

# PIC-simulation of efficient cherenkov X-band and V-band HPM sources with moderately relativistic electron beams

V.P. Tarakanov<sup>1,2</sup>, E.M. Totmeninov<sup>3</sup>, I.V. Pegel<sup>3,4</sup>

<sup>1</sup>Joint Institute for High Temperatures, Russian Academy of Sciences, Moscow, Russia, karat@tarak.msk.su

<sup>2</sup>National Research Nuclear University MEPhI, Moscow, Russia

<sup>3</sup>Institute of High Current Electronics SB RAS, Tomsk, Russia, totm@lfe.hcei.tsc.ru

<sup>4</sup>National Research Tomsk Polytechnic University, Tomsk, Russia

## Introduction

Efficient sources of high-power repetitively-pulsed microwave sources with moderately relativistic electron beams have several advantages. Firstly, high-voltage drivers of smaller dimensions and power capacity are required to power these devices, which allows building mobile devices. It is also important that, in the sources operating in repetitively pulsed mode, reducing the energy of electrons in the spent electron beam lowers the thermal load on the collector (and therefore the cooling requirements), and, to an even greater extent, reduces the collector bremsstrahlung and the requirements for X-ray protection.

## X-band Twistron with efficiency 54%

A new scheme of high-power microwave oscillator of twistron type [1] using a moderately relativistic high current electron beam is presented (Fig. 1). In this device the reflector position relative to the SWS sets the amplitude and phase relationships between RF current in the electron beam and the fields of main harmonics at the SWS inlet. Next, it is advisable to choose the location of electron beam deposition where the electron bunches reach maximum compactness. It is also appropriate that the slope of the SWS at this location is nearly perpendicular to electron trajectory. In this case, the electric field acting on electrons is represented by z-component only.

In numerical experiment using axisymmetric version of completely electromagnetic PiC-code KARAT [2], a 54% conversion efficiency of electron beam power to electromagnetic radiation was demonstrated. With 230 kV accelerating voltage, 1.7 kA electron beam current, and 1.9 T guiding magnetic field strength, the simulated microwave power was 210 MW at 9.7 GHz (Fig. 2). The "electronic efficiency" of the source reaches 64% (Fig. 1).

With a special phasing, the energy exchange between the beam and the RF field is non-monotonous along the interaction space (Fig. 1). The electron bunch is first boosted by the field of 0<sup>th</sup> harmonic of forward wave. As a result, it is shifted to the center of decelerating phase of -1<sup>st</sup> harmonic of the backward wave. The kinetic energy of the bunch is extracted by RF field on a short section (with a length close to corrugation period), and the intensity of the extraction achieves its maximum near the beam dumping location, where the beam coupling to longitudinal RF field is maximized due to steep (normal) tilt of the SWS surface (Fig. 3).

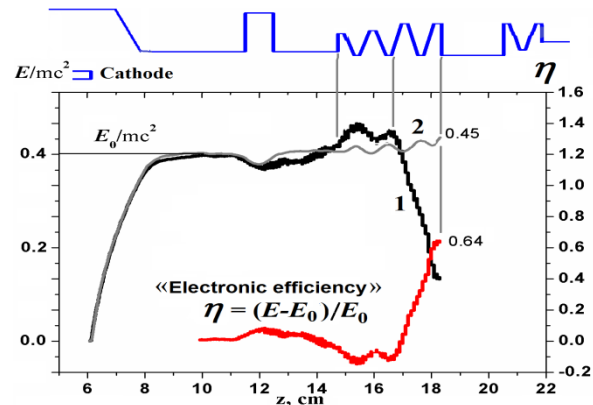


Fig. 1. Dimensionless kinetic energy of electrons versus longitudinal coordinate [(1) saturated steady-state oscillation; (2) prior to oscillation buildup] and the "electronic efficiency"  $\eta = (E - E_0)/E_0$  obtained in KARAT simulation

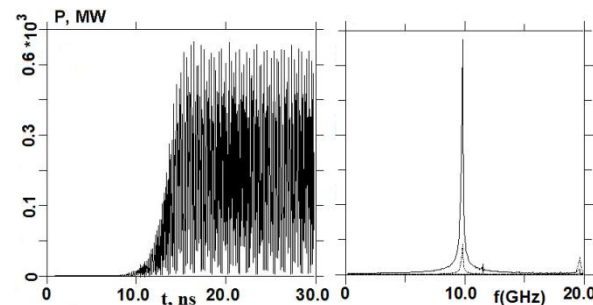


Fig. 2. Simulated non-averaged waveform of microwave power and the radiation spectrum of the oscillator

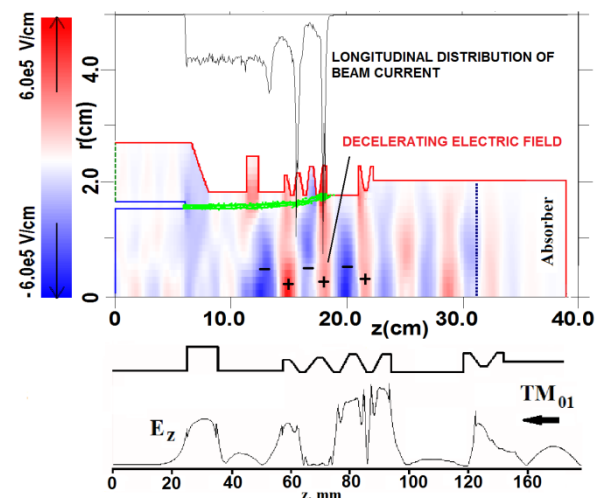


Fig. 3. Longitudinal distribution of beam current, grayscale map of RF electric field strength (z-component) – top; "cold" longitudinal distribution of electric field z-component at 9.7 GHz at the radius of the electron beam – bottom

### V-band Orotron with efficiency 34%

A scheme of V-band high power microwave oscillator of orotron type [3] with oversized ( $D/\lambda \sim 2.7$ ) electrodynamic structure is presented. The proposed device operates the axisymmetric  $TM_{03}$  mode of a rippled circular waveguide, while the output mode is  $TM_{02}$ . The mean radius of the slow-wave structure (SWS) is  $R_0 = 6.9$  mm, the length is 18 mm, and the period and amplitude of corrugation are 3.3 mm and 0.6 mm, respectively (Fig. 4). The electron beam radius is  $R_{\text{beam}} = 6.1$  mm. The plain waveguide section separating a coaxial diode with magnetic insulation and the SWS is supercritical with respect to  $TM_{03}$  mode, and the same is true about the waveguide attached downstream of the SWS. That is why radiation generated in the SWS in the form of "trapped"  $TM_{03}$  mode can be released only owing to transformation into some mode having smaller radial index and lower critical frequency — in the particular case, the mode  $TM_{02}$ .

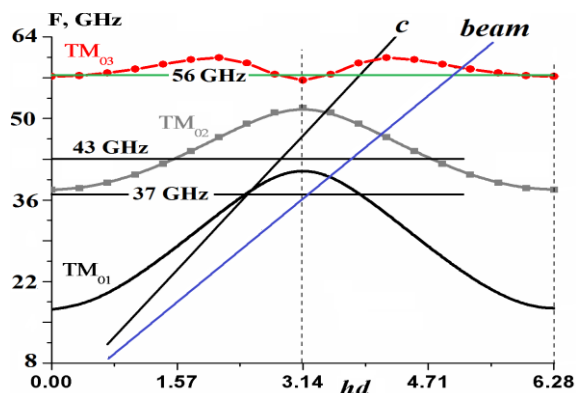


Fig. 4. Dispersion curves of lower axisymmetric electric modes in an infinitely long rippled circular waveguide: "c" marks the speed of light line, and "beam" denotes the electron beam velocity line

Cyclotron mode selection is an efficient method to discriminate between different modes in microwave devices employing tubular electron beams transported in longitudinal magnetic field. The method is based on the phenomenon of cyclotron absorption of electromagnetic waves by magnetized beam electrons. The intensity of absorption for a particular wave depends on its radial structure. Properly choosing the electron beam radius allows efficient absorption of all symmetric waves except the desired working mode.

The simulated output microwave power was 190 MW with 34% efficiency when using 2.5 kA, 220 keV electron beam transported via 2.2 T magnetic field and oscillation frequency 56 GHz (Fig. 5, 6).

Single-mode operation of the oscillator is ensured by using cyclotron mode selection [4] of concurrent modes  $TM_{01}$  (37 GHz) and  $TM_{02}$  (43 GHz). In the orotron being considered, the resonant magnetic field (energy of electromagnetic wave is converted into kinetic energy of electrons rotating in magnetic field) is about 3.0 T. It is near the field of the selected excitation of  $TM_{03}$  mode observed in the simulations. Indeed, for this mode, the squared amplitude of radial electric field (which determines the intensity of cyclotron absorption of any symmetrical TM waves) is proportional to

$$J_1^2(v_{03}R_{\text{beam}}/R_0) = 0.019, \text{ which is much smaller than } J_1^2(v_{01}R_{\text{beam}}/R_0) = 0.324 \text{ (for } TM_{01} \text{ mode) and } J_1^2(v_{02}R_{\text{beam}}/R_0) = 0.088 \text{ (for } TM_{02} \text{ mode).}$$

As for competing non-axisymmetric modes, they can be depressed by interrupting the azimuthal conductivity of the electrodynamic structure (for example, by cutting longitudinal slits through its wall [3]).

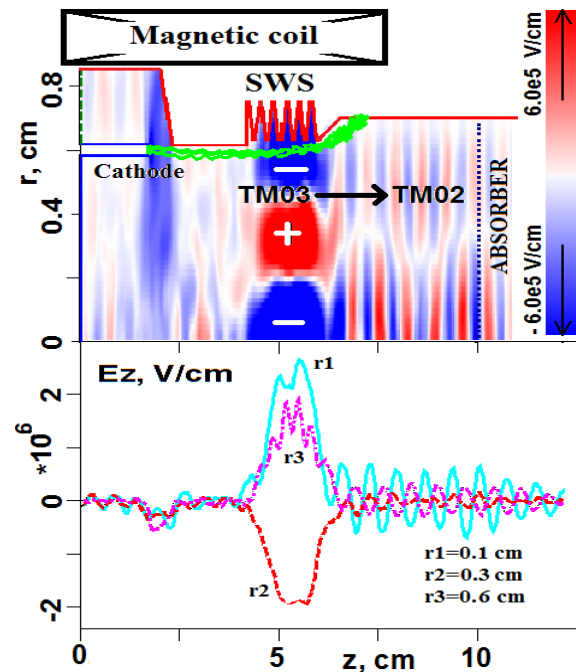


Fig. 5. Snapshot of the driving electron beam and electric field strength (top); longitudinal distributions of the electric field ( $z$ -component) at different radii

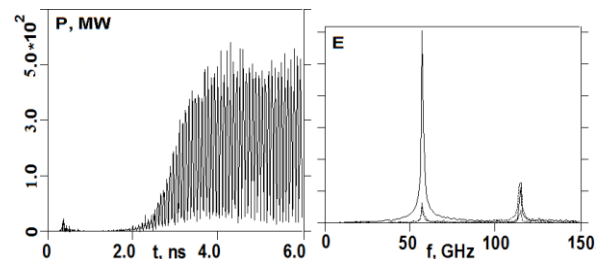


Fig. 6. Simulated waveform of electromagnetic field power flow and spectrum of electric field oscillation in the output waveguide of the orotron

### References

1. Totmeninov E.M., Pegel I.V., Tarakanov V.P. Highly efficient X-band relativistic twistor // *Laser and Particle Beams*. 2016. V. 34. No. 4. P. 601-605.
2. Tarakanov V.P. Multipurpose electromagnetic code KARAT // in *Mathematical Modeling: Problems and Results*, 2003. Nauka. Russia. Moscow, P. 456-476.
3. Totmeninov E.M., Pegel I.V., Tarakanov V.P. Efficient 58-GHz relativistic orotron with combined mode selection // *Physics of Plasmas*. 2017. V.24. No. 5, 053106.
4. Abubakirov E.B., Denisenko A.N., Kovalev N.F., Kopelovich E.A., Savel'ev A.V., Soluyanov E.I., Fuks M.I., Yastrebov V.V. Relativistic backward wave oscillator using a selective mode converter // *Tech. Phys.*, 1999, V. 44. No. 11, P. 1356-1359.