Study of the steady-state and high-performance plasma operation in the Large Helical Device

S. Masuzaki for the LHD experimental group

1. National Institute for Fusion Science, Toki, Japan

Abstract: Sustaining of the steady state high performance plasma is crucial issue to realize the energy supply by nuclear fusion reactor. In the Large Helical Device (LHD), the long-pulse operation regime has been extended. A high temperature plasma was sustained for 54 min with 1.6GJ of heating energy. Dispersion of the divertor heat load is a key issue for sustaining high temperature long-pulse plasma, and was performed by magnetic axis swing operation. On the other hand, the high density regime with an internal diffusion barrier (IDB) was found in short-pulse operations. The central density of up to ~1x10^{21} m^{-3} has been achieved in the discharges with an IDB formation, and the central pressure has reached 1.3 times atmospheric pressure. To extend the duration time of the high density discharge with an IDB, the edge particle control using the closed helical divertor is considered to be necessary.

Keywords: Large Helical Device, long pulse discharge, internal diffusion barrier, particle control

1. INTRODUCTION

Sustaining of the steady-state high-performance plasma is crucial for realizing the energy supply by nuclear fusion reactor. In the Large Helical Device (LHD) [1], the world largest super-conducting heliotron-type device, the plasma confining magnetic configuration is produced by external magnetic coils without the plasma current unlike tokamaks, and thus this type of device is suitable for steady-state plasma operation. Equipment of the intrinsic divertor structure (helical divertor) is one of the characteristics of the heliotron-type devices [2]. Figure 1 shows poloidal cross-sectional views in LHD. The intrinsic helical divertor looks like double-null poloidal divertor in tokamaks. Development of high-performance plasma regimes and sustaining high-temperature plasma for long duration by using the particle control with the helical divertor are major experimental goals in LHD.

In this paper, present statuses of the long-pulse plasma operation and the high-performance plasma operation are described. The modification plan of the in-vessel structure at the helical divertor to conduct the effective particle control is also described.

2. LONG-PULSE OPERATION IN LHD

In LHD, electron cyclotron heating (ECH) and ion cyclotron range of frequencies (ICRF) heating devices have been developed for long-pulse operation in LHD [3, 4]. A continuous wave (CW) ECH system which has the injection power of 110 kW has been operated with the frequency of 84 GHz, it resonates at 3 T. Six ICRF antennas are installed on the torus out-board side at the vertically elongated cross-sections [4], and four antennas were connected to the power supplies through specially developed ceramic feed-throughs, coaxial lines and liquid impedance tuners. The ICRF heating was conducted by use of minority heating with helium as the majority ions and hydrogen as the minority ions.

In the experimental campaign in 2005 FY, a long-pulse operation with the duration time of 54 min and input energy of 1.6 GJ was performed successfully [5]. Figure 2 shows the time evolutions of plasma parameters in the operation. ICRF and ECH were injected simultaneously and continuously. The averaged heating power was 380 kW for ICRF and 110 kW for ECH. The line-averaged electron density was \(0.4 \times 10^{19} \text{ m}^{-3}\) and central electron and ion temperature were 0.8 – 1 keV. Figure 3 shows the maximum injected energies of major long-pulse operation devices versus discharge duration time, and it shows that LHD has extended the long-pulse operation regime.

At this stage, the unexpected termination of the long-pulse operation is attributed by radiation collapse due to uncontrollable gradual or abrupt density rises [7]. The former is caused by the out-gassing from plasma facing components, such as graphite divertor plates and ICRF antenna protectors with their temperature rises. The out-gassing could be reduced by the repeating long-pulse discharges or dispersion of the heat load on the divertor by the magnetic axis swing [8]. From the spectroscopic observations, the abrupt density rise was considered to be due to iron impurity injection from the first wall panels which are made of stainless-steel (SUS316L) or the deposited iron layer on the divertor plates [9]. One of the
causes of the iron injection is sparks or arcing, but the mechanism of the abrupt iron injection has not been understood.

3. EXTENTION OF HIGH-DENSITY REGIME WITH AN IDB

The extremely high-density regime with an internal diffusion barrier (IDB) was found in LHD with the central fueling by the ice pellet injection under the local island divertor (LID) configuration during the experimental campaign in 2005 FY [10]. The LID configuration is an alternative divertor configuration in LHD. A feature of the LID configuration is equipping a divertor pump system. A closed divertor module is inserted into m/n=1/1 magnetic island produced at the peripheral region of the main plasma region by external perturbation field, and particle and heat flux from the main plasma is collected by the divertor plates in the closed divertor module [10]. Therefore plasma-surface interaction is localized in the closed divertor module, and that enable the particle control relatively easy. In the experimental campaign in 2006 FY, the high-density regime was also observed under the intrinsic helical divertor configuration with pellet fueling. The central density of up to ~1x10^{21}m^{-3} was achieved in the discharges with an IDB formation.

Figure 4 shows comparisons of electron density, temperature and pressure profiles in a gas-fueled plasma and a plasma with an IDB measured by Thomson scattering under the intrinsic helical divertor configuration. The line-averaged density is the same for both cases. The density profiles in these two plasmas are largely different from each other. In the case with an IDB, the central density sharply peaked while the profile is hollow in the gas-fueled case. There are sharp bends at R ~ 3.65 m and 4.3 m in the high-density plasma case, and that is an IDB. The electron temperature in the center region is higher in the high-density plasma case than the gas-fueled case. As the result, the electron pressure in the center region is much higher in the high-density plasma than the gas-fueled plasma. For the high central electron

Fig. 2 Plasma parameters of the 54 min discharge with 1.6 GJ input energy: input power of ICRF and ECH, line-averaged density, electron and ion temperature and magnetic axis radius are shown [5].

Fig. 3 Maximum injected energies of major long-pulse operation devices are plotted versus discharge duration time. The LHD has extended the envelope of long-pulse plasma operations.

Fig. 4 Comparisons of (a) electron density, (b) electron temperature and (c) electron pressure profiles in a gas fueled plasma and a plasma with an IDB under the helical divertor configuration. The line-averaged density is the same for both cases. The original magnetic axis position is R = 3.75 m. The magnetic field and the heating power are 2.64T and 11MW of NBI, respectively [12].
pressure in the high-density plasma, the peak of the pressure profile is shifted about 0.3 m outward from the original magnetic axis position (R = 3.75 m) due to a Shafranov shift.

So far, the mechanism of the IDB formation is not understood. In the case of the helical divertor configuration, there is no active divertor pump system at this stage, and the recycled neutral particles increase with decreasing of the wall pumping capacity [13]. In such case, the electron density before the pellet injection increases, and the IDB formation has not been observed. From this observation, relatively low electron density seems to be necessary to form an IDB, and thus particle control such as pumping is essential. An operational magnetic configuration in which the IDB is not formed in the helical divertor configuration while it is formed in the LID configuration was found. The neutral pressure in the edge region is smaller in the LID configuration than in the helical divertor configuration while it is unclear whether that is caused by the difference of neutral pressure or the divertor configuration itself.

By using a repetitive ice pellet injector [14], the quasi steady state operation with IDB was demonstrated under the LID configuration. To sustain steady state plasma with an IDB, active divertor pumping is necessary.

4. DESIGN OF CLOSED HELICAL DIVERTOR SYSTEM

For long-pulse operation and high-performance plasma, edge neutral particle control is strongly required. The LID configuration has divertor pump system. However, the particle and heat flux concentrates to the LID divertor plates, and it is difficult to apply the LID configuration to prospective steady-state high-performance discharges. From the view point of the dispersion of particle and heat load on plasma facing component, the helical divertor configuration is more suitable for steady-state discharges than the LID configuration. It is planned to install a baffle structure in the helical divertor to reduce the leakage of neutral particles from the divertor region and to increase the neutral pressure in there. That is the closed helical divertor concept. Figure 5 shows a schematic view of a concept of the closed helical divertor in LHD. Behaviors of the divertor plasma and neutral particles under the closed helical divertor configuration are analyzed using the three dimensional transport code, EMC3-EIRENE [15,16], and the optimization of the configuration is currently underway.

5. SUMMARY

The present status of the long-pulse operation and the extension of high-density regime with an IDB are described. Both of them needs particle control using the intrinsic helical divertor. Closure of the helical divertor by installation of baffle structure and pump system in the vacuum vessel is planned to obtain the active particle control in LHD.

REFERENCES