Phase-Imposing Initiation of Cherenkov Superradiance Emission by an Ultrashort-Seed Microwave Pulse

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For the first time, we demonstrate experimentally the possibility of Cherenkov superradiant generation with a phase imposed by an ultrashort seed microwave pulse. The phases of seed and initiated Ka-band microwave pulses were correlated with the accuracy of 0.5–0.7 rad for the power ratio down to −35 dB. Characteristics of such a process were determined in the frame of a basic theoretical model that describes both spontaneous and stimulated emission of an electron beam moving in corrugated waveguides. The obtained results open up opportunities of reaching extremely high radiation power density in phased arrays of short-pulse coherently operating microwave generators.

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In recent years, significant progress has been achieved in the generation of high-power ultrashort microwave pulses based on Cherenkov superradiance (SR) of extended electron bunches moving in periodic slow-wave structures (SWS) and interacting with a backward propagating wave [1–3]. With the use of this effect, new types of microwave sources have been developed which are capable of producing uniquely short ($T_{SR} \sim 0.2$–1 ns) electromagnetic pulses at the record peak power level up to 2–3 GW in the centimeter and millimeter wave bands. A promising direction for further significant enhancement of the intensity of pulsed radiation is associated with the coherent summation of the output signals from multiple SR sources.

At the present time, coherent combining of high-power microwave sources is developed extensively [4–8]. The conventional approach to achieve this goal is based on the use of a master oscillator, which determines both the generation frequency and the phases of slave sources [9]. This method is applicable for the case of a relatively long-pulse and steady-state generation. However, in the case of ultrashort SR pulses, it is possible to avoid frequency locking if the parameters of microwave structures and electron bunches coincide with sufficient accuracy so that the frequency difference $\Delta\omega$ between independent SR channels satisfies the condition

$$\Delta\omega \ll 1/T_{SR}. \tag{1}$$

Nevertheless, there is one more critical requirement for the coherent combining of independent microwave sources. It is the in-phase start-up that can be provided by a seed signal at a frequency close to the frequency of the free-running (autonomous) regime of SR generation. In the case of superradiance, the spontaneous emission of electron bunch sharp edges can be used as such a signal. This method has been successfully tested in experiments with X-band and Ka-band SR emission [10,11] where, to achieve acceptable similarity of current pulses, a single pulse from a high-voltage driver [12,13] was split into 2 or 4 channels. As a result, the coherent summation of superradiant emission was obtained with respective fourfold and 16-fold radiation intensity gains in the maximum of the interference diagram. In the Ka band, it allowed us to reach an extremely high intensity of the generated electromagnetic field equivalent to the radiation from a single source with the power of 10 GW [11].

Meanwhile, the state of the art in the development of high-voltage drivers with a subterawatt power level [14] opens up the prospects for a drastic increase in the number N of combined SR channels and, correspondingly, in the microwave power flux density which is proportional to N^2. However, for $N > 4$, sequential splitting of a primary voltage pulse leads to the loss of the pulse front steepness due to dispersion effects in branch points. As a result, the intensity of emission from the electron bunch leading edge decreases and becomes insufficient to provide excess over the noise level. In such a situation, the in-phase start-up of multiple SR generators can be provided by ultrashort external electromagnetic seed pulses injected synchronously into the interaction spaces of the combined sources. Actually, a seed pulse substitutes the impact of spontaneous emission from the leading edge of an electron bunch used in Refs. [10,11].

In this Letter, based on a simple theoretical model, we analyze Cherenkov SR emission with a phase imposed by a seed electromagnetic pulse. For such seed pulses, we determine the intensity sufficient to suppress the influence of the noise emission caused by electron density fluctuations and the bunch edges. The results of the theoretical analysis are confirmed in experiments, where Ka-band subgigawatt SR pulses with an imposed phase have been obtained for the first time.

We begin our analysis with the inclusion of an external seed pulse into the theoretical model developed in Ref. [11] that describes Cherenkov spontaneous emission from the current pulse edges and the density fluctuations as well as the stimulated emission caused by electrons self-bunching. We assume that an electron bunch with a length $l_b \gg \lambda$ moves with a longitudinal velocity $v_0 = \beta_0 c$ in a planar waveguide with the gap between the walls b_0 and periodic corrugation $b(z) = b_1 \sin \bar{h}z$, where $\bar{h} = 2\pi/d$, b_1 and d are the corrugation amplitude and period. The phase imposition is carried out near the SWS input, where the seed pulse slightly modulates the electron density and, after that, leaves the interaction space (Fig. 1). Under the assumption of weak corrugation ($b_1 \ll d$), the structure of both external and radiated electromagnetic fields in the considered model is close to the TEM mode of a regular planar waveguide. Yet the presence of corrugation leads to the appearance of a small longitudinal component of the electric field $E_z = -\bar{h}b_1 \cos(\bar{h}z)E_x$, due to which the interaction of electrons through their radiation occurs.

To describe the development of self-bunching and consequent emission of a powerful superradiant pulse, we represent the electron bunch as a set of macroparticles with current $J_i = \sigma_i \delta[t - (z - z_i)/v_0]$, where z_i is the initial position of the ith macroparticle, σ_i is its linear charge density, and $\delta(x)$ is the Dirac delta function. In new independent variables $\xi = z - v_0 t$, $\tau = t$, after averaging in τ, the electrons' motion equations can be written in the form (see Ref. [11] for details)

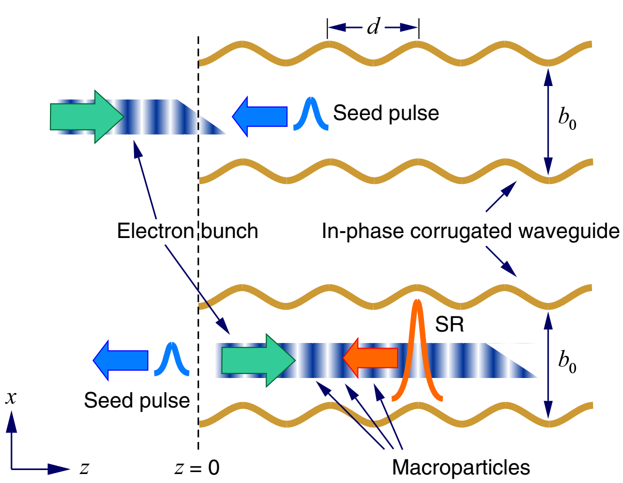

FIG. 1. Schematic of initiation of Cherenkov SR emission by an external microwave pulse.

$$\frac{dp_i(\tau)}{d\tau} = \sum_{j\neq i} F_{z,j}(\xi_i(\tau) - \xi_j(\tau - \tilde{\tau}_{ji})) + F_z^{\text{ext}}[\xi_i(\tau), \tau],$$
$$\frac{d\xi_i(\tau)}{d\tau} = \frac{p_i(\tau)}{m\gamma_i(\tau)} - v_0. \quad (2)$$

Here,

$$F_{z,j}(\xi) = -\frac{\pi e\omega \bar{h} b_1^2 |\sigma_j|}{cb_0} \cos\left(\frac{\omega\xi}{v_0}\right), \qquad \xi < 0 \quad (3)$$

is the average longitudinal force with which the ith macroparticle acts on other macroparticles via a wave with the frequency $\omega = \bar{h}v_0/(1+\beta_0)$ radiated in the $-z$ direction, $\tilde{\tau}_{ji}$ is the wave propagation delay from the jth electron at the position of the ith electron,

$$F_z^{\text{ext}}(\tau,\xi) = \frac{e\bar{h}b_1}{2} E_0\left((1+\beta_0)\tau + \frac{\xi - \xi_0}{c}\right)\cos\varphi(\xi,\tau) \quad (4)$$

is the external longitudinal average force created by a seed pulse with an envelope $E_0(t)$ and a carrier frequency ω_0, where $\varphi(\xi,\tau) = \varphi_0 - \omega\xi/v_0 + \Delta\omega(1+\beta_0)\tau + \Delta\omega\xi/c$, ξ_0 is the initial position of the pulse leading front, φ_0 is the initial phase, and $\Delta\omega = \omega_0 - \omega$. The electromagnetic field radiated by the whole bunch can be found as a sum of the fields from macroparticles which have entered the interaction space

$$E_x(\tau,\xi) = \frac{2\pi b_1 \omega}{cb_0} \sum_i \sigma_i \cos\left[\bar{h}v_0\tau + \omega\left(\frac{\xi}{c} + \frac{\xi_i(\tau - \tilde{\tau}_i)}{v_0}\right)\right]. \quad (5)$$

Initially, at $\tau = 0$, all macroparticles have the same longitudinal momenta corresponding to v_0 and are distributed on an interval $[-l_b; 0]$ with the averaged density profile $\sigma_0(\xi)$ and small fluctuations determined by parameter $r_0 \ll 1$,

$$\sigma_i = \sigma_0(\xi_i)(1 + r_0 u_i), \quad (6)$$

where $u_i \in [-1, 1]$ are random numbers.

Based on Eqs. (2) and (5), simulations of superradiant emission were carried out for physical parameters close to the parameters of the experiments: the electron energy of 250 keV, the gap between the waveguide plates of 0.2 cm, corrugation with the period of 0.33 cm and the amplitude of 0.013 cm, and the operating frequency of 37 GHz. The current pulse had the trapezoidal density profile $\sigma_0(\xi)$ with the duration of the flat part of 1.4 ns, fronts of 300 ps, and the maximum line current density of 850 A/cm. In Fig. 2, the results of the simulations are presented for the ratio of the peak power of a seed pulse P_1 to the power of a free-running SR pulse P_2 of 0.1 and the frequency of the

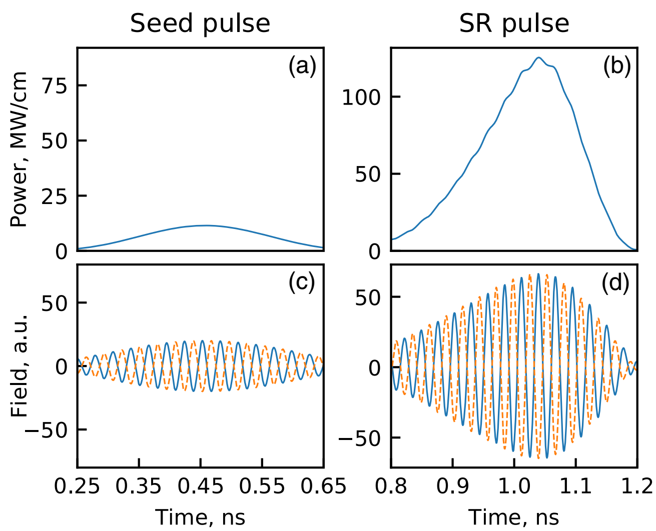

FIG. 2. Results of simulations based on Eqs. (2), (5) with parameters close to the experimental ones. Averaged temporal profiles of the seed (a) and initiated superradiant (b) pulses. Instantaneous field amplitudes for two seed pulses (c) with initial phases of 0 (solid line) and π (dashed line). Because of the phase of generation being imposed, two initiated SR pulses (d) also reproduce the phase difference of π.

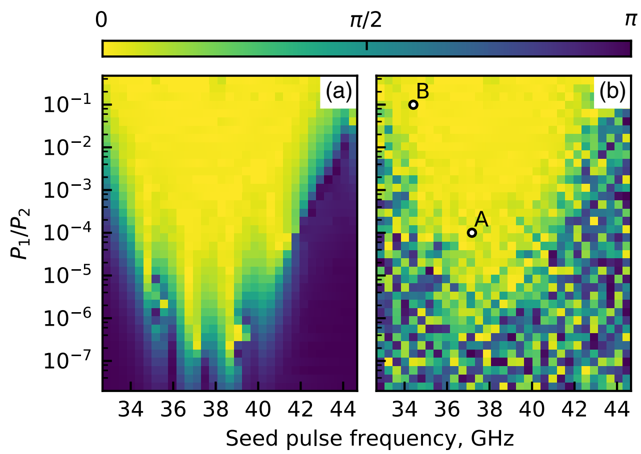

FIG. 3. Zones of SR emission with the imposed phase without (a) and with (b) current fluctuations ($r_0 = 0.05$). For each pair of the seed pulse frequency and the power ratio between the seed and the SR pulses on the diagrams, we calculate the absolute deviation from π of the phase shift between two SR pulses initiated by two seed pulses with the phase difference of π. Phase imposition occurs in the light (yellow) areas and is absent in the dark (blue) areas.

seed pulse of 34.5 GHz that corresponds to the experimental situation (see below). Temporal profiles of the 300 ps bell-shaped seed and initiated SR pulses are shown in Figs. 2(a) and 2(b), respectively. The seed pulse met the electron bunch near the SWS entrance as shown in Fig. 1. To demonstrate the possibility of phase imposition, we simulated the process of SR initiation by two seed pulses with the same peak power but with the relative phase difference of π [solid and dashed lines in Fig. 2(c)]. Because of the phase imposition, two initiated SR pulses plotted by solid and dashed lines in Fig. 2(d) reproduce the same phase difference.

Simulations show that this effect can be achieved for rather weak seed signals in the wide frequency band if the intensity of the corresponding spectral component of the seed pulse is sufficient to suppress the influence of noise and radiation from the bunch leading edge. For chosen parameters, in the absence of current fluctuations, the minimally sufficient peak power of a seed pulse can be at the level of 10^{-5}–10^{-6} from the peak power of free-running generation [Fig. 3(a)]. In the presence of fluctuations, the zone of SR generation with the imposed phase is lifted towards the area with larger values of P_1/P_2. For a noise level $r_0 = 0.05$ [Fig. 3(b)], the robust phase imposition is achieved for the minimum power ratio $P_1/P_2 \approx 10^{-4}$ when frequency of the seed pulse is close to the free-running frequency 37 GHz [point A in Fig. 3(b)] and for $P_1/P_2 \approx 10^{-1}$–10^{-2} when this pulse has the frequency of 34.5 GHz corresponding to the experimental situation [Fig. 2 and point B in Fig. 3(b)]. Outside the zone of the phase imposition the phases of SR pulses take random values.

The principle scheme of the experimental setup used for the observation of Ka-band SR generation with the imposed phase is presented in Fig. 4. It includes two precisely synchronized high-current RADAN accelerators [15] which form nanosecond electron bunches for the seed (SR_1) and driven (SR_2) generators, respectively. Both generators possess the same cylindrical SWS with a tapering corrugation, in which tubular electron bunch transported in the guiding magnetic field of 2 T excites the backward propagating TM_{01} wave. The transmission of the

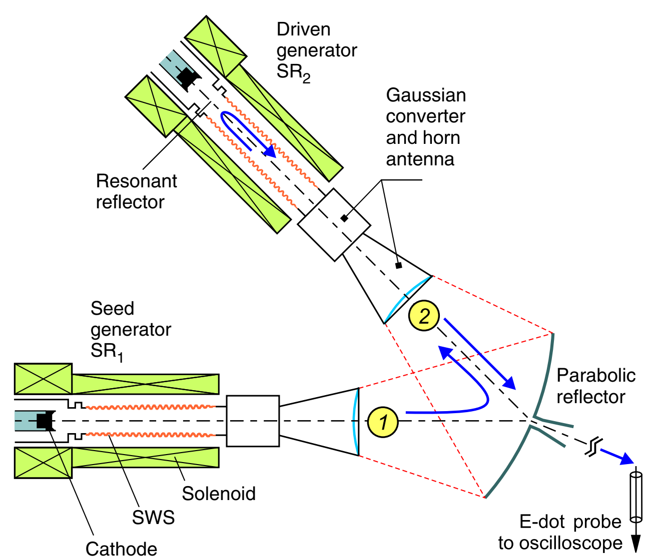

FIG. 4. Layout of the experimental setup.

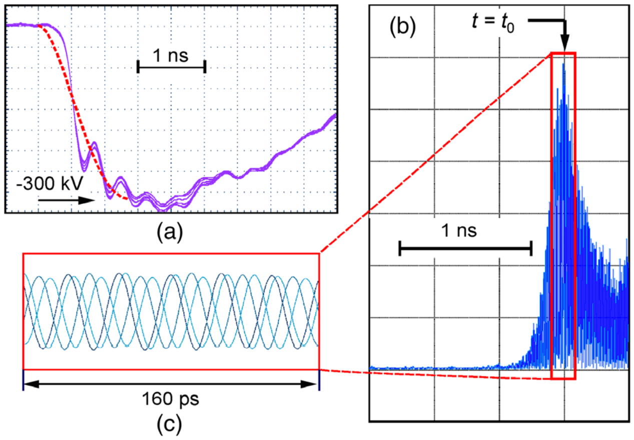

FIG. 5. Free-running regime of the second SR generator: (a) accelerating voltage pulses feeding the generator, (b) typical 0.5 GW/300 ps superradiant pulse, (c) occasional phase spread of SR pulses in several shots caused by the jitter in the amplitude of voltage pulses.

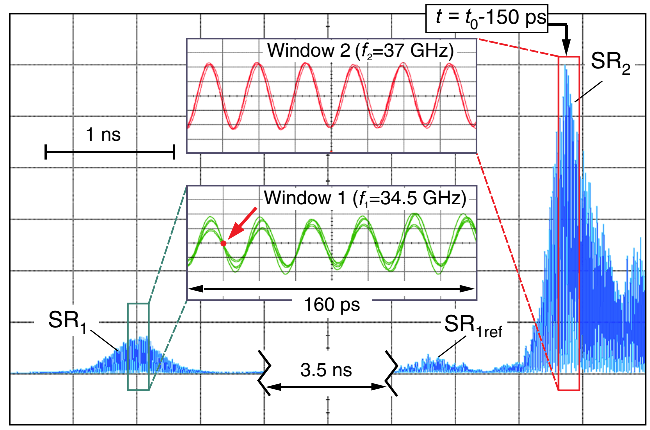

FIG. 6. Generation of SR pulses with an imposed phase: SR_1 is the seed signal, SR_{1ref} is its reflection from the driven source reflector, and SR_2 is the initiated superradiant pulse from the driven generator. Windows 1 and 2 represent zoomed microwave carrier waveforms of the SR_1 and SR_2 pulses for several sequential shots.

seed SR pulse with a power attenuation factor of 0.75 into the interaction space of the driven generator is carried out by a quasioptical system consisting of Gaussian wave-beam converters and a parabolic reflector [15]. The seed and initiated SR pulses are recorded by an E-dot probe and a wideband (59 GHz) oscilloscope, Keysight DSAZ594A, that allows us to measure the microwave carrier signal (radio-pulse) directly.

In Fig. 5(a), several stored −300 kV accelerating voltage pulses feeding the driven SR_2 generator are presented. Such pulses initiate the explosive electron emission at a graphite cathode, providing formation of electron bunches with the current of 2 kA and the rise time of ~300 ps. A typical 0.5 GW/300 ps SR pulse [2] with the central frequency of 37 GHz generated in the free-running regime is shown in Fig. 5(b). As one can see in Fig. 5(c), where zoomed oscilloscope traces for several shots are presented, the jitter in the amplitude of accelerating pulses [Fig. 5(a)] leads to the occasional phase spread in pulse-to-pulse generation.

In experiments with phase imposition, the peak power of the seed SR_1 source was deliberately reduced to −10 dB by decreasing the accelerating voltage amplitude. It was accompanied by a corresponding decrease in the generation carrier frequency to $f_1 \approx 34.5$ GHz. Signals from both the seed and driven SR sources were recorded with a delay of ~6 ns in a single oscilloscope trace (Fig. 6). Zoomed microwave carrier waveforms of the SR_1 and SR_2 pulses are presented in windows 1 and 2, respectively, for several sequential shots. For the phase correlation analysis, a certain phase of the SR_1 pulse in the first shot (shown by the arrow in window 1) was selected as a reference point, and the pulses in the subsequent shots were shifted to this position. Related shifts of the initiated SR_2 pulses stored in window 2 clearly demonstrate that the correlation between the SR_1 and SR_2 sources was better than 2–3 ps (the phase correlation is of 0.45–0.7 rad). However, in contrast with the conventional Adler's method [9], the seed pulse does not influence the frequency of the driven generator, which remains equal to the free-running one ($f_2 \approx 37$ GHz, see window 2 in Fig. 6).

One more important factor is related to the instability of the seed pulse amplitude (Fig. 6, window 1) caused by the time jitter in the synchronization between two SR generators. In fact, such jitter leads to variations in the seed pulse delay with respect to the injection of an electron bunch in the driven generator. It can be accompanied by a significant reduction of the seed pulse power at the "beam–wave meeting point" near the SWS input. Nevertheless, it does not lead to violation of the SR pulses phase correlation (Fig. 6, window 2). These observations gave grounds for additional experiments with lower power ratio between seed and driven pulses below −30 dB, which was achieved by using two aperture-type microwave absorbers installed in points 1 and 2 of the microwave quasioptical circuit (see Fig. 4). In these experiments, which were carried out for the case of relatively long 2-ns microwave pulses of the driven source (like in Ref. [15]), its phase-imposed excitation was observed at the free-running frequency for seed power attenuation as low as −35 dB, which is rather close to the threshold value of −40 dB predicted from simulations [Fig. 3(b), point A].

Thus, in this Letter, we demonstrated—both theoretically and experimentally—the feasibility of Cherenkov superradiant emission with a phase imposed by a seed ultrashort pulse. In the experiments, the correlation of phases between the seed signal and the initiated 300 ps/0.5 GW SR pulse was clearly observed for the power ratio of −10 dB, and in the case of long-pulse 2-ns generation, for the power ratio of down to −35 dB. As the seed pulse must only prevent the start-up initiated by a spontaneous emission from the current noise and bunch leading front, the power of this seed pulse can be significantly less than values following from the Adler theory [9]. Taking into account that the existing high-voltage drivers [14] are capable of feeding a large number of independent channels, generation of subgigawatt pulses with a controlled phase has significant practical importance as a key step towards the development of phased arrays producing extremely high power (subterawatt) short-pulse radiation.

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