REMOTE STEERING ANTENNA SYSTEM AND ITS APPLICATION TO ECH/ECCD EXPERIMENTS ON THE TRIAM-1M TOKAMAK

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A remote steering antenna designed as a symmetric direction antenna is prepared for Electron Cyclotron Heating (ECH) and Current Drive (ECCD) experiments on the TRIAM-1M tokamak. The steering angles of 8-19 degrees are available in the design, in addition to the angle near 0 degrees. The antenna was tested in both of high and low power levels. The fraction of radiated power to injected power at the antenna was roughly evaluated at the low power test. The angle radiated from the antenna was checked from both of the intensity and phase measurements at the low power test. Several percentage losses at the antenna were evaluated from calorimetric measurements at the high power test. The antenna was evaluated to work correctly. The ECH/ECCD experiments, using the remote steering antenna have been started on the TRIAM-1M tokamak. Preliminary experimental results are shown.

1. Introduction

A square corrugated waveguide antenna is one of attractive candidates for the remote steering launcher in Electron Cyclotron Heating / Current Drive (ECH / ECCD) at International Thermonuclear Experimental Reactor (ITER). The movable mirrors to control the launching angle is not required in a vacuum vessel of the device, where is neutron-irradiated, and is in strong magnetic field. The simple structure of the antenna system is advantageous on the point of view of maintenances. Recently, the remote steering antenna attracts a lot of interests in both of theoretical and experimental works. The antenna in the extended operating region is recently proposed [1].

The TRIAM-1M tokamak has super-conducting magnet coils to generate the high field up to 8T. The system with a 170GHz gyrotron was prepared for the ECH experiments with a fundamental heating scenario [2]. The circular corrugated waveguide was used as a launcher for the experiments. For the ECCD experiment, a new antenna system that makes the launching angle controllable is needed. A Matching Optics Unit (MOU) for the beam to couple into the antenna with steering angles is also required. In the tokamak, there is a long distance between the plasma and the device port, and are not enough space for a mirror array to be installed in the vessel, due to the large bell jar for the magnets. The remote steering antenna is one of a few choices for us to carry out the ECCD experiments. An operating frequency and a heating scenario are in the same manner for ECH/ECCD on ITER. The antenna was designed and fabricated for the ECH/ECCD experiments on the TRIAM-1M tokamak in relation to the ITER. The antenna was tested at both of low and high power levels, and has begun to use for the ECH/ECCD experiments on the tokamak.

The contents in this paper are the followings. Design and fabrication of the antenna system are introduced in Section 2. The low and high power test results are shown in Sections 3. Preliminary experimental results using the antenna system are reported in Section 4, and finally, a summary is given in Section 5.

2. Design and Fabrication of Antenna System

2-1. Square Corrugated Waveguide Antenna

Figure 1 shows a counter plot on calculated fractions of the output power to incident power in a symmetric direction antenna, as a function of an incident angle and a length of the antenna. A side of the square cross section of the antenna is fixed at 31.75mm. The maximum power that is transmitted in the antenna is 200kW in our system. The evacuated circular corrugated waveguides with a diameter of 31.75mm has been used in the transmission line, and at the old waveguide antenna. Similar cross-section area retains to avoid arcing events in the antenna. In the figure, the calculation of the electric field component in perpendicular to a steering plane is shown. The output power was evaluated in the TEM00 mode of the beam at the output aperture of the antenna in the calculation. There is no normal operation region without a break in the incident angles from 0 to about 15 degrees in a case of an asymmetric direction antenna. The antenna performances at low and high power levels in the case were reported [3,4]. Our launcher was designed as a symmetric direction antenna in the extended operating region, shown in the figure at an antenna length of 2.075m. It is a first application for the extended operating region of the symmetric direction antenna. The steering angles of 8-19 degrees are available, in addition to the angle near 0 degrees. Using this antenna, the both ECH and ECCD experiments are possible. The antenna is made of Aluminum, and the aluminum welding technique is used to evacuate the antenna and to make a water-cooling channels.

2-2. Matching Optics Unit for Antenna

A Matching Optics Unit (MOU) with a mirror array for the beam to couple into the antenna with steering angles is also prepared. In order to locate this MOU section in the existing transmission line with small modification, a mirror array system composed of four mirrors is adopted. A designed evolution of beam sizes along the propagation is shown in Figure 2. The last forth M4 mirror can be moved along the propagation axis from the third M3 mirror, and rotated to control the steering angles. The MOU is connected to the evacuated corrugated-waveguide at a side of M1 mirror, and the antenna at another side of M4 mirror. It has a differential pumping port, and a gate valve between M4 mirror and the antenna. There is not a vacuum window between the evacuated waveguide line and the tokamak. Water-cooled absorbers are installed inside the MOU, and temperature increased at the cooling water is a measure of a transmission loss at the MOU in the calorimetric measurements

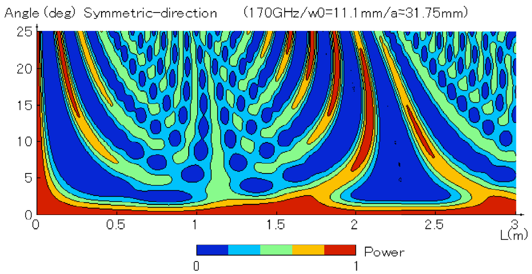


Figure 1: Counter plot of the fractions at a symmetric direction antenna with a side of 31.75mm.

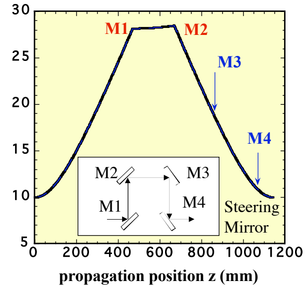


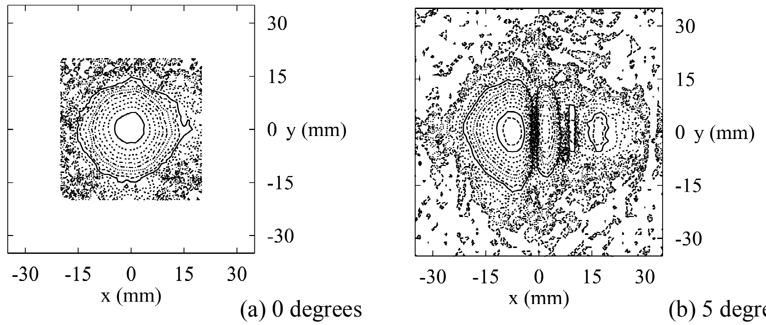
Figure 2: Evolution of beam size at MOU for the antenna.

3. Evaluation of Antenna System at Low and High Power Levels

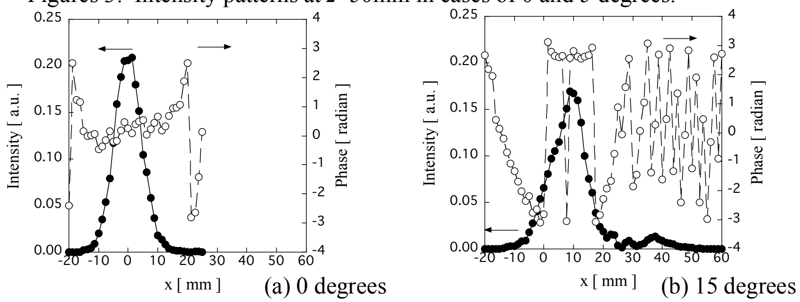
In order to test the antenna system at the low power level, a facility at National Institute for Fusion Science [5] was used. A Gaussian beam radiated from a circular corrugated waveguide with a diameter of 31.75mm was injected to M1 mirror at the MOU. The electric field of the incident beam had both components, E_x and E_y, in parallel and perpendicular to the steering *x-z* plane, with 45 degrees polarization. Since the antenna has four corrugated walls, the 45 degrees polarization can be transmitted at the antenna without depolarization [3]. Here, the *z*-axis was the beam propagating-axis. The intensity and phase profiles in both components were measured in the *x-y* plane at the operating frequency of 170GHz.

First, the MOU was checked at the low power test. The beam sizes were evaluated as 14mm at the gate valve output flange. The beam size is designed as 10mm at the center of the gate valve, as shown in Fig.2. The beam to the antenna is checked to be desirable, but it should be done if this beam quality is kept for a larger steering angle case. The beam passes through the gate valve after M4 mirror. The beam does not go through a center of the valve in the steering cases. If the valve has too small diameter aperture, and/or is too thick, the beam is affected by the valve, and cannot pass it correctly. Intensity and phase patterns were measured at the gate valve output flange. It was confirmed that the incident beam is preferable even in 17.5 degrees case, as designed. In order to evaluate incident power to the antenna, the intensity pattern are integrated over the *x-y* plane.

The antenna was connected to the MOU at the low power test stand. The both of the E_x and E_y components in the output beam were measured. The detector stage was rotated according to the steering angle. Figures 3 show intensity patterns of the output beam in the E_x component at *z*=50mm in cases of 0 and 5 degrees. The counter plots are drawn at Log scale by a step of 2dB. The *z*-axis was set to propagating axis that was expected according to the steering angle. An origin of the *z* coordinate was at an output aperture of the antenna. The pattern in the 0 degrees case shows a circular Gaussian beam, but that in the 5 degrees is deformed, and has beam center offsets and side lobes. Figures 4 shows intensity and phase profiles in the *x* direction in the cases of 0 and 15 degrees in the E_y component. The intensity profile in the case of 15 degrees also has beam offset and small side lobes. The phase profiles are flat near the beam centers in both cases. That means the beam propagates along the *z*-axis. The output direction of the beam corresponds to the incident steering angle.



Figures 3: Intensity patterns at *z*=50mm in cases of 0 and 5 degrees.



Figures 4: Intensity and phase profiles in the x direction in cases of 0 and 15 degrees.

In order to evaluate the fraction of output and input power at the antenna, the intensity patterns of the output beams also are integrated over the *x-y* plane. The dependence of evaluated fraction on the steering angle is shown in Figure 5. Since the 2 dimensional measurements of the intensity patterns took a long time (typically several hours), there was a thermal drift in an IF amplifier with +/-0.5dB. Errors in the figure come from this uncertainty. It is noted that the fractions of output to input powers at the antenna near 5 degrees were calculated as low, provided that the TEM00 mode was only taken into account. Since the fractions are evaluated with total input and output power from the measurements, those in the measurements are different from the calculation results.

Tests at the high power level were carried out using the existing transmission line. The MOU and the antenna were connected to the corrugated waveguide line. Location of them was different from an application in the TRIAM experiments a little. The beam with a power level of 120kW at a duty of 0.5% was injected to the MOU from a backside of M4 mirror. A coupling mirror was prepared for the beam to couple into the antenna. A dummy load was connected after the MOU or the antenna to evaluate the fraction. The cooling-water of 2 and 10 liter per minutes was run at the MOU and the antenna, and the temperatures increased at the cooling water were measured. The input beam to the antenna was checked using IR-image measurements. A PVC plate was used for a target in the measurements. The beam center, axis and size were checked with Moment Method [6]. The transmission loss at the MOU was only several percentages for the total power. The fractions at the high power test are also shown in Figure 5. High fraction rates of about 0.95 are evaluated. The power losses at the antenna are evaluated as several percentages from temperatures increased at the cooling water.

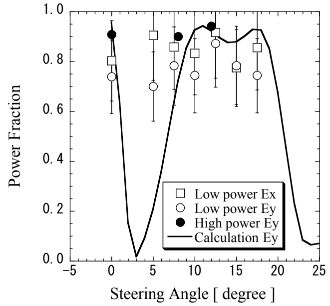
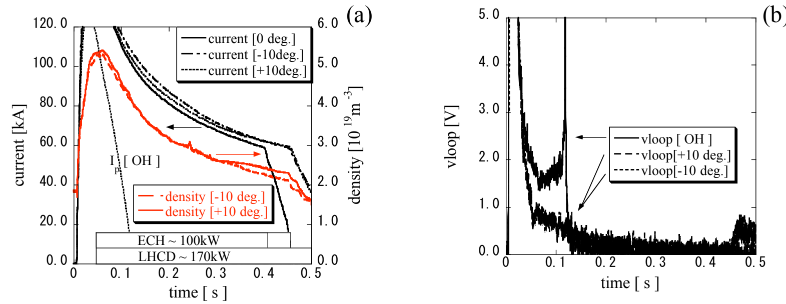


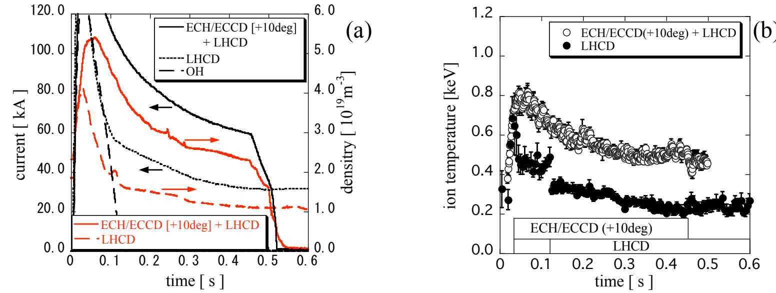
Figure 5: Power fractions evaluated at low and high power tests and calculated.

4. Preliminary ECH/ECCD experimental results on the TRIAM tokamak

The ECH/ECCD experiments, using the remote steering antenna, for the first time in the world, have been started in the TRIAM-1M tokamak. The Electron Cyclotron (EC) wave with a power level of 100kW was injected to the Ohmic discharge plasma with steering angles of 0 and +/- 10 degrees. Figures 6 show the plasma current and density, and the loop voltage in the experiment. With the EC wave, the loop voltage decreased and the current was sustained. The Lower Hybrid (LH) wave also was injected, but it could not sustain the plasma current without the EC wave at this density. The effect of ECH/ECCD was clearly observed, but there was not clear dependence of the current on the incident direction, that is, the sign (+/-) of the steering angles. The incident wave was linearly polarized in the steering plane, and in parallel to the toroidal magnetic field. The incident wave polarization was not optimized for the ECCD experiments. Figures 7 show the plasma current and density, and the ion temperature for LH current drive plasmas with and without ECH. The density and ion temperature with ECH were two times higher than those without ECH. They with ECH are comparable to those observed in an improved mode on the current drive efficiency at the LH current drive experiment [7].



Figures 6: (a) Plasma current and density and (b) loop voltage in the high density case.



Figures 7: (a) Plasma current and density and (b) ion temperature in comparison with and without ECH/ECCD.

5. Summary

A remote steering antenna was designed and fabricated for the ECH/ECCD experiments on the TRIAM-1M tokamak. The antenna was designed as a symmetric direction antenna in the extended operating region. The output angle was checked from the intensity and phase measurements in the low power test. The fraction was measured in both of the low and high power tests. The antenna was evaluated to work correctly. The ECH/ECCD was effective to sustain the high plasma current, density and ion temperature, but there was no clear dependence on the incident direction. Detailed experiments to confirm the effect of ECCD are planed after installation of polarizers to optimize of incident polarization.

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