# GENERATION OF SUPERRADIANT PULSES BY BACKSCATTERING OF PUMPING WAVE ON THE INTENSE ELECTRON BUNCH*

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*Abstract*

At the first time the generation of superradiance pulses in the process of stimulated backscattering of powerful pump wave by intense electron bunch (250 keV, 1 кA, 600 ps) has been observed experimentally. Using a relativistic 38 GHz BWO as a pump wave source, the short 200 ps superradiance pulses of scattered radiation with peak power ~1 MW were obtained. Due to the Doppler up-shift, in the spectrum of scattered radiation high frequency 150 GHz component was presented

## INTRODUCTION

Recently a significant progress was achieved in the generation of subnanosecond pulses in the millimeter and centimeter wave bands utilizing the cyclotron and Cherenkov mechanisms of superradiance (SR) of electron bunches [1-3]. The maximal peak power in the case of Cherenkov SR exceeded gigawatt level [3]. This paper is devoted to the novel mechanism of superradiance in the case of the stimulated backscattering of powerful pump wave by intense electron bunch. In this situation, due to the Doppler up-shift effect the radiation frequency can significantly exceed the frequency of the pump wave:

$$\omega_s = \omega_i \frac{1+V_{||}/V_{ph.i}}{1-V_{||}/V_{ph.s}}, \tag{1}$$

where $V_{||}$ is the translational electron velocity, $V_{ph.i,s}$ are the phase velocities of the pump wave (index *i*) and the scattered wave (index *s*). If the radiation of powerful laser undergoes backscattering at the electron beam with energy about 1-2 MeV the frequency of scattered radiation will belong to ultraviolet band. In the case when the pump wave is generated by relativistic microwave generator (for example BWO) it is possible to produce radiation at the short millimeter and submillimeter wave bands. In this paper we present a basic theoretical description of the superradiance regime of stimulated backscattering. The results of theoretical consideration are confirmed by the first experimental observation of above SR mechanism.

## BASIC MODEL

Let us consider the backscattering of the powerful pump wave by the hollow electron bunch with injection radius $R_b$ and duration $\Delta t_b$ that moves through a cylindrical waveguide with radius $R$ along homogeneous guiding magnetic field $\mathbf{H_0} = H_0 \mathbf{z_0}$. Under assumption of the fixed pump wave amplitude, the generation of short single pulse of scattered radiation (SR pulse) can be described by the nonstationary equation for scattering signal amplitude $A_s$ and the averaged equations for electrons' motion in the field of combination wave:

$$\begin{gathered}\frac{\partial a_s}{\partial \zeta} + \frac{\partial a_s}{\partial \tau} = i f(\tau) a_i g \frac{I}{\pi}\int_0^{2\pi} e^{-i\theta} d\theta_0 \\ \frac{\partial^2 \theta}{\partial \zeta^2} = \mu\, Im\left\{a_s a_i\, g e^{-i\theta}\right\}\end{gathered}. \tag{2}$$

Here $\zeta = \omega_c z/c$, $\tau = \omega_c c\left(t - z/V_{||}\right)\left(1/V_{gr} - 1/V_{||}\right)^{-1}$, $a_{i,s} = eA_{i,s}/2m_0\gamma c^2$ are the dimensionless amplitudes of pump and scattered waves, $\theta = \omega_c t - k_c z$ is the electrons phase with respect to the combination wave, $\omega_c = \omega_s - \omega_i$, $k_c = h_s + h_i$, $h_{i,s}$ are the longitudinal pump and scattered wave numbers, $\mu = \gamma_0^{-2}\beta_{||}^{-3}$, $I = \left(eJ_0/mc^3\right)\cdot\left(2\gamma_0 h_s k_c R^2 N_s\right)^{-1}$, $J_0$ is the electron current, $N_s$ is the norm of the scattered wave. Factor

$$g = J_{n_i-1}\left(k_{\perp i}R_b\right)J_{n_s-1}\left(k_{\perp s}R_b\right)\Omega/\left(\Omega-\omega_H\right) \tag{3}$$

describes the increase of oscillation velocity of electrons near the cyclotron resonance, $\omega_H = eH_0/m_0 c\gamma_0$ is the gyrofrequency, $\Omega = \omega_i + h_i V_{||}$ is the bounce frequency, $k_{\perp i,s}$ is the transverse wave number, $J_n(x)$ is the Bessel function, $n_{i,s}$ are the azimuth indices of the waveguide modes. Function $f(\tau)$ defines the profile of electron current with normalized duration $\tau_b = \Delta t_b \omega_c c\left(1/V_{gr} - 1/V_{||}\right)^{-1}$.

Equations (2) describe the joint combinational action of the pump and the scattered waves on the electrons. Such an action leads to selfbunching that starts from small initial density perturbations. As a result the amplitude of scattered wave grows. In the absence of external feedback the synchronization of radiation from different parts of extended electron bunch is provided by slippage of the scattered wave with respect to electrons due to a difference between the electron velocity and the electromagnetic wave group velocity. As a result the scattered wave radiates in the form of a single short pulse, as is shown in Fig.1. The parameters of simulation are chosen in accordance with the performed experiment. The pump wave with 100 MW power and 38 GHz frequency has the transverse structure of the $TE_{11}$ mode. This wave

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undergoes the backscattering by the 250 keV, 1 kA, 200 ps electron bunch guided in 24 kG magnetic field. According to the simulation the duration of the scattered SR pulse is about 50 ps with peak power ~25 MW. According to waveguide dispersion the scattered wave frequency should be about 150 GHz.

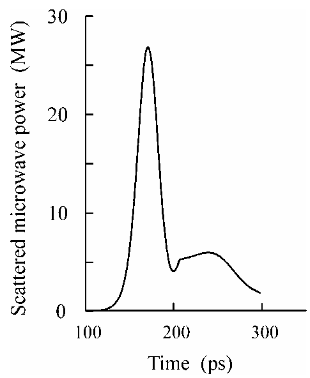


Figure 1: Superradiance pulse of scattered radiation.

## KARAT PIC-CODE SIMULATIONS

The possibility of the observation SR in the process of backscattering has been tested also using the particle-in-cell (PIC) code KARAT. In simulation we used the simplified two-dimensional axial symmetric model of the scattering. The pump wave with frequency 38 GHz and power 100 MW represents the $TE_{01}$ wave in contrast to the experimental situation. The guiding magnetic field was 28 kG.

As it is seen from Fig.2 scattered radiation has the form of the short pulse with the duration less than 100-200 ps and peak power about 3 MW. The radiation spectrum has a component with frequency about 150 GHz.

Nevertheless the spectrum of radiation is rather wide. It may be explained by the dispersion of electron velocities as well as by excitation of several waveguide modes. Above factors also may result to the reduction of the peak power in comparison with the model described above.

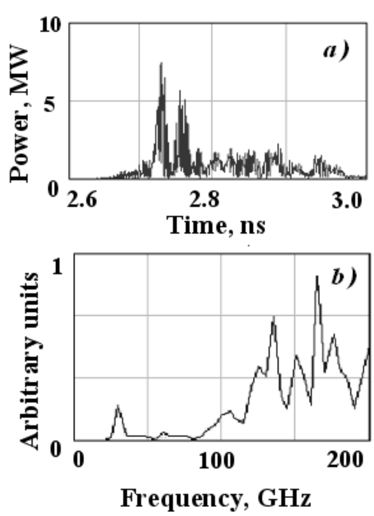


Figure 2: Results of KARAT PIC code simulations: (a) scattered SR pulse, (b) spectrum of SR pulse

## EXPERIMENTAL SET-UP

Experiments on the observation of the stimulated backscattering in the superradiance regime were carried out at Institute of Electrophysics (Ekaterinburg, Russia) based on two synchronized nanosecond and subnanosecond high-current RADAN-303 accelerators [4-5]. The 4 ns electron beam from the first accelerator was used to drive the low frequency pump wave generator. The pump wave undergoes backscattering with frequency up-conversion on the subnanosecond electron bunch produced by the second accelerator. The general view of experimental set-up is shown in Fig.3.

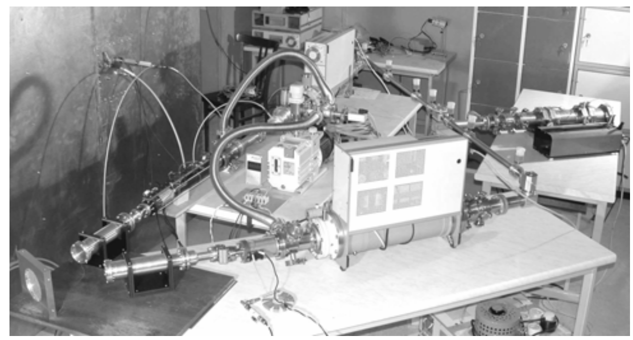

Figure 3: Experimental set-up

In experiments the pump wave was generated by relativistic BWO with operating frequency 38 GHz. For transmission of the pump wave to the scattering section a specially designed quasioptical mirror has been used. The mirror possessed the high reflectivity 95% at the pump wave frequency 38 GHz. The partial transparency of the mirror for the scattered radiation at frequencies above 60 GHz was provided by the mesh of holes with diameter of 3 mm having a step of 4 mm.

## EXPERIMENTAL RESULTS

Oscilloscope trace of the 4 ns, 100 MW pump wave pulse with duration is shown in Fig.4a. In absence of subnanosecond electron bunch, the signal from BWO registered by detector installed after quasioptical mirror is shown in Fig.4b. This signal is caused by parasitic high-frequency radiation from the pump wave generator at the harmonics of operating frequency. Presence of such harmonics in a spectrum of the pump wave is confirmed by the direct simulation based on PIC-code KARAT.

In the scattering section with 30 cm length the low frequency pump wave underwent stimulated backscattering by the high current relativistic subnanosecond bunch (250 keV, 1 кA, 600 ps). It is important to note that in absence of the pump wave the background noise radiation of electron bunch was below the threshold sensitivity of a microwave detector. When the pump wave generator was switched on, the short powerful pulse could be observed, as is shown in Fig.4c. This pulse has rather short duration (about 200 ps) and can be interpreted as a superradiance pulse. SR pulses were observed in a large area of magnetic field detuning.

The maximal peak power was obtained for field strength 20-25 kG when the magnetic field strongly affects the amplitude of electron oscillations.

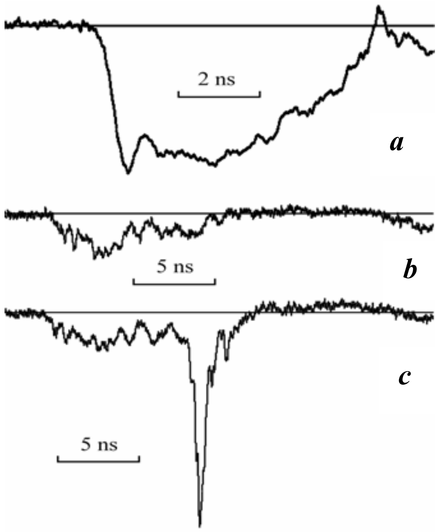


Figure 4: (a) Pulse of the pump wave. (b) High frequency component of BWO radiation in the absence of electron e-bunch registered by detector after quasioptical mirror. (c) Superradiance pulse caused by backscattering of pump wave by electron bunch.

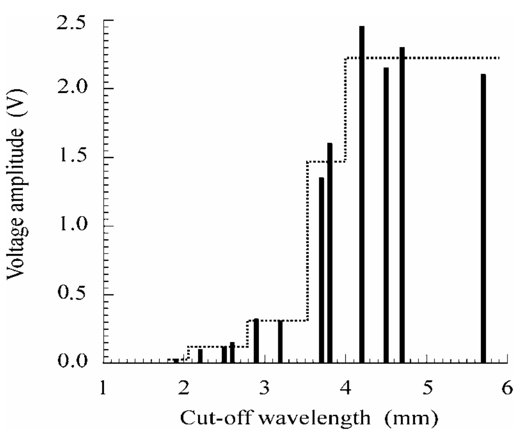


Figure 5: Spectrum measurements. Relative amplitudes of detector signal after filters with different cut-off frequencies.

To analyze the radiation spectrum a set of cut-off waveguides was used. Amplitudes of detector signals after filters with different cut-off frequencies are shown in Fig.5. Locations of vertical lines correspond to the cut-off wavelengths of different filters and the lengths of lines are proportional to the signals registered by the detector. Obviously the jumps of dashed line characterize the content of different spectrum components in the scattered radiation. The main components of radiation concentrate at the interval within wavelength $3.5 \div 4.2$ mm. But at the same time there are high frequency components with wavelength around 2 mm, which is rather close to the calculated one. However it should be noted that detector sensitivity decreases with frequency. So the real fall of intensity of high frequency components should be less than detector indications shown in Fig.4. A rather wide spectrum of scattered radiation can be explained by the spread of electron velocities in the real electron bunch as well as by excitation of several waveguide modes. Integral (over frequency spectrum) peak power of SR pulse amounts up to 1 MW. It was estimated basing on the power level indicated by microwave detector taking into account the aperture of the reception antenna, the distance from a radiator and the width of the radiation pattern.

## CONCLUSION

As a result of the experiments the effect of generation of short electromagnetic pulses was observed in the process of stimulated backscattering of the powerful pump wave by the intense electron bunch. Scattered radiation had the form of ultrashort pulse with peak power of 1 MW and duration of 200 ps. Due to the Doppler frequency up-conversion the spectrum of scattered radiation included the frequencies up to 150 GHz that exceeded the pump wave frequency in several times. This process can be interpreted as a superradiance of electron bunch since the radiation of the short pulse occurs in the absence of external high frequency signal and in the absence of external cavity and correspondingly cannot be attributed to traditional amplification or oscillation regimes. Due to the development of selfbunching inside the extended electron bunch the peak power of scattered signal significantly exceeds the power of the spontaneous radiation of electrons in the pump wave and the duration of scattered pulse was essentially shorter than the duration of the background noise.

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