Fusion product diagnostics planned for Large Helical Device deuterium experiment[a)]

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Deuterium experiment on the Large Helical Device (LHD) is now being planned at the National Institute for Fusion Science. The fusion product diagnostics systems currently considered for installation on LHD are described in this paper. The systems will include a time-resolved neutron yield monitor based on neutron gas counters, a time-integrated neutron yield monitor based on activation techniques, a multicollimator scintillation detector array for diagnosing spatial distribution of neutron emission rate, 2.5 MeV neutron spectrometer, 14 MeV neutron counter, and prompt γ-ray diagnostics. © *2010 American Institute of Physics.* [doi:10.1063/1.3492383]

I. INTRODUCTION

The Large Helical Device (LHD) at the National Institute for Fusion Science (NIFS) is the world's largest superconducting magnetic confinement device, providing good particle confinement and a high beta with the quasisteady-state operation.[1] Currently, the operation of LHD is performed with hydrogen and/or helium gases. To obtain higher performance heliotron plasmas and a prospect of reactor based on LHD concept, deuterium experiments are in plan on LHD. Activation analyses for LHD are being carefully carried out toward the deuterium experiment.[2] One of the key physics subjects in the LHD deuterium experiment is to enhance the understanding of energetic ion-related physics such as a ripple transport, anomalous transport of energetic beam ions caused by Alfvénic modes and turbulences. Because most of neutrons will be produced by beam-plasma reactions in LHD, neutron diagnostics play an important role not only in measuring fusion output but also in assessing global confinement property of beam ions. Deuterium experiments also can provide a new opportunity to study confinement of MeV ions isotropic in the velocity space in heliotron plasmas. Note that in addition of tokamaks,[3] neutron diagnostics have been employed in small or medium sized stellarator/heliotron devices.[4–6] Deuterium discharges are also in plan in the large superconducting stellarator Wendelstein 7-X which is now under construction and a required neutron measuring system has been discussed.[7] A preliminary list intended to satisfy the needs for energetic-ion physics in LHD includes (1) ex-vessel neutron counters and activation-foil system, (2) neutron profile monitor, (3) 2.5 MeV neutron spectrometer, (4) 14 MeV neutron diagnostic, and (5) prompt γ-ray diagnostic. This paper describes the conceptual plan for fusion product diagnostic integration onto LHD.

II. NEUTRON EMISSION RATE EXPECTED IN LHD

Neutron measurement has been one of key diagnostics in deuterium experiments providing fusion reactivity, dynamics of "fuel" ions such as ion temperature, energy distribution, and radial diffusion of energetic beam ions.[3] It is also very important in a viewpoint of radiation safety. In existing magnetically confined fusion plasma experiments, target plasmas initiated by Ohmic heating in tokamak and/or electron cyclotron resonance heating (ECRH) in heliotron/stellarator are auxiliarily heated by intense high-energy neutral beams (NBs). In such a heating scheme, most of D–D neutrons are produced by so-called beam-plasma interactions. One of conspicuous characteristics of LHD is that it is equipped with three negative-ion-source based high-energy NB injectors that provide fairly high-energy beam ions in the tangential direction with injection energy E_b/power P_{nb} of 180 keV/16 MW. In addition to these, there exists a positive-ion source based perpendicular NB injector with E_b/P_{nb} of 40 keV/7 MW. Also, a second positive NB injector will be available soon, injecting beam ions with E_b of 60 keV, perpendicularly. Those high-energy beam ions will play a significant role in producing D–D neutrons. A maximum neutron emission rate over 1×10^{16} (n/s) is expected in LHD

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TABLE I. Proposed neutron diagnostic systems for LHD.

Objects	Physics information	Detector candidates
Total neutron yield	•Fusion output •Global confinement of beam ions	•^{3}He gas counter •^{235}U fission chamber •^{238}U fission chamber •Activation foil (shot-integrated)
Neutron profile	•Deposition profile of beam ions •Radial transport of beam ions	•Multichannel neutron collimator •Neutron scintillator (NE213/Stilbene/NE451)
Neutron energy spectrum	•Velocity distribution of beam ions (•Ion temperature if no fast-ion tail)	•Associated-particles coincident counting (APCC) spectrometer •^{3}He gas counter
Triton burn-up	•Global confinement property of MeV ion	•Activation foil (shot-integrated) •Scintillation fiber
γ-ray	•D$-^{3}$He reactivity • Global confinement property of MeV ion	•High Z γ-ray scintillator (e.g., BGO, LaBr3:Ce)

when all NBs are injected into a deuterium target plasma simultaneously. Note that the D–D neutron rate expected in LHD is comparable to that observed in deuterium discharges of large tokamaks, i.e., JET,[3] TFTR,[8] JT-60U,[9] and DIII-D.[10]

III. NEUTRON DIAGNOSTICS PLANNED FOR LHD

A proposed comprehensive set of neutron diagnostics intended to satisfy the need in LHD deuterium experiment is given in Table I. The three systems, i.e., ex-vessel neutron yield monitor, profile monitor, and D–D neutron spectrometer will be described in turn, concentrating mainly on a broad policy in choosing neutron detectors and the stage of progress on design work for each task. Although a time-resolved triton burn-up detector and prompt γ-ray detector are important in investigating MeV ion confinement in LHD, they will not be described here for lack of space.

A. Ex-vessel total neutron yield monitor

In deuterium-NB heated deuterium plasmas, the neutron emission rate can vary widely in orders of 10^4-10^6 in a time scale of slowing-down time of beam ions after NBs are turned off. Alfvénic modes that can potentially cause anomalous losses of beam ions may lead to a rapid drop of neutron rate in a much shorter time scale. The detector system having a wide dynamic range is therefore required. The neutron detection system is being considered for total neutron emission rate measurement on LHD, consisting of ^{3}He gas counter, ^{235}U, and ^{238}U fission ionization chambers (FCs).[11] These three counters are different in sensitivity to neurons, and accordingly, this detector set is capable of covering wide range in the neutron emission rate. These counters are known to be reliable in a long-term stable operation. The epithermal ^{3}He gas counter is the most sensitive to neutrons, whereas the fast-neutron detector ^{238}U FC with neutron threshold energy of $\sim$1.45 MeV has the least sensitivity. It is expected that pulse signals from the ^{3}He counter will saturate in a high power NB heating phase since its dynamic range is intrinsically narrow. In orders of $\sim10^2$ and this counter will be applicable to only low neutron yield shots, e.g., ECRH plasma and/or ion cyclotron resonance heated (ICRH) plasma with a minority heating scheme. The most important counter on LHD will be an epithermal ^{235}U FC, taking the responsibility from midrange to high-range for neutron emission rate. A counting-Campbelling circuit[12] based on Campbell's mean square voltage theorem will be employed for the ^{235}U FC. The choice of FC combined with the Campbelling circuit allows a wide range counting capability and excellent discrimination against counts due to γ-ray events in the ionization chamber because of high Q-value. Because of those backgrounds mentioned above, FCs have been employed to measure total neutron rate in high neutron yield fusion experiment as a standard neutron yield monitor. The most important and indispensable work to evaluate total neutron yield/emission rate is to perform *in situ* calibration of neutron counters placed around the torus together with neutron transport simulations. The neutron calibration on LHD will be carried out along the standardized neutron calibration technique discussed in the workshop on neutron calibration held at Princeton Plasma Physics Laboratory in 1988.[13] The method consists of placing a known strength ^{252}Cf spontaneous fission neutron source (the mean neutron energy $\sim$2.1 MeV) inside the LHD vacuum vessel at a number of locations which approximate the plasma position and determining the counter response. Judging from the calibration experiences in large tokamaks that are comparable to LHD in the machine dimension and D–D neutron rate,[14] the ^{252}Cf source having a neutron strength of $\sim 1\times10^{8}$ (n/s) is required for LHD. A schematic drawing of *in situ* neutron calibration method on LHD is shown in Fig. 1. The neutron source transfer system consisting of train and track will be employed in the calibration experiment.

Although the mean energy ($\sim$2.1 MeV) of neutrons emitted from calibration ^{252}Cf source is close to energy of

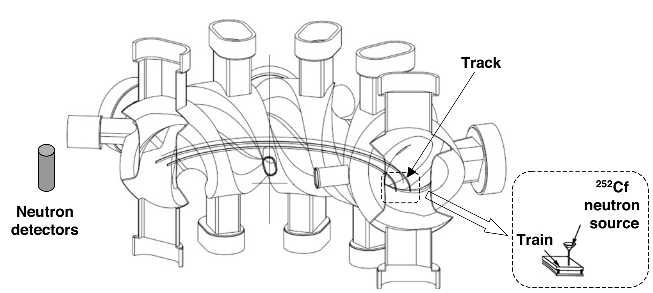

FIG. 1. Schematic drawing of neutron calibration method planned for LHD.

D–D neutron, neutron energy spectra between ^{252}Cf and D–D neutron are quite different. The neutrons emitted from ^{252}Cf have a broad spectrum whereas the D–D neutron energy peaks around 2.5 MeV. In addition, ^{252}Cf is a point neutron source but D–D neutrons are actually produced in a plasma volume source. Effect of the differences between calibration source and plasma source on the calibration factor has to be therefore investigated because neutron transports in the vicinity of the device may be different between ^{252}Cf and D–D neutrons. To do this, three-dimensional neutron transport calculation is indispensable. A program that generates an input file of complicated LHD machine geometry for Monte Carlo code MCNP (Ref. 15) has been so far developed. The MCNP calculation shows that neutron counters located around LHD will measure mostly scattered and partially thermalized neutrons. It is also shown that the energy spectrum of neutrons originating in D–D source at the possible counter location is similar to that of neutrons from ^{252}Cf source.[16] An activation foil system will be also used to assess absolute 2.5 and 14 MeV neutron fluxes. The metal foil to be irradiated is positioned very close to the plasma using a pneumatic rabbit system. After removal of the sample, the induced radioactivity is measured using a high-resolution semiconductor detector. This method is essentially insensitive to γ-ray and is valuable in cross checking neutron yield evaluated from the fission chamber output. The activation foil system also can contribute to triton burn-up study if the metal foil having neutron threshold energy over 2.5 MeV is chosen.

B. Neutron profile monitor

Information of neutron profile connects with a profile of beam ions in deuterium NB-heated deuterium plasmas since generated neutrons are dominated by those from beam-plasma reactions. Neutron profile diagnostic is therefore valuable not only in obtaining information of beam ion profile but also in discussing radial transport of beam ions due to Alfvénic modes excited by super-Alfvénic beam ions and/or excitation condition of Alfvénic modes sensitive to radial profile of beam ions. Full-scale neutron profile diagnostics have been installed in fusion devices recording D–D neutron rate over 1×10^{16} (n/s).[17–19] The diagnostic port on LHD has a long throat since the whole plasma device is set in the cryostat for superconducting coils. A 2 m thick concrete floor will be used for the neutron shield of profile detectors and multichannel cylindrical collimators. The detector set will be placed at the cave inside the floor and views LHD plasmas vertically at vertically elongated cross-section. Figure 2(a) shows a schematic drawing of the cross-section where cylindrical collimators and detector set will be installed. A couple of scintillation detectors, i.e., organic scintillators such as stilbene and NE213, and fast-neutron scintillator NE451, are being considered for possible candidates for the neutron detector. These detectors and necessary electronics are being tested in NIFS to experience the performance of n-γ discrimination. In addition to a conventional analog n-γ discrimination circuit, a novel technique based on the digital-signal processing (DSP) will be applied to the neutron scintillator to enhance the maximum counting rate

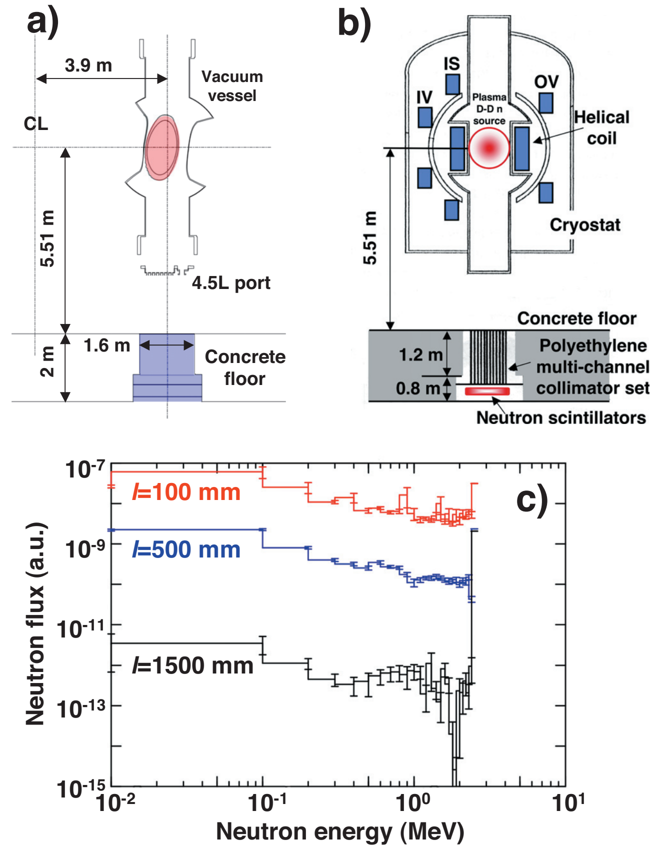

FIG. 2. (Color) (a) Schematic drawing of the LHD poloidal cross-section where cylindrical collimators and detector set will be installed. (b) LHD modeled in the MCNP code for collimator design study. (c) Neutron energy spectra expected at the position of center detector for three different collimator lengths.

capability.[20] The DSP system also makes pulses due to 14 MeV neutrons visible.[21] The MCNP code was used to design the neutron collimators on LHD. The MCNP model developed for this purpose is shown in Fig. 2(b). The polyethylene collimator consisting of 12 channels is considered. Figure 2(c) shows the neutron energy spectra at the center channel detector calculated for three different collimator lengths. In this calculation, the target spatial resolution is set to be 100 mm and to keep it, the ratio of length to diameter of collimator is fixed. As can be seen, scattered neutrons will be dominant when the collimator length is short. A rate of scattered neutron becomes lower as the collimator length becomes longer. A sharp peak of 2.5 MeV neutrons can be recognized when the collimator length is set to be 1.5 m. We also have checked the ratio of uncollided 2.5 MeV neutron flux to scattered neutron flux as a function of the collimator length. The result is consistent with that deduced from Fig. 2(c) as expected. The MCNP calculation suggests that the collimator having 24 mm $\phi\times1500$ mm long is suitable for the neutron profile diagnostic on LHD.

C. D–D neutron spectrometer

Neutron spectrometry on fusion experiments was originally proposed for fuel ion temperature diagnostic by measuring Doppler broadening of neutron energy spectrum.[22] The fuel ion temperature can be measured if fuel ions have a

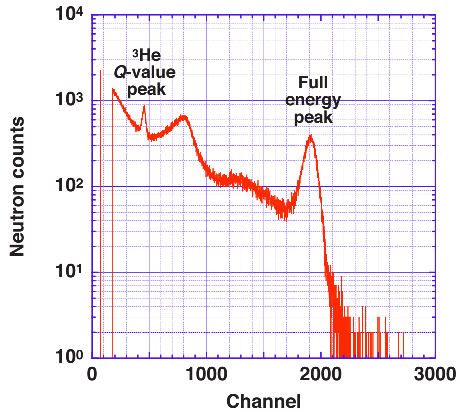

FIG. 3. (Color online) Pulse height spectrum of ^{3}He gas counter (RS-P4-0840-218) when monoenergetic D–D neutrons were irradiated. The counter is not covered by moderator.

Maxwellian velocity distribution. It should be noted that in most of the existing experiments, target plasmas are auxiliarily heated by high-energy NBs and/or ICRH. In such a case, fuel ions are no longer Maxwellian, having high-energy ion tail and consequently, a neutron energy spectrum mainly reflects velocity distribution of energetic ions. Neutron spectrometry in NB-heated and/or ICRH plasmas can therefore contribute to the study of energetic-ion behavior in magnetically confined fusion plasmas. Possible candidates to measure neutron energy spectrum in LHD are (1) ^{3}He gas counter and (2) novel spectrometer based on associated-particles coincident counting (APCC) technique. We have examined energy resolution of an ^{3}He gas counter owned in NIFS at an accelerator-type fusion neutron facility NFS. An ^{3}He gas counter is characterized by easy handling and does not require complicated electronics. The tested gas counter is a commercial product of GE Reuter-Stokes Co. [model: RS-P4-0840-218, size: 1 in. $\phi \times 40$ in. long in the sensitive area, gas pressure: 271.2 psia (^{3}He+CO_2)], having a cylindrical shape. In this test, the ^{3}He gas counter was naked, i.e., without a moderator and the long axis of counter was set to be parallel to monoenergetic D–D neutron beam. Signals from the gas counter were fed into a preamplifier (ORTEC-142PC) connected to a main shaping amplifier (ORTEC-570). Figure 3 shows a pulse height distribution measured in this test. A full energy peak due to D–D neutrons can be clearly recognized and the energy resolution to D–D neutrons is evaluated to be about 6% if the spectrum on the high-energy side only is considered. As seen in Fig. 3, the full energy peak for D–D neutrons is not symmetric due to the so-called wall effect.[11] This is actually a drawback if the behavior of the energetic beam ion is going to be discussed from a neutron spectrum because neutrons generated by beam-plasma reactions have normally an asymmetric peak in the energy spectrum due to the slowing down distribution of beam ions. Another drawback is that the ^{3}He gas counter is intrinsically slow in counting rate capability. Moreover, the practical counting rate for the full energy peak becomes even lower because the counter is essentially sensitive to thermal neutrons and the cross-section of ^{3}He (n,p)T to D–D neutron is fairly small. As an alternative method, we are now developing the APCC D–D neutron spectrometer[23] to aim high-energy resolution and high-counting rate capability. This APCC spectrometer was originally developed at Nagoya University for 14 MeV neutron spectrometry on ITER.[24] Currently, the system is being optimized for D–D neutrons and we have so far achieved the energy resolution of ~7% to D–D neutrons. The APCC spectrometer provides a symmetric peak to monoenergetic D–D neutrons and seems to be promising as a D–D neutron spectrometer for the study on beam ion behavior in LHD.

IV. SUMMARY

Conceptual plan of neutron diagnostic system and the stage of progress for its design toward the LHD deuterium experiment are described. A comprehensive set of neutron diagnostics will consist of a time-resolved neutron rate monitor, a time-integrated neutron yield monitor, neutron profile monitor, D–D neutron spectrometer, triton burn-up neutron counter, and γ-ray diagnostics. The maximum D–D neutron rate in LHD is expected to be over 1×10^{16} (n/s), comparable to that observed in large tokamaks. Because produced neutrons are dominated by those coming from beam-plasma interaction, neutron diagnosing system will play an important role not only in assessing fusion output but also in studying energetic-ion behavior. Our further efforts to design neutron-diagnosing system on LHD have to be continued. The next important task will be to find locations suitable for neutron rate monitor and to decide detector's specifications with a help of three-dimensional Monte Carlo neutron transport calculation.

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