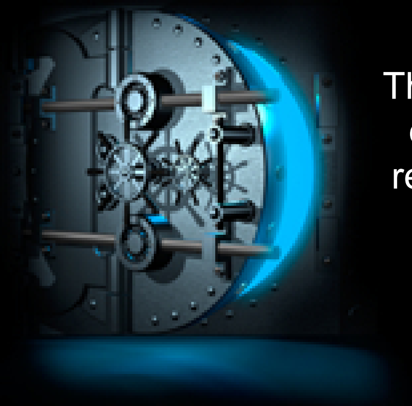

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Ball Lightning Study

Eric W. Davis

Warp Drive Metrics
4849 San Rafael Ave.
Las Vegas, NV 89120

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14. ABSTRACT

This study was tasked with the purpose of conducting a major literature review of the ball lightning phenomenon to explore the observations, experimental tests, and theories. The best ideas and tests were segregated for further analysis and are summarized in this report. A combined bibliography of references was assembled and is presented. The focus of this study was to review and analyze the axially symmetric force-free time-harmonic plasmoid model developed by Nachamkin (1992) for a previous Air Force Research Laboratory study. The intent of the Nachamkin model was to bring together a unique blend of properties proposed by investigators exploring the genre of microwave plasmoid resonance ball lightning models. The main goal of this study is to evaluate and propose experiments to demonstrate the generation of axially symmetric force-free plasmoid ball lightning in the laboratory. Two key experiments were identified and discussed in the report with enough detail to form the basis of future research proposals. An investigation was also conducted into additional promising theories and experiments that might lead to generating ball lightning plasmoids in the lab. Three alternative ball lightning concepts similar to axially symmetric force-free time-harmonic plasmoids were identified and evaluated for their experimental potential, and are described in the report in detail as proposed experiments. The first new concept is the atmospheric maser caviton, the second concept is based on electromagnetic vortex plasmoids generated by micro-discharge devices and sustained by quantum vacuum energy, and the third concept is a b3 10 USC 130 program the Air Force funded in the 1950s-60s.

15. SUBJECT TERMS

ball lightning; Nachamkin model; microwave; plasmoid resonance; axially symmetric; force-free; atmospheric maser caviton; electromagnetic vortex plasmoids

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NOTICE

FOREWORD

This special technical report, entitled "Ball Lightning Study," presents the results of an in-house study performed under JON 48470159 by AFRL/PRSP, Edwards AFB CA. The Principal Investigator/Project Manager for the Air Force Research Laboratory was Dr. Frank Mead.

This report has been reviewed and is approved for release and distribution in accordance with the distribution statement on the cover and on the SF Form 298.

Franklin B. Mead Jr.
FRANKLIN B. MEAD, JR.
Project Manager

Ronald E. Channell
RONALD CHANNELL
Chief
Propellants Branch

Philip A Kessel
PHILIP A. KESSEL
Technical Advisor
Space & Missile Division

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Table of Contents

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List of Figures and Tables

Glossary

AC – Alternating Current
AF – Air Force
AFB – Air Force Base
AFRL – Air Force Research Laboratory
AG – Aerojet-General
BL – Ball Lightning
CCT – Condensed-Charge Technology
CIA – Central Intelligence Agency
CW – Continuous Wave
DC – Direct Current
ERC – Engineering Research and Consulting
EV – Electromagnetic Vortex
LBLGE – Laboratory Ball Lightning Generation Experiment
MHD – Magneto-hydrodynamics
NSA – National Security Agency
RF - Radio Frequency
SEM – Scanning Electron Microscope
SRI - Stanford Research Institute
STM – Scanning Tunneling Microscope
UFO – Unidentified Flying Object
UHF – Ultra High Frequency
USAF – United States Air Force
VHF – Very High Frequency
WTE – Wind Tunnel Experiment
ZPE – Zero Point Energy

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This study would not have been possible without the very generous support of Dr. Franklin Mead, Senior Scientist at the Advanced Concepts Office of the U.S. Air Force Research Laboratory (AFRL)-Propulsion Directorate at Edwards AFB, CA. Dr. Mead's collegial collaboration, ready assistance, and constant encouragement were invaluable to me. Dr. Mead's professionalism and excellent rapport with "out-of-the-box" thinkers excites and motivates serious exploration into advanced concepts that push the envelope of knowledge and discovery. The author owes a very large debt of gratitude and appreciation to both Dr. David Campbell, Program Manager, Engineering Research and Consulting, Inc. (ERC) at AFRL, Edwards AFB, CA, and the ERC, Inc. staff, for supporting the project contract and for making all the paperwork fuss totally painless. Dr. Campbell and his staff provided timely assistance when the author needed it, which helped make this contract project run smoothly.

There are several colleagues who provided many important contributions to this study that I wish to acknowledge. First, I would like to express my sincere thanks and appreciation to my longtime friend, colleague and "physics guru" Dr. Hal Puthoff, Institute for Advanced Studies-Austin, for our many discussions on ball lightning, for discussing the possibility that electromagnetic zero-point energies could play a role in ball lightning phenomenon observed in certain lab experiments, and for generously offering the assistance of his lab staff. I would especially like to thank and give my sincere gratitude to Scott Little, Institute for Advanced Studies-Austin, and George Hathaway, Hathaway Consulting, for their extensive help with and many discussions on technical issues contributing to the development of ball lightning plasmoid experiments. Additionally, I would like to thank Dr. Jim Benford, President of Microwave Sciences, Inc., for his help and discussions on this topic, and thanks also to Dr. Peter Handel, Univ. of Missouri, for discussing with me at length his atmospheric maser-caviton model of ball lightning and for providing me with technical information that I used in this study. Special thanks to Dr. Bob Schiller, Dept. of Electrical & Computer Engineering at Univ. of Nevada-Las Vegas, for his valuable help with obtaining hard to find technical articles and for our many discussions on the Ball Lightning topic. Furthermore, I would like to offer my debt of gratitude and thanks to my business manager (and spouse), Lindsay K. Davis, for typing the combined reference list and for all the hard work she does to make the business end of Warp Drive Metrics run smoothly. Last, I would like to thank Dr. Jack Nachamkin for his very brief, but important, contribution to this study.

Eric W. Davis, Ph.D., FBIS
Warp Drive Metrics
Las Vegas, NV

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Preface

This Ball Lightning (BL) Study is divided into four phases. Phase I of the study was tasked with the purpose of conducting a major literature review of the ball lightning phenomenon to explore the observations, experimental tests and theories. The best ideas and tests were segregated for further analysis and are summarized in this report. A combined bibliography of references was assembled. Phase II is a review and analysis of the axially symmetric force-free time-harmonic plasmoid model developed by Nachamkin (1992) under a previous Air Force Research Laboratory contract. The intent of this model was to bring together a unique blend of properties proposed by investigators exploring the genre of microwave plasmoid resonance ball lightning models. The main goal of this study is to propose experiments to demonstrate the generation of axially symmetric force-free plasmoid ball lightning in the laboratory. Phase III is an investigation into additional promising theories and experiments that might lead to possible ball lightning plasmoids. Phase IV is the final report.

Ball lightning is a very rare and very complex atmospheric phenomenon. It has attracted the attention of people and scientists for many generations. The phenomenon has generally been known for hundreds, if not thousands, of years in recorded human history. Throughout history ball lightning has been believed by the thousands of eyewitnesses (or victims!) to be anything ranging from evil spirits, angelic manifestations, Unidentified Flying Objects (UFOs) or psychic-elementals to balls of exotic matter, meteors/fireballs, optical illusions, ignis fatuus (will-o'-the-wisp) or atmospheric (weather-related) electrical manifestations. All these phenomena share with ball lightning the common feature that they emanate from the sky, and are transient, alarming when appearing, and totally unpredictable. The same can also be said about UFO/paranormal phenomena, which still receives much derision and disdain from most of the scientific community, whereas ball lightning has enjoyed almost 200 hundred years of increasing scientific investigation (and acceptance).

This author has spent nearly six years exploring anomalous atmospheric (and other) phenomena while collaborating with many fellow explorers from academia, U.S. military and intelligence agencies, and aerospace/defense industry. These people work with a "thinking out-of-the-box" mindset, since this paradigm has been the proven way to push the envelope of scientific exploration. My colleagues have joined me in rejecting the strict orthodox interpretation of Ockham's Razor because we recognize the fact that Ockham's Razor is not an empirical natural law since it is actually more a convenient prejudice than a useful rule for guiding investigation. Rothman (1988) points out that if any two theories equally fit all the known observed facts of a phenomenon, then there is no difference which of the two theories one chooses because either theory is no more valid than the other. It is interesting to note that even Feynman's (1965) famous rewording of Ockham's Razor can be criticized because "the simplest explanation means different things to different people" (Rothman, 1988). We adopt the new mindset when exploring ball lightning phenomenon in spite of the ongoing difficulties it presents for scientific investigation. It is in this spirit to which the author dedicates this study.

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Chapter 1 - Introduction

1.1 Introduction

Ball lightning (BL) is a rare but multifaceted atmospheric phenomenon. It has attracted the attention of people and scientists for generations. The phenomenon has generally been known for hundreds, if not thousands, of years in recorded human history. Historical explanations for what BL is vary. Such explanations generally run the gamut from evil spirits, angelic manifestations, unidentified flying objects (UFOs) or psychic-elementals to balls of exotic matter, meteors/fireballs, optical illusions, ignis fatuus (will-o'-the-wisp) or atmospheric (weather-related) electrical manifestations. All these phenomena share with BL the common feature that they emanate from the sky, and are transient, alarming when appearing, and totally unpredictable. It is interesting to note that many well-known phenomena (i.e., St. Elmo's Fire, ignis fatuus, fireballs/bolides, aerial pyrotechnics, auto headlights, soap bubbles, blimps/weather balloons, flying insects/birds, aircraft lights, etc.) share some of the same characteristics as BL.

Fortunately the past (nearly) 200 years has witnessed increased data collection and analysis of eyewitness reports along with the active participation of the scientific community to explore BL, thus allowing for proper scientific investigation to take place in order to get a handle on the phenomenon. Among scientists this topic has not been without controversy over that long period of time. There are many eyewitness reports from scientists and professionally trained observers whose credibility and reliability cannot be dismissed in spite of the notoriously unreliable reports received from laypersons faced with alarming and unexpected phenomenon. This fact, in addition to the large number of rigorously investigated eyewitness reports, slowly led to the acceptance of BL as being a real phenomenon. It later became possible to separate BL from the esoteric and other atmospheric phenomena thanks to the detailed analysis of the large eyewitness database. Table 1 presents a list of the collections of eyewitness observational data on BL. More than two thousand scientific papers have been published and many thousands of BL reports documented since about 1838.

Scientific investigation into BL reached the point where scholarly articles and scientific conferences were established to facilitate a formal study of the phenomenon. As a result of this activity, convergence was finally reached in the last century on what BL is. We also have a clear representation of BL's quantitative parameters. Even though BL gained widespread acceptance among the scientific community it is difficult to understand why there is such strong interest when one can presume that the phenomenon can be completely understood on the basis of known physical laws. This presumption is wrong simply for the reason that the phenomenon is rare and has not been amenable to direct repeatable examination or testing by specialists, and it has demonstrated properties and effects that challenge presently understood physical principles. This fact has led to the development of a cottage industry of theoreticians and experimentalists who have worked since the last century to develop a proper laboratory model for BL within the context of known or newly proposed physical principles. Because BL is a rare phenomenon, it has taken a very long time to begin to understand the reality of the processes, structures, and elements of a different nature that encompass its multifaceted nature.

It is not the purpose of this project study to reinvent the wheel and rehash all that has already been done and published on this topic. For a complete review with in-depth information on BL phenomenon, the reader should see the excellent book by Stenhoff (1999). This work contains approximately 2,400 references on the subject. This study will focus on briefly outlining the known observations and properties of BL, including the experimental tests and theories that have been developed. A bibliography

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This study was tasked with the purpose of conducting a major literature review of the ball lightning phenomenon to explore the observations, experimental tests, and theories. The best ideas and tests were segregated for further analysis and are summarized in this report. A combined bibliography of references was assembled and is presented. The focus of this study was to review and analyze the axially symmetric force-free time-harmonic plasmoid model developed by Nachamkin (1992) for a previous Air Force Research Laboratory study. The intent of the Nachamkin model was to bring together a unique blend of properties proposed by investigators exploring the genre of microwave plasmoid resonance ball lightning models. The main goal of this study is to evaluate and propose experiments to demonstrate the generation of axially symmetric force-free plasmoid ball lightning in the laboratory. Two key experiments were identified and discussed in the report with enough detail to form the basis of future research proposals. An investigation was also conducted into additional promising theories and experiments that might lead to generating ball lightning plasmoids in the lab. Three alternative ball lightning concepts similar to axially symmetric force-free time-harmonic plasmoids were identified and evaluated for their experimental potential, and are described in the report in detail as proposed experiments. The first new concept is the atmospheric maser caviton, the second concept is based on electromagnetic vortex plasmoids generated by micro-discharge devices and sustained by quantum vacuum energy, and the third concept is a b3, 10 USC 130 [redacted] program the Air Force funded in the 1950s-60s.

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of the important literature accessed within this work is presented. Special attention will be paid to the best ideas and test results that have been accomplished in this field. From this we will select particular lab experiments that will be proposed to test the best ideas.

Table 1. Collections of Eyewitness Observational Data on Ball Lightning

AUTHORS	YEAR	NUMBER OF CASES ANALYZED
Arago	1859	30
Brand	1923	215
Humphreys	1936	280
McNally	1966	513
Rayle	1966	112
Dmitriev	1969	45
Arabadji	1976	250
Grigor’ev, Dmitriev	1978, 1979	327
Charman	1979	76
Stakhanov	1979, 1985	1,022
Keul	1981	80
Grigor’ev, Grigor’eva	1986	2,082
Ohtsuki, Ofuruton	1987	2,060
Egely	1987	300

Chapter 2 - Observations and Properties

2.1 Observational Properties and Definition

BL characteristics have been delineated from the numerous surveys of eyewitness reports to provide the following gross definition (adapted from Stenhoff, 1999; Smirnov, 1987d, 1990):

- It is reported to be associated with thunderstorms of average violence; appears during/after medium-heavy rainfall; and is seen following a downward lightning stroke (i.e., appearing immediately after a strong electric field pulse caused by the lightning)
- It is luminous, of uniform brightness across its surface, bright enough to be visible in daylight
- Shape: predominantly spherical (89 ± 1% probability); ellipsoid, rings, rods and irregular shapes have been reported
- Modal diameter: 20 – 50 cm
- Lifetime: ~ $10^{0.95 \pm 0.25}$ seconds (1 – 2 minutes in exceptional cases)
- Velocity through air: 4 ± 1 m/sec
- Motion: moves independently, randomly through air predominantly in a horizontal direction; motion is not convective; spinning or rolling has been reported
- Color: variable color - white, blue/violet, yellow, red, orange (observer dependent)
- Odor: reported odors are described as sharp or acrid (reminiscent of ozone, burning sulfur or nitric oxide)
- Sound: very few reports of sound not related to formation or decay of BL; witnesses describe hissing, buzzing, or fluttering sounds
- Decay: either silently or explosively (50 ± 20%), or by slow extinction or bifurcation
- Behavior inside interior structures: known to form and travel within aircraft fuselages and buildings, along with ability to pass through barriers intact
- Damage and traces: many observers report significant traces and/or severe damage to the exteriors and interiors of ground structures after the disappearance of the BL
- Mechanical, electrical and thermal effects upon people and objects have been attributed to the phenomenon
- Types of BL: Group A (BL events that follow a lightning flash to the ground) and Group B (BL events seen in midair and not connected to a lightning flash)
- The size, luminosity and general appearance of BL are reported to remain approximately constant throughout its lifetime and decay

What has been left out above is a category relating the various forms of injuries and/or death induced upon people and animals by BL. The problem has been that reports of such events contain insufficient information, and it was never clear that BL ever made contact with victims. The effects of ordinary lightning could readily explain many, if not all, of such reports. The above list is a summary of all the information that has been compiled from statistical surveys that were conducted by numerous investigators on historical and contemporary BL reports. The reader should refer to Stenhoff (1999) for a complete description and summary of these surveys, with the survey references listed therein.

The vast majority of BL reports have been made by eyewitnesses. In addition to this, there have also been BL events that were photographed by cameras and recorded on film and videotape. While the eyewitness records number in the thousands, the photographic and film/video record is extremely sparse due to the rarity of the phenomenon. The photographic evidence presently numbers 65 photos published to date. These and other unpublished photos suffer from exceptionally poor quality lacking in sufficient detail to conduct analysis and obtain useful data. Instrumented recordings of BL have always occurred as a matter of chance. The photographic/film/video evidence of BL is highly questionable because such data obtained by chance will remain a matter of controversy. While video/film instruments can record data, there will still be room for error in subsequent analysis and interpretation.

Dedicated instrumented monitoring of various geographical regions for BL phenomenon has not been conducted to date, at least as is known within the public domain. Project Hessdalen has been in operation for 19 years in Norway, and it is a dedicated instrumented (autonomous) remote monitoring system that is concerned with the detection of UFO phenomenon (Strand, 1993, 2002). The phenomenon this system has detected and recorded in the Hessdalen valley somewhat resembles BL phenomenon. However, it is not clear from the analysis done by Hessdalen project scientists that true BL has been detected.

There is also the very extensive, wide-ranging global geophysical surveillance done around the Earth (covering the undersea, land, air, and space-orbital regions) by the various U.S. intelligence agencies. Decades of extensive geophysical monitoring led to the accumulation of very large datasets that were classified (as sensitive compartmented information) by intelligence agencies owning numerous instrumented (in situ or remote) sensor platforms operating over a wide range of acoustic, electromagnetic, gravitational, electric and magnetic spectrum. It is highly likely that significant BL events have been detected and recorded by one or more of these surveillance systems over the years. However, access to this data for scholarly research was not possible until the advent of Project MEDEA by the Central Intelligence Agency (CIA) (Richelson, 1998). MEDEA is the codename for a project done by a CIA thinktank group called JASON. Unfortunately, MEDEA scientists have focused on geophysical research topics that do not include BL, and the chairman of the group tightly controls the topics so it is not known at this time if BL data exists or even if it can be culled from the surveillance datasets (CIA Environmental Intelligence representative, CIA JASON representative, private communications, 1999).

2.2 Inferred Properties

There are additional physical parameters that have been estimated for BL phenomenon on the basis of statistical analysis performed on the surveys of eyewitness reports in addition to on-site examination of the various traces or physical damage induced on nearby objects, the ground, animals, persons and the environment. Such traces, damage or injuries contained measurable components from which scientific investigators were able to make a number of physical estimates. It is beyond the scope of this study to repeat here all the relevant cases and their detailed analysis. Instead, we will tabulate the important results. The inferred properties are (adapted from Smirnov, 1987d, 1990; Stenhoff, 1999):

- Luminous output power: *several x* 10^2 Watts or *several x* 10^3 lumen in lightning units
- Light energy output: ≤ 100 J
- BL energy (average): $10^{1.3 \pm 0.2}$ kJ
- BL energy density (average): $10^{0.7 \pm 0.5}$ J/cm^3 (or $10^{6 + (0.7 \pm 0.5)}$ J/m^3)
- BL power (based on the part of lightning energy that goes into BL origin): 0.2 – 2 kW (compares well with BL luminous output power above)
- Electric charge: observational data from McNally (1966), Rayle (1966) and Stakhanov (1979, 1985) indicate that BL is attracted to metallic objects, but this data is vague and no specific estimates could be made to ascertain the magnitude and/or sign of charge on BL
- Thermal effects: these are difficult to separate from electrical effects since thermal effects of ordinary lightning is a consequence of electrical joule heating, and the present observational database lacks the quality necessary to ascertain the magnitude of thermal effects
- Optical density: unknown

- Probability of appearance: $10^{-8 \pm 0.5}$ km^{-2} min^{-1}
- Temperature: *several x* 10^3 K

It should be pointed out that temperature estimates are not realistic as investigators apply the Wien Displacement Law ($\lambda_{max}T = 2.9 \ x \ 10^{-3}$ m-K) to obtain blackbody temperatures based on the reported colors of BL, and this temperature is a theoretical ideal. Doing this to report a temperature leads to inconsistencies, as BL colors are known to vary from observer to observer. Barry (1980) pointed out that the source of luminous energy within BL might not even be thermal.

It is impractical to attempt a survey of all proposed BL theories that could account for the above phenomenological properties. In what follows, we will consider only some of the more prominent proposals. We also do not consider theories requiring new laws to be proposed solely to account for BL.

Chapter 3 - Ball Lightning Theories and Experiments

3.1 Phenomenological Models

The combined elements of observed and inferred properties together form the mean phenomenological model for BL. Many investigators have attacked the problem of forming a BL model hypothesis using different approaches. The varied published hypotheses tend to explain the nature of BL as a whole or they treat its separate aspects or they do both. BL research remains an immature discipline even after almost 200 years of discussion within the scientific community. This is largely because there is still no consensus on the physical mechanism(s) responsible for the phenomenon. Different concepts for physical mechanisms have been proposed and categorized, and there is significant overlap that occurs between many concepts within categories. The various concepts that have been proposed are strictly based on the presently known scientific principles of physics, chemistry, meteorology, etc.

However, a significant fraction of the theoretical literature can be best described as “rubbish” (Uman, 1987). This is so because the continuing lack of a conclusive scientific explanation for BL has led to the consideration of many exotic, speculative theories co-opted from other areas of science. These include, but are not limited to, such concepts as magnetic monopoles, exotic states of quantum (superconducting, degenerate, Bose-Einstein condensates, lattice-vortex superfluids, fermionic or bosonic vortices, etc.) matter, micrometeorites of antimatter, micro black holes, exotic sonoluminescence, Rydberg matter, exotic metastable states of matter (such as plasmas, nuclear or atomic), cosmic ray focusing, radioactive air species, nuclear isotope formation and decay processes in air, etc. These exotic theories are unrealistic or contradictory because they fail to reproduce most or even some of the defined BL phenomenology within the context of both the known and observed meteorology and eyewitness observational reports, but most are physically impossible given the known atmospheric physical parameters. While a few are testable theories, the majority are untestable theories. However, there are researchers who have conducted unique experiments demonstrating very novel BL manifestations in the lab (Puthoff, private communication, 2002; Corum and Corum, 1990a,b, 1989, 1988, undated papers). We will address these experiments in more detail in Chapter 5.

Therefore, in this report we will briefly summarize those theories and experiments that have met intense scrutiny for both their theoretical efficacy and their experimental testability in the laboratory. From this will be culled a small number of the best theories that we will propose for future investigation by the Air Force Research Laboratory (AFRL). This will also include alternative theories that are “out-of-the-box”, but that are realistic in the context of the known BL phenomenology. It should be noted that not all the best theories are able to completely describe BL, this has been an elusive feature in the work done to date over the most recent 40 years of research. It has even been suggested that there may be several independent (non-prosaic) mechanisms that are responsible for the generation of BL reports (Hill, 1960; Hubert, 1996; Sinkevich, 1997).

The goal of every BL model is to explain or predict as many of the observed and inferred properties (outlined in Chapter 2) as possible. We note that Hubert’s 1996 report is the first ever attempt to actually correlate the reported BL properties with particular models. A scheme for classifying BL models was provided by Finkelstein and Rubenstein (1964). They identified two models that are distinguished by how the BL model is powered:

- Chemical or gas burner models (atmospheric gas components under combustion)
- Electrical models (charges, electric currents and/or electric or magnetic fields)

These models are then either (Uman, 1969, 1984, 1986):

- Self-powered – run on internal energy sources until they are consumed
- Externally-powered – derive their energy from external resources

Investigators have further categorized each model according to whether the matter within BL is (Finkelstein and Rubenstein, 1964):

- Stationary
- Turbulent
- Oscillatory
- Whether the electromagnetic quantities are direct current (DC), alternating current (AC) or noisy in the case of the electrical models

Last, investigators have grouped models together by similarity.

3.1.1 Ball Lightning Formation Models

Theoretical and experimental models proposing a formation mechanism for BL are not entirely germane to this study. That is because many models published in the literature only provide very mundane explanations for BL formation. It is because such models are not well established that we only summarize them here. Generally these models are strictly valid to the circumstances of BL formation at the point of impact of ordinary lightning. The following are the present models known to date:

- Lightning currents heating materials on the ground and initiating chemical reactions or combustion (Seguir, 1852; Fieux, Gary and Hubert, 1975; Hubert, 1975; Singer, 1971; Stenhoff, 1992)
- BL consisting of globules of molten metal at red heat or metal vapor generated by electrical discharges (Charman, 1979)
- High-current electrical short circuits producing luminous phenomena resembling BL (Brand, 1923; Silberg, 1962, 1965, 1978; Lowke, Uman and Liebermann, 1969; Golka, 1991; Dijkhuis and Pijpelink, 1989)
- Processes analogous to the ablation of solid surfaces by high-powered pulsed lasers, generated by natural coherent radiation produced by thunderclouds with low electrical to radiation energy conversion efficiency (Wooding, 1972)
- BL produced by nonideal plasma bunching by ionizing a vapor with a laser having its photon energy close to the ionization energy (Yakovlenko, 1992)
- BL produced by a frozen shock wave from a point explosion that is blocked by laser radiation along its front (Ignatovich, 1992)
- BL produced by atmospheric maser caviton created by the population inversion in some rotational energy levels of water vapor present in a volume of air (Handel, private communication, 2002); note that for other reasons we will revisit this model in Chapter 5
- BL formed by erosion products that would be released when lightning strikes and melts sand to form fulgurites (Andrianov and Sinitsyn, 1977)
- BL produced by plasmoids created from an erosion discharge in a cylindrical channel with dielectric walls (Avramenko, et al., 1990, 1992)
- Formation of BL from linear lightning channels/strokes; many concepts have been proposed with variations on the theme of how lightning strokes could manifest into plasmoids, ionized balls of air, plasma balls, rotating spherical vortex of ionized air, "pinch effect" plasma balls, electrified

vacuum bubble balls, sausage/kink plasma instabilities, etc. (Plante, 1875; Ritchie, 1961; Bruce, 1964; Wooding, 1963; Uman, 1962, 1967, 1968; Johnson, 1965; Singer, 1971; Charman, 1979; Kozlov, 1975, 1978; Hubert, 1996; Ohnishi and Suganuma, 1997)

Many of these models fail to account for BL formation within rooms and aircraft fuselages. We will not be concerned here with the various criticisms that have been published on these and the following models as this is beyond the scope of the present study.

3.2 Ball Lightning Models: Driven by an Internal Energy Source

3.2.1 Heated Sphere of Air

This is the class of models describing BL as a heated sphere of air (Uman, 1968). These spheres are hot (~ 10,000 K) on the inside (model radii varying from 5 – 20 cm) with very slow cooling by radiation and conduction. During cooling, the radius of the ball remains fairly constant. However, this model suffers from two problems: a) such hot spheres undergo rapid upward convective motion in the absence of external restraining forces; b) and the luminous intensity drops by one order of magnitude or more for every 1,000 K drop in temperature during radiative cooling. These two facts are not consistent with the reported properties of BL (see Section 2.1). Lowke, Uman and Liebermann (1969) refined this concept by proposing three new models invoking the addition of trace impurities mixed with air (sodium vapor, carbon vapor, copper vapor) in a questionable attempt to cure the declining luminosity and upward convection problems. These models are unable to explain the formation of BL within aircraft and ground structures, where structural metal is dominant. They generally fail to quantitatively predict the broad observed/inferred properties of the phenomenon. No experiments testing this model were found in the literature.

3.2.2 Chemical Reaction of Air Components

These models describe the formation of BL by complex chemical reactions (or combustion) involving oxygen, ozone, hydrogen, hydrocarbons and oxides of nitrogen. Intense research exploring the various gas (chemical) reaction channels and their subsequent ionization and recombination processes was done by Arago (1854), Thornton (1911), Schonland (1950), Smirnov (1975, 1976, 1977), Dmitriev (1967a, b), Barry (1967, 1968, 1980a), Powell and Finkelstein (1970), Lowke et al. (1969), Ofuruton and Ohtsuki (1989, 1990), Turner (1994). These investigators report schemes where BL is a cloud of slowly burning combustible aerosol particles of like charge, an explosive mixture of hydrogen and oxygen or other gases, luminous spheres of reacting gases, etc. These BL models are variously powered by many schemes involving thunderstorm electric fields or lightning fields or lightning currents as the energy source, with the chemical reactions taking over as the internal source of energy for the BL. These models are unable to explain the formation of BL within aircraft and ground structures, and they fail to explain why BL form as small spherical regions in air. They possess varying degree of inconsistency in predicting the many other observed/inferred properties of the phenomenon. Lastly, no experiments testing this class of model has been done.

3.2.3 Electrostatic Charging of Air Impurities

This class of BL schemes entails the electrostatic charging of particles (dust, pollen, aerosols, fractal structures, cloud droplets, hydrocarbon polymer threads, aerogels, etc.) by various mechanisms to cause light-emitting reactions in air (de Tastes, 1884, 1885; Corum and Corum, 1990a). More complex versions of this genre have included magneto-hydrodynamics (MHD) or hydrodynamic vortex in which complex electric/magnetic fields and spherical concentrations of charged air particulates have been proposed and tested by Frenkel (1940), Leonov (1965), Singer (1971), Cawood and Patterson (1931), Aleksandrov et

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al. (1982), Mukharev (1986), Smirnov (1987, 1993), Gaidukov (1997), Corum and Corum (1990a), as well as in several undated papers. An examination of the literature shows that lab experiments were limited to the few that tested certain facets concerning the formation of complex air particle aggregates or clusters crucial to a given BL model. None of the experiments demonstrated the full complexity of the model being tested nor did they successfully reproduce the many BL properties, or their first results were not repeatable in latter experiments.

3.2.4 Ions

This class of BL models suggests that BL is a spherical ball of (positive or negative) molecular ions comprised of air gases and/or water droplets such that the inside of the BL is an attenuated charged gas or like an electrically charged shell of water molecules, etc. (Singer, 1971; Hill, 1960; Crew, 1972; Charman, 1979; Stakhanov, 1973, 1974). Plasma physics is not applicable here because low charge density, low temperature and a lack of free electrons describe this class. This model is also plagued by excessively short ion recombination and charge exchange lifetimes (~ milliseconds) so it is a physically impossible BL model. No experiments have been done to test this class of model.

3.2.5 Plasmoid and Plasma Vortex Ring

This is the class of models describing BL as a closed-loop current, produced at the instant of a thunder discharge, within a plasmoid producing a magnetic self-containment field. Plasmoids were first (experimentally) discovered by Bostick (1956, 1957) to be equilibrium configurations of a compact geometric structure composed of plasma whose form and stability is determined by the magnetic field it carries along with itself. In order for the lifetime of this BL model to be long enough to match observations, the plasma energy density must be high. Many theoretical and experimental investigations were done on plasma vortex ring phenomenon (Bostick, 1956, 1957; Hogberg and Vogel, 1961; Bostick et al., 1965; Wells, 1962, 1964, 1966; Wells and Schmidt, 1963). Shafranov (1957) was the first to explore this concept for BL by analyzing the equilibrium conditions for bounded plasmas in a magnetic field. The usual structure of plasmoids is that of a vortex ring comprising an axially symmetric ring (or torus) with a helical current. It is assumed in these models that internal energy of BL derives from ion recombination processes. Wooding (1963) followed up on this theme. The conditions necessary for stable equilibrium of plasmoids (embedded in external gravitational and magnetic fields and external gas) are defined by the virial theorem (*the sum of gravitational, electric, magnetic and internal fluid energies of a closed plasma system is zero*). Work done by Finkelstein and Rubenstein (1964) on plasmoid stability in the atmosphere showed that internal energy, stability and lifetime matching BL properties could be determined. The applicability of the virial theorem to these models, impacting the estimated plasmoid lifetimes vs. observed BL lifetimes, has been the source of heated debate among investigators. In spite of this, there is experimental evidence (Andrianov and Sinitsyn, 1976) showing that plasmoids have substantially greater lifetimes than those found in plasmas without self-containment. Many other variations on the theme of plasma vortex rings have been proposed:

- A mathematical model that BL is composed of a solid, positively charged core (hail, stone, or piece of metal) at its center, with a pure electron layer and a plasma layer surrounding the core, and the electron and plasma layers trapping an electromagnetic field. (Muldrew, 1990)
- Bergstrom (1973) replaced magnetic confinement of the plasmoid with a strong dielectric-diamagnetic attraction that overcomes the repulsion of electric charge by a strong, short-range interaction.
- Alanakyan (1994) proposed a model similar to Muldrew's involving the self-localization of an electromagnetic vortex under conditions that produced a partial charge separation in the plasma that formed near the vortex.

- Witalis (1990) proposed that BL forms as a positive-pulse corona discharge caused by a strong transient electric field thus producing room-temperature plasma by photoionization. This model requires the quantum Ramsauer effect in room temperature air plus the Hall magneto-hydrodynamic (MHD) effect to give a self-magnetized, self-contained BL whirl structure.
- Wolf (1915) proposed that a pulse of conventional lightning creates a rapidly rotating electron vortex ring, with electrons ionizing air by collisions and producing a vacuum within the sphere.
- Neugebauer (1937, 1977) proposed a dense plasma ball comprised of free electrons and ions with the containment energy provided by quantum mechanical exchange forces. This model was revised and extended by Dijkhuis (1981, 1982, 1988, 1991), invoking Bose-Einstein condensation during the formation of the ball.
- Nickel (1989) and Coleman (1993, 1997) propose that vortex motion of a gas could preserve its spherical geometry.
- Meissner (1930) and Flint (1939) suggested various schemes around the idea that BL could be a vortex formed at the meeting point of two misaligned, oppositely directed lightning strokes.
- A proposal by Faye (1890, 1891) suggests that BL is a rotating highly charged sphere originating from whirlwinds, cyclones or tornadoes. Dauvillier (1965) refined this scheme. An alternative to this was proposed by Voitsekhovskii and Voitsekhovskii (1974); whereby, the formation of a vortex occurs in a Rayleigh-Taylor-like area of charge instability where a region of high charge density is above one of lower charge density within an electrostatic field.

Several salient features of BL phenomenon were reproduced with varying degrees of success in the many experiments reported in the literature. Most of the struggle with theoretical models in this genre has been in their satisfying the virial theorem. However, this model has been revised and extended by investigators exploring the microwave radiation powered and microwave plasmoid resonance models. We will discuss these in the following sections.

3.2.6 Microwave Radiation Powered Models

These models propose that BL consists of a radiation cavity bounded by highly ionized, conducting spherical walls carrying large surface currents, inside which resonates (reflection by cavity walls) intense, high frequency microwave fields that energize the ball (Dawson and Jones, 1969). This system is proposed to originate from a large current in a lightning conductor or a loop in a lightning channel. An alternative to this is Jennison's (1973, 1987, 1990) proposal that BL is formed by a phase-locked loop of electromagnetic radiation of a particular wavelength in the intense field associated with lightning activity. A further evolution of this scheme was developed by Endean (1976, 1978, 1992, 1993, 1997) such that BL consisted of electromagnetic field energy trapped in an evacuated spherical cavity that is separated from the surrounding air by an ionized sheath. A spin-off of Endean's scheme was proposed by Zheng (1990, 1992); however, the plasma cavity shell is expelled from an air-filled cavity by ponderomotive forces and the trapped radiation energy generates plasma continuously by ohmic heating to prevent the shell from diffusing away. Most of these models provide a good quantitative analysis for the size, shape, lifetime, energy, luminosity and temperature of BL properties. We will return to microwave powered schemes and discuss experimental considerations of them in a later section.

3.3 Ball Lightning Models: Driven by an External Energy Source

This class of models includes direct current discharge and microwave resonance models. These have many advantages over the internally powered models such that they do not have difficulties with the virial theorem because they do not require a high energy density in order to have a long lifetime. The thunderstorm direct current (DC) electric fields provide a large enough pool of energy that BL can last as long as the field is present. Townsend (1910) was the first to provide a theoretical basis for the physical interpretation of the crude earlier experiments performed in the late 19th century. Nauer (1953, 1956) repeated and extended these early investigations.

3.3.1 Direct Current Discharge

This class of the external energy source models, and their hybrids, propose a localized luminous glow discharge surrounded by a Townsend discharge, or electrical discharges containing fractal aggregates (Finkelstein and Rubenstein, 1964; Powell and Finkelstein, 1970; Powell et al., 1966; Smirnov, 1993; Turner, 1994; Lowke, 1996). Some models are based on heated air, while others are based on metastable molecular states of nitrogen and oxygen. In this model, BL is created and is powered by the thunderstorm electric fields; the electric field lines go through a window and generate a charge build-up on the glass causing it to break down and electrically conduct acting as an electrode that emits a ball on the inside of the building (more frequently in older buildings since modern buildings have a metallic structure possibly giving rise to a Faraday cage effect); while inside of structures the BL becomes internally powered by gas molecular excitation/dissociation energy. Outside of structures, the lifetime of BL is dependent on the lifetime of thunderstorm electric fields (~ min), while its lifetime inside of structures depends on gas molecular excitation/dissociation lifetimes (~ sec). Experimental work testing aspects of this concept involved radio frequency discharges (Powell and Finkelstein, 1970). It is not clear whether air discharge BL can actually be transferred into aircraft fuselages (which are excellent Faraday cages) through the window given that the inside dc electric field will be much weaker than the outside thunderstorm field. This and other BL properties have not been specifically tested.

3.3.2 Microwave Plasmoid Resonance Models

This class of models describes BL to be externally powered by the resonant absorption of intense radio standing waves in the microwave spectrum. Kapitza's (1955) work is the formal starting place for all research into this model. The condition driving this model is the characteristic oscillations of a sphere, which gives the relationship between resonance (wavelength λ) and the external dimensions of BL (diameter d): $\lambda = 3.65d$ ($\lambda > 3.65d$ when ionization is weak). The Kapitza model describes BL according to the following process:

- Following the creation of an ionized lightning channel, a small volume V ($<< \pi d^3/6$, d is final diameter) of weakly ionized plasma is excited by absorption of radio waves according to the resonance condition.
- This excitation increases the ionization level and the BL volume grows until it stabilizes at d; a negative feedback process maintains a stable BL size against changes in temperature.
- BL color would be dictated by the prevailing air chemistry and related ionization level.
- The BL is formed at antinodes in a standing-wave pattern (set up by reflections along a normal to the ground surface), which occur on surfaces parallel to the ground at heights of $(2n + 1)\lambda/4$ (n = even integers).
- BL motion would follow the motion of the antinode independent of wind direction with no convection.
- BL would be formed close to the ground surface at a height of $\lambda/4$ (the radius of the BL).
- BL decay occurs silently if its energy supply was terminated and it slowly radiates away its remaining energy; or decay occurs explosively if rapid cooling produced a shock wave as the BL fills with air.
- BL appearance within structures is explained by apertures (windows, chimneys, etc.) acting as waveguides into the structure; BL appearance in aircraft fuselage was never addressed, but new possibilities were discussed. (Stenhoff, 1999)

From the reported diameters of BL (10 – 50 cm), we can deduce the resonant wavelengths required by the resonant condition to be 36.5 – 182.5 cm (164.4 – 821.9 MegaHertz, aka the Kapitza range), and such radio frequency (rf) emissions in this range have not been directly detected in the atmosphere. However, experimental lightning research has shown that intense rf emissions generated by various lightning (or atmospheric electrical) phenomena possessed frequencies/intensities at the lower end of the Kapitza range, thus providing direct evidence for the existence of even more intense rf emissions that are required by the model (Brook and Ogawa, 1977; Le Vine, 1980; Willett et al., 1989; Massey and Holden, 1995; Jacobson et al., 1998). What is interesting to note in further support of Kapitza's model is that Babat's (1947) experiments showed that spherical, electrodeless plasmoid discharges at both standing wave nodes and antinodes could be produced, while plasmoid confinement was shown to be possible by applying three orthogonal standing waves (Shapiro and Watson, 1963). Additionally, experiments with a 250 cm resonant cavity produced bright plasmoid luminosities by 75 MHz rf waves (Powell et al., 1966, 1967), and these lasted ~ 0.5 seconds. However, plasmoids produced in a 15 cm Pyrex® tube persisted for 1 sec after the power was turned off (Powell and Finkelstein, 1970). The gases used were N_2, O_2, nitrous oxide, air (mixtures of N_2 and O_2), with plasmoid colors ranging from blue (N_2), yellow-white (air), orange (N_2O), to white (O_2).

One attempt to test Kapitza's model was the experimental production of plasma fireballs in air at atmospheric pressure by microwave interference (Ohtsuki and Ofuruton, 1991) using a 2.45 GigaHertz magnetron operating at 1 – 5 kW to generate the microwaves. The investigators reported that the duration of various fireballs was seconds to minutes, while the phenomenon exhibited properties agreeing with many key observed BL properties. Another experiment reported the production of spherical, ellipsoidal or crescent-shaped plasma fireballs in air at atmospheric pressure using the Ohtsuki and Ofuruton setup plus an electrical discharge. This setup generated 5 cm balls lasting 0.5 sec using very low microwave power. A very interesting result from this experiment is that the investigators showed that such plasma balls existed independently of a metal cavity.

Many other experiments of this genre use simple kitchen microwave ovens to produce a variety of cavity-formed plasmoids (see for example, Golka, 1994). The world wide web has references to hundreds of such experiments performed by amateur BL enthusiasts. The setup is simply to mount a burning candle, a dry or burnt candlewick, matchsticks or burnt matches, pencils or burnt pencils, toothpicks or burnt toothpicks, etc. inside of a kitchen microwave oven and turn the power on. The result is the formation of plasmoid fireballs, which would float around as long as there is microwave energy present inside the oven-cavity. Enthusiasts have posted many photos of such home-based experiments on the web. The significance of using burnt objects in this setup is the suspicion or hypothesis that carbon products were the source of the more spectacular plasmoids seen in these experiments.

A theoretical model extending Kapitza's work proposed that BL is a maser-caviton, in which BL is a localized nonlinear high-field soliton forming a cavity (of trapped electromagnetic radiation) surrounded by plasma with an atmospheric maser providing the source of very high frequency (VHF) energy (Handel, private communication, 2002). In this model an atmospheric maser is activated in air by a population inversion of forbidden transitions (rotational levels of H_2O) that are caused by a 10 kV/m lightning stroke electric field; BL is then formed at an antinode of the maser-generated standing wave (Handel, 1975, 1988, 1989, 1997; Handel and Leitner, 1994). Two stable formation modes of this model were identified to be a cool orange BL and a hot white BL. The standing wave was shown to induce a resonant cavity leading to the formation of a stable quasi-spherical caviton moving horizontally at the level of the antinode. The atmospheric maser power source would occupy a volume of several cubic kilometers in the case of BL formed in air, or the space within which it was created when BL formed within metallic enclosures. Decay of the caviton within metallic enclosures would lead to an insignificant (quiet) release of energy because the (small volume) maser possesses only a few hundred Joules of stored energy, and the decay of an open-air caviton would induce maser spiking before population inversion was completed leading to a violent release of energy. From these features Handel showed that his model uniquely and consistently reproduces all the important observed properties of BL. Verification of key aspects of this model came from experiments in which fast-moving humid air in a wind tunnel was passed through a large electric field (from 80 kV capacitor plates) that generated VHF waves at frequencies of 207 and 247 MHz (Handel, private communication, 2002). Handel also cites the results from the Ohtsuki and Ofuruton (1991) experiment as providing further experimental support for his model. Due to the high degree of theoretical and experimental success of this model we will return to it in a later chapter and discuss experimental proposals.

One last BL model that loosely falls within the present category is the one proposed by Nachamkin (1992). It is a model for a self-contained microwave plasmoid vortex resonance described in terms of the theory of time-harmonic electromagnetic fields having the force-free form for their electric field, magnetic field, and electric current. This model is the primary focus for this study and will be discussed in the next chapter.

Chapter 4 – The Nachamkin Plasmoid Model

4.1 Force-Free Time-Harmonic Plasmoids

Nachamkin (1992) proposed a physical model for long-lived high energy density (spherical) resonant plasmoids in terms of the time-harmonic solutions of Maxwell's equations wherein the electric and magnetic fields are parallel to each other and both have the force-free (Beltrami) form, and a time-harmonic electric current field also having the force-free form accompanies these. This means that the functional forms of the time-varying electric, magnetic and current vector fields are identical within a constant phase and factor. This model essentially describes a force-free, time-harmonic standing electromagnetic wave trapped in a stabilizing plasma vortical mode. This model is an attempt to combine Kapitza's standing-wave plasmoid model with Wells' model of a vortical field that is identical to a component of the electromagnetic field (Wells, 1964).

A critical resonance frequency, depending on the size of the plasmoid, was derived such that below this frequency the time-harmonic current cannot be carried by the plasma electrons and the plasmoid decays. While above this frequency, local perturbations of the current tend to increase the plasmoid total energy leading to its stabilization. The fields on the current-carrying plasma electrons induce electromechanical stresses (i.e., *pressures* ∝ *local electric field energy*) that can be balanced by reduced pressures arising from the vortical fluid motion of the supporting plasma. The pinch effect due to the time-varying electric current adds to the plasmoid stability. The plasma velocity field of the vortical motion also has the force-free form such that its functional form is identical to, within a constant phase and factor, the forms of the electric, magnetic and current fields. At a resonant size, the free-space time-harmonic fields have parallel electric and magnetic fields over the surface of the spherical plasmoid, hence making the internal/external fields continuous at the plasmoid boundary and thus eliminating surface currents.

Nachamkin (private communication, 2002) notes that the model may not describe all species of stable plasma excitations found within the plasmoid category. Also, the model is incomplete because it does not address the manufacture of a force-free plasmoid or the nature of the external fields it interacts with. The model does not take into account the sensitivity of ionization and radiative recombination rates to gas density (as a function of frequency and electric field amplitude). It is not certain if ionization and recombination processes can influence the pinch effect stability by driving changes in the plasmoid charge density. Handel (private communication, 2002) argues that Nachamkin's model is not a BL model because it does not address the formation of the plasmoid from the initial lightning stroke electric field, and it does not offer testable predictions for the structure, appearance and behavior of the plasmoid in comparison with know BL properties.

Nachamkin (1992) offers limited physical parameters from the model based on his examination of a 10 cm radius BL containing 1 MJ of energy. Note that this assumption for the BL energy content is between one and two orders of magnitude larger than the inferred average BL energy content reported in the literature ($10^{1.3 \pm 0.2}$ kJ, see Section 2.2). The additional assumption was made that the plasmoid is formed at 1 atmosphere (sea level) at 0 °C. From this the electric field strength within the plasmoid was estimated to be $E_0 = 3.566 \, x \, 10^9$ volts/m, which gives rise to a harmonic standing-wave frequency of 126 GHz ($\lambda \approx 0.24$ cm), a plasmoid electron charge density $\rho_e = -32.63$ coul/m^3 amounting to $8.532 \, x \, 10^{17}$ electrons, and a surface gas speed (not overall BL translational speed) of $u_s = 1.431 \, x \, 10^3 \, sin\theta$ m/s (θ = polar angle). The 126 GHz standing-wave frequency is more than two orders of magnitude higher than any known atmospheric (electrical and specifically lightning) emissions detected by researchers, while the ~ 10^9 volts/m plasmoid field is also orders if magnitude above known lightning-induced fields. More importantly, these numbers are not consistent with known BL phenomenology. Reasonable lab experiments can be made using 2.45 GHz microwave generators, since this frequency is already above the upper end of known atmospheric electrical/lightning emissions. To incorporate a 126 GHz microwave generator in lab experiments is problematic concerning generation of plasmoid discharges because available low power 126 GHz generators operate at too low a threshold for discharge generation, while higher power generators operate at peak power pulse-widths too short (~ 10^{-9} – 10^{-12} sec) to accommodate both sustained discharge formation and adequate diagnostic measurement times. Various 126 GHz generators and their accompanying equipment run ≥ \$0.5M in overall cost. There are no other derived/estimated physical parameters offered by Nachamkin in support of his model that can be compared with known BL phenomena.

The primary purpose of this study is to propose experiments that can possibly generate a force-free time-harmonic standing electromagnetic wave trapped in a stabilizing plasma vortical mode. Two experiments, differing in their implementation, were identified as offering the highest capability for achieving this goal.

4.2 Experiment #1

An extensive search of the experimental plasma physics literature came to a focus on the experimental work done originally by Högberg and Vogel (1961), which was later extended by Wells (1962, 1964) and Wells and Schmidt (1963). Their experiments reported the plasma gun formation of axially symmetric force-free plasmoids (aka plasma vortex rings) containing trapped (electromagnetically confined) toroidal and poloidal magnetic, electric and velocity fields. A standing-wave resonant cavity was not needed to accomplish the formation of the force-free (electromagnetically confined) plasmoids in this experiment. We propose this to be a key experiment with which the Nachamkin force-free plasmoid model can be tested. This experiment is excellent because with certain modifications it can be exploited for developing plasmoid weapon or rocket propulsion test articles.

4.2.1 Description of Apparatus and Procedure

The plasma vortex rings are generated by a conical θ-pinch (aka punch coil) plasma gun, which is an induction pinch with a cone-shaped single turn coil. This is essentially what is also called an electrodeless plasma gun. A 15 kJ capacitor bank with operating maximum voltage of 25 kV energizes the gun, although these values can be changed as desired. The ¼-cycle rise time for the punch coil field is 2.5 μsec, and the peak field in the throat of the cone is 70 kG. The coil can be crowbarred (i.e., preventing the magnetic field from changing sign) so that the current does not reverse. A positive or negative bias field can be applied by an auxiliary coil and slow capacitor bank. A small quantity of cold gas is injected into the punch coil, which is pre-ionized by a separate single-turn strap coil oscillating at 400 kilocycles, and then accelerated by the conical coil. The plasma is propelled down the axis of a DC solenoid, producing a steady 4 kG magnetic field over a length of 1.5 m, which provides the B_z (magnetic) guide field for the plasma. The guide field is energized and observations of the plasma are made with diagnostic instruments and probes located at a window at the mouth of the punch coil and at other window ports along the drift tube. The diameter of the drift tube is 15.24 cm. The cold gas pressure is approximately 100 mTorr before pre-ionization. We propose to operate the system for tests from vacuum to 1 atm pressure (1 atm = 1 atmospheric pressure = 760 Torr). The apparatus configuration is shown in Figure 1. Figure 2 shows the apparatus when modified by adding a 45.72 cm vacuum chamber, which minimizes wall support for the plasma structures as they are formed.

The following plasma diagnostics equipment are used to measure the characteristics of the plasmoid:

- 4 mm microwave bridge for measuring the electron density
- 8 mm microwave bridge for measuring the plasmoid rotation by measuring phase shifts due to rotation; a vertical slit smear camera can also be used as a second diagnostic for this
- shielded magnetic pickup loop for measuring the magnetic fields trapped in the plasmoid
- floating double probes (adjustable-depth single wire micro-coax) for measuring the electric fields trapped in the plasmoid
- external pickup loop to monitor the vacuum magnetic field of the punch coil
- a recording framing (CCD or film) camera (50 nanosec exposure time and 5 µsec apart) is used to study the plasmoid structures emerging from the punch coil
- fast ionization gauge to monitor the velocity and density distribution of neutral gas flowing from the pulsed gas valve, this is necessary to ensure that plasmoid velocities determined by time of flight measurements are indicative of macroscopic mass flow and not of plasma disturbances moving down the drift tube already filled with neutral gas molecules
- computer-based optical spectrometer system to provide emission spectroscopic analysis of the plasmoid in the drift tube to determine the temperature and particle number densities
- digital thermometer with thermocouples to measure the temperature of the flowing gas both upstream and downstream of the plasmoid

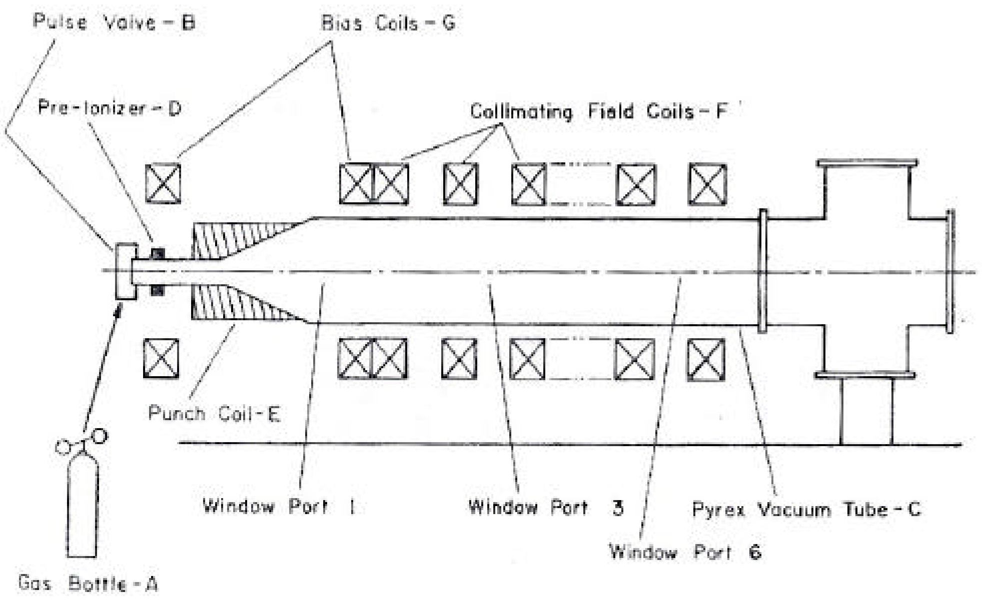

Figure 1. Punch Coil Plasma Gun (from Wells and Schmidt, 1963).

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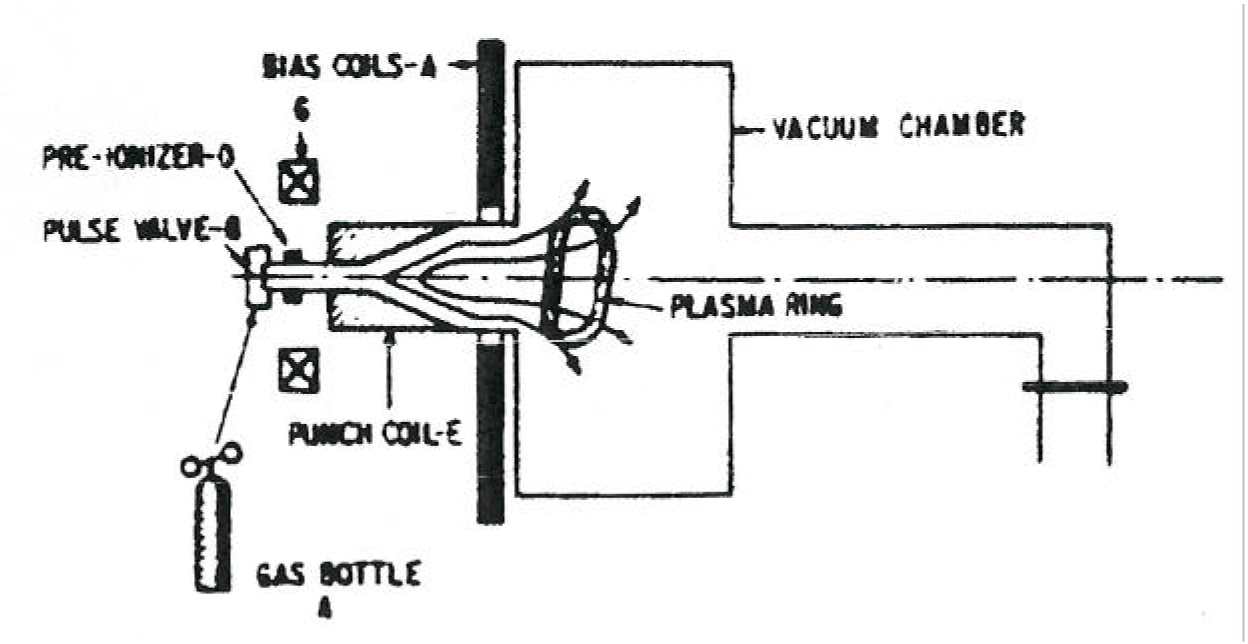

Figure 2. Modified Punch Coil Plasma Gun (from Wells, 1964). Note the insertion of the 45.72 cm vacuum chamber after the bias coils to minimize wall support for the plasmoids.

There is one plasmoid structure formed for each half-cycle of the punch coil oscillation. The plasmoids move close to the walls and contain trapped toroidal and poloidal magnetic fields. The punch coil field will change sign as the plasmoids move down the short section of the 15.24 cm tube. The poloidal magnetic field will initially have opposite polarity to that of the punch coil because eddy currents induce the poloidal field. The punch coil field and the trapped poloidal field then become parallel aligned when the former reverses in the second half-cycle of the gun current. The plasmoid structures are observed in the 15.24 cm tube with bias coil A not activated and/or with it activated. After the plasmoids leave the 15.24 cm tube near window port 1, they enter the 45.72 cm chamber where the bias coil A field begins control of plasmoid development.

4.2.2 Experiment #1 Cost Estimates

Cost estimates for this experiment are based on new equipment and is outlined in the following:

- high voltage capacitor: $1,500
- triggered spark gap for 60 kA: $5,000
- trigger source: $5,000
- ceramic end plates: $1,000
- variable pressure plasma tube assembly: $2,000
- custom B-field coils: $5,000
- capacitor bank supply and ignitron switch for coils: $10,000
- high vacuum system: $10,000
- computer-based optical spectrometer system: $20,000
- floating double probes: $2,000
- magnetic probe pickup coils and external pickup loop: $700
- oscilloscopes (2 ea.): $3,000
- voltmeters (4 – 5 ea.): $750

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- gas tanks (air, N_2, N_2O, mixtures of N_2 and O_2, argon): $1,500
- fast ionization gauge: $3,000
- 4 mm microwave bridge: $15,000 – 20,000
- 8 mm microwave bridge: $15,000 – 20,000
- pulsed gas valve: $1,000
- recording framing camera (film or CCD, ~ 100,000 – 200,000 frames/sec): cost is $50,000 - 200,000 or more, can be borrowed from Navy or Air Force (AF) lab sources
- vertical slit smear camera: $50,000 – 100,000, can be borrowed from Navy or Air Force lab sources
- digital thermometer with thermocouples: $500
- precision gas mass flow rate meter: $2,000
- data acquisition computer and related software (LabView, SigmaPlot, etc.): $4,000
- miscellaneous cabling, cabinets, hardware and electronic components: $3,000

Total estimated raw (new) equipment cost is $110,950 – 120,950 (not including the cost of the recording framing and vertical slit smear cameras, which can be borrowed). The labor cost for a competent technician to work about two months to get this set up, calibrated and working is estimated to be $20,000 (including overhead). The labor cost for two more months to perform a rigorous series of experiments is estimated to be $20,000. Total estimated labor is $40,000. The total overall cost estimate is then $150,950 – 160,950. Not included in this estimate is the time for the principal investigator(s) to evaluate the data and assist the technician during the experiments, and other miscellaneous lab overhead. If good used equipment is substituted, then the total estimated raw equipment cost would drop by a factor of 1.5 – 2.

4.3 Experiment #2

An alternative experimental option was discovered that affords an excellent chance to test the Nachamkin model via a modified Kapitza-type experimental setup involving free-floating plasmas generated in a microwave resonance cavity operating at high pressure. This experiment was originally designed to explore the promise of microwave heated rocket engines for future propulsion systems (Balaam and Micci, 1989). We propose this to be the second key experiment with which the Nachamkin force-free plasmoid model can be tested.

4.3.1 Description of Apparatus and Procedure

We now describe the apparatus of Balaam and Micci (1989). A microwave resonant cavity operating in TM_{012} mode generates the plasmoid discharges. A 10.2 cm diameter quartz sphere contains the plasmoid allowing it to be free-floating and visually accessible to the experimenter, and two 20 mm inside diameter cylindrical tubes are located at the top and bottom to connect to the outside gas system. The resonant cavity is a circular brass waveguide that is terminated at one end by a stationary brass plate (stationary short) and at the other end by a sliding brass plate (sliding short). A low ripple, variable power magnetron generating power up to 3 kW at 2.45 GHz, supplies microwave power. The microwave energy is transmitted via a rectangular waveguide from the magnetron to a 3-port circulator that channels the reflected microwave power to a water load to prevent magnetron damage. Thermistor power sensors are used to measure the forward and reflected power. Connected to the circulator is a 2-port waveguide directional coupler for connection to the power sensors. Microwave power is introduced into the resonant cavity by means of a coaxial probe, whereby, a rectangular to coaxial waveguide transition is used to convert the microwave power from a rectangular to a coaxial propagation mode.

The resonant cavity dimensions are: diameter = 177.8 mm; internal depth = 219.08 mm; wall thickness = 3.175 mm; opening = 57.15 x 57.15 mm (machined in the cavity wall and covered with a copper grid). The cavity opening allows direct viewing of the plasmoid within the quartz sphere without leaking microwaves into the lab. A rectangular brass bar is soldered to the side of the cavity. Fifteen diagnostic holes are drilled through the bar and cavity wall to allow insertion of a micro-coax probe for measuring electric fields and magnetic pickup loops for measuring magnetic fields trapped in the plasmoid. Iterative adjustment of the position of the coupling probe and the sliding short tunes the cavity for minimum reflected power. Gas is introduced into the system from compressed sources, and controlled with a regulator and precision valve upstream of the discharge area. A vacuum pump is engaged for experiments below 1 atm. Diagnostic gauges/meters and thermocouples are installed upstream and downstream from the discharge in order to measure the mass flow rate and temperature rise of the flowing gas. Figure 3 shows the microwave power system and resonant cavity, and Figure 4 shows the quartz sphere inside the resonant cavity.

The following diagnostics equipment are used to measure the characteristics of the plasmoid:

- Shielded magnetic pickup loop for measuring the magnetic fields trapped in the plasmoid
- Floating double probes (adjustable-depth single wire micro-coax) for measuring the electric fields trapped in the plasmoid
- A recording framing (CCD or film) camera (50 nanosec exposure time and 5 µsec apart) is used to study the plasmoid structures
- Computer-based optical spectrometer system to provide emission spectroscopic analysis of the plasmoid to measure the temperature and particle number densities
- Digital thermometer with thermocouples to measure the temperature of the flowing gas both upstream and downstream of the plasmoid
- Thermistor power sensors to measure forward and reflected microwave power
- Vertical slit smear camera to measure plasmoid rotation (it is not yet clear whether an 8 mm microwave bridge measuring plasmoid rotational phase shifts would work in this setup)

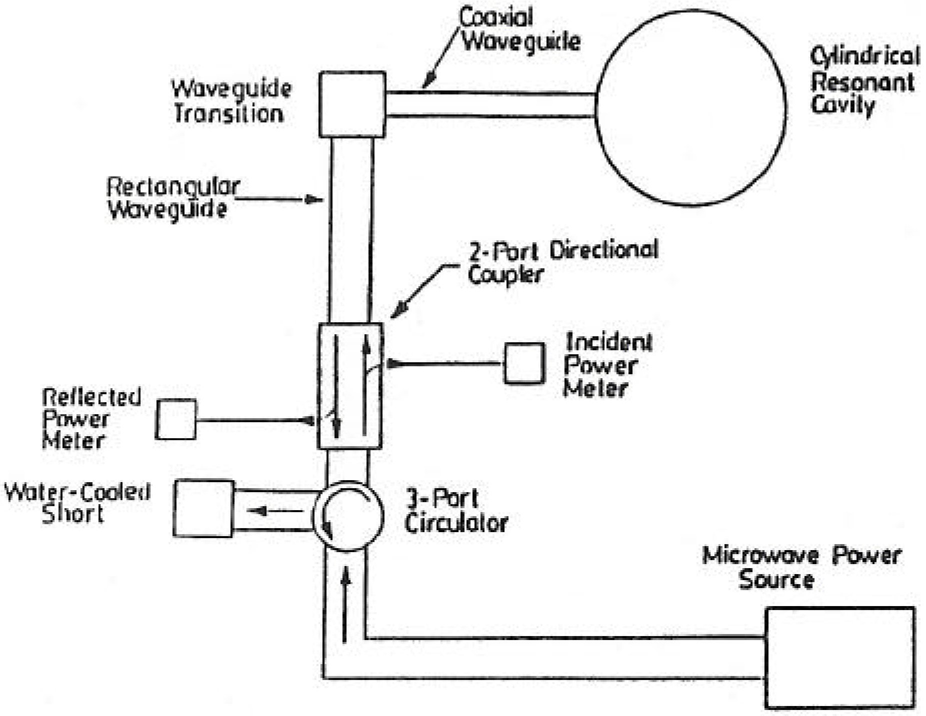

Figure 3. Microwave Power Generation and Transmission System (from Balaam and Micci,

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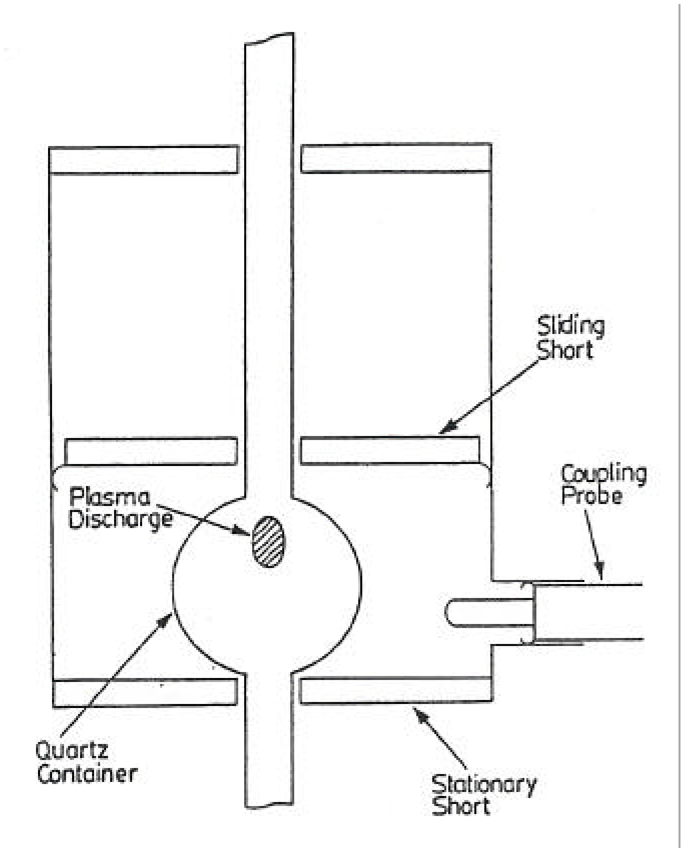

Figure 4. The Quartz Container and Coupling Probe Inside the Resonant Microwave Cavity (from Balaam and Micci, 1989).

The high-pressure gas (air, N_2, N_2O, mixtures of N_2 and O_2, argon) is introduced into the system upstream of the discharge area and then enters the microwave resonant cavity. The cavity, operating in TM_{012} mode (2.45 GHz), then generates the plasmoid discharge within the quartz sphere, which is designed to allow the plasmoid to be free-floating and unable to contact the solid surfaces. Input power can be varied up to 3 kW with gas pressures varied from 1 atm to vacuum, and mass flow rates up to 4.63 $x\ 10^{-4}$ kg/sec (gas flow velocity of ~ 3.0 m/sec) or higher if desired. The diagnostic equipment is operated to make the necessary measurements and system monitoring. At each value of input power, chamber pressure and mass flow rate; measurements are to be made of the plasmoid electric/magnetic fields (at each of the diagnostic ports), reflected power from the cavity, plasmoid rotation and emission spectroscopy.

4.3.2 Experiment #2 Cost Estimates

Cost estimates for this experiment are based on new equipment and is outlined in the following:

- 3 kW microwave power supply: $20,000
- 3-port circulator: $5,000
- water-cooled short: $2,000
- 2-port directional coupler: $5,000
- reflected power meter: $2,000

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- incident power meter: $2,000
- waveguide transition: $500
- rectangular and coaxial waveguides: $500
- custom made cylindrical cavity: $1,500
- custom quartz vessel: $500
- high vacuum system: $10,000
- computer-based optical spectrometer system: $20,000
- floating double probes: $2,000
- magnetic probe pickup coils: $700
- oscilloscopes (2 ea.): $3,000
- voltmeters (4 – 5 ea.): $750
- gas tanks (air, N_2, N_2O, mixtures of N_2 and O_2, argon): $1,500
- precision pressure gauge: $1,500
- precision gas mass flow rate meter: $2,000
- recording framing camera (film or CCD, ~ 100,000 – 200,000 frames/sec): cost is $50,000 - 200,000 or more, can be borrowed from Navy or AF lab sources
- vertical slit smear camera: $50,000 – 100,000, can be borrowed from Navy or AF lab sources
- digital thermometer with thermocouples: $500
- data acquisition computer and related software (LabView, SigmaPlot, etc.): $4,000
- misc. cabling, cabinets, hardware and electronic components: $3,000

Total estimated raw (new) equipment cost is $87,950 (not including the cost of the recording framing and vertical slit smear cameras, which can be borrowed). The labor cost for a competent technician to work about two months to get this set up, calibrated and working is estimated to be $20,000 (including overhead). The labor cost for two more months to perform a rigorous series of experiments is estimated to be $20,000. Total estimated labor is $40,000. The total overall cost estimate is then $127,950. Not included in this estimate is the time for the principal investigator(s) to evaluate the data and assist the technician during the experiments and other miscellaneous lab overhead. If good used equipment is substituted, then the total estimated raw equipment cost would drop by a factor of 1.5 – 2.

4.4 Experimental Facilities

Competent and experienced facilities capable of carrying out the proposed experiments are widespread. We only have to choose from among a number of them that are willing to conduct these experiments. The following facilities have been identified as being potential sites for this purpose:

- Air Force Research Laboratory, Edwards AFB, CA
- Institute for Advanced Studies at Austin/EarthTech, Int’l, Inc., Austin, TX
- Hathaway Consulting, Toronto, Canada
- Los Alamos National Lab Plasma Physics Laboratory
- Johns Hopkins University Departments of Electrical Engineering and Physics
- Pennsylvania State University Departments of Aerospace Engineering and Electrical Engineering
- University of Nevada-Las Vegas Departments of Electrical Engineering and Physics

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Chapter 5 – Alternative Ball Lightning Concepts

5.1 Alternative Approaches

This chapter presents three additional theoretical/experimental BL concepts that are considerably "out-of-the-box" in their approach. It is necessary to present a small subset of alternative BL models for this report in order to consider approaches that are credible and which have demonstrated some measure of, or potential for, success in reproducing BL in the lab. The first proposal was briefly reviewed in Section 3.3.2, and we expand discussion on that in the following section because of the high degree of success the investigator reported in reproducing BL. The second proposal is an approach that was discovered by accident during a series of lab experiments designed to look for other phenomena. The last proposal is based on a still-classified 40+ year-old United States Air Force (USAF) weapons project involving the creation and projection of BL-like pulsed-train plasmoids.

5.2 Maser-Soliton Theory (MST)

Nachamkin (private communication, 2002) suggested a mechanism he thought would generate force-free, time-harmonic plasmoids in a lab experiment. It was on the basis of his suggestion that I turned to Peter Handel's theoretical/experimental BL proposal. In addition, I believe that Handel's proposal is the best one to model the unpublished atmospheric ionic channel hypothesis Dick Spalding (Sandia National Laboratory) proposes to explain BL and many other unusual phenomena (Spalding, private communication, 2002). As discussed previously in Section 3.3.2 Peter Handel proposes a model whereby BL is explained as a nonlinear, quasi-stationary state of plasma and trapped electromagnetic field (Langmuir soliton or caviton), manifesting an ultra-low temperature high frequency (HF) discharge. The discharge is at the antinode of a standing electromagnetic wave (in the horizontal antinodal planes of a standing wave between ground and cloud), fed by an atmospheric (H_2O) maser that can be cubic kilometers in volume. The field digs its own cavity in the plasma due to an initial localized resonance and the well-known ponderomotive forces. The resulting soliton is described by a solution (ground state or excited states) of the nonlinear Schrödinger-like equation that describes the partially ionized plasma and the electromagnetic field. The electromagnetic field has a strong longitudinal or electrostatic component that can be interpreted in terms of Langmuir waves. Any photon generated by the maser has a similar spatial distribution of its electromagnetic field amplitude as the one that stimulated its emission. Handel discovered that it is a peculiarity of large atmospheric masers to allow for a new type of HF electric discharge such that it occurs at low temperatures at atmospheric pressure. Such a BL discharge is stable at an antinode of the standing wave generated by the maser because of the low temperature and atmospheric buoyancy force, in which the maser provides instantaneous feedback to the BL. The field pulse associated with lightning is what causes the maser.

Handel's model combines the energy balance equation of the fireball with the expression describing the exponential temperature dependence of the plasma conductivity, whereby he obtains a power/temperature characteristic with two stable branches that are separated by a branch, which is unstable when driven by RF or UHF sources. One of the "usually stable" branches and part of the "usually unstable" branch represents the hot-white BL, while part of the other "usually stable" branch and an adjacent part of the "usually unstable" branch corresponds to the colder orange BL.

Handel describes the underlying physical mechanism for the generation of BL in his model as follows (Handel, private communication, 2002; and excerpted from Handel, 2002):

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"The rotational energy levels of the water molecule include many closely spaced pairs linked by forbidden transitions in the VHF domain. A sudden, very strong and short electric field pulse, caused by lightning, can induce a population inversion on some of these closely spaced pairs of energy levels. In the absence of very high pointed conductors, the equipotential surfaces are planes, and the population inversion can develop over volumes of many cubic kilometers. When the electric field increases to values of the order of 10^4 V/m, some of the forbidden transitions will become weakly allowed and will feed a large atmospheric maser that exceeds the critical volume. The latter is defined large enough to yield more photons per unit time through stimulated emission than the loss rate which is mainly caused by the absence of a cavity.

Due to this maser action, a standing electromagnetic wave will be present below the cloud in the vicinity of the earth as in Kapitza's model. If in a certain point the local plasma frequency of ions coincides with the maser frequency, a resonance process will lead to local enhancement of the electric field, to ponderomotive forces which pump out the ions from the high field region, creating a resonant cavity in the plasma, finally leading to the formation of a plasma soliton known as a high-pressure caviton (Handel and Schneider, 1985). The caviton is an eigenfunction-solution of the non-linear Schrödinger equation describing the field-plasma interaction with the ponderomotive force included, physically represented by an almost empty sphere containing the resonant high electric field and ions mode.

The caviton is thus a stable quasi-spherical configuration of trapped electromagnetic field, surrounded by plasma and moving horizontally at the level of a standing field antinode, being noticed as ball lightning. The sudden demise of the caviton fed by a large atmospheric maser in open air will lead to spiking of the maser, observed as an instantaneous large release of energy like a giant spark, and interpreted as a powerful explosion. On the other hand, the sudden demise of the caviton in closed spaces (inside a house, airplane, etc.) will not lead to noticeable energy releases or explosions, because the volume of the maser equals the volume of the closed space which is relatively small in this case, and the total energy associated with the population inversion in the water vapor contained in it is limited usually to a few hundred Joules."

The new and unusual technical features of this model, as compared to all previous theoretical and experimental models, which make it extremely novel to explore are as follows (Handel, 2002):

- The quality factor of a large maser with no cavity walls is approximately given by $f{*}D/c$, where f is the maser frequency, D is its smallest dimension, c is the speed of light; for f = 500 MHz and D = 10 km the quality factor is $1.67 \; x \; 10^4$.
- Most of the closely laying pairs of rotational H_2O energy levels correspond to forbidden transitions that become allowed in the presence of an applied electric field, this could switch on stimulated maser emission while the electric field regenerates after a lightning flash.
- The rise time of a photon avalanche (i.e., maser spike) is inversely proportional to the maser volume, becoming extremely short ($\leq 10^{-14}$ s) for atmospheric masers.
- The above three items together explain how an atmospheric maser can extract RF energy before water molecule collisions have a chance to dissipate most of it.
- The maser becomes much more intense at low frequency due to the proportionality of the spontaneous emission rate with the cube of the frequency.
- This is a new type of high-frequency discharge that is estimated to be an order of magnitude colder than typical laboratory arc discharges, but is nevertheless present in air at atmospheric pressure.
- On flat terrain the lightning electric field pulse will lead to maser action for a period of from several seconds to a minute due to the low rate of forbidden transitions between closely spaced pairs of H_2O rotational energy levels.
- Inside closed spaces (aircraft, buildings) the total maser energy, assuming total inversion of all water molecules, is several hundred Joules so there is no BL explosion; however, in open air the

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volume of the maser is several cubic kilometers so an enormous instantaneous avalanche of photons leads to laser-like “spiking”, and thus a BL explosion (~ kiloJoules) occurs.

- Different combinations of the power/temperature characteristic solution branches lead to either white or orange BL.

5.2.1 Outline of Proposed Experiments

Handel (2002) outlined four different experimental proposals to test aspects of his theoretical model and to generate BL in the lab. We will be interested here in two of these experiments. Handel has not developed detailed descriptions of apparatus, experimental procedures, or detailed experiment costing so I will outline the important features here. The reader should keep in mind that both in situ and external diagnostic and other peripheral equipment required for the experiments would not be much different from those listed in Chapter 4.

5.2.2 Wind Tunnel Experiment

This experiment repeats a previous (and successful) exploratory experiment conducted by Handel and two of his students in the mid-1970s at the now-defunct McDonnell-Douglas Lightning Research Facility. In this case, moist air is rushed through a portion of a wind tunnel between a pair of capacitor plates parallel to the flow. The capacitor applies a strong electric field pulse into the flow. The portion of the wind tunnel right after the plates has metallic walls and represents a tunable high-Q electromagnetic Helmholtz resonator from which the signal is coupled out. The procedure involves:

- Detecting and recording the VHF signals right after the pulse
- Measuring a reduction in the absorption at certain frequencies, close to the resonant frequencies of the H_2O asymmetric rotor molecule
- Repeating the experiment with various levels of constant applied electric field that may cause the forbidden transition frequencies of H_2O vapor to become weakly allowed through the Stark effect
- Introducing electron-absorbing impurities to the H_2O vapor in order to prevent the formation of electric discharges in the applied electric field

Handel points out that the resonant frequencies are broadened “into oblivion” at atmospheric pressure by the large frequency of intermolecular collisions (collision frequencies scale as the square of the density or pressure). High Q-factors of the cavity employed lead to the manifestation of frequency narrowing phenomenon, which corresponds (in the time domain) to diverting energy away from intermolecular collisions due to the large volume of the (atmospheric) maser. This causes both a large Q (even without cavity walls) and an extremely short rise-time of the maser signal. And the short rise-time is needed in order to extract energy before collisions can dissipate it. No schematic of the setup is available.

5.2.3 Laboratory BL Generation

This experiment is based on a 10 – 20 kW klystron amplifier with negative feedback for simulating the behavior of an atmospheric maser. The klystron is connected through a directional coupler to a tuned resonator that serves as discharge chamber. From there a wave-guide completes the loop. An optical feedback enhances the natural tendency of the klystron to spike almost instantaneously when the load decreases. The BL discharge sought is a glow at atmospheric pressure and at much lower temperature than the lowest temperature arc discharge obtained at normal pressure. At such low temperatures there are no electrons to sustain the discharge, so a large klystron spike is automatically caused by the sudden decrease of the load just when the discharge is dying. This process will rekindle the discharge by extracting electrons through cold Fowler emission. The large klystron spike will automatically stop the klystron power (just like in an atmospheric maser), and the optical feedback system acts (as a fast reaction system) to repeat the spiking process. Figure 5 shows a schematic of the experimental setup.

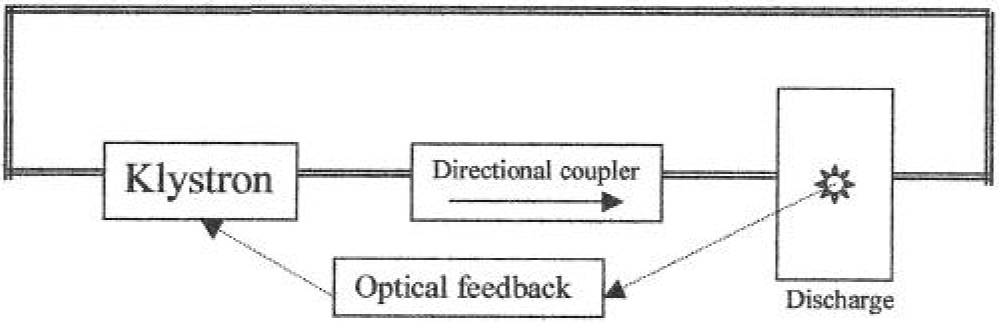

Figure 5. Schematic of Experiment to Emulate an Atmospheric Maser With a Klystron (from Handel, 2002).

5.2.4 Provisional Equipment List and Cost Estimates

Wind Tunnel Experiment (WTE):

Wind tunnel with humidity control	$6,000 lease (from Washington Univ.-St. Louis) to improvise
Marx-bank (Impulse) Lightning Generator (0.5 – 1 MV, ≥ 10 kA, nanosec – µsec rise-time)	$200,000 – $300,000 (includes required accessories)
Large (1.83 m x 1.83 m x 3.66 m) copper-metallic (high-Q) Helmholtz resonator with window	$5,000 – $6,000
Wideband amplifier/receiver/detector (300 – 1000 MHz)	$3,000
Kodamax high resolution camera	$40,000
Computer-based optical spectrometer system	$20,000
Oscilloscopes (est. need 4)	$6,000
Voltmeters (est. need 4-5)	$750
Data acquisition computer and related software (LabView, SigmaPlot, etc.)	$4,000
Miscellaneous cabling, cabinets, hardware and electronic components	$3,000

Laboratory Ball Lightning Generation Experiment (LBLGE):

CW RF Klystron Amplifier (10 kW or larger output, 775-900 MHz; 120 V, 3-phase, 60 Hz input; 3 1/8” coax output)	$85,000 (includes required accessories)
Circulator (water cooled)	$5,000
Optoelectronic feedback (photometric cell, fiber optics, etc.)	$1,500 – $2,000
Discharge chamber/resonator (0.305 m long x 0.213 m diameter cylinder) with window	$2,000 – $3,000
Wave guides (evacuated)	$2,000 – $3,000
Wideband amplifier/receiver/detector (300 – 1000 MHz)	$3,000
Kodamax high resolution camera	$40,000
Computer-based optical spectrometer system	$20,000

- Oscilloscopes (est. need 4): $6,000
- Voltmeters (est. need 4-5): $750
- Data acquisition computer and related software (LabView, SigmaPlot, etc.): $4,000
- Miscellaneous cabling, cabinets, hardware and electronic components: $3,000

The provisional raw (new) equipment cost estimate is $287,750 – $388,750 (at a minimum) for the WTE and $172,250 – $174,750 (at a minimum) for the LBLGE. Handel (2002) proposes a three-year (but part-time) project schedule involving himself (as the PI), two research assistants, two graduate students (all at the Univ. of Missouri-St. Louis) and one subcontractor. The labor cost is:

- Principal investigator: $14,695 per year (for 2-months in the summer)
- Two research assistants: $35,340 per year
- Two graduate students: $38,000 per year
- Staff benefits: $20,000 per year
- Subcontractor: $50,000 per year

Note that the raw (new) equipment cost would drop to $40,000 for year 2 and $10,000 for year 3 of the project for either of the two experiments (Handel, 2002). Total estimated labor is $158,035 per year or $474,105 for all three years. Additional item costs cited by Handel are:

- Miscellaneous materials/supplies: $2,000 per year
- Travel (foreign/domestic): $2,500 per year
- Publication charges: $2,000 per year
- Indirect costs (university overhead charges): 49% of (labor + misc. materials/supplies + travel): $79,642 per year (rounding off to nearest dollar)

The total of the above additional items is $86,142. The total overall (yearly) cost estimate (equipment + labor + additional items) is then $531,927 – $632,927 (WTE) and $416,427 – $418,927 (LBLGE) for year 1, $284,177 for year 2 (either experiment), and $254,177 for year 3 (either experiment). The grand total for all three years of the project is $1,070,281 – $1,171,281 for the WTE and $954,781 – $957,281 for the LBLGE. Note that I used more detailed and somewhat different cost breakdown and estimates in the above than that provided by Handle (2002). If good used equipment is substituted, then the total (provisional) estimated raw equipment cost would drop by a factor of 1.5 – 2, and drop even more if in-house or borrowed equipment were supplied. If the project can be scheduled for a one-year, full-time operation, then we can significantly reduce the grand total to approximately the year 1 cost or less.

5.3 Electromagnetic Vortex (EV) Phenomenon

This section describes an alternative BL concept that really stretches "out-of-the-box" thinking. I say this not because there is some off-the-wall BL theory involved, but because there is extensive multiyear, repeated (but not independently repeated as of this date) experimental data that led to the discovery of a new BL phenomenon existing in the microscale regime. The experimental data and subsequent applications development of EV is very rich while a first-order theoretical model for it has been developed. In 1976 K. R. Shoulders (founder of microelectronic field emission devices while at Stanford Research Institute (SRI), doing contract work for the National Security Agency (NSA)), H. E. Puthoff (a physicist then at SRI; presently at the Inst. for Advanced Studies at Austin) and Bill Church (enterprising businessman/financier with a gift for intuitive insight into tough out-of-the-box physics concepts) came together to undertake exploratory work to find a new energy source at the elementary particle level (not involving nuclear processes).

Shoulders began examining the plasma vortex (aka force-free plasmoids) work of Wells and Bostick (see, for example, references 51-53 and 446-449) because he was originally influenced by theories of elementary particle structure formed from vortical flows of a primeval substance. Shoulders was motivated by the possibility of stable, quantized force-free structures that could be taken apart by some process that would yield energy gain. Bostick later met with Shoulders and stated that he had been observing strange electron concentrations (he called vortex filaments) that formed in an electron beam he made using a plasma focus machine (and also the TX-25 relativistic electron beam machine). Bostick was apparently very puzzled by these objects because their electron concentration violated the space charge law. The vortex filaments were striking exposed materials (metals, dielectrics, ceramics, etc.), boring straight through them and exploding with a large force. Shoulders later renamed the vortex filaments “EV” (aka charge cluster).

Shoulders then went to work and immediately reproduced Bostick’s unusual EV phenomenon by using low voltage/low power micro-arc discharge (aka condensed-charge emission) devices. The EV was much easier to detect and observe using micro-arc discharge devices because they were usually obscured in large high-power machines by the surrounding plasma “mess”. But Shoulders was unable to pin down precise physical characteristics of the EVs because observational resolution was too low due to certain aspects of the apparatus design. After many modifications of the apparatus and subsequent experimental trials Shoulders was finally able to ascertain the high-resolution characteristics, which led to a major discovery. It was discovered that EVs were not filaments at all, but instead were (approximately) 1 μm spherical beads and the beads formed chains. These EV chains were observed to strike surfaces without rotation, translation, or skewing. And the EV beads appeared to be not vortical at all. Further experimental work ascertained the following physical properties of the EV (as claimed by Shoulders, 1987):

- EVs are spherically shaped beads of pure charge (i.e., high-density charged plasma clusters).
- Measured EV-bead diameter: 1 – 20 μm, with 20 μm being the maximum size observed
- Residual negative charge carried by EV: ~ 10^{10} electrons (3 μm bead) – 10^{14} electrons (10 μm bead)
- EV charge density: $6.6\ x\ 10^{23}$ electrons/cm^3 (approx. that of a solid)
- It is not known whether or not EVs shed electrons and get smaller in flight.
- Some EVs explode in space once a lower critical charge/charge density is reached.
- EV charge/mass: ≈ electron charge/mass ($1.7588\ x\ 10^{11}$ Coulomb/kg)
- Internal electric field strength: $> 10^{8}$ V/m (?)
- Deflection of an EV by external fields of known polarity shows that it responds as an electron.
- Ion content of an EV: $<< 1$ per 10^{5} electrons
- An EV is capable of being excited into emission of a narrow band of electron energies by various means including electromagnetic excitation.
- Sudden explosion of an EV leads to copious emission of X-rays.
- Exploding EVs leave impact craters (round or ring-shaped) or holes in materials (metals, ceramics, dielectrics, glass, etc.).
- An EV can be transported through space without emission of electrons or photons.
- The charge of an EV can be dumped suddenly on an electrode leading to a large time rate of change of voltage on that electrode.
- Coupling between adjacent EVs produces quasi-stable structures (chains).
- EV surface current density: $6\ x\ 10^{11}$ amps/cm^2 (10 μm bead)
- Rate of electron emission from EV: ~ 10^{25} electrons/sec or $1.7\ x\ 10^{6}$ amps (for EV translational speed of $c/10$)
- EV lifetime: $3\ x\ 10^{-11}$ sec (in accord with observations on heavily loaded or disturbed EVs)
- EVs can bore smooth channels/ducts through solid materials (metals, ceramics, dielectrics, glass, etc.).

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- An EV can split up into several EVs that later recombine back into a single EV.
- Black (optically invisible) EVs have been generated in low pressure (10^{-2} – 10^{-3} Torr) hydrogen gas; traveling further and less lossy through low-pressure gas than in vacuum; leaving typical EV tracks/marks on witness plates (note: black BL has been reported in the literature cited in Chapters 1 and 2).

Scanning electron microscope (SEM), scanning tunneling microscope (STM), pinhole electron camera and optical microscope videos/photos of EVs in action clearly show that they strongly resemble macroscopic ball lightning. Figure 6 shows an example of an EV moving away from its source and shedding electrons while giving off light as it was dying. We can then consider EVs to be a form of microscopic ball lightning that possesses very unusual properties compared to their macroscopic cousins. EVs definitely qualify to be considered a form of "plasmoid torpedo" based on their damaging effects on materials. Figure 7 shows a SEM photograph of the damage inflicted by a single EV burst fired into an aluminum-oxide ceramic plate. The EV bored through the ceramic forming a smooth symmetrical channel along its path. The numbers in the above list are alarming since they do not correspond to anything that is familiar from plasma, electromagnetic and electronic device physics. EVs remain intact far longer than would seem possible from initial energy input and space charge law considerations. But EVs represent a phenomenon that has been observed for several decades by (field emission and discharge device) investigators who were largely unable to explain them. Shoulders is the first to isolate EVs in the lab, determine their characteristics, and invent many new technology applications from them.

Figure 6. An EV (large blob at bottom) Moving at a Downward Angle Away From its Source (Smaller Blob Near Center of Photo), and Shedding Electrons While Giving Off Light (from Shoulders, 1987).

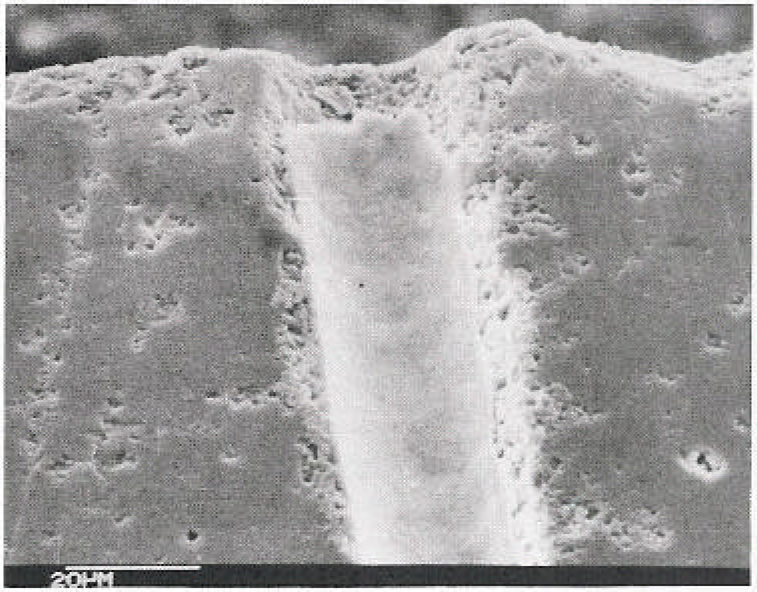

Figure 7. A SEM Photograph (20 µm scale) of the Damage Inflicted by a Single EV Burst Fired into an Aluminum-Oxide Ceramic Plate – Note the Smooth Symmetrical Channel Bored into the Ceramic by the EV (from Shoulders, 1987).

The best theoretical model to explain the manifestation of EVs during micro-arc discharge device operation is based on applying the quantum vacuum electromagnetic zero point energies/fluctuations (ZPE) concept. Such a concept based on the ZPE work of Puthoff (1987, 1988, 1990, 1993) and Cole and Puthoff (1993) has been proposed. While Puthoff, Shoulders and co-workers were investigating approaches to obtaining energy from vacuum ZPE by way of exploiting EV phenomenon, the emerging laboratory evidence led them to consider that the Casimir effect may be a major contributing mechanism to the generation of EVs in micro-arc discharges. Puthoff (private communication, 2002) proposes that the generation of a relatively cold, dense, non-neutral (charged) plasma results in charge-condensation effects that may be attributable to a Casimir-type pinch effect. In a hypothesized EV-based energy-generation process one would envision a “Casimir-fusion” process that would mimic the nuclear fusion process in its cycle of operation. Puthoff’s first-order model suggests that the process would begin (like its nuclear counterpart) with an initial energy input to a plasma to overcome a Coulomb barrier followed by a condensation of charged particles that are drawn together by a strong, short-range attractive potential (a Casimir rather than nuclear potential), and with an accompanying energy release of some form. Extensive laboratory work demonstrated that EVs have the unique property that their formation energy requirement (taken together with electrical circuit and heat losses) is below the level required for break-even operation, such that net useful energy is generated. Shoulders claimed that anomalous EV observations together with corresponding calorimetry measurements showed excess heat generation at the micro to mW level that is 30 times the total input energy. However, further experimentation demonstrated that EV energy generation cannot be scaled up yet due to plasma losses, which increase with an increase in the power scale (Puthoff, private communication, 2002).

Shoulders, Puthoff and coworkers spent many years exploring and exploiting EVs, devising many different ways to generate them in the lab and scale up their energy generation capability. There are more than a dozen different devices used to generate EVs in the lab, and nearly as many new, patented microelectronics technology derived from EVs known as condensed-charge technology (CCT). Example

CCTs are the various EV source generators (metal vapor electrode, surface source, EV launcher, inorganic/organic gas sources, electrodeless source, field emission source, film field emission source, multielectrode source, etc.), picopulser (an EV picosecond pulse generator), RF generator, EV synchronizer, aperiodic waveform generator, direct current output device, EV-based display device, EV picoscope, electron camera, point X-ray source (for radiation oncology or industrial applications), EV circulators for energy storage devices, etc. (See, Shoulders, 1987 for complete historical, experimental and schematic documentation of the various EV apparatus and applications.)

The fact that EVs are a form of micro-ball lightning that can bore through and even destroy (by explosive impact) solid materials, can (possibly) generate more energy than is required to form them, are point-sources of (copious) X-rays, and are compact (self-contained) balls of condensed high-density charge demonstrates a clear need for further research to investigate their potential application to weapons, defense technology, and aerospace propulsion and power. A key problem to explore would be the plasma losses EVs exhibit when their output power is scaled up. It is for these reasons that I recommend the funding and implementation of an experimental program to study EVs.

5.3.1 Basic EV Experiment – Description of Apparatus and Procedure

There are a variety of experimental apparatus designs to choose from, each of which depends on what EV effects one wants to generate along with their level of complexity. It is beyond the scope of this study to examine and propose all of them. However, for the purpose of demonstrating the basic EV phenomenon we can use one of the simpler apparatus described by Shoulders (1987). The operating EV circuit comprises:

- An EV source (a mercury-wetted copper wire cathode surrounded by a cylindrical ceramic nozzle with a 76.2 μm inside-diameter open-aperture at one end, such that the cathode is pushed into the ceramic nozzle to within 0.5 mm of the aperture)
- An anode (EV collector)
- A ground plane
- A glass tube filled with Xenon gas at 3 Torr (to separate and guide EVs to the anode)
- A power supply (±2 – ±5 kV pulse or direct current)
- Input resistor (500 – 1,500 ohms) and load resistor (50 ohms)
- One capacitor (1 – 2 μFarads)
- One lab oscilloscope

See Figures 8, 9 and 10 for schematics of the basic EV experimental apparatus circuit, its EV source, and examples of other EV sources

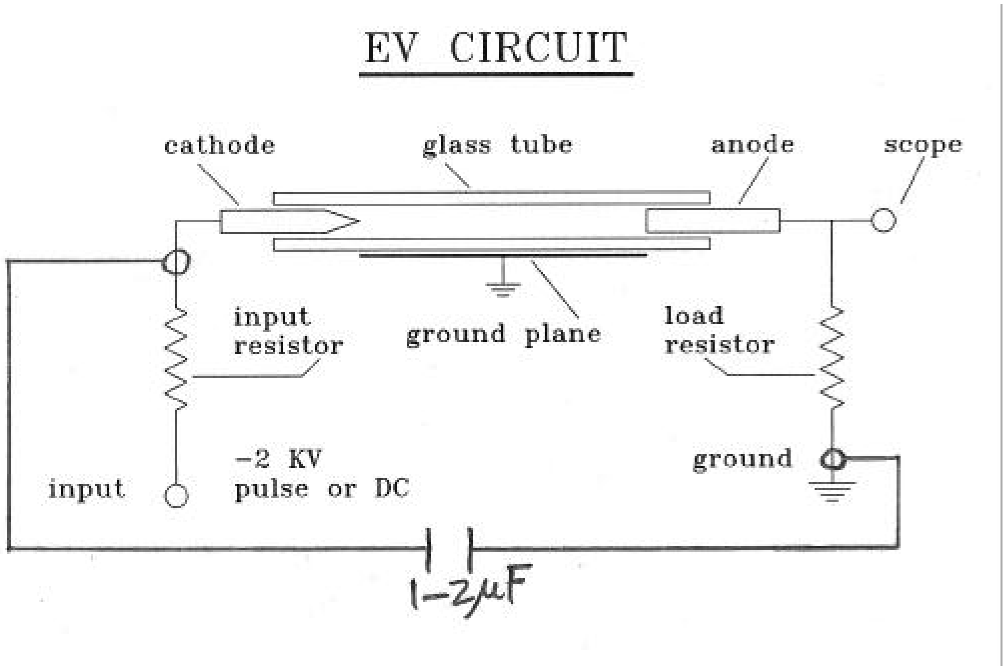

Figure 8. Schematic of the Basic EV Experimental Apparatus Circuit (from Shoulders, 1987).

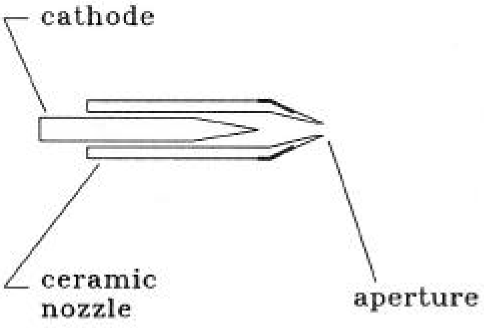

Figure 9. Schematic of the Basic Experiment EV Source (from Shoulders, 1987).

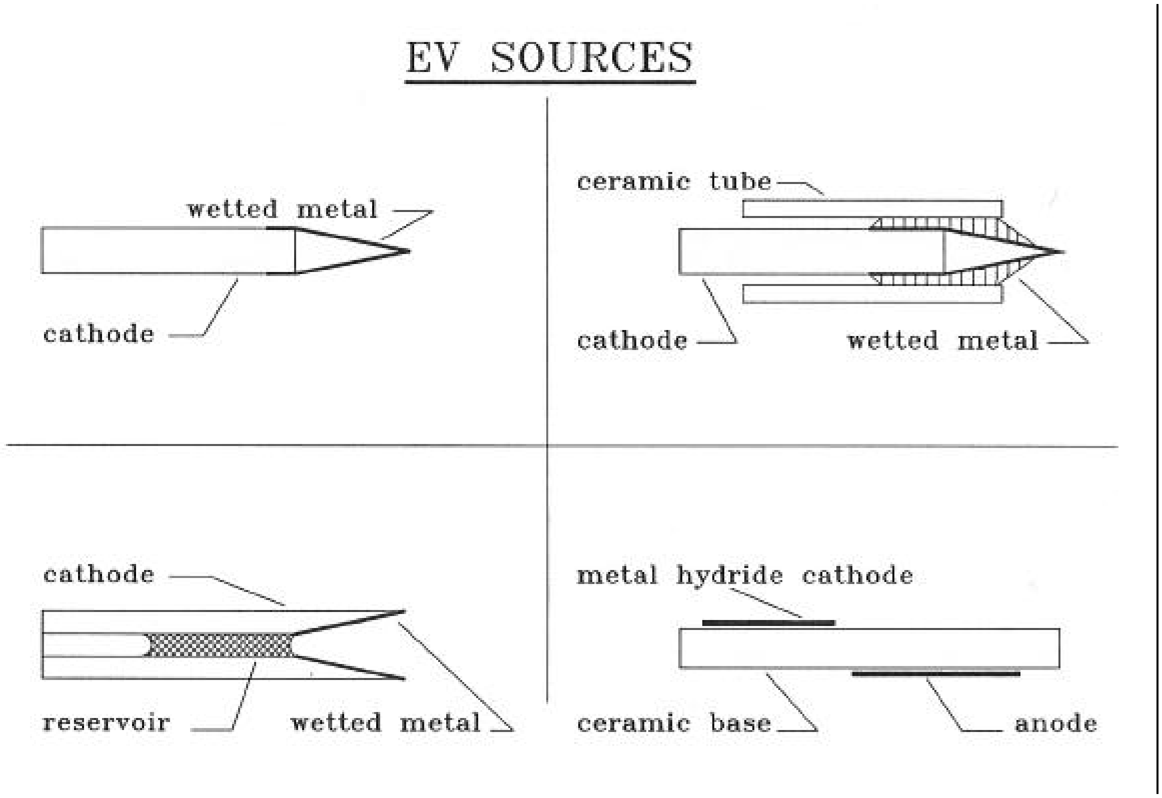

Figure 10. Examples of Other EV Sources (from Shoulders, 1987).

The peak energy at the cathode is limited to a value that is just high enough to generate an EV. This is done by putting a current-limiting (input) resistor in the cathode circuit, and placing it as close as possible to the EV source. This resistor is made to be an integral part of the EV source by firing the resistor into the ceramic material comprising the source. The capacitor is connected from the ground to the cathode as shown in the figure. The glass tube (filled with low pressure gas) provides a long path-length region between the EV source (cathode) and collector (anode), and it functions to filter out everything (i.e., the disorganized plasma discharge components) except the EV, and guide them to the anode. The anode is an electrode operating at ground potential and functions to collect EVs transported through the glass tube from the cathode source. A load resistor connects the anode to the ground, and this is the point where an oscilloscope or other current measuring device is connected. The load resistor must be sufficiently low so that the voltage will not rise too high and reflect EVs arriving at the anode. A reasonable maximum is 500 volts for EVs made with a 2 – 5 kilovolt pulse, and lower voltages are better. An interesting “EV law” Shoulders discovered is that the anode size defines an upper limit to the collected EV size (or current). The current can vary from 1 to 6 amps, however, it was found that 1 amp of anode current is produced by a chain of three to five 1μm diameter beads (with an overall diameter of 3 μm). The pulse repetition rate for the cathode EV source can range from several kHz to several MHz. Observations can be recorded by optical photography (through a microscope fitted with a TV camera), SEM photography, STM photography, and pinhole electron camera photography. An oscilloscope with adequate bandwidth is required to measure the voltage since the voltage rise-rate is very high. Therefore, a wideband (100 GHz), low voltage (50 V) oscilloscope is necessary, and this device could be (assembled as) a small chip structure located close to the experiment.

5.3.2 Basic EV Experiment Cost Estimates

Cost estimates for this experiment are based on new equipment and is outlined in the following:

- EV Circuit (outlined in Section 5.3.1): $100 – $200
- Ordinary lab oscilloscope (1 – 2 ea.): $1,500 – $3,000
- SEM/STM: leased or borrowed
- Pinhole electron camera: $100 - $200
- Xenon gas (25 L bottle): $995
- Power supply [0 – 15 V dc, < 500 mA (no load), < 1.5 A (full load) input; 0 – ±5 kV dc, 2 mA, 10 Watts output; where output is proportional to input voltage; pulsed power can be rigged by modifying EV circuit]: $200 - $500
- Microscope with TV camera: $3,000 – $5,000
- Voltmeters (1 – 2 ea.): $150 - $300

Total estimated raw (new) equipment cost is $6,045 – $10,195. The labor cost for a competent technician to work about two months to get this set up, calibrated and working is estimated to be $20,000 (including overhead). The labor cost for two more months to perform a rigorous series of experiments is estimated to be $20,000. Total estimated labor is $40,000. The total overall cost estimate is then $46,045 – $50,195. Not included in this estimate is the time for the principal investigator(s) to evaluate the data and assist the technician during the experiments, and other miscellaneous lab overhead. If good used equipment is substituted, then the total estimated raw equipment cost would drop by a factor of 1.5 – 2. This experiment can be set up and conducted at the Institute for Advanced Studies at Austin (Texas) since this is where the majority of the EV work has been done in the past. If, in addition to the above basic EV experiment, one desires to experiment with the other EV device applications described by Shoulders (1987), then one needs to merely add $100 – $200 for the cost of each additional EV device circuit to the above overall cost estimate.

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214 Nuclear Engineering Laboratory
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NASA Glenn Research Center
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21000 Brookpark Road, MS: 86-2
Cleveland, OH 44135

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DARPA/ATO
3701 N. Fairfax Dr.
Arlington, VA 22203

Dr. [redacted] (1 CD)
Sr. Analyst, Director for Intel Production
Missile & Space Intel Center
Defense Intelligence Agency
Washington, DC 20340-6054

Dr. [redacted] 1 CD)
NASA Glenn Research Center
21000 Brookpartk Road, MS: 5-10
Cleveland, OH 44135

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SA---
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