ICRF Heating and High Energy Particle Production in the Large Helical Device

T.Mutoh, R.Kumazawa, T.Seki, K.Saito, T.Watari, Y.Torii[1], N.Takeuchi[1], T.Yamamoto[1], M.Osakabe, M.Sasao, S.Murakami, T.Ozaki, T.Saida[2], Y.P.Zhao[3], H.Okada[4], Y.Takase[5], A.Fukuyama[4], N.Ashikawa, M.Emoto, H.Funaba, P.Goncharov[2], M.Goto, K.Ida, H.Idei, K.Ikeda, S.Inagaki, M.Isobe, O.Kaneko, K.Kawahata, K.Khlopenkov, T.Kobuchi, A.Komori, A.Kostrioukov, S.Kubo, Y.Liang, S.Masuzaki, T.Minami, T.Mito, J.Miyazawa, T.Morisaki, S.Morita, S.Muto, Y.Nagayama, Y.Nakamura, H.Nakanishi, K.Narihara, Y.Narushima, K.Nishimura, N.Noda, T.Notake[1], S.Ohdachi, I.Ohtake, N.Ohyabu, Y.Oka, B.J.Peterson, A.Sagara, S.Sakakibara, R.Sakamoto, M.Sasao, K.Sato, M.Sato, T.Shimozuma, M.Shoji, H.Suzuki, Y.Takeiri, N.Tamura, K.Tanaka, K.Toi, T.Tokuzawa, K.Tsumori, K.Y.Watanabe, Y.Xu, H.Yamada, I.Yamada, S.Yamamoto[1], M.Yokoyama, Y.Yoshimura, M.Yoshinuma, K.Itoh, K.Ohkubo, T.Satow, S.Sudo, T.Uda, K.Yamazaki, K.Matsuoka, O.Motojima, Y.Hamada, M.Fujiwara

National Institute for Fusion Science, Toki, 509-5292, Japan
1) Department of Energy Engineering and Science, Nagoya University, 464-8603, Japan
2) Graduate University for Advanced Studies, Hayama, 240-0193, Japan
3) Institute of Plasma Physics, Academia Scinica, Hefei, Anhui, China
4) Kyoto University, Kyoto, Japan
5) Graduate School of Frontier Sciences, The University of Tokyo 113-0033, Japan

e-mail contact of main author: mutoh@nifs.ac.jp

Abstract. Significant progress has been made with Ion-Cyclotron Range-of-Frequencies (ICRF) heating in the Large Helical Device (LHD). This is mainly due to better confinement of the helically trapped particles, and less accumulation of impurities in the region of the plasma core. During the past two years, ICRF heating power has been increased from 1.35 MW to 2.7 MW. Various wave-mode tests were carried out using minority-ion heating, second-harmonic heating, slow-wave heating, and high-density fast-wave heating at the fundamental cyclotron frequency. This fundamental heating mode extended the plasma-density range of effective ICRF heating to a value of $1 \times 10^{20} m^{-3}$. This was the first successful result of this heating mode in large fusion devices. Using the minority-ion mode gave the best performance, and the stored energy reached 240 kJ using ICRF alone. This was obtained for the inward-shifted magnetic axis configuration. The improvement associated with the axis shift was common to both bulk plasma and highly accelerated particles. For the minority-ion mode, high-energy ions up to 500 keV were observed by concentrating the heating power near the plasma axis. The confinement properties of high-energy particles were studied for different magnetic axis configurations using the power-modulation technique. It confirmed that the confinement of high-energy particles with the inward-shifted configuration was better than that with the normal configuration. The impurity problem was not serious when the plasma boundary was sufficiently far from the chamber wall. By reducing the impurity problem, it was possible to sustain the plasma for more than two minutes using ICRF alone.

1. Introduction

The performance of Ion-Cyclotron Range-of-Frequencies (ICRF) heating has progressed steadily in the Large Helical Device (LHD) [1-9]. This is mainly due to better confinement of the helically-trapped particles, which was improved by the use of the inward-shifted configuration of the magnetic-confinement field [1],[2]. From the start of the LHD experiment, confinement of the helically-trapped particles was a major problem that needed to be solved for successful ICRF heating, and the success of the helical-fusion program. During the past two years, the ICRF

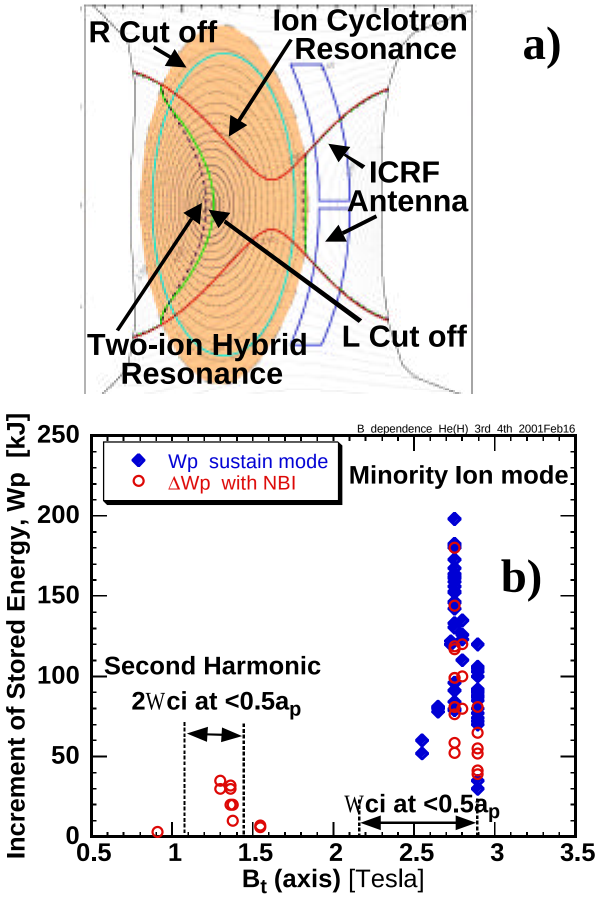

Fig.1 a) Resonance and Cut-off surfaces in LHD cross section in minority ion mode (B_0=2.75T, 38.5MHz, He(H:30%)plasma)

b) Plasma stored energy vs. magnetic field strength.Diamonds are ICRF sustained mode and circles are additional heating to NBI plasma.

heating power was increased from 1.35 MW to 2.7 MW to better resolve this problem.

Various wave-modes were tested, and the properties of accelerated-particle confinement examined. Tests were carried out using minority-ion heating, second-harmonic heating, slow-wave heating, and high-density fast-wave heating at the fundamental cyclotron-frequency. In Fig.1(a), the resonance and cut-off surfaces for the minority-ion mode are shown in a poloidal cross-sectional view of the LHD. ICRF antennas are located on the outer side of the toroid, and the mod-B contour had a saddle-point. The heating performance depended on the magnetic field-strength as shown in Fig.1(b). The increment of the stored plasma energy due to ICRF pulse is plotted versus magnetic field-strength at the axis. The frequency was fixed at 38.5 MHz. Good results were obtained mainly for the minority-ion heating mode at a magnetic field of 2.75 T, and the stored energy reached 240 kJ using ICRF alone. As shown in Fig.1(a), at the optimum magnetic-field strength, the resonance was located near the saddle point of the mod-B contours, and not at the magnetic axis. Under this condition, the area of cyclotron-resonance acceleration was greatest due to the small gradient of the magnetic field strength. For fields near 1.3 T, second-harmonic heating was also tested as a means of providing additional heating for the NBI plasma [10].

Those data were obtained for the inward-shifted magnetic axis configuration. The improvement associated with the axis-shift appeared to be common to both bulk plasma and highly-accelerated particles. Until now, there has been no direct indication of improved confinement of high-energy particles. In this paper, comparisons between inward-shifted and normal configurations using the power-modulation technique are shown.

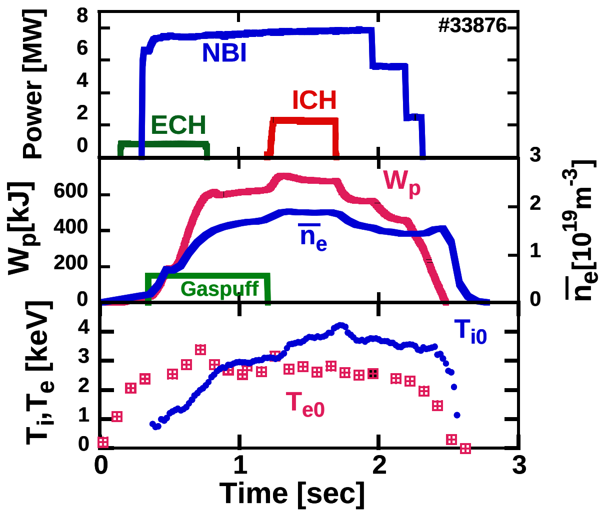

Fig.2 Temporal evolution of ICRF additional heating to NBI sustained plasma. (B_0=2.8T, R_{ax}=3.53m)

2. ICRF Heating Performances

After the last IAEA conference [6], the experimental program included the installation of six loop-antennas that raised the input power to 2.7 MW. By using this system, plasmas with high stored energy and high ion-temperatures were achieved in conjunction with NBI heating. Figure 2 shows time traces of the plasma parameters. ICRF power of 2 MW was applied to the NBI-sustained plasma, and clear increases were observed in stored plasma energy (W_p) and central ion temperature (T_{io}) measured from Ar*XVII* spectrum.

A sustained plasma using ICRF alone was also achieved. In Fig. 3, the plasma stored-energy achieved using ICRF alone is plotted as a function of ICRF power. Data for two different magnetic configuration parameters are shown: γ=1.254 and γ=1.259. Both cases are the minority-heating mode with a majority of helium ions and a minority of protons. For the case of the larger γ parameter, the distance from the plasma boundary to the chamber wall is around 1 cm. The radiation power was quite large and sustaining the plasma was quite difficult. In the case of the smaller γ parameter, the clearance was almost double, and the plasma performance was greatly improved as shown in Fig. 3. The stored energy and the plasma density were both increased by raising the ICRF power. Results of slow-wave mode (Ion Cyclotron Wave heating) with low plasma density are also shown.

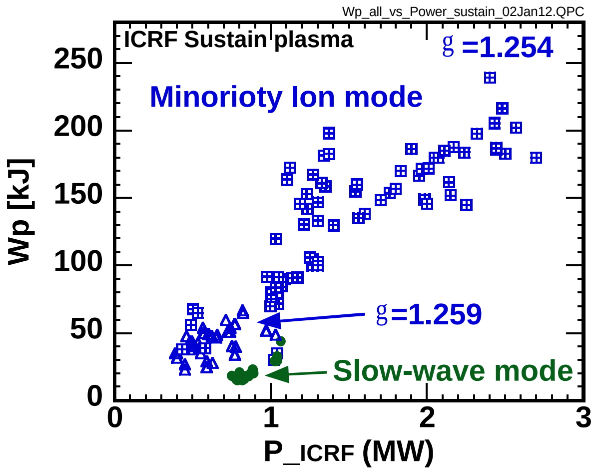

Fig.3 Stored energy of ICRF sustained plasma versus ICRF power. Minority Ion mode (He:majority,H:minority), Slow-wave (H:100%), B=2.75-2.9T, 38.5MHz,

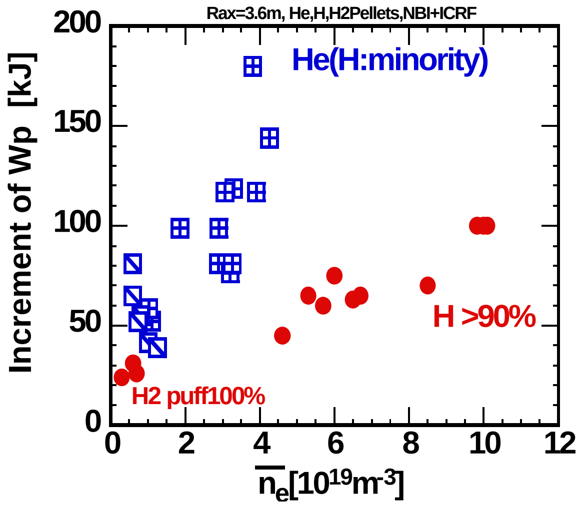

Fig.4 Increment of stored energy (Wp) of ICRF heating on NBI plasma. (Squares: minority ion heating, Closed circles:fundamental cyclotron frequency heating,38.5MHz, 2.75-2.8T)

3. Fundamental-Cyclotron-Frequency Heating in High-Density Plasma

Of the several wave-heating modes, the most interesting result was achieved using high-density fundamental-cyclotron-frequency heating, which is thought to be a fast-wave mode. This mode had previously been abandoned due to its very small wave-damping rate. However, for LHD, effective heating was observed in high-density plasmas up to a density of 1 x 10^{20} m^{-3}. In Fig.4, the increment of the plasma-stored energy was plotted for a wide range of plasma densities, from 0.3 to 10 x 10^{19} m^{-3}. In the high-density region, only the fast-wave mode can propagate and heat the plasma. The plasma was built-up by injecting hydrogen gas, hydrogen pellets and injected proton beams. Therefore, almost 100% of the ions were protons.

From the observation of electron-cyclotron emission (ECE) at the power turn-off time, it was clear that the majority of the wave power was transferred to the ions by ion-cyclotron damping. The substantial damping rate was considered to be due to the presence of NBI-beam particles and/or a large magnetic-field ripple. The efficiency was about half that of the minority-ion heating mode, as shown in Fig. 4. However, this fast-wave of the fundamental cyclotron frequency is still effective for the heating of high-density plasma and these data are the first successful results in large fusion devices.

4. High-Energy-Particle Production and Confinement

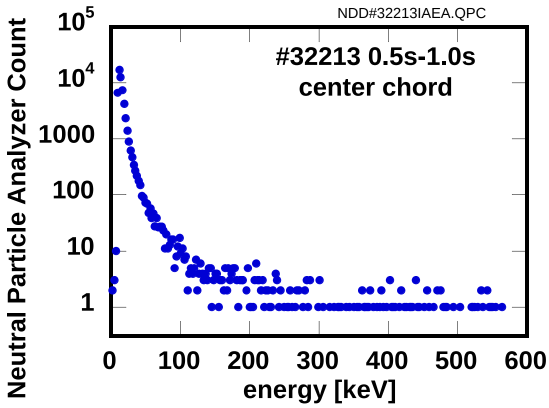

Fig.5 Energy distribution of minority protons for the axis resonant condition in ICRF sustained plasma. (B_0=2.5T, R_{ax}=3.6m)

In the minority-ion-heating mode, a high-energy tail component is produced in velocity space. This non-thermal tail extends up to an energy of 500 keV, as shown in Fig. 5. In this case, the cyclotron resonance is located on the magnetic axis. Under this condition, the heating-volume is small, and the power-density is high compared to the saddle-point resonance (see Fig.1(a)). Consequently, in this condition, the tail component grew more rapidly. The smooth distribution in velocity space implies that there is no apparent high-energy particle-loss channel such as suspected to be a serious problem in the helical systems.

However, the confinement properties for high-energy particles are still important subjects in LHD. The bulk plasma confinement with a magnetic axis radius (R_{ax}) of 3.6m was better than that of R_{ax}=3.75m. Therefore the properties of high-energy-tail confinement are also compared for NBI plasmas having different magnetic axes using the ICRF modulation technique [10][11]. Target plasma parameters were almost kept identical. Figure 6 shows the time dependence of the fast particle flux (by Silicon-diode detector, Si-FNA) and its associated phase delays from the modulated power phase. The ICRF power has a sinusoidal envelope of 4 Hz. As long as the confinement of accelerated high-energy particles was

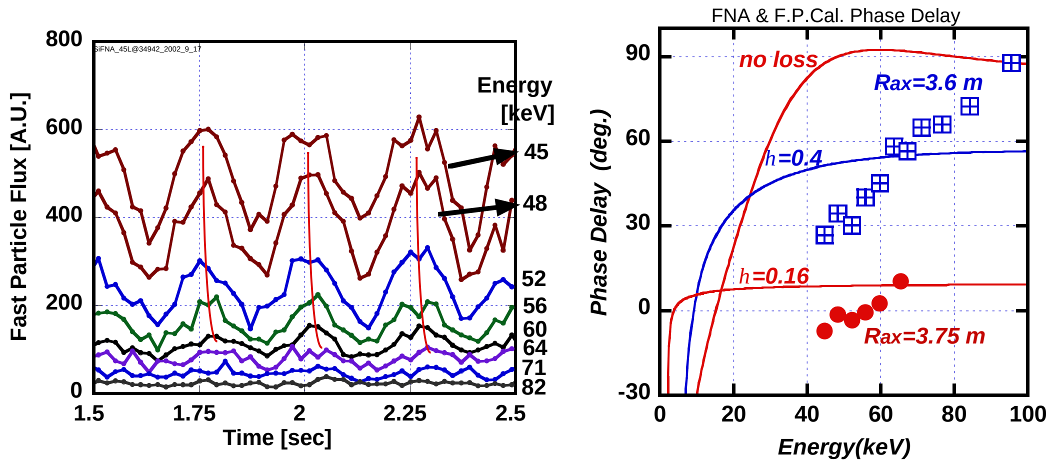

Fig.6 Time traces of Si-FNA flux for different particle energy with ICRF power modulation. (Left) Phase delay of Si-FNA flux from modulated ICRF power phase. Solid lines are Fokker-Planck Calculation in three cases, no loss and with a particle loss channel of transfer efficiency from fast particles to bulk plasma of 0.4 and 0.16. (Right)

shorter than the relaxation process time, the phase delay of the particle flux should be small. The phase delay of the flux for the inward-shifted configuration (Rax=3.6m) was larger than that of the normal configuration (Rax=3.75m) as shown in Fig. 6. The solid curves are the calculated phase delay by the time dependent Fokker-Planck equations, which includes artificial particle loss effects [10]. The particle confinement for R_{ax}=3.75 m was clearly worse than that for R_{ax}=3.6m. These results are the first direct observation of an improvement in high-energy particle-confinement for the inward-shifted configuration.

5. Long-Pulse Experiment

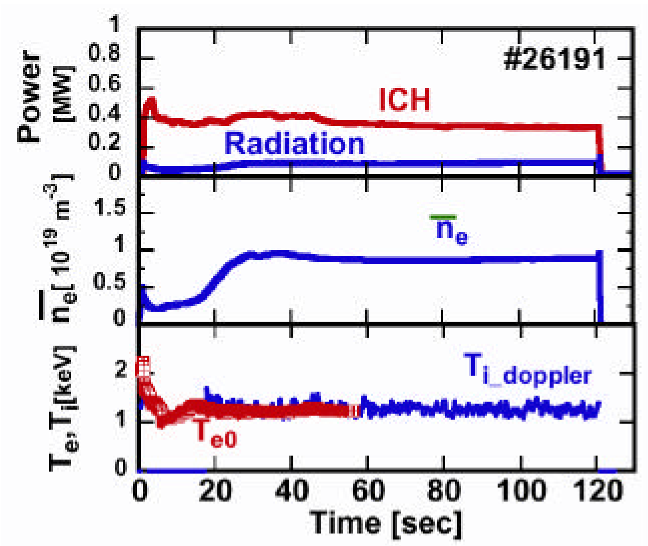

Fig.7 Long pulse plasma sustainment by ICRF for 2 minutes.
(B_0=2.75T, R_{ax}=3.6m, He gas, one antenna loop)

During the ICRF pulse, the impurity effect was sensitive to the separation between the plasma boundary and the chamber wall. At the correct distance (the same as γ=1.254 in Fig.3), the impurity effect can be suppressed to a small level, resulting in a longer pulse operation. An operation of two-minute duration was successfully performed at an ICRF power of 0.5 MW, an electron density of 0.9 x 10^{19} m^{-3}, and with an electron and ion temperature of 1.3 keV. (See Fig. 7) The radiation power stayed at a low level of around 25% of the input ICRF power. The achievement of long pulse-operation in the minority-ion mode is an indirect indication of the good confinement of helically-trapped particles and no impurity-ion accumulation in the LHD.

6. Summary

High-power ICRF heating up to 2.7 MW was successfully achieved. Various heating modes were tested, and the minority-ion-heating mode was shown to provide the best performance. Fast-wave heating at the fundamental cyclotron-frequency in high-density plasmas was demonstrated for the first time. When using the power-modulation technique, the inward-shifted configuration was shown to be advantageous for high-energy particle confinement.

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