Energy capacity of an electromagnetic vortex in the atmosphere

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The self-localization of an electromagnetic vortex is investigated under conditions such that partial charge separation occurs in the plasma that forms near the vortex: outside the vortex there is an excess of electrons and inside it there is an excess of positive charges. It is shown that the presence of unneutralized charges increases the energy content of the vortex without increasing the energy dissipation of the high-frequency field in the plasma. The lifetime of the vortex can thereby be substantially increased. A mechanism is examined for confining a positively charged solid object in the interior of the vortex. This body serves as ballast and can retard the buoyant rise of the vortex in the atmosphere. The question of the formation of a hydrodynamic vortex at the periphery of an electromagnetic vortex by transfer of momentum from a high-frequency field to the surrounding medium is discussed; this affects the nature of the motion of the vortex in a free atmosphere. It is shown that the properties of the vortex are consistent with some of the properties of ball lightning.

1. INTRODUCTION

The interaction between a high-frequency electromagnetic field and a plasma can cause redistribution of the charged-particle density and give rise to a low-density closed region in the plasma within which the electromagnetic field is localized. Losses of electromagnetic field energy occur mainly at the periphery of this region, where dense plasma is in contact with the high-frequency field.

Alanakyan[1] showed that the equations of nonlinear electrodynamics admit solutions in the form of a self-localized electromagnetic vortex. In the two-dimensional case, this is an electromagnetic wave propagating in a circle and forming an annular waveguide channel in the plasma. A three-dimensional ring-shaped vortex forms a tubular toroidal waveguide in which the wave propagates in a spiral, i.e., the wave vector of the wave has a component along the major and minor circumferences of the torus. Note that the interior and exterior regions of the vortex are separated by a potential barrier produced by the spatially nonuniform high-frequency electromagnetic field (through the action of ponderomotive forces). The plasma pressure in the interior region is related to the structure of the electromagnetic field. In particular, it is possible to have a situation in which there is practically no plasma in the interior region, and the pressure of the external plasma is balanced by the pressure of the high-frequency field. A case can also arise in which the vortex compresses the plasma in the interior region to a pressure larger than the plasma pressure outside the vortex. Note that in this treatment the plasma is quasineutral and fully ionized. The lifetime of the vortex can be estimated by dividing the value of the energy contained in the vortex by the energy lost per unit time. The vortex energy is directly proportional to the pressure of the surrounding gas and to the volume occupied by the vortex. Energy losses of the electromagnetic field result primarily from electron—ion collisions in the peripheral region of the self-sustaining waveguide. The magnitude of the losses depends on the electron temperature, the plasma pressure, and the composition of the ionized gas. Under atmospheric conditions, when the dimensions of the vortex are of order tens of centimeters, the lifetime of the vortex treated in Ref. 1 is found to be considerably less than the average lifetime of ball lightning, which is found from observational data to be tens of seconds.[2–4]

The present work is devoted to the treatment of an electromagnetic vortex under conditions in which partial charge separation occurs: in the external region of the vortex there is an excess of electrons, while in the internal region there is an excess of positive charges. We study the case in which the pressure on the waveguide region due to the Coulomb attraction of the charges is larger than the thermal pressure of the gas. In this case the magnitude of the electromagnetic energy of the vortex is found to be proportional to the square of the number of particles of the unneutralized charge, and can be much larger than the energy of a vortex in a quasineutral plasma. We show that this object is electrically neutral as a whole, and the term "unneutralized charge" is used here only in respect to the external or the internal region of the vortex.

It is important to note that the presence of unneutralized charge does not lead to additional dissipation of the energy of the high-frequency field. This is because the particles carrying the excess charge penetrate further into the waveguide region under the action of the Coulomb forces than the particles of a quasineutral plasma, and they turn out to be almost totally insulated from the other components of the plasma.

The plasma object in question, located in a dense gas, has the following structure. In the neighborhood of the electromagnetic vortex a plasma layer forms with hot electrons, while outside the hot plasma in the surrounding gas a jacket consisting of low-temperature recombining plasma is found.[5] Note that the hot plasma has a sharp boundary, and here on the boundary with the cold plasma a double

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electric layer develops, which controls the flow of charge particles from the hot plasma.[6] The ions are accelerated by the electric field of the double layer, while the electrons, which pass over a potential barrier, lose a large part of their energy. A cold recombining plasma forms from these particles. We note that the flux of neutral particles from the cold region to the hot region is directed opposite the flux of neutral particles, which is equal to the flux of ions (electrons), so that the system is in dynamic equilibrium.

We note a number of properties of the vortical plasma formation that are compatible with those of ball lightning. Instances are well known (see, e.g., Refs. 2 and 3) in which ball lightning has passed through a slit or orifice whose dimensions are smaller than the visually observed dimensions of the ball lightning; it has happened that ball lightning has melted such a hole in glass and passed through it. These manifestations can be explained by properties of the plasma structure near the electromagnetic vortex. The point to note is that the energy of the vortical plasma structure is concentrated mainly in the waveguide region and in the plasma layer adjacent to this region with hot electrons. The structure of the hot region is essentially independent of the processes that take place in the low-temperature plasma, whose spatial dimensions can be larger than those of the waveguide and the hot-plasma layer adjacent to it. Moreover, the structure of the cold plasma can be restored if it is disrupted.

Let us now discuss the motion of ball lightning. Ordinarily ball lightning moves rectilinearly with constant velocity. Even in the last century[7] a resemblance was noted between the autonomous behavior of the motion of ball lightning and the motion of an annular hydrodynamic vortex, whose displacement velocity is close to the maximum rotational particle velocity. However, under atmospheric conditions the lifetime of 10-cm hydrodynamic vortices is found to be less than the lifetime of ball lightning. We direct our attention to the electromagnetic vortex and note that a high-frequency field transfers momentum as well as energy to the surrounding medium in connection with dissipative losses. This gives rise to the formation of a ring-shaped hydrodynamic vortex in the neighborhood of a ring-shaped electromagnetic vortex. The associated viscous losses of the hydrodynamic vortex are balanced by the momentum derived from the electromagnetic field, so that the lifetime of the hydrodynamic vortex is determined by that of the entire vortical formation.

Another question which requires investigation is associated with the fact that the average density of material in ball lightning cannot differ much from the density of the surrounding air. It is evident that if a low-density region were present in the interior of ball lightning it would float upward in the atmosphere, unless it were balanced by a corresponding ballast. Note that a number of recent treatments[8,9] have suggested the hypothesis that ball lightning has a polymer structure. Singer[2] also suggested that there is a connection between ball lightning and organic polymers. The point is, a plasma containing organic molecules can exhibit intense polymerization processes.[10] The polymerization time is inversely proportional to the particle density in the plasma. Such polymeric compounds can form in a linear lightning discharge, where the plasma is subjected to strong compression due to the pinch effect. Bichkov[9] studied an electrically charged network and showed that a network made of monomer methane and cellulose of mass 1 mg with transverse dimensions of order 1 cm can have a charge $\approx 10^{-5}$ C. In the present work we show that an electrically charged solid object can be confined in the interior region of an electromagnetic vortex. This body serves on the one hand as ballast and on the other as an accumulation of positive charges.

To conclude the article we discuss a possible mechanism for the occurrence of such a vortical structure associated with a pulsed electrical discharge.

2. BASIC EQUATIONS

Consider a plane electromagnetic vortex such that in cylindrical coordinates the electric field of the wave is in the z direction:

$$E_z = E(r)\exp(iq\varphi - i\omega t), \qquad (1)$$

where q is an integer which characterizes the number of waves propagating around the ring-shaped self-sustaining waveguide.

The amplitude of the electric field as a function of r is given by the equation

$$\frac{1}{r}\frac{d}{dr}\left(r\frac{dE}{dr}\right) - \frac{q^2}{r^2}E = -\frac{\omega^2}{c^2}\left[1 - \frac{4\pi e^2}{\omega^2}\left(\frac{n_e}{m} + \frac{n_i}{M}\right)\right]E, \qquad (2)$$

where n_e and m (n_i and M) are the electron (ion) density and mass. Note that in Eq. (2) the term proportional to the ion density can be important where there are unneutralized ions.

We are interested in the solution of this equation which goes to zero in the limits $r \to 0$ and $r \to \infty$. We will consider the case in which the thickness of the layer of hot plasma is considerably greater than the depth to which the magnetic field penetrates into the plasma and greater than the thickness of the double layer that forms at the boundary of the hot plasma and the weakly ionized gas. In studying the spatial profile of the electric field amplitude we will use the subscript ∞ to denote variables inside the hot plasma at points far from both plasma boundaries.

Note that the dynamic equilibrium between the hot plasma and the surrounding gas results from processes that take place in the double layer. Here neutral particles incident on the plasma undergo ionization, and a reverse flow of charged particles from the plasma to the surrounding gas develops. We note that the thickness of the double layers is characterized by the effective mean free path of a neutral particle with respect to ionization through collision with electrons in the hot plasma.[6] When the vortex is formed in the mixture of heavy and light gases, self-cleansing of heavy particles from the plasma takes place in the double layer.[11] Heavy particles do not reach the interior of the plasma because they are ionized in the double-layer region, where the constant electric field is large, and are expelled by this field back into the surrounding gas.

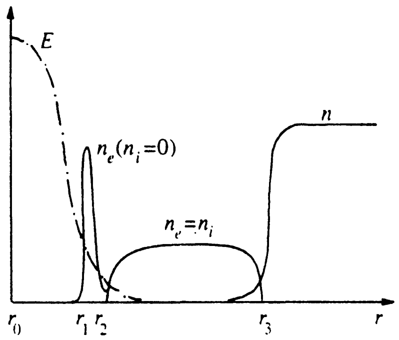

FIG. 1.

The mean free path of heavy particles into the plasma is short because their thermal velocity is smaller and their ionization cross section larger than that of the light particles. Taking this effect into account, in future we will assume that the hot plasma consists essentially of hydrogen ions and electrons.

In the hot plasma far from the double layer, all forces acting on a charged particle are in balance. We have

$$T_e \frac{d}{dr} n_e - e n_e \frac{d}{dr} \varphi + n_e \frac{e^2}{4m\omega^2} \frac{dE^2}{dr} = 0, \qquad (3)$$

$$T_i \frac{d}{dr} n_i + e n_i \frac{d}{dr} \varphi + n_i \frac{e^2}{4M\omega^2} \frac{dE^2}{dr} = 0. \qquad (4)$$

Here φ is the potential of the constant electric field due to charge separation in the plasma and due to the presence of unneutralized charges in the interior. This field is described by the Poisson equation

$$\frac{1}{r}\frac{d}{dr}\left(r\frac{d\varphi}{dr}\right) = 4\pi e(n_e - n_i). \qquad (5)$$

We restrict ourselves to considering the case in which the amplitude $E(r)$ of the high-frequency field has a single extremum. The extremal point is denoted by r_0. We assume that in the external region at the vortex ($r > r_0$) there are unneutralized electrons, while in the internal region ($r < r_0$) there are unneutralized positive charges.

3. EXTERIOR REGION OF THE VORTEX

Figure 1 presents a qualitative picture of the spatial distribution of the high-frequency electric field amplitude, the charged-particle densities n_e and n_i, and the neutral gas density n in the interior of the vortex.

There are practically no particles in the region $r_0 < r < r_1$, and consequently the electromagnetic field has vacuum properties. The unneutralized electrons are concentrated in the layer $r_1 < r < r_2$. We will devote particular attention to studying the structure of this layer. Then, for $r_2 < r < r_3$ we have a layer of hot, fully ionized quasineutral plasma in which the electron temperature is much greater than that of the ions. The spatial profile of the electromagnetic field and the plasma density under conditions such that the plasma pressure is balanced by that of the high-frequency field has been studied in a number of papers,[12–14] whose results we will use in what follows. In the region $r > r_3$ we have a dense, weakly ionized gas. In Fig. 1 this region is represented only by the spatial profile of the neutral gas component.

To simplify the treatment we assume that the effective thickness of the waveguide region is small compared with the radius of curvature of the waveguide:

$$r_0 \gg \Delta r = c/\sqrt{\omega^2 - k^2c^2}, \qquad (6)$$

where $k = q/r_0$.

Before proceeding to analyze the spatial structure of the plasma, we find an important global relation which characterizes the energy density of the electromagnetic vortex. We multiply the right and left sides of Eq. (2) by dE/dr and integrate over r from r_0 to ∞. Using Eqs. (3) and (5) and taking into account the inequality (6), we find

$$\frac{E_0^2}{16\pi} = \frac{\omega^2}{\omega^2 - k^2c^2} \times \left[T_e n_{e\infty} + 4\pi e^2 \int_{r_1}^{r_2} dr \int_{r_1}^{r} dr' n_e(r) n_e(r') \right], \qquad (7)$$

where $E_0 = E(r_0)$ is the maximum value of the electric field amplitude.

Relation (7) implies that the vortex energy is proportional to the sum of the plasma thermal pressure and the pressure of the unneutralized electron charge on the waveguide region resulting from the forces of Coulomb expansion toward the positively charged interior region of the vortex. Note that under conditions such that the role of the unneutralized charge is negligible, i.e., the second term in square brackets is small in comparison with the first, relation (7) reduces to the formula obtained by Talanov[13] for the case of a self-focused planar arc. If in addition we set $\omega \gg kc$, then we have the well-known formula found by Volkov.[12] We will be interested in the other limiting case, in which the vortex energy is primarily determined by the forces of Coulomb attraction of the charges. From relation (7), we see that in this case the vortex energy is proportional to the square of the number of unneutralized electrons.

To obtain a localized solution, we study the spatial distribution of the quantities which characterize the medium in the field in three regions: the waveguide region, the region of unneutralized electrons, and in the layer of quasineutral plasma. Then we match these solutions for the high-frequency electric field at the boundaries. This is possible under conditions such that the typical distance over which the amplitude of the electric field varies is large compared with the thickness of the transition regions.

Note that the ions are confined by a constant electric field resulting from the charge separation. From Eq. (4), neglecting the pressure of the high-frequency field on the ions, we have

$$n_i = n_{i\infty} \exp(-e\varphi/T_i). \qquad (8)$$

In the plasma the potential φ is determined by quasineutrality. Here we take $\varphi \approx T_i/e$. Since the ions are cold ($T_i \ll T_e$), they essentially avoid the region of unneutralized electrons, where $\varphi \gtrsim T_e/e$. Note that in the region $r_1 < r < r_2$, where the electrons are unneutralized, we will be neglecting the electron thermal pressure, assuming that the pressure due to the Coulomb attraction of the electrons toward the central region dominates. The thickness of the transition layer, where both types of pressure are important, is characterized by the electron Debye radius.

Using relations (2) and (3) for the amplitude of the electric field in the quasineutral plasma, we have

$$\frac{d^2\varepsilon}{dx^2} = [\alpha \exp(-\gamma\varepsilon^2) - 1]\varepsilon. \tag{9}$$

Here we have introduced the dimensionless variables

$$\varepsilon = \frac{eE}{mc\omega}, \quad x = \frac{\omega}{c} r \sqrt{1 - \frac{k^2c^2}{\omega^2}},$$

$$\alpha = \frac{\omega_{L\infty}^2}{\omega^2 - (kc)^2}, \quad \gamma = \frac{mc^2}{2T_e},$$

where ω_L is the electron Langmuir frequency.

The solution of Eq. (9), which implicitly describes the electric field of the wave that falls to zero in the limit $\varkappa \to \infty$, is found in Refs. 12 and 13:

$$x - x_2 = \int_{\varepsilon}^{\varepsilon_2} \frac{d\varepsilon}{\{(\alpha/\gamma)[1 - \exp(-\gamma\varepsilon^2)] - \varepsilon^2\}^{1/2}}. \tag{10}$$

Here and below we will use number subscripts to denote quantities evaluated at the corresponding points. For example, we write $\varepsilon_2 = \varepsilon(r_2)$.

For the region $r_1 < r < r_2$, using Eqs. (2), (3), and (5), and neglecting the term which characterizes the electron thermal pressure in (3), we find

$$\frac{d^2\varepsilon}{dx^2} = \left(\frac{1}{2}\frac{d^2(\varepsilon^2)}{dx^2} - 1\right)\varepsilon. \tag{11}$$

Equation (11) admits a solution in the following form:

$$x_2 - x = \int_{\varepsilon_2}^{\varepsilon} \left\{\frac{1 - \varepsilon^2}{(\alpha/\gamma)[1 - \exp(-\gamma\varepsilon_2^2)] - \varepsilon^2}\right\}^{1/2} d\varepsilon. \tag{12}$$

Note that Eq. (12) satisfies the continuity of ε and $d\varepsilon/dx$ at the point $x = x_2$.

Using Eq. (12), together with Eqs. (3) and (5), we find the unneutralized electron density as a function of the amplitude of the high-frequency electric field:

$$n_e = \frac{n_{e\infty}}{\alpha}\left\{1 + \frac{\alpha/\gamma\,[1 - \exp(-\gamma\varepsilon_2^2) - 1]}{(1 - \varepsilon^2)^2}\right\}. \tag{13}$$

In this limit Eqs. (12) and (13) are physically meaningful under the condition

$$\frac{\alpha}{\gamma}[1 - \exp(-\gamma\varepsilon_2^2)] > 1. \tag{14}$$

Note that the density of the unneutralized electrons increases as r decreases from r_2 to r_1. This results from the action of the Coulomb forces, which press electrons toward the waveguide region. At the boundary with the quasineutral plasma at the point $r = r_2$, the electron density determined by Eq. (13) must equal the plasma density. Under the present conditions, this holds for

$$\exp(-\gamma\varepsilon_2^2) \ll 1. \tag{15}$$

We note that the electrons are confined by the high-frequency field when the electron mean free path over a period of the field oscillation is small in comparison with the characteristic distance over which the field varies. Using inequalities (14) and (15), we find

$$\frac{\omega}{\omega_{L\infty}} \gg \frac{v_e}{c} > \frac{\sqrt{\omega^2 - k^2c^2}}{\omega_{L\infty}}.$$

Note that under condition (15), the pressure of the hot plasma (equal to the pressure of the surrounding gas) is balanced primarily by the pressure of the high-frequency field. In this case the presence of unneutralized electrons has little effect on the rate at which energy is lost by the high-frequency field in the plasma.

Note that the unneutralized electrons can significantly reduce field energy losses in the plasma when these electrons have a constant velocity component parallel to z. In this case the plasma pressure can be balanced by the magnetic field pressure generated by the constant electric current. Then the plasma may remain stable, since it is stabilized by the pressure of the surrounding gas. In the present work these questions are not discussed, since they require special treatment.

We note that the thickness of the layer of unneutralized electrons and the boundary value of the electric field amplitude ε_1 depend on the total number of unneutralized electrons. The number of these electrons per unit length in the z direction is determined by

$$N = 2\pi r_0 \int_{r_1}^{r_2} n_e dr.$$

Substituting the electron density given by relation (13) into this formula we find

$$\rho = x_\omega \varepsilon_i \sqrt{\frac{\alpha/\gamma - \varepsilon_1^2}{1 - \varepsilon_1^2}}, \tag{16}$$

where $\rho = N2e^2/mc^2$. Note that when the number of unneutralized electrons is sufficiently high, in the limit $\rho/x_0 \gg \sqrt{\alpha/\gamma}$, we have $1 - \varepsilon_1 \ll 1$.

Now we match the solution (12) with the solution in the waveguide region, where $\varepsilon = \varepsilon_0 \cos(x - x_0)$ holds. Under conditions (14) and (15) we find the following relations:

$$\varepsilon_1^2 = 1 - \frac{\alpha - \gamma}{\gamma\varepsilon_0}, \tag{17}$$

$$x_2 - x_1 = \int_{\varepsilon_2}^{\varepsilon_1} \sqrt{\frac{1 - \varepsilon^2}{\alpha/\gamma - \varepsilon^2}}\, d\varepsilon. \tag{18}$$

In the limit $\rho/x_0 \gg 1$ ($\varepsilon_1 \approx 1$, $\varepsilon_2 \ll 1$) we have for the thickness of the layer of unneutralized electrons from Eq. (18)

$$x_2-x_1=\frac{\pi}{2}\sqrt{\frac{\gamma}{\alpha}}.$$

The dependence of the maximum value of the amplitude of the hot plasma frequency electric field E_0 on the number of unneutralized electrons can be found from relations (16) and (17) or by using Eq. (7), in which we must neglect the electron thermal pressure in comparison with the pressure associated with the Coulomb attraction of the charges. We have

$$E_0=2\sqrt{2}\frac{\omega}{\sqrt{\omega^2-k^2c^2}}\frac{e}{r_0}N. \quad (19)$$

In order to determine how well electrons are confined by the high-frequency field, we estimate the probability for an electron to reach the central part of the waveguide region. For electrons confined by the high-frequency field, from Eq. (3) we have the following relation (the Boltzmann distribution):

$$n_e=n_{e\infty}\exp\left[\frac{e}{T_e}\left(\varphi-\frac{eE^2}{4m\omega^2}\right)\right]. \quad (20)$$

Using the Poisson equation (5) and Eq. (19), we can show that under the condition

$$Ne^2>mr_0(r_1-r_0)(\omega^2-k^2c^2) \quad (21)$$

we have $eE^2/4m\omega^2>\varphi$, in the central part of the waveguide region. Note that inequality (21) is easily satisfied in this case, when the electron Coulomb pressure is much larger than the atmospheric pressure and the typical spatial dimensions of the vortex are at most of order tens of centimeters. Hence it follows from Eq. (20) that electrons essentially never get into the central region of the waveguide, since under these conditions we have $e^2E_0^2/4m\omega^2T_e\gtrsim 10^2$.

4. INTERIOR PART OF THE VORTEX

Consider the case when there is a positively charged solid insulator in the interior region of the vortex (e.g., a polymer network such as that studied in Ref. 9), and no plasma. In this case Eq. (2), which describes the amplitude of the electric field, reduces to a Bessel equation. Thus, for $0<r<r_0$ we have

$$E=E_0J_q(r)/J_q(r_0). \quad (22)$$

Taking into account that $q\gg 1$, we have for the radius of curvature of the waveguide and for the thickness of the waveguide region

$$r_0=\frac{c}{\omega}(q+0.8q^{1/3}),\quad \Delta r=\frac{c}{\omega}q^{1/3}. \quad (23)$$

Let us discuss how the object is confined to the central part of the interior region of the vortex. Note that as the object approaches the waveguide region, its surface begins to be disrupted by the high-frequency field. Then positively charged particles are pulled away from the surface of the object along with neutrals. These charged particles are accelerated by the electric field of the charged body, pass through the waveguide region and are neutralized, and then reach the layer of unneutralized electrons. It is clear that the Coulomb force responsible for repulsion between the positively charged particles and the solid body will assist its return to the central part of the interior of the vortex, where the high-frequency field essentially vanishes.

This confinement mechanism evidently leads to a gradual loss of mass and positive charge associated with the solid object. Let us estimate the charge flow needed in order to balance the weight of the object. We note that the momentum flux of the charged particles at the point $r=r_1$ must be equal to the weight of the object:

$$P=M'v_1I, \quad (24)$$

where M' is the mass of a charged particle, v_1 is the velocity of that particle at the point $r=r_1$, and I is the number of charged particles leaving the surface of the solid object per unit time (the charge flow rate). For the particle velocity we have $v_1=(eU/2M')^{1/2}$, where U is the potential difference between the surface of the object and the unneutralized electron layer. In estimating magnitudes we can assume $U=Ne\Delta r/2r_0$. Using Eq. (24) we find the following relation, which determines the charge efflux:

$$I=\frac{2P}{e}\left(\frac{r_0}{NM'\Delta r}\right)^{1/2}. \quad (25)$$

Dividing the total number of unneutralized positive elementary charges in the solid object by the charge efflux determined by Eq. (25), we find the characteristic time for the destruction of the solid object. This time or the dissipation time for the high-frequency field energy will determine the lifetime of the vortex.

Assume that the low-density region in the toroidal vortex occupies a volume $\approx 10\ \text{cm}^3$. Then the mass of the solid object which serves as ballast must be of order 10^{-2} g. For $r_0/\Delta r\approx 10$ under conditions such that the charge is carried off by a carbon atom ($M'\approx 10^{-23}$ g), using Eq. (25) we find $I[\text{s}^{-1}]\approx 3\times 10^{22}\text{N}^{-1/2}$, where N is measured in cm^{-1}. In the solid object, the total number of unneutralized charges is equal to $2\pi RN$, where R is the major radius of the torus. If $R\approx 1$ cm, then we have for the lifetime of the object $\tau_p[\text{s}]=2\pi RN/I\approx 3\times 10^{-22}N^{3/2}$. For $N\approx 10^{15}\ \text{cm}^{-1}$ we find $\tau_p\approx 10$ s. Note that a solid object will be better confined by the high-frequency field if the charge is removed from the surface of the object by a particle heavier than carbon.

Now we briefly discuss the case in which the interior of the vortex contains only positive hydrogen ions confined by the pressure of the spatially nonuniform high-frequency field. The spatial distribution of the ions can be found by the same technique we used in treating the structure of the layer of unneutralized electrodes. However, this problem can be solved more simply if we note that the ions are concentrated mainly in a thin layer whose thickness is small compared with the length which characterizes the spatial variation of the high-frequency field. The ion layer region is indicated in Fig. 2 by the point $r=r_i$. In the region $0<r<r_i$ we have $E\propto J_a(r)$. In the waveguide region $(r_i<r<r_1)$, the electric field amplitude is characterized by

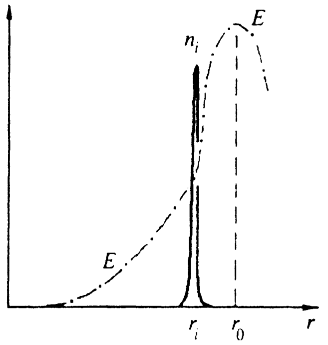

FIG. 2.

a superposition of first- and second-order Bessel functions. Under these conditions, when $r_0 \gg \Delta r$ holds, we can show that in this region

$$E = E_0 \cos\left[\frac{\omega}{c}\sqrt{1-\frac{k^2c^2}{\omega^2}}(r-r_0)\right].$$

Matching the solutions at the point $r=r_1$, we must take into account the jump in the derivative

$$\left.\frac{dE}{dr}\right|_{r_i} = \frac{2e^2N}{Mc^2r_i}E(r_i), \tag{26}$$

due to the ion current. Moreover, in order to describe the spatial profile of the field completely in the interior of the vortex, we must use relation (4), which characterizes the force balance acting on an ion. Neglecting the ion thermal pressure in this expression and using the Poisson equation (5), we have

$$\left.\frac{d}{dr}E^2\right|_{r=r_i+0} = 4M\omega^2N/r_i. \tag{27}$$

We note that to confine the ions, it is necessary that the high-frequency field be sufficiently strong: $E(r_i) \gtrsim (M/m)E_i$. This is achieved when the number of unneutralized charged particles is large,

$$N > \frac{r_0}{\Delta r}\frac{Mc^2}{e^2}.$$

5. SOME PROPERTIES OF THE VORTICAL PLASMA FORMATION

The energy losses from the high-frequency field in the plasma result primarily from electron–ion collisions. Under conditions such that the high-frequency field balances the pressure of the hydrogen plasma, the energy lost by the field per unit time per unit length of the plasma cylinder is determined by (see, e.g., Ref. 15)

$$Q \approx [\mathrm{W}]\,5.4\times10^{-17} r_0 T_e^{-1/2} n_{e\infty}^{3/2}, \tag{28}$$

where r_0 is measured in cm, the temperature is measured in eV, and the plasma density is measured in cm^{-3}. Note that at atmospheric pressure we have $n_{e\infty}T_e = 6\times10^{17}$.

Using Eq. (19), we find for the electromagnetic energy of the vortex per unit length (in the z direction)

$$W \approx 2\Delta r^3 \frac{e^2\omega^2}{r_0c^2}N^2. \tag{29}$$

Under conditions such that $r_0 \approx 1$ cm, $\Delta r \approx 0.3$ cm, $T_e \approx 10^2$ eV, $n_{e\infty} \approx 6\times10^{15}\ \mathrm{cm}^{-3}$, $\omega \approx 10^{13}\ \mathrm{s}^{-1}$, using Eqs. (28) and (29) we find for the lifetime of a vortex

$$\tau = [\mathrm{s}]\,\frac{W}{Q} \approx 6\times10^{-30}N^2.$$

Note that the number of uncompensated charges in a polymer network of the size considered here can reach $N \approx 3\times10^{14}\ \mathrm{cm}^{-1}$ (see Ref. 9, for example). We can show that the electric breakdown threshold of the polymer grid is quite high. For methane and cellulose monomers, for instance, it can reach 2×10^7 V/cm.

The dissipation of the momentum of the electromagnetic vortex per unit time per unit length of the plasma cylinder is equal to Q/c. As a result of collisions between electrons and heavy particles, this momentum is transferred to the surrounding gas and leads to the formation of a hydrodynamic vortex. The typical rotational velocity of air particles in a slab vortex can be found by taking into account the fact that in steady conditions the momentum received by the gas particles is equal to the momentum losses due to the air viscosity. We have

$$v_0 \approx Q/2\pi c\eta,$$

where η is the coefficient of air viscosity. Under normal conditions we have $\eta = 2\times10^{-4}$ poise. For the parameters of the vortex given above we find $v_0 \approx 10$ m/s.

Note that in addition to the vorticity, the behavior of the vortex motion in the free air can be affected by an external electric field if the electric charge throughout the plasma is not fully neutralized, and also by the gravitational field of the earth if the mean density of the object as a whole differs from that of air.

Let us discuss the form that such a plasma object can assume. A toroidal plasma configuration will obviously be

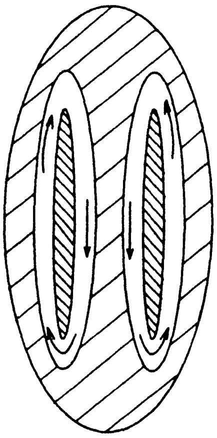

FIG. 3.

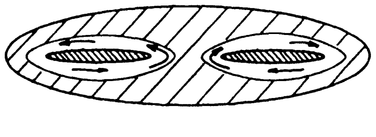

FIG. 4.

observed if the major radius R in the ring-shaped vortex is much larger than the minor radius r_0. In the opposite case, when these radii are comparable, the plasma in the vicinity of the vortex will have the shape of an oval or a sphere. Note that the presence of a solid insulator in the inside of the vortex can have a substantial effect on the shape of the plasma. This is because the electromagnetic wave will flow around the dielectric, propagating over its surface. The explanation for this is that the interaction between the electromagnetic field and the surface of the insulator gradually destroys the insulator surface, and engenders a flux of neutral and positively charged particles from the interior. The presence of charge and momentum fluxes facilitates the reduction in the pressure exerted by the electron layer and plasma on the waveguide region.

Figure 3 shows a cross section of the plasma in the case when the insulator has the shape of a tube. (Here the insulator is indicated by heavier cross-hatching than the plasma, and the possible direction of propagation of the electromagnetic waves is shown by the arrows.) In the limit when the length of the tube is much greater than its diameter the surrounding plasma will have the shape of an elongated oval. It is possible that precisely such a cigar-shaped plasma was observed by Avramenko *et al.*,[16] who used a pulsed erosion discharge in a cylindrical channel with insulating wall made of polymethylmethacrylate. Finally, if the insulator has the shape of a flat washer (Fig. 4), then we can obtain a plasma in the shape of a disk.

The mechanism for the formation of an electron vortex in a quasineutral plasma was discussed in Ref. 15, where it was shown that when an electromagnetic ray propagates under self-focusing conditions, narrowing the waveguide channel can cause a vortex to develop. The reason for the constriction of the channel may be the pinch effect, which arises in a pulse discharge. Note that when the electromagnetic ray winds around, charge separation can occur: under the action of the spatially and temporally nonuniform electromagnetic field part of the plasma, electrons can be expelled from the region where polymerization occurs. Consequently, a positively charged polymer is formed, surrounded by an electromagnetic vortex. Then the unneutralized electrons are found in the external region of the vortex.

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