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ICRF HEATING IN CHS

ABSTRACT

ICRF heating experiments with five poloidal half-turn antennas have been carried out in Compact Helical System (CHS). These antennas designed for the inward shifted magnetic configuration (R_{ax}=92.1cm) were installed in the high field side of helical field. A high power RF pulse is applied to a deuterium plasma with hydrogen minority initiated by ECH or NBI. The plasma performance was mainly affected by the oxygen radiation which was reduced by more than 2 times by boronization. The plasma stored energy reached 2.2 kJ with 590 kW of RF power from 5 antennas and was sustained to the end of the RF pulse(60msec). Two-component ion energy spectrum was observed by NPA. The combined heating with NBI was also successful and achieved the increase in the stored energy of 0.8 kJ with 450 kW of RF power from 5 antennas.

Keywords : ICRF heating, minority heating, helical system, boronization

1. Introduction

Ion cyclotron range of frequency (ICRF) heating is a powerful and convenient method to heat plasmas not only for tokamak but also for currentless systems like stellarator/heliotron/torsatron [1-4]. ICRF can heat the ion and/or the electron by changing gas species (or minority ratio) and structures of the resonance layers. An operation regime of a magnetic field strength for ICRF heating is wider than that for ECH, because it is easy to change the operating frequency continuously and widely. A combination of NBI and ICRF heating is also attractive from the point of view of the ion heating in the high density regime. However ICRF heating in helical systems has not yet succeeded in sustaining a heated plasma by high power ICRF alone.

Recently, five half-turn antennas for the fast wave excitation were installed in the CHS device, and ICRF heating experiments have been carried out to investigate availability of ICRF heating in a low-aspect-ratio helical system. Boronization was done for the vacuum chamber wall conditioning frequently. The global energy confinement time of the ICRF heated plasma is compared with that of the NBI heated plasma and with that estimated by LHD scaling. This paper demonstrates availability of ICRF heating in a low-aspect-ratio helical system.

2. Experimental setup

CHS is a low-aspect-ratio helical device with two continuous helical windings (ℓ=2) and 8 field periods (m=8) [5]. The major and minor radii are 1 m and 0.2 m, respectively. The rotational transform at the center and at the periphery are 0.3 and 1.0, respectively. The maximum magnetic field strength is 2.0 T. The available RF transmitters are 20-45 MHz/1.2 MWx2 and 20-45 MHz/1.0 MWx1.

Five half-turn antennas were designed for ICRF heating in CHS. Each antenna has single layer Faraday Shield (FS) and side guard limiters made of stainless steel. Each element of FS was arranged along the magnetic field line on the last closed magnetic surface. They were designed to fit the inward shifted magnetic configuration (Rax = 92.1 cm) in vacuum and installed in the high field side (beneath the helical conductor) of the helical field. Four antennas (referred to P-port antennas) with 4 cm width and 40 cm length were installed at the slant ports at every other helical period. The other antenna (referred to U-port antenna) with 16 cm width and 40 cm length was installed at the vertically elongated position. The P-port antennas are fed in pairs by separate coaxial feed lines and the U-port antenna is fed by its own coaxial feed line. Three feed lines were connected to the separate transmitters. The frequency of the transmitters was 26 MHz.

Working gas was a pure deuterium or a mixed gas of hydrogen as a minority in deuterium with various mixture ratios. The magnetic field strength was adjusted to control the location of the resonance and cut-off layers. The ICRF power was applied to the afterglow of ECH (53.2 GHz/200 kW) or to the NBI (40 kV/1 MW and/or 36 kV/0.8 MW) heated plasma. Boronization with decaborane ($B_{10}H_{14}$) was done to reduce the radiation loss.

3. Experimental results

Boronization has been done in CHS to reduce the radiation loss from impurities especially from oxygen. Vaporized decaborane ($B_{10}H_{14}$) was injected into a helium glow discharge through toroidally distributed 4 valves.

Before boronization, helium glow discharge cleaning and titanium gettering were done for vacuum wall conditioning. When RF power of 200 kW was applied to the U-port antenna, the plasma stored energy reached its peak value of 0.6 kJ at the line averaged electron density of $2x10^{19}m^{-3}$ about 20 ms after RF switched on. However, the stored energy began to decrease as the radiation loss increased. Various impurity lines (OV, CIII, TiXII, etc.) were observed by the VUV spectroscopy, and it was found that the plasma performance was mainly affected by the oxygen radiation.

After boronization, the stored energy lasted to the end of the RF pulse. Figure 1 shows the time evolution of the total RF power, line averaged electron density and the plasma stored energy when power was applied simultaneously to the U-port and P-port antennas. The magnetic field strength was 1.7 T. The plasma stored energy reaches 2.2 kJ with 590 kW of RF power and the averaged electron density of $4.2x10^{19}m^{-3}$ 40 ms after RF switched on. For this discharge the hydrogen minority ratio H/(H+D) measured spectroscopically was about 30 % in spite of the pure deuterium gas puffing. The recycling particle from the boronized wall was mainly hydrogen. The radial profiles of the electron temperature and density measured with Thomson scattering are shown in Fig. 2. The electron density profile is hollow and the temperature profile is peaked with the central temperature of 300 eV.

The ion energy spectrum was measured with fast neutral particle energy analyzer (NPA) which can not separate particle species. Two-component energy spectrum was observed as shown in Fig. 3 when the plasma stored energy was 0.4 kJ at the averaged electron density of $1x10^{19}m^{-3}$. The bulk and tail components were about 360 eV and 1.4 keV, respectively. The ion temperature with NPA was comparable to or a little lower than the electron temperature.

High ion temperature of 550 eV with 600 kW of RF power was observed with NPA. The plasma stored energy was 2 kJ at the averaged electron density of $2x10^{19}m^{-3}$ and the central electron temperature was 400 eV that is lower than the ion temperature. In this case, the ion temperature was higher than the electron temperature.

Figure 4 shows dependences of the peak value of the stored energy on the magnetic field strength. The averaged electron density was kept almost constant as shown in Fig. 4. The minority ratio in this experimental series was about 30

%. The optimum magnetic field strength in the stored energy was 1.7 T. At this magnetic field strength, the two-ion hybrid resonance layer locates near the magnetic axis. The dependence of the stored energy on the magnetic field strength was a little weaker than that before boronization.

The combined heating experiment with ICRF and NBI was also carried out successfully. The increase in the stored energy of 0.8 kJ due to ICRF heating was observed when RF power of 450 kW was applied to the NBI initiated plasma with 3 kJ at the averaged electron density of $2.5\times10^{19}m^{-3}$.

The comparison of the global energy confinement time (τ_E) with the LHD scaling is shown in Fig. 5. In the case of the ICRF heated plasma except for a high T_i discharges, τ_E is 50-70 % of NBI heated plasmas'. In the case of the high T_i plasmas, the confinement characteristic is comparable to that of NBI heated plasma and close to the LHD scaling.

4. Summaries

Boronization reduced the radiation loss from oxygen by more than 2 times. After boronization, the ICRF wave has sustained the heated plasma during the ICRF pulse. The stored energy of 2.2 kJ with 590 kW of RF power was achieved by ICRF alone, which showed roughly comparable heating to NBI and ECH. The simultaneous heating of the ion and the electron by ICRF was achieved in a low-aspect-ratio helical system. Combination with NBI was also effective. The global energy confinement time of the high T_i plasma is close to that estimated by LHD scaling.

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FIGURE CAPTIONS

Fig. 1. Time evolution of plasma parameters.

ICRF : ICRF heating pulse,
ECH : ECH pulse for target plasma production,
W_{dia} : plasma stored energy measured with the diamagnetic loop,
$\bar{n}_e$: line averaged electron density.

Fig. 2. The electron density and temperature profiles measured with Thomson scattering.

Fig. 3. Energy spectrum of the ICRH plasma measured with NPA. The plasma stored energy was 0.4 kJ at the averaged electron density of $1\times10^{19}m^{-3}$.

Fig. 4. Dependences of the diamagnetic stored energy (W_{dia}) and the line averaged electron density ($\bar{n}_e$) on the magnetic field strength (B_T).

Fig. 5. Comparison of the global energy confinement time with LHD scaling. The cross signs are the data after boronization and the others are before boronization.

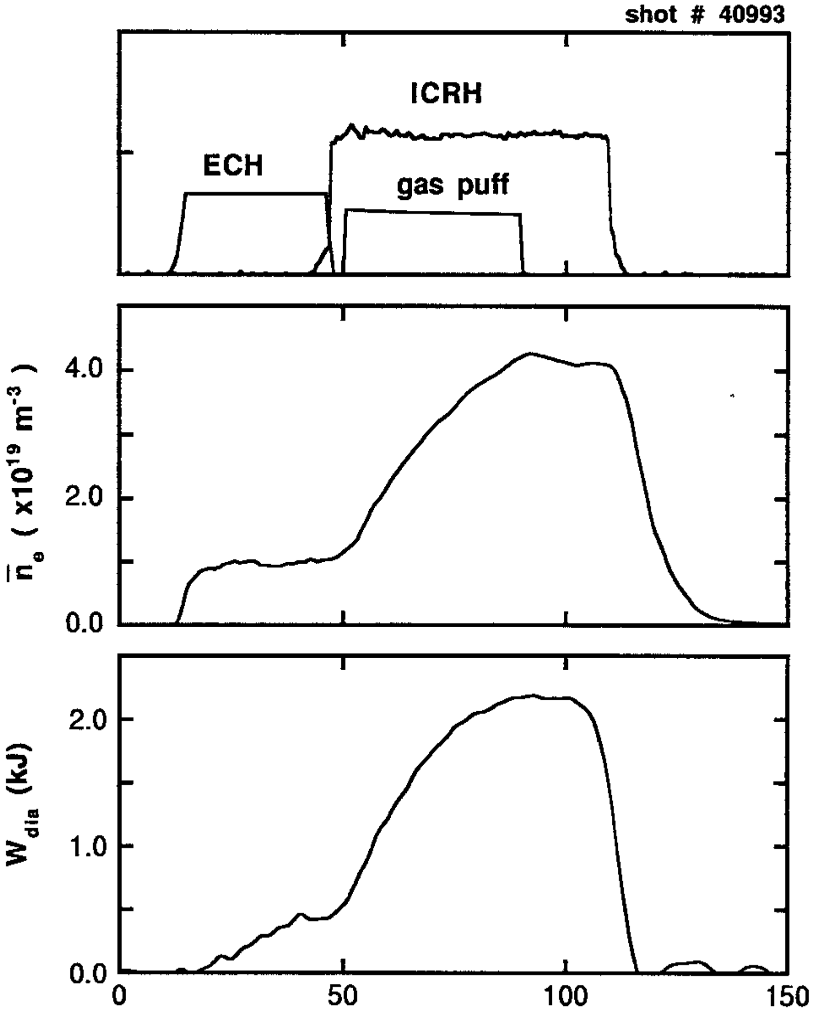
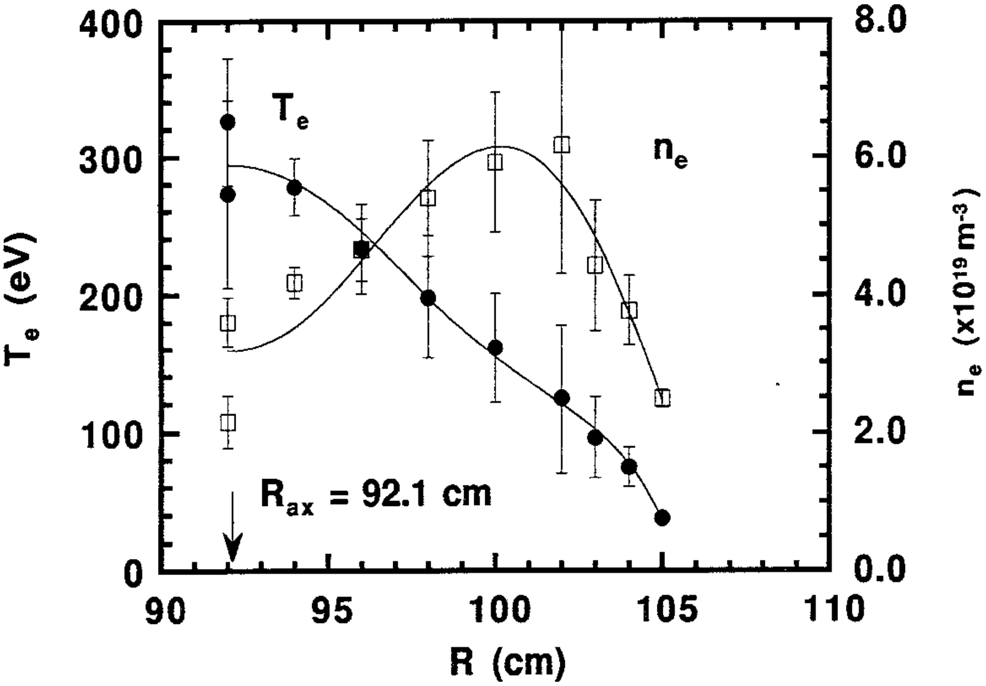

shot # 40993
ICRH
ECH
gas puff
$\bar{n}_e$ (x10^{19} m^{-3})
4.0
2.0
0.0
W$_{dia}$ (kJ)
2.0
1.0
0.0
0
50
100
150
time (ms)

Fig. 1



400
300
200
100
0
T_e (eV)
8.0
6.0
4.0
2.0
0.0
n_e ($\times 10^{19}$ m^{-3})
90
95
100
105
110
R (cm)
T_e
n_e
R_{ax} = 92.1 cm

Fig. 2

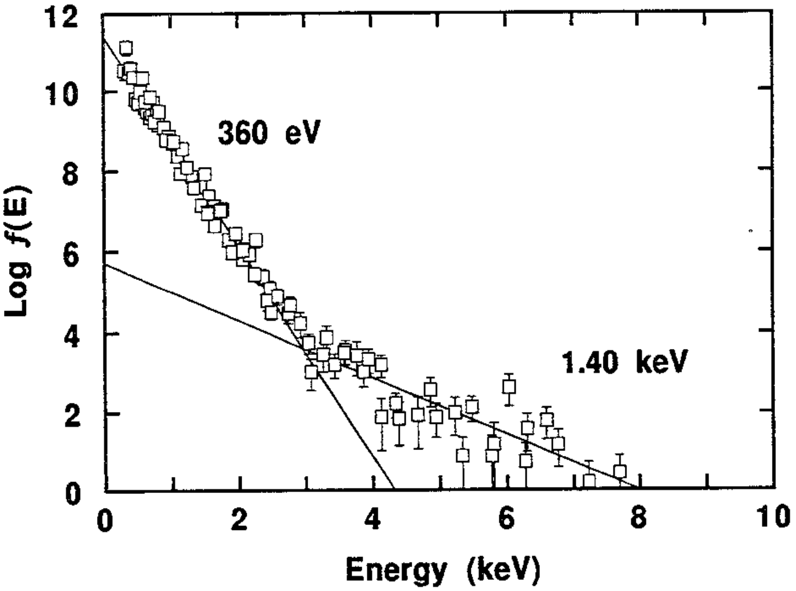
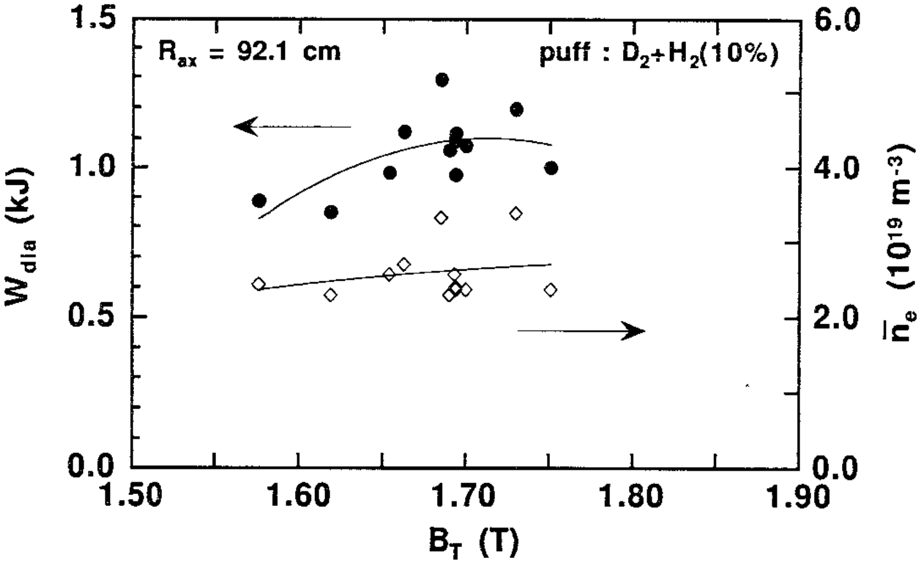


Fig. 3



R_{ax} = 92.1 cm
puff : D_2+H_2(10%)
W_{dia} (kJ)
$\bar{n}_e$ (10^{19} m^{-3})
B_T (T)
1.5
1.0
0.5
0.0
6.0
4.0
2.0
0.0
1.50
1.60
1.70
1.80
1.90

Fig. 4

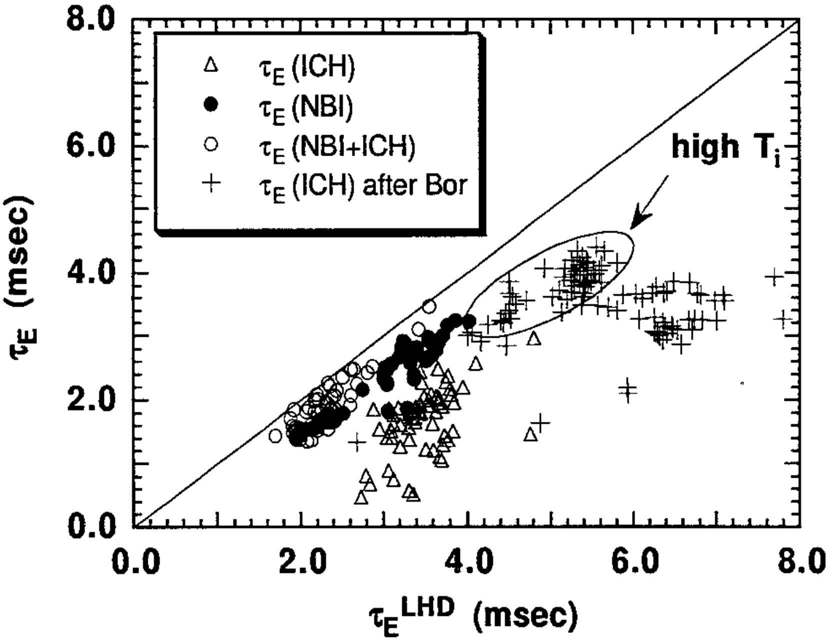

8.0
6.0
4.0
2.0
0.0
0.0
2.0
4.0
6.0
8.0
τ_E (msec)
τ_E^{LHD} (msec)
△ τ_E (ICH)
● τ_E (NBI)
○ τ_E (NBI+ICH)
+ τ_E (ICH) after Bor
high T_i

Fig. 5

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