Investigation of return stroke in spark discharge in water using Gaussian processes

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Abstract: Nanosecond imaging of the streamer-to-spark transition for discharges ignited at the water-heptane interface is reported. The fine temporal resolution allows the observation of a fast ionization wave propagating in water back to the anode—the return stroke (RS)—following the streamer phase. Using Gaussian processes, the velocity of the RS, usually only seen during lightning, was estimated to be about 1300 ± 20 km/s in a 4 mm electrode gap.

1. Introduction

Pulsed discharges in liquids are transients and stochastic plasmas with tree-like structures. When the voltage is high enough near the anode, the strong electric field initiates a positive ionization wave (IW), the streamer, propagating toward the cathode with various speed regimes depending on the experimental conditions [1]. If the conditions allow it, the streamer can reach the cathode and transit to a spark discharge where strong ionization and fast heating occur along the channel. In a liquid, the dynamic of this transition is difficult to measure due to the stochasticity of the discharge process but more importantly to discharge's short space- and time-scales. The most detailed reports of this transition are for gaseous discharge in large gap conditions [2]. As in lightning during thunderstorms, the first IW is followed by a second faster one called the return stroke (RS). When the IW reaches the ground, the potential at its front drops to almost zero, and a potential wave propagates back into the channel, inducing a strong electric field wave ionizing the gas. The RS observed in lightning is in the range of 20-50% of the speed of light.

In this work, we produce millimeter-scale discharge in water using a low dielectric liquid layer on top of it to facilitate its occurrence [3]. The streamer-to-spark transition is imaged, and the RS propagation is observed. The RS speed is estimated using a Gaussian process method.

2. Experiments and results

The discharges are ignited at the heptane-water interface using pulsed high voltage: amplitude of 20 kV, duration of 500 ns, and repetition rate of 1 Hz. The copper anode tip is placed at the interface, 4 mm above the ground submerged in water. The exposure time of the ICCD was 1 ns. The delay between the discharge and ICCD is controlled using a delay generator to reconstruct the temporal behavior.

The upper part of Figure 1 illustrates the streamer-to-spark transition and the propagation of the RS from the ground to the anode. To estimate the RS velocity, one must assess the time of passage of the light front for the different heights. To achieve this, the light intensity at various heights is first calculated and displayed as a function of time. Then, the time of passage is commonly determined by looking at the time intercept of a linear fit of light intensity rise [4]. However, there are not enough data points to perform a reliable fit. To overcome this issue, a Gaussian Process [5] is used to interpolate both the missing data points and their uncertainties. The calculated smooth light evolutions near both the cathode and the anode are represented with their corresponding uncertainty in the bottom part of Figure 1. With the new curves, the time of passage can be determined for all the different positions and the velocity can be estimated to be ~1300 ± 20 km/s. The fact that the velocity is much slower than lightning can be explained by the lower diameter, conductivity, and temperature of the plasma channel.

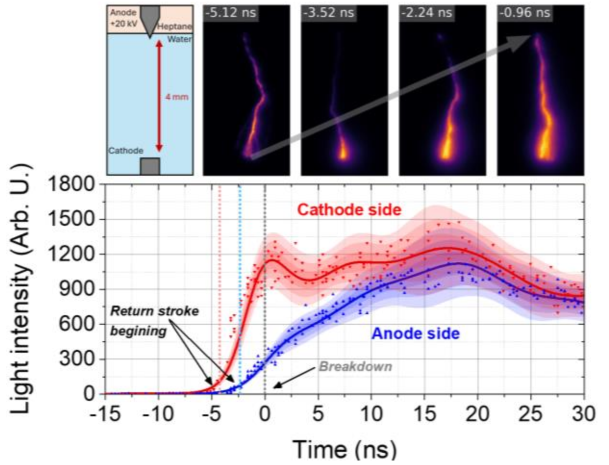

Fig. 1. Return stroke morphology (top), and light evolution near the cathode and anode side (bottom).

3. Conclusion

Analysis of time-resolved streamer-to-spark images of a spark discharge in liquid water and the use of Gaussian processes allowed the estimation of the return stroke velocity to be about 0.43% of the speed of light. This speed is related to the plasma geometry and thermodynamic properties and will be further investigated.

References

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