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Planning of Steady-State NBI Heating Experiments in LHD

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Abstract

The steady-state NBI heating experiments are newly proposed and planned in Large Helical Device (LHD). The LHD-NBI system, using the negative ions, is now under construction, which is designed to inject 180 keV-15 MW of the neutral beam for pulsed operation of 10 sec. The injection energy and power of the proposed steady-state NBI system are 80 keV and 1 MW, respectively, at the first-phase of LHD experiments, and 120 keV and 3 MW, respectively, at the second-phase. The pulse duration is 30 min. Using an LHD-NBI prototype negative ion source, which is now under conditioning, a long-pulse operation was tried, and a negative ion beam of 700 kW has been produced for 10 sec. The temperature rise due to the heat load was almost saturated, indicating a possibility of the proposed steady-state operation of the LHD-NBI system with one injector. The detailed structure of steady-state NBI system, the initial results of long-pulse negative ion beam production with the prototype source, and the experimental scenarios of steady-state NBI heating are described. The steady-state neutral beam injection will start in 1999.

Keywords:

steady-state NBI heating, Large Helical Device, negative-ion-based NBI system, particle control, long-pulse operation, heat load, cryo-sorption pump, beam dump

1. Introduction

The Large Helical Device (LHD) [1], which is the world-largest superconducting experimental fusion device, aims at the steady-state operation, and the vacuum vessel is designed so that a heat load of 3 MW would be removed continuously. The ECH and ICH are prepared as heating power sources for the steady-state LHD experiments, due to their better accessibility to the plasma production and the plasma control. On the other hand, the NBI heating in LHD is projected for achievement of a high ion temperature, a high $n\tau T$ and a high-β[2], and 180 keV-15 MW injectors using negative ions are now under construction for 10 sec injection.

Recently, in the course of R&D of a negative ion source for the LHD-NBI system, we achieved a long-pulse production of a high-power negative ion beam of 330 kW for 10 sec from 1/5 grid area, and a saturation of the temperature rise of the grounded grid, which suffers the maximum heat load, was observed [3]. This means a possibility to operate the LHD-NBI system in steady-state with an injection power of 1.5 MW using one injector.

The steady-state ECH experiment should cope with the burn-out problem of the O-ring and the viewing port, and the impurity induced by the ICH could block the steady-state plasma sustaining. On the other

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hand, the NBI heating is free from these problems, and the steady-state particle control experiments would be conducted with the steady-state neutral beam injection. Therefore, the steady-state NBI heating is attractive and prospective in LHD. Including large-scaled tokamaks, no steady-state neutral beam injection experiments have been tried, and no realistic project of the steady-state NBI heating has been proposed, except for ITER. In this paper, we newly propose the steady-state NBI heating experiments in LHD, and clarify the ability as a steady-state LHD-NBI system. The initial results of long-pulse negative ion beam production with a prototype source and the experimental scenarios of steady-state NBI heating are also described.

2. Specification of Steady-State NBI System

The specification of the LHD-NBI system is summarized in Table 1. Using two beamlines (BL1 and BL2), 180 keV-15 MW of the neutral beams are injected for 10 sec [4]. The neutral beams are injected tangentially and are balanced each other, as shown in Fig. 1. Two ion sources are installed to each injector and a negative ion source producing 180 keV-40 A of the negative ion beam is required to achieve the LHD-NBI specification.

Table 1 Specification of the negative-ion-based LHD-NBI system.

	High-power pulsed injection	Steady-state injection	
Injection power	15 MW	1 MW	3 MW
Beam energy	180 keV	80 keV	120 keV
Beam species	H	H	H
Pulse duration	10 sec	30 min	30 min
Number of injector	2 (BL1 & BL2) (tangential & balanced)	1 (BL2)	1 - 2
Number of ion source	4 (2 per injector)	2	2 - 4

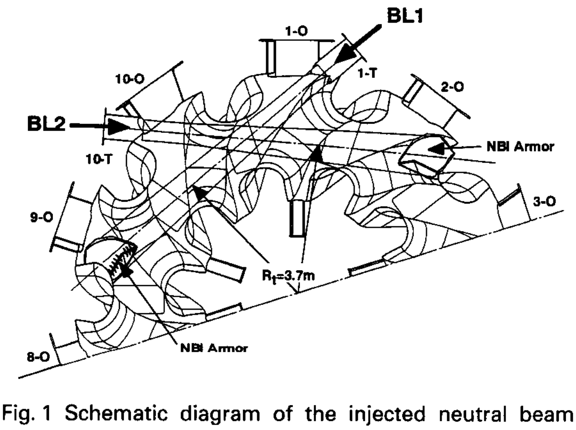


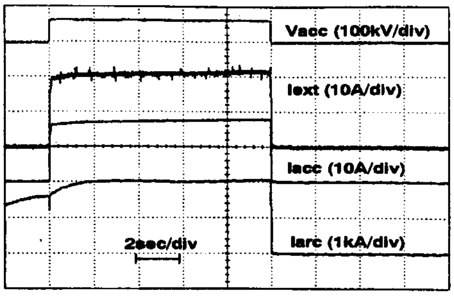
Fig. 1 Schematic diagram of the injected neutral beam path, the location of the injection ports, and the beam facing armors in LHD.

In the LHD-vacuum vessel, a beam facing armor is installed for each injector, as shown in Fig. 1, to protect the vessel wall against the shine-through neutral beams. The armor is designed for the maximum heat load of 150 W/cm^2 for 10 sec, corresponding to 10% of shine-through in 180 keV-7.5 MW injection. By considering a duty factor of 1/30 (10 sec per 5 min), the ability of continuous heat removal of the armor is 5−6 W/cm^2. To satisfy this heat load condition, the shine-through rate should be lowered to 1−2% for 1−3 MW steady-state injection, which requires high-density target plasmas and lower injection energies. We have determined that the specification of the steady-state NBI system is 1 MW-80 keV to 3 MW-120 keV using one injector, as indicated in Table 1. In the case of 1 MW-80 keV injection, the target plasma density is required to be more than 5×10^{13} cm^{-3}, and that is more than 8×10^{13} cm^{-3} in the case of 3 MW-120 keV injection.

In the LHD-NBI system the power supplies are designed for a beam production for 10 sec with a duty factor of 1/30, and, therefore, 1/3-current operation of the specification would be possible in steady-state with a small modification. The beam dumps made of swirl tube can remove a heat load of 1.5 kW/cm^2 or more continuously and, therefore, be operated for the steady-state injection. A continuous gas pumping of the cryosorption pump was experimentally confirmed for 30 min [5], and, however, it is hard to operate it for longer duration due to the cooling ability of the refrigerator.

3. Long-Pulse Operation of Negative Ion Source

The R&D of a negative ion source for the LHD-NBI system has progressed, and, until now, we have produced 16.2 A of the negative ion current [6], accelerated the H^- ions with 13.6 A to 125 keV [7], and focused multibeamlets with an averaged divergence angle of 9 mrad [8]. In the negative ion source, the negative ions accompany the electrons, which are accelerated together with the negative ions and lead to the heat load of the downstream grid. The suppression of the accelerated electrons is important for the long-pulse operation of the negative ion source. We have shaped the extraction grid hole so that the secondary electrons generated on the extraction grid would be prevented from leaking into the acceleration gap [9]. As a result, the accelerated electrons have been much suppressed



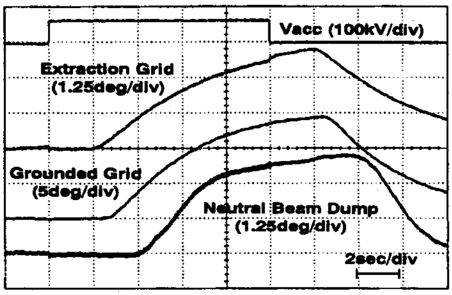


Fig. 2 Example of the time evolution of the acceleration voltage and current, the extraction current, the arc current, and the water temperature rises of the extraction grid, the grounded grid and the neutral beam dump located 13 m downstream, with a prototype LHD-NBI source. The H$^-$ ion beam power is about 700 kW (73 keV).

and the heat load of the grounded grid is reduced [3]. Based on these results, a prototype negative ion source for the LHD-NBI system has been designed and fabricated, which has a three-grid single-stage accelerator with a grid area of 25 cm × 125 cm [10]. The ion source is now under conditioning with short-pulse high-power beam production, and a long-pulse operation was tried. Figure 2 shows an initial result of the long-pulse beam production. The H$^-$ ion beam power is about 700 kW (73 keV), and the beam is incident on the neutral beam dump located 13 m downstream. The power supply currents are stationary for 10 sec. The water temperature rises of the extraction and the grounded grids are almost saturated and would be steady for longer duration. Although the negative ion beam production has not been optimized for reduction of the heat load of the grounded grid, the water temperature rise is around 15 degrees. Therefore, the steady-state neutral beam production of 1 MW using two sources should be possible in the LHD-NBI system.

4. Experimental Scenarios of Steady-State NBI Heating

The manufacture of the first beamline (BL1) has been already finished, and the modification is required for the steady-state injection to some extent. On the other hand, the second beamline (BL2), as shown in Fig. 3, is now in manufacture and the design of the power supplies and the cryo-sorption pump is a little changed from that of the BL1 for the steady-state injection of 1 MW-30 min. Therefore, at the start of the LHD steady-state experiments in 1999, the steady-state NBI heating is possible with an injection power of 1 MW using the BL2. By the up-grade and the further modification, steady-state injection of 3 MW should be operated at the second-phase of LHD experiments.

In the steady-state plasmas, the wall recycling is unity and the injected particles must be pumped out to keep the steady-state plasma. The particle flux of injected neutral beam is 0.3–0.7 Pa m^3/sec, which is much smaller than the pumping speed of the local island divertor (LID) [11], 3–4 Pa m^3/sec. Therefore, the steady-state particle control experiments are planned in the steady-state NBI heating. The beam-driven current also has an influence on the steady-state plasma, and the combination with the ECH and ICH should bring new subjects in the steady-state experiments, such as the current cancellation, the impurity control, and the potential control.

5. Summary

We newly propose and plan the steady-state NBI heating experiments in LHD. The LHD-NBI system is originally designed with a pulsed operation for 180 keV-15 MW-10 sec injection. The design and structure of one beamline (BL2) has been modified a little for 80 keV-1 MW-30 min injection. In future 120 keV-3 MW-30 min injection would be possible by the

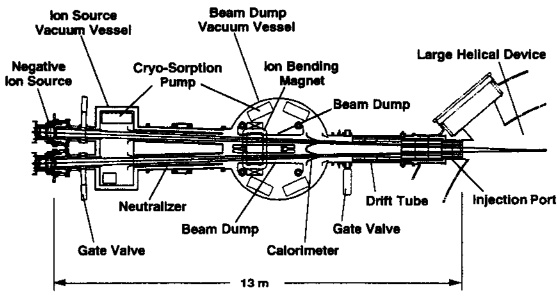


Fig. 3 Schematic diagram of the second beamline (BL2) of the negative-ion-based LHD-NBI system.

further modification. A prototype negative ion source for the LHD-NBI system has produced 700 kW−10 sec of the negative ion beam. The temperature rise of the highest heat load component is almost saturated, and the steady-state operation of the ion source is prospective. The steady-state NBI heating should contribute to the steady-state LHD experiments such as steady-state particle control, plasma-wall interaction, and divertor experiments. The steady-state NBI heating experiments will start in 1999.

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