GENERATION OF NARROW BAND SHORT MM WAVE SUPERRADIANCE PULSES IN A NON-UNIFORM PLANAR WAVEGUIDE*

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Abstract

A method for suppressing of spurious transverse modes excitation in the process of supperradiance from intense electron bunch is described. Such method based on the use of the waveguide with variable geometry (in the case of planar waveguide it is distance between plates). In such waveguide phase velocities of the different modes varied over longitudinal coordinate. For given waveguide profile variations are increased with increasing transverse mode indexes. As a result modes with large Brillouin angles (including near cut-off modes) which are responsible for low frequency radiation suppress more effectively than modes with small Brillouin angles. For the case of planar geometry this effect demonstrated both in the frame of the averaged equations and the full PIC-simulations.

INTRODUCTION

Recently significant progress was achieved in production of ultrashort pulses in millimeter wave band based on supperradiance from intense electron bunch [1-3]. One of the problems for advance generators based on such mechanisms in shorter (first of all sub-mm) wave bands is the spectrum broadening caused by the simultaneous excitation by an electron bunch several waveguide modes in oversized waveguide. For example at the fig.1 the dispersion diagram of the 1 MeV electron beam propagating through the planar waveguide with 1 cm gap is shown. Electron beam interacts simultaneously with three propagating modes (the interaction at the cut-off frequency with the TE_1 mode could be neglected): with TE_2 mode at the frequency of about 50 GHz, with TE_1 mode at the frequency of about

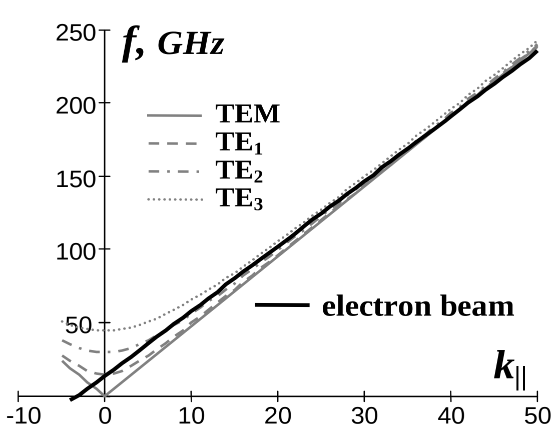

Figure 1: Dispersion diagram of the 1 MeV electron beam and planar waveguide with 1 cm gap.

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150 GHz and with the fundamental TEM mode at the frequency of about 200 GHz.

To suppress spurious interaction we suggest using the non-uniform waveguide with tapered radius (cylindrical geometry) or distance between plates (planar geometry). In such a waveguide the phase velocities of the different modes varied over longitudinal coordinate. For given waveguide profile variations are increased with increasing transverse mode indexes. As a result modes with large Brillouin angles (including near cut-off modes) which are responsible for low frequency radiation suppress more effectively than modes with small Brillouin angles. In planar waveguide situation is even more preferable because phase velocity of fundamental TEM mode is totally independent on the distance between plates.

BASIC MODEL

Let us assume, that a sheet electron beam with initial velocity $\vec{v}_0 = v_0\vec{z}$ passes through a planar undulator with period d and homogeneous magnetic field with strength $\vec{H}_0$ in a planar waveguide with gap between plates b (Fig.2). We also assume that the system is infinite over the y-axis and the electron beam excites the TE_n-mode of a planar waveguide with n variations over the transverse coordinate x. Vector-potentials of the periodic undulator field (subscript u) and operating mode (subscript s) may be presented as

$$\vec{A}_u = \mathrm{Re}\{A_u ch(k_u x)\exp(ik_u z)\vec{y}\},$$
$$\vec{A}_s = \mathrm{Re}\{A_s(x,z)\exp(i\omega t - ik_\parallel z)\vec{x}\}$$

where $A_s(x,z)$ is the slowly-varying amplitude of the synchronous wave, $k_u = 2\pi/d$. The reference frequency ω was chosen to be the frequency at exact undulator synchronism $\omega - k_\parallel v_\parallel \approx \Omega$, where $k_\parallel{}^2 = k^2 - k_\perp{}^2$, $k = \omega/c$, $k_\perp = n\pi/b$, $\Omega = k_u v_\parallel$ is the bounce-frequency.

Using the independent variables

$$\zeta = \frac{kCZ}{\beta_\parallel^3\gamma_0^2},\ \tau = \frac{kC(t - z/v_\parallel)}{\beta_\parallel^3\gamma_0^2(1/v_\parallel - 1/v_{gr})}$$

superradiance process can be described by the following equations:

$$\frac{\partial a}{\partial\zeta} + \frac{\partial a}{\partial\tau} = f(\tau)\int_0^{2\pi} e^{-i\theta}d\theta_0$$
$$\frac{\partial u}{\partial\zeta} = \mathrm{Re}\{ae^{i\theta}\} \quad \frac{\partial\theta}{\partial\zeta} = u - \Delta \qquad (1)$$

with the boundary conditions

$$a|_{\tau=0} = a_0,\ a|_{\zeta=0} = 0,\ u|_{\zeta=0} = 0,$$
$$\theta|_{\zeta=0} = \theta_0 + r\cos(\theta_0),\ \theta_0 \in [0,2\pi)$$

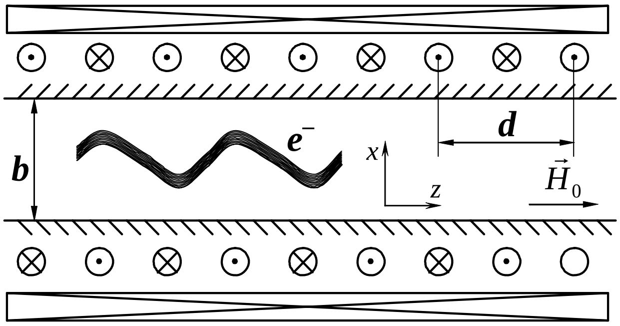

Figure 2: Scheme of the basic model.

The following dimensionless variables have been used:

$$a = \frac{eA_s}{2mc^2}\frac{eA_u}{2mc^2}\frac{\beta_\parallel^3 k_u c}{C^2}\left(\frac{1}{\Omega-\omega_H}-\frac{1}{\Omega+\omega_H}\right)$$

is the wave amplitude, $\theta = \omega t - \left(k_\parallel + k_u\right)z$ is the electron phase with the respect to the synchronous wave, $u = C^{-1}\left(1-\gamma/\gamma_0\right)$ is the relative electron energy,

$$C = \frac{eI}{mc^3}\frac{c\gamma_0}{4\pi N_s}\left[\frac{eA_u}{2mc^2}\beta_\parallel^3 k_u c\left(\frac{1}{\Omega-\omega_H}-\frac{1}{\Omega+\omega_H}\right)\right]^2$$

is the Pierce parameter, ω_H is the cyclotron frequency, I is the electron beam current, N_s is the norm of the operating wave,

$$\Delta = \frac{\beta_\parallel^3\gamma_0^2}{C}\left(\frac{k_\parallel + k_u}{k}-\frac{1}{\beta_\parallel}\right)$$

is the mismatch from the undulator synchronism, $f(\tau)=1$, $\tau \in [0,T]$, where T is the normalized duration of the electron bunch.

Let is consider the influence of the variation of the mismatch of the undulator synchronism over the longitudinal coordinate on the superradiance process. We choose the simplest linear dependence: $\Delta(\zeta) = \Delta_0\,\zeta/L - \Delta_0$. Fig.3 demonstrates the results of the simulation of Eqs. (1) for $L = T = 30$ in the case of non-dispersive wave ($\Delta_0 = 0$, which corresponds to excitation

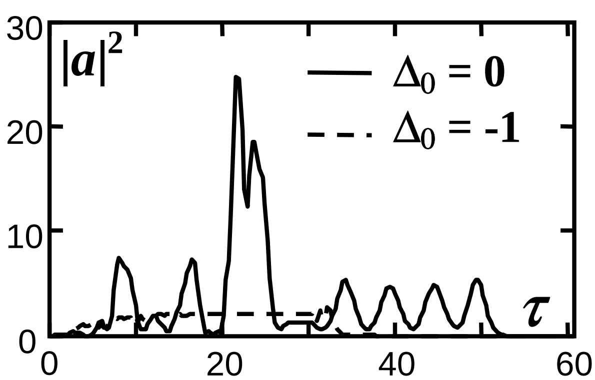

Figure 3: Simulation of averaged equations: output signal in case of uniform (Δ_0 = 0) and non-uniform waveguide (Δ_0 = -1).

TEM mode) and wave with dispersion ($\Delta_0 = -1$, which corresponds to excitation TE_1 mode). In the first case we see formation of powerful superradaince spike. In the second case output radiation is practically suppressed.

PIC-SIMULATIONS

The 2-D version of the PIC-code KARAT was used for additional simulations. The 110 cm length planar waveguide was excited by the 1 MeV, 100 A/cm, 600 ps electron bunch which was transported through the periodic undulator with period 2 cm and 2 kOe strength and guiding magnetic field with strength of 22 kOe (Fig.4a). For regular waveguide simulation showed that the spectrum of the output signal includes three main frequencies (Fig.4c), which correspond to the simultaneous excitation of the TEM, TE_1 and TE_2 modes.

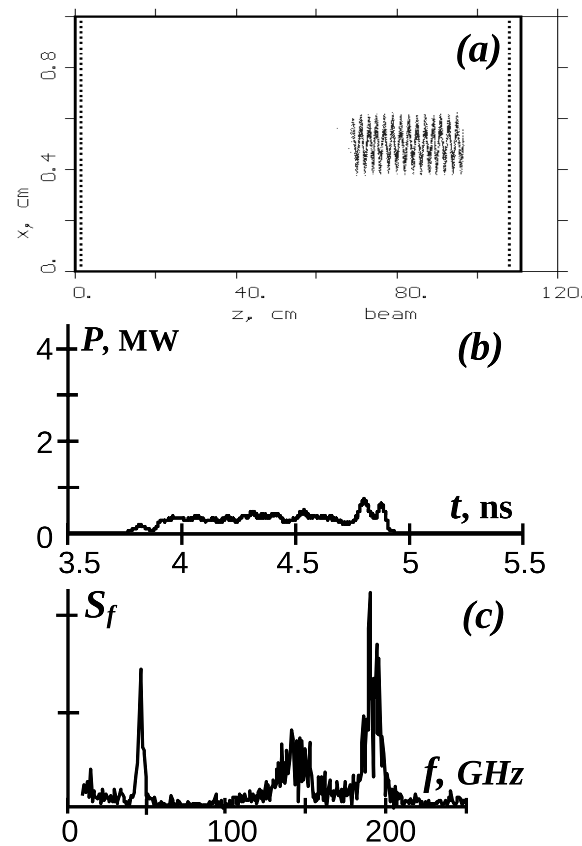

Figure 4: PIC-simulations of superradiance in the uniform oversized waveguide: *(a)* is the geometry of interaction space (solid lines denotes the ideal conductor, dash lines marked the boundary of the microwave absorption layers); *(b)* is the output signal and *(c)* is the spectrum of output radiation.

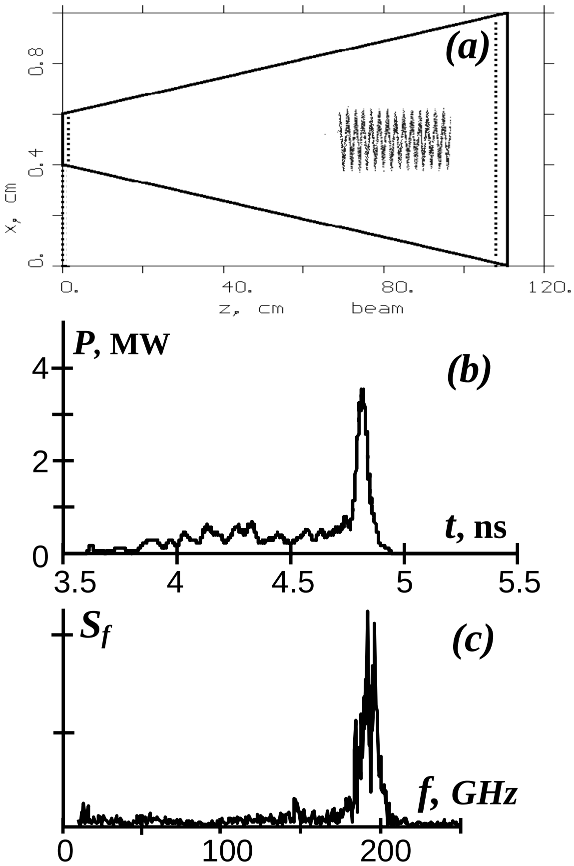

Figure 5: PIC-simulations of superradiance in the uniform oversized waveguide: *(a)* is the geometry of interaction space; *(b)* is the output signal and *(c)* is the spectrum of output radiation.

Fig.5 demonstrated the results of simulation of superradiance in the waveguide with linearly increased gap between plates from 0.2 to 1 cm (fig.5a). In this case all spurious modes were suppressed and the output radiation includes one powerful spike (fig.5b). As a result the spectrum of output radiation is concentrated near the operating frequency of 200 GHz corresponding to excitation fundamental TEM mode (fig.5c).

CONCLUSION

A method of suppressing excitation of spurious modes in the process of supperradiance from intense electron bunch in the planar oversized waveguide is considered. The simulations of the averaged equations and PIC-simulations were carried out and it was shown that in the planar waveguide with linearly increasing gap between plates the SR pulse associated with excitation of single transverse mode could be obtained.

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