Upgrade of ICRF Antennas by Utilizing Impedance Transformers in LHD*)

Kenji SAITO[1,2], Tetsuo SEKI[1], Hiroshi KASAHARA[1], Ryosuke SEKI[1,2], Shuji KAMIO[1], Goro NOMURA[1] and Motonari KANDA[1]

[1] *National Institute for Fusion Science, National Institutes of Natural Sciences, Toki, Gifu 509-5292, Japan*
[2] *Department of Fusion Science, The Graduate University for Advanced Studies, SOKENDAI, Toki, Gifu 509-5292, Japan*

(Received 26 December 2021 / Accepted 2 February 2022)

For the high-power and long-pulse ion cyclotron range of frequencies (ICRF) heating of plasma in the Large Helical Device (LHD), two types of ICRF antennas are used. One is the Field-Aligned-Impedance-Transforming (FAIT) antenna. It has an In-Vessel Impedance Transformer (IVIT) in the vacuum region of the antenna and shows the possibility of high-power injection despite the short antenna head. To enhance the performance more, an Ex-Vessel Impedance Transformer (EVIT) was attached outside the LHD vacuum vessel. As a result, the injectable power increased. The other is the Handshake form (HAS) antenna. Plasma can be efficiently heated by adjusting the phase difference between currents in straps. However, the injectable power from the HAS antenna was originally small. Therefore, later an EVIT was attached to it. Moreover, the transmission line in the vacuum region was remodeled to form an IVIT. By utilizing these impedance transformers, the performance of the HAS antenna was drastically improved.

Keywords: ICRF heating, FAIT antenna, HAS antenna, IVIT, EVIT, LHD

DOI: 10.1585/pfr.17.2405009

1. Introduction

One of the plasma heating methods in the Large Helical Device (LHD) [1] is Ion Cyclotron Range of Frequencies (ICRF) heating. This is a method of plasma heating using electromagnetic waves emitted from antennas. Currently, there are two types of ICRF antennas installed in the LHD as shown in Fig. 1. One is the Field-Aligned-Impedance-Transforming (FAIT) antenna [2], and the other is the Handshake form (HAS) antenna [3]. In this paper, we describe the development of the FAIT antenna and the subsequent improvement of the HAS antenna. The ICRF heating equipment for the LHD was originally designed with specifications for a wide frequency range from 25 to 100 MHz. In particular, it has been confirmed that minority ion heating at 38.47 MHz heats the plasma efficiently [4, 5], and a world record on the injected energy in a long-pulse operation has been achieved [6]. However, in the electron heating using mode converted ion Bernstein waves [4, 7] or in the herium-3 heating with three ion-species [8], the frequency must be lowered to approximately 25 - 28 MHz. At such a low frequency, a high-power operation is not possible because the voltage in the transmission line increases and the electrical breakdown in insulators is likely to occur. Therefore, a project was started in 2011, where ICRF heating devices were optimized for a high-power and long-pulse operation by abandoning scenarios of the mode conversion heating and the helium-3 heating, and specializing in the proven frequency of 38.47 MHz. Although there was a scenario of second harmonic heating of light hydrogen using a high frequency of around 77 MHz, the second harmonic heating can also be performed at a frequency of 38.47 MHz with deuterium. First, the FAIT antenna with high-power capability was born in this project by adopting a newly devised In-Vessel Impedance Transformer (IVIT) [9]. An Ex-Vessel Impedance Transformer (EVIT) [10] was also designed and installed to the FAIT antenna to increase high-

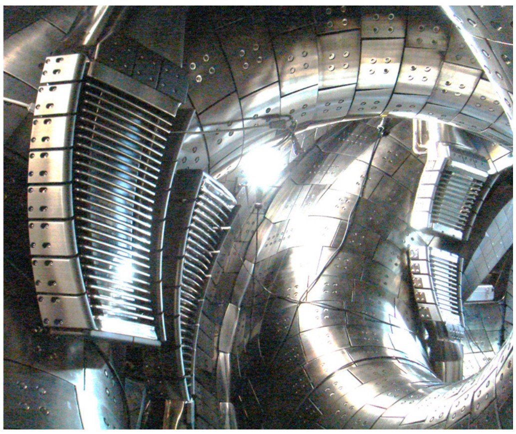

Fig. 1 Heads of HAS antenna (left hand side) and FAIT antenna (right hand side) in LHD vacuum vessel.

author's e-mail: saito@nifs.ac.jp

*) This article is based on the presentation at the 30th International Toki Conference on Plasma and Fusion Research (ITC30).

power capability further. High-power capability is preferable not only for high-power injection but also for safe operation. The technology of these two types of impedance transformers developed for the ICRF heating in LHD is also useful for other fusion devices, and it was adopted in Compact ICRF Antenna (CIA) in the Korea Superconducting Tokamak Advanced Research (KSTAR) with some modifications [11,12]. In section 2, the development of the FAIT antenna will be described. The improvement of the HAS antenna by adopting an EVIT will be shown in section 3. Upgrades of these antennas are concluded in section 4.

2. FAIT Antenna and the Improvement with EVIT

Loading resistance R is defined by the following equation:

$$P = P_\mathrm{f} - P_\mathrm{r} = \frac{1}{2}R\left(\frac{V_\mathrm{max}}{z_\mathrm{c}}\right)^2. \quad (1)$$

Where, P is the input power into the ICRF antenna, that is the difference between the forward power P_f and the reflected power P_r in the transmission line, and not only the injected power into plasma but also the power loss at the antenna is included slightly in this definition. V_max is the maximum voltage on the transmission line with the characteristic impedance z_c that is 50 Ω in the LHD. High voltage in the transmission line causes the electrical breakdown in the insulator in the line. Large loading resistance is preferable since the input power increases with fixed voltage, or voltage decreases with fixed power. Therefore, the distance between the antenna head and the plasma should be as small as possible to increase the loading resistance [13,14]. Another advantage of the narrow gap between the antenna head and the plasma is avoidance of the local heat load on divertor plates and the chamber wall. With the experiments using former ICRF antennas, the increase of temperatures on divertor plates and the chamber wall near the ICRF antennas reduced to less than half by decreasing the distance Δ between the Faraday shield in antennas and the last closed flux surface of the plasma in the mid plane in front of the ICRF antennas from 12 cm to 6 cm [15]. This may be due to the decrease of the number of accelerated particles in front of the antennas [16]. Therefore, the front shape of the antenna head of the FAIT antenna was designed to keep the narrow gap of 1.8 cm between the side limiter and the ergodic layer with the connection length from wall to wall of more than 12.5 m by tracking the magnetic field line of a typical magnetic configuration where the major radius of the magnetic axis is 3.65 m. Then the distance Δ is 5.8 cm. Figure 2 shows the upper and lower FAIT antennas. The distance Δ is changeable by swinging the antenna head around the pivot. To protect the ceramic feedthrough, which separates the internal vacuum region and the external pressurized region, and to increase the loading resistance, a transmission line in the vacuum region forms an IVIT, which is optimized at the frequency of 38.47 MHz. From the experimental results, for a short pulse operation, input power of 2 MW per antenna is expected with the standard loading resistance of 6.8 Ω at a distance Δ of 6 cm with the line-averaged electron density of $2 \times 10^{19}\ \mathrm{m}^{-3}$ and the maximum applied voltage ever of 38.5 kV on the transmission line. However, the possibility of breakdown in the transmission line is too high with the voltage of 38.5 kV. Once electric breakdown occurs in the pressurized region, withstand voltage does not recover, unlike in the vacuum region. We normally set the interlock level at 35 kV and operate with a voltage of less than 30 kV for safe operation. To achieve power of 2 MW with a voltage of 30 kV instead of 38.5 kV, loading resistance must be increased 1.6 times larger according to Eq. (1). Therefore, an EVIT was developed to increase the loading resistance, that is to increase the output power with lower voltage on the transmission line. According to calculation, the loading resistance increases by a factor of 2.5 [10]. In 2019, the EVIT was attached to the FAIT antenna outside the LHD. Figure 3 shows the relation between the distance Δ and the loading resistance R. In these experiments, line-averaged electron density was in the range of $0.8 - 1.5 \times 10^{19}\ \mathrm{m}^{-3}$, the major radius of the magnetic axis was 3.6 m and the strength of the magnetic field on the axis was 2.75 T. Only a lower FAIT antenna was used because the loading resis-

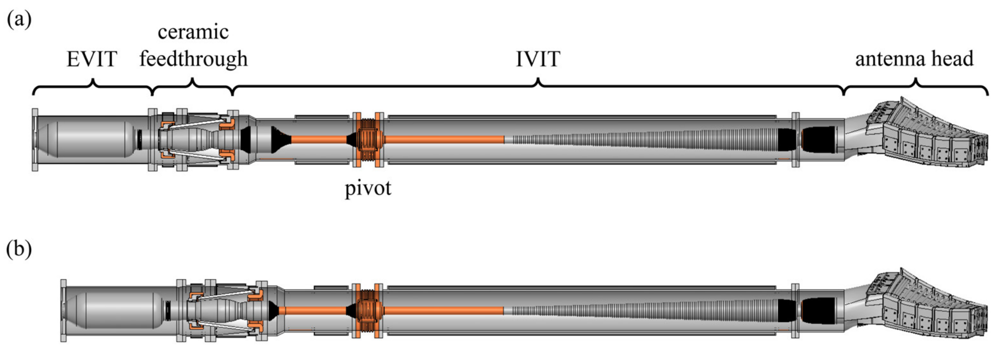

Fig. 2 Inside of transmission line in FAIT antenna for (a) upper port and (b) lower port. They have different structures between ceramic feedthrough and pivot due to difference of length between LHD port and antenna head by 15 cm. The orange parts consist of cupper or copper-plated stainless steel for the suppression of the heat generation and for the heat removal.

tance depends on the power ratio and the difference of current phases between upper and lower antennas due to the mutual coupling. The former data 'without EVIT' were obtained in a series of experiments, whereas the new data 'with EVIT' were obtained in various plasma discharges and timings. Therefore, other parameters such as density profile were not fixed in the new data, which caused the scattering in the loading resistance. With the EVIT, the loading resistance was drastically increased. Although, there was some scattering in the loading resistance with the EVIT, the increase factor was reasonable compared to the

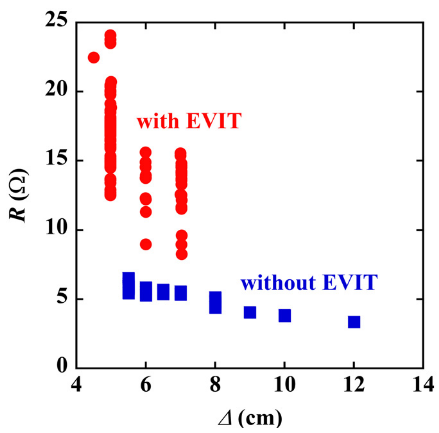

Fig. 3 Increase of loading resistance by EVIT on FAIT antenna (lower port antenna). Data on 'without EVIT' are same as those in reference 10 and loading resistances for 'with EVIT' (shot numbers: 154899-166473) are registered in LHD experiment data repository (https://www-lhd.nifs.ac.jp/pub/Repository.html) with the diagnostics name of ICH-DC45.

simulated increase factor of 2.5. Therefore, the high power of 2 MW per antenna will be possible in a short pulse operation.

3. HAS Antenna and the Improvement with IVIT

The HAS antennas were installed in the LHD in 2010 and it was clarified that high efficiency of plasma heating could be attained by adjusting the phase difference of the current flowing in the straps in the two antenna heads [17]. However, they were originally not suitable for high-power operation due to their small loading resistance. To increase the loading resistance, in 2014 the EVIT was installed, and it was confirmed that the loading resistance was approximately doubled [10]. However, the EVIT cannot improve the performance of the antenna in the vacuum region. In 2010, the ceramic feedthrough in the lower port HAS antenna was cracked, probably by the arcing at the feedthrough. Moreover, temperature rise around ceramic feedthrough per injected power was approximately three times higher than that of the FAIT antenna during a long-pulse operation [2]. To solve these problems, as well as to attain larger loading resistance for a safe and high-power operation, HAS antennas were improved by adopting IVITs according to the design in reference 9, which were optimized at the frequency of 38.47 MHz as FAIT antennas. By using HFSS (High Frequency Structure Simulator, ANSYS), electromagnetic simulation was conducted for the lower port antenna, as shown in Fig. 4 with an impedance of $40.5 + 212.1\,j\,\Omega$ at the inlet of the antenna head. With this impedance, the loading resistance of the original HAS antenna with neither the IVIT nor the EVIT was the same

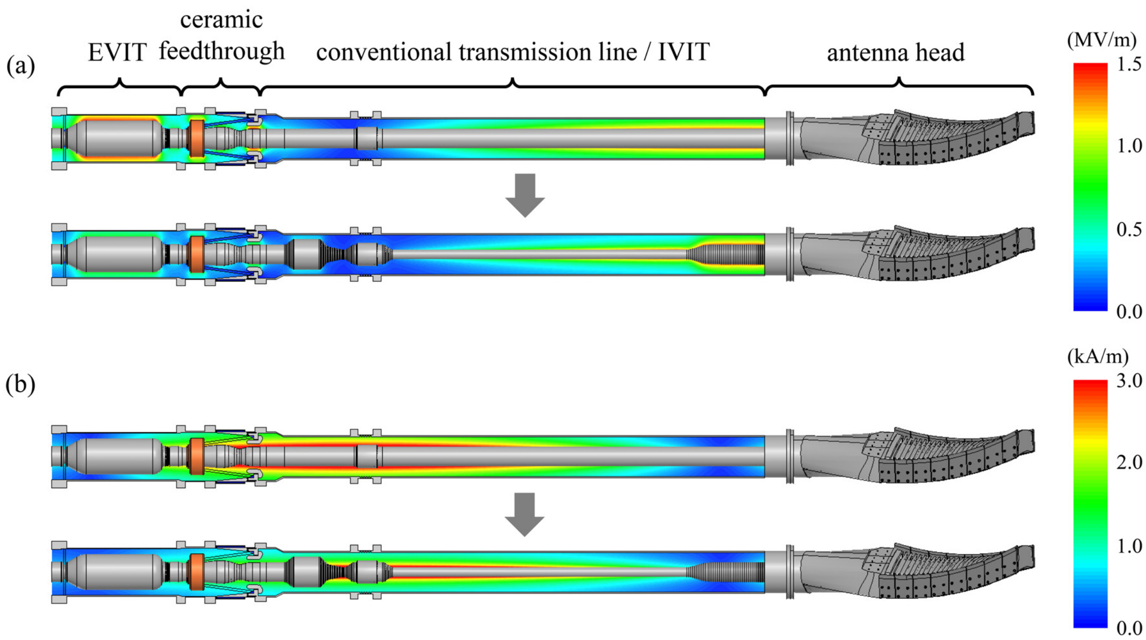

Fig. 4 Simulation of electromagnetic field in transmission line in HAS antenna (lower port antenna) before and after improvement with IVIT. (a) Amplitude of electric field. (b) Amplitude of magnetic field. Input power at the inlet of EVIT is 1 MW.

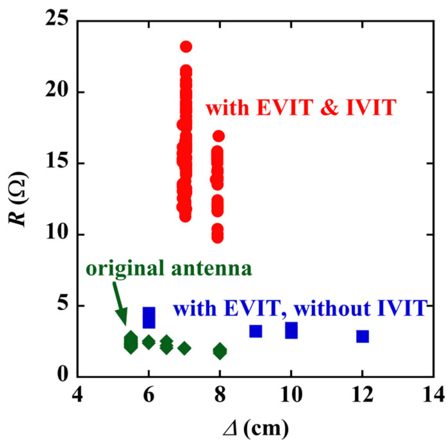

Fig. 5 Increase of loading resistance by EVIT and IVIT on HAS antenna (lower port antenna). Data on 'original antenna' and 'with EVIT, without IVIT' are same as those in reference 10 and loading resistances for 'with EVIT & IVIT' (shot numbers: 162633-169943) are registered in the LHD experiment data repository (https://www-lhd.nifs.ac.jp/pub/Repository.html) with the diagnostics name of ICH-DC35.

as the experimentally obtained loading resistance of 2.3 Ω at around Δ = 6 cm, as shown in Fig. 5, and the voltage node position on the transmission line was the same as that of vacuum injection. The simulations showed that for the same input power, both the current and the voltage in the ceramic feedthrough were halved by the improvement. In addition, the loading resistance became four times higher and the power-loss ratio in the coaxial transmission line from the inlet of the EVIT to the inlet of the antenna head reduced to 40% of the original power-loss ratio of 0.068. The improved HAS antenna was installed in the LHD in 2020 and started to be used for ICRF heating experiments. As shown in Fig. 5, it was confirmed that the loading resistance R was increased by almost the same factor as the simulation, compared to that before the upgrade with the IVIT, though there was some scattering. In these experiments, only the lower HAS antenna was used, and the major radius of the magnetic axis and the strength of the magnetic field on the axis were fixed at 3.6 m and 2.75 T, respectively. The line-averaged electron density was in the range of 0.8 - 1.5×10^{19} m^{-3}. Scattering in the loading resistance in the new data 'with EVIT & IVIT' was caused by the scattering of other parameters, for the new data were gathered from various discharges and timings. Since the experimental result on the loading resistance agrees with the simulation, the lower voltage and current at the ceramic feedthrough and the higher transmission efficiency are also expected, as in the simulation. The IVIT in the upper port antenna has the same structure as that in the lower port antenna, since the length between the port and antenna head differs by only 7 cm. The upper port antenna also showed high loading resistance as the lower port antenna. In experiments, the input power of 1 MW/antenna was attained with the maximum voltage on the transmission line below 25 kV.

4. Conclusion

Two types of impedance transformers enhanced the performance of ICRF antennas in the LHD. For the reduction of voltage in the transmission line, an EVIT was installed to the FAIT antenna. Experiments showed that the loading resistance increased as expected by electromagnetic simulation. The loading resistance of the HAS antenna was originally low. Therefore, an EVIT was attached to the HAS antenna and the loading resistance was doubled. For the improvement of the HAS antenna in the vacuum region, except the antenna head, and for the further increase of the loading resistance, the inner conductor in the vacuum region was remodeled to form an IVIT. The measured loading resistance was increased as electromagnetic simulation. These upgrades with impedance transformers on the FAIT and HAS antennas enabled the higher-power operation of ICRF heating in the LHD.

Acknowledgments

The authors thank the LHD experiment group members and technical staff members for their contributions to this work.

[1] Y. Takeiri *et al.*, Nucl. Fusion **57**, 102023 (2017).
[2] K. Saito *et al.*, Fusion Eng. Des. **96-97**, 583 (2015).
[3] H. Kasahara *et al.*, Proc. 38th EPS Conf. Strasbourg, P2.099 (2011).
[4] K. Saito *et al.*, Nucl. Fusion **41**, 1021 (2001).
[5] K. Saito *et al.*, Fusion Sci. Technol. **58**, 515 (2010).
[6] K. Saito *et al.*, J. Nucl. Mater. **363-365**, 1323 (2007).
[7] K. Saito *et al.*, Proc. 17th Topl. Conf. Radio Frequency Power in Plasmas, Clearwater, Florida, p.71 (2007).
[8] K. Saito *et al.*, Plasma Fusion Res. **15**, 2402015 (2020).
[9] K. Saito *et al.*, Fusion Eng. Des. **88**, 1025 (2013).
[10] K. Saito *et al.*, Journal of Physics: Conf. Series **823**, 012007 (2017).
[11] K. Saito *et al.*, Fusion Eng. Des. **154**, 111496 (2020).
[12] H.Y. Lee *et al.*, J. Korean Phys. Soc. **78**, 1067 (2021).
[13] S. Moriyama *et al.*, Jpn. J. Appl. Phys. **44**, 6224 (2005).
[14] T. Seki *et al.*, Plasma Fusion Res. **5**, S2101 (2010).
[15] K. Saito *et al.*, NIFS annual report 2005-2006, p.131.
[16] K. Saito *et al.*, J. Nucl. Mater. **337-339**, 995 (2005).
[17] S. Kamio *et al.*, Proc. 42nd EPS Conf. Lisbon P5.154 (2015).