

# Peculiarities of Cherenkov Radiation by a Train of Bunches Moving Inside a Partially Dielectric Loaded Waveguide

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#### 1. Introduction

The presence of medium may essentially influence the characteristics of the radiation from charged particles. Moreover, the medium gives rise to new types of the radiation processes [1-5]. Examples of the latter are the Cherenkov Radiation (CR), transition radiation, diffraction radiation etc. These processes are used as sources for the electromagnetic radiation in wide range of frequencies, in particle detectors, as well as for radiation source diagnosing. In addition, by a comparison of the measured spectral and angular characteristics of the radiation with the theoretical ones the relevant parameters of the medium can be extracted.

In this report we consider the CR from a train of bunches of charged particles traveling along the axis of a partially dielectric loaded cylindrical waveguide.

The CR in waveguides with dielectric filling has been widely discussed in the literature (for an early review see [1] and references given in [6]). In particular, special attention has been paid to the radiation on periodical structures inside the waveguide (see e.g. [7-12] and references therein). In [7] the radiation from a charged particle traveling along the axis of an infinite waveguide completely filled with a layered (spatially periodic) medium is considered. However, the case of the CR generation was not discussed in that

reference and it has been investigated in [9-11]. In these works, it was shown that CR may self-amplify due to the presence of a waveguide and of a periodic medium.

### 2. Problem setup

Consider a train of bunches of relativistic charged particles uniformly moving with velocity v along the axis of an infinitely long cylindrical waveguide with perfectly conducting walls. The radius of the waveguide will be denoted by R and cylindrical coordinates  $r, \varphi, z$  with the axis z along the waveguide axis will be used. We shall assume that the finite part of the waveguide is loaded by a medium with weak absorption of the radiation. An example of a waveguide loaded by a plate is shown in Fig.1 (for the electromagnetic field of the bunch intersecting a dielectric plate in a waveguide, or a vacuum gap located in a dielectric loaded waveguide see [12, 15]).

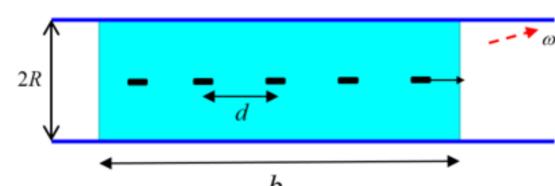


Fig.1. Geometry of the problem

Let the permittivity  $\varepsilon$  and permeability  $\mu$  of the medium are independent of the transverse coordinates  $r, \varphi$ . We denote by  $I_n(\omega)$ 

the spectral density of the radiation energy on the *n*-th mode of the waveguide, passing the waveguide cross section (during the whole period of the bunch motion) at large distances from the plate and corresponding to the radiation from a single particle. Then, for the corresponding energy of the radiation emitted by the train of electron bunches we can write

$$W^* = \sum_{n=1}^{\infty} \int_{\omega_n}^{\infty} F(\omega) I_n(\omega) d\omega = \sum_n W_n^*$$
 (2.1)

where  $\omega_n$  is the cutoff frequency for the *n*-th mode and  $W_n^*$  is the energy radiated on that mode. In (2.1) the factor  $F(\omega)$  is determined by the train structure and is presented as (see [16])

 $F(\omega) = n_q n_b [1 - f_q(\omega) f_m(\omega)] + n_q^2 n_b^2 f_q(\omega) f_m(\omega),$  (2.2) here  $n_q$  being the number of particles in the bunch,  $n_b$  - the number of bunches in the train, d - distance between bunches. For the Gaussian distribution of the bunch particles with standard deviation  $\sigma$  the coherence factor is given by  $f_q = \exp(-\omega^2 \sigma^2 / v^2)$ , in case of equidistant bunches  $f_m = \frac{\sin^2(\omega dn_b/2v)}{n_b^2 \sin^2(\omega d/2v)}$ . The formula for  $I_n(\omega)$  in the general case when the waveguide is loaded with an arbitrary number of equidistant plates is given in [11] (see also [9, 10]).

#### 3. Numerical results

In Fig.2 the spectral density of the radiation energy from an electron passing trough a dielectric plate in waveguide, depending on the quantity  $\omega R/c$  is presented. The permittivity and permeability for the material of the plate given by  $\varepsilon_b = \varepsilon_b' + i\varepsilon_b'' = 1.7(1+10^{-4}i)$  and  $\mu_b = 1$ . The energy of electron is 10 MeV, for the remaining parameters we have taken  $R=1\,\mathrm{cm}$ ,  $b=40\,\mathrm{cm}$ .

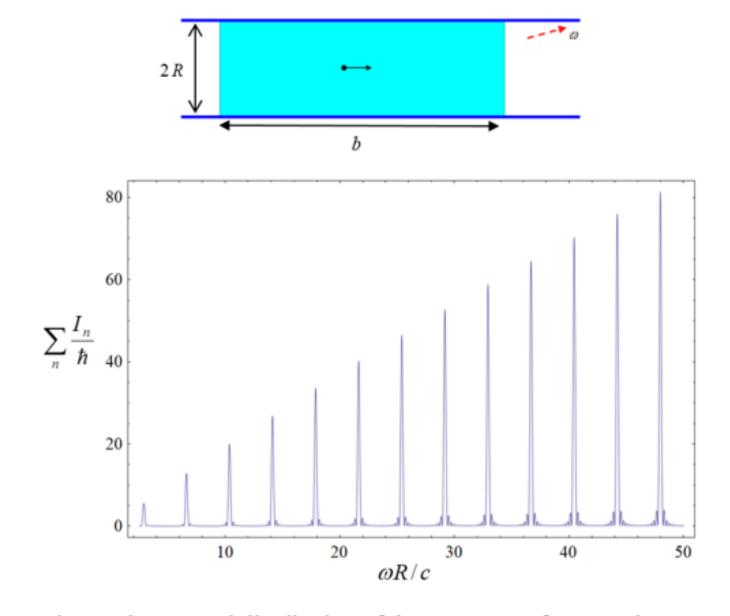


Fig. 2. The spectral distribution of the CR energy from an electron passing trough a dielectric plate in waveguide. For details see the text

In Fig.3 the spectral distribution of the CR energy from a train of thin bunches has presented. Number of electrons in bunch  $n_q=10^9$ , the characteristic rms longitudinal size of bunches  $\sigma=0.03$  cm, number of bunches in train  $n_b=5$ . In Fig.3a distance between bunches  $d=8R\sqrt{\varepsilon v^2/c^2-1}=6,67$ cm =  $d_{opt}$ .

In Fig.3b,c  $d = 0.95d_{opt}$ ,  $1.05d_{opt}$  respectively.

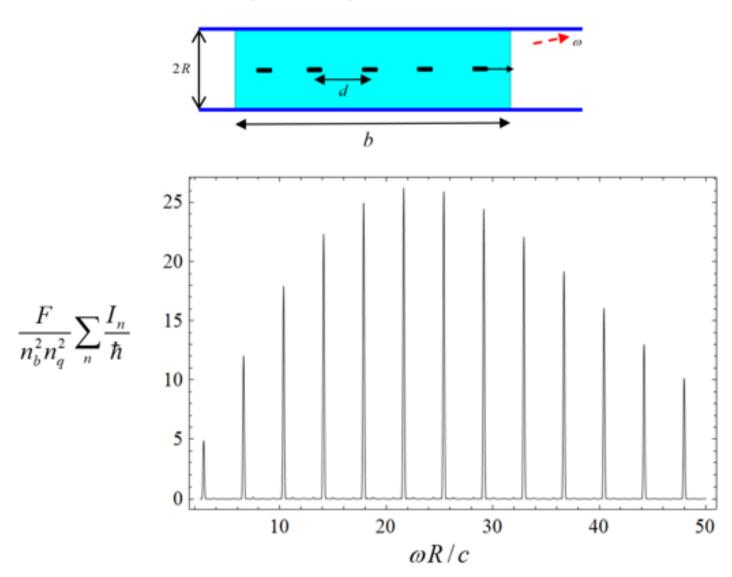


Fig. 3a. The spectral distribution of the CR energy from a train of electron bunches passing trough a dielectric plate in waveguide

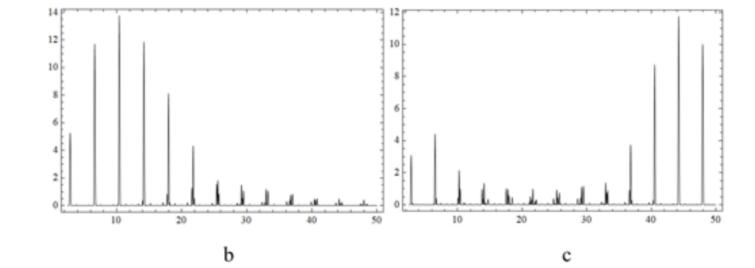


Fig. 3b,c. The same as in Fig.3a in case of  $d=0.95d_{opt}$  (b) and  $d=1.05d_{opt}$  (c)

As can be seen from Figs.2;3a, in case of the optimal choice of the distance between bunches, the train radiates quasi-coherently in a wide frequency range (from 10 to 200 GHz ( $\omega R/c = 2-40$ ), on the first 10 waveguide modes) and, that at a small deviation from the optimal value of distance of bunches (5%), the train radiates incoherently (see Figs.3b,c).

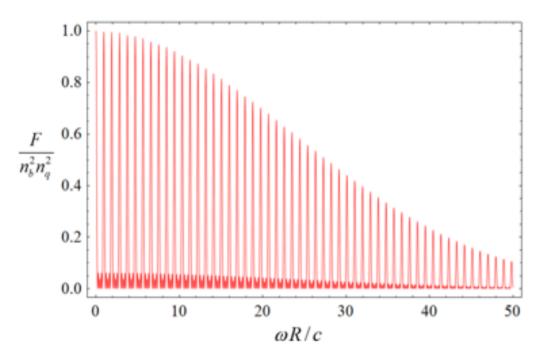
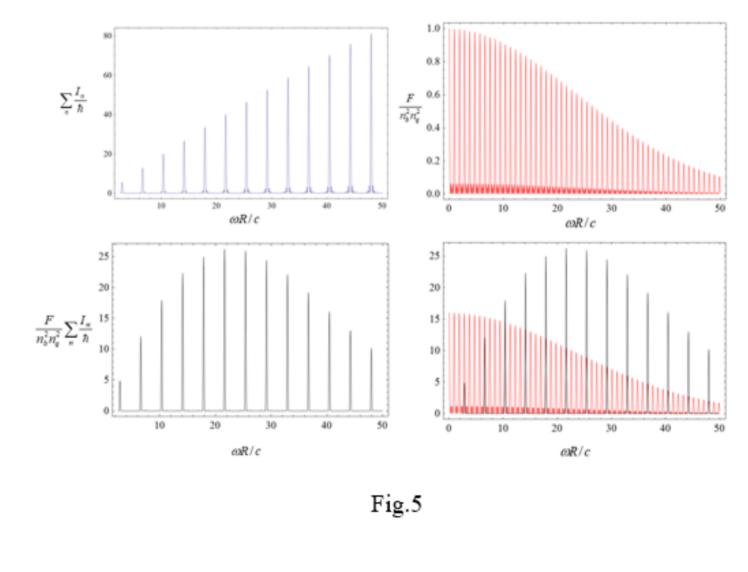


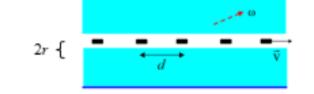
Fig.4. The dependence of the structure factor  $F(\omega)$  on cyclic frequency

To illustrate this circumstance, in Fig.4 the dependence of the train structure factor  $F(\omega)$  on cyclic frequency, at the optimal choice of the distance between bunches is presented. As can be seen from Fig.4, in the region up to 200GHz there are narrow regions, where  $F/(n_b^2 n_q^2) > 1/n_b$ , which means that in these regions the radiation will be quasi-coherent. The parameters of the problem can be chosen in such a way, that the frequency regions where the main part of the radiation of a single particle is concentrated, coincide (in position and width) with the regions where the structure factor of the train of bunches has maximum values (see Fig.5).

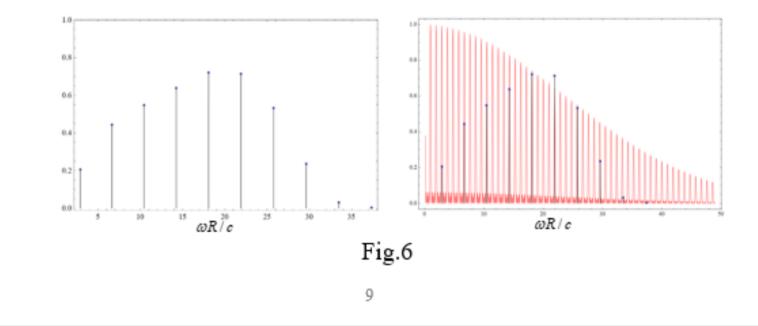


Thus, at an optimal choice of the problem parameters, the presence of a train leads not only to a redistribution of radiation over frequencies, but also to an increase in the energy losses of each bunch in a wide frequency range.

Obviously, in the experimental study of this phenomenon, it will be necessary to create an empty cavity in the center of the dielectric plate. Taking into account this circumstance, we theoretically studied the radiation of a train of equidistant unidimensional electron bunches traveling along the axis of hollow channel in the central part of dielectric-lined waveguide (see [18]).



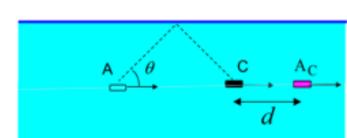
In this case, the CR is generated at discrete frequencies (waveguide modes). In Fig.6 the power of radiation (in arbitrary units) on the first 10 modes is presented,  $d=0.99d_{opt}=6.59$ cm,  $\varepsilon_h = \varepsilon_h' = 1.7$ , r = 0.05cm, other parameters are the same as in Fig.3a.



As we can see from the data above, in the presence of a channel, it remains possible to generate coherent radiation from train in sufficiently large frequency range (including the first eight modes).

# 4. Visual explanation

Below we provide a simple model that reproduces the basic features of the numerical results. In what follows, a bunch of particles is considered as a point charge (charged particle) to simplify the presentation.



Consider the Cherenkov wave (dotted line) emitted by the first bunch at point A. While propagating, at some time moment the wave will approach the bunch trajectory at point C. By this point in time, it will lag behind its source (the first bunch), which, moving at superluminal speed, will be at the point  $A_{\mathbb{C}}$ . In this case, the second bunch of the train is to the left at a distance d from the first one, and if

$$d_0 = CA_C = 2R\sqrt{\varepsilon v^2/c^2 - 1}$$

then it will be in the vicinity of point C simultaneously with the wave Thus, in the areas directly adjacent to each of the bunches (with the exception of the first), two processes will simultaneously occur: emission and interference of waves. The in-phase superposition ( $d=4d_0$ ) of electromagnetic oscillations would go with an amplification of field in the zone of radiation formation. As a result, the force retarding the motion of bunches also increases, and an additional work performed by the external force constraining the uniform motion of bunches shall be used for formation of higher power resonant CR stimulated on the large number of neighboring modes. This explains the resonant increase (stimulation) of the quasi-coherent CR on a large number of waveguide modes.

# 5. Summary

We have investigated the CR from a train of electron bunches traveling along the axis of a partially dielectric loaded cylindrical waveguide. It is shown, that by special choice of the values of problem parameters, it is possible to generate quasi-coherent radiation from bunches in a train, on several waveguides modes simultaneously. A visual explanation of the obtained results is given. The effect considered can be used to develop high-power sources of the coherent CR in giga and terahertz spectral ranges, e.g., for the amplification of the coherent CR observed in [17].

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