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V.N.Strel'tsov

# SOME PROBLEMS OF RELATIVISTIC ELECTRODYNAMICS

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## I. INTRODUCTION

Of course, this article would have to begin with one of the basic problems of relativistic electrodynamics, namely, the relativistic covariant definition of momentum and energy of an electromagnetic charge field (as a solution of the famous problem 4/3).

Paper /1/ published at one time began in this way. However, this problem has been recently looked into in detail /2/. Therefore, we are going to touch upon only its "historical aspect" here.

In this case, as before, we shall have in mind Laue's more recent method /3/ based on relativistic transformations of an energy-momentum tensor of an electromagnetic field and space volume.

Remined that the essence of the indicated problem lies in the appearance, e.g., of a supplementary coefficient 4/3 in the expression for momentum in comparison with the corresponding relativistic formula. At one time this difficulty was removed mathematically (in the frame of this approach) in Kwal's article /4/ which remained absolutely annoticed, just in this article another formula was proposed for the transformation of a space volume element:

$$dV_0 = dV_0^*(1-\beta^2)^{-1/2} = dV_0^*\gamma \tag{1}$$

instead of the usual Lorentz squeeze

$$dV = dV^*(1-\beta^2)^{1/2}. \tag{2}$$

Here $dV_0^*$ and $dV_0$ are the time components of a covariant 4-vector of a volume element in the rest system S* of an object and motion (S)$dV = dV_0$, $\beta c = v_x$ is the motion velocity S*-system relative to S. As is seen, according to (1) the space volume of a moving object should increase by a factor of $\gamma$, where $\gamma$ is the Lorentz-factor.

In addition, for the other components $dV_i$ we have:

$$dV_1 = -\beta dV_0^*\gamma/c, \quad dV_2 = dV_3 = 0. \tag{3}$$

However, it should be noted that still earlier, as it seems for the first time

Fermi [5] has drown his attention to a contradiction between the Abraham-Lorentz theory of electromagnetic mass and the relativity theory. His solution was based on the covariant formulation of Hamilton's principle. This was due to the variation connected with the normal section of the world tube of a charge field, whereas in the frame of the usual approach the variation is due to the demand $t = const$. Just the latter (Enstein's) condition leads to the contraction effect.

Although the formula of space volume transformation was not considered in Fermi's approach, the introduction of a normal (non-simultaneous) section of the world tube was in essence an implicit introduction of the so-called asynchronous formulation of relativity theory [6] proposed much later which has not been generally recognized up to now. Though, as Fermi noted, the usual approach (based on the condition $t = const$) explicitly contradicts the principle of relativity. We want to add Gamba's article [7] to these papers, in particular, the generally accepted procedure of calculation of the energy and momentum of an electromagnetic charge field in different system of reference (S and S*) related to integration over volumes at $t = const$ and $t^* = const$, respectively, is criticized.

As integration is performed over different hupersurfaces, then, as noted by the author, calculation results should concern different totalities of physical events whereas Lorentz transformations deal with the same totality of events.

The latter condition is naturally fulfilled in the frame of the radar formulation of relativity (see, e.g., [8]) which is based on light or retarded distances directly measured in an experiment*.

The concept of relativistic length [9] based on the radar method of measuring distances leads just to increasing the longitudinal sizes of moving objects. Below we shall cencern some aspects of electrodynamics directly connected with the radar interpretation and also a relativistic covariant descriprion of the interaction of a charge and current system with an external field and one elementary derivation of the known formula $\mathcal{E} = mc^2$.

## II. LIENARD-WIECHERT'S POTENTIALS AND RELATIVISTIC LENGTH

We consider the expression for Lienard-Wiechert's 4-potential

$$A^i = \frac{eu^i}{R_k u^k}. \qquad (4)$$

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*Finiteness of light velocity (electromagnetic interaction) is taken into account in a direct way.

where $u^i$ is the 4-velocity of charge e; $R^k$, the 4-vector of a retarded distance $R^k = [\,c(t-t'),\ \vec{R}-\vec{R}'\,]$ ; $x^{i'}$ the charge coordinates; and $x^i$, the coordinates of an observation point with $R^k$ "light vector", i.e.,

$$R_k R^k = 0. \tag{5}$$

Let for simplicity the charge moves along the x axis (S-system), and we are interested in the value of potentials at a fixed point of the axis, i.e.,

$$\phi = \frac{e}{R_x(1-\beta)},\quad A_x = \frac{e\beta}{R_x(1-\beta)},\quad A_y = A_z = 0. \tag{6}$$

In so doing, in proper reference system (S*), where the charge is at rest, we obtain

$$\phi^* = \frac{e}{R^*_x},\quad A^*_x = A^*_y = A^*_z = 0. \tag{7}$$

If we use the formulae of transformations for potentials, we get the expression

$$R_x = R^*_x(1+\beta)\,\gamma \tag{8}$$

describing the law of distance transformation between charge and observation point from the S*- to the S-system.

As is seen, equation (8) differs from the habitual formula of Lorentz contraction.

At the same time it is obvious that $R_x$ coincides with distance $\ell_f$ which a light signal covers (in the radar method of measurement) when it runs after the corresponding end of rod (forward). The rod is oriented and moves along the x axis. At high velocities $\ell_f$ is simply equal to a double value of relativistic length $\ell_r$ .

Remind that

$$\ell_r = \ell^* \gamma \quad \text{("elongation formula")} \tag{9}$$

where $\ell^*$ is the length of a rod at the rest.

Following from (4), the formula for Lienard-Wiechert's electrical potential $\phi$ in polar coordinates takes the form

$$\phi = \frac{e}{R_r(1-\beta\cos\theta)}. \tag{10}$$



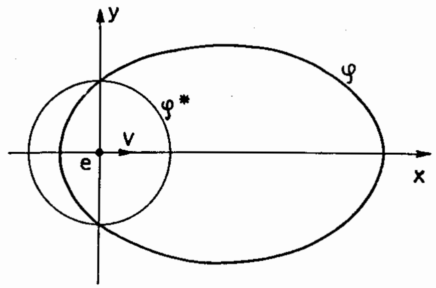


Fig.1. Lienard-Wiechert's equipotential ellipse, $\beta$=0.75. Circle-Coulomb equipotential.

Based on (10), equipotential curves for relativistic charge can be drown. Evidently, they will be given by equation

$$R_r = \frac{e/\phi}{1-\beta\cos\theta} \tag{11}$$

being the polar equation of ellipse, $(e/\phi)$ is a focal parameter and $\beta$ ellipse eccentricity.

Such a curve is presented in Fig.1 for $\beta = 0.75$ ( $\gamma = 1.5$), the circle corresponds to the Coulomb potential (charge at rest).

As we can see from the figure and from formula (11), with growing charge velocity its field stretches forward and affects greater distances /10/. Such a character of field behaviour is defined by the retardation factor

$$\kappa = 1 - \vec{\beta}\vec{n}_r ,$$

where $\vec{n}_r = \vec{R}_r/R_r$. In particular, it is not difficult to see that

$$R_x \approx 2\gamma^2. \tag{12}$$

So, one can say that a kind of "relativistic long-range" takes place.

It should be also noted that at velocities of our interest ($\beta \approx 1$) for example, the field component $A^1$ will behave evidently in a similar way.

It is important to emphasize that the longitudinal size of a field is essentially given by a characteristic retarded distance when a source runs after its field which corresponds to quantity actually defining relativistic length.

Using, obtained on the basis of (4), the known formulae for a field created by a moving charge, one can draw the corresponding curves of equal intensity /11/.

The field described by them will be stretched forward as illustrated in Fig.2, the behaviour of the field lines may be obvious and usual for us as presented in Fig.3.

Of course, the most important thing here is that the transition from "instant" to retarded distances has substantially changed the first picture: as in the case of the longitudinal sizes of objects, we have an increase of the field longitudinal sizes in the direction of charge motion instead of squeeze.

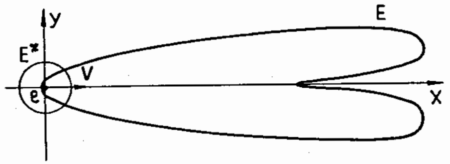


Fig.2. Lines of an equal electric field of a charge at rest (circle) and in motion ($\beta$=0.98).

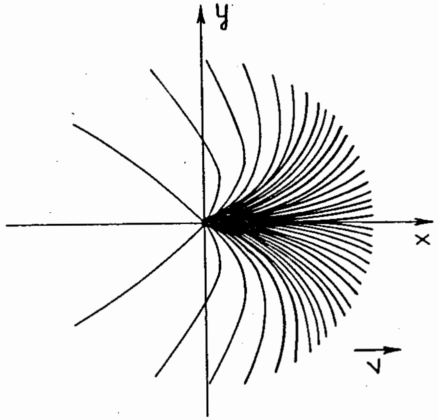


Fig.3. Electric field (force lines) of a moving charge $\beta$= 0.75.

## III. ON THE CHARGE OF A CURRENT-CARRING CONDUCTOR

Let us consider the element of a linear conductor at rest in the S*-system directed along x* axis which current with density $j^1_* = -j^*_\pm$ flows along.

The densities of negative and rest positive charges $\rho^*_-$ and $\rho^*_+$ are equal inside the conductor, and the total density is $\rho^* = 0$.

Thus, from the view point of an observer from the S*-system the wire does not take a charge:

$$\Delta Q^* = \rho^* \Delta V^* = 0\,, \tag{13}$$

where $\Delta Q^*$ is the charge and $\Delta V^*$ the volume of the considered element of the conductor.

Let us transit now to such reference system relative to which negative charges creating the current with density $j^1_*$ are at rest.

Based on the formulae of transformation for quantities $\rho$ and j and taking into account that

$$\rho^*_+ = -\rho^*_-,\quad j^*_- = -\beta c \rho^*_- \gamma$$

and $j_- = 0$ we have

$$\rho_- = \left(\rho^*_- + \frac{\beta}{c} j^*_-\right)\gamma = \rho^*_- \gamma^{-1}, \tag{14}$$

$$\rho_+ = -\rho^*_- \gamma, \tag{15}$$

$$j^1 = j_+ = -\beta c \rho^*_- \gamma. \tag{16}$$

From here on taking into account that the total density of charges

$$\rho = \rho_- + \rho_+ = -\beta^2 \rho^*_- \gamma \tag{17}$$

we conclude that the product is

$$\rho \Delta V \neq 0$$

independently of the transformation form of space volume.

On the basis of the fact that the density of charges $\rho$ is no longer equal to zero in the S-system, it is often concluded (see, e.g.,[12a]) that a charge appears in a moving current-carrying conductor.

However, it should be emphasized that in the frame of the relativity theory a charge is an invariant quantity and does not have to charge when passing from one reference system to the other one. Therefore conclusion that a neutral current-carrying conductor takes a charge as a result of motion follows from the noncovariant definition of quantity $\Delta Q$.

To solve the suggested question, we are going to calculate the charge $\Delta Q$ in the frame of dimensional representation based on the formula

$$\Delta Q = j^i \Delta V_i\,. \tag{18}$$

Here $j^i$ is the 4-current density and $\Delta V_i$ the 4-vector of a volume element defined according to[2] so that

$$\Delta V^*_i\, (\Delta V^*, 0, 0, 0), \text{ i.e., } \quad V^*_1 = 0,$$

and so $\Delta Q^*$ is indeed given by equality (13).

However, from the point of view of the S-system on the basis of (3), quantity $\Delta V_1$ is no longer equal to zero and is defined by the formula $\Delta V_1 = -\beta\, \Delta V^*_0 \gamma$. As a result for quantity $\Delta Q$ we find

$$\Delta Q = j^0 \Delta V_0 + j^1 \Delta V_1 = (-\rho^*_- \beta^2 \gamma)\, \Delta V^* \gamma + (-\beta c \rho^*_- \gamma)\,(-\beta \Delta V^* \gamma) = 0. \tag{19}$$

Thus, in complete agreement with the demand of charge invariance we have that the conductor is also electrically neutral from the view point of the S-system*.

It should be noted that the considered example can in principle serve as the basis of an indirect experiment on the control of the transformation

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*Although we have that $\mathrm{div}\vec{E} \neq 0$ as $\rho \neq 0$ now.

formula of space volume since for another definition of $\Delta V_i$ we have that $\Delta Q^* \neq 0$.

Let us dwell now on the physical meaning of formula (18) which can be written in the form

$$\Delta Q = \frac{\partial Q}{\partial t}\,\Delta t + \frac{\partial Q}{\partial x}\,\Delta x \qquad (18')$$

in the simplest case of one space dimension.

In accordance with our approach in the proper reference system, we have $\Delta t^* = 0$ and the charge of a conductor element is defined only by the product of the density by the length of this element.

However, $\Delta t$ is no longer equal to zero in any improper reference system where the conductor is moving.

Therefore, it also is necessary now to take into account the second term describing the charge at a fixed space point. It is obvious that this term is especially relativistic and it takes into account the relativity of simultaneity ($\Delta t^* = 0$, but $\Delta t \neq 0$). It is important to note that an arbitrary change of the lines (hypersurfaces in the general case) of integration (in calculating, using (18′), the total charge in the S-system) say, transition to the straight line $t = \text{const}$, leads to the disappearance of the second term, consequently, to the noted violation of the demand of relativistic covariance. The previously obtained results should be also taken into account in other similar cases, say, for consideration of the behaviour of an electrically neutal current-carrying frame (e.g.,[13a]).

## IV. ENERGY-MOMENTUM TENSOR OF ELECTRICAL MATTER

As is known, the energy of interaction of a system of charges and currents with an external electromagnetic field, which potentials are $\phi$ and $\vec{A}$, is defined by the expression (see, e.g.[13b]):

$$\mathcal{E}^* = \int (\rho^* \phi^* + \vec{j}^* \vec{A}^*)\, dV^*, \qquad (20)$$

where index "*" shows that the used reference system coincides with the rest system (S*) of the considered conductors with charges and currents.

In the frame of four-dimensional representation, equation (20) can be rewritten in the form

$$P_*^0 = \int (2 j_*^0 A_*^0 - \frac{1}{2}\delta^{00} j_*^k A_k^*)\, dV_0^*, \qquad (21)$$

where $\delta_{ik}$ is Kronecker's symbol, or

$$P_*^0 = \int S_*^{00}\, dV_0^*. \qquad (21')$$



The quantity $S^{00}$ so introduced can be interpreted as an energy density in volume units. Moreover it can be considered to be a component of the symmetric energy momentum tensor of electrical matter [14] taking the form*:

$$S^{ik} = j^i A^k + A^i j^k - \delta^{ik} j^\ell A_\ell \,. \qquad (22)$$

The tensor $S^{ik}$ can be expressed only in terms of the 4-current density if the solution of an inhomogeneous wave equation for potential $A^i$ is used.

At one time this solution was found by Herglotz [16] in an explicit covariant form

$$A^i = \frac{1}{4\pi^2} \int \frac{j^i}{R^2}\, d\Omega, \qquad (23)$$

where $R^2 = R^k R_k$ is the distance squared between the fixed point and the charge (current) element and $d\Omega$ the 4-volume element.

Using (22), it is easy to obtain an explicit form of other components $S^{11}$ and $S^{01}$ describing the streams of the momentum and energy x-component, find:

$$S^{11} = j^1 A^1 - j^2 A^2 - j^3 A^3 - j^0 A^0, \quad S^{01} = S^{10} = j^0 A^1 + j^1 A^0 \,. \qquad (24)$$

We form divergence $S^{ik}$ now. In this case we get

$$-\frac{\partial S^{ik}}{\partial x^k} = F^i_k j^k + A^i \frac{\partial j^k}{\partial x^k} + j^i \frac{\partial A^k}{\partial x^k} + A^k \left(\frac{\partial j^i}{\partial x^k} - \frac{\partial j_k}{\partial x_i}\right). \qquad (25)$$

It is easy to see that the second and third terms (25) disappear on the basis of the equation of continuity and the Lorentz condition.

In the case of the following equality

$$\mathrm{rot}^i_k\, j = 0 \qquad (26)$$

which, say, takes place for nonvortex currents, only the known expression, called the density of Lorentz 3-force, is left on the right.

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*At one time the nonsymmetric tensor was discussed in the reference [15].

So, the following known equality

$$- \frac{\partial T^{ik}}{\partial x^k} = F^i_k j^k \qquad (27)$$

can be presented as

$$\frac{\partial R^{ik}}{\partial x^k} = 0. \qquad (28)$$

where $R^{ik} = T^{ik} - S^{ik}$ and $T^{ik}$ is the energy-momentum tensor of an electromagnetic field.

It should be also pointed out that in the case of holding equality (26), intensities obey a free wave equation.

Taking into account the equation continuity the components $j^k$ obey such an equation too. As charges themselves cannot move with light velocity, the noted fact should be considered as that the density of charges (currents) can change from point to point with light velocity. An electromagnetic wave is the agent causing this change.

For the wave equation for potentials, Lorentz calibration can be changed for the condition

$$\frac{\partial A^k}{\partial x^k} = \chi, \text{ where } j^i = - \frac{\partial \chi}{\partial x_i}. \qquad (29)$$

However, it is obvious that in the general case instead of (28) we nevertheless have

$$\frac{\partial R^{ik}}{\partial x^k} = A^\ell \operatorname{rot}_\ell j^i. \qquad (28')$$

In conclusion we should like to note that in the most general case according to the demand of covariance equality (21´) has to be

$$P^0_* = \int S^{0k}_* \, dV^*_k. \qquad (30)$$

Although in the general case $S^{0k}_* \neq 0$ equality (21´) nevertheless holds on the assumption (according to sect.III) that $dV^*_\alpha = 0$.



## V. POWER-FORCE TENSOR

We consider the tensor of kinetic energy-momentum

$$\theta^{ik} = J^i u^k \qquad (31)$$

or in an explicit symmetric form

$$\theta^{ik} = \frac{1}{2}(J^i u^k + J^k u^i) \qquad (31')$$

where $J^i$ is the 4-current of mass density. In particular for

$$J^i = \mu^* u^i, \qquad (32)$$

where $\mu^*$ is the proper mass density, we lead to the usual expression /17/

$$\theta^{ik} = \mu^* u^i u^k. \qquad (31'')$$

Note that, e.g., components $\theta^{0k}$ can be easily obtained from the formula for the 4-vector of energy-momentum

$$p^k = m u^k \qquad (33)$$

in which in the case of continuous material distribution mass m is simply replaced by mass density $J^0$ and so on.

As the relativistic force $F^k$ (Minkowski's forse) as well as $p^k$ is a 4-vector, then the density of 4-force should be defined by the 2nd rank tensor on the same basis. Taking into account that power is expressed by $F^0$, we designate the inproduced quantity as the power-force tensor /18/. For a "kinetic modification" of this quantity, i.e., proceeding from the expression

$$F^k = m w^k, \qquad (34)$$

where $w^k$ is 4-acceleration, we obtain

$$P^{ik} = J^i w^k \qquad (35)$$

or in an explicit symmetric form

$$P^{ik} = \frac{1}{2}(J^i w^k + J^k w^i). \qquad (35')$$

On the other hand, in particular, $P^{ik}$ can be introduced from the kinetic tensor $\theta^{ik}$

$$P^{ik} = \frac{1}{2} \frac{d\theta^{ik}}{d\tau} . \qquad (36)$$

However, we are interested in the electromagnetic power-force tensor. In this case we have to proceed for Lorentz 4-force.

$$F^k = e F^k_\ell u^\ell . \qquad (37)$$

Using the density 4-vector of electrical current $j^i$ for the tensor of Lorentz' relativistic force density, we find

$$P^{ik} = j^i F^k_\ell u^\ell . \qquad (38)$$

or in an explicit symmetric form

$$P^{ik} = \frac{1}{2} (j^i F^k_\ell u^\ell + j^k F^i_\ell u^\ell) . \qquad (38')$$

It should be noted that now we can get the known equality (27) only fulfilling the condition $j^i = \rho * u^i$, which means the equality of 4-velocities of system elements and all the system as a whole.

## VI. ON ONE ELEMENTARY DERIVATION OF THE FORMULA $\mathcal{E} = mc^2$

An elementary derivation of the theorem of equivalence of mass and energy, in particular connected with the proof that the inertial mass $\mathcal{E}/c^2$ should be ascribed to the energy of electromagnetic radiation $\mathcal{E}$, is given in Einstein's paper /19/ and also in a series of monographs and text books (see, e.g., /12b, 20/). For this a hollow cylinder at rest is considered. Inside the cydinger near the wall of one of the bases (A), there is a device which sends a certain amount of radiant energy $\mathcal{E}$. Since the radiation pressure on the wall is equal to the density of radiant energy, then the cylinder gets, inder the action of radiation, the velocity, equal to $\mathcal{E}/Mc$, where M is the cylinder mass. The cylinder covers the distance $x = \mathcal{E}L/Mc^2$ for the time which is equal (accurate to the terms above the first order) to L/c, where L is the cylinder length, needed for a light to cover the way along the cylinder. Then the cylinder stops after light absorption. If light had no mass, the movement of the cylinder would mean the displacement of the mass centre without the action of external forces. This contradicts the basic principles of mechanics.



Therefore it is necessary to attribute some mass to light (m). In this case the following condition should be fulfilled

$$Mx - mL = 0 .$$

From here it follows that

$$m = \frac{\mathcal{E}}{c^2} . \qquad (39)$$

Although formula (39) obtained in this way is true, the above discussions obviously contain an inaccuracy /21–23/. Namely, these papers suppose that all the cylinder acquires a velocity at the instant of radiation. But this would be possible only in that case if pertrubation would propagate from one end of cylinder to its other end instantaneously. However, as we known, the last fact is in contradiction with the basic statement of relativity theory that no interaction can be conveyed with velocity larger than the light velocity*. At the same time one cannot also agree with the notion /21/ that the motion of the cylinder basic B towards electromagnetic momentum should be also taken into account in the considered experiment.

Thus, Einstein's mental experiment is not strict, and the elimination of nonstrictness due to taking into account the cylinder deformation and the following restoration of its form, deprives experiment of simplicity and clearness.

The principal and foregoing reasonings can be kept if instead of the considered mental experiment (in Born's modification), one uses, for example, such an experiment in which the object A (of mass M/2)** is at a distance $L_1 = L[1 + (M/2)c^2/\mathcal{E}]^{-1}$ from the left end of the cylinder at the instant of light radiation (see Fig.4). In this case only the indicated object acquires a velocity $v = 2\mathcal{E}/(Mc)$ as a result of radiation. The proposed experimental setup does not demand to take the cylinder deformation into account since light and the object A will achieve the corresponding cylinder bases simultaneously.

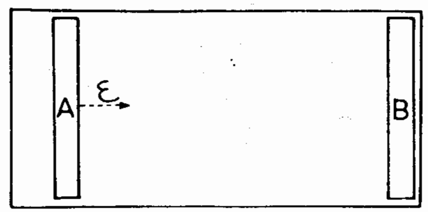


Fig.4. Illustration of one elementary derivation of the relation $\mathcal{E} = mc^2$.

*Indeed, light achieves the other end of the cylinder much earlier than perturbation does.

**We consider that the cylinder mass is small in comparison with the masses of the objects A and B, the thickness of which is disregarded as well.

## VII. CONCLUSION

At one time electrodymanics served the basis for the creation of relativity theory. However, later on the application of this theory, especially its four-dimensional representation, allowed one to relativize electrodynamics. In particular, for continuous distribution of matter taking into account the demand of relativistic covariance allowed one to introduce energy-momentum tensor of electrical matter and the power-force tensor. Moreover, the application of the radar formulation of relativity theory permitted some available difficulties of relativistic electrodynamics to be removed. Among them are the problem 4/3, charge appearance in a moving (neutral) current-carrying conductor and so on.

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Стрельцов В.Н.


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Некоторые вопросы релятивистской электродинамики


Некоторые вопросы электродинамики рассматриваются с точки зрения локационной формулировки теории относительности. Эта формулировка опирается на световые или запаздывающие расстояния, ее следствием является увеличение продольных размеров движущихся объектов ("формула удлинения"). На основе потенциалов Лиенара-Вихерта показано, что в терминах запаздывающих расстояний эквипотенциальные поверхности имеют форму эллипсоидов вращения, вытянутых в направлении движения электрического заряда. Устранена трудность, связанная с появлением заряда в движущемся (нейтральном) проводнике с током. Рассмотрены тензор энергии-импульса электрической материи (во внешнем поле) и тензор мощности-силы. Указано на неточность в одном известном элементарном выводе соотношения эквивалентности массы и энергии.



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Strel'tsov V.N.


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Some Problems of Relativistic Electrodynamics


Some problems of electrodynamics are considered from the point of view of the radar formulation of relativity theory. This formulation is based on light or retarded distances, the increasing of longitudinal sizes of moving objects is its consequence ("elongation formula"). Based on Lienard-Wiechert's potentials it is shown that in terms of retarded distances equipotential surfaces take the form of rotation ellipsoids, stretched in the direction of electric charge motion. The difficulty connected with the appearance of charge in a moving (neutral) current-carrying conductor is overcome.



The investigation has been performed at the Laboratory of High Energies, JINR.

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