

V-band frequency hopping microwave reflectometer in LHD^{a)}

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In order to measure the internal structure of fluctuation, the broadband frequency tunable system, which has the ability of fast and stable hopping operation, is applied in the Large Helical Device. One of the important issues of density fluctuation measurements using this reflectometer is the study of energetic particle driven magnetohydrodynamics instability. During one plasma discharge, the launching frequency changes from one frequency to another frequency, which this operation is called as frequency hopping, and the cutoff position can be scanned in the wide area. As a hopping source, a synthesizer is used because it has a quite stable and low phase noise. The frequency component of the source output is multiplied to V-band (50–75 GHz) region for plasma measurements in extraordinary mode polarization. Also this system has a heterodyne detection with single side band frequency modulation for sensitive phase and amplitude measurement. We can obtain the radial profile of Alfvén eigenmodelike oscillation in a neutral beam injected plasma.

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I. INTRODUCTION

For the preparation study of the future burning plasma, the experimental information on the internal structure of the energetic alpha particle driven magnetohydrodynamics (MHD) instabilities, such as toroidal Alfvén eigenmodes, is important and studying in several magnetic confinement devices.^{1–4} Usually MHD phenomena can be observed by magnetic probes and these toroidal and poloidal mode numbers and traveling directions are obtained by the conventional analytical technique. However, in some large plasma experimental devices, the magnetic probe often failed to detect fluctuations which are located in the core region.¹ For the comparison with the simulation results, such as a global mode analysis code CAS3D3,⁵ direct measurements of the internal radial distribution of these modes are necessary.

In the Large Helical Device⁶ (LHD) we apply the microwave reflectometer system for measuring the radial distribution of the fluctuation. Microwave reflectometer has a potential of localized measurement by using the cutoff effect in the plasma core region. The density perturbations δn , associated with the displacement ξ of a shear Alfvén mode, is described in the equatorial plane by²

$$\frac{\delta n}{n} = -\nabla \cdot \xi - \xi \cdot \frac{\nabla n}{n} \cong \left(\frac{-2\hat{R}}{R^2} + \frac{\hat{n}}{L_n} \right) \cdot \xi. \quad (1)$$

Here n is the plasma density, \hat{n} is the density unit vector normal to the magnetic surface, R is the major radius, \hat{R} is the unit vector along a major radius direction, and L_n is the density scale length. The phase fluctuations $\delta\phi$ of reflecto-

meter signal are given by $\delta\phi = (4\pi/\lambda)(\delta n/n)L_n$ for the ordinary mode and $\delta\phi = (4\pi/\lambda)(\delta n/n + \delta B_z/B_t \cdot f_{cef}/f_{pe}^2)/(1/L_n + f_{cef}/f_{pe}^2 \cdot 1/L_B)$ for extraordinary mode in the one dimensional screen model. Here, λ is the wavelength of the probing wave, δB_z is the magnetic fluctuation, B_t is the magnetic field strength, and L_B is the magnetic field scale length. Therefore, reflectometers can measure the internal structure of MHD phenomena such as energetic particle mode and Alfvén eigenmodes.

In order to measure the radial distribution of fluctuation in the wide range, a reflectometry needs a lot of probing frequency components and there are two methods. One is the multichannel system, and another is the wide band frequency source system. In the former case, many microwave sources need a lot of cost and also the spatial resolution is limited. On the other hand, when the plasma condition can be assumed to be steady during a frequency scanning period, the radial profile can be measured by using the latter system. In this case the source frequency is swept step by step in the whole frequency range. This type of frequency sweep is referred to as frequency hopping.^{7,8} The step width and step number are arranged by the characteristic time of the measured fluctuation frequency. In this paper, we describe the frequency hopping reflectometer system in Sec. II and present some experimental results in Sec. III, and then we summarize the present results in Sec. IV.

II. EXPERIMENTAL APPARATUS

The schematic of frequency hopping V-band reflectometer system is shown in Fig. 1. A microwave synthesizer (Anritsu Co. Ltd., model MG3692B) is used as a source with a low phase noise. The output frequency is easily changed by the external controlled signal. The hopping operation of output frequency is shown in Fig. 2. The output frequency in-

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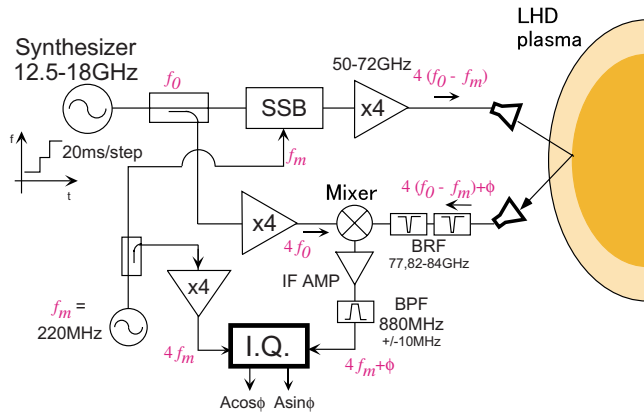


FIG. 1. (Color online) Schematic of the V-band frequency hopping microwave reflectometer. f_0 is carrier frequency (12.5–18 GHz), f_m is modulation frequency (220 MHz), and ϕ is plasma fluctuation component.

increases step by step. High level of the lock status signal means that the synthesizer frequency is locking. The typical value of the locking time (T_{lock}) is 20 ms, the setup time (T_{setup}) is 6 ms, and the step number is 20. Also for the direct phase measurement, the single side band (SSB) frequency modulation is utilized. The source output is split into the probe and the reference signal. The SSB modulator driven by a 220 MHz quartz oscillator shifts the frequency of the probe signal for the heterodyne *I-Q* detection. The output frequency is quadruple followed by an active multiplier to bring the launching frequency up to 50–72 GHz (V-band). The modulated microwaves launch from the outboard side along the inverse major radius direction on equatorial plane. The polarization of launching wave is set on the extraordinary mode (*X*-mode) and the right-hand cutoff layer is used as the reflected surface because the electron density profile is sometimes flat in the LHD experiments. The reflected wave is received and mixed with unmodulated reference wave and intermediate frequency signal is amplified and led to *I-Q* detection. The output signals of *I-Q* demodulator, which are described by $A \cos \phi$ and $A \sin \phi$, are acquired by real-time data acquisition system⁹ based on a compact PCI digitizer and the sampling rate is usually 1 MHz during the whole plasma discharge.

Evaluation of system performance is carried out before LHD plasma experiments. Using a metal mirror as a reflector,

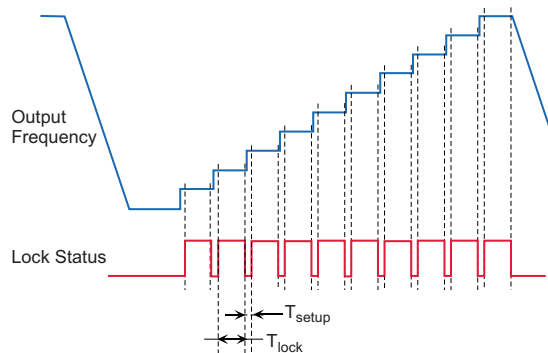


FIG. 2. (Color online) Timing diagram of the frequency hopping operation. The output frequency increases step by step. High level of lock status signal means that the synthesizer frequency is locking.

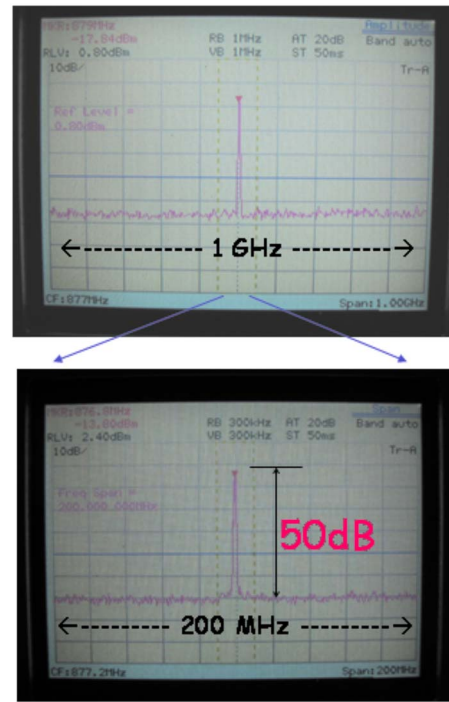


FIG. 3. (Color online) Frequency spectrum of the reflectometer output using a metal mirror. The input carrier frequency $f_0=60$ GHz is modulated at $f_m=880$ MHz.

tor, the frequency spectrum of reflected wave is shown in Fig. 3. In this test, the input carrier frequency $f_0=60$ GHz and it is modulated at $f_m=880$ MHz. We can suppress the side band and obtain the sharp peaking spectrum of 880 MHz by using the bandpass filter which band width is 20 MHz. Also, the noise level is shown in Fig. 4. The phase perturbation level is about 1/30 fringe. In the case of $L_n=50$ mm, this value corresponds to $\delta n/n \sim 10^{-4}$.

III. EXPERIMENTAL RESULTS

Here, we show a preliminary experimental result of this hopping system for the radial distribution measurement of

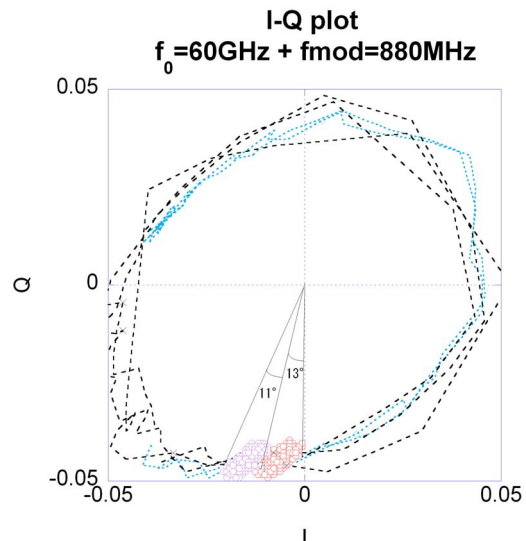


FIG. 4. (Color online) *I-Q* plot of the reflectometer output using a metal mirror. Two test results are plotted and each duration time is 1 s. The dotted line is obtained when the reflector moves for making the circle image.

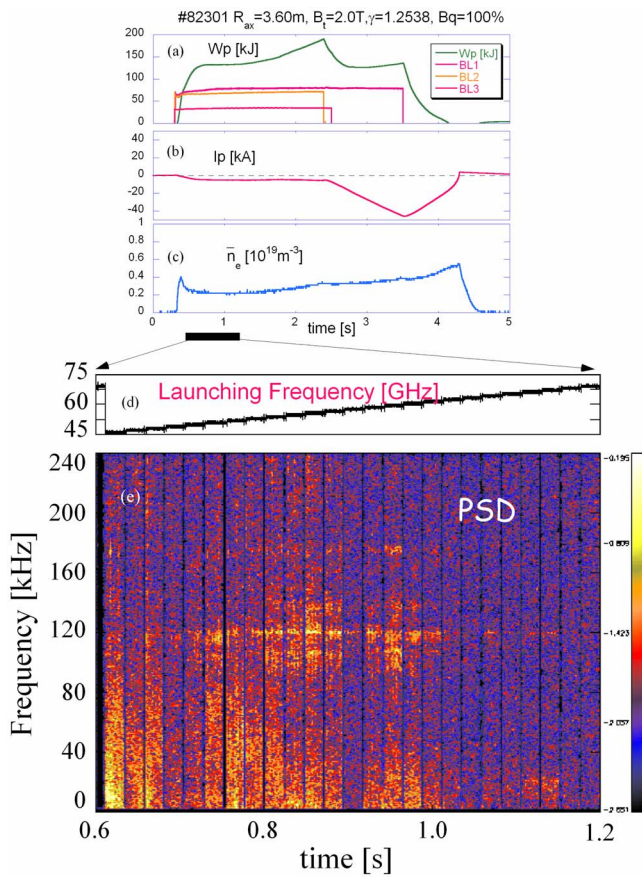


FIG. 5. (Color online) (a) Time evolution of the plasma stored energy together with tangential negative NB injection, (b) the plasma current, and (c) the averaged electron density. (d) Time evolution of the launching frequency; (e) the frequency spectrogram.

density fluctuation. The experiment is carried out on the axial magnetic field strength of 2.0 T, the averaged electron density is under $0.4 \times 10^{19} \text{ m}^{-3}$, and three tangential neutral beams are injected with constant power shown in Fig. 5. During $t=0.6-1.5$ s the plasma condition is mostly steady and then the fluctuation frequency keeps constant. The source frequency is swept from 48 to 72 GHz and the step size is 1 GHz with 20 ms duration in this plasma discharge. Figure 5(f) shows the frequency spectrum of the hopping reflectometer signal. We can see continuous coherent frequency components of about 120 kHz in the finite launching frequency range. The toroidal mode number of this coherent fluctuation $n=1$ was measured by the magnetic probe. The radial fluctuation profile of the frequency components of 110–130 kHz is shown in Fig. 6(c). Here, ξ is calculated by $\xi \sim \delta\phi(1 + f_{ce}/f_{pe}^2 \cdot L_n/L_B) / [(4\pi/\lambda) \cdot (1 + L_n/2qR \cdot f_{ce}/f_{pe}^2)]$. It can be seen that this mode is large around $\rho=0.3$. The calculated shear Alfvén spectra are also shown in Fig. 6(b). The frequency gap of around 120 kHz is located near $\rho=0.25$. It is in good agreement with the measured profile data.

IV. SUMMARY AND FUTURE WORKS

Frequency hopping reflectometer system is installed in the LHD, and we performed the electron density fluctuation profile measurement for the study of the internal structure of

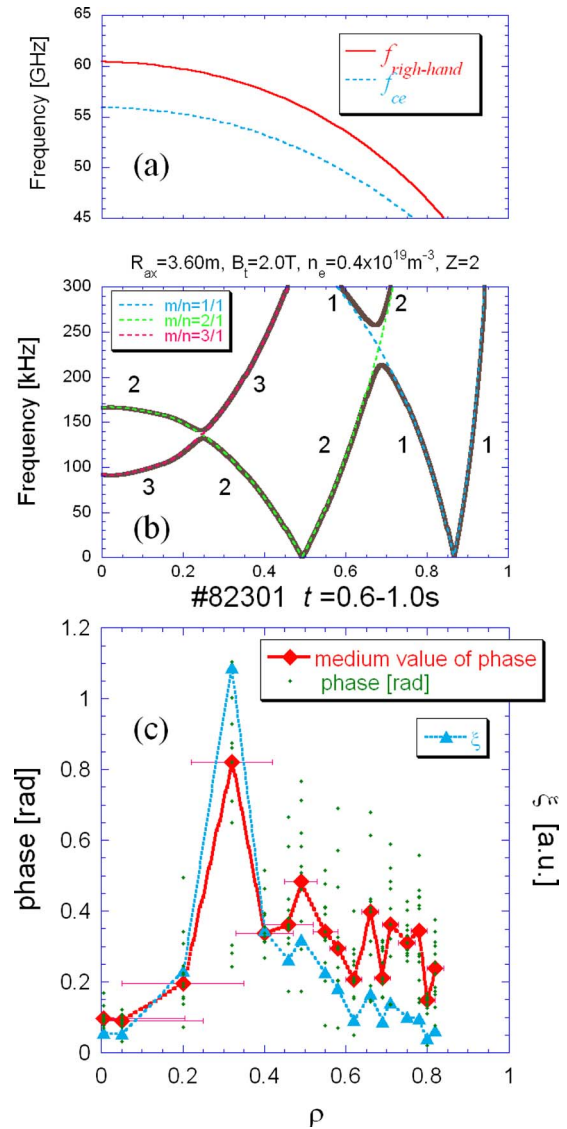


FIG. 6. (Color online) (a) Radial profiles of the right-hand X-mode cutoff frequency (red solid line) and electron cyclotron frequency (blue dotted line). (b) Radial profile of the shear Alfvén spectra of $n=1$. Each number expresses the poloidal mode number. (c) The amplitude of phase fluctuation (green dots), with frequency components of 110–130 kHz, and medium value at each radial position (red line with diamond) and calculated radial displacement (blue line with triangle).

Alfvén eigenmodes. The system utilizes a synthesizer as a source for the low phase noise and SSB modulator for the direct phase measurement. In the system test, the signal-to-noise ratio is high enough for the fluctuation measurements. In the LHD plasma experiment energetic particle driven mode can be observed and its radial distribution can be obtained. More improvements, such as a power amplifier of the probe beam and a narrower bandpass filter, are planned for the achievement, and new system of ka-band frequency range is planned to install for a high β plasma experiment; it will contribute to the physics study of Alfvén eigenmodes in the near future.

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