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Generation of nanosecond S band microwave pulses based on superradiance

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Abstract

Modeling carried out demonstrates possibility of generation of gigawatt power level S band microwave pulse with duration of several nanoseconds using superradiation of short electron beam moving along slow-wave periodical structure. A 10 ns / 500 keV / 5 kA accelerator of Kanazawa University can be used in such experiments. It is shown that significant increasing peak power can be obtained by optimization of voltage and current pulses waveforms. Required increasing of electron energy and current by the end of electron pulse can be achieved by using self-acceleration of a short beam passing through a system of passive cavities.

1. Introduction

One attractive method of generating ultrashort electromagnetic pulses is stimulated emission from a spatially localized ensemble (bunches) of electrons. Radiation from such bunches may be considered as a classical analogue of an effect in the quantum electronics known as Dicke's superradiance [1-3]. In this process incoherent emission induces a small macroscopic polarization in the inverted medium which gives rise to the growth of an electric field and consequently an increasing polarization in space and time. After a delay a highly directional pulse of peak output power proportional to N^2 is emitted, where N is the number of emitters. In the classical region, a similar effect is involved in the process of stimulated emission in spatially localized ensembles of electrons. Naturally, superradiance of classical electrons may be associated with different mechanisms of stimulated emission (bremshstrahlung, Cherenkov, cyclotron etc [4-17]). Different types of SR were studied theoretically [4-12] and were recently observed experimentally [13-18] at infrared and millimeter wavelength bands. RADAN accelerator producing intense subnanosecond electron bunches (250-300 KeV, 1-2 kA, 0.3-1 ns) has been used in these experiments [19].

The maximal peak power of SR pulses was associated with Cherenkov emission from an electron bunches moving through a periodical slow-wave structure and interacting with backward wave. Based on these mechanisms, generations of SR pulses have been observed experimentally at all millimeter waveband through the frequencies 35-150 GHz. For example, at central frequency 39 GHz (K band) peak power exceeded 200 MW with pulse duration less then 300 ns. Obviously, theoretical and experimental studies of superradiance should be continued in different directions. Expanding frequency range including short and long wavelengths bands is one of the interesting applications. In the case of generation of SR pulse at centimeter (X and S) wave bands, an electron pulse duration should be increased in correspondence with increasing wavelength. As a result, nanosecond accelerators can be used for production of driving electron pulse. In Section 1 of this paper planning experiments on observation of SR at the S band based on 10 ns high-current accelerator of Kanazawa University are discussed. According to simulations carried out 10 ns, 500 keV, 5 kA electron beam from this accelerator can be used for Cherenkov type SR emission to produce powerful 2-3 ns S band microwave pulses. Section 2 of present work devoted to problem of increasing peak power of SR pulses. In the previous theoretical works it was assumed that the electron pulses with a top plate waveform are the most suitable for SR as the case of steady state generation. It is shown in this paper that an accelerating voltage and current amplitude should increase over electron pulse duration to enhance peak amplitude of microwave pulse due to nonstationary nature of SR emission. One of the effective ways to realize such pulse variation it is using self-acceleration of a short beam passing through a system of passive cavities [20].

2. Simulation of S band Superradiative Emission of 10 ns Electron Beam Moving in Periodical BWO Structure

For planning experiments on observation of S band SR emission a high current accelerator (5 kA, 500 keV, 10 ns) of Kanazawa University should be exploited. The typical voltage and current pulses waveforms are shown in Fig. 1. Presently the accelerator equipped with a cold emission cathode of 2.4 cm diameter forming a tubular electron beam. For discussed experiments cathode diameter will be increased up to 5 cm. The electron beam will be transported in homogeneous 1 T magnetic field of pulsed solenoid. Electrons moving along rectilinear trajectories will interact with synchronous spatial harmonic of backward wave propagating in a periodical waveguide. The synchronism condition can be presented in the from

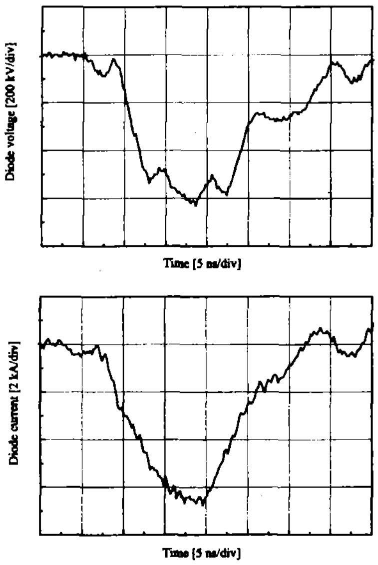

Fig. 1 Voltage and current waveforms

$$\omega = \left(-h + h_c\right)V_0, \qquad (1)$$

where ω and h are the wave frequency and longitudinal wave number of fundamental harmonic respectively, $h_c = 2\pi/\lambda_c$, and λ_c is the corrugation period, $V_0 = \beta_0 c$ is the electron velocity.

Dispersion diagram presented in Fig. 2 demonstrates that radiation frequency of 4.6 GHz (S band) is expected for electron energy of 500 keV and the corrugation period of 3 cm and mean waveguide diameter of 3.2 cm.

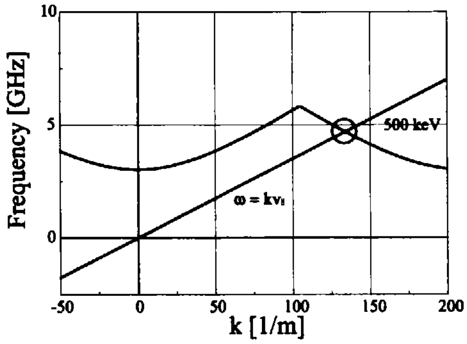

Fig 2 Dispersion diagram

Because emitted wave has negative group velocity under condition (1), cut-off narrowing should be used at cathode side of slow-wave structure to reflect wave in the positive direction where output window is installed. Meander-like corrugation should be performed using set of rings of variable internal diameter. The depth of corrugation is about 0.6 cm. At the right end corrugation depth decreases adiabatically for matching with output waveguide.

Simulation of S band superradiatiative emission of 10 nanosecond electron beam passing through the periodic waveguide structures was carried out using the particle in cell code KARAT. The number of macroparticles involved in the simulation was about 5000. The mesh used consisted of 100x1200 points.

The system geometry (all sizes in centimeters) and the positions of electrons 5 ns after the beam injection are shown in Fig. 3. The piecewise approximation was used to describe the voltage pulse with total duration 12 ns. Note that we used a model with self-consistent emission that includes simulation of electron beam formation. In the example presented the peak current was 4 kA. The phase planes (p_z, z) (Fig. 4) show a development of modulation of the electron longitudinal momentum. This modulation results in visible modulation of bunch density (Fig. 3) at moment of time 5 ns. The dependence of RF output power on time is presented in Fig. 5a. The main spike of peak power 400 MW corresponds to the expected backward wave emission. Its central frequency of 4.6 GHz (see, the spectrum in Fig. 5b) corresponds to the frequency that can be found from the synchronism condition (1).

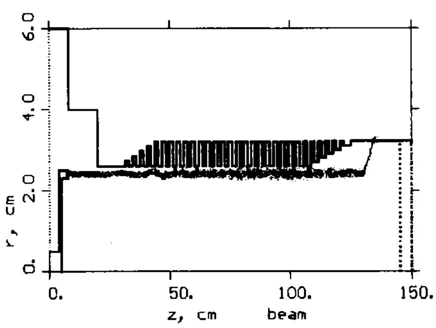

Fig. 3 Geometry of interaction space and positions of electrons at time t = 5 ns

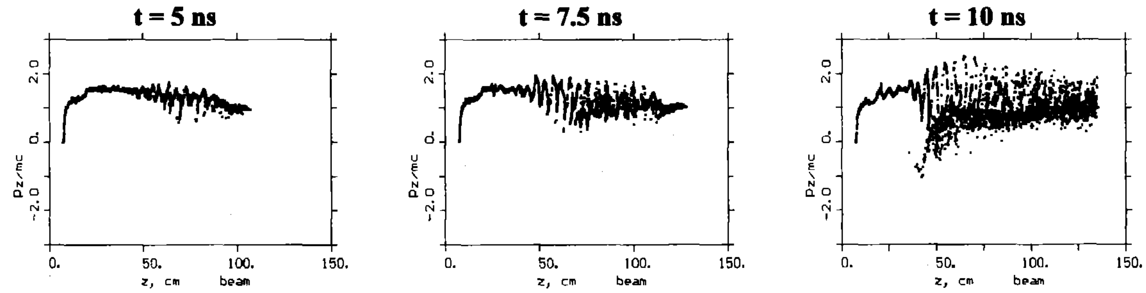

Fig 4 Evolution of positions of electrons at phase plane (p_z, z)

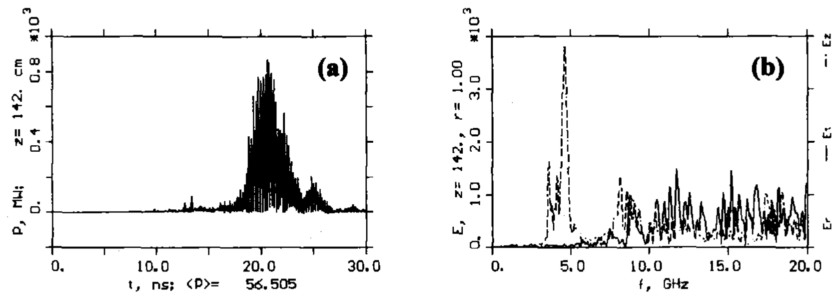

Fig 5a Microwave pulse (a) and its spectrum (b)

3. Increasing of peak power of superradiation pulse by variation of acceleration voltage and current amplitude

In the previous theoretical works [4-12] it was assumed that the electron pulses with a top plate waveform are the most suitable for SR (similar to the case of steady state generation). It is shown in this section that due to nonstationary nature of SR emission to enhance peak amplitude of microwave pulse an accelerating voltage should change over electron pulse duration. In the case of SR from an electron bunch moving through a periodical slow-wave structure and interacting with backward wave, a mechanism of this enhancement can be explained by following way. When a short SR pulse occurs inside interaction space and propagates towards a gun side, it is appropriate to feed this pulse by electrons with longitudinal velocities more and more exceeding phase velocity of the wave. Due to increasing in time SR pulse amplitude, the SR pulse can effectively extract energy from electrons with velocities strongly different from a synchronous value. Based on average time-domain model and PIC code simulations it is shown that optimization of profile of voltage and current pulses provides possibility for increasing peak power of SR pulses in several times.

We start consideration with a model based on equation for wave amplitude and averaged motion equations of relativistic electrons. The longitudinal electric field of the synchronous wave can be presented in the form

$$E_z = Re\left[E_z^s(\mathbf{r}_\perp)A(z,t)exp(i\omega(t - z/V_0))\right]$$

where $E_z^s(\mathbf{r}_\perp)$ describes the transverse distribution and $A(z,t)$ describes a temporal evolution of the longitudinal distribution. The interaction of the electrons with radiation can be described by the following equations

$$\frac{\partial a}{\partial \tau} - \frac{\partial a}{\partial \zeta} = -f(\tau)\frac{GI}{\pi}\int_0^{2\pi} e^{-i\theta} d\theta_0 \qquad (2)$$

$$\frac{\partial \theta}{\partial \zeta} = \frac{1}{\sqrt{1-\gamma^{-2}}} - \frac{1}{\sqrt{1-\gamma_0^{-2}}} \qquad (3)$$

$$\frac{\partial \gamma}{\partial \zeta} = Re\left(a(\zeta,\tau)e^{i\theta}\right). \qquad (4)$$

Here we are using dimensionless variables:

$a = eE_z^s(r_b)A/(mc\omega)$, $\tau = \omega(t - z/V_0)(1/\beta_0 + 1/\beta_{gr})^{-1}$, $\zeta = \omega z/c$, $\theta = \omega t - h_s z$ is the electron phase with respect to the synchronous wave, $h_s = hc - h$, $G = Zc/2\beta_0^2$, Z is the coupling impedance of the TM_{01} mode, $I = eJ_0/mc^3$, J_0 is the electron current, $\gamma = \left(1-\beta_0^2\right)^{-1/2}$ is relativistic mass factor, $V_{gr} = \beta_{gr}c$ is the electromagnetic wave group velocity. The function $f(\tau)$ describes the unperturbed electron density $f(\tau) = 1, \tau \in [0,T]$, where T is the dimensionless duration of the electron bunch.

$$T_e = \omega t_{e.pulse}\left(1/\beta_0 + 1/\beta_{gr}\right)^{-1}. \qquad (5)$$

When emission start up related with electron density fluctuations, it is described by parameter q<<1 and the boundary conditions can be presented in the form

$$\theta|_{\zeta=0} = \theta_0 + q\cos\theta_0, \theta_0 \in [0,2\pi], \gamma|_{\zeta=0} = \gamma_0$$
$$a|_{\zeta=L} = 0, a|_{\tau=0} = 0 \qquad (6)$$

where $L = \omega l/c$ is the dimensionless length of the interaction region.

Peak power of radiation can be defined as

$$P = \frac{m^2c^5}{e^2}\frac{|a|^2}{4G} \qquad (7)$$

In fig. 6, temporal dependence of radiation power in the case of voltage and current pulses of constant amplitude (top plate pulses) is shown by curve 1. Curve 2 corresponds to the situation when accelerating pulse amplitude grows from 300 keV to 900 keV. Curve 3 correponds to the case when electron current also grows in time from 4 kA to 12 kA. We see that for the last case a peak power of SR pulse increases in 2 times in comparison with SR pulse generating from top plate electron pulse with current 8 kA and electron energy 600 keV. Note that total energy in the both electron pulses is approximately the same. It is also seen that optimization of driving electron pulse results in shortening of microwave pulse.

In Fig. 7 it is presented that instant efficiency of energy extraction $\eta = 1 - <\gamma>/\gamma_0$ in the case of top plate and optimal electron pulses. We see that efficiency increases in the case of variable accelerating voltage. It is resulted in even more remarkable increase of SR pulse amplitude because higher efficiency corresponds to part of electon pulse with higher current.

Fig. 8 demonstrates evolution over Z axis position of electons at phase plane (γ, θ) for electon fraction injected at τ = 25. We see that the most of electons are decelerated at the end of interaction space.

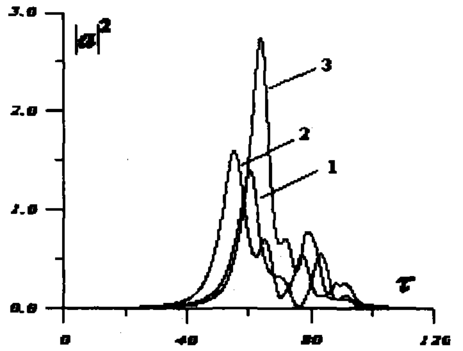

Fig. 6 Dependence of normalized radiation power on time for rectangle electron pulse curve 1, for electron pulse with only voltage variation curve 2, for pulse with variable both voltage and current curve3.

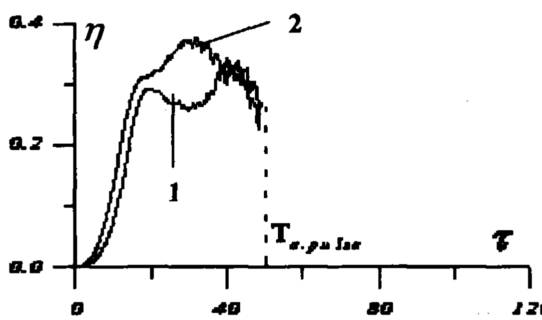

Fig. 7 instant efficiency of energy extraction in the case of rectangle (curve 1) and optimal (curve2) electron pulses

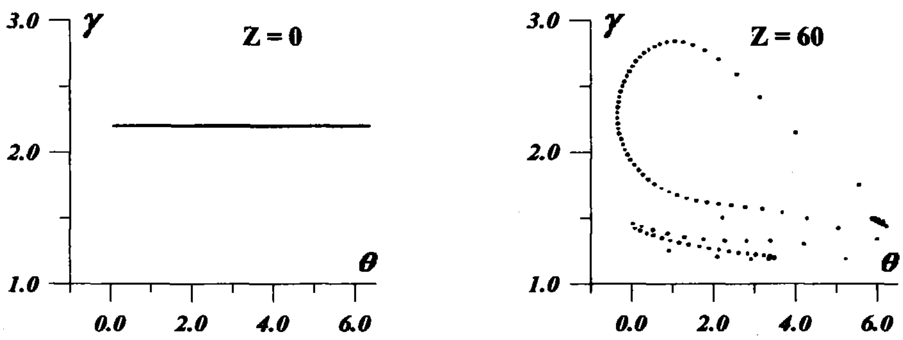

Fig. 8 Evolution of phase plane for electron fraction injected at time τ = 25

4. PIC code simulation of SR from electron pulse with variable voltage and current

The results on enhancement of amplitude of SR pulse obtained in the frame of the model based on averaged equations agree with result of PIC code simulation. In this Section in difference with Sect. 2 we consider simple model that not includes beam formation. In Fig. 10a SR pulse presented in the case of voltage and current pulse variation corresponding to Fig. 1. Maximal power amounts 4 GW for average power of electron beam 4.8 GW that corresponds to instant efficiency > 80%. For comparison, Fig. 10b corresponds to SR pulse emitted by top plate electron pulse with mean voltage 6 kV and current 8 kA (the kinetic energy in such a beam equal to optimal one). We see that the gain in the SR pulse peak power exceeds factor of 2. It is also observed that pulse became much shorter than in the case of top plate electron beam. The pulse duration at the half of pulse amplitude is less then 1.5 ns. In Fig. 12 shown dependence on time several electrons injected in consecutive moments. We see that the most of electrons are decelerated in the case of the pulse of optimal waveform.

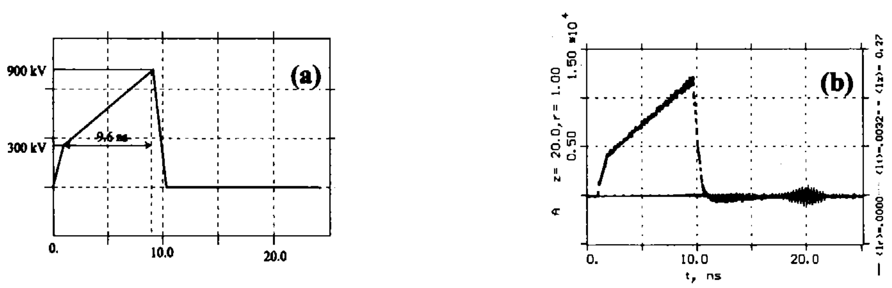

Fig. 9 Optimal accelerating voltage (a) and current (b) pulse profiles

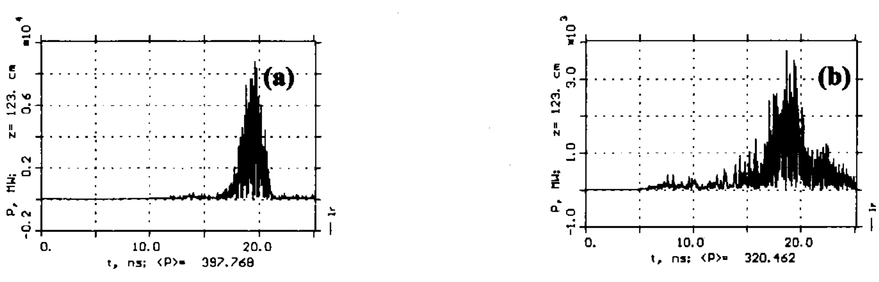

Fig. 10 (a) SR pulse for the case of optimal electron pulse
(b) SR pulse for the case of rectangle electron pulse with the same energy

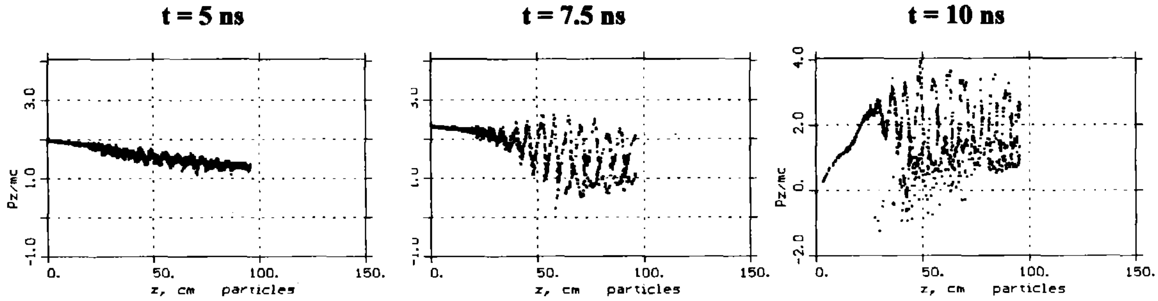

Fig 11 Evolution of positions of electrons at phase plane (p_z, z) in the case of optimal electron pulse

5. Conclusion

Modeling carried out in this paper demonstrates possibility of generation of gigawatt power level S band microwave pulse with duration of several nanoseconds using superradiation of short electron beam moving along slow-wave periodical structure. A 10 ns. 500 keV, 5 kA accelerator of Kanazawa University can be used in such experiments. It is shown that significant increasing peak power can be obtained by optimization of voltage and current waveforms. Note that required increasing of electron energy and current by the end of electron pulse can be achieved by using self-acceleration of a short beam passing through a system of passive cavities [20].

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