

Development of a Frequency Comb Sweep Microwave Reflectometer in the Linear Device PANTA

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A frequency comb sweep microwave reflectometer is developed in PANTA to realize multi-point electron density measurements with high temporal resolution. A radial profile of the electron density is successfully reconstructed from simultaneous 17-point measurements with 2- μ s temporal resolution. This result demonstrates the reliability and feasibility of the system for electron density profile diagnostics.

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The dynamic evolution of an electron density profile and its fluctuations are essential for studies of turbulence transport. For example, turbulence intermittency, which increases the radial transport and leads to flat density profiles, has been observed in different devices [1–3]. To observe the evolution of the density profile and its fluctuations, a frequency comb microwave reflectometer has been employed in the linear device PANTA [4]. The profile of the density is reconstructed according to the phase delay between the incident and reflected waves of 29 frequency channels.

However, an ambiguity of 2π exists in the observed phase delay, leading to a half-wavelength uncertainty of the cut-off layer location. To solve this problem, a frequency comb sweep microwave reflectometer is developed. Compared to frequency modulated continuous wave (FMCW) reflectometers employed in other devices [5–7], the comb sweep reflectometer has the advantage of a narrow frequency sweep range for each channel. Therefore, the sweep period is short for the same sweep rate, i.e., the temporal resolution is improved.

Figure 1 illustrates the circuit diagram of the comb sweep microwave reflectometer. The sweep frequency signal is generated by a voltage controlled oscillator (VCO) with a maximum sweep range of 0.5 GHz. After being mixed with a high-frequency (23.9 GHz) wave generated by a phase locked oscillator (PLO), the high-frequency sweep signal (28.0–28.5 GHz) is again mixed with the comb frequency signal and the comb sweep frequency microwave is generated. After being filtered and amplified, one channel is directly transferred to the digital storage oscilloscope (DSO) of which the sampling rate is 160 GHz as the reference signal, and another channel is launched into

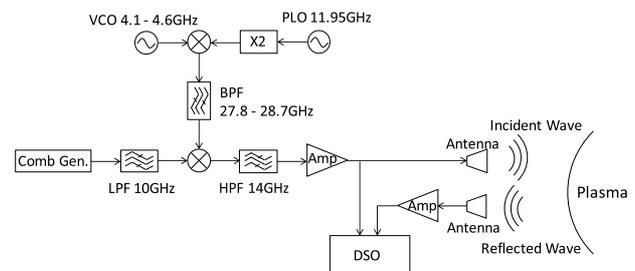


Fig. 1 Block diagram of the frequency comb sweep microwave reflectometer.

the plasma by a dual-band rectangular horn antenna at ordinary mode (O-mode). The reflected wave is received by another antenna and transferred to the DSO. By calculating the beat frequency of the incident and reflected waves, the phase difference and time of flight of the reflected wave can be obtained for further calculations.

The microwave was injected toward a metal target (benchmark test). The time–frequency spectrum of the incident wave is presented in Fig. 2 (a). It is clear that the entire frequency range of the system is from 15.5 GHz to 26 GHz, with a frequency interval of 0.5 GHz. The output frequency of each channel is swept as triangular-wave. To distinguish the adjacent channels, the frequency sweep range of each channel is set to approximately 0.4 GHz (e.g., 18.05–18.45 GHz) and the incident frequency is regarded as the center of the sweep range (e.g., 18.25 GHz) for the calculations. The sweep period is approximately 2 μ s, during which all incident channels share the same phase. The highest temporal resolution is therefore 2 μ s.

Due to the time of flight of the incident wave, the frequency of the incident wave is different from that of the

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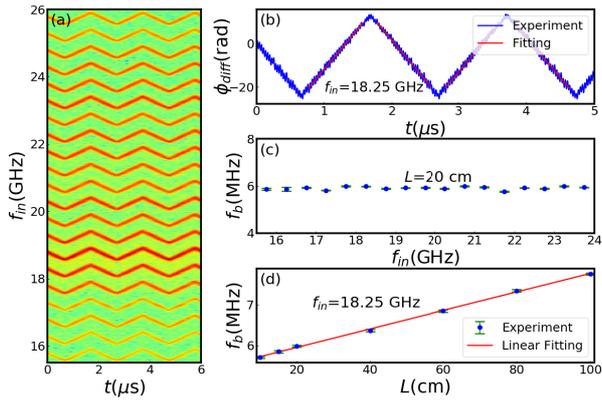


Fig. 2 (a) Time–frequency spectrum of the incident wave. (b) Temporal evolution and linear fitting of the phase difference. (c) Beat frequency versus the incident frequency. (d) Beat frequency versus the distance.

reflected wave at the antennas, and the beat frequency f_b between the incident and reflected waves is finite. The time of flight can therefore be evaluated from f_b via the following process. A digital bandpass filter corresponding to the frequency sweep range of each channel (e.g., 18–18.5 GHz) is first applied to the original signal to obtain the single frequency channel signal $x_k(t)$, where k denotes the incident (in) or reflected (ref) wave. The instantaneous phase $\phi_k(t)$ is then obtained by applying the Hilbert transform to $x_k(t)$. The phase difference between the incident and reflected waves is

$$\phi_{diff}(t) = \phi_{ref}(t) - \phi_{in}(t). \quad (1)$$

Figure 2 (b) presents the temporal evolution of $\phi_{diff}(t)$ at the incident frequency of 18.25 GHz. The absolute value of the time derivative of ϕ_{diff} represents the beat frequency,

$$2\pi f_b = \frac{(d\phi_{diff}/dt)_{up} - (d\phi_{diff}/dt)_{down}}{2}, \quad (2)$$

where $(d\phi_{diff}/dt)_{up}$ and $(d\phi_{diff}/dt)_{down}$ denote the time derivative of ϕ_{diff} in the frequency-rising and frequency-dropping phases, respectively, of the incident wave and are assumed to be constant during the sweeping period. In fact, $\phi_{diff}(t)$ appears to be linearly swept. To obtain the beat frequency more accurately, data of two sweep periods (i.e., 4 μ s) are used to extract the beat frequency, and the red lines shown in Fig. 2 (b) are obtained via linear fitting of $\phi_{diff}(t)$. The value of f_b is found to be nearly the same and independent of the incident wave frequency f_{in} within a certain frequency range (15.5 GHz < f_{in} < 24 GHz, 17 channels), as shown in Fig. 2 (c). The time of flight is therefore calculated as

$$\tau = \frac{f_b}{df_{in}/dt}, \quad (3)$$

where $2\pi f_{in} = d\phi_{in}/dt$ and $\bar{}$ denotes an average over the period of the incident frequency sweep (df_{in}/dt is typically

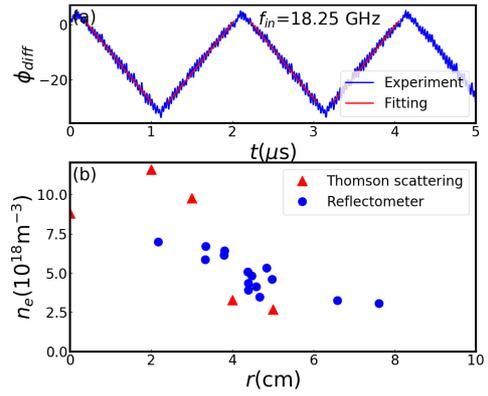


Fig. 3 (a) Phase difference in the plasma experiment. (b) Density profile reconstructed via the comb sweep reflectometer.

0.4 GHz/1 μ s = 4×10^{14} Hz/s). τ usually includes the effects of unnecessary flight paths, e.g., distribution cables. Therefore, calibration is necessary to determine the distance between the target and the antenna, L . Figure 2 (d) illustrates the relationship between f_b and L at an incident frequency of 18.25 GHz. The result shows that f_b has a good linear relationship with L as expected.

The comb sweep reflectometer was applied to a PANTA experiment (RF power of 6 kW, magnetic field of 0.09 T). The value of ϕ_{diff} with a plasma cut-off layer, which also has a good linear relationship with time, is shown in Fig. 3 (a). The beat frequency and the time of flight are calculated using Eqs. (2) and (3), and the location of the cut-off layer can therefore be determined. The electron density profile is reconstructed as shown in Fig. 3 (b). The density profile is consistent with the result obtained in the similar discharge via Thomson scattering system, which is shown by the red triangles in Fig. 3 (b). Both systems reveal a large density gradient near $r = 4$ cm. This demonstrates the reliability of the comb sweep reflectometer.

The determination of the beat frequency is a key issue for the spatial resolution. In this experiment, the largest error for f_b is nearly 0.15 MHz, and an error of 0.1 MHz for f_b leads to an error of 4 cm for the radial position. Therefore, the absolute error of the radial profile in this experiment is generally large, even though the relative error is lower than 3%. The error can be reduced by increasing the power of the incident wave and keeping the incident wave frequency more stable, which will be improved in the future. When the error is sufficiently small, the measurement of the density fluctuation will be possible by performing a temporal analysis for the beat frequency of each frequency channel.

In this article, the frequency comb sweep microwave reflectometer developed in PANTA is presented. The sweep range of each frequency channel is approximately 0.4 GHz, with a repetition frequency of 0.5 GHz. The tem-

poral resolution reaches $2\ \mu\text{s}$. Use of a DSO allows the beat frequencies between waves with multi-frequency components to be calculated. The benchmark test demonstrates a good linear relationship between the beat frequency and the distance between the antenna and the target. During a plasma experiment, the radial profile of electron density is reconstructed. Even though the absolute error is large, the relative error is lower than 3%. This indicates that the frequency comb sweep reflectometer is reliable for further plasma experiments in PANTA.

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