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CROSS-CORRELATION SPECTROSCOPY STUDY OF NEGATIVE POLARITY TRANSIENT SPARK DISCHARGE EVOLUTION IN AMBIENT AIR

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A streamer-to-spark transition in a self-pulsing transient spark (TS) discharge of negative polarity in air was investigated using cross-correlation spectroscopy. The temporal evolution of the TS was recorded for several spectral bands and lines: the second positive system of N_2 (337.1 nm), the first negative system of N_2^+ (391.4 nm), and atomic oxygen (777.1 nm). The results enable the visualization of the different phases of discharge development including the streamer, followed by the return stroke. The transition to the spark was not recorded due to relatively long (0.3-1.5 μs) and irregular duration of the streamer-to-spark transition phase.

1. Introduction

The transient spark (TS) is a dc-operated, self-pulsing and filamentary discharge with typical repetition rate in the range 1-10 kHz. Fundamental research of the positive polarity TS characteristics revealed that it is initiated by a streamer, followed by the short spark current pulse [1]. The spark current pulses have maximum amplitude in the range of a few Amps, but are sufficiently short (~10-100 ns). Thus, significant heating of the treated gas is avoided and the generated plasma is non-equilibrium and highly reactive, with an electron density up to 10^{17} cm^{-3} [2]. These reactive plasma properties predetermine the TS for several biomedical and environmental applications [3]. For this purpose, the negative polarity TS in argon was also extensively studied [4]. On the other side, the fundamental research of the negative polarity TS in ambient air was not performed yet.
In this paper we explore the evolution of the negative polarity TS discharge in air at a pulse repetition frequency ~2 kHz. Having high spatio-temporal resolution, sensitivity and a trigger designed for the investigation of self-pulsing randomly appearing discharges, the cross-correlation spectroscopy was used [5, 6] for the visualization of the negative polarity TS discharge evolution in ambient air.

2. Experimental setup

The negative polarity TS was generated in dry atmospheric pressure air between steel electrodes in point-to-plane configuration. The gap length was d = 4 mm. The DC high voltage (HV) power supply was connected to the point cathode via a series resistor R = 6.85 MΩ while the plate electrode was grounded (Figure 1). The velocity of the air flow was about 0.5 $m.s^{-1}$, parallel to the inter-electrode axis. The radius of curvature of the anode tip was of the order of 100 μm.
The discharge voltage was measured by an HV probe (Tektronix P6015A) and the discharge current was measured by a current monitor (Pearson Electronics 2877 1V/A) and by a 50 Ω resistor shunt. The voltage and current signals were recorded by a digitizing oscilloscope (Tektronix DPO 4104 bandwidth 1 GHz, or Tektronix TDS2024 with bandwidth 200 MHz).
The cross-correlation spectroscopy (CCS) was used to explore the entire evolution of the TS discharge. The emission from the discharge corresponding to the second positive system (SPS) of N_2 (0-0 transition at 337.1 nm), the first negative system (FNS) of N_2^+ (0-0 transition at 391.4 nm), and the emission lines of atomic oxygen (777.1 nm) were recorded.
The idea of CCS is to accumulate single photons together with their time information from high-frequency repetitive discharge events. The time information of each photon is determined from its correlation to the integral light pulse of the same discharge, i.e. cross-correlation method. Therefore, the light pulses are investigated by two photomultipliers (PMTs). The PMT 1 detects the single photons after spatial and spectral separation, while PMT 2 defines the relative timescale of the light pulses being

investigated. Both pulses are processed by the time-correlated single photon counter (TC-SPC), details being described elsewhere [5, 7]. The spectral resolution of the main-signal (PMT 1) is given by diffraction in a Czerny-Turner type monochromator with adjustable entrance and exit slits, grating with 1200 grooves/mm (blaze 300 nm). The spatial resolution is achieved by imaging the main-signal on the entrance slit of the monochromator via an achromatic lens (L), and a rotating mirror (RM) controlled by a scanning device.

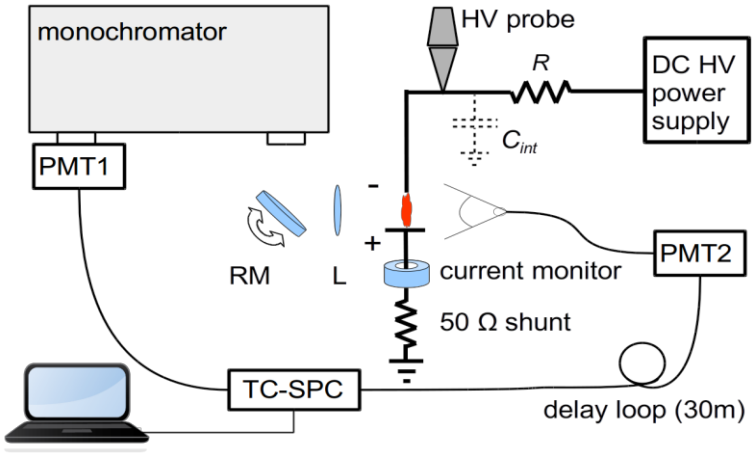


Fig. 1. Schematic of the experimental setup, PMT – photo multiplier, TC-SPC – time correlated single photon counting board, RM – rotating mirror, L – lens, R – external resistor.

3. Results and Discussion

The current and voltage waveforms of the negative TS (Fig. 2) looks almost like inverted waveforms of positive TS discharge [1]. The discharge is initiated by the negative streamer resulting in relatively large current peak with the amplitude around -100 mA. In the following streamer-to-spark transition phase, the current drops to approximately -20 mA. During the gas breakdown phase, the voltage on the cathode drops to almost zero and the a short (~25 ns) spark current pulse with amplitude -15 A is formed due to discharging of the internal capacity C_{int} (see Fig. 1) of used electric circuit. The repetition rate of charging and discharging of C_{int} can be controlled by generator voltage $V_{g.}$, but we were not able to achieve frequency around 10 kHz as with positive polarity TS [8] and we had to study negative polarity TS with repetition rate ~2 kHz.

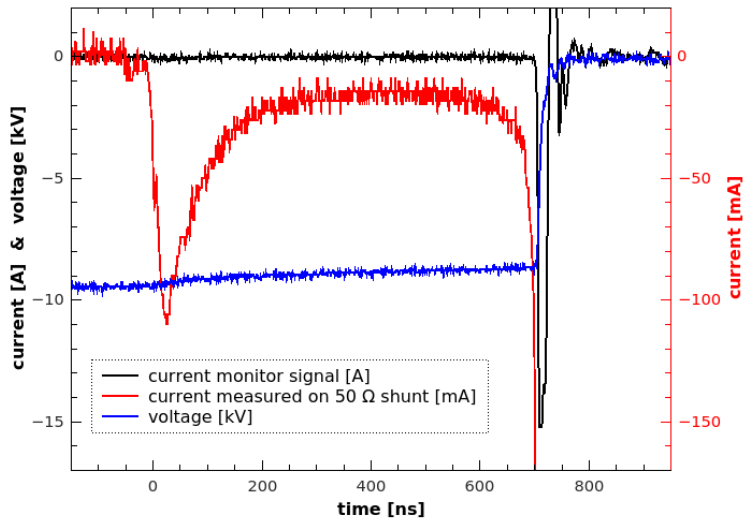
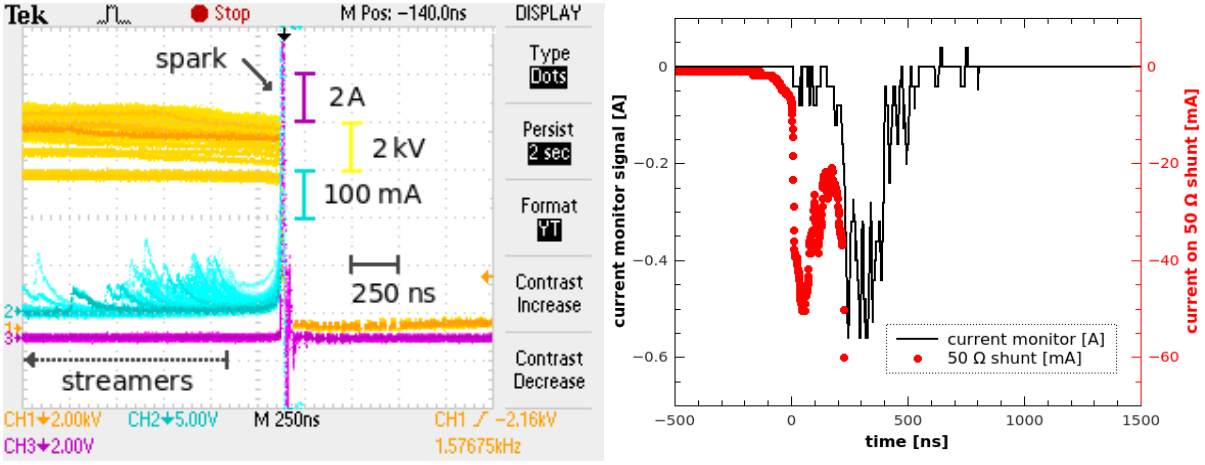


Fig. 2. Typical negative polarity TS waveforms, single pulse, repetition rate ~ 2 kHz, C_{int} ~ 30 pF.



a) b)

Fig. 3. Accumulated negative polarity TS waveforms (persist 2 s) triggered on spark current pulse, all signals inverted (a), and averaged TS current waveforms (128 pulses) triggered on the beginning of the streamer (b).

The CCS study of positive TS around 10 kHz was able to visualize the whole discharge evolution, starting from the primary streamer transforming to spark within ~10 ns. The streamer-to-spark transition for positive polarity TS at ~10 kHz was not only fast, but also relatively regular. In the negative TS with 2 kHz repetition rate, the streamer-to-spark transition delay is much longer, 0.3-1.5 μs, and very irregular (Fig. 3a). As a result, the averaged spark current pulses are much broader, when triggered on the beginning of the streamer current pulse (Fig. 3b). We must take this fact into account when we analyze the CCS visualization of the negative TS (Fig. 4 and 5). The CCS records were also averaged over many TS pulses, and they are also influenced by the random duration of the streamer-to-spark delay. For this reason, the CCS images show correct time evolution only for the initial streamer phase of the negative TS discharge, the following spark phase is blurred like the spark current signal on Figure 3b.

The evolution of negative TS starts near the point electrode (cathode) and the emission of the SPS strongly dominates during this phase (Fig. 4, time t = 2-5 ns, distance from the anode x = 3-4 mm). This shining area (SPS emission) propagates through the gap and it reaches the anode within a few nanoseconds (Fig. 5, t ≈ 10 ns). However, the intensity of the SPS emission is much weaker near the anode. This SPS emission propagating from the cathode towards the anode is probably related to the negative streamer. In the same moment when the SPS emission approaches the anode, the emission of FNS and atomic oxygen appears in the whole gap (Fig. 4, t ≈ 10 ns). The signal from the emission of exited oxygen atoms, not shown here, follows the same patterns as the FNS emission.

Unlike in the FNS system, we observed another propagating event in the SPS signal, starting from the anode (Fig. 5, t ≈ 20 ns, x ≈ 0-1 mm) and moving towards the cathode. A similar development was previously observed in the TS in argon and helium[4], and discussed as a backward propagating streamer. It was assumed that negative oxygen ions, remaining from the streamer propagation, drift along the electric field lines.

4. Conclusions

We investigated evolution of negative polarity TS discharge with approximate repetition rate 2 kHz by cross-correlation spectroscopic technique. The cross-correlation spectroscopy was demonstrated to be a suitable technique for the investigation of such self-pulsing and erratically appearing discharges. However, we were not able to see whole evolution of the TS discharge due to relatively long (0.3-1.5 s)

and variable streamer-to-spark transition phase. Further investigation is needed to provide better synchronization of CCS records with measured current and voltage waveforms.

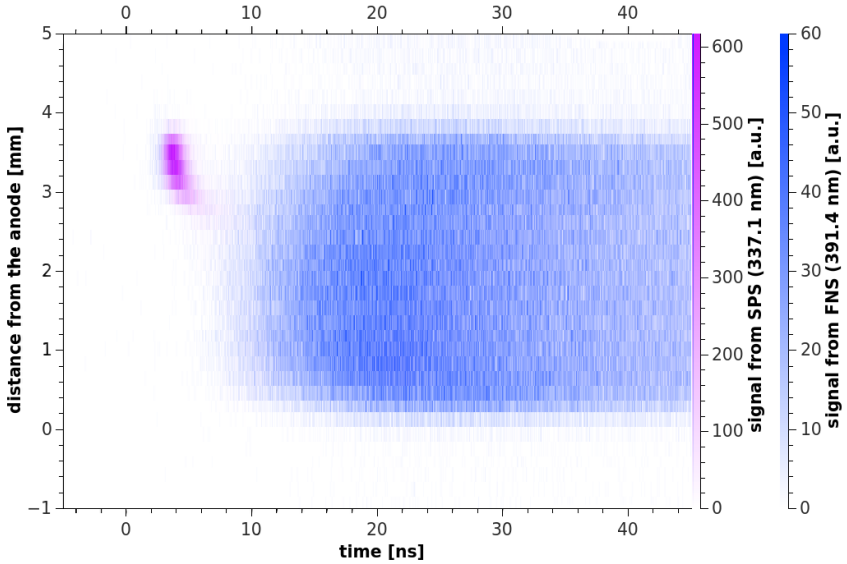


Fig. 4. Cross-correlation spectroscopy record of the TS evolution, negative polarity, cathode at the top, repetition rate ~2 kHz, gap 4 mm, overlapped signal from the SPS and FNS emission.

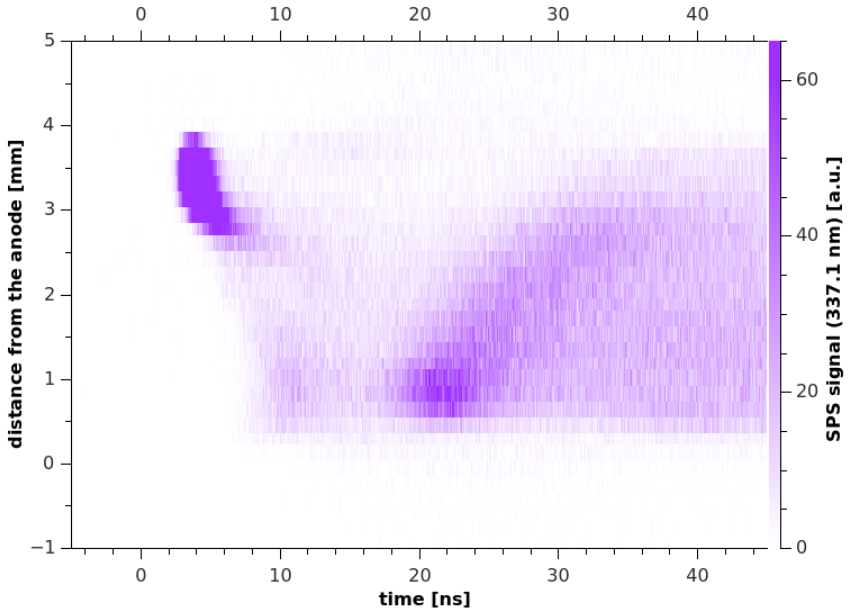


Fig. 5. Cross-correlation spectroscopy record of the TS evolution, negative polarity, cathode at the top, repetition rate ~2 kHz, gap 4 mm, SPS emission signal rescaled, with initial phase saturated.

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