The Structure of Nanosecond Repetitively Pulsed Spark Discharges in Air

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***Abstract*—Nanosecond repetitively pulsed (NRP) spark discharges have been generated in room-temperature air at atmospheric pressure. Single-shot image sequences of NRP spark discharges show that the path of the spark discharge channel can change with each pulse as well as during a single pulse, suggesting that several filaments can be generated within a single discharge event.**

***Index Terms*—Atmospheric pressure plasmas, discharge channel, nanosecond discharges, spark discharges.**

NANOSECOND repetitively pulsed (NRP) spark discharges are generated in air at atmospheric pressure by applying high-voltage nanosecond-duration pulses at high pulse-repetition frequencies (*PRFs*) [1]. Such discharges demonstrate effects such as ultrafast heating and high atomic-oxygen production [1], [2] that are interesting for applications such as combustion [3], [4]. Unlike other nanosecond discharges at low *PRF* characterized by strong runaway-electron and X-ray production [5], NRP discharges rely on high *PRF* to build up a highly reactive and preionized discharge channel. In this paper, we present an investigation of the discharge channel dynamics of NRP sparks in ambient air.

NRP spark discharges are generated between two 150-μm-diameter tungsten wires in a pin-to-pin configuration. Ambient air flows parallel to the interelectrode axis at $\sim$1 m/s. An FID Technologies generator (model FPG-12-SU-PL) produces positive voltage pulses on the anode and negative pulses on the cathode, with rise/fall times of 5 ns and amplitudes of up to 7 kV into an open circuit. The positive and negative pulses arrive simultaneously at the electrodes, providing a total potential drop of up to 14 kV across the electrodes. The *PRF* can be varied up to 100 kHz. The voltage across the electrodes is measured with a 400-MHz-bandwidth high-voltage probe (LeCroy PPE6KV), and the discharge current is measured with a Pearson coil current monitor (model 110). The probe signals are recorded with a 500-MHz Tektronix TDS5054B oscilloscope.

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Fig. 1(a) shows a digital camera image of an NRP spark discharge in ambient air taken with an exposure time of 2.5 ms, during which 100 pulses are applied. We see that the discharge is filamentary, although it is not clear whether several filaments are generated simultaneously or if a single filament bends about in the direction lateral to the interelectrode axis. Fig. 1(b) shows representative current and voltage measurements of NRP spark discharges. The voltage waveform is truncated by the discharge because the plasma resistance rapidly decreases upon the formation of the discharge. The maximum total current is about 15 A, which is consistent with previous work on NRP sparks [1].

To capture the plasma dynamics from a single pulse, a Cordin 222C-16UV intensified CCD (ICCD) camera system has been used to acquire the single-shot image sequences. Light is focused by the objective onto a beam splitter, which sends light into eight individual ICCD cameras. All of the cameras are synchronized by a common trigger signal, but the gate delay setting of each camera is controlled individually. This allows the acquisition of a sequence of images of the discharge produced by a single pulse. The high-voltage pulse generator and the camera were synchronized using a Stanford Research Systems DG535 pulse delay generator.

The NRP spark discharge is initially homogeneous and remains so up to the moment of peak emission intensity, which is consistent with previous work on NRP spark discharges at 1000 K [1]. Then, emission tapers off first in the middle of the discharge and then near the electrodes. Fig. 1(c) shows two examples of image sequences of NRP spark discharges. Each image has been acquired using a different camera, each with a 10-ns gate and all synchronized to the trigger generator. The gate delay is different for each camera in order to capture the various steps in discharge development. Only one filament exists at any given moment, and the discharge path deviates away from the interelectrode axis. The filaments from Fig. 1(c) take different paths from the anode to the cathode, demonstrating that the many filaments shown in Fig. 1(a) are the accumulated light from different discharges, each composed of a single filament. The filament diameter ranges from 50 to 200 μm. Most interestingly, the images from Fig. 1(c) show that, even during one discharge, the path changes. This effect is only conclusive when acquiring a single-shot image sequence. It is unclear whether this is because a single discharge moves around or because a single pulse produces several discharges. As the discharge duration is only 10 ns, the channel movement cannot be due to gas dynamic phenomena.

In conclusion, we have demonstrated that NRP spark discharges in room-temperature ambient air at atmospheric

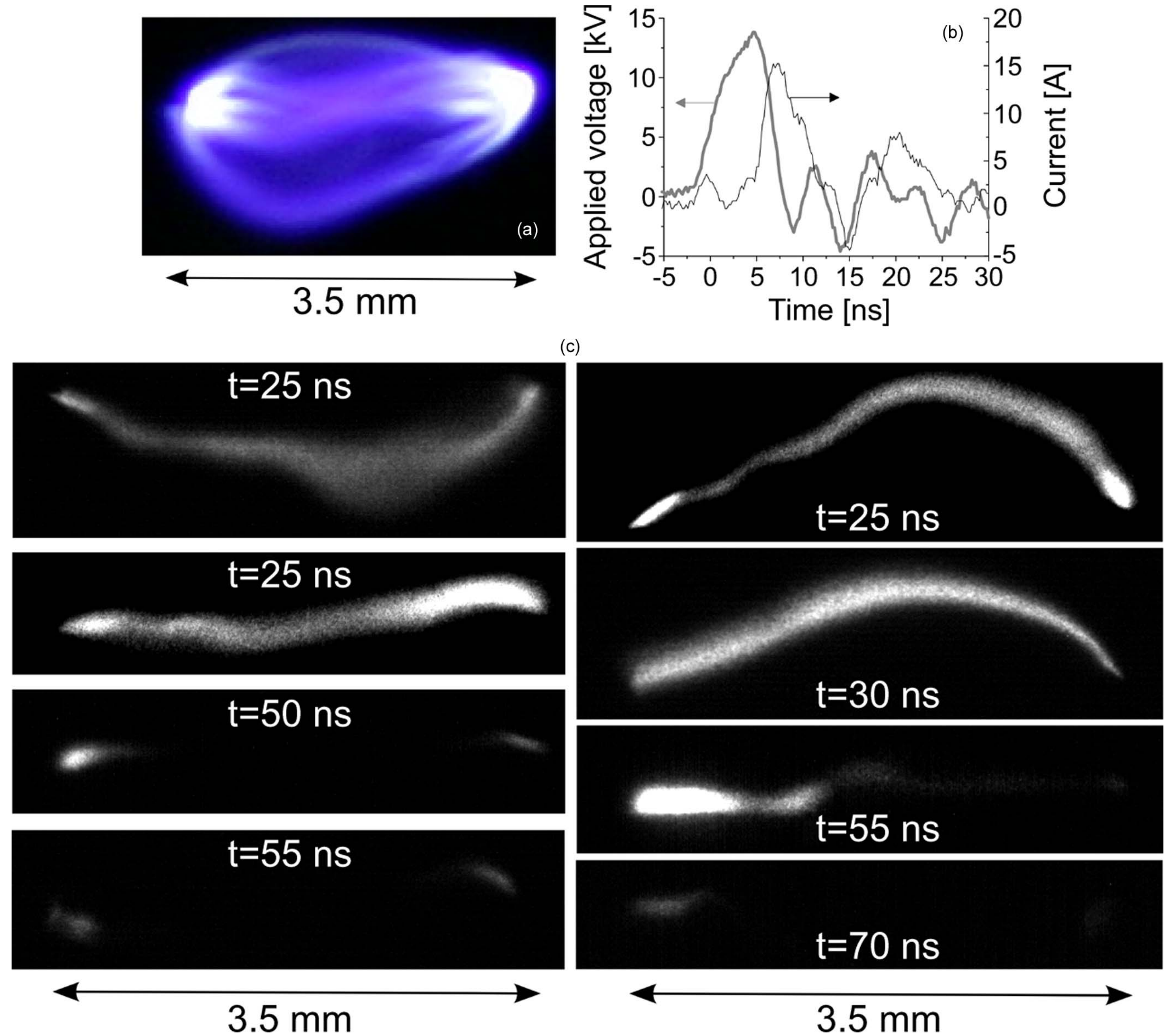

Fig. 1. For an NRP spark discharge with $d = 3.5$ mm, $V_p = 14$ kV, and $PRF = 40$ kHz. (a) Digital camera image with an exposure time of 2.5 ms. (b) Measured applied voltage and total current. (c) Single-shot image sequences, with the relative gate delay indicated in each frame. Each vertical sequence of four frames was acquired during and after a single applied high-voltage pulse. The exposure time of each frame is 10 ns.

pressure exist as only one filament at a time when a pin-to-pin electrode configuration is used. Not only does the spark channel vary considerably in location for each pulse but it also varies during the same pulse.

REFERENCES

[1] D. Z. Pai, D. A. Lacoste, and C. O. Laux, "Nanosecond repetitively pulsed discharges in air at atmospheric pressure—The spark regime," *Plasma Sources Sci. Technol.*, vol. 19, no. 6, p. 065015, Dec. 2010.

[2] G. D. Stancu, F. Kaddouri, D. A. Lacoste, and C. O. Laux, "Atmospheric pressure plasma diagnostic by OES, CRDS and TALIF," *J. Phys. D, Appl. Phys.*, vol. 43, no. 12, p. 124002, Mar. 2010.

[3] H. Do, M. G. Mungal, and M. A. Cappelli, "Jet flame ignition in a supersonic crossflow using a pulsed nonequilibrium plasma discharge," *IEEE Trans. Plasma Sci.*, vol. 36, no. 6, pp. 2918–2923, Dec. 2008.

[4] G. Pilla, D. Galley, D. A. Lacoste, F. Lacas, D. Veynante, and C. O. Laux, "Stabilization of a turbulent premixed flame using a nanosecond repetitively pulsed plasma," *IEEE Trans. Plasma Sci.*, vol. 34, no. 6, pp. 2471–2477, Dec. 2006.

[5] T. Shao, C. Zhang, Z. Niu, P. Yan, V. F. Tarasenko, E. K. Baksht, A. G. Burahenko, and Y. V. Shut'ko, "Diffuse discharge, runaway electron, and X-ray in atmospheric pressure air in an inhomogeneous electrical field in repetitive pulsed modes," *Appl. Phys. Lett.*, vol. 98, no. 2, pp. 021503-1–021503-3, Jan. 2011.