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大型ヘリカル装置の重水素実験における中性子計測と高エネルギー粒子閉じ込め研究の進展

Progress on integrated neutron diagnostics for LHD deuterium plasma experiment and energetic particle confinement study

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For realizing a steady state fusion burning plasma, energetic ion confinement has been widely studied because the plasma is sustained by deuterium–tritium fusion born energetic alpha particles. Close attention has been paid to studying the confinement of energetic particles, such as beam ions and ion cyclotron tail ions. Approaching a steady state fusion burning plasma, a study of energetic particle confinement in stellarators and helical systems has been led by the Large Helical Device (LHD) [1]. In hydrogen campaign, the study was mainly conducted using the charge-exchanged neutral particle analyzer and escaping energetic ion diagnostics. We started the deuterium experiment in March 2017 to obtain further advances in helical-type plasma performances and to understand plasma physics. Additionally, the deuterium experiment aims to demonstrate the capability of energetic particle confinement in helical systems toward a steady state fusion burning plasma. In neutral beam (NB)-heated LHD plasma experiments, neutrons are mainly created by beam-thermal reactions owing to extreme NB injection. Therefore, neutron has the information regarding the beam ions confined in the plasma core area. The neutron diagnostic of LHD was planned in the construction stage of LHD [2]. Installation of neutrons and gamma-ray detectors were scheduled for measuring the total neutron emission rate (S_n) and fuel ion temperature as well as enhancing an energetic particle confinement study. Neutron diagnostics plan began taking shape subsequently in 2010 [3]. Candidate detectors for measuring S_n, neutron emission profile, neutron energy spectrum, triton burnup, and high-energy gamma-ray were proposed for the executing energetic ion confinement studies. The abundance of neutron diagnostics is compared with that installed in large tokamaks, i.e., JET, TFTR, and JT-60U [4]. Since expected S_n has similar intensity compared with deuterium operation executed in large tokamaks, the energetic particle confinement study conducted in LHD is expected to be the same level of study conducted in large tokamaks.

A comprehensive set of neutron diagnostics has been developed for developing the energetic particle confinement study and radiation management in LHD. We advanced the development and establishment of comprehensive neutron measurement hardware following the strategy. The five systems, i.e., the ex-vessel NFM, neutron activation system (NAS), VNC, scintillating fiber (Sci-Fi) detector, and neutron fluctuation (NF) detector have been regularly utilized (Fig. 1). An arrangement of diagnostics with NB injectors is depicted in Fig. 1. In LHD, negative ion source-based NB (N-NB) injectors whose acceleration energy reaches 180 keV tangentially inject and mainly create co- or counter-going transit beam ions, while positive ion source-based NB (P-NB) injectors whose acceleration energy is up to 60/80 keV perpendicularly inject and mainly create helically trapped beam ions. Moreover, using these intense NB injectors, a study of energetic particle confinement is conducted.

Integrated neutron diagnostics developed for LHD deuterium operation was installed and operating properly. Based on the neutron diagnostic plan in LHD, the NFM [5], NAS [6], VNC [7], Sci-Fi detector [8], and NF [9] were established. NFM having a wide dynamic range, fast time response, and high noise tolerance was utilized for measuring S_n. Characterization of S_n of LHD plasmas, fuel ion temperature evaluation, global confinement of beam ion, investigation of knock-on tail formation, and study of beam–beam nonlinear collision was conducted. To measure

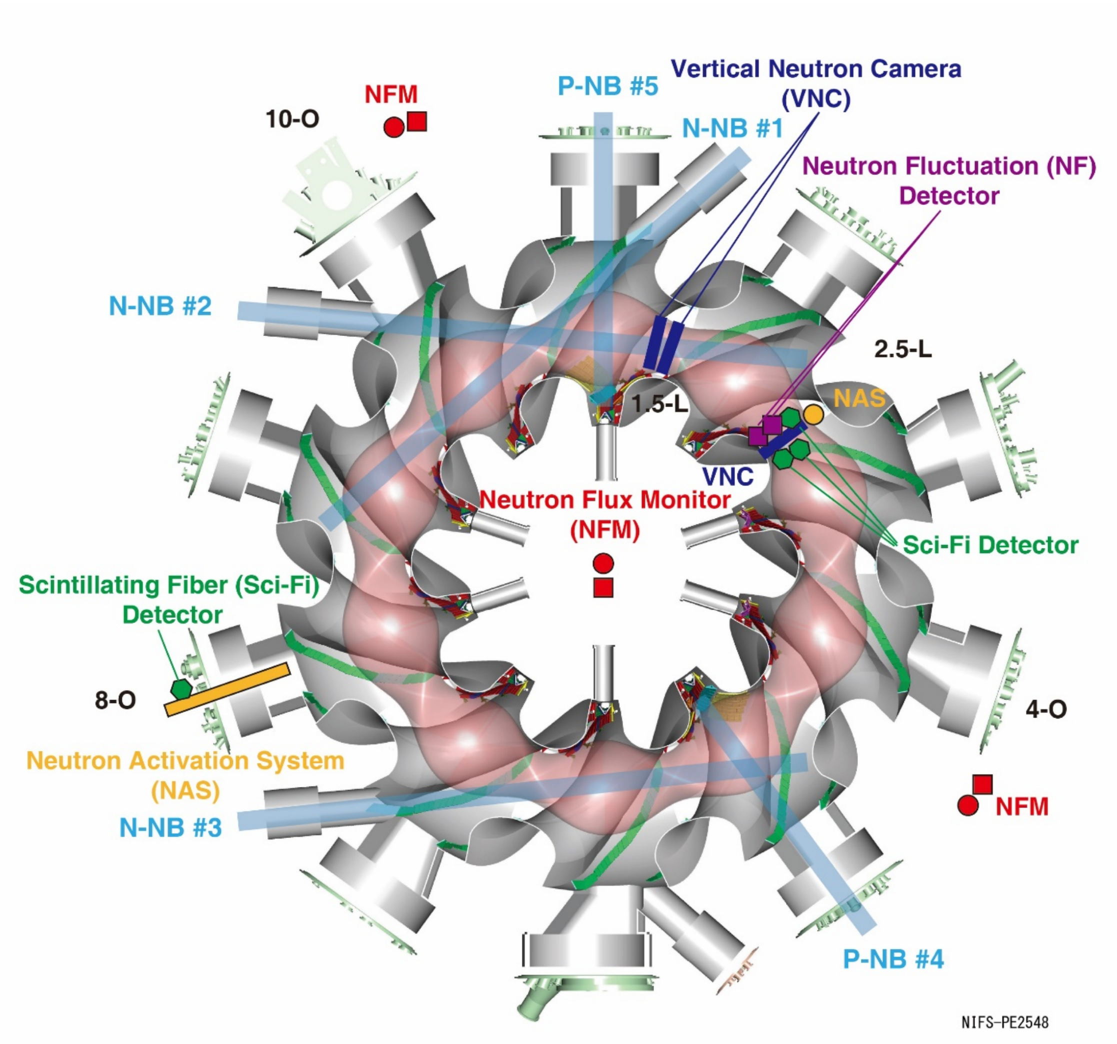

Fig. 1 Arrangement of comprehensive neutron diagnostics in LHD

shot-integrated DD or DT neutron fluence, NAS having two irradiation ends was utilized. Additionally, a cross check of NFM, anisotropy of DD neutron emission, and neutron spectra measurements were performed. To measure the radial profile of the neutron emission, VNCs installed at three toroidal angles were utilized. Measurement of neutron emission profile in N-NB or P-NB-heated plasmas and study of energetic ion transport owing to energetic ion driven MHD instability was conducted. Three types of Sci-Fi detector were developed for time-resolved measurement of DT neutron flux. The time evolution of the secondary DT neutron emission rate was compared with numerical simulation based on classical confinement of energetic ions. Furthermore, the dependence of DT neutron emission rate on the magnetic axis position was surveyed. NF detector having a fast time response was utilized to measure the rapid change of S_n. In EIC discharge, the rapid decay of S_n was measured. Energetic particle confinement study in LHD was largely advanced by utilizing integrated neutron diagnostics.

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