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Development of a microwave AM reflectometer for electron density profile measurement in Heliotron J

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A microwave reflectometer is developed for electron density profile measurement in Heliotron J. An amplitude modulation (AM) type system is adopted to reduce density fluctuation effects. The carrier frequency ranges from 33 to 56 GHz, and the modulation frequency is 100 MHz. The X-mode is selected as the propagation mode in order to measure a hollow density profile typically which is observed in ECH plasmas. A test-bench examination using an aluminum reflection plate shows that the measured phase shift agrees well with that expected from the change in the plate position if the dependence on the RF signal power is taken into account. A numerical program to reconstruct density profile from the measured phase shift data has been also developed. The result confirms that the program works well for modeled flat or hollow density profiles.

Keywords: reflectometer, amplitude modulation, electron density profile, Heliotron J

1. Introduction

Measurement of electron density is one of the important issues to understand the plasma confinement and transport. Microwave reflectometer is widely used for density profile and density fluctuation measurements [1, 2]. The advantage of electron density profile measurement by reflectometer is that the time evolution of local electron density profile is possible to measure during a plasma discharge with good time and spatial resolutions. It has few limitation of installation port and does not need any assumption of the shape of magnetic surfaces.

Several types of reflectometer have been developed such as a frequency modulation (FM) reflectometer, an amplitude modulation (AM) and a pulse radar reflectometer. The electron density profile measurement by AM reflectometer has been carried out in T-10 tokamak [3], W7-AS [4], TJ-II [5] and HL-2A [6]. The advantages of the AM method are that it can suppress the effect of density fluctuations in profile measurement and that it can avoid the fringe jump by setting the whole of phase shift less than 2π.

In Heliotron J, it is an urgent task to obtain the electron density profile. The goal of this study is to develop a microwave reflectometer for Heliotron J and to investigate the particle transport from the density profile measurement.

In this paper, we describe current status of a microwave AM reflectometer system for electron density profile measurement in Heliotron J. We show results of characteristics test in a test stand and the program to reconstruct the density profile from the measured phase shift data.

2. Design of the reflectometer system

2.1 Basic design

Heliotron J is a medium-sized helical-axis heliotron device ($\langle R_0 \rangle = 1.2$ m, $\langle a \rangle = 0.17$ m, $B_0 \leq 1.5$ T) with an L/M = 1/4 helical coil [7]. The main purpose is to explore the optimization of the field configuration in helical-axis heliotron. The plasma heating systems are a second-harmonic X-mode ECH (70GHz, 500 kW), a two-loop-antennae ICH system (19-23.2MHz, 600 kW) and two tangential beam NBI systems (30kV, 700 kW). The electron density ever attained is $\bar{n}_e \leq 4.0\times10^{19}$ m^{-3}.

The main goal of this reflectometer is to measure the electron density profile in the wide confinement region. As a first step, however, the low density plasma ($\bar{n}_e \leq 1.0\times10^{19}$ m^{-3}) is targeted. The sweeping time of the carrier frequency is set as less than 1 ms, which is shorter than the typical energy confinement time of Heliotron J plasma.

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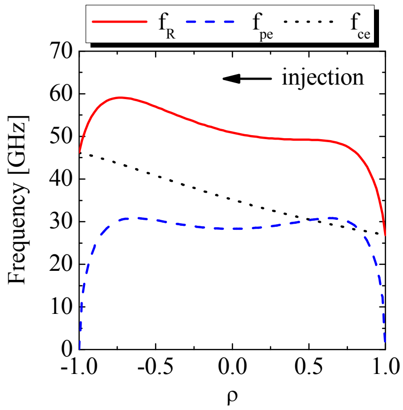

Fig.1 Characteristic frequencies along the line-of-sight of reflectometer for a hollow electron density profile

Figure 1 shows the radial profiles of the right-hand cut-off frequency, f_R, the plasma frequency, f_{pe}, and the electron cyclotron frequency, f_{ce}, along the line-of-sight. The electron density profile is assumed to be hollow, given by

$$n_e(r) = n_e(0)\{1-(r/a)^6\}[1-0.4\times\{1-(r/a)^2\}] \qquad (1)$$

Here $n_e(0)$ is determined to satisfy the condition, $\bar{n}_e = 1.0\times10^{19}$ m^{-3}.

In helical systems, a hollow density profile is typically observed in ECH plasma. In such a profile, the central density cannot be measured by using the O-mode. Since there is an appropriate gradient of magnetic field in Heliotron J, the X-mode is selected as the propagation mode. By using the carrier frequency of 33-56 GHz (nearly Q-band), it is possible to obtain density profile over the full range of plasma radius for low-density plasmas.

2.2 Schematic of the AM reflectometer

Figure 2 shows the schematic of the designed AM reflectometer. A pulse generator supplies a triangular-wave of 1 kHz to a voltage controlled oscillator (VCO) of 8.25-14 GHz. The frequency band of 33-56 GHz is generated by the VCO and a ×4 frequency multiplier. A Q-band waveguide transmission of 8 m long is used for transmission in order to suppress the resonant attenuation which is observed when using oversized waveguides. After transmission, the microwaves are modulated in amplitude with the frequency of 100 MHz by using a PIN modulator. Low-pass filters are assembled to remove the effect of 70 GHz ECH. Horn antennae are used for launching and receiving microwaves. A heterodyne detection system is applied to detect the reflected signal. A phase meter consists of a frequency down-converter (from 100 MHz to 5 MHz) and a phase detector. The phasemeter also measures the RF signal

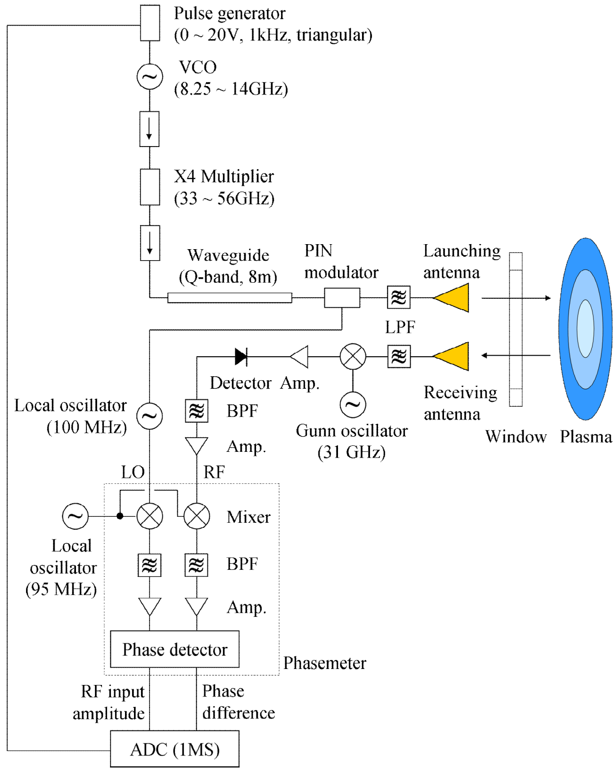

Fig.2 Schematic of the AM reflectometer.

power to correct the power dependence of the phase comparator. The outputs of the pulse generator, the RF input amplitude and the phase difference are stored by a data acquisition system with the sampling time of 1 μsec.

3. Measurement results in test stand

The performance of each microwave component has been measured in a test stand before installing the system in Heliotron J. Figure 3 shows the dependences of the frequencies and intensities of the VCO and the multiplier on the VCO input voltage. The output frequencies are controlled stably by the VCO input voltage, and the output intensities are almost constant for the operation range of the VCO input voltage. Figure 4 shows the phase outputs and signal intensities of the modulated signal at the front and end of the 8 m Q-band waveguide transmission. In the whole range of carrier frequencies, the phase output is

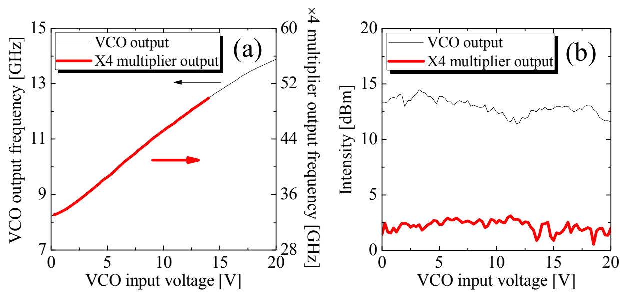

Fig.3 Dependence of VCO and ×4 multiplier output (a)frequencies and (b)intensities on VCO input voltage.

almost flat. However, since the intensity is weak, it needs to amplify the signal for reliable measurement.

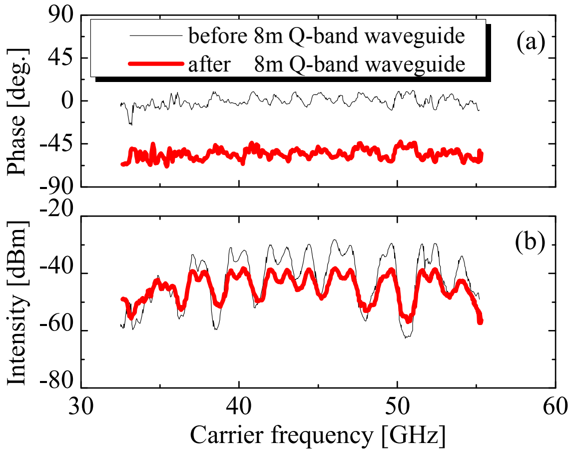

Fig.4 Dependence of (a) the phase output and (b) the modulated signal intensities on the carrier frequency before and after the 8 m Q-band waveguide transmission.

The phase measurement has been conducted by using an aluminum reflection plate instead of plasma. The length of the transmission line is changed by moving the plate in the range of 30 cm at an 1 cm interval. Figure 5 (a) shows the dependence of the phase shift on the plate displacement. It can be seen that the phase output of the phasemeter depends on the RF input amplitude. This dependence is

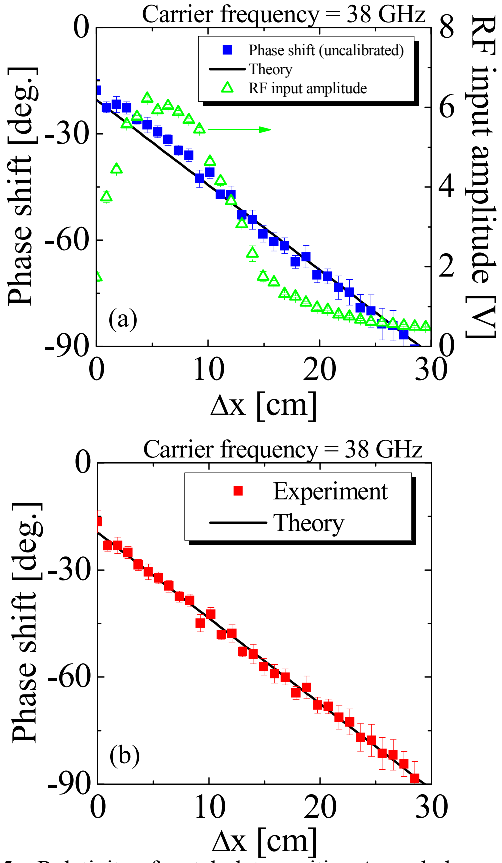

Fig.5 Relativity of metal plate position Δx and phase shift (a)uncalibrated and (b)calibrated.

caused by the characteristic of the limiting amplifier in the phasemeter. Figure 5 (b) shows the corrected phase shift data by using the calibration data of the phase output. The calibration reduces the root-mean-square error from 2.4 degree to 1.4 degree. The phase shift agrees well with that expected from the change of the plate position when the amplitude dependence is taken into account.

4. Density profile reconstruction method

4.1 Algorithm of profile reconstruction

The phase shift of the probe signal from the reference signal is written as

$$\phi(f_n) = \frac{4\pi f_n}{c}\int_a^{r_n} N_X(r, f_n)\mathrm{d}r \qquad (2)$$

where f_n is the carrier frequency, r_n is the position of cutoff layer corresponding to f_n and N_X is the refractive index of X-mode. By using Eq. (2), the position of the cutoff layer is determined, and the density profile can be reconstructed.

The algorithm to reconstruct the density profile is as follows. By considering the difference between two phase shift data, the phase shift caused by the difference of the transmission length outside LCFS between the probe and the reference signals can be removed.

$$\begin{aligned}\frac{4\pi f_{n+1}}{c}&\int_{r_n}^{r_{n+1}} N_X(r, f_{n+1})\mathrm{d}r \\ &= \phi(f_{n+1}) - \phi(f_n) \\ &-\left[\frac{4\pi f_{n+1}}{c}\int_a^{r_n} N_X(r, f_{n+1})\mathrm{d}r - \frac{4\pi f_n}{c}\int_a^{r_n} N_X(r, f_n)\mathrm{d}r\right] \qquad (3)\end{aligned}$$

At the cutoff layer, the left-hand side of Eq. (3) can be approximated as $\Delta r_n\ N_X(r_n,\ f_{n+1})/2$ since $N_X(r,\ f_{n+1})=0$. Here $\Delta r_n = r_{n+1} - r_n$ is given by

$$\begin{aligned}\Delta r_n = \frac{2}{N_X(r_n, f_{n+1})}&\left[\phi(f_{n+1}) - \phi(f_n) - \frac{4\pi f_{n+1}}{c}\int_a^{r_n} N_X(r, f_{n+1})\mathrm{d}r\right. \\ &\left.+\frac{4\pi f_n}{c}\int_a^{r_n} N_X(r, f_n)\mathrm{d}r\right] \qquad (4)\end{aligned}$$

The integral term of Eq. (4) can be calculated by using a trapezoid formula. Consequently, the density profile can be reconstructed if the initial density value is determined by other diagnostics, for example, Langmuir probe.

4.2 Results of reconstruction using model profiles

In order to validate the reconstruction algorithm, model electron density profiles are reconstructed by the program calculating Eq. (4). The profile is chosen as a flat or hollow density one. The electron density is assumed as the line-averaged density, $\overline{n}_e=1.0\times10^{19}$ m^{-3}, and the edge density, $n_e(\rho=1)=0.2\times10^{19}$ m^{-3}. Here ρ denotes the normalized minor radius.

The reconstruction results are shown in Fig. 6. Here, the cutoff layer position of 33 GHz is assumed to be located at ρ=1. At the both profiles, the density profiles are reconstructed with the error less than 5 % in the center region. This indicates that the program can reconstruct density profile in the whole plasma region with the sufficient accuracy for density profile measurement. For a high-density model (2.0×10^{19} $m^{-3} \leq \bar{n}_e \leq 3.0\times10^{19}$ m^{-3}), the density gradient at the edge region can be evaluated within 10 % accuracy.

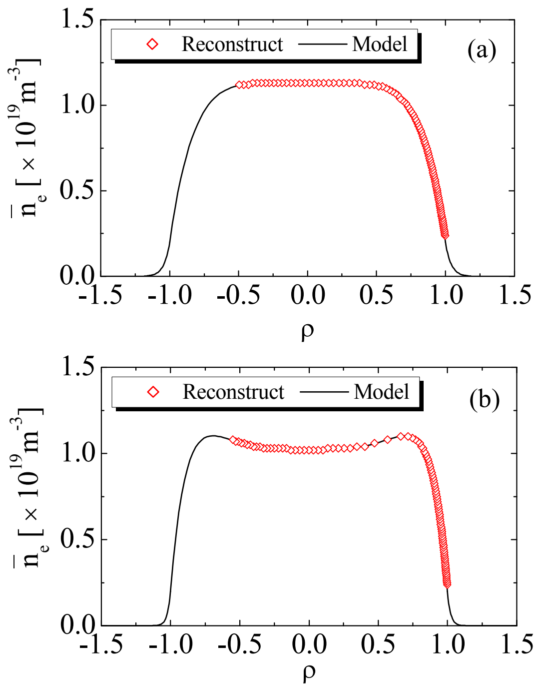

Fig.6 Reconstructed profiles, (a) flat density profile and (b) hollow density profile at $\bar{n}_e=1.0\times10^{19}$ m^{-3}.

5. Summary

The AM reflectometer is developed for the electron density profile measurement in Heliotron J. The measurement results in a test stand show that each microwave component works well and the phase shift is measured as designed.

A program to reconstruct density profile from the relative phase shift data has been developed. The program has been examined by using modeled density profiles such as flat and hollow ones. The result confirms that the program works well for the modeled shapes of the density profile model with accuracy of fewer than 5 % for low density at the plasma central region.

The reflectometer system is under installation in Heliotron J. In order to measure the profile with satisfactory accuracy, it is necessary to improve detection system sensitivity and S/N ratio. Therefore, we plan to install more sensitive detector and Q-band microwave amplifier. The electron density profile will be measured in ECH, NBI and ICRF plasmas in the near future.

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