BALL LIGHTNING EXPLAINED AS A STABLE PLASMA TOROID

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Abstract

Spinning plasma toroids are created using high power electric arcs similar to lightning bolts. The spinning toroids are observed to be stable in atmosphere with no confining magnetic fields. Spinning toroids have the appearance of spheres, or balls, and create bright light through collisions with neutrals in the atmosphere. The spinning toroids are observed to last for more than 200 milliseconds in partial atmosphere. This paper describes the initiation apparatus and parameters. An explanation for the plasma toroid is presented that it is a hollow toroid of electrons where all the electrons travel in parallel paths orthogonal to the toroid circumference and reside in a thin outer shell of the toroid. The electron motion creates a current in the surface that in turn creates an internal magnetic field. Equations are presented detailing the initiation of the plasma toroid, and detailing the plasma toroid itself. The stability analysis for the plasma toroid has been completed that explains how the plasma toroid remains stable in atmosphere. The spinning plasma toroid has the appearance of Ball Lightning, in observations, computer simulations, and equations. The plasma toroid explains how a plasma ring can be stable in atmosphere with no external magnetic fields, and how it can contain many electrons with high energy. Ball lightning is often reported as a ring current, in toroid shape, and since a spinning ring appears as a sphere or ball, the spinning plasma toroid provides an explanation for Ball Lightning. The technology of the plasma toroid has the potential for new applications in propulsion and energy generation and storage.

I. OBSERVATION

Spinning plasma toroids (SPT's) have been created in the labs of Electron Power Systems, Inc. for a number of years using high power electric arcs similar to lightning bolts. The SPT's are observed to be stable in atmosphere with no confining external magnetic fields. SPT's have the appearance of spheres, or balls, and create bright light through collisions with neutrals in atmosphere. The SPT's are observed to endure for more than 200 milliseconds in partial atmosphere of 0.1 to 10 Torr. A plasma toroid is shown schematically in Fig. 1.

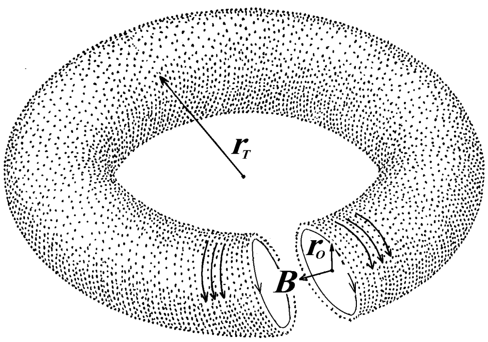

Figure 1. The Plasma Toroid with Parallel Electron Orbits, and Internal Magnetic Field.

A method for generating stable plasmas has been demonstrated and patented [1]. Proof of concept experiments are being completed. A project is underway to scale the results up to a demonstration unit. A typical SPT as generated is shown in Fig. 2. Typically, the SPT is spinning rapidly after initiation. In this figure it has been slowed down with high-speed video at 1/10,000 shutter speed. The picture is of SPT tilted toward the camera.

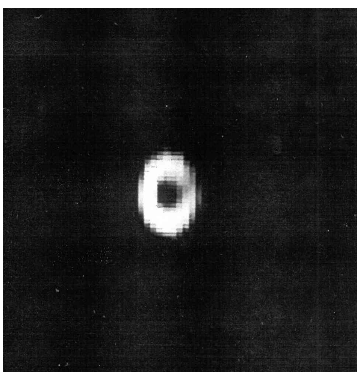

Figure 2. A Stable Plasma Toroid Observed in an Arc Discharge Experiment

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The SPT has the appearance of Ball Lightning in that it looks like a bright ball in atmosphere. Ball lightning is often reported as a ring current [2], which would occur when the spinning is stopped. It will be difficult to prove that any phenomenon is ball lightning until a natural occurrence is captured and definitively analyzed. Until then, the SPT is an explanation that conforms to the reported observations. The conclusion is that the stable plasma toroids produced at EPS, Inc. are a potential explanation for ball lightning.

II. INITIATION

An SPT forms in an electric arc when initiating conditions are correct. An arc forms a circular magnetic field as shown schematically in Fig. 3. An arc is created between two electrodes using well-known techniques [3].

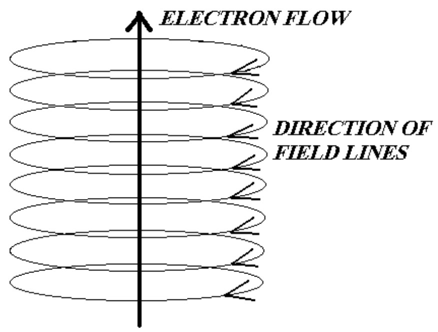

Figure 3. Circular Magnetic Field Formed by an Initiating Arc.

The electrons flow in the arc from the initiating cathode as shown schematically in Fig. 4.

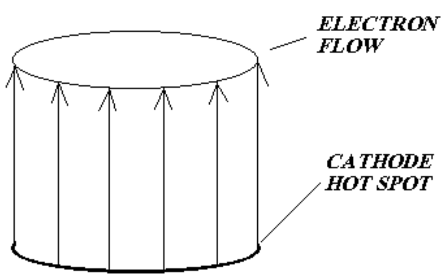

Figure 4: Electrons from the Cathode Hot Spot

The arc from the cathode hot spot has a substantially uniform current density [4], as shown schematically in Fig. 5. The arc creates a magnetic field, which is weakest in the center and strongest at the edges of the arc.

The electron energy is well known [3]. There is a ballistic region of one mean free path where the electrons from the cathode are accelerated to energies up to 14 eV. Normally the velocity of the electrons is great enough and the magnetic field of the arc is small enough that the electrons will not orbit, but will move in the direction of the arc.

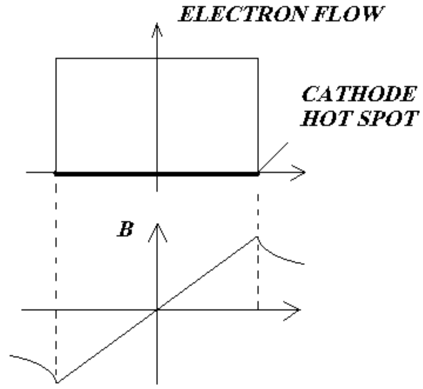

Figure 5. Distribution of the Electrons and B Field in the Initiating Arc

However, if conditions change sufficiently in the arc, the electrons in the outer edge of the distribution will begin to orbit. If the magnetic field strength in the arc increases above a critical level, it will cause the electron radius to decrease and the electrons will begin to orbit inward as shown in Fig.6. This can occur, for example, if the arc current increases with constant radius, or if the arc diameter decreases for a constant current. If the magnetic field strength increases above a critical point, the electrons will be trapped as in Fig.6. Note the mean free path must be greater than the circumference of the electron radius, which is consistent with the references [3]. Fig. 6 shows the capture of two orbits, since the figure is a cross section.

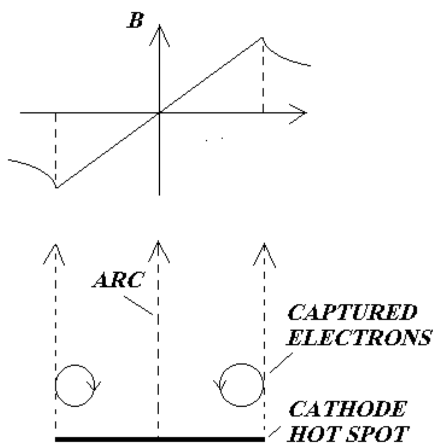

Figure 6. Schematic of Capturing of Electrons at the Edge of the Arc

Fig. 7 is a top view of this process and shows that electrons will be captured all around the arc if conditions are right. The orbits will be generally the same radius, and generally parallel.

If initiating conditions are right, and enough orbits form, the orbits will generate an internal magnetic field similar in concept to a classical toroidal solenoid. With proper initial conditions, the individual orbits will join into a single toroid shown in Fig. 1.

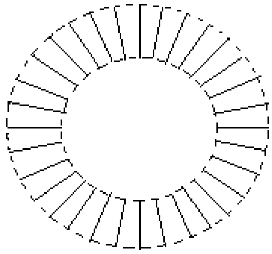

Figure 7. Top View of the Orbits of Captured Electrons.

The initiation phase process can be calculated using well-known formulas consistent with experimental observations. During the initiation phase, at the time the electrons begin to orbit, ions will be trapped within the electron orbit. It is well known that ions are plentiful in the arc due to the arc dynamics. Many ions have a velocity much less than the electron velocity, so as the electrons form their orbit they will capture numerous ions in the process.

The role of the ions is important since they act to neutralize the space charge of the electrons. The ions also act to attract the electrons and to hold them in orbit. The forces of equilibrium of the SPT can be calculated as follows. For simplicity, a discrete particle model is used here; whereas a fluid model is available [5] that describes the physics of the electron flow in the SPT.

The solenoid field equation can 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 per orbit and is equal to eV/d_e , and V is the electron velocity. After the initiation phase, if conditions are correct, the SPT will transition into a state where the forces reach equilibrium, offsetting each other. In this way collective forces are established within the toroid to stabilize its geometry.

The forces on a single electron can be defined. Since the electrons form a thin cylindrical shell, 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 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 ions attract the electrons with a force:

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

where 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:

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

Since 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 experiments, this is the atmospheric pressure in which the arc is formed. The atmospheric force on a single ion is:

$$F_P = P\, k_O\, d_i^2 = F_{Containment} \tag{8}$$

where P is the pressure. For the SPT 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 is relative to the surface of the SPT and shows the direction of the forces.

The results of this analysis are consistent with the virial theorem stating that plasma cannot be stable by itself, since the atmosphere pressure keeps the SPT in equilibrium in atmosphere. A theoretical treatment of the stability of the plasma toroid in atmosphere has been completed [5]. Note that the equations predict that the containment force can be applied with other methods.

III. DATA

The observed data relative to the SPT in Fig.2 demonstrates the SPT equilibrium of forces using the above equations. The radius of the toroid is observed as

0.002 m, and the radius of the electron orbit is observed as 6.73E-4 m, resulting in a toroid aspect ratio of 3:1. The pressure is 1.32E-04 atmosphere (0.10 Torr). The electron energy is measured as 4.0 eV at the outer portions of the arc.

With three assumptions, we can calculate all of the forces above. The first is that the electrons are equally spaced, providing a geometric ratio of orbit distance to electron distance of $k_O = 0.87$. Secondly, the theoretical treatment assumes an ion fraction of 1.01 [5], which is used here. Finally, d_e and d_i are assumed to be close, with d_i smaller by the ion fraction.

All the forces can now be expressed as a function of d_e. Equating F_r to the arc magnetic force produces precisely the electron radius with arc current at 100 amperes and with electron energy of 4.0eV. The resulting electron velocity is 1.19E+6 m/s. The precise electron energy has not been measured at the point of origin, but is consistent with measurements by others [3]. Also, the arc current is observed to be split between hot spots and is not precisely measured, but is consistent with the total arc current divided by the number of hot spots.

From equation (9), d_e is calculated as 1.31E-07 m, at which value the balance of forces in the SPT is demonstrated. The total electron charge is calculated as 1.2 E-9 Coulombs, and there is a similar amount of ions.

One additional assumption has been made here and in the theoretical treatment [5], that the mean free path (mfp) of the electrons in the SPT surface is much greater than the mfp of a single electron in atmosphere. The rationale for this is that the electrons follow each other in orbit, and so experience collisions from the sides of the orbits, but not in the direction of travel. The theoretical treatment of this issue remains to be completed.

IV. BALL LIGHTNING DESCRIPTION

The formulas and analysis above can be extended to a configuration that is consistent with reported observations of ball lightning sizes [2]. The above formulas allow for a wide range of examples, all of which demonstrate equilibrium. One example is constructed here with toroid radius of 10 cm, an average observation. Electron energy is selected as 1000 eV, consistent with the voltages reported in the lightning event, but not measured. This electron energy value is not critical and can vary from a few eV to many thousands without upsetting the equilibrium since F_r is much less than F_e or F_i or F_P. Keeping the aspect ratio at 3:1, the arc current to form this radius is 1600 amperes, consistent with lightning return strokes reported by Uman [6].

From equations (9) and (10), d_e is calculated as 1.40E-08 m, at which value the equilibrium of forces in the ball lightning size SPT is demonstrated. The total charge is calculated as 2.56 E-4 Coulombs.

V. APPLICATIONS

The technology of the plasma toroid has potential for new applications. It has the potential to produce a high specific impulse, high thrust propulsion system [7]. The SPT also has potential for energy storage [1]. Four patents are issued and others applied for.

VI. SUMMARY

Spinning plasma toroids (SPT's) are generated in partial atmosphere using high power electric arcs that simulate lightning. The SPT's exhibit properties similar to those reported for ball lightning. A theory and equations has been developed that explain the observations, and how a plasma toroid can achieve stability in atmosphere with no external magnetic fields. The SPT's have several applications of potential value.

VII. ACKNOWLEDGMENTS

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