Time evolution of nanosecond runaway discharges in air and helium at atmospheric pressure

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Time- and space-resolved fast framing photography was employed to study the discharge initiated by runaway electrons in air and He gas at atmospheric pressure. Whereas in the both cases, the discharge occurs in a nanosecond time scale and its front propagates with a similar velocity along the cathode-anode gap, the later stages of the discharge differ significantly. In air, the main discharge channels develop and remain in the locations with the strongest field enhancement. In He gas, the first, diode "gap bridging" stage, is similar to that obtained in air; however, the development of the discharge that follows is dictated by an explosive electron emission from micro-protrusions on the edge of the cathode. These results allow us to draw conclusions regarding the different conductivity of the plasma produced in He and air discharges. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4772774]

I. INTRODUCTION

Nano- and sub-nanosecond discharge in air and He gas at elevated pressures $\geq 10^5$ Pa is a widely researched subject.[1–6] The common approach to obtaining such a discharge without pre-ionization sources is the application of a high voltage (HV) pulse with amplitude of 50–300 kV and duration of 150 ps–20 ns.[1–3] The important feature of this discharge is the non-homogeneity of the electric field distribution in the cathode-anode (CA) gap, which is ensured by the form of the cathode. A cathode for such a discharge type has a small curvature radius and the main geometries used are tube, ball, and planar sharp-edge.[6] A common feature of these discharges is high energy runaway electrons (RAEs), which carry out the pre-ionization of the discharge gap.[1] The studies were performed using He, air, Xe, Kr, Ar, and SF_6 gases.[3,5–9] A lot of effort was dedicated to understanding the dynamics of the discharge and its form. It was found that the discharge has the form of streamers that originate on the cathode and propagate toward the anode.[2] The streamers' form depends on the pressure and CA gap. At an air pressure of $P < 2 \times 10^5$ Pa, the streamers have a slightly misshaped diffuse conical form, while at $P > 2 \times 10^5$ Pa they have the form of contracted channels.[4,6] The velocity of the ionization front propagation was measured for a variety of pressures and CA gap lengths, using a time-of-flight technique[2,10] and fast-framing photography.[6]

However, data are still lacking for the temporal and spatial evolution of this type of discharge in different gases and plasma parameters. In this study, we present the results of fast framing photography of the discharge in He, and compare these results to those obtained in air.[6] The parameters of the plasma studied by spectroscopic methods will be published elsewhere.

II. EXPERIMENTAL SETUP

An all solid state generator that delivers HV pulses with durations of 1 ns, 5 ns, and 20 ns at full width half maximum (FWHM) and amplitudes in the range 50–250 kV depending on the gas pressure and CA gap length (d_{CA}) was used in the experiments. The design of the generator is the similar to the one described in Ref. 11. The generator consists of a low-voltage energy storage unit with a semiconductor rectifier as a switching element and a HV oil-filled unit. The operation of the latter is based on magnetic compression of initially stored electrical energy and the final stages of the energy compression use semiconductor opening switches and sharpening diodes. In the present study, the discharge was initiated by the application of an HV pulse with a 5-ns duration at FWHM and amplitude of 230 kV in He gas at $P = 10^5$ Pa, with $d_{CA} = 2$ cm. The discharge voltage and current waveforms (see Fig. 1(b)) were measured with a capacitive voltage divider and self-integrated Rogowski coil placed inside the oil-filled coaxial transmission line in the vicinity of the cathode, behind the insulator separating the oil and air filled volumes. A flat anode made of Al was placed at a distance of 2 cm from the cathode, which was made of a stainless steel blade. The optical emission from the discharge was observed through a transparent Perplex window by a fast intensified framing 4QuickE camera, with a minimal exposition time of 1 ns (see Fig. 1(a)). The spectral range 350–700 nm of the light emission that was obtained was determined by the

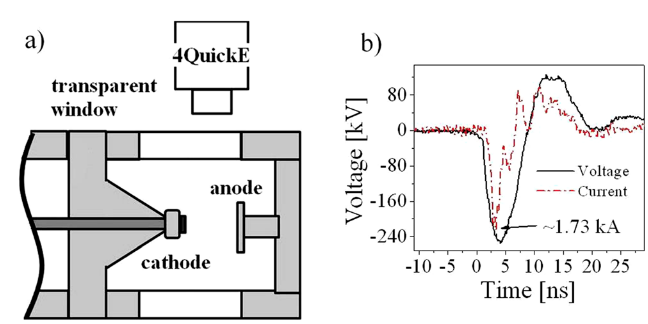

FIG. 1. (a) Experimental setup for time- and space-resolved fast framing photography; (b) Voltage and current waveforms obtained in He gas at $P = 10^5$ Pa with $d_{CA} = 2$ cm.

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Perplex window and the photocathode of the camera. The operation of the 4QuickE camera, which had an adjustable internal time delay, was triggered by a synchronization pulse delivered from the first magnetic compression stage of the HV generator. The triggering of the camera had a time jitter of ±1 ns, allowing observation of different stages of the discharge at different time delays, τ_d, with respect to the onset of significant for registration light emission on the cathode edge. Each recorded frame is related to a separate discharge event. However, frames obtained in different shots of the generator but at the same value of τ_d showed an ionization front at approximately the same distance from the anode in the first 1.5 ns of the discharge, in both He and air. This allows one to consider the frames at subsequent times as a time evolution of a single discharge. The signals from the voltage divider and the synchronization pulse produced by the camera were recorded using a TDS 694C oscilloscope (3 GHz, 10 Gs/s), and the CCD image was simultaneously recorded via the software of the fast framing camera. Thus, each image was assigned to its time with respect to the appearance of light on the cathode edge.

The experiments were carried out in He gas and air. The gas changing order was He → Air → He → Air in order to observe whether possible erosion of the cathode might impact the results.

III. EXPERIMENTAL RESULTS

The optical measurements with the fast framing camera allowed us to observe the time- and space-resolved evolution of the light-emitting discharge plasma formation in the gap. The discharge in He gas showed some significant differences as compared with that in air. The fast framing photography of the discharge in air was widely investigated in the past[2,4,5] to obtain the dependence of the plasma front propagation velocity on the CA distance and gas pressure.[6] In addition, the phenomenon of a "secondary" plasma channel was introduced.[6] In the present study, we repeated the experiments in air with a fixed $d_{CA} = 2$ cm and focused on the later times, $\tau_d > 2$ ns, of the discharge. In air, the plasma channels are generated on the cathode's edge and advance toward the anode. The frames of the described stages are shown in Fig. 2. The time delay in the major (brightest and widest) plasma channels was obtained at either the top or bottom edge of the cathode, or on both the edges, where one obtains the strongest enhancement of the electric field. The first of these channels bridges the 2 cm long CA gap in approximately 1.3 ns. Channels that do not originate on the top/bottom edge either deviate toward the major channels or decay. Let us note that, although the CA gap is bridged by a light emitting plasma channel, the HV pulse is not terminated. This implies that these plasma channels have a relatively large resistivity. The further development of the discharge takes place along the established channel. Namely, the original plasma "hot" spot at the cathode edge apparently heats up and produces a much more intense light emission. This intense light emitting front propagates along the channel, from the cathode to the anode, with a velocity ~30% lower than the velocity of the propagation of the initial plasma front. In Ref. 6, this stage of the discharge was termed the formation of a "secondary," denser plasma channel. The HV stage of the 5 ns FWHM pulse is terminated approximately when this secondary plasma reaches the anode. Subsequently, the light intensity of the bridging channel decays, and at $\tau_d \sim 9$ ns only the light emitting cathode "hot" spots remain, whose emission continues up to $\tau_d \leq 15$ ns. In the case of He gas, the first stage of the discharge is similar to that obtained in air, i.e., the major plasma channels are produced on the top/bottom edge of the cathode and bridge the CA gap in ~1.5 ns (see Fig. 3). However, the subsequent development of the discharge is rather

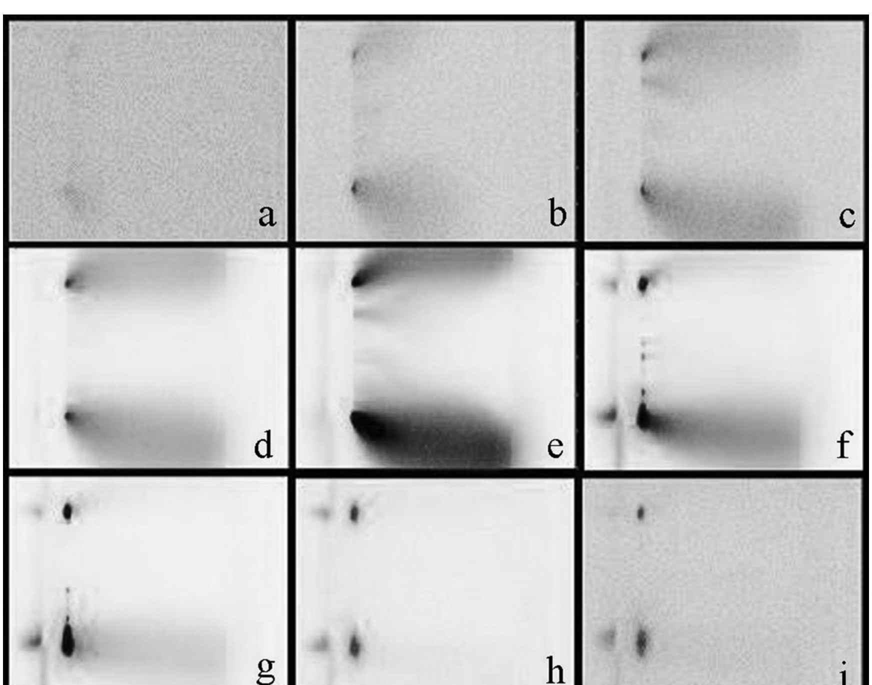

FIG. 2. Different stages of the discharge in air at $P = 10^5$ Pa. Times of frames with respect to the onset of light emission: (a) 0.2 ns, (b) 0.9 ns, (c) 1.3 ns, (d) 1.8 ns, (e) 3.6 ns, (f) 8.7 ns, (g) 9.3 ns, (h) 10.7 ns, (i) 13 ns.

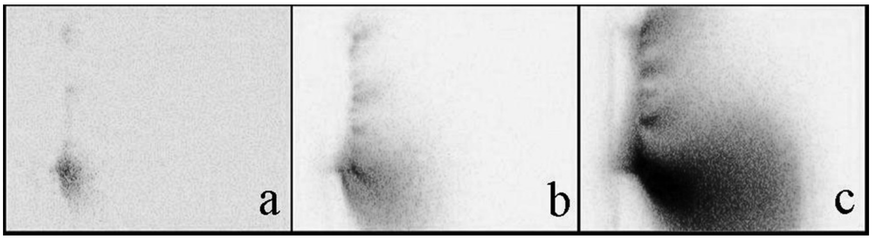

FIG. 3. First stage of the discharge development in He gas at $P = 10^5$ Pa. Times of frames with respect to the onset of light emission: (a) 0.2 ns, (b) 0.8 ns, (c) 1.4 ns.

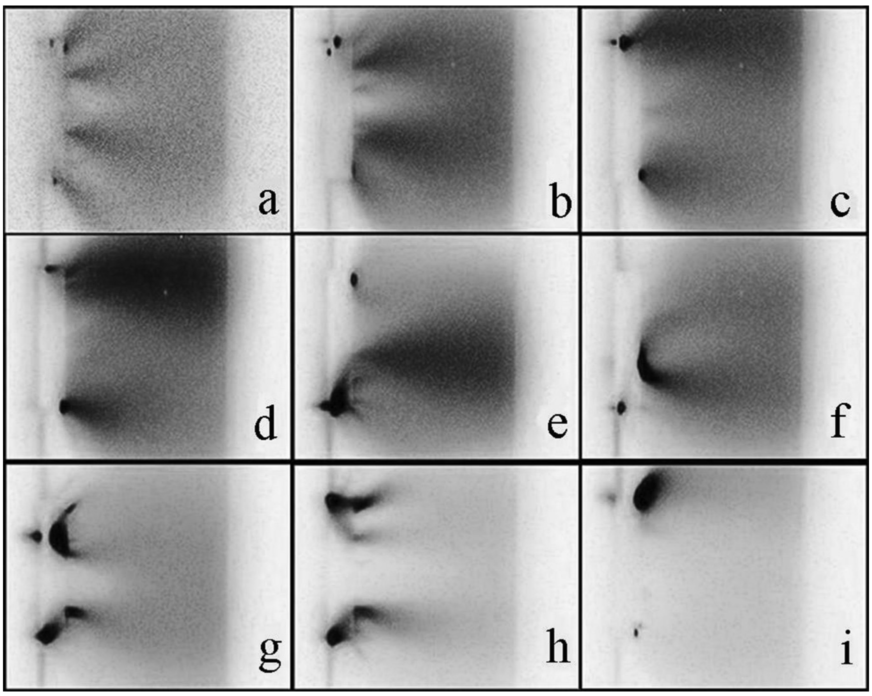

FIG. 4. Late discharge stages in He gas at $P = 10^5$ Pa. These frames were taken with a $\sim$10 times lower gain than the frames shown in Fig. 3 in order to refrain from saturation and allow a spatial resolution in the late stages when the CA gap is filled with the plasma. Times of frames with respect to the onset of light emission: (a) 2 ns, (b) 2.2 ns, (c) 2.5 ns, (d) 3 ns, (e) 6.3 ns, (f) 7.5 ns, (g) 9.7 ns, (h) 15.2 ns, (i) 16.7 ns.

different. Frames depicting the evolution of plasma channels in the stages following the "bridging" of the gap by major channels are shown in Fig. 4.

One can see that the further generation of intense light emitting plasma is not limited to the established top/bottom plasma channels. On the contrary, the frames show established dense plasma channels originating from the plasma spots that appear randomly in the middle of the blade cathode. In addition, the light emitting plasma continues in the CA gap approximately twice longer than in air. At $\tau_d > 20$ ns, the cathode spots serve as the only remaining intense light emitting sources with no "dense" channels being present in the CA gap. In addition, one can see in Figs. 5(b)–5(e) that simultaneously with the plasma channels originating from a "hot" spot on the cathode there are plasma channels extending from the cathode to the anode but without a "hot" spot on its cathode end. This phenomenon occurred very often among the recorded frames. Another peculiarity is in the form of the plasma channels, i.e., the majority of the plasma channels have a narrow origin on the cathode, and spread toward the anode, while the minority, but still a non-negligible percentage, of the frames showed channels with a significant

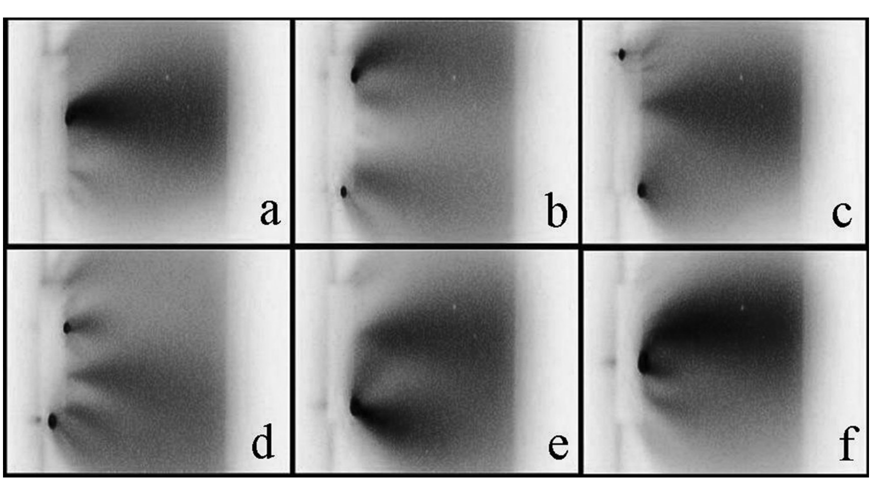

FIG. 5. Different forms of discharge channels during $3\,\text{ns} < \tau_d < 5\,\text{ns}$ with respect to onset of light emission. (a) Single channel bridging the CA gap; (b–e) "simultaneous" presence of channels with and without "hot spots" at the origin; (f) channel "bent" at the cathode vicinity. He gas at $P = 10^5$ Pa.

curvature (see, Figs. 4(f) and 5(b), 5(f)). We are accustomed to seeing a similar curvature in channels that originate on the top/bottom blade's edge in the first stage of the discharge in both air and He. However, these curved channels in Figs. 4(f) and 5(b), 5(f) originate in the middle of the cathode.

IV. DISCUSSION

Fast framing photography shows that only the initial stages of the discharge in He gas are similar to those in air, with light emitting streamers originating on the cathode top/bottom edge where the electric field is strongest, and advancing toward the anode, bridging the CA gap in approximately 1.5 ns. Later evolution of the He gas discharge in the "bridged" gap is influenced by the random appearance of "hot" spots along the cathode edge. These spots are apparently explosive emission centers[12] that appear at the micro-protrusions that always exist on the surface along the cathode's edge. The time at which the explosive centers form depends very strongly on the electric field and can be significantly shorter than 1 ns for an electric field $>10^8$ V/cm. These spots also produce strong light emitting discrete plasma channels throughout the gap, even if there already established plasma channels generated from the cathode top/bottom edges "hot" plasma spots in the first stage of the discharge. This, however, may only occur in the case when the CA gap is not "shortened" by the primary plasma channels, i.e., there is still a significant electric field, sufficient to initiate explosive emission at the cathode. The larger resistivity of the plasma in the case of the discharge in He gas can be related to the ionization potential of He, which is significantly higher than that of N_2 and O_2 molecules. In addition, according to the spectroscopic analysis (these data will be published elsewhere), the He plasma density is $\sim 10^{16}\,cm^{-3}$ and the electron temperature does not exceed a few eV. Such plasma would be very resistive due to the dominant role of electron neutral collisions.[13] Visual inspection of the frames also showed that the discharge in He gas is much more diffusive than that in air.

Another important experimental result in the case of the He gas discharge is related to the simultaneous observation of plasma channels that originate at different locations on the cathode edge, with and without "hot" plasma spots, at $\tau_d > 3$ ns (i.e., after primary plasma channels has bridged the CA gap). We do not yet know the precise explanation for the presence of discharge channels without "hot" plasma spots at their cathode side, and additional research is required. Nevertheless, two straight forward considerations can be discussed. First, one can consider that there are two kinds of channels, which differ in their nature. For instance, one can consider that the "no hot spot" plasma channels are generated by the avalanching of the electrons emitted due to field emission from the cathode. This mechanism does not require the formation of explosion emission centers. Due to the exponential dependence of the field emission current density on the applied electric field, one can expect the formation of discharge channels originating only at the cathode locations with an enhanced electric field, for instance, at the apex of the microscopic whiskers that always exist at the surface of the cathode edge. The quantity of field emitted electrons is sufficient to produce avalanching, resulting in the plasma channel formation; however, the whisker is not heated enough to be exploded.

Second, one can consider that the plasma channels without a "hot" plasma spot at the cathode side were initiated nonetheless by electron emission from explosive emission centers generated as a result of the whiskers' micro-explosions. However, the lifetime of these explosion centers should be <1 ns. In earlier research[12] with a vacuum diode and an HV pulse having an amplitude of several tens of kV and duration >3 ns, the generation and decay of explosive plasma centers were obtained throughout a single discharge. This phenomenon was explained by the instability and evolution of the liquid drop governed by the pressure of the plasma formed as a result of the micro-protrusion explosion. The present experiments were carried out in He gas at atmospheric pressure and with a significantly larger applied electric field, and one cannot rule out that the lifetime of explosive emission centers is ≤ 1 ns. Thus, the capture of such processes in a frame with an exposition of 1 ns can be used to estimate the lifetime scale of an explosive emission center as ~ 1 ns. Such frames were captured in a time interval of $2\,\text{ns} < \tau_d < 15\,\text{ns}$. Thus, the generation and decay of the plasma channels from randomly appearing explosive centers could occur several times during a single discharge.

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