Progress of long pulse discharges by ECH in LHD

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Abstract

Using ion cyclotron heating and electron cyclotron heating (ECH), or solo ECH, trials of steady state plasma sustainment have been conducted in the superconducting helical/stellarator, large helical device (LHD) (Ida K et al 2015 Nucl. Fusion 55 104018). In recent years, the 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 the 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 min discharge with a line average electron density \( n_{e_{\text{ave}}} \) of 1.1 \( \times 10^{19} \) m\(^{-3} \), a central electron temperature \( T_{e0} \) of over 2.5 keV, and a 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 min discharge with \( n_{e_{\text{ave}}} \) of 0.15 \( \times 10^{19} \) m\(^{-3} \) and \( T_{e0} \) of 1.7 keV, and the 30 min discharge with \( n_{e_{\text{ave}}} \) of 0.7 \( \times 10^{19} \) m\(^{-3} \) and \( T_{e0} \) of 1.7 keV.

Keywords: plasma, ECH, LHD, steady state, long pulse

(Some figures may appear in colour only in the online journal)

1. Introduction

The large helical device (LHD) [1–3] in the National Institute for Fusion Science (NIFS) is furnished with superconducting coils and has great advantages 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 the 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. These 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 of up to 1 h have been carried out by using ion cyclotron heating (ICH) with electron cyclotron heating (ECH) in the LHD [5–8]. So far, as the most successful achievement, a 48 min discharge with \( n_{e_{\text{ave}}} \) of 1.2 \( \times 10^{19} \) m\(^{-3} \), and \( T_{e0} \) 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 long pulse discharges longer than 5 min in \( n_{e_{\text{ave}}}-T_{e0} \) parameter space obtained in three major long pulse tokamaks: TRIAM-1 M [9], EAST [10], and Tore Supra [11], and the 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 has excellent $T_p$, 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 part of the WEST project [12].

In addition, long pulse discharges sustained with solo ECH have been investigated in the LHD [13–16], because ECH is considered to be unique and the most reliable heating technique for future fusion reactors. Development of high power EC-wave oscillator tubes, gyrotrons, has made good progress [17]. The requirements of the ITER: frequency of 170 GHz, output power of $>1$ MW, operation time of $>1000$ s, and oscillation efficiency of $>50\%$ have already been achieved [18]. ECH power injection antennas can be placed away 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 magnetohydrodynamics 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. Experience 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 topic of long pulse discharges by ECH that 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 long pulse discharges using EC-waves is introduced in section 3. Finally, the contents of this paper are summarized in section 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 a 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 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, $B_0$, 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

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 figure 2. The gyrotrons and the LHD are connected by evacuated waveguide power transmission lines. The length of each transmission line is ~100 m. The fundamental (second harmonic) resonance magnetic field of frequency 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 a precise description of the technical and operational subjects of these gyrotrons, including a photo of one of them, see [19–21]. Each of the 77 and 154 GHz gyrotrons generates more than 1.0 MW port-through power at pulse operation of 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, adding 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 the 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 figure 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 a combination of turning on–off operations of the 77 GHz gyrotrons should be adopted for long pulse experiments. Each of the 154 GHz gyrotrons works well for long pulse operation,

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**Figure 1.** A summary of the achievements of long pulse discharges longer than 5 min in $n_e-T_{ei}$ 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).
without noticeable increase of internal pressure, in contrast to the 77 GHz gyrotrons, due to their 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 using EC-waves

3.1. Quasi-steady 30 min discharge

A stable 65 min discharge sustained with a 84 GHz, 110 kW EC-wave in second harmonic X-mode polarization was performed in 2005 with a magnetic axis position $R_{ax}$ of 3.6 m and a 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 $\sim 0.15 \times 10^{19} \text{ m}^{-3}$ 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 the 2-OLR port) and #2 (155 kW, perpendicular injection from the 9.5-U port), and an 84 GHz gyrotron (130 kW, perpendicular injection from the 1.5-L port) of the upgraded ECH system at that time [15, 16]. To mitigate the increase in the gyrotron internal pressure, 77 GHz gyrotrons #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 the resonance layers of 77 and 84 GHz waves in fundamental O-mode polarization are about on-axis and at $\rho \sim 0.3$, respectively. Each EC-wave beam was 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 a bolometer. A time average $n_{e, ave}$ of $\sim 0.7 \times 10^{19} \text{ m}^{-3}$, 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 proportional relation. It is considered that the influx of small dusts or flakes of carbon released from the plasma-facing components to the plasmas would cause temporal increases in $n_{e, ave}$ [7]. The process of accumulation and exfoliation of the 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 figure 5.

In the series of discharges, sustainment of higher density plasmas such as an $n_{e\text{ ave}}$ of $\sim 1 \times 10^{19} \text{ m}^{-3}$ 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 30 min discharge is the influx of carbon from the plasma facing components to the plasma. From the poloidal bolometer array measurement, variation of the 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 timing 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 coarsely 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 154 GHz#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 154 GHz#2 gyrotron was applied to the long pulse experiment for the first time, together with the existing 154 GHz#1. Using the EC-waves from the 154 GHz#1, 154 GHz#2, 77 GHz#1 and 77 GHz#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 investigation of 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 (154 GHz#1), 91 kW (154 GHz#2), 110 kW (77 GHz#1), and 163 kW (77 GHz#2), respectively. The beam directions were toroidally oblique, and on-axis second 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 $P_{\text{inj}}$ was about 350 kW in total.

Figure 6 shows the waveforms of the most successful ~39 min discharge #131059: from top to bottom, $P_{\text{inj}}$, central ion temperature and $n_{e\text{ ave}}$ measured with an interferometer, radiation signal from the carbon impurity (CIII), and radiation power measured using a bolometer. The feed gas was hydrogen. The density $n_{e\text{ ave}}$ was kept quite stable at $1.1 \times 10^{19} \text{ m}^{-3}$ 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 the suppression of the carbon influx. The mixed material accumulated on the specific divertor plates is considered to be flaked off the plates due to the 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 2D images at the termination timing of the discharge \#131059. A CCD camera captured the occurrence of sparks at the divertor area between the humps of helical coils, and intense emission of CIII was seen in the 2D spectroscopic measurements. Together with the significant increase in the CIII signal at the termination timing, as seen in figure 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 conditions and time sequence as 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 difficulty 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 a 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 minute 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 minute period including 900 s, 374 kW was applied by the two 154 GHz and 77GHz#2 (163 kW). 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 an increase in $T_e$ 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 $n_{e\text{ ave}}$, simultaneously achieved in the long pulse ECH discharges sustained for longer than ~30 min in the LHD. It is worth noting that about a 3-fold increase in the heating power results in 6 and 1.5 times increases in $n_{e\text{ ave}}$ and $T_{e0}$, respectively. Here, data obtained with temporally increased power and/or internal transport barrier formation are excluded from the data set.

4. Conclusions

In recent years the ECH system in the LHD has been upgraded by applying 77 and 154 GHz gyrotrons and constructing new antenna systems. The modification of the configuration of the closed divertor plates and the improvement of the gas fueling system has contributed to the suppression of the influx of carbon impurity and to the effective control of the electron density. These upgrades and improvements extended the plasma parameter of the long pulse ECH discharges in the LHD extensively from the former record: $n_{e\text{ ave}} = 0.15 \times 10^{19} \text{ m}^{-3}$ and $T_{e0} = 1.7 \text{ keV}$ 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 $n_{e\text{ ave}} = 0.7 \times 10^{19} \text{ m}^{-3}$ and $T_{e0} = 1.7 \text{ keV}$ was accomplished using 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 $n_{e\text{ ave}} = 1.1 \times 10^{19} \text{ m}^{-3}$ and $T_{e0} > 2.5 \text{ keV}$ 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 an area for improvement.

To investigate SSO with a 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 operation of the 77 GHz gyrotrons are necessary.

To prevent terminations of long pulse discharges, suppression of accumulation and release of the carbon-majority mixed material layer on and from the surface of plasma-facing components would be indispensable. A trial replacing of some divertor carbon plates with those coated with a thin tungsten layer [26] showed noticeable reduction in the accumulation of carbon at the position facing the tungsten-coated plates. So far, with a limited number of only 6 tungsten-coated divertor plates out of 1800 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 challenging issue to be investigated in order to perform further long pulse discharges.

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