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Application of Ultrashort-Pulse Reflectometer to a HYPER-I Device Plasma

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Abstract

The ultrashort-pulse reflectometry is considered as a tool for determining the electron density profile in a large magnetic fusion device. We have been developing an ultrashort-pulse reflectometer. This device has higher spatial and temporal resolution than other conventional diagnostics to measure electron density profiles and fluctuations. We have succeeded to obtain the desired range of the millimeter wave from an ultrashort-pulse for a plasma measurement. We have installed the reflectometer on HYPER-I device and operated using a real plasma. In this paper we show the reflectometer configuration and the preliminary experimental results..

Keywords:

plasma diagnostics, electron density, microwave, ultrashort-pulse, time-of-flight

1. Introduction

A plane electromagnetic wave, which is launched perpendicularly to the external magnetic field into a plasma, is distinguished between the ordinary mode (O-mode) and the extraordinary mode (X-mode) for the direction of the electric field component. When these waves arrive at the critical density regions, they can not propagate and then reflect. In the case of O-mode operation, the critical layer is determined only by the electron density profile. We have aimed to develop an Ultrashort-Pulse Reflectometer (USPR) that has higher spatial and temporal resolution than other conventional diagnostics. Ultrashort-pulse reflectometry experiments were initially carried out on CCT tokamak [1], subsequently on GAMMA 10 tandem mirror [2], also on SSPX [3]. Because an ultrashort-pulse has broad band frequency components in a Fourier-space, an USPR can take a place of multichannel pulsed radar reflectometers [4]. When an ultrashort-pulse is launched into a plasma, each frequency component reflects from the corresponding cut-off layer. If the time-of-flight measurement of each frequency component pulse is done, the electron density profile and the fluctuations simultaneously can be determined. In this paper, the USPR system is described in Sec. **2**. Section **3** gives the calibration experiment and preliminary results on the HYPER-I device [5] are presented in Sec. **4**. We summarize the present results in Sec. **5**.

2. Experimental apparatus

2.1 Transmitter design

Our ultrashort-pulse reflectometer uses an impulse of –2.2 V, 23 ps full-width half-maximum. To extract the desired frequency range from this impulse, a 50 cm R-band rectangular waveguide is used. When an ultrashort-pulse is launched into the waveguide, it is transformed into electromagnetic waves with a broad frequency spectrum. This transformation is due to the dispersion effect in the waveguide. The group velocity v_g in the waveguide is given by

$$v_g = c\sqrt{1-\left(\frac{c}{2af}\right)^2}\ ,$$

where c is the velocity of light, a is the long side length of the rectangular waveguide, and f is the frequency of the electromagnetic wave in vacuum. The output from the 50 cm R-band waveguide, which is fed by the driver pulse, is shown in Fig. 1(a). The resultant frequency component is shown in Fig. 1(b). Consequently the frequency component of the output wave gradually changes from high to low. Then we obtain the chirped millimeter wave that has the frequency components between 26 and 40 GHz. The USPR system has been installed on the HYPER-I device is shown in Fig. 2.

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The chirped wave (26 – 40 GHz) is amplified by a power amplifier and divided from the incident wave to produce the reference wave by a directional coupler. The reference wave is detected by a Schottky barrier diode detector to obtain the reference pulse. The reference pulse is transmitted to a constant fraction discriminator (CFD).

2.2 Receiver design

The reflected wave is mixed with continuous wave from a 42 GHz local oscillator. The output of the mixer is amplified by an intermediate frequency (IF) amplifier (2 – 18 GHz) and then divided to six channels. Each IF signal is filtered by bandpass filters with the center frequencies of 3, 5, 7, 9, 11 and 13 GHz and with the band width is ± 0.5 GHz. The six signals are detected by Schottky barrier diode detectors to obtain the reflected pulses. The detected pulses are amplified by pulse amplifiers and leaded to CFDs.

2.3 Data acquisition system

Positions of cut-off layers are estimated from time-of-flight (TOF) measurement technique. The reference pulse is used as the start signal and the reflected pulse is used as the stop signal for a time-to-amplitude converter (TAC). As this TAC can be operated every 2.5 µs, the fluctuation measurement is available in this time scale. The TAC outputs an analog voltage proportional to the time difference between the start signal and the stop signal. The TAC output is transmitted to an analog to digital converter and the digital data is stored by a personal computer.

3. Calibration experiment

In the calibration experiment, we use a metallic plate at different positions to simulate the reflection from a plasma. We measure the reflected pulse and the TAC output voltage with changing the position of the plate. The TAC output voltage is proportional to the delay time. The detected pulses, which IF is 13 GHz, are shown in Fig. 3(a). Here, the distance is changed from 50 cm to 170 cm with the increment of 20 cm. Figure 3(b) shows the value of the delay time. It is found that the linearity of this TOF measurement is good and the value is also reliable. When the distance is changed from 50 cm to 66 cm, the value of the delay time is obtained, which is shown in Fig. 3(c). The spatial ambiguity of USPR is estimated from the maximum deviation width of the delay time. The maximum width of the deviation is 80 ps and it corresponds to 6 mm in a real space.

4. Experimental result

HYPER-I device consists of a cylindrical vacuum chamber (30 cm in diameter and 200 cm in axial length) and 10 magnetic coils to produce magnetic field of 1 kG along the chamber axis. The plasma is generated by electron cyclotron resonance heating using a microwave of frequency 2.45 GHz. We use the O-mode operation in HYPER-I argon plasma experiments. At first we use one channel system. In the condition (condition (A)) that the operation pressure is

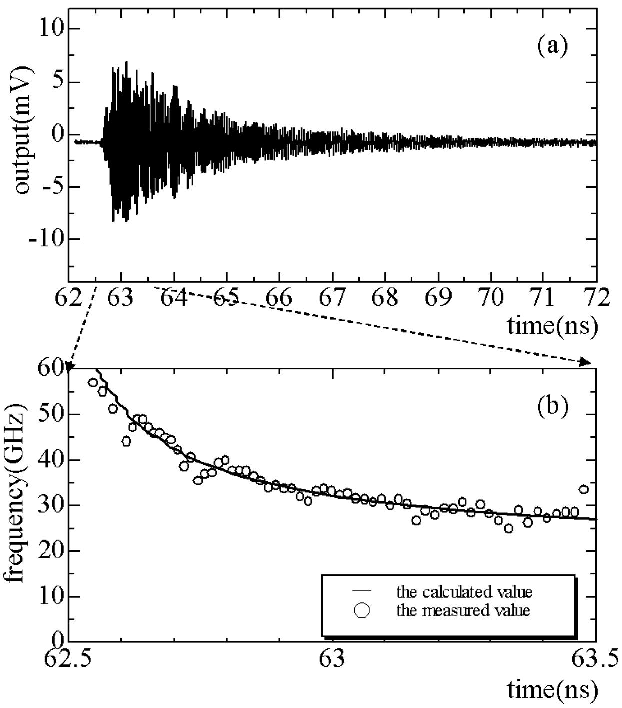

Fig. 1 (a) 40 – 26 GHz chirped waveform propagating through a 50 cm R-band waveguide. (b) Open circle are time evolution of the frequency component of the chirped waveform from 62.5 ns to 63.5 ns, and the solid line is the calculated value by using the theoretical equation.

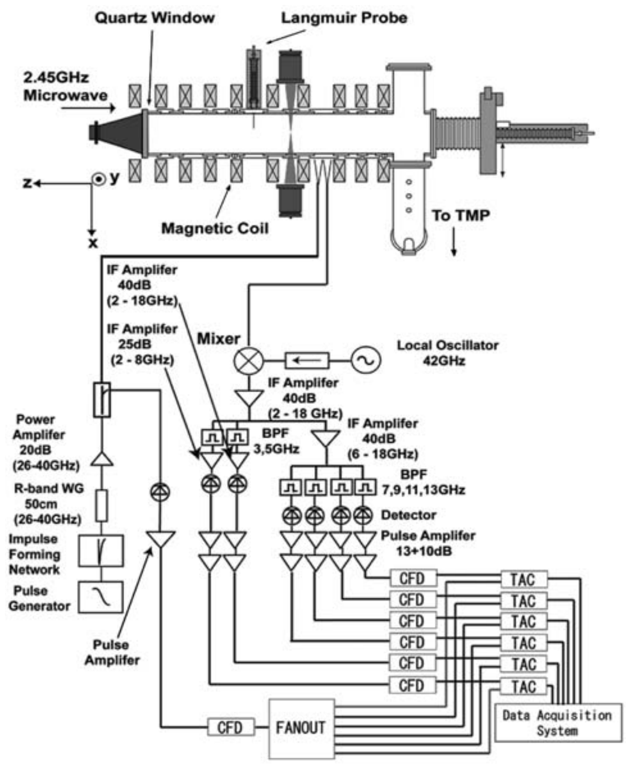

Fig. 2 Schematic view of USPR, which is used for plasma experiments with HYPER-I device.

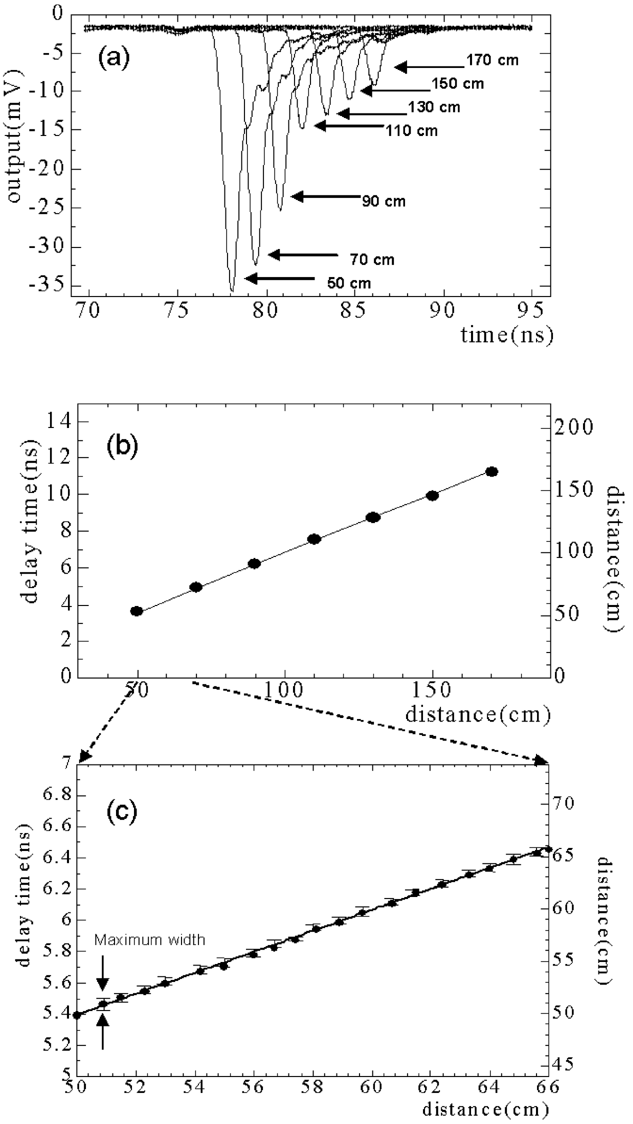

Fig. 3 (a) The detected pulses amplitude (IF = 13 GHz) observed at different positions. (b) The change of the delay time as a function of the distance between the antenna and the plate. (c) Enlargement of the upper figure in the case that the distance is changed from 50 cm to 66 cm.

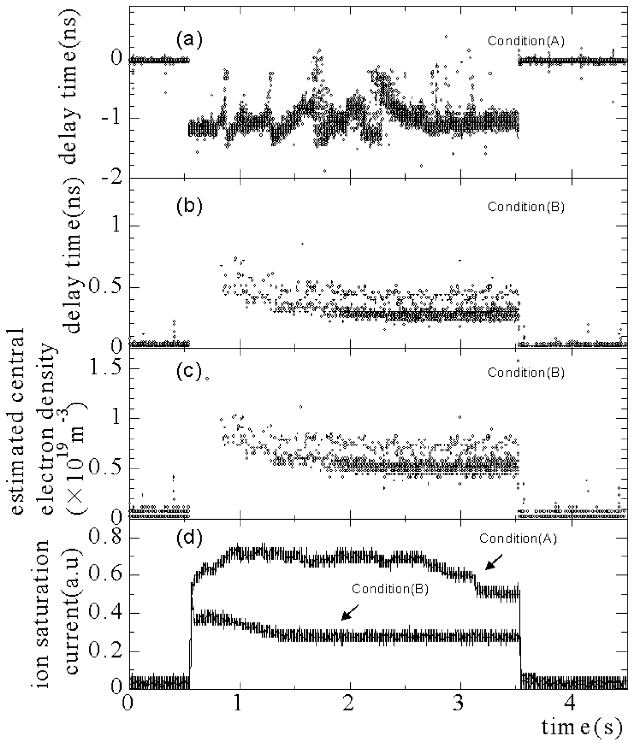

Fig. 4 (a), (b) Time evolutions of the delay time of the reflected pulse in condition (A) and (B), respectively. (c) Time evolution of the estimated central electron density estimated in condition (B). (d) Time evolution of the ion saturation current measured by the Langmuir probe.

5.3 Pa and the heating power is 12 kW, the time evolution of the delay time of reflected pulse is shown in Fig. 4(a). The frequency of this signal is 35 GHz. Here, the delay time is subtracted by the delay time of the pulse reflected from the opposite inner wall of the chamber in the vacuum. When the value of the measured delay time becomes negative, it means that the existence of the cut off density corresponding to the probing frequency is established in the plasma. In another condition (condition (B)) that the operation pressure is 2.5 Pa and the heating power is 10 kW, the result is shown in Fig. 4(b). The value of the delay time is larger than that from the wall of the vacuum chamber. Time traces of ion saturation current measured with a langmuir probe are shown in Fig. 4(d). As is shown in Figs. 4(b) and 4(d), both the time behaviors of the delay time and the ion saturation current are similar. This signal represents the time evolution of electron density at a fixed spatial point. In condition (B), the plasma density seems to be lower than that in condition (A). When the plasma density is below the critical one, the launched pulse is not reflected from the plasma and reflected back from the opposite wall. In condition (B), the USPR is considered to be working as a delayometer [6]. Because the group velocity of the microwave pulse in a plasma is lower than that in the vacuum, the time of flight increases. The delay time of the plasma is given by

$$\tau_{pe} = \frac{2}{c}\int_{-l}^{l}\left(\frac{1}{\sqrt{1-f_{pe}^{2}(x)/f^{2}}}-1\right)\mathrm{d}x\,,$$

where f_{pe} is the plasma frequency, f is the probing frequency and l is the radius of the plasma. By using an assumption of the parabolic density profile such as

$$n_e(r) = n_e(0)\left(1-(r/l)^2\right),$$

we can determine the electron density. Where r is the distance from the center of the plasma. The estimated central electron density is also shown in Fig. 4(c). The central electron density is estimated to be about 0.7×10^{19} m^{-3}.

Next, we show multichannel experiment results. The experiment is performed in the condition that the operation pressure is 5.3 Pa and the heating power is 32 kW. The TOF

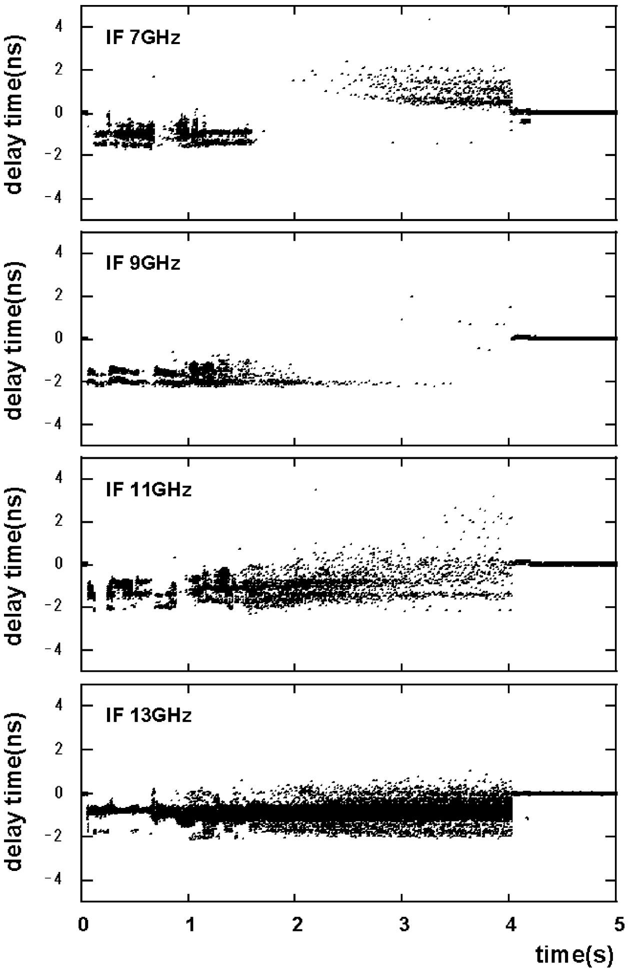

Fig. 5 Time evolutions of the delay time for the four channel system. Each IF is 7, 9, 11, 13 GHz, which correspond to the electron density of 1.5, 1.4, 1.2, 1.0 × 10^{19} m^{-3}, respectively.

measurements for each channel are shown in Fig. 5. All pulses reflected from the plasma are observed until t = 1.6 second. Subsequently, the reflected signal, corresponding to the higher density, can not be observed and then that appears with large delay. Because the plasma density gradually decreases with time, the critical layer of this frequency disappears and then this channel becomes a delayometer.

5. Summary

We have been developing an USPR that can measure an electron density profile and fluctuations simultaneously. We have succeeded to obtain the desired range of millimeter wave from an ultrashort-pulse for a plasma measurement. We have developed the receiver system with high sensibility. The spatial ambiguity of 6 mm has been achieved in calibration experiments. The USPR experiment was performed in the HYPER-I device plasmas. Multi channel system has been constructed for accurate TOF measurements.

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