

# Electrodynamic model of ball lightning

## Abstract

The paper considers a hypothesis of the structure of ball lightning core as an ensemble of dynamic electric capacitors. The dynamic capacitor is an object consisting of spatially separated charges – electrons and protons. Electrons, due to the action of mutually orthogonal electric and magnetic fields, move in a circle, oscillating in the radial direction. The magnetic field is generated by the movement of protons around the electron ring. The number of protons exceeds the number of electrons, due to which the dynamic capacitor has a positive electric charge. The system of dynamic capacitors is located inside a spherical shell consisting of water molecules polarized in the electric field of the charge of the dynamic capacitor. The shell creates a force that prevents the expansion of dynamic capacitors. It is shown that 1900 dynamic capacitors with a radius of 0.5 cm with a total kinetic energy of 6.36 MJ can fit in ball lightning with an internal shell radius of 6.2 cm. In this case, the energy density in the core of ball lightning can be about  $6.4 \cdot 10^9 \text{ J/m}^3$ . This is comparable with the result of measurements of energy density of natural ball lightning.

**Keywords:** Ball lightning; Movement of electrons and ions in an electric and magnetic field; Dynamic electric capacitor.

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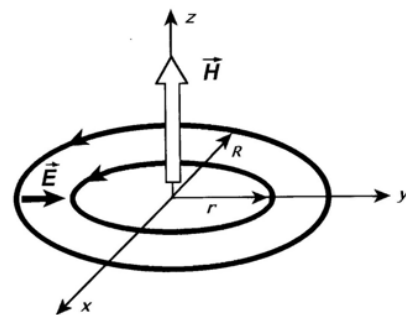
## Introduction

### The principle of the dynamic electric capacitor

In a series of articles describing the properties of ball lightning, we discussed the possibility of existence of two types of ball lightning: 1) with a low-activity core of stationary ions and 2) with a core of moving ions and electrons (systems of “dynamic electric capacitors”).<sup>1-5</sup> The study of the structure of ball lightning possessing an energetically active core is of great interest, since they are objects with a high energy density  $\rho_E = 10^{10} \text{ J/m}^3$  and higher.<sup>6</sup> The construction of a model of ball lightning usually begins with determining the principle of its structure. In 1859, de Tesson, a member of the French Academy of Sciences, proposed the idea of a ball lightning device in the form of an electric capacitor made of two charged coaxial spheres, between which there is an insulator - compressed air.<sup>7</sup> Let the radius of the outer sphere be  $R_{out} = 10 \text{ cm}$  and the radius of the inner sphere be  $R_{in} = 9 \text{ cm}$ . The capacitance of such a capacitor is  $C = 4\pi\epsilon_0\epsilon/(R_{in}^{-1} - R_{out}^{-1})$ . (Here  $\epsilon_0 = 8.854 \cdot 10^{-12} \text{ F/m}$  is the electric constant and  $\epsilon$  is the permittivity of the insulator material). Substituting  $\epsilon = 1$  and the numerical values of  $R_{in}$  and  $R_{out}$  into this expression, we find  $C = 1.23 \cdot 10^{-10} \text{ F}$ . Taking the value of the electric field strength between the electrodes equal to the breakdown strength of air  $E_{bra} = 3 \cdot 10^6 \text{ V/m}$ , we find the potential difference between the electrodes  $U = E_{bra} (R_{out} - R_{in}) = 3 \cdot 10^4 \text{ V}$  and the energy stored in the capacitor,  $W_c = CU^2/2 = 5.53 \cdot 10^{-2} \text{ J}$ . The energy can be increased in two ways. The voltage between the electrodes can be raised. In this case, with a 10-fold increase in voltage, the energy will increase 100-fold. The limit to voltage growth is set by the electrical strength of the gap between the electrodes. It can be increased by creating a high vacuum in the gap or filling it with a dielectric with high electrical strength. Currently, the electrical strength of the best insulators does not exceed  $U_{brd} = 10^9 \text{ V/m}$ . Substituting this value and  $\epsilon = 2.5$  into the expression for energy, we find  $W_{ed} = 1.54 \cdot 10^4 \text{ J}$ . As we can see, the energy stored in the capacitor has increased by  $3 \cdot 10^5$  times, but its value is still  $10^3$ - $10^5$  times less than the measured values of the energy of ball lightning.<sup>6</sup> The second method is the accumulation of energy not in the form of stretched molecular bonds, as in the case considered, but in the form of the kinetic energy of particles. In<sup>8</sup> the device of a “hydromagnetic

capacitor” is described, which is a plasma rotating in an axial magnetic field  $H$ . In this capacitor the charges are spatially separated: positive ions move along an orbit of large radius, and electrons move along an orbit of small radius. The linear velocity of plasma rotation  $v_0 = E/\mu_0 H$ , where  $\mu_0 = 1.2566 \cdot 10^{-6} \text{ V}\cdot\text{s/A}\cdot\text{m}$  is the magnetic constant, and  $E$  is the electric field strength in the space between the regions of positive and negative charges. Due to the rotation of the plasma, the kinetic energy of a unit volume  $W_k = \rho v_0^2/2$  ( $\rho$  is the plasma density) is added to the energy of the electric field stored in a unit volume of the capacitor,  $W_c = \epsilon_0 E^2/2$ .

To some extent we are the successors of the ideas of de Tesson and the authors of the hydromagnetic capacitor. Taking the device of a “hydromagnetic capacitor” as a basis, we will present a diagram of charges movement, when the radial electric field and axial magnetic field are created due to the proper movement of electrons and protons (Figure 1).<sup>9-11</sup> For simplicity of presentation, we will assume that the orbits of protons and electrons lie in the same plane.



**Figure 1** Scheme of charges movement in a dynamic electric capacitor. The inner ring is formed by electrons, and the outer one by protons. The magnetic field  $H$  is generated by rotating protons, the electric field  $E$  creates a centripetal force that holds the protons in orbit.

Protons (outer ring) move along an orbit of radius  $R$  under conditions of equality of the centrifugal force and the Coulomb force of their attraction to the electron ring of radius  $r$ . Due to the rotation of the protons, a magnetic field  $H$  is generated inside the orbit, the vector

of which has a component perpendicular to the plane of the orbit. We will assume that the protons rotate counterclockwise, therefore the magnetic field they create will be directed upward from the  $XY$  plane. Under the action of this field and the orthogonal electric field  $E$ , existing in the space between the electron and proton rings, the electrons drift in the direction of the vector product of  $E$  and  $H$  (that is, they also move counterclockwise) with a velocity:<sup>12,13</sup>

$$v_d = [E \cdot H] / \mu_0 H^2, \tag{1}$$

For a sufficiently strong magnetic field, determined from the condition:<sup>14</sup>

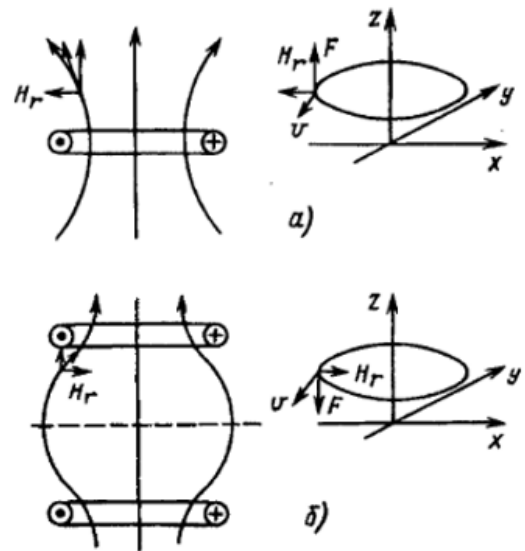
$$H \geq (\epsilon_0 / \mu_0)^{1/2} E, \tag{2}$$

the drift of electrons in the direction opposite to the vector  $E$  will be suppressed, and they will move (at a speed close to the speed of light) in a circular orbit of radius  $r$ , while performing radial oscillations with an amplitude of:<sup>15</sup>

$$\Delta r = (2mE) / (e\mu_0^2 H^2). \tag{3}$$

Here  $m$  is the electron mass and  $e$  is its charge. The amplitude  $\Delta r$  must be less than the distance between the electron and proton orbits:  $\Delta r < R - r$ . In the considered dynamic capacitor, in which protons move along an orbit due to the centripetal force created by the charge of the electron ring, there is no need for material charge carriers such as metal electrodes of the capacitor. Moreover, the presence of such electrodes could cause autoelectronic emission of charges already at an electric field strength of  $E = 10^8$  V/m, which would significantly limit the energy capabilities of our capacitor.<sup>16</sup>

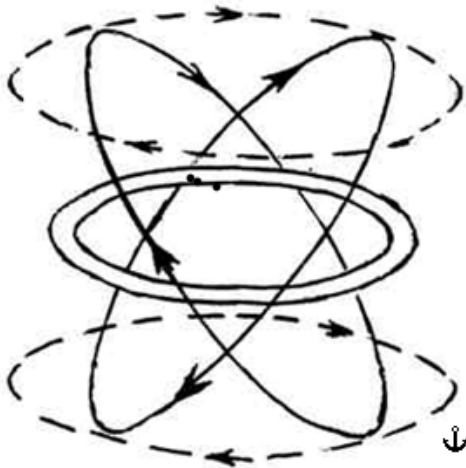
Let us analyze how to ensure the stability of electron motion in the plane of the electron ring. Figure 2a shows the type of magnetic field lines created by a flat current loop (protons rotating along a flat orbit). The protons rotate clockwise, the magnetic field in the center of the coil is directed along the  $Z$  axis. In Figure 2a) it is seen that the component  $H_r$  of the magnetic field created by the proton ring is positive inside the proton orbit at  $z > 0$  (i.e. the component of the magnetic field vector  $H_r$  is directed radially outward from the center of the ring) and negative at  $z < 0$ . If an electron moving counterclockwise with a velocity  $v$  along an orbit lying in the  $XY$  plane exits the orbital plane, then the Lorentz force  $F = -e\mu_0 [v \cdot H_r]$  directed along the  $Z$  axis will act on it, which will take it even further from the orbital plane. The same will happen with an electron displaced in the opposite direction of the  $Z$  axis. In order for the electrons that exited the orbital plane to return back, the signs of  $H_r$  must be opposite to those considered.



**Figure 2** Forces acting on electrons in a magnetic field created by the motion of protons. a) On the left – lines of force of the magnetic field created by a flat current loop. On the right – type of forces acting on the electron ring located above the plane of the current loop. b) On the left – lines of force of the magnetic field created by two loops with current. On the right – type of forces acting on the electron ring located above the plane equidistant from the current rings.

The magnetic field of the required configuration can be obtained using two coaxial current rings of the same radius, spaced along the  $Z$  axis at a distance  $z > R$  (see Figure 2b). In this case, near a plane equidistant from the planes of both rings, the radial component of the magnetic field  $H_r$ , found by summing the magnetic field strengths of two turns, turns out to be negative when an electron leaves the central plane upward and positive when it shifts in the opposite direction. Therefore, the Lorentz force will return the electrons to the specified plane.

The considered principle of axial focusing of charged particle orbits in a “barrel-shaped” magnetic field has been known for a long time and is used in cyclotrons and betatrons.<sup>17,18</sup> It is also known from the theory of betatrons that it is possible to stabilize the radius of the electron orbit if the rate of decrease in the axial magnetic field strength along the radius  $H_z(r) = \text{const}/r^n$  is less than the rate determined by the formula  $H_z'(r) = \text{const}/r$ , that is, if the condition  $n < 1$  is met.



**Figure 3** Scheme of orbital motion of protons in the electric field created by the electron ring. The motion of protons generates a magnetic field equivalent to the current of two coils with current.

The proton orbits, unlike the electron orbits, will not lie in the  $XY$  plane. Due to Coulomb repulsion, the protons will most likely leave this plane and will move along numerous orbits inclined at different angles to the  $XY$  plane (Figure 3). In this case, the magnetic fields arising from the movement of the protons along the  $Z$  axis will mutually compensate each other and only the field caused by the azimuthal movement of the protons will remain. This field is equivalent to the field created by two current coils spaced apart along the axis. Thus, our system will resemble a sphere with cut poles, filled with proton orbits, inside which electrons move in a ring. This system is close to the configuration of a cylindrical capacitor.

### Properties of a dynamic electric capacitor

Let us consider a cylindrical capacitor with an outer electrode of radius  $R = 0.5$  cm, an inner electrode of radius  $r = 0.35$  cm, and a height of  $h = 0.5$  cm. The capacitance of such a capacitor is  $C = 2\pi\epsilon_0 h / \ln(R/r) = 0.78 \cdot 10^{-12}$  F. Let such a capacitor contain electric field energy  $W_c = 100$  J. In this case, the potential difference across its electrodes is  $U = (2W_c/C)^{1/2} = 1.6 \cdot 10^7$  V, and its charge is  $Q = CU = 1.25 \cdot 10^{-5}$  C. The electric field strength in the gap between the electrodes,  $E = U/(R - r) = 1.07 \cdot 10^{10}$  V/m, significantly exceeds the air breakdown field ( $E_{bra} = 3 \cdot 10^6$  V/m), so there must be a deep vacuum in the space between the electrodes. Equating the force  $F_c = eE$  acting on a proton in an electric field  $E$  to the centrifugal force  $F_c = m_p v_p^2/R$ , we find the speed of its orbital motion  $v_p = 7.15 \cdot 10^7$  m/s and the frequency of its revolution in orbit  $f_p = v_p / 2\pi R = 2.28 \cdot 10^9$  s $^{-1}$ . (Here  $m_p = 1.673 \cdot 10^{-27}$  kg is the mass of the proton). Let us assume that our system is electrically neutral, that is, the total charge of electrons  $Q_e = 1.25 \cdot 10^{-5}$  C is equal to the total charge of protons  $Q_p$ . In this case, the current created by the movement of protons will be equal to  $I_p = Q_p f_p = 2.85 \cdot 10^4$  A, and the magnetic field strength at the center of the orbit created by this current will be equal to  $H = I_p / 2R = 2.85 \cdot 10^6$  A/m. To prevent radial motion of electrons in the field  $E$ , the condition  $H \geq (\epsilon_0/\mu_0)^{1/2} E = 2.654 \cdot 10^{-3} E$  must be met.<sup>11</sup> For an electric field strength  $E = 1.07 \cdot 10^{10}$  V/m, this condition means that  $H \geq 2.84 \cdot 10^7$  A/m must be. As we can see, this value is an order of magnitude greater than the value of  $H$  that we found. To create a current that will keep the electrons in orbit, it is necessary to increase the number of protons by 10 times, that is, to increase their total charge to  $Q_p = 1.25 \cdot 10^{-4}$  C. Due to this, the system under consideration will have an excess positive charge  $Q = Q_p - Q_e = 1.125 \cdot 10^{-4}$  C. With an electric field strength of  $E = 1.07 \cdot 10^{10}$  V/m and

a magnetic field strength of  $H = 2.84 \cdot 10^7$  A/m, the amplitude of radial oscillations of electrons will be  $\Delta r = 2mE/e\mu_0^2 H^2 = 10^{-2}$  cm, which is 15 times less than the distance between the electron and proton orbits. The kinetic energy of protons in a dynamic electric capacitor is  $W_p = Q_p m_p v_p^2 / 2e = 3.34$  kJ, which exceeds  $We$  by 33.4 times.

Based on the simple analysis presented, two important conclusions can be made: 1) in a dynamic electric capacitor, the number of protons exceeds the number of electrons, i.e. it has an uncompensated positive charge; 2) the energy in a dynamic capacitor is stored in the form of the kinetic energy of protons.

Now let us return to the discussion of the problem of how to hold the expanding system of moving charges under consideration in a limited volume. The expansion of proton orbits could, in principle, be restrained by the attraction of electrons if the latter, in turn, were held in orbit by a “rigid” external magnetic field. But since the magnetic field in which the electrons move is created by a proton ring capable of expansion, this field also turns out to be “non-rigid”. Therefore, to ensure the existence of our system, other forces must be present in it which prevent its expansion. For example, such a force could be the force of atmospheric pressure acting on the shell inside which the system of moving charges is located. We have long been tacitly assuming the existence of a certain shell separating the vacuum cavity in which the charges move from the atmosphere. This shell most likely consists of water molecules. Paradoxically, it is the presence of an uncompensated charge, which would seem to only aggravate the problem of particle retention (since the Coulomb repulsion force of like charges is added to the centrifugal force), that allows the existence of an object capable of providing compression of the energy core of a dynamic capacitor.

### Ball lightning model with an active energy core

Let us consider a spherical shell with an internal radius  $R = 6.2$  cm and a wall thickness  $a$ , inside which there is an energy core with a positive charge  $Q$ . This charge creates an electric field of intensity  $E = Q/4\pi\epsilon_0 R^2$  at the location of the shell. Under the influence of this field, polarization of water molecules will occur: negative charges will appear on the inner side of the shell, and positive charges on the outer side. It can be assumed that with complete polarization of the shell in a strong field, the surface charge density  $\sigma$  will be proportional to  $N_s$  – the number of water molecules per unit area of the shell. The distance between water molecules in an ice crystal is  $3 \cdot 10^{-10}$  m. Consequently, there are  $N_s = 10^{19}$  water molecules per square meter. The water molecule has an electric dipole moment  $p_w = 6.327 \cdot 10^{-30}$  C·m, and the distance  $d$  between the oxygen atom and the plane in which the hydrogen atoms are located is  $0.588 \cdot 10^{-10}$  m. Thus, the molecule can be considered a dipole of length  $d$ , at the ends of which are charges  $q_d = p_w/d = 10^{-19}$  C. The total charge of the ends of the dipoles on an area of 1 m $^2$  is equal to  $\sigma = q_d \cdot N_s = 1$  C/m $^2$ . The dipole moment of a unit area of a shell of thickness  $a$  is equal to  $D = \sigma \cdot a = a$  C/m. The force with which a unit area of the shell is attracted to a charge  $Q$  is equal to  $P_{cp} = D \cdot \text{grad } E = -2DQ/4\pi\epsilon_0 R^3 = -2DE/R$ . The force  $F_{cp}$ , which pulls the shell toward the center, is found by multiplying  $P_{cp}$  by the shell area  $S = 4\pi R^2$ :  $F_{cp} = (2DE/R) \cdot (4\pi R^2) = 2\sigma a Q/\epsilon_0 R$ . If the inner radius of the shell is  $R = 6.2$  cm, the charge of the energetic core is  $Q = 10^{-2}$  C, and the shell thickness is  $a = 1$  cm, then the force pulling it together is equal to  $F_{cp} = 3.64 \cdot 10^8$  N. Let us assume that this force compensates for the centrifugal force  $F_{cp} = M_p v_p^2/R$  of protons with a total mass  $M_p$ , moving in an orbit with a radius of  $R = 6.2$  cm at a velocity  $v_p$ . In this case, the kinetic energy of the protons is  $W_p = M_p v_p^2 / 2 = F_{cp}^1 \cdot R / 2 = 11.3$  MJ. Thus, we come to the conclusion that the dielectric shell, inside which there is an electric charge, due to the

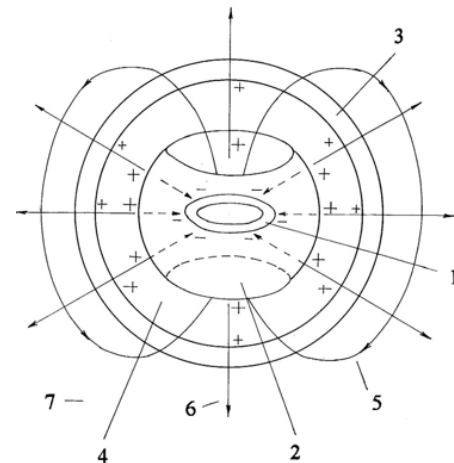
force caused by the gradient of the electric field strength, is capable of resisting the expansion of the core of ball lightning, which has the energy of ten MJ.

Let us note that the shell is also acted upon by forces stretching it in the direction of the sphere radius. Indeed, the inner surface of the shell lined with the negative ends of the charges is acted upon by a force directed toward the center of the sphere, while the outer surface filled with positive charges is acted upon by a force tending to tear the shell. The force directed toward the center of the sphere is compensated by the pressure force of the expanding core of the ball lightning, whereas the force acting on the outer surface of the shell can only be compensated by the force of mutual attraction of the liquid molecules. In the case under consideration, the shell with an inner radius of  $R = 6.2$  cm is stretched by a force of  $F_{cp} = 3.64 \cdot 10^8$  N. The negative pressure of this force is  $P_{cp} = 7.5 \cdot 10^9$  N/m<sup>2</sup> =  $7.5 \cdot 10^4$  atm. The pressure on the water surface caused by the mutual attraction of molecules is  $P_{mol} = 1.7 \cdot 10^4$  atm.<sup>19</sup> It can be expected that in a shell of water molecules polarized in a strong electric field, the value of the molecular pressure on the water surface will be somewhat greater than  $1.7 \cdot 10^4$  atm. Nevertheless, the limitation of the tensile strength of the shell may be one of the reasons for the existence of a limit on the energy of ball lightning.

The system we have constructed has unusual thermodynamic properties. Despite the fact that it has high energy, it is highly ordered and, therefore, its entropy can be quite low. If we understand the entropy  $S$  as a function of the logarithm of the number of states  $N$  occupied by the system:  $S = k_B \ln N$  ( $k_B$  is the Boltzmann constant), we can see that the system of moving charges, firstly, occupies an insignificant part of the volume of the shell cavity (the movement of electrons and protons occurs along certain orbits, and the rest of the space is free of matter), and, secondly, the spectra of admissible values of the energies of electrons and protons are also quite narrow.<sup>20</sup> In addition, the temperature of the system  $T = dW/dS$  ( $W$  is the energy of the system), which characterizes the degree of chaos of the particle motion, is low. If the movement of charge carriers occurs without collisions and the charges are uniformly distributed along the length of the orbit, then the temperature  $T$  can be noticeably lower than room temperature. A similar situation occurs in supersonic gas flows, in which, despite the high speed of movement of molecules along the jet axis, the speed of their chaotic movement in the direction perpendicular to the axis is small and is characterized by a low temperature.<sup>21</sup>

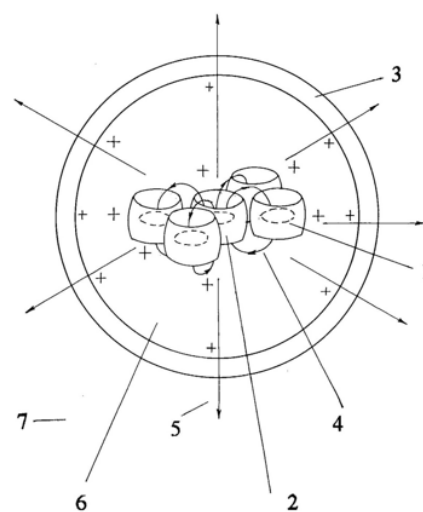
The above circumstances (ordering, absence of collisions, low temperature) are decisive for the process of reflection of dynamic electric capacitors, forming the energetic core of ball lightning, at the shell wall. Since at the moment of reflection the velocity of the orbital motion of the proton is directed almost tangentially to the shell, only the component of the proton momentum, caused by the expansion of the proton orbit in the radial direction, acts on it. The value of this fraction of the momentum is many orders of magnitude less than the total momentum of the proton. However, the value of the transferred momentum cannot exceed a fixed value of a large, but still finite quantity determined by the total mass of the protons, their velocity, orbital radii and Coulomb repulsion of charges. In contrast, long-term retention of a disordered system of particles (for example, chaotically moving charges) inside the shell is, in principle, impossible. Indeed, among these charges there will always be a small fraction of very fast particles, collisions with which the shell will not withstand. Moreover, due to the conservation of the Maxwellian distribution of particle velocities in the system, the loss of these fast particles will be constantly replenished.

According to the model under consideration, ball lightning may look like the one shown in Figure 4.



**Figure 4** The structure of ball lightning with a single-element energy core: 1 – electron ring, 2 – protons, 3 – shell, 4 – vacuum, 5 – magnetic field, 6 – electric field, 7 – atmosphere.

Inside the spherical shell there is an energy core in the form of a single dynamic electric capacitor, represented by a combination of the geometric place of proton orbits (a sphere with cut poles) and an internal electron ring. This system manifests itself in the external environment by the presence of an electric field (in the form of an electric monopole) and a magnetic field (in the form of a magnetic dipole). The configuration shown in Fig. 5 is also possible, when inside the shell there is an energy core consisting of a large number of small dynamic capacitors. For example, in a shell with an internal radius  $R_{cn} = 6.2$  cm it is possible to place  $N = (R_{cn}/R_c)^3 = 1900$  capacitors with a radius  $R_c = 0.5$  cm (the characteristics of which we have considered above). The total electrical energy of these capacitors will be  $W_{e\Sigma} = W_c N = 190$  kJ, the kinetic energy of protons  $W_{p\Sigma} = 6.36$  MJ, and the total uncompensated charge  $Q_{\Sigma} = 2.14 \cdot 10^{-1}$  C. In ball lightning with a multi-element core, the magnetic fields of individual elements will most likely close on each other, and in external space it will manifest itself only as an electric monopole.



**Figure 5** The structure of ball lightning with a multi-element energy core: 1 – electron ring, 2 – protons, 3 – shell, 4 – magnetic field, 5 – electric field, 6 – vacuum, 7 – atmosphere. Only a small part of the dynamic capacitors is shown. In fact, the internal cavity of the shell is densely filled with these objects.

## Conclusion

According to the above, the core of ball lightning, which has a large energy reserve, has a complex structure. Inside the shell there is not hot gas, but an ensemble of rather complexly organized elements - dynamic electric capacitors consisting of electrons and protons moving in closed orbits. The speed of charge movement is close to the speed of light. This makes it possible to generate synchrotron and undulator radiation in the form of a narrow beam.<sup>22</sup> The ordered movement of charges in closed orbits opens up the possibility of converting the energy of their motion into electromagnetic radiation of the radio range. Due to the orbital motion of protons, the elements of the core of ball lightning have their own angular momentum. This can explain the reason for the occurrence and cessation of the rotation of ball lightning.<sup>23</sup> The size of the elements of the core of ball lightning can be different. Ball lightning with a size of dynamic capacitors of 1 mm - 1 cm is able to pass through small holes.<sup>4,24</sup>

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