Spectroscopic Diagnostics of Ambient Ball Plasmoid Discharges: Revealing the Underlying Physical Chemistry of Ball Lightning

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Introduction

For the past few decades there has been increasing interest in understanding non-equilibrium air plasmas, particularly at atmospheric pressure. Significant progress has been made in the understanding of these plasmas, however the nature of air as a discharge medium makes tailoring experiments and theoretical models of air plasmas extremely difficult. Due to the high collisionality of air plasmas at atmospheric pressure, recombination should occur very quickly, however some plasma systems last much longer than current models predict.

A ball plasmoid discharge is an example of one of the enigmatic plasmas. Models of plasmas under similar discharge conditions show that this plasmoid should recombine within a few milliseconds [1,2], however visible emission from the plasmoid structure is observed for much longer. Therefore, there must be some underlying chemical or physical mechanism that is stabilizing the plasmoid.

It is plausible that the excitation and subsequent reactions involving nitrogen metastables in non-equilibrium air plasmas serve as a "furnace" of sorts, generating additional electrons and reactive species throughout the plasmoid's lifetime. A more detailed understanding of the behavior of nitrogen metastables in ball plasmoids could reveal fundamental insight into stabilization mechanisms of ball lightning—a naturally occurring phenomenon that has perplexed society for centuries. Many of the observables pertaining to ball lightning are also seen in ball plasmoid discharges: a roughly spherical, luminous object composed of charged species that lasts orders of magnitude longer than what current models predict.

Ball Plasmoids

The discharges that we produce in our laboratory are approximately 20 cm in diameter and last approximately 400 ms. Discharge currents above 10 Amps are commonly observed. There are three distinct phases to plasmoid formation [5]:

1. Pre-initiation: current begins to flow in the system. Energy is increasing to the cathode spot threshold.
2. Buildup: streamers extend over surface of the electrolyte, thermionic emission begins, current flows more freely and increases with streamer surface area.
3. Detachment: plasmoid detaches from electrodes. Discharge current reaches maximum. Ball lasts with no external power.

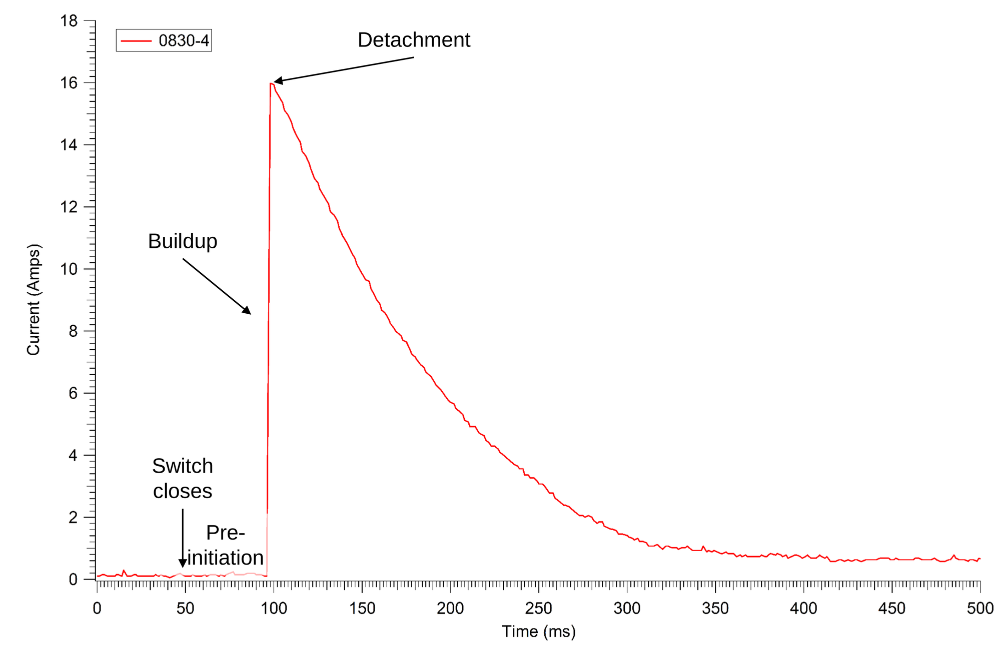

Figure 3. A current trace of a typical ball plasmoid discharge. Phases of the discharge are labeled.

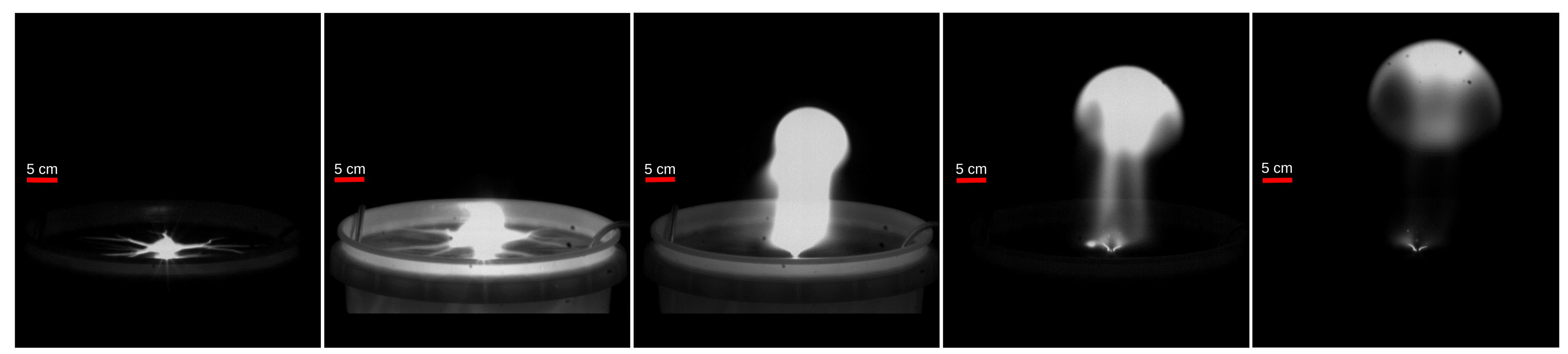

Figure 4. A series of images obtained from one plasmoid discharge at 7000 V. Images recorded with a Phantom V5.2 high-speed camera at 1000 fps (990 µs exposure time) at a resolution of 1152 x 896 pixels (images are cropped to remove dark space). Scale bar included is 5 cm.

Absorption Spectroscopy

Although emission spectroscopy is useful, there are several limitations applying OES to non-equilibrium air plasma diagnostics. To circumvent these potential issues, we will perform high-resolution absorption spectroscopy using a modeless pulsed broadband dye laser (BDL). We will use an optical system similar to what is shown in Figure 6, which is based on previous experiments performed by the Glumac group [9] at UIUC.

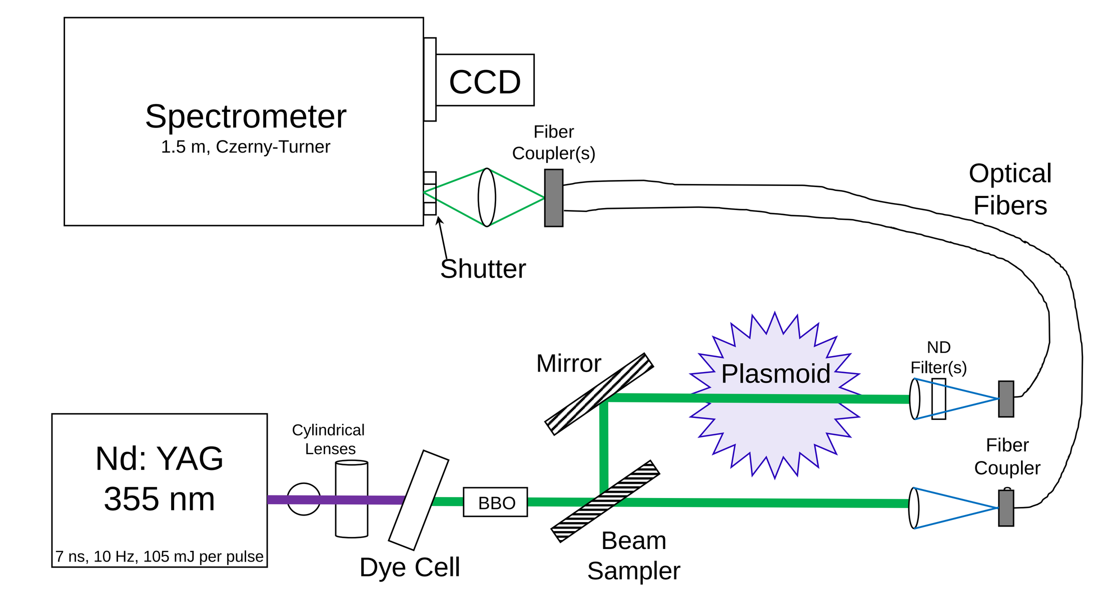

Figure 6. Proposed broadband dye laser configuration for absorption spectroscopy measurements.

In short, a pulsed Nd:YAG laser pumps a solution of an organic dye that fluoresces, and this emitted light is collected and focused into a beam. This beam is then passed through the plasmoid and compared with a reference beam at the detector– this allows for a Beer-Lambert type analysis to determine optical thickness of the plasmoid and number densities of plasmoid components.

We expect to report absorption spectra of important ball plasmoid constituents (OH, N_2, N_2^+, etc.) with high spectral and temporal (microsecond) resolution. We will be the first to report number densities of ball plasmoid constituent molecules, and we will be able to estimate the gas temperature across the lifetime of the discharge. Furthermore, this technique could be combined with the optics shown in Figure 5 to allow for spatially-resolved absorption measurements to be collected.

Circuitry and Parameters

We use a high-voltage, capacitive discharge over the surface of a grounded electrolyte to generate ball plasmoids [3,4]. A 10 kV DC power supply is used to charge a capacitor bank (1.958 mF max capacitance). Under normal operating conditions, plasmoids are generated at potentials between 3000 and 8000 V. Discharge energy is on the order of kiloJoules. This discharge also generates a tremendous amount of current– 126 Amps have been observed with the setup shown below. An Arduino Uno board controls the timing of the switches which control current flow through the system and records current and voltage measurements.

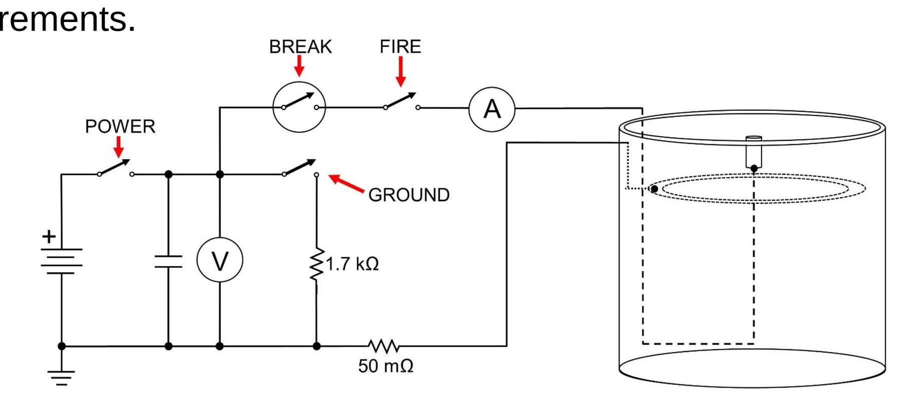

Figure 1. Schematic of discharge circuit. A and V are a Hall effect sensor and voltage divider, respectively.

Figure 2 below shows images of some of the electronics associated with this experiment including the capacitor bank (composed of Papa, Mama, and Baby Bear), the switch box (which contains high voltage switches and power resistors), and the electrode setup (which is submerged in five gallons of weakly conductive water).


Figure 2. Photos of (left to right) capacitor bank, switching box, and electrode setup.

A Metastable Furnace?

One possible explanation for these discrepancies may be hidden in the kinetics of nitrogen excited states in air discharges: nitrogen metastable states are extremely long-lived and are known to participate in energy pooling reactions and associative ionization [6]. The two lowest-lying metastable electronic states of nitrogen are the A $^3\Sigma_u^+$ and a' $^1\Sigma_u^-$ states, and these states are likely populated during the discharge. There are two potential reactions / collisions involving these states that are of interest:

$$N_2\,(A,\ 6.22\ eV) + N_2\,(a',\ 8.57\ eV) \rightarrow N_2^+(X,\ 15.58\ eV) + N_2\,(X) + e^- \quad -0.79\ eV \quad (1)$$

$$N_2\,(a',\ 8.57\ eV) + N_2\,(a',\ 8.57\ eV) \rightarrow N_2^+(X,\ 15.58\ eV) + N_2\,(X) + e^- \quad 1.56\ eV \quad (2)$$

The radiative lifetimes (τ) of the A $^3\Sigma_u^+$ and a' $^1\Sigma_u^-$ states are 2 and 0.5 seconds, respectively [7], which is a very relevant timescale to ball plasmoid chemistry. Furthermore, there is no direct transition from the A state to the ground state in the visible, as the $A^3\Sigma_u^+ \rightarrow X\ ^1\Sigma_g^+$ is a spin-forbidden electronic transition—therefore relaxation processes must proceed by different channels. The triplet A state is well-known to be involved in energy pooling reactions and associative ionization (Reactions 1 and 2). Reaction 1 is endothermic under normal conditions, however vibrational excitation of ground-state nitrogen molecules and a high background gas temperature makes this reaction favorable in ball plasmoids (as does a three-body collision with a free electron).

We think that the plasmoid is being sustained by the production of additional free electrons via the two reactions shown above. These reactions must occur throughout the plasmoid's lifetime, and nitrogen must serve as a molecular energy reservoir for the plasmoid. Targeted spectroscopic studies of the relevant transitions of nitrogen will help to confirm our hypothesis.

Emission Spectroscopy

Optical emission spectroscopy (OES) is the most widely-used and versatile of the plasma diagnostic techniques. We have performed OES of ball plasmoid discharges with several portable instruments and are the first to observe a much richer ball plasmoid chemistry than previously thought (see Figure 4 below). Other groups [8] have reported collecting emission from OH radical and CaOH, however we have identified emission from NO, OH, NH, N_2, NH^+, W, Al, Cu, and H_α. High resolution studies are currently in progress. We are particularly interested in the first and second positive systems of nitrogen ($B^3\Pi_g \rightarrow A^3\Sigma_u^+$ and $C^3\Pi_u \rightarrow B^3\Pi_g$, respectively) as these transitions will be pertinent to the population of the nitrogen metastable $A^3\Sigma_u^+$ state.

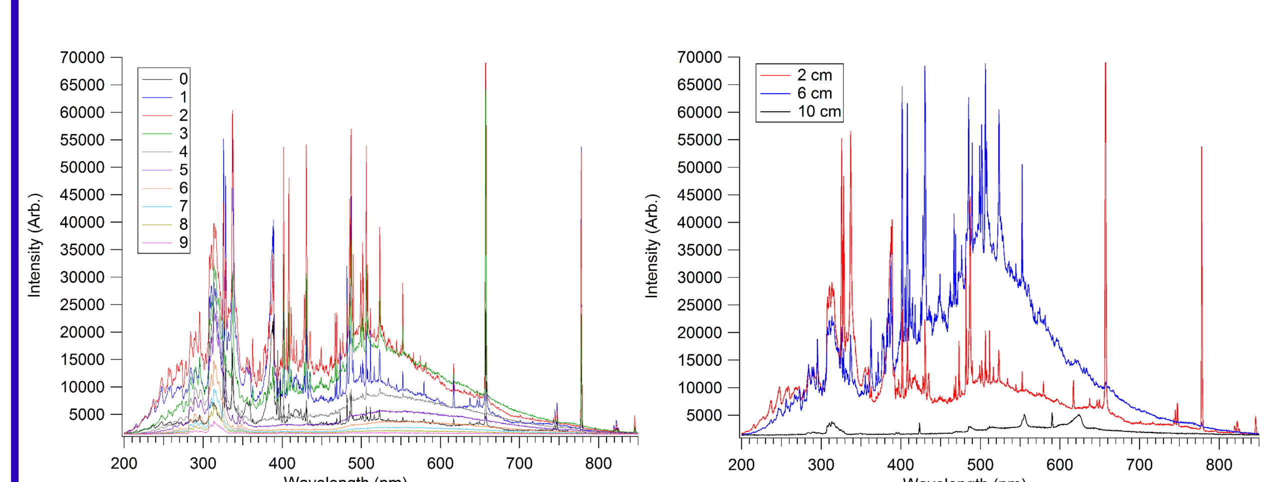

Figure 4. Example preliminary emission spectra collected from plasmoid discharges. Left: series of spectra collected from one discharge, right: series of spectra collected at different heights relative to cathode level.

It is likely that OES measurements are complicated by the optical thickness of the plasmoid– we are collecting light from only the surface of the plasmoid. Self-absorption also greatly complicates emission spectra of non-equilibrium air plasmas. We plan to record emission spectra using optical fibers positioned *inside* the discharge. This will allow for simultaneous monitoring of the bulk of the plasmoid and the plasmoid-air interface.

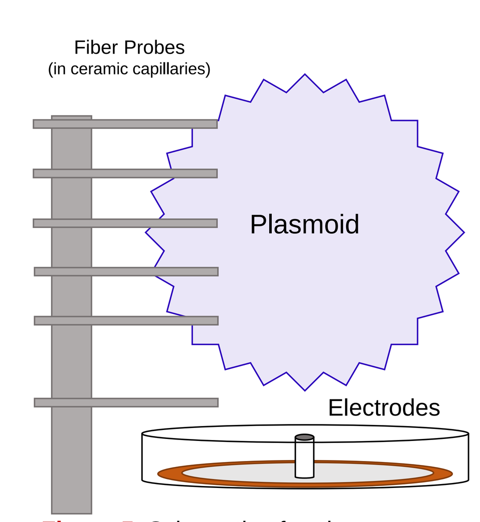

Figure 5. Schematic of probe spectroscopy setup. Probes will be oriented vertically along the discharge axis.

Microwave Interferometry

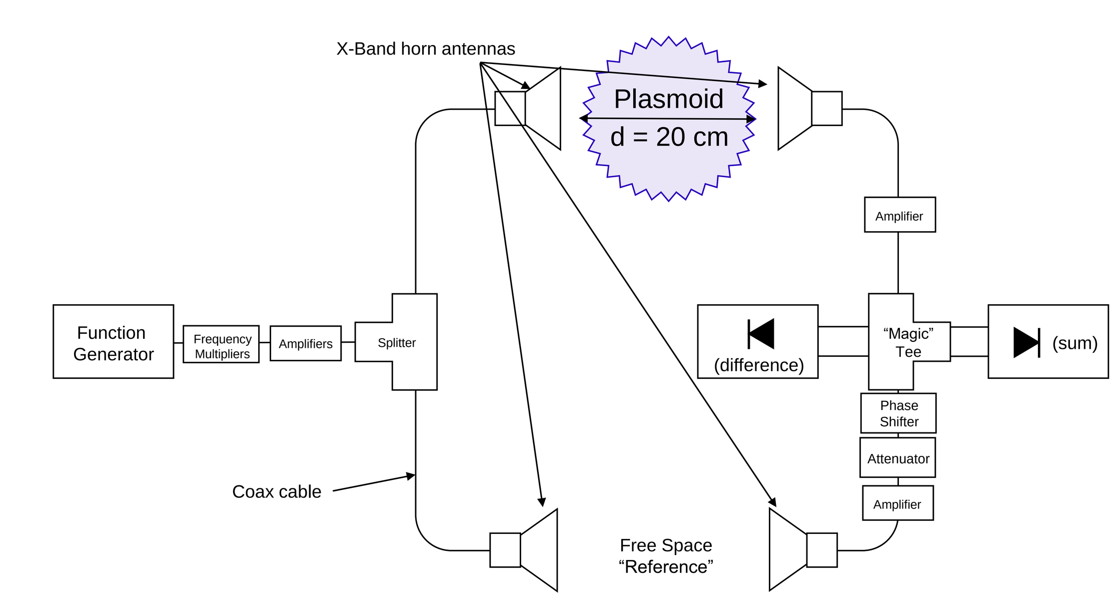

Figure 7. Proposed design of full-bridge X band microwave interferometer for electron density measurements.

Microwave interferometry is a technique that has been used since World War II to measure the electrical properties of plasmas—specifically electron density and collisional frequency. Mach-Zender type X-band (8-12 GHz) full-bridge interferometers have been shown to accurately measure electron densities of many types of plasma [10] and this technique will be particularly advantageous to ball plasmoid analysis. We are designing an interferometer that will be used to measure the phase shift and attenuation of an X-band beam through ball plasmoids. This will facilitate a measurement of the electron number density across the plasmoid's lifetime.

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