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An Experimental Model of Ball Lightning

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University of Tennessee - Knoxville

To the Graduate Council:

I am submitting herewith a thesis written by Madras Parameswaran Sriram entitled "An Experimental Model of Ball Lightning." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Electrical Engineering.

Igor Alexeff, Major Professor

We have read this thesis and recommend its acceptance:

Douglas J Birdwell, Paul B Crilly

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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Anne Mayhew

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Dean of Graduate Studies

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AN EXPERIMENTAL MODEL OF BALL LIGHTNING

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Madras Parameswaran Sriram
August 2004

ABSTRACT

A form of ball lightning was generated in the laboratory. Plasma spheres several centimeters in diameter were produced in atmospheric pressure air. These spheres persisted up to ½ a second after power turn –off. A mathematical model was derived that predicts the observed lifetime. The theory predicts that the sphere lifetime should scale as the radius squared, which means large spheres should exist for many seconds. We also generated ball lightning in a zero gravity environment. The object was to eliminate convection, which had been observed to reduce the size of a ball generated by a two – dimensional electric arc. The result was large balls that survived the duration of the experiment – about ½ second.

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Chapter I

Introduction

Lightning is one of the major wonders of nature and its existence has excited people for thousands of years. Lightning was defined by Uman [1] as a transient high –current electric discharge whose path lengths is generally measured in kilometers. Lightning discharges occur in air when the electric field associated with an accumulation of charge within a localized region become sufficiently large to cause ionization and breakdown of an air path as well. Lightning discharges can occur from clouds to the ground, between clouds, within clouds, from clouds to open air, and from air as well. A cloud-to-cloud discharge is generally composed of several intermittent discharges and is followed by a ground – to –cloud discharge. The total lightning event is normally termed as flash, which last for hundreds of milliseconds. Many component discharges, termed as *strokes*, often make up a flash, and individually last for tens of milliseconds. Multiple second strokes are generally separated by 40 -50 milli-seconds. The stroke in turn is initiated by smaller discharges- the leader discharges. The cloud to ground channel breakdown which precedes the return stroke is termed the *stepped leader*. The stepped leader propagates downward as a series of discharges. It is thought by some investigators that some characteristics of the lightning can lead to formations of various lightning phenomenon, including ball lightning.

1. 1 Existence of Ball Lightning

The term *ball lightning* has been applied to singular, luminous, persistent, globular mass occasionally observed in the atmosphere and associated with thunderstorms and natural lightning (2). Ball Lightning is the most fascinating and enigmatic atmospheric electricity phenomenon. Although known and described since the antiquity, it is certainly the least understood, and perhaps the most misunderstood, of all atmospheric phenomena. The investigation on this atmospheric phenomenon of lightning

is still largely dependent upon observational reports and discussions. Ball lightning represents atmospheric luminous forms, which occur infrequently in nature, and when they do, trained observers are not normally present. Moreover on site investigations is hampered by the inability to cause and generate atmospheric discharges of ball lightning at will.

The very existence of ball lightning has been questioned, and many scientists have been and are still skeptical .The skepticism surrounding ball lighting is apparently a result of its infrequent occurrence and observation and report by generally untrained observers. The reports and descriptions have varied so greatly from occasion to occasion that the scientist who looks for consistency is frequently infected by doubt and skepticism. Many scientists all over the world have conducted the research on the study of phenomenological characteristics of the ball lightning in laboratories for centuries. This phenomenon of Ball Lightning has been observed for a long time, but the nature of these luminous balls has been unknown.

1.2 Characteristics of Ball lightning

General characteristics

It is reported to be a single, self-contained entity that is highly luminous, mobile, and globular in form and appears to behave independently of any external force. The ball lightning phenomenon is known by many other terms: globular lightning, balls of fire, lightning balls, *kugelblitz, globes de fu, tonnerre en boule, coup de foudre en boule, foudre globulaire, fulimini globulaire, sharovoyi molnii, kugelynet* to name a few.

The properties and characteristics of ball lightning have been deduced by number of researchers from surveys and statistical analyses of collected reports. The characteristics of ball lightning are such as to distinguish it from other natural electrical phenomena that occur in the atmosphere.

The entire source of inspiration for this has been Dr. Igor Alexeff own account of the amazing phenomenon. He as a kid has seen ball lightning in nature. This is a first hand account from him "It followed a lightning strike. The ball appeared immediately after the lightning discharge. The event occurred during a street baseball game. A storm stated, and it began to rain, but we lost the ball and started looking for it. There was a big

bang overhead, and we looked up to see a bright orange ball the size of a basketball about 30 feet overhead. The light intensity was not very bright – the ball was clearly visible, but not dazzling. It persisted for several seconds. It had moving ripples in the surface, so it was not an after image. There was no noticeable sound or odor associated with it. It seemed to be slowly descending on us. As it was above me, I ran as fast as I could to get away from it, and so did not observe how it dissipated"

The general characteristics of ball lightning may be categorized according to the various physical properties.

Shape and size: Ball lightning has been reported with spherical, oval, teardrop and even rod shapes. Dimensions of these spherical oval shaped ball lightning vary from a few centimeters to several meters. The most common diameter reported is 10- 40 cm. reports on the size of the teardrop shape indicate smaller dimensions, usually less than 20 cm. The rod shape is the least reported. Extreme sizes of 27m have been reported [3]. The balls viewed from closer distance have been reported with smaller diameters; while the larger dimensions have been reported for distant sightings in which the estimation of the size is dependent on the distance of the object, which could itself only be approximated. The dimensions of ball lightning are of importance for the calculation of its energy density and the postulates regarding the formation of its mechanism.

Color: Most ball lightning reports indicate as having had red and orange colors according to the surveys [4] [5] [6]. Other colors included white green, and purple were occasionally reported. A color change [7] with time has been reported by only a few of the observers. These changes fall into three categories: red to white, violet to white and yellow to white.

Structure: In general there are three structural types. First a solid appearance with a dull or reflecting surface or a solid core within a translucent envelope; second a rotating surface, suggestive of internal motion and stress; and third, and a structure with a burning appearance. All three structures are observed with each shape but not with equal frequency. The burning structure has been reported most often with the spherical and oval shapes, a red or red yellow color, and a diameter less than 40cm.

Motion: The single most distinctive property of ball lightning is its motion. In general, ball lightning is generally observed in descending motion, apparently from a cloud. It usually assumes either a random or horizontal motion several meters above the ground. The motionless state often results after an initial random or horizontal motion, although it can occur sooner. Ball lightning is often observed to undergo a sudden attraction to a grounded object. It darts quickly to the grounded object and decays nosily on contact. Ball lightning has also been reported to move against the wind.

Sound: A characteristic hissing sound is often associated with the presence of ball lightning, but only a few first person reports are available in the account so consequently we may conclude that ball lightning is a soundless phenomenon.

Odor: Many observers have reported a distinct odor accompanying the presence of ball lightning. The odor is described as a sharp and repugnant, resembling ozone, burning sulfur or nitric oxide. As might be understood the odor has been reported in cases where the distance between the ball and the observer is small.

Lifetime: A lifetime of a ball lightning is most often reported to be only about 1-2 seconds. A lifetime of this length was reported in about 80% of the cases reported. In about 40 % of the cases, the lifetime was deduced from the data given by the observer.

Decay: ball lightning has been observed to decay in two modes. One is the silent decay, associated with a decrease in brightness and diameter. The second one designated as the explosive mode is associated with a loud violent sound.

Lightning Dependence: The occurrence of ball lightning is commonly associated with natural lightning events during thunderstorms, tornadoes, earthquakes and other such stressful conditions in nature. About 90% of the ball lightning observations have been reported during thunderstorm activity. It is also widely believed that natural lightning is not a required for the formation of ball lightning.

Attraction to enclosures: Approximately 10% of the observers report an affinity of ball lightning for enclosures. In general, once inside a room, a ball lightning often decreases its speed to a slow circular motion. Some observers report that ball lightning posses a motionless, hovering state within state within in room, while others report that ball lightning moves in a random process.

Chapter II

Literature survey

2.1 Ball lightning as an electrical Discharge

The explanation of ball lightning as particular form of electrical discharge produced under favorable but rare conditions in nature has received the most extensive consideration of all the theories of ball lightning. In contrast to chemical, ionic, and charged particle theories in which the ball lightning is in sense a secondary phenomenon composed of substances generated in a preliminary flash of lightning, this concept suggests that ball lightning in itself an electrical discharge or a specific region of one. Faraday earlier viewed this possibility with doubt on grounds that the behavior displayed by these luminous spheres was quite different form electrical discharges known to him [8]. He held that the balls cannot be related to lightning or any discharge to atmospheric phenomenon because if electrical they should travel with high velocity and have a very short existence. Soon after the publication of Faraday's opinion, however the leading British authority, Snow Harris suggested that ball lightning is comparable to other forms of lightning in that it results from an electrical discharge, not one producing a spark discharge [9].

In the one and quarter centuries that following these suggestions numerous experimental and theoretical investigations of the electrical discharges were made, often for elucidating the nature of ball lightning. In early experiments with an induction coil discharging in air to an insulating material such as glass or varnished board wet with water, du Moncel and others produced reddish globes, which were regarded to be small models of ball lightning [10]. In another theory a mechanism of formation was proposed which would indicate a close relation ship between ball lightning and zigzag lightning. According to this theory a glow or brush discharge, the tip of which is most luminous and constitutes the ball lightning itself, is generated by protrusion from a storm cloud [11].

The observed motion of the glowing sphere was held to be in propagation of this discharge rather than the actual motion of any object .The transmission of electricity to the advancing fireball is aided by the presence of water drops. The arrival of ball lightning at the ground completes a conducting path along which a flash of ordinary may instantly occur. This theory depicted ball lightning as an especially luminous front on the advancing leader.

Experimental study of electrical discharges in gases at reduced pressure and in air continued in attempts to duplicate the impressive natural displays seen during storms. Spherical forms were obtained in low–pressure gas tube with an induction coil [12].The studies of Plante beginning in 1875 with electrical discharges produced between insulated condenser plates by larger and larger lead storage batteries were directed primarily at the problem of ball lightning. Small luminous globes were formed initially with a 40 element battery and the later with 1600 cells providing approximately 4000v. At the lowest voltages investigated small spheres were produced between platinum wire electrodes in salt water [13]. It should be recognized that these various experiments did not produce an independent, self contained, luminous phenomenon and depended on the continuation of the discharge for their continued existence. Plante suggested that studies with the voltaic currents could eventually show the electric charge on ball lightning which he predicted to be positive. He proposed that ball lightning is generated by a slow and partial discharge from storm clouds containing a great quantity of electricity when a portion of the cloud or a humid highly conducting column of air approaches the ground [14]. Plante specifically related the experimental results to natural ball lightning. The experiments were widely accepted at that time as being definitely related to the natural phenomenon. That is to say, ball lightning was seen predominately related to electrical thunderstorm activity. Ball lighting was considered to be a direct result of the electrification of the atmosphere and directly related to discharge processes under admittedly poorly understood and rarely occurring conditions. Plante's experiments were considered to be a major contribution to the understanding of ball lightning [15], although it was recognized that major problems remained, including the shape of the ball, its entrance into houses, and the identity of the natural equivalent of the laboratory wire electrode.

Continued studies of the electrical discharge with the positive electrode a plate covered with an insulating material, as in du Moncel's work, produced red spheres [16]. With Crooke's discharge experiments on a discharge flame in air produced between electrodes in the secondary of an alternating current inductions coil as a basis, Hesehus studied [16] the effect of a 10,000-volt alternating current discharge with a different, electrode materials and shapes. Metal plates, water surfaces, water columns and wet sponges were used as electrodes. Between a copper plate and water surface 2 to 4 cm distant a very mobile discharge of varying shape was produced. Sometimes there was conical flame; sometimes oval or ball shapes were formed, changing with time .The color varied with the potential from red to yellow to blue, violet and white. The fireball was never stationary but oscillated back and forth across the plate while emitting a crackling noise. Often it separated into several fragments, which then reunited. No heat was felt from the discharge at distance of few inches. Discharges resembling bead lighting were formed with water columns; the discharges investigated in these studies were evidently not markedly different from those produced in earlier experiments. The generation of ball lightning with the help of alternating currents was then considered unlikely by Jens [17]. Luminous globes were formed at the negative pole when two fine metal points connected to an electrostatic machine were placed on the sensitive emulsion of a photographic plate [18] .The detachment of such a ball from the very luminous negative pole left at that point dark, and the small globe traveled slowly on the plate in complicated path to the positive pole , sometime pausing momentarily on the way . Sometimes the ball continued to the positive point .on arrival of the ball at the other electrode the luminosity disappeared and the electrical source behaved as if the two poles were connected by a conductor. Development of the photographic plate made the path visible.

In detailed series of experiments with the direct energy current electrical discharges, Topeler greatly extend the work of Plante in providing the basis for a theory of ball lightning. Five types of discharge were distinguished with the increasing current provided by the electrodes in air: the dark discharge; the glow discharge; the tufted or brush discharge; Toepler's brush arc, a striated discharge with layers, separating the luminous regions; and davy's voltaic arc, the flame like discharge. Toepler concluded

that all the possible forms of lightning are brush discharge differing only in current [19] and that the striated brush, a transition between the tufted discharge and the voltaic arc, most resembled ball lightning. The position of the glowing region between the electrodes once formed could be changed by varying the current supplied. He studied the luminosity of the discharge as a function of the current in his experiments. Toepler suggested that from these observations that the generation of ball lightning in nature takes place in the conducting channel remaining from a previous flash of ordinary lightning. If additional current enters the still conducting channel from other parts of the storm cloud, the segmented discharge can occur, forming either ball or bead lightning. Ball lightning is thus indicated to be of very low energy; only the initial lightning or a flash occurring later in the same path can account for any destruction. The color of ball lightning would depend on the current in the channel as on the experiments in which a weak current gave a bluish while increasingly stronger currents gave red, brick red, orange red and finally white.

Toepler's theory required the absence of wind or else uniform motion of air along the straight chain of beads. Ball lightning on the other hand may move extensively .One investigator concluded on this basis that Toepler's theory applies only to bead lightning and not to bead lightning [20], which is a markedly different phenomenon. The flight of ball lightning into houses would result from travel with the wind according to Toepler’s theory. Motion against the wind reported in several reports wasn’t explained.

Fifty years after Toepler’s initial work consideration of the problem of ball lightning was directed again at the direct current discharge, in part because of theoretical difficulties of confinement in plasma models. Further experimental study was made of the discharge between the positive point and a plane or ring electrode [21]. With the exception of the usual corona phenomenon the only stable discharge obtained was the linear one. Luminous spheres formed in an RF discharge and considered possible experimental models of ball lightning [22] showed temperatures of 2000-2500 deg K. The effect of such temperatures was investigated with helium filled soap bubbles, which approximate the density of air at 2200 Deg K. The soap bubbles themselves contributed little weight since they fell down slowly when filled with air. Helium filled bubbles 20-35

cm in diameter rose in air, attaining a maximum velocity of approximately 120cm/sec. The larger bubbles oscillated more into oblate spheres, and these flattened bubbles encountered greater drag, which prevented them from reaching higher velocities.

The existence of ball lightning in airplanes for longer than the decay period associated with the experimental RF discharges was attributed to the excitation of the rf responses in the air craft fuselage by an external dc discharge. A similar model of ball lightning was investigated with both thermal conductivity and functions of the temperature rather than the field of current [23]. Such a globe would be in a region of hot air, and in the thermal model the temperature is maintained by external electrical power, and only thermal conduction is considered a mode of power loss. The initial condition suggested for formation of the discharge as a volume of heated air, possibly the conducting and cooled channels remaining from a flash of lightning as in Toepler's theory a ball formed in this way with a 20cm diameter and a central temperature of 5000Deg k is described as having the energy of 2000 joules and radiating 100 W of visible light. Heat loss was permitted only by thermal conduction, with the usual energy and momentum balances and mass conservation in the ball. The hot sphere would rise rapidly in the absence of the large force required to hold it in position against the great buoyancy of such a ball in air.

The classification of ball lightning as some form of an electrical discharge, which provides a basis for relating it to other storm discharges, has received the most extensive consideration of all theories of ball lightning. It possesses the signal advantage of utilizing an ample source of energy which all recognize to be in storms.

2.2 Plasma Models of Ball lighting

Plasma of high charge is involved in theories, which deal with the questions of high energy and long existence by suggesting that the ball is formed initially with the necessary energy somehow stored in its contents. An alternative is provided by an external source of energy, the natural electrical activity of the thunderstorm, supplied to a luminous mass continuously over its lifetime. The plasma description of ball lightning was anticipated in early suggestions long before the extensive studies of this field in experiment and theory provided the knowledge. Ball lightning was described in 1905[24]

as a rotating spherical vortex composed of ionized air separated from the cylindrical discharge channel of lightning. The formation of the electron vortex ring by pulse in ordinary lightning was suggested in 1915. The ring was depicted rotating rapidly with its electrons ionizing the entrained by collisions and thus producing a vacuum inside the ball [25].The ring current and a spherical structures of ball lightning based in a hydrodynamic vortex were both suggested as ball lightning forms and investigated by magneto hydrodynamic considerations, omitting more detailed charged particle interactions [26].The basic of strong external field's to assist in the difficult problem of obtaining an equilibrium structure for a plasmiod generated under natural conditions resulted in several theories relying on self–confinement. The conversion of a plasma rod into a plasmiod with the structure of the hill vortex was suggested as a mode of formation of ball lightning from a segment of ordinary lightning [27], [28]. The cylindrical rod has a strong-trapped magnetic field but no electric field. The charged particles revolve around the axis of the rod, and the ions and electrons were described as flowing in opposite directions along the rod. The electric dipole given by the charge separation and the magnetic field cause the respective particles to form an umbrella at each end of the rod. The umbrellas of opposite charge then extend toward each other producing a closed a conduction path though the center of the rod, around the outer path, and back to the center once more, giving a spherical outer surface. This resembles a plasma vortex with the exception that the external magnetic field used in the hydrodynamic analogy is absent. The theoretical structure presumably derived on the basis of this model was actually that of a torus with positive ions flowing as a ring current and electron current at the surface around the cross section of the ring as in previous toroidal structures. Thin rings with the electrons in a very thin outer shell [29] and thick rings more closely approaching a ball shaped mass [30] were considered. The formation of torus with positive ion current was suggested to result from disrupting the channel of linear lightning [31]. A self contained ball lightning vortex with a toroidal magnetic field and electrons and ions flowing in poloidal currents enclosing the field was considered a product of a similar transformation of a suddenly isolated segment of lightning [32].

The formation of ball lightning as a plasma vortex ring by a pulse from a lightning stroke, especially through a hole in a solid surface struck by the flash was suggested [33].A magnetic field was viewed as trapped in the ring , as in the plasmoids produced by strong currents pulses in thin wire electrodes. A particle density greater than that of a gas at atmospheric pressure by a factor of several hundred might result from the shock wave of the lightning channel. A high kinetic energy of vortitcity up to hundreds of joules may be provided. An estimate of a lifetime of some seconds was made for the magneto hydrodynamic vortex from an approximate rate of radiation of the plasma energy, but recombination rates were not specifically considered.

An alternative form of ball lightning as a plasmoid was suggested from the “inverted ion magnetron” [34]. The confinement according to this model results from the earth’s magnetic field and a high radial electric field provided by a liner lightning discharge. The relative strength of the magnetic and electric fields is thus the reverse of that commonly found in the laboratory plasma experiments. A Spiral wave instability of ions was credited with high-energy production in this rotating plasma device. No quantitative description in terms of reasonable fields or the plasma instability was given, and experimental confirmation of the mechanism at atmospheric pressure was not shown.

Chapter III

Experimental

3.1 Spark Discharge

Our experiments were based on three major setups, a powerful spark discharge, a Marx generator set up and an arc discharge set up.

At first, we used a powerful spark discharge. The results, shown in Fig3.1, revealed a confinement time of less than one millisecond. The reason for this short confinement time is obvious – depositing 400 Joules of work in a few cubic centimeters of air produces a thermal pressure of thousands of atmospheres, resulting in the sphere being lost rapidly by a super sonic shock wave. At this high pressure, the sphere is essentially unconfined, and expands at the rate given by the atom thermal velocity – 10 exp 6 cm/second. This expansion produced by a short impulse of power feed may explain why so many experimenters have not been able to produce long – lived plasma balls in the past.

This photograph was taken with a high-speed camera, which runs down to 11,000 frames per second.

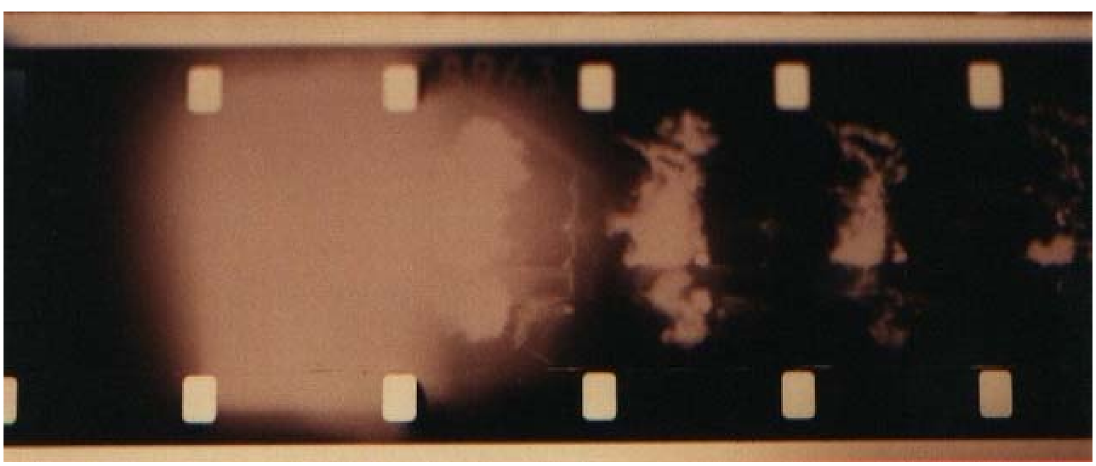

Figure 3.1 Photographs of the high voltage spark discharge taken with a high –speed-framing camera**.**

2.1 Marx Generator

Marx Generator is a clever way of charging a number of capacitors in parallel, then discharging them in series. Originally described by E. Marx in 1924, Marx generators are probably the most common way of generating high voltage impulses for testing when the voltage level required is higher than available charging supply voltages.

The charging voltage is applied to the system. The stage capacitors charge through the charging resistors (Rc). When fully charged, either the lowest gap is allowed to breakdown from over voltage or it is triggered by an external source (if the gap spacing is set greater than the charging voltage breakdown spacing). This effectively puts the bottom two capacitors in series, overvoltaging the next gap up, which then puts the bottom three capacitors in series, which over voltages the next gap, and so forth. This process is referred to as "erecting". A common specification is the erected capacitance of the bank, equal to the stage capacitance divided by the number of stages. The basic circuit diagram for a Marx generator set up is shown in Fig3.2 [1] .The Marx generators set up required two huge capacitors which are shown in the, these capacitors were originally were used for a fusion project. The capacitors had a value of 5.5 microfarad. We also used a series of water resistors, which had a value of about 5 KΩ.The basic set up is shown in Fig 3.3. Figure 3.4 shows the photograph of the discharge when the capacitors were shorted out with laboratory lights on.

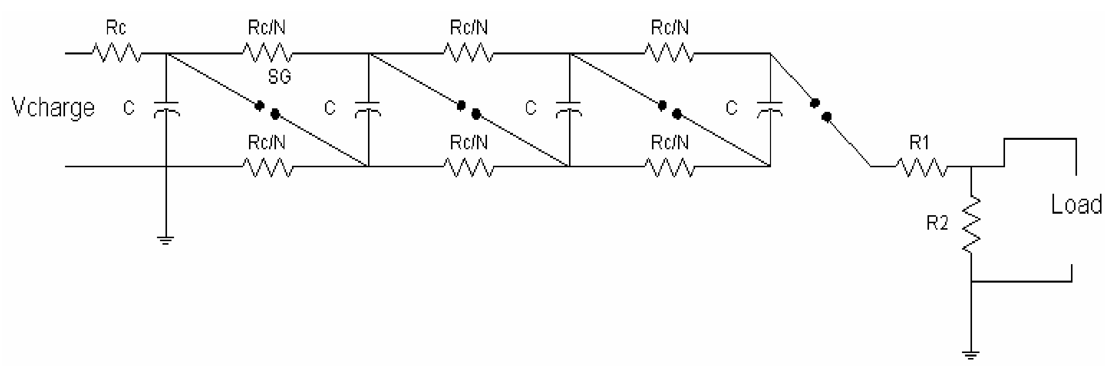

Figure 3.2 Circuit diagram for a Marx Generator

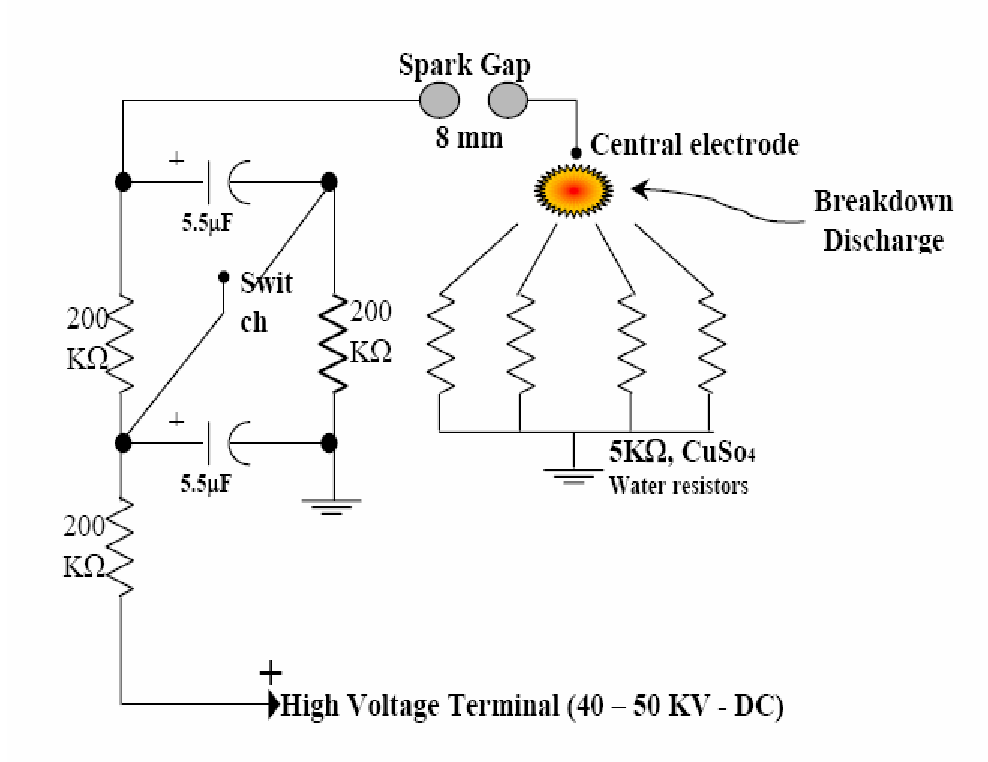

Figure 3.3 Marx Generator set-up

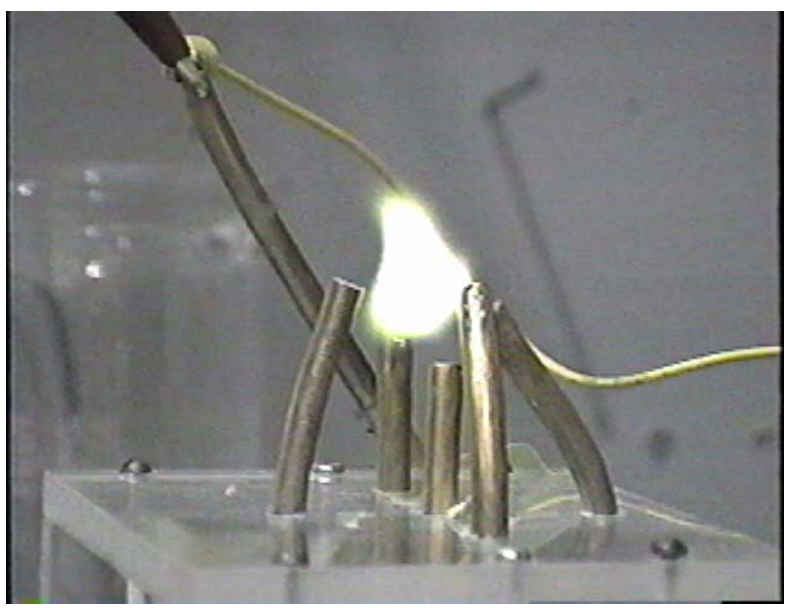

Figure 3.4 Photograph of the Marx Generator Discharge with the laboratory lights on.

Figure 3.5 Photograph of Spark discharge with the laboratory lights turned off

The figure 3.3 shows the set up of the entire Marx generator system. We used water resistors for the setup, each of which was about 5 KOhms. The breakdown occurred between the electrodes. This above set up did not give very promising results and the discharge lasted for less than quarter of a second. In the photographs we can see the ball totally disconnected from the electrodes, but the lifetime of the discharge was very low, as we couldn't see the ball floating in the air for a period of time even after the video obtained was slowed down to very low speeds. Figure 3.5 shows the same discharge when the laboratory lights are turned off. This clearly shows the ball floating in the air after the power has been turned off. These images have been obtained from the video of the whole experiment, which was shot with an ordinary hand held video camera. As a result these images do not have a very good resolution on them, but they do show the ball floating in the air without any power.

3.3 Arc Discharge

This experiment did not require a whole lot of set up equipment and materials. We used up to seven neon sign transformers for the arc discharge. The apparatus was powered by six neon sign transformers, which each produced 15 KV at 60 mA. The pulsing was controlled by a General Radio pulse generator, which operated a small DC relay. The small relay in turned operated a large AC power relay. Both the on and the off time of pulsing could be controlled. The arc apparatus is composed of up to seven neon sign transformers, each with a separate cathode arranged in a horizontal ring, feeding to a common central anode as shown in Fig. 3.6.The secondary of the transformers is at 15,000 volts and the primary is at around 120 V. The transformers run at 60ma and 60 Hz. To produce a ball rather than a line, we developed a plasma arc in the form of a disc. The arc is operated for about ¼ second. Upward convection forms a sphere. In this manner, we create a plasma sphere several centimeters in diameter that is confined by atmospheric pressure. Figure 3.7 is a photograph of the entire set–up of the experiment. This photograph shows all the six transformers and the electrodes. Figure 3.8 gives the close up view on the electrode geometry.

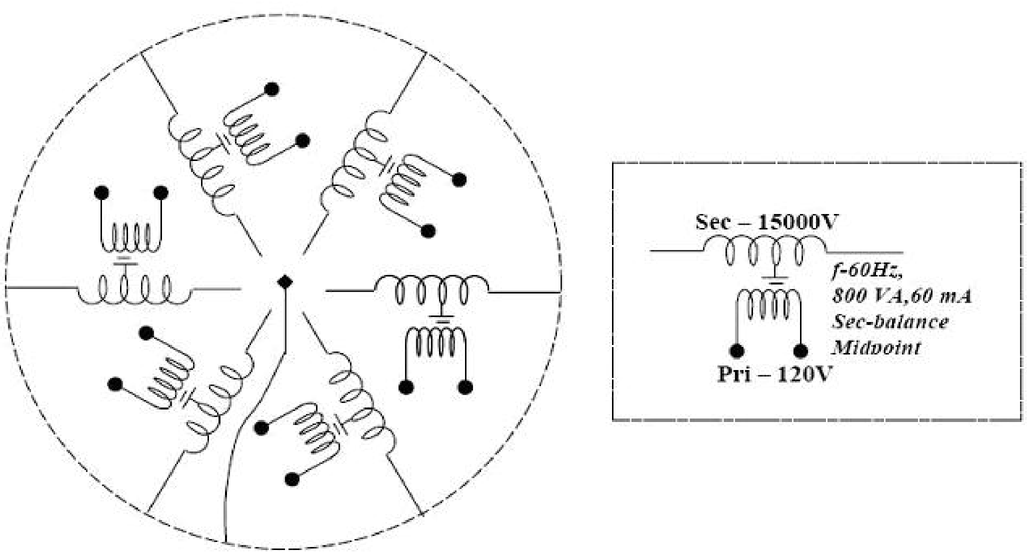

Figure 3.6 Wiring Diagram for the Arc Discharge set-up

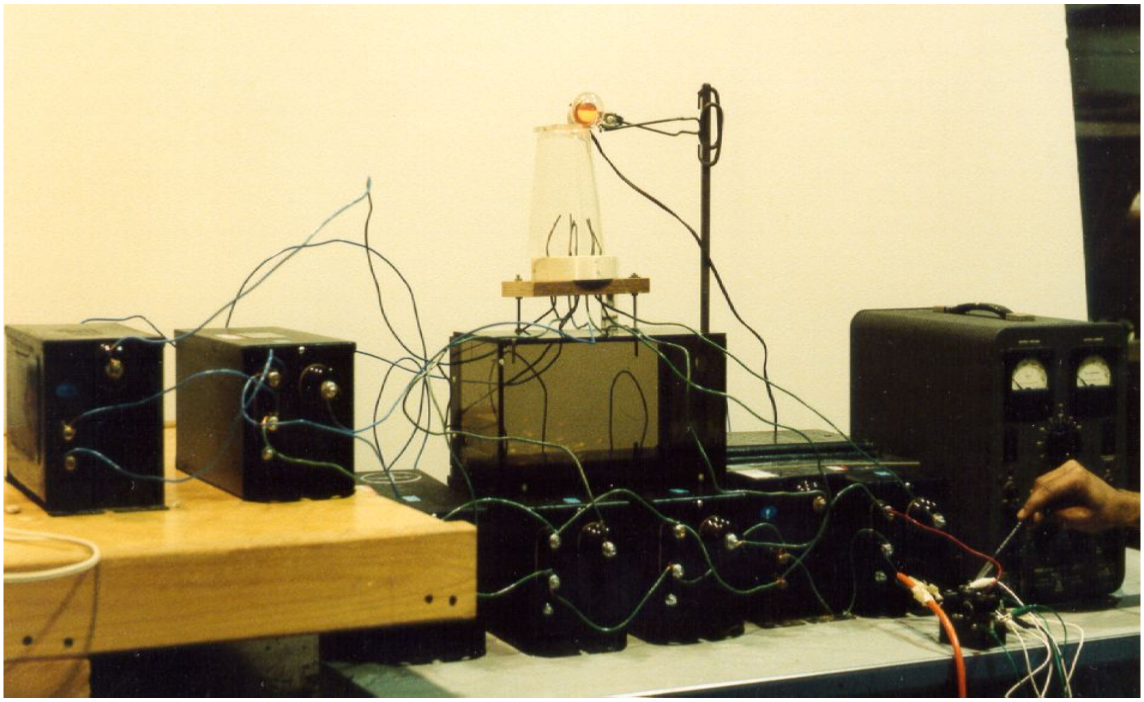

Figure 3.7 The Experimental set-up

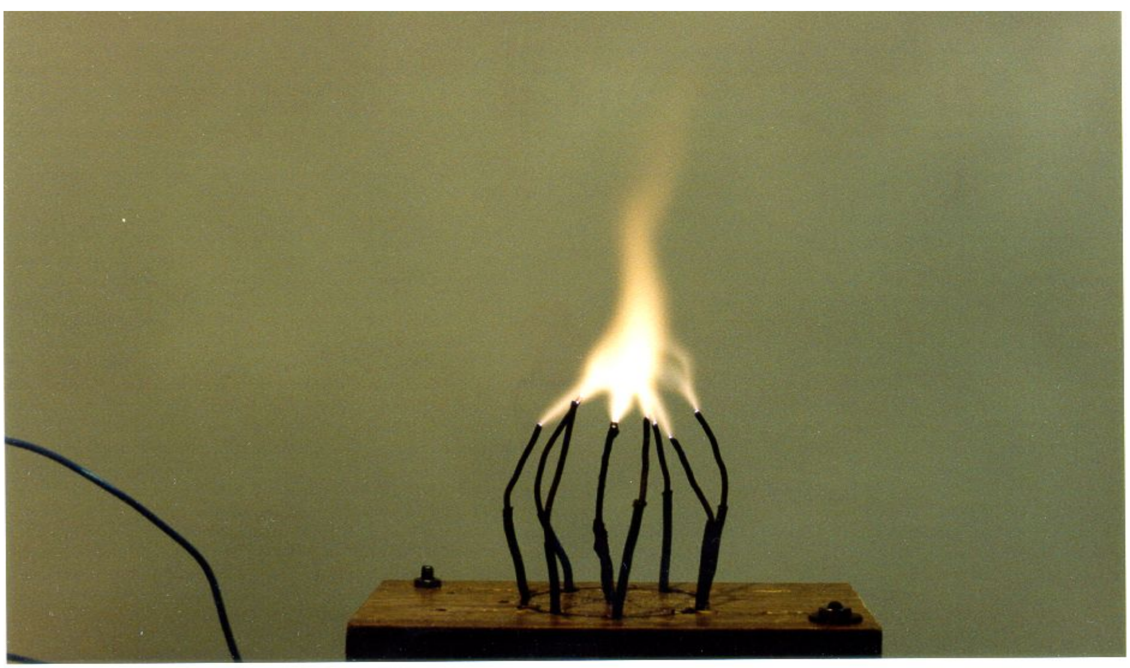

Figure 3.8 Close up view on the electrode geometry

The energy should be put into the ball slowly; to ensure pressure equilibrium thus we prevent the shock wave from destroying the ball. Photographs were made showing ball generation, rising after power turn – off, and dissipating The photographs was made with a Canon T – 90 Camera, an f 1.2 lens, Fuji color ASA 800 film and an exposure time of 1/30 second. We have taken a lot of photographs of the discharge, and we have captured a series of photographs, which clearly show the discharge formation, and the ball rising up in the air. These shots of the arc are random photographs and are not in the specific sequence at which they were taken. Figure 3.9 is a photograph, which shows the arc initiation. Figure 3.10 shows the arc in it entirety after the discharge has reached the steady – state. We have taken a lot of shots with a 35mm and have about more than 100 photographs of the discharge. Figure3.11 and Figure 3.12 show the arc formation and the ball floating up in the air.

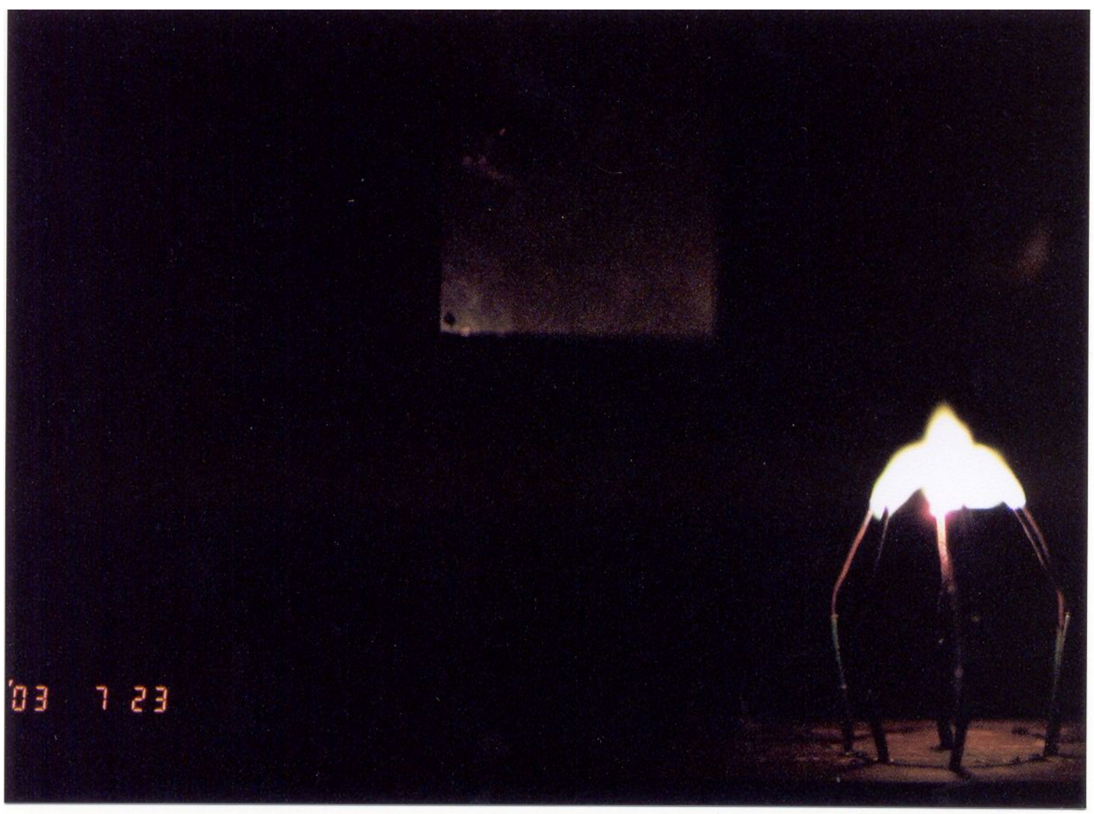

Figure 3.9 Arc Initiation process

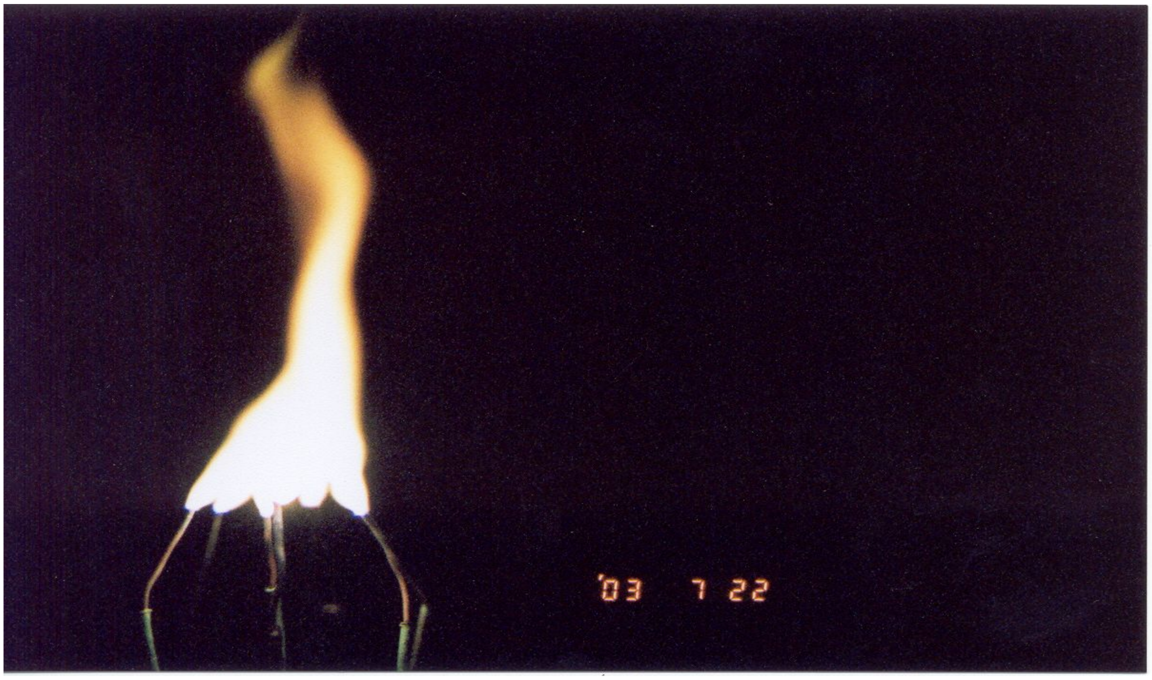

Figure 3.10 The Arc discharge in its steady state.

Figure 3.11 Ball floating in the air, and arc discharge initiation at the bottom

Figure 3.12 The ball floating in the air

Streak Photographs of the discharge were taken so as to get a brief idea of the time for which the ball lasts. To obtain the lifetime of the plasma spheres, streak photographs were made, showing the ball's position versus time, as shown in Fig.3.13. To provide a time base, a neon lamp operating at 60 Hz was included. These photographs show lifetimes of up to ¼ second. Other photographs using a tape recorder showed lifetimes up to ½ second. To increase the size of the ball, we enclosed it in a cone of fused quartz, open at the bottom. The object was to reduce heat losses during the time of ball formation, since we had limited input power. The results, with the ball enclosed in a cone, demonstrated larger initial ball size and increased lifetime. Photographs made with a high speed-framing camera at 100 frames/sec showed up to 18 successive images after power turn off. The problem in getting more images is in the limited light gathering power of the camera. In order to see the formation of the ball, we have enclosed the discharge in various types of enclosures and we have more than 4 hours of video depicting the formation of the ball and it floating up in the air. In the discharge in the cone, we reduced the effects due to convection and a result we were able to get multiple shots of the ball. These videos help us to analyze the ball and its properties, we also are able to obtain images from these videos, but they do not have a very good resolution as a result of it.

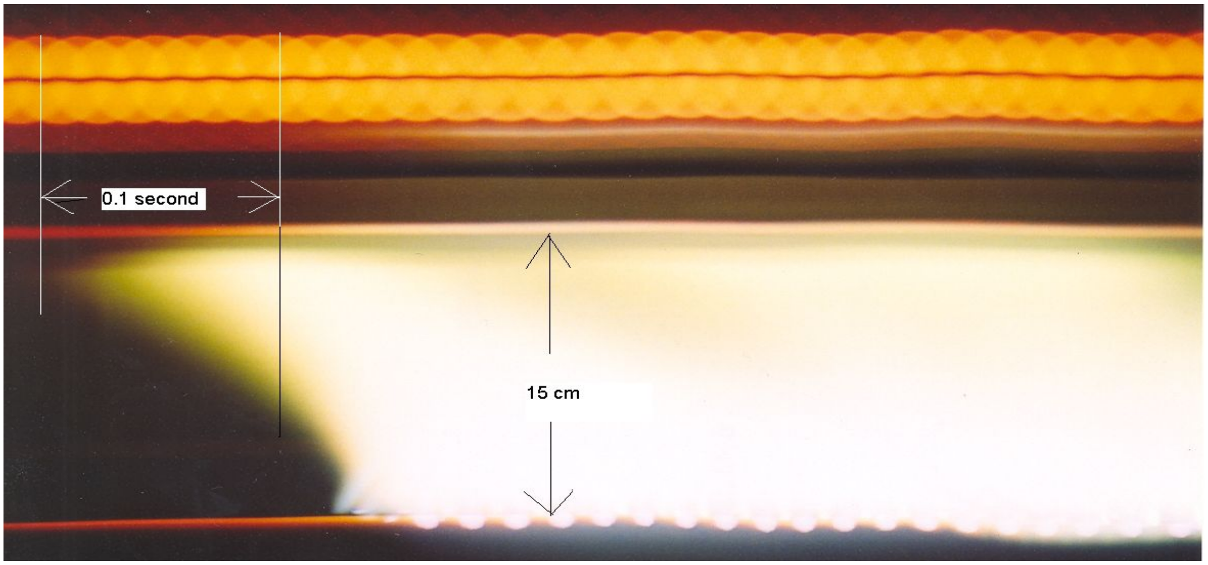

Figure 3.13 Streak Photograph of the Arc discharge

We have tried enclosing the discharge in such a way to increase the lifetime of the ball, but the best results were obtained from the discharge in a cone. So in order to increase the lifetime in a cone we enclosed the inside of the cone with fiberglass as thermal insulation material fused quartz, open at the bottom. The object was to reduce heat losses during the time of ball formation, since we had limited input power. The results, shown in Fig.3.14, demonstrated larger initial ball size and increased lifetime. Photographs made with a high speed-framing camera at 100 frames/sec showed up to 18 successive images after power turn off. The problem in getting more images is in the limited light gathering power of the camera. In order to see the formation of the ball, we have enclosed the discharge in various types of enclosures and we have more than 4 hours of video depicting the formation of the ball and it floating up in the air. In the discharge in the cone, we reduced the effects due to convection and a result we were able to get multiple shots of the ball formation and its decay .We have tried enclosing the discharge in such a way to increase the lifetime of the ball, but the best results were obtained from the discharge in a cone. So in order to increase the lifetime in

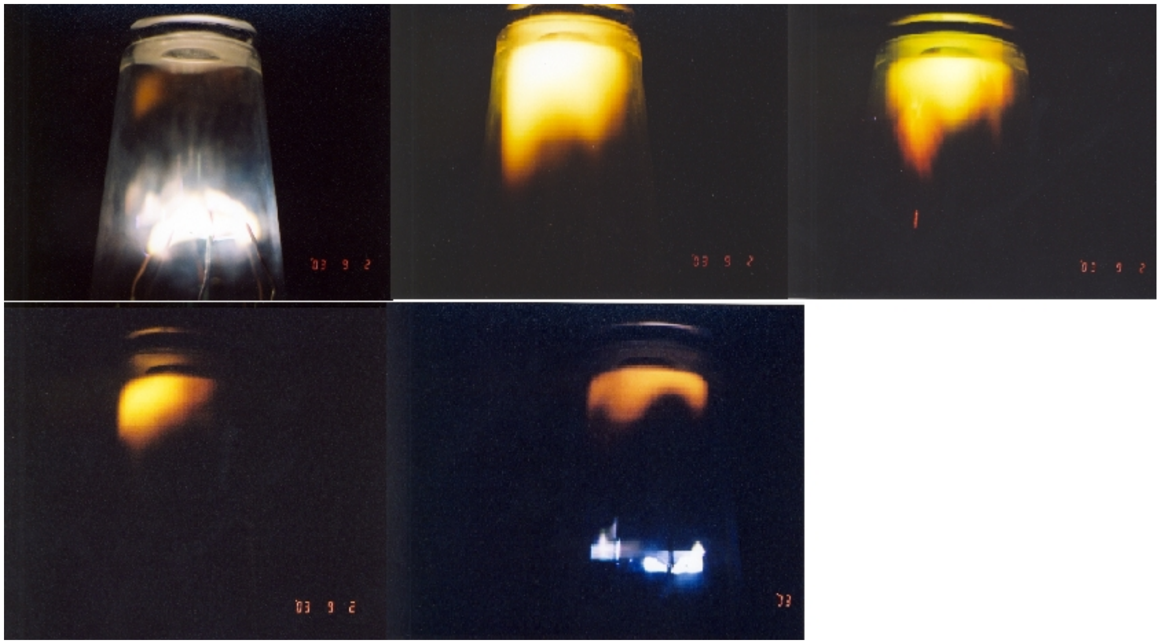

Figure 3.14 Sequence of the ball in a cone

a cone we enclosed the inside of the cone with fiberglass as thermal insulation material as shown in Figure 3.15.The insulation did not make much of a difference as we got similar results as compared to that without the insulation. We also took streak photographs of the discharge in air and the various enclosures to get an idea of the time for which the ball lasts. In order to obtain panoramic of the discharge, we placed two mirrors on either side of the discharge and used a Russian camera with a moving lens to obtain the images. In these images it is clearly proved in principle that the ball exists for a certain period of time as we can see from Figure 3.16, which is a collage of four images taken with the panoramic camera. The ball floats and this can be found in the image at the bottom right corner of the collage. One of the problems with ball lightning is that it occasionally appears to move against the wind. An object that is conducting or that has a high dielectric constant is pulled into an increasing electric field. An example is a fragment of paper attracted to an electrically charged comb. We attempted to see if the ball were attracted to an electrically charged metal plate, and found that it was, as shown in Fig.3.17.

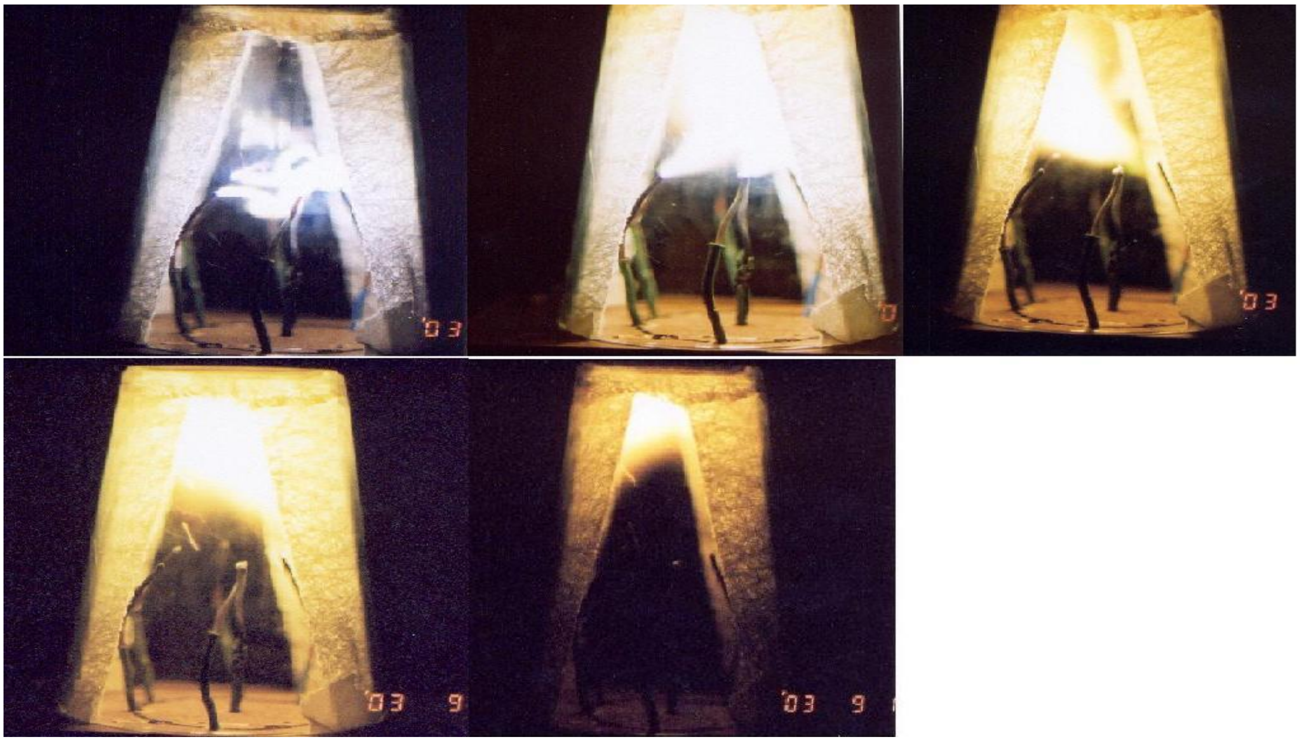

Figure 3.15 Arc formation in a cone with insulation

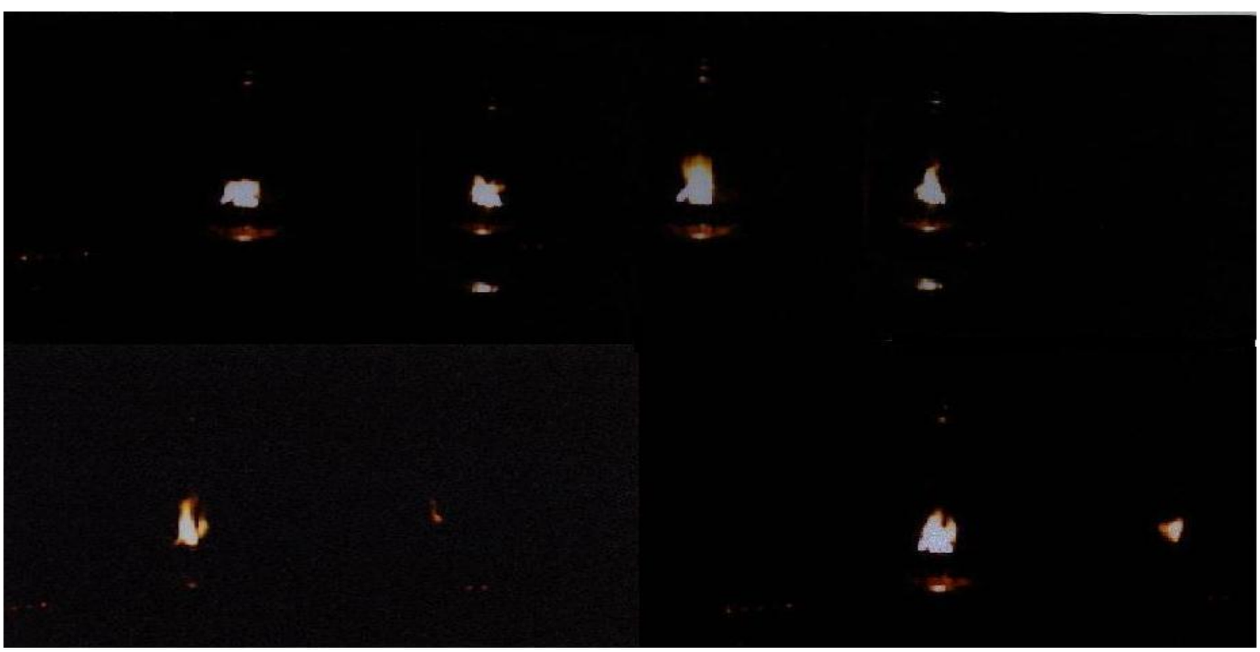

Figure 3.16 Collage of photographs taken with the Russian camera (panoramic)

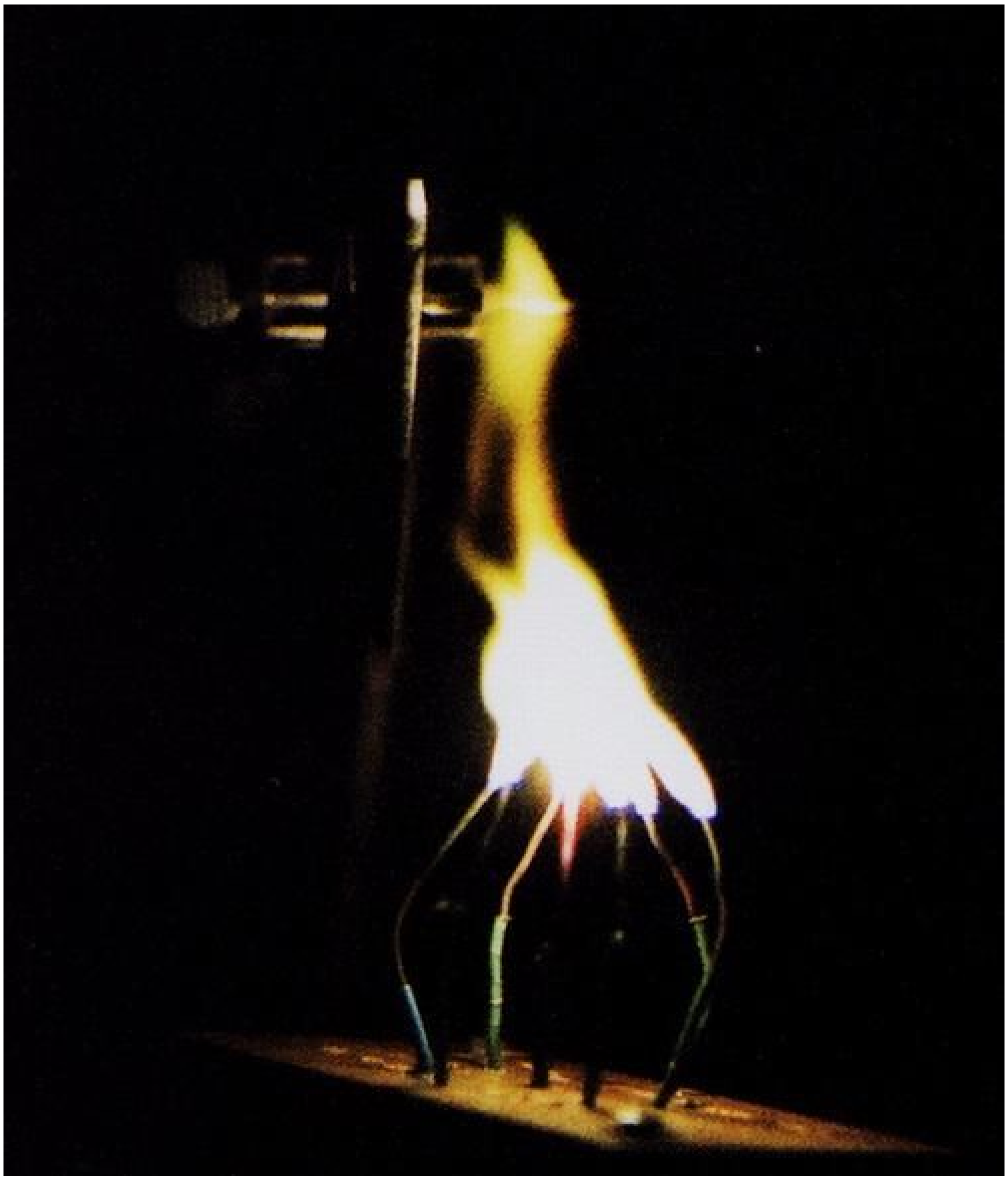

Figure 3.17 Ball attracted to the plate

The theory is based on the published measurements on energy loss in an electric arc in air. According to these measurements, the primary loss of heat is by conduction, convection is small, and radiation is negligible. First, we used an infrared thermometer to measure the radiation temperature of the plasma in steady – state operation. The surprising result was a radiation temperature of 95 degrees F, which suggests that radiation losses are low. Second, another method of observation, which suggests that the plasma is formed from an arc and was not glow or corona plasma, was spectroscopic. The spectrum emitted by the plasma ball was observed by and photographed through a small prism spectroscope. Near the electrodes, unidentified spectral lines were clearly visible. However, far from the electrodes and in the ball, only a broad band in the red and a broad band in the green were visible. The spectrum is shown in Fig.3.18, for which a region near the electrodes was chosen, so that a spectral line appears along with the two bands. This demonstrates that the bands are not simply out – of – focus spectral lines. Continuum radiation was not observed, which suggests that incandescent particles were not present. This result agrees with that reported in Cobine, which states that the radiation from an electric arc in air is weak, and corresponds to the emission of molecular bands.

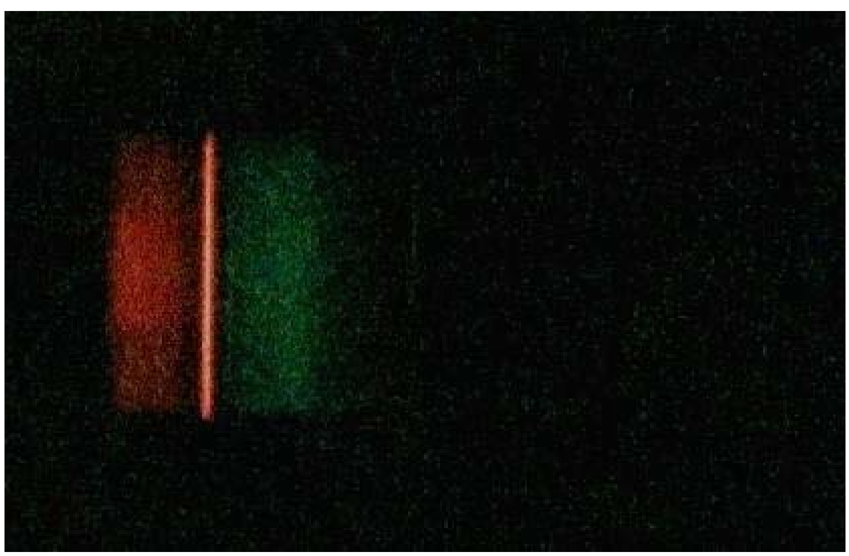

Figure 3.18 The spectrum emitted by the plasma ball

We have analyzed the discharge using high –speed film cameras which give us upto 25 frames on the ball floating in the air when enclosed in a cone. We have also analyzed the discharge using a high-speed digital camera, which does not give very good results because of the low light gathering power of the camera. Figure3.19 show the sequence of the discharge, as we can see the ball does not seem to last a long time in the photographs because of the inhibitions on the camera. In order to increase the optical emission of the discharge we placed sodium inside the central electrode as shown in figure 3.20, based on a paper on electrical discharge as a route to ball lightning [35]. The sodium did increase the optical emission as we got a very bright arc from the addition of sodium to the discharge but the lifetime of the ball was reduced tremendously. Figure 3.21 shows a photograph of the arc discharge after the addition of sodium, the arcs luminosity is increased but the lifetime of the arc is reduced, as we were not able to obtain more frames of the ball floating up in the air.

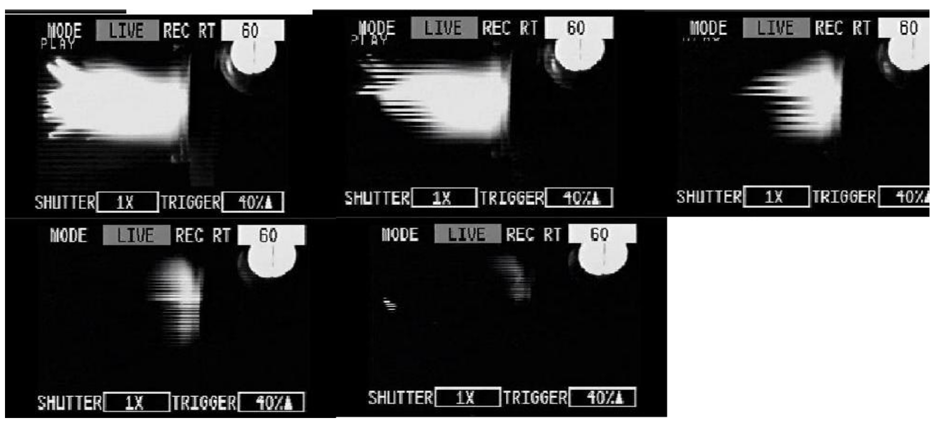

Figure 3.19 High speed digital camera Images

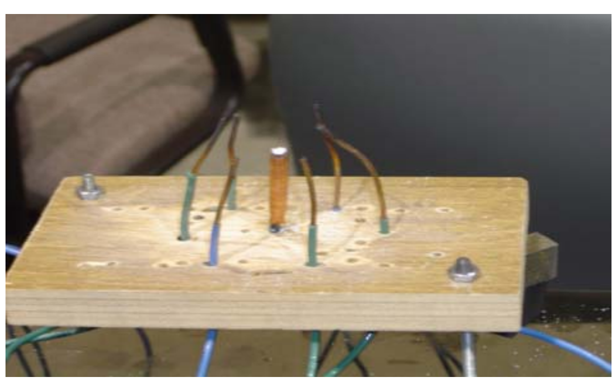

Figure 3.20 Discharge set up with sodium

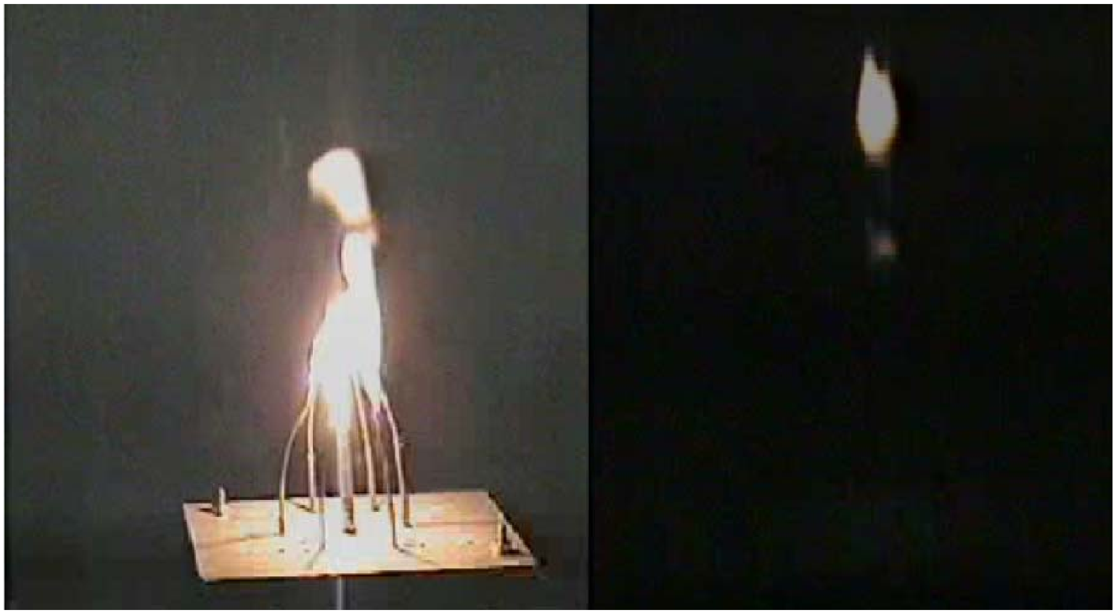

Figure 3.21 Arc Discharge with addition of sodium

Various combination of placing the electrode have been tried out during those process, but the central electrode formation leads to best results. The other combinations included placing the electrodes across each other, and close so that a discharge that is formed, the above formation is shown in figure 3.22.Figure 3.22 shows the discharge across the electrodes, which are placed close to each other to form the discharge. The electrodes were mounted on a wooden platform for better stability. Then the electrodes were placed in a crossed way to get a better discharge as shown in the figure 3.23. The above arrangement was studied using a motion video camera, but the best arrangement of the electrodes that gave us the best confinement times was placing a central electrodes and rest of electrodes discharging to the central electrode thus forming a bigger ball as shown in the figure 3.24. The figure 3.24 shows a ring of cathode electrodes discharged to a central electrode to produce a horizontal sheet of plasma rather than a line. Vertical convection then converted the sheet into a sphere about 1 centimeter in radius. This electrode configuration was found to be better than the ones mentioned above.

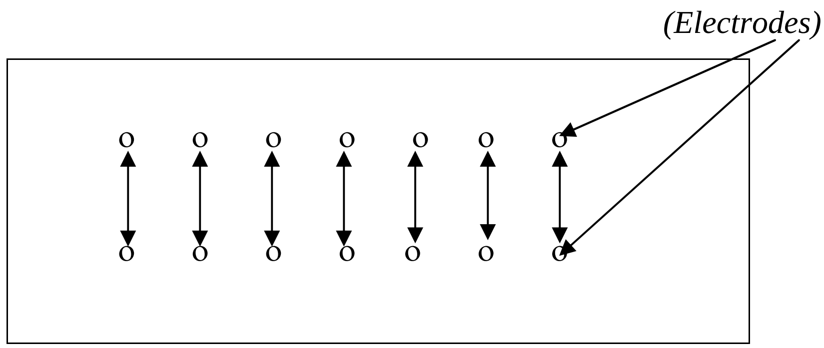

Figure 3.22 Straight Electrode geometry

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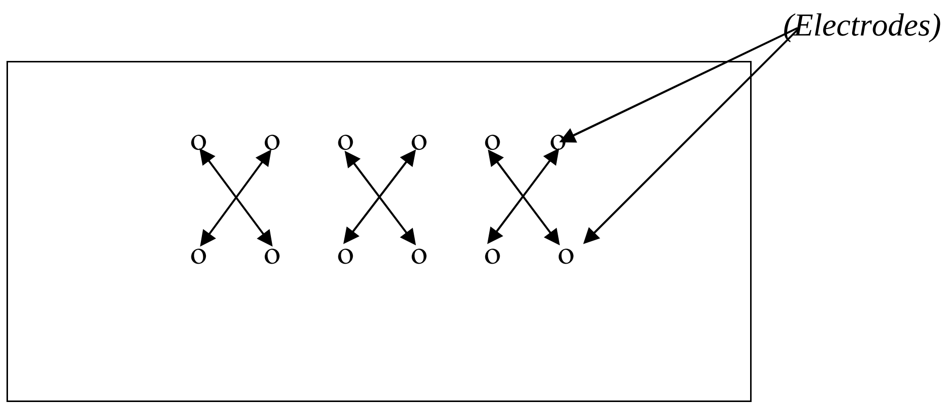

Figure 3.23 Crossed electrode geometry

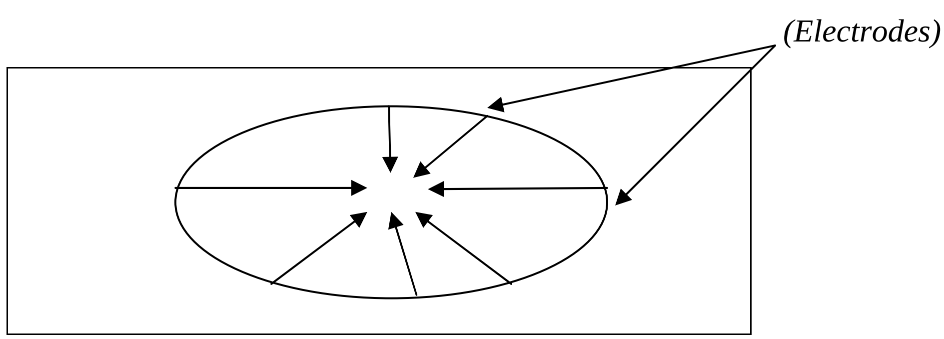

Figure 3.24 Circular electrode geometry

Rotational Transformation

In order to reduce the convection effects and the effects due to gravity, we used a set up which would rotate the arc at a certain speed which would reduce the convection effects and bring the arc discharge more stability by forming a spherical discharge. The set up is shown in figure 3.25. Figure 3.26 shows the close up view on the electrodes inside the conical enclosure. All the seven transformers were coupled so as to obtain a arc discharge across the two electrodes inside the cone. This set up had the similar pulsing arrangement like the previous experiments. The cone was rotated using a drill machine whose speed could be adjusted according to the requirements. The entire set up was clamped to the table to give it more stability during the rotation process. The conical enclosure was rotated and the arc discharge was turned on. We photographed this event using a 35 mm camera and a high speed video camera. When the conical discharge was rotated the arc formed a spherical shape as shown in figure3.27. We got as many 25 frames on the high –speed film camera which suggests that the ball lasted for a long time.

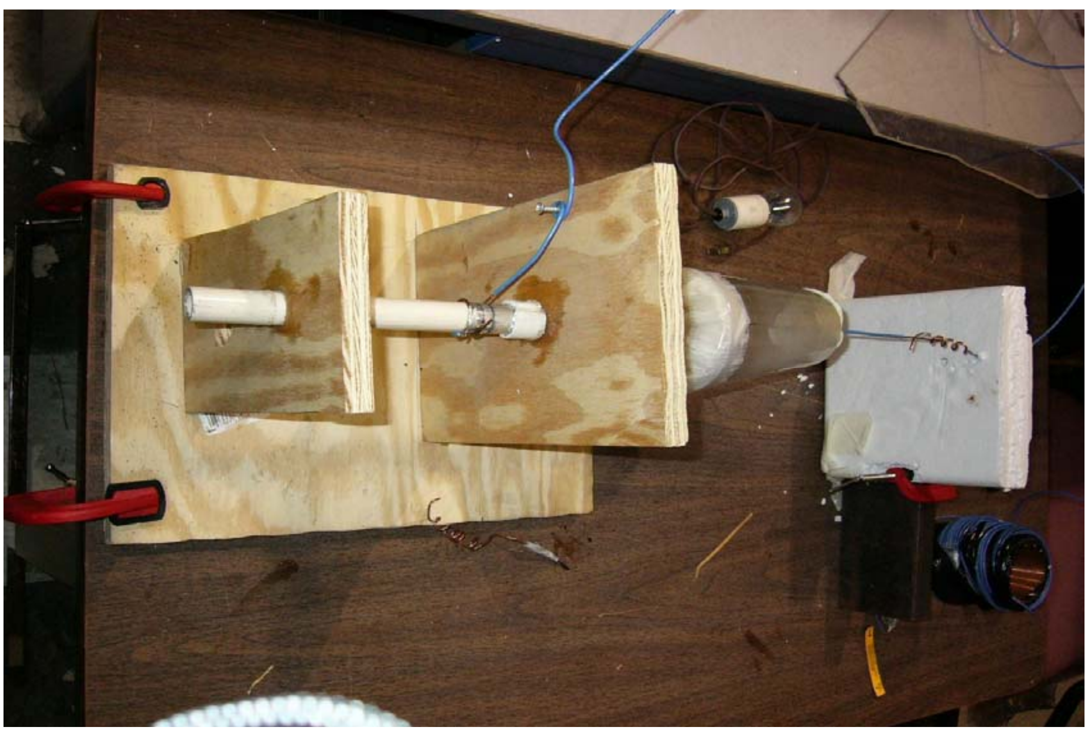

Figure 3.25 Rotational Transformation set -up

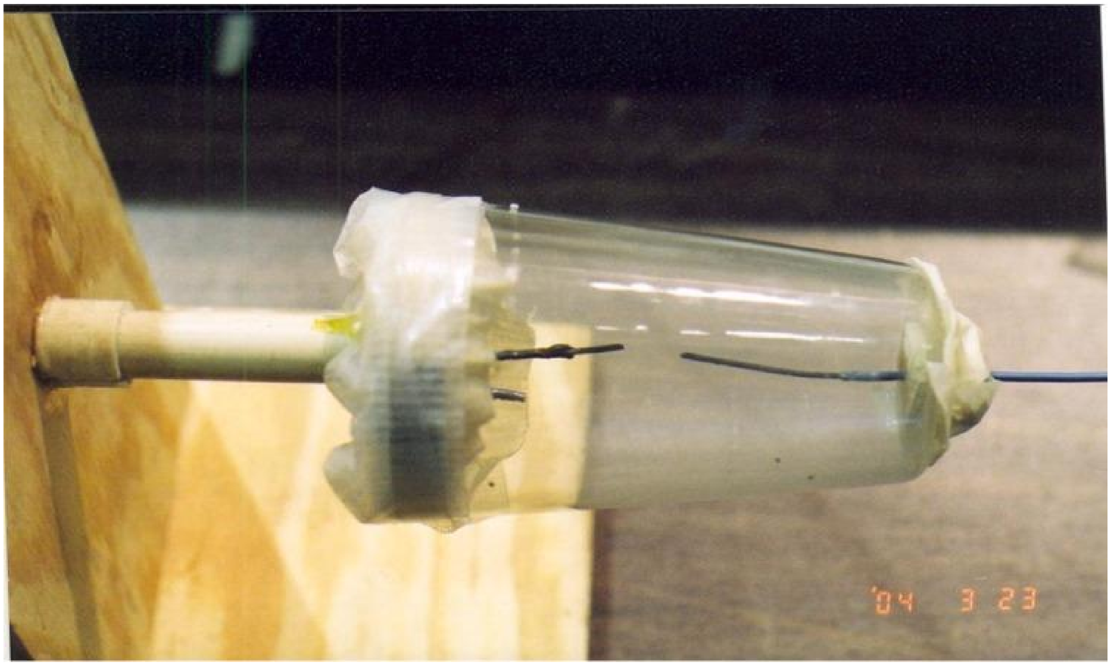

Figure 3.26 Close up on the electrodes in the set –up

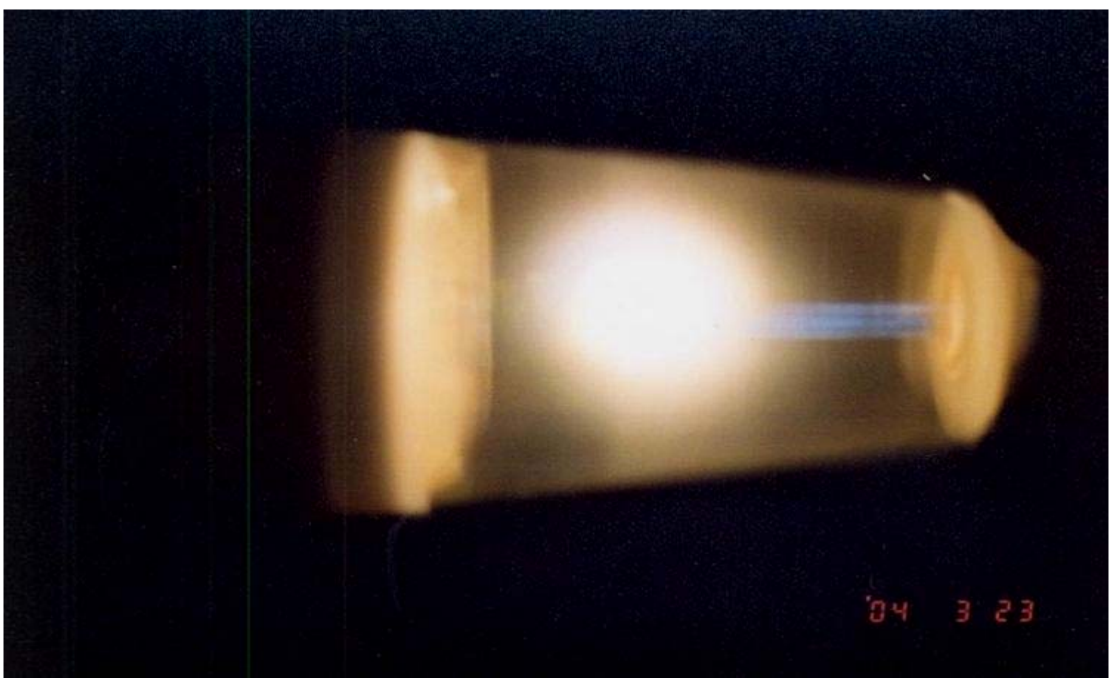

Figure 3.27 Discharge Initiating

The discharge was pulsed, in this set up, so in order to find out if the ball lasted during the period when the discharge was off, we connected a neon bulb to the setup which pulsed along with the discharge. Figure 3.28 and Figure3.29 shows the sequential photograph of the discharge with the neon bulb on and off. In figure 3.29 the neon lamp is off and the ball is floating in the air, this clearly shows in principle the ball exists for a period of time after the discharge is turned off. We found that the ball persisted longer than the pulse – off time, about ½ a second. We have also taken streak Photographs of the discharge to get an idea of the life time of the ball. Figure 3.30 shows a streak photograph which shows the discharge off and the next discharge starting due to the pulsing. This photograph shows the ball existing after the discharge is turned off till the next discharge starts. Figure 3.31 shows a streak photograph of the discharge with the ball floating in the air after the discharge has been turned off.

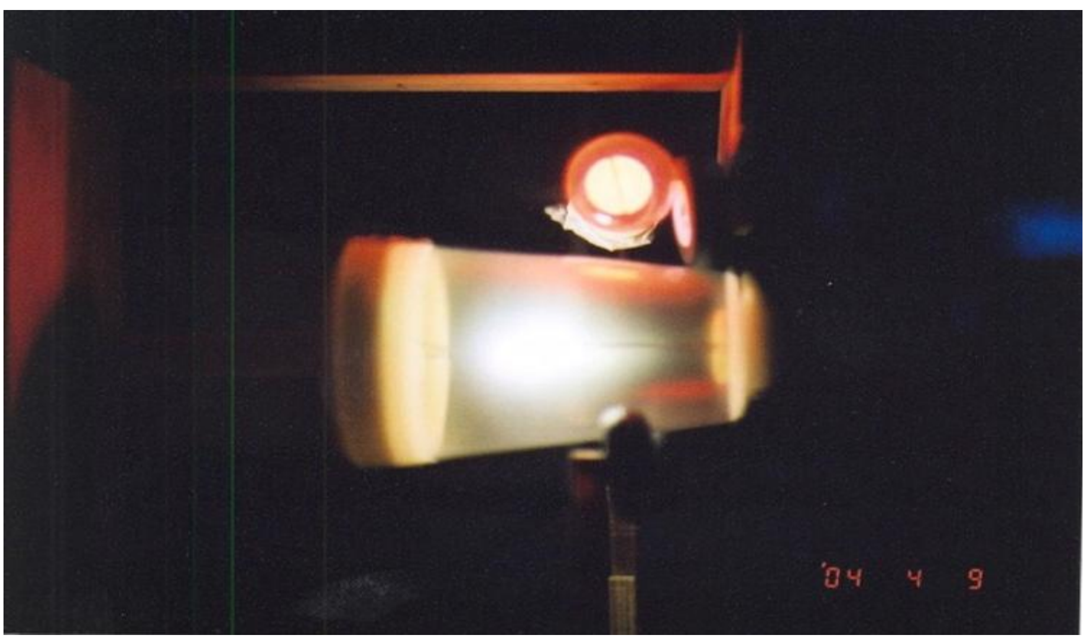

Figure 3.28 Discharge with a neon bulb

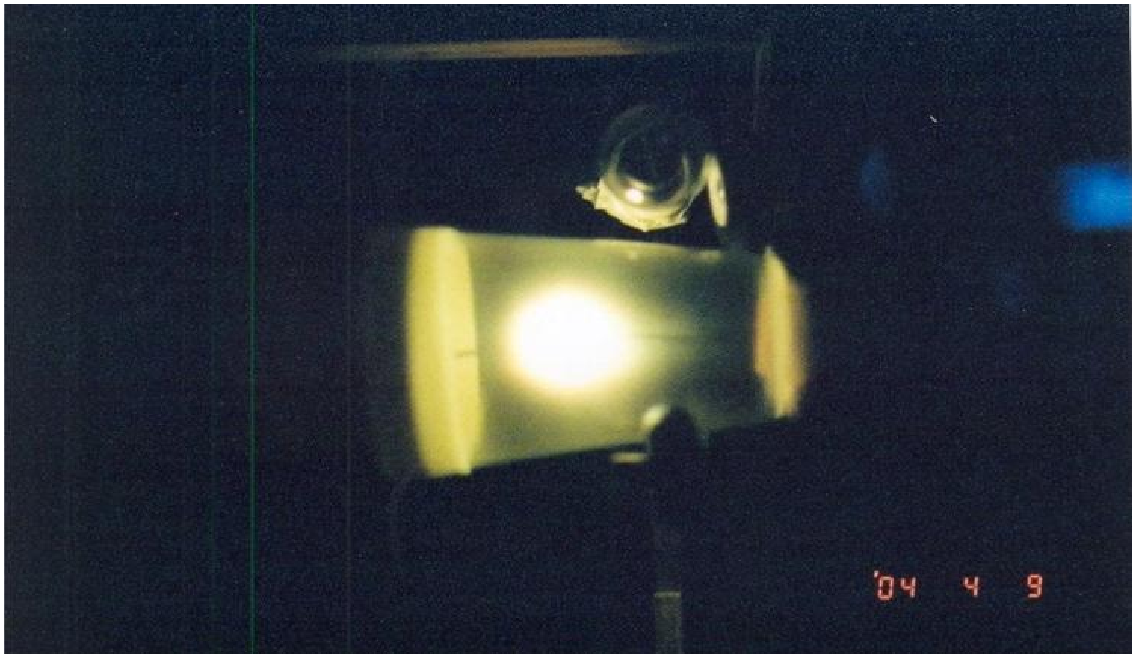

Figure 3.29 Discharge with the neon bulb off

Figure 3.30 Streak Photograph of the Discharge (Continuous)

Figure 3.31 Streak Photograph of the Discharge

Chapter 4

Results

We attempted to ball lightning in air in the laboratory and we were very successful in doing so. At first, we used a powerful spark discharge. The results, revealed a confinement time of less than one millisecond. The reason for this short confinement time is obvious – depositing 400 Joules of work in a few cubic centimeters of air produces a thermal pressure of thousands of atmospheres, resulting in the sphere being lost rapidly by a super sonic shock wave. At this high pressure, the sphere is essentially unconfined, and expands at the rate given by the atom thermal velocity – 10 exp 6 cm/second. This expansion produced by a short impulse of power feed may explain why so many experimenters have not been able to produce long – lived plasma balls in the past.

The Second model the arc discharge model of ball lightning is one of its kind. We have obtained lifetimes greater than half a second which has never been done in a laboratory before. We have predicted its formation and observed its presence. This ball is simply a sphere of hot air confined by atmospheric pressure air. We have produced balls which exist for more than half a second in air.

The two conditions necessary for its production are:

1. A slow time of formation which prevents the ball from being disrupted by a supersonic shock wave; and
2. A horizontal two - dimensional plasma source, which produces a sphere, rather than a one-dimensional plasma source, which produces an arc.

The plasma ball is bright orange in color, which agrees with observations of Dr.Igor Alexeff, as well as with other observers.

I emphasize that there are possibly several other forms of ball lightning and this model is just one form of ball lightning.

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Vitae

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