Density Increase during Steady-state Plasma Discharge on the Large Helical Device

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The long pulse plasma discharge with 150 sec operation was achieved in the minority heating method of an ion cyclotron range of frequency (ICRF) heating on the Large Helical Device (LHD). The plasma of \(n_e = 0.5 \sim 1.0 \times 10^{19} \text{m}^{-3}\) and \(T_{e0} = T_{i0} = 1.5 \sim 2.0 \text{keV}\) was sustained with the ICRF heating power of \(P_{RF} = 0.5 \text{MW}\). However the electron density was gradually increased after the half discharge duration from \(n_e = 0.5 \times 10^{19} \text{m}^{-3}\) to \(1.0 \times 10^{19} \text{m}^{-3}\) at the end of the discharge. The observed electron density increase was closely related with a local increase in \(H_e\) intensity near the location of the ICRF heating antenna in the toroidal direction. The maximum temperature in the divertor plates was observed to be 400°C and is explained by calculating orbits of high-energy ions accelerated at the ion cyclotron resonance in front of the ICRF heating antenna.

1. Introduction

The ion cyclotron range of frequency (ICRF) heating was successfully carried out on the LHD employing the inward-shifted magnetic axis as well as installing the divertor plates [1~3]. It is experimentally proved that the optimized heating mode is obtained when the ion cyclotron resonance layer is located at the saddle point of the mod B surface. In this heating mode, minority ions absorb most of the injected RF power to form a high-energy ion tail and its energy is efficiently transferred to the bulk plasma [4]. A trial of a long pulse plasma discharge using an ICRF heated plasma was started in 1999. A long discharge of 68 sec was achieved in the plasma with \(n_e = 1.0 \times 10^{19} \text{m}^{-3}\) and the electron temperature on the axis \(T_{e0} = 2.0 \text{keV}\) with \(P_{RF} = 0.7 \text{MW}\) [5, 6]. The pulse length was limited by the RF generator problem. Then it was gradually prolonged from 68 sec to 127 sec in 2001 [7, 8]. The plasma duration time was seemed to be limited to the electron density increase up to the critical density depending the heating power; however data were not enough to analyze the cause of the density increase.

In this paper a long pulse plasma discharge sustained by ICRF heating only is reported. In Sec.2 the typical plasma discharge of the long pulse operation is described. Reasons limiting the plasma duration are analyzed. Then experimental data are compared with results obtained from an orbit calculation of high-energy ions accelerated at the ion cyclotron resonance layer. Then we summarize.

2. Experimental results

Time evolutions of plasma parameters of the long pulse plasma discharge are plotted in
Fig.1(a); this is the longest plasma discharge so far achieved in the ICRF heated plasma. The plasma with the electron density $n_e=5\sim 6\times 10^{18}\text{m}^{-3}$, and the electron temperature and the ion temperature on the magnetic axis $T_{e0}=T_{i0}=2.0\text{keV}$ was sustained with the ICRF heating power of $P_{RF}=0.5\text{MW}$. After 90 seconds the electron density was observed to be increase with the time accompanied an increase in the radiated power ($P_{rad}$) and to end up to $n_e=1\times 10^{19}\text{m}^{-3}$ with $P_{rad}=250\text{kW}$ before the plasma suddenly disappeared at 150 seconds. The power supply from the RF generator was automatically ceased monitoring an increased reflected-power due to shrinking the plasma radius, when the plasma was collapsed. Besides several plasma parameters time evolutions of the vacuum pressure, the visible emission of H$\alpha$ and HeI normalized by the electron density, and the temperatures increase in the divertor plates and in the vacuum wall are plotted in Fig.1(b): The vacuum pressure is increased by $3\times 10^{-5}\text{Pa}$ from $P_V=2\times 10^{-4}\text{Pa}$ after 90s. The intensity of H$\alpha$ signal (3-O vacuum port, which is near the ICRF heating antenna) was doubled. The temperature of the divertor plate (3-I, 3rd inboard section) was increased to 400$^\circ\text{C}$; as the time constant of the divertor plate is an order of 100s, the measured temperature is almost saturated. On the other hand the vacuum vessel temperature was increased by 3$^\circ\text{C}$; however as the time constant of the vacuum vessel is about 1 hour, the temperature increase was found to be small.

An electron density limit of the ICRF heated plasma was examined in the series of the experiments as shown in Fig.2. Experimental data are plotted in $P_{ICH}(\text{MW})$-$n_e(10^{19}\text{m}^{-3})$ plane. The critical electron density $n_{ecr}$ at the heating power range of $0.2\text{MW}< P_{ICH} <1.5\text{MW}$ is given in the following relation; $n_{ecr}(10^{19}\text{m}^{-3})=1.8P_{RF}(\text{MW})$. When the electron density is increased up to $n_{ecr}$, a radiated power fraction $P_{rad}/P_{RF}$ is proportionally increased with a ratio of $n_e/n_{ecr}$, which is plotted by open circles in Fig.3. When the electron density was increased to $n_e=1\times 10^{19}\text{m}^{-3}$ at 150s as shown in Fig.1(a), $P_{rad}/P_{RF}$ reaches 50% and then the plasma was terminated. In Fig.3 the behavior of $P_{rad}/P_{RF}$ of this long pulse discharge is depicted against the normalized electron density $n_e/n_{ecr}$.

A toroidal asymmetry in H$\alpha$ intensity [9] is plotted with open circles in Fig.4. This is an increased ratio, which is the value at $t=150\text{sec}$ normalized by that at $t=90\text{sec}$. It is easily found that the increase in H$\alpha$ is prominent in 3-O and is about 2.5 times larger than that in 8-O. The ICRF heating antennas are installed at 3.5, that is between 3-O and 4-O. This increase in the H$\alpha$ intensity is assumed to be attributed to the temperature increase in the graphite plates located near 3-O in the toroidal direction. A toroidal asymmetry in the temperature increase in the inboard side divertor plate is also shown in Fig.4. It is found that the temperature increase in the 3-I (No.3 of inboard side divertor plate) is prominent. The 3-I divertor plate of 400$^\circ\text{C}$ is thought to be a candidate of a hydrogen out-gassing source. This local temperature increase is compared with a calculation result of a particle orbit analysis. Two cyclotron resonance layers are separately located on the mod B surface in the employed magnetic configuration. The behavior of high-energy ions started at the cyclotron resonance layer (CRI) was examined using a full orbit calculation code [10, 11] under the RF electric field strength of 20kV/m [12]. About two thousands of high-energy ions with a
low initial energy were started from the upper (referred to as UICR) and the lower (referred to as LICR) ion cyclotron resonance layers in various initial phase difference against the RF electric field. The starting position was selected in 100 positions from R=4.15m to =4.20m (the last magnetic closed surface is at R=4.14m) along the ion cyclotron layer. Some of them hit the divertor plates within one circulation along the toroidal direction. The toroidal distribution of loss energy of high-energy ions is plotted in Fig.5 to compare the measured temperature increase as shown in Fig.4. This orbit calculation suggests that the local temperature increase in divertor plates can be mitigated in two ICRF heating scenarios, in which the ion cyclotron resonance is located on the magnetic axis in the minority heating or is located near the low magnetic field region in the mode conversion heating; there exists no ion cyclotron resonance layer in front of the ICRF heating antennas.

3. Summary

The long pulse plasma with 150sec operation was achieved on the LHD. The plasma of \( n_e=0.5\sim1.0\times10^{19} \text{ m}^{-3} \) and \( T_{e0}=T_{i0}=1.5\sim2.0 \text{keV} \) was produced with the ICRF heating power of \( P_{\text{ICH}}=0.5\text{MW} \). More than 70MJ of the heating energy was injected. However the density increase limited the plasma pulse length. The local temperature increase in the divertor plates is thought to be a cause of the increase in the electron density. It can be understood counting loss energy of high-energy ions accelerated at the ion cyclotron resonance layers on the outer board side of the torus in front of ICRF heating antennas in the orbit calculation.

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References

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Fig. 1(a) Time evolutions of plasma parameters, the electron density $n_e$, the electron $T_{e0}$ and the ion temperature $T_{i0}$ on the magnetic axis and the radiated power $P_{\text{rad}}$ with the He gas puffing rate and the ICRF heating power $P_{\text{RF}}$.

Fig. 1(b) Time evolutions of the vacuum pressure $P_V$, the visible light emission of Hα and HeI, the temperature increase at the vacuum wall and at the divertor plates.

Fig. 2 The relation between the critical electron density and the ICRF heating power.

Fig. 3 The fraction of the radiated power to the ICRF heating power vs. the ratio of the electron density to the critical electron density.

Fig. 4 Toroidal distribution of temperature of the inboard divertor plates and ratio of Hα.

Fig. 5 Toroidal distribution of loss energy of high-energy ions to divertor plates.