# Multi-Channel Microwave Reflectometer with Fermi Antenna Receivers

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We have evaluated a Fermi antenna newly designed in X band for use in a multichannel reflectometer. The advantages of the Fermi antenna are that it can be adopted as an array antenna owing to its planer shape and fabricated with a low cost due to its compactness and a light-weighted structure. The radiation-beam widths in the E- and H-plane are almost equal to each other and the side-lobe levels are low. Plasma behaviors in the HITOP device are measured by reflectometry using two Fermi antenna receivers. Time evolution of the cutoff layer and plasma rotation velocity measured by the reflectometer are in good agreement with an electrostatic probe measurement.

Keywords: Fermi antenna, multi-channel receiver, microwave reflectometer, imaging antenna, plasma measurement

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## 1. Inroduction

Understanding mechanism of anomalous transport in magnetically confined plasmas is one of the most important subjects on fusion researches. Reflectometry is now widely used in various magnetically confined plasmas [1]. It has an advantage of detecting local plasma density behavior with a high spatial resolution. Microwave imaging reflectometry is recently developed as one of the advanced diagnostic systems [2] and provides excellent advantages compared with conventional systems. To compose this system, it is necessary both to design an optical system and to develop an imaging antenna array. Several imaging antennas, such as a bow-tie antenna, a Yagi-Uda antenna, a dual-dipole antenna, have been developed [3]. A tapered slot antenna (TSA) that we are developing is one of the candidates.

The TSA has been firstly developed in electrical communication researches [4]. It has a nearly symmetrical radiation pattern compared with that of a bow-tie antenna and its bandwidth is relatively broad. It can be adopted as an array antenna owing to its planer shape, its compactness fabricated with low cost and a light-weighted structure. Recently, a new TSA called “Fermi antenna” in the frequency range of 35 GHz and 60 GHz has been developed in Tohoku University [5, 6].

The purpose of this research is to establish a mulchichannel microwave reflectometer with the Fermi antenna. We have constructed a microwave reflectometer system with two channels of the Fermi antenna receiver.

## 2. Characteristics of the Fermi Antenna

The Fermi antenna has a tapered structure defined by the Fermi-Dirac function and a corrugated structure along the outer edge of the antenna to reduce side-lobe intensity. The Fermi-Dirac function is defined the following equation:

$$f(x) = \frac{a}{1 + \exp[b(x + c)]} \quad (b < 0, c < 0), \tag{1}$$

where $a$, $b$ and $c$ are constant values. It is found experimentally that the radiation-beam widths in the E- and H-plane are almost equal to each other and the side-lobe levels are low in the Fermi antenna.

We designed a Fermi antenna with a corrugated structure in X-band according to a scaling law given in Refs. 3 and 4. Figure 1 shows the geometry and dimensions of the “Fermi antenna” designed at 12 GHz. The radiation pattern

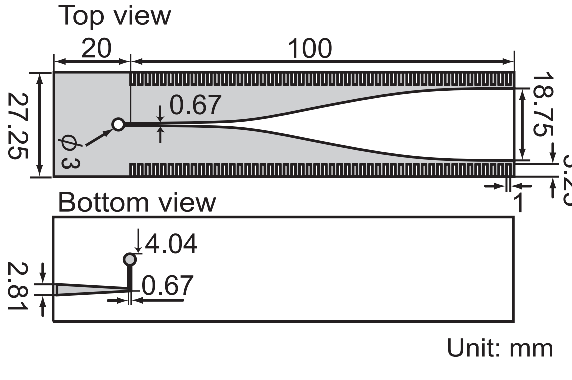

Fig. 1 Designed Fermi antenna with corrugated structure. Thickness of the substrate is 1.2 mm.

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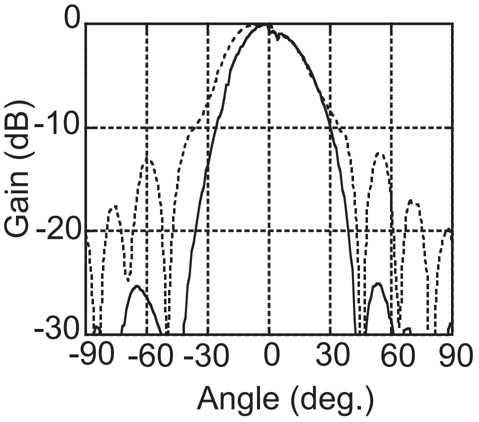

Fig. 2 Radiation patterns of the Fermi Antenna at 12 GHz. The solid line denotes E-plane radiation. The dotted line denotes H-plane radiation.

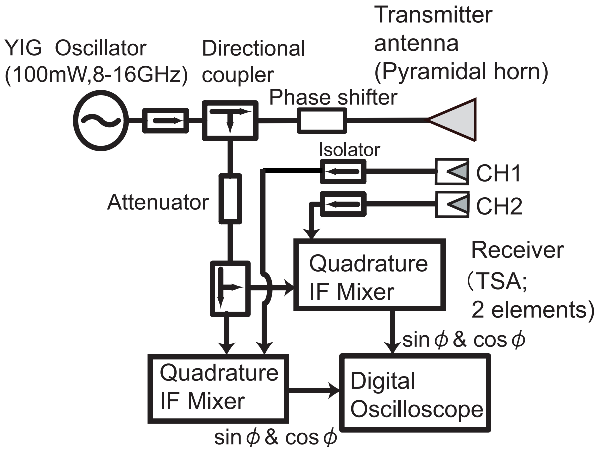

Fig. 3 Diagram of the microwave reflectometer system with two-channel Fermi antenna receivers.

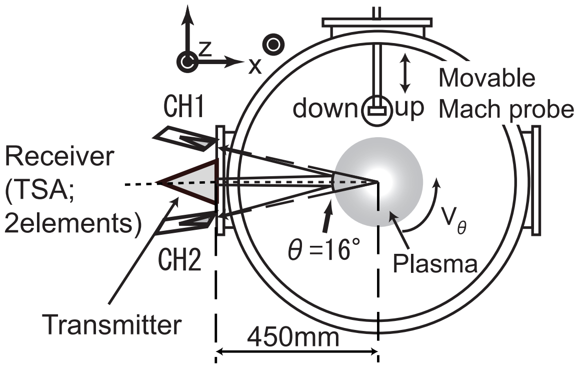

Fig. 4 Schematic of the experimental setup. Cross section of the HITOP device is shown with the antennas.

of the Fermi antenna is shown in Fig. 2.

We obtained a 3 dB-beamwidth of 32 degrees in the E-plane and 37 degrees in the H-pane at 12 GHz. Directivity of a fermi antenna with corrugated structure is 2 dB better than that of a linear TSA without the corrugation. By optimizing the strip line structure according to the equivalent circuit model, a VSWR less than 2 is obtained in the bandwidth of 8-18 GHz [7].

## 3. Microwave Reflectometer with the Fermi Antenna Receivers

We have constructed a microwave reflectometer system with two channels of the Fermi antenna receiver. The reflectometer system is shown in Fig. 3. The system can be operated in the frequency range of 8 to 16 GHz with a YIG oscillator. The YIG oscillator can deliver up to 100 mW and is operated at a fixed frequency in the measurements. A pyramidal horn antenna is used as a transmitter, and two Fermi antennas are used as a receiver. A reflected wave is received by each of the TSA and mixed with an unperturbed local oscillator wave by use of a quadrature IF mixer. Homodyne-detected signals are recorded by an oscilloscope and analyzed by a personal computer.

Firstly, we measure a phase difference of the reflected wave by using a flat metal plate and a rotational metal cylinder as a target instead of a plasma. The results are in good agreement with the predicted ones in the mockup experiment [7].

## 4. Experimental Setup and Results

After these mockup experiments, we have measured a HITOP plasma by using this reflectometer with two Fermi antenna receivers. The HITOP devices has been constructed at Tohoku university in order to investigate various MHD phenomena and to develop plasma propulsion devices [8]. The HITOP consists of a large cylindrical vacuum chamber (diameter, 0.8 m; length, 3.3 m) with eleven main and six auxiliary magnetic coils, which generate a uniform magnetic field up to 0.1 T. A high power, quasi-steady magneto-plasma-dynamic arcjet (MPDA) is installed at one end-port of the HITOP as a source of a fast flowing plasma. A discharge current $I_d$ up to 10 kA is supplied with the quasi-steady duration of 1 ms. Helium gas is used as a working gas. We can control the plasma density by changing a magnetic field and a discharge current. A plasma in an MPDA is accelerated axially by $J_r \times B_\theta$ force, where $J_r$ is a radial discharge current and $B_\theta$ is a self-induced azimuthal magnetic field. In an axial magnetic field $B_z$, interaction between $B_z$ and $J_r$ results in an azimuthal electromagnetic force $J_r \times B_z$, which rotates the plasma azimuthally. We investigated the rotating plasma in HITOP, and observed rigid-body rotation of the core plasma [9].

Figure 4 shows the experimental setup for the reflectometer measurement. Cross section of the HITOP device is shown with the reflectometer antennas. The microwave is emitted into the vacuum chamber through a vacuum window made of teflon (diameter in 0.15 m, width in 0.012 m). These antennas are located at $Z = 2.46$ m from the MPDA

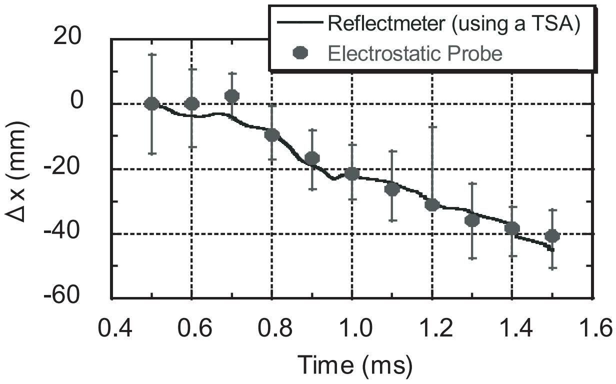

Fig. 5 Time evolution of cutoff layer measured by a electrostatic probe and a reflectometer with a Fermi antenna. $\Delta X$ is the displacement value of cutoff layer from the cutoff position at $t = 0.5$ ms.

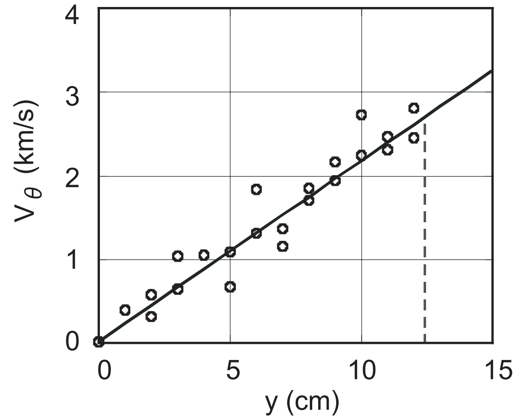

Fig. 6 Spatial profile of the plasma rotational velocity measured by a Mach probe. The rotational velocity are calculated by Eq. (2). The dotted line corresponds to the cutoff layer at $f = 12$ GHz.

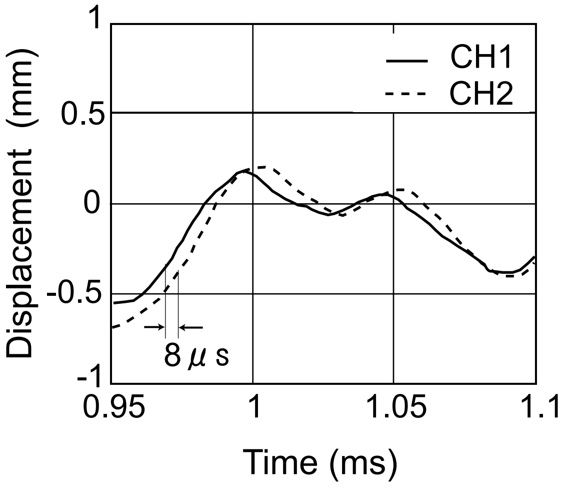

Fig. 7 Time evolutions of displacement length measured with the two reflectometer systems.

source. Spatial profiles of the plasma density and rotational velocity are measured by a movable Mach probe. The Mach probe consists of two plane probe tips facing downstream and upstream to the rotational plasma flow. A Mach number ($M_i$) can be obtained from the ratio of ion saturation current densities collected by each tip [10]. The rotational velocity ($V_\theta$) is calculated by the Mach probe data as follows;

$$V_\theta = M_i \cdot C_s = 0.4ln(\frac{J_{up}}{J_{down}}) \cdot \sqrt{\frac{k(\gamma_e T_e + \gamma_i T_i)}{m_i}}, \tag{2}$$

where $C_s$ is an ion acoustic velocity, $J_{up}$ and $J_{down}$ are current densities collected by upstream and downstream probe tips, respectively. $T_e$ and $T_i$ are electron and ion temperatures, respectively, and $m_i$ is ion mass $\gamma_e$ and $\gamma_i$ are the specific heat ratios for electrons and ions, respectively.

Figure 5 shows time evolution of cutoff layer measured by the electrostatic probe array and the reflectometer with a Fermi antenna. The cutoff layer is estimated from the measured radial density profile using an electrostatic probe. A good agreement is obtained between the reflectometer and the electrostatic probe measurements.

The plasma rotation velocity is measured by a Mach probe as shown in Fig. 6. The rotational velocity increases linearly with increasing the radial position, which indicates the plasma rotates as a rigid body. During a quasi-steady discharge, the radial position corresponding to the cutoff frequency of 12 GHz is estimated to be 12.5 cm from the density profile measured by an electrostatic probe. The rotational velocity at the cutoff position is obtained as 2.6 km/s from the Mach probe, which is derived by Eq. (2) using, an ion temperature obtained by an electrostatic energy analyzer. The two Fermi antenna receivers face to different reflecting positions in the plasma. These appears a time delay in the reflectometer signals measured by the two receivers as shown in Fig. 7. These antennas are set obliquely at located $\theta = 16$ degrees to each other. Rotational velocity ($V_\theta$) is calculated from the measured delay time ($\tau$) of the cut off layer displacement as the following equations.

$$\Delta t = \frac{360^\circ}{\theta/2}\tau, \tag{3}$$

$$V_\theta = r\frac{2\pi}{\Delta t}, \tag{4}$$

where the position of the cut off layer is $r = 12.5$ cm at 12 GHz. The time delay of 8 μs corresponds to the rotational velocity of 2.2 km/s at the cutoff surface. The rotational velocity measured by the reflectometer and the Mach probe agrees well with each other. The dotted line corresponds to the cutoff layer at $f = 12$ GHz.

## 5. Summary

We have designed and fabricated a Fermi antenna with corrugated structure in X-band, and measured fundamental characteristic such as a VSWR and radiation patterns of the Fermi antenna. The directivity and the side lobe level of the Fermi antenna with a corrugated structure are improved from those of the linearly tapered slot antenna. We have measured a HITOP plasma by using the reflectometer with two Fermi antenna receicers. Time evolution of cutoff layer measured by the electrostatic probe array and the reflectometer is in good agreements. Rotational velocity of the plasma is estimated from a time delay of the cutoff layer displacement measured by the two antenna receivers The obtained rotation velocity agrees well with that obtained by a Mach probe.

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