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High-power microwave amplifier based on overcritical relativistic electron beam without external magnetic field

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The high-power scheme for the amplification of powerful microwave signals based on the overcritical electron beam with a virtual cathode (virtual cathode amplifier) has been proposed and investigated numerically. General output characteristics of the virtual cathode amplifier including the dependencies of the power gain on the input signal frequency and amplitude have been obtained and analyzed. The possibility of the geometrical working frequency tuning over the range about 8%–10% has been shown. The obtained results demonstrate that the proposed virtual cathode amplifier scheme may be considered as the perspective high-power microwave amplifier with gain up to 18 dB, and with the following important advantages: the absence of external magnetic field, the simplicity of construction, the possibility of geometrical frequency tuning, and the amplification of relatively powerful microwave signals.
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Since the early 1980s, the beam-plasma systems using intense electron beams with virtual cathode (VC) attract great attention of scientific community in the area of plasma physics and high-power microwave (HPM) electronics.[1–9] Usually, such systems are considered as the sources of the impulses of high-power microwave radiation (up to several gigawatts power level) for such applications as plasma physics and techniques, high energy density physics, accelerator physics, radar and communication technologies, and as setups for ion acceleration and plasma heating.[3,6,7,10–15] VC oscillators (VCOs) (such as vircators, reditrons, and virtodes) are a special class of bremsstrahlung microwave generators, whose operation is based on the formation of a VC in an electron beam (usually relativistic) with overcritical current.[1,3,7,16–18] The main advantages of VCOs are the following: very high output microwave radiation power, a simple construction (let us emphasize that vircators can operate without external focusing magnetic field), fast rise time, the possibility of a simple frequency tuning and regime switching (tunability), rather short operation region and low demands on the quality of the electron beam.[4,6,7,19–23] The last property is of great importance when the oscillator is fed with short and low-quality beam formed by an explosion emission electron injector.[24]

At the same time, the important problem of HPM electronics is the development of effective high-power microwave amplifiers, especially the final amplifiers for the amplification of relatively power signals.[7] A perspective way for the solution of this problem is the use of the intense relativistic electron beam (REB) with near-critical or overcritical current as the active media of the amplifier. The formation of a VC in such system may provide the amplification of the input microwave signal on retention of the main advantages of VCOs.[25] This idea was first proposed in the work,[25] where the simple modification of vircator with the external signal input was experimentally investigated and the relatively effective amplification of the signal (with a gain of 4.5 dB) has been observed. By analogy with VCO, the amplifier based on the use of an electron beam in the regime of the VC formation may be called VC amplifier (VCA).

Nevertheless, many problems concerning the analysis of VCA's amplification mechanisms and characteristics and the development of the optimal schemes of VCA are still uninvestigated. In the context of the modern HPM electronics development, the solution of the above-mentioned problems is very important and timely. So, the present work is devoted to the 3D numerical study of the promising VCA scheme that is based on the well-known special scheme of the double-gap relativistic vircator with external electromagnetic feedback (virtode[26]) described and investigated in Refs. 27 and 28. The double-gap virtode has been chosen as the base for the amplifier development because of its following undoubted advantages in comparison with usual vircators: generation frequency stability, relatively high efficiency (one of the highest among VCOs), and the convenience of the external signal input.

Let us consider the scheme and the numerical model of the proposed VCA (see Fig. 1) and its differences from the virtode scheme.[27] The investigated VCA consists of a two-section (double-gap) rectangular radio frequency cavity. To the left of the resonating cavity, there is the cylindrical electron gun region 1 where a cathode 4 produces a solid cylindrical electron beam 10. In front of the cathode, there is the first anode grid 5. The rectangular resonator is divided into two parts (gaps) 2 and 3, the length of the first is adjustable, controllable by the tuning plunger 11 as shown in the figure. An aluminum foil between this gap 7 acts as the second grid. As distinct from the virtode, the VCA does not contain a

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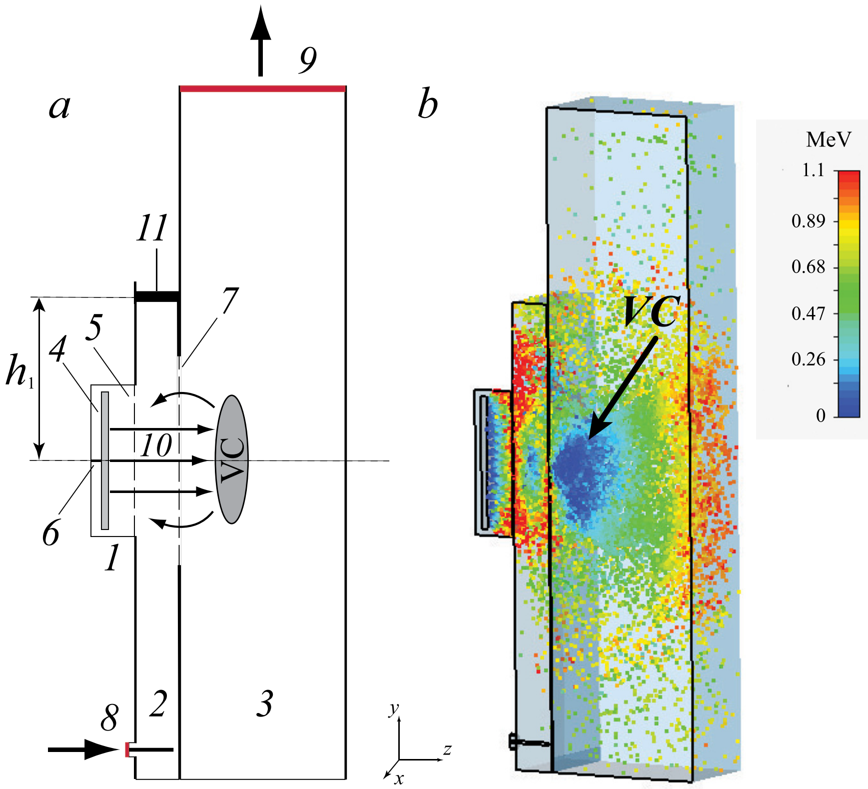

FIG. 1. (a) The scheme of the proposed virtual cathode amplifier. Here, 1—the electron gun region, 2—the first gap of the resonator, 3—the second gap of the resonator, 4—the cathode of the electron gun, 5—the anode grid, 6—a voltage generator (the discrete voltage port), 7—the second grid, 8—the input coaxial waveguide (the input waveguide port), 9—the output rectangular waveguide (the output waveguide port), 10—schematically shown solid electron beam, 11—tuning plunger. "VC" denotes schematically the virtual cathode area; h_1 defines the position of the plunger relative to the symmetry axis. VCA operates without external magnetic field. (b) The model of the VCA with a REB in CST Particle Studio shown in cross section. One can see the formation of VC in the second gap 3 of the VCA under the external signal effect in the first gap 2. The frequency and amplitude of the input signal are $f_{in} = 1.14$ GHz and $A_{in} = 6$ kV.

window between the two gaps of the resonator that provides the electromagnetic feedback in the virtode. The amplified (input) signal is introduced into the VCA through the coaxial waveguide 8 connected to the side wall of the first resonator gap. The output signal is extracted from the top of the device's second gap 9 that operates, actually, as the rectangular waveguide. The considered VCA operates without the application of an external magnetic field. So, the first gap in the VCA model serves as the premodulating area, where the input signal interacts with the REB, and the second gap—as the interaction space, where a VC is formed and radiates an electromagnetic microwave power.

Analyzing the relativistic VCA, it is necessary to take into account the effects that were insignificant for the weakly relativistic systems, in particular, the influence of the self-magnetic fields of a REB.[14,29] For that reason, the 3D fully electromagnetic particle-in-cell solver from CST Particle Studio is used in this work for the accurate numerical investigations of processes occurring in the relativistic VCA.

The discrete voltage port acts as the voltage source in the considered VCA model and provides the accelerating voltage pulse of 1.1 MV between the cathode and the anode grids for 300 ns with the smooth rise time of 10 ns. The cathode acts as the particle source inside the gun region. The electron beam is emitted using the DC emission model with a current of $I_0 = 16.9$ kA. This value is above the first critical current, I_{cr1}, and slightly below the second critical current, I_{cr2}, of the double-gap virtode

$$I_{cr1} < I_0 < I_{cr2}, \tag{1}$$

where $I_{cr1} \approx 10$ kA is the current above which VC starts to reflect electrons (the first critical current) and $I_{cr2} \approx 17.6$ kA is the current above which the part of reflected electrons increases essentially and microwave generation becomes possible (the second critical current).[27,28,30] The VCA power output is modelled with the help of the waveguide port 9 that simulates an infinitely long rectangular waveguide connected to the structure and is characterized by very low levels of reflections. The similar model was used earlier for the simulations of the aforementioned double-gap virtode[27] that have shown a good agreement with the experimental studies.[31]

The parameters of the considered VCA scheme with a REB were chosen in the process of its optimization as follows: the cathode radius—49 mm, the electron gun radius—54 mm, the distance (along the y-axis) between the gun center and the system bottom—227 mm, the distance (along the z-axis) between the cathode and the anode grids—21.5 mm, the resonator width (along the x-axis)—140 mm, the height (along the y-axis) of the first gap—347 mm, that corresponds to $h_1 = 120$ mm, the distance between the anode grid and the second grid—30 mm, the distance between the second grid and the system end—119 mm, the position of the output waveguide along the y-axis relative to the system bottom—494 mm, the position of the input coaxial waveguide along the y-axis relative to the system bottom—21 mm, the inner and the outer radii of the input waveguide—1 mm and 5 mm, and the length of the part of the input waveguide inner core inside the first gap—28 mm. The important parameter here is the position of the input waveguide that was defined from the conditions of the minimization of the signal reflected back to the input waveguide and the maximization of the interaction efficiency of the electron beam with the input signal that provide a maximal amplification efficiency. Note that the power leak through the input waveguide leads to an essential decrease of amplification coefficient. The optimal allocation of the input was defined when carried out in CST Particle Studio optimization procedure.

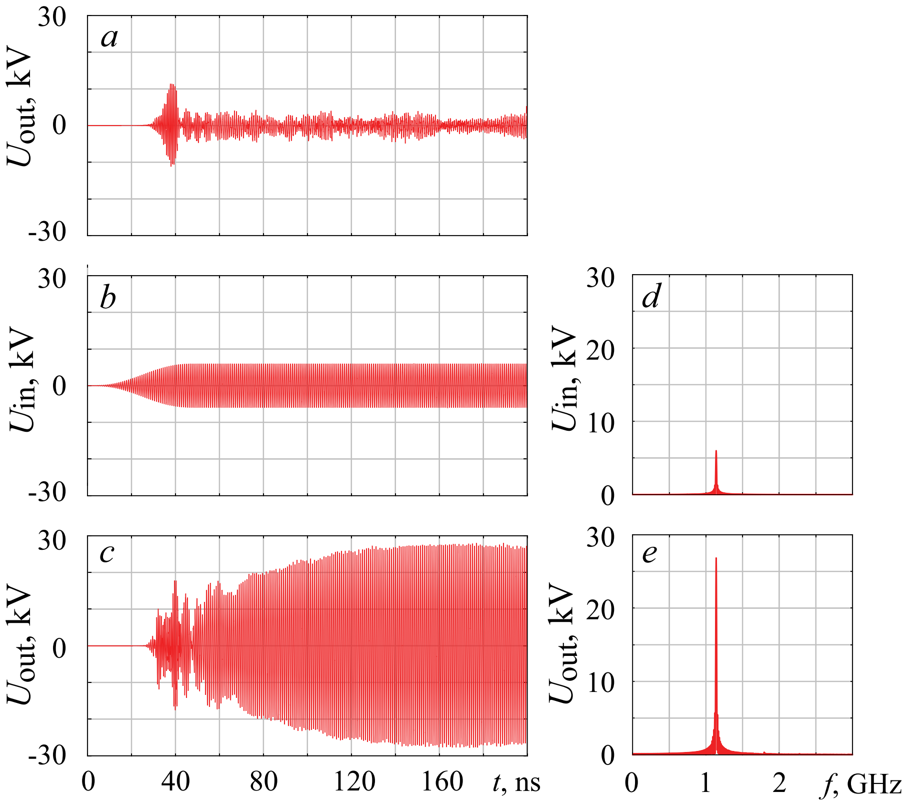

FIG. 2. The output signals (a) and (c) at the first TE-mode of the output waveguide and the signal fed to the input waveguide (b) of the VCA. The signal (a) corresponds to the case when no signal is fed to the input waveguide and the signal (c)—to the case when the signal (b) is fed to the input waveguide. Figures (d) and (e) demonstrate the amplitude Fourier spectra of the signals (b) and (c) in the stable regime, respectively. The frequency of the input signal is $f_{in} = 1.14$ GHz, its amplitude $A_{in} = 6$ kV, and the amplitude of the amplified signal (c) $A_{out} = 28$ kV.

Let us consider the results of the numerical investigation of the VCA model and its output characteristics. Fig. 2 demonstrates the VCA output signals and the amplitude Fourier spectra at the working TE-mode of the output rectangular waveguide for the cases without (Fig. 2(a)) and with (Fig. 2(c)) input signal that is shown in Fig. 2(b). One can see that the investigated VCA does not demonstrate the stable output microwave radiation in the absence of the input signal except for the small time interval at the beginning of the pulse when there is a short burst at the output signal due to the transient processes in the device (Fig. 2(a)). This result indicates that generation process is not developed in the system with near-critical current (1) and without coupling window and external input signal. Also we may conclude that under such conditions a developed oscillating VC is not formed in the second gap of the VCA, and the REB is the active media able to amplify an external signal. This effect shown in Figs. 2(b)–2(e) demonstrates the corresponding amplitude spectra. Actually, the input signal is amplified by 4.7 times in amplitude due to VC formation under external microwave signal influence. Fig. 1(b) illustrates the VC formation (marked by arrow "VC") in the second gap under the external signal applied to the first gap of VCA without magnetic field. The amplified output signal (Fig. 2(c)) has a stable amplitude and frequency after the transient process (see Fig. 2(e)) that takes as a rule about 80 – 120 ns, while the rise time of the input signal is 40 ns. As a consequence, the double-gap VCA can be considered as a typical regenerative amplifier such as, for example, backward wave oscillator operating below its self-excitation threshold and providing microwave amplification in regenerative amplification regime.[24,32]

Fig. 3 demonstrates the dependency of the power gain of the VCA on the input signal frequency. One can see that the proposed VCA is a narrow-band amplifier with bandwidth ~0.6% whose working frequency (where K reaches the maximal value, see Fig. 3) $f_{w1} \approx 1.14$ GHz is determined by the frequency of the TM_{110} mode of the first gap. This mode has one variation of E_z-field along the y-direction of the first gap with the maximum in the region of the electron beam propagation, so it interacts with a REB in the best way and modulates it at the frequency of the input signal. From the physical point of view, the introduction of the input signal into the system and the subsequent REB modulation switch it in the regime with a developed VC (into the second gap) that results in the signal amplification. The second small peak on the $K(f_{in})$ dependency at the frequency $f_{w2} \approx 1.35$ GHz corresponds to the excitation of the TM_{120} mode of the first gap, but the interaction efficiency of the REB with this mode is relatively low for the investigated VCA. Narrow frequency band is obviously a strong selective property of the

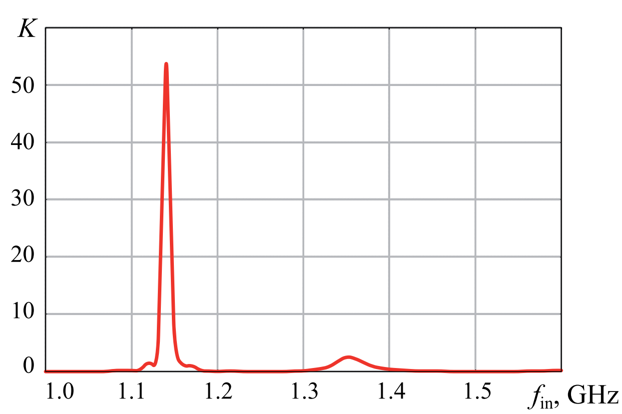

FIG. 3. The dependency of the power gain K of the VCA on the input signal frequency f_{in}; $A_{in} = 0.5$ kV.

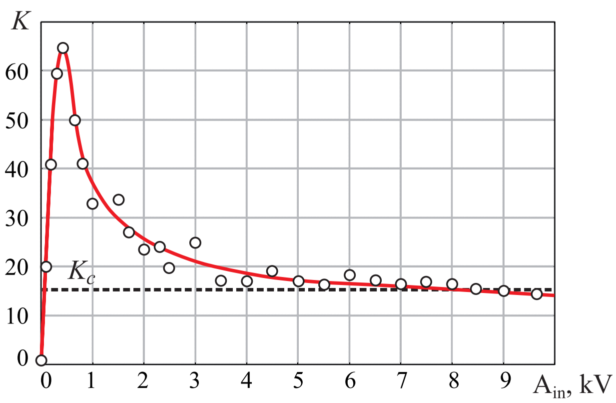

FIG. 4. The dependency of the power gain K of the VCA on the input signal amplitude A_{in}; $f_{in} = 1.14$ GHz. The dots denote the data of the numerical studies and the curve—approximation.

VCA, which also decreases the electron beam noises effect on the operation of the device.[24]

For the analysis of the influence of the input signal amplitude A_{in} on the amplification coefficient of the VCA, the dependency $K(A_{in})$ was obtained and shown in Fig. 4. The optimal value of A_{in} corresponding to the maximal power gain $K \approx 65$ is about 0.5 kV. The input signal with lower amplitude $A_{in} < 0.5$ kV does not provide a proper modulation of the beam resulting in the significant decrease of the power gain K. The introduction into the VCA of the more powerful input signal with amplitude $A_{in} > 0.5$ kV causes the overmodulation of the REB that has a negative impact on the VC formation process and, hence, leads to the decrease of the power gain. Also the power leak through the input waveguide rises with the growth of A_{in}. Nevertheless, these undesirable effects are stabilized for $A_{in} > 4$ kV, and the power gain K approaches the value $K_c \approx 15$ for $A_{in} \approx 10$ kV (see Fig. 4).

In spite of the VCA turned out to be a narrow-band amplifier, it is possible to realize its working frequency tuning over a wider range by means of the mechanical tuning of the first resonator gap, changing the position of the top plunger. This idea is illustrated in Fig. 5(a), where the dependencies $K(f_{in})$ obtained for different heights of the first gap are shown. Actually, the change of the first gap geometry leads to the variation of the working mode frequency and, as a consequence, to the tuning of the VCA working frequency: the greater the resonator height, the lower the working frequency (see the curve $f_w(h_1)$ in Fig. 5(b)). The carried out investigations show that the geometric tuning in the considered VCA makes possible the frequency tuning of the device up to 8%–10% of the mean frequency (~1.14 GHz), with the power gain K being practically constant up to 1.15 GHz (see the curve $K_{max}(f_w)$ in Fig. 5(c)). The decrease of K for $f_w >$ 1.15 GHz is the consequence of the reduction in the interaction efficiency of the electron beam with the fields of the first gap resonator, as its height decreases with the frequency growth. Also, the signal input (whose allocation was optimized for $h_1 = 120$ mm) becomes nonoptimal with a relatively strong change of the resonator height. Note that the working frequency is limited from above because of the height of the first gap in the considered VCA (based on the known virtode scheme[26,27]) cannot be less than the electron

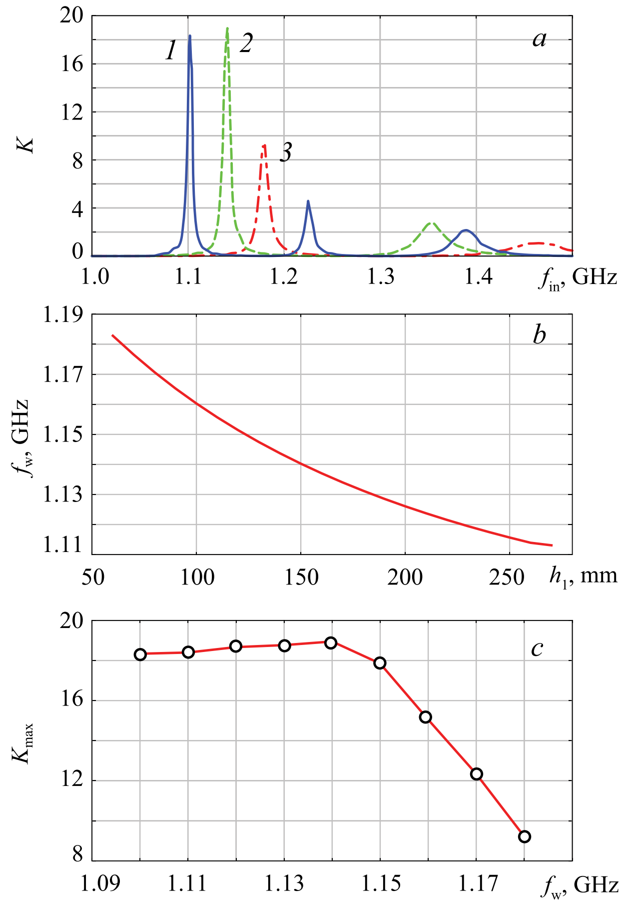

FIG. 5. (a) The dependencies of the power gain K of the VCA on the input signal frequency f_{in} for different positions of the plunger h_1: curve 1 corresponds to $h_1 = 270$ mm, 2—$h_1 = 120$ mm, and 3—$h_1 = 60$ mm (this value is close to the electron gun radius); $A_{in} = 6$ kV. (b) The dependency of the VCA working frequency f_w on the position of the plunger h_1. (c) The dependency of the maximal power gain K_{max} on the working frequency f_w.

beam radius. Nevertheless, the VCA may be advanced to the higher frequency range by reducing its character dimensions, particularly the electron gun radius owing to the basic physical concepts underlying the VCA amplification mechanism are not changed with the decrease of the device dimensions.

So, the obtained results demonstrate that the proposed virtual cathode amplifier scheme may be considered as the perspective high-power microwave amplifier with the following important advantages: the absence of external magnetic field, the simplicity of construction, the possibility of geometrical frequency tuning, and the amplification of relatively power microwave signals, with maximal power gain being about 18 dB and mean power gain—about 12 dB. The last VCA feature allows one to consider it as the perspective high-power relativistic final amplifier.

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[1] R. A. Mahaffey, P. A. Sprangle, J. Golden, and C. A. Kapetanakos, "High-power microwaves from a non-isochronous reflecting electron system," Phys. Rev. Lett. **39**, 843 (1977).
[2] A. N. Didenko, Y. Krasik, S. P. Perelugin, and G. P. Fomenko, "Generation of power microwave radiation of relativistic beam in triode system," Tech. Phys. Lett. **5**, 321 (1979).
[3] D. J. Sullivan, J. E. Walsh, and E. A. Coutsias, "Virtual cathode oscillator (vircator) theory," in *High Power Microwave Sources*, edited by V. L. Granatstein and I. Alexeff (Artech House Microwave Library, 1987), Vol. 13.
[4] V. L. Granatstein and I. Alexeeff, *High Power Microwave Sources* (Artech House Microwave Library, 1987).
[5] S. H. Gold and G. S. Nusinovich, "Review of high-power microwave source research," Rev. Sci. Instrum. **68**, 3945–3974 (1997).
[6] A. E. Dubinov and V. D. Selemir, "Electronic devices with virtual cathodes (review)," J. Commun. Technol. Electron. **47**, 575 (2002).
[7] J. Benford, J. A. Swegle, and E. Schamiloglu, *High Power Microwaves* (CRC Press, Taylor and Francis, 2007).
[8] L. Li, L. Liu, G. Cheng, Q. Xu, H. Wan, L. Chang, and J. Wen, "The dependence of vircator oscillation mode on cathode material," J. Appl. Phys. **105**, 123301 (2009).
[9] L. Li, G. Cheng, L. Zhang, X. Ji, L. Chang, Q. Xu, L. Liu, J. Wen, C. Li, and H. Wan, "Role of the rise rate of beam current in microwave radiation of vircator," J. Appl. Phys. **109**, 074504 (2011).
[10] A. E. Dubinov, Y. I. Kornilova, and V. D. Selemir, "Collective ion acceleration in systems with a virtual cathode," Phys.-Usp. **45**, 1109–1129 (2002).
[11] D. Biswas, "A one-dimensional basic oscillator model of the vircator," Phys. Plasmas **16**, 063104 (2009).
[12] R. A. Filatov, A. E. Hramov, Y. P. Bliokh, A. A. Koronovskii, and J. Felsteiner, "Influence of background gas ionization on oscillations in a virtual cathode with a retarding potential," Phys. Plasmas **16**, 033106 (2009).
[13] V. Baryshevsky, A. Gurinovich, P. Molchanov, S. Anishchenko, and E. Gurnevich, "2-D simulation and experimental investigation of an axial vircator," IEEE Trans. Plasma Sci. **41**, 2712–2716 (2013).
[14] S. A. Kurkin, A. E. Hramov, and A. A. Koronovskii, "Microwave radiation power of relativistic electron beam with virtual cathode in the external magnetic field," Appl. Phys. Lett. **103**, 043507 (2013).
[15] S. A. Kurkin, A. A. Badarin, A. A. Koronovskii, and A. E. Hramov, "Higher harmonics generation in relativistic electron beam with virtual cathode," Phys. Plasmas **21**, 093105 (2014).
[16] A. E. Hramov, A. A. Koronovskii, and S. A. Kurkin, "Numerical study of chaotic oscillations in the electron beam with virtual cathode in the external non-uniform magnetic fields," Phys. Lett. A **374**, 3057–3066 (2010).
[17] S. A. Kurkin, A. A. Koronovskii, and A. E. Hramov, "Output microwave radiation power of low-voltage vircator with external inhomogeneous magnetic field," Tech. Phys. Lett. **37**, 356–359 (2011).
[18] N. S. Phrolov, A. A. Koronovskii, Y. Kalinin, S. A. Kurkin, and A. E. Hramov, "The effect of an external signal on output microwave power of a low-voltage vircator," Phys. Lett. A **378**, 2423–2428 (2014).
[19] S. C. Burkhart, R. D. Scarpetty, and R. L. Lundberg, "A virtual cathode reflex triode for high power microwave generation," J. Appl. Phys. **58**, 28 (1985).
[20] R. F. Hoeberling and M. V. Fazio, "Advances in virtual cathode microwave sources," IEEE Trans. Electromagn. Compat. **34**, 252–258 (1992).
[21] S. A. Kurkin and A. E. Hramov, "Virtual cathode formation in annular electron beam in an external magnetic field," Tech. Phys. Lett. **35**, 23–25 (2009).
[22] A. E. Hramov, A. A. Koronovsky, S. A. Kurkin, and I. S. Rempen, "Chaotic oscillations in electron beam with virtual cathode in external magnetic field," Int. J. Electron. **98**, 1549–1564 (2011).
[23] K. R. Clements, R. D. Curry, R. Druce, W. Carter, M. Kovac, J. Benford, and K. McDonald, "Design and operation of a dual vircator HPM source," IEEE Trans. Dielectr. Electr. Insul. **20**, 1085–1092 (2013).
[24] E. B. Abubakirov and A. P. Konyushkov, "Peculiarities of backward-wave amplification by relativistic high-current electron beams," IEEE Trans. Plasma Sci. **38**, 1285–1291 (2010).
[25] M. V. Fazio, J. Kinross-Wright, B. Haynes, and R. F. Hoeberling, "The virtual cathode microwave amplifier experiment," J. Appl. Phys. **66**, 2675–2677 (1989).
[26] N. N. Gadetskii, I. I. Magda, S. I. Naisteter, Y. Prokopenko, and V. I. Tchumakov, "The virtode: A generator using supercritical REB current with controlled feedback," Plasma Phys. Rep. **19**, 273 (1993).
[27] A. S. Shlapakovski, T. Queller, Y. Bliokh, and Y. E. Krasik, "Investigations of a double-gap vircator at sub-microsecond pulse durations," IEEE Trans. Plasma Sci. **40**, 1607–1617 (2012).
[28] B. M. Kovalchuk, S. D. Polevin, R. V. Tsygankov, and A. A. Zherlitsyn, "S-band coaxial vircator with electron beam premodulation based on compact linear transformer driver," IEEE Trans. Plasma Sci. **38**, 2819–2824 (2010).
[29] A. E. Hramov, S. A. Kurkin, A. A. Koronovskii, and A. E. Filatova, "Effect of self-magnetic fields on the nonlinear dynamics of relativistic electron beam with virtual cathode," Phys. Plasmas **19**, 112101 (2012).
[30] V. S. Voronin, Y. T. Zozulya, and A. N. Lebedev, "Self-consistent stationary state of a relativistic electron beam in a drift space," Sov. Phys. Tech. Phys. **17**, 432–436 (1972).
[31] S. A. Kurkin, A. A. Koronovskii, A. E. Hramov, and A. O. Rak, "Optimization of the double-gap vircator with electromagnetic feedback in CST particle studio," in *IEEE International Vacuum Electronics Conference* (2014), pp. 389–390.
[32] S. E. Tsimring, *Electron Beams and Microwave Vacuum Electronics* (John Wiley and Sons, Inc., Hoboken, New Jersey, 2007).