Achievement of One Hour Discharge with ECH on LHD

Y Yoshimura, S Kubo, T Shimozuma, H Igami, T Mutoh, Y Nakamura, K Okkubo, T Notake, Y Takita, S Kohayashi, S Ito, Y Mizuno, S Inagaki, M Kojima, M Kobayashi, S Sakakibara, T Tokuzawa, H Nakanishi, K Narihara, S Masuzaki, J Miyazawa, T Morisaki, A Komori, O Motojima and LHD experimental group

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

E-mail: yoshimura.yasuo@lhd.nifs.ac.jp

Abstract. The potential of continuous plasma sustainment of Large Helical Device (LHD) was successfully demonstrated by a one hour discharge with 110 kW electron cyclotron heating (ECH) power. The ECH power of frequency 84 GHz generated by a continuous-work (CW) gyrotron is transmitted through an evacuated waveguide transmission line and injected to the LHD vacuum vessel using waveguide antenna. The plasma density was kept at about $1.5 \times 10^{18}/m^3$ and the electron temperature at the plasma center over 1 keV. Due to the low injection power the density was not so high but the plasma was quite stable. The power injection was terminated manually at 3900 seconds from the limitation of the setting of data acquisition, not for any troubles on devices.

1. Introduction

Stable and continuous plasma sustainment is one of the main goals of LHD project. LHD generates magnetic field for plasma confinement with its superconducting coil sets such as helical coils and poloidal coils [1]. No need of excitation of toroidal plasma current, contrary to tokamaks, is one of the great advantages of the device. By CW plasma sustaining experiment on LHD without the difficulty of plasma current control, issues which may appear in future long pulse operation planned for ITER [2] such as heat removal and gas fueling or wall pumping can be investigated. So far on LHD long pulse operation has been tried and a discharge of 756 second plasma sustainment was achieved in the 7th experimental campaign in F. Y. 2003 [3,4]. In that discharge, the pressure inside the evacuated waveguide gradually increased during the power transmission up to the interlock threshold level 1.3 Pa, then the power transmission was terminated. The temperature all over the transmission line much increased up to 100 degrees by transmission loss. After the experiment, heat removal and vacuum pumping of the transmission line were enforced and further long pulse operation was tried in the 8th experimental campaign in F. Y. 2004.

In this paper, achieved further long pulse plasma discharge by ECH for 3900 seconds as a result of the improvement of the transmission system is reported. In section 2, equipments such as CW gyrotron, high voltage power supply and transmission line are described. The experimental results are given in section 3. Problems remain to be solved and future plans are stated in section 4. Finally, section 5 concludes the contents of this paper.
2. Equipments for CW-ECH experiments

2.1. CW gyrotron
The CW gyrotron is a diode, collector potential depression (CPD) type tube produced by GYCOM. It is operated with beam voltage of 66 kV and beam current of 10 A. The nominal output power from a matching optic unit (MOU) is 200 kW for CW operation and 500 kW for 10 seconds. The output window is made of CVD diamond.

The MOU consists of two mirrors inside its vacuum vessel. The mirrors shape the gyrotron output beam to a circular Gaussian with the waist size of 10.2 mm at the waveguide mouth in the MOU so that the Gaussian beam effectively couples with the waveguide transmission mode \( HE_{11} \) in the waveguide of inner diameter 31.75 mm.

2.2. High voltage power supply
ECH system on LHD consists of 9 gyrotrons (4- 168 GHz, 2- 84 GHz, 2- 82.7 GHz and a 84 GHz-CW) and 4 sets of power supply system (PS) [5]. The CW gyrotron is connected to a PS with other two 84 GHz ones. Because of the difference of cathode voltages for the CW one (-49 kV) and the 84 GHz ones (-63 kV), they can not be operated simultaneously. The capacity of the PS is –65 kV, 126 A for 10 seconds and 42 A for CW operation.

2.3. Power transmission line
For power transmission from the CW gyrotron to LHD, evacuated waveguide transmission line is used. Main part of the line is alternatively shared with an 84 GHz gyrotron (#5) by using two waveguide switches as seen in Fig. 1. The inner diameter of the waveguides is 31.75 mm and totally corrugated for suppression of transmission loss of the \( HE_{11} \) transmission mode. Beam focusing mirrors inside LHD vacuum vessel for #5 gyrotron have no cooling channel so that CW power is injected from waveguide antenna of inner diameter of 88.9 mm. The transmission efficiency defined as LHD port through power divided by MOU output power is about 70 %.

Figure 1. A schematic view of the transmission line for CW gyrotron. An evacuated waveguide transmission line for #5 gyrotron was modified using two waveguide switches. The CW power is injected from waveguide antenna.
The waveguide antenna setting was designed so that the radiated beam aimed at the magnetic axis position $R_{ax}$ of 3.53 m, which is considered as the optimized configuration for particle confinement on LHD [6]. Applying Gaussian beam optics, the radiated power is evaluated to have a beam radius of 72 mm at the equatorial plane within which 86% of total power is included. Tapering up the waveguide diameter is effective for keeping the beam radius at the equatorial plane smaller. If the beam is directly radiated from 31.75 mm waveguide, the beam radius is much expanded to 186 mm there.

After the experience of the 756 second plasma sustainment which was terminated by pressure increase inside the transmission line, cooling and pumping of the line were enforced. To remove the transmission loss energy on the waveguides, most of the surface of the waveguides was covered with water cooled thin copper jackets except the section inside LHD vacuum vessel. The number of waveguide pumping section, that is, pumpout-tee, was increased from 1 to 8 and each of them was connected to turbo pumps or an evacuated duct.

3. Experimental results

3.1. Optimization of experimental configuration for power injection from waveguide antenna

The beam injection direction from waveguide antenna for CW ECH experiment is planned and designed so that the beam center should aim at the magnetic axis position $R_{ax}$ of 3.53 m. However, sufficient accuracy (1 degree direction error results in 5 cm displacement at the equatorial plane) for the construction of vacuum-tight waveguides in the available space at the injection port could not be secured. The beam direction needed to be confirmed experimentally.

The poloidal cross section where the waveguide antenna was installed, with $R_{ax}=3.53$ m and magnetic field at the plasma axis $B_{ax}$ of 1.5 T, is shown in figure 2. In the figure, concentric ellipses denote flux surfaces, thin curves: mod-$B$ surfaces, thick curves: 1.5 T - 2nd harmonic resonance surface, and the nearly vertical lines: designed beam path (the center line shows the beam axis and the lines on both sides show the beam radius).

![Figure 2](image)

**Figure 2.** The poloidal cross section where the waveguide antenna is installed. Flux surfaces, mod-$B$ surfaces and the designed beam path are drawn. Thick lines denote 1.5 T surfaces, that is, 2nd harmonic resonance surface for 84 GHz wave.
Figure 3. Result of magnetic axis scanning experiment searching the optimized configuration for CW-ECH experiment. Closed circles denote the maximum stored energy at each magnetic axis position with on-axis 2nd harmonic resonance conditions, and the open circles with higher field condition.

Previous to a trial of the long pulse discharge, magnetic axis position scanning experiment was performed to search an optimized experimental configuration. Because at the former period of the 8th experimental campaign the CW gyrotron has not been available for plasma experiment, #5 gyrotron was used for the experiment. The $R_{ax}$ was scanned from 3.43 m to 3.75 m with shot-by-shot manner keeping the magnetic field $B_{ax}$ as 1.5 T to keep on-axis second harmonic resonance condition. Fundamental resonance condition on axis is not realized for $R_{ax}$ over 3.43 m. Under the limitation of the highest coil current, setting $R_{ax}$ larger results in decreasing of the maximum value of $B_{ax}$.

Plasma start-up was supported by 82.7 GHz power of 300 kW, 50 ms and 84 GHz power of 240 kW, 600 ms injected from the waveguide antenna for CW power injection, sustained the plasma. During the $R_{ax}$ scanning experiment, other experimental conditions such as gas puffing and ECH power were kept constant. The result is summarized in figure 3 which plots the maximum stored energy during the 600 ms pulse for each $R_{ax}$ position. It shows that setting $R_{ax}$ of 3.6 m results in the highest stored energy, not around $R_{ax}$ of 3.53 m. The main reason would be a setting error of the waveguide antenna though some portion of the result can be attributed to the change of plasma volume by $R_{ax}$ shift (plasma volume is maximum, 29.3 m$^3$ with $R_{ax}$=3.6 m while that with 3.5 m is 24.2 m$^3$).

The 756 second discharge was performed with $R_{ax}$=3.5 m and $B_{ax}$=2.93 T. The 3 T fundamental resonance surface was positioned slightly (about 4 cm) inside of the torus, in other words, closer to the inner helical coil. High field configurations were also tried and compared with the results of 2nd harmonic conditions. The maximum stored energy obtained with the high field conditions were about 14 kJ for both $R_{ax}$=3.55 m, $B_{ax}$=2.86 T and $R_{ax}$=3.6 m, $B_{ax}$=2.79 T while the maximum in the 2nd harmonic condition was 31 kJ with $R_{ax}$=3.6 m, $B_{ax}$=1.5 T. Also in the high field configurations setting $R_{ax}$ at 3.6 m should be better for the beam to aim at the magnetic axis, while setting the magnetic axis position outside results in decreasing the magnetic field on the axis. The experimental results in the
high field configuration cases would be explained by the compromise of these contradictory conditions.

3.2. Discharge over one hour with ECH

Referring to the result of the configuration optimizing experiment, the trial of the CW plasma sustainment was performed with $R_{ax}=3.6$ m and $B_{ax}=1.5$ T. For the long pulse discharge, data acquisition settings such as sampling time were changed so that the data could be processed for 3932 seconds (30 ms sampling, 128 kword).

At first, using several shots of duration up to a few hundred seconds, optimized gas flow rate was searched and gradual increase with an increment step of 0.0002 Pam$^3$/s for every 5 seconds up to 0.003 Pam$^3$/s was determined. Then the discharge #56068 was started with this gas fueling scenario. Plasma start-up was supported by 82.7 GHz power of total 420 kW, 300 ms pulses and the CW power sustained the plasma. Time traces of ECH power monitor output, gas flow rate, line averaged electron density and electron temperature measured with ECE system are plotted in figure 4. Until about 1900 seconds, density was kept nearly constant at $1.5 \times 10^{19}$/m$^3$ though the gas flow rate was controlled sometimes to compensate gradual decrease of the density.

![Figure 4](image)

**Figure 4.** Time traces in the 3900 second discharge. Top column is a plot of injection power evaluated from power monitor on a miterbend, the second: gas flow rate, the third: line averaged electron density and the bottom: electron temperature at averaged minor radius of 0.136 measured with ECE system.
At about 1900 seconds, gas flow rate was increased for trial of plasma sustainment at higher density. However, increase of gas flow rate up to 0.006 Pam$^3$/s caused uncontrollable density increase up to $3.2 \times 10^{18}$/m$^3$ then the flow rate was decreased again. Three more times increasing the density was tried. However at each trial rapid density increase occurred and keeping the density at moderate level could not accomplished with the ECH port through power of 110 kW.

From the hydrogen (H) molecular gas flow rate, supply rate of H atoms can be evaluated. By time-integration of the atom supply rate, total number of H atoms supplied by gas fueling is calculated. Also, total number of H atoms pumped by pumping system of vacuum vessel is evaluated using pumping speed (730 m$^3$/s) and pressure inside the vessel (around $1 \times 10^5$ Pa during the discharge, gradually decreasing). Those values are plotted against time in figure 5. The difference between the atom numbers of supplied and pumped is considered as the number of wall-pumped atoms. The number of supplied atoms is much larger than that of pumped, and it can be seen that the wall-pumping is not saturated for 3900 seconds. The atom supply rate for the discharge was much lower than that of usual LHD experiment, typically around $10^{22}$/s. So even for the 3900 second discharge, total amount of supplied atoms is not larger compared with those of short pulse experiments. Large excess of gas flow rate than pumping rate has been observed for short pulse experiments up to a few tens of seconds on LHD [7, 8].

![Figure 5. Hydrogen atom supply rate, total number of H atoms supplied by gas fueling and total number of H atoms pumped by pumping system of vacuum vessel are plotted against time. The difference between the atom numbers of supplied and pumped is considered as the number of wall-pumped atoms.](image)

On the other hand, even though the wall-pumping is not saturated, the way of response of density against the gas flow rate seems to be changed during the discharge. For examples, while the gas flow rate was kept constant, the density started decreasing at 1600 seconds. Though the gas flow rates were set at the same value, the density around 1600 seconds was kept nearly constant or gradually decreasing while that around 3300 second was rapidly decreasing. Though the gas flow rate around 3500 seconds was lower than that around 2400 seconds, the density was increasing at around 3500
seconds while that around 2400 seconds was slightly decreasing. So far there is no systematic explanation for the behavior but the data from this long pulse discharge and future long pulse discharges will contribute to understanding of wall pumping and particle balance, and now investigation is under way.

Limited by available data acquisition time, operation of CW gyrotron was stopped at 3900 seconds.

3.3. Stability of gyrotron and transmission line during long pulse operation
During the 3900 second discharge, gyrotron operation was quite stable and there was no sign which indicated a difficulty for further long time operation. Gyrotron operational parameters such as cathode voltage, collector current, ion pump current which is proportional to the pressure inside gyrotron, body voltage, body current are plotted in figure 6. Increments of coolant temperature of gyrotron body, MOU and gyrotron output window are also plotted. All the parameters are kept nearly constant until the end of the discharge.

Pressure inside the waveguide measured at about middle point of the transmission line, at MOU and at the head of a turbo pump which pumps the evacuated duct for waveguide evacuation are plotted in figure 7. The interlock threshold level against pressure increase was set at 1.3 Pa and the pressure during the discharge at each position was kept in much lower level than the threshold. Temperature increments of several positions of the transmission line such as miterbends, edge of vacuum window disc set close to LHD show saturation except the waveguide antenna inside the LHD vacuum vessel which has no cooling channel. For water cooling of the transmission line of about 72 m, the line was divided into 3 sections and at each section a cooling channel was set in series. The difference in saturated temperature of miterbends comes from the series connection of cooling channel.

![Figure 6](image)

**Figure 6.** Time traces of parameters concerning with gyrotron operation. All the voltages, currents and temperature increments of coolant are kept nearly constant until the end of the discharge.
Figure 7. Time traces of (a) pressure measured at some points on the transmission system and (b) increment of temperature of several positions of the transmission line. All the values are saturated and kept in safe level except for the temperature of waveguide antenna which has no cooling channel.

4. Problems remain to be solved and future plans

For further long time plasma sustainment with higher electron temperature and density, increase of injection power with lower transmission loss, and cooling of waveguide antenna or mirror antenna are key issues. Power reflection from the transmission line to CW gyrotron must be minimized for stable operation with higher output power. Waveguide filter inserted next to the MOU as seen in figure 1, which removes unexpected mode other than HE_{11} mode, works for this purpose. Soon a miterbend with filtering function will be tested. If it works, exchanging miterbends to those would contribute to higher gyrotron output power and decreasing temperature increase of waveguides.

Also a plan of evacuation of existing inner diameter 88.9 mm waveguide is under way. Because transmission loss decreases in reverse ratio to cube of diameter, using waveguide with larger diameter will contribute to decreasing the transmission loss. Though the first trial of evacuating 88.9 mm waveguide will be performed for other gyrotron of pulse operation, this will useful for CW power transmission in the future.

As for cooling of injection antenna inside LHD vacuum vessel, from the view point of engineering, cooling of mirror antenna is much easier than setting cooling structure on the long, not simple shaped taper waveguide. Also, injecting focused beam from movable mirror is effective for higher plasma parameter and it expands experimental flexibility.

5. Conclusions

By enforcement of pumping and cooling of CW power transmission line for ECH on LHD, a discharge over one hour, 3900 seconds, was achieved successfully. This result clearly shows the potential of continuous plasma sustainment of LHD having super conducting magnets. Gyrotron operation and state of transmission line except temperature of a waveguide antenna for power injection
to LHD were quite stable and there was no sign which indicated a difficulty for further long time operation. For further long time plasma sustainment and higher power injection, cooling of injection antenna inside LHD vacuum vessel and decreasing transmission loss are key issues.

References
[1] Motojima O et al. 1999 Phys. Plasmas 6 1843
[2] Aymar R 2001 Fusion Eng. Des. 55 107
[3] Kubo S et al. 2005 Plasma Phys. Control. Fusion 47 A81
[4] Ohkubo K et al. 2004 Proc. 20th IAEA Fusion Energy Conf. FT/P7
[5] Shimozuma T et al. 2001 Fusion Eng. Des. 53 525
[6] Murakami S et al. 2002 Nucl. Fusion 42 L19
[7] Miyazawa J et al. 2003 J. Nucl. Mater. 534 313
[8] Miyazawa J et al. 2004 Nucl. Fusion 44 154