Time-resolved emission spectroscopy and imaging of transient spark in atmospheric air

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Abstract: Transient spark (TS), self-pulsing nanosecond repetitive discharge of streamer-to-spark transition type was studied using fast photomultiplier tube and fast iCCD camera coupled with a monochromator. Emission profiles and images of single TS pulse at different frequencies f help to understand the influence of the repetition frequency on the streamer-to-spark transition process. Streamer-to-spark transition is governed by the increase of the gas temperature T_g in the plasma channel. The initial T_g at the beginning of the streamer is ~300 K, though it increases with f up to ~500 K at 10 kHz. The transition to spark occurs at ~1000 K. This heating accelerates with increasing f, leading to a decrease of the average streamer-to-spark transition time from a few μs to ~100 ns.

Keywords: streamer-to-spark transition, nanosecond time-resolved spectroscopy and imaging

1. Introduction

Atmospheric pressure plasmas generated by electrical discharges in air present considerable interest for a wide range of applications. New types of discharges are therefore still being developed and studied. Here we present a relatively novel streamer-to-spark transition discharge in air at atmospheric pressure named transient spark (TS). It is initiated by a streamer, which transforms to a short (<100 ns) high current (~1-10 A) spark pulse due to the discharging of the internal capacity C of the reactor. The repetition frequency f of discharging and charging of C from 1 to 20 kHz can be achieved [1].

We observed significant differences between two modes of TS with small and high repetition frequencies [2], studied by time-integrated optical emission spectroscopy. Below ~3 kHz, the emission of O, N and N^+ atomic lines and N_2 2^{nd} positive system dominates in the spectra, but at higher f these atomic lines almost disappear. In order to understand the fundamental phenomena related to the evolution of TS and its changes due to increasing f, we employed in this study a fast photomultiplier tube, as well as a 2-m monochromator coupled with fast iCCD camera.

2. Experimental set-up

Experiments were carried out at room temperature in atmospheric pressure air with a radial flow of about 20 cm/s. The distance between stainless steel needle electrode and planar copper electrode (point-to-plane configuration) was 4 mm. A DC High Voltage (HV) power supply connected via a series resistor (R = 4.92-9.84 MΩ) limiting the total current was used to generate a positive TS discharge. The discharge voltage was measured by a high voltage probe Tektronix P6015A and the discharge current was measured on a 50 Ω or 1 Ω resistor shunt. The 1 Ω resistor shunt was used to measure the TS transient spark current pulse, whereas the 50 Ω resistor shunt was used to measure the current from the streamer. Both voltage and current signals were recorded by a 200 MHz digitizing oscilloscope Tektronix TDS2024.

The emission spectra were obtained using a 2-m monochromator Carl Zeiss Jena PGS2 covering 200-800 nm and providing spectral resolution of 0.06 nm, coupled with an intensified CCD camera (Andor Istar). The iCCD camera was triggered by a generator of 5 V rectangular pulses with the rise time less than 5 ns.

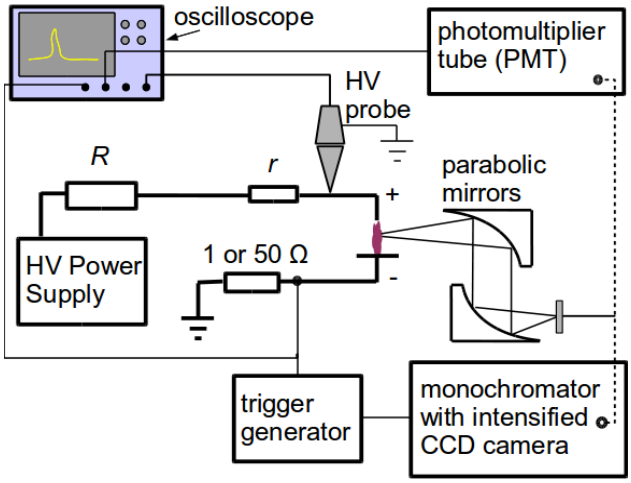

Figure 1. Schematic of the experimental set-up, HV - high voltage, *R, r* - resistors.

This generator was triggered directly by the current signal, causing an additional delay of less than 10 ns. This delay, plus the delay caused by the transmission of the signal by BNC cables, was compensated by using 10 m long optical cable (Ocean Optics P400-10-UV-VIS), to see the whole emission profile. For imaging, we could not use this optical fiber and therefore cannot acquire the emission from approximately 25 ns after the beginning of a trigger event (streamer or spark current pulse, depending on used resistor shunt).

For time-resolved optical emission measurements, a photomultiplier tube (PMT) module with a 2.2-ns rise time (Hamamatsu H955) was also used. Its signal was recorded using the oscilloscope. The PMT was triggered by the emission signal itself. Whenever it was necessary to isolate a specific spectral transition for PMT measurements, a band pass interference filter, e.g. for the N_2 (C-B, 0-0) transition, was inserted into the optical path. The experimental set-up is depicted in Fig. 1.

3. Results and Discussion

When the high voltage U_{00} applied to the stressed electrode is progressively increased, we first observe a streamer corona. When the breakdown voltage is reached, a transition to TS occurs at the discharge voltage U_{TS}. The typical current and voltage waveforms are shown in Fig. 2. During the high current phase the voltage drops to zero due to the resistive fall on the ballast resistance *R*.

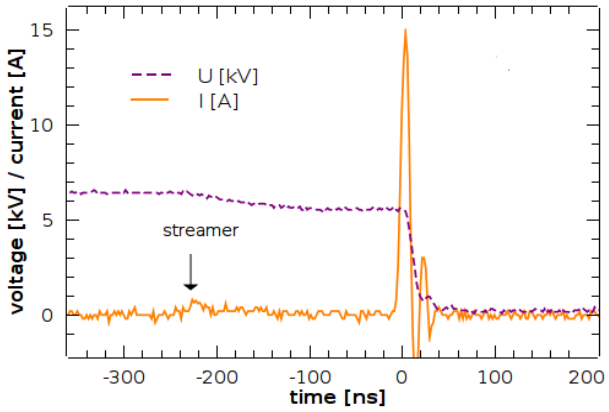

Figure 2. Typical TS current and voltage waveform, $f \sim 1$ kHz, $R = 6.6$ MΩ, $C \approx 26$ pF.

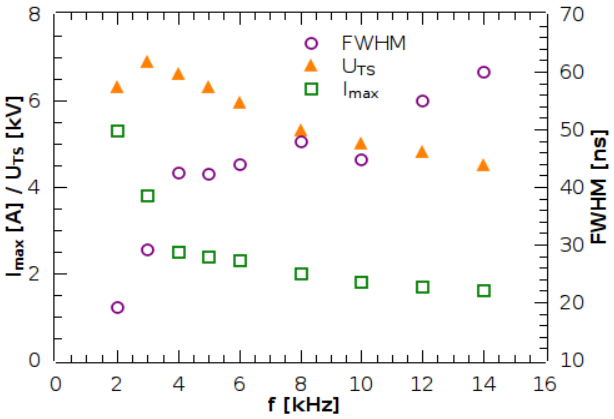

Figure 3. Dependence of TS properties on *f*: peak current I_{max}, full width at half maximum FWHM of current pulses, and breakdown voltage U_{TS}, $R = 6.6$ MΩ, $C \approx 26$ pF.

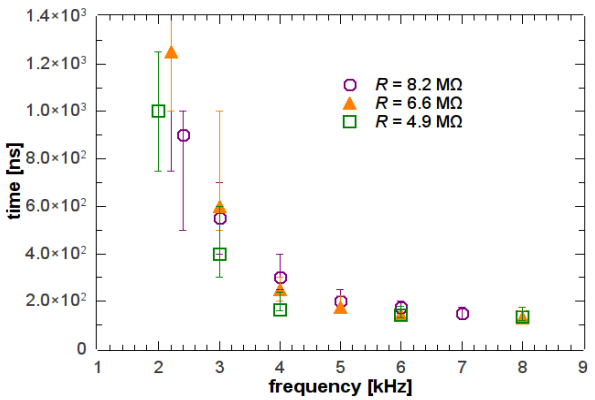

Figure 4. Dependence of streamer-to-spark transition time on *f*.

Then, during the quenched phase, the system capacity *C* (composed of the internal capacity of the electrodes, the capacity of the HV cable and of the HV probe) is recharged by a growing potential on the stressed electrode. For typical *R* and *C*, the repetition frequency *f* of this process is in the order of several kHz and grows with increasing U_{00} [1].

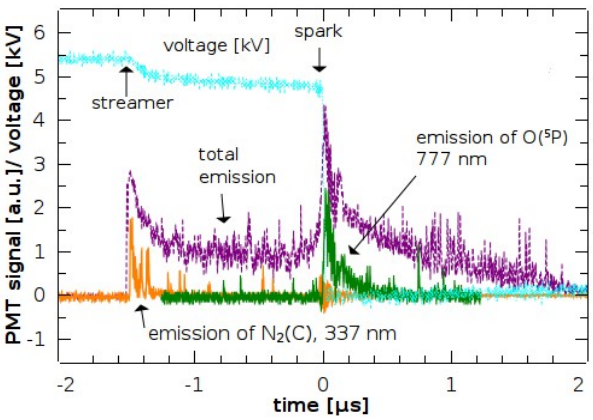

Figure 5. Typical PMT emission profiles of TS at 2.5 kHz.

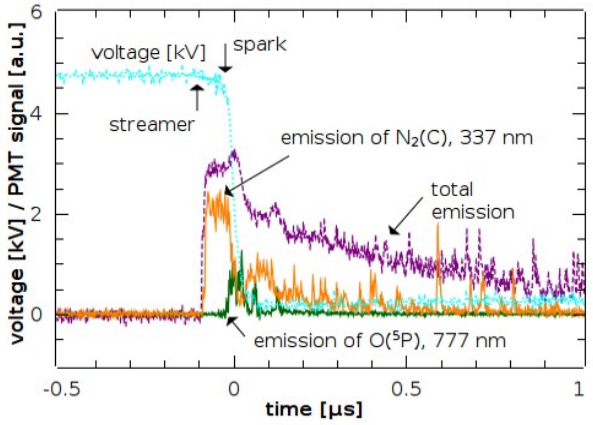

Figure 6. Typical PMT emission profiles of TS at 6 kHz.

This is accompanied by changes of TS properties. With increasing f, current pulses get smaller and broader (Fig. 3). It is interesting that U_{TS} also depends on f, as well as streamer to spark transition time τ (Fig. 4). At lower frequencies, the delay between streamer and spark formation is very random and it can vary from several µs to a few hundred ns. As f increases, τ decreases down to ~100 ns and it becomes more regular.

Emission profiles obtained by PMT also reflect changes of current waveforms and τ with increasing f . At lower f, one can see two peaks of the total emission: the first one is produced by the streamer, and the second one by the spark (Fig. 5). The emission during the 'streamer' peak can be mostly attributed to the $N_2(C)$ species, whereas the 'spark' peak is mostly due to the excited atomic species. As τ shortens with the increasing f, these two emission peaks approach each other (Fig. 6) until they merge.

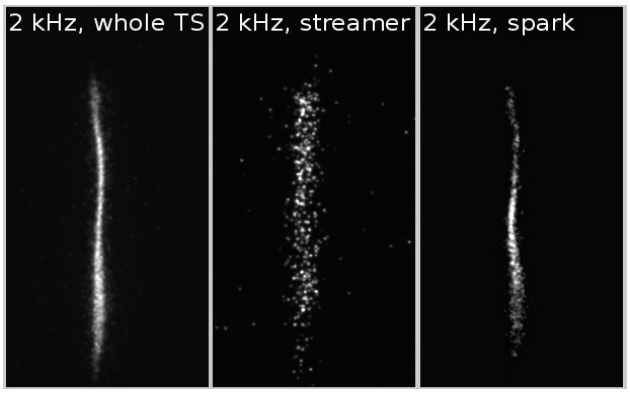

Figure 7. iCCD images of TS at 2 kHz.

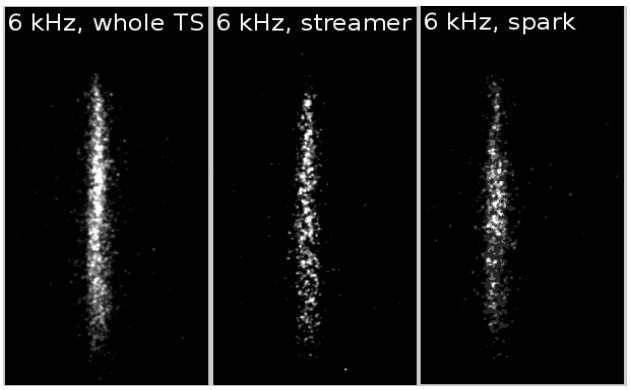

Figure 8. iCCD images of TS at 6 kHz.

However, the emission from $N_2(C)$ does not change much with f, while the emission intensity of excited atomic species decreases significantly. In the 'high' f TS regime, we actually mostly see the streamer, whereas at the 'low' f we mostly see the spark. This was confirmed by time-resolved images obtained by iCCD camera. The image covering the whole TS pulse and the image of spark channel only are very similar at lower frequencies (Fig. 7), whereas the streamer image is different. On the contrary, at 'high' f, the images of the whole TS pulse, streamer and spark phase (Fig. 8) are all similar. Even during the spark, we mostly see the emission from $N_2(C)$ species produced by the streamer. At 'low' f, we see the shrink of the plasma channel diameter during the streamer-to-spark transition from ~300 µm down to less than ~100 µm. On the other side, at higher frequencies, τ is much shorter and no decrease of plasma diameter can be observed.

Changes of electric parameters of TS with f, mainly the decrease of U_{TS}, could be explained by the increase of 'steady-state' gas temperature T_g, calculated from the emission spectra of N_2 2nd positive system, from the initial 20 ns after the

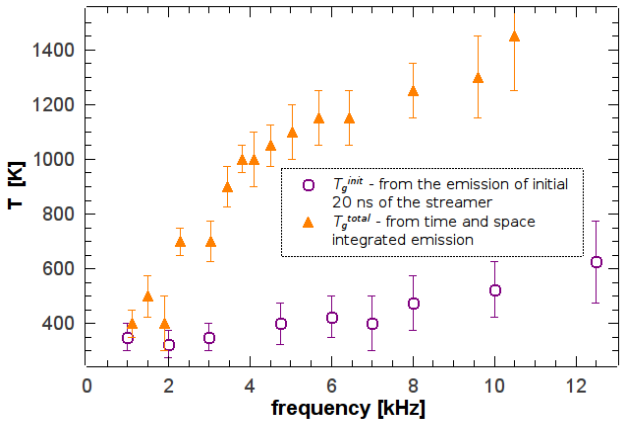

Figure 9. The rotational temperature of $N_2(C)$ as a function of *f*.

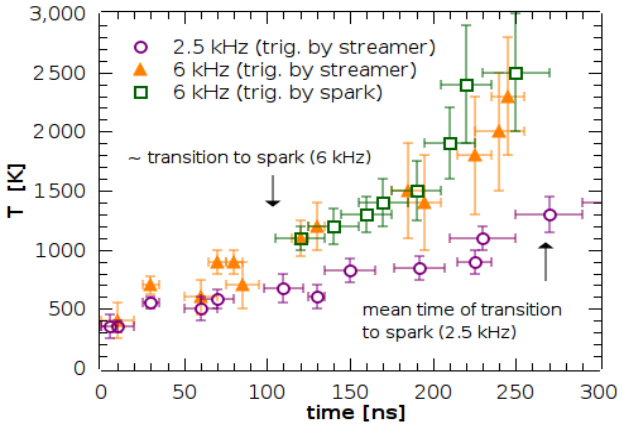

Figure 10. Temporal evolution of the gas temperature.

beginning of the streamer (T_g^{init}, Fig. 9). Here we assume that in our plasma T_g equals to the rotational temperature T_r of $N_2(C)$ species, obtained by fitting the experimental spectra of N_2 2nd positive system with the simulated ones (using Specair program [3]). As we can see, the increase of T_g^{init} is small compared to the increase of T_g^{total}, calculated from time integrated emission of TS (typical integration time 300 μs – 3 ms). However, even this small increase of T_g^{init} is enough to keep an average *E/N* in the gap ~70 Td when the gap potential at the breakdown voltage U_{TS} decreases with *f* from about 7 kV to 4.5 kV (Fig. 3). The value of T_g^{total} we previously used to describe the increase of T_g with increasing *f* has actually no physical meaning. It is necessary to use time-resolved emission spectroscopy to characterize the temporal changes of TS temperature (Fig. 10).

At both f = 2.5 kHz and 6 kHz we observed an approximately linear increase of T_g with time, from initial ~300 and ~400 K, respectively. This heating is faster at 6 kHz, but in both cases the streamer-to-spark transition occurs when T_g ~1000 K. We thus suppose that the increase of T_g is a dominant mechanism responsible for the streamer-to-spark transition in TS. The reason why the delay between the streamer and spark phase shortens with *f* can be explained by a faster growth of T_g with increasing *f*. However, this will require further research and deeper analysis, including kinetic modeling .

4. Conclusions

We investigated transient spark, a DC-driven self-pulsing streamer-to spark transition discharge in atmospheric air. TS is characterized by the very short spark pulse duration (~10-100 ns) with the peak current 1-10 A. TS can be maintained at low energy conditions (0.1-1 mJ/pulse) and so the generated plasma cannot reach LTE conditions. The current pulse can lead to temporary increase of T_g to ~2500 K, but the global temperature remains relatively low. Even at ~10 kHz, each streamer-to-spark sequence starts at ~500 K.

Subsequent increase of the gas temperature to ~1000 K governs the transition the spark. Shortening of the average streamer-to-spark transition time with increasing TS frequency can be explained by an acceleration of temperature growth. The reason for this acceleration will require further research.

Acknowledgements

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