J. Plasma Fusion Res. SERIES, Vol. 3 (2000) 345–351

Long-Pulse Neutral-Beam-Heated Discharges in Large Helical Device

TAKEIRI Yasuhiko, NODA Nobuaki, NAKAMURA Yukio, KAWAHATA Kazuo, OSAKABE Masaki, OKA Yoshihide, KANEKO Osamu, TSUMORI Katsuyoshi, IKEDA Katsunori, IDA Katsumi, KADO Shinichiroh, SATO Motoyasu, MUTOH Takashi, SHIMOZUMA Takashi, YAMADA Syuichi, EMOTO Masahiko, FUNABA Hisamichi, GOTO Motoshi, IDEI Hiroshi, INAGAKI Shigeru, ISOBE Mitsutaka, KOBUCHI Takashi, KUBO Shin, KUMAZAWA Ryuhei, MASUZAKI Suguru, MINAMI Takashi, MIYAZAWA Jun-ichi, MORISAKI Tomohiro, MORITA Shigeru, MURAKAMI Sadayoshi, MUTO Sadatsugu, NAGAYAMA Yoshio, NAKANISHI Hideya, NARIHARA Kazumichi, NISHIMURA Kiyohiko, OHDACHI Satoshi, OZAKI Tetsuo, PETERSON Byron Jay, SAGARA Akio, SAKAKIBARA Satoru, SAKAMOTO Ryuichi, SASAO Hajime, SASAO Mamiko, SATO Kuninori, SEKI Tetsuo, SHOJI Mamoru, SUZUKI Hajime, TANAKA Kenji, TOI Kazuo, TOKUZAWA Tokihiko, DE VRIES P. C., WATANABE Kiyomasa, WATARI Tetsuo, YAMADA Ichihiro, YAMAGUCHI Satarou, YOKOYAMA Masayuki, YOSHIMURA Yasuo, YAMAZAKI Kozo, SUDO Shigeru, OHKUBO Kunizo, YAMADA Hiroshi, KOMORI Akio, OHYABU Nobuyoshi and MOTOJIMA Osamu

National Institute for Fusion Science, 322-6 Oroshi-cho, Toki 509-5292, Japan

(Received: 19 January 2000 / Accepted: 12 April 2000)

Abstract

Long-pulse neutral beam heating has been achieved in the Large Helical Device (LHD), with a negative-ion-based neutral beam injector (NBI). The pulse duration of the neutral-beam-heated discharge is extended easily without special feedback stabilization for plasma control. As a result, a high-temperature (1.5–1.8 keV) plasma with a density of ($1.5 - 2.0 \times 10^{19}$ m^{-3}) was sustained for 80 sec with a reduced injection power of 100 keV – 0.5 MW. Long-pulse quasi-steady-state plasmas, where almost no change of the plasma quantities is observed, are realized by feedback density control with fueling gas-puffing. Wall pumping effect enables the density control by the gas-puffing and is maintained in the present long-pulse discharge duration. On the other hand, slow relaxation oscillation phenomena with a period of 1–2 sec were observed, lasting for 20 sec. They are characterized by alternate profile expansion and contraction of the electron temperature, observed just like "breathing" on a TV monitor. Core radiation loss by iron would play an important role in the "breathing" discharges. The temperature of the LHD vacuum vessel was increased by 10°C at maximum in the 80-sec injection. The injector operation including negative ion sources was stable, and the temperature rises of the cooling water for the heat load components were less than 10°C and all saturated. The injector will be up-graded step by step for an extension of the injection duration to 30 min.

Keywords:

long-pulse heating, neutral beam injection, Large Helical Device, steady-state operation, wall pumping, relaxation oscillation

*Corresponding author's e-mail: takeiri@lhd.nifs.ac.jp

1. Introduction

The Large Helical Device (LHD) is the world-largest superconducting heliotron-type helical system, where the confining magnetic field is generated by only external superconducting coils without plasma current [1-3]. Therefore, the LHD has the ability to operate in steady state in principle, and the steady-state plasma sustainment is one of the major objectives of the LHD. To achieve it, long-pulse heating experiments are planned with ECH, ICH and NBI [4]. A negative-ion-based neutral beam injection (NBI) system is designed as a major heating device for the LHD to inject 180 keV – 15 MW neutral beam for 10 sec. By modification of the power supplies, the injection pulse length could be extended to 30 min with a reduced injection power of 1–3 MW [5].

The long-pulse NBI heating experiments have been performed step by step, and 0.6 MW – 21 sec injection in the second campaign of the LHD [6], and 0.75 MW – 35 sec and 0.5 MW – 80 sec injections in the third campaign were achieved. The quasi-steady-state plasmas, the densities of which were controlled by gas-puffing, were obtained, while the plasma relaxation oscillation with a period of 1–2 sec was observed lasting for 21 sec [7].

In this paper, the results of the long-pulse NBI heating in the LHD are summarized, and the discharge characteristics of both the stationary and the oscillating plasmas are described. The injector performance in the long pulse injection is also presented, as well as the LHD vacuum vessel. The present limitation of the long-pulse NBI heating and the future prospectives towards steady-state heating are discussed.

2. LHD-NBI System

The LHD with a major radius of 3.9 m is equipped with a negative-ion-based NBI system, which is designed to inject 180 keV – 15 MW of hydrogen neutral beam for 10 sec using two injectors (BL1 and BL2) [8,9]. The injectors are arranged as tangential injection with opposite injection directions each other. Two large negative ion sources are attached side-by-side to one injector. In the second campaign of the LHD experiments, the injection energy was reduced below 110 keV because of relatively low-density target plasmas at 1.5 T. Two injectors injected about 2 MW of neutral beams individually with an energy of 100–110 keV for a pulse duration of around 1 sec [3]. In the third campaign where the LHD magnetic field strength was increased to 2.75 T, the injection energy was raised to

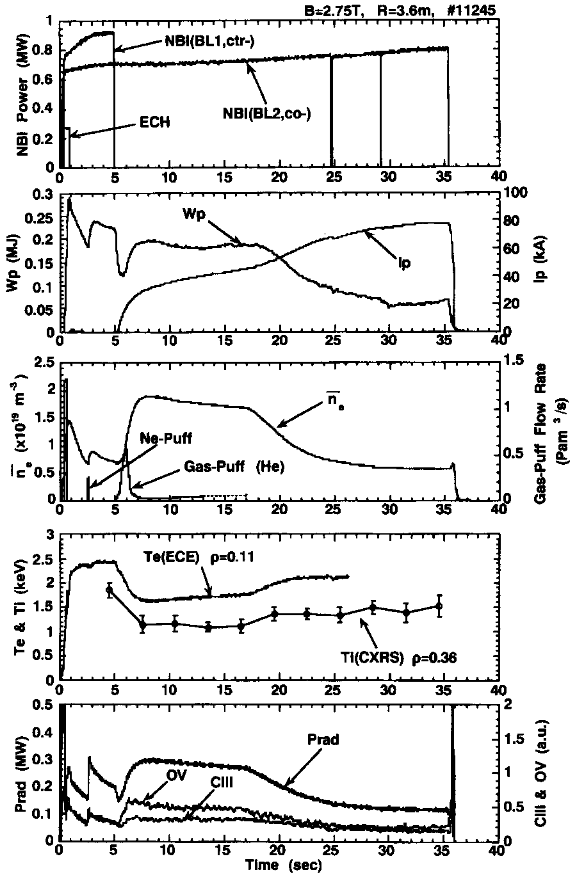

Fig. 1 Time evolution of various plasma parameters for a long-pulse shot for 35 sec.

160 keV, and the injection power in a short-pulse duration of 1–2 sec was also raised to about 3 MW in one injector.

For the long-pulse NBI heating, the NBI system is planned to be up-graded year by year for 3 MW – 30 min injection by modification of the power supplies [5]. At present only one injector (BL2) of co-injection can be operated for an extended pulse length of above 10 sec. While the maximum injection duration is 35 sec in the case of a motor generator (MG) for an input AC power source, it could be further extended in the case of a commercial line, which limits an injection power below 0.7 MW due to the line capability.

The heat load components such as beam dumps are actively water-cooled for continuous heat loads. The inner surface of the tangential injection port is covered annually with molybdenum protection plates, and the diameter and the length are 0.52 m at minimum and 2 m, respectively. The averaged tangential radius of the injected beam is 3.7 m.

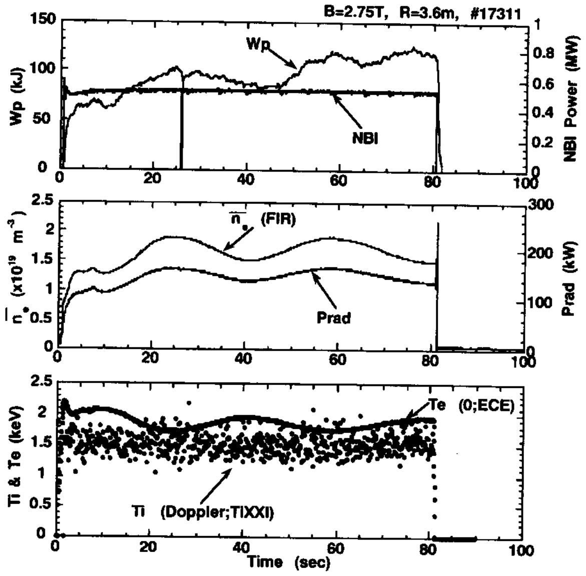

Fig. 2 Time evolution of various plasma parameters for a long-pulse shot for 80 sec.

The shine-through neutrals are incident on a beam facing armor plate installed inside the LHD vacuum vessel. The armor plate is made from carbon tiles mechanically attached to a stainless steel back plate cooled by water.

In the LHD vacuum vessel a heat load of 1.5 MW can be removed continuously. The divertor traces are covered with stainless steel plates in the second campaign and with carbon tiles in the third campaign. The vacuum vessel wall was conditioned intensively by helium glow discharge.

3. Plasma Properties of Long-Pulse Discharges

3.1 Long-pulse neutral beam heating

In the second campaign with a magnetic field strength of 1.5 T, a quasi-steady-state plasma discharge lasted for 21 sec with a line-averaged electron density of 0.3×10^{19} m^{-3} and a central plasma temperature of around 1 keV [6,7]. The injection energy and power were 66 keV and 0.6 MW, respectively. The discharge duration is easily extended until the plasma is terminated by radiative collapse or the beam injection stops.

In the third campaign, where the LHD magnetic field was raised to 2.75 T, the pulse duration of the neutral-beam-heated discharge was extended with a higher density. Figure 1 shows the time evolution of various plasma parameters for a long-pulse shot for 35 sec. The magnetic axis position is 3.6 m, and the injection energy and power of co-injector (BL2) are 104 keV and 0.75 MW, respectively. The counter-injection (BL1) of 102 keV and 0.9 MW is added for the first 5 sec to the co-injection for 35 sec. The line-averaged electron density is kept at $(1.9 - 1.7) \times 10^{19}$ m^{-3} until 17 sec by feedback control with the helium gas-puffing, where the central electron temperature was about 1.7 keV. After the gas-puffing stops, the density is decreased to 0.6×10^{19} m^{-3}, indicating wall pumping, and the electron temperature is increased to 2.2 keV. The density can be controlled with the gas-puffing, which is ascribed to the wall pumping effect. A superior confining magnetic field configuration of 2.75 T and 3.6 m resulted in expansion of the operational regime of the density and temperature. The radiation power and the impurity emission line intensities are stationary in each period with and without the gas-puffing. As the divertor traces are covered with carbon tiles in the third campaign, the radiation power is reduced compared with the 21 sec shot in the second campaign [10].

For extension of the plasma discharge duration, the MG was replaced by the commercial AC line as an input AC power source. The capability of the commercial line, however, limits the injection power to about 0.7 MW. Figure 2 shows the time evolution of various plasma parameters in an extended NB-heated discharge using the commercial AC line. The injection energy and power are 100 keV and 0.5 MW, respectively, and the LHD magnetic field strength and the axis position are 2.75 T and 3.6 m, respectively. The neutral beam is successfully injected for 80 sec, and the line-averaged electron density stays at $(1.5 - 2.0) \times 10^{19}$ m^{-3} controlled by manual operation of the helium gas-puffing. The central ion temperature, measured by the Doppler broadening of TiXXI is around 1.5 keV, and the radiation power is kept at a low level for 80 sec. The wall pumping effect continues during the shot and enables the density control with the gas-puffing for 80 sec.

3.2 Stationary long-pulse discharges

Using the feedback density control with the gas-puffing, a quasi-steady-state plasma is obtained for 10 sec with a constant density. An example of the quasi-steady-state discharge is shown in Fig. 3. The injection energy and power are constant of 120 keV and 1.4 MW, respectively. The feedback control with the hydrogen gas-puffing starts at $t = 1$ sec for keeping a pre-setting density. As a result, a relatively high-density plasma of

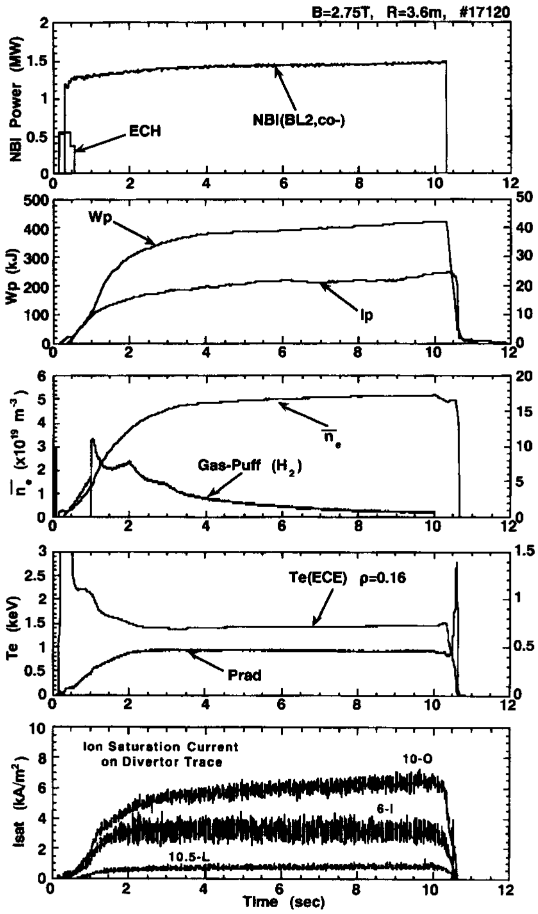

Fig. 3 Time evolution of various plasma parameters for a stationary long-pulse shot.

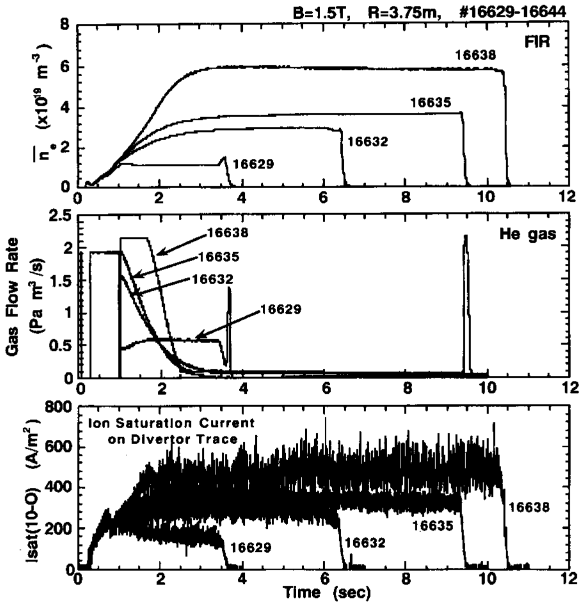

Fig. 4 Time evolution of line-averaged electron densities, gas flow rates, and the ion saturation current densities in stationary discharges with various densities.

5.1×10^{19} m^{-3} is sustained stationary. The electron temperature is also constant of around 1.5 keV and the other parameters, such as the stored energy, the plasma current, and the radiation power, reach a steady state in 2–4 sec. The supplied particles into the LHD vacuum vessel are the injected beam and the puffing gas. The injected particle rate of atomic hydrogen is 7.3×10^{19} s^{-1} including the shine-through particles. The puffing gas particle rate of atomic hydrogen is gradually decreased from 1.3×10^{21} s^{-1} at $t = 4$ sec to 0.40×10^{21} s^{-1} at $t = 9$ sec, while the rising rate of the plasma electrons is constant of 1.8×10^{19} s^{-1} during $t = 4$–9 sec. Assuming $Z_{eff} = 1$, it is found from the particle balance that the main fueling source is the gas puffing and that a strong wall pumping is recognized. On the other hand, from the ion saturation current density on the divertor plate, as shown in Fig. 3, the total flux from the plasma is roughly estimated at 8×10^{22} s^{-1}, and it is found that the recycled particles dominate the high-density stationary plasma. Here, considering the following simple particle balance,

$$\mathrm{d}N/\mathrm{d}t = S - N/\tau_p + R(N/\tau_p) = S - N/\tau_p^* , \quad (1)$$

the effective particle confinement time τ_p^* is defined as

$$\tau_p^* = \tau_p/(1 - R) , \quad (2)$$

where N is the plasma particle number, S the particle fueling rate, R the recycling rate, and τ_p the particle confinement time. In Fig. 3 the τ_p^* is gradually increased from 1.1 sec at $t = 4$ sec to 3.3 sec at $t = 9$ sec. Assuming that the particle confinement time is the same as the energy confinement time, the recycling rate can be evaluated, and is increased from 0.73 at $t = 4$ sec to 0.91 at $t = 9$ sec. In the hydrogen discharge the strong wall pumping effect is gradually deteriorated and the recycling rate is, in turn, increased.

The energy confinement time is estimated at around 0.3 sec in the steady-state period, which is about 1.4 times as long as the international stellarator scaling ISS95 [11]. This enhancement factor is similar to the short-pulse experiments below 2 sec [12], meaning that the plasma confinement properties in the long-pulse shots are not so different from the short-pulse ones.

In the helium discharge, the wall pumping effect is weaker than that in the hydrogen discharge. Figure 4 shows the line-averaged electron density, the helium

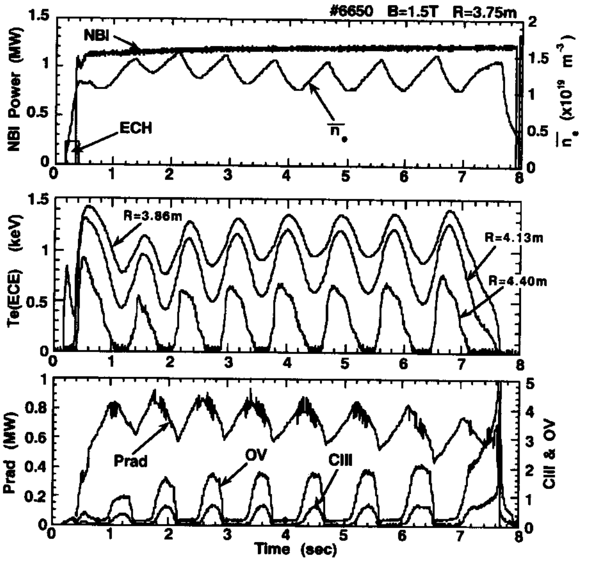

Fig. 5 Example of a "breathing" oscillation long-pulse shot.

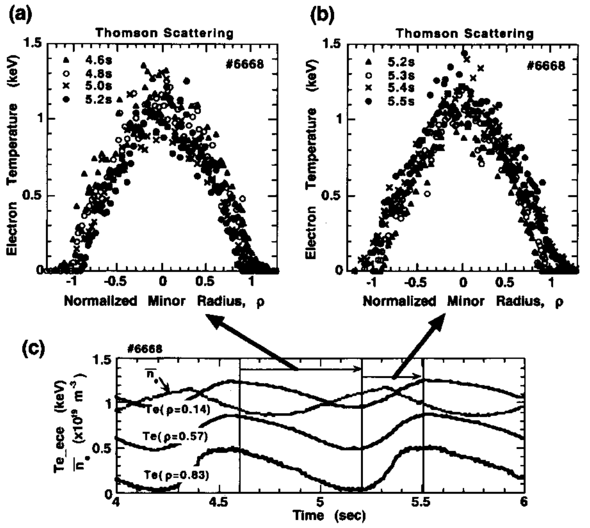

Fig. 6 (a) and (b) Time variation of the electron temperature profile, and (c) corresponding time evolution of the ECE signal and the line-averaged electron density.

gas-puffing flow rate, and the ion saturation current density on the divertor near the front port (10-O) in stationary discharges with various densities sustained by the feedback control with the gas-puffing. The LHD magnetic field strength and the magnetic axis position are 1.5 T and 3.75 m, respectively, and the injection energy and power are 113 keV and 1.1 MW, respectively. In constant density phase, the gas-puffing flow rate is low, and the density seems to be determined by the supplied gas in the first 2 sec, meaning that the recycled particles sustain the density, except for the lowest density discharge of 1×10^{19} m^{-3}. The ion flux to the divertor tends to be larger in higher density discharges, indicating larger amount of the recycled particles. The effective particle confinement time is roughly estimated at 0.9 sec for the lowest density of 1×10^{19} m^{-3}. With an increase in the density, it is increased to 23 sec for the highest density of 6×10^{19} m^{-3}, and the recycling rate is also increased from 0.933 to 0.995. The wall pumping is weaker in the helium discharge, and, however, is still effective to keep the density constant in long-pulse beam injection.

3.3 Oscillating long-pulse discharges

In the second campaign, where the divertor traces were covered with stainless steel plates, slow plasma oscillations were observed at higher densities than those in the stationary plasmas [7]. The observed plasma relaxation oscillation lasted for 21 sec, and the plasma density, the plasma temperature, and the impurity radiation all oscillate with a period of 1–2 sec. Observation of the plasma via a tangential TV monitor revealed alternate expansion and contraction, similar to "breathing". Figure 5 shows an example of the "breathing" shot. The amount of the gas-puffing, provided only at the start of discharge, is a little more than that in a stationary shot. As a result, the density is increased, and the plasma shows the relaxation oscillation. The density decrease occurs rapidly compared with the density increase and causes a sudden increase in the divertor flux. The time variation of the electron temperature profile measured with the Thomson scattering is shown in Figs. 6 (a) and (b), and the corresponding time evolution of the ECE signal and the line-averaged electron density is shown in Fig. 6 (c). As shown in Figs. 6 (a) and (b), the electron temperature profile is oscillating over whole plasma minor radii, and the profile shape is not largely changed. The shrinking and expanding observed on the TV monitor correspond to the profile shrinking and expanding, respectively, of the electron temperature. At a temperature minimum timing, the edge electron temperature is very low, and the plasma is observed to be shrinking and so-called "detachment". As shown in Fig. 5, the radiation power is gradually increased during the high electron temperature and shows a maximum before the temperature minimum timing. The time evolution of the radiation power corresponds to the iron concentration in

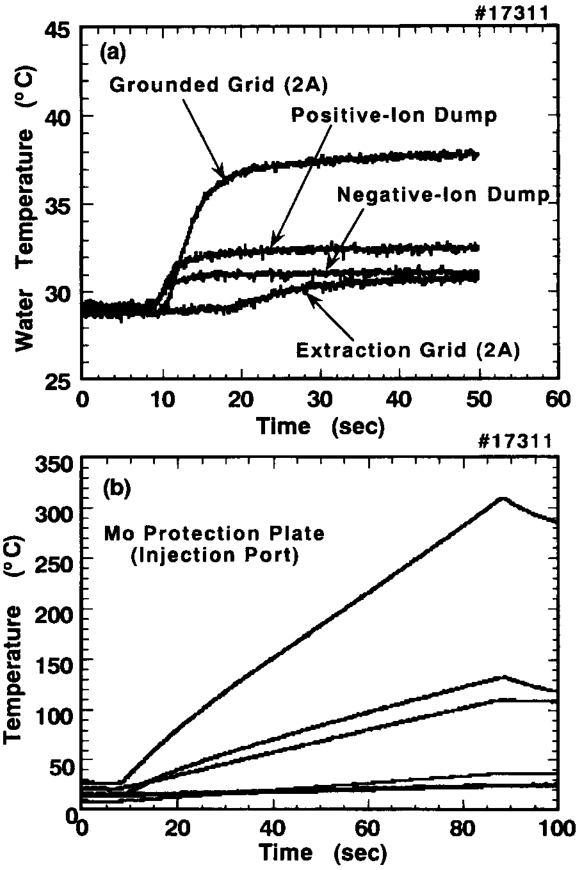

Fig. 7 (a) Cooling water temperature rises of the heat load components in the injector, and (b) temperature rises of the molybdenum protection plates in the injection port, for the 80-sec shot.

the core plasma, estimated using an average-ion, coronal-equilibrium model [10].

The possible scenario of the sequence in "breathing" is as follows [7,10]. In the density decreasing phase, where the plasma is expanding, an interaction between the plasma and the divertor wall becomes stronger, resulting in an increase in the impurity influx, especially iron. The increase in the iron influx leads to an increase in the core radiation loss and the electron temperature is gradually decreased. As a result, the plasma is shrinking, bringing a reduction of the plasma-wall interaction, i.e., a reduction of the iron influx. In this period, the density is increased, resulting in an increase in the absorbed power. Then, the plasma temperature could be recovered, leading to the next plasma expansion. In the third campaign, where the carbon divertor tiles are installed, no breathing oscillation has been observed in the same operational conditions. The iron concentration is dramatically reduced in the third campaign, indicating that the core radiation loss due to iron would play an important role in the breathing oscillation.

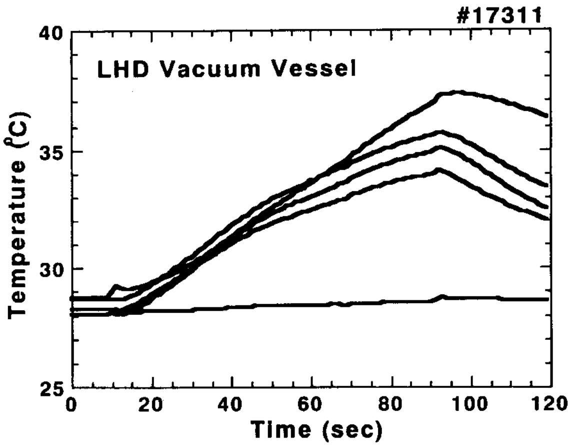

Fig. 8 Time evolution of the LHD vacuum vessel temperature for the 80-sec shot.

4. Hardware Characteristics

In the long-pulse injection, the temperature rise of heat load components in the injector is almost saturated. Figure 7 (a) shows the cooling water temperature rises of the grounded and the extraction grids of the ion source and the residual ion beam dumps for the 80-sec shot. The temperature rises of these components are less than 10°C and reach constant values. However, the temperature rises of the molybdenum protection plates in the injection port, which are inertially cooled, show no saturation and reach 300°C at the pulse end, as shown in Fig. 7 (b). The further temperature rise would cause out-gassing, resulting in the beam blocking [7]. Presently, the temperature rise of the protection plates limits the pulse duration. Active cooling structure is required for the injection port protection to the further extension of the injection pulse duration.

The LHD vacuum vessel temperature is shown in Fig. 8, for the 80-sec shot. The vacuum vessel is water-cooled with stainless steel channels welded directly to the plasma-facing surface of the vacuum vessel. The temperature rise of the vacuum vessel is less than 10°C for the 80-sec injection. Protecting panels (first wall) are partially installed on the cooling channels, and all surface will be covered with the panels for 3 MW steady-state plasma heating to minimize the heat flow to the vacuum vessel facing the 80 K shield. The carbon divertor temperature rise is about 50°C at maximum observed with an IR camera.

5. Summary

Long-pulse plasma discharges have been achieved in the superconducting LHD, heated with a negative-ion-based neutral beam injector. The injection duration was extended to 80 sec with an injection power of 100 keV – 0.5 MW. The sustained plasma density and temperature are $(1.5 - 2.0) \times 10^{19}$ m^{-3} and 1.5–1.8 keV, respectively. The density can be controlled by the gas-puffing due to the wall pumping effect, while the density is sustained by the recycling. On the other hand, slow relaxation oscillation was observed in long-pulse discharges, lasting for 20 sec, in the case of stainless-steel divertor plates. The radiation loss due to iron would cause the "breathing" oscillation. The injector operation was stable and the temperature rise of the heat load components was saturated in the present long-pulse injection. Active water-cooling of the injection port and full installation of the first wall on the LHD vacuum vessel are required to the further long-pulse injection for several tens minutes.

Acknowledgements

The authors gratefully acknowledge Professor M. Fujiwara, Director-General, for his continuous encouragement and support. They are also grateful to E. Asano, T. Kawamoto, and R. Akiyama for their excellent long-pulse operation of the NBI system. Efforts by the operation group to operate the superconducting LHD are greatly appreciated.

References

[1] A. Iiyoshi *et al.*, Nucl. Fusion **39**, 1245 (1999).
[2] O. Motojima *et al.*, Nucl. Fusion **40**, 599 (1999).
[3] M. Fujiwara *et al.*, Plasma Phys. Control. Fusion **41**, B157 (1999).
[4] N. Noda *et al.*, J. Plasma and Fusion Res. SERIES **1**, 130 (1998).
[5] Y. Takeiri *et al.*, J. Plasma and Fusion Res. SERIES **1**, 405 (1998).
[6] Y. Takeiri *et al.*, Rev. Sci. Instrum. **70**, 4260 (1999).
[7] Y. Takeiri *et al.*, Plasma Phys. Control. Fusion **42**, 147 (2000).
[8] O. Kaneko *et al.*, *Proc. the 16th IAEA Fusion Energy Conference (Montreal, Canada, 1996)* Vol. 3, p. 539.
[9] Y. Takeiri *et al.*, *Proc. the 17th IEEE/NPSS Symp. on Fusion Engineering (San Diego, 1997)* Vol. 1, p. 409.
[10] B.J. Peterson *et al.*, this conference.
[11] U. Stroth *et al.*, Nucl. Fusion **36**, 1063 (1996).
[12] O. Motojima *et al.*, this conference.