MICROWAVE RADIATION STIMULATED BY ATOM OR ION BEAMS

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Abstract

Perspectives of high-frequency stimulated emission source applying accelerated beams of charged atoms which ones are widely used at present are analyzed. Radiation mechanism based on high-frequency intratomic electronic transitions due to anomalous Doppler's effect on slow waves is considered, while the low-frequency oscillations of atoms are neglected. Several slow surface wave systems with dielectric layers are estimated. In aggregate process has a complex nature since photon radiation is accompanied by excitation of atoms with following emission of more high-frequency photons. Requires to parameters of such systems and atomic beams for observation of stimulated emission needed for diverse applications are established.

INTRODUCTION

In the present work one of new possibilities of generation (specially created or as an attendant effect) high-frequency radiation with the help of fast beams of atoms or ions is considered. Fluxes of atoms, in which electrons remain in ground states, as well as system with excited atoms, can be unstable and be sources of high-frequency coherent electromagnetic radiation.

From an electrodynamical point of view an atomic flux is a flow of electron oscillators which ones due to anomalous Doppler's effect even in non-excited state can be a source of induced radiation. Here radiation of photons is supported by transferring of the particle kinematic energy. Besides the effect is accompanied by an inverse change of interior states of oscillators. Said is concerning to beams of both neutral atoms and positive and negatively ionized ones (if to neglect the interaction of latter with rather low frequency oscillations where the ions figure only as unstructured massive charges; therefore further specially is not stipulated charge states of atoms).

This mechanism, marked on a heuristic level still in [1,2], discovers broad application in systems with electronic beams (see, for example, [3]). Now analysis of atomic systems acquires also practical interest in connection with wide possibilities for deriving fast atomic and ion beams on modern accelerators.

One of the key moments is the estimation of excitation requirements of the mentioned above radiation of high-frequency collective instability in originally undisturbed flow of atoms. The anomalous Doppler effect can be watched in systems with slow (in comparison with an atom beam) electromagnetic waves. One of them can be the gaseous medium. This case is parsed (apparently for the first time) in work [4] (author and T. Novikova). It was indicated that in similar system the effect of stimulated radiation can be watched, at least in infrared range of radiation. By analogy with a known case of Cerenkov instability of a charged beam in plasma [6], the marked effect of induced radiation of atoms can be described as manifestation of atomic two-stream instability (including, as well as in a plasma physics, case of a motionless gas).

However practical observation of effect will be enough difficult. In particular, the processes of a dissipation are an actual hindrance to development of induced high-frequency excitation, that defines rather small lifetime of exited states of atoms in a beam and gas. Therefore it is necessary to utilize here a dense gas and intensive beams rather accelerated.

Therefore it is expediently to analyze other varieties of systems with atomic beams, for example, systems with different dielectric elements. In particular, the system is of interest, in which walls of the drift chamber are plated with a dielectric layer possessing high coefficients of a refraction and transparence in the region of presupposed radiation frequencies. In such a scheme the excitation of slow surface waves (like as Smith-Purcell's waves) is possible, which ones can actively interact with slipping beams of particles. Let's remind that Cerenkov free electron lasers which ones have the similar scheme was experimentally tested, at least, in far infrared region[5].

ANALYTIC APPROACH. ESTIMATIONS

Consider a conventional boundary problem being analog to practical systems. The monochromatic atomic beam is injected with velocity $v_e = \beta_e c$ where c is the light velocity, along the axis z in half-infinite space $(z \geq 0)$ of a travelling chamber near to its lateral wall plated with a dielectric layer. In an initial point of the chamber, a triggering signal is put in as an electromagnetic wave propagating along axis z :

$$(\mathbf{E}, \mathbf{B}) = (\mathbf{E}, \mathbf{B})_{\mathbf{0}}\, exp(i(kz - \omega t)).$$

Here ω and k are frequency and wave vector of a signal. Allowing fast damping of a amplitude wave across the chamber, it is possible to neglect curvature of a wall and be restricted to considering of a flat one-dimensional problem. Then the excited slow wave has configuration: $\mathbf{E} = (E_x, 0, E_z)$, and $\mathbf{B} = (0, B_y, 0)$.

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Here axes $(x,\, y)$ are directed across and along a wall of the chamber; the system is homogeneous along the axis y.

Evolution of a signal during its propagation together with a beam along system will be featured by the dispersion equation [6]:

$$\kappa_1\, tan\,(\kappa_1\, a) \,=\, -\, \epsilon_1\, \kappa_2\, /\epsilon_2 \qquad (1)$$

where $\kappa_1 \,=\, \sqrt{\epsilon_1\, \omega^2\, /c^2 \,-\, k^2}$, $\kappa_2 \,=\, \sqrt{k^2 \,-\, \epsilon_2\, \omega^2/c^2}$, ϵ_1 is a permittivity of dielectric layer with thickness at a, and ϵ_2 is permittivity of atomic medium. The latter generally consists from atomic gas filling the chamber near wall volume (a sub-index p), and atomic beam (sub-index b). Therefore [7]

$$\epsilon_2 \,=\, 1 \,+\, \frac{\omega_p^2}{2\,\Omega_p\,(\Omega_p - \omega - i\Gamma_p)} + \frac{\omega_b^2\,\omega_l^2}{2\,\Omega_b\,(\Omega_b + \omega_l + i\Gamma_b)\,\omega^2}, \qquad (2)$$

where

$$\omega_{p,b}^2 = (4\pi\, e^2\, N_{p,b}\, f_{p,b})/m. \qquad (3)$$

Here e and m are charge and mass of electron, $N_{p,b}$ is atom density of gas and beam, $f_{p,b}$ and $\Omega_{p,b}$ are oscillator force and frequencies of electron transitions in the nearest exited atom states (other transitions are neglected), $\Gamma_{p,b}$ are values opposites to times of life in exited states, $\omega_l \,=\, \omega - k\, v_e$.

In virtue of said above, the terms in which atoms, if they are not neutral and act as massive unstructured charges, are omitted in the ratio (2). Further it is necessary to say that frequencies of excited waves are close to resonant ones. It is important also that atomic beam is lowly relativistic. Due to this the difference between longitudinal and cross components of beam dielectric tensor can be neglected.

Let's address at first to a case when it is possible to neglect the influence of gas in the vacuum chamber. Dispersion properties of a waves in "cold" system (without beam) are defined by the equation (1) at $\omega_b^2 \,\rightarrow\, 0$ and $\epsilon_2 \,\rightarrow\, 1$.

The influence of a beam is strongest near to frequency $\omega \,\simeq\, k\, v_e - \Omega_b$ (slow beam wave is "working" here; stable fast wave $\omega \,\simeq\, k\, v_e + \Omega_b$ is not taken into account in the equation (1)). The interaction of a beam with environment gets resonant character if values of frequencies and wave vectors simultaneously coincide with one of own values of these parameters ω_0 and k_0 for waves in cold system:

$$\omega_0 = k_0\, v_{ph}\, ; \;\; \omega_0 = k_0\, v_e - \Omega_b \qquad (4)$$

where v_{ph} is phase velocity of a wave in cold system. Obviously, the resonant conditions (4) are consistent, if $v_e \,>\, v_{ph}$. Then the frequency generated is $\omega_0 \,=\, \Omega_b/(v_e \,-\, v_{ph})$.

Believing now condition (4) executed, we write down $k = k_0 + \delta\, k$. Considering $\mid \delta\, k \mid \ll k_0$ also we obtain from (1) and (2) the equation:

$$\delta\, k\,(\delta\, k \,-\, i\eta) \,=\, -Q, \qquad (5)$$

where $\eta \,=\, \Gamma_b/v_e,\; Q \,=\, (\pi^2\, \omega_b^2\, \Omega_b)/(4\, a^3\, c^3\, k_0^4)$. Here we use in virtue of $k_0\, a \,\gg\, 1$ that the solution of the cold dispersion relation gives $\kappa_1\, a \,\sim\, \pi/2$.

Estimation for increment of assumed spatial amplifications of the initial signal follows from here:

$$Im\;\delta\;\,k \,=\, \left(-\sqrt{4\,Q \,+\, \eta^2} \,+\, \eta\right)/2 \qquad (6)$$

Amplification (i.e. stimulated radiation) takes place if $Im\delta\, k \,<\, 0$ [8]. We see the equation (6) gives no threshold condition for development of a stimulated radiation.

Swift development of a stimulated process can be observed only in the case of using a very intensive atomic beam when

$$\omega_b^2 \,\geq\, \frac{\Gamma_b^2\, c^3\, a^3\, k_0^4}{\pi^2\, v_e^2\, \Omega_b} \qquad (7)$$

Practically, for low current beams we have $4\,Q \,<\, \eta^2$, and $Im(\delta)\, k \,\sim\, Q\, v_e/\Gamma_b$. So we should not neglect a signal absorption in the dielectric layer. Therefore we must make a change $\epsilon_1 \,\rightarrow\, \epsilon_1 \,+\, i\,\delta\,\epsilon_1$. Then the first multiplier undergoes a modification

$$\delta\, k \,\rightarrow\, \delta\, k \,-\, i\,\zeta$$

where

$$\zeta \,=\, \frac{\epsilon_1\, v_{ph}^2/c^2 \,-\, 1}{\epsilon_1{}^2\, a}\,\delta\,\epsilon_1 \,\simeq\, \frac{\pi^2\, \beta_e}{4\, k_0^2\, a^3}\,\frac{\delta\,\epsilon_1}{\epsilon_1}$$

In this case an amplification appears if threshold condition is carried through: $Q \,>\, \zeta\, \eta$, and the increment value is

$$Im\delta\, k \,=\, \left(-\sqrt{4\,Q \,+\, (\zeta \,-\, \eta)^2} \,+\, \zeta \,+\, \eta\right)/2$$

For transparent media there is the condition $\zeta \,\ll\, 1$, and a signal absorption reveals very weakly. For high current beams a stimulated radiation can take place also in a low transparent dielectric.

Judging by (5) and (8), reasonably acceptable minimal values of density beam corresponds to intratomic transitions in infra-red radiation with $\Omega_p \,<\, 10^{15} \,\div\, 10^{14}\, c^{-1}$, i.e. with length of a radiated wave $\lambda \,>\, 1.5 \,\div\, 15$ mkm. However only long-lived transitions with $\Gamma_{p,b} \,\simeq\, 10^7\, c^{-1}$ can participate in stimulated process. At last, the atomic beams should be enough accelerated with $\beta \,\geq\, 0.1$, that corresponds to energy of particles about $\geq\, 5$ MeV / nucleon.

Therefore beams of the accelerated negative ions of light atoms can be real objects for observation of the phenomena examined there (for example, H^-, widely used nowadays in experiments [9]). So, at $\Omega_b \,=\, 10^{14}\, c^{-1}.\beta_e \,=\, 0.1 - 0.3$, development length of instability makes tens centimeters for slipping beams with density at several $10^{19} atom/cm^2$.

However here it is necessary to make one rather important addition. The beam, sliding along a wall of the chamber, will inevitable form a gas cloud. Density of gas can reach the rather large values, and the thickness of a cloud will surpass considerably a wave length of radiation generated. To estimate influence of gas it is necessary to address again to the relation (1) and to use the relation (2). Atomic gas, marked in (2) by sub-index p, changes a spatial distribution of electromagnetic waves, and can make damping of their amplitude. So the wave spatial distribution in cold system ($\omega_b^2 \rightarrow 0$)is described by function $exp(-\kappa_2 x)$ where only the real part of second number in ϵ_2 is present.

We see that the wave spatial cross-decreasing can be weakened for a sufficiently dense atomic medium. Moreover if $Re\,\epsilon_2\,\omega_0^2\,/\,c^2 > k_2^2$, the wave character is changed principally: the wave cross structure becomes oscillatory. In this case a wave generated is deeply penetrating in beam zone. In result the increment of agitation rises considerably (see [10] too). Besides the beam boundary can be displaced from a chamber wall, that is realized in practical schemes.

But this conclusion is correct only in certain frequency strip. Really, $Re\,\epsilon_2$ obtains a maximum if $\omega_0 \rightarrow \Omega_p + \Gamma_p$, and $Re\,\epsilon_2 \rightarrow 1$ as $\sim 1/\Delta$ where detuning $\Delta = |\Omega_p - \omega_0|$. In the same time the imaginary part (responsible for signal damping) $Im\,\epsilon_2 \rightarrow 0$ as $\sim 1/\Delta^2$. Therefore since, as a rule for gas atoms, $\Omega_p \gg \Gamma_p$ in frequency strip with $\Omega_p \gg \Delta \gg \Gamma_p$ gas damping is not important.

CONCLUSION

Present work is aimed at to attract attention on very interest and non-ordinary phenomenon – on high frequency radiation by fast flux of heavy particles with complex structure. Ones of objects for possible application of heavy particle fluxes are different plasma traps. Radiation provoked by particle flux can signal about state of gas and plasma densities, pollution of chamber wall and so on.

Of cause it is necessary to analyze (for estimation of information obtained) the influence of various accompanying processes - excitation, ionization and the dispersion of atoms of a beam and gas. Nevertheless we may assume that these processes have an effect only for subsequent stages, because an effective cross-section of atomic collisions already for slightly relativistic particles does not exceed about $10^{-19}\,cm^2$.

Therefore the doubtless interest represents the investigation of further dynamics of considered above processes, which (after fast excitation of beam during of radiation on slow wave) can result in additional radiation of photons (on fast wave !).

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