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Ball Lightning Events Explained as Self-Stable Spinning High-Density Plasma Toroids or Atmospheric Spheromaks

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ABSTRACT Spinning plasma toroids, or spinning spheromaks, are reported as forming in partial atmosphere during high-power electric arc experiments. They are a new class of spheromaks because they are observed to be stable in partial atmosphere with no confining external toroidal magnetic fields, and are observed to endure for more than 600 ms. Included in this paper is a model that explains these stable plasma toroids (spheromaks); they are hollow plasma toroids with a thin outer shell of electrons and ions that all travel in parallel paths orthogonal to the toroid circumference—in effect, spiraling around the toroid. These toroids include sufficient ions to neutralize the space charge of the electrons. This model leads to the name Electron Spiral Toroid Spheromak (ESTS). The discovery of this new class of spheromaks resulted from work to explain ball lightning. A comparison is made between the experimental observations of spheromaks in partial atmosphere and reported ball lightning observations; strong similarities are reported. The ESTS is also found to have a high ion density of $>10^{19}$ ions/cm^3 without needing any external toroidal magnetic field for containment, compared, for example, to tokamaks, with ion density limits of ~10^{15} ions/cm^3. This high ion density is a defining characteristic and opens the potential to be useful in applications. The ESTS is a field reversed configuration plasma toroid.

INDEX TERMS Ball lightning, electron spiral toroids, high ion density, plasma toroids, spheromaks, field reversed configuration.

I. INTRODUCTION

Spheromaks are self-organized plasmas in a toroidal shape, in which an internal magnetic field is produced by the internal current flow in the plasma [1]. Spheromaks have been studied since the 1950s [2]–[4] because of their potential in the field of nuclear fusion as a plasma confinement device or a reactor fueling device [5], [6]. There is also potential as an intense X-ray generating device because the spheromak can be magnetically compressed and accelerated [7], [8].

Many laboratories are currently conducting spheromak experiments with spheromaks formed in high vacuum and at high energy. For example, this work is reported by the Princeton Plasma Physics Laboratory, Los Alamos National Laboratory, the University of Washington, the University of New Hampshire, and the Swarthmore Magnetofluids Laboratory, to name just a few [9]–[13]. The work at these labs is reported as conducted in large spheromak containment chambers that are necessary to create high-vacuum environments and to provide external magnetic containment.

This paper presents observations of spheromaks that are produced in partial atmosphere in a laboratory, using electric arcs that are similar to lightning events [14]–[16].

The spheromaks reported here are stable without any external toroidal magnetic field for containment. They are formed in partial atmosphere in a bell jar, rather than in the high vacuum in large containment chambers, as reported in most spheromak research [17]. This is a new class of spheromaks, called Electron Spiral Toroid Spheromaks, or ESTSs, and was first reported in 2001 by Chen [18]. An excerpt from that paper notes, ‘‘It is found that a class of self-organized [ESTS] equilibria exists with or without an externally applied toroidal magnetic field. It is shown that in the absence of any applied toroidal magnetic field, the [ESTS] equilibria are stable at high electron densities, i.e., at high toroidal self-magnetic fields, although they are unstable at low electron densities, i.e., at low toroidal self-magnetic fields.’’ Chen's paper was written to analyze and explain the stable plasma toroid experimental results from the laboratory of Electron Power Systems, Inc., (EPS).

II. OBSERVATIONS

Electron Spiral Toroid Spheromaks (ESTSs) have been created at Electron Power Systems, Inc. for a number of years by using high-power electric arcs with similar current densities and pulse widths to lightning events [19]. The ESTSs are observed to be stable in partial atmosphere with no confining external toroidal magnetic fields. ESTSs formed by arcs are often observed to be spinning, and so have the appearance of spheres that create light through collisions with neutrals in atmosphere. A method for generating ESTSs has been patented [20]. In the latest experiments, the ESTS is formed around the electric arc, as shown in Fig. 1 — a new observation (patent pending). Ongoing experimental work to increase the ESTS density produced the fully formed ESTS in Fig. 2.

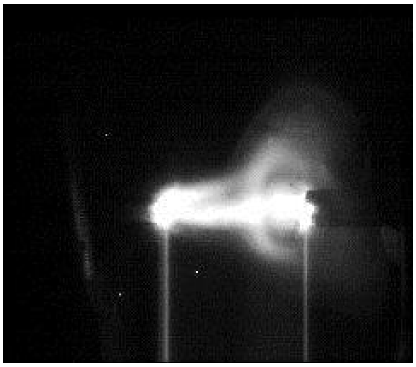

FIGURE 1. Plasma toroid, or spheromak, formed around an electric arc in 1/8 atmosphere of nitrogen.

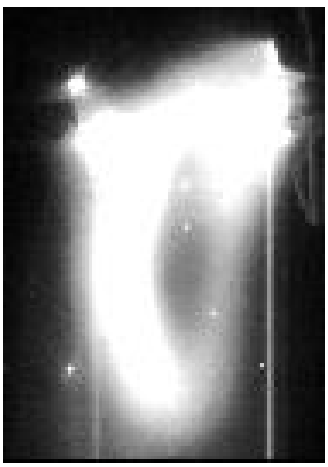

FIGURE 2. A 7.9 cm Electron Spiral Toroid Spheromak moving away from the initiating arc at the top of the image.

The observation in Fig. 2 is consistent with the behavior of a smaller 0.5 cm ESTS, which for many years has been observed and reported to form from an arc, and then leave the arc while maintaining its shape, as seen in Fig. 3.

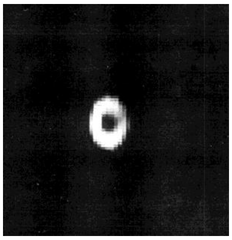

FIGURE 3. A 0.5 cm ESTS observed during an electric arc experiment.

The ESTS in Fig. 3 is observed to endure for more than 200 milliseconds (msec) in 1/8 atmosphere of nitrogen before passing out of the field of view of the experiments. Pressures used have been in the range of 1/16 atmosphere to 1/2 atmosphere; although the upper limit has not been explored to date and it is expected that they can form in full atmosphere. ESTSs formed by an arc (as in Fig. 3) and leaving the arc are normally spinning rapidly after initiation. In Fig. 3 the spinning has been effectively slowed using a high-speed video camera at 1/10,000 second shutter speed. The size of the earliest ESTSs observed was 0.2 cm to 1.0 cm [19].

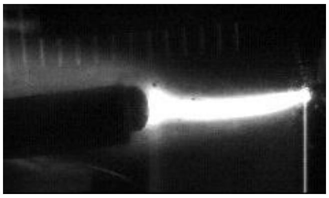

FIGURE 4. A typical stable arc used to form an ESTS (note bell jar shield in upper left of image).

Although the initial observations of small ESTSs were interesting, useful applications were seen to require a method to scale up the size of the ESTSs. A method was recently developed to scale up the ESTSs to 8 cm, as shown in Figs. 1 and 2. First, it was necessary to form stable arcs of high energy, which was done as shown in Fig. 4. The arcs accommodated currents in a wide range, from hundreds of amperes to a few thousand amperes. This range of currents will produce arcs with currents consistent with lightning events [16].

Using a combination of experiments and analysis, we recently found an arc arrangement that allowed us to form large spheromaks around the arc, as shown in Fig. 1. A typical large spheromak is shown in Fig. 2. Work continues to increase the density and to characterize more accurately the properties of these large spheromaks.

III. PROPOSED MODEL

During the ESTS initiation phase, electrons are observed to leave the arc and to begin to orbit around it. In the model presented here, ions are trapped within the electron orbits because ions are plentiful in and near the arc, due to the arc dynamics; ions also form outside the ESTS, near its surface, from collisions with neutrals. The role of the ions is

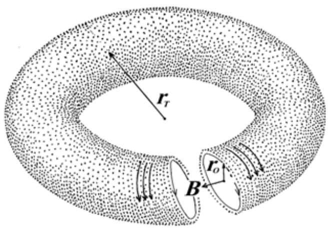

FIGURE 5. The ESTS with parallel electron orbits and internal magnetic field.

important because they act to neutralize the space charge of the electrons. The ions internal to the ESTS also act to hold the electrons in orbit. The model is shown in Fig. 5.

The physics for the self-stable spheromak were first published by Chen [18], followed by a set of engineering formulas published by Seward in 2001 [19] with the solenoid field equation used to approximate the magnetic field inside the toroid:

$$B = \frac{\mu_0 i}{k_0 d_e} = \frac{\mu_0 e V}{k_0 d_e^2} \tag{1}$$

where $-e$ is the electron charge, k_O is the spacing between orbits, d_e is the electron distance, "i" is the current and is equal to eVn/d_e where V is the electron velocity and n is the number of electrons. After the initiation phase, if conditions are correct and enough electrons form into the surface, the ESTS will transition into a state in which the forces reach equilibrium. In this way, collective forces are established within the toroid to stabilize its geometry.

The forces on a single electron can be defined. We assume for this model that the electrons form a thin toroidal shell, and therefore the force on a single electron from the other electrons is:

$$F_e = \frac{e^2}{\varepsilon_0 k_0 d_e^2} \tag{2}$$

The magnetic force on each electron due to the internal magnetic field is:

$$F_m = \frac{\mu_0 e^2 V^2}{k_0 d_e^2} = \frac{e^2 V^2}{\varepsilon_0 k_0 d_e^2 c^2} \tag{3}$$

The internal ions attract the electrons with a force:

$$F_i = \frac{e^2}{\varepsilon_0 k_0 d_i^2} \tag{4}$$

Where $d_e = f_i d_i$ is the ion distance and f_i is the ratio of ions to electrons. The force of rotation on each electron is:

$$F_r = \frac{mV^2}{r} \tag{5}$$

Where m is the electron mass and r is the electron orbit radius. The forces acting on the ions are, similarly:

$$F_{ion} + F_{rotation} = F_{magnetic} + F_{confinement} \tag{6}$$

Because F_r and F_m are small relative to F_i, this reduces to the following equality, which can be defined as the ion equilibrium condition:

$$\frac{e}{\varepsilon_0 k_0 d_i^2} = F_{containment} \tag{7}$$

This says that the ion equilibrium condition can be met with a containment force. In our model, we calculate that this is the atmospheric pressure in which the arc is formed. The atmospheric force on a single ion is:

$$F_P = P k_0 d_i^2 = F_{containment} \tag{8}$$

Where P is the pressure. For the ESTS to be in equilibrium, the forces on the electrons and ions must be in balance. For the electrons this is described as:

$$F_e - F_i + F_r + F_m = 0. \tag{9}$$

For the ions, this is described as:

$$F_i - F_P = 0 \tag{10}$$

Note that the sign of each force is relative to the surface of the ESTS.

The results of this analysis are consistent with the Virial theorem because the atmosphere pressure keeps the ESTS in equilibrium in atmosphere. A theoretical treatment of the stability of the plasma toroid in atmosphere has been completed, [18], [21] and these two references should be read together because the first assumes a fixed ion background while the second considers the ion motion.

IV. APPLYING THE PROPOSED MODEL TO THE EXPERIMENTS

The observed data relative to the ESTS in Fig. 2 demonstrate the ESTS equilibrium of forces using the above equations and model. The first ESTS data and balance of forces were originally reported for 0.5 cm ESTSs [19].

The radius of the toroid in Fig. 2 is observed as 0.033 m, and the radius of the electron orbit is observed as 0.0066 m, resulting in an overall diameter of 7.9 cm, with an aspect ratio of 5:1. The pressure is 0.125 atmospheres of nitrogen. The electron energy in the surface of the ESTS is estimated as 10^{-6} eV with electron velocity of 593 m/s.

With three assumptions we can calculate all of the forces in the model. The first assumption is that the electrons are equally spaced, providing a geometric ratio of orbit distance to electron distance of $k_O = 0.87$. Second, the theoretical treatment assumes an ion fraction utilized in the theoretical treatment of 1.001 [18]. Finally, d_e and d_i are assumed to be close, with d_i smaller by the ion fraction.

Because the background pressure provides the restoring force, using equation (9) above, d_e is calculated as 7.69×10^{-8} m, at which value the forces within the ESTS are in equilibrium.

The original proposed model demonstrated equilibrium for an electron surface of a single electron shell a single electron thick, and similarly, an ion surface a single ion thick [19]. The reason for this one shell was a tacit assumption that the ESTS contained only particles captured within the ESTS volume at time of formation. It turns out that observations suggest that this limitation is too restrictive. The ESTS forms around the arc and is seen to continue to accumulate charged particles for as long as initiating conditions remain in place, observed for a few hundreds of msec to date.

The model has been extended here to an ESTS with multiple thin shells. This suggests that an electron shell is the outermost surface, with an ion shell next, then an electron shell, then an ion shell, and so forth. The alternating electron and ion shells would maintain the charge neutrality. This series of shells would continue to accumulate as long as the force balance remains in equilibrium, which by this model would be limited by the total internal magnetic field strength because it increases with the increasing number of shells.

The balance of forces holds for each shell. In addition, the number of shells sets the overall limit to the number of charged particles by setting the limit to the internal magnetic field, which acts to repel electrons. The example analyzed here achieves the balance of forces up to a maximum of 486 shells, and a total of 2.67×10^{-10} Coulombs of charged particles. The internal magnetic field at these values is 6.09 Tesla, using the formula for a closed solenoid.

The equations above have been incorporated into a computer model of the ESTS that is found to be useful to describe and predict the experimental results.

V. BALL LIGHTNING COMPARISON TO EXPERIMENTAL ESTS OBSERVATIONS

Ball lightning is seen to occur in atmosphere during or in the proximity of lightning events, and is reportedly in spherical form, or toroidal form [14]–[16], [22]. The case is made here that ball lightning could be a spheromak. This is based mainly on the experiments reported here because they produce spheromaks that exhibit characteristics ascribed to ball lightning.

Many researchers have been intrigued by ball lightning because it has been reported thousands of times over the past 2,000 years. Researchers have offered explanations of ball lightning, but the non-reproducibility of ball lightning in atmosphere has made it difficult to reproduce it definitively in a laboratory or to develop its theoretical explanation [23]. Attempts using microwaves to produce ball lightning in atmosphere in laboratories, for example, have been reported [24], [25]. Also reported have been attempts to use direct current discharges to produce ball lightning, [26]–[28] but there is, as yet, no consensus that these results provided a definitive ball lightning explanation [29].

Experiments reported here are based on producing lightning-level electric arcs in partial atmosphere. Initially, the experiments produced small, bright, spinning spheres that left the arc. In analysis of these with a high-speed camera at shutter speeds of 1/10,000 second, the spinning was found to be stopped and the small, bright spheres were seen to be small rings or toroids. Based on these observations, Chen was able to derive the physics of a new class of plasma toroids, or spheromaks that remain stable in partial atmosphere with or without an external toroidal magnetic field for containment, as long as the density of the plasma toroid is greater than a critical value [18].

It is interesting to compare the experimental observations with what is known about ball lightning. There are thousands of published reports of ball lightning sightings, as noted in the references, with Ohtsuki summarizing 2013 descriptions for example [22]. A summary of observed ball lightning properties is located on Wikipedia.org and includes: ‘‘they are generally spherical with fuzzy edges; their diameters range from 1–100 cm; their brightness corresponds to that of a domestic lamp; many are described as having rotational motion.’’ These are consistent with the experimental observations reported here.

The fuzzy edges are likely the ions formed around the edges as background gas neutrals collide with the ball lightning, and the same effect is seen around spheromaks during the experiments as seen in Fig. 1. The diameters reported are consistent with the computer model above, and the experiments to date have produced spheromaks of 0.2–14 cm, with no known upper limit. The brightness is consistent with observations of the experiments. Finally, the small ESTSs of Fig. 3 have always been observed as spinning during the experiments.

Of particular note here are reports that ball lightning does occur in ring form. Ohtsuki reported nine such observations, which appears to be a strong clue and perhaps even a confirmation that ball lightning may be a spheromak [22]. Note that a spinning ring with no holding forces applied will spin randomly about any of its three axes, and so a spinning ring might appear randomly as a sphere, or a band, or an oval, or a ring, all of which Ohtsuki reports. All of these shapes and more have been observed during experiments at EPS. As part of a research contract, our consultants produced a computer simulation of a spinning toroid and demonstrated that these and other shapes would be expected to occur.

The multiple shell model for the ESTS proposed above are also consistent with observations of ball lightning. The one observer who reportedly has witnessed the formation of ball lightning in air noted that the ball lightning formed while ‘‘blowing up like a balloon’’ over a period of several seconds [17]. He reported that the ball lightning was seen to come out of a telephone receiver, expand to about the size of a soccer ball over many seconds, then float around the room, gently bounce off his face (leaving no burn marks), and then settle on his mother’s stomach (as she was lying on a bed); it ended with a loud bang, without hurting anyone.

What is observed during ESTS formation experiments is that the ESTS remains in place while forming, and under the right circumstances electrons and ions can be added, likely in outer shells, causing the density to increase visibly, as evidenced by the ESTS brightness increases. This would increase the overall total charge to a point greater than that contained in the original volume. The model allows for this possibility. The implication of this is that the ESTS ion density can be quite high, as predicted by the computer model; this is presently being studied experimentally.

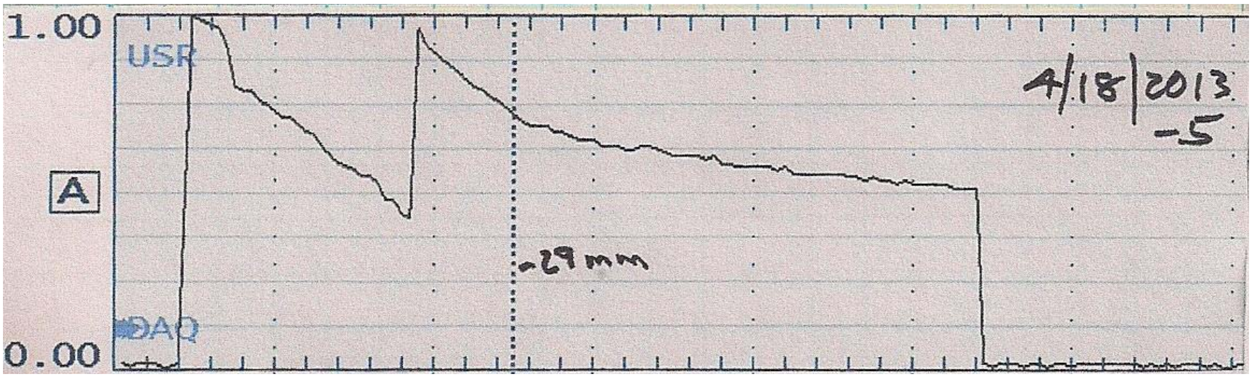

FIGURE 6. Normal arc current characteristic when no ESTS is present; horizontal scale is 40 millisec/mark; vertical is 3.68 amperes/mm with 5 mm/mark; 4/18/2013-5 is the date and the experiment ID.

FIGURE 7. A current trace showing the point of ESTS formation at 860 msec; the –25 at that point is the 25 mm current trace measurement, which equates to 92 amperes (for one of three identical power supplies).

A word of caution: the published observations of ball lightning are descriptions made by normal people under unusual circumstances, and as a result, have not yet led to a definitive explanation of ball lightning. The experimental observations reported here give a good picture of a stable plasma toroid, or spheromak, which resembles ball lightning. A definitive experiment to tie the two together would be interesting.

A suggested definitive experiment would be to record many lightning strikes at a tall building or antenna that repeatedly attracts lightning. A video camera with a fast shutter speed could be left over time in a weatherproof housing to record many strikes. With luck, a ball lightning would pass by and be recorded in stop action to reveal its toroidal shape. Note that care must be taken to set the light filtering of the event correctly, and experience indicates that two cameras would be better — one with a filter setting to observe the bright sphere, and the second at an appropriate filter setting and shutter speed to reduce the brightness in order to ''stop'' the spinning.

VI. HIGH ION DENSITY MEASUREMENTS

Work has been completed to measure the density of the ESTS on a preliminary basis. Ion density was measured to be greater than 10^{17} ions/cm^3 with no confining toroidal magnetic field.

We first discovered that the formation of the ESTS caused a significant change in the current of the arc. Fig. 6 shows the normal arc current characteristic when no ESTS is present. The power supply is capacitive and exhibits the expected exponential curve. For explanation, the trace shows the characteristic of a drawn arc, with the electrodes touching at the start, the drawing apart, and, at approximately 360 msec the significant increase in current. This dual current approach is used to protect the electrodes at the start of the event.

Fig. 7 demonstrates that the arc current undergoes a significant change that occurs at the time that the ESTS forms. This change in current is measured as 5 mm on this trace, but because three power supplies are used to reach the current required, and three traces are made during each event, the total current is measured as 18.4 amperes for 40 msec, or 0.737 Coulombs of charge per 40 msec. This current goes directly into the ESTS, which is consistent with the video observations. Because this is a charge neutral plasma and ESTS, no magnetic confinement is needed to hold this charge in place.

The experiment ends at approximately 1,080 msec. In this case, the ESTS was still forming at 200 msec at the end of the experiment, for a full charge of 3.68 Coulombs.

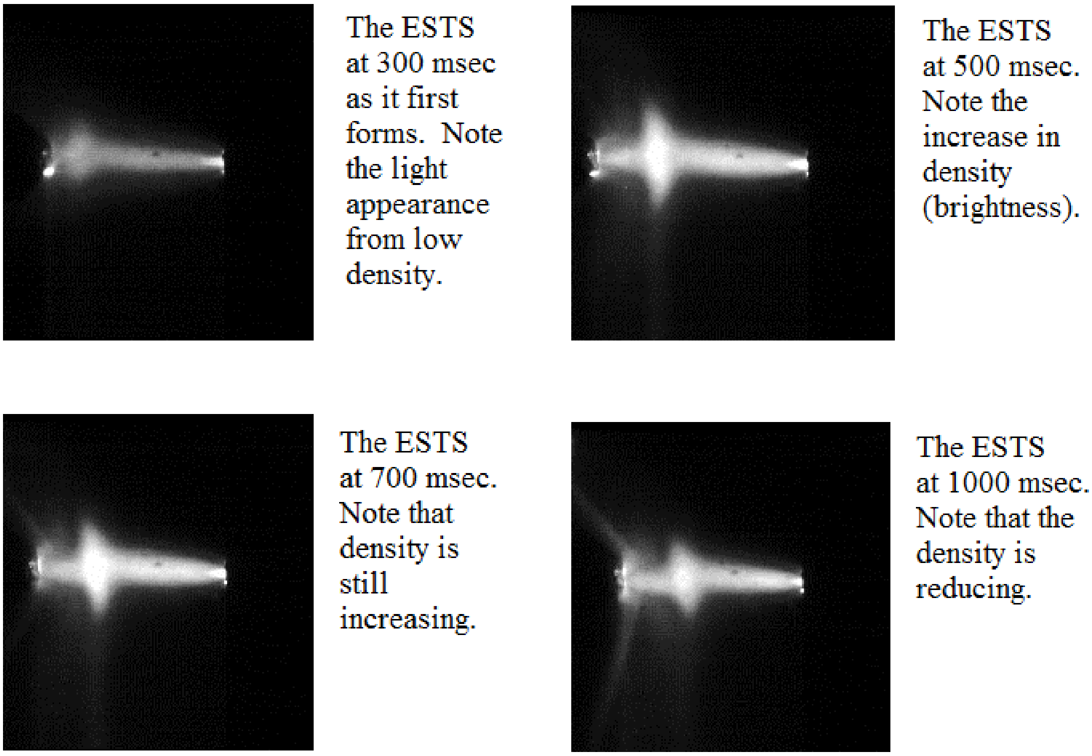

FIGURE 8. Photos showing the ESTS at different times during the experiment, and the changes in density.

The density of the ESTS can be estimated using this initial estimate of charged particles. The ESTS volume is calculated as 7.7×10^{-7} m^3 with toroid radius of 0.00625 m and orbit radius of 0.0025 m, as observed. Density is the electrons/volume calculated as 2.98×10^{25} electrons/m^3 or 2.98×10^{19} electrons/cm^3. Because the number of ions and electrons has to be essentially equal to ensure charge neutrality, the ion density is the same as the electron density, or 2.98×10^{19} ions/cm^3. More work is in progress to verify this initial set of results. The computer model calculates the density as greater than 10^{17} ions/cm^3 with conservative assumptions and supports densities greater than 10^{19} ions/cm^3.

Fig. 8 shows the ESTS at different times during the experiment. It is a side view only, and the shape is a band rather than the more characteristic toroidal shape of Figs. 1–3. This set of images is from a different experiment than was either Fig. 6 or Fig. 7. Fig. 8 shows the increasing density with time, which appears visually as increased brightness. The density reduces late in the experiment as the power supply discharges and is unable to maintain the conditions necessary to increase the density. With a longer experiment we project that the density will increase above the critical density needed to remain stable, as seen in Fig. 3.

VII. FIELD REVERSED CONFIGURATION PLASMA TOROID

The ESTS is a new kind of FRC (Field Reversed Configuration) plasma toroid. An FRC plasma toroid is a plasma configuration starting as a plasma beam and then formed into a toroid by using externally applied magnetic fields. As the FRC plasma toroid forms, the internal magnetic field inside the plasma toroid is reversed compared to the externally applied magnetic fields [32]. The cited reference here is a particularly excellent reference on the Internet that provides further diagrams and discussion and is agreed to by a long list of notables in the FRC field.

There are two significant features of the ESTS that separate it from all other FRCs that we have seen reported to date. First, there are no externally applied magnets needed to shape the ESTS because the ESTS is formed around an electric arc, and the arc itself provides the shaping magnetic field under the proper circumstances. This one feature makes the ESTS initiator small in mass and size compared to all other reported approaches. The second feature of the ESTS is that it has high density, high enough that it will remain self-stable without any externally applied magnetic field containment as described by Chen. These two features have a significant positive impact on applications.

VIII. POTENTIAL APPLICATIONS

Work has been done to determine useful potential applications for the ESTS and several are briefly described here. The first potential application is an air defense beam, because the ESTS is stable in air and also can potentially be accelerated to high velocities (calculated as 600 Mach) to then hit a target at 65 Km distance in less than a second.

The second potential application is a new method for creating X-rays, given that ESTSs have been accelerated in experiments and calculations show that they can potentially be accelerated and then stopped on a target to create X-rays across a wide range (of soft-to-hard X-rays) by controlling the acceleration of the ESTS.

The third potential application is an improved colliding spheromak fusion energy process. By comparison, the Tokamak approach can achieve approximately 10^{15} ions/cm^3. A colliding spheromak fusion process reported by Wells in the 1980's reportedly achieved ion densities of 10^{16} ions/cm^3 [32]. The ESTS is measured to have greater than 10^{19} ions/cm^3 on a preliminary basis potentially leading to an improved colliding ESTS fusion process. Because no confining toroidal magnetic field is needed, the apparatus needed for this is calculated to be similar in size to a neutron tube, and a potential product would be a 10kW backup generator, which could potentially lead to a clean, practical fusion energy process and product.

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