Chapter 1

Introduction

1.1 Overview

Historically, the study of atmospheric-pressure plasmas (APP's) is indistinguishable from the study of plasmas as a whole. However, the detail of the measurements and calculations associated with APP's has been limited by their complexity. From a computational perspective, the high pressure and number of potential reactions present a difficult challenge. Likewise, the high pressure can significantly complicate the data analysis for a number of plasma diagnostics. Aside from the high pressures, the large electric fields, short time scales, and general randomness of APP's make even the most basic observations a feat.

In the last several decades, some of this has begun to change. High-powered computing has allowed simulations with remarkable detail.

Similarly, advances in technology has enabled plasma diagnostics in regimes that were experimentally inaccessible. As a result, the body of knowledge regarding APP's has greatly increased. Sometimes, the motivation for this work is scientific curiosity. More often, the study of APP's has been driven by a broad range of applications.

Among the first plasma applications were provided by APP's: ozone generation and lighting. Aside from these items, plasma welding, polymer treatment, combustion, and plasma televisions have become widely accepted. However, a large number of new applications may soon be added to this list, including: treatment of tissue wounds, altering airflow over airfoils, and destruction of industrial pollutants.

Unsurprisingly, each case has demands a different kind of plasma. The original arc discharges were created between two graphite rods connected to immense battery banks. In contrast, a modern research reactor studying plasma-assisted combustion might use a fast-switching semiconductor circuit. Over the years, several types of APPs have been developed for a variety of situations: dielectric-barrier, corona, thermal arc, RF, microwave, pulsed, and more.

Within this group[1], the repetitively-pulsed nanosecond discharge (RPND) has created considerable interest. Generally speaking, a RPND is a plasma generated by a repetitive electrical pulse applied between two electrodes. The pulse voltage if often > 1 kV, lasts anywhere from

[1]The interested reader is referred to Starikovskaia's review [1] which provides a general overview of APP's in the context of plasma-assisted combustion

$<$ 1–100 ns, and is repeated over a thousand times each second. The result is a wave of ionization (and light) which crosses from the powered electrode to the grounded one.

A RPND can fill volumes of several liters with a relatively uniform plasma. Though they can cause significant excitation of the background gas, they generally produce very little heating (in some cases no more than a few kelvin above room temperature). In addition, the excitation can be changed with adjustments to the magnitude or duration of the electrical pulse. Each of these characteristics are highly desirable in one or more of potential applications for APP's.

Given all of these promising properties, RPND's have been the subject of substantial study by several research groups. However, much of this work has focused on the physics of RPND's in air. Unfortunately, air's large number of constituent elements can lead to notable complexity. In turn, this can obscure some of the more fundamental questions relation to RPND's: how do they form, how is the energy distributed between excited particles, what kind of spatial variation can be expected?

This paper details a study of each of these questions in a helium RPND. Specifically, the densities of one particular excited atom are measured for a variety of pressures and locations. This is complemented by measurements of the light emissions for the same set of parameters. A simple model of a RPND is used to predict several char-

acteristics of the plasma based on the excited state densities: electron density, electric field, and light emission. The measured light emissions are interpreted to show how the energy is distributed in the gas, and how it changes over time. Finally, they are compared with the estimated light emissions to check the validity of several common assumptions.

The remainder of this chapter is comprised of a review of the associated literature, as well as a discussion of basic discharge theory. Chapter **??** covers the experimental setup as well as some general observations of the RPND. Next, the measurement of the excited state densities is presented, followed by the chapter on the light emission measurements. Chapter **??** explores the global model used to interpret the excited state densities, as well as some supporting particle-in-cell simulations. Finally, the paper concludes with a discussion of how the models and measurements impact the present understanding of RPND's.

1.2 Literature Review

Though RPND's are very much a product of twentieth century research, they are fundamentally similar to a number of other pulsed discharges such as electrical sparks and lightning. Though Loeb united these disparate fields under the title of "ionizing waves of potential gradient"

in 1964 [2] (we use the more familiar term, fast ionization waves), the underlying subjects had been under study since the Greeks who generated sparks by rubbing together amber and fur.

Despite these early observations, it was Leibniz in 1671 who first came to the conclusion that sparks were an electrical phenomena [3]. Subsequently, Franklin's famous kite experiment led him to a similar conclusion on the nature of lightning. Franklin was also involved in explaining the principles of Leyden jars, develop by Musschenbroek. The Leyden jar was the first reliable way to store electrical energy and proved a boon to later research.

In 1835, Wheatstone made the first attempt to measure the speed of electricity through a gas [4]. In his work, Wheatstone used a Leyden jar connected to two metal spheres, separated by a small gap. Once the charge in the jar reached a critical level, a spark would form in the gap. Figure 1.1 shows the experimental sketch provided by Wheatstone. Though the measurement is notable for its early date, it was later revisted with much more accuracy by Thomson [5]. Perhaps the most important outcome of Wheatstone's study was the observation by Zahn [6] that the speed of the light was *not* accompanied by a similar motion of the emitting particles.

Thomson's work concerned both the speed and direction of light in a pulsed discharge. Unlike Wheatstone's study, Thomson used an elongated tube, 15 m in length, and 5 mm in diameter, upon which he

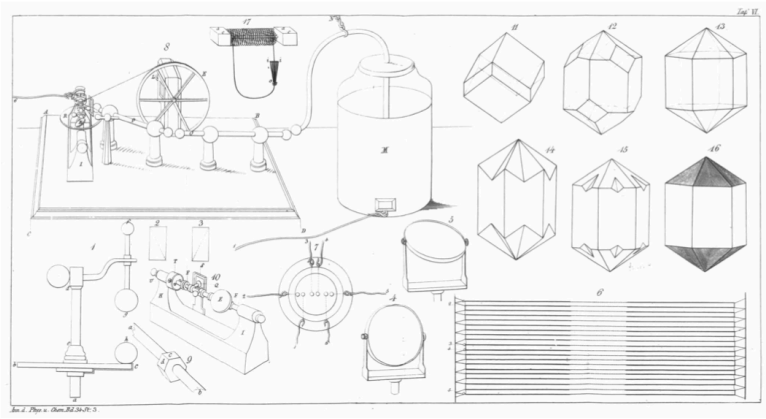

Figure 1.1: The experimental sketches of Wheatstone showing a traditional spark gap connected to a Leyden jar and electrostatic generator.

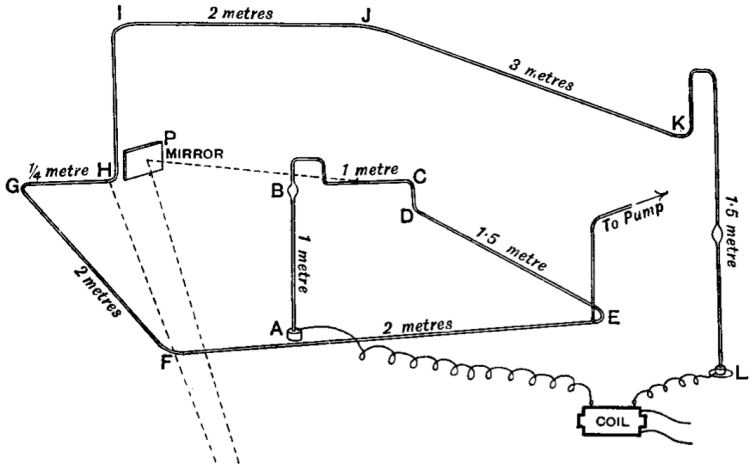

Figure 1.2: A sketch of J.J. Thomson's early experiments on fast ionization waves in long vacuum tubes.

drew a vacuum. The original sketch of Thomson's discharge apparatus can be seen in figure 1.2. Through a clever arrangement of mirrors, Thomson determined that the electricity had a speed approaching 1×10^{10} cm/s, and travelled from the anode to the cathode.

It was later, in 1930, that Beams would determine that the wave always initiated at the high voltage electrode, regardless of polarity [7]. In addition, Beams measured the current at the low potential electrode. He detected a current pulse which did not appear until after the light had completely crossed the gap. He came to the conclusion that the luminous front was likely the result of a moving region of ionization.

As observed by Loeb [2], there was a distinct set of researchers who were attempting to study lightning. Despite Franklin's earlier realization that lightning was an electrical phenomena, it was still unclear that it shared a common origin with light pulses in rarefied gases. The endeavor was ambitious; lightning was only predictable in the loosest sense of the word. In addition, it was not clear what exactly could be measured.

In most cases, the study of lightning concentrated on time-resolved photography, pioneered by Boys[2][8], and refined by Schonland [9]. This technique was later adopted by Allibone and Meek [10] to observe the evolution of a laboratory-generated spark.

By 1935, fast ionization waves had been under study for nearly 50 years. However, there was still no adequate explanation for the speed of the discharge. Similarly, Beams' observation that the wave always

[2]In the same article, Boys anticipated a number of other atmospheric physics studies by proposing that rockets be fired at thunderclouds. Unfortunately, he lived in a village of thatched houses and could not conduct the experiment for fear of fire.

travelled from the high voltage to the low voltage electrode (regardless of polarity) could not be accounted for. Based on observations made with fast pulses, Flegler and Raether to developed a new theory of breakdown for sparks in air [11] which was capable of, at least partly, explaining the fast ionization wave phenomena. Independently, Loeb and Meek developed a similar theory in 1940 [12].

1.3 Basic Theory

Basic theory of gaseous breakdown.

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