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Long-living plasmoids from an atmospheric water discharge

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Abstract
Ball-like plasmoids were generated from discharging a capacitor bank via a water surface. In the autonomous stage after current zero they have diameters up to 0.2 m and lifetimes of some hundreds of milliseconds, thus resembling ball lightning in some way. They were studied by applying high speed cameras, electric probes, calorimetric measurements, and spectroscopy. The plasmoids are found to consist of a true plasma surrounded by a cold envelope. Decreasing electron densities in the order of 10^{20}–10^{22} m^{-3} were measured from Stark broadening in the initial (formation) phase. The electron temperature is estimated to be 2000–5000 K during most of the plasmoid's lifetime. The temperature of the neutral particles can exceed 1300 K. Calcium hydroxide molecular band emission is the major source of visible radiation in the autonomous phase. Chemiluminescence reactions between dissociation products of water and dissolved calcium are proposed as a source for this emission. The plasmoid's colder boundary layer consists of electric double layers that may be attributed to the characteristic shape of the balls.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Recently, the generation of luminous plasmoids at atmospheric pressure produced from a medium current water discharge were described in a number of papers (see [1–3] and the references therein). These experiments are all based on those first described by Shabanov [4] in 2001. The plasmoids have been described as a cold hydrated plasma with a temperature of about 330 K [2, 5], not containing positive charges [1].

The experiments received remarkable attention in and outside the physics community because they are associated with the mysterious phenomenon of ball lightning. Reviews of this topic have been written by Smirnov [6] and Turner [7] among others. Some more recent publications in the area include a ball lightning theory based on the oxidation of silicon-containing nanoparticle networks, developed by Abrahamson and Dinniss [8, 9]. Also of interest are recent experiments using a dc arc discharge on a silicon wafer to produce small glowing objects, conducted by Paiva *et al* [10].

This work repeats the experiments of Shabanov [4], adding a variety of diagnostics to get better insight into the phenomenon and in particular understand the energy storage mechanism that enables the autonomously radiating behavior. After a short explanation of the experimental setup, the results of the various diagnostics will be discussed. Most attention is given to spectroscopy. A short discussion and conclusions follow at the end.

2. Experimental setup

Figure 1 shows a schematic of the experimental setup. It is similar to that in [1–3] as far as the discharge system is concerned. The cylindrical discharge vessel made of glass or plastics is filled with tap water or distilled water with salt additives. A copper ring at the bottom of the vessel serves as

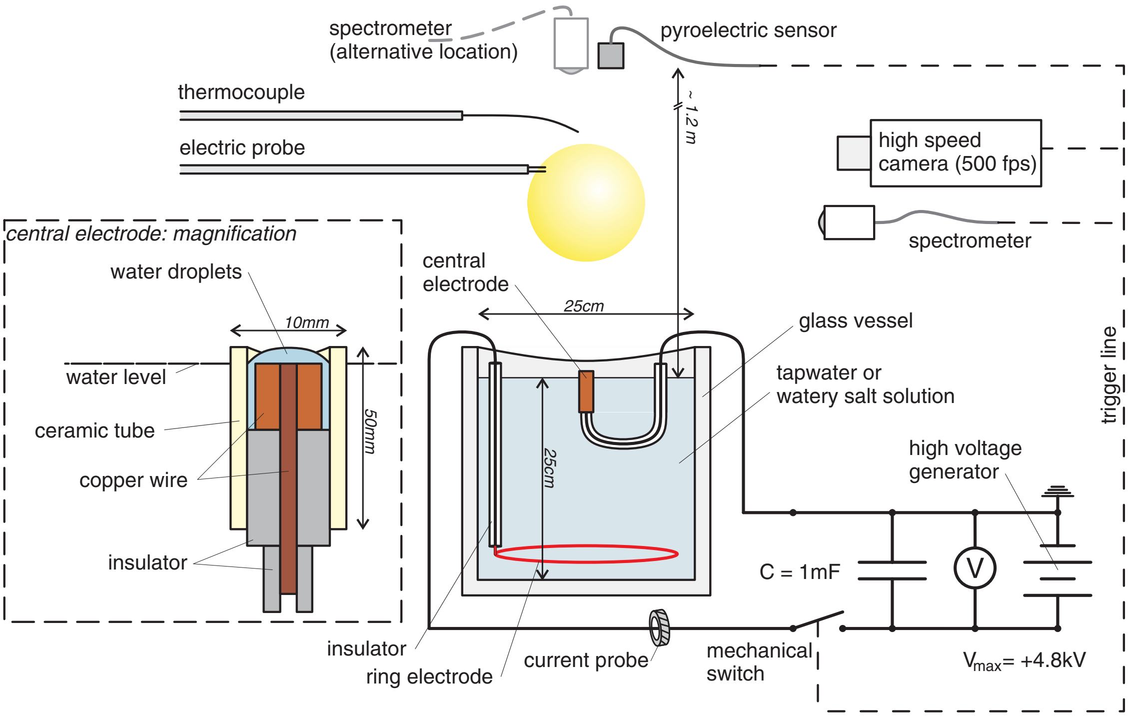


Figure 1. Schematic of the experiment and overview of diagnostics. A magnification of the central electrode is pictured in the dashed box on the left-hand side.

an anode, while the cathode is the central electrode protruding some millimeters above the water surface. Some droplets of water are present on the cathode, which is isolated from the main body of water by a ceramic tube. A capacitor bank of 1 mF charged to 4.8 kV is switched to the anode causing a discharge with currents between 10 and 100 A. Increasing voltage and/or capacity showed an increase in current as well as in size and light intensity of the plasmoids, whereas voltages below 2 kV usually did not result in a discharge.

The discharge switch is an oil filled high voltage relay switch ('normal-off'). Its switching poles are connected to a 220 V circuit, which is switched using a secondary relay switch, controlled by a pulse generator. For safety reasons, the discharge current was kept under about 100 A by limiting the amount of salt additives in the water. After 100–150 ms, controlled by the switching pulse-width, the current is shut down to obtain an autonomous object without external energy supply. Switching pulses shorter than 100 ms do not quench the current earlier, which is a limitation of the switch design. On the other hand, using longer switching pulses did not introduce any major changes to the appearance of the plasmoids. The latter did, however, result in some 'afterburning' above the central electrode and the occurrence of smaller 'secondary plasmoids' rising more rapidly, after the main one.

As diagnostics have been used high speed video cameras (500 frames per second), various probes, medium resolution ($\lambda/\Delta\lambda \approx 20\,000$) absolutely calibrated échelle spectrometer with large spectral range (300–800 nm), high resolution ($\lambda/\Delta\lambda \approx 100\,000$) spectrometer, thermocouples (Ni–Cr, up to 1200 K, response time 20 ms), pyroelectric sensors with high sensitivity (>97%) in the spectral range 0.2–20 μm and precision scales to measure the mass loss of the system.

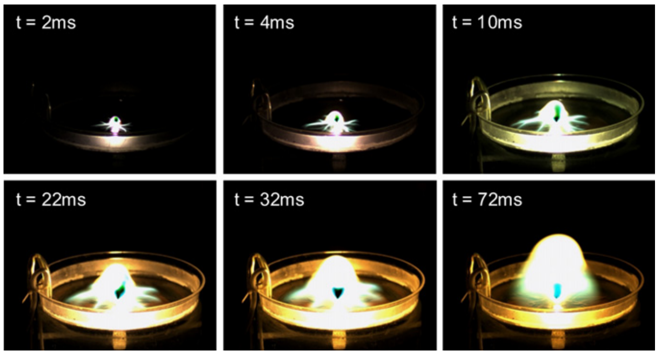


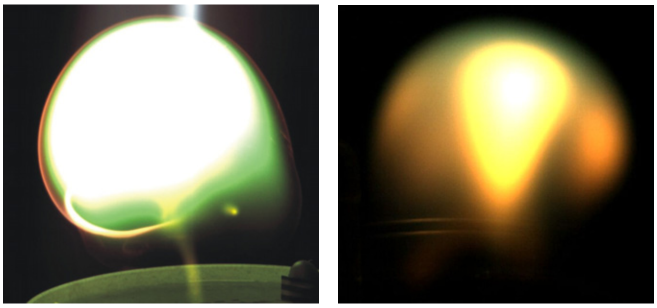
Figure 2. Series of frames recorded using the high speed camera at different times t after triggering the discharge.

3. Results

3.1. Camera recordings

Figure 2 shows the plasmoid's appearance at various times after triggering the capacitor discharge. Initially, the 'streamers' form a spider-like pattern closely above the water-air interface. Above the central electrode the slowly expanding plasma ball emerges. Figure 3(*a*) shows the plasmoid 30 ms after current zero ($t \approx 160$ ms). The jet-like structure above the balls is due to a camera effect. At this high camera exposure one sees a distinct boundary of the ball, while at lower exposure inner structures can be seen which are much brighter than the background and change their position rapidly inside the boundary (figure 3(*b*)).

The velocity and the size of the plasmoids can be determined as a function of time from the high speed camera recordings. This is shown in figure 4(*a*). The velocity reaches a



(a) (b)

Figure 3. Video captures taken at approximately 30 ms after current zero ($t \approx 160$ ms). The diameter of the ball is ~12 cm; the magnification in both images is approximately equal. (*a*) High exposure video capture showing the distinct boundary layer. (*b*) Low exposure video capture showing the inner structure of the plasma ball.

constant value of 0.8 ± 0.1 m s^{-1} after about 50 ms and does not change at current zero. Knowing the velocity of the plasmoid, the height over the central electrode can be converted into the time of arrival of the ball at a certain position and vice versa. This was used for all diagnostic tools. The ball radius increases from about 4 cm at 30 ms up to 8 cm at 250 ms. The inner structures as shown in figure 3(*b*) have a higher upward velocity up to 3 m s^{-1} until they reach the upper periphery where they are slowed down and bent to the sides to form a toroidal structure towards the end of the lifetime.

3.2. Power, energy and gas temperature

For a typical shot the energy delivered from the capacitor bank to the discharge is about 8 kJ. The current I_{dis} and ring electrode voltage V_{ring} of a discharge with tap water are shown in figure 4(*b*). The maximum discharge current, as well as the brightness of the plasma balls can be increased by adding salts to the water, increasing the conductivity.

Calorimetric measurements yield that on average about 5 kJ is spent on heating and evaporation of water; about 0.1 g water is evaporated per shot. Thus about 3 kJ is available for the formation of the plasma ball. Figure 4(*c*) shows the radiation power in the wavelength range 0.2–20 μm, measured with a pyroelectric sensor. In total, about 0.7 kJ is radiated. Hence, a fraction of $0.7/3 = 0.23$ of the available energy is converted into radiation.

The thermocouples measured about 900 K at $t \approx 235$ ms and 600 K at $t \approx 260$ ms. For $t \approx 200$ ms the thermocouples indicated 1300 K and more, but were damaged during the measurement so that this result is not reliable. The true gas temperature for $t < 200$ ms may thus be considerably higher. On the other hand, a sheet of paper can stop the plasma ball without catching fire, thus corroborating the existence of a cool outer layer surrounding the hotter core plasma.

3.3. Probe measurements

3.3.1. Floating potential and space charge. Single (and double) Langmuir probes used to measure the floating potential (difference) consisted of wires with 0.1 mm diameter and a length of about 2 mm. They were connected to a scope via resistors of 50 MΩ, thus in a nearly floating state. In the initial phase ($I_{\text{dis}} > 0$) single probes show signals reaching up to 200 V. The polarity is positive when applying positive high voltage to the ring electrode and negative for negative high voltage.

As the discharge current reaches zero, the voltage drops sharply to values <1 V. The polarity is then positive, irrespectively of the polarity of the high voltage. By measuring at several heights the (central) floating potential as a function of time can be deduced. This shows a roughly linear decrease from values around 0.5 V at 250 ms to 0.05 V at 600 ms. These results have been presented elsewhere [11].

The floating potential difference ΔV between small double probes at a separation $\Delta x = 0.2$ mm (aligned vertically) showed in some cases sharp peaks with duration <1 ms, as the rising ball passed through the probes. These can be attributed to double layers within the ball or at its boundary. Ignoring gradients in T_{e} on this small scale, the electric field can be obtained from this difference as $E = \Delta V/\Delta x$. This function can be differentiated and converted to $\mathrm{d}E/\mathrm{d}x$ using the known velocity v_{ball} of the ball:

$$\mathrm{d}E/\mathrm{d}x = v_{\text{ball}}^{-1}\,\mathrm{d}E/\mathrm{d}t. \quad (1)$$

The Poisson equation then yields the space charge density $\rho = \epsilon\,\mathrm{d}E/\mathrm{d}x$. Figure 5 shows the vertical space charge distribution deduced in this way at three different measurement heights, assuming $\epsilon = \epsilon_0$.

3.3.2. Other probe measurements. With non-biased probes (same size as before) towards the end of the initial phase, one measures currents up to 10 μA from the positively charged ball. In the autonomous phase at $t \approx 260$ ms these values have decreased to around 20 nA. These currents must consist of flows of positively charged ions. Positively or negatively biased probes in the autonomous phase show no current saturation at increasing voltage. Also in the autonomous phase, sweeping double probes at various distances (in the range of 4–20 mm) show incomplete saturation at voltages in the range −10 to 10 V.

The absence of saturation currents is probably caused by collisions in the plasma sheath, due to the high neutral density at atmospheric pressure. Therefore, the currents can hardly yield data on the plasma density. Because for floating voltage measurements the currents are small, the resistance of the sheath will have less influence.

3.4. Spectroscopy

3.4.1. Overview spectra. In spectra recorded from discharges with tap water, lines of the following atomic species have been identified: Ca, Cu, Na, Al, K, Sr, Mg, Fe and H. Lines of Ca^+, Sr^+ and Mg^+ ions were also observed. These are all species with relatively low lying excited states <5 eV (except for H; its lines rapidly disappear), meaning the electron temperature can hardly exceed 1 eV. Molecular bands of OH (A–X) and CaOH (A–X) and (B–X) electronic transitions have been identified.

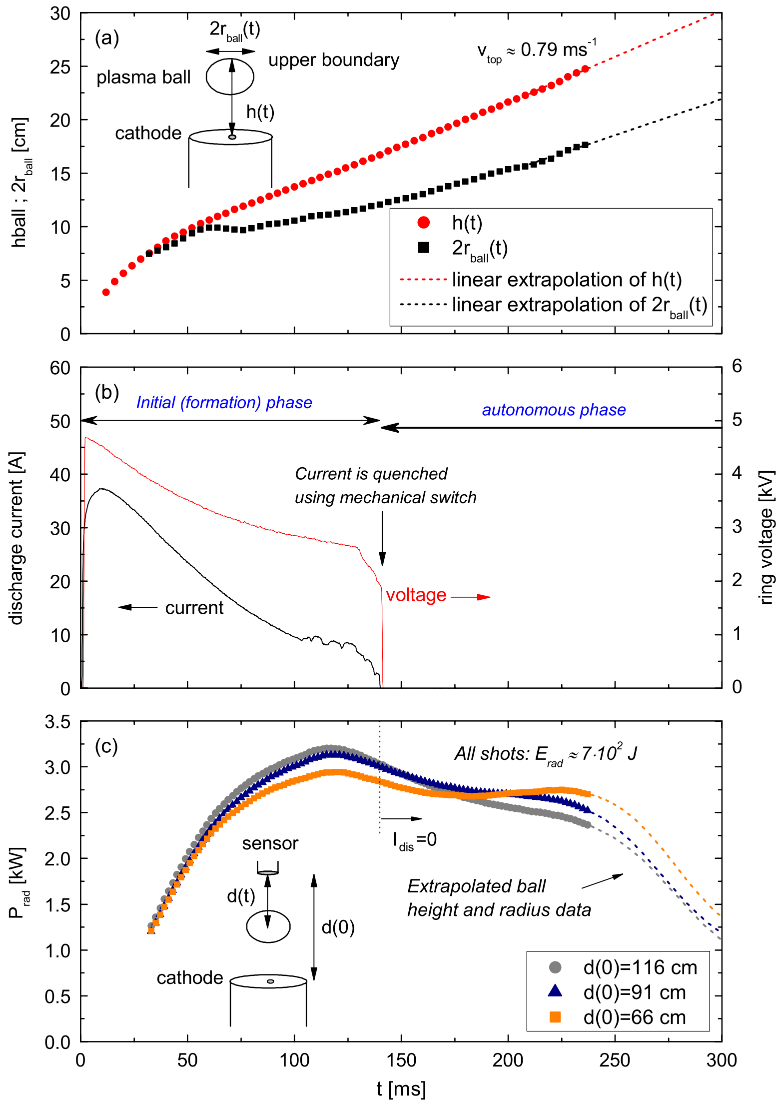


Figure 4. Time-dependent parameters of the plasmoid: (*a*) height and diameter measured using the high-speed camera; (*b*) discharge current and voltage; (*c*) radiation power measured using a pyroelectric sensor with high sensitivity in the range 0.2–20 μm. The lifetime is divided into an initial (formation) phase and an autonomous phase based on the discharge current value.

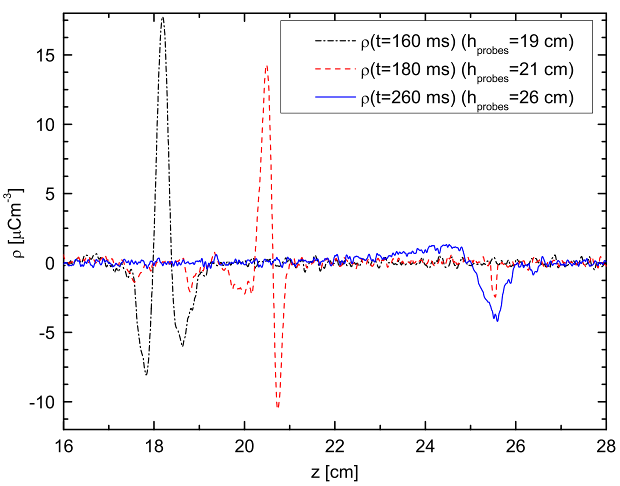


Figure 5. Space charge density as a function of the height z above the electrode at three different times, assuming $\epsilon = \epsilon_0$.

The time-development of the emission spectra can be seen in figure 6, for a series of shots with approximately 0.3 g l^{-1} calcium chloride added to the water in the vessel.

The Cu I resonance lines (324.8 nm, 327.4 nm) are extremely optically thick throughout most of the lifetime, whereas the initially comparably thick Ca I resonance line (422.7 nm) decreases more rapidly in optical thickness. For both species clear self-reversal is visible, due to absorption in the cooler boundary layer. Ca II resonance lines (393.4 nm and 396.7 nm) are optically thick initially but close to optically thin at $t \simeq 150$ ms, having a ratio of nearly 2 : 1. The ion lines show no self-reversal indicating a lower ion density in the outer region.

Radiative transitions from higher excited states are mostly optically thin and rapidly decrease in intensity. In the autonomous phase, the bulk of the visible radiation belongs to the green and orange/red CaOH molecular bands, determining the plasmoids characteristic color. Besides, the strong atomic and ionic resonance lines remain.