High Power ICRF Heating in LHD in the 4-th Campaign

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Abstract

This paper reports the results of high power ICRF heating experiments in the LHD conducted in the 4th campaign in 2000. During this campaign 2.7 MW of ICRF power injection became possible with increased numbers of ICRF antennas and reinforcement of the RF power amplifiers. ICRF heating power was added to NBI heating power and expanded the range of operational power. ICRF heating was also applied to low BT plasmas in high beta experiments where principles of second harmonic heating was proved. In the long pulse experiment, a 2-minutes duration of ICRF was attained.

Introduction

The ICRF heating experiment in the 3rd campaign in 1999 demonstrated its viability in helical systems by successful 1.35MW power injections [1-4] and by a 1 minute long pulse operation [2]. The importance of high energy particle confinement in ICRF heating being well realized [5,6], these results are taken as suggesting that the heliotron devices are furnished with good confinement properties of trapped ions. A specific interest arising here is to what power the high performance of the ICRF heating is maintained. The power sources were reinforced in the 4-th campaign to facilitate an examination of the ICRF heating in a higher power regime. The experiment began with survey of the heating performance in various magnetic configurations, by means of changing magnetic field strength, gamma value, magnetic axis position, and quadrupole component. Finally, the injection power reached maximum of 2.7MW and significant deterioration has not been observed. ICRF heating contributed in various LHD experiments as useful power added to NBI, and new regimes of ICRF heating were explored.

1) Highest Stored Energy

ICRF heating was conducted in minority heating regime with H minority ions and He bulk ions. In Fig.1, the locations of cyclotron layer, cut-off layer and two- ion-hybrid layer are shown. It was confirmed in the experiment that the best heating is obtained at BT =2.75T with fixed frequency of 38.47MHz as confirmed in the previous experiment [4]. The dependence of the performance of ICRF heating on the magnetic axis was investigated in this campaign. The heating result with R=3.6m was found better than that obtained with R=3.75m, which agree with the previously report. Due to the improvement of the antennas and power sources, ICRF injection of 2MW power level was realized with good reproducibility.

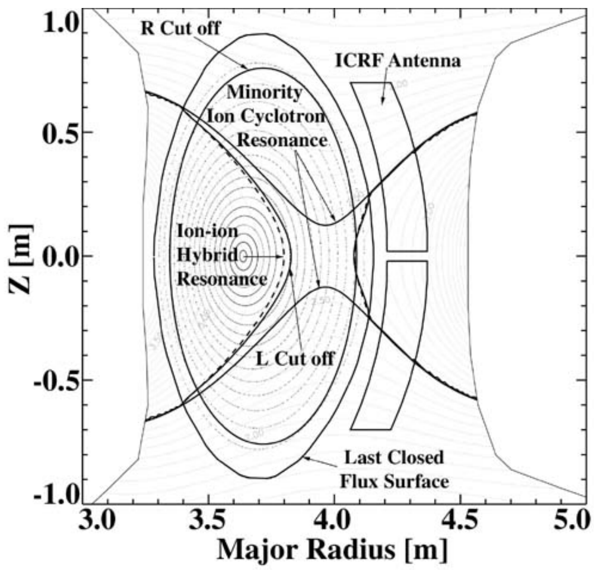


Fig.1 The resonance and cutoff diagram in the optimum heating regime. The antenna is located in the toroidal section where plasma cross section is vertically elongated. In front of the antenna, there is a region where magnetic field has weak non-uniformity.

In the shots with ICRF power only, a new record stored energy of 240kJ was obtained and maximum operational density of $3\times10^{19}m^{-3}$ was attained.

In the highest stored energy shot shown in Fig.2, ICRF power was added to 5 MW NBI power. The stored energy was boosted up above 1 MJ by addition of 100 kJ. The shot was obtained with pellet injection and at the maximum energy the density is around $1\times10^{20}m^{-3}$ indicating that ICRF heating works well at such very high plasma density. In this shot with pellet injection, He ions may be mostly replaced by H ions and, therefore, ICRF heating is supposed to be working at heavy minority ion heating regime.

2. Long Pulse Operation

In the long pulse experiment, ICRF power sustained the plasma for two minutes. It is a new record doubling previous one obtained in the 3rd campaign. As shown in Fig.3, operational plasma density is $0.9\times10^{19}m^{-3}$ and applied power is 0.4MW. Electron and ion temperatures are same, 1.3keV. The radiation loss was kept to low level facilitating the long pulse shot. Feed back control of gas puffing was applied for it is important to keep the plasma density in proper range.

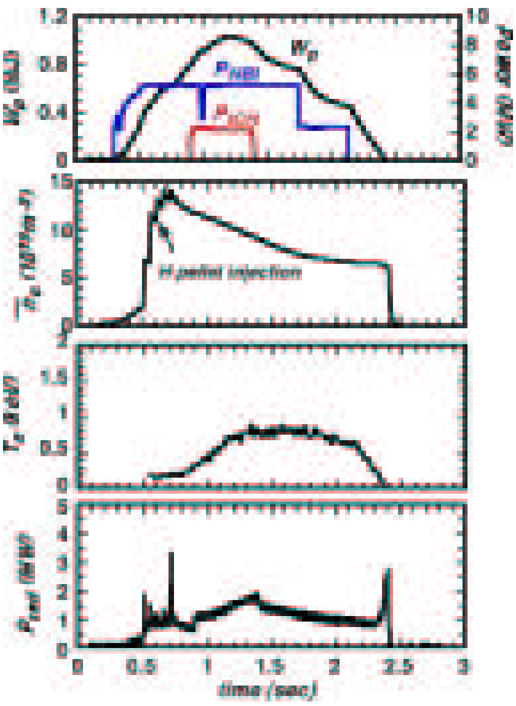


Fig.2 The highest energy shot.

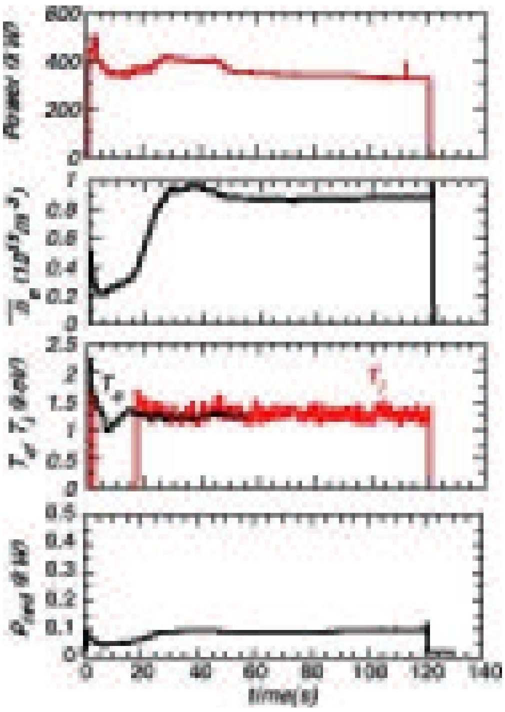
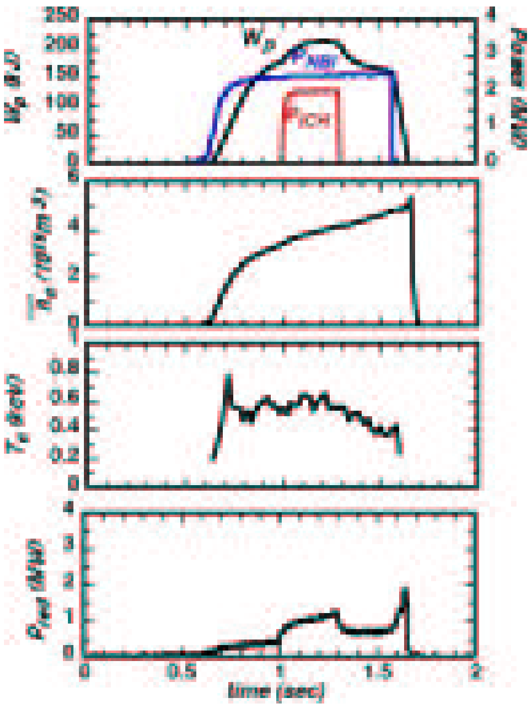


Fig.3 The longest pulse shot.

3. Second Harmonic Heating

ICRF heating was used in high beta experiments added to NBI. With frequency of 38.47 MHz, the ICRF heating is in the second harmonic heating regime with BT~1.3T. As shown in Fig. 4, operational plasma density is about $4\times10^{19}m^{-3}$ and electron temperature is about 0.6keV. The stored energy increases by about 50 kJ with the superposition of ICRF. High energy protons up to 150keV have been observed as measured with diamond FNA detector [7,8]. This shot demonstrates utility of second harmonic heating. Heating efficiency is around 0.5 and it increases with increasing beta value as theories predict. Therefore, this heating regime will improve its performance in experiments with higher power particularly in use in high beta experiments.



extremely high energy ions, this shot may signify favorable high energy particle confinement. Since second harmonic heating is known to create t of LHD adding to the previous results obtained for fundamental heating [1].

Fig.4 ICRF applied to high beta experiment: The best performance of 2nd harmonic heating is obtained with BT=1.375T, half the optimum BT(=2.75T) for the fundamental heating. The second harmonic layer has the same shape as the fundamental layer shown in Fig.1.

References

[1]MUTOH, T., et al., Phys. Rev. Letters,85(2000)4530
[2] KUMAZAWA, et al., Physics of Plasmas, 8(2001)2139
[3]SEKI, T., et al., J. Plasma and Fusion Research (Proc. 10th Toki Conf., 2000), JSPS&NFR,
[4]SAITOH, K. et al., ““Ion and Electron Heating in ICRF Heating Experiments on LHD”, Nuclear Fusion, in print
[5]WATARI, T., , Plasma Phys. Control.Fusion, 40(1998)A13
[6]MURAKAMI, S., et al., Nucl. Fusion, 39(1999)1165
[7]KRASILNIKOV, A.V., et al., Nuclear Fusion, 39(1999)1111
[8]SASAO, M., “Study of Energetic Ion Transport in the Large Helical Device”, IAEA Conference, 2000, Sorento, (EX9/1)