Time-resolved poly-diagnostics of atmospheric ns He jet discharge

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Abstract: A nanosecond He jet discharge with voltage front rise of about $3{\cdot}10^{11}$ V/s is studied by time-resolved optical emission, absorption and laser-induced fluorescence spectroscopy. The propagation of fast ionization waves is clearly visualized. The dynamics of He metastable states is quantified in the discharge gap, tube and effluent regions. In the burst regime He metastable production can be significantly boosted in the gap, whereas in the effluent this effect is absent and He metastables are formed only by ionization waves.

Keywords: nanosecond discharge, ionization waves, He metastables, plasma diagnostics.

1. The motivation

The repetitively pulsed ns- discharges have high application potential in several important domains, such as surface treatment [1], molecular pollutant degradation [2], gas reforming including CO_2 conversion [3] and nitrogen fixation [4]. These discharges are normally characterized by high degree of non-equilibrium, exhibiting high ro-vibrational excitation and low gas temperature at the same time [5, 6]. The Ar or He jet discharges operating in ambient air with admixtures (such as O_2, N_2, H_2O, ...) often result in generation of various plasma radicals which are crucial in bio-medical treatment and in the other domains. Among these radicals, the ground state NO, OH, O, N, etc. and Ar/He metastable atoms are of a high importance. The mentioned metastable states are normally responsible for Penning ionization in plasma [7] whereas the ground state radicals are important for surface and plasma chemistry. In order to shed more light on He metastables (He^{met}) dynamics in the ns jet discharge configuration, this work is focused on the time-resolved behavior of He^{met} density as well as on the time-resolved behavior of ro-vibrational excitation, electron density, electric field and ionization wave propagation in this discharge.

2. The setup

The ns discharge based on a single thyristor circuitry [8], arranged in jet geometry containing high-voltage electrode gap and a quartz tube has been used, as shown in Fig. 1. The discharge has been operating in pulse regime having about 150 ns voltage pulse width and 10 ns current pulse width. The peak voltage was equal to about 9 kV whereas peak current varied from 1.5 A to 5 A depending on conditions. Pure He gas or He with dry air has been supplied through the discharge system with the total gas flow up to 2 standard liter per minute (slm). The detailed discharge description can be found elsewhere [6]. The main discharge parameters are given in Table 1.

For discharge diagnostics optical emission spectroscopy – OES (for rotational and electron density analysis), atomic absorption spectroscopy – AAS (for He^{met} number density calibration) or laser-induced fluorescence – LIF (for time-resolved detection of He^{met} 2s $^3S_1$ state) were implemented, as shown in Table 2.

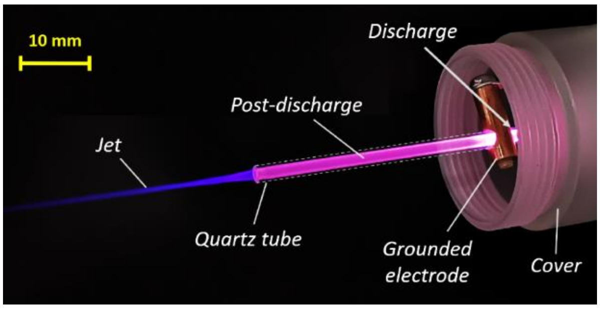

Fig. 1. Appearance of ns jet discharge in pure He flow.

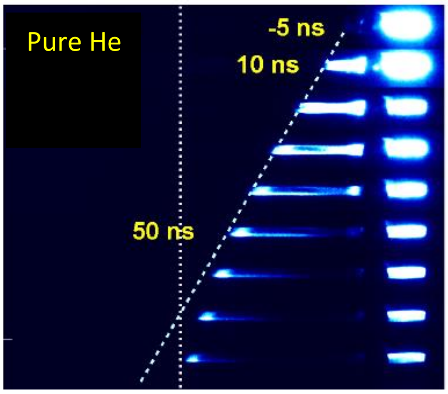

Fig. 2. FIW propagation in the discharge tube. He filter (at 587 nm) was used. Time step is 10 ns.

Table 1. The main ns discharge parameters.

Parameter	***Value***
Peak voltage	About 9 kV
Peak current range	1.5 – 5 A
Voltage pulse width	About 150 ns
Current pulse width	10 ns
Pulse rep. rate (PRR)	60 Hz – 2.5 kHz
Gas flow	0.5 slm, 2 slm
Gases used	He, dry air
Electrode gap width	10 mm
Quartz tube length	35 mm
DC consumed power	20 W (at PRR = 600 Hz)

Table 2. The diagnostic tools used.

Device/parameter	***Name/value***
Spectrometer	SOL instruments MSDD1000
Spectr. focal length	1 m
Light detector	Andor DH340-18U ICCD
Laser used for LIF	LiopStar dye laser
Dye solution used	DCM + ethanol
Probed states of He	**2s ^{3}S$_1$** (LIF, AAS) and **2s ^{1}S$_0$** (AAS)
Excitation wavelength	319.9 nm (LIF)
Emission wavelength	447.2 nm (LIF)
Absorption wavelengths	388.9 nm, 501.6 nm (AAS)

3. The main results

Due to the rapid voltage front rise (~ $3{\cdot}10^{11}$ V/s) the fast ionization waves (FIWs) are formed in the discharge channel (tube) in our case. Their propagation is clearly detected in the tube [9], as shown in Fig. 2. In our case FIWs have velocity of about $4\text{-}5{\cdot}10^5$ m/s causing additional excitation and ionization of He (as well as of other gases) in the tube and in the effluent. As a result of electron avalanche formation in the gap area [9] He metastables are generated abruptly, as shown in Fig. 3, which is followed by a slow density decay. The main mechanism for He^{met} generation in the gap is suggested to be the electron impact ($He + e \rightarrow He^{met} + e$), whereas the collisional quenching defines their slow decay after the pulse ($He^{met} + He \rightarrow He + He$; $He^{met} + N_2 \rightarrow He + N_2$; etc…). In the pure He flow the collisional quenching rate coefficient for He 2s $^3S_1$ state of $\sim 4{\cdot}10^{-14}$ cm^3 s^{-1} was found. According to our estimations the number He^{met} density exceeds 10^{13} cm^{-3} in the gap area. A retarded He^{met} formation in the effluent area (violet curves in Fig. 3) confirms the FIWs to be the main mechanism for He^{met} formation in this area. The found retardation corresponds to FIW velocity of about $5{\cdot}10^5$ m/s in this case, well-correlating with [6, 9]. The peak number density is found significantly lower in the effluent.

Additionally, the *burst mode* has been also examined and found beneficial for He^{met} production. At the burst repetition rate (BRR) of 360 Hz with 3 pulses in the burst, a significant increase in He^{met} density (density boost) has been found at the burst delay of about 350 μs, as shown in Fig. 4. In this case the ratio of He^{met} density after i-th burst pulse normalized to the density after the 1st pulse (denoted as α_i) exceeds 7 after 3rd pulse. A clear explanation for this effect is not found yet, requiring additional measurements. The apparent density boost might be related to either an optimum gas residence time in the gap at certain burst delay, or to additional He^{met} formation as a result of interaction with vibrationally excited N_2 (always presented in flow as natural admixture) formed during the previous pulse. Since the found density boost may also strongly affect production of the other important radicals, the future work is scheduled in this direction.

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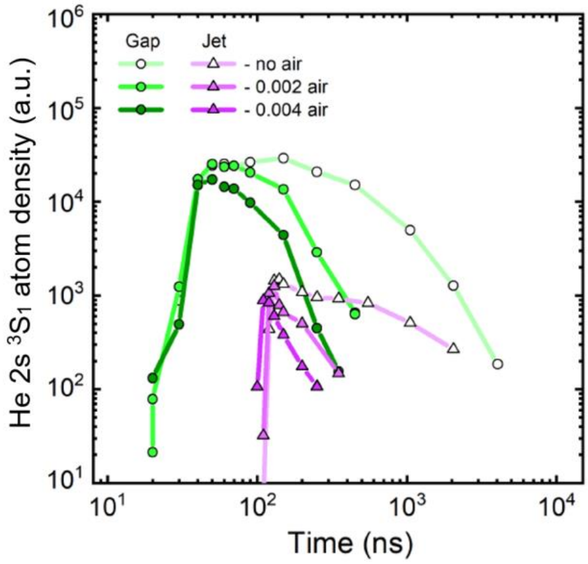

Fig. 3. Evolution of relative He^{met} density after the plasma pulse in the **gap** and **jet** (effluent) areas.

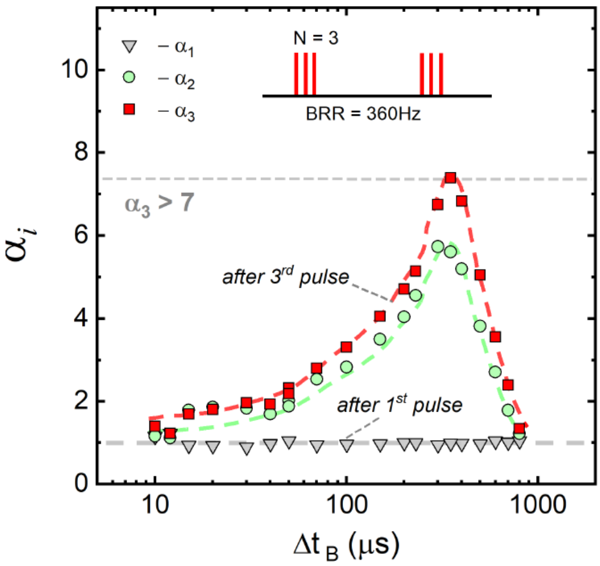

Fig. 4. He^{met} density boosting factor after i-th pulse (α_i) vs. the burst delay time (Δt_B). Pure He case.

4. References

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