Progress of Long Pulse Discharges by ECH in LHD

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Abstract. Using ion cyclotron heating (ICH) and electron cyclotron heating (ECH), or solo ECH, trials of steady state plasma sustainment have been conducted in the superconducting helical/stellarator device LHD (Ida K *et al* 2015 *Nucl. Fusion* **55** 104018). In recent years, ECH system has been upgraded by applying newly developed 77 and 154 GHz gyrotrons. A new gas fueling system applied to the steady state operations in the LHD realized precise feedback control of line average electron density even when the wall condition varied during long pulse discharges. Owing to these improvements in the ECH and the gas fueling systems, a stable 39 minutes discharge with the line average electron density n_{e_ave} of 1.1×10^{19} m^{-3}, the central electron temperature T_{e0} of over 2.5 keV, and the central ion temperature T_{i0} of 1.0 keV was successfully performed with ~350 kW EC-waves. The parameters are much improved from the previous 65 minutes discharge with n_{e_ave} of 0.15×10^{19} m^{-3} and T_{e0} of 1.7 keV, and the 30 minutes discharge with n_{e_ave} of 0.7×10^{19} m^{-3} and T_{e0} of 1.7 keV.

1 Introduction

The Large Helical Device (LHD) [1−3] in the National Institute for Fusion Science (NIFS) is furnished with superconducting coils and has a great advantage in stable and long pulse plasma sustainment. In contrast to tokamaks, the magnetic field configuration for plasma confinement in the LHD is completely generated by superconducting helical and poloidal coils so that excitation of toroidal plasma current is not required. Therefore, the LHD is suitable for performing investigations on subjects such as heat removal and plasma-wall interaction, which require stable long pulse discharges without the difficulty of plasma current sustainment. Those investigations are necessary and profitable for future steady state operation (SSO) up to 1000 s planned in the international thermonuclear experimental reactor (ITER) [4].

Intensive studies on long pulse discharges up to 1 hour have been investigated by using ion cyclotron heating (ICH) with electron cyclotron heating (ECH) in LHD [5−8]. So far, as the most successful achievement, a 48 minutes discharge with n_{e_ave} of 1.2×10^{19} m^{-3}, T_{e0} and T_{i0} of 2 keV was performed with 940 kW ICH and 240 kW ECH [3, 8]. Figure 1 shows a summary of the achievements of the long pulse discharges longer than 5 min. in n_e - T_{e0} parameter space obtained in three major long pulse tokamaks: TRIAM-1M [9], EAST [10], and Tore Supra [11], and the several discharges in the LHD. The Tore Supra tokamak achieved the highest parameter but the pulse duration time T_p was ~6 min. On the other hand, as a stellarator, the LHD plasma is excellent at T_p, and the plasma parameter shows significant improvement from the former data (purple points) to the recent data (red points). Such ITER-oriented investigation plans using long pulse operations of ICH and lower hybrid current drive systems up to 1000 s are ongoing as the WEST project [12].

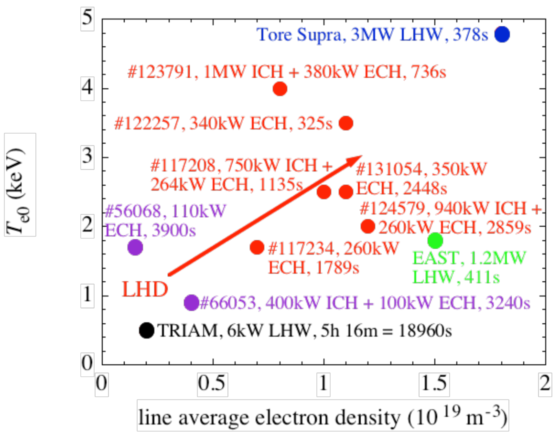

Figure 1. A summary of the achievements of the long pulse discharges longer than 5 min. in n_e - T_{e0} parameter space obtained in the major long pulse devices. The parameter of the LHD plasmas shows significant improvement from the former data (purple) to the recent data (red).

In addition, long pulse discharges sustained with the ECH only have been investigated in LHD [13−16], because ECH is considered as the unique and most reliable heating technique for the future fusion reactors. Development of the high power EC-wave oscillator tubes, gyrotrons, have made a fine progress [17]. The requirements from the ITER: frequency of 170 GHz, output power of > 1 MW, operation time of > 1,000 s, and oscillation efficiency of > 50 % have been achieved already [18]. ECH power injection antennas can be placed apart from plasmas, avoiding intense neutron flux from burning plasmas, and localized power deposition by ECH is suitable for plasma pressure and/or current profile control for suppression of MHD activities. Also, the heating mechanism of ECH does not depend on the gas species while that of ICH strongly depends on minority/majority gas species and their ratio. Experiences of long pulse discharges by ECH using hydrogen/helium/deuterium gasses can contribute to the investigation of the dependence of the wall condition/pumping on the gas species.

In this paper, research and experimental activities on the topics of long pulse discharges by ECH which have been performed in the LHD are described as follows. Section 2 describes the LHD, the ECH system, and improvements in the ECH system conducted in recent years. Significant progress in the long pulse discharges using EC-waves is introduced in Sec. 3. Finally, the contents of this paper are summarized in Sec. 4.

2 ECH system on the LHD and its upgrade

2.1 LHD

The LHD is a helical device with toroidal period number m = 10 and polarity l = 2. The magnetic field structure including rotational transform for plasma confinement is completely generated by external superconducting magnets such as a pair of helical coils and three pairs of poloidal coils. The magnetic axis position R_{ax} of LHD plasmas can be adjusted in the range from 3.42 to 4.1 m. In the typical case of R_{ax} = 3.6 m, the averaged minor radius is 0.58 m, the plasma volume is 30 m^3, and the maximum magnetic field at the magnetic axis averaged in the toroidal direction, B_t, is 2.85 T. The vacuum vessel made of stainless-steel (SUS-316L) is covered with SUS-316L protecting plates, and the helical divertor plates are made of isotropic carbon graphite.

2.2 ECH system and its recent upgrade

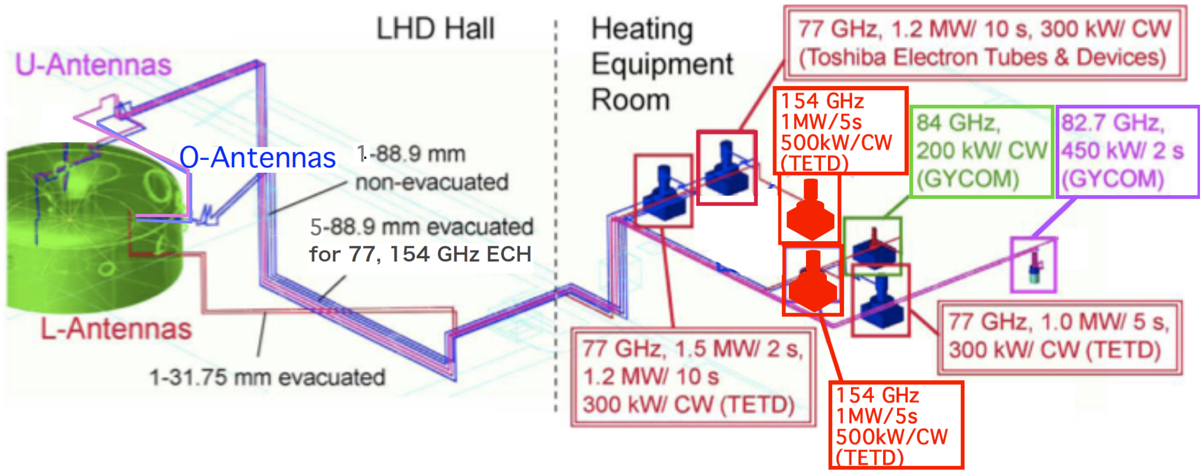

Figure 2. Schematic view of the gyrotrons in the heating equipment room, transmission lines, and LHD in NIFS.

The ECH system in NIFS is furnished with seven working gyrotrons. The oscillation frequencies are 77 (three gyrotrons installed in 2007, 2008, and 2009), 154 (two gyrotrons installed in 2012 and 2014), 84 (1), and 82.7 (1) GHz. The gyrotrons are installed in the heating equipment room as seen in Fig. 2. The gyrotrons and LHD are connected with evacuated waveguide power transmission lines. The length of each transmission line is ~100 m. The fundamental (2nd harmonic) resonance magnetic field of the frequency of 77 (154) GHz is 2.75 T. The 77 and 154 GHz gyrotrons have been newly developed by collaboration with the University of Tsukuba and installed on the LHD ECH system in recent years. For the precise descriptions of the technical and operational subjects of these gyrotrons, including photo of one of them, see references 19−21. Each of the 77 and 154 GHz gyrotrons generates more than 1.0 MW port-through power at pulse operation up to a few seconds.

The antenna systems in a top port (5.5-U for 77GHz#3) and in an equatorial port (2-O) are used for the 77 and 154 GHz power injections. In the 2-O port, four antenna systems (2-OLR for 77GHz#1, 2-OLL for 154GHz#1, 2-OUR for 77GHz#2, and 2-OUL for 154GHz#2) are installed. Figure 3 shows a drawing of mirror sets of four antenna systems.

The upper two antennas, 2-OUR and UL, were newly installed in 2014 corresponding to the increase in the number of gyrotrons, additionally to the previously installed lower two antennas LR and LL. The 2-OUL antenna was designed for power injection from the 154GHz#2 gyrotron. The power injection port for the 77GHz#2 gyrotron was relocated from 9.5-U top port to the 2-O port, using the other new 2-OUR antenna and reconstructing the transmission line in 2014. The EC-wave beams are injected from the lower right side of Fig. 3 and transmitted by the mirrors counting down the numbers of mirrors noted in the figure.

The 77 GHz gyrotrons suffer gradual increases of internal pressure during long pulse operation delivering power to LHD. To mitigate the problem, quasi-steady operation by combination of turning on-off operations of the 77 GHz gyrotrons should be adopted for long pulse experiments. Each

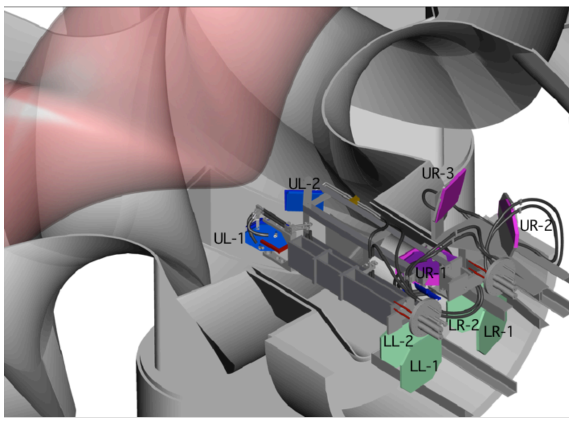

Figure 3. A drawing of mirror sets of four antenna systems installed in the 2-O port.

of the 154 GHz gyrotrons works well for long pulse operation, without noticeable increase of internal pressure contrary to the 77 GHz gyrotrons, due to its short wavelength reducing wave diffraction inside the gyrotron tube and furnished sub-window to remove stray wave power inside the tube.

3 Recent achievements in long pulse discharges by EC-waves

3.1 Quasi-steady 30 min. discharge

A stable 65 min. discharge sustained with 84 GHz, 110 kW EC-wave in 2nd harmonic X-mode polarization was performed in 2005 with the magnetic axis position R_{ax} of 3.6 m and the toroidal average magnetic field on axis B_t of 1.48 T [13, 14]. Due to a lack of sufficient heating power, the electron density was restricted to a rather low level: the line average electron density measured with a millimeter wave interferometer, n_{e_ave}, was ~0.15×10^{19} m^{-3} and the central electron temperature T_{e0} was 1.7 keV in the 65 min. discharge.

In the LHD's 16th experimental campaign in 2012, a quasi-steady 30 min. discharge was performed using two 77 GHz gyrotrons #1 (110 kW, toroidally oblique power injection from 2-OLR port) and #2 (155 kW, perpendicular injection from 9.5-U port), and an 84 GHz gyrotron (130 kW, perpendicular injection from 1.5-L port) of the upgraded ECH system at that time [15, 16]. To mitigate the increase in the gyrotron internal pressure, 77GHz#1 and #2 were operated alternately with 2 min. intervals, while the 84 GHz gyrotron was operated continuously. R_{ax} and B_t were 3.64 m and 2.72 T, respectively. With this configuration, the innermost positions of resonance layers of 77 and 84 GHz waves in fundamental O-mode polarization are about on-axis and at ρ ~0.3, respectively. Each EC-wave beam aimed at these innermost positions. The working gas for the discharge was helium. These experimental conditions were selected for optimization of IC-heating performed before and after the ECH discharges.

Figure 4 shows the waveforms of n_{e_ave} and the ECH injection power P_{inj}, radiation from carbon (CIII), and the radiation power measured with bolometer. Time average n_{e_ave} of ~0.7×10^{19} m^{-3}, much higher than the previous 65 min. discharge, was successfully sustained by time average P_{inj} of 260 kW.

The negative and positive spikes with 2 min. intervals in n_{e_ave} are caused by 2 s overlaps of two power inputs from two 77 GHz gyrotrons at every power switching timing. The temporal increases in heating power result in the temporal decreases in n_{e_ave}, and the decreases are followed by increases due to overshoots caused by the feedback control of the electron density used at that time.

Most of the other positive spikes seen in n_{e_ave} are associated with the spikes in the signal of spectroscopic measurement of CIII, though the intensities of them are not in

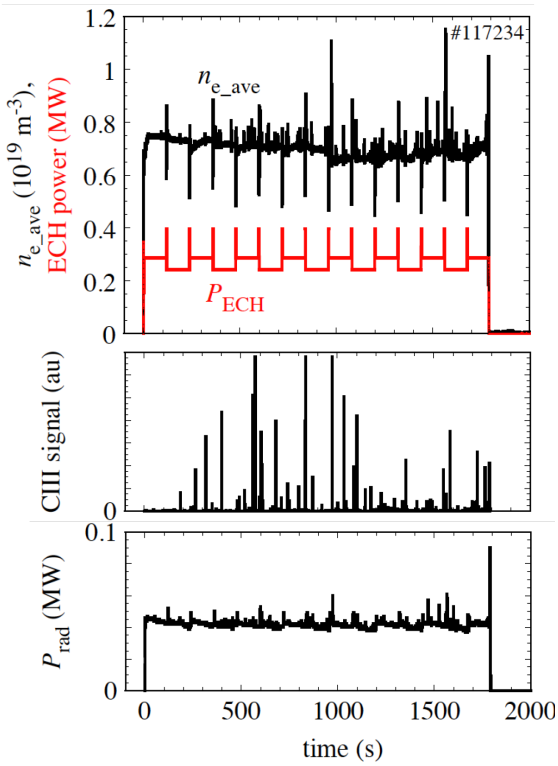

Figure 4. Waveforms of the line average electron density and the ECH injection power, CIII signal, and the radiation power in the 30 min. discharge #117234. Two 77 GHz gyrotrons were operated alternately and one 84 GHz gyrotron was operated continuously.

proportional relation. It is considered that influx of small dusts or flakes of carbon released from the plasma-facing components to the plasmas would cause the temporal increases in n_{e_ave} [7]. The process of accumulation and exfoliation of carbon/iron mixed material on the plasma facing components, and the effects of the mixed material on the wall condition and the wall pumping are intensely investigated [22, 23] using the long pulse discharges performed with ICH and ECH.

Though the spikes of the CIII signal occur frequently, there is no indication of an accumulation of impurities such as carbon and/or heavier elements as seen from the waveforms of the CIII signal and the radiation power.

The central electron temperature T_{e0} is 1.7 keV. The electron temperature and density profiles at 1500 s, near the end of the discharge, are plotted in Fig. 5.

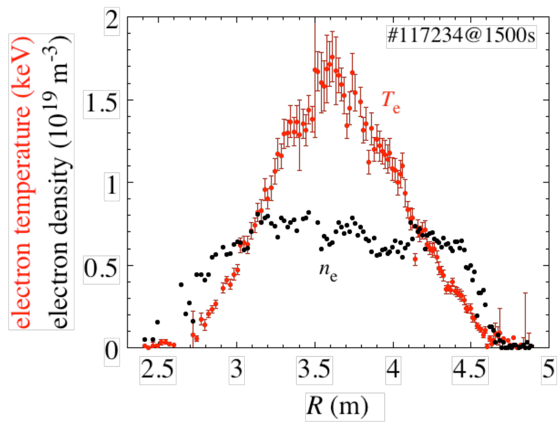

Figure 5. Electron temperature and density profiles measured at 1500 s with Thomson scattering in the 30 min. discharge #117234.

In the series of discharges, sustainment of higher density plasmas such as n_{e_ave} of $\sim 1\times10^{19}$ m^{-3} was attempted. However, no discharge longer than 1 min. could be sustained with this heating power. In these discharges, T_{e0} were lower than 1 keV.

It is feasible that the cause of the termination of the discharge is influx of carbon from the plasma facing components to the plasma. From the poloidal bolometer array measurement, variation of peak position of the line-integrated radiation power from the plasma edge to the inner side was recognized. The timing of the start of the increase in the bolometer signal viewing the plasma edge region matched the timings of the increase in the radiation signal of CIII and the decrease in the edge electron temperature, within the time resolution of 30 ms of the bolometer signal. The time resolution was set rather coarse in the long pulse discharges.

3.2 High performance quasi-steady 39 min. discharge sustained with higher ECH power

During the 16th experimental campaign in 2012, though the 154GHz#1 gyrotron was applied to the LHD experiment in short pulses up to 3 s, it was not used for the long pulse experiments due to a shortage of conditioning of the gyrotron for long pulse operation.

In the 18th campaign in 2014, the new 154GHz#2 gyrotron was applied to the long pulse experiment for the first time, together with the existing 154GHz#1. Using the EC-waves from the 154GHz#1, 154GHz#2, 77GHz#1, and 77GHz#2 gyrotrons, a long pulse plasma sustainment was attempted. The magnetic configuration was R_{ax} = 3.6 m and B_t = 2.75 T. Both of the helium discharges and hydrogen discharges were performed. Precise investigations on the differences between those discharges concerning the plasma performance, plasma-wall interaction, and other topics are currently underway.

The injection powers from the gyrotrons were 120 kW (154GHz#1), 91 kW (154GHz#2), 110 kW (77GHz#1), and 163 kW (77GHz#2), respectively. The beam directions were toroidally oblique, and on-axis 2nd harmonic X-mode (154 GHz) and fundamental O-mode (77 GHz) heatings were aimed. The output power of each gyrotron was kept moderate to ensure stable and safe operation. Two 154 GHz gyrotrons were operated continuously, and two 77 GHz gyrotrons were operated alternately. The time average P_{inj} was about 350 kW in total.

Figure 6 shows the waveforms of the most successful ~39 min. discharge #131059: from top to bottom, P_{inj}, central ion temperature and n_{e_ave} measured with the interferometer, radiation signal from carbon impurity (CIII), and radiation power measured with bolometer. The fed gas was hydrogen. The density n_{e_ave} was kept quite stably at 1.1×10^{19} m^{-3} using a newly developed gas fueling system furnished with mass-flow controllers and a new feedback control scheme for density [24].

Modification of the design of divertor plates, at the edge position of the closed divertor configuration where accumulation of the carbon-majority mixed material layer tend to grow, would contribute to suppress the carbon influx. The mixed material accumulated on the specific divertor plates is considered to be taken away off the plates due to intense heat flux and resultant increase in the surface temperature of the plates [7, 22, 25]. Also in this ECH discharge there is no indication of an accumulation of impurity.

By adjusting the time sequence of the ECH powers, the overlap periods of 77 GHz powers were shortened to ±0.4 s, which also contributed to the stably controlled density. Unfortunately, the Thomson scattering measurement failed in the data acquisition procedure in this discharge.

High speed monitoring of plasmas, vacuum vessel, and in-vessel components is in progress [25]. Figure 7 shows 2-D images at the termination timing 2351 s, or, 39 min. 11 s of the discharge #131059. A CCD camera captured the occurrence of sparks at a divertor area between the humps of helical coils, and intense emission of CIII was seen

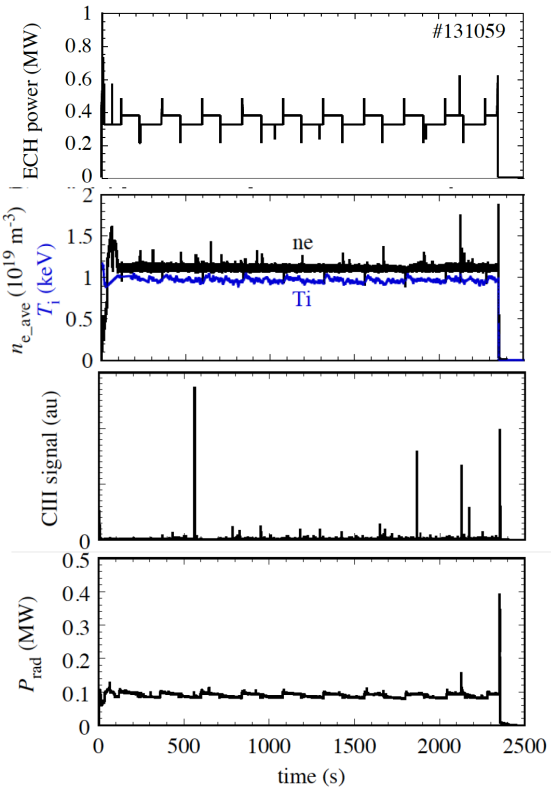

Figure 6. From top to bottom, waveforms of the ECH injection power, central ion temperature and line average electron density, radiation signal from carbon (CIII), and radiation power measured with bolometer obtained in the 39 min. discharge #131059.

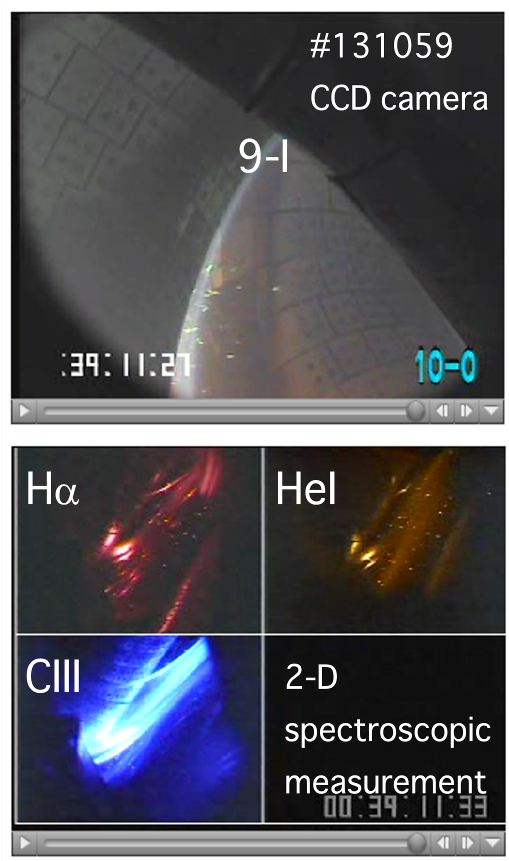

Figure 7. 2-D images by CCD camera and spectroscopic measurements for Hα, HeI, and CIII at the termination timing of the 39 min. discharge #131059.

in the 2-D spectroscopic measurements. Together with the significant increase in the CIII signal at the termination timing, as seen in Fig. 6, it can be concluded that intense and continuous influxes of carbon from around the divertor plates caused the termination.

A discharge #131054 was performed with nearly the same experimental condition and time sequence with that of #131059. The #131054 was sustained for 2448 s, however, the Thomson scattering measurement and the interferometer for the line average electron density measurement each encountered trouble at ~938 s and ~2040 s, respectively. In the discharges #131059 and #131054, the EC-wave power varied depending on the timing and the situation. When sudden increase in the electron density was detected, the EC-wave injection of 247 kW power and 4 s pulse length from the 5.5-U port was triggered in order to suppress the increase in the density and to maintain sustainment of the plasmas. In the discharge #131054, during the two minutes period including 800 s, two 154 GHz (211 kW) and 77GHz#1 (110 kW) waves were applied so that the total power was 321 kW, while during the two minutes period including 900 s, 374 kW was applied by the two 154 GHz and 77GHz#2 (163 kW).

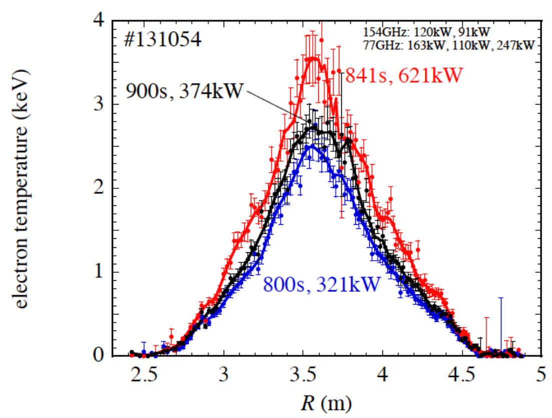

Figure 8. Electron temperature profiles at 800 s with P_{inj} = 321 kW, at 841 s with P_{inj} = 621 kW, and at 900 s with P_{inj} = 374 kW, measured with Thomson scattering in the discharge #131054 which is similar to the 39 min. discharge #131059.

During the 4 s period including 841 s, two 154 GHz, 77GHz#2, and the 77GHz#3 from the 5.5-U port (247 kW) were applied so that the total power was 621 kW. Figure 8 shows the variation of the electron temperature profile corresponding to the variation of the EC-wave power in the discharge #131054. The increase in the heating power results in the increase in T_{e0} and in the widening of the T_e profile, that is, the increase in the heating power results in the sustainment of robust plasmas against impurity influx, and will contribute to the achievement of stable long pulse discharges.

Figure 9 exhibits the progress in the plasma parameters T_{e0} and n_{e_ave} simultaneously achieved in the long pulse ECH discharges sustained longer than ~30 min. in LHD. It is worth noting that about 3 times increase in the heating power results in 6 and 1.5 times increases in n_{e_ave} and T_{e0}, respectively. Here, data obtained with temporally increased power and/or internal transport barrier formation are excluded from the data set.

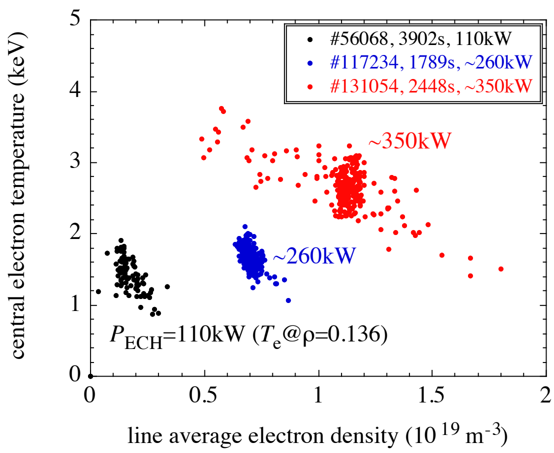

Figure 9. Progress in the central electron temperature and line average electron density achieved simultaneously in the long pulse (>~30 min.) ECH discharges in LHD.

4 Conclusions

In recent years the ECHs system on the LHD has been upgraded by applying 77 and 154 GHz gyrotrons and constructing new antenna systems. The modification of configuration of the closed divertor plates and the improvement of the gas fueling system contributed to suppression of the influx of carbon impurity and to effective control of the electron density. These upgrades and improvements extended the plasma parameter of long pulse ECH discharges in LHD extensively from the former record: n_{e_ave} = 0.15×10^{19} m^{-3} and T_{e0} = 1.7 keV by 110 kW 84 GHz EC-wave for 65 min. established in 2005. In the LHD's 16th experimental campaign in 2012, a quasi-steady 30 min. discharge with n_{e_ave} = 0.7×10^{19} m^{-3} and T_{e0} = 1.7 keV was accomplished by two alternately operated 77 GHz gyrotrons with time average injection power of 130 kW and 130 kW 84 GHz EC-wave, and thus 260 kW in total. In the 18th experimental campaign in 2014, a higher performance plasma with n_{e_ave} = 1.1×10^{19} m^{-3} and T_{e0} = 2.5 keV for 39 min. was successfully achieved by applying the higher power of ~350 kW: 211 kW from the continuously operated two 154 GHz gyrotrons, and 110 kW and 163 kW from the alternately operated two 77 GHz gyrotrons. Here it should be noted that the number of long pulse discharges in the tight experimental schedule of the LHD, especially for the long pulse discharges by solo ECH, are not enough because the long pulse discharges require considerable machine time. Thus, the technique and performance of long pulse discharges might remain a matter of improvement.

To investigate steady state operation with the plasma parameter more relevant to fusion plasmas, increasing the heating power is a key issue. Increasing the output power of each gyrotron in long pulse operation and, ensuring stable long pulse operations of the 77 GHz gyrotrons are necessary.

To prevent terminations of long pulse discharges, suppressions of accumulation and release of the carbon-majority mixed material layer on and from the surface of plasma-facing components would be indispensable. Trial of replacement of some divertor carbon plates to those coated with thin tungsten layer [26] showed noticeable reduction in the accumulation of carbon at the position facing to the tungsten-coated plates. So far, with the limited number of only 6 tungsten-coated divertor plates out of 1,800 carbon plates (0.2 % of the total surface area), no radiation signal of the tungsten from the plasmas of not only long pulse discharges but also short pulse discharges with higher heating power including NBIs has been observed. Preventing plasma termination caused by carbon impurity is a deep issue to be investigated in order to perform further long pulse discharges.

Acknowledgments

The authors would like to express their thanks to NIFS staff for performing the LHD experiments. This work was supported by JSPS KAKENHI Grant Numbers 21560862 and 24561029.

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