27th EPS Conference on Contr. Fusion and Plasma Phys. Budapest, 12-16 June 2000 ECA Vol. **24B** *(2000) 396 -399*

High-Density Long-Pulse Discharges Sustained by Neutral Beam Injection in Large Helical Device

Y. Takeiri, Y. Nakamura, N. Noda, M. Osakabe, Y. Oka, K. Kawahata,
O. Kaneko, K. Tsumori, K. Ikeda, M. Sato, T. Mutoh, H. Funaba, M. Goto,
K. Ida, S. Inagaki, S. Masuzaki, J. Miyazawa, T. Morisaki, S. Morita,
Y. Nagayama, K. Narihara, K. Nishimura, B. J. Peterson, S. Sakakibara,
R. Sakamoto, M. Sasao, K. Sato, H. Suzuki, T. Tokuzawa, K. Ohkubo,
S. Sudo, H. Yamada, A. Komori, N. Ohyabu, O. Motojima,
and LHD Exp. Groups G2 and G1

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

Abstract

The operational regime of long-pulse neutral-beam-heated discharges was expanded in the Large Helical Device. A high-temperature (1.5 – 1.8 keV) plasma with a density of (1.5 – 2.0) x 10^{19} m^{-3} was sustained for 80 sec with an injection power of 0.5 MW. High-density plasmas of more than 5 x 10^{19} m^{-3} were obtained stationary for 10 sec with higher powers of 1.4 MW. The energy confinement time was around 1.5 times as long as the international stellarator scaling ISS95, which was similar to the short-pulse shots. Wall pumping effect enabled the density control by the gas-puffing in the long-pulse discharges.

1. Introduction

The Large Helical Device (LHD) is the world-largest superconducting helical system, and the confining magnetic field is generated by only external superconducting coils without plasma current [1]. Long-pulse steady-state operation is one of the major objectives of the LHD, and long-pulse neutral beam heating has been carried out with a negative-ion-based neutral beam injector (NBI) [2].

In 1998, the magnetic field strength was 1.5 T and stainless steel plates were installed on the divertor traces. A stationary plasma with a density of 0.3 x 10^{19} m^{-3} was sustained for 21 sec at an injection power of 0.6 MW. On the other hand, plasma relaxation oscillation, so-called “breathing”, was observed for 20 sec at a higher density, and high-density stationary plasmas were not sustained for a long duration [3]. In 1999, the magnetic field strength was raised to 2.75 T and the stainless steel plates were replaced with carbon plates in the divertor region. The injection power and energy of the neutral beam were also increased. As a result, high-density plasmas were sustained stationary for a long discharge duration.

In this paper, we report the confinement properties and the particle balance of the long-pulse NBI heated plasmas in the LHD.

2. Confinement Properties

The LHD is equipped with a negative-ion-based neutral beam injection (NBI) system, which consists of two injectors arranged as tangential and balanced injection [4]. A co-injector is designed to extend the injection duration over 10 sec with a reduced power, although it is limited to 10 sec with a counter-injector. The AC input power for the NBI operation is usually provided with the motor generator (MG) for an injection duration below 35 sec. The MG is replaced with the commercial AC line to extend the injection duration longer than 35 sec. However, the injection power should be reduced to below 0.7 MW for the commercial AC line due to the line capacity. The injected gas species is hydrogen.

The time evolution of various plasma parameters are shown in Fig. 1, for a long-pulse NBI plasma 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 B = 2.75 T and R = 3.6 m, respectively. It is found that the injection duration is successfully extended to 80 sec. The density is controlled by manual operation of the helium gas-puffing, and the line-averaged electron density is maintained at (1.5 – 2.0) x 10^{19} m^{-3}. Slow deviation of the

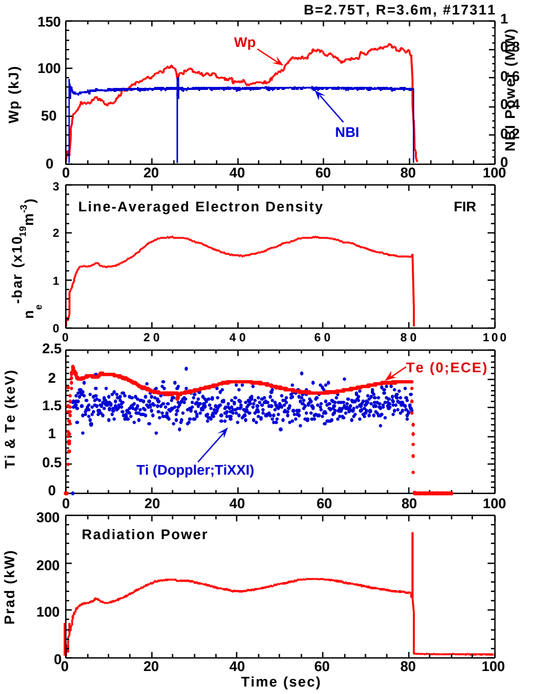

Fig. 1 Time evolution of various plasma parameters for the 80-sec shot.

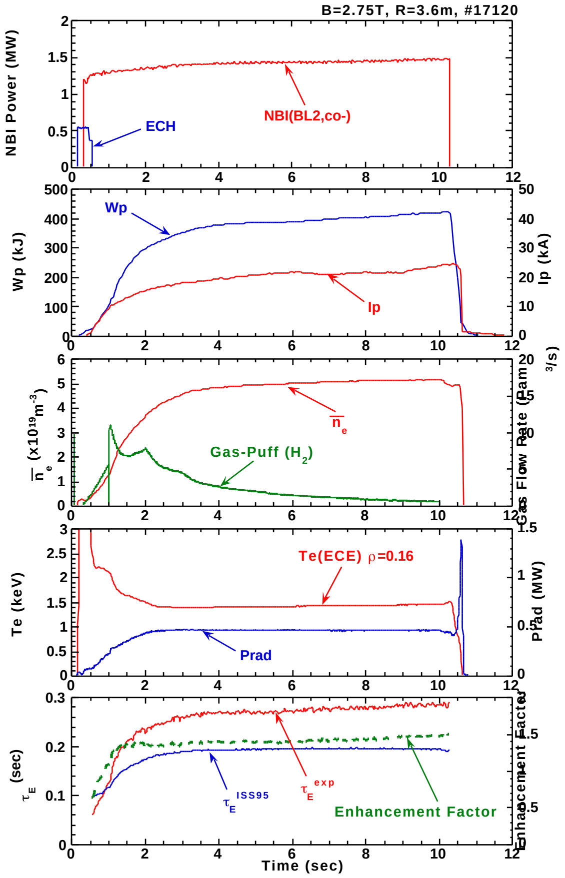

Fig. 2 Time evolution of various plasma parameters for the 120keV-1.4MW-10sec shot.

density results from the manual control of the gas-puffing. The wall pumping effect is confirmed and continues during the shot for 80 sec, which enables the density control with the gas-puffing. The central ion temperature, measured by the Doppler broadening of TiXXI is around 1.5 keV. The radiation power is kept at a low level during the shot, and is about 30 % of the heating power, which is lower than that in the stainless steel divertor. By replacement of stainless steel with carbon for divertor materials, the iron concentration was much reduced, and reduction of the core radiation loss was observed [5].

The plasma density can be kept constant by feedback control of the gas-puffing. Figure 2 shows the time evolution of various plasma parameters for a high-density stationary shot. The injection energy and power are constant of 120 keV and 1.4 MW, respectively. The feedback control of the hydrogen gas-puffing starts at t = 1 sec to achieve and keep a pre-setting density. After t = 4 sec, a high-density plasma of 5 x 10^{19} m^{-3} is sustained stationary, and the other plasma parameters, such as the temperature, the stored energy, the plasma current, and the radiation power, reach a steady state. The temporal variation of the energy confinement time, τ_E^{exp}, is estimated, and the τ_E^{exp} is increased with an increase in the density. As shown in Fig. 2, the τ_E^{exp} is compared with the international stellarator scaling ISS95, τ_E^{ISS95}, and is about 1.5 times as long as it. This enhancement factor is similar to the short-pulse experiments for 1 - 2 sec [6], meaning that the discharge duration is easily extended keeping the plasma confinement properties in the short-pulse shots.

After installing the carbon divertor plates, the ratio of the radiation power to the heating power is not increased with the density, and remains at 30 - 40 % even in the high-density plasmas. Figure 3 shows the time traces of the stored energy and the radiation power for long-pulse plasmas with different densities. The magnetic field strength and the 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 each shot, the density is maintained constant with the feedback control

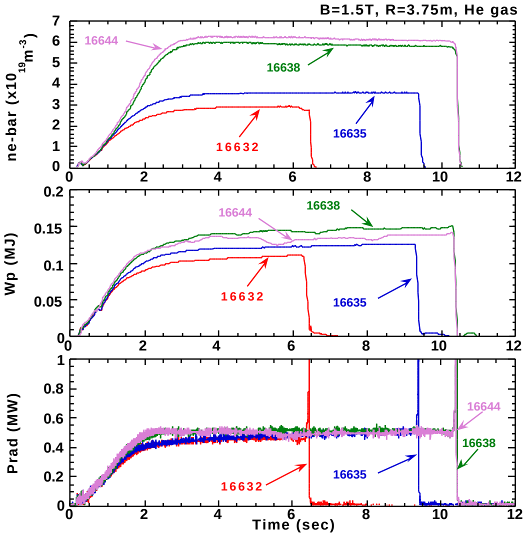

Fig. 3 Time traces for the long-pulse stationary helium discharges.

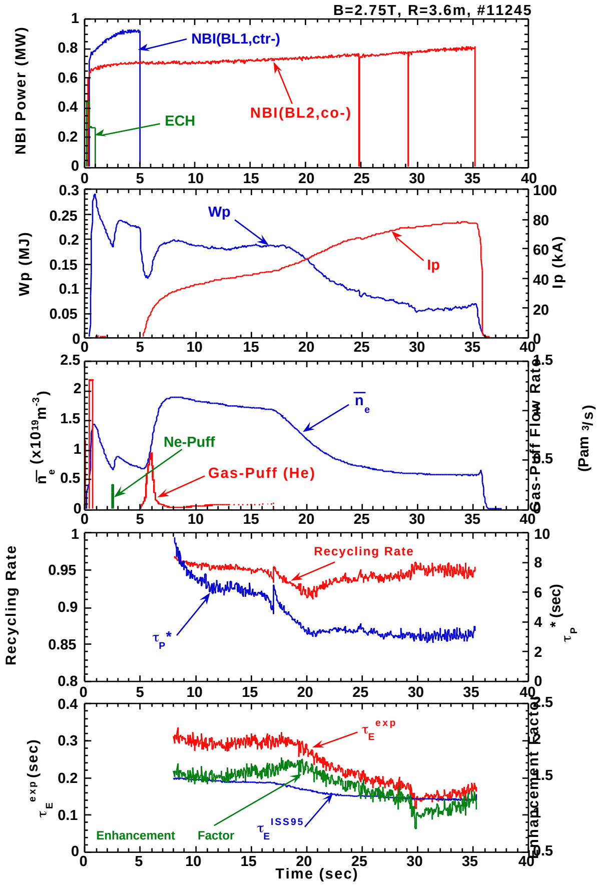

Fig. 4 Time evolution of various plasma parameters for the 35-sec helium discharge.

of helium gas puffing. The radiation power is not changed in time, and it is found that the radiation power is almost the same for plasmas with different densities. A high-density plasma of 6 x 10^{19} m^{-3} is sustained stationary although a weak fluctuation is observed in the stored energy. In the case of stainless steel divertor plates, the "breathing" relaxation oscillation limited the density to less than 1 x 10^{19} m^{-3} for the same magnetic field configuration and strength. In this case the radiation power was 40 - 60 % of the heating power for stationary plasmas and was larger for the "breathing" plasmas with higher densities [7]. The reduction of the radiation power with the carbon divertor would contribute to sustenance of the high-density stationary long-pulse plasmas.

3. Particle Balance

One of the important issues on the long-pulse experiments is a particle-wall interaction. As shown in Figs. 1 and 2, the wall pumping effect leads to the density control by the gas-puffing. Here, the following simple particle balance equation is considered,

$$dN/dt = \eta S - N/\tau_p + R(N/\tau_p) = \eta S - N/\tau_p^*, \qquad (1)$$

and the effective particle confinement time τ_p* is defined as

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

where N is the plasma particle number, S the particle source rate, R the recycling rate, τ_p the particle confinement time, and η is the particle fueling efficiency into plasma. The supplied (source) particles into the LHD vacuum vessel are the injected hydrogen beam and the hydrogen or helium puffing gas. In the following particle balance analysis, Z_{eff} = 1 is assumed. Figure 4 shows a long-pulse shot lasting for 35 sec with helium gas-puffing. In this shot, for the first 5 sec, the co- and counter-neutral beams are injected, and after 5 sec, only the co-injection sustains the plasma with an injection energy and power of 104 keV and 0.75 MW, respectively. The feedback control of the gas-puffing starts at t = 5 sec and ends at t = 17 sec. The effective particle confinement time τ_p* is experimentally evaluated to be about 5 sec from a density decay at t = 17 sec when the gas-puffing stops. Using this experimentally obtained τ_p*, the fueling efficiency η is estimated at around unity, meaning that the supplied particles are almost fueled into the plasma in the helium discharge. Time evolutions of the τ_p* and the recycling rate, which are estimated with eqs. (1) and (2) assuming $\eta = 1$, are also shown in Fig. 4. For the estimation of the recycling rate the particle confinement time τ_p is assumed to be equal to the energy confinement time τ_E^G. The recycling rate is as high as 95 %, and is not changed largely except for a few seconds after the stop of gas-puffing. Although the wall pumping effect is small in the helium discharge with a high recycling rate, it is still effective to the density control by the gas-puffing.

On the other hand, for hydrogen discharge, the wall pumping effect is much higher, and the puffing gas amount is much larger to obtain the same density as that in the helium discharge. Figure 5 shows the τ_p*, evaluated from the density decay at the stop of gas-puffing, as a function of the integrated supplied particles, which is equivalent to the wall loading. The experimentally obtained τ_p* is increased with an increase in the wall loading, suggesting an increase in the recycling rate due to degradation of the wall pumping effect. The fueling efficiency η, estimated from the τ_p* in Fig. 5, is as low as 20 - 60 %. For the hydrogen gas-puffing, the fed gas particles would be screened [8], and the screening effect has an influence on the fueling efficiency. A large amount of the puffing gas which is not fueled into the plasma would be absorbed directly in the wall.

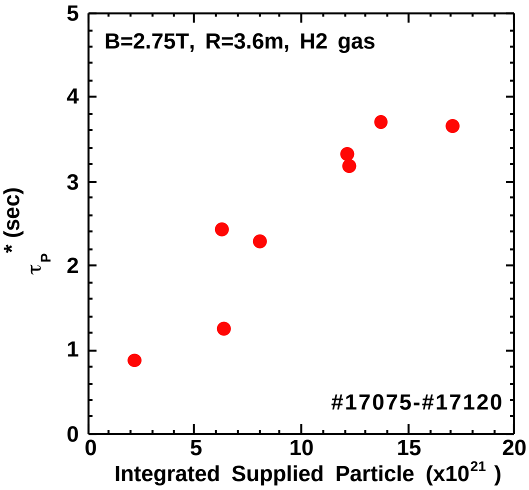

Fig. 5 Effective particle confinement time τ_p as a function of the integrated supplied particle.*

5. Summary

The discharge duration of the neutral-beam-heated plasma was extended to 80 sec with a relatively high-density of (1.5 - 2.0) x 10^{19} m^{-3}. By replacement of stainless steel with carbon for the divertor materials, the core radiation power was reduced, which would contribute to sustenance of high-density long-pulse plasmas. A stationary plasma with a density over 5 x 10^{19} m^{-3} was obtained for 10 sec by feedback density control with fueling gas-puffing, and the confinement properties were similar to those in the short-pulse shots. The wall pumping effect enables the density control by the gas-puffing, and the simple particle balance analysis shows that the recycling rate is gradually increased in the hydrogen discharge while it is almost constant at a relatively high value closed to unity in the helium discharge. The further extension of high-density long-pulse discharges is required for investigation of the density control for a saturated wall where the wall pumping effect is not expected any more.

References

[1]A. Iiyoshi, *et al.*, Nucl. Fusion **39**, 1245 (1999).
[2]Y. Takeiri, *et al.*, Rev. Sci. Instrum. **70**, 4260 (1999).
[3]Y. Takeiri, *et al.*, Plasma Phys. Control. Fusion **42**, 147 (2000).
[4]O. Kaneko, *et al.*, *Proc. the 16th IAEA Fusion Energy Conference (Montreal, Canada, 1996)* Vol. 3, p. 539.
[5]B.J. Peterson, *et al.*, to be published in J. Nucl. Mater.
[6]H. Yamada, *et al.*, this conference.
[7]Y. Nakamura, *et al.*, to be published in J. Nucl. Mater.
[8]S. Morita, *et al.*, Proc. 26th EPS Conf., Maastricht (1999), p.1345.