Radiation from the shock wave front caused by its movement in plasma

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Abstract. In the work the possibility of electromagnetic radiation of shock wave in collisional plasma is theoretically explored, radiation which stimulated specifically by movement of the shock wave. Radiation occurs across the shock wave movement and for experiments in cold plasmas—at frequency of high-frequency radiation.

1. Introduction
It is well known from calculations that at the front of shock wave in a collisional plasma charge separation occurs [1,2,3], caused by the fact that the mass of electrons is much smaller compared to the mass of atoms and molecules and electron mobility is higher than for ions. When moving of the shock wave from one part of plasma to another part the plasma quasineutrality is restored in a scale comparable with Debye sphere radius. Recovery involves acceleration of the charges, resulting in electromagnetic radiation. Because the Debye radius in cold plasma is small relative to the resolution of measurement devices, you can assume that the radiation comes from a point in space at the front of the shock wave. The frequency of this radiation is due to the speed of the shock wave and the Debye radius. For the conditions of the experiments that are carried out on electromagnetic shock tube of Ioffe institute [4] frequency estimated as frequency of HF radiation, so radiation is not shielded. Radiation of this kind can be thought as radiation of the dipole system on the shock wave surface. This model is useful for finding the radiation power, which turned out to be higher than the power of electromagnetic interference, so radiation is quite registered. Radiation occurs strictly in the selected direction, which, however, may be changed due to curvature of shock wave front. Therefore, registration of the radiation in experiments is possible that can be used to measure the speed of the shock wave by the frequency of radiation. There's no need for measuring the time of wave moving between two points. The same effect is possible and for passage of a shock wave in a solid, apparently, in piezo active media.

2. The physical basis for radiation from the front shock wave
Effect of charge separation in the shock wave front in cold plasma has been predicted [1,2], it is confirmed by modern calculations [5]. Separation of charges due to high electron mobility compared with ions, as well as the substantial difference in masses of electrons and ions. After the passage of the
liquid particles of the shock wave front, the plasma quasineutrality is violated. Restoration of the plasma quasineutrality, as it is known [1], cannot occur at distances less than Debye-Hückel radius:

\[ r_0 = \left[ 4 \pi N_e e^2 \left( \frac{1}{T_e} + \frac{1}{T_i} \right) \right]^{1/2} \]

(1)

Therefore, the characteristic distance of restoring neutrality should be considered as the Debye-Hückel radius, despite the fact that the width of the density jump at the front is by orders of magnitude less. In the calculation of the charge separation also takes place within roughly the Debye-Hückel radius [3]. When restoring the acceleration of charges takes place. Acceleration leads to electromagnetic radiation. During the movement the shock wave moves from one liquid to another particle, and in each particle radiation occurs. Since the detection of radiation in sufficiently dense plasma is carried out with a fairly low resolution, it can be assumed that the energy emitted from the front shock wave at each point of space. It can also be assumed with some degree of approximation that the radiation at each point of the species is similar to the dipole of plasma radiation.

3. Estimation of radiation parameters

Estimations of parameters of radiation are rationally get for installations with the speed of the shock wave from 1000 ms\(^{-1}\) to 3000 ms\(^{-1}\), Debye-Hückel radius in the center of the discharge 2.3\(\times\)10\(^{-9}\) m. On the basis of these two characteristic values, the speed of the shock wave and Debye-Hückel radius, it is possible to estimate the frequency of radiation. It is equal to 10\(^{8}\)\(\times\)10\(^{10}\) Hz, which corresponds to high-frequency radiation. If the frequency of radiation less than the plasma frequency:

\[ \omega_p = \left( \frac{4 \pi n_e e^2}{m_e} \right)^{1/2} \]

(2)

radiation should be fully reflected inside the volume occupied by plasma.

Plasma frequency in experiments [4] for concentration of electrons 5\(\times\)10\(^{11}\) cm\(^{-3}\) is equal to 4\(\times\)10\(^{10}\) Hz so the radiation has no reflection at increasing of wave speed or at reducing of concentration of charged components roughly an order of magnitude. As is well known, the intensity of the radiation \(I\) of oscillated dipole is described by physical law, which is expressed by the formula [9]:

\[ \frac{dI}{d\Omega} = \frac{p_\theta^2}{4 \pi c^2} \sin^2 \theta \]

(3)

Where the differential of solid angle \(\Omega\): \(d\Omega = \sin\theta \, d\varphi \, d\theta\). Here \(\varphi\)–transversal beam angle with respect to the axis of the dipole, \(\theta\)–direction angle of radiation with respect to the axis of the dipole, \(p\) – dipole moment, two dots above the letter – the second time derivative, \(c\) is the speed of light.

It is well illustrated (3) that \(dI\) is proportional to the third degree of \(\sin\theta\). This means that the radiation is almost perpendicular to the direction of the dipole, because, \(\sin\theta = \cos(\pi / 2 - \theta)\) and exponentiation of numbers less than one reduces the value. For example, for \(\theta = 30^\circ\), \(\pi / 2 - \theta = 60^\circ\), third degree of cosine equals 0.125, i.e. by comparing with the central ray the density of the radiation falls in the order. Therefore, the radiation attenuation with distance will be back to the distance from the source of approximately in the first degree, but not the second, because the energy is distributed on the circle rather than on the sphere. As a result, a larger distance from the radiation source radiation from the dipole will be less faded out than for other types of radiation. For the analysis of characteristic parameters of the radiation of dipole oscillations can be seen as a harmonic oscillations with a given frequency \(\omega\). Then the second derivative of the dipole moment: \(\ddot{p} = -\omega^2 p\). So this intensity of radiation per unit of angle \(\theta\), generated of the surface unit of shock wave equals:
Where $N_e$ — the number of electrons in cm$^3$, degree of 2/3 of this number arises from the requirement to account of electron density specifically on the surface of the shock wave. Here it is believed that the dipole moment $p = er_p$. If shock wave is flat, then in formula (4), the right side, should be multiplied by the surface area of the front. Substituting the values into the formula we get that $10^{-5}$ W is radiated from each cm$^2$ of the shock wave along the tangent to its front in unit of solid angle.

For experiments in plasma [4] radiation intensity is about $10^{-5}$ W for electromagnetic waves with a wavelength on the order of 10 mm for both the cyclotron radiation, and for braking radiation for electron-ion interaction. The same order of intensity, apparently, must be and behind the front of shock wave. To allocate emission of investigated type it is required a registration of emission at the distance which is sufficient for attenuation of "noise" radiation, which is damped with increasing of distance from the source faster than the radiation perpendicular to dipole axis.

4. Taking into account the curvature
The curvature of the front shock wave can be taken into account by integrating the intensity of the radiation at the height $y$ of the beam from all parts of the surface front. For a two-dimensional problem and without consideration of the refraction on the shock wave front and the diffraction the energy flux density distribution $i$ along the detection surface $\rho$ has the form:

$$
\frac{dl}{d\theta} = \frac{\omega^2 e^3 r_p^2}{4\pi c^2} \sin^3 \theta \cdot N_e^{2/3} \tag{4}
$$

$$
i(\rho) = \frac{\omega^4 e^6 r_p^3}{4\pi c^3} N_e^{2/3} \int_0^\rho \sin \left[ \frac{\pi}{2} + \arctg \left( x'(y) \right) + \arctg \left( \frac{\rho - x(y)}{y} \right) \right] \left[ y \left( 1 + \left( \frac{\rho - x(y)}{y} \right)^2 \right) \right]^{-1} dy \tag{5}
$$

$x (y)$ — the shape of the shock wave, $h, H$-minimum and maximum distance to radiation detector, $\rho$ — the distance from the maximum intensity for flat wave.
Figure 1. Modification of the energy flux density distribution $i$ along the detection surface $\rho$ as a result of changes in the shape of the shock front: 1 – flat shock wave, 2 – shock wave of elongated elliptical shape, semi-minor axis $a$ in $k = 8$ times less than semi-major axis, 3– $k = 4$. Shock wave moves to left. $H=0.3$ m, $h=0.1$ m.

Results of calculations are presented in Figure 1 for shock wave of elliptic shape with semi-minor axis $a$ in $k$ times smaller than semi-major axis $b$:

$$x(y)=a\left(1-\left(\frac{y-y_0}{b^2}\right)^{1/2}\right), \quad b=\frac{H-h}{2}; \quad x'(y)=\frac{1}{k}\frac{y-y_0}{(b^2-(y-y_0)^2)^{1/2}}, \quad y_0=\frac{H+h}{2} \quad (6)$$

It is shown that the shockwave of an elliptical form ($k = 8$ and $4$) in the points of the maximum drop in intensity due to the curvature of the surface of the shock wave is less than 20%.

5. Conclusions
So, it is shown that, with appropriate selection of the conditions of the experiment, plasma parameters and shock waves velocity, the registration of radiation perpendicular to the shock waves velocity caused by the shock wave movement can be held in collision plasma. Registration of this radiation will confirm theoretically predicted separation of charge at the front of the shock wave. Finally registration of this kind of radiation gives rise to adjustments in the law of conservation of energy at the transition across the shock wave, because there is radiation of energy from the front in the form of electromagnetic waves. It should be noted that such an effect is possible in the plasma of a solid body, which expands the possible scope of its application.

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