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Particle Balance Study in Long-Pulse Discharges in LHD

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Abstract

Plasma density behavior has been studied in long pulse discharges with a neutral beam injection on LHD by using a global particle balance equation. The main external particle sources originate from gas puffing, beam particles and gas flow from the beam duct. The wall acts as a large sink and wall pumping is still effective for a long pulse discharge with the duration of 80 sec. This pumping effect is observed in both hydrogen and helium discharges.

Keywords:

global particle balance, source and sink, long pulse discharge, wall pumping

1. Introduction

Particle control is one of most important issues in demonstrating a steady state operation with high performance plasma. Many methods of particle control through control of the sources such as gas puffing, neutral beam fueling, or pellet fueling have been explored in fusion devices. Particle balance for long time requires the provision of the corresponding particle sinks. For previous fusion devices, this has been accomplished by conditioning the walls so as to provide net absorption of the incident particle flux for some period of time. The future direction towards long pulse or steady state operation requires the use of pumped divertors and a systematic understanding of their effect on plasma particle control and wall recycling.

The Large Helical Device (LHD) is the largest superconducting machine in the world and came into operation in 1998 [1]. Since a stationary magnetic field for plasma confinement can be produced, this device is greatly suitable to study the physics and technologies for steady state operation. Long pulse experiments were started by extending the pulse duration of NBI with an injection power of 1 MW [2,3]. Up to the present, an 80 s NBI heated discharge has been achieved with a plasma density of about 1.7×10^{19} m^{-3}. In this paper, we describe the results on particle control and particle balance in the long pulse discharges by NBI alone on LHD.

2. Experimental Arrangement

The LHD is a heliotron type device with a set of $l = 2/m = 10$ continuous helical coils, which is free from current drive and disruption. The major and minor radii are 3.9 m and 0.6 m, respectively. All external magnetic coils (helical and poloidal coils) are made of superconducting coils and then LHD has the capability of steady state operation. The plasma experiments on LHD have been started with a stainless steel inner wall where water cooling channels were directly welded for the capability of steady state operation with an injection power of 3 MW. In the third experimental campaign, a large number of carbon divertor plates have been installed at four divertor legs, which rotate helically

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around the torus. The heat removal capability is 0.3 MW/m^2. The vacuum vessel wall and the divertor plates have been conditioned by discharge cleaning of helium (or hydrogen) glow and ECR (2.45 GHz) plasmas. Titanium gettering with a coverage area of 20% has been mainly performed in the latter half of experimental campaign. At present, LHD has an open divertor configuration and no active pumping system such as a cryopump in the divertor.

The main heating facilities of LHD consist of ECH, NBI and ICH systems. The ECH (84Ghz) with 500 kW is principally employed to generate a target plasma for additional heating by other heating devices. Two negative-ion-based neutral beam injectors (total power of 4 MW for 3 s) are arranged in tangential direction (co- and counter-injection). One of them (co-injection) is capable of long pulse operation up to 90 sec with a reduced power of 0.5 MW at an energy of 100 keV.

3. Plasma Density Behavior

3-1 Stainless steel divertor plate case

In the initial long pulse experiments, the NBI heated plasma was terminated by radiative collapse due to impurity accumulation and density rise. The discharge duration was extended by wall conditioning of injection port in the NBI heating system and plasma vessel. The surface of vacuum vessel was conditioned by many high power short-pulse discharges, He glow discharge cleaning and Titanium gettering. This wall conditioning suppressed the increase rate of plasma density during the long pulse discharge (Fig. 1) and allowed us to achieve a long pulse discharge with a duration of 21 s with no active pumping system as shown in Fig. 2. However, when the amount of He gas puffing increased at the startup phase, the radiation power increased by metal impurity accumulation due to sputtering of stainless steel divertor plate and the operational regime of plasma density was limited to less than 5×10^{18} m^{-3} by a relaxation oscillation phenomena ("breathing"), where expansion and contraction of the core plasma was repeated with a period of 1 ~ 2 sec (Fig. 3). The detailed information of breathing plasma will be given in ref. 4 and the mechanism of this event will be discussed elsewhere [5].

3-2 Carbon divertor plate case

When we started long pulse experiments at the last stage in the 3rd campaign, the wall surface of plasma vessel including the carbon divertor plates has been already well conditioned by He (or H) glow discharge cleaning and Titanium gettering. In this wall condition, we observed no impurity accumulation and no density

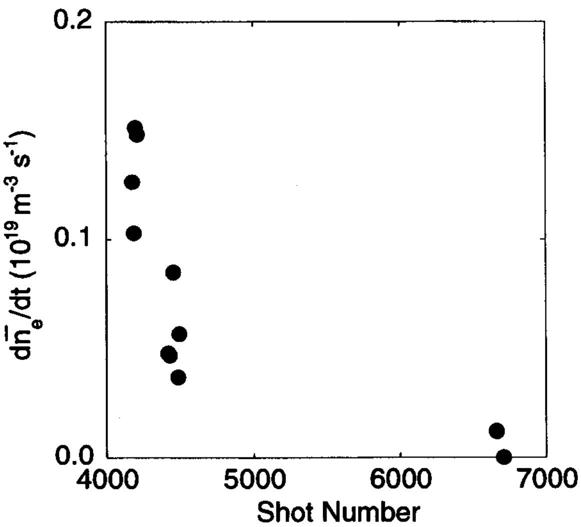

Fig. 1 Effect of wall conditioning on long pulse operation. The increase rate of plasma density is estimated at about 5 s and decreases with the number of plasma discharge because of daily wall conditioning (He glow, Titanium gettering).

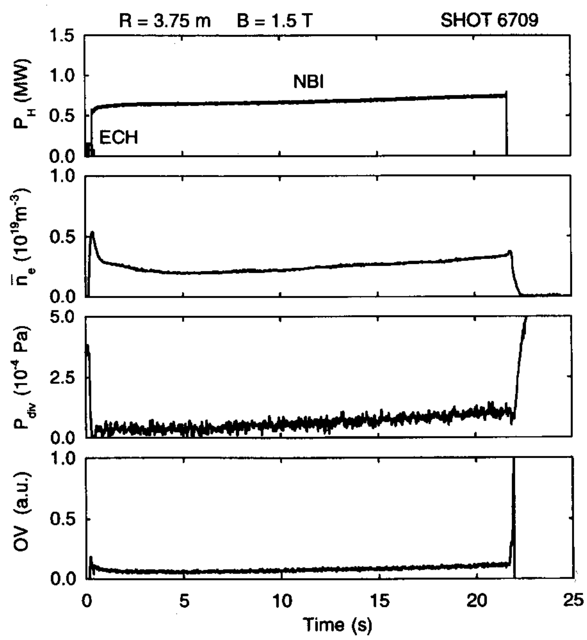

Fig. 2 Quasi-steady-state discharge with stainless steel divertor plates. There is no external gas puffing during NBI heating. This type of discharge is restricted in low density regime.

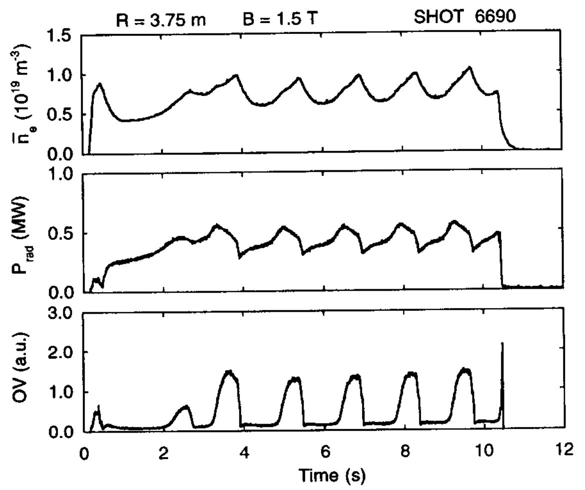

Fig. 3 Long pulse discharge with a slow relaxation oscillation. Gas puffing is also performed only in the rising phase of plasma density but the amount is little more than that in Fig. 2.

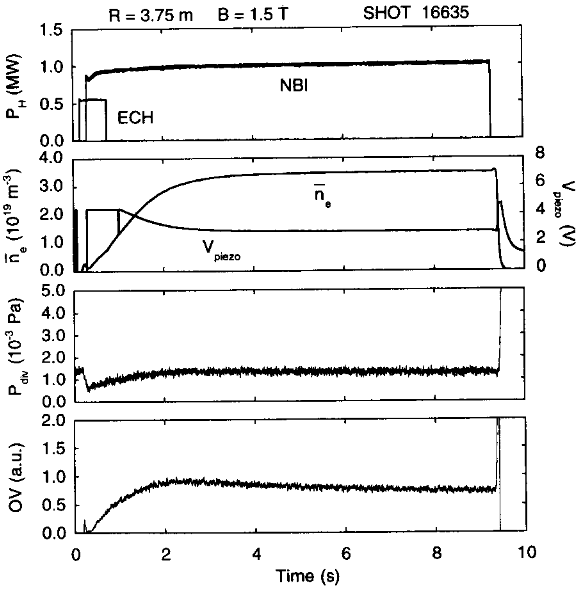

Fig. 4 Typical long pulse discharge with carbon divertor plates. The plasma density is feedback controlled by the gas puffing system. The amount of gas injection decreases with time and is kept almost constant at the end of discharge.

rise in long pulse operation. If the gas was puffed only at the rising phase of plasma density, the plasma density decreased with time after the termination of gas puffing due to wall pumping. A distinctive feature of the discharge with carbon divertor plates appeared in the high density operation, which was impossible with the stainless steel divertor plates. Figure 4 shows a typical long pulse discharge with a high density of 3.5×10^{19} m^{-3}. The plasma density is controlled by a gas puff system with feedback loop, in which a signal of the plasma density measured with FIR interferometer is taken. The quasi-steady-state plasma density can be raised up to ~ 6×10^{19} m^{-3} without any oscillations as seen in the case of the stainless steel divertor plates. The extension of discharge duration was also attempted and we have achieved an 80 s long pulse discharge with a density of $1.5 \sim 1.9 \times 10^{19}$ m^{-3}. In this discharge, the gas puffing rate was gradually reduced with time but the wall pumping was still effective at the end of the discharge in spite of He gas puffing.

4. Global Particle Balance

Here we investigate a global particle balance by estimating the gas sources and sinks. The wall particle loading rate during the discharge can be described by

$$\Gamma_{wall} = \Gamma_{puff} + \Gamma_{NBI} + \Gamma_{NBI}^{gas} - \frac{dN_p}{dt} - \frac{dN_0}{dt} - \Gamma_{pump} \qquad (1)$$

where Γ_{puff} is the gas puff fuelling rate, Γ_{NBI} is the energetic beam particle fuelling rate, Γ_{NBI}^{gas} is the cold particle fuelling rate from gas in the beam line, dN_p/dt is the neutral loss rate due to plasma formation, dN_0/dt is the neutral gas buildup rate, Γ_{pump} is the pump exhaust rate and Γ_{wall} is the wall pump rate. This type of particle balance has been used for many other tokamak discharges. As an example of low density discharge, we present particle balance at 10 s after the initiation of long-pulse discharge in Fig. 2. Since the external gas puffing was performed only in the startup phase, $\Gamma_{puff} = 0$. Γ_{NBI} is calculated to be 0.044 Pam^3/s from the beam parameters (E_b = 66 keV, P_{in} = 600 kW) excluding the shine-through particles (62%). The neutral gas flux from the beam duct is estimated to be 0.037 Pam^3/s from the pressure measurement in the beam drift tube. The neutral loss rate due to plasma formation is estimated as the rate of change in the hydrogen inventory. In this analysis we assume $Z_{eff} = 1$ and flat density profiles typical of LHD discharges by gas puffing. With these assumptions, the hydrogen inventory is roughly equal to the electron inventory, which can be estimated as the product of the line averaged electron density and the plasma volume (V_p), i.e. ($N_p \approx N_e \approx \bar{n}_e V_p$). The contribution of this term to particle balance is very small because the electron density is almost constant during the discharge. Since the divertor pressure decreases abruptly with the initiation of discharge and it is kept almost constant at the low level of 10^{-4} Pa, $dN_0/dt = 0$. The particle exhaust by a pumping system (pumping speed of 67 m^3/s) is not so large (Γ_{pump} = 0.004 Pam^3/s) because the divertor pressure is very low as indicated above. The wall pump rate, Γ_{wall}, can be readily calculated to be 0.072 Pam^3/s from the eq. (1). One should note that the major external particle sources originate from the beam particles and the gas flow from the beam line and the wall acts as a main particle sink. Furthermore, the particle source for plasma formation almost originates from the recycling particles in the long-pulse discharge. On the other hand, in the high density discharge (Fig. 4), the beam particle fueling rate increases with increasing the plasma density because of the decrease of shine-through particles (Γ_{NBI} ~ 0.12 Pam^3/s) and the gas puffing rate is ~ 0.014 Pam^3/s at the end of the discharge. The gas particle flux from the beam line is ~ 0.04 Pam^3/s. Since the plasma density and divertor pressure are kept almost constant at the latter half of the discharge, the fourth and fifth terms in eq. (1) are negligible. The external pumping rate Γ_{pump} is ~ 0.018 Pam^3/s. Therefore the wall pumping rate can be evaluated to be ~ 0.16 Pam^3/s. In this discharge, the wall is only loaded by the particle input ($\Gamma_{NBI} + \Gamma_{NBI}^{gas}$) from the NBI system. The beam particle fueling rate is small compared to those in tokamaks because the beam power is still low (< 1MW) and the beam energy is high (> 100 keV). Therefore, the wall loading rate is not so large in comparison with that (> several Pam^3/s) in large tokamak devices. As observed in the Tore Supra experiments, we can also expect enhanced wall pumping due to enhanced diffusion with absorption along the inner surfaces of the graphite divertor tiles and enhanced codeposition of hydrogen [6]. In fact, the preliminary results for the discharges with hydrogen gas puffing show a strong wall pumping. However, the wall pumping capability decreases with increasing the wall loading. Accordingly, an active pumping system will be required for a high power (3 MW) and steady state (1 h) operation, which is our target in near future.

It is very important to compare the results on wall pumping with those in long pulse tokamak machines. In our experiment, the wall loading rate (~ 0.16 Pam^3/s) is mainly caused by the beam particle fueling and less than that (~ 0.7 Pam^3/s) in Tore Supra. The integrated wall load (1.5 Pam^3) is also much less than that (~ 40 Pam^3) [7]. Therefore, we have to perform more long pulse and high density operation in order to compare the wall pumping capability between two machines.

5. Conclusions

Particle balance in long pulse discharges by NBI alone on LHD was investigated. The gas flow from the beam line as well as the beam particles was the main external particle source in the low density discharge. The plasma density can be feedback controlled by adding a gas puffing, leading to a high density discharge (6×10^{19} m^{-3}) and a long pulse operation (80 s). The wall acts as a large particle sink and the wall pumping is still effective for such discharges up to the present. In order to realize a high power and steady-state operation (3 MW, 1h), further investigation on wall recycling and the development of active pumping system will be required.

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