Imaging of Transient Spark in Atmospheric Air by Fast iCCD Camera

Mario Janda and Zdenko Machala

***Abstract*—A transient spark (TS) pulsed discharge of streamer-to-spark transition type is studied using fast iCCD camera and fast photomultiplier tube. Emission profiles and images of single TS pulse at different frequencies help to understand the influence of repetition frequency on the streamer-to-spark transition process.**

***Index Terms*—Atmospheric pressure plasmas, imaging, plasma diagnostics, sparks.**

TRANSIENT spark (TS) is a pulsed dc-driven streamer-to-spark transition discharge with a concept similar to the prevented spark [1]. It is initiated by a streamer, which transforms to a short (~10–100 ns) high-current (> 1 A) spark due to the discharging of the internal capacity C of the reactor. The charging and discharging of C repeat with the frequency f from ~l to 15 kHz. The increase of f, achieved by increasing the onset voltage, is accompanied by a change of emission characteristics of TS [2]. Below ~3 kHz, the emission of O, N, and N^+ atomic lines and N_2 second positive system dominates in the spectra, but at higher frequencies, these atomic lines almost disappear.

In order to understand this phenomenon, we employed a photomultiplier tube (Hamamatsu H955) with 2.2-ns rise time and appropriate narrow-band optical filters, as well as an iCCD (ANDOR Istar) camera with 2-ns gate. Experiments were carried out at room temperature in atmospheric pressure air with a radial flow of ~0.2 m/s. The distance between the stainless steel electrodes in point-to-plane configuration was 4 mm. A dc high-voltage (HV) power supply connected via a series resistor (6.56–9.84 MΩ) was used to generate a positive TS discharge. The discharge voltage was measured by an HV probe Tektronix P6015A, and the current was measured on a 50- or 1-Ω resistor shunt. All electric signals were recorded by a 200-MHz oscilloscope Tektronix TDS2024. The iCCD camera was triggered by a generator of 5-V rectangular pulses, which was triggered directly by the current signal (either by streamer measured on 50-Ω shunt or spark measured on 1-Ω shunt). The photographs were taken by a digital camera Olympus E-410.

At lower frequencies, TS seems to consist of many separate bluish white narrow plasma channels [Fig. 1(a)], which occupy relatively large volume of the gas. In reality, only one channel exists in a moment, and as we decrease the exposure time t_e [Fig. 1(a)–(c) with t_e values of 0.1, 0.05, and 0.01 s, respectively], one can see less and less channels. At "high" f, the color changes to bluish violet, and TS looks almost like a stable constant-current high-pressure glow discharge [3], [4] [Fig. 1(d)]. In reality, there exist many channels with short duration, but they all occupy almost the same space. The decrease of t_e [Fig. 1(d)–(f)] leads only to the decrease of the intensity, with the remaining impression of a diffuse single-channel discharge.

Fig. 1(m) and (n) shows the typical current and voltage waveforms of TS at 2 and 6 kHz, respectively. With increasing f, current pulses get smaller and broader, and streamer-to-spark transition time τ shortens. Below ~3 kHz, τ is very random, and it can vary from a few hundreds of nanoseconds to several microseconds. At higher f [Fig. 1(n)], a gradual transition to spark in about 100 ns occurs. Emission profiles obtained by PMT reflect these changes of current waveforms as well. At lower f, one can see two peaks of the total emission: The first one is produced by the streamer, and the second one is produced by the spark. 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 until they merge. However, the emission from $N_2(C)$ does not change much with f, while the emission intensity of excited atomic species decreases significantly. This can actually explain the change of the discharge color with the increasing f. 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 the iCCD camera. The image covering the whole TS pulse and the image of spark channel only are very similar at lower frequencies [Fig. 1(g) and (i)], while at "high" f, the images of the whole TS pulse, streamer phase, and spark phase [Fig. 1(j)–(l)] 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. This is in agreement with calculations of Naidis [5]. On the other side, at higher frequencies, τ is much shorter, and no decrease of plasma diameter can be observed.

Manuscript received November 30, 2010; revised May 9, 2011; accepted May 11, 2011. Date of publication June 13, 2011; date of current version November 9, 2011. This work was supported in part by the AFOSR, Air Force Material Command, USAF, under Grant FA8655-09-1-3110, by the Slovak Research and Development Agency under Grant APVV SK-FR-0038-09, and by the Slovak grant agency VEGA under Grants 1/0293/08 and 1/0668/11.

The authors are with the Division of Environmental Physics, Faculty of Mathematics, Physics and Informatics, Comenius University, 842 48 Bratislava, Slovakia (e-mail: janda@fmph.uniba.sk; machala@fmph.uniba.sk).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TPS.2011.2157175

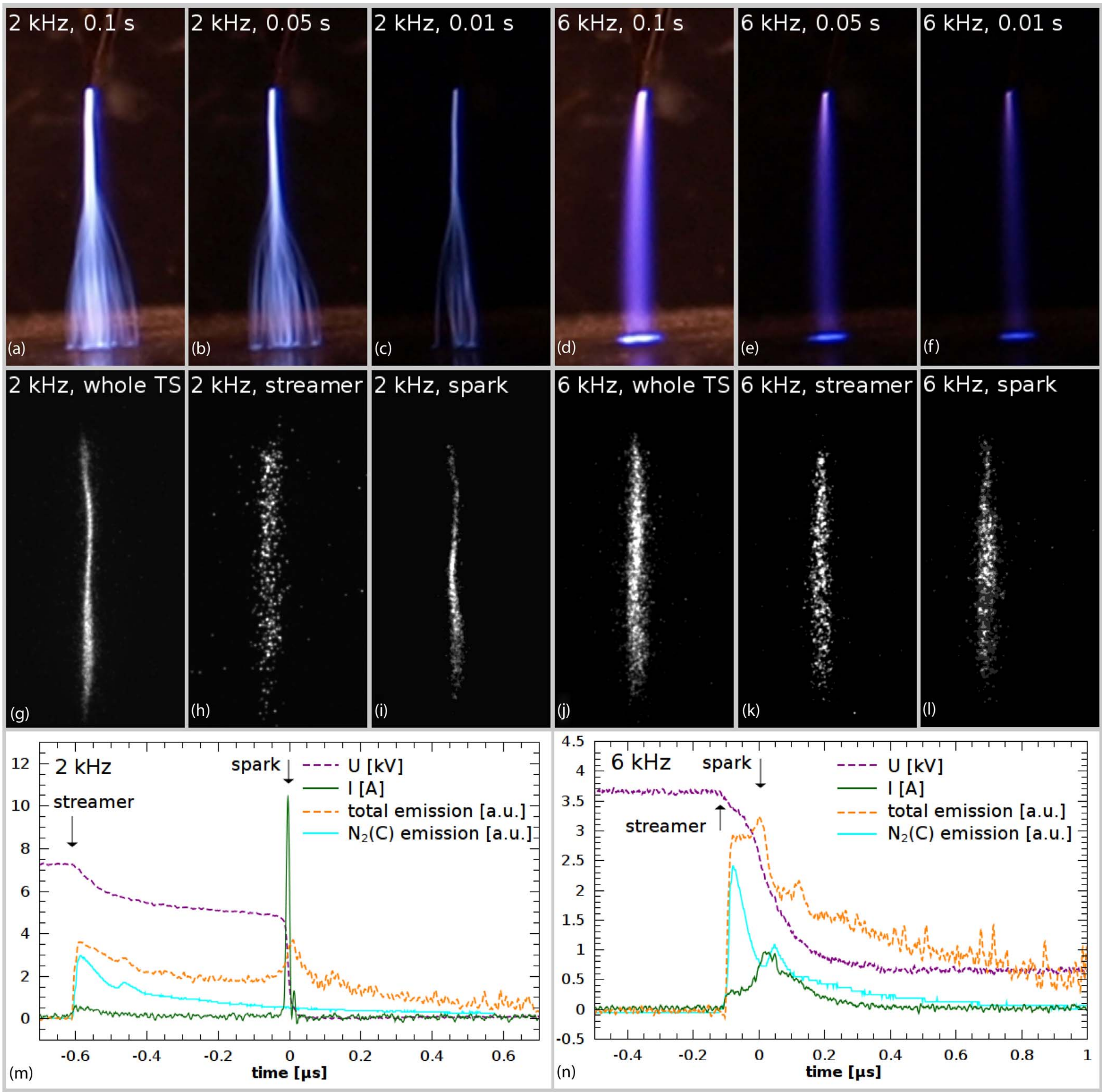

Fig. 1. (a)–(f) Photographic images of TS at 2 and 6 kHz with different exposure times, (g and j—whole TS; h and k–streamer phase; and i and l—spark phase) iCCD images of a single TS channel, and (m and n) typical voltage and current waveforms with PMT signals of the total emission (200–800 nm) and N_2 second positive system at 337 nm.

References

[1] F. Bastien and E. Marode, "The determination of basic quantities during glow-to-arc transition in a positive point-to-plane discharge," *J. Phys. D, Appl. Phys.*, vol. 12, no. 2, pp. 249–263, Feb. 1979.
[2] M. Janda and Z. Machala, "Transient-spark discharge in $N_2/CO_2/H_2O$ mixtures at atmospheric pressure," *IEEE Trans. Plasma Sci.*, vol. 36, no. 4, pp. 916–917, Aug. 2008.
[3] Y. S. Akishev, A. A. Deryugin, I. V. Kochetov, A. P. Napartovich, and N. I. Trushkin, "DC glow discharge in air flow at atmospheric pressure in connection with waste gases treatment," *J. Phys. D, Appl. Phys.*, vol. 26, no. 10, pp. 1630–1637, Oct. 1993.
[4] L. Yu, C. O. Laux, D. M. Packan, and C. H. Kruger, "Direct-current glow discharges in atmospheric pressure air plasmas," *J. Appl. Phys.*, vol. 91, no. 5, pp. 2678–2686, Mar. 2002.
[5] G. V. Naidis, "Simulation of streamer-induced pulsed discharges in atmospheric-pressure air," *Eur. Phys. J. Appl. Phys.*, vol. 47, no. 2, p. 22 803, 2009.