J. Plasma Fusion Res. SERIES, Vol.1 (1998) 334–337

# Development and Fabrication of Steady State Fast Wave Antenna for LHD

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(Received: 30 September 1997/Accepted: 22 October 1997)

## Abstract

The ICRF antenna for LHD has been developed and tested in a test stand. All parts of the antenna system was originally designed to stand for the high voltage and the high heat load from the plasma and the RF dissipation loss during long operation time. In the test stand the R&D antenna consisting of these parts is tested for the steady state operation of 30 minutes at the antenna current of 800 A successfully. Ceramic feedthroughs of several types were newly designed and tested for the RF voltage of above 40 kV in steady state. These results are incorporated in the design and fabrication of the real plasma heating antenna of LHD. A pair of the fast wave antennas for LHD is fabricated. These antennas are the largest ones for the helical device and are also the first trial device to carry out the really steady state heating of above 1 MW. The launcher section is designed to fit the plasma surfaces and the magnetic field of LHD. The swing motion of the antenna can change its position to control the plasma coupling and the heat load. The heat load of the steady state operation is the serious problem. The ANSYS heat conduction calculation of the carbon protectors shows the antenna position control is very effective to reduce the heat load of the protectors.

## Keywords:

ICRF heating, LHD, steady state heating, ICRF antenna, ceramic feedthrough, fast wave heating

## 1. Introduction

The ICRF heating of LHD is planned to start within a year from the first plasma. In LHD, two kinds of ICRF launcher has been designed and fabricated. One is the fast wave loop antenna[1] and the other is the folded wave guide antenna[2]. The fast wave antenna is planned to be used as the one of the steady state heating tools. Steady state plasma heating and sustaining is one of the main programs of the LHD having superconducting magnetic windings. The development program of the required RF technology was started in 1993. All parts of the system have been newly designed and tested. The R&D results concerning the transmitter, the transmission line, the impedance matching stubs and the R&D antenna were already reported[3-4]. The main specifications of the fast wave ICRF antenna are listed in Table 1.

## 2. R&D of Steady State Antenna Technology

Many developing items were tested in the ICRF test stand consisting of the transmitter, the impedance matching circuits, the ceramic feedthrough, the vacuum chamber and the R&D antenna. The test circuit has no artificial dummy load, therefore the voltage standing wave ratio (VSWR) between the antenna loop and the

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Table 1 LHD ICRF Fast Wave Antenna Specifications

| | |
|---|---|
| Frequency | 20-60 MHz |
| Type of antenna | single strap loop |
| Wave exciting side | mainly from high B field side |
| Sizes of loop section | 60cm(height), 46cm(total width) 30cm(center strap width) |
| Materials | stainless steel & CC composite |

first stub tuner is very large, around 200. To stand for the high RF voltage, the coaxial transmission line has the large diameter of 240 mm and it is filled with a sulfur hexafluoride ($SF_6$) or nitrogen gas of 3 atms. The efficient cooling system is inevitable for the steady state operation. Therefore the inner conductor has a cooling water channel inside through the test circuit. The coaxial transmission line is a demountabe system, so the connecting couplers were specially designed and used[3].

Due to the low loss and the high VSWR circuit, the high RF voltage and high current tests were carried out by the relatively low RF power for lower than 100 kW. The results of the high voltage and the long pulse operation is shown in Fig. 1. The left axis indicates the RF voltage on the ceramic feedthrough, it is almost the maximum point along the transmission line. The right axis indicates the RF current on the antenna loop and also equals to the maximum current value along the transmission line. The figure shows two series of tests using two different ceramic feedthroughs. In both cases, we successfully operated high voltage/current tests at around 40 kV/800 A. These operations were limited by the outgas from the vacuum chamber which finally caused the RF discharge and the impedance mismatching. The situation would be quite different with the LHD experiment in which the plasma coupling resistance of several ohms can be expected. This steady state operation test confirms the performance and the reliability of the present system design.

Various types of vacuum feedthrough ceramics were tested in the test stand. Four types of alumina ceramic feedthroughs and one type of a silicon nitride ($Si_3N_4$) composite ceramic feedthrough were tested. Among them two types worked very well. One is the cone type alumina ceramics having gas blowing cooling channels from the outside. The photograph of the cone type ceramic feedthrough is shown in Fig. 2. The shape of the ceramic is similar to that of the Princeton type. Another good type is the cylindrical shape and is made of silicon nitride composite ceramics. In this $Si_3N_4$ type, the vacuum sealing method is with a viton O-ring, while in the other cases the sealing method is brazing. These two types can stand for the RF voltage of over 38 kV for 30 minutes. On the contrary the other type feedthroughs (Disk type and Crank type) could not stand for 25 kV for 30 minutes. For the LHD antenna system, the cone type alumina ceramic feedthrough will be used at first.

## 3. Design and Fabrication of the LHD Fast Wave Heating Antenna

Results of the R&D experiment are translated to the design of the LHD heating antenna. One pair of the ICRF fast wave antennas for the LHD has been designed and fabricated. These antennas will be inserted from the top and the bottom vertical ports of the LHD

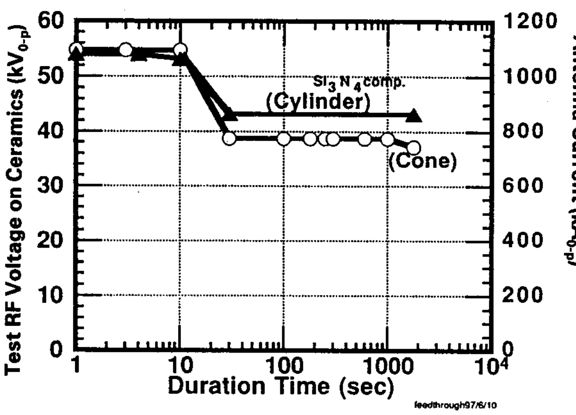


Fig. 1 Successful test records of R&D antenna are plotted. Two kinds of feedthrough were used in the tests.

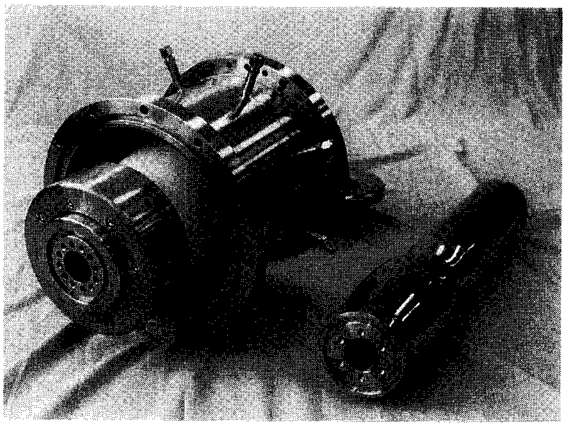

Fig. 2 Photograph of the cone type feedthrough. Gas cooling nozzles are located around the outer conductor.

vacuum chamber. The cross sectional view of LHD and one set of the fast wave antennas is shown in Fig. 3. Inside the chamber, loop section is located at the outward side of the toroid and the height from the launcher section to feedthrough is about 3.2 m. These antennas are designed to launch the high power of over 1 MW per each antenna loop for steady state of over 30 minutes. The LHD antenna has principally the same electrical and cooling structures as the tested R&D antenna.

The antenna structures inside the chamber can move to change the clearance between the plasma surface and the antenna Faraday screen by 0 to 15 cm. This movement is caused by the pivot motion and the length from the antenna top to the pivot point is about 3 m. In the R&D antenna, this kind of movement was checked during RF operation with no troubles. This motion will give us important advantages by controlling the antenna position to fit the LHD experimental plans. The relation of the launcher movement between plasma and the chamber wall is explained in Fig. 4. The positions of the plasma surface, the chamber wall and the antenna at the nearest and the farthest positions from the plasma are shown. This figure shows the separation eliminate the interaction with the plasma easily.

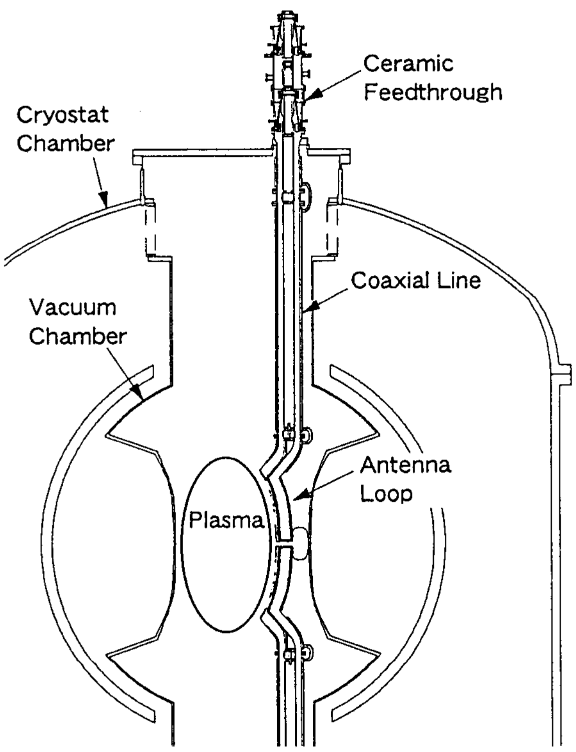


Fig. 3 Cross sectional view of the fast wave ICRF antenna in LHD.

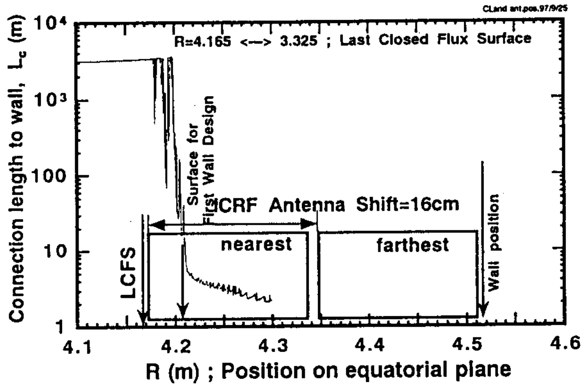


Fig. 4 Antenna moving range is shown in a equatorial plane. The nearest and the farthest positions of antenna are drawn by boxes.

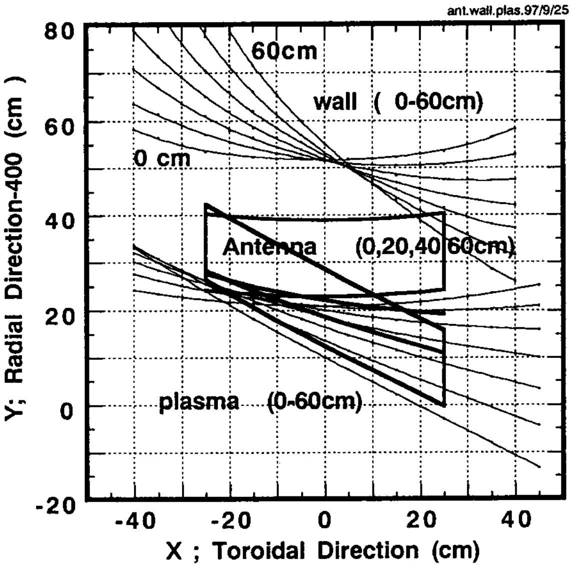


Fig. 5 The horizontal cross sectional cuts of the antenna, the plasma surface and the vacuum chamber wall at the different altitudes.

The cross sections of the antenna, the plasma surface and the vacuum chamber wall are shown in Fig. 5 at the different altitude planes from the equatorial plane. The loop section is twisted to fit the helically deformed LHD plasma. The configurations of the LHD magnetic surfaces can be controlled by changing the poloidal magnetic field. But the outer most closed magnetic surface especially on the high field side does not change much. So the fitting of the antenna shape to plasma surface is kept over a wide range of the configurations. The photograph of the antenna loop section without protectors is shown in Fig. 6. The antenna is

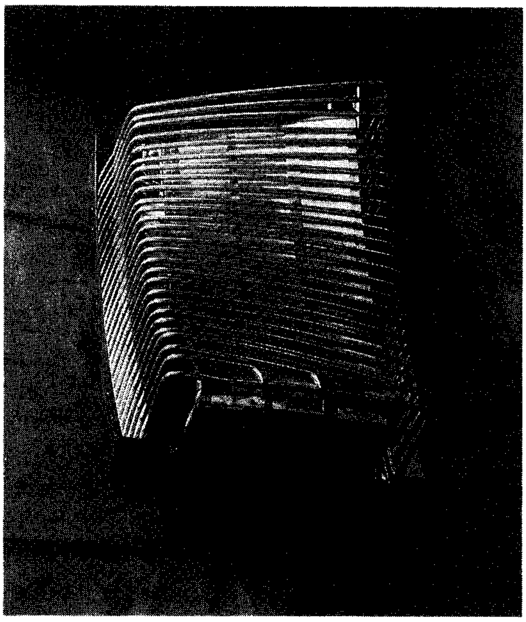

Fig. 6 Photograph of the loop section of the LHD fast wave antenna with Faraday screen pipes.

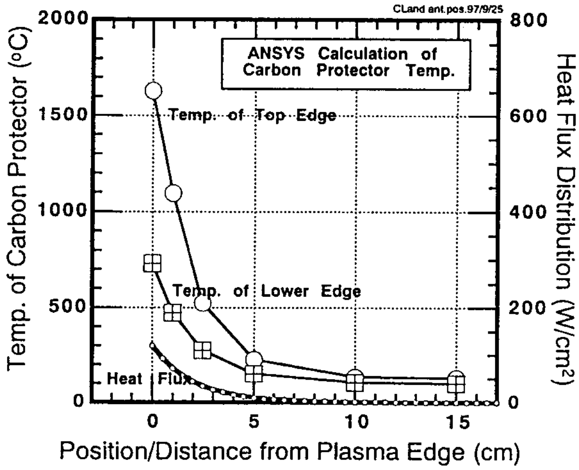


Fig. 7 Calculated temperature increments of the carbon side protector by ANSYS code are shown by changing the top edge position.

designed so that the circulating water removes the dissipated RF loss and the plasma heat load from all parts. The flow path continues through the outer conductor of the coaxial line, launcher return conductor, carbon side protector holder, Faraday screen pipes, center current strap and inner conductor of the coaxial line in series. The water flows on the path of a so-called "single stroke of the brush" to eliminate complicated piping structures outside.

## 4. Discussion and Summary

The experiments of the R&D antenna confirmed the performances of the cooling system for the RF dissipated power loss and of the high stand off voltage. But it does not include the plasma heat load. The total performance of the cooling system have to fit to the 3 MW steady state plasma heating. The severest heat load is the charged particle influx to the carbon protectors along the magnetic field lines on the both antenna sides. On the assumed heat load distribution, the temperature increments of the carbon plates are calculated by using the finite element calculation code ANSYS. It considered the radiation power from the plasma surface, the particle heat load along the magnetic field and the RF dissipation of the induction current. Figure 7 shows the calculated temperatures of the highest point and the lower edge on the carbon protector by changing the antenna position. The assumed particle heat flux distribution is also shown in the figure. The temperatures of the top edge decreases from 1600°C to less than 500°C by increasing the distance of over 3 cm. It is still reasonable distance to get the substantial plasma coupling resistance.

The results of the above R&D experiments and calculations are incorporated in the LHD antenna design and fabrication. It is considered that the high stand off voltage technique, the sufficient cooling ability and the flexibility of antenna position will give us the reliable high power and steady state operation of an ICRF antenna in LHD.

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