Terahertz characterization of pulsed plasmas

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Abstract: Broadband terahertz pulses have been used to characterize the time evolution of electron density and collision rate of rapidly evolving argon plasmas. Peak densities of $n_e \geq 10^{13}$ cm^{-3} and collision rates of $\gamma_p \geq 10^{11}$ s^{-1} are measured.

OCIS codes: (350.5400) Plasmas; (300.6530) Spectroscopy, ultrafast; (300.6270) Spectroscopy, far infrared

1 INTRODUCTION

Plasma physics relies on a diverse set of diagnostic techniques for evaluating the temperature, density, fluid dynamic, and other physical properties of the medium [1]. Of these, a particularly important technique uses electromagnetic waves to probe the propagation phenomena. In a simple model of an isolated plasma, the plasma frequency determines the boundary of transparency for electromagnetic wave propagation and depends on electron density, n_e, according to $\omega_p \equiv \sqrt{(n_e e^2)/(\epsilon_0 m)}$ or, $f_p = \omega_p/(2\pi) \approx 9 \times 10^3 \sqrt{n_e(\mathrm{cm}^{-3})}$. Below f_p the plasma is strongly absorbing and above f_p the plasma is transparent and strongly dispersive. In the range of laboratory plasma densities, *e.g* $10^8 \leq n_e \leq 10^{12}$, we find 90 MHz $\leq f_p \leq$ 9 GHz. Thus, continuous-wave microwave sources are ideal for probing the transparent regions of *steady-state* plasmas in this range [2].

However, since many plasmas are not in the steady state, the physical properties of interest vary with time and an electromagnetic probe suffers from time-varying attenuation and dispersion. In the extreme case, if the plasma frequency rises above the probe frequency, the probe is entirely absorbed. A broadband diagnostic, such as a THz pulse, which spans a large spectrum both above and below the plasma frequency can continue interacting with the plasma as the density and other physical properties evolve. Recent work by Jamison, *et al.* [3], has demonstrated the efficacy of this approach. In the work presented here, we extend this idea to the characterization of rapidly evolving plasmas at different base pressures and constant initial ionization conditions. We also correlate the optical fluorescence with the onset of ionization and the buildup of plasma density as the electrons thermalize.

2 EXPERIMENTAL SETUP

Figure 1 shows a diagram of the experimental setup. The generation of the THz pulses takes place in the usual way by using photoconductive switches fabricated on high-resistivity GaAs [4]. Gold-on-chrome electrodes were patterned lithographically and bonded to copper blocks with silver paint. The copper blocks serve both as heat sinks and mounting points for the 100 volt DC bias supply. A 100 MHz repetition-rate Ti:sapphire oscillator illuminates the GaAs through an acousto-optic modulator which chops the beam at 600 Hz. With about 300 mW average power, 30 fs pulses in an 80 μm diameter spot, a fluence of $\approx 6\mu\mathrm{J/cm}^2$ is deposited on the GaAs transmitter. The generated THz pulse is directed through a vacuum chamber with off-axis ellipsoidal mirrors which produce a waist $\approx$ 2 mm in diameter in the center of the chamber.

An argon plasma is created in the vacuum chamber using a short high-voltage pulse to periodically ionize the gas. A UHF planar triode is used to switch a 1.5 kV, 10 ns pulse, at a 10 KHz rate onto a pair of slightly curved cylindrical electrodes in the vacuum chamber with their axes parallel to the THz beam propagation. The cylinders are 12 mm in diameter, 75 mm long and separated by 20 mm. They are bent slightly to produce the highest electric field in the center of the chamber where the THz beam is focused. Depending on the pressure, the plasma extends from several millimeters to 4 cm in length. Since the plasma is being pulsed at a relatively low duty cycle ($1\!:\!10^4$) and our THz generation and sampling pulses run at 100 MHz, we used a gated averager (boxcar integrator) to select out a 60 ns window within the duration of the plasma. Thus about six THz pulses sample the plasma every period of the 10 kHz high voltage pulse. By increasing the delay time of the window in the boxcar integrator in steps and measuring the full electric field of the THz pulse by scanning a mechanical delay stage, we map out the time evolution of the density and collision frequency using the procedure described below.

The receiver consists of a standard electro-optic sampling crystal (ZnTe) with quarter-wave plate and balanced photodiodes. The photodiode signals are passed through the gated boxcar integrator and then to a lockin amplifier which synchronously detects the signal's 600 Hz modulation.

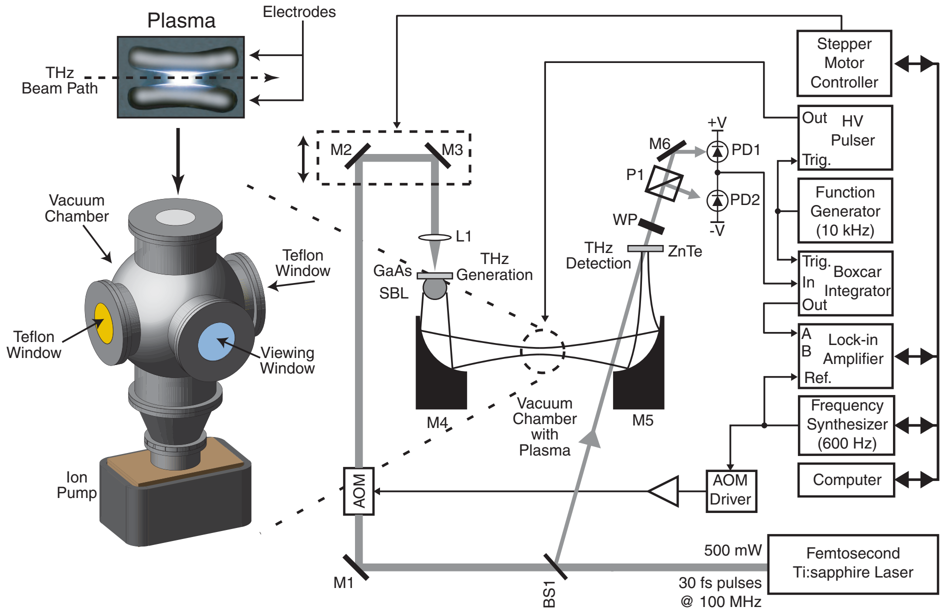

Figure 1: Experimental setup for performing THz plasma spectroscopy. Inset shows vacuum chamber with teflon windows which provide very low loss transmission for broadband THz pulses. Above chamber shows photo of electrodes with glowing plasma. Legend: AOM; acousto-optic modulator, SBL; silicon ball lens, ZnTe; zinc-telluride crystal, WP; quarter-wave plate, PD1,2; photodiodes, M4/M5; off-axis ellipsoidal mirrors, BS1; beamsplitter, M2/M3; mirrors on stepper-motor delay stage.

3 RESULTS AND DISCUSSION

The THz pulses passing through the vacuum chamber were measured both with and without plasma present. In the usual approach of time-domain spectroscopy (vector network analysis), we form the ratio of the spectra of the above waveforms and relate this *complex transfer function* to a simple Lorentz model for the ionized gas which includes the electron density, n_e and the collision frequency γ_p;

$$\mathcal{H}(\omega) = \exp\left[i\frac{\omega}{c}\left(\int_0^L \sqrt{1-\frac{n_e(z)e^2}{\epsilon_o m(\omega^2+i\omega\gamma_p(z))}}\,dz - L\right)\right] \approx \exp\left[i\frac{\omega L}{c}\left(\sqrt{1-\frac{n_e e^2}{\epsilon_o m(\omega^2+i\omega\gamma_p)}}-1\right)\right] \qquad (1)$$

The integration is carried out along the path L of the THz beam. The last expression obtains when we approximate the plasma as having uniform density throughout its volume. This is, of course, unrealistic but this simple model allows us to get a handle on the range of possible values of n_e and γ_p. We estimated the length L from photographs of the glowing plasma for each different pressure studied and used this in all calculations in Eq. 1. We are currently working to develop analytical expressions for the plasma density based on the fluorescence which will improve the accuracy of this model.

Because of the relatively low signal-to-noise ratio of our unamplified system (50 dB/Hz), we have developed a time-domain method for finding the density and collision rate. First we measure the THz pulse both with (reference) and without a plasma (data). Then we Fourier transform the reference pulse, apply the propagation law (1), and inverse transform. The resulting calculated pulse is compared against the actual data and an error function is formed by finding the root-mean-square of the difference between the two. This error function is minimized in a two-dimensional domain of n_e vs. γ_p. The procedure is repeated for various time delays after the initial ionization and the entire process is repeated at pressures of 10, 30 and 50 torr. Figure 2a shows the results of these time-resolved density measurements for the three different values of argon gas pressure. Note that a peak electron density of $n_e > 2 \times 10^{13}$ cm^{-3} corresponding to a plasma frequency $\omega_p = 2\pi \times 40$ GHz is clearly resolved as well as the low density plasma produced at a pressure of 10 torr. The ringing in the 50 torr data is presumed to be caused by reflections on the transmission line between

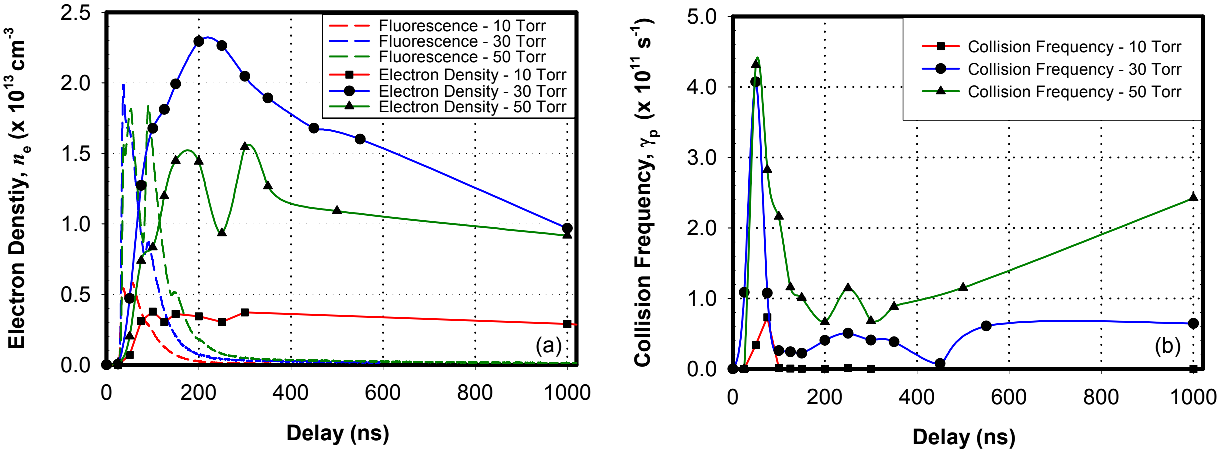

Figure 2: Broadband THz time-domain spectroscopy of plasma. a) Electron density (solid) n_e as a function of time delay between ionizing current pulse into the plasma and THz probing pulses. Also shown is the optical fluorescence signal (dashed) from a high-speed photodiode monitoring the plasma light. Argon pressures=10 torr (squares/red), 30 torr (dots/blue) and 50 torr (triangles/green). b) Electron collision frequency γ_p calculated from same data as part (a).

the high voltage pulser and the time-varying impedance presented by the plasma and is currently under study. In the same figure is also shown a record of the fluorescence emitted from the plasma measured with a high-speed photodiode (dashed lines). The relationship between the electron density and the fluorescence is complicated by the different mechanisms that could be involved (recombination, bound-bound transitions, free-free transitions (Bremsstrahlung), etc.). We believe that it is consistent with the initial high-energy electron burst causing deep level ionization followed by rapid de-excitation and fluorescence. During the high energy non-equilibrium phase, secondary and tertiary ionization proceeds to build up the plasma density as the current pulse trails off. Evenutally the electrons cool due to collisions and and the density begins to fall as the plasma begins to diffuse and recombine. The peak densities at the pressures indicated result in an ionization rate of $\approx 10^{-5}$. By about 200-300 ns, assuming local thermodynamic equilibrium, we can apply the Saha equation [1] and estimate a peak electron temperature of $T_e \approx 6 \times 10^3$ K.

Figure 2b shows the corresponding collision rates based on the minimization procedure described above. In the early stages of the evolution of the plasma, the rapid rise in collision frequency is due to the rapid generation of the background ions which produce a much stronger effect due to long range Coulomb interaction [5] and is strongly correlated with the optical fluorescence. As the plasma heats and the density peaks, the collision frequency goes down because of the high electron velocity and thus lower cross section: $\gamma_p \propto (kT_e)^{-3/2}$. Later, as the plasma cools and the density is reduced, the collision frequency rises again.

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References

[1] R. H. Huddletsone and S. L. Leonard, eds., *Plasma Diagnostic Techniques*. New York: Academic Press, 1965.

[2] M. A. Heald and C. B. Wharton, *Plasma Diagnostics with Microwaves*. New York: John Wiley and Sons, 1965.

[3] S. P. Jamison, J. Shen, D. R. Jones, R. C. Isaac, B. Ersfeld, and D. A. Jaroszynski, “Plasma characterization with terahertz time-domain measurements,” *J. Appl. Phys.*, vol. 93, pp. 4334–4336, April 2003.

[4] G. Zhao, R. N. Schouten, N. van der Valk, W. T. Wenckebach, and P. C. M. Planken, “Design and performance of a THz emission and detection setup based on a semi-insulating GaAs emitter,” *Rev. Sci. Inst.*, vol. 73, pp. 1715–1719, April 2002.

[5] F. F. Chen, *Introduction to Plasma Physics and Controlled Fusion*. New York: Plenum Press, second ed., 1984.