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Electron density and temperature measurement of an atmospheric pressure plasma by millimeter wave interferometer

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In this paper, a 105 GHz millimeter wave interferometer system is used to measure the electron density and temperature of an atmospheric pressure helium plasma driven by submicrosecond pulses. The peak electron density and electron-neutral collision frequency reach 8×10^{12} cm^{-3} and 2.1×10^{12} s^{-1}, respectively. According to the electron-helium collision cross section and the measured electron-neutral collision frequency, the electron temperature of the plasma is estimated to reach a peak value of about 8.7 eV. © *2008 American Institute of Physics*.
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Atmospheric pressure nonequilibrium plasmas have received increased attention recently because of several emerging applications.[1–3] When millimeter wave interferometer system is used to measure electron density of an atmospheric pressure plasma, the wave frequency ω, plasma frequency ω_{pe}, and collision frequency ν are comparable, the phase shift coefficient β and its amplitude attenuation coefficient α are determined by the electron density n_e as well as the ν.[4] If we assume the plasma is homogeneous, then the total phase change $\Delta\varphi$ and attenuation ΔA for interferometric signal can be obtained by $\Delta\varphi=\int_0^d(\beta_0-\beta)dr$ and $\Delta A=\int_0^d(\alpha_0-\alpha)dr$, where β_0 and α_0 are the free space values and d is the thickness of the plasma. Therefore, according to the measured phase shift $\Delta\varphi$ and the attenuation ΔA, the electron density n_e and collision frequency ν can be obtained from the measured $\Delta\varphi$ and ΔA. Furthermore, the collision frequency is a function of the electron temperature and collision cross section. Therefore, under certain conditions, it is also possible to extract the electron temperature from the measured collision frequency.

In this letter, a 105 GHz quadrature millimeter wave interferometry system is used to measure the electron density and electron temperature of an atmospheric pressure nonequilibrium helium plasma. The plasma is generated by a modified dielectric barrier discharge. The schematic of the discharge system is shown in Fig. 1. The applied voltage, the pulse width, and the pulse frequency of the high voltage pulses are fixed at 9 kV, 500 ns, and 1 kHz, respectively. Details on the experiment setup, current, and voltage characteristics can be found in Ref. 5.

A block diagram of the interferometry system is shown in Fig. 2. Calibration is achieved by setting the level set attenuator to the maximum attenuation position with the Gunn Oscillator turned on and measuring the dc voltage output of both mixers. This is done with plasma off. These measurements will serve as the reference (relative zero) point for all future measurements. Then the attenuator and the phase shifter are set to zero. I/Q readings are recorded while the phase shifter is rotated through the full 360° of phase. When plotted on the I/Q graph, these measurements yield a calibration circle.

The measured *I*-*Q* curve is plotted in Fig. 3 with plasma on (solid line) and off (dash dot line). When the plasma is turned on, the millimeter wave undergoes phase shift and attenuation, as shown in Fig. 3 with the solid line. According to the measured phase shift and attenuation, the electron density and collision frequency can be obtained, which are shown in Figs. 4 and 5, respectively. During the primary discharge, Fig. 4 shows that the electron density increases to its first peak of 8×10^{12} cm^{-3} in tens of nanoseconds. This duration corresponds to part 1 of the *I*-*Q* curve in Fig. 3, where the millimeter wave shows strong phase shift and attenuation. Then the electron density decays to 4.1×10^{12} cm^{-3}. This period corresponds to part 2 of the *I*-*Q* curve.

Due to the secondary discharge which occurs at the falling edge of the applied voltage pulse, the electron density increases again. Correspondingly, Fig. 3 shows that after part 2 of the *I*-*Q* curve, the wave shift and attenuation undergo another increase (part 3 of the *I*-*Q* curve) before they go back to the original point. This measurement is consistent with the *I*-*V* characteristics of the discharge,[5] where two distinct discharges per voltage pulse are observed.

Figure 5 shows the calculated collision frequency vs time. The collision frequency ν can be expressed as $\nu=n_0(2kT_e/m_e)^{1/2}\sigma_0$. Here n_0, T_e, m_e, and σ_0 are, respectively, the neutral particle density, electron temperature, electron mass, and electron-neutral collision cross section, and k is the Boltzmann constant. The neutral particle density n_0 can

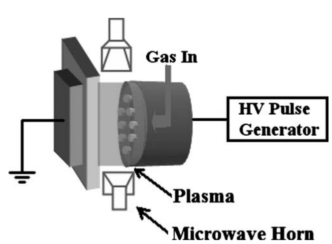

FIG. 1. Schematic of the discharge system.

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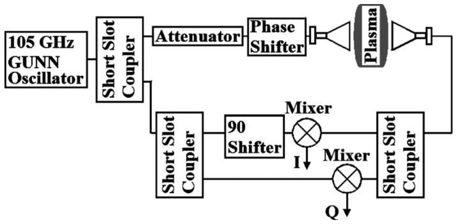

FIG. 2. A block diagram of the interferometry system.

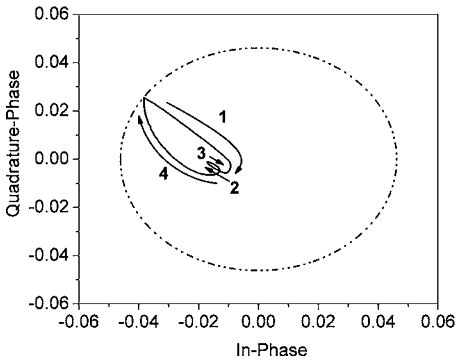

FIG. 3. *I-Q* chart with plasma off (dashed line) and with plasma on (solid line).

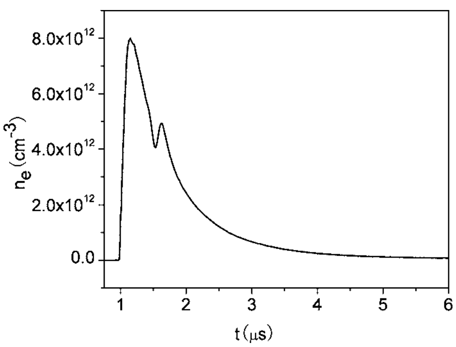

FIG. 4. Measured electron density vs time.

be treated as a constant since the gas temperature is close to the room temperature.[5] The electron-helium collision cross section is nearly a constant when T_e is below 10 eV.[6] Hence, the change of collision frequency with time is mainly related to the electron temperature. Let $\sigma_0 = 5 \times 10^{-20}$ m^2,[6] then T_e can be estimated based on the electron-helium collision frequency. Figure 6 shows the estimated electron temperature versus time. The electron temperature reaches its peak of 8.9 eV during the primary discharge. It decays to about 0.5 eV at 2 μs. It should be mentioned here that we are able

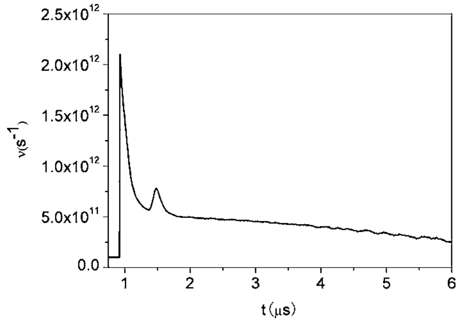

FIG. 5. Measured electron collision frequency vs time.

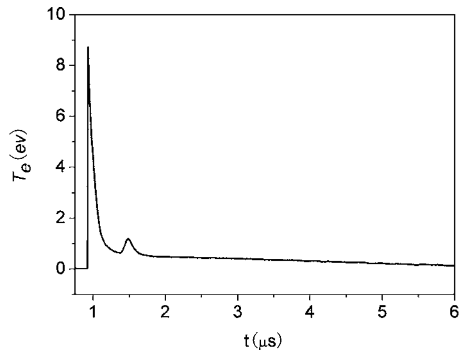

FIG. 6. The calculated electron temperature vs time.

to estimate the electron temperature from the measured electron collision frequency because the electron-helium collision cross section is nearly a constant for electron temperature less than 10 eV. If the working gas is other than helium, such as air, then it will be more difficult to extract the electron temperature from the electron collision frequency since the electron nitrogen/oxygen collision cross section depends strongly on the electron temperature.

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