Reflectometry for Density Fluctuation and Profile Measurements in TST-2

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A reflectometer in Ka-band was designed, constructed and applied to the TST-2 spherical tokamak in order to detect density fluctuations induced by the radio frequency (RF) heating wave, and to measure the density profile. The optics of the reflectometer consists of two concave mirrors to make a small microwave beam spot inside the plasma. Using Kirchhoff integration, the parameters of the optics were optimized to achieve a high throughput (i.e. the ratio of the received to the launched powers) in various measurement conditions. Using the reflectometer, the density fluctuations in the frequency range of RF were detected and the electric field excited by RF (21 MHz/260 kW) was estimated to be about 1.3 kV/m.

Keywords: reflectometry, spherical tokamak, high harmonic fast wave, heating, density fluctuation

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1. Introduction

Microwave reflectometry is a useful diagnostic for measuring the electron density in fusion plasmas and very sensitive to density fluctuations at plasma cutoff layers. Using this feature, reflectometry is often used for detecting the density fluctuations induced by radio frequency (RF) heating waves in fusion plasmas such as GAMMA10 [1] and DIII-D [2]. At the TST-2 spherical tokamak in the University of Tokyo [3], RF heating experiments using high harmonic fast wave (HHFW) with a frequency of 21 MHz and a power of 260 kW is carried out [4]. HHFW is a fast wave which is a several harmonics of the ion cyclotron wave and the frequency is in the range between the ion cyclotron frequency and the lower hybrid frequency, and is an attractive wave for electron heating and current drive in spherical tokamaks. HHFW heating experiments with an injection power of 6 MW have been tested in NSTX [5], and density fluctuations by HHFW in the edge plasma was detected by reflectometry [6]. In order to study wave physics and to develop an efficient heating and/or current drive method, it is crucial to measure internal electric field. Injected HHFW excites radial electron density oscillations in plasmas, and a reflectometer can detect the density oscillations by measuring the phase oscillation of the reflected microwave. The feature of our reflectometer is that by sweeping the probe frequency, the density profile, and fluctuations representing the RF electric field are simultaneously obtained.

Measured phase fluctuation $\tilde{\phi}$ can be approximated by $4\pi\tilde{r}/\lambda$, where $\tilde{r}$ is the fluctuating radial position of the cutoff surface, and λ is the wavelength of the injected microwave inside the plasma, which is usually 1.7 times the wavelength in vacuum λ_0 [7]. As a result, electron density fluctuation $\tilde{n}_e$ is written by

$$\tilde{n}_e = \frac{\partial n_e}{\partial r}\tilde{r} \sim \frac{1.7\lambda_0}{4\pi}\frac{\partial n_e}{\partial r}\tilde{\phi}. \tag{1}$$

TST-2 has major/minor radii of about $R_0/a = 0.38/0.25$ m. The toroidal magnetic field B_t at the target region of the plasma is about 0.1 T, the central electron density n_{e0} is about $2 \times 10^{19}\,\mathrm{m}^{-3}$, and the electron temperature is about 400 eV. Using these parameters, the dielectric tensor for HHFW, the Landau damping and magnetic pumping terms can be calculated. Since the single pass absorption is expected to be small, the HHFW shows multiple-pass absorption (and propagation). Therefore electric fields are enhanced compared to the single pass case. In order to estimate the enhanced electric field, we use the volume-averaged power for the absorption power density, and typical values for the damping terms. Note that the distribution of these values is neglected. The estimated poloidal electric field E_p is about 2 kV/m. By substituting $E_p \times B_t$ drift to the continuous equation of the electron density n_e, the fluctuation of the density $\tilde{n}_e$ is [2]

$$\tilde{n}_e \sim \frac{E_p}{\omega_{rf} B_t}\frac{\partial n_e}{\partial r} = \frac{\lambda_{rf}}{2\pi c}\frac{E_p}{B_t}\frac{\partial n_e}{\partial r}. \tag{2}$$

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Substituting this equation into eq. (1), the phase shift of the reflectometer induced by the HHFW is

$$\tilde{\phi} \sim \frac{2}{1.7}\frac{\lambda_{rf}}{\lambda_0}\frac{E_p}{cB_t} = 0.08\,\text{rad}. \tag{3}$$

where $\lambda_0 = c/25.85\,\text{GHz}$ is used for example. Assuming $\partial n_e/\partial r \sim n_e/a$, $\tilde{n}_e/n_e$ becomes about 0.1 %, which is not difficult to measure by a standard reflectometer. This article describes the construction of the reflectometer and the first results of the RF induced density fluctuation measurements.

2. Designing the Reflectometer

The microwave optics of the reflectometer was designed by using Kirchhoff integration. Its performance was also tested to examine whether it can detect density fluctuations of the order of eq. (3). Kirchhoff integration is a very useful method to calculate the propagation of electromagnetic waves [8]. By an assumption that the wave is a plane wave locally, Kirchhoff integration can calculate three-dimensional propagation of the wave very fast. Kirchhoff integration equation is derived from Helmholtz equation and Green's theorem and that is

$$E = \frac{1}{4\pi}\int_S \left(\psi\frac{\partial E}{\partial n} - E\frac{\partial \psi}{\partial n}\right) \mathrm{d}S, \tag{4}$$

where E is a scalar electric field and ψ is a wave function. The integrating surface S is taken as a wall with an opening screen and a hemisphere. If the radius of the hemisphere is large enough, the integration along the hemisphere is zero because wave field vanishes at the infinite distance. Thus, to calculate the propagation from one screen to another screen, the only information necessary for the calculation is the complex amplitude of the electric field (and its gradient) on the first screen. Kirchhoff integration at each optical element along the microwave path (i.e. the mirrors, the cutoff surface, and the antennas) was carried out for various configurations, and the final outputs (i.e. the complex electric fields) were compared.

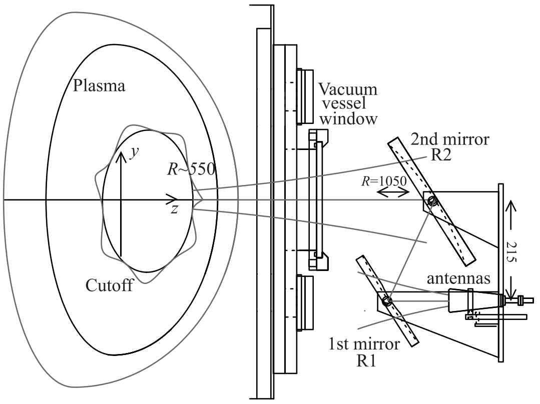

Fig. 1 Optimized arrangement of the reflectometer.

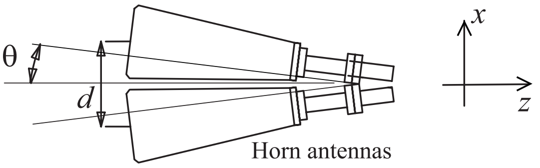

Fig. 2 Top view of the horn antennas.

Figure 1 shows the arrangement of the optics optimized through the calculation. Two concave aluminum mirrors were located between the horn antennas and the vacuum window. The purpose of using concave mirrors is to make a small illuminating spot at the plasma cutoff surface and to collect most of the reflected wave including specular reflection and scattering [9]. By localizing the target spot, the reflectometer becomes sensitive to the fluctuation induced by RF even if the wavelength is short. The values optimized by calculation were z position of the second mirror, radius of the first and the second mirrors R1 and R2, inclined angles θ of the horn antennas and the distance d between the two antennas (see Fig. 2). The positions of the first mirror and the antennas were located as close as possible to the vacuum vessel, and not to interrupt the path of the microwave. The optimized arrangement is determined so that the system shows a high throughput in all the frequency range for typical radial positions of the cutoff surface. Using the optimized arrangement, the performance of the fluctuation measurement was calculated. As a result, the reflectometer can detect density fluctuations with a poloidal wavelength larger than $5\lambda_0$, as long as the radial amplitude of the fluctuating cutoff surface is smaller than 5 rad. When the amplitude is larger than this level, the microwave is scattered at the cutoff surface seriously, and the measured phase is deformed seriously. The fluctuation estimated in eq. (3) is smaller than 5 rad so that it is able to detect by this reflectometer system.

A reflectometer was constructed using the optimized parameters. In order to confirm the design of the optics, horizontal and vertical beam profiles of launched microwave (i.e. illuminating spot) are measured, and the profiles are compared with the prediction of Kirchhoff integration. The measurement plane corresponded to $R = 550\,\text{mm}$ in the plasma. Figure 3 shows the comparison between measured profiles and the calculation. The profile is broad in x (horizontal) direction and narrow in y (vertical) direction. The two results show a good agreement both in x and y directions. From this comparison, the calculations using Kirchhoff integration were proved to be reliable.

Figure 4 is a schematic of the reflectometer system. A voltage controlled oscillator (VCO) with frequencies of 6.625-10 GHz is controlled by a tuning voltage 5-25 V. The microwave from VCO is quadrupled by a Ka-band active multiplier (26.5-40 GHz) and the wave power emitted from the multiplier is about 100 mW. A 25.85 GHz Gunn oscillator is also available for the microwave source. The microwave from the source is split into two by a −3 dB di-

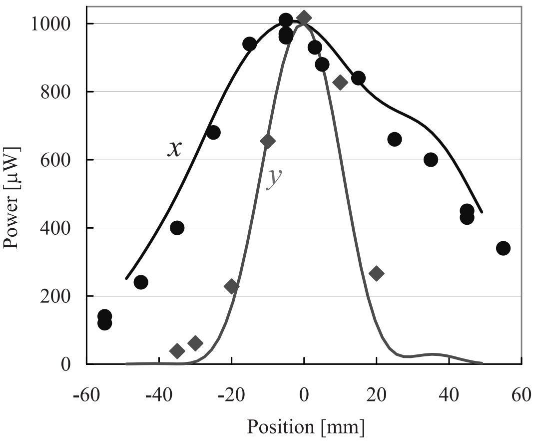

Fig. 3 Measured and calculated power emitted from the reflectometer. Circles and squares are the measured powers and solid lines are the calculated results.

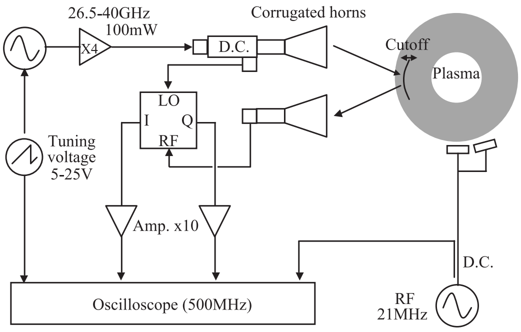

Fig. 4 Schematic of the reflectometer.

rectional coupler; one goes to the plasma in O-mode and reflected at the cutoff surface, and the other is used as the local for an inphase-quadrature (I-Q) demodulator. The I-Q demodulator produces the sine and the cosine components of the reflected wave. Therefore we obtain the complex amplitude, which includes phase and amplitude information. Two outputs of the I-Q demodulator are amplified and measured by a fast oscilloscope with a sampling frequency of 500 MHz. Frequency responses of these components are fast enough to measure the phenomena around the RF frequency (21 MHz). By using the I-Q demodulator, phase tracking becomes simple and accurate, and the density profile reconstruction becomes reliable as a result. Thus, measurement of the density fluctuation and the density profile becomes possible with this system.

3. Experimental Results

In RF heating experiments, the noise from the RF wave source is a serious problem especially for fluctuation measurements. The RF noise enters the system via several paths; one is through the frequency control voltage line of the VCO (FM noise), another is through the cables such as those from the I-Q demodulator to the oscilloscope (pickup noise). In order to separate the FM noise and the pickup noise, a 25.85 GHz stable Gunn oscillator was used and compared with the system with the VCO. Gunn oscillator is considered to be less sensitive to the RF noise, since the frequency is fixed and it has no frequency control line. Figure 5 shows power spectra S of the reflectometer using Gunn (sum of the two I-Q outputs) during the RF injection with the targets of plasma and a metal mirror covering the vacuum window. The noise in the Gunn system shows a very sharp spectrum at the RF frequency (21 MHz) and the noises of I-Q outputs are almost the same (i.e. inphase well correlated waveforms). Therefore the dominant noise is considered to be a pickup noise at the detection part. On the other hand, in the VCO system, additional FM noises are seen at the both side of the pickup noise in the spectrum. The FM noise, which is defined as pure frequency (or phase) modulation at the noise frequency (i.e. 21 MHz) without amplitude modulation, was confirmed. The RF noise is modulated by the beat frequency f_b (around 0.5 MHz) to produce noises at $f_{rf} \pm f_b$. Since the RF signal is also modulated by the beat frequency, the pickup noise falls in a different frequency range from the signal, while the FM noise does not. Fortunately, in our VCO system, the FM noise is much weaker than the pickup noise.

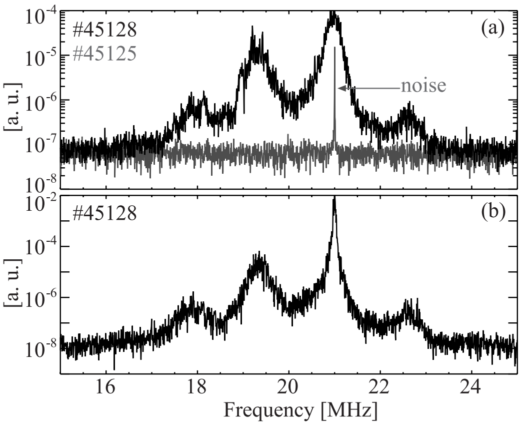

Fig. 5 Power spectra of the output of the (a) reflectometer and (b) RF pickup probe during the RF injection period. Noise level was measured by covering the vacuum vessel window with a metal plate. A Gunn oscillator with frequency of 25.85 GHz was used for microwave source.

From Fig. 5, it is clear that the spectrum of the RF pickup noise is very sharp while that of the RF induced density fluctuation is broad. This broadening is believed to be caused by the scattering of RF by slow density fluctuations inside the plasma. There are also some other peaks well separated from 21 MHz. These side peaks are considered to be caused by parametric decay instabilities. The frequency differences of the side peaks from 21 MHz are multiples of the ion cyclotron frequency (around 1.7 MHz). These side peaks are also observed from RF pickup probes inside the TST-2 vacuum vessel, and they show similar power spectra to the reflectometer. Consequently, the RF

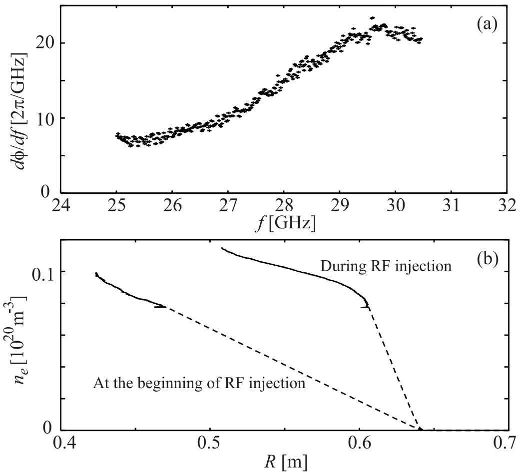

Fig. 6 Frequency derivative of the phase, which represents the group delay (a), and the density profiles reconstructed by the reflectometer (b). Profiles at the beginning of RF injection and during RF injection are over plotted. Dotted curves represent the assumed profiles at the edge.

noise is very sharp (around 10 kHz), and the height is smaller than that for the signal in most cases. Therefore we can neglect the noise effect when we use an integrated power with a frequency width larger than a few tens of kHz.

The rms amplitude of the RF induced phase fluctuation $\tilde{\phi}$ is obtained from the power spectrum S. When $\tilde{\phi}$ is much smaller than 2π, the outputs of the I-Q demodulator can be expressed by

$$A \exp(i\phi_0 + i\tilde{\phi}) \sim A \exp(i\phi_0)(1 + i\tilde{\phi}), \tag{5}$$

where A is the complex amplitude of the output, and ϕ_0 represents the slow phase variation. Therefore, $\tilde{\phi} = (\int S\, df)^{0.5}/A$. In the case of Fig. 5, integration of S from 17 to 23 MHz yields an rms amplitude of 6 mV and $\tilde{\phi} = 0.05$ rad by using the average complex amplitude of $A = 120$ mV. From eq. (3), the excited polodial electric field by RF is $E_p \sim 1.3$ kV/m, which is of the same order as the predicted value of $E_p \sim 2$ kV/m. The density fluctuation $\tilde{n}_e/n_e$ is obtained from eq. (1) if we know the density scale length. The scale length can be obtained directly from the profile measurements. A similar discharge with that in Fig. 5 was measured by the reflectometer with the VCO source. Figure 6 shows reconstructed density profiles, and the density scale length is around a at the core and about an order of magnitude shorter at the edge. Since the system measures the density above 0.78×10^{19} m^{-3}, we assume straight density profiles at the edge (dotted line in Fig. 6(b)). The measured position for the fixed frequency shown in Fig. 5 was just around the knee of the profile, and the profile changes from a straight one to a one with a knee during the HHFW injection. If we consider the change in the profile and resultant ambiguity in the density scale length, the RF induced density fluctuation is in the range of 0.03 % to 0.2 %.

4. Summary

In summary, a reflectometer in Ka-band was designed, constructed, tested and applied to TST-2 to measure the density fluctuation induced by RF and the density profile. The arrangement of the reflectometer was optimized by the calculation using Kirchhoff integration to collect the reflected microwave as large as possible in wide condition. The capability of fluctuation measurement was also investigated by the calculation. Using the reflectometer, internal density fluctuations induced by HHFW heating were detected, and the poloidal electric field excited by HHFW was calculated to be about 1.3 kV/m, which was in the same order as the prediction.

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