ICRF Heating Experiment on LHD in Foreseeing a Future Fusion Device*)

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Plasma heating experiment using the ion cyclotron range of frequencies (ICRF) heating has been carried out. Aiming at the high power and long pulse heating and application to the future fusion device, the antenna without Faraday shield was tested and newly developed antenna, called FAIT antenna, was used. Steady state experiment was progressed by using the high power ICRF heating with those antennas. Plasma discharge length about 48 minutes was achieved with the heating power of 1.2 MW and a line-averaged electron density of 1.2×10^{19} m^{-3}. The injected heating energy reached 3.36 GJ and it is highest in the fusion plasma experiments. We will promote the high power steady state research involving the evaluation of the antennas and heating performance.

Keywords: ICRF heating, ICRF antenna, Faraday shield, LHD, steady state operation

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1. Introduction

Ion cyclotron range of frequencies (ICRF) heating is one of the important tools for the Large Helical Device (LHD) [1, 2] and future fusion devices. On the other hand, there are many technical and engineering problems in the ICRF antennas in considering the application to the fusion devices.

One of the problems is impurity influx with injection of the ICRF power to the plasmas. This problem was serious from early phase of the ICRF heating experiment in the fusion plasma research. It was thought that the parallel RF electric field to the magnetic field line near the antenna was the cause of the impurity influx. Then, the Faraday shield (FS) was considered necessary to block such an electric field. FS has many small and complicated elements. Cooling structure is required for long pulse operation and future fusion devices. If it is possible to remove the FS, the design and manufacturing become much easier. The ICRF heating experiments using the FS less antenna have been carried out in tokamak devices [3–6]. Those results were different from the device-to-device and the pulse length was short. Therefore, high power and long pulse experiments have been awaited. We removed a Faraday shield of upper antenna of existing Poloidal Array (PA) antenna.

Another important subject in the fusion reactor is high-power injection per antenna because the number of the port for the plasma heating devices will be limited in the reactor. Then, we developed a new antenna for high power and steady state heating. This antenna is characterized by the field-aligned structure at the antenna head and an impedance transformer between the antenna head and the vacuum feedthrough. Thus, we named the new antenna FAIT antenna.

Using the PA antennas with and without FS, and FAIT antennas, and HAS antennas, higher power was injected and parameter region of the steady state plasma was extended. The HAS antenna has two straps in toroidal direction and the parallel wave number is controllable [7]. The maximum ICRF power increased from 3 MW to 3.3 MW in short pulse length to date. The ICRF power for the long pulse operation increased from 0.4 MW to 0.9 MW.

In Section 2, experimental results of the FS less antenna will be presented. The feature and experiment of the FAIT antenna are described in Section 3. The experimental results using FS less antenna and FAIT antenna will be shown in Section 4. Progress of steady state operation will be remarked. Summary will be presented in Section 6.

2. Experiment Using Faraday Shield Less Antenna

A Faraday shield of upper antenna of PA antennas was removed as shown in Fig. 1 for investigation of the influence of FS. The wave frequency was 38.47 MHz and the magnetic field was 2.75 T. The minority heating scheme in the helium majority and hydrogen minority plasma was used. By removing the FS, the vacuum loading resistance was reduced to 0.422 ohm from 0.750 ohm. Comparing upper and lower antenna, plasma loading resistance with

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Fig. 1 Photo of the PA antenna without FS (upper) and with FS (lower).

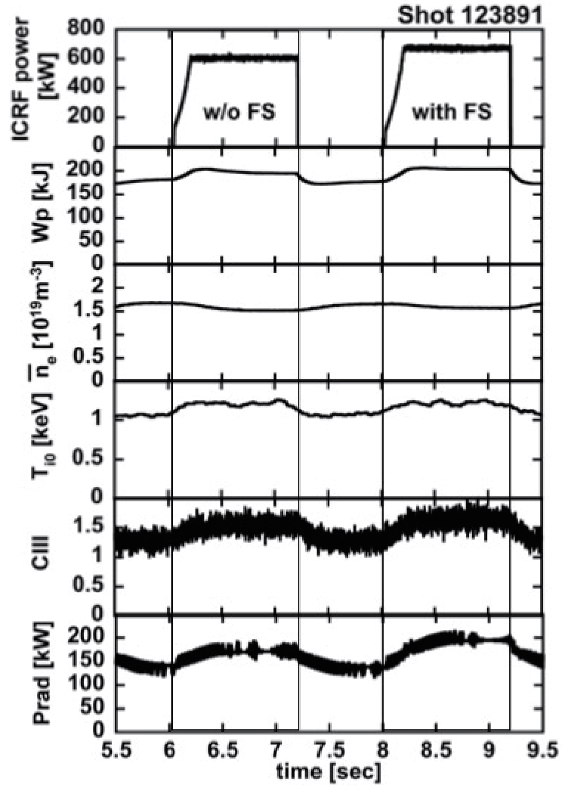

Fig. 2 Time evolution of ICRF power, plasma stored energy, line-averaged electron density, ion temperature, CIII intensity, and radiation loss power in comparison of with and without FS antenna.

and without FS antenna was investigated. The plasma loading resistance without FS was higher than that of with FS antenna by 1.3 times or more. This means that the higher power can be injected from the antenna without FS if the same forward power is supplied from the RF transmitter.

Time evolution of the plasma parameters was compared in the same plasma discharge as shown in Fig. 2. The plasma was sustained by ECH and ICRF heating using the other ICRF antennas. Almost same ICRF power of about 600 kW was injected from the each antenna. Almost same behaviors were seen in the plasma stored energy, line-averaged electron density, and ion temperature. Increases of CIII intensity and radiation loss power are slightly smaller in the case of without FS in this discharge. Particularly harmful influence was not observed during the injection from the antenna without FS.

3. Characteristics and Experiment of FAIT Antenna

FAIT antenna was manufactured and installed in LHD as shown in Fig. 3 with the aim of a high power and steady state heating [8].

Head of the FAIT antenna is tilted 12 degrees and the current strap is aligned vertical to the magnetic field line. This field-aligned structure has advantages for reducing the impurity influx and so on as reported from the Alcator C-Mod [9]. The length of the current strap is 39 cm and shorter than that of the existing antennas. The short strap length has advantage to reduce the voltage increase at the current strap.

The impedance transformer is incorporated at the inside of the transmission line between the antenna head and the vacuum feedthrough. In practice, the diameter of the inner conductor was modified to increase the loading resistance and reduce the RF voltage of the transmission line and feedthrough. The optimization was carried out at the frequency of 38.5 MHz. The engineering design value of the maximum injection power per strap is 1.6 MW.

Figure 4 compares the plasma loading resistance of FAIT antenna with that of HAS antenna. The HAS antenna has the same strap width and longer strap length than that of the FAIT antenna [7]. So, the shorter strap length of FAIT antenna reduces the antenna loading resistance. However, the plasma loading resistance of the FAIT antenna is higher than that of the HAS antenna. This means that the higher power is possible to be injected and the impedance transformer works well as we expected.

The optimization of the impedance transformer was done so as to reduce the RF voltage around the vacuum feedthrough also. This effect was observed in a temperature increase of the vacuum feedthrough. The power normalized temperature rise of the FAIT antenna was about one-third of that of the HAS antenna. The temperature increase during the long pulse discharge was extremely reduced and this is significant contribution of the impedance transformer.

Fig. 3 Photo of the FAIT antenna.

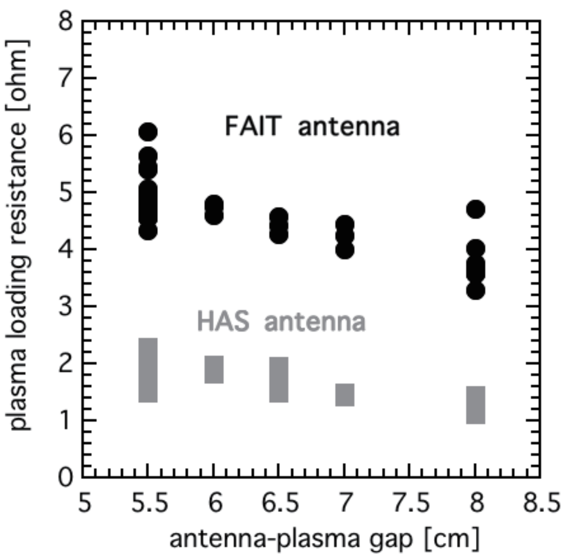

Fig. 4 Comparison of the plasma loading resistance of the FAIT antenna and the HAS antenna as a function of the antenna-plasma gap.

4. ICRF Heating Results with Faraday Shield Less Antenna and FAIT Antenna

The FS less antenna and the FAIT antenna were used for the high power and steady state experiments similar to other antennas. The maximum injected power of the FS less antenna and the FAIT antenna was 0.8 MW and 1.1 MW per strap to date. The total injected power reached about 3.3 MW.

In the long pulse discharge, the FS less antenna and

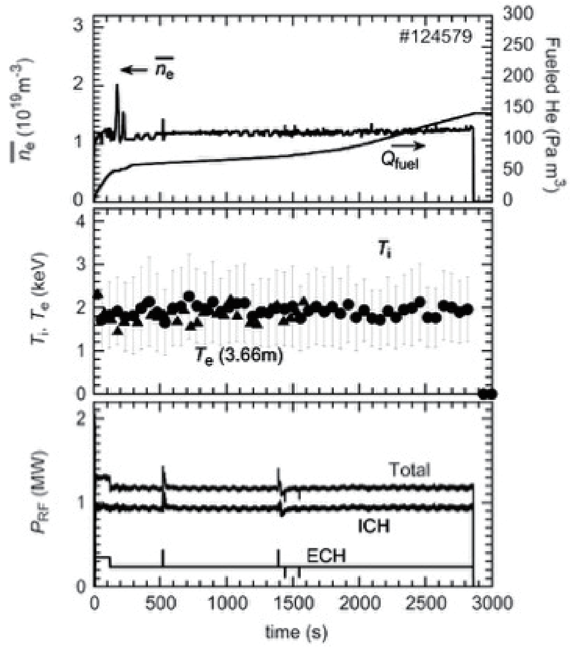

Fig. 5 Time evolutions of the plasma parameters during the 48 minutes discharge.

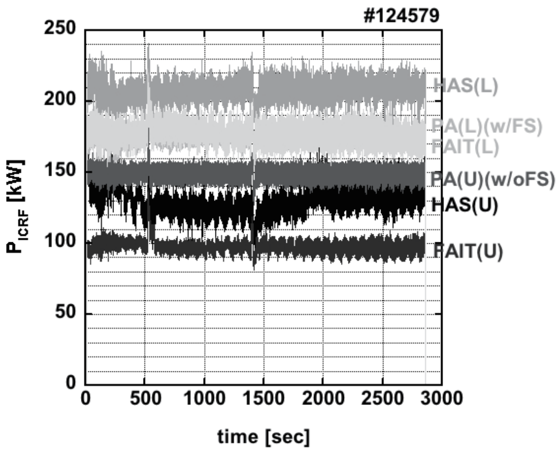

Fig. 6 Injection power of the ICRF antennas during the 48 minutes discharge.

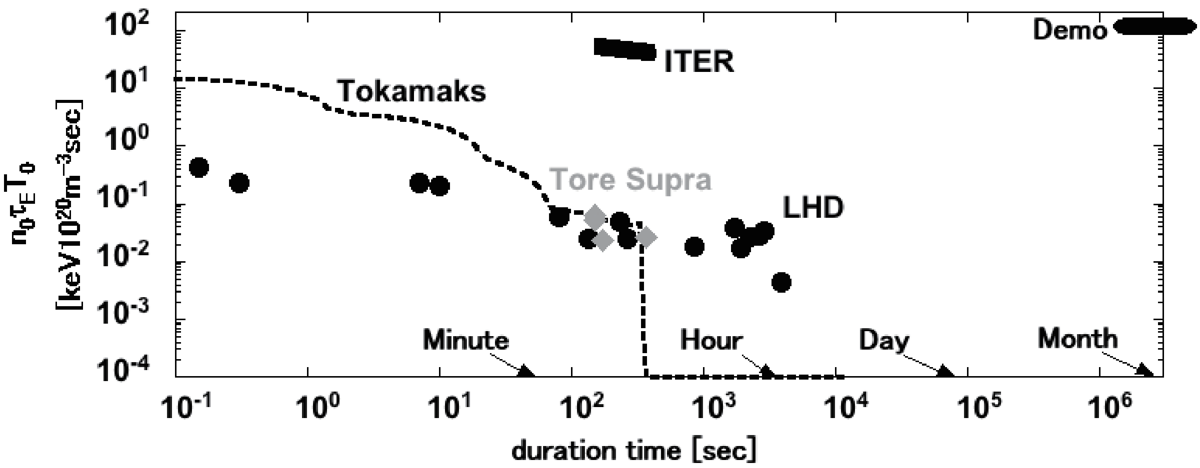

Fig. 7 Achieved fusion triple product as a function of the plasma duration time.

FAIT antenna were also used and contributed to the extension of the parameter region of the steady state discharge. Figure 5 shows the time evolution of plasma parameters during the 48 minutes operation. The line-averaged electron density and ion and electron temperatures were kept constant. Details of the ICRF power were shown in Fig. 6. Maximum of six antennas was used for the first time and the power was scattered to each antennas almost equally. With respect to the PA(U) antenna, the injection power during the long pulse operation was limited to below about 50 kW before removing the FS because the arcing occurred between the FS and the current strap. After removing the FS, the arcing did not occur. The injection power of FAIT(U) antenna was smaller because the transmitter had a problem. The total ICRF power reached 0.9 MW. In this discharge, the line-averaged electron is 1.2×10^{19} m^{-3} and ion and electron temperatures are 2 keV. The heating power of 1.2 MW was injected and the plasma duration time was 47 minutes and 39 seconds. The injected heating energy reached 3.36 GJ and this is the highest value in the fusion plasma experiments. Plasma was terminated by the intensive and continuous impurity influx. It originated at the mixed-material layers and the layers grew during the long pulse operation.

Figure 7 shows the fusion triple product as a function of the plasma duration time. Envelope of tokamak experiments and Tore Supra results are plotted together. The plasma duration time progressed step by step in LHD. Higher performance experiments are awaited.

5. Summary

ICRF heating using Faraday shield less antenna and FAIT antenna was carried with a view to applying to a future fusion device. Both antennas showed good results and contributed to the high power and steady state operation. The plasma parameters during the steady state operation were extended with high heating power and the highest injected heating energy was achieved. Steady state experiments are developed steadily but further progress of the plasma parameters and duration time is required.

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[1] O. Kaneko *et al.*, Nucl. Fusion **53**, 104015 (2013).
[2] K. Saito *et al.*, J. Nucl. Mater. **363-365**, 1323 (2007).
[3] R. Van Nieuwenhove *et al.*, Nucl. Fusion **32**, 1913 (1992).
[4] J. Sorensen *et al.*, Nucl. Fusion **33**, 915 (1993).
[5] J.-M. Noterdaeme *et al.*, AIP Conf. Proc. **355**, 47 (1995).
[6] D.W. Swain *et al.*, Nucl. Fusion **37**, 211 (1997).
[7] H. Kasahara *et al.*, Plasma Fusion Res. **5**, S2090 (2010).
[8] K. Saito *et al.*, Fusion Eng. Des. **88**, 1025 (2013).
[9] M. Greenwald *et al.*, Nucl. Fusion **53**, 104004 (2013).