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Transverse Plasma Resonance in the Nonmagnetized Plasma and its Practical Use

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Transverse Plasma Resonance in the Nonmagnetized Plasma and its Practical Use

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I. Introduction

In explosions of nuclear charges, as a result of which a hot plasma is formed, electromagnetic radiation takes place in a very wide frequency range, down to the long-wave radio range. But to date, those physical mechanisms that could explain the origin of such radiation are unknown. It is known that plasma resonance is longitudinal, but longitudinal resonance can not radiate transverse radio waves. The existence in the non-magnetized plasma of any other resonances, other than the plasma resonance, was previously unknown. However, it turns out that in a bounded unmagnetized plasma there can be a transverse resonance with respect to the propagation direction of the wave. It is this resonance that can be the cause of radiation of radio waves during explosions of nuclear charges. This resonance can be used to create high-power lasers and to heat the plasma [1].

II. Plasma in the Two-Wire Circuit

For explaining the conditions for the excitation of this resonance let us examine the long line, which consists of two ideally conducting planes, as shown in Fig 1.

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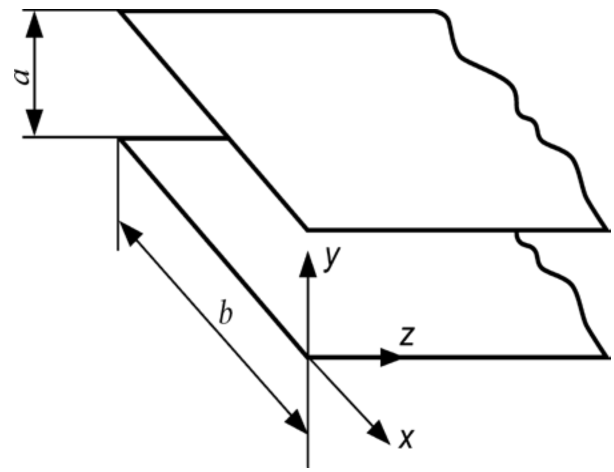

Fig. 1: The two-wire circuit, which consists of two ideally conducting planes

Linear (falling per unit of length) capacity and inductance of this line without taking into account edge effects they are determined by the relationships $C_0=\varepsilon_0\frac{b}{a}$ и $L_0=\mu_0\frac{a}{b}$. Therefore with an increase in the length of line its total capacitance $C_\Sigma=\varepsilon_0\frac{b}{a}z$ and summary inductance $L_\Sigma=\mu_0\frac{a}{b}z$ increase proportional to its length.

If we into the extended line place the plasma, charge carriers in which can move without the losses, and in the transverse direction pass through the plasma the current I, then charges, moving with the definite speed, will accumulate kinetic energy. Let us note that here are not examined technical questions, as and it is possible confined plasma between the planes of line how. This there can be, for example, magnetic traps or directed flows of plasma. The case also of other plasma media of the type of semiconductors can be examined. In this case only fundamental questions, which are concerned transverse plasma resonance in the nonmagnetic plasma, are examined.

Since the transverse current density in this line is determined by the relationship $j=\frac{I}{bz}=nev$, that summary kinetic energy of all moving charges will be written down

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$$W_{k\Sigma} = \frac{1}{2}\frac{m}{ne^2}abzj^2 = \frac{1}{2}\frac{m}{ne^2}\frac{a}{bz}I^2 . \quad (1)$$

Relationship (1) connects the kinetic energy, accumulated in the line, with the square of current; therefore the coefficient, which stands in the right side of this relationship (1) before the square of current, is the summary kinetic inductance of line.

$$L_{k\Sigma} = \frac{m}{ne^2}\cdot\frac{a}{bz} . \quad (2)$$

Thus, the parameter

$$L_k = \frac{m}{ne^2} \quad (3)$$

presents the specific kinetic inductance of charges. Relationship (3) is obtained for the case of the direct current, when current distribution is uniform. We also will not thus far consider the ionic constituent of current, since at the high frequencies she is considerably less than electronic constituting.

Subsequently for the larger clarity of the obtained results, together with their mathematical idea, we will use the method of equivalent diagrams. The section, the lines examined, long dz can be represented in the form the equivalent diagram, shown in Fig. 2 (a).

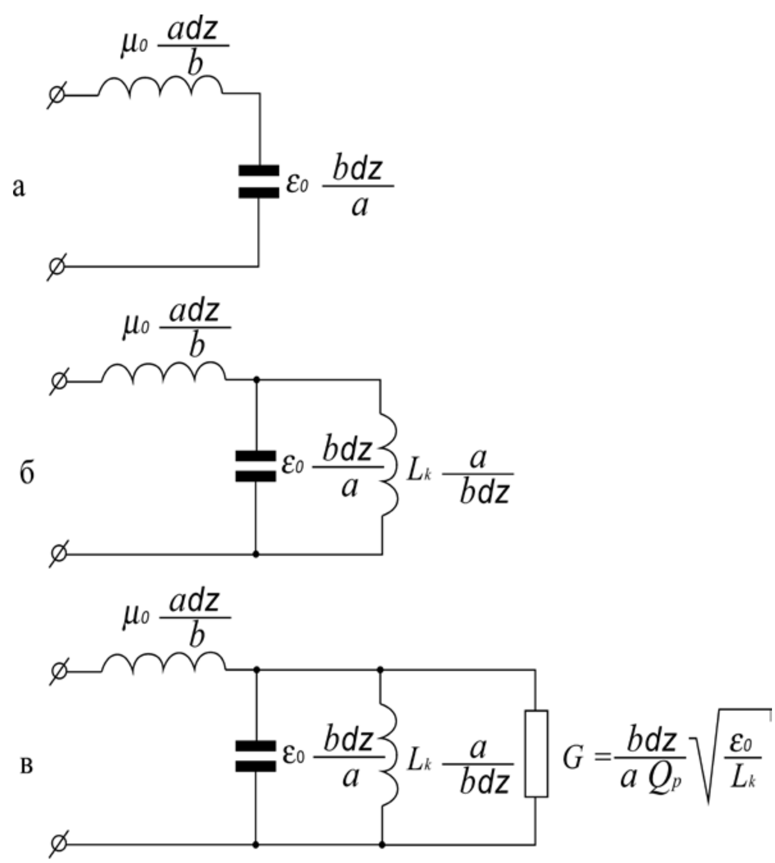

Fig. 2: a - the equivalent the schematic of the section of two-wire circuit

б - the equivalent the schematic of the section of the two-wire circuit, filled with plasma without the losses;
в - the equivalent the schematic of the section of the two-wire circuit, in which there are ohmic losses.

From relationship (2) is evident that in contrast to C_Σ and L_Σ the value $L_{k\Sigma}$ with an increase in z does not increase, but it decreases. This is understandable from a physical point of view, connected this with the fact that with an increase in z a quantity of parallel-connected inductive elements grows. For the case, when the length of line is considerably lower than the length, which is extended in it wave, it is equivalent to the parallel circuit with the lumped parameters, capacity and inductance of which is determined by the following relationships: $C = \frac{\varepsilon_0 bz}{a}$, $L = \frac{L_k a}{bz}$ in series with which is connected the inductance $\mu_0\frac{adz}{b}$.

But if we calculate the resonance frequency of this outline, then it will seem that this frequency generally not on what sizes depends, actually:

$$\omega_\rho^2=\frac{1}{CL}=\frac{1}{\varepsilon_0 L_k}=\frac{ne^2}{\varepsilon_0 m} \quad .$$

Is obtained the very interesting result, which speaks, that the resonance frequency macroscopic of the resonator examined does not depend on its sizes. Impression can be created, that this is plasma resonance, since the obtained value of resonance frequency exactly corresponds to the value of this resonance. But it is known that the plasma resonance characterizes longitudinal waves in the long line they, while occur transverse waves. In the case examined the value of the phase speed in the direction z is equal to infinity and the wave vector $\mathbf{k}=0$. In this case the wave number is determined by the relationship:

$$k_z^2=\frac{\omega^2}{c^2}\left(1-\frac{\omega_\rho^2}{\omega^2}\right), \qquad (4)$$

and the group and phase speeds

$$v_g^2=c^2\left(1-\frac{\omega_\rho^2}{\omega^2}\right), \qquad (5)$$

$$v_F^2=\frac{c^2}{\left(1-\frac{\omega_\rho^2}{\omega^2}\right)} \quad , \qquad (6)$$

where $c=\left(\frac{1}{\mu_0\varepsilon_0}\right)^{1/2}$ - speed of light in the vacuum.

For the present instance the phase speed of electromagnetic wave is equal to infinity, which corresponds to transverse resonance at the plasma frequency. Consequently, at each moment of time pour on distribution and currents in this line uniform and it does not depend on the coordinate z, but current in the planes of line in the direction z is absent. This, from one side, it means that the inductance L_Σ will not have effects on electrodynamic processes in this line, but instead of the conducting planes can be used any planes or devices, which limit plasma on top and from below. With the explosion of nuclear charges the boundaries of the cloud of explosion can be the boundaries, which limit plasma.

From the relationships (6) it is not difficult to see that at the point $\omega=\omega_p$ we deal concerning the transverse resonance with the infinite quality. The fact that in contrast to the Langmuir, this resonance is transverse, will be one can see well for the case, when in the plasma dissipative losses will occur and the quality of this resonance will not be equal to infinity. In this case $k_z\neq 0$, and in the line will be extended the transverse wave, the direction of propagation of which will be perpendicular to the direction of the motion of charges. The examination of this task was begun from the examination of the plasma, limited from two sides by the planes of long line. But in the process of this examination it is possible to draw the conclusion that the frequency of this resonance generally on the dimensions of line does not depend.

Before to pass to the more detailed study of this problem, let us pause at the energy processes, which occur in the line in the case of the absence of losses examined. Pour on the characteristic impedance of plasma, which gives the relation of the transverse components of electrical and magnetic, let us determine from the relationship

$$Z=\frac{E_y}{H_x}=\frac{\mu_0\omega}{k_z}=Z_0\left(1-\frac{\omega_\rho^2}{\omega^2}\right)^{-1/2} \quad ,$$

where $Z_0=\sqrt{\frac{\mu_0}{\varepsilon_0}}$ - characteristic (wave) resistance of vacuum. The obtained value Z is characteristic for the transverse electrical waves in the waveguides. It is evident that when $\omega\to\omega_p$, then $Z\to\infty$, and $H_x\to 0$. When $\omega > \omega_p$ in the plasma there is electrical and magnetic component of field, and the specific energy of these pour on it will be written down

$$W_{E,H}=\frac{1}{2}\varepsilon_0 E_{0y}^2+\frac{1}{2}\mu_0 H_{0x}^2 .$$

Thus, the energy, concluded in the magnetic field, in $\left(1-\frac{\omega_\rho^2}{\omega^2}\right)$ of times is less than the energy, concluded in the electric field. Let us note that this examination, which is traditional in the electrodynamics, is not complete, since. in this case is not taken into account one additional form of energy, namely kinetic energy of charge carriers. Occurs that pour on besides the waves of electrical and magnetic, that carry electrical and magnetic energy, in the plasma there exists even and the third - kinetic wave, which carries kinetic energy of current carriers. The specific energy of this wave is written:

$$W_k=\frac{1}{2}L_k j_0^2=\frac{1}{2}\cdot\frac{1}{\omega^2 L_k}E_0^2=\frac{1}{2}\varepsilon_0\frac{\omega_\rho^2}{\omega^2}E_0^2 .$$

Consequently, the total specific energy of wave is written as

$$W_{E,H,j}=\frac{1}{2}\varepsilon_0 E_{0y}^2+\frac{1}{2}\mu_0 H_{0x}^2+\frac{1}{2}L_k j_0^2 \quad .$$

Thus, for finding the total energy, by the prisoner per unit of volume of plasma, calculation only pour on E and H it is insufficient.
At the point $\omega=\omega_p$ is carried out the relationship

$$W_H = 0$$
$$W_E = W_k ,$$

i.e. magnetic field in the plasma is absent, and plasma presents macroscopic electromechanical resonator with the infinite quality, ω_p resounding at the frequency.

Since with the frequencies $\omega > \omega_p$ the wave, which is extended in the plasma, it bears on itself three forms of the energy: electrical, magnetic and kinetic, then this wave can be named electromagnetokinetic wave. This term, which completely reflects physics of processes for the wave examined, earlier was not used and it was for the first time used in the works [2,3]. Kinetic wave represents the wave of the current density $\mathbf{j}=\frac{1}{L_k}\int \mathbf{E}dt$. This wave is moved with respect to the electrical wave the angle $\frac{\pi}{2}$.

Until now, the physically unrealizable case has been considered, when there are no losses in the plasma, which corresponds to an infinite Q-factor of the plasma resonator.If losses are located, moreover completely it does not have value, by what physical processes such losses are caused, then the quality of plasma resonator will be finite quantity. For this case of Maxwell's equation they will take the form:

$$rot\ \mathbf{E} = -\mu_0 \frac{\partial\ \mathbf{H}}{\partial\ t},$$

$$rot\ \mathbf{H} = \sigma_{p.ef}\ \mathbf{E} + \varepsilon_0 \frac{\partial\ \mathbf{E}}{\partial\ t} + \frac{1}{L_k}\int \mathbf{E}dt. \tag{7}$$

The presence of losses is considered by the term $\sigma_{p.ef}\mathbf{E}$, and, using near the conductivity of the index ef, it is thus emphasized that us does not interest very mechanism of losses, but only very fact of their existence interests. The value σ_{ef} determines the quality of plasma resonator. For measuring σ_{ef} should be selected the section of line by the length z_0, whose value is considerably lower than the wavelength in the plasma. This section will be equivalent to outline with the lumped parameters:

$$C=\varepsilon_0 \frac{bz_0}{a}, \tag{8}$$

$$L=L_k \frac{a}{bz_0}, \tag{9}$$

$$G=\sigma_{\rho.ef} \frac{bz_0}{a}, \tag{10}$$

where G - conductivity, connected in parallel C and L.

Conductivity and quality in this outline enter into the relationship:

$$G=\frac{1}{Q_\rho}\sqrt{\frac{C}{L}} ,$$

from where, taking into account (8 - 10), we obtain

$$\sigma_{\rho.ef} = \frac{1}{Q_\rho}\sqrt{\frac{\varepsilon_0}{L_k}} . \tag{11}$$

Thus, measuring its own quality plasma of the resonator examined, it is possible to determine $\sigma_{p.ef}$. Using (11) and (7) we will obtain

$$rot\ \mathbf{E} = -\mu_0 \frac{\partial\ \mathbf{H}}{\partial\ t},$$

$$rot\ \mathbf{H} = \frac{1}{Q_\rho}\sqrt{\frac{\varepsilon_0}{L_k}}\ \mathbf{E} + \varepsilon_0 \frac{\partial\ \mathbf{E}}{\partial\ t} + \frac{1}{L_k}\int \mathbf{E}dt. \tag{12}$$

The equivalent the schematic of this line, filled with dissipative plasma, is represented in Fig. 2 (в).

Let us examine the solution of system of equations (12) at the point $\omega = \omega_p$, in this case, since

$$\varepsilon_0 \frac{\partial\ \mathbf{E}}{\partial\ t} + \frac{1}{L_k}\int \mathbf{E}dt=0 ,$$

and further we will obtain

$$rot\ \mathbf{E} = -\mu_0 \frac{\partial\ \mathbf{H}}{\partial\ t},$$

$$rot\ \mathbf{H} = \frac{1}{Q_P}\sqrt{\frac{\varepsilon_0}{L_k}}\ \mathbf{E}.$$

These relationships determine wave processes at the point of resonance.

If losses in the plasma, which fills line are small, and strange current source is connected to the line, then it is possible to assume:

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$$rot\ \mathbf{E} \cong 0,$$

$$\frac{1}{Q_p}\sqrt{\frac{\varepsilon_0}{L_k}}\ \mathbf{E} + \varepsilon_0 \frac{\partial\ \mathbf{E}}{\partial\ t} + \frac{1}{L_k}\int \mathbf{E}dt = \mathbf{j}_{CT}, \quad (13)$$

where $\mathbf{j}_{CT}$ - density of strange currents. After integrating (13) with respect to the time and after dividing both parts to , we will obtain

$$\omega_p^2\ \mathbf{E} + \frac{\omega_p}{Q_p}\cdot\frac{\partial\ \mathbf{E}}{\partial\ t} + \frac{\partial^2\mathbf{E}}{\partial\ t^2} = \frac{1}{\varepsilon_0}\cdot\frac{\partial\ \mathbf{j}_{CT}}{\partial\ t}. \quad (14)$$

If we relationship (14) integrate over the surface of normal to the vector of and to introduce the electric flux of we will obtain:

$$\omega_p^2 P_E + \frac{\omega_p}{Q_p}\cdot\frac{\partial\ P_E}{\partial\ t} + \frac{\partial^2 P_E}{\partial\ t^2} = \frac{1}{\varepsilon_0}\cdot\frac{\partial\ I_{CT}}{\partial\ t}, \quad (15)$$

where I_{CT} - strange current. Equation (15) is the equation of harmonic oscillator with the right side, characteristic for the two-level laser [4]. If the source of excitation is absent, then we deal concerning "cold" laser resonator, in which the fluctuations attenuate exponentially

$$P_E(t) = P_E(0)\ e^{i\omega_P\ t}\cdot e^{-\frac{\omega_P}{2Q_P}\ t},$$

i.e. the macroscopic electric flux $P_E(t)$ will oscillate with the frequency ω_p, relaxation time in this case is determined by the relationship:

$$\tau = \frac{2Q_P}{\omega_P}.$$

The problem of developing of laser consists to now only in the skill excite this resonator.

If resonator is excited by strange currents, then this resonator presents band-pass filter with the resonance frequency to equal plasma frequency and the passband $\Delta\omega = \dfrac{\omega_p}{2Q_p}$.

Another important practical application of transverse plasma resonance is possibility its use for warming-up and diagnostics of plasma. If losses in the plasma are small, which occurs at high temperatures, the quality of plasma resonator is also great, and can be obtained the high levels of electrical pour on, and it means high energies of charge carriers.

III. Conclusion

Work examines transverse plasma resonance in the nonmagnetized plasma, limited by two planes. This resonance can explain low-frequency radiation spectrum with the explosions of nuclear charges, since the cloud of the explosion of nuclear explosion is limited. It can be used for creating the powerful laser generators with collective plasma oscillations, and also for the warming-up of plasma.

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