POSSIBLE WAY OF TANDEM FREE ELECTRON LASER REALIZATION ON CHANNELING RELATIVISTIC PARTICLES

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Abstract

In the report the possibilities of FEL optimization and creation of tandem laser are considered. One of the optimal ways of coherent hard radiation generation is connected with the creation of FEL on channeling relativistic particles in perfect crystals [1]. The main role in solution of such problem plays the full Doppler effect [2]. The possibility of creation of tandem FEL, where one particle can radiate multiple times on one transition, is predicted for the first time. For such laser the intensive process of consecutive generation of two types of photons with different frequencies on the same radiating transition is possible and this double photon generation leads to the restoration of the initial state of quantum system. This effect allows to predict the possibility of multiple repeat of radiation cycle. The pumping source for such laser is the kinetic energy of moving particles. In such systems there is no need for inversion and absorption on radiation frequency is totally absent. The main problem of realization of tandem FEL is connected with the need of mediums with positive susceptibility in high frequency range, possible ways to solve this problem are also regarded.

INTRODUCTION

One of the most important problems of modern laser physics is the creation of lasers of X-Ray and Gamma range. This problem cannot be solved with use of usual nuclear systems, because with the frequency transition magnification the lifetime decreases proportionally frequency power minus three. In particular for the creation of the laser with a wavelength one angstrom a power of one watt on atom is needed. Usage of lasers on free electrons where frequency pinch can be achieved by the Doppler effect is perspective.

High frequencies can be received at use of very strong fields. Such fields exist in crystals.

One of the optimal ways of coherent hard radiation generation is connected with the creation of FEL on channeling relativistic particles (positrons or electrons) in perfect crystals.

Usually attention is paid only to one feature of a Doppler effect - magnification of frequencies of radiation and absorption at the increase of motion speed. One more feature of a Doppler effect is caused by a law of momentum conservation and it leads to level splitting. The formula for a "classical" Doppler effect is the following:

$$\omega = \frac{(\varepsilon_2 - \varepsilon_1)/\hbar}{\gamma(1-\beta n(\omega)\cos\theta)} \qquad (1)$$

Here and ε_2 and ε_1 are energies of the excited and basic levels, $\beta = v/c$, $\gamma = 1/\sqrt{1-\beta^2}$ - the relativistic Lorentz-factor, θ - an angle between a direction of radiation (absorption) and a direction of a motion.

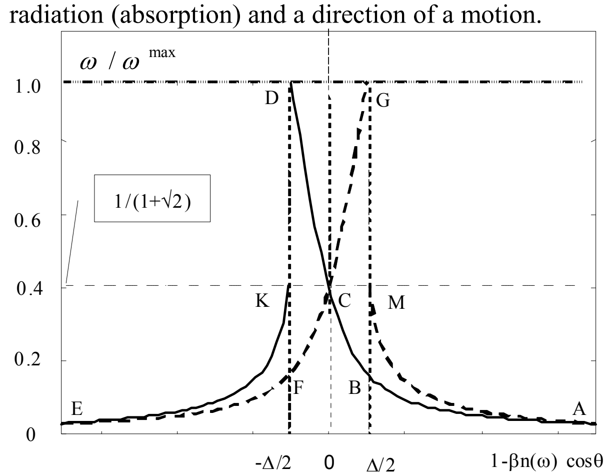

Figure 1. Radiation (AD, KE) and absorption (AM, GF) frequencies for normal and abnormal Doppler effects.

The full analysis of radiative processes in the region of parameters near the critical condition $\beta n(\omega)\cos\theta = 1$ has been made for the first time in [2]. In case of radiation particles moving with the speed $\beta = v/c$ in a medium with a refractive index $n(\omega)$ the Doppler effect for absorption and radiation is not reduced to trivial absorption and radiation frequencies splitting. The results of this research are presented in a Fig. 1, and the effect by analogy to "normal", "abnormal" Doppler effects can be termed "the full Doppler effect" as it includes all features of spectrums in all regions of parameters.

The strongest influence of recoil on radiation and absorption spectrums corresponds to the region of parameters, close to a condition $\beta n(\omega)\cos\theta = 1$, and especially in the interval $|1-\beta n(\omega)\cos\theta| \le \Delta/2$ and near its boundaries. Value of Δ is defined by expression [2]

$$\Delta = \sqrt{8\frac{\varepsilon_2 - \varepsilon_1}{\gamma^2 mc^2}[(n(\omega))^2 - 1]} \qquad (2)$$

and determines where the transition from a normal Doppler effect (branch AD and AM) to the abnormal effect (branches KE and GE) takes place.

In this interval there is a number of unique effects which has to be considered in detailes.

THE STIMULATED PROCESSES IN THE FIELD OF COEXISTENCE OF NORMAL AND ABNORMAL DOPPLER EFFECTS

The problem of realization of laboratory X-ray and gamma lasers has been viewed in [1]. The analysis has shown that the main problem of its realization is related to the necessity of maintenance of inverse densities of population on working pair of levels simultaneously with the low radiative broadening of these levels. It is very difficult to provide such requirements on the basis of stationary nuclear and atom systems with very short lifetime because of the necessity to use extremely intensive excitation. The system can be optimized using as the active medium resonant energy levels of moving particles in the channel. For them necessary inverse population is reached by simple crystal rotation to the direction of the beam. But it has to be noticed that channeling process leads to a great broadening of levels, which is caused by small dechanneling length. Presence of levels broadening leads to the increase of threshold particles beam density, which is needed to start generation. One of the possible ways to solve the problem is to use unique features of a Doppler effect for channeling particles in the region of extreme parameters Δ. We will number some of possible unique effects which can be realized only within the interval Δ.

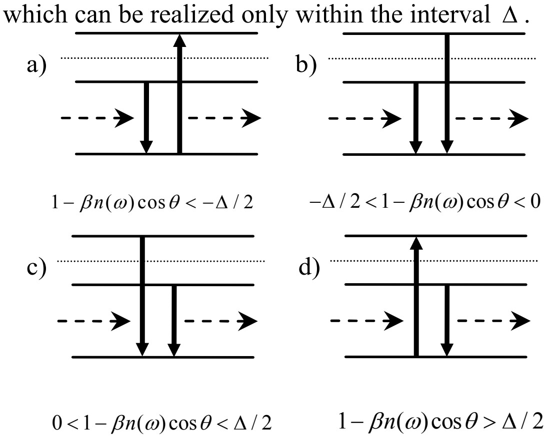

Figure 2. The change of the directions of radiative transitions for radiation and absorption depending on $1-\beta n(\omega)\cos\theta$ value.

It is well-known that the stimulated radiative processes lead to the transitions between traversal energy levels of a moving particle. In "standard" optics it is considered that the activity of the stimulated absorption and radiation leads to opposite processes: to the magnification or reduction of traversal particle energy. At the same time within the interval $|1-\beta n(\omega)\cos\theta| < \Delta/2$ situation is different. In this region simultaneous existence of both "normal" radiation and the "abnormal" absorption is possible. Both processes lead to identical effect: reduction of the energy, corresponding to a traversal motion of particles, with simultaneous magnification or reduction of energy, corresponding to a longitudinal motion (fig. 2 b, c).

Such process of the stimulated transitions to lower energy levels of traversal motion allows to decrease influence of dechanneling process. It is interesting to notice that for the realization of such effect there is no need to use resonant narrow external light source. For this purpose there is enough to use any source of a hard radiation with frequencies and angular diagramme in this interval or even overlapping it.

From the dependences presented in a Fig. 1 it can be seen that at $|1-\beta n(\omega)\cos\theta| < \Delta/2$ frequencies of radiation and absorption differ for all values of parameters excluding a point $1-\beta n(\omega)\cos\theta = 0$, reaching peak and very great difference on interval border, where $\omega_{\max}/\omega_{\min} \approx 5.88$. This circumstance leads to the possibility of realization of system, for which the radiation on certain frequency and under a certain angle will not be accompanied by resonant absorption. Such effect leads to possibility of the full exception of self-absorption at the realization of coherent hard radiation laser type source on the basis of such systems.

THE POSSIBILITY OF TANDEM SELF-SUPPORTED SYSTEM OF GENERATION OF THE STIMULATED RADIATION ON THE BASIS OF CHANNELING PARTICLES SYSTEM

The reviewed features allow to predict potential possibility of creation of unique tandem systems of laser generation with extremely high efficiency of transfer of a kinetic energy of the accelerated particles to the energy of laser generation. To base this process we will consider features of radiation near to the left border of an analyzed interval $1-\beta n(\omega)\cos\theta = -\Delta/2$ (line DKF in a Fig. 1).

In particular near the left boundary in the value of parametres

$$1-\beta n(\omega)\cos\theta = -\Delta/2 - \delta_1 \qquad (3)$$

process of the "abnormal" radiation on the frequency

$$\omega_{rad}^{anom} \le \sqrt{2\frac{mc^2(\varepsilon_2-\varepsilon_1)}{\hbar^2(n^2-1)}}, \qquad (4)$$

leads to the transitions upwards in the system of moving particle levels and to the "preparation" of this system for the subsequent "normal" radiation. Accordingly, at the value of parametres

$$1-\beta n(\omega)\cos\theta = -\Delta/2 + \delta_2 \qquad (5)$$

there will be higher frequency of "normal" radiation

$$\omega_{rad}^{norm} \le (1+\sqrt{2})\sqrt{2\frac{mc^2(\varepsilon_2-\varepsilon_1)}{\hbar^2(n^2-1)}}, \quad (6)$$

and transition downwards between the same levels. It corresponds to the system "preparation" for the subsequent "abnormal" radiation. It is essential that the frequency of absorption in the given interval $[-\Delta/2-\delta_1, -\Delta/2+\delta_2]$ appears much lower than both frequencies of radiation and does not influence resonant interaction.

This combination of consecutive radiative processes corresponds to the positive feedback and allows to predict the possibility of creation of unique tandem emissive two-steps laser system, where each of the emissive transitions prepares system for the following one. Such process can be repeated multiple times, and it leads to the possibility of consecutive multiphoton generation on the same two-level transition. Energy of radiation is taken from the kinetic energy of a moving particle. This process is much more effective in comparison with usual lasers, where the highest efficiency corresponds to the generation of only one quantum on working excited transition.

One of possible variants of such system with the use of two pairs of mirrors for the creation of two one-dimensional resonators is presented on fig. 3. At such positions of Fabry–Pérot resonators, frequency of both generated waves are different and are determined by the equations (3) and (5). In each resonator amplification occur only in one direction shown by dash line.

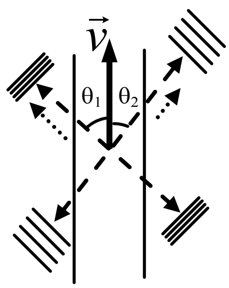

Figure 3. The scheme of tandem laser in the interval range $[-\Delta/2-\delta_1, -\Delta/2+\delta_2]$ near the condition $1-\beta n(\omega)\cos\theta \approx -\Delta/2$.

Such cycle can be realized in laser system with the use of only one Fabry–Pérot resonator (Fig. 4). For this purpose it is necessary to provide a requirement that the frequency of the abnormal radiation in the region $-\Delta/2-\delta_1$ is two times lower than the frequency of normal radiation in a point $-\Delta/2+\delta_2$. In that case it is possible to use Fabry–Pérot resonator with the longitudial length of periodic resonances L with frequencies $\omega_n = n\omega_1$, $\omega_1 = \pi c/L$. Requirement $\omega_{rad}^{norm} = 2\omega_{rad\,(\max)}^{anom}$ shows, that such system is possible if $\delta_2 \approx \Delta/8$, $\delta_1 << \delta_2$.

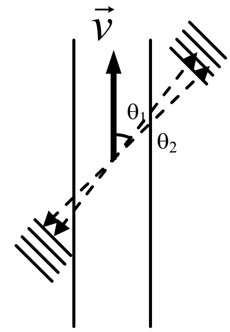

Figure 4. The scheme of tandem laser in the interval range $[-\Delta/2-\delta_1, -\Delta/2+\delta_2]$ near the condition $1-\beta n(\omega)\cos\theta \approx -\Delta/2$ with one Fabry–Pérot resonator.

One more scheme of tandem laser with the use of ring single-frequency resonator can be used for generation of colliding waves of identical frequency (Fig. 5), running over a resonator contour in opposite directions. Process amplification of each wave occur only at its motion along those trajectory which coincides with a direction of a beam motion (4→1, 3→2). In this case intervals EK and CA near the region Δ are used.

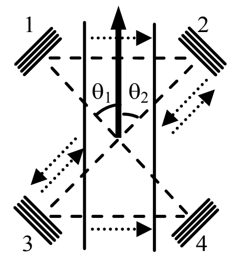

Figure 5. The scheme of tandem laser in the interval range $[-\Delta/2-\delta_1, -\Delta/2+\delta_2]$ near the condition $1-\beta n(\omega)\cos\theta \approx -\Delta/2$ with ring Fabry–Pérot resonator.

The main problem of such tandem laser schemes realization consists in the fact that all unique radiative effects reviewed above can be received only in the area of parameters Δ. For their realization maintenance of such parametres of system at which it is possible at least the existence of this area is needed. The size of this area is desirable to be wide enough. As it can be seen for the existence of such area the presence of mediums with positive susceptibility in a range of an extreme Cherenkov condition is obvious. The order of frequencies (energies) suiting to this condition corresponds to the soft part of a X-ray region (10^3 eV) for not ultrarelativistic electrons and positrons. For ultrarelativistic light particles or the nonrelativistic heavy particles this energy is much greater.

REFERENCES

[1] Vysotskii V.I., Kuzmin R.N. Gamma-Ray Lasers, MSU Publ. House, Moscow, 1989.

[2] Vysotskyy M.V., Vysotskii V.I. // Nuclear Instr. and Methods in Physics Research B, 2006, V. 252, P. 75-80.