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The Performance of ICRF Heated Plasmas in LHD

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The Performance of ICRF Heated Plasmas in LHD (EX8/4)

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Abstract: An ICRF Heating experiment was conducted in the third campaign of the LHD in 1999. 1.35 MW of ICRF power was injected into the plasma and 200kJ of stored energy was obtained, which was maintained for 5 sec only by ICRF power after the termination of the ECH. The impurity problem was so completely overcome that the pulse length was easily extended to 68 sec at a power level of 0.75 MW. The utility of a liquid stub tuner in steady state plasma heating was demonstrated in this shot. The energy confinement time of the ICRF heated plasma has the same dependences on plasma parameters as the ISS95 stellarator scaling with a multiplication factor of 1.5, which is a high efficiency comparable to NBI. Such an improvement in performance was obtained by applying various measures, including 1)scanning of the magnetic field intensity and minority concentration, 2)improvement of particle orbit due to a shift of the magnetic axis, and 3) reduction of impurities by means of Ti-gettering and the use of carbon divertor plates. In the optimized heating regime, ion heating turned out to be the dominant heating mechanism, different from that of in CHS and W7-AS. Due to the high quality of the heating and the extended parameter range far beyond that of previous experiments, the experiment can be regarded as the first complete demonstration of ICRF heating in stellarators.

1. Introduction

Ion Cyclotron Range of Frequency Heating is presently an established heating scheme in tokamaks though there have been a difficulties where impurity problems ultimately limited the high power injection, causing disruptions of the plasma. Whether ICRF heating works as well in helical systems as in tokamaks has been the subject of increasing attention. The establishment of ICRF heating has special importance in helical systems because it is directly related to the improvement of the orbits of the trapped ions [1]. Since helical systems have advantages over tokamaks with regard to the issues of the current disruption and current drive, study of the high energy particles associated with ICRF heating is one of the most important subjects of current reserch.

ICRF heating in helical systems has rather a longer history than that in tokamaks. It has been investigated in C-stellarator[2], Heliotron-E[3], L-2[4], ATF[5], CHS[6-7] and W7-AS[8],

which report improved performances in recent experiments.
An ICRF heating experiment was first conducted on the Large Helical Device (LHD) in the second campaign conducted in 1998[9-10]. The experiment , however, ended with limited success for the LHD device was in the starting-up phase.
This paper reports results of the experiments carried out in 1999, in which a significant new measure was taken. The experimental set up is explained in section 2. Typical shots are shown in section 3 to summarize the achievements of the third campaign. It is followed by the descriptions of 1) impurity control methods, 2)optimization of the heating regime and understanding of the physics of ICRF heating in LHD configuration reached, and 3)the behavior of high energy particles, which suggests improved particle confinement. In section 4, the effect of an inward shift of the magnetic axis is discussed as a possible explanation of the improved performance of the ICRF heating compared to that in the experiment in the 2nd campaign.

2. Experimental setup
The LHD is a Large Helical Device of Heliotron/Torsatoron type with super conducting l=2/m=10 windings [11-12]. The major radius R and averaged minor radius are 3.75m and 0.5m, respectively. ICRF heating in the LHD has the final goal of injecting 10MW for 10 sec. and 3MW in steady state. Seven years (from 1991 to 1997) were devoted to the R&D in order to support this mission technologically. The results of the R&D are reported in previous publications[13-16]. The hardware developed includes steady state amplifiers[13], water-cooled antennas[13-14], and liquid stub tuners[15].

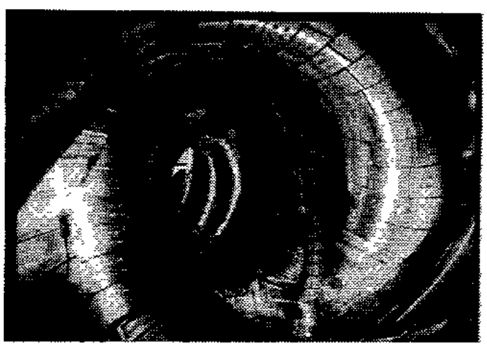

Fig.1 The ICRF antenna used in the experiment. The antenna is located in the toroidal section where the cross section is vertically elongated.

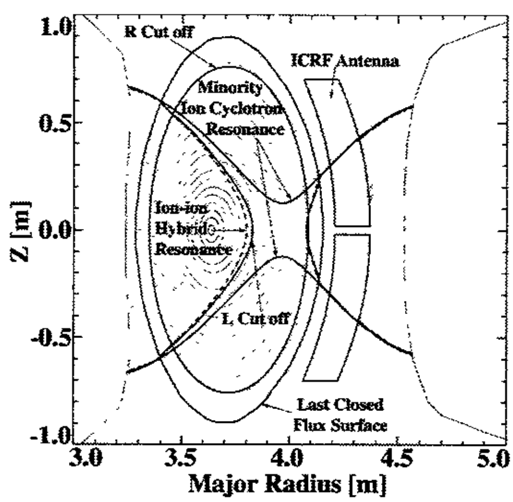

Fig.2 The location of the cyclotron-, two-ion-hybrid-, and cutoff- layers in the optimized heating regime in LHD.

As depicted in Fig.1, the antenna is located in the toroidal section, where the plasma is vertically elongated. The antenna surface is twisted so as to follow the shape of the plasma surface, and its position is variable in order to adjust the distance from the plasma. In the ICRF experiments in the LHD, helium plasma was mainly used and hydrogen minority ions were introduced to facilitate minority heating or two-ion-hybrid regimes. Figure 2 shows the locations of cyclotron, cut-off, and two-ion-hybrid resonance layers by which heating regimes are characterized. They are dependent on $\omega / \omega_{c,H}$, the frequency normalized to the cyclotron frequency on the magnetic axis.

ICRF heating had been attempted in the second campaign. However, the results were not conclusive where BT was set to 1.5 T with a frequency of 25.6MHz, as the LHD itself was in its starting phase [9-10]. ICRF heating was attempted again in the third campaign (1999) and a drastically improved heating performance was obtained [17-20]. The improvement is partly attributed to the increase in the magnetic field, now 2.75 T in most of the experiment. The frequency was accordingly raised from 26.5MHz to 38.47MHz and brought about an enhanced loading resistance. The liquid stub tuner was modified from a phase shifter type to a three-stub tuner type to enhance the over-all stand-off voltage of the tuner. In order to avoid arcing in the transmission line, a voltage limit of 35kV was imposed. The utility of liquid stub tuners was thus demonstrated in experiments.

Another factor to be noted is advances in the condition of the wall. The LHD has a well defined natural divertor which must have played a role in relation to the impurity problem, though a direct comparison of the result without a divertor can not be made. Carbon divertor plates were installed in the third campaign . In Fig. 3, the radial profiles of the radiation power before and after the installation of the carbon divertor plates are compared; the latter has a more hollow profile suggesting that heavy impurity has been eliminated [21].

Titanium gettering was further introduced to reduce oxygen. Since a high density plasma can be sustained by increasing ICRF power and reducingd impurities, the range of possible operational density regime was increased in the third campaign. In turn, higher power can be injected at high density plasma due to the increased loading resistance. It is this virtuous circle that made possible the remarkable improvement in the performance of the ICRF heating in the third campaign. Figure 4 shows how the injected power increased in successive shots after the application of Ti-gettering. The plasma stored energy increased even more, due both to the increased power and to the improved confinement associated with the higher density attained.

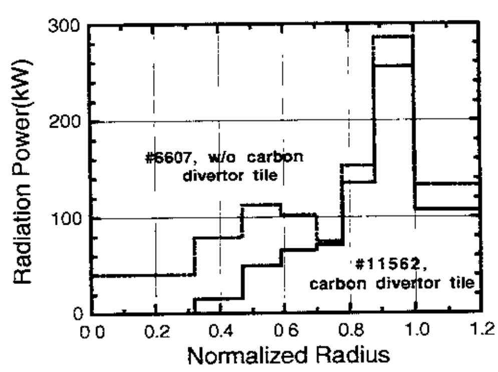

Fig.3 The radiation profiles of with and without carbon divertor plates.

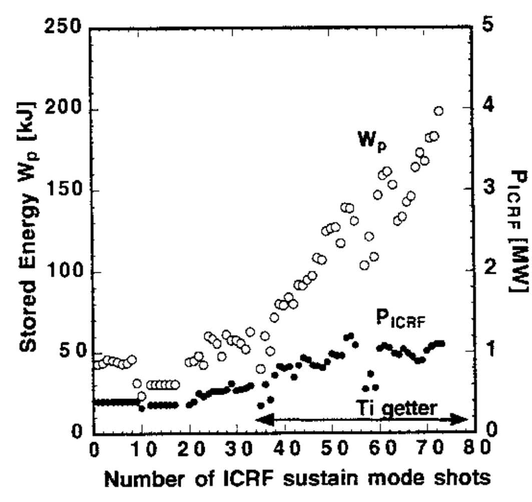

Fig.4 The improvement of the performances of the plasma after Ti-gettering was applied.

3. Experimental Results

In the process of optimization of ICRF heating, a series of experiments was conducted by scanning the magnetic field strength and minority concentration ratio. Due to the unique

magnetic configuration of the LHD, wave propagation and absorption themselves are interesting subjects of investigation.
Since the magnetic field intensity decreases with increasing radius along the larger axis and increases along the shorter axis, the wave can incident both from the low field side and the high field side with respect to the cyclotron layer(see Fig.2). Shown in Figure5 are the locations of the cyclotron layers for various value of the magnetic field intensity. It is easily seen in this figure that a higher fraction of the power is launched from the high field side with a higher value of the magnetic field. The power absorbed by electrons can be determined in the experiment from the decay of the electron temperature. The power absorbed by electrons normalized to the injected power is plotted in Fig. 6 versus the magnetic field intensity. The remaining power is taken to be absorbed mostly by ions. Figure 6 clearly shows that electron heating is dominant with a higher value of the central magnetic field and ion heating takes its place as the magnetic field decreases. It is suggestive that the same paradigm established in tokamaks can be applied to a helical system, where the distribution of the magnetic field is different; one only has to consider a homotopy from one to the other.

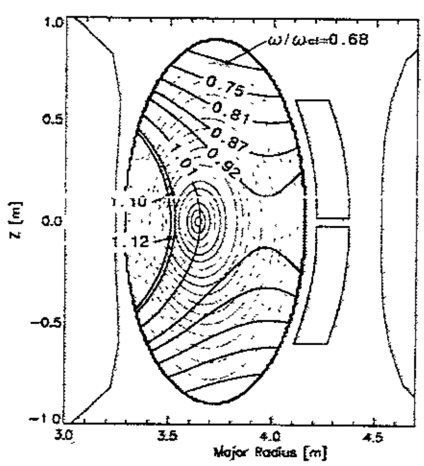

Fig.5 The location of the cyclotron layers: it moves with the magnetic field intensity

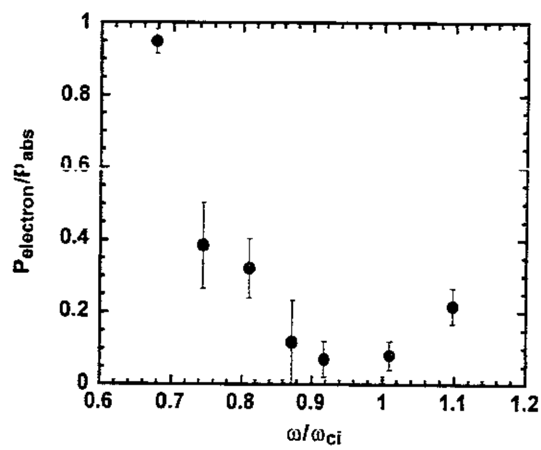

Fig.6 The fraction of the power absorbed by electrons.

The best heating efficiency was obtained with $\omega/\omega_{c.H} = 0.92$, the contour of which is shown in Fig. 5. It was regarded as the optimal heating regime and used in most of the experiments in the third campaign. After these optimization efforts, ICRF power of up to 1.3MW was injected into the plasma with consistent success allowing for various experiments under different conditions. Three typical shots are described in the followings.
1) ICRF self sustained plasma
In the past, many ICRF heating experiments suffered from a rise in impurities, which often led to a thermal collapse of the plasma when the impurity radiation power exceeded the heating power. Therefore the simple fact that ICRF could sustain the plasma indicates that the impurity problems have been overcome. In the shot shown in Fig.7, 1.3MW of ICRF power is injected to sustain the plasma for 5 seconds following the turning off of the ECH. The plasma parameters are Wp~200kJ, $n_e \sim 1.8\times10^{19}m^{-3}$ and Te~ Ti~ 2keV, with which the relevance of the ICRF heating in helical systems is demonstrated..
2) Once the impurity problem is solved in ICRF heating, it is relatively easy to extend the latter to longer pulse operation. The longest pulse was obtained in the last week of the third campaign, where 0.8MW of ICRF power sustained a plasma for 68 sec with the following parameters:

Wp~110kJ, n~$1\times10^{19}m^{-19}$, and Te~ Ti~ 2keV. As shown in Fig. 8, the radiation loss is suppressed to a low level with no sign of impurity accumulation.

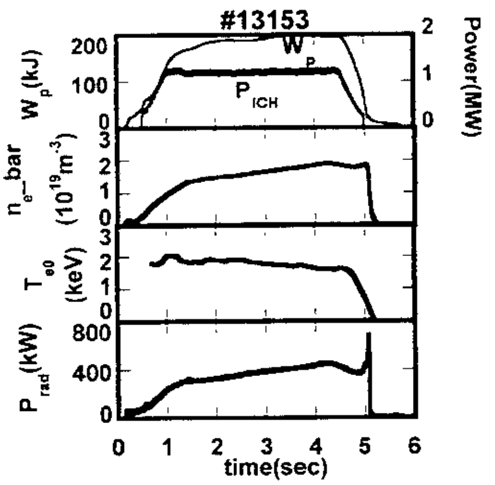

Fig 7 Time evolutions of the plasma sustained by ICRF only.

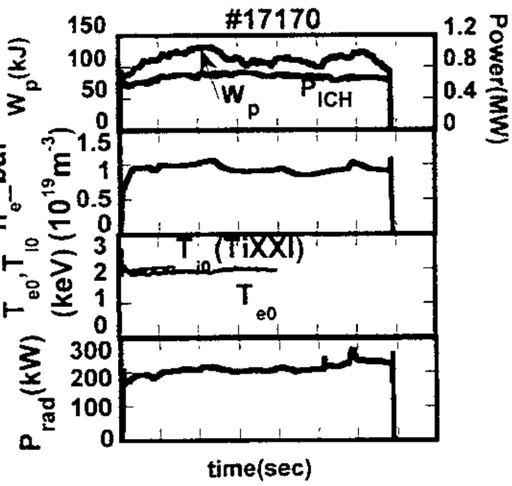

Fig.8 Time behavior of ICRF sustained longest pulse shot.

3) Application of ICRF power to an NBI target plasma.

ICRF was applied to a NBI target plasma as shown in Fig. 9. The ICRF power was 1.3MW and a stored energy increment of 100kJ was obtained. This indicates that ICRF can contribute to future high power experiments as a reliable heating scheme. ICRF heating of theNBI target was observed for the highest plasma densities obtained of $6\times10^{19}m^{-3}$.

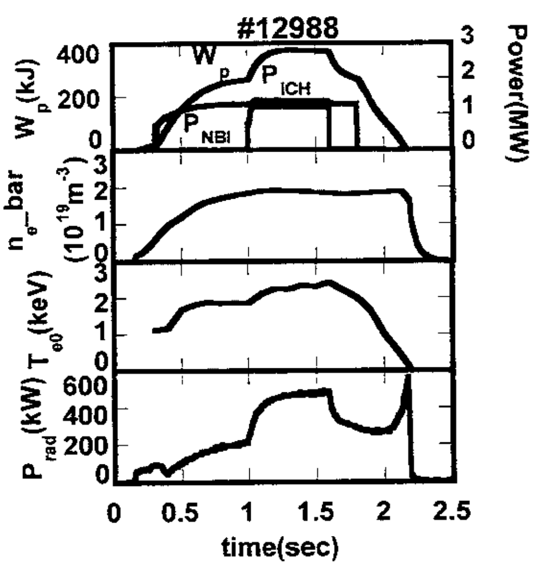

Fig.9 ICRF Heating superposed on NBI target plasma

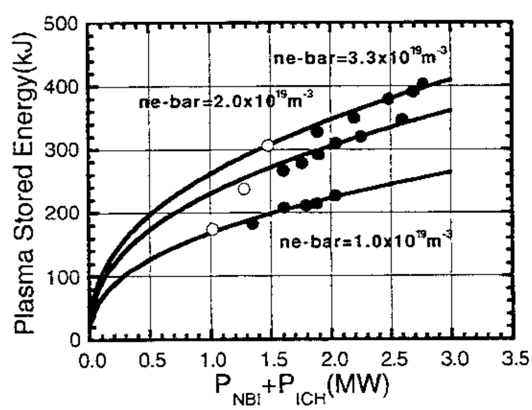

Fig.10. power dependence of the stored energy

With the expanded power level and density range ICRF heating was first used in the confinement study. The power dependence of the confinement time is shown in Fig.10 with plasma density taken as a parameter. The data involves ICRF, NBI, and NBI+ICRF data and is found to follow the ISS95 scaling with multiplication factor above 1.5. Therefore, the heating efficiency of the ICRF heating is as good as that of NBI.

It has been assumed that electron heating is the easiest way to demonstrate the utility of ICRF in helical systems. It is noted from this point of view that ion heating is dominant in the heating regime adopted in the third campaign. It is also our expectation that ion heating may well be utilized in larger devices where energy relaxation is increased. A diamond FNA detector was introduced in the experiment to measure the high energy tail of hydrogen ions[22-23]. Figure 11 shows the energy spectrum of the hydrogen ions before and after the switching on of RF. It is noted that the high energy tail extends to 200keV, indicating that high energy ions are well confined. Since the detector views the plasma almost perpendicular to the magnetic field, the observed high energy tail is that of the trapped particles. Figure 12 shows the effective temperature of the high energy tail plotted versus the formula given by Stix[24]. The unsaturated linear relation indicates that the particles are confined for a long enough time to equilibrate with electrons.

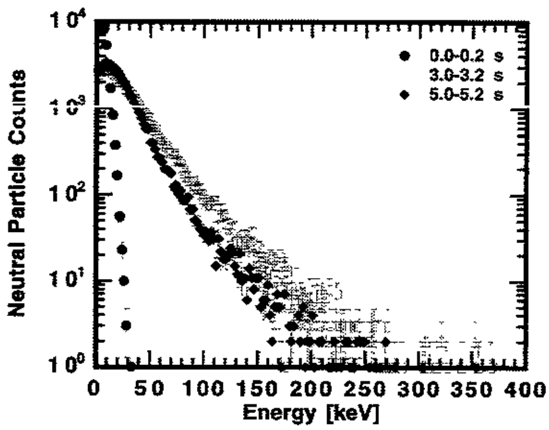

Fig.11 spectrum of high energy ions

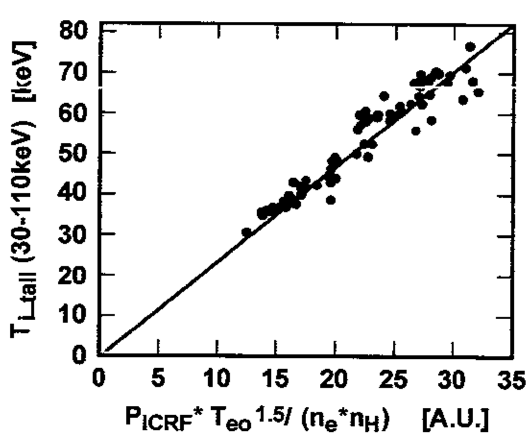

Fig.12 The power dependence of effective temperature of minority ions

4. Discussion

As one of the reasons for the improved performance of the ICRF heating in the LHD, the improved particle orbit of trapped particles is considered. In Figures 9(a) and (b), drift orbits of high energy trapped ions with different major radius R=3.75 m and R=3.6m are compared. The former is the standard configuration of LHD adopted in the 2nd campaign and the latter is the inward shifted configuration adopted in the 3rd campaign. It is found that, while the drift orbit travels across the flux surfaces in the standard configuration, the drift orbits in the inward shifted configuration do not. The Flux-surface-averaged Fokker-Planck equation is generally used in tokamaks in the studies of behavior of high energy particles. However it may not be relevant in helical systems where drift orbits are possibly misaligned to flux surfaces unless they are properly optimized. Here, the Monte-Carlo Orbit code [25] was used to analyze the observed difference in the performance due to the magnetic axis shift. In figures 10(a) and (b) heating efficiency, the ratio of the power transferred to electrons and He ions to the power absorbed by minority ions, are compared between the two cases of different magnetic axis.

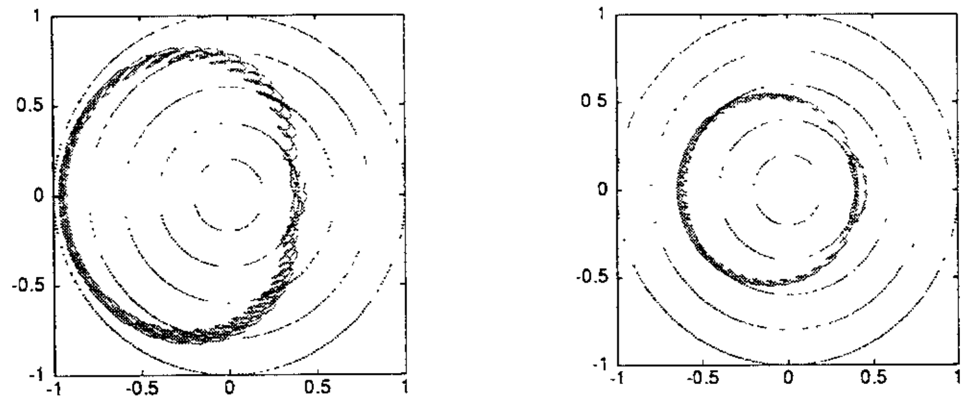

Fig.13. The drift surface of a trapped particle in the case of: (a); R=3.75 m and (b); R=3.6m

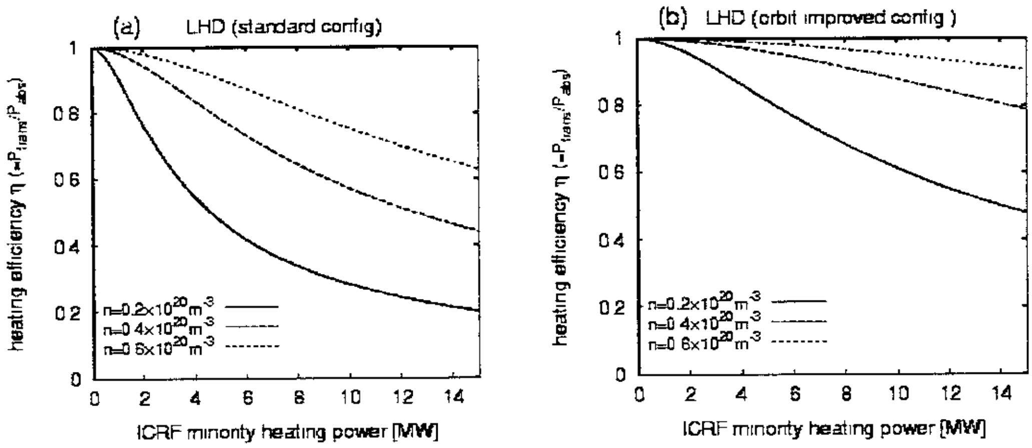

Fig. 14 The heating efficiency of the two cases: (a); R=3.75 m and (b); R=3.6m

A Remarkable improvement in the heating efficiency is observed in the inward shifted case particularly in the high power region. The difference of the efficiency from unity may not be large in the power range of 1.35MW injection. However, this difference may be important from the point of view that energetic particles impinging on the wall are assumed to generate an impurity influx. It is also noted that the bulk ions are subject to the same loss mechanism in the collision less regime.

the largest among existing stellarators, which enhances relaxation and may also have served for improvement in the performance. An inward-shifted LHD plasma is known to violate the Mercier stability criterion, and this was the reason that R=3.75m was taken as the standard configuration. The good performance described in this paper is therefore linked to another important finding that violation of the criterion do not cause deterioration in stability or energy confinement[26].

Conclusion

The ICRF Heating Experiment in theLHD in 1999 showed a remarkable improvement in performance. Due to the high quality of the heating and the extended parameter range, it can be regarded as a complete demonstration of the effectiveness of ICRF heating in stellarators. In the optimization of the heating regime, a series of experiments was conducted by scanning the magnetic field intensity and minority concentration. This enabled a comprehensive study of the mechanism of the ICRF heating in the unique magnetic field of the LHD. It was found that both electron heating and ion heating regimes are attainable, the choice of which primarily depends on the magnetic field intensity. The proper choice of the heating regime was one of the key elements of the success of the experiment. Ion heating is the dominant heating mechanism in the optimized heating regime, which distinguishes this experiment from those in CHS and W7-AS.

The magnetic axis of the plasma was shifted inward in the present experiment and the particle orbit is considered to be improved. It was confirmed in the experiment that high energy minority ions extending to 300keV are confined in the plasma. The improved confinement of high energy particles is thought to be another key to the success of this experiment.

Metalic impurities were reduced by the installation of carbon divertor plates and light impurites were reduced by the application of Ti-gettering. Thus the impurity problem was solved and a 68sec long pulse shot was realized, suggesting the utility of ICRF heating for steady state plasma heating.

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