DIAMAGNETIC PERTURBATIONS IN MEDIA CAUSED BY IONIZING RADIATION

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Diamagnetic perturbations in media produced by intense ionizing radiation are studied. It is shown that diamagnetism is produced predominantly by fast electrons. Estimates are given of the perturbation in the magnetic field and of the bursts of radio waves accompanying powerful bursts of ionization. It is noted that these effects can be utilized for remote dosimetry and for recording bursts of ionization, for the investigation of the behavior of fast electrons in a medium, for the transmission of force to a medium from an inhomogeneous magnetic field, etc.

REGIONS of media on a laboratory, terrestrial, or astronomical scale are often subjected to ionizing radiation. If an external magnetic field is applied to the medium, then whenever the density and energy of free electrons is sharply increased a diamagnetic moment will appear in a portion of the medium the variations in which will give rise to wavelike and quasistationary electromagnetic perturbations. Such processes can occur in the laboratory when a portion of a medium is irradiated by an intense flux of x rays or γ rays, and in the atmosphere or the ionosphere under the influence of sharp intense bursts of ionizing radiation, in the case of spark discharges in media etc.

1. ARTIFICIAL DIAMAGNETIZATION OF MEDIA

We investigate the diamagnetism of a medium due to the diffusion of free electrons produced by an ionizing agency. This diamagnetism is caused by the transverse drift of the diffusing electrons under the action of the Lorentz force due to the interaction between the external magnetic field and the diffusion velocity. We assume that at each instant of time we have a given electron spectrum $\eta_e(t, \epsilon, \mathbf{r})$, where ϵ is the kinetic energy of the electrons and $\mathbf{r}$ is the position vector of the volume element under consideration. The diamagnetic moment per unit volume of the medium (c.f., for example,[1]) is given by

$$M_1(r,t) = -\int_0^{\varepsilon_m} \frac{\eta_e \varepsilon_\perp}{H} \frac{l_s^2}{l_s^2 + \rho_H^2} d\varepsilon,$$

where ρ_H is the radius of curvature of the electron trajectories, $\epsilon_\perp$ is the transverse (with respect to the magnetic field H) fraction of their kinetic energy, and $l_s(\epsilon)$ is the scattering mean free path of the electrons; within a wide range of electron energies $l_s(\epsilon) = C\epsilon^2/Z^2 d$ where d is the density and Z is the atomic number of the material of the medium.

It follows from the nature of the integrand that as the electron energy increases their diamagnetic activity also increases sharply. This enables us in a number of cases of practical interest to neglect the diamagnetic contribution of the slow electrons in spite of the fact that their density can exceed by many orders of magnitude the density of the high energy electrons responsible for the diamagnetism. In particular, in the case of air ionized by γ rays or by hard x rays the greatest diamagnetic effect is due to the energetic Compton electrons, while the secondary electrons produced by them make only a small contribution.

If in the integration we pick out the most effective electron groups of volume density n_e we can distinguish two characteristic cases: for $l_s^2(\epsilon_{eff}) \gg \rho_H^2$ (medium of low density, or a strong magnetic field, or high electron energies) we obtain $M_1 \approx n_e\epsilon_\perp/H$ ($\sim 1/H$); for $l_s^2(\epsilon_{eff}) \ll \rho_H^2$ (medium of high density, or a weak magnetic field, or low electron energies) we obtain $M_1 \approx n_e\epsilon_\perp l_s^2/H\rho_H^2$ ($\sim H$). For example, in the nonultrarelativistic case $M_1 \approx n_e r_0 H l_s^2$, where r_0 is the classical electron radius.

The effect of artificial diamagnetization of media in a beam of x rays can be established under laboratory conditions. We assume that a volume of the medium, surrounded by a coil for recording the signal and by a metallic shell to screen it from induced effects, is traversed by an x-ray beam. The potential difference appearing between the ends of the coil as the intensity of the x-ray beam is varied is given by

$$\mathscr{E} \approx \frac{\nu}{c}\dot{\mu} H \pi a^2 = \frac{2\pi^2\nu}{c}\dot{n}_e l_s^2 r_0 H a^2 \text{ for } l_s^2 < \rho_H^2.$$

For example, for $\epsilon \approx 50$ kev in air $l_s = 10^{-4}\epsilon^2/P \sim 0.25$ cm for P = 1 atm; for an attainable (using a pulsed current in the tube of the order of several hundred milliamperes) density of such electrons $n_e \sim 10^4$ electrons cm^{-3} (the density $n_e = q_e\tau_e$ does not depend on the pressure, since the number of electrons produced per cm^3 per second is $q_e \sim P$, while their lifetime is $\tau_e = 1/P$) and for $H \sim 10^3$ oe, number of turns $\nu \approx 10^3$ and turn radius $a \approx 10$ cm we obtain $\mathscr{E} \approx 10^{-8}/T$ v/sec $> 10^{-2}$v if the time during which the intensity of the beam changes is $T < 10^{-6}$ sec. In the case of powerful ionization bursts in the atmosphere[2] changes in local magnetic susceptibility are possible down to values close to the value of the magnetic susceptibility for an ideal diamagnetic substance $\mu = 0$.

2. EMISSION OF RADIO WAVES DUE TO IONIZATION BURSTS IN A MEDIUM SITUATED IN A MAGNETIC FIELD

In those cases when diamagnetic perturbations due to radiation bursts occur sufficiently suddenly they must be accompanied by bursts of radio waves. These bursts can be utilized for remote dosimetry or for recording bursts of ionization in a medium subjected to an external magnetic field. The changes in the total magnetic moment due to the total instantaneous number N_e of high-energy electrons

$$M(t) = \int_V M_1(t)dV = N_e(t)\frac{\varepsilon}{H}\frac{l_s^2}{l_s^2 + \rho_H^2},$$

will determine the intensity and the spectral distribution of the magnetic dipole radiation for wavelengths exceeding the dimensions of the region subjected to ionization. The intensity of the radiation is given by

$$W_\omega d\omega = (8\pi/3c^3)|\ddot{M}_\omega|^2 d\omega,$$

where

$$\ddot{M}_\omega = -i\omega\dot{M}_\omega \text{ for } \dot{M}(\pm\infty) = 0$$

or

$$\ddot{M}_\omega = -\omega^2 M_\omega \text{ for } M(\pm\infty) = 0.$$

For example, in the case of a sudden appearance or disappearance of a magnetic moment M_0 during a time T (the condition for sudden change is $\omega T \ll 1$) we obtain

$$W_\omega d\omega = (2\omega^2/3\pi c^3) M_0^2 d\omega.$$

The integrated rate of radiation of energy is given by

$$dW/dt \approx \ddot{M}^2/c^3 \approx M_0^2/c^3T^4.$$

Let us make an estimate of the electromagnetic radiation accompanying a powerful burst of γ radiation[2] which produces relativistic Compton electrons in a volume of dimensions of the order of the mean free path for the quanta (in air the mean free path for absorption is $L_\gamma \approx 3 \times 10^4 P^{-1}$ cm). The scattering mean free path for electrons in air is $l_s = 10^{-4}\epsilon_{kev}^2/P$, therefore $l_s \approx 10^2$ cm $\ll \rho_H \approx 10^4$ cm for $\epsilon \approx 1$ Mev and for the earth's magnetic field $H \approx 0.3$ oe. The instantaneous total number of Compton electrons in a volume of dimensions of the order of the mean free path for the γ quanta is $N_e \approx N_\gamma\tau_e/T$, where τ_e is the electron lifetime before they lose their energy; $\tau_e \approx 10^{-7}P_{atm}^{-1}$ sec. For $T \sim 3$ μsec the intensity of the burst $dW/dt \approx (N_\gamma 10^{-20})^2$ kw, where N_γ is the total number of γ quanta emitted in the burst.

In order to obtain more definite information with respect to the spectrum of the radiation it is necessary to know the specific form of the function M(t). From the equation for the balance of the number of Compton electrons

$$\dot{N}_e + N_e/\tau_e = \dot{N}_\gamma(t),$$

we obtain on setting $\dot{N}_\gamma(t) = N_{\gamma_0}\exp(-t/T)$

$$N_e \approx \frac{\dot{N}_{\gamma_0}}{1/\tau_e - 1/T}\{e^{-t/T} - e^{-t/\tau_e}\},$$

and consequently

$$M_\omega \approx r_0 l_s^2 H (N_e)_\omega \approx \frac{1}{2\pi} r_0 l_s^2 H \dot{N}_{\gamma_0}\frac{1}{(i\omega - 1/\tau_e)(i\omega - 1/T)},$$

$$W_\omega = \frac{8}{3}\frac{\pi}{c^3}\omega^4|M_\omega|^2$$

$$\approx \frac{2}{3\pi c^3}\{r_0 l_s^2 H\dot{N}_{\gamma_0}\}^2\frac{1}{1+(\omega\tau_e)^{-2}}\frac{1}{1+(\omega T)^{-2}}.$$

We now discuss another case of a burst of diamagnetism which arises when a cluster of accelerated electrons falls on the boundary of a dense medium in the presence of a longitudinal magnetic field. In this case the diamagnetism is associated with the appearance of transverse components of the velocities as a result of Coulomb scattering. For example, if the total number of electrons in the bunch is $N_e \sim 10^{10}$, their energy is given by $\epsilon \approx 1$ Mev, the density of the medium is $d \sim 1$ g/cm^3 ($l_s \approx 0.1$ cm) and the intensity of the field is $H \approx 10^4$ oe ($\rho_H \approx 0.1$ cm $\approx l_s$), we obtain $M_0 \sim 1$ cm^3 oe. The loss of electrons in this case is unimportant since the time during which the electrons lose their energy $\tau_e \sim \epsilon/\epsilon_x' c \sim 3 \times 10^{-11}$ sec, i.e., it is comparable with the duration of the incidence of the bunch $T \sim a/c \sim 3 \times 10^{-11}$ sec if the dimensions of the bunch are $a \sim 1$ cm. The total rate of radiation of energy is given by dW/dt

$\approx M_0^2/c^3T^4 \sim M_0^2/a^3T \sim 3$ kw. The ratio of the energy of this radiation to the energy of the bremsstrahlung (or transition radiation) in the portion of the spectrum determined by $\omega T \lesssim 1$ is given by

$$W_{\omega \text{diam}}/W_{\omega \text{brems}} \approx (\varepsilon\omega T)^2/(eHa)^2 \sim 3 \cdot 10^{-2}$$

for the numerical values given above. By reducing the density of the medium and the intensity of the field it is possible to increase the intensity of the burst of radiation due to the diamagnetism. In its nature and in its polarization this magnetic dipole radiation differs from the electric dipole field of the bremsstrahlung or transition radiation from the bunch, and this will facilitate discrimination between bursts of radiation. In some cases it is necessary to take into account the effect on the radiation of the motion of the localized diamagnetization produced. Such effects can occur, in particular, in cosmic ray showers in which the zone of high energy electrons and of high ionization density moves with high velocities.

We note that pulsed diamagnetic perturbations should also be expected from spark discharges in a longitudinal magnetic field. These perturbations must be more rapid and must produce more radiation than perturbations associated with the gas kinetic spreading of the plasma produced by a spark in a magnetic field. (This question is discussed in greater detail in [3].)

3. FORCES EXERTED BY INHOMOGENEOUS MAGNETIC FIELDS

The production of diamagnetism in a portion of a medium by a concentrated ionizing agency can give rise to forces being exerted on such media by inhomogeneous magnetic fields. For example, a dense medium situated in the radiation field of a reactor will experience a volume force

$$F_1 \approx M_1 \frac{\partial H}{\partial Z} = \dot{n}_\gamma \frac{\tau_e}{L_\gamma} \varepsilon_\perp \frac{l_s^2}{l_s^2 + \rho_H^2} \frac{1}{H} \frac{\partial H}{\partial Z},$$

tending to expel the medium from the magnetic field ($F_1 \sim 100$ dyne for $\dot{n}_\gamma \sim 10^{18}$ quanta/cm^2 sec, $l_s \sim \rho_H$ and $(1/H)(\partial H/\partial Z) \sim$ cm^{-1}). This effect can be increased by repeating it many times. For example, if in a constant corrugated axially symmetric field the ionizing radiation is increased on those sectors where the field gradient has the same direction, then the expelling effect will be additive. This effect can be utilized for the dosimetry of powerful radiation fluxes, and for the creation of circulation in media. In particular, one can attain high velocities of gas efflux from a constant inhomogeneous or modulated magnetic field by utilizing as a local ionizing agency powerful beams of radio waves, electron beams, etc.

In conclusion we note that the well-known effects restricting the diffusion of electrons and reducing the diamagnetism of an electron gas (for example, the effect of Coulomb fields and the transition to ambipolar diffusion, the reflection of electrons from the boundaries of the volume etc.; with respect to ambipolar diamagnetism cf. [1]) do not play any appreciable role in the majority of processes discussed by us. In these processes the carriers of diamagnetism—high-energy electrons —are continually being produced and are lost, and as a consequence of the dissipation of their energy a large number of slow secondary electrons are formed which hinder the formation of appreciable Coulomb fields capable of affecting the diffusion of energetic electrons. The countercurrent of these secondary electrons gives a small contribution to the diamagnetism due to the low mobility of slow electrons. Indeed, the ratio of the densities of azimuthal currents of slow and fast electrons $J_s/J_f \approx n_{es}u_sk_s(n_{ef}u_fk_f)^{-1} \approx k_s/k_f$, where k are the electron mobilities, and u are the directed radial velocities which are acted upon by the magnetic field and give rise to the appearance of azimuthal diamagnetic currents (in accordance with the condition for the equality of the densities of the countercurrents we have $n_su_s \approx n_fu_f$).

[1] H. Alfvén, Cosmical Electrodynamics, Oxford, 1950, Ch. 3.

[2] M. H. Johnson and B. A. Lipmann, Phys. Rev. **119**, No. 3 (1960).

[3] G. A. Askar'yan, J. Tech. Phys. (U.S.S.R.) **31**, 781 (1961), Soviet Phys.-Tech. Phys. **6**, in press.

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