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Long-Pulse Heating and Plasma Production by Neutral Beam Injection in Large Helical Device

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Abstract
We have achieved long-pulse NBI heating in Large Helical Device (LHD). A quasi-steady-state plasma was sustained for 21 sec with an injection power of 0.6 MW, where the central plasma temperature was around 1 keV with a line-averaged electron density of 0.3×10^{19} m^{-3}. At higher densities, relaxation oscillation phenomena were observed for 20 sec at a period of 1 - 3 sec. We have also achieved plasma production by NBI alone. The density build-up time was several hundreds msec, and the produced plasma showed the same characteristics as an ECH-initiated plasma. These results indicate unique characteristics of LHD where only external superconducting coils generate the plasma confinement magnetic field.

1. Introduction

Negative-ion-based neutral beam injection (NBI) heating started in September, 1998, in Large Helical Device (LHD), which is the world largest superconducting helical system [1,2]. In the first NBI heating experiments (the second experimental campaign in LHD), high stored energy (430 kJ), high plasma temperature (2.3 keV), and long energy-confinement time (0.26 sec) were obtained, under injection conditions where the injection power was < 3.7 MW, the injection energy < 110 keV, and the pulse width < 2 sec [3]. LHD has an ability of steady-state operation in principle because the confinement magnetic field is generated by the external superconducting coils without the plasma current. Steady-state operation is one of the major missions of LHD, and the long-pulse/steady-state experiments are planned with ECH, ICH and NBI [4]. Therefore, in parallel to experimental studies on core plasma confinement, we made long-pulse NBI experiments towards steady-state heating with a reduced injection power.

On the other hand, plasma initiation by ECH is a unique characteristic in the helical system producing currentless plasmas, and neutral beams are usually injected into the ECH-produced target plasmas as an additional heating. However, since the ECH utilizes a given EC resonance magnetic field, the magnetic field strength is restricted in experiments to the resonance field. We achieved NBI-initiated plasma production for the first time, which gives no experimental constraint on the magnetic field strength.

In this paper, we focus on the results of both long-pulse NBI plasma heating and plasma production by NBI itself.

2. Negative-Ion-Based LHD-NBI

The LHD-NBI system is designed to inject 180 keV - 15 MW of hydrogen neutral beam using two injectors arranged tangentially and balanced, as shown in Fig. 1 [5,6]. One injector has two large negative ion sources attached side-by-side. Four negative ion sources have produced 25 A of negative ions with an energy of around 110 keV in the teststand [7], which enables to inject neutral beams of 4 - 5 MW into the LHD plasmas.

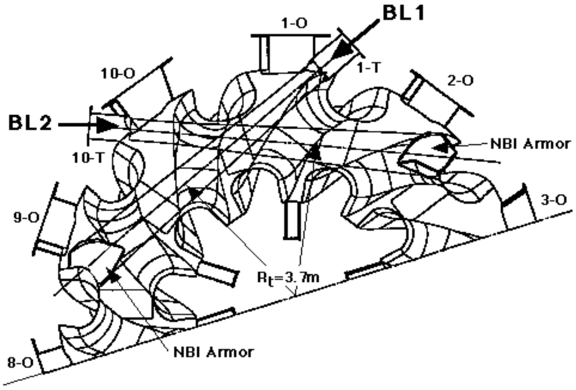

Fig. 1 Schematic diagram of injection direction in the negative-ion-based LHD-NBI system.

In the second experimental campaign, the negative-ion-based NBI system worked successfully, and two injectors injected about 2 MW of neutral beams individually. The achieved total injection power was 3.7 MW with an energy of 100 - 110 keV for a pulse duration of around 1 sec [3].

Although the nominal injection duration is 10 sec, the NBI system is planned to be up-graded year by year for 3 MW - 30 min injection by modification of the power supplies [8]. In the second campaign, only one injector (BL2) could be operated for an extended pulse length of 35 sec with an injection power below 1 MW.

For both experiments of long-pulse heating and NBI plasma production, the LHD magnetic field strength and the major radius of magnetic axis are 1.5 T and 3.75 m, respectively. The injected gas into the torus is helium.

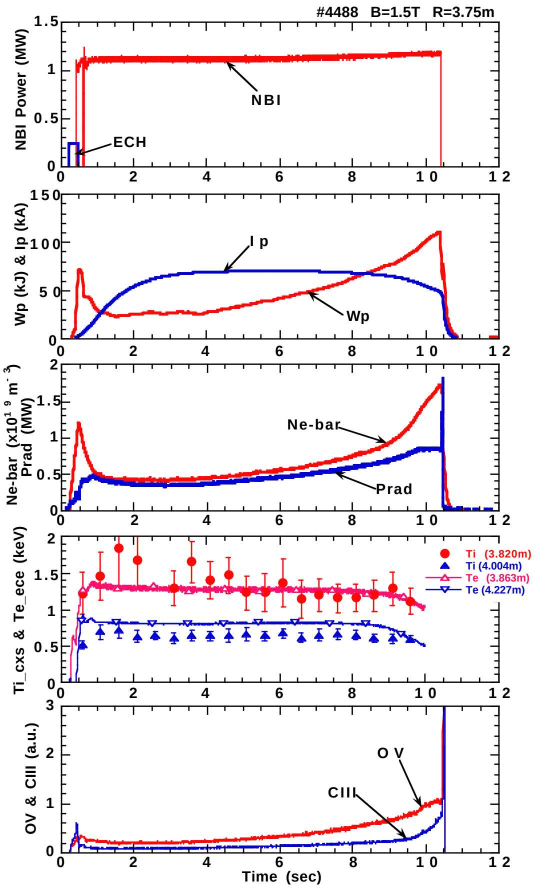

Fig. 2 Time evolution of various plasma parameters for the 80keV-1.1MW-10sec shot.

3. Long-Pulse NBI Heating

To demonstrate the capability of long-pulse NBI plasma heating and maintenance in LHD, 80 keV - 1.1 MW of neutral beam was injected for 10 sec into ECH-produced target plasmas using one beamline of co-injection (BL2). Figure 2 shows the time evolution of various plasma parameters. The line-averaged electron density is gradually increased 0.5 to 1.0 x 10^{19} m^{-3} and shows a rapid increase at around 8 sec toward the pulse end. The stored energy is also increased toward the pulse end, corresponding to the confinement scaling with a positive density dependence in the helical system. The central ion and electron temperatures are above 1 keV, and are decreased near the pulse end due to the density increase. The pulse duration had been determined by beam blocking, which was caused by the out-gas from molybdenum protection plates inside the injection port. Reduction of the plasma injection power by the beam blocking resulted in uncontrollable density rise, and the plasma was terminated by radiative collapse. The out-gas at the injection port by bombardment of the re-ionized beam was reduced shot by shot, leading to extension of the heating pulse duration, and in about 20 shots of injection for longer than 1 sec, the 10 sec shot was achieved.

After the above 10 sec shot and the following several hundreds of short pulse shots, an NBI heated plasma was sustained for 21 sec in a quasi-steady-state with a reduced injection power of 66 keV - 0.6 MW, as shown in Fig. 3. The line-averaged electron density is almost constant in time at around 0.3 x 10^{19} m^{-3}, and the central ion temperature is also constant at around 1 keV. The radiation power is nearly stable as well as the impurity emission line intensities. The particle balance analysis shows that weak wall pumping suppresses a density rise. Active pumping would be required to keep a constant density for a longer injection duration where the wall is saturated.

At higher densities, plasma oscillations were observed for 20 sec, where the plasma density, the plasma temperature and the impurity radiation oscillate at a period of 1 - 3 sec. Synchronously alternate plasma shrinking and expanding, just like 'breathing', were observed on a visible TV monitor with a tangential line-of-sight. This shrink and expansion corresponded to decrease and increase in the electron temperature, respectively. Figure 4 shows the time evolution of various plasma parameters for the 'breathing' relaxation oscillation plasma. In an increasing phase in the line-averaged electron density, the density

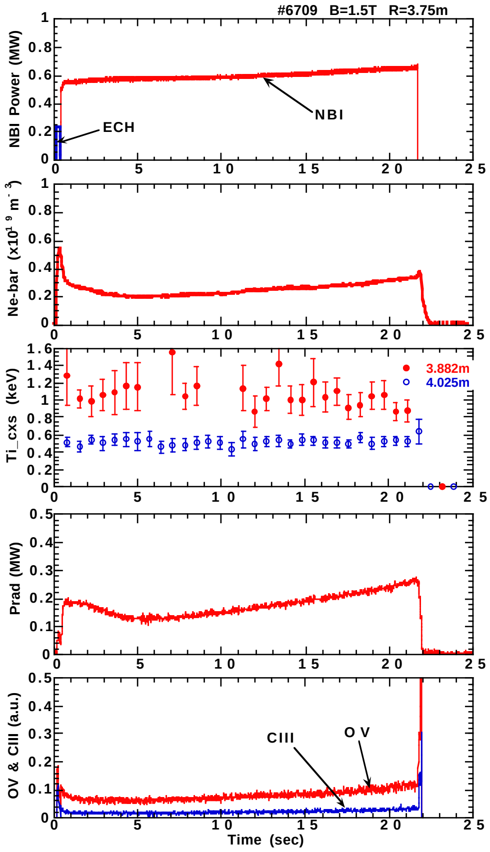

Fig. 3 Time evolution of various plasma parameters for the 66keV-0.6MW-21sec shot.

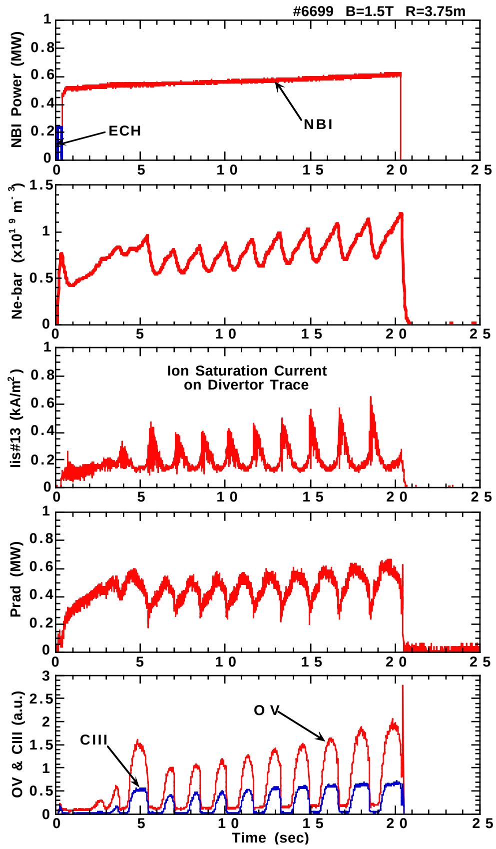

Fig. 4 Example of the relaxation oscillation plasma shot lasting for 20sec.

profile is gradually center-peaked. However, the profile becomes flat or hollow rapidly in a decreasing phase in the density, which is similar to density clamping phenomena observed in a short-pulse shot. The electron and ion temperatures start to increase a little before the density peak timing, and show a maximum a little before the density bottom timing. In a density clamping (decreasing) phase, an increase in diverter flux is observed in electrostatic probes measured at a diverter trace. The impurity emission lines of OV and CIII show larger intensities at a period of the density increase, i.e., the temperature decrease. The mechanism of this 'breathing' relaxation oscillation is speculated as follows. The density clamping leads to an increase in the particle outflux, and an interaction between the plasma and the diverter wall becomes stronger, resulting in an increase in the impurity influx. The increase in the impurity influx lowers the electron temperature and the plasma is shrinking, bringing a reduction of the plasma-wall interaction, i.e., a reduction of the impurity influx. At this period, the density is increased as center-peaked, resulting in an increase in the absorbed power at the center. Then, the plasma temperature could be recovered, leading to the next density clamping. The another speculation is a power balance between the absorbed power and the radiation power, which determines temperature boundary in the plasma edge region. This boundary moves inside and outside the plasma column according to the power balance, leading to change of neutral particle penetration length into plasma, which would change the density profile. This density profile change influences the absorbed power, and the temperature boundary moves as the absorbed power would balance with the radiation power. The further theoretical and experimental studies are required on this 'breathing' phenomena.

4. Plasma Production by NBI alone

A normal operation of the NBI heating is started with an ECH discharge as a target plasma. We tested, however, to initiate the discharge without the ECH target plasma, and successfully produced the plasma by only neutral beam injection. Figure 5 shows an example of the NBI plasma production. The beam energy was 97 keV. At a low background gas pressure of 10^{-3} Pa, the plasma is initiated and gradually built up to 10^{18} m^{-3} during several hundreds of milliseconds by only neutral beam injection. Then, with a proper amount of gas puffing, high stored-energy plasmas are obtained. The NBI-produced plasmas show the same characteristics as those with the ECH target plasma. A possible explanation is given as follows. A part of the injected neutrals are ionized by a collision with the background gas, and the ionization efficiency is about 2 % in this case. The generated high-energy ions are confined until neutralized by a charge exchange collision with the background gas, the lifetime of which is about 0.3 ms. During this lifetime, the high-energy ions circulate in the torus and ionize the background neutrals. The high-energy ion density is estimated to be about 10^{13} - 10^{14} m^{-3}, and the ionization rate by these high-energy ions is the order of 10^{18} m^{-3}/s. The electron heating mechanism by the high-energy ions is important to the further build-up of the density, because the heated electrons would play a dominant role of the successive ionization increasing in geometrical progression. The estimated electron heating time is also an order of several hundreds of milliseconds.

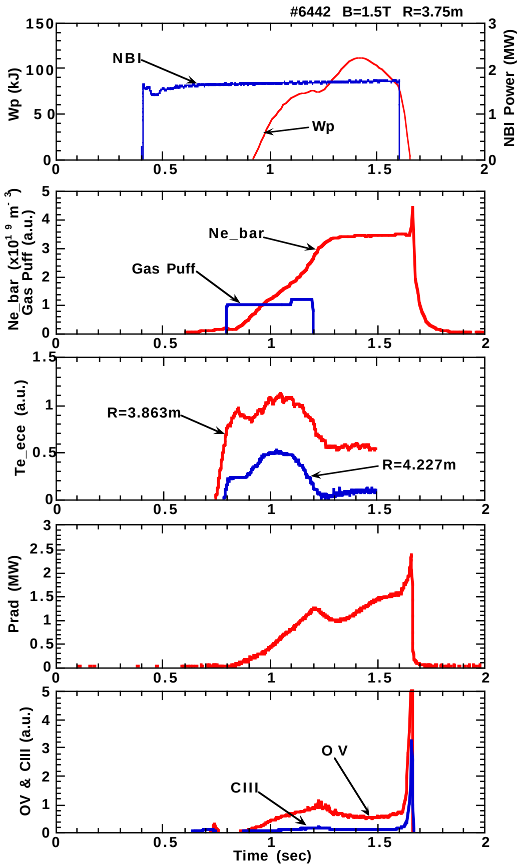

Fig. 5 Example of the NBI-produced plasma shot.

The high-energy ion density is determined with both the ionization cross section of injected neutrals and the neutralization cross section of high-energy ions by collisions with the background gas. At higher injection energy above 100 keV, the former cross section is much higher than the latter. Impurities and a large amount of background gas cool the heated electrons and prevent the electron ionization. Therefore, the efficient NBI plasma production would require higher injection energy, lower impurity and a proper amount of the background gas.

5. Summary

Experimental results of long-pulse NBI heating up to 21 sec and NBI plasma production are reported. These results show the unique characteristics of the helical system where the confinement magnetic surface is produced by only external coils independent of the plasma properties. Moreover, good confinement of high-energy ions ionizing the background gas is also indicated in the NBI plasma production. In the future plan, 1 MW - 1 min injection heating is the next target for the long-pulse experiments, and the NBI plasma production will be utilized for experimental studies on the magnetic field dependence of the confinement and high-beta experiments at lower fields.

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