

# STUDY OF THE RADIO-FREQUENCY DRIVEN SHEATH IN THE ION CYCLOTRON SLOW WAVE ANTENNAS

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## Abstract

Formation of the radio-frequency driven sheath and resulting parasitic antenna loading in the ion cyclotron slow wave antennas are studied experimentally in the linear divertor plasma simulator NAGDIS-II. A phased loop antenna array with a poloidal mode of  $m=0$  is used in the present ICRF heating experiment. A large DC voltage drop of about several hundreds volts is induced on the loop antennas with and without Faraday screen during high power RF heating and causes the additional power dissipation ( $P_{sh}$ ) due to the heat flux to the antenna current strap of ions accelerated by the RF driven DC sheath potential. This parasitic antenna loading is measured by calorimetric method and compared with that obtained from the conventional measurement of the antenna voltage and current.

## 1. Introduction

The electrostatic Faraday screen (FS) is generally used to suppress the strong electrostatic interaction between the ICRF antenna and edge plasmas near the antenna. It is recognized that FS suppresses the electrostatic field parallel to the magnetic field ( $E_{//}$ ), and particle and heat fluxes into the antenna current strap effectively. Even with FS, however, impurity generation from FS is a severe problem in high power ICRF heating experiments.[1],[2] Recent researches on the ICRF antenna-edge plasma interaction have shown that the RF driven sheath on the FS has a key role on the impurity generation from FS by ion sputtering. [3]~[6] The ion flow accelerated in the RF driven sheath causes an additional heat load on the antenna structure and gives a power loss in the RF system, transferring energy the RF field to the antenna material surface through the ion bombardment. In addition, the RF driven sheath may bias the edge plasma potential near the ICRF antenna and drive steady state convective cells in the scrape-off layer. These induced convective cells are possible to modify the particle and heat transport in the scrape-off layer .[7],[8]

So far, the effects of RF driven sheath on the ICRF antenna-plasma interaction are studied theoretically and analyzed using experimental data of high power ICRF heating in large tokamaks. In the present experiment using a linear plasma device, both the DC and RF voltages on the antenna current strap and FS of the loop antenna for ICRF slow wave heating are measured and compared with theoretical estimation. Simultaneously the plasma heat load to the antenna current strap and FS is measured with calorimetry to obtain the additional RF power dissipation by the RF induced sheath. The net radiated RF power for the excitation of ICRF slow waves is estimated from the conventional RF power measurement and the antenna heat load.

## 2. RF Driven Sheath and Antenna Heat Load

A steady state DC potential  $V_0$  (RF driven DC sheath) is produced by rectification of the induced antenna voltage ( $V_{rf}$ ) in the sheath, confining electrons and maintaining quasineutrality. In the parallel plate model of RF driven sheath this rectified DC potential is given by[6]

$$\frac{eV_0}{T_e} = \chi_B + \ln[I_0(\xi)], \quad (1)$$

where,  $\xi = eV_{rf}/T_e$ ,  $\chi_B = 0.5 \ln(m_i/2\pi Z m_e)$  and  $I_0$  is a modified Bessel function. In large  $V_{rf}$  limit,  $x \gg 1$  the asymptotic value of  $V_0$  is given by

$$eV_0 \sim eV_{rf} - (T_e/2) \ln(2\pi e V_{rf}/T_e) + \chi_B. \quad (2)$$

The power dissipation in the RF driven sheath ( $P_{sh}$ ) is also calculated from  $V_{rf}$  and current flow into the antenna structure. The sheath power dissipation  $P_{sh}$  is given by

$$P_{sh} = A \langle \Gamma \rangle T_e I_1(\xi) / I_0(\xi), \quad (3)$$

where  $\langle \Gamma \rangle (= Zn_i c_s)$  is the time averaged particle flux into the antenna and  $A$  is a surface area of the antenna structure. For  $x \gg 1$ ,  $P_{sh}$  is simplified to  $P_{sh} \sim An_i c_s (ZeV_{rf})$ . As shown in eq. (2) the large  $V_{rf}$  limit gives  $V_0 \sim V_{rf}$ , and the sheath power dissipation is simply dominated by the power delivered to the antenna by ions accelerated in the rectified potential  $V_0 \sim V_{rf}$ .

The RF power dissipation given by eq. (3) is an additional dissipated power for the RF heating system and also additional heat load to the antenna structure. The power coupled to the plasma through wave excitation  $P_{rf}$ , and the dissipated power in the RF driven sheath are independent loss channels driven by antenna current. In this case the antenna loading resistance  $R_L$  is given by

$$R_L = \frac{P_{rf} + P_{sh}}{I_{ant}^2} \quad (4)$$

where  $I_{ant}$  is the antenna current. In Ref. 6 it is shown that  $P_{rf}$  and  $P_{sh}$  have different scalings like  $P_{rf} \propto V_{ant}^2 \propto I_{ant}^2$  and  $P_{sh} \propto V_{ant} \propto I_{ant}$ , respectively. From these scalings the antenna loading resistance is dependent on the RF power. In high RF power limit,  $P_{rf} \gg P_{sh}$ ,  $R_L$  becomes constant, and  $R_L$  scales as  $1 / \sqrt{P_{rf}}$  at low power level  $P_{sh} > P_{rf}$ . The conventional measurement of  $R_L$  can not separate the  $P_{sh}$  contribution from the antenna loading. In the present work the antenna heat load due to RF sheath dissipation is discriminated with calorimetric method and compared with the theoretical estimation shown above. The antenna voltage, and particle flux into the antenna current strap and FS are also measured separately. From these observations the net antenna loading resistance given by  $R_L = P_{rf}/I_{ant}^2$  and the real coupling efficiency for ICRF slow wave excitation are obtained.

### 3. Experiment

RF heating experiments have been carried out in a linear divertor plasma simulator NAGDIS-II.[9] The RF system for ICRF slow wave heating is shown in Table-I. The antenna current coil is made by copper tube and water-cooled. Both the antenna coil and FS are isolated from the vacuum chamber in order to avoid direct DC discharges between the hot cathode of NAGDIS-II plasma generator and antenna structure. A schematic diagram of one of the phased 4 loop antenna array is shown in Fig. 1. In the present experiment the magnetic field at the antenna section is kept at 0.23 T and the electron density at the column center is about  $5 \times 10^{18} \text{m}^{-3}$  and about  $3 \times 10^{17} \text{m}^{-3}$  near the antenna. The driving frequency is fixed at 780 kHz, where  $\omega / \omega_{ci} = 0.91$  for singly ionized  $\text{H}_e$  ion.

#### 3.1 Measurement of Antenna Voltage and Heat Load to the Antenna

The antenna voltages of current loop and FS with respect to the vacuum chamber, both RF amplitude and DC sheath voltage are measured through RF voltage dividers. Typical antenna voltage waveforms during RF heating are shown in Fig. 2, taking the antenna current as a parameter. In the present antenna system RF voltage is applied between each end of the antenna current coil (balance feeding). The measured RF voltages are induced by the electrostatic coupling between the powered antenna, and FS and vacuum chamber. In Fig. 3 DC sheath voltage of the antenna current coil is shown as a function of the induced RF voltage (0 to peak voltage) on the

Power Source	Static Induction Transistor(SIT)
Operating Frequency	0.5 ~ 1.5 MHz
Output Power	14 kW per unit in CW mode 20 kW per unit in 1 second pulse
Output Impedance	~ 0.6 ohm

**Table-I Specification of SIT invertor RF power supply in NAGDIS-II**

antenna coil. The DC voltage in the figure is obtained by averaging RF voltages measured at each feeding point of the loop antenna. Both the RF amplitude and negative DC sheath voltage increases linearly with antenna current, which means that  $V_{rf}$  and  $V_0$  is proportional to  $\sqrt{P_{rf}}$ . The electron temperature near the antenna during RF heating is about 3~5 eV, which gives  $\xi = eV / T_e \gg 1$  in our experimental condition. In this region eq. (2) shows  $V_0 \sim V_{rf}$ , which agrees with the experimental results without FS shown in Fig. 3. On the other hand the DC sheath voltage with FS is  $V_0 \sim 2V_{rf}$  much larger than that without FS. Since the antenna conductor with FS is surrounded by the FS elements and side guard limiters, the density is much smaller than that outside the FS, roughly two orders of magnitude lower. The simple sheath theory may not be applied to the analysis of RF driven sheath as described in the previous section. The induced RF and DC voltage of FS is about 20 ~ 30 V, much smaller than that of the antenna current coil because the RF electric field of the antenna near field parallel to the magnetic field is effectively shielded.

The ion flux into the antenna coil and FS is directly measured or estimated from the plasma density and electron temperature near the antenna location, which are measured by fast scanning Langmuir probe. The heat loads to the antenna coil and FS measured by calorimetry are shown in Fig. 4 as a function of the antenna current. The plasma heat load shown in the figure is obtained from the difference of the heat load with and with RF input to the antenna. The experimental error of the present heat load measurement is estimated about  $\pm 30$  W. Without FS the antenna heat load increases nearly in proportion to the antenna current. The antenna heat load without FS is compared with the theoretical estimation using eq. (3). Theoretically estimated heat load is about 40 % larger than the experimental value. This difference might be caused by the experimental errors and theoretical assumption that the plasma potential during RF heating does not change. The particle flux into the antenna coil is strongly suppressed by FS and consequently, the heat flow into the antenna coil with FS is much less than that without FS. The ion flux into the antenna coil with FS (Ion current  $\sim 50$  mA) gives the estimated heat load of about 30~60 W at the maximum RF power, which agrees roughly with the experimental one. The heat load to FS is also measured during RF heating. The heat load to FS does not change significantly from that without RF. The RF sheath dissipation of FS is roughly estimated to be less than 20 W in the present experimental condition.

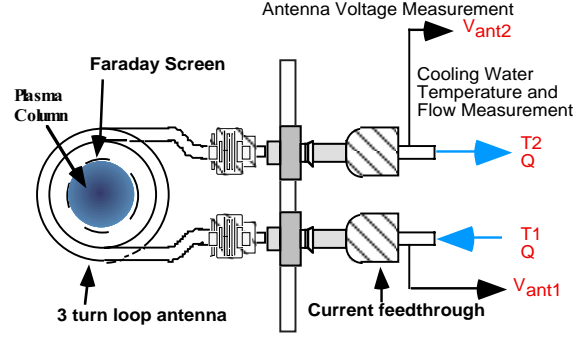


Fig. 1 Cross-sectional view of 3 turn loop antenna. The antenna diameter is 80 mm.

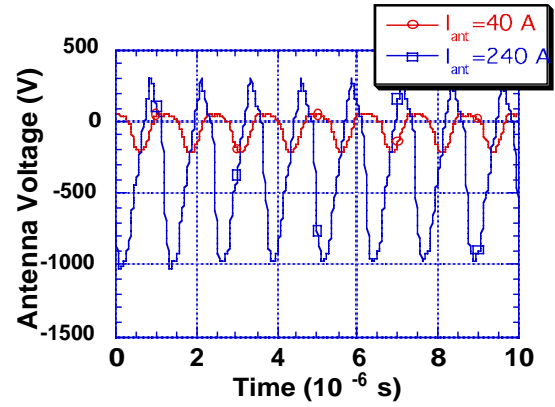


Fig. 2 Voltage waveform of the antenna current coil without FS. The driving frequency is 780 kHz

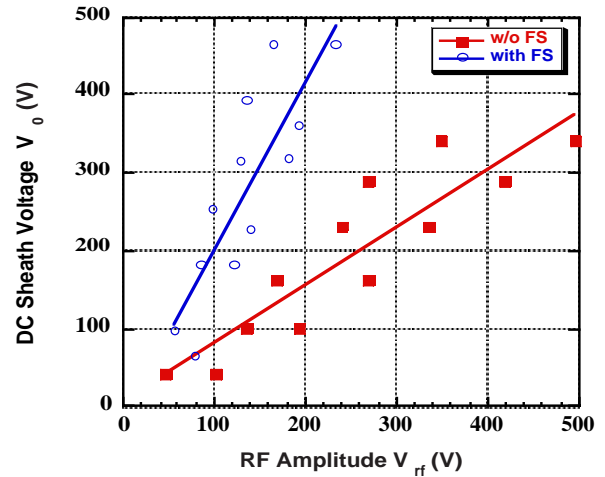
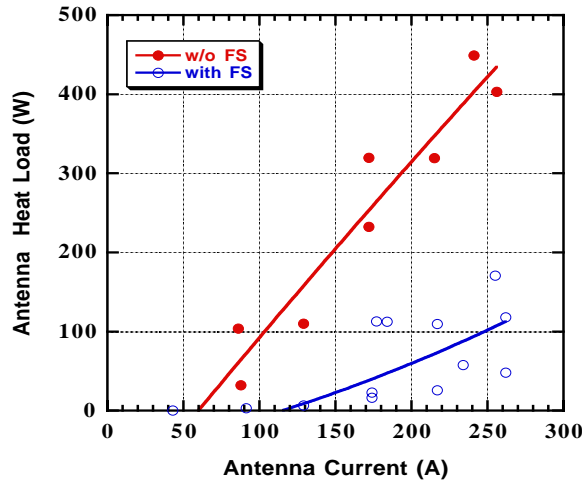
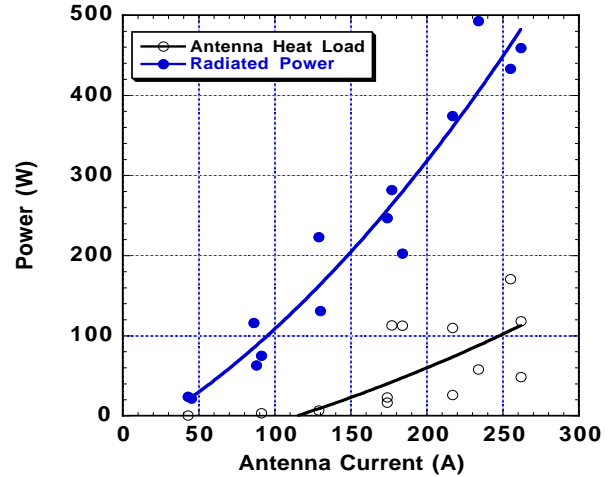


Fig. 3 RF driven DC sheath voltage as a function of induced RF voltage on the antenna current coil with and without FS.



*Fig. 4 Heat load to the antenna current coil as a function of the antenna current*



*Fig. 5 Radiated RF power calculated from the antenna voltage and current and antenna heat load as a function of the antenna current.*

### 3.2 Estimation of the Antenna Loading

The net radiated RF power can be estimated by subtracting the antenna heat load from the total RF power dissipation except for the RF circuit loss. The radiated power evaluated from the conventional measurements of RF voltage and current of the antenna and antenna heat load measured by calorimetry are shown in Fig. 5. Without FS the antenna heat load is much higher and almost comparable to the RF power. On the other hand the antenna heat load is much smaller than the RF power with FS. In the present experiment the measured antenna heat load includes both the RF sheath dissipation and the electron and ion heat flow from the presheath. The heat flow due to the energetic electrons and ions generated by excited slow waves is not clear so far. It can be concluded that the most of RF power is dissipated by RF driven sheath in the case of the antenna without FS. With FS the effective reduction of the RF sheath dissipation is obtained and 80% of the RF power is dissipated by radiation.

### 4. Summary

The RF amplitude and RF driven DC sheath voltage induced on the ICRF slow wave antenna are directly measured and compared with the theoretically estimated one using simple sheath theory. Without FS the antenna current coil directly touches the high density edge plasmas and induced DC sheath voltage agrees well with that of theoretical estimation. The antenna heat load measurement shows that the RF dissipation caused by the RF induced DC sheath is nearly comparable to the RF input power to the antenna. With FS the antenna heat load is greatly suppressed to about 20 % of input RF power.

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