Proceedings of the 2001 Particle Accelerator Conference, Chicago

BEAM OF NEUTRAL OR CHARGED ATOMS AS A SOURCE OF STIMULATED MICROWAVE RADIATION

V.Grishin*, T. Novikova , Nuclear Physics Institute of Moscow State University
119899 Moscow, Russia

Abstract

High-frequency electromagnetic dynamics of charged or neutral atom beams which are widely used at present is analyzed. One of perspective mechanisms of radiation bound with high-frequency intratomic electronic transitions is considered. As it is shown a flux of fast nonexcited atoms, due to anomalous Doppler's transitions on slow waves in a gas or plasma, can be unstable and be a source of stimulated high-frequency radiation. As a whole process has a complex nature since photon radiation is accompanied by excitation of atoms with following emission of more high-frequency photons. The possible parameters of such physical systems are estimated.

1 INTRODUCTION

In present work is paid attention that beams of atoms in which electrons remain in ground sates, as well as system with excited atoms, can be unstable and be source of high-frequency coherent electromagnetic radiation.

From an electrodynamics point of view an atomic stream is an electronic oscillators flow which due to abnormal Doppler effect, even in nonexcited state can be a source induced radiation. Here radiation of photons is ensured by energy transmission of fast particles. Thus there is an inverse change interior states of oscillators - their auto - excitation.

This phenomenon marked on a heuristic level still in Ref. [1,2] now obtains a

practical concern in connection with broad opportunities for deriving fast atomic and ion beams on modern accelerator. (about manifestations of this effect in systems with electronic by beams see, for example, Ref. [3]). Said is concerning to beams of both neutral atoms and positive and negatively ionized ones if to neglect interaction of latter with rather low frequency by oscillations when the ions figure only as unstructured massive charges (therefore further it is not indicated charge states of atoms).

The purpose of the present work is to estimate requirements of induced radiation excitation in primary undisturbed flow of atoms.

2 THEORETICAL APPROACH AND RESULTS

The abnormal Doppler's effect can be observed in systems with slow (in comparison with an atom beam) electromagnetic waves. As one of them can be the gaseous medium. Thus the gas can also have some translational velocity. Then by analogy with known by case Cherenrov's instability of a charged beam in plasma[4], the marked effect of induced radiation of atoms can be termed as an atomic double-streams instability (including, as well as in a plasma physics, case of rest gas that always is possible ”to provide” by coordinate system transformation).

Certainly the situation observed at atom motion through a gas, will be enough complicated. In particular dissipation processes are a real hindrance to development of induced high-frequency excitation that is defined rather small lifetime excited atoms.

Let's consider conventional so-called boundary task being analog of practical systems. The broad monochromatic atomic beam is being injected along axis z in a chamber semibounded in space $(z \geq 0)$ and filled by a cold rest gas (or thermal and translational velocities of gas atoms are small enough). The beam velocity is $v = \beta c$ where c is light velocity. Triggering signal as transversal linear-polarized wave $E = E_0\, exp(i(kz - \omega\, t))$ is being given in the chamber in an inicial point. Then electromagnetic evolution of all the system is described by dispersion equation [4]:

$$-k^2\, c^2\, + \omega^2\, \epsilon_\perp = 0, \qquad (1)$$

where $\epsilon_\perp$ is cross component of the dielectric tensor of composed medium. In this case [5]

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

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 electronic mass, $N_{p,b}$ are densities of gas and beam atoms, $f_{p,b}$ and $\Omega_{p,b}$ are oscillator force and frequencies relevant to transitions of oscillators in proximate exited states (other transitions are neglected), $\Gamma_{p,b}$ is quantity, inverse to lifetimes in excited states, $\omega_l = \omega - k\, v,\ \gamma$ is relativistic factor of beam atoms.

Thus it means that dielectric medium consists , how is mentioned, from gas (subcoefficient p) and fast beam (subcoefficient b) nonexcited atomic oscillators. By virtue of said above in the ratio (2) only the high-frequency oscillations are taken in account. Also it is necessary to note that

---

* grishin@depni.npi.msu.su

0-7803-7191-7/01/$10.00 ©2001 IEEE.

frequency intervals of excited waves are close to resonant values (see further).

Without a beam, waves in a nonexcited gaseous medium are damping with maximal decrement near to a point $\omega \;\simeq\; \Omega_p$. The effect of a beam is strongest near to frequencies $\omega \;\simeq\; k\,v - \Omega_b$ (it is a slow beam wave; stable fast wave $\omega \;\simeq\; k\,v + \Omega_b$ in the equation (1) is not taken into account). The interaction of a beam with gas medium gains a resonant character if values of frequencies and wave vectors simultaneously coincide with eigenvalues of these quantities ω_0 and k_0 for waves in gas volume or

$$k_0^2\,c^2 = \omega_0^2\,\left(1 + \frac{\omega_p^2\,(\Omega_p - \omega_0)}{2\,\Omega_p\,((\Omega_p - \omega_0)^2 + \Gamma_p^2)}\right) \tag{4}$$

where

$$\omega_0 = k_0\,v - \Omega_b. \tag{5}$$

The last relations determine the requirements to minimum densities of a gaseous medium (it is apparent $\omega_0 \sim \Omega_p$ because $\Omega_p \gg \Gamma_p$):

$$\omega_p^2 \;>\; 4\,\Gamma_p\,(\Omega_p \,+\, \Omega_b)^2\,/(\Omega_p\,\beta^2\,). \tag{6}$$

Proposing now requirement (5) carried out we note $k = k_0 + \delta\,k$, considering $\mid \delta\,k \mid \ll k_0$. Then we obtain from (1) and (2) a relation:

$$(\delta\,k \,-\, i\zeta)\,(\delta\,k \,-\, i\eta) \;=\; -Q \tag{7}$$

where $\zeta \simeq (\Omega_p + \Omega_b)/(2\,c\,\beta\,\Delta)$ at $\Delta = (\Omega_p - \omega_0)/\Gamma_p > 0$, and $\eta \;=\; \Gamma_b/v,\;\; Q \;=\; (\omega_b^2\,\Omega_b)/(4\,(\Omega_p \,+\, \Omega_b)\,c^2)$. Estimate for an increment of an initial signal spatial amplification follows from here:

$$Im\delta\,k \;=\; \left(-\sqrt{4\,Q \,+\, (\zeta \,-\, \eta)^2} \,+\, \zeta \,+\, \eta\right)/2 \tag{8}$$

The amplification takes place, i.e. $Im\delta\,k \,<\, 0$ [6], if density of a beam is sufficient high so $Q \,>\, \zeta\,\eta$ or

$$\omega_b^2 \;>\; 2\,\gamma\,\Gamma_b\,(\Omega_p \,+\, \Omega_b)^2/(\Omega_b\,\beta^2\,\Delta). \tag{9}$$

By (5) and (8), reasonablly reasonable minimum values of densities beam and the gaseous medium have for transitions corresponding to long-wave infrared radiation with $\Omega_{p,b} \;<\; 10^{15} \,\div\, 10^{14}\,c^{-1}$, i.e. with length of a radiated wave $\lambda \;>\; 1.5 \,\div\, 15$ mkm (here some ”reserve” is made , regarding straggling of parameters, for example straggling on energies of particles). Besides only enough long-lived transitions with $\Gamma_{p,b} \;\simeq\; 10^7\,c^{-1}$ can participate in induced process. At last the atomic beams should be accelerated enough with $\beta \;\geq\; 0.1$ that corresponds to energy of particles about $\geq\; 5$ MeV/ nucleon . Therefore beams of accelerated negatively ionized atoms of light atoms (for example H^- , widely used nowadays in experiments [7]) there can be a real objects for observation. So at $\Omega_{p,b} \;=\; 10^{14}\,c^{-1}.\; \beta \;=\; 0.1 - 0.3$, length of instability development for ampere beams are made tens of centimeters in resonant frequency band at $\Delta \;\sim\; 10 \div 10^3$.

Effect of different attendant processes - excitation, ionization and dispersion of atoms of a beam and gas - will have an effect only on subsequent stages since an effective section of atomic collisions does not exceed about $10^{-19}\,cm^2$ already for low relativistic particles .

Naturally it is necessary to note that a gas medium considered above is not the unique example of systems with slow waves. So some systems with superficial waves are now discussed in the accelerator theory. One of versions is a dielectric surface along which an atomic beam is injected. Here, a rather slow superficial wave (for a dielectric with large enough refraction factor and small losses) - a sort of Smith-Purcell’s wave, can be propagated. However an appreciable lack of similar system is sharp decrease of a wave amplitude far from dielectric surface that decreases the efficiency of beam-wave interaction.

Therefore doubtless interest represents the further dynamics analysis of processes considered above. Here the beam can produce (after excitation on first stage) a secondary radiation of photons on fast wave with $\omega \;\simeq\; 2\gamma^2\,\Omega_b$.

3 REFERENCES

[1] V.L.Ginsburg // USSR, 1947, N_0 56, p. 145.

[2] V.L.Ginsburg, Teoreticheskaia physika i astrophysika.-M.: Nauka, 1981.

[3] M.V.Neslin, Dynamika puchkov v plasme. M.: Energoisdat, 1982.

[4] A.F.Aleksandrov, L.S.Bogdankevich, A.A.Rukhadse., Osnody elektrodinamiki plasmy. M.: Vysshaia shkola, 1978.

[5] A.S.Davydov, Quantovaia mekhanika. M.: GIFML, 1 963.

[6] A.I. Akhieser I.A. Akhiese, P.B.Polovin, Elektrodinamika plasmy. M.: Nauka, 1974.

[7] H.Massey, Negative ions.-New York, Cambrige, 1976.