## LITERATURE CITED

1. S. E. Graybill and S. V. Nablo, Bull. Am. Phys. Soc., 12, No. 6, 961 (1967); W. I. Link, IEEE Trans. Nucl. Sci., 14, No. 3, 777 (1968).
2. N. F. Kovalev, V. I. Petrukhina, and A. V. Smorgonskii, Radiotekh. Élektron., 20, No. 7, 1547 (1975).
3. N. F. Kovalev et al., Pis'ma Zh. Éksp. Teor. Fiz., 18, No. 4, 232 (1973).
4. S. P. Kuznetsov and D. I. Trubetskov, Lectures on Microwave Electronics (Third Winter Workshop for Engineers) [in Russian], Vol. 5, SU (1975), p. 88; Izv. Vyssh. Uchebn. Zaved., Radiofiz., 20, No. 2, 300 (1977).
5. V. N. Shevchik and D. I. Trubetskov (editors), Electronics of Backward-Wave Tubes [in Russian], SU (1975), Chap. 3.
6. M. B. Golant and A. S. Tager, Vopr. Radioélektron., Ser. Élektron., No. 5, 26 (1964); I. K. Vikulov and B. D. Khomutinnikov, Vopr. Radioélektron., Ser. 1, Élektron., No. 11, 3 (1964); I. K. Vikulov and A. S. Tager, Radiotekh. Élektron., 12, No. 2, 2146 (1967).
7. G. N. Rapoport, Dokl. Akad. Nauk SSSR, 117, No. 3, 411 (1957); Izv. Vyssh. Uchebn. Zaved., Radiotekh. Élektron., 9, No. 3, 483 (1964); Radiotekhn., 1, No. 5, 599 (1958).
8. V. N. Shevchik and D. I. Trubetskov, Analytic Computational Methods in Microwave Electronics [in Russian], Sovet-skoe Radio, Moscow (1970).
9. L. A. Vainshtein and V. A. Solntsev, Lectures on Microwave Electronics [in Russian], Sovet-skoe Radio, Moscow (1973).
10. A. I. Akhiezer, G. A. Lyubarskii, and Ya. B. Fainberg, Zh. Tekh. Fiz., 25, 2526 (1955); V. A. Solntsev and A. S. Tager, Radiotekh. Élektron., 5, No. 7, 1100 (1960).
11. S. P. Kuznetsov, L. A. Pishchik, and D. I. Trubetskov, Central Research Institute of Electronics, No. 4303/76; Abstract in VIMI Report, No. 17 (1976).
12. M. A. Neimark, Linear Differential Operators [in Russian], Nauka, Moscow (1969).
13. B. P. Bezruchko, N. S. Ginzburg, and S. P. Kuznetsov, Lectures on Microwave Electronics (Fourth Winter Workshop for Engineers) [in Russian], Vol. 5, SU (1978), p. 236.
14. W. J. Kleen and K. Poeschl, Introduction to Microwave Electronics [Russian translation], Part 2, Sovet-skoe Radio, Moscow (1963).


# EXPERIMENTAL INVESTIGATION OF NONLINEAR NONSTATIONARY PROCESSES IN A TYPE *O* BACKWARD-WAVE TUBE OSCILLATOR


B. P. Bezruchko and S. P. Kuznetsov



UDC 621.385.633



The settling process for oscillations in a type *O* backward-wave oscillator is experimentally investigated. It turns out that the nature of the process corresponds qualitatively to the nonlinear theory developed earlier. In the cw mode, when the beam current adequately exceeds the starting value, the theoretically predicted modulation of the output signal is observed. The current value and frequency corresponding to the offset of modulation are in satisfactory agreement with theory.


## §1. Introduction

Paper [1] proposed a nonlinear theory of transients in a relativistic type *O* backward-wave tube (BWT), based on the method of slowly varying amplitudes and without allowance for the effect of space charge, spread in electron velocities, distributed attenuation in the waveguide, and reflection at the waveguide end. For the particular case of a low-efficiency BWT, the derived equations coincided (to within normalization) with the corresponding equations of a nonrelativistic BWT with a small Pearce parameter [2] ($C \ll 1$).


Saratov State University. Translated from Izvestiya Vysshikh Uchebnykh Zavedenii, Radiofizika, Vol. 21, No. 7, pp. 1053-1059, July, 1978. Original article submitted February 27, 1977.

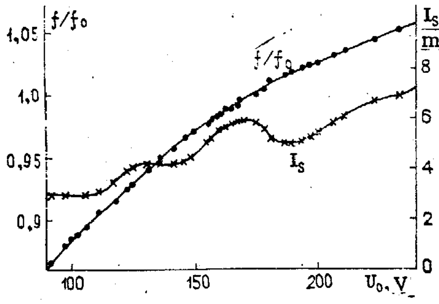


Fig. 1

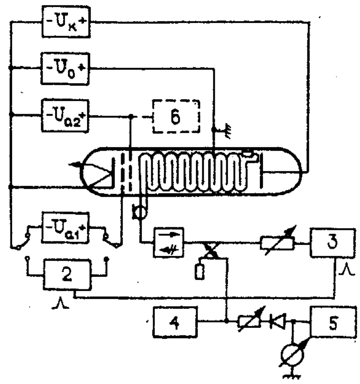


Fig. 2

Fig. 1. Starting current and frequency of onset of generation of tube as a function of accelerating voltage.

Fig. 2. Diagram of experimental set-up: 1) tube under study; 2) pulse generator; 3) high-speed oscillograph; 4) microwave spectrum analyzer; 5) low-frequency spectrum analyzer; 6) SSG.

Numerical solution of these equations [1] showed that the transient terminates in the establishment of a steady state only for ratios of the operating electron current to the starting current $I/I_S < 3.25$; the amplitude approaches the steady-state level in the manner of attenuating oscillations. If, however,

$$I > I_m = 3.25\, I_S, \tag{1}$$

a more complex self-oscillatory mode (self-modulation) arises in which the output signal is amplitude and phase modulated. On the basis of computer-obtained data, it was found that at currents close to $I_m$ the dimensionless modulation period $T(L/v_0 + L/v_{gr})^{-1}$ is 1.5; i.e., the modulation has a frequency

$$f_m = T^{-1} = 0.67\,\frac{v_0}{L}\left(1 + \frac{v_0}{v_{gr}}\right)^{-1}. \tag{2}$$

Here L is the tube length, $v_0$ is the beam velocity, and $v_{gr}$ is the absolute value of the group velocity of the wave. Similar results were obtained in simulating the transients in an ultrarelativistic high-efficiency BWT; in this case self-modulation arose at smaller $I/I_S$ values.

Since the results of [1] have no analog in the stationary nonlinear theory of BWT [3], it is of interest to verify them experimentally; obviously, it is simplest to do so using a nonrelativistic BWT. In the literature available to us, however, there are no experimental data which might be compared directly with [1].*

Nonstationary phenomena were investigated using a laboratory prototype of a type O BWT with an opposing-post delay system and magnetic beam focusing. The geometrical length of the interaction space L = 5 cm, while the cross-sectional area of the beam $S \approx 2\ \text{cm}^2$. The principal electrical parameters of the prototype are apparent from Fig. 1.

We can approximately determine the quantities in (2) by using the tuning characteristics. We set $v_0 \approx v_{ph}$ ($v_{ph}$ being the phase velocity of the wave). Then the formula

$$v_0 = 5.9 \cdot 10^7 \sqrt{U_0(B)},\ \text{cm/sec} \tag{3}$$

and the definition of group velocity yield the expression

$$1 + \frac{v_0}{v_{gr}} = \frac{1}{2}\,\frac{d(\lg U_0)}{d(\lg f)}. \tag{4}$$

The quantity $(1 + v_0/v_{gr})^{-1}$ was found on the basis of (4) by graphic differentiation of the relationships between $\log f$ and $\log U_0$ with a step of 0.1.

Figure 2 shows the experimental set-up. The constant voltages on the electrodes were supplied from standard power sources. Under pulse conditions, the first anode was fed cutoff voltage pulses (Fig. 3a) from

*In [4], for example, only the overall duration of the transient for $I/I_S \le 2.4$ is cited and compared with the linear theory.

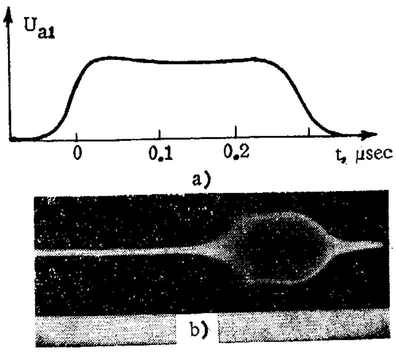


Fig. 3. Shape of cutoff pulse fed to first anode of tube (a) and oscillogram of BWT output-signal envelope in process of settling from noise (b); $U_0 = 150$ V, $I/I_S \approx 2$.

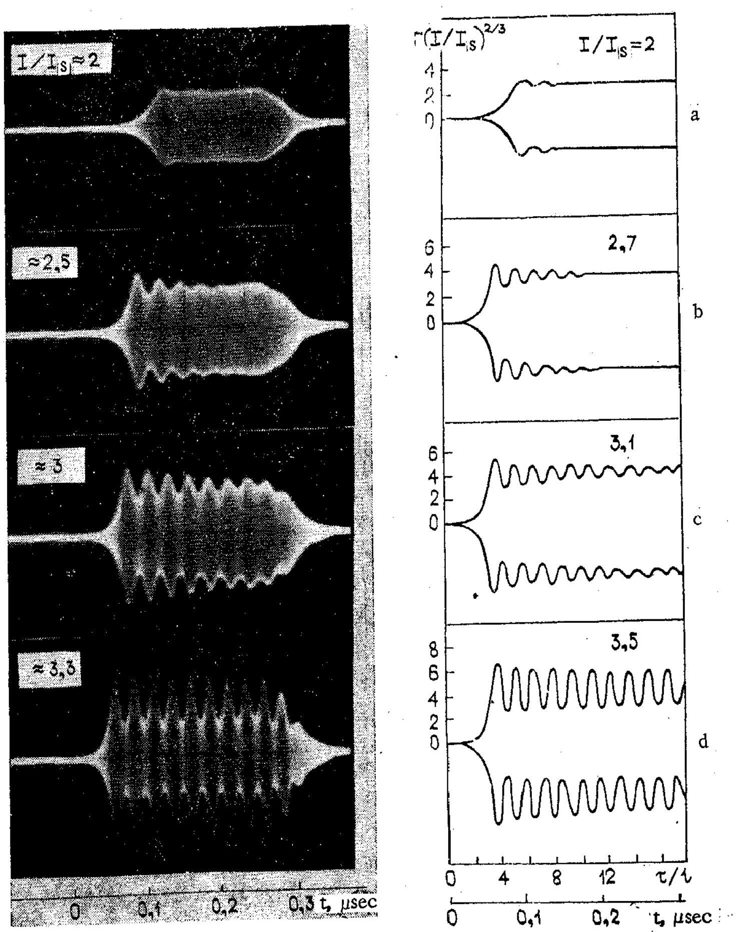


Fig. 4. The left side of the figure shows oscillograms of the transient in the BWT for the settling process from an auxiliary signal, $U_0 = 150$ V. The right side shows the analogous theoretical plots based on the data of [1], under the assumption that the signal power at t = 0 is 50 dB below the level corresponding to $F(I/I_S)^{2/3} = 1$. The scale on the ordinate axis is chosen in such a way that the steady-state levels in the figure and in oscillogram a coincide.

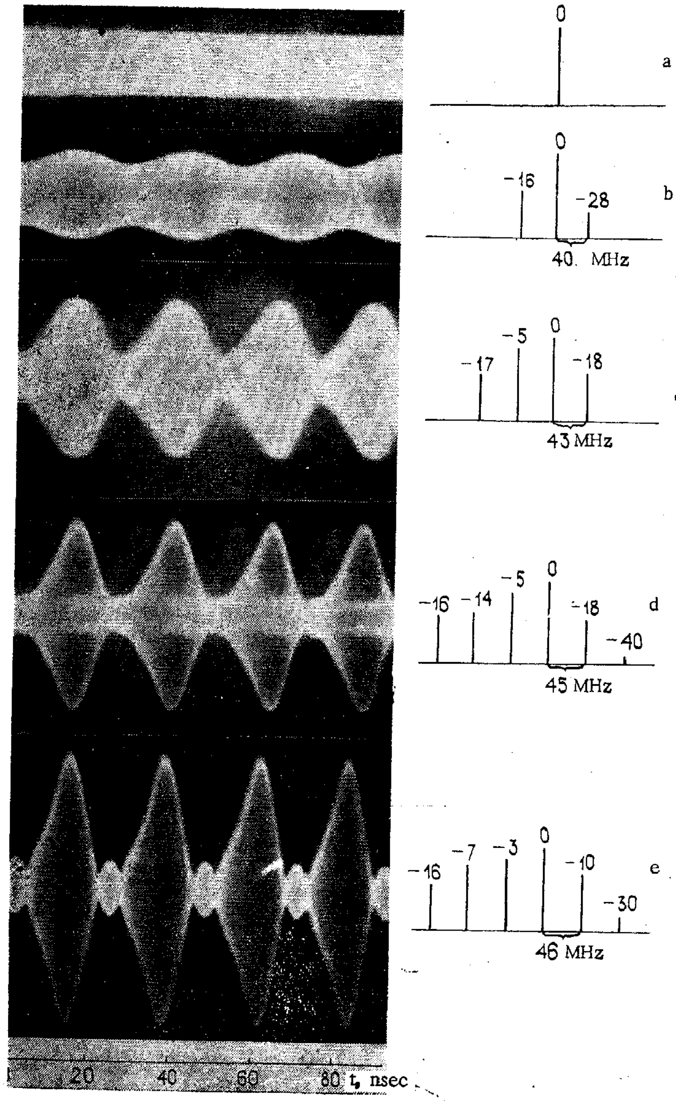


Fig. 5. Oscillograms and microwave spectra of BWO output signal in cw mode for $U_0 = 100$ V, $I/I_S = 2.5$ (a), 3.9 (b), 5.6 (c), 6.9 (d), 9.7 (e). The numbers next to the spectral line indicate the approximate level in decibels relative to the fundamental.

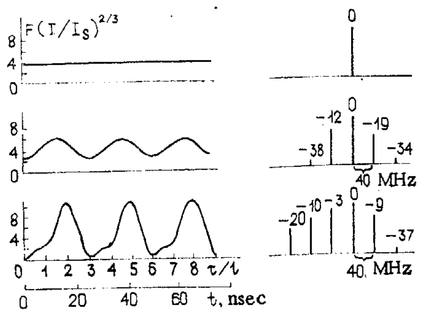

Fig. 6

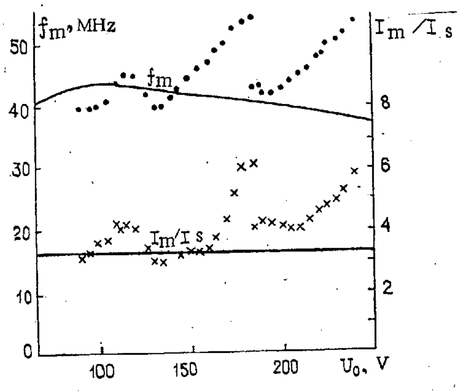

Fig. 7

Fig. 6. The left side shows theoretical plots of the BWO output signal amplitude as a function of time under steady-state conditions [3], $I/I_S = 2.5$ (a), and in a mode of steady-state self-modulation [1], $I/I_S = 3.5$ (b), 5.6 (c). The right side shows the corresponding microwave spectra obtained by numerical Fourier analysis of the complex signal amplitude. The numbers indicate the level of the components relative to the fundamental in decibels.

Fig. 7. Experimentally measured ratios of current to starting value at which self-modulation begins (crosses) and the corresponding frequency (points) as a function of accelerating voltage. The solid lines represent calculations using formulas (1) and (2).

a pulse generator. The width of the leading edge of the pulse was 30-50 nsec, this being much less than the duration of the linear settling phase of the oscillations. The same generator was used to trigger slave sweep of the high-speed oscillograph, whose y input was fed the BWT output signal directly. Under cw conditions, together with observation of the time picture on the oscillograph screen, we investigated the microwave spectrum of the signal and the amplitude-modulation spectrum (using a direct detection arrangement with a low-frequency spectrum analyzer).

## §2. Transient in Type O BWT Oscillator (Pulse conditions)

Under pulse conditions, the oscillograph screen displays the BWT output-signal envelope in the settling process. The process is of a pronounced fluctuation nature (the initial portion of the output-signal pulse is markedly smeared). The photograph yields directly the value of the oscillation increment, $\alpha \sim 0.05$ nsec$^{-1}$ (it is more convenient to use Fig. 4a; see below) and the duration of the linear phase, $t' \sim 180$ nsec. From this we find that the signal power at the very beginning of the process is around $8.7\ \alpha t' \sim 80$ dB than under steady-state condition, and corresponds to the shot-noise level in order of magnitude, this being approximately $10 \log (8\pi^2 efC/I) \sim -75$ dB [1].

To obtain a clear picture on the oscillograph screen, a fairly weak external signal was fed to the tube from the SSG (Fig. 2, dashed line), this providing a "primer" for the transient without having virtually any effect on its subsequent development.*

Figure 4 gives analogous theoretical plots in addition to oscillograms of the transient. In plotting the former, the time dependences of the oscillation amplitude as obtained in [1] were used; they were joined together with those obtained from the linear theory on the segment of exponential growth.

It is obvious from Fig. 4 that there is good qualitative agreement between theory and experiment. What is important is that the nature of the process changes in the same way as $I/I_S$ is varied. The period, the initial "swing," and the decrement in amplitude oscillations about the steady-state value correspond approximately to the theoretical value. For large $I/I_S$ a single-frequency steady-state mode of self-oscillation is not established, but rather we find nonattenuating modulation (as could be established by increasing the duration of the cutoff pulses), which is considered in greater detail in the section to follow for the case of a cw mode.

*By reasoning as at the beginning of Sec. 2, we can find that, given an external signal, the initial oscillation level in the BWT is 40-50 dB lower than the steady-state value and 20-30 dB higher than the shot-noise level.

## §3. Self-Modulation of Output Signal under cw Conditions

Under cw conditions in the BWT, when the beam current exceeds the starting value we encounter single-frequency oscillations whose amplitude increases with the current (Fig. 5a). When the current exceeds some value $I_m$, self-modulation appears. Its shape is initially quasisinusoidal, and, in addition to the fundamental, its spectrum contains only two prominent side components (Fig. 5b). Then, for $I/I_s \geqslant 5.6$, the modulation assumes the form of a sequence of characteristic "spikes" with a shallower leading slope and a steeper trailing slope (Fig. 5c–e), as was predicted in [1] (see the theoretical plots in Fig. 6). Here the signal spectrum consists of a series of equidistant components, whose amplitude decreases with increasing distance from the fundamental. Note that similarities in the nature of the modulation were observed between theory and experiment for somewhat different $I/I_s$ values. The increase in modulation frequency with the current is more pronounced in experiment than in theory.

Figure 7 shows the result of measurements, at various points of the working range, of the ratio $I_m/I_s$ and the modulation frequency $f_m$ for $I \approx I_m$, and also calculations of these quantities based on formulas (1) and (2). The agreement between the theoretical and experimental $I_m/I_s$ and $f_m$ values is satisfactory. The abrupt jumps in the experimental relationships are evidently to be explained by wave reflection from the ends of the tube.

Our comparison of theory [1] and experiment shows that the major nonstationary phenomena and their behavior as a function of the beam current are correctly described by the theory. The observed discrepancies reduce to quantitative corrections and can evidently be accounted for by factors not allowed for in the theory (reflection, space charge, distributed attenuation). It is not possible, however, that more pronounced influence of these factors could lead to qualitative changes in the processes.

## LITERATURE CITED

1. N. S. Ginzburg, S. P. Kuznetsov, and T. N. Fedoseeva, Izv. Vyssh. Uchebn. Zaved., Radiofiz. (in press).
2. V. N. Shevchik and D. I. Trubetskov (editors), Electronics of Backward-Wave Tubes [in Russian], SU (1975), Chap. 3.
3. G. N. Rapoport, Dokl. Akad. Nauk SSSR, 117, No. 3, 411 (1957); N. F. Kovalev, V. I. Petrukhina, and A. V. Smorgonskii, Radiotekh. Élektron., 20, No. 7, 1574 (1975).
4. A. V. Brown, Proc. IRE, B-105, Suppl. No. 10, 486 (1958).