observed by ^{6}LiF pellet injection at a *t* of ~3.87 s. The ^{3}He proportional counter placed at the 4-O port of the neutron flux monitor [71, 72] showed that S_n at this discharge was below 3×10^{9} n/s. Therefore, the expected pulse count rate of the $LaBr_3$:Ce detector due to the neutron effect was negligibly small below 0.2 counts per 10 ms. Figure 6 bottom shows the gamma ray spectrum obtained at *t* of 3.9 to 4.1 s with 20 shot accumulations. The observed gamma ray peak at ~0.48 MeV was potentially due to the ^{6}Li(d, p'γ)^{7}Li reaction.

4. Summary

Fast-response gamma ray diagnostics based on a 1-inch diameter and 1-inch height $LaBr_3$:Ce scintillator were installed in the LHD to advance energetic ion physics research in fusion plasmas. The radiation shield for the $LaBr_3$:Ce detector was redesigned based on the three-dimensional radiation transport code to suppress the unwanted neutron and gamma ray effect on the detector. In situ calibration of the $LaBr_3$:Ce detector was performed using a ^{60}Co gamma ray source. The $LaBr_3$:Ce detector could be operated under S_n below 10^{13} n/s. The operation limit was expanded by more than two orders of magnitude compared with the previous large volume $LaBr_3$:Ce detector due to the decrease in $LaBr_3$:Ce scintillator size and increase in lead thickness. A gamma ray peak at ~0.48 MeV, possibly induced by the ^{6}Li(d, p'γ)^{7}Li reaction, was observed in the ^{6}LiF pellet injection hydrogen neutral beam heated deuterium plasmas.

Acknowledgments

We are pleased to acknowledge the assistance of the LHD Experiment Group. This work is partly funded Program Management Unit for Human Resources and Institutional Development, Research and Innovation, PMU-B (B37G660016). One of the authors, K. Ogawa, is pleased to acknowledge the assistance of Y. Takeuchi of Nihon University, S. Hasegawa of Rikkyo University, S. Nozaki of Gifu University, and S. Takasu of Fukui University.

Data availability

The data supporting the findings of this study are available in the LHD experiment data repository at https://doi.org/10.57451/lhd.analyzed-data.

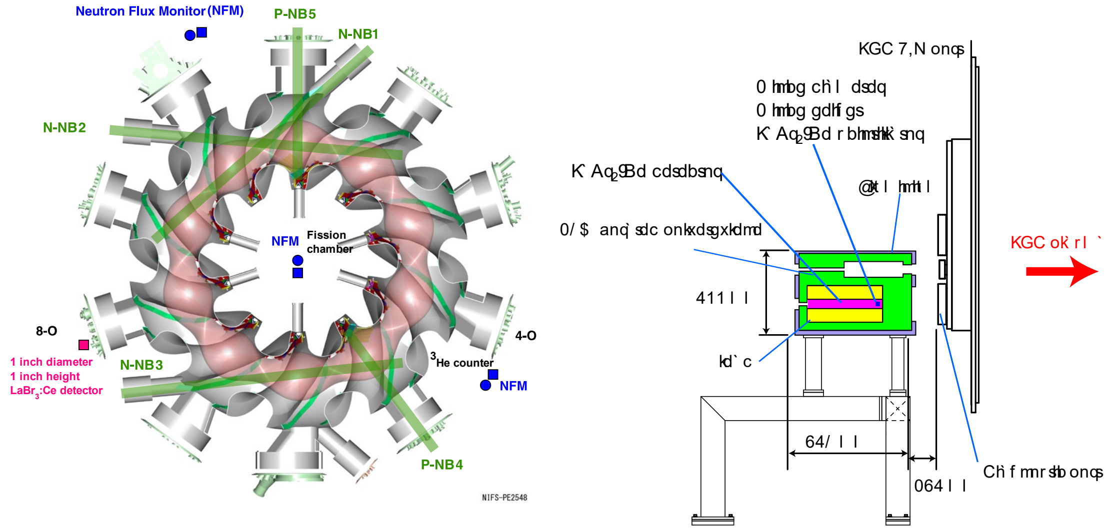

Figure 1. (left) Top view of the LHD, $LaBr_3$:Ce detector, neutral beam injections, and neutron flux monitor. (right) Cross section of gamma ray diagnostics and diagnostic port. $LaBr_3$:Ce detector is immersed into the radiation shielding composed of 72.5 mm thick lead and 10% borated polyethylene.

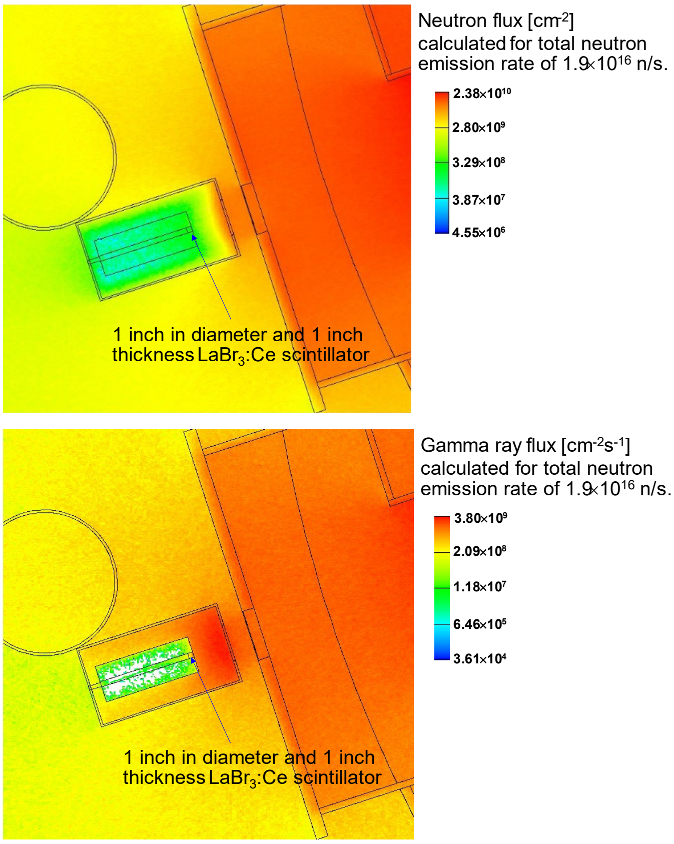

Figure 2. Two dimensional flux maps of the three dimensional radiation transport calculation for (left) neutron and (right) gamma ray. Here, total neutron emission rate was set to 1.9×10^{16} n/s.

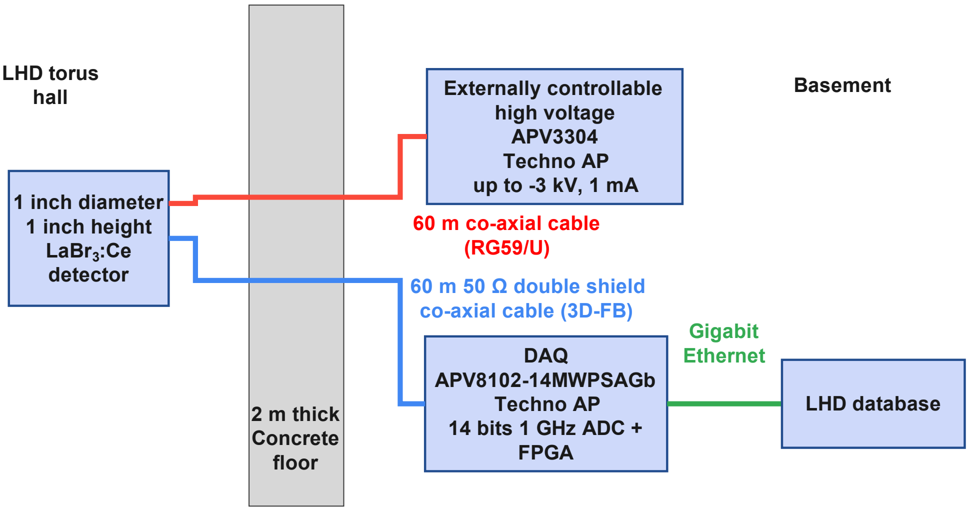

Figure 3. Block diagram of the gamma ray diagnostics.

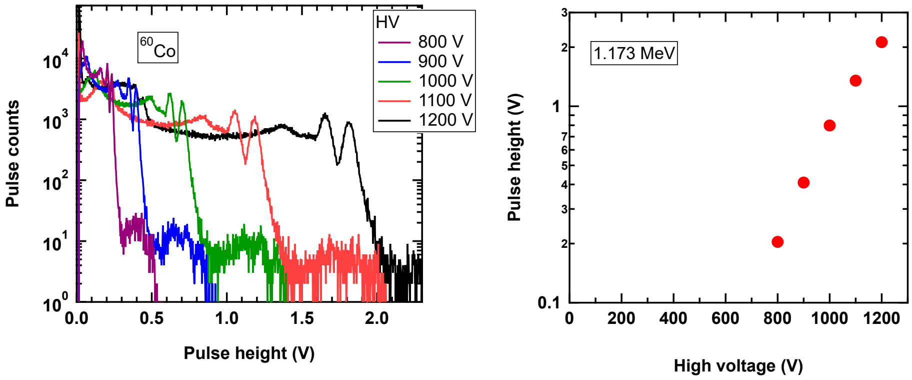

Figure 4. (left) Pulse height spectrum obtained in an in situ calibration of $LaBr_3$:Ce detector using ^{60}Co gamma ray source with changing high voltage. (right) Pulse height due to 1.173 MeV gamma ray as a function of high voltage applied to the detector.

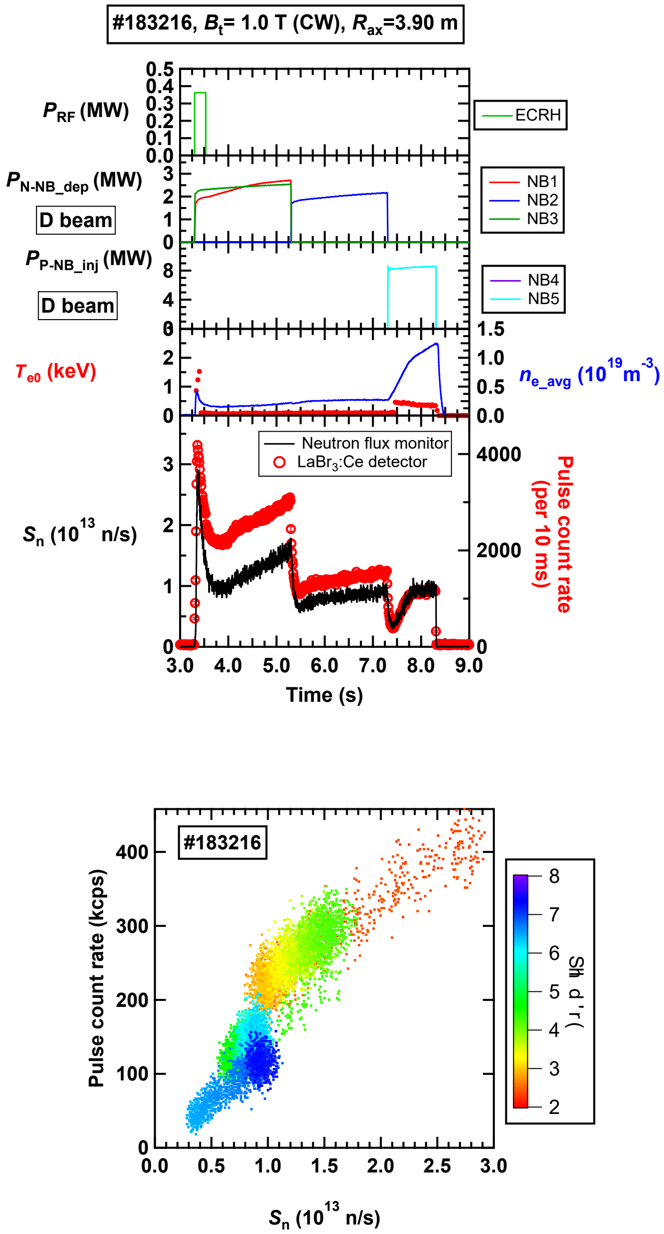

Figure 5. (top) Time evolution of relatively low total neutron emission discharge. (bottom) Pulse count rate as a function of total neutron emission rate. Pulse count rate linearly increases with S_n below an S_n value of 1.0×10^{13} n/s.

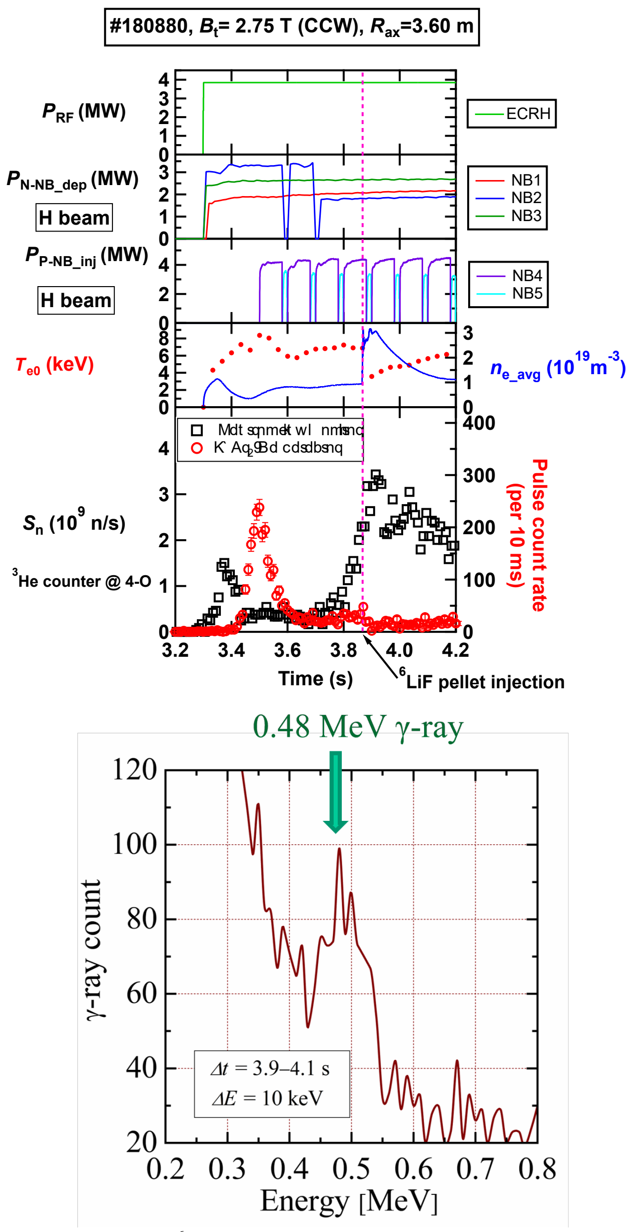

Figure 6. (top) Time evolution of the ^{6}LiF pellet injection discharge. Here, all neutral beam injection (NB) injects a hydrogen beam into the deuterium plasmas. (bottom) Gamma ray spectrum obtained by summation of 20 discharges.

References

[1] V. G. Kiptily, F. E. Cecil and S. S. Medley *Gamma ray diagnostics of high temperature magnetically confined fusion plasmas* 2006 *Plasma Physics and Controlled Fusion* **48** R59 10.1088/0741-3335/48/8/R01

[2] S. S. Medley, F. E. Cecil, D. Cole, M. A. Conway and F. J. Wilkinson *Fusion gamma diagnostics* 1985 *Review of Scientific Instruments* **56** 975 10.1063/1.1138009

[3] F. E. Cecil and F. J. Wilkinson *Measurement of the Ground-State Gamma-Ray Branching Ratio of thedtReaction at Low Energies* 1984 *Physical Review Letters* **53** 767 10.1103/PhysRevLett.53.767

[4] F. E. Cecil, L. K. Len and R. J. Peterson *The reaction 10B(d, n)11C as an ion temperature plasma diagnostic* 1980 *Nuclear Instruments and Methods* **175** 293 10.1016/0029-554x(80)90743-0

[5] V. G. Kiptily, J. M. Adams, L. Bertalot, A. Murari, S. E. Sharapov, V. Yavorskij, B. Alper, R. Barnsley, P. d. Vries, C. Gowers, L. G. Eriksson, P. J. Lomas, M. J. Mantsinen, A. Meigs, J. M. Noterdaeme, F. P. Orsitto and J. E. contributors *Gamma-ray imaging of D and4He ions accelerated by ion-cyclotron-resonance heating in JET plasmas* 2005 *Nuclear Fusion* **45** L21 10.1088/0029-5515/45/5/l01

[6] M. Nocente, D. Rigamonti, V. Perseo, M. Tardocchi, G. Boltruczyk, A. Broslawski, A. Cremona, G. Croci, M. Gosk, V. Kiptily, S. Korolczuk, M. Mazzocco, A. Muraro, E. Strano, I. Zychor, G. Gorini and J. E. T. Contributors *Gamma-ray spectroscopy at MHz counting rates with a compact LaBr(3) detector and silicon photomultipliers for fusion plasma applications* 2016 *Rev Sci Instrum* **87** 11E714 10.1063/1.4961073

[7] I. N. Chugunov, A. E. Shevelev, D. B. Gin, V. G. Kiptily, G. Gorini, M. Nocente, M. Tardocchi, D. N. Doinikov, V. O. Naidenov and E. M. Khilkevitch *Development of gamma-ray diagnostics for ITER* 2011 *Nuclear Fusion* **51** 10.1088/0029-5515/51/8/083010

[8] V. G. Kiptilyi, A. V. Livke, V. I. Nagornyi, Y. Y. Nefedov, M. V. Savin, V. I. Semenov and V. A. Chirkin *Investigation of the parameters of neutron filters* 1998 *Technical Physics* **43** 471 10.1134/1.1259008

[9] I. N. Chugunov, A. E. Shevelev, D. B. Gin, V. O. Naidenov, V. Kiptily, T. Edlington and B. Syme *Testing the neutron attenuator based on 6LiH for γ-ray diagnostics of plasmas in the JET tokamak* 2011 *Instruments and Experimental Techniques* **51** 166 10.1134/s0020441208020024

[10] V. G. Kiptily, A. E. Shevelev, V. Goloborodko, M. Kocan, E. Veshchev, T. Craciunescu, E. M. Khilkevitch, I. Lengar, I. A. Polunovsky, K. Schoepf, S. Soare, V. Yavorskij and V. L. Zoita *Escaping alpha-particle monitor for burning plasmas* 2018 *Nuclear Fusion* **58** 10.1088/1741-4326/aab676

[11] F. E. Cecil and S. S. Medley *Gamma ray measurements during deuterium and 3He discharges on TFTR* 1988 *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **271** 628 10.1016/0168-9002(88)90333-6

[12] S. S. Medley, A. L. Roquemore and F. E. Cecil *Absolute calibration of fusion gamma ray detector on TFTR* 1992 *Review of Scientific Instruments* **63** 4857 10.1063/1.1143531

[13] R. M. Magee, K. Ogawa, T. Tajima, I. Allfrey, H. Gota, P. McCarroll, S. Ohdachi, M. Isobe, S. Kamio, V. Klumper, H. Nuga, M. Shoji, S. Ziaei, M. W. Binderbauer and M. Osakabe *First measurements of p11B fusion in a magnetically confined plasma* 2023 *Nature Communications* **14** 10.1038/s41467-023-36655-1

[14] S. S. Medley, S. D. Scott, A. L. Roquemore and F. E. Cecil *Performance of the fusion gamma diagnostic on TFTR* 1990 *Review of Scientific Instruments* **61** 3226 10.1063/1.1141641

[15] F. E. Cecil, H. Liu, J. C. Scorby and S. S. Medley *Prompt gamma ray diagnostics of advanced fuel fusion plasmas* 1990 *Review of Scientific Instruments* **61** 3223 10.1063/1.1141640

[16] M. Osakabe, H. Takahashi, H. Yamada, K. Tanaka, T. Kobayashi, K. Ida, S. Ohdachi, J. Varela, K. Ogawa, M. Kobayashi, K. Tsumori, K. Ikeda, S. Masuzaki, M. Tanaka, M. Nakata, S. Murakami, S. Inagaki, K. Mukai, M. Sakamoto, K. Nagasaki, Y. Suzuki, M. Isobe, T. Morisaki and T. L. E. Group *Recent results from deuterium experiments on the large helical device and their contribution to fusion reactor development* 2022 *Nuclear Fusion* **62** 042019 10.1088/1741-4326/ac3cda

[17] Y. Takeiri *The Large Helical Device: Entering Deuterium Experiment Phase Toward Steady-State Helical Fusion Reactor Based on Achievements in Hydrogen Experiment Phase* 2018 *IEEE Transactions on Plasma Science* **46** 2348 10.1109/Tps.2017.2784380

[18] Y. Takeiri *Prospect Toward Steady-State Helical Fusion Reactor Based on Progress of LHD Project Entering the Deuterium Experiment Phase* 2018 *IEEE Transactions on Plasma Science* **46** 1141 10.1109/Tps.2017.2771749

[19] Y. Takeiri *Advanced Helical Plasma Research towards a Steady-State Fusion Reactor by Deuterium Experiments in Large Helical Device* 2018 *Atoms* **6** 69 10.3390/atoms6040069

[20] H. Nuga, R. Seki, K. Ogawa, S. Kamio, Y. Fujiwara, H. Yamaguchi, M. Osakabe, M. Isobe, S. Murakami and M. Yokoyama *Analysis of NB Fast-Ion Loss Mechanisms in MHD Quiescent LHD Plasmas* 2021 *Plasma and Fusion Research* **16** 2402052 10.1585/pfr.16.2402052

[21] H. Nuga, R. Seki, K. Ogawa, S. Kamio, Y. Fujiwara, M. Osakabe, M. Isobe, T. Nishitani and M. Yokoyama *Studies of the fast ion confinement in the Large Helical Device by using neutron measurement and integrated codes* 2020 *Journal of Plasma Physics* **86** 10.1017/s0022377820000525

[22] K. Ogawa, M. Isobe, T. Nishitani, S. Murakami, R. Seki, M. Nakata, E. Takada, H. Kawase, N. Pu and L. E. Grp *Time-resolved triton burnup measurement using the scintillating fiber detector in the Large Helical Device* 2018 *Nuclear Fusion* **58** 034002 ARTN 034002
10.1088/1741-4326/aaa585

[23] K. Ogawa, M. Isobe, T. Nishitani, R. Seki, H. Nuga, S. Murakami, M. Nakata, N. Pu, M. Osakabe, J. Jo, M. Cheon, J. Kim, G. Q. Zhong, M. Xiao, L. Q. Hu and L. E. Grp *Time dependent neutron emission rate analysis for neutral-beam-heated deuterium plasmas in a helical system and tokamaks* 2018 *Plasma Physics and Controlled Fusion* **60** 095010 ARTN 095010
10.1088/1361-6587/aad4b7

[24] K. Ogawa, M. Isobe, H. Kawase and T. Nishitani *Neutron Flux Measurement Using a Fast-Neutron Scintillation Detector with High Temporal Resolution on the Large Helical Device* 2018 *Plasma and Fusion Research* **13** 3402068 10.1585/pfr.13.3402068

[25] K. Ogawa, M. Isobe, H. Kawase, T. Nishitani, R. Seki, M. Osakabe and L. E. Grp *Effect of the helically-trapped energetic-ion-driven resistive interchange modes on energetic ion confinement in the Large Helical Device* 2018 *Plasma Physics and Controlled Fusion* **60** 044005 ARTN 044005
10.1088/1361-6587/aaab1f

[26] K. Ogawa, M. Isobe, H. Kawase, T. Nishitani, R. Seki, M. Osakabe and L. E. Grp *Observation of enhanced radial transport of energetic ion due to energetic particle mode destabilized by helically-trapped energetic ion in the Large Helical Device* 2018 *Nuclear Fusion* **58** 044001 ARTN 044001
10.1088/1741-4326/aaab18

[27] K. Ogawa, M. Isobe, S. Sugiyama, H. Matsuura, D. A. Spong, H. Nuga, R. Seki, S. Kamio, Y. Fujiwara, H. Yamaguchi, M. Osakabe and L. E. Grp *Energetic particle transport and loss induced by helically-trapped energetic-ion-driven resistive interchange modes in the Large Helical Device* 2020 *Nuclear Fusion* **60** 112011 10.1088/1741-4326/ab6da0

[28] K. Ogawa, M. Isobe, H. Nuga, S. Kamio, Y. Fujiwara, M. I. Kobayashi, S. Sangaroon, E. Takada, R. Seki, H. Yamaguchi, S. Murakami, J. Jo and M. Osakabe *A study of beam ion and deuterium-deuterium fusion-born triton transports due to energetic particle-driven magnetohydrodynamic instability in the large helical device deuterium plasmas* 2021 *Nuclear Fusion* **61** 096035 10.1088/1741-4326/ac0d8a

[29] K. Ogawa, M. Isobe, S. Kamio, H. Nuga, R. Seki, S. Sangaroon, H. Yamaguchi, Y. Fujiwara, E. Takada, S. Murakami, J. Jo, Y. Takemura, H. Sakai, K. Tanaka, T. Tokuzawa, R. Yasuhara and M. Osakabe *Studies of energetic particle transport induced by multiple Alfvén eigenmodes using neutron and escaping energetic particle diagnostics in Large Helical Device deuterium plasmas* 2022 *Nuclear Fusion* **62** 112001 10.1088/1741-4326/ac6f66

[30] E. Takada, A. Fujisaki, N. Nakada, M. Isobe, K. Ogawa, T. Nishitani and H. Tomita *Development of Fast-Neutron Directional Detector for Fusion Neutron Profile Monitor at LHD* 2016 *Plasma and Fusion Research* **11** 2405020 10.1585/pfr.11.2405020

[31] K. Ogawa, M. Isobe, T. Nishitani, E. Takada, H. Kawase, T. Amitani, N. Pu, J. Jo, M. Cheon, J. Kim, M. Miwa, S. Matsuyama and I. Murata *High detection efficiency scintillating fiber detector for time-resolved measurement of triton burnup 14 MeV neutron in deuterium plasma experiment* 2018 *Rev Sci Instrum* **89** 10I101 10.1063/1.5032118

[32] N. Pu, T. Nishitani, K. Ogawa and M. Isobe *Scintillating fiber detectors for time evolution measurement of the triton burnup on the Large Helical Device* 2018 *Rev Sci Instrum* **89** 10I105 10.1063/1.5035290

[33] E. Takada, T. Amitani, A. Fujisaki, K. Ogawa, T. Nishitani, M. Isobe, J. Jo, S. Matsuyama, M. Miwa and I. Murata *Design optimization of a fast-neutron detector with scintillating fibers for triton burnup experiments at fusion experimental devices* 2019 *Rev Sci Instrum* **90** 043503 10.1063/1.5074131

[34] K. Ogawa, M. Isobe, S. Sangaroon, E. Takada, T. Nakada, S. Murakami, J. Jo, G. Q. Zhong, Y. Zhang, S. Tamaki and I. Murata *Time-resolved secondary triton burnup 14 MeV neutron measurement by a new scintillating fiber detector in middle total neutron emission ranges in deuterium large helical device plasma experiments* 2021 *AAPPS Bulletin* **31** 10.1007/s43673-021-00023-2

[35] N. Pu, T. Nishitani, M. Isobe, K. Ogawa, H. Kawase, T. Tanaka, S. Y. Li, S. Yoshihashi and A. Uritani *In situ calibration of neutron activation system on the large helical device* 2017 *Rev Sci Instrum* **88** 113302 10.1063/1.5009475

[36] M. Isobe, K. Ogawa, T. Nishitani, N. Pu, H. Kawase, R. Seki, H. Nuga, E. Takada, S. Murakami, Y. Suzuki, M. Yokoyama, M. Osakabe and L. E. Grp *Fusion neutron production with deuterium neutral beam injection and enhancement of energetic-particle physics study in the large helical device* 2018 *Nuclear Fusion* **58** 082004 ARTN 082004
10.1088/1741-4326/aabcf4

[37] M. Isobe, K. Ogawa, T. Nishitani, H. Miyake, T. Kobuchi, N. Pu, H. Kawase, E. Takada, T. Tanaka, S. Y. Li, S. Yoshihashi, A. Uritani, J. Jo, S. Murakami, M. Osakabe and L. E. Grp *Neutron Diagnostics in the Large Helical Device* 2018 *IEEE Transactions on Plasma Science* **46** 2050 10.1109/Tps.2018.2836987

[38] K. Ogawa, M. Isobe and M. Osakabe *Progress on Integrated Neutron Diagnostics for Deuterium Plasma Experiments and Energetic Particle Confinement Studies in the Large Helical Device During the Campaigns from FY2017 to FY2019* 2021 *Plasma and Fusion Research* **16** 1102023 10.1585/pfr.16.1102023

[39] M. Isobe, H. Yamanishi, M. Osakabe, H. Miyake, H. Tomita, K. Watanabe, H. Iwai, Y. Nomura, N. Nishio, K. Ishii, J. H. Kaneko, J. Kawarabayashi, E. Takada, A. Uritani, M. Sasao, T. Iguchi, Y. Takeiri and H. Yamada *Fusion product diagnostics planned for Large Helical Device deuterium experiment* 2010 *Rev Sci Instrum* **81** 10D310 10.1063/1.3492383

[40] S. Kamio, K. Saito, R. Seki, H. Kasahara, M. Kanda, G. Nomura and T. Seki *Study of ion cyclotron range of frequencies heating characteristics in deuterium plasma in the Large Helical Device* 2021 *Nuclear Fusion* **62** 10.1088/1741-4326/ac359d

[41] H. Matsuura, S. Sugiyama, K. Kimura, S. Kajimoto, T. Nishitani, K. Ogawa, Y. Kawamoto, M. Isobe and M. Osakabe *Observation of a nuclear-elastic-scattering effect caused by energetic protons on deuteron slowing-down behaviour on the Large Helical Device* 2020 *Nuclear Fusion* **60** 066007 10.1088/1741-4326/ab7e00

[42] H. Matsuura, K. Kimura, D. Umezaki, K. Ogawa, M. Isobe, Y. Kawamoto, T. Oishi, M. Goto, N. Tamura, M. Osakabe, T. Nishitani and S. Sugiyama *Indirect energy transfer channel between fast ions via nuclear elastic scattering observed on the large helical device* 2022 *Physics of Plasmas* **29** 10.1063/5.0097720

[43] Y. Kawamoto and H. Matsuura *Method for determining the shape and size of a knock-on tail using the Doppler-broadened γ-ray emission spectrum* 2019 *Fusion Engineering and Design* **144** 62 10.1016/j.fusengdes.2019.04.062

[44] H. Matsuura, S. Sugiyama, S. Kajimoto, D. Sawada, Y. Nishimura and Y. Kawamoto *Knock-on Tail Formation Due to Nuclear Elastic Scattering and Its Observation Method Using <i>γ</i>-Ray-Generating ⁶Li+d Reaction in Tokamak Deuterium Plasmas* 2016 *Plasma and Fusion Research* **11** 1403105 10.1585/pfr.11.1403105

[45] H. Matsuura, M. Nakamura and Y. Nakao *Use of γ-Ray-Generating 6Li+D Reaction for Verification of Boltzmann-Fokker-Planck Simulation and Knock-on Tail Diagnostic in Neutral-Beam-Injected Plasmas* 2007 *Plasma and Fusion Research* **2** S1078 10.1585/pfr.2.S1078

[46] K. Ogawa, M. Isobe, H. Nuga, R. Seki, S. Ohdachi and M. Osakabe *Evaluation of Alpha Particle Emission Rate Due to the p-(11B) Fusion Reaction in the Large Helical Device* 2022 *Fusion Science and Technology* **78** 175 10.1080/15361055.2021.1973294

[47] K. Ogawa, S. Sangaroon and M. Isobe *Large Volume and Fast Response Gamma Ray Diagnostic in the Large Helical Device* 2023 *Plasma and Fusion Research* **18** 2402016 10.1585/pfr.18.2402016

[48] K. Krmer, T. Schleid, M. Schulze, W. Urland and G. Meyer *Three Bromides of Lanthanum: LaBr2, La2Br5, and LaBr3* 1989 *Zeitschrift fr anorganische und allgemeine Chemie* **575** 61 10.1002/zaac.19895750109

[49] https://www.shalomeo.com/Scintillators/Scintillation-Crystal-Materials/LaBr3-Ce/product-395.html

[50] C. J. Werner, J. S. Bull, C. J. Solomon, F. B. Brown, G. W. McKinney, M. E. Rising, D. A. Dixon, R. L. Martz, H. G. Hughes, L. J. Cox, A. J. Zukaitis, J. C. Armstrong, R. A. Forster and L. Casswell 2018 *MCNP Version 6.2 Release Notes*. Office of Scientific and Technical Information (OSTI))

[51] T. Nishitani, K. Ogawa, H. Kawase, N. Pu, T. Ozaki and M. Isobe *Monte Carlo calculation of the neutron and gamma-ray distributions inside the LHD experimental building and shielding design for diagnostics* 2019 *Progress in Nuclear Science and Technology* **6** 48 10.15669/pnst.6.48

[52] M. Kobayashi, T. Tanaka, T. Nishitani, K. Ogawa, M. Isobe, A. Kato, T. Saze, S. Yoshihashi, M. Osakabe and L. E. Grp *First measurements of thermal neutron distribution in the LHD torus hall generated by deuterium experiments* 2018 *Fusion Engineering and Design* **137** 191 10.1016/j.fusengdes.2018.09.013

[53] S. Yoshihashi, H. Yamada, M. Kobayashi, T. Nishitani, A. Yamazaki, M. Isobe, K. Ogawa and A. Uritani *Evaluation of Induced Radioactivity Generated during LHD Deuterium Plasma Experiments* 2022 *Plasma and Fusion Research* **17** 2405096 10.1585/pfr.17.2405096

[54] K. Ogawa, M. Isobe, T. Nishitani, S. Murakami, R. Seki, H. Nuga, S. Kamio, Y. Fujiwara, H. Yamaguchi, Y. Saito, S. Maeta, M. Osakabe and L. E. Grp *Energetic ion confinement studies using comprehensive neutron diagnostics in the Large Helical Device* 2019 *Nuclear Fusion* **59** 076017 ARTN 076017
10.1088/1741-4326/ab14bc

[55] M. I. Kobayashi, N. Suzuki, T. Saze, H. Miyake, K. Nishimura, H. Hayashi, T. Kobuchi, K. Ogawa, M. Isobe and M. Osakabe *The Evaluation of a Simple Measurement Method using NaI(Tl) Scintillation Survey-Meter for Radiation Safety Management of Radioactivated Armor Tiles of LHD Vacuum Vessel* 2021 *Radiation Safety Management* **20** 20 10.12950/rsm.210416

[56] T. Tanaka, M. Kobayashi, S. Yoshihashi, A. Uritani, K. Watanabe, A. Yamazaki, T. Nishitani, K. Ogawa and M. Isobe *Measurement of Thermal and Epithermal Neutron Flux Distribution in the Torus Hall of LHD using Activation Method in the First Deuterium Experiment Campaign* 2019 *Plasma and Fusion Research* **14** 3405162 10.1585/pfr.14.3405162

[57] M. Osakabe, Y. Takeiri, T. Morisaki, G. Motojima, K. Ogawa, M. Isobe, M. Tanaka, S. Murakami, A. Shimizu, K. Nagaoka, H. Takahashi, K. Nagasaki, H. Takahashi, T. Fujita, Y. Oya, M. Sakamoto, Y. Ueda, T. Akiyama, H. Kasahara, S. Sakakibara, R. Sakamoto, M. Tokitani, H. Yamada, M. Yokoyama, Y. Yoshimura and L. E. Grp *Current Status of Large Helical Device and Its Prospect for Deuterium Experiment* 2017 *Fusion Science and Technology* **72** 199 10.1080/15361055.2017.1335145

[58] K. Ogawa, M. Isobe, T. Nishitani and T. Kobuchi *The large helical device vertical neutron camera operating in the MHz counting rate range* 2018 *Rev Sci Instrum* **89** 113509 10.1063/1.5054818

[59] H. Nakanishi, M. Ohsuna, M. Kojima, S. Imazu, M. Nonomura, M. Hasegawa, K. Nakamura, A. Higashijima, M. Yoshikawa, M. Emoto, T. Yamamoto, Y. Nagayama and K. Kawahata *Data Acquisition and Management System of LHD* 2010 *Fusion Science and Technology* **58** 445 10.13182/fst10-a10830

[60] C. Cazzaniga, M. Nocente, M. Tardocchi, G. Croci, L. Giacomelli, M. Angelone, M. Pillon, S. Villari, A. Weller, L. Petrizzi and G. Gorini *Response of LaBr3(Ce) scintillators to 2.5 MeV fusion neutrons* 2013 *Review of Scientific Instruments* **84** 123505 10.1063/1.4847056

[61] M. P. Taggart and J. Henderson *Fast-neutron response of LaBr3(Ce) and LaCl3(Ce) scintillators* 2020 *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **975** 10.1016/j.nima.2020.164201

[62] S. Sugiyama, H. Matsuura and T. Goto *Neutron Incident Angle and Energy Distribution at Vacuum Vessel for Beam-Injected Deuterium Plasmas in the Large Helical Device* 2016 *Plasma and Fusion Research* **11** 2403049 10.1585/pfr.11.2403049

[63] S. Sugiyama, T. Nishitani, H. Matsuura, M. Isobe, K. Ogawa, T. Tanaka, S. Yoshihashi, A. Uritani and M. Osakabe *Observation of neutron emission anisotropy by neutron activation measurement in beam-injected LHD deuterium plasmas* 2020 *Nuclear Fusion* **60** 10.1088/1741-4326/ab90c9

[64] S. Sangaroon, K. Ogawa, M. Isobe, M. I. Kobayashi, Y. Fujiwara, S. Kamio, H. Yamaguchi, R. Seki, H. Nuga, S. Toyama, M. Miwa, S. Matsuyama, E. Takada, S. Murakami, G. Q. Zhong and M. Osakabe *Neutron energy spectrum measurement using CLYC7-based compact neutron emission spectrometer in the Large Helical Device* 2021 *Journal of Instrumentation* **16** C12025 10.1088/1748-0221/16/12/c12025

[65] S. Sangaroon, K. Ogawa, M. Isobe, M. I. Kobayashi, Y. Fujiwara, S. Kamio, H. Yamaguchi, R. Seki, H. Nuga, E. Takada, S. Murakami, G. Q. Zhong and M. Osakabe *Observation of significant Doppler shift in deuterium-deuterium neutron energy caused by neutral beam injection in the large helical device* 2022 *AAPPS Bulletin* **32** 5 10.1007/s43673-022-00036-5

[66] T. Shimozuma, H. Takahashi, S. Kubo, Y. Yoshimura, H. Igami, Y. Takita, S. Kobayashi, S. Ito, Y. Mizuno, H. Idei, T. Notake, M. Sato, K. Ohkubo, T. Watari, T. Mutoh, R. Minami, T. Kariya, T. Imai and L. E. Grp *Ecrh-Related Technologies for High-Power and Steady-State Operation in Lhd* 2010 *Fusion Science and Technology* **58** 530 Doi 10.13182/Fst58-530

[67] Y. Takeiri, O. Kaneko, K. Tsumori, M. Osakabe, K. Ikeda, K. Nagaoka, H. Nakano, E. Asano, T. Kondo, M. Sato, M. Shibuya, S. Komada and L. E. Grp *High Performance of Neutral Beam Injectors for Extension of Lhd Operational Regime* 2010 *Fusion Science and Technology* **58** 482 Doi 10.13182/Fst10-A10834

[68] M. Yoshinuma, K. Ida, M. Yokoyama, M. Osakabe and K. Nagaoka *Charge-Exchange Spectroscopy with Pitch-Controlled Double-Slit Fiber Bundle on LHD* 2010 *Fusion Science and Technology* **58** 375 10.13182/fst10-a10823

[69] T. Akiyama, K. Kawahata, K. Tanaka, T. Tokuzawa, Y. Ito, S. Okajima, K. Nakayama, C. A. Michael, L. N. Vyacheslavov, A. Sanin, S. Tsuji-Iio and L. E. Grp *Interferometer Systems on Lhd* 2010 *Fusion Science and Technology* **58** 352 Doi 10.13182/Fst10-8

[70] I. Yamada, K. Narihara, H. Funaba, T. Minami, H. Hayashi and T. Kohmoto *Recent Progress of the LHD Thomson Scattering System* 2017 *Fusion Science and Technology* **58** 345 10.13182/fst10-a10820

[71] D. Ito, H. Yazawa, M. Tomitaka, T. Kumagai, S. Kono, M. Yamauchi, T. Misawa, T. Kobuchi, H. Hayashi, H. Miyake, K. Ogawa, T. Nishitani and M. Isobe *Development of a Wide Dynamic Range Neutron Flux Measurement Instrument Having Fast Time Response for Fusion Experiments* 2021 *Plasma and Fusion Research* **16** 1405018 10.1585/pfr.16.1405018

[72] M. Isobe, K. Ogawa, H. Miyake, H. Hayashi, T. Kobuchi, Y. Nakano, K. Watanabe, A. Uritani, T. Misawa, T. Nishitani, M. Tomitaka, T. Kumagai, Y. Mashiyama, D. Ito, S. Kono, M. Yamauchi and Y. Takeiri *Wide dynamic range neutron flux monitor having fast time response for the Large Helical Device* 2014 *Rev Sci Instrum* **85** 11E114 10.1063/1.4891049