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# Relativistic backward-wave oscillator with longitudinal-slotted diffraction output

© V.V. Kladukhin, S.P. Khramtsov, V.Yu. Yalov

Institute of Electrophysics, Ural Branch, Russian Academy of Sciences, Yekaterinburg, Russia
E-mail: laepr@iep.uran.ru

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The results of experimental studies evaluating the influence of longitudinal slits in a conical diffraction outlet, combined with an electron collector, of a 10 GHz relativistic BWO (Backward-Wave Oscillator) with an operating mode $TM_{01}$ are presented. It has been shown experimentally that replacing a solid conical waveguide with a similar longitudinal-slotted waveguide has little effect on the performance of the BWO. The use of a longitudinally slotted diffraction outlet instead of a continuous one makes it possible to reduce the volume of plasma and microparticles formed on the diffraction outlet surface under the action of an electron beam, and to improve their adsorption and removal.

**Keywords:** relativistic microwave generator, backward wave oscillator, diffractive output, electron collector

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High-current relativistic backward-wave oscillators (BWOs) of the centimeter range using a conical adiabatic diffraction outlet combined with an electron collector have been designed and studied throughout the past few decades [1–3]. It was noted that diffraction outlets get clogged with collector plasma, desorbed gases, vapors, and microparticles of the collector material under the influence of incident electrons. This has a negative effect on BWO operation in frequency modes and in the process of generation of long microwave pulses. A significant change in operation modes of plasma-relativistic microwave generators induced by plasma, microparticles, and the ion background produced in the collector region under the influence of an electron beam was noted in [4]. In view of this, design solutions altering the conditions under which the above effects manifest themselves are of interest. This change may be achieved by using slotted waveguide systems instead of solid ones.

Since the studied BWOs generate axially symmetric TM waves, it is technically possible to substitute traditional solid axially symmetric waveguide systems with their longitudinally slotted counterparts.

In what follows, we present the results of an experimental study of the change in BWO performance parameters occurring when a solid conical diffraction outlet combined with an electron collector is substituted with its longitudinally slotted counterparts. The transparency of such collectors to an electron beam is also estimated.

Experiments were performed using a three-centimeter BWO with the $TM_{01}$ operating mode that, just like the one used in [5], had a solid slow-wave system (SWS) with rectangular corrugation and a resonance reflector-modulator (RRM) proposed in [6]. The SWS length was 120 mm, the larger corrugation diameter was 32 mm, the corrugation depth in the main SWS part was 2 mm, the period was 15 mm, and the SWS–RRM distance ($L_{dr}$) was 20.5 mm. The schematic BWO diagram is presented in Fig. 1, *a*.

A high-current thin-walled hollow electron beam (*e-beam* in Fig. 1, *a*) used in the BWO had the following parameters: the electron energy was $\sim 650$ keV, the beam current was $\sim 8$ kA, the duration of pulses of the accelerating voltage and the electron-beam current was $\sim 15$ ns, and the operating mode was single-pulsed. The hollow beam was shaped by a graphite cathode (electron emitter, *Cath*) with a circular explosive emission edge and an axially symmetric guiding magnetic field ($H_0$ produced by a pulse solenoid (*Sol*). A high-voltage generator (based on a 25 Ω forming line) connected to the 80 Ω BWO input via a transforming line was used to shape nanosecond accelerating voltage pulses.

The magnetic field was uniform at the regular section of the BWO slow-wave system, and its maximum magnitude was 30 kOe. The cathode edge was in a weakly converging magnetic field that provided slight compression of the electron beam. The diameter of the cathode emission edge was $\sim 34$ mm, the outer diameter of the electron beam at the central SWS part was $\sim 26$ mm, and the thickness was $\sim 0.4$ mm. A conical diffraction outlet (MW *out*) combined with an electron collector (*Col*) was designed as a separate section to facilitate its replacement. Microwave radiation was output into the atmosphere following conversion of the $TM_{01}$ operating mode into the $TE_{11}$ mode with a converter and subsequent shaping of a Gaussian beam with a conical horn.

Solid, lamellar, and wire diffraction outlets (collectors) made from nonmagnetic stainless steel were used in the study. All three types of outlets had one and the same size: the inlet inner diameter was 32 mm, the outlet inner

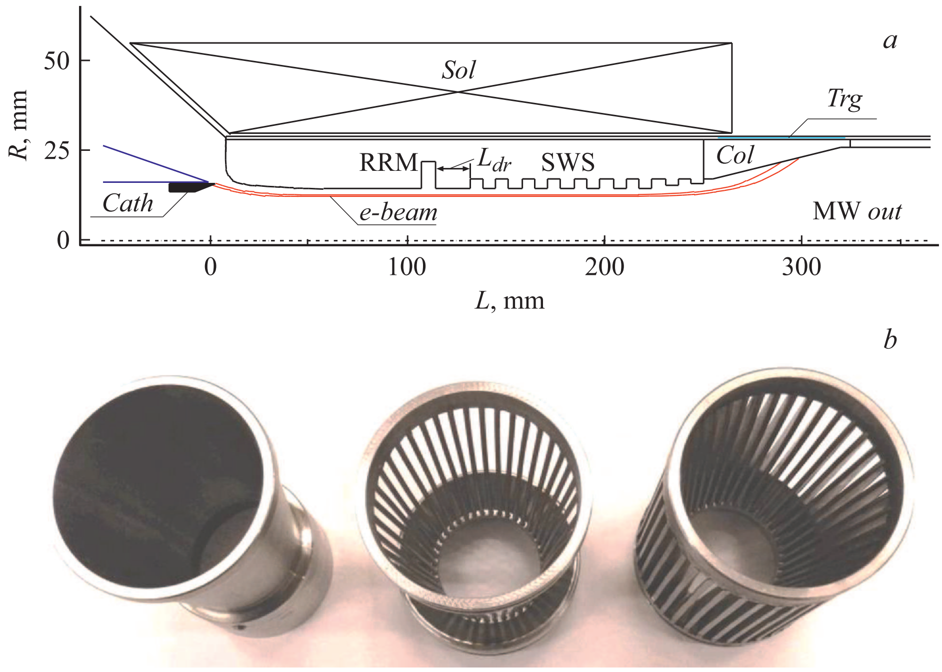


**Figure 1.** *a* — schematic diagram of the BWO; *b* — external appearance of solid (left), wire (center), and lamellar (right) diffraction BWO outlets.

diameter was 52 mm, and the length was 74 mm. The wire outlet had 40 rods 1.5 mm in diameter arranged regularly along a circumference. The lamellar one featured the same number of regularly arranged 1.5-mm-thick plates with their inner edges having a round shape (similar to the shape of rods). The end fixing of plates and wires was implemented by smooth joint them with transition cylinders with a length of $\sim 7$ mm that were also made from nonmagnetic stainless steel. The electron beam was deposited on the collectors on a ring with a diameter of $\sim 45-46$ mm where the ratio of the area of slits to the surface area of wire and lamellar collectors was $\sim 0.6$. The external appearance of collectors is presented in Fig. 1, *b*.

Oscilloscopes were used to record the shape and the magnitude of nanosecond pulses of the accelerating voltage (measured with a capacitance divider installed in the cathode holder region), the electron beam current (measured with a Rogowski coil that was also installed there), and microwave radiation (measured with a hot-electron detector positioned at a distance of $\sim 5$ m from the phase center of the horn) in the course of experiments. In addition, bell-shaped 18 ms pulses of the solenoid supply current were measured using a shunt in the solenoid supply circuit.

The structure of the electron beam and its transverse size were monitored by tracks on caprolon targets in the working volume of the BWO and by tracks on targets ($Trg$) made from a 0.2-mm-thick vinypros film in the collector region.

Since higher harmonics, which have the capacity to distort significantly the readings of the used microwave hot-electron detector even if their power fraction is relatively minor [7], may be present at the output of a BWO with a diffraction outlet, their manifestations were minimized prior to the principal measurements by altering the phase shift between the fundamental and the second harmonics. This was done by changing the length of the receiving waveguide path of the detector.

Microwave radiation pulses for all designs of the diffraction outlet were detected by the microwave detector starting from $H_0 = 18$ kOe. The pulse power increased with $H_0$ as it grew to 30 kOe. The duration of microwave radiation pulses for all designs of the diffraction outlet fell within the $6-8$ ns range and varied insignificantly when the diffraction outlet or the magnitude of the guiding magnetic field were changed. The dependences of the relative power and the duration of microwave radiation pulses on the magnitude of the guiding magnetic field are presented in Fig. 2, *a*. The duration of pulses was measured at the level of 0.5.

Characteristic oscilloscope records of the accelerating voltage, the electron beam current, and the microwave detector readings at intensity $H_0 = 28$ kOe of the guiding magnetic field for solid, lamellar, and wire diffraction outlets are presented in Fig. 2, *b*.

Tracks of the electron beam at vinypros targets mounted downstream of lamellar and wire collectors are presented in Fig. 3. The tracks are indicative of the transparency of these collectors for the electron beam. The total power of the output BWO radiation was estimated as $P = p_{\max} S_e$ for all designs of the diffraction outlet at $H_0 = 28$ kOe and was found to be equal to $\sim 0.9$ GW. Here, $p_{\max}$ [W/cm$^2$] is the energy density of microwave radiation at the center of the

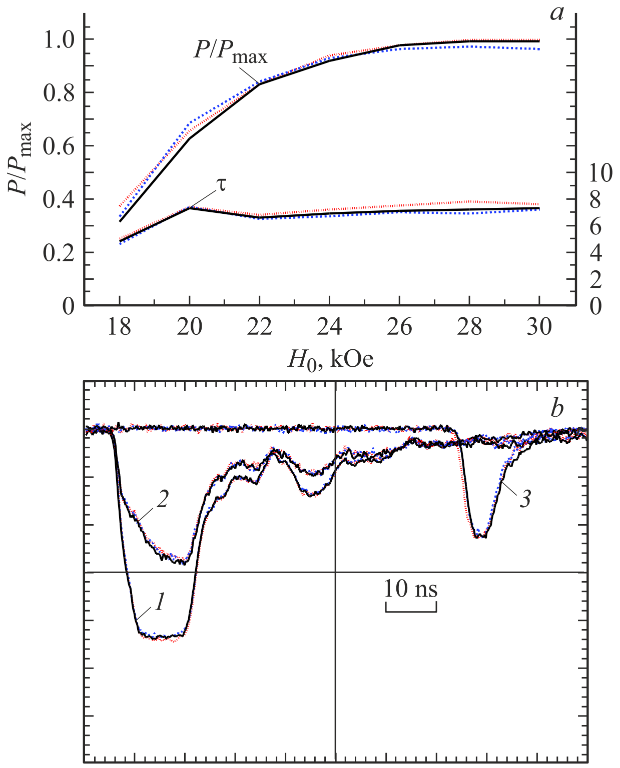


**Figure 2.** *a* — dependences of the relative power $(P/P_{max})$ and the duration of microwave radiation pulses $(\tau)$ on the magnitude of the guiding magnetic field; *b* — oscilloscope records of pulses: *1* — accelerating voltage, *2* — beam current, *3* — microwave radiation. Solid, dashed, and dotted curves correspond to solid, wire, and lamellar collectors, respectively.

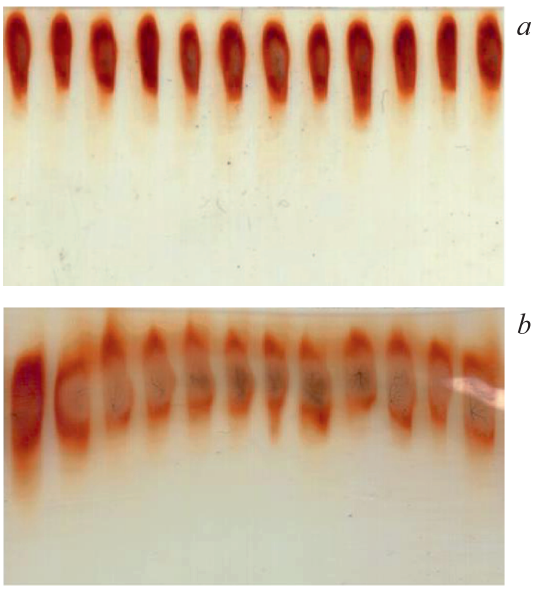


**Figure 3.** Tracks of the electron beam. *a* — lamellar collector, *b* — wire collector.

output Gaussian beam and $S_e$ [cm$^2$] is the cross-section area of the Gaussian beam at relative power $p_{max}/e$.

The results of our experiments revealed that the replacement of a solid diffraction outlet with its wire or lamellar counterparts has only a minor effect on the shape of the output microwave radiation pulse and does not affect its power. Concerns regarding the reflections from longitudinally slotted diffraction outlets having a potentially negative effect on the BWO operation and the microwave radiation output were proven unfounded.

It follows from the study of tracks on the targets that the wire collector is substantially more transparent than the lamellar one. This is probably attributable to the deposition of a significant fraction of electrons on the faces of the lamellar outlet.

The transition from a solid collector to a longitudinally slotted one provides an opportunity to reduce the volume of collector plasma, desorbed gases, vapors, and microparticles produced on the collector surface under the influence of an electron beam; prevent their localization in the diffraction outlet region; suppress surface reflections of microparticles; intensify their adsorption and removal.

The filter properties of longitudinally slotted diffraction outlets (suppression of TE waves in the output radiation) should also be mentioned among the advantages of such outlets.

### Conflict of interest

The authors declare that they have no conflict of interest.

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