Observation of a nonlinear phenomenon of the density fluctuations on Zheda Plasma Experiment Device (ZPED)

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Abstract

An O-mode microwave reflectometry system has been developed to measure the density fluctuation on Zheda Plasma Experiment Device (ZPED). The microwave frequency range of this diagnostic system is from 10 GHz to 18 GHz, corresponding to the cutoff densities from $0.13\times10^{19}m^{-3}$ to $0.4\times10^{19}m^{-3}$. The density fluctuations are measured with a fixed microwave frequency for plasma in different magnetic field. It has been observed that the density fluctuation power changes with the magnetic field nonlinearly: the density fluctuations increase linearly with the magnetic field when the magnetic field is less than the critical magnetic field, while almost no change when the magnetic field is larger than the critical magnetic field.

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I. INTRODUCTION

In magnetic confinement fusion devices the anomalous transport across the magnetic field is thought to be caused by plasma turbulence, which is the main reason of the particles and energy loss from the confinement regions [1, 2]. Study and control the anomalous transport is a key issue on how to improve the plasma behavior in magnetic confinement fusion devices. The experimental and theoretical results of the turbulence transport research indicate that E×B flow plays an important role in suppressing the turbulence, which is believed to be the main cause to drive the anomalous transport. Fortunately, advanced diagnostic tools have been developed for the turbulence transport research, such as Langmuir probes [3-5], Beam Emission Spectroscopy [6, 7], microwave reflectometry [8-13].

We report the microwave reflectometry diagnostic to measure the plasma turbulence in Zheda Plasma Experiment Device (ZPED), which is a linear magnetized helicon plasma device. The plasma density and the density fluctuations are measured using the microwave reflectometry on ZPED for the first time. We compare the density fluctuations in different magnetic fields. A nonlinear phenomena of the density fluctuation with the magnetic field increase is observed.

II. EXPERIMENTAL SETUP

A. Cylindrical magnetized plasma device

Zheda Plasma Experiment Device (ZPED) is a cylindrical magnetized plasma device at Institute for Fusion Theory and Simulation (IFTS). The schematic diagram of the ZEPD and the main structure parameters are shown in Fig. 1.

The device consists of a stainless cylindrical vacuum chamber, which has an overall length of 2.0 m and a diameter of 0.3 m. A calibrated mass flow controller provides gas injection at the head of the helicon source, as shown by the yellow arrow in Fig. 1. The plasma is produced by a 13.56 MHz, 7.5 cm radius helicon antenna, which is localized inside of metallic material box, as shown in Fig. 1 A. This helicon source has the forward rf power 2.0 kW with reflected power less than 20W. The power of the helicon

launch in the ZPED is about 1.6 kW. However, this power of the helicon source is flexible to change according to the experimental requirements.

The chamber is surrounded by 10 electromagnet coils, as shown in Fig. 1 C. The engineering structure for each electromagnet coil: the internal diameter is 410 mm, the external diameter is 724 mm and the coil thick is 94 mm as shown in Fig. 1 H. The copper conductor cable of each electromagnet coil is total length of 410 m. The weight is 150 kg for each electromagnet coil. The designed maximum current is 210 Ampere for a safety operation with the power supply of 10.2 kW. Thus, the electromagnet coils produce an axial magnetic field (B), which can be actively set up to about 3000 Gauss (3.0 kG) near the center of the vacuum chamber. The plasma is operated by a helicon source in ZPED.

A low pressure of the vacuum chamber is provided by the 1000 liter per second turbopump system located at the end of the ZPED, as shown in Fig. 1 E. The work gas pressure is about 0.1 Pa and the vacuum is less than 10^{-5} Pa. The ZPED cooling system is very important to keep the machine operation with a long time, thus the cooling water is designed to pass through the center of the each copper conductor cable. The cooling tubes are localized at the top of the ZPED, as shown in Fig. 1 G.

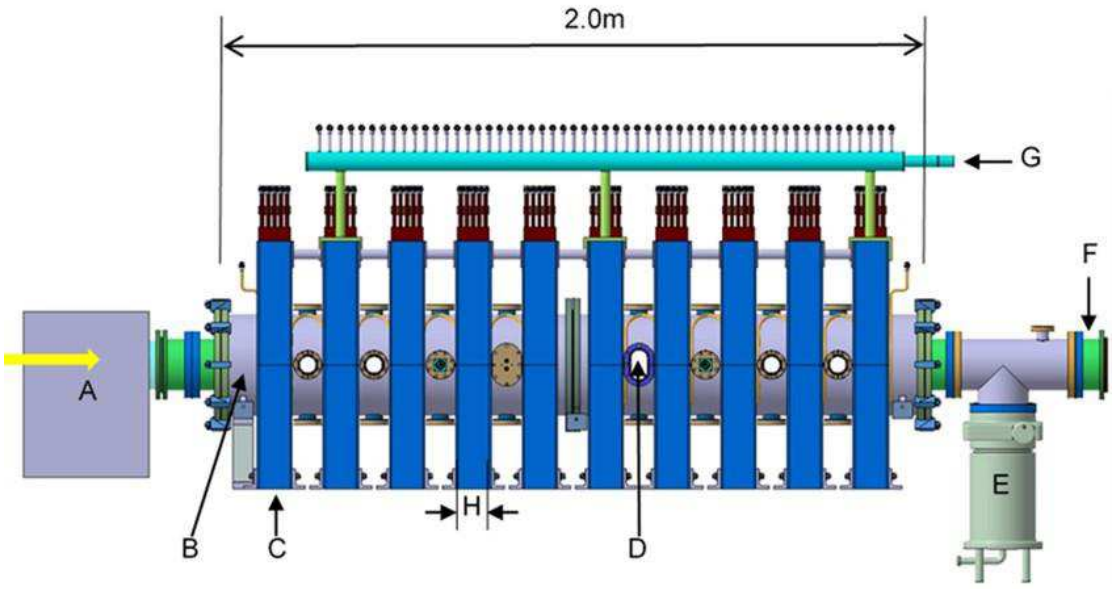

FIG. 1 Schematic diagram of the ZEPD. A to G represent the Helicon plasma source, the vacuum chamber, the magnetic coils, the diagnostic window for the microwave reflectometry, the throttle valve and pump system, the glass observation window and

the water cooling tubes, respectively. The ZPED has an overall length of 2.0 m and a diameter of 0.3m. The gas fueling system is located at the head of vacuum chamber, as shown by the yellow arrow.

A comparison result on the magnetic field is shown in FIG. 2. Here, the blue squares are from the measurement results using the Hall effect monitor and the red curve is from the calculation based on the Ampere law. It indicates that the magnetic field is larger than 2 kG from the 2nd magnetic coil to the 9th magnetic coil. The magnetic fields at the both ends of the machine drop to about 1.5 kG. This means that good experimental conditions are in the region of the flat magnetic field profile from the 2nd magnetic coil to the 9th magnetic coil, as shown in FIG. 2 by the black dashed lines.

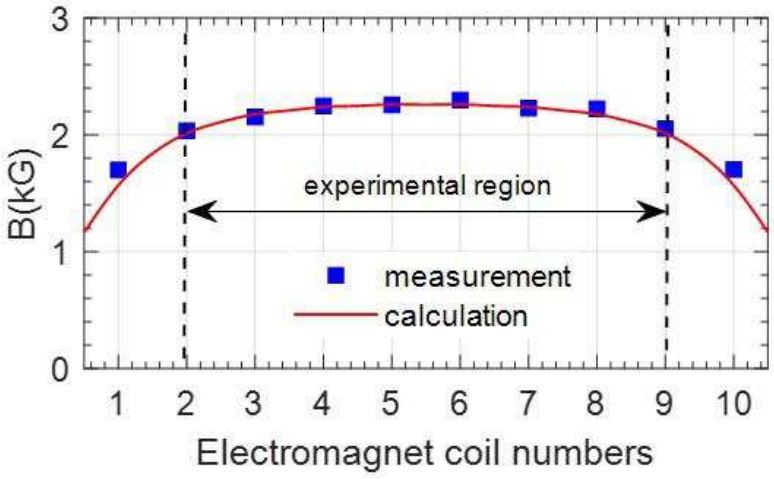

FIG. 2. A comparison result on the magnetic field.

B. Microwave reflectometry diagnostic system

O-mode broadband microwave reflectometry system has been installed in ZPED. It is localized at the glass window as shown in Fig. 1 D. In this region of the microwave reflectometry, the magnetic field is flat. The local density and density fluctuation can be measured using the microwave reflectometry. The microwave frequency of the this diagnostic system used in ZPED is Ku band (12-18 GHz), while the available operation frequency is from 10 to 18 GHz, which covers a density range from $0.13\times10^{19}m^{-3}$ to $0.4\times10^{19}m^{-3}$. The real diagnostic equipment of the microwave reflectometry diagnostic system is shown in Fig. 3. Five main parts are indicated: ① the video-frequency

amplifier to provide the power supply to the VCO source, ② the VCO source to produce the microwave frequency from 10-18 GHz, ③ the directional coupler, ④ the I/Q phase discriminator system, and ⑤ I/Q signal amplifier. This diagnostic also includes some auxiliary equipment, the isolators, the antennas and sampling system with 5MHz [14]. In figure 3, the red arrow, the green arrow and two blue arrows represent the launch signal, received signal, and the I/Q signal, respectively.

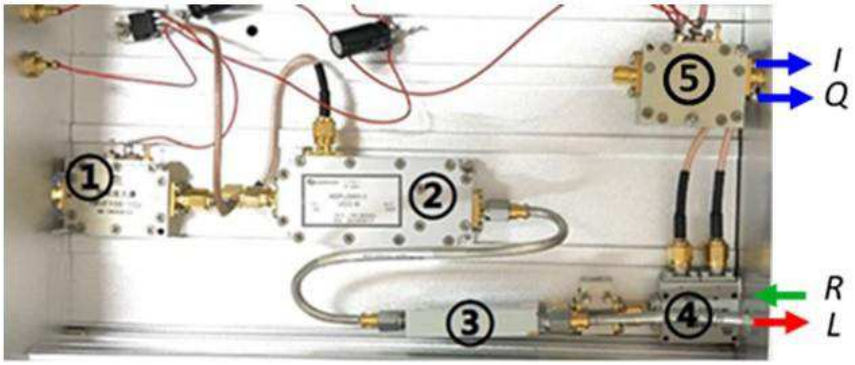

FIG. 3. The microwave reflectometry diagnostic system on ZPED. ① the video-frequency amplifier to provide the power supply to the VCO source, ② the VCO source to produce the microwave frequency from 10-18 GHz, ③ the directional coupler, ④ the I/Q phase discriminator system, and ⑤ the I/Q signal amplifier. The red arrow, the green arrow and two blue arrows represent the launch signal, received signal, and the I/Q signal, respectively.

The frequency of the VCO source is controlled by input voltage from 0 to 8 V. A calibration curve of the microwave frequency vs input controlled voltage is shown in Fig. 4 (a). A calibration curve of the power of the microwave reflectometry is shown in Fig. 4 (b). The output power of the microwave reflectometry is about from 12 dBm to 15 dBm, almost 16-32 mW. It is enough to get signal with high s/n ratio to measure the local density based on our experimental requirements.

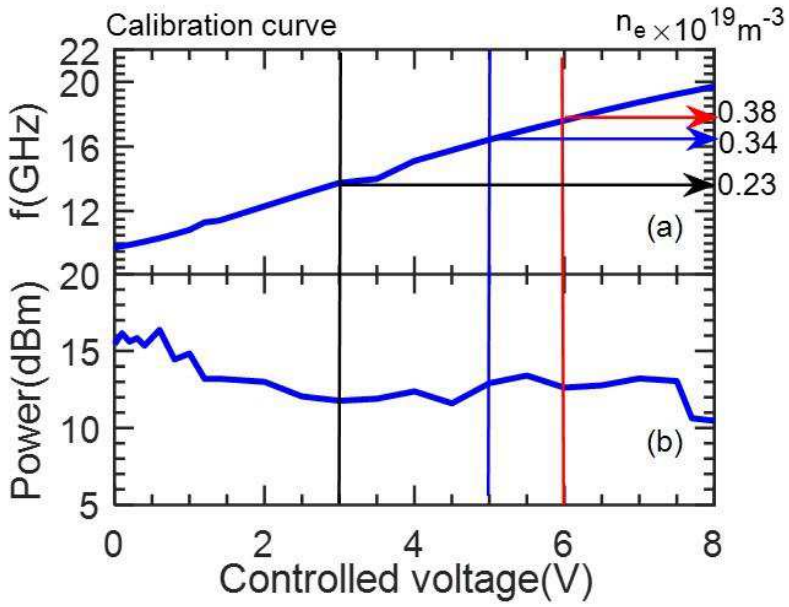

FIG. 4. (a) the calibration curve of the microwave frequency and (b) the output power of microwave reflectometry at different controlled voltage.

One can preset a voltage to get the microwave frequency for an experiment based on the calibration curve. The density at the cutoff layer for each microwave reflectometry frequency is calculated using the formula (frequency equals plasma frequency):

$$n_e=(\varepsilon_0 m_e \omega^2)/e^2$$

Here, the n_e is the plasma density of the cutoff lay, the m_e is the electron mass, the ω is the microwave reflectometry and the ε_0 is the permittivity, and the e is the electron charge quantity. In order to probe the possible maximum density with the magnetic field 2.0 kG on ZPED, a scanning microwave frequency was operated from 10 GHz to 18 GHZ via the controlled voltage from 0 to 8 V. When the controlled voltage is 6 V, there is no reflected signal from the I/Q phase discriminator. This means that there is no cutoff density in the plasma with the microwave frequency of 17. GHz. In other words, the plasma density is less than $0.38\times10^{19}m^{-3}$. A useful reflected signal is obtained in the experiment when the controlled voltage is 5 V, corresponding to the microwave frequency is 16.5 GHz and cutoff density is $0.34\times10^{19}m^{-3}$. The cutoff densities with different microwave frequency are shown in Fig. 4 (a) by the different color arrows. It indicates that the core density is $0.34\times10^{19}m^{-3}$ at least on ZPED with the magnetic field 2.0 kG. A comparison of the parameters is presented in table I.

TABLE I. Parameter comparison under B=2.0 kG on ZPED

Controlled voltage (v)	Power (dBm/mW)	*f*(GHz)	Cutoff density ($10^{19}m^{-3}$)
6	12.6/18.2	17.5	0.38
5	12.9/19.5	16.5	0.34
3	11.8/15.1	14.0	0.24

III. EXPERIMENTAL RESULTS

The electron density and the electron temperature were measured at magnetic field ~ 0.4 kG in the core plasma on ZPED [15]. The electron temperature is about 5 ev and the density maximum is about $0.3\times10^{18}m^{-3}$ with the magnetic ~0.4 kG. An influence of the Langmuir probe measurements increases when the magnetic field increases in the experiments on ZPED, especially, a big influence for the Langmuir probe measurement is at the edge region of the plasma. We did not find the possible causes of the influence on the measurement from the Langmuir probes or the rf source.

An excellent experiments were carried out on ZPED with fixed microwave frequency 14 GHz (cutoff density, $0.24\times10^{19}m^{-3}$) to measure the density fluctuations. Typical density fluctuation auto-power spectra are shown in Fig. 5. Here, we can see that density fluctuation amplitude increases with the magnetic field. Similar results have been reported in a few special articles [5, 16-18]. Especially, in this experiment, a clear change of the density fluctuation amplitude was observed during the magnetic field increase from 0.65 kG to 1.4 kG, as shown in Fig. 5. However, a saturation of the density fluctuation amplitude was also observed as the magnetic field is larger than 1.4 kG.

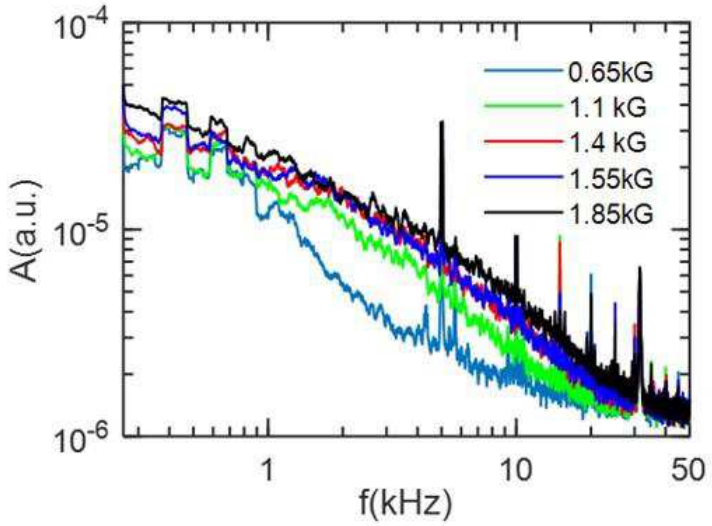

FIG. 5. Auto-power spectra of the density fluctuations with different magnetic field.

We focused on the analysis for the density fluctuation with the turbulence frequency ranging from 1kHz to 20kHz in this experiment. Here, we compared the integrated amplitude of the density fluctuations over the frequency range from 1kHz to 20kHz. The integrated amplitudes of the density fluctuations increase linearly with the magnetic field, while the integrated amplitude is almost no change when the magnetic field is larger than 1.25 kG. This means that there is a nonlinear phenomenon of the density fluctuations with the magnetic field increase, as shown in Fig. 6 by the dashed lines, and a critical value of the magnetic field is shown by the red line in this figure.

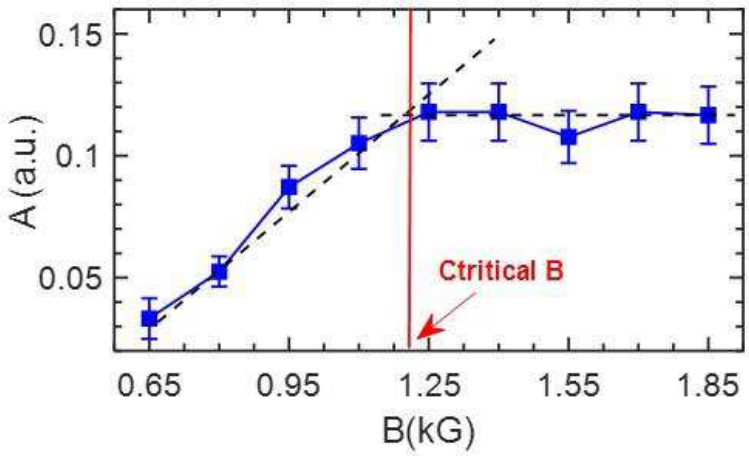

FIG. 6. A nonlinear phenomenon of the density fluctuations with the magnetic field increase exists in this experiment, as shown by the dashed lines. A critical of the magnetic field is shown by the red arrow.

IV. SUMMARY AND DISCUSSIONS

The first plasma experiments have been carried out on the Zheda Plasma Experiment Device (ZPED) at IFTS. The ZPED consists of a stainless cylindrical vacuum chamber with overall length of 2.0 m and a diameter of 0.3 m. An O-mode microwave reflectometry system has been successfully developed to measure the density fluctuation on ZPED. The frequency range of this diagnostic system is from 10 GHz to 18 GHz, corresponding to the cutoff densities are from $0.13\times10^{19}m^{-3}$ to $0.4\times10^{19}m^{-3}$. The experiments were carried out with fixed microwave frequency 14 GHz (cutoff density $0.24\times10^{19}m^{-3}$) to measure the density fluctuations. Typical density fluctuation spectra have been obtained using the microwave reflectometry. The density fluctuation amplitude increases with the magnetic field. However, a saturation of the density fluctuation amplitude was also observed when the magnetic field is larger than 1.4 kG, which is the critical value of the magnetic field for the saturation level of the density fluctuations. This suggests a nonlinear phenomenon of the density fluctuations exists when the magnetic field increases on ZPED plasma.

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