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Long Pulse Discharge of MW-ICRF Heated Plasma on the Large Helical Device

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1. Introduction

Achieving a long pulse plasma discharge is one of the main purposes of experiments on the Large Helical Device, (LHD) and attempts have been carried out in every experimental campaign. A long pulse plasma discharge of 1905 sec (with a total input energy of the plasma heating exceeding 1.3J) was achieved at less than 1MW in the 8^{th} experimental campaign, i.e., in 2004, using mainly ion cyclotron range of frequency (ICRF) heating power [1~4]. In the 9^{th} experimental campaign it was carried out with high power ICRF heating of more than 1MW. The plasma was terminated by the gradual density increase accompanying the increase in the radiated power or the sudden penetration of heavy impurity ions, e.g., of Fe; the former problem was overcome by aging graphite tiles with many long pulse plasma discharges up to 1.5MW of heating power, but the latter was an unsolved issue to be overcome in further trials of the long pulse operation with a higher heating power. This paper reports the experimental results for the long pulse plasma discharge using mainly ICRF heating in the 9^{th} experimental campaign on the LHD.

2. Experimental results

2-1. Long pulse duration time in MW-level ICRF heated plasma discharge

In the 9^{th} experimental campaign trials were carried out of the long pulse discharge with more than 1MW of ICRF heating. The time evolutions of plasma parameters of a typical long pulse discharge are shown in Fig.1. A plasma of $n_e=1\times10^{19}m^{-3}$, $T_e\sim T_{io}=1.2\sim1.3keV$ was sustained for 285 s. with an applied power of an ICRF heating power, $P_{ICH}=1.33MW$ and an ECH (Electron cyclotron heating) power, $P_{ECH}=0.11MW$. At almost the middle of the plasma discharge the metal impurity penetrated the plasma accompanied by sparking on the vacuum vessel surface, which would have led to a decrease in the electron temperature with a sudden increase in the electron density and terminated the plasma. In this discharge, however more ECH power of 330kW was injected from another ECH power system for 0.6 s. at 178.4 s., being triggered by the sudden increase in the electron density. The summarized result achieved in the 9th experimental campaign is shown in Fig.2, where the plasma duration time is plotted against the RF heating power (a summation of P_{ICH} and P_{ECH}~0.1MW in every plasma discharge). Open circles were obtained in the 8th campaign, and solid circles and squares in the 9th campaign. It was found that the plasma duration time was extended to a higher RF heating power region in the 9th campaign. Solid squares denote a plasma discharge with an instantaneous ECH power injection and solid circles one without it. It is easily seen that the effectiveness of the ECH power injection is clear in the power range of 1.4 to 1.6MW. However the plasma duration time was decreased with the increase in the total RF heating power, though the plasma operation region was extended. The scaling law of the discharge duration time τ against P_{RF}, $\tau(sec) = 1{,}200\exp\{-P_{RF}(MW)\}$ is plotted using a dotted line.

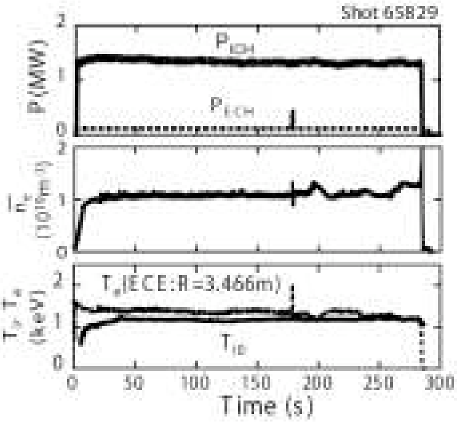

Fig.1 Time evolutions of plasma parameters, P_{ICH} and P_{ECH}, n_e, and T_e and T_i in 1.3MW plasma discharge.

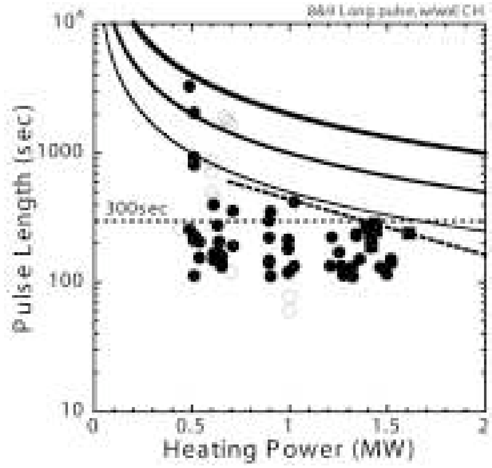

Fig.2 Plasma pulse length vs. heating power.

2-2. Effect of ECH power injection on elongation of plasma duration time

As described above the penetration of heavy impurities resulted in the reduction of the electron temperature and the collapse of the plasma. A trial of the instantaneous ECH power injection (which we call ECH camphor injection) was carried out to restore the electron temperature using the sudden increase in the density as a trigger, as shown in Fig.3. A small amount of heavy metal penetrated at 178.2 sec, but the subsequent density increase was less than 25% (the level set to launch ECH power injection as the trigger threshold) and was not enough to trigger such ECH power injection. Heavier metal penetrated at 178.4 s. accompanied by a sudden increase in the electron density and a reduction of the electron temperature. Then the ECH power was simultaneously injected as shown in Fig.3; the electron temperature was increased to 2.1keV and the electron density was decreased to $0.9\times10^{19}m^{-3}$, as often observed in the high electron temperature plasma discharge [5, 6].

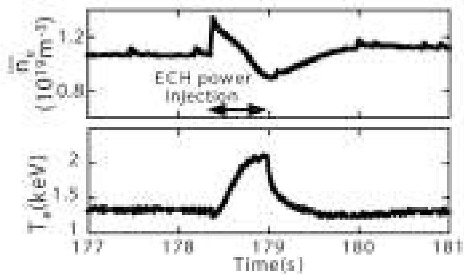

Fig.3 Time evolutions of n_e and T_e before and after ECH power injection at 178.4sec.

The effect of the ECH injection was confirmed in a series of 12 plasma discharges (n_e~1x$10^{19}m^{-3}$ with $P_{ICH}+P_{ECH}$=1.4~1.6MW). The average duration time of the plasma discharge was 136.6 s. without the ECH power injection and 235.6 s. with it. In accordance with t-test of statistics the possibility that ECH injection was effective was deduced to be 93%. However, when the second penetration occurred, further elongation has not been achieved so far even though more ECH power has been injected. It is thought that at the second penetration a larger heavy impurity might be penetrating, and the ECH power of 300kW for 0.6 s. is not enough to restore the plasma. An injection of ICRF heating power up to 1MW for 1~2 sec is planned as a camphol injection in the next (10^{th}) experimental campaign.

2-3. Longest plasma discharge of almost 1 hour

The longest plasma discharge achieved up to the 8^{th} campaign was 31 m. 45 s. (1905 s.) [1-4]. In the 9^{th} campaign the longest plasma discharge achieved was 54 m. 28 s. (3268 s.), as shown in Fig.4. A heating power of 0.6MW was started at the beginning of the plasma discharge. However as sparking was observed several times near both pairs of antennas, the ICRF heating power was reduced and ended up at 0.4MW at the end of the plasma discharge. The injection energy achieved by integrating the RF heating power exceeded 1.6GJ, which is larger than that achieved in the 8^{th} experimental campaign. The plasma was terminated by an impurity penetration at the end of the plasma discharge.

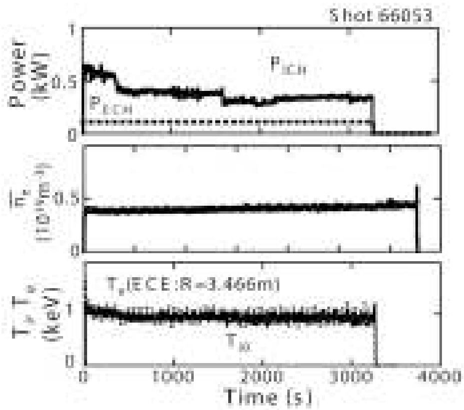

Fig.4 Time evolutions of plasma parameters, P_{ICH} and P_{ECH}, n_e, and T_e and T_i in the longest plasma discharge.

2-4. Poloidal phasing in upper and lower antennas

Two antennas are installed from the upper and the lower LHD vacuum ports and compose a pair antenna. In contrast to usual operations, here we vary the phase difference between them. The phase difference is employed at zero as shown in Fig.5, because the plasma loading impedance is maximized in usual operation. Figure 5 shows the dependence of the temperature increase in the vacuum wall near the divertor plates on the phase difference. Here the temperature increase is normalized by the ICRF heating power radiated from two antennas, which was varied with the phase difference due to the consequential plasma loading resistance. It is easily seen that the temperature increase is reduced in the opposite phase, i.e., in the higher poloidal mode number. It is thought that the wall temperature increase has an intimate relation to the high-energy ions accelerated between the last closed magnetic surface and the ICRF heating antennas in front of them. In the LHD magnetic

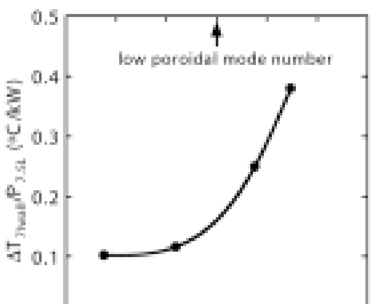

Fig.5 Temperature increase in vacuum wall vs. phase difference between upper and lower antennas.

configuration, unlike in tokamaks, two ion cyclotron resonance layers are located at both the upper and lower antennas in this plasma discharge. A drift orbit of high-energy ions due to the magnetic gradient should be taken into account in further analysis.

2-5. Sparking leading to plasma collapse

During the long pulse plasma discharge sparking was frequently observed especially just before the plasma collapse. It seemed that a heavy impurity such as Fe penetrate the plasma, which was often detected using VUV spectrum [3]. The sparking was found between the divertor tiles, whose position was sometimes different in different plasma discharges. These were near the place where the temperature increase was observed, as shown in Fig.5. The relation between the frequency of sparking (closely related to the plasma duration time) and the poloidal phase control was not examined as well as the toroidal phase control in the 9th experimental campaign: it remains as subject for further experiments. It is now an open question why sparking occurs between the divertor tiles, but there seems to be an intimate relation between wall temperature increase and frequent sparking. A saturation time of divertor plate temperature for plasma heat removal is about 300 s. as shown in Fig.2. According to a rough estimation it can be asserted that long pulse operation of more than 30min. will be achieved at up to 1.3MW heating when the sparking problem is solved.

3. Summary

The steady-state plasma discharge using ICRF heating was successfully carried out on the LHD. The plasma duration time was extended to 285 s. at a heating level of 1.3MW. However it decreased with the heating power. The longest discharge in the 9th experimental campaign was about one hour, i.e., 54min. and 28 s. with an average heating power of 0.5MW and an injected heating energy of 1.6GJ. Instantaneous ECH power injection at the moment of impurity penetration was effective for elongating the plasma duration time. However, sparking occurring on the surface vacuum chamber, accompanying the impurity metal penetration was an issue to be resolved in a long pulse plasma operation in the near future.

Acknowledgement

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