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Design and experimental testing of W-band planar surface-wave oscillator driven by sheet high-current relativistic electron beam

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Abstract. The paper presents the results of theoretical and experimental studies of W-band planar surface-wave oscillator driven by sheet high-current relativistic electron beam with experimentally realized parameters on the basis of the "SINUKI" accelerator (IAP RAS, N. Novgorod, 1 kA / 650 keV / 17 ns). In simulation of the oscillator nonlinear dynamics, we used both advanced quasi-optical approach and direct 3D PIC modeling. In the experiment, the microwave generation with a frequency of about 75 GHz was registered by microwave detector; measured pulse duration was about 4 ns. The output power measured by the calorimetric method was about 25 MW which is in a satisfactory agreement with the theoretical predictions. The important specific of the experimental set-up is the use of highly efficient side wall absorber for the implementation of a single-mode single-frequency generation regime.

Keywords: surface wave, Cherenkov radiation, millimeter wavelength range, sheet high-current relativistic electron beam

1. Introduction

At the moment, considerable experience has been accumulated in the experimental study of relativistic Cherenkov surface-wave oscillators (SWOs) [1]. In such sources, a rectilinear electron beam interacts synchronously with the slow fundamental harmonic of the electromagnetic field propagating in a waveguide with periodic corrugation of the side walls. The amplitude of this harmonic decreases with distance from the corrugation, forming a surface wave, which allows to use electrodynamic systems with a significantly larger dimensions compared to conventional relativistic backward wave oscillators [2, 3] operating on the lower modes of corrugated waveguides. The surface wave is, in fact, a supermode consisting of regular waveguide modes with correlated phases; thus, the problem of ensuring the spatial coherence of radiation is partially solved in the SWO.

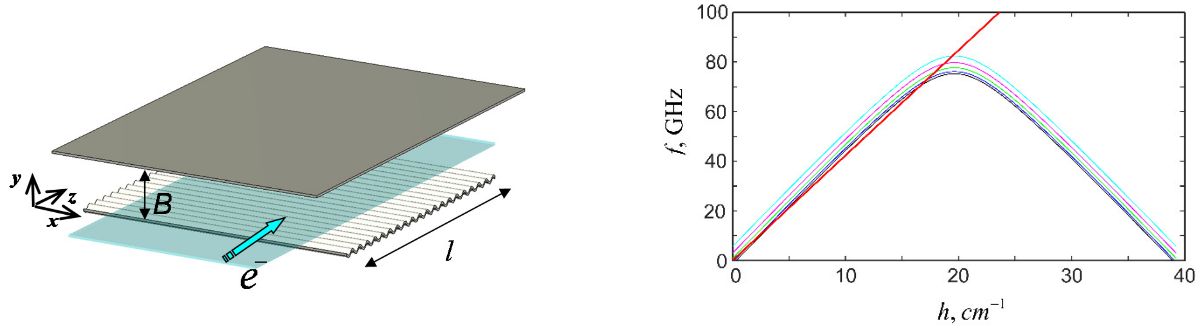
In most experimental studies of SWOs, radiation from tubular electron beams in cylindrical waveguides was used. In this paper, we study the possibility of implementing planar SWOs driven by sheet relativistic electron beams (see Fig.1a) [4–6]. The main advantage of this configuration is the possibility of using planar waveguides that are open at the ends, which provides an additional mode selection mechanism for the corresponding open transverse coordinate x, thereby making it possible to increase the integral operating current of the oscillator due to the use of wider (on the scale of the wavelength) cathodes. The development of powerful 75 GHz SWO is being carried out at the IAP RAS on the basis of the "SINUKI" high-current accelerator (1 kA / 650 keV / 17 ns). At present, experiments on the formation of a sheet high-current relativistic electron beam with up to 2 cm width have been carried out.

2. Three-dimensional quasi-optical model of planar SWO

Let us consider a three-dimensional planar model of a surface-wave oscillator (Fig.1a). We assume that the electron beam moves along a flat plate which has a section of length l_z with a shallow sinusoidal corrugation

$$b(z) = b_1 \cos(\bar{h} z), \tag{1}$$

where $\bar{h} = 2\pi / d$, d – period and $b_1 << d$ – amplitude of the corrugation. Let us assume that the periodical structure has a finite dimension l_x along the transverse coordinate x and coincides with the width of sheet electron beam l_x^e.



(a) **(b)**

Fig.1. (a) Schematic of the interaction space of SWO driven by a rectilinear sheet electron beam. (b) Dispersion curves of normal surface modes with different number of variations along the transverse coordinate *x*. Beam line – red curve.

Radiation fields in this electrodynamic system are represented as a superposition of two counter propagating quasioptical wave beams, the magnetic field of which can be written as [6]

$$H_x = \mathrm{Re}\left[C_+(z,x,y,t)e^{i(\omega t - kz)} + C_-(z,x,y,t)e^{i(\omega t + kz)}\right], \tag{2}$$

where ω – frequency, $k = \omega/c$. In the Bragg resonance condition $k \approx k_0 = \bar{h}/2$, the coupling and mutual scattering of the counter-propagating wave beams with field (2) arise on the corrugated surface. Amplitudes of coupled wave beams are described by a set of equations [6]

$$\begin{gathered}\frac{\partial C_+}{\partial z} + \frac{\partial C_+}{c\partial t} + i\frac{\partial^2 C_+}{\bar{h}\partial y^2} + \frac{\partial^2 C_+}{\bar{h}\partial x^2} = i\alpha C_- \delta(y), \\ -\frac{\partial C_-}{\partial z} + \frac{\partial C_-}{c\partial t} + i\frac{\partial^2 C_-}{\bar{h}\partial y^2} + \frac{\partial^2 C_+}{\bar{h}\partial x^2} = i\alpha C_+ \delta(y)\end{gathered}, \tag{3}$$

where δ(*y*) – delta function and $\alpha = \bar{h}b_1/4$ – the coupling coefficient which is proportional to corrugation depth. In the case of electrodynamic system closed from transverse directions (SWO with this "closed" system was initially implemented in the experiments), boundary conditions for equations (3) at the corresponding ends of the system have the following form

$$\hat{C}_+\Big|_{X=\pm L_x/2} = 0, \hat{C}_-\Big|_{X=\pm L_x/2} = 0. \tag{4}$$

In this case we can introduce the concept of modes with a different number *m* of field variations along the transverse coordinate x and represent the solution of these equations in the following form

$$\hat{C}_\pm(X,Z,Y,\tau) = \hat{C}_\pm^m(Z,Y,\tau)\sin(mPX), \tag{5}$$

where $P = \pi / L_x$. As a result, the fields of each mode are described by the equations

$$\begin{gathered}\frac{\partial C_+}{\partial z} + \frac{\partial C_+}{c\partial t} + i\frac{\partial^2 C_+}{\bar{h}\partial y^2} + m^2 C_+ = i\alpha C_- \delta(y), \\ -\frac{\partial C_-}{\partial z} + \frac{\partial C_-}{c\partial t} + i\frac{\partial^2 C_-}{\bar{h}\partial y^2} + m^2 C_- = i\alpha C_+ \delta(y).\end{gathered} \tag{6}$$

For the infinite in longitudinal direction periodic system, representing the solution of equations (6) in the form

$$C_{\pm} \sim \exp(i\Omega t \mp i\Gamma z - g_{\pm} y),\ g_{\pm} = \sqrt{-\bar{h}(\Omega / c \mp \Gamma)}$$

– normal to the surface wavenumbers, we obtain dispersion characteristics for different transverse modes (see Fig.1b) for the parameters of slow-wave structure and electron beam used in the experiments. As it follows from the Fig.1b, the dispersion curves of the modes lay below the light cone, and these modes can be excited by a rectilinear electron beam.

To analyze the mode competition scenario, we take into account the interaction with the electron beam, supplementing equations (6) with the equations for electron motion. Self-consistent system of equations for SWO can be written in the form

$$\begin{gathered}
\frac{\partial \hat{C}_+}{\partial Z} + \frac{\partial \hat{C}_+}{\partial \tau} + i\frac{\partial^2 \hat{C}_+}{\partial Y^2} + i\frac{\partial^2 \hat{C}_+}{\partial X^2} + \sigma \hat{C}_+ \delta(Y) = i\alpha \hat{C}_- \delta(Y) - \frac{1}{B_e}\frac{\partial}{\partial Y}\left(F(X,Y)J\right), \\
-\frac{\partial \hat{C}_-}{\partial Z} + \frac{\partial \hat{C}_-}{\partial \tau} + i\frac{\partial^2 \hat{C}_-}{\partial Y^2} + i\frac{\partial^2 \hat{C}_-}{\partial X^2} + \sigma \hat{C}_- \delta(Y) = i\alpha \hat{C}_+ \delta(Y), \\
\left(\frac{\partial}{\partial Z} + \beta^{-1}\frac{\partial}{\partial \tau}\right)^2 \theta = \mathrm{Re}\left[\frac{\partial \hat{C}_+}{\partial Y} e^{i\theta}\right].
\end{gathered} \tag{7}$$

Boundary conditions for the electron beam are as follows:

$$\theta\big|_{Z=0} = \theta_0 \in [0, 2\pi),\ \left(\frac{\partial}{\partial Z} + \beta_0^{-1}\frac{\partial}{\partial \tau}\right)\theta\bigg|_{Z=0} = \hat{\Delta}, \tag{8}$$

where $\theta = \omega_0 t - k_0 z$ – phase of electron relative to co-propagating wave, $\hat{\Delta} = \Delta / k_0 G$, $\Delta = k_0(1-\beta_0)/\beta_0$ – synchronism detuning at the operating frequency.
At the absence of the external longitudinal waves, the boundary conditions for the equations (7) are as follows:

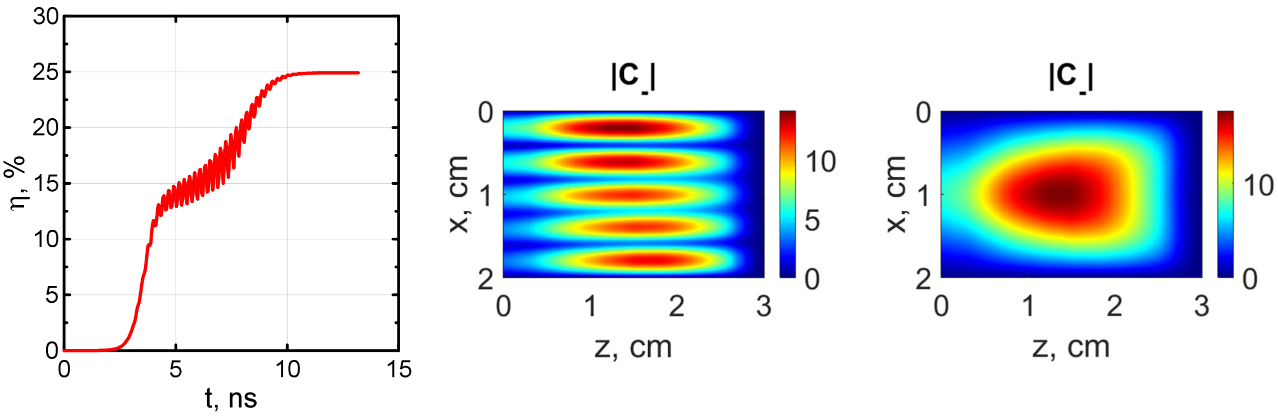
$$\hat{C}_+\big|_{Z=0} = 0,\ \hat{C}_-\big|_{Z=L} = 0, \tag{9}$$

where $L_z = Gk_0 l_z$. In equations (7) and (8) the parameters are normalized as follows:

$$Z = Gk_0 z,\ X = \sqrt{2G}k_0 x,\ Y = \sqrt{2G}k_0 y,\ \tau = G\omega_0 t,\ \hat{C}_{\pm} = i\frac{\sqrt{2}eC_{\pm}\mu}{mc\omega_0\gamma_0 G^{3/2}},\ \hat{\alpha} = \alpha\sqrt{2/G},$$

$$G = \left(4\sqrt{2}\pi\frac{eI_0}{mc^3}\frac{\mu}{\gamma_0}\frac{1}{k_0}\right)^{2/3}$$

– is the amplification parameter (an analogue of the Pierce parameter), I_0 is linear current density, $\mu = (\gamma_0)^{-2}(\beta_0)^{-3}$ is the parameter of electron inertial grouping, $\sigma = (1+i)k_0\delta/G$ is the parameter of Ohmic losses, δ is a skin depth, $\gamma_0 = 1/(1-(\beta_0)^2)^{0.5}$ is the Lorentz factor, function $F(X, Y)$ defines the profile of the electron beam in two transverse coordinates. Further, it is assumed that the electron density is uniformly distributed over the electron beam cross section. Accordingly, $F(X, Y) = 1$ at $X \in \left[-L_x^e/2, L_x^e/2\right]$ and $Y \in [B_g, B_g + B_e]$, where $B_g = \sqrt{2G}kb_g$.



(a) **(b)** **(c)**

Fig.2. Simulation of multimode nonlinear dynamics of 75 GHz SWO with transversely closed electrodynamic system within the framework of the averaged approach. (a) Efficiency as a function of time, in a regime with excitation at the initial stage of the mode with 5 transverse variations $m = 5$ and hopping at the final stage to the mode with one field variation $m = 1$. (b), (c) Spatial structures of wave $\hat{C}_-$ at (z, x) plane for $t = 5$ ns and $t = 10$ ns correspondingly. ($l_z = 30$ mm, $l_x = 20$ mm, $I \approx 1$ kA, $U = 650$ kV).

Electron efficiency in steady-state regime of oscillations with amplitudes $C_\pm \sim \exp(i\hat{\Omega}\tau)$, where $\hat{\Omega} = (\omega - \omega_0)/G\omega_0$ is the detuning of the operation frequency from the Bragg frequency, is defined by the following relations:

$$\eta = \frac{G\hat{\eta}}{\mu\left(1-\gamma_0^{-1}\right)}, \hat{\eta} = \frac{1}{2\pi B_e L_x}\int_{-L_x/2}^{L_x/2}\int_0^B\int_0^{2\pi}\left(\frac{\partial\theta}{\partial Z} - \hat{\Delta}\right)\Bigg|_{Z=L} F(Y)d\theta_0 dY dX. \quad (10)$$

The research parameters were chosen close to the parameters of the experiments currently being carried out on the basis of the "SINUKI" accelerator (IAP RAS, N. Novgorod). The oscillator is designed for the operation frequency 75 GHz. The device is driven by 20 mm wide sheet electron beam with a thickness of 1 mm, current 1 kA and electron energy 0.65 MeV. A sinusoidal-profile corrugation with a period of 1.6 mm, a groove depth of 0.46 mm, and length of 20 periods was assumed. At the given parameters, the mode with 5 transverse variations is the most closed to π-mode as it follows from the dispersion curves given in Fig.1b. Accordingly, it has the maximum increment. Nonlinear dynamics modeling based on equations (7), (8) shows that at the initial stage, the specified mode is actually excited. However, further there should be a hopping to the generation of the mode with one transverse field variation, which has a smaller time increment, but a higher value of the electronic efficiency (see Fig.2). In the experiments the duration of electron beam current pulse may be insufficient for the observation of such transitions from one to another mode generation. It should be mentioned that for other initial values of the electron energy, other scenarios of mode competition were observed in the simulation; and the region of excitation of a single mode with one transverse field variation was very limited and unstable for small variations in the electron energy.

Stable regime of generation of single mode with one transverse field variation can be implemented for a system open in the transverse direction. In this case, the boundary conditions were assumed cyclic and were set at a considerable distance from the real ends of the system. At the same time, it was assumed that the rest of the space was filled with an absorber, which, under the condition $\sigma L_x >> 1$, excluded the mutual influence of the flows emitted from the ends. In this case, the dynamics of the system was significantly simplified and reduced to stable excitation of a single mode with one transverse variation and an output power of 40 MW when the electron beam width was of 2 cm. These results were confirmed by three-dimensional numerical PIC-simulation of planar SWO generation regimes with different boundary conditions.

3. Experimental studies of W-band planar SWO

In the experiment, the sheet electron beam was injected from a blade cathode and guided by uniform 3 T magnetic field. 1 kA sheet beam with transverse dimensions of 20×0.7 mm^2 was obtained [7, 8]. The beam was aligned parallel to the corrugated surface in order to minimize the distance between the beam and the corrugation, as well as to minimize the beam interception. The important specific of the experimental SWO was the use of highly efficient side wall absorber for realization of open edge configuration. Reflection coefficient of the absorber were measured at frequencies from 100 to 200 GHz (see Fig.3) using a Michelson interferometer [9]. Linear extrapolation to the frequency of about 75 GHz gives the value of reflection coefficient of about 0.2. Stable generation of microwave pulses with the carrier frequency of about 75 GHz was obtained in the experiments. The carrier frequency was measured by the set of high-pass filters with different cut-off frequencies. Typical oscillogram of microwave pulse measured by microwave detector and the cathode voltage pulse are demonstrated in Fig.4.

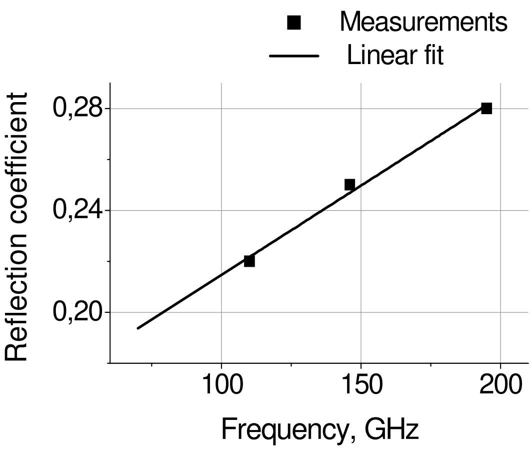


Fig.3. Measured reflection coefficients of absorber used in experimental studies of SWO.

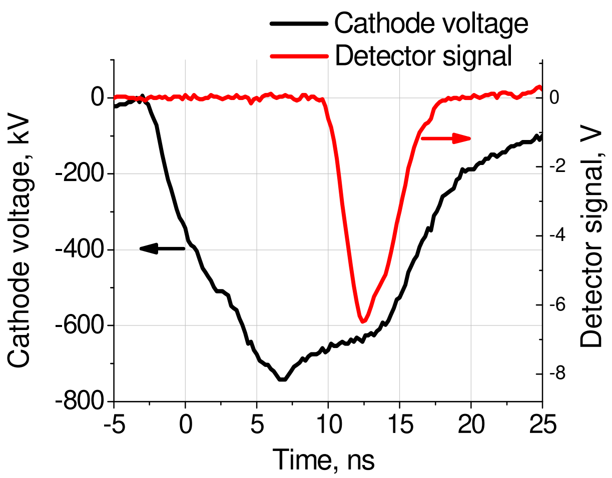


Fig.4. Cathode voltage (black) and output radiation pulse (red) of SWO obtained in the experimental study.

Microwave pulse duration was about 4 ns and the peak power was about 25 MW according to pulse energy measurements performed by calorimeter [10]. The value of peak power was less than in theoretical predictions which can be explained by energy and velocity spread in high-current electron beam, which are not fully modeled even in three-dimensional numerical PIC-simulation. The beam thickness could also may be greater in the experiments compared to that used in simulations.

4. Conclusion

Theoretical and numerical studies of W-band planar surface-wave oscillators have shown that open transverse boundary conditions provide stable single-mode generation in wide enough range of electron beam energies and currents, as well as the fast start of oscillations. In the initial experiments where open boundaries are modeled by the absorber installed at the walls of the planar surface-wave oscillator we obtained the generation of output microwave pulses with the following parameters: central frequency of 75 GHz; pulse duration of about 4 ns; and peak power of about 25 MW.

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5. References

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