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# Relativistic microwave oscillators with high power flux in a free space and interaction zone

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In the recent two decades, high-power microwave (HPM) generators producing short Ka-band and X-band pulses were intensively investigated (see Refs. [1–6] and citation therein). For generation of HPM pulses with duration of units of nanosecond and less influence of microwave breakdowns of electrodynamics systems, expansion of cathode and collector plasmas, and electron beam structure distortions becomes insignificant. Though the pulse duration is short, the radiating energy rises if coherent summation of radiation from several generators is provided. When the power in each channel is high, the wave beam could be formed where power flux density is limited only by breakdown strength of the media. Using approaches of the phased arrays, the directional pattern (DP) of summarized radiation could be steered. This is achievable from pulse to pulse, as well as during a single nanosecond pulse if summarized wave beams have a shifted frequencies. The related experiments with Ka-band microwave pulses are presented below.

Super-powerful microwave pulses containing about ten oscillations could be formed in the mode of Cherenkov superradiance (SR) of electron flux propagating in elongated slow-wave structure (SWS) [1]. As a result of a single-pass, high gain amplification of initial electromagnetic (EM) perturbation, the power of SR pulse may exceed the power of the driving beam [2]. This is also because of SR pulse is shorter than the electron beam (in space) and less than its propagation time throughout the entire SWS. If the interaction with following slow wave continuous, the beam energy transfer to SR occurs due to the wave-to-particles slippage [1]. For the case of counter wave (backward synchronous harmonic) SR pulse accumulates the energy from incoming “fresh” electrons [3].

Beam-to-wave power conversion factor $K = (1–1.4)$ was obtained for relativistic superradiance Ka-band backward-wave oscillators (BWOs) [1—3]. In the recent experiments [4], voltage pulses (Fig. 1; a, b) applied to explosive electron emission (EEE) cathode formed electron beams with power of ~ 2–3 GW. This was sufficient to excite a 29-GHz SR pulse (Fig. 1, c) with $K$~1. It was revealed that in the presence of high electric fields at the SWS wall ( $E \approx 2$ MV/cm) arise breakdowns. However, rf power limitation was delayed enough to ensure SR pulse passage throughout the entire SWS. Electric field of ~1 MV/cm was achieved in quasi-stationary (QS) BWO having the SWS two times shorter than SR oscillator. This QS BWO generated 2-ns pulse with power of 0.6 GW.

Figure 2 demonstrates, that both SR and QS oscillators have (from shot to shot) generation phases linked to the voltage pulse front (Fig. 1, a) at the point of maximum derivative by time. Obviously, the faster rise time of the beam current (that correlates with the voltage front steepness), the stronger a wideband, phase-imposing seed EM perturbation is formed, when the beam is injected into SWS.

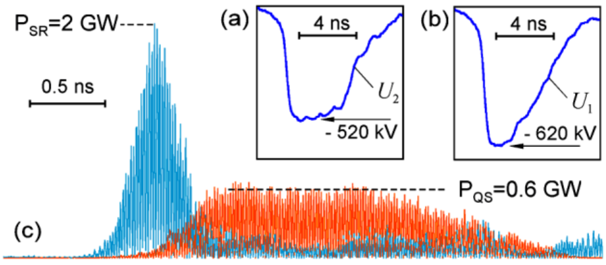

**Fig. 1.** (a, b) Voltage pulses fed e-beams with power of 2 GW and 3 GW, respectively. (c) Time referenced SR and QS pulses formed by BWOs in the case of the voltage (a)

One can see (Fig. 2) that SR oscillator demonstrates a fewer phase spread as compared to QS BWO. Apparently, this is the result of shortened “transient” time for a single-pass amplification of a seed EM signal by SR mechanism (Fig. 1, b) when initial current perturbation does not include information about the further voltage pulse form and/or its amplitude deviations. Besides, delayed achievement of the Cherenkov interaction condition is more probable for elongated SR-SWS where a seed EM perturbation comes back and meets the beam front with electrons, which already attained proper interaction energy.

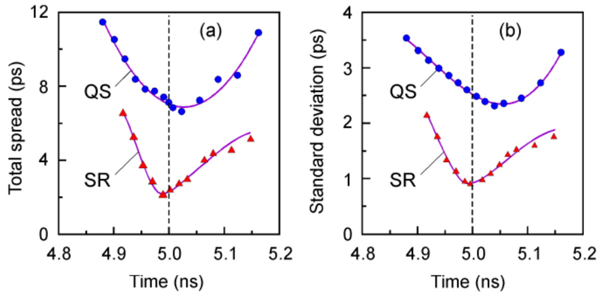

**Fig. 2.** Total phase spread (a) and corresponding standard deviation (b) for rf pulses of QS BWO and SR BWO depicted in Fig. 1 (c). Period of microwave oscillations is ~34 ps. Time “5 ns” corresponds to the maximum of time derivative of the voltage pulse front in Fig. 1 (a)

Stability of voltage pulses feeding EEE cathodes has less priority for the phase synchronization between several HPM generators. In the first place the pulses should be identical. This was proven (see, e.g., Ref. [5] and citation therein) when in-phase operation of multi-channel BWOs (X-band and Ka-band) was provided by a split of a single voltage pulse. Figure 3 (a) shows the radiation pattern of 2-D (2x2) array of 38-GHz, 0.6-GW SR BWOs. In the case of in-phased summation, power density in the pattern maximum achieves the value, which is equivalent to a single source with power of $0.6\times 4^2 \approx 10\,\text{GW}$. A 200-ps width makes SR pulses insensitive to incomplete rf breakdowns of an air near vacuum windows (Fig. 3; b, c). Rearrangement of radiator's array for quasi-stationary generation (~200 MW, 3-ns FWHM) when frequency of a certain channel is shifted [6], transfers the radiation summation into waves beating, and this blurs the radiation pattern (Fig. 3; d). With that, the power flux in the main antenna direction during a single pulse varies from zero to squared maximum as much times as it defined by the frequency detuning.

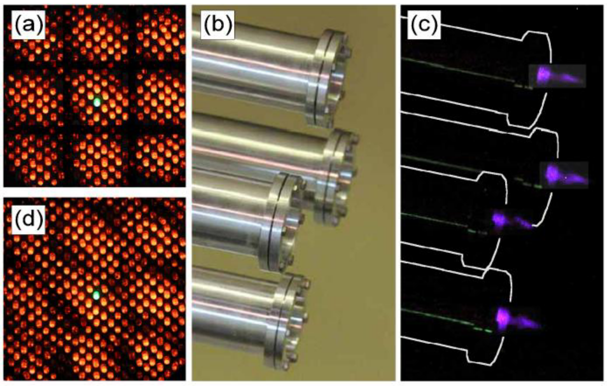

**Fig. 3.** DP of four-SR-BWO array reproduced at a single shot by a matrix neon-valve panel: in-phase operation (a); a frequency shift in one channel (d); (b) – Four horns; (c) – Breakdowns of the air near vacuum windows

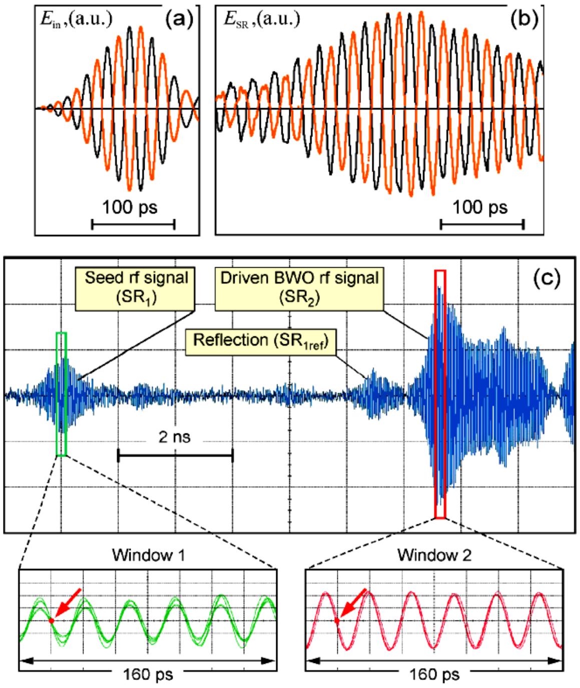

**Fig. 4.** (a) – Seed rf pulses (30 kW) with counter phases (0-black; π – orange) and (b) phased response of driving 400-MW SR pulse (PIC-simulation). (c) – Experiment on phase-imposed SR excitation by an external seed rf signal

Phase-imposing BWO excitation occurs when ultra-narrow external rf signal power-level overshoot the perturbation produced by the beam front. With that, excitation of auto-oscillator doesn't move to conventional amplification regime. Particle-in-cell simulation (Fig. 4; a, b) demonstrates such capability of phase imposing. Experiments were performed using two precisely synchronized electron accelerators RADAN [7] where SR BWO served as a master oscillator. Both quasi-stationary and superradiative Ka-band BWOs were explored in this regime as a driven oscillator. It was confirmed that phases of the seed and the initiated Ka-band pulses correlated within units of picoseconds on a time scale (Fig. 4; c) for the power ratio between them minimized down to -35 dB. It is important that driven oscillators were excited by seed signal earlier than in a free-running regime and at its own frequency regardless to the imposing frequency detuning up to 5% (compare windows #1 and #2 in Fig. 4, c).

In conclusion, the above described results demonstrate high radiation power density in the interaction space of an ultra-short-pulse oscillators as well as steering the pattern of coherently operating HPM generators.

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