The impact of ICRF heating using newly installed phasing antenna in LHD

H. Kasahara[1], K. Saito[1], T. Seki[1], R. Kumazawa[1], G. Nomura[1], F. Shimpo[1], S. Kubo[1], T. Shimozuma[1], H. Igami[1], T. Wakatsuki[2], H. Watada[3], H. Idei[3], S. Masuzaki[1], T. Mutoh[1] and LHD experiment group[1]

[1]*National institute for fusion science, Toki, Japan*

[2]*The university of Tokyo, Kashiwa, Japan*

[3]*The university of Kyoto, Kyoto, Japan*

[3]*The university of Kyushu, Kasuga, Japan*

1. Introduction

In order to achieve a fusion reactor, steady-state discharges have been studied in Large Helical Device (LHD), and a stable-long-pulse discharge with the time length of 54 min. 28 sec. [1] is demonstrated in helical plasma. The helical plasma on LHD doesn't need a continuous driving torque for a plasma current, and a plasma disruption event in tokamaks does not occur. However, the heat-handling problem for diverter and the local heat load for additional heating power losses is same issue between in helicals and in tokamaks. These heat handlings which are not important for short pulse discharges (less than a few minutes)

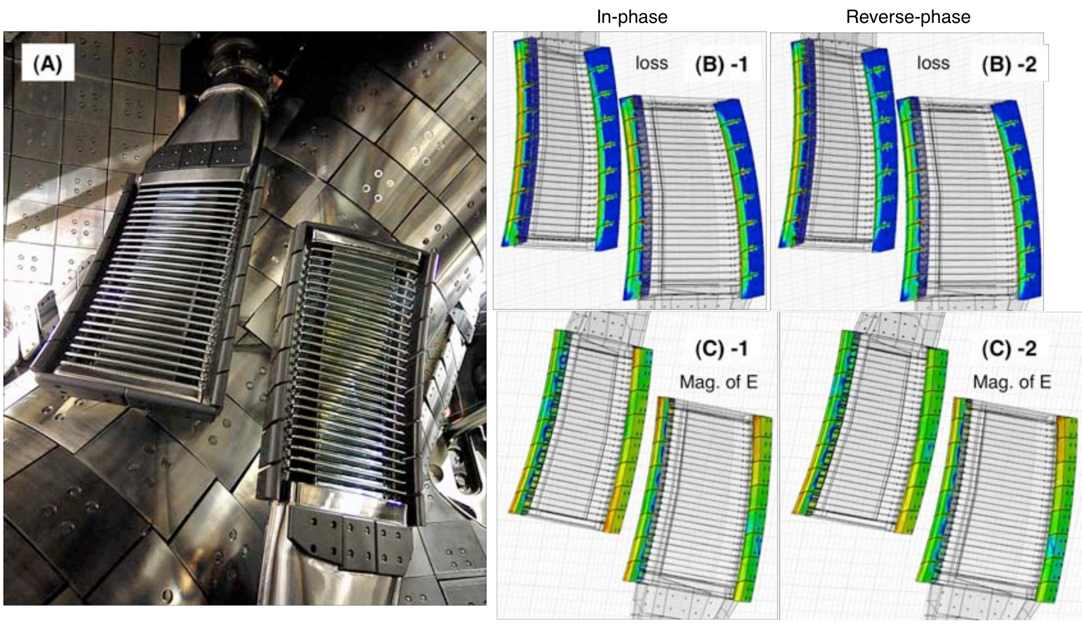

Figure 1. A toroidal phasing antenna which is installed at 3.5 U and L port in LHD (A). RF power supplies from upper(3.5U) and lower port(3.5L) to these antennas, and the gap between the antenna protector and the last closed flux surface of plasma is controllable to change these antenna position, independently. (B)-1 and (B)-2 show the surface RF losses on the carbon protectors, and (C)-1 and (C)-2 show the maximum magnitude of electric field on the carbon protectors. In the reverse-phase operation, the total RF loss is small, and the intensity of edge electric field is weak in reverse-phase.

are critical issues to sustain the steady-state discharge [2], and in order to mitigate these heat flux to local places a toroidal phasing antenna is designed by using a three-dimensional electromagnetic solver [3, 4].

2. A toroidal phasing antenna in a helical plasma

A toroidal phasing antenna has been studied for tokamak experiments, and a toroidal double-loop array antenna with the reverse-phase reduce the RF sheath potential around the antenna [5]. In order to design a toroidal phasing antenna in LHD, the plasma surface and RF current profile on the strap is re-optimized to decrease in the local hot spot temperature around the antenna, and figure 1 shows the actually installed toroidal phasing antenna (the HAS antenna) in LHD and the electromagnetic calculation results for surface loss densities and magnitudes of maximum electric magnetic field on the carbon protectors. The antenna is named from the antenna shape, and it is similar to the hand-shake form. The (B) and (C) in Fig. 1 indicate the decrements in the RF loss density and the maximum intensity of electric field on the surface of carbon protectors with the in-phase and the reverse-phase. These decrements are not drastically changed, and these with the reverse-phase are clearly improved than these with the in-phase.

3. Initial ICRF heating experiment using the HAS antenna

The HAS antenna was installed in LHD at 2010, and the initial ICRF heating experiment in various toroidal phases was done. Compared with previous poloidal array antennas [1], it is necessary to shorten the gap between plasma and the antenna protector by 3 ~ 4 cm to get

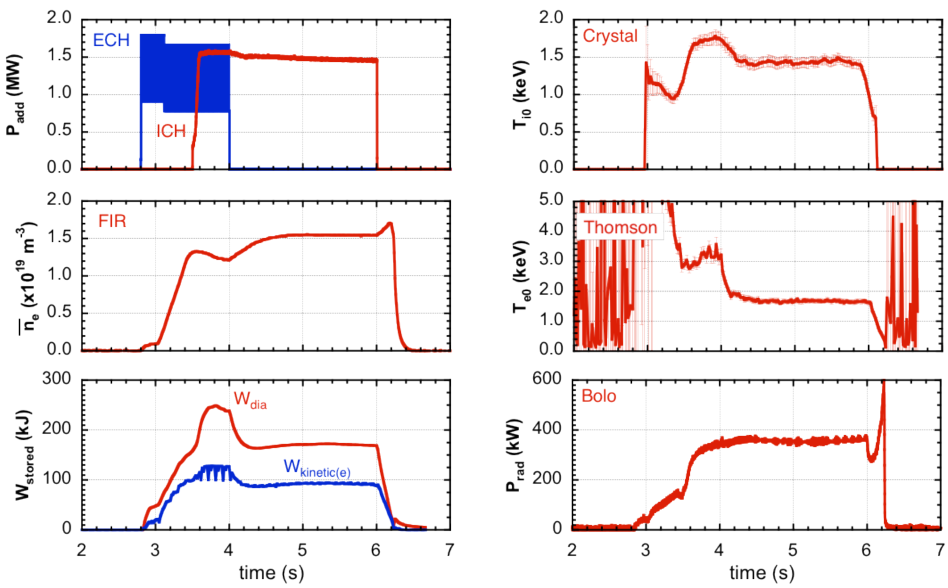

Figure 2. Initial ICH experiment using the HAS antenna with the reverse-phase, and the ICRF power of 1.5 MW sustains the stable helium plasma (hydrogen minority) with n_{e0} of $1.5x10^{19}$ m^{-3}, T_i of 1.8 keV and T_e of 1.5 keV.

the same plasma loading in the HAS antenna case. The decrement in the plasma loading is predicted, because the excited wavenumber with the reverse-phase is larger than that with the in-phase and that of the poloidal array antenna. Since an excited wave with large wavenumber can't propagate around plasma edge with the lower density than L cut-off density, and this operation with the large wavenumber decreases in a plasma loading and edge plasma damping. Figure 2 shows stable helium plasma as a hydrogen minority and the discharge is sustained only by using ICRF with the revere-phase and the power of 1.5 MW. The plasma parameters are as follows: the centre electron density n_{e0} of $1.5x10^{19}m^{-3}$, the core plasma temperature T_{e0} of 1.8 keV and T_{i0} of 1.5 keV during ICH.

Figure 3 shows the heating efficiencies (η) in various toroidal phases, and it is estimated by using the RF power modulation [6].

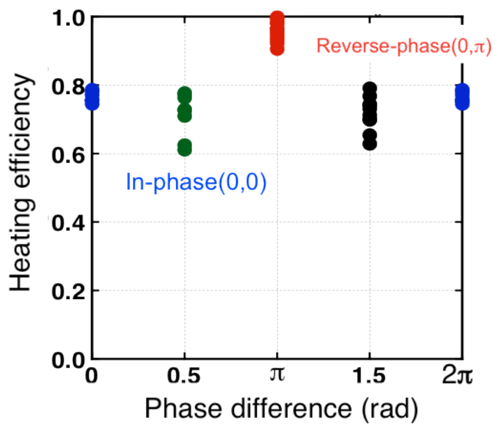

Figure 3. Comparistion with various toroidal phases, the heating efficiencies with the reverse-phase is higher than those with the other toroidal phases for the HAS antenna.

$$\eta = \frac{\omega_{\mathrm{mod}}}{\sin\delta}\frac{|\delta W_p|}{|\delta P_{ICH}|} \quad \ldots \; (1)$$

In equation (1), the ω is modulation frequency and the δ is the phase difference between the RF power rising and the increases in the stored energy. The W_p is the stored energy, and P_{ICH} is the injected ICRF power. The heating efficiencies using the HAS antenna in various toroidal phases are large, and relatively higher density plasma can sustain for the similar RF injection power using the poloidal array antenna in LHD. The heating efficiency with the reverse-phase is particularly-highest and the good heating efficiency is achieved like the prediction of that a fast wave with large wavenumber causes good core plasma heating.

In quasi-steady-state discharges (~ a few minutes) using the HAS antenna, local heat flux on the carbon protectors for the antenna is decreased, and the divertor temperature around the antenna is reduced. Figure 4 shows the toroidal and poloidal geometries of thermocouples on the divertor tiles and the increment in the thermocouple temperatures for the poloidal antenna (B) and the HAS antenna with reverse-phase (C). On the poloidal antenna, the increment in the temperature around the antenna is large, and the local the temperature goes up to 300 degrees C by the injection power of 350 kW. In the HAS

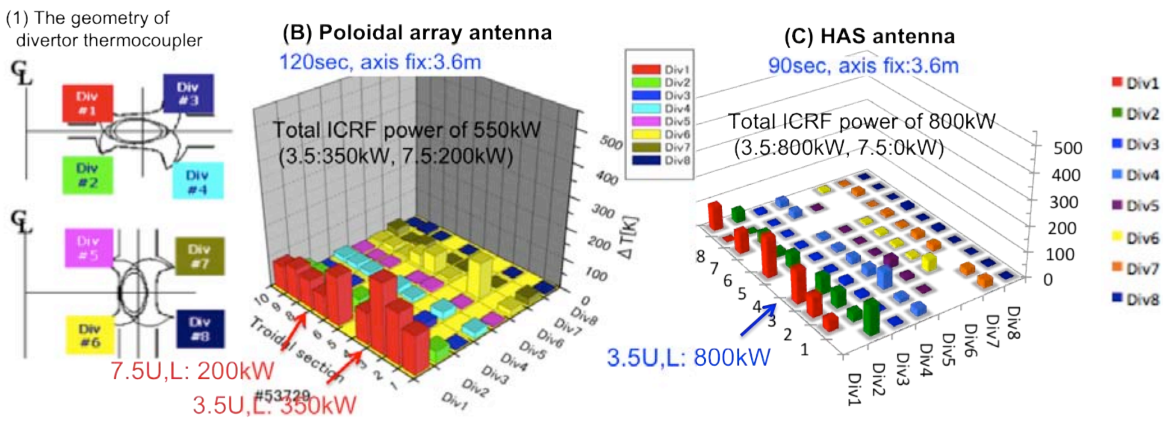

Figure 4. Comparing with local heat flux by using the thermocouples on the divertor tils between the poloidal array antenna (B) and the HAS antenna(C). The left figures (1) show the geometry of divertor thermocouple position. The thermocouples of Div1 ~ Div4 are installed in the horizontally long cross section, and the others of Div 5 ~ Div8 are installed in the vertically long cross section. ICRF antennas are installed in the vertically long cross section at toroidal port 3, and for poloidal array antenna experiment the other one-pair poloidal antenna is additionally installed at port 7.

antenna experiments, the heat-removable-ability of the divertor is improved, and the increment in the temperature goes down to 250 degrees C by that of 800 kW which is twice in the poloidal antenna.

4. Discussion and Summary

The toroidal phasing antenna, the HAS antenna, is installed in LHD, and minority ion heating experiments in various toroidal phases have been studied. Compared with the poloidal array antenna, the heating efficiency using the HAS antenna with the reverse-phase is larger (>80 %), and the increment in the divertor temperature around the antenna is reduced from 300 degrees C to 250 degrees C in spite of the twice injected RF power, locally. These experimental results suggest that the reverse-phase heating is useful to reduce the edge plasma heating which is related to increase in local divertor heat flux around the antenna, and it is important to carry out the succeed at a stable long pulse discharge.

Acknowledgement

We would like to thank the technical staff and collaborators of RF heating experiments for their effort to support the experiment in LHD. This work is supported by NIFS10URR003 and NIFS10URR701.

References

[1] R. Kumazawa, T. Mutoh, K. Saito, Y. Nakamura, et al., *Nucl. Fusion* **46**, S13-S21 (2006).
[2] H. Kasahara, T. Seki, K. Saito, R. Kumazawa, T. Mutoh, et al., *Fusion Eng. Des.* **83**, 253-255 (2008).
[3] H. Kasahara, T. Seki, K. Saito, R. Kumazawa, T. Mutoh et al., *Plasma Sci. and Technol.* **12**, 15-19 (2010).
[4] H. Kasahara, T. Seki, K. Saito, R. Kumazawa, T. Mutoh et al., *Plasma and Fus. Res.* **5**, S2090 (2010).
[5] S. J. Wukitch, B. LaBombard, Y. Lin, et al., *Jounal. Nucl. Material* **390-391**, 951-954 (2009).
[6] Y. Torii, T. Watari, R. Kumazawa, K. Saito et al., *Plasma Phys. Control. Fusion* **43**, 1191-1201 (2001).