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DIRECTED COHERENT RADIATION DUE TO BREAKDOWN NEAR THE TRACK OF AN IONIZING PARTICLE

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Directed emission of radio waves produced as a result of breakdown near the track of an ionizing particle in a medium located in an electric field is considered. It is shown that a strong asymmetry of the radiation arises if the particle velocity is comparable to or exceeds the propagation velocity of the radio waves in the medium. It is pointed out that the effect can be used to obtain sharply directed radiation and also to determine the velocity of the particle initiating the breakdown by measuring the angle of maximum emission.

INTRODUCTION

THE well-known forms of radiations which arise as a result of the motion of a particle in a medium (for example, Cerenkov radiation, radiation by heterogeneities of a medium etc.) draw energy from a moving particle and have comparatively low intensity. It seemed interesting to us to examine radiation effects which, although still produced by charged particles, draw their energy from external fields.

One of the possible versions of this effect is the radiation which arises as a result of the breakdown near the track of an ionizing particle in a medium with an electric field the intensity of which is close to breakdown. Easier conditions for the breakdown and its localization near the track can be ensured, for example, by the use of two-phase media (porous media, media with voids and bubbles filled with a special gas, blocks of corrugated plates which form closed spaces between the plates, etc.) and also by the use of media with inclusions that have a smaller breakdown strength (semiconductor inclusions, semiconductors with impurities, etc). Radiation from pre-breakdown currents or from currents at the start of breakdown, initiated by the particle, can be observed also in a one-phase medium (gas, liquid, semiconductor, etc.).

We consider the properties of coherent radiation due to breakdown near the track.

COHERENT RADIO EMISSION DUE TO BREAKDOWN NEAR THE TRACK OF A PARTICLE:

Let us assume that as a particle moves through a medium localized breakdowns are formed near the particle's track under the action of a strong external electric field. It is obvious that one can speak of coherence of the radiation in this case if the statistical delay of the breakdowns following the flight of the particle through a given point of a medium is small in comparison with the period of the propagated waves. Experiments with parallel-plate spark counters (see, for example, [1,2]) have demonstrated that the spread of the delay and the time of buildup to half intensity of the spark is of the order of a fraction of a nanosecond for the size of sparks of interest to us. This shows that coherent effects can be expected in the decimeter band. It is precisely for these waves that a medium with small heterogeneities will not act like a homogeneous medium. We assume henceforth that the requirements for coherence can be ensured and that the medium is homogeneous for radio waves. Coherent generation of micro-wave and optical radiation as a result of breakdown near the track is possible in semiconductors.

If the distance from the point of reception exceeds the length of the tract segment along which the conditions for breakdown are realized, then one can use the expression for the wave field of a system of dipoles:*

$$\mathbf{E}(t) = \frac{1}{c^2 R_0}\left[\left[\int d\ddot{\mathbf{P}}\left(t - \frac{R}{c}\right)\mathbf{n}\right]\mathbf{n}\right],$$

$$\mathbf{H}(t) = \frac{\sqrt{\varepsilon}}{c^2 R_0}\left[\int d\ddot{\mathbf{P}}\left(t - \frac{R}{c}\right)\mathbf{n}\right],$$

where $R = R_0 - \mathbf{r}\cdot\mathbf{n}$, $d\ddot{\mathbf{P}} = \ddot{\mathbf{P}}_1 dz$, and $\mathbf{P}_1(t)$ is the resulting dipole moment per unit breakdown-current track length.

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*$[\mathbf{Pn}] = \mathbf{P} \times \mathbf{n}$.

Transforming to Fourier components and integrating along the track of the particle we obtain the spectral component of the wave field

$$\mathbf{E}_\omega = \frac{1}{c^2 R_0} e^{ik'R_0} L \frac{2\sin\{k'(c'/v - \cos\theta) L\}}{k'(c'/v - \cos\theta) L} [[(\ddot{\mathbf{P}}_1)_\omega \mathbf{n}]\,\mathbf{n}],$$

where $k' = \omega/c'$, v is the speed of the particle, c' is the speed of propagation of the radio waves, L is the length of the track segment, and θ is the angle between the track and the direction of observation. The appearance of an abrupt asymmetry follows already from the above formula with $v \gtrsim c'$ for $\cos\theta = c'/v$ (the sharpness of the directivity is $\Delta\theta \sim \pi/k'L \sin\theta$).

In the case of a localized breakdown as the result of the abrupt occurrence of dipole moments we have

$$(\ddot{\mathbf{P}})_\omega = i\omega(\dot{\mathbf{P}})_\omega \approx i\omega \mathbf{P}_{max}/2\pi \quad \text{at} \quad \omega\tau \ll 1,$$

where τ is the breakdown time.

In the case of an exponential growth of the breakdown current we have $J_1 = \dot{P}_1 = J_{10}e^{\alpha t}$ for t in the interval from 0 to τ and $J_1 = 0$ for all remaining t. Then we obtain

$$(\ddot{P})_\omega = \frac{i\omega}{2\pi} \frac{J_{10}}{\alpha + i\omega} \{e^{(\alpha + i\omega)\tau} - 1\}.$$

The spectral intensity of the radiation is

$$\mathscr{E}_\omega = \frac{\sqrt{\varepsilon}\,\omega^2 J_{10}}{2\pi^2 c^3 R_0^2} \frac{L^2}{\alpha^2 + \omega^2} \frac{\sin^2 \varkappa L}{(\varkappa L)^2} \left\{(e^{\alpha\tau} - 1)^2 + 4e^{\alpha\tau}\sin^2\frac{\omega\tau}{2}\right\} \sin^2\varphi,$$

where $\kappa = k'(c'/v - \cos\theta)$ and φ is the angle between the direction of the breakdown field and the direction of the reception. At $\alpha\tau \gg 1$ and $\omega t \ll 1$ we obtain the spectral intensity of radiation

$$\mathscr{E}_\omega \approx \frac{\sqrt{\varepsilon}}{2\pi^2 c^3} \omega^2 \frac{L^2}{R_0^2} \frac{\sin^2 \varkappa L}{(\varkappa L)^2} P^2_{10} \sin^2\varphi,$$

where P_{10} is the maximum value of the linear dipole moment. For example, if the breakdown encompasses the interior of spherical voids, then $P_{10} \approx \nu_1 a^3 E_0$, where ν_1 is the linear number of voids which the track of the particle touches upon, a is the radius of the void, and E_0 is the breakdown field.

Let us estimate the power of the incoming radio wave at the angle of maximum intensity. For $L/R \sim 0.1$, $\nu_1 \sim 1$, $a \approx 0.3$ cm, $E_0 \approx 30$ kV/cm and $\omega \sim 3 \times 10^9$ cps we obtain $\mathscr{E}_\omega \Delta\omega \approx 10^{-2} c^{-3} \omega^2 \Delta\omega \approx 10^{-12} \Delta\omega$ erg, which for $\Delta\omega \approx 0.1\omega \approx 3 \times 10^9$ and for a signal duration $\tau \sim 1/\Delta\omega \approx 3 \times 10^{-10}$ second corresponds to radiation power $\Delta\omega \approx 1$W, which is definitely known to be sufficient for the reception of the radiation.

CONCLUSION

The considered effect may find broad application, for example, for the production of bursts of sharply directed radiation and also for the measurement of the speed of flight of a particle based on the pattern of the direction of the radiation, as measured by a system of receivers.

The effect also is of interest for the recording of the frequency of a sequence of fronts of radio or light bursts from spark discharges near the track of the particle in a periodic medium and for an estimate of the speed of a particle based on the frequency of the transient bursts and the angle of reception.

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[1] Babykin, Plakhov, Skachkov, and Shapkin, Atomnaya énergiya No. 4, 38 (1956).

[2] E.K. Zavoĭskiĭ and G. E. Smolkin, ibid. No. 4, 46 (1956).

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