Long-living Plasmoids from a Water Discharge at Atmospheric Pressure

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Abstract. Ball-like plasmoids were generated when 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 milliseconds, thus resembling ball lightning in some way. They were studied by applying high speed cameras, probes, calorimetric measurements, and spectroscopy. The plasmoids are found to consist of a true plasma confined by a cold envelope. Inside, there occur rapid changes due to the formation of more dense structures having diameters of 2-3 cm. The electron densities are in the range of 10^{14}-10^{15} m^{-3}, the temperature of the neutral particles can exceed 1300 K while the electron temperature is estimated to be 3000-6000 K. The energy sources for the luminescence seem to be provided by chemical reactions.

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 [1-5]. The phenomenon is described as a cold hydrated water plasma having temperatures of about 330 K [1, 2] and not containing positive charges [3]. The present work repeats these experiments, adding a variety of diagnostics to get better insight into the phenomenon.

2. Experimental setup

Fig. 1 shows a schematic of the experimental setup. It is similar to that in refs. [1-5] 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 anode, while the cathode is the central electrode protruding some millimetres above the water surface. 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. After 100-150 ms the current is shut down to obtain an autonomous object without external energy supply. As diagnostics have been used: high speed video cameras (500 frames per second), various probes, high resolution spectrometers, 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 balances to measure the mass loss of the system.

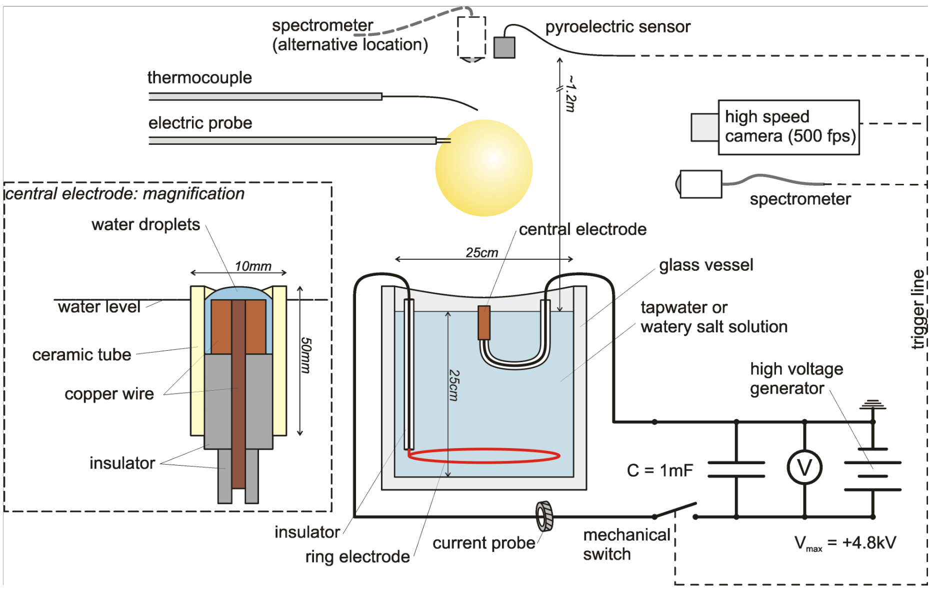

Fig. 1: Schematic of the experiment

3. Results

3.1 Camera Records

Fig. 2 shows the initial stage of the discharge 15 ms after ignition and fig. 3 the plasmoid 30 ms after current zero. At high light amplification one sees a distinct boundary of the ball (fig. 4), while at lower amplification inner structures can be seen which are much brighter than the background and change their position rapidly inside the boundary (fig. 5). All pictures have been taken with 1 ms exposure time.

Fig 2: Initial Stage of the Discharge

Fig .3: Plasmoid 30 ms after current zero. The diameter is about 0.2 m.

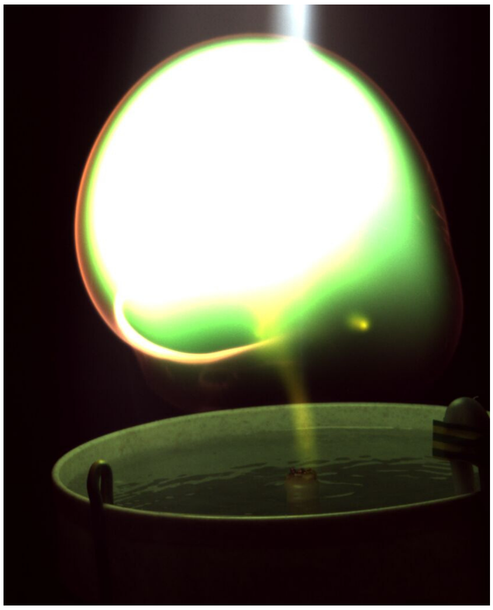

Fig 4: Boundary Layer

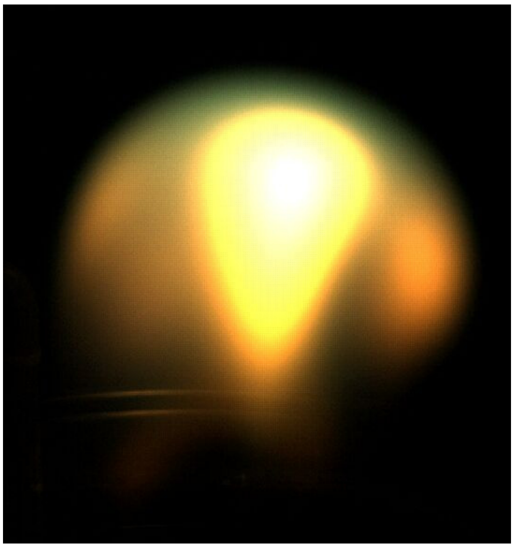

Fig. 5: Inner structure

In figures 2 and 3, the jet like-structures above the balls are due to a camera effect.

From the high speed camera recordings velocity and size of the plasmoids can be determined as a function of time. This is shown in figure 6. The velocity reaches a constant value of 0.8 ±0.1 m/s after about 50 ms and does not change at current zero. With the help of this graph height over the central electrode can be converted into time of arrival of the ball at a certain position and vice versa. This was used for all diagnostic tools.

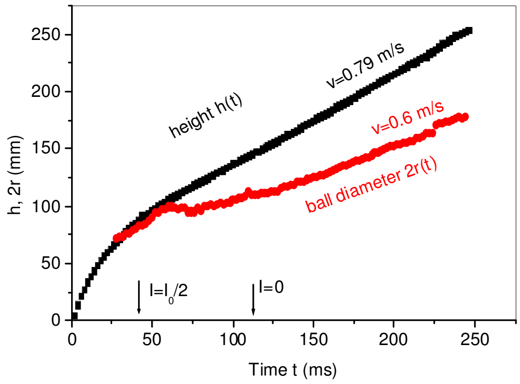

Fig. 6: Height h(t) of the upper ball boundary over the central electrode and size 2r(t) of the ball

3.2 Power and Energy

For a typical shot the energy delivered from the capacitor bank to the discharge was about 8 kJ. Calorimetric measurements yield about 5 kJ spent on heating and evaporation of water. Thus about 3 kJ is available for the formation of the ball plasma. Figure 7 shows the radiation power in the wavelength range 0.2-20 μm, measured with the pyroelectric sensor. In total about 0.7 kJ are radiated. Hence, a fraction of 0.7/3=0.23 of the available energy is converted into radiation. About 0.1 g water is evaporated per shot.

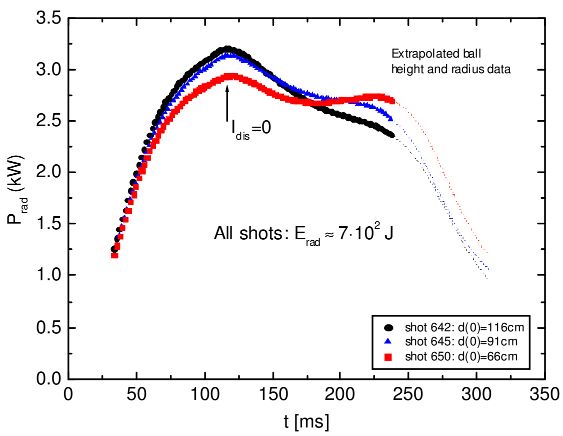

Fig. 7: Radiated power

The thermocouples measured about 900 K at t=170-200 ms and 600 K at t=230 s. At earlier times the temperature reached 1300 K and more, but this is no longer reliable because the thermocouples were damaged then. On the other hand, a sheet of paper positioned above the ball did not burn, thus corroborating the existence of a cool outer layer surrounding the hotter core plasma.

3.3 Probe Measurements

Flat probes (area 2.6 cm^2) showed the existence of positive currents that saturated at bias voltages > 1 V. Because of the inhomogeneous plasma structure the current densities had a broad distribution with two peaks corresponding to the different regions depicted in figure 5. At t=170 ms the peaks are at (1-2)x10^{-2} and (5-7)x10^{-2} A/m^2, respectively.

Figure 8 shows the signal of a single floating probe around t=250 ms. It has a duration of about 20 ms. With 0.8 m/s velocity (figure 6) the peak corresponds to a zone extending over about of 2 cm. This coincides with the bright inner structure to be seen in figure 5.

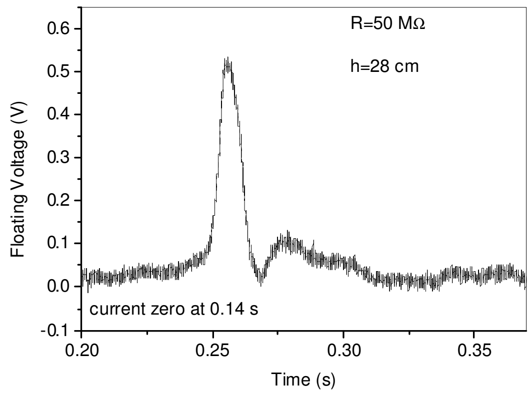

Fig. 8: Signal of a floating probe

Figure 9 illustrates the dependence of the floating voltage on the time. Because of the fluctuations of the inner structure there is a large spread of the data. But the general tendency is: the voltage amounts to about 0.5 V up to t=0.3 s. During 0.3 to 0.6 s it decreases down to 0.05 V. There is still a signal at 650 ms.

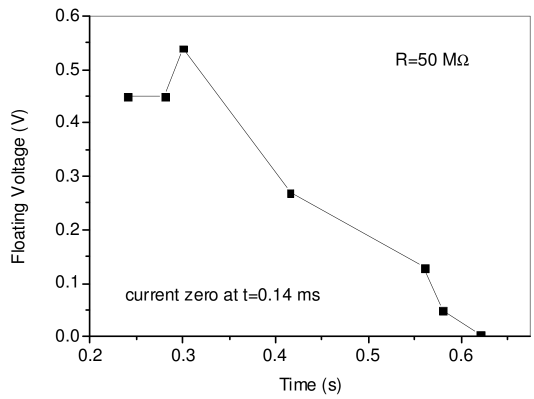

Fig. 9 Dependence of the floating voltage of inner ball structures on the time

Small double probes with diameters of 0.3 mm showed in some cases sharp peaks with duration < 1 ms that can be attributed to double layers within the ball or at its boundary. When floating and at a separation of 0.6 mm these probes showed potential differences around 2 V at h=19 cm.

3.4 Spectroscopy

Figure 10 shows spectra taken with a high resolution échelle spectrometer at various times for plasmoids being produced from tap water. This is a preliminary measurement, detailed studies are not yet completed. The spectra are dominated by the lines of alkaline and earth alkaline atoms. OH and CaOH molecules also contribute at later times. At early times one sees many lines of calcium. At the end sodium prevails.

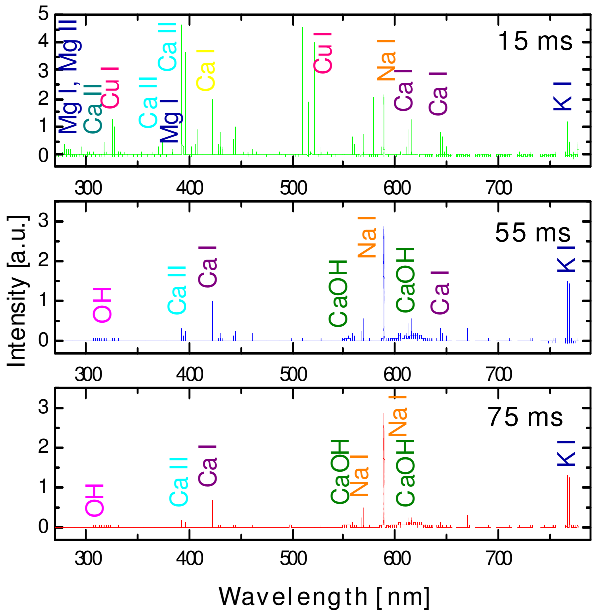

Fig. 10: Typical spectra taken 15, 55 and 75 ms after ignition, respectively

3.5 Miscellaneous

In the autonomous stage after quenching the current zero the stored total charge was less than 10^{-10} C. No currents >1 mA could be found, so magnetic fields can be neglected.

4. Discussion

The plasmoids appear to be more energetic as compared to refs. [1-4]. Taking the radiated power from figure 7 and the ball size from figure 6 at t=180 ms and applying the Stefan-Boltzmann law one obtains a temperature of 920 K, in agreement with the direct reading of the thermocouples (about 900 K). This seems to be at variance to the small velocity (i.e. small buoyancy) in figure 6. A possible explanation is the existence of water droplets within the ball which increases the average density. The cold boundary (figure 4) protects large obstacles as for example a sheet of paper.

Positive floating voltages and saturated positive currents to biased probes testify the existence of positive charges, as well as the existence of ionized particle lines in the spectra (e.g. CaII, MgII).

The spectra are dominated by elements with small excitation energy, while lines with energies > 5 eV are absent. So the electron temperature will hardly exceed 1 eV. A lower bound could be deduced from figure 9. In this figure, going back from 600 ms to 300 ms, the voltage increases by about a factor 10. Assuming an approximate proportionality between floating voltage and electron temperature as in the case of non-collisional sheaths, in the beginning the temperature will be at least ten times higher than room temperature, i.e. 0.3 eV. A similar conclusion can be drawn when the transients of the probe signal are attributed to double layers the width of which is determined by the Debye length. Ball velocities of 1 m/s and peak widths of 0.5 ms result in values of 0.5 mm. Combined with the plasma density deduced from the saturation currents one arrives at T_e=0.3-0.4 eV.

The saturation currents indicate electron densities in the range 10^{14}-10^{15} m^{-3}. Of course, these are rough estimates because for more exact data it must be considered that the probes operate in a collisional regime. Light emission and electrical signals can be found between 200 and 500 ms after shutdown of the generating current. This constitutes an analogy to ball lightning and rises the question which mechanism delivers the necessary energy (700 J radiation). Magnetic fields can be ruled out, and the electric field energy of is much too small. Hence, only chemical processes remain. It is hoped to obtain more information on the reaction channels in near future.

5. Conclusions

The observed plasma balls consist of a thin plasma with electron densities of 10^{14}-10^{15} m^{-3} and electron temperatures of 0.3-1 eV. The temperature of the neutral particles is higher than assumed previously. It can reach values above 1200 K.

6. References

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