

DEVELOPMENT OF RF-UNDULATORS AND POWERING SOURCES FOR COMPACT EFFICIENT COMPTON FEL-SCATTRONS*

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Abstract

Conception of Compton-type FELs operating up to X-ray band is under development currently at IAP RAS. This concept is aimed at reducing energy of a driving relativistic electron beam and thereby increasing efficiency of the electron-wave interaction in FEL, as well as achieving relative compactness of the generator. The basis of this concept is RF-undulators of a new type - the so-called 'flying' undulators. Results of current research of these RF-undulators, their simulations and 'cold' tests in the Ka-band are presented. For powering RF-undulators spatially-extended narrow-band Cerenkov masers are developed in the specified frequency range. In order to achieve the required sub-gigawatt power level of the pumping wave in a strongly oversized oscillator, we exploit the original idea of using two-dimensional distributed feedback implemented in the 2D doubly-periodical slow-wave structures. The design parameters of Ka-band surface-wave oscillator intended for powering RF-undulators, results of its simulation and initial experimental studies are discussed.

INTRODUCTION

Free electron lasers (FELs) are the most powerful sources of coherent radiation in the ranges up to X-rays and are being actively developed around the world. However, the main challenge of these projects are related currently with the gigantic size of the facilities, low efficiency of the electron-wave interaction and strong requirements to the quality of driving beams. As a way to solve these problems, development of Compton FELs can be considered. The use of the counter-propagating pumping wave (so-called RF-undulator) of the mm- wavelength band (instead of "traditional" magnetostatic undulators, the period of which is limited to several centimeters) makes it possible significantly reduce the energy of driving electron beam required for operation in the X-ray range, resulting in a decrease in the length of both the accelerator and the FEL interaction region (by increasing the FEL electron-wave interaction parameter), and enhance the efficiency of radiation generation.

The conception of Compton FEL-scatteron has been developing in recent years at IAP RAS. The basis of this concept is a novel scheme of RF-undulator - the so-called "flying" undulator [1]. Simulations of various schemes of

such undulators, including the ones with profiled parameters were conducted currently. It is shown that the use of these undulators allows realization of a non-resonant multi-pulse trapping regime [2], which leads to a decrease in sensitivity to the quality (i.e. energy and velocity spread) of the driving beam and, thus, to a further increase in the efficiency of this type FEL [3].

Experimental studies of the prototype of pumping system (including RF-undulators and RF-power sources) for FEL-scatteron were started at IAP RAS in the Ka-band. The required high power level in powering pulsed relativistic masers is planned to be achieved by extending their transverse size and exploiting novel two-dimensional (2D) distributed feedback mechanism to maintain narrow-band operation in strongly oversized systems. Operation principles, design parameters and results of simulation of Ka-band Surface-Wave Oscillator (SWO) intended for the experiments on powering "flying" rf undulator are discussed in this work.

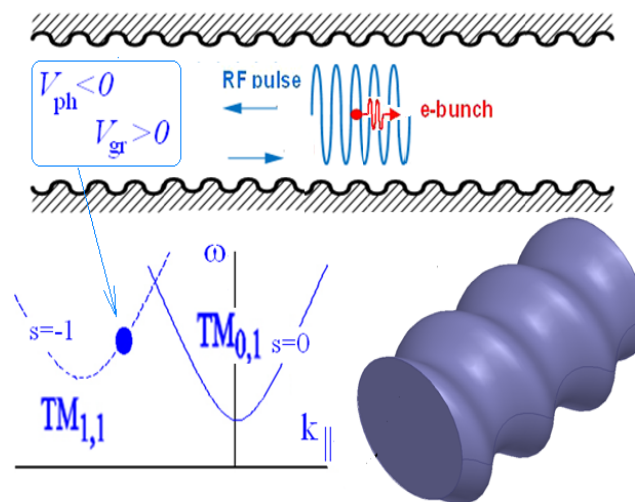


Figure 1: Flying RF-undulator. Microwave system and dispersion diagram of the operating undulator wave.

FLYING RF UNDULATOR

The "flying" RF-undulator [1] represents a powerful short pulse of coherent microwave radiation propagating synchronously with the electron bunch (Fig. 1). The microwave system of this RF-undulator consists of a cylindrical waveguide section with helical corrugation, which ensures the presence in the microwave pulse of a wave component with a backward (with respect to the direction of the electron bunch propagation) phase velocity but, simultaneously, with a group velocity close to the speed of light. Thus, the proximity of the group velocity of the microwave pulse wave and the electron bunch velocity realizes a long-time electron-wave interaction, while the

* Work is partially supported by the Russian Foundation for Basic Research (grant # 18-02-40009). Experimental facilities are developed and exploited in the frame of the Russian State Task Program (project #0035-2019-0001) and the RAS Presidium Project no.10 (#0035-2018-0022).

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presence of a counter-propagating partial wave provides the stimulated scattering of the RF pulse into the short-wavelength radiation with a high Doppler frequency up-conversion factor.

At present, a prototype model of a “flying” RF-undulator (Fig. 2 a) with an operating frequency of around 33.5 GHz was made in the form of a cylindrical waveguide section with a diameter of 12.2 mm having a single-turn helical corrugation of a period of 6 mm and an amplitude of 3 mm, providing coupling and mutual scattering of partial waves $TM_{0,1}$ (zero spatial harmonic) and $TM_{1,1}$ - type (-1 harmonic).

According to the 3D simulations, this corrugation under the operating parameters forms a normal wave with a group velocity close to the speed of light ($\sim 0.7c$), which possesses a weak frequency dispersion. It is important that this normal wave contains about 50% of the partial wave $TM_{1,1}$, counter-propagating with respect to the electrons. The wave-number of the counter-propagating component of the RF-wave in this prototype model corresponds to the effective undulator period $d_u \approx 5.4$ mm, and the calculated undulation factor under the design parameters is $\sim 0.1 - 0.15$ when the RF-pulse power is ~ 0.5 GW. Circular polarization of operating wave gives twice the factor of electron-wave interaction (in comparison with the planar undulator). Note, that near the waveguide center (where the electron beam is transported) “parasitic” transverse field of the forward-propagating partial wave $TM_{0,1}$ is absent. Results of the “cold” tests of the undulator prototype model are shown in Fig. 2 b and coincide well with the simulations.

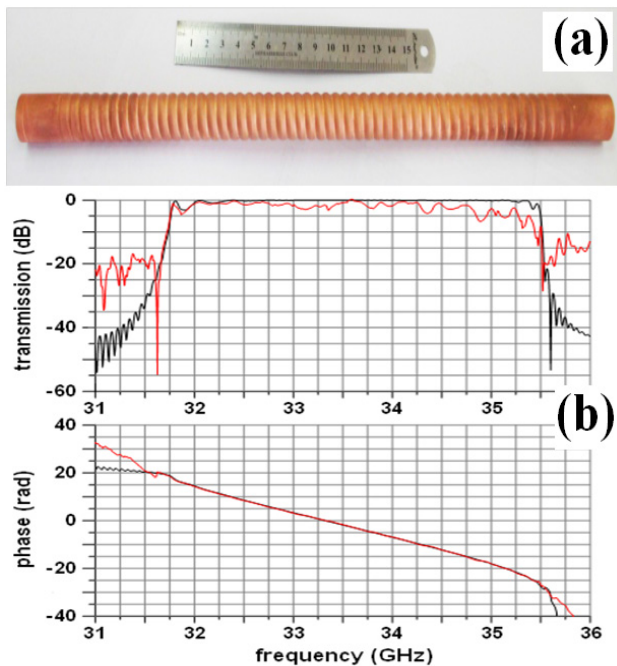


Figure 2: (a) Photograph of the prototype model of “flying” RF-undulator and (b) results of the 3D simulations (black curves) and “cold” tests (red curves) of transmission of the $TM_{0,1}$ wave (top) through this undulator and phase of the transmission (bottom).

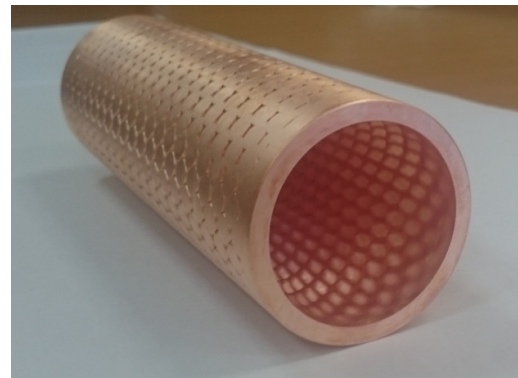


Figure 3: Photograph of cylindrical slow-wave structure with the inner 2D sinusoidal corrugation (oversize parameter $\varnothing/\lambda \sim 5$) for operation at Ka-band.

POWERFUL KA-BAND 2D SURFACE-WAVE OSCILLATOR

Powerful spatially-extended Ka-band SWO is constructed based on the high-current explosive-emission accelerator «Sinus-6» 0.5 MeV / 5 kA / 25 ns. Oscillators of such type are preferable among the relativistic Cherenkov masers due to the larger values of the electron-wave coupling impedance. This project is a promising development of our original concept of the radiation power enhancement in relativistic masers by extending the cross-section of their interaction space while maintaining the beam current density and the electromagnetic fluxes densities at a moderate level.

The radiation power enhancement in relativistic Cherenkov masers is intended by extending cross-section of the interaction space while keeping the beam current density and the electromagnetic fluxes densities at the moderate level. The use of large-size electron beams and strongly oversized (in the wavelength scale) electrodynamic systems (Fig. 3) is aimed on advance of the oscillators into the short-wavelengths up to submillimeter band and achievement of the record power levels. To ensure high coherence of the radiation (necessary for pumping resonant structures of RF-undulators) we proposed to exploit two-dimensional distributed feedback [4, 5] realized (in the case of Cherenkov masers) by two-dimensional (2D) double-periodical slow-wave structures. This novel feedback mechanism is a universal method for obtaining coherent radiation in spatially-extended relativistic masers of different types [6 - 8].

For the generator operating at Ka-band, the 2D slow-wave structure of cylindrical geometry was designed with an average diameter $\varnothing = 4.6$ cm (perimeter of about 16 wavelengths), length of 8.4 cm having 2D sinusoidal corrugation of 7 mm period, 2.5 mm amplitude and 16 azimuthal turns (Fig.3). In the 2D SWO slow-wave structure combines the properties of a slow-wave system realizing conditions for an effective Cherenkov interaction with a high-current rectilinear sheet REB, and a high-Q resonator utilizing the mechanism of 2D distributed feedback and providing selective excitation of the operating mode in the strongly oversized system. Considered

scheme of the oscillator is characterized by the presence of the four electromagnetic (e.m.) energy fluxes propagating in the axial $\pm z$ and the transverse (azimuthal) $\pm\phi$ directions. To provide single-output of radiation from the 2D SWO, additional coaxial reflector was designed for installation at the up-stream side (cathode-side) of the generator.

Simulations of 2D SWO based on the “Sinus-6” accelerator were carried out using PIC code CST Studio Suite. Parameters for the simulations were taken close to the experimental conditions. In the preliminary electron-optical experiments, hollow electron beam of the mean diameter 4.4 mm was realized and guided through the interaction space by the solenoidal axial magnetic field of about 1.4 T. Results of simulations are presented in Fig. 4 and demonstrate establishment of narrow-band oscillation regime under the design parameters. The output power reaches 0.5 GW under the electron efficiency of $\sim 25\%$. In this case, mode pattern of the operating synchronous slow wave demonstrates azimuthally symmetric distribution (Fig. 5) and contains of the waveguide modes of the $TM_{0,n}$ type (see Fig. 4 a). Experiments on realization and experimental studies of the 2D SWO are in progress currently based on the “Sinus-6” accelerator.

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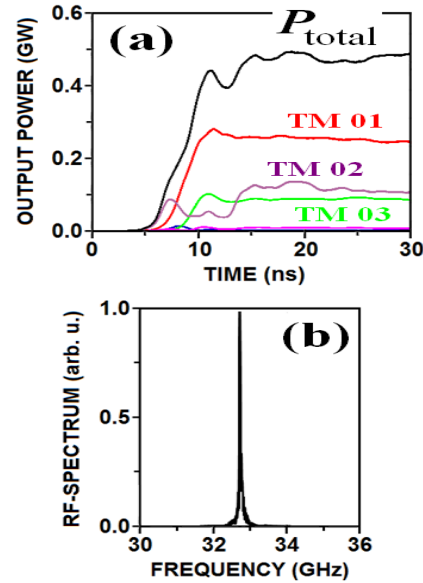


Figure 4: Results of 3D PIC simulations of sub-GW Ka-band 2D SWO. (a) Time dependence of the total output power and partial powers associated with different waveguide modes. (b) Radiation spectrum in the steady-state generation regime.

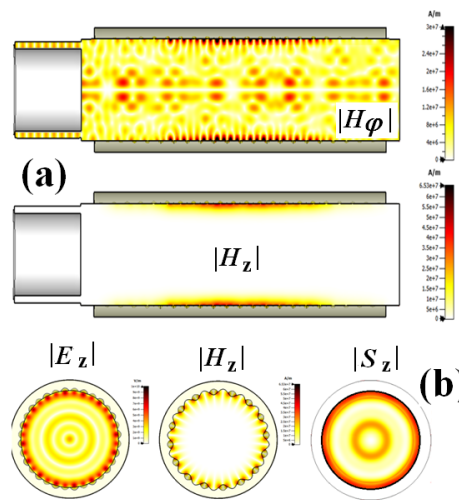


Figure 5: Spatial instantaneous structure of the RF-field in the sub-GW Ka-band 2D SWO (simulations): (a) H_ϕ and H_z components in the longitudinal cross-section and (b) E_z and H_z components in the transverse cross-section inside the interaction region, as well as the axial component of the Poynting vector S_z of the output radiation. Components H_ϕ and E_z correspond to interference of the axially propagating wave beams (interacting with the electrons partial waves) and H_z to interference of transversely (azimuthally) propagating partial wave beams (“waves of synchronization”).