CASCADE IONIZATION INDUCED IN A MEDIUM BY AN INTENSE LIGHT FLASH

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Cascade growth of the ionization induced in a medium by a strong light flash is considered. It is shown that decomposition of excited atoms under the action of the light field may play an important role in the development of the electron cascade. Diamagnetic disturbances produced by light focused on a medium in an external magnetic field are considered. The dependence of the induction signals from these disturbances on the conductivity, size, and velocity of the hot zone is presented. The results can be used to estimate the interaction force between the heated zone and magnetic field; this force may be used to drive a plasma out of an inhomogeneous field, to accelerate a plasma, to fill traps, etc.

CASCADE ionization induced in a medium by intense light has been the subject of two experimental[1,2] and one theoretical[3] paper. In the present article we consider cascade-growth conditions that differ from those considered by Zel'dovich and Raĭzer[3]. We are interested in larger light-field intensities, $E_0 > 10^7$ V/cm, which ionize the excited atoms, accelerating and by the same token facilitating the development of the ionization cascade.

1. HEATING OF ELECTRONS

The heating of electrons in an intense light field is connected with the absorption of quanta when electrons collide with atoms and ions. If the kinetic energy ϵ of the electron exceeds the energy $\hbar\omega$ of the light quantum (this is usually the case, since the energies of interest to us, those of electrons capable of ionizing and exciting atoms, are approximately 10 eV, whereas the quantum energy of a powerful monochromatic flux is $\hbar\omega \sim 1$ eV), then the main increment of electron energy (defined as the difference between the absorption of the quanta and the stimulated emission of quanta upon collision—these processes were considered in detail in [3]) is described by the well-known classical formula

$$d\varepsilon / dt \approx e^2 E_0^2 \nu / 2m(\omega^2 + \nu^2) = W_\nu \nu,$$

where ν —effective collision frequency, e and m —charge and mass of the electron, E_0 and ω —amplitude and frequency of the light wave, and W_ν —energy transferred from the light to the electron in the mean per collision (usually $W_\nu \ll \hbar\omega$).

Thus, the condition for the heating of the electrons to grow is $W_\nu > f\Delta$, that is, $E_0 > (mf\Delta)^{1/2}\omega/e$, where f —probability of transferring an energy Δ to the atom upon collision. For example, for elastic collisions ($f = 1$, $\Delta \approx 2\epsilon m/M_i$), an increase in the electron temperature occurs when $E_0 \gtrsim (\epsilon/M_i)^{1/2} m\omega/e < 10^6$ V/cm. For inelastic collisions with $\epsilon \gtrsim \Delta \sim 10$ eV and $f \sim 10^{-2}$, the inelastic losses are overcome when $E_0 \gtrsim 10^7$ V/cm.

We are interested in the range of intensities $E_0 \gtrless 10^7$ V/cm, at which the excitation and cascade ionization of atoms are intense.

2. IONIZATION OF THE MEDIUM

The appearance of new free electrons is due not only to the ionization of the atoms by collision with electrons, but also by the ionization of excited atoms under the influence of the light. As shown below, the disintegration of the excited atoms can facilitate and greatly increase the growth of ionization. Indeed, during the collisions the electron absorbs or spontaneously emits light quanta $\hbar\omega \sim 1$ eV. This means that the electron energy experiences fluctuations of the order of $\hbar\omega$. Recognizing that the distances between the excited levels are of the same order, we arrive at the conclusion that if the electrons excite atoms, then a large fraction of the atoms should be excited to the second and third levels. However, such atoms are ionized with great probability by the light wave. The probability of the many-quantum photoeffect[4] is equal to

$$W \approx \left(\frac{I\omega}{8\hbar}\right)^{1/2} \left(\frac{(2mI)^{1/2} a_0}{\hbar}\right)^3 \left(\frac{e^2 E_0^2}{3m\omega^2 I}\right)^{\langle I/\hbar\omega + 1\rangle},$$

where I(n) —energy necessary for the ionization of the atom, n —number of the levels, a_0 —Bohr radius, and the symbol ⟨. . .⟩ denotes the whole-number part of the quantity. Substituting the numerical values, we obtain for the majority of atoms $I(n = 2) < 2\hbar\omega$ and consequently $W > 10^9\ sec^{-1}$ for $E_0 \gtrsim 10^7$ V/cm, that is, the overexcited atom disintegrates within a time much shorter than the time of light flash. Such overexcited atoms will be called active, and their number will be denoted by N_A^*. As already noted above, the probability f_A^* of formation of overexcited atoms is commensurate with the probability for the formation of excited atoms f^*, since $I_A^* - I^* \approx \hbar\omega$. For atoms with low ionization potential, even the atoms at the first excitation level will be active.

The fact that the energy of the excited atoms immediately goes over into the development of a cascade under the influence of the large electric field intensity of the light is greatly influential during the initial stage of the growth of the number of free electrons, making this stage more productive. At large excited-atom concentrations there come into play impacts of the second kind and ionization of the excited atoms by the electrons, which also return part of the excitation energy to the electron cascade.

We shall be interested first in the initial stage of electron multiplication, a stage not obscured by secondary processes such as recombination or impacts of the second kind. We assume that some initial number of free electrons has become heated as a result of quantum absorption, and has entered into the range of energies in which inelastic processes are possible. The growth of electron temperature has slowed down and the absorption of energy is connected essentially with formation of excited atoms. The fact that the numbers of the produced excited, active-excited, and ionized atoms are commensurate, and also that the number of excited atoms is proportional to the energy absorbed by the electrons from the light field, simplifies the calculation of the electron cascade, making it possible to introduce an average absorbed energy J per produced ion. The inclusion of the excited atoms in the cascade may greatly reduce the value of J, making it closer to the ionization energy.

Let us estimate the growth of the number of electrons in the volume where the light field is localized. The change in the number of active excited atoms is

$$dN_A^* / dt \approx N_e \nu f_A^* - w(E_0) N_A^*.$$

Since for the active atoms $w(E_0)T \gg 1$, where T —time of the flash, an equilibrium value $N_A^* \approx N_e \nu f_A^*/w$ is rapidly attained. Substituting this value into the equation for the electron cascade and recalling that $f^* \approx f_A^*$, we obtain

$$\frac{dN_e}{dt} \approx N_e \frac{1}{J}\frac{d\varepsilon}{dt} - Q = N_e W_\nu \frac{\nu}{J} - Q,$$

where Q —electron losses connected with the diffusion drift ($Q_{dif} \sim DN_e/R_{eff}^2$, where R_{eff} —effective dimension of the volume of the field), or with recombination (this process is small during the initial stages of cascade development, when the density is low) and with the drift induced by the average striction force:

$$F_{\text{eff}} \approx \frac{e^2}{m\omega^2} \nabla (E_0^2)_{\text{av}} \qquad (Q_{\text{stric}}/Q_{\text{dif}} \approx W_\nu/\varepsilon \ll 1).$$

When the plasma density increases, the ambipolarity greatly limits the drift of the free electrons.

Neglecting electron leakage, we obtain during the initial growth of the cascade

$$N_e \approx N_e(0) \exp (W_\nu \nu J^{-1} t),$$

that is, the cascade growth time is $\theta = kt_1 = kJ/W_\nu \nu$, where k —necessary number of generations. For example, when $W_\nu \approx 10^{-1}$ eV ($E_0 \sim 3 \times 10^7$ V/cm), $J \sim 10$ eV, $k \sim 10$, and $\nu = n_a \sigma_a v_e \approx 3 \times 10^{11}\ sec^{-1}$, we get $\theta \lesssim 3 \times 10^{-8}$ sec.

Multiple-quantum or cascade ionization of atoms can lead to an increase in the absorption of powerful light and to the production of plasma trails of intense light beams, capable of guiding or reflecting radio waves and of disturbing fields and waves, etc.

3. DIAMAGNETIC PERTURBATION DUE TO THE IONIZATION OF A MEDIUM IN A BEAM OF INTENSE LIGHT

Let us consider the perturbation of an external magnetic field by a flash of ionization induced by a focused light; we are interested not only in the probability of obtaining additional information on the properties and dynamics of plasma diffusion, but also in the possibility of acting on such a plasma by means of external inhomogeneous magnetic fields.

When the ionization concentration increases, the main perturbations of the magnetic field are connected with the motion of conducting layers of the medium, since the ambipolarity decreases the diffusion and the diamagnetism of the free electrons.

Let us calculate the magnetic moment of the eddy currents produced in quasi-spherical[1)] outward flow of a medium with conductivity $\sigma(r,t)$ in a constant external magnetic field H_0.

The small initial dimensions of the hot region allow us to neglect, at not very high temperatures, the effective crowding out of the field (the time for the field to return is $t \sim 4\pi\sigma c^{-2}R_0^2 \sim 10^{-6}R_0^2$ at temperatures on the order of several eV; for example, for $R_0 \approx 10^{-2}$—10^{-1} cm we obtain $t \sim 10^{-10}$—10^{-8} sec). We can therefore neglect the change in the magnetic field and assume that the eddy currents are connected with the electric field of "induction by motion":

$$E_\varphi(r,t) = c^{-1}v_r H \sin\theta.$$

The magnetic moment of the eddy currents is

$$M_z = \frac{4\pi H}{3c^2}\int_0^{R(t)} \sigma(r,t)\,v_r(r,t)\,r^3\,dr.$$

Let us assume that the expansion is self-similar, that is, $v_r(r,t) = v_R(t)r/R(t)$, and then

$$M_z \approx \frac{4\pi}{3c^2}\frac{v_R(t)}{R(t)}H\int_0^{R(t)} \sigma(r,t)\,r^4\,dr.$$

Introducing the notation

$$\sigma_{\text{av}}(t) = 5R^{-5}(t)\int_0^{R(t)} \sigma r^4\,dr,$$

we obtain

$$M_z \approx \frac{4\pi}{15c^2}v_R(t)H\sigma_{\text{av}}(t)R^4(t).$$

To estimate the degree of perturbation of the fields, let us compare this magnetic moment with the moment of an ideal diamagnetic sphere $M_z^{\text{id}} = -R^3H/2$. The ratio is

$$M_z / M_z^{\text{id}} \approx 8\pi v_R \sigma R / 15c^2.$$

For typical values of the velocities of hydrodynamic expansion, $v_R \sim 3\times10^6$ cm/sec and $R_0 \sim 10^{-2}$—10^{-1} cm, we obtain $M_z/M_z^{\text{id}} \approx 10^{-2}$—$10^{-1}$, that is, for this range of quantities the distortion of the field is small and the field can be regarded as homogeneous with respect to the calculation of the eddy currents. At high hot-region temperatures, conductivities, and dimensions, the perturbation of the field is close to that produced by an ideal diamagnetic sphere.

The voltage induced at the terminals of a coil of N turns surrounding a plasma sphere at a distance ρ from the variable dipole $M(t)$ in a plane perpendicular to the dipole direction is

$$\mathscr{E} = \frac{2\pi}{c}\frac{\dot{M}N}{\rho} = \frac{8\pi^2 NH}{15c^3\rho}\frac{d}{dt}\{\sigma_{\text{av}}(t)R^4(t)\dot{R}(t)\}.$$

For example, for $\rho \approx 1$ cm, $N \approx 100$, $\sigma \approx 10^4$ cgs esu, $R \sim 10^{-2}$—10^{-1} cm, $H \approx 10^3$ Oe, and a characteristic process time $\sim 10^{-8}$ sec we obtain an emf ranging in order of magnitude from fractions of a volt to several volts.

Thus, the signal can yield information even concerning the initial stage of the outward expansion of the hot region. This stage is of greatest interest in the case of filling of magnetic traps during an ionization flash of matter in a magnetic field[5], when the initial electron temperatures determine the rate of scattering of the ions captured by the field of the trap.

When the outflow of the ionized region extends over larger dimensions, it is possible to observe the diamagnetic effect from the earth's magnetic field.

Concerning the radiation produced by a spark in a magnetic field see [6].

The diamagnetism of the hot zone makes it possible to act on it by means of an inhomogeneous magnetic field in order to accelerate the ionized cloud or to eject it into a trap (for example, the spark in the gas is ejected to the vacuum via a device that restrains the pressure drop).

The force exerted by an inhomogeneous field is $F = M_z\,\partial H/\partial z \approx R^3\nabla(H^2)$ when the field is strongly perturbed by the plasma. This force can ensure an ejection rate $u \sim H/(4\pi\rho)^{1/2}$, where ρ_m —density of matter. The small dimensions of the hot zone make it possible to use very strong fields $\sim 10^5$—10^6 Oe and attain large directional velocities of ejection of ionized matter, which can be used for various plasma and pre-thermonuclear experiments.

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[1] R. G. Meyerhand and A. F. Haught, Phys. Rev. Lett. **11**, 401 (1963).

[2] R. W. Mink, J. Appl. Phys. **35**, 252 (1964).

[3] Ya. B. Zel'dovich and Yu. P. Raĭzer, JETP **47**, 1150 (1964), Soviet Phys. JETP **20**, 772 (1965).

[4] L. V. Keldysh, JETP **47**, 1945 (1964), Soviet Phys. JETP **20**, 1307 (1965).

[5] Askar'yan, Delone, and Rabinovich, JETP **46**, 814 (1964), Soviet Phys. JETP **19**, 555 (1945).

[6] G. A. Askar'yan, ZhTF **31**, 781 (1961), Soviet Phys. Tech. Phys. 6, 566 (1962).

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[1)] It is not difficult to consider quasi-cylindrical outward flow, which is obtained when the volume of the focus is elongated.