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ICRF Heating Using Antennas with Controlled Wave-number on LHD
LHDにおける波数制御アンテナによるICRF加熱

Ryuhei Kumazawa, Tetso Seki, Takashi Mutoh, Kenji Saito, Hiroshi Kasahara, Goro Nomura, Fujio Shimpo, Yanping Zhao[1)], J.G. Kwak[2)] and LHD Experiment Group

熊沢隆平, 関哲夫, 武藤敬, 斎藤健二, 笠原寛史, 野村吾郎, 新保富士夫, Yanping Zhao[1)], J.G. Kwak[2)], LHD実験グループ

National Institute for Fusion Science,322-6 Oroshi-cho, Toki 509-5292, Japan
[1)]Institute of Plasma Physics, Academia Sinica, Hefei, Anhui 230031 China
[2)]Korea Atomic Energy Research Institute, Daejeon, 305-353 Korea

核融合科学研究所 〒509-5292 岐阜県土岐市下石町322-6

The large helical device (LHD) has fifteen experiment cycles so far. The ion cyclotron range of frequencies (ICRF) heating has been carried out successfully on LHD. A long pulse plasma discharge up to about one hour (54 minutes) has been achieved using the poloidal array (PA) antennas. In the 14th experiment cycle (2010) the toroidal array (TA) antenna was newly installed. This TA antenna consists of two antennas arrayed in the toroidal direction and has a controllability of the wave number along the magnetic field line. In the 15th experimental cycle (2011) the plasma with high density up to $3.6\times10^{19}m^{-3}$ was sustained with 2MW of the injected RF power using both PA and TA antennas. In this experimental cycle the optimized plasma heating condition was precisely examined against the minority hydrogen ratio in the wide range of the plasma density. In addition the long pulse plasma discharge in the higher density with the higher RF power was achieved.

1. Introduction

The large helical device (LHD) has fifteen experiment cycles so far. Many experiment results have been achieved, i.e., the high performance plasmas with the high density, the high beta, and the high ion and electron temperature. An ion cyclotron range of frequencies (ICRF) heating has been carried out successfully: High RF power heating up to 1.5MW and the long pulse plasma discharge up to about one hour (54 minutes) have been achieved using the poloidal array (PA) antennas [1-2]. In the 14th experiment cycle (2010) the toroidal array (TA) antenna was installed [3]. This newly installed TA antenna consists of two antennas arrayed in the toroidal direction. In the 15th experimental cycle (2011) the poloidal array (PA) antenna was installed again.

2. ICRF heating antennas

The TA antenna has a controllability of the wave number along the magnetic field line $k_{//}$ with changing the phase difference between them. When two TA antennas are seen from the plasma axis, they look like to handshake each other and so they are called as HAS (Handshake) antenna. In the 15th cycle another pair of the poloidal array (PA) antennas was installed again. Therefore the ICRF heating experiment was carried out using four antennas.

An RF power with frequency of 38.5MHz was supplied to each antenna from the each RF generator, which consists of three stage amplifiers, i.e., 5kW, 100kW and 1MW of the RF power level in each amplifier. An impedance matching system with the liquid stub tuners was employed to reduce the reflected RF power from the ICRF heating antenna. A real-time impedance matching was capable with changing the liquid height during the ICRF heating.

A minority heating method for the ICRF heating was employed: The minority ion was a hydrogen ion with the He ion as the majority. The magnetic field strength on the plasma axis, i.e., R_{ax}=3.6m was employed as B=2.75T.

3. Experimental results

3-1. Plasma discharge with higher density

The plasma was sustained with ICRF heating power up to 0.5~2MW and sometimes with the assist of ECH power up to 0.2~0.6MW. First the trial of achieving the higher density plasma was carried out. In general the maximized density was almost proportional to the injected RF power. The plasma collapse occurred when the radiated power exceeds to about 40% of the absorbed RF power to the plasma. The highest density plasma with $n_e=3.6x10^{19}m^{-3}$ was sustained for 10 seconds with the ICRF heating power of 2.0MW and the ECH power of 0.37MW. Then the plasma stored-energy (W_p) attained to 300kJ.

3-2. Plasma stored energy with ICRF heating

In the series of the plasma sustained only with the ICRF heating and the ECH power, the wide range of the plasma density, $n_e=0.6\sim3.6x10^{19}m^{-3}$ were obtained with the injected heating RF power P_{RF} up to 2.35MW. The plasma stored-energy W_p was increased with the density n_e and P_{RF} in the following equation of the ISS04 scaling [4];

$$W_p \propto n_e^{0.54} P_{RF}^{0.39}$$

These data are plotted in the plain of $W_p/P_{RF}^{0.39}$ vs. n_e. The envelope of data points has a scaling of $n_e^{0.54}$, but many data were found below the envelope in the higher ($> 2.5x10^{19}m^{-3}$) and the lower ($< 1x10^{19}m^{-3}$) density. It was thought the smaller W_p was caused with the non-optimized ratio of the minority hydrogen ion as described later.

3-3. ICRF heating efficiency and coefficient of ISS04

It was thought that the ICRF heating efficiency should have been a key parameter to determine the attained W_p. It mainly depends on the minority hydrogen ion ratio to the bulk helium ion. Employing ISS04 the ICRF heating efficiency η was derived as follows;

$$\eta \propto W_p^{2.56} n_e^{-1.38} P_{RF}^{-1}$$

In the wide range of n_e ($0.6\sim3.8x10^{19}m^{-3}$), W_p (70kJ~300kJ) and P_{RF}(0.5MW~2.35MW), η were plotted against H/(H+He). Here the intensity ratio of the visible Hα to that of HeI at the periphery of the plasma [5] was employed to evaluate the η in place of minority hydrogen ion ratio. The calculated η was an arbitral unit, but it increased from 1.0~2.5 with H/(H+He), i.e., 10~30%. On the other hand the η_{RF} was deduced with the break-in slope of W_p and the RF power modulation method. However the dependence of η_{RF} on H/(H+He) was opposite to that of η.

Then it was proposed that the ISS04 scaling might have another coefficient, referred to as C_{eff}, which depended on H/(H+He) in the ICRF heating. These data were plotted again against H/(H+He) in accordance with

$$C_{eff}\eta_{RF}^{0.39} \propto W_p n_e^{-0.54} P_{RF}^{-0.39}$$

The C_{eff} indicates how the plasma heating method depends on the energy confinement time. The minority ion heating was employed in this ICRF heating scenario. First the high-energy minority hydrogen ion is produced with the RF electric field. This energy is transferred to the bulk electron and bulk helium ion. This power fraction depends on the relation between the energy distribution of the minority hydrogen ion and the electron temperature. When the density of the minority hydrogen ion n_H is increased, i.e., the larger H/(H+He), the tail hydrogen ion temperature decreases with n_H, and the power from the hydrogen ion with the high-energy flows mainly to the bulk helium ion. It was thought that the above C_{eff} was improved with the increase in the heating power flow to the bulk ions.

3-4. Fueling hydrogen to ICRF heated plasma

Three methods were succeeded in fueling hydrogen to the RF plasma; one was a conventional puffing of the mixed helium gas with hydrogen gas, and the second and the third were the hydrogen pellet injection and the super sonic hydrogen injection with the repetition rate of a few Hz.

3-5. Long pulse plasma discharge

A long pulse plasma discharge was carried out using only RF power, e.i., ICRF heating power and ECH power. The plasma of $n_e=2x10^{19}m^{-3}$ and W_p=170kJ was sustained for 93 seconds with P_{ICH}=1.6MW and P_{ECH}=0.6MW. The plasma of $n_e=1.4x10^{19}m^{-3}$ and W_p=130kJ was sustained for 320 seconds with P_{ICH}=0.8MW and P_{ECH}=0.3MW.

Summary

The ICRF heating was carried out using the new TA antenna and the PA antenna. The higher density of $3.6x10^{19}m^{-3}$ was sustained for 10 seconds with P_{ICH}=2MW and P_{ECH}=0.37MW. The higher plasma stored-energy was found at ~20% of H/(H+He). In this range of H/(H+He) the ICRF heating efficiency was degraded, but the coefficient of the energy confinement was much improved in ~20% of H/(H+He). The duration time of the long pulse discharge was extended in the higher density with the higher RF heating power.

Acknowledgments

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