Measurement of electron temperature and electron density in filamentary nanosecond surface dielectric barrier discharge

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Abstract: An experimental study of measuring electron temperature in nanosecond surface dielectric barrier filamentary discharge and near afterglow and electron density in afterglow is presented. Short camera gate (5 ns) was applied to get time-resolved results. Electron temperature was measured by optical emission spectroscopy combining with N^+ spectra in modeling. The electron density was determined by Stark broadening effect of H_α line (656.3 nm) and nitrogen atomic line (746 nm).

Keywords: filamentary discharge, electron temperature, electron density, optical emission spectroscopy.

1. Introduction

It has been found that plasma of nanosecond surface dielectric barrier discharges (nSDBD) can be efficiently used for plasma assisted ignition/combustion (PAI/PAC) [1] and plasma assisted aerodynamics [2]. Since the filamentary nSDBD at high pressure in a single short regime was obtained in 2014 [3], the key parameters (electron temperature T_e, electron density n_e, etc.) and physics of filamentation are not well studied yet. The aim of this work is to study T_e and n_e.

2. Theoretical methods

Boltzmann plot has been widely used for measuring the electron temperature [4]. The electron temperature can be determined from the relative intensity of a few excited levels emission lines. Taking into account that the intensity of the lines changes with time, and that the input from the adjacent lines can be significant. In this work, all the atomic lines of nitrogen ion NII in a specific wavelength range from NIST data base [5] were used to modelling the electron temperature.

In addition, for measuring the electron density, emission line broadening effects of H_α line (656.3 nm) and nitrogen atomic line (746 nm) were carried out. Generally, the broadening width in the spectra is the combination result of multiple affects that contain natural, resonance, Van der Waals and Stark broadening for Lorentz part and Doppler and instrumental broadening for Gaussian part. And in most cases, the real (experimental) spectra are the convolution of these two broadening parts, also recognized as Voigt profile. Full width at half maximum FWHM ($\Delta\lambda_V$) for Voigt profile:

$$\Delta\lambda_V \approx \sqrt{\left(\frac{\Delta\lambda_L}{2}\right)^2 + (\Delta\lambda_G)^2} + \frac{\Delta\lambda_L}{2} \tag{1}$$

This is an approximate Voigt nonlinear curve fitting equation where $\Delta\lambda_L$ and $\Delta\lambda_G$ are the FWHM for Lorentz and Gaussian profiles respectively.

In practice, when calculating electron density ne from H_α spectra, only Stark effect was considered since other broadening width is negligible in our experimental spectra. However, for nitrogen atomic line (746 nm), Van der Waals and instrumental broadening affects cannot be ignored which in the same order as Stark effect.

3. Experimental setup

The experiments of electron temperature measurement were carried out with the cylindrical configuration of the electrode system [6] with the gear-like high voltage electrode (fig.1) connecting to the high voltage pulse generator FPG 12-1PM (FID GmbH) provided single shot pulses of positive polarity, 20 ns FWHM, 2 ns rising time. The amplitude of a high voltage pulse was fixed and equal to 24 kV (+48 kV on the high-voltage electrode) during all the experimental series.

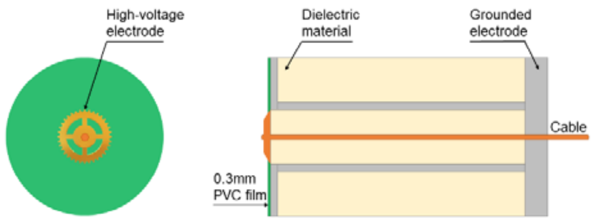
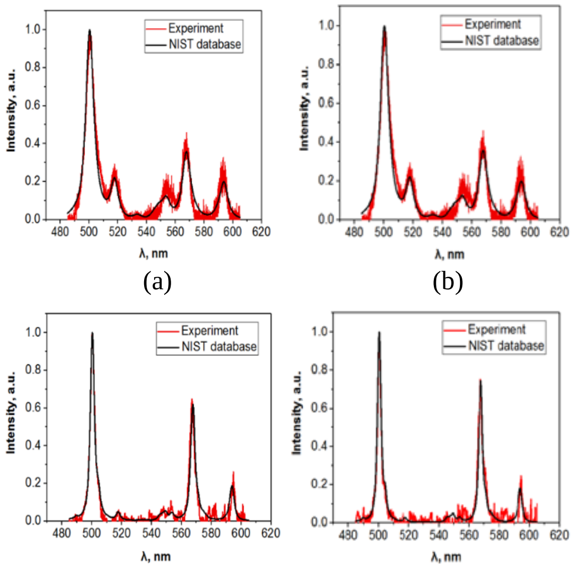


Fig. 1. Configuration of cylindrical electrode system.

The discharge was installed into a closed high-pressure chamber filling with nitrogen of 6.8 bar. A focusing lens (f=60 mm) was placed in front of the window of discharge chamber in order to get the image of a single filament on the slit of the spectrometer. The spectra in the wavelength range 485-605 nm were recorded by Acton spectrometer (SP-2500) with Pi-Max4 Princeton Instrument ICCD camera. A neutral density filter (cut-on ~400 nm) cutting the light below the wavelength of 400 nm was installed in front of the entrance slit to avoid the second diffraction order.

4. Results and discussion

The electron temperature measurement experiments were conducted each 5 ns beginning from the start of the filamentary phase of the discharge. Before dealing with quantum efficiency, the background noise and the CW background emission were subtracted from experimental spectra. The N^+ emission lines ranging from 485 to 605 nm were considered for the analysis of the electron temperature in a single selected filament. The spectroscopic data about the N^+ lines was acquired from NIST database [5]. The apparatus function of the optical system as well as the Stark broadening [7] of the lines were taken into account when calculating the theoretical spectra (fig.2, black curves).



(a) (b) (c) (d)

Fig. 2. Experimental (red curves) and calculated (black curves) spectra (a)(b) in discharge; (c)(d) in afterglow.

The results of the time-resolved electron temperature and the synchronized time-resolved electrical current are shown in fig.3. During first 5-10 ns after streamer-to-filament transition, the electron temperature drops down dramatically, then stays at relatively low level at the end of the discharge slightly decreasing in the afterglow.

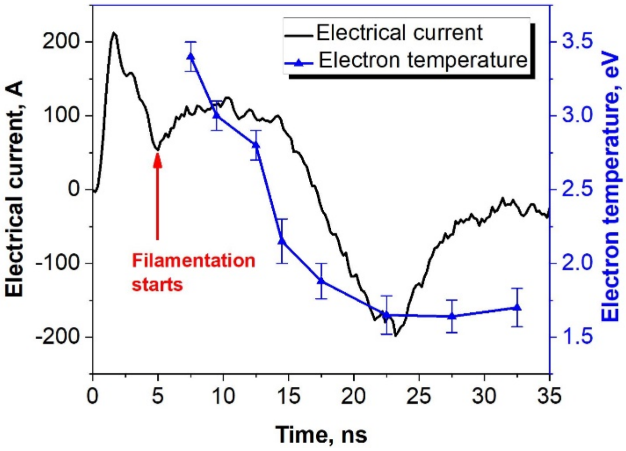


Fig. 3. Measured electron temperature corresponding synchronized with electrical current.

Time-resolved electron density was calculated from emission line broadening of H_α line (656.3 nm) and nitrogen atomic line (746 nm) respectively.

For H_α line Stark broadening, Gigosos. et al. [8] suggested a way to calculate electron density with Full width half area (FWHA) for $n_e > 5\times10^{14}$ cm^{-3},

$$FWHA: \Delta\lambda_{Stark}(nm) = 1.098nm \cdot \left(\frac{n_e}{10^{17}cm^{-3}}\right)^{0.67965} \quad (2)$$

This method can filter out the dependence of electron temperature T_e and gas temperature T_g, which sometimes are unknown. H_α line Stark broadenings in different time in afterglow are shown in fig.4.

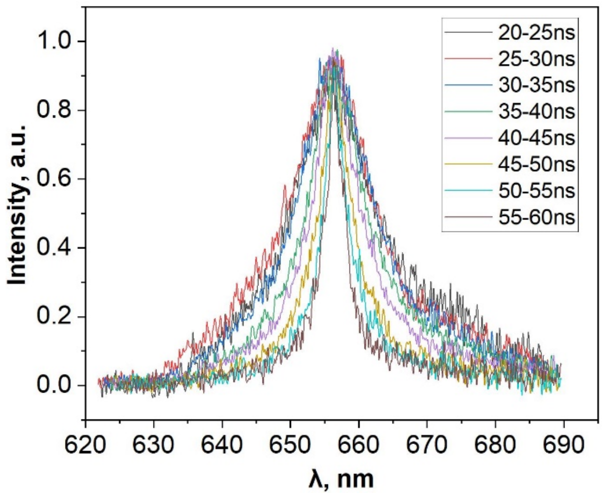


Fig. 4. H_α line Stark broadenings at different time steps.

In nitrogen (746 nm) broadening, the FWHM of Stark effect can be written as [9]:

$$FWHM: \Delta\lambda_{Stark}(nm) = 2 \times 10^{-16} n_e \omega_e(T_e) \cdot \left[1 + 1.75\left(1 - R n_e^{-\frac{1}{6}} T_e^{-\frac{1}{2}}\right) \cdot \alpha_e(T_e)\right] \quad (3)$$

where ω_e is an electron impact parameter, α_e is the ion broadening parameter and R is a constant value (0.067425). Both of ω_e and α_e are affected by electron temperature T_e. In our experiment, T_e in the afterglow is 20000 K. And for nitrogen (746 nm), when T_e equals to 20000 K, parameters ω_e and α_e are equal to 6.28×10^{-3} and 0.028 respectively [9].

To calculate n_e from Stark broadening of nitrogen (746 nm), it's necessary to subtract contribution of other effects (Van der Waals broadening $\Delta\lambda_{V\ dWaals}$ and instrumental broadening $\Delta\lambda_i$) from measured broadening width $\Delta\lambda_m$. According to equation (1), the width contributed only by Stark effect is:

$$\Delta\lambda_{Stark} = \frac{(\Delta\lambda_m)^2 + (\Delta\lambda_i)^2}{\Delta\lambda_m} - \Delta\lambda_{V\ dWaals} \quad (4)$$

The results of electron density n_e corresponding with voltage is shown in fig.5. And we can see that the electron density separately determined from Hα line (656.3 nm) and nitrogen atomic line (746 nm) agree very well. The density of electrons drops in near afterglow, starting from 5×10^{18} cm^{-3} and decreases to 5×10^{17} cm^{-3} after 40 ns in the afterglow.

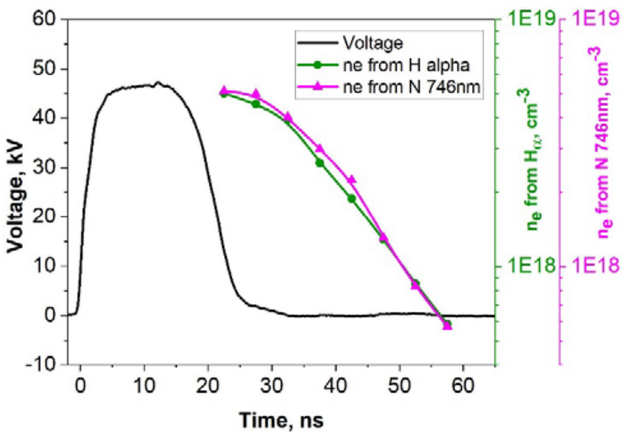


Fig. 5. Electron density measured from H_α and nitrogen (746 nm) corresponding with voltage.

5. Conclusion

Experimental measurements of the electron temperature and electron density in filamentary discharge and early afterglow provide the values $T_e\approx3.5$ eV in the discharge, $T_e\approx1.6$ eV and ne = 5×10^{18} cm^{-3} in early afterglow.

6. Acknowledgements

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7. References

[1] S. M. Starikovskaia, Journal of Physics D: Applied Physics, 47(2014), 353001.

[2] S. B. Leonov, V. Petrishchev and I. V. Adamovich, Journal of Physics D: Applied Physics, 47(2014), 465201.

[3] S. A. Stepanyan, A. Y. Starikovskiy, N. A. Popov & S. M. Starikovskaia, Plasma Sources Science & Technology, 23.4(2014), 045003.

[4] Lo, A., Cessou, A., Lacour, C., Lecordier, B., Boubert, P., Xu, D. A. & Vervisch, P., Plasma Sources Science and Technology, 26.4(2017), 045012.

[5] Kramida, A., Ralchenko, Yu., Reader, J., and NIST ASD Team (2018). NIST Atomic Spectra Database (ver. 5.6.1), [Online]. National Institute of Standards and Technology, Gaithersburg, MD.

[6] S. A. Shcherbanev, S. A. Stepanyan & S. M. Starikovskaia, 22nd International Symposium on Plasma Chemistry, July 5-10(2015), Antwerp, Belgium.

[7] S. A. Shcherbanev, A. Yu. Khomenko, S. A. Stepanyan, N. A. Popov & S. M. Starikovskaia, Plasma Sources Science & Technology Letters, 26(2017), 02LT01.

[8] Gigosos, M. A., González, M. Á., and Cardeñoso, V., Spectrochimica Acta Part B: Atomic Spectroscopy, Vol. 58, No. 8(2003), pp. 1489–1504.

[9] Griem, H. R., Plasma spectroscopy, New York: McGraw-Hill(1964).