Progress towards RF Heated Steady-State Plasma Operations on LHD by Employing ICRF Heating Methods and Improved Divertor Plates

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Abstract A long pulse plasma discharge experiment was carried out using RF heating power in the Large Helical Device (LHD), a currentless magnetic confining system. Progress in long pulse operation is summarized since the 10th experimental campaign (2006). A scaling relation of the plasma duration time to the applied RF power has been derived from the experimental data so far collected. It indicates that there exists a critical divertor temperature and consequently a critical RF heating power P_{RFcrit}=0.65MW. The area on the graph of the duration time versus the RF heating power was extended over the scaling relation by replacing divertor plates with new ones with better heat conductivity. The cause of the plasma collapse at the end of the long pulse operation was found to be the penetration of metal impurities. Many thin flakes consisting of heavy metals and graphite in stratified layers were found on the divertor plates and it was thought that they were the cause of impurity metals penetrating into the plasma. In a simulation involving injecting a graphite-coated Fe pellet to the plasma it was found that 230μm in the diameter of the Fe pellet sphere was the critical size which led the plasma to collapse. A mode-conversion heating method was examined in place of the minority ICRF heating which has been employed in almost all the long-pulse plasma discharges. It was found that this method was much better from the viewpoint of achieving uniformity of the plasma heat load to the divertors. It is expected that P_{RFcrit} will be increased by using the mode-conversion heating method.

1. Introduction

The Large Helical Device (LHD) is the largest superconducting fusion experiment device in the world and is equipped with one pair of continuous helical coils, i.e., l=2 and m=10 [1]. The magnetic field strength at the magnetic axis R=3.9m is 3T and the average plasma radius is 0.6m. LHD plasma experiments were started in 1998 and many physical and technological topics have been reported over one decade [2-4]. One of the main goals of the LHD project is the steady-state sustainment of a high performance plasma. The magnetic configuration of the LHD has intrinsically a rotational transform and the function of diverting the plasma [5]. Therefore it has outstanding advantages for steady-state plasma discharge operation. The intrinsic helical divertor has four legs extended from the last closed magnetic surface (LCMS) of the LHD plasma. The distribution of particles and the plasma heat load emitted from the LCMS is not uniform, but the distribution of the high plasma heat load is able to be significantly changed by sweeping the magnetic axis R_{ax} by Δ=a few cm (Δ /R_{ax}<1%). This is important because the plasma duration is limited by the metal impurity penetration from the divertor plates due to the increase in the divertor temperature as described later in detail.

On the other hand the long pulse plasma discharges have been carried out in superconducting tokamak devices: A heating energy of 1.1GJ was successfully injected for 6min. in Tore Supra [6] and more than 5hours of plasma discharge was achieved in TRIAM-1M[7].

Steady-state plasma discharge experiments in the LHD were started in the third campaign of 1999. Many experimental data have been obtained up to the 10^{th} campaign of 2006 [8, 9], before the last IAEA conference. Long-pulse plasmas can be easily sustained in the currentless LHD magnetic configuration using RF power, i.e., ion cyclotron range of frequency (ICRF) heating of 2MW and electron cyclotron heating (ECH) of a few hundred kW. The world record, 1.6GJ, was achieved in the input heating energy (a product of plasma duration time and heating power) employing the magnetic axis swing to disperse the plasma heat load [9]. In this paper progress towards the steady state plasma discharge since the last IAEA conference is reported.

In Section 2, we introduce two ICRF heating modes: a minority heating and a mode conversion heating. Recent progress in the steady-state plasma discharge with the minority heating is described in Section 3. In section 4 a typical plasma collapse due to a heavy impurity metal penetration is introduced and the experimental result of externally injecting an Fe pellet to the plasma is described. A preliminary result achieved employing the mode conversion ICRF heating is introduced in Section 5, showing that the temperature increase in the divertor plates can be mitigated in this heating method. Section 6 is a summary of this paper.

2. ICRF Heating Modes

Two ICRF heating methods have been carried out in the long pulse plasma operations. One is a minority ion heating (MIH) and the other is a mode-conversion heating (MCH). Layers of an ion cyclotron resonance, an ion-ion hybrid resonance and an L cut-off are depicted for MIH and MCH in the upper and in the lower column of Fig.1, respectively. Calculated conditions in both cases are as follows. The magnetic field strength at the magnetic axis is 2.75T. The applied radio frequency is 38.47MHz in MIH and 28.4MHz in MCH. The toroidal wave number employed in the RF antenna is $5m^{-1}$. The electron density at the magnetic axis is $1\times10^{19}m^{-3}$ and its profile is the same as that measured in the experiment. The plasma consists of He ions as a majority and H ions as a minority. The ratios of H to He ions are 5% and 50% in MIH and in MCH, respectively. It should be noted that the position of the ion cyclotron resonance layer is located in front of the RF antennas in MIH but not in MCH, as shown

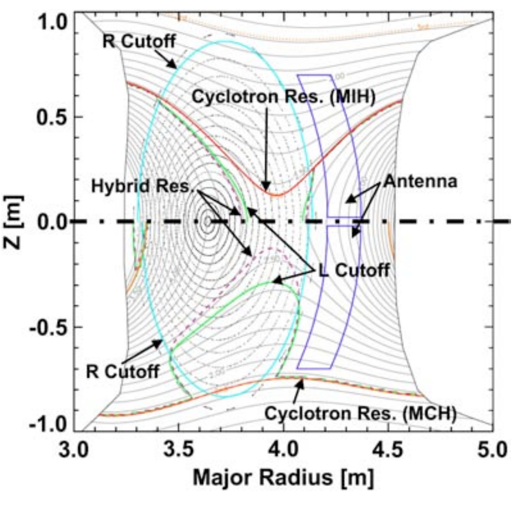

Fig.1 ICRF heating Scenarios of minority ion heating (MIH in upper part) and mode conversion heating (MCH in lower part). Ion cyclotron resonance layer (ICRL) is located in front of antennas in MIH but not in MCH. High energy ions are produced near ICRL in MIH, and electrons are heated near hybrid resonance layer in MCH

in Fig.1. High-energy ions are produced near the ion cyclotron resonance layer in MIH, are trapped in the local minimum B field and directly hit the inner divertor plates [10]. On the other hand in MCH the fast wave is mode-converted to an ion Bernstein wave (IBW) at the ion-ion hybrid resonance layer and the bulk electrons are heated by IBW. The MCH in the LHD is superior to that in tokamaks with regard to mode-conversion efficiency. A full mode-conversion efficiency is possible in the LHD, but it is at most only a quarter in tokamaks because the fast wave approaches the ion-ion hybrid resonance layer from the lower magnetic field side.

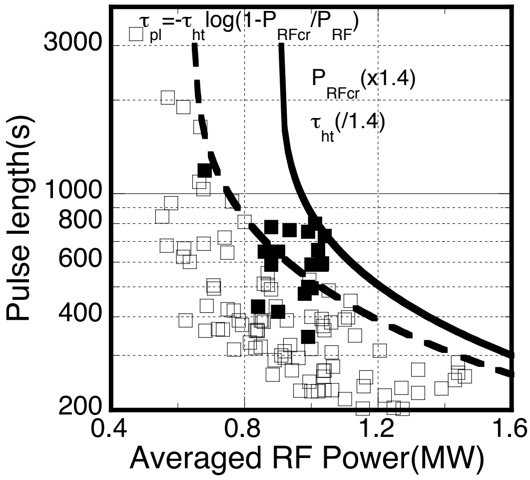

Fig.2 Experimental data so far achieved in pulse length (PL) and RF heating power (P_{RF}): Maximum PLs are fitted to a empirical scaling using t_{ht}, P_{RF} and P_{RFcr}. PL is limited by P_{RFcr}, which is closely related to critical diverter temperature. By replacing divertor plates with improved heat-removal capability, PL is extended to be longer.

3. Extension of Plasma Pulse Length

The experimental data obtained so far are plotted in the pulse length τ_{pl} and the heating power P_{RF} as seen in Fig.2. Open and solid squares are data obtained before and after the last IAEA conference, respectively. In general the time evolution of the divertor temperature T_{div} is expressed as

$$T_{div}(t) = T_{div0} \cdot \left\{ 1 - \exp(\frac{t}{\tau_{hr}}) \right\} \tag{1}$$

Here τ_{hr} is the time constant of the heat removal of divertor plates. T_{div0} is the saturated divertor temperature and is proportional to the heating power, i.e., $T_{div0} \propto P_{RF}$. When the divertor temperature T_{div} reaches a critical temperature of T_{divcr}, where $T_{divcr} \propto P_{RFcr}$ (P_{RFcr} is a critical RF heating power), the pulse length τ_{pl} is determined using the above equation. In the above equation T_{div} and T_{divcr} are converted to P_{RF} and P_{RFcr}, then

$$\tau_{pl} = -\tau_{hr} \cdot \log(1 - \frac{P_{RFcr}}{P_{RF}}) \tag{2}$$

The relation of P_{RFcr} and τ_{hr} is determined from the envelope of the experimental data (open squares). Then P_{RFcr} is determined to be 0.65MW. In accordance with eq.(2) τ_{pl} becomes infinitive in the case of $P_{RF}<P_{RFcr}$. In fact the pulse length reaches half an hour for P_{RF}=0.65MW and one hour for P_{RF}=0.45MW, respectively, as plotted with open squares in Fig.2.

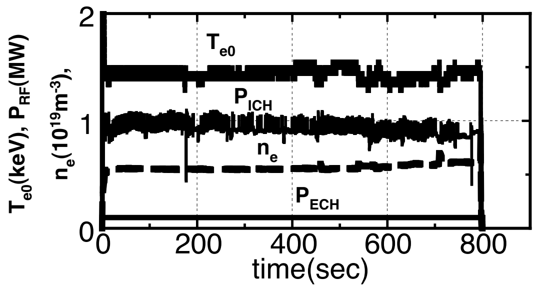

Fig.3 Time evolutions of plasma sustained by high RF power. Plasma of n_e= 0.5~0.6x$10^{19}$$m^{-3}$, T_{e0}=1.5keV is sustained for 800 seconds with P_{RF}=1MW.

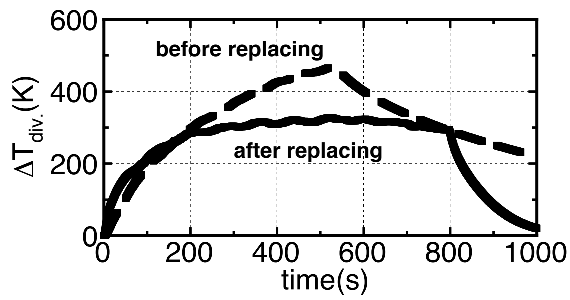

Fig.4 Comparison of divertor temperature increase ($DT_{div.}$) after replacing improved divertor plates with that before. $DT_{div.}$ is saturated within 400s and becomes lower than that before replacing.

After the last IAEA conference it was decided that the experimental target was achieving a long-pulse plasma discharge with a heating power of more than 1MW. One of the solid squares in Fig.2 shows that a plasma duration of 800 sec was achieved with an RF heating power of 1.1MW. In Fig.3 time evolutions of plasma parameters are shown. A plasma of n_e=6x10^{18}m^{-3} and T_{e0}=1.5keV was sustained for 800 seconds with P_{ICH}=1.0MW and P_{ECH}=0.1MW (f=77GHz) at B=2.75T, employing the magnetic axis swing to disperse the plasma heat load to the graphite divertors.

As seen in Fig.2, the solid squares exceed the scaling relation. The extension of the operational area beyond the scaling relation is due to replacing the divertor plates with the improved ones with a better heat removal capability. The distribution of the high plasma heat load among the 2,000 divertors is identified experimentally and theoretically. Among them eighty plates in the inner-horizontal divertors were replaced with new ones before the LHD 11th experimental campaign was started. Figure 4 shows a typical example of the time evolutions of the divertor temperature increase in the same divertor position in similar plasma discharges. The temperature increase in the new divertor was observed to become lower than that in the old one by 30%, as shown in Fig.4. It is also found that the saturating time of the temperature increase is shorter in the improved divertor. Therefore the new scaling relation (taking into account an improved heat-removal time-constant of 0.7τ_{hr} and a new critical RF power of x1.4P_{RFcr}) agrees with the experimental data as shown with the solid line in Fig.2. However, a one hour discharge with P_{RF}=0.8~0.9MW to verify the increase in P_{RFcr} has not been achieved yet.

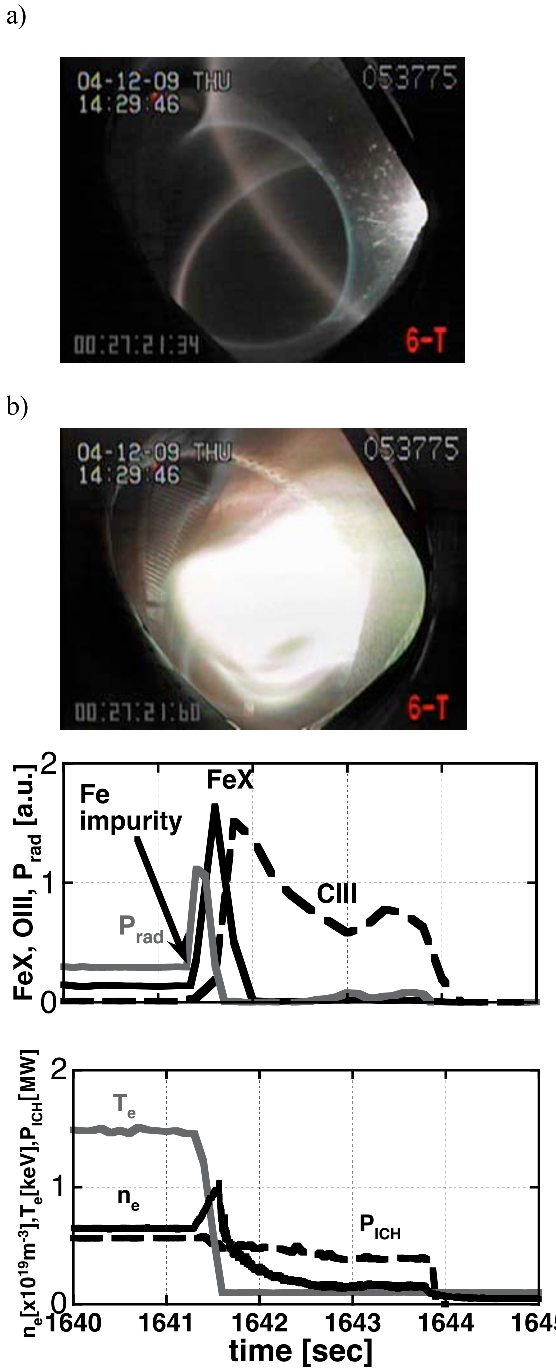

Fig.5 Time evolutions of plasma parameters at plasma collapse (~1641sec) by penetrating Fe impurity in long-pulse plasma operation. a) and b) are pictures at t=1641.34s (just Fe impurity penetrating to the plasma and at t=1641.60s (The intensity of Fe-X line becomes the maximum), respectively.

4. Plasma Collapse by Fe Impurity External Injection

The plasma collapse was frequently observed at the end of long-pulse plasma operation.

There are two main causes: One is out-gassing of hydrogen atoms from the heated divertor plates. However this is easily overcome by using many sequent long-pulse plasma discharges. The other is a metal impurity penetration to the plasma. When the input heating energy exceeds 300~400MJ and the divertor temperature consequently reaches about 500°C, many brilliant objects are observed to penetrate to the plasma. When a sudden increase in the Fe spectrum line is observed at the end of the long-pulse plasma, an increase in the electron density and in the radiated power and a sudden decrease in the electron temperature follow it and lead to plasma collapse.

The phenomena of a typical plasma collapse are shown in Fig.5. In this plasma operation the plasma was normally sustained for 1,641 seconds. At t=1,641.34 seconds the hot impurity (Fe) was observed to start from the inner graphite divertor plates as seen in Fig.5-a). Simultaneously when the intensity of Fe-X line, the decrease in the electron temperature, and increases in electron density and the radiated power were observed as shown in Fig.5. Then the intensity of Fe-X had its maximum at t=1,641.60 seconds (0.26 second later after the time as seen in Fig.5-b). In this case the reflected RF power was not increased, so the interlock system did not trip the RF generator. However the RF power was manually stopped 2 seconds later when we judged that the plasma would not be restored.

We found many thin metallic flakes on the divertor plates when the experimental campaign was over, as shown in Fig.6. They are about 8μm in thickness and have a very fine and stratified structure with thickness of the individual stratified layers ranging from 5 to 100nm. Each layer can be roughly categorized as a high-Z or low-Z material layer. It was found using EDS (Energy dispersive X-ray spectroscopy) mapping data that the high-Z and the low-Z layers are mainly composed of the Fe, Cr and Ni (material of the first wall of the vessel) and by C (divertor

Fig.6 Thin metallic flakes on the graphite divertor plates.

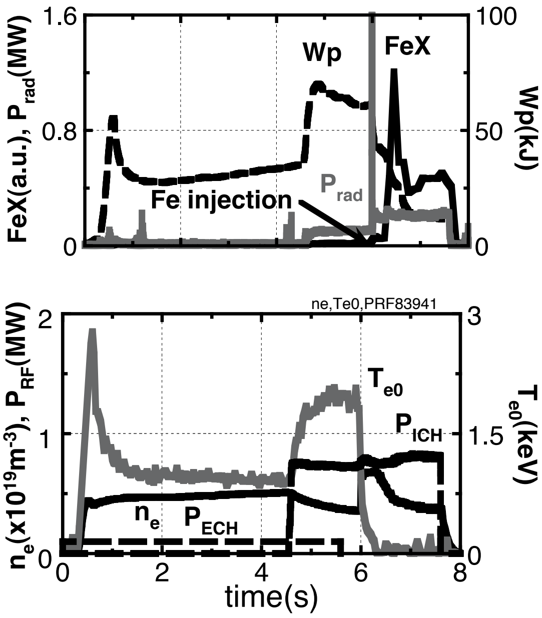

Fig.7 Time evolutions of plasma parameters in plasma collapse experiment by externally injecting Fe pellet.

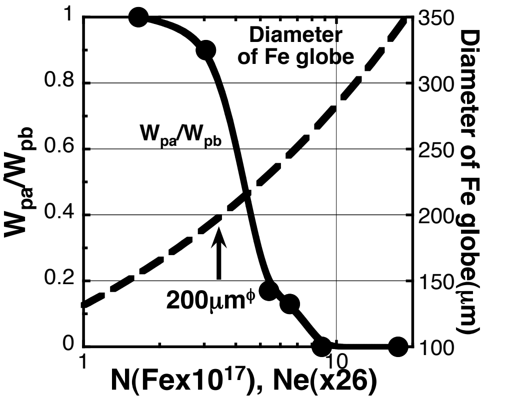

Fig.8 Dependence of plasma collapse on injected ion atomic number: It is evaluated by ratio of plasma-stored energy after to that before injection Fe pellet.

material), respectively. It is thought that the high-Z and the low-Z layers developed during the main plasma discharges and He glow discharges, respectively [11]. A series of experiments was carried out by externally injecting Fe pellets to examine how large the size of Fe impurities must be to lead to the collapse of the ICRF heated plasma. The pellets are encapsulated in a polystyrene polymer ball (1×10^{19} particles of C atoms) to simulate the real metallic flakes on the divertor plates [12]. Time evolutions of plasma parameters are plotted in Fig.7, for the case when a Fe/C pellet with 250 μm in a diameter was injected. Here the initial plasma was produced by ECH (Electron cyclotron heating, f=82.6GHz) power of ~100kW, and an ICRF heating power of 0.7MW was injected to further sustain the plasma. Then the Fe/C pellet was injected at 6 seconds. In Fig 7 a sudden decrease in T_e and a sudden increase in Fe-X are observed, as they are in the long-pulse operation in Fig.5. Here a ratio of W_{pa} to W_{pb} was employed to evaluate the plasma collapse level. W_{pa} and W_{pb} are the stored plasma energy after and before the plasma collapse. In Fig.8 W_{pa}/W_{pb} is plotted against the number of injected Fe atoms. It was found that the Fe atom number of 5×10^{17} particles (that is an Fe sphere with a diameter of 230μm) was the critical number for the plasma collapse. When the metallic flakes (8μm in thickness) of a few mm^2 penetrate to the RF heated plasma, it is thought that the plasma will collapsed.

5. Mode Conversion Heating

In the series of steady-state plasma experiments, a mode conversion heating (MCH) was preliminarily tried instead of minority ion heating (MIH). It is thought that the main cause of the plasma collapse occurring near the end of the steady state plasma is an increase in the temperature on some particular divertor plates, i.e., the inner divertor plates. As described in Sec. 2, there is no ion cyclotron resonance layer in front of the ICH antenna in MCH (as seen in the lower part of Fig.1). It was reported that high-energy ions accelerated there hit locally on the inner divertor plates and therefore the temperature of the divertor plates intensively increased [8, 10]. It is expected that the increase in the divertor temperature can be mitigated in the MCH plasma.

Time evolutions of the plasma parameters of a typical plasma discharge sustained by MCH are shown in Fig.9. A plasma of n_e=0.5~0.75$\times10^{19}m^{-3}$ and T_{e0}=0.5~0.6keV was sustained for 90 seconds with RF heating power of 0.4~0.5MW (including 0.1MW of ECH power). It is found that the RF power suddenly decreased by 0.1~0.2MW a few times during the plasma discharge. This was because the RF power was tripped at one of the ICRF heating antennas with the RF voltage interlock, e.g., V_{RF}=38kV. The frequency applied, f=28.4MHz was lower than that in MIH, i.e., f=38.47MHz in order to move the ion cyclotron layer out from the front of the antenna. Thus, the plasma resistance in MCH for the ICH antenna is lower than that in MIH for two reasons; one is the increase in the imaginary perpendicular wave number in the evanescent region between the antenna and the R-cutoff layer. It is thought that the other reason is that the normalized length of the antenna becomes shorter at the lower frequency and therefore the transformed impedance at the transmission line becomes smaller [13]. Therefore two improvements are proposed for MCH at f=28.4MHz: One is an inserting a pre-stub tuner at the place where the standing RF voltage becomes less than half near the ceramic feed-though, and the other is substituting a new antenna of longer length.

The divertor temperature increase in the MCH plasma is compared with that in the MIH plasma using plasma discharges with the same plasma parameters, heating power and duration time. It is clearly found that the non-uniformity is mitigated and the maximum temperature increase in divertors becomes lower by a factor of 3 in the MCH plasma, as shown in Fig.10. This mainly comes from the fact that there are no accelerated ions accelerated in front of the RF antennas in MCH. On the other hand, it is found that the prominent increase in the divertor temperature on the 3rd and 4th toroidal sections is due to high energy ions produced in front of the the 3.5UL antennas in MIH.

In Fig.2 the extended area for the long pulse operation in the MCH plasma is calculated using eq.(2). The critical power of P_{RFcr} is increased by a factor of three as described in the previous section. As seen in Fig.11 an estimated plasma pulse length τ_{pl} is plotted against P_{RF} with the dotted line. The new P_{RFcr} becomes 1.9MW. Then it is expected that the duration time of a plasma sustained by RF heating power of 1.5~1.6MW will be extended to more than one hour. In addition to this, that the employment of the improved divertor plates will also extend the plasma duration time at the higher RF heating, e.g., P_{RF}=2.5MW. Six antennas have been already installed to the LHD and reliable operations of 0.5MW for 1 hour have been achieved in four RF generators [8]. This year another two RF generators with the same performance as the present four generators have been put into operation. Therefore steady-state plasma operation using the high power of P_{RF}=2.5MW will be tried after this IAEA conference.

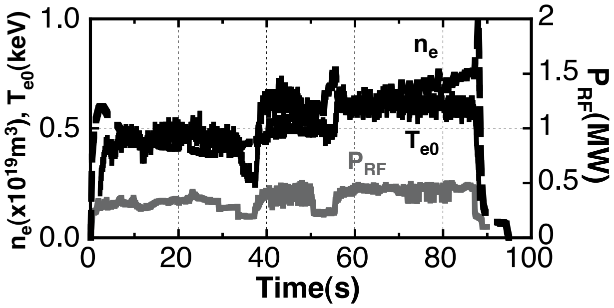

Fig.9 Time evolutions of plasma parameters sustained by mode conversion heating.

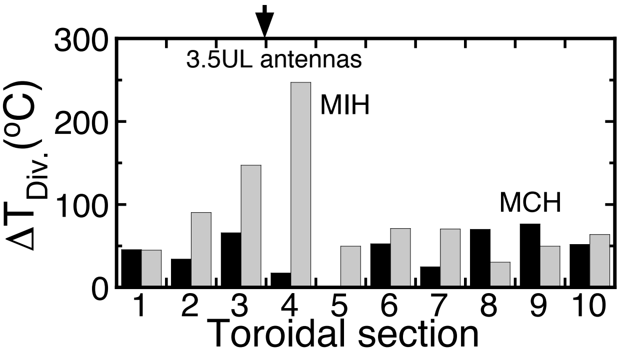

Fig.10 Comparison of divertor temperature increase ($DT_{div.}$) in MCH with that in MIH. The maximum $DT_{div.}$ is 3 times higher than average one in MIH, in which high-energy ions produced in front of antennas locally hit divertor plates. On the other hand $DT_{div.}$ is rather uniform in MCH.

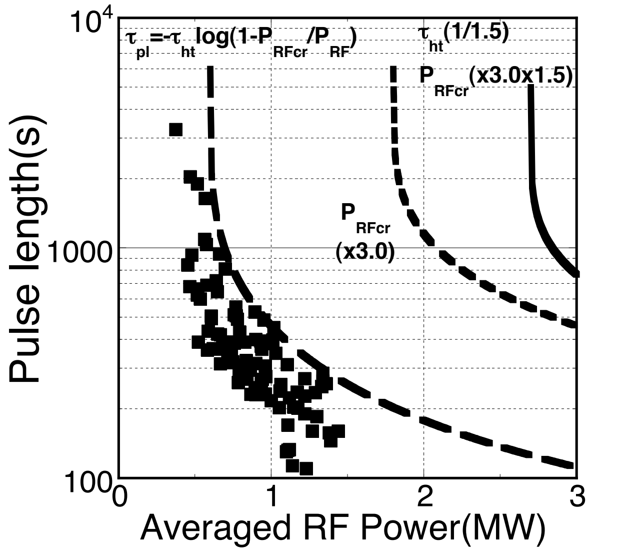

Fig.11 Future parameter range in pulse length (PL) and RF heating power (P_{RF}), when the plasma is sustained by MCH: the critical PRF is increased by a factor of 3. In addition the heat removal capability is increased by a factor of 1.5.

6. Summary

We summarize this paper as follows. The long pulse plasma discharge at the MW level using RF heating power (ICRF heating and EC heating) has been tried for recent years in the LHD. A scaling relation between the plasma pulse length and the applied RF heating power has been deduced from the many data so far obtained. It indicates that the temperature of the divertors is a key parameter limiting the plasma duration time. Taking into account the fact that the divertor temperature is proportional to the RF heating power, it suggests that there exists a critical RF heating power P_{RFcrit}. Before the LHD experimental campaign of 2006, eighty divertor plates at the places with the highest plasma heat load were replaced with new divertor plates with better thermal heat conduction capability. Then the operative area was extended in the plasma pulse length and the RF heating power at the RF power of 1MW level.

In recent years a minority heating method of the ICRF heating has been mainly employed in trials of the long pulse plasma discharge. Another method, mode-conversion heating, was preliminarily tried. It was found that the uniformity in the temperature increase in the divertor plates was better by three times than that in the minority heating method. It is deduced that there is no ion cyclotron resonance layer in front of the antenna in the mode-conversion heating. Therefore it is expected that the pulse length will be able to be extended by employing the mode-conversion heating method in the future LHD long pulse operation.

The main cause of the plasma collapse at the end of the long pulse plasma discharge is identified to be penetrating metal impurities. It was verified that a sudden increase in the Fe-X line in the VUV measurement was observed following the appearance of brilliant metal impurities starting from the inner divertor plates. It is thought that the source of the metal impurities is the thin stratified layers on the divertor plates. They consist of heavy metals Fe, Cr and Ni, and of light metal C. A pellet of Fe with a C coating was injected to the RF heated and sustained plasmas to simulate the metal impurity penetration. It was found that the critical diameter of the impurity pellet was 230μm (5×10^{17} atoms of Fe). This Fe volume is equal to the thin layer (~8μm) of a few mm^2.

Acknowledgements

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