§6. Electron Energy Distribution Function (EEDF) Measurement in the Frequency Domain with the Aid of a Differentiator Circuit Using an Electrostatic Probe on MAP-II Divertor Simulator

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A major problem associated with the measurement of the electron energy distribution function (EEDF) based on the commonly used "Druyvesteyn method"[1] is the accurate determination of the second derivative. The most commonly used method to obtain the second derivative of the probe current (I) with respect to the probe voltage (V) is to perform numerical differentiation of the I–V characteristic.

In this study, we designed a differentiator circuit with a circuit simulator (LTspice) that can simulate circuit characteristics such as the gain and phase, including the operational amplifier. As a result, taking derivatives both in the temporal and Fourier domains are possible. The phase delay caused by a low-pass filter is corrected by performing a Fourier transform of both the I_e and d^2I_e/dt^2 signals.

The Fourier transform of the second time derivative of $x(t)$ is proportional to the frequency squared multiplied by the Fourier transform of $x(t)$, having a phase delay at 180°:

$$F\left[\frac{d^2x(t)}{dt^2}\right]=-\omega^2 F\left[x(t)\right] \qquad (1)$$

where F denotes the Fourier transform operator. Equation (1) indicates that the amplitude increases without limit with ω^2. Therefore, a low-pass filter needs to be implemented, which then causes a phase delay in the high-frequency components. In order to obtain the second time derivative of the probe current with high accuracy, the linearity of the gain should be conserved, and the phase difference should be maintained at 180° over the frequency of interest.

In order to compensate for the errors caused by the phase delay, the phase of the second time derivative is corrected on the basis of the Fourier transform of the original probe signal:

$$\frac{d^2I_p(t)}{dt^2}=F^{-1}\left[\left|F\left[\frac{d^2I_p(t)}{dt^2}\right]\right|\exp\left(i\left(\varphi_F(I_p(t))+\pi\right)\right)\right] \qquad (2)$$

where | | denotes the amplitude, and φ_F is the phase component of the Fourier transform. A fast Fourier transform (FFT) is used to calculate the Fourier transform.

Fig.1 (a) shows the I–V characteristic for the experiment conducted in MAP-II divertor simulator [2]. The results for the EEDF calculated by the originally detected second derivative with and without phase correction are shown in Fig.1 (b). The dotted lines are the Maxwell distribution functions for T_e = 4.03 eV, which is determined from a logarithmic plot of the I–V characteristic normalized to the electron density. Fig.1 (c) shows a logarithmic plot of $EEDF(\varepsilon)\varepsilon^{-1/2}$ known as the electron energy distribution probability function (EEPF). Assuming the EEDF has a Maxwell distribution, the reciprocal of the slope of the EEPF corresponds to the electron temperature.

We have revealed that the discrepancy in the electron density and temperature obtained from the EEDF with phase correction is smaller than that without phase correction[3,4], suggesting that the phase correction played a crucial role in the EEDF measured using a differentiator circuit.

Note: MAP-II device has been disassembled and has been moved to Tsukuba University.

Acknowledgement

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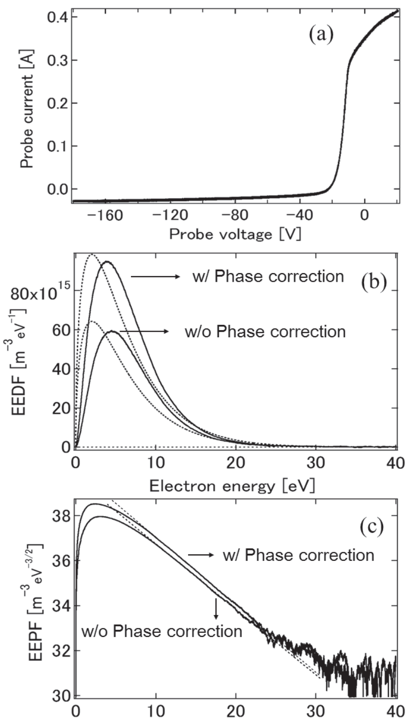

Fig.1 (a) I-V characteristic (MAP-II shot #26410). (b) EEDFs calculated from the second time derivative with and without phase correction. The dotted lines indicate Maxwell distributions (4.03 eV) normalized to the electron density. (c) EEPFs