Investigations of a Double-Gap Vircator at Submicrosecond Pulse Durations

Anatoli S. Shlapakovski, Tal Queller, Yuri P. Bliokh, and Yakov E. Krasik

***Abstract*—The results of investigations of a double-gap vircator driven by a 20 Ω and 500-ns generator operating in the output voltage range 400–600 kV are presented. The vircator generated microwave pulses with a peak power of up to 200 MW at ∼5% efficiency and the frequency varied from 2.0 to 2.3 GHz depending on the cavity geometry. The limitations on the microwave pulse duration not related to the cathode plasma expansion are addressed. On the one hand, the microwave generation is terminated because of the plasma formation at the foil separating the cavity sections, so that the virtual cathode (VC) electron space charge is neutralized by the plasma ion flux. On the other hand, if the electron beam energy deposition into the foil is reduced, a substantial delay in the start time of the microwave generation appears, which has been studied in detail. With these limiting factors, the microwave pulse full duration varied from 100 to 350 ns; the maximal full width at half maximum duration achieved in the experiments was ∼180 ns. Measurements of the current transmitted through the vircator cavity indicated the existence of a VC in spite of the absence of microwave generation during the delay. The experimental dependence of the microwave generation starting current on the diode voltage is presented, and possible mechanisms behind the generation delay are discussed. Simplified numerical simulations emphasize the role of the portion of electrons that are reflected from the VC, the number of which must be sufficient for the microwave generation to occur.**

***Index Terms*—High-power microwaves, microwave pulse shortening, vircators.**

I. Introduction

Virtual cathode oscillators (VIRCATORS) as noted in [1] are probably the most popular of high-power microwave sources for many reasons. Particularly attractive is the fact that an electron beam in a vircator is generated in a planar or coaxial diode and interacts with RF fields in a cavity or waveguide without an external magnetic field being applied. This advantage, however, causes microwave pulse shortening due to the cathode plasma expansion across the anode-cathode (AK) gap. The latter is particularly important in the submicrosecond (sub-μs) time scale when the decrease in the diode voltage and increase in the current during the accelerating pulse lead to a change in the vircator's characteristic frequencies, i.e., unbalanced resonances, radiation frequency chirping, and a drop in the output power [1]. Meanwhile, it was shown [2]–[6] that for such cathode materials as velvet or CsI-coated carbon fibers, the relatively low plasma expansion velocity is $\leq 10^6$ cm/s at current densities up to hundreds of A/cm^2. Thus, other factors that limit the duration of the microwave output pulse become important, such as the plasma formation within the cavity of the vircator. In addition, an accelerating voltage may not have a flat-top part depending on the generator used, which is often the case in the sub-μs time scale [7]–[9]. With regard to the latter, the double-gap vircator with electron beam premodulation [10] is a vircator promising for operation at sub-μs time scale.

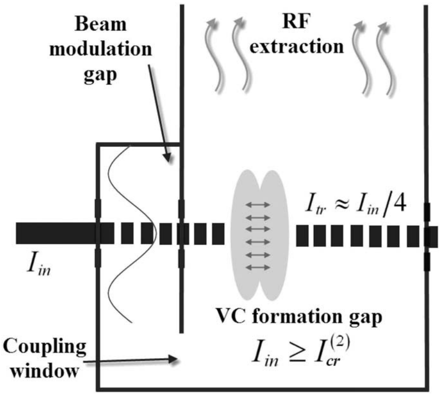

Fig. 1. Schematic of the double-gap vircator interaction space.

As has been proposed and realized earlier in the virtode [11], in the double-gap vircator, feedback is introduced that allows increased efficiency and frequency stability. This is achieved with a single-mode two-sectional RF cavity (see Fig. 1): the electron beam passes through the first, short section, and forms the virtual cathode (VC) in the second, longer one. An RF field modulates the beam in the first gap, and thus the feedback is realized, so that the radiation frequency is set by the geometry. The main condition that provides relatively efficient (5–7%) microwave generation in the double-gap vircator is that the beam current I_{in} only slightly exceeds the critical value that limits beam propagation through the second gap. This condition embodies the idea that a microwave generation mechanism that is based on the self-oscillations of the VC is less efficient than that based on the instability that develops from the two-stream quasistationary state with the VC [12]. In Fig. 1, $I_{cr}^{(2)}$ is the "second critical current" [13], above which no one-stream stationary state of the beam within an equipotential gap exists. According to the 1-D model of the two-stream stationary state

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The authors are with the Department of Physics, Technion-Israel Institute of Technology, Haifa 32000, Israel (e-mail: shl@physics.technion.ac.il; kt@techunix.technion.ac.il; bliokh@physics.technion.ac.il; fnkrasik@physics.technion.ac.il).

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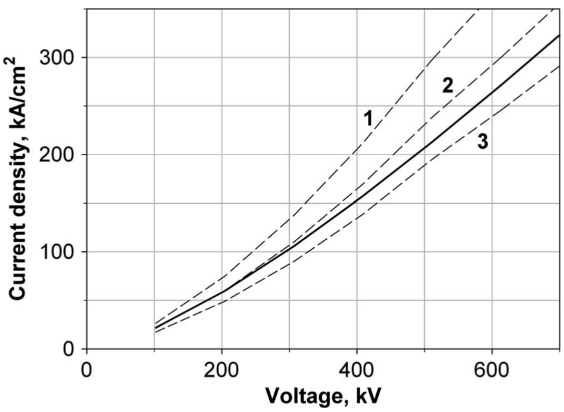

Fig. 2. Solid curve—second critical current density for the planar 5-cm gap calculated according to [13]. Dashed curves—relativistic Child-Langmuir current density for planar diodes with AK gaps of: 1–17 mm; 2–19 mm; 3–21 mm.

[13], if $I_{in} \approx I_{cr}^{(2)}$, the current I_{tr} transmitted through the cavity is $\approx$25% of I_{in}.

The fact that for efficient microwave generation slight supercriticality of the beam current is needed suggests that the double-gap vircator is a good candidate for operation at sub-μs time scales. Indeed, the dependence of the space-charge-limiting current on the kinetic energy of electrons injected into the cavity is actually the same as the voltage dependence of the Child-Langmuir current. Hence, the condition for efficient generation can be maintained for hundreds of nanoseconds in cases when the accelerating voltage changes. The calculation that illustrates this issue is shown in Fig. 2. One can see that for the given length of the second cavity gap, there is an optimal AK gap of the planar diode (19 mm, curve 2), at which the condition $I_{in} \geq I_{cr}^{(2)}$ is satisfied over a wide range of diode voltages. Thus, investigations of double-gap vircators powered by sub-μs generators are of interest.

The first such experimental studies were performed using a generator based on inductive energy storage [14]; later, the water pulse-forming line was employed [15]. In [14], [15], accelerating voltages approached 1 MV, and a peak output microwave power of $\sim$1 GW was obtained at $\sim$5% generation efficiency. Radiation frequency stability during the pulse was demonstrated; however, the microwave pulse was shortened ($\sim$50 ns full width at half maximum (FWHM) with the inductive storage and $\leq$100 ns FWHM with the water pulse-forming line). The results of numerical simulations [14], [15] showed that one could expect longer pulses, even if one takes into account changes in the diode impedance. Therefore, the pulse shortening was explained by the appearance of plasma in the modulating gap of the vircator cavity. This plasma was synthesized in the simulations [14], [15] by turning on the electron and ion emission from the modulating section walls, which resulted in the termination of the microwave generation.

Experiments with lower ($\leq$ 600 kV) accelerating voltages were carried out in [16]–[18] (pulse durations $\leq$ 600 ns). In [16], the microwave power was $\leq$ 100 MW with an FWHM of microwave pulses of $\sim$100 ns, so that the RF breakdown in the vircator cavity was rather improbable. Thus, it was supposed that the microwave pulse duration depends mainly on the expansion of the cathode plasma. This effect was studied by comparing the operation of the vircator when using different cathode materials. The velvet cathode gave the best results in terms of the duration of the microwave pulse: the maximum full pulse length achieved was almost 400 ns, though, with unstable power during the pulse. An important finding in [16] was the delay in the beginning of the microwave generation with respect to the start of the accelerating pulse: the delay increased with the increasing AK gap and could reach 300 ns. This was an additional factor that limited the duration of the microwave pulse in that study. The delay has been explained by the role of electrons returning back into the cavity from the AK gap; however, as is shown below, this has not been confirmed.

In a recent work [17], a novel, coaxial double-gap vircator was implemented. The coaxial configuration fits the compact linear transformer driver (300 kV, 20 kA, 250 ns) used in the experiments very well. In these experiments, in which a velvet cathode was employed, a microwave peak power of $\sim$300 MW was obtained at 130 ns FWHM pulse duration. A delay of up to 100 ns in microwave generation was also observed, but the authors did not comment on this effect.

Finally, in [18], for the first time, light emitted from within the vircator cavity was observed. Due to the improved design of the velvet cathode, the microwave output power was increased in comparison with [16] up to 200 MW (at the diode voltage of $\sim$500 kV and current of $\sim$10 kA). The AK gap in these experiments was fixed, and it was short enough to leave the effect of generation delay aside; as a result, the generated microwave pulses were suitably reproducible, with a full duration in the range 150–200 ns (FWHM duration in the range 80–130 ns). It was found that the surface plasma appears at the foil that separates the cavity sections. In addition, measurements of the current transmitted through the cavity indicated plasma formation. Thus, the destruction of the VC by the plasma ions was identified as the reason for the shortening of the microwave pulse.

The plasma production, as was shown in [18], is caused by sufficient energy density being deposited into the foil by beam electrons. Calculation results showed that the deposited energy density reaches 100 J/g, considered the threshold for the plasma formation [19], quickly enough, particularly when the contribution of electrons reflected from the VC[1] is taken into account. Therefore, to lengthen the microwave pulse, the amount of deposited energy should be reduced. This can be achieved by a decrease in the beam current, i.e., by an increase in the AK gap. However, when the AK gap is increased, the effect of generation delay comes into force to shorten the microwave pulse. Hence, optimizing a sub-μs double-gap vircator for maximum output pulse length is a problem of compromising between the two phenomena that lead to the pulse shortening from the opposite ends.

In this paper, new results of double-gap vircator investigations using the sub-μs generator [16], [18] are presented, and the aforementioned limitations on the microwave output pulse duration are addressed. In Section II, we briefly describe the experimental setup and preliminary experiments concerning

[1] It should be noted that the contribution of reflected electrons to the anode plasma production was also mentioned in [9] with regard to the triode vircator.

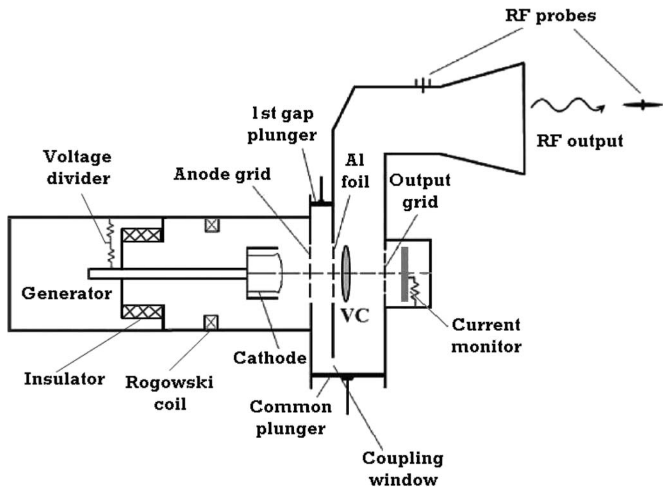

Fig. 3. Experimental setup.

the problem of the generation delay, namely, experiments at different operating frequencies (cavity modes). In Section III, data showing dependences of the generation delay versus diode parameters are presented, and the evolution of the current traversing the vircator cavity is analyzed. An important finding here is that the VC exists during the delay, although microwave generation does not occur. In Section IV, the voltage dependence of the generation starting current is presented and analyzed for the possible mechanisms causing the generation delay. A specific question is: What is the relationship between the generation starting current and the space-charge-limiting current? The results of the numerical simulations that confirm some explanations are also presented.

II. Setup and Preliminary Experiments

In the present research, the vircator was powered by a 20 Ω, 500-ns generator based on 21 pulse-forming networks with a maximal stored energy of 5 kJ at ±50-kV charging voltage. The setup of the double-gap vircator experiments is shown in Fig. 3. The electron beam is injected into the first section of the rectangular cavity through the stainless steel anode grid having ∼76% transparency. The lengths of the first and second sections are 1 cm and 6 cm, respectively, the width of the cavity is 10 cm, and the height of the sections and size of the coupling window are varied by adjusting plungers. In the plate separating the first and second sections, an aluminum foil of ~ 7.6 μm thickness is tightened. The beam current transmitted through the cavity is measured by a low-inductance Faraday cup (FC) with a graphite collector placed ∼7 cm behind the grid (the same as the anode one), which covers the opening in the cavity back wall. The operation of the vircator with the output grid was checked to ensure that was the same as when the back wall of the cavity is plain. The diode current is measured by a Rogowski coil (RC), and the accelerating voltage is measured by an active divider.

The microwave radiation is extracted through a horn antenna. The RF signal was registered by a 2.5-GHz Tektronix TDS7254B oscilloscope using a EG&G D-dot probe ACD-11(R) located at the axis of the antenna, 5 m away from the antenna aperture, and by a B-dot probe placed at the narrow wall of the WR-430 rectangular waveguide before the antenna input. The radiation power can be evaluated from the measured RF voltage, since we know the transmission coefficients for the probes and attenuation of cables.

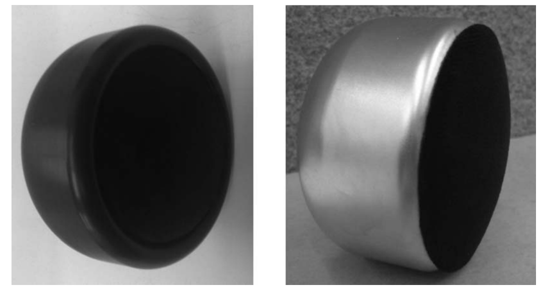

Fig. 4. Left: velvet cathode with the screening electrode coated with ceramics. Right: velvet cathode used in [16].

The external view of the velvet cathode used in the experiments is presented in Fig. 4 (left). Compared to the cathode used in [16] and shown in Fig. 4 (right), this is an improved design that allows a substantial enhancement of the microwave generation efficiency due to reduced current losses caused by a radial divergence of the electron beam. Some experiments carried out with the cathode of [16] should, nevertheless, be mentioned here. In these experiments, the longest microwave pulse durations at a stable frequency were obtained and preliminary studies of the generation delay were performed. In Fig. 5, the data for a typical shot resulting in a long microwave output pulse are presented. It is seen that the full microwave pulse duration is ∼350 ns and the radiation frequency remains almost unchanged during the entire pulse; the radiation pulse waveform, however, exhibits a fast drop. In the case of Fig. 5, the AK gap $d_{AK} = 19$ mm and the cavity geometry is characterized by the wide coupling window [16], so that there are two variations of the RF field between the adjusting plungers.

The effect of microwave generation delay was found in [16], when increasing the AK gap in an attempt to match the diode impedance to the optimal value for efficient operation, ~ 50 Ω, which was determined in earlier experiments [10], [14], [15]. It is seen from Fig. 5 that for $d_{AK} = 19$ mm, the impedance is ≤ 30 Ω. It was assumed in [16] that the microwave generation might be delayed at large AK gaps because the radiation frequency set by the cavity was higher than the frequency of electron oscillations between the VC and the real cathode. It was supposed therefore that by changing the cavity geometry to obtain a lower frequency, it could be possible to sustain vircator operation with a duration ≤300 ns without the generation delay that occurs with a large AK gap. To check this hypothesis, the coupling window of the cavity was decreased in size, so that the standing wave in the modulating gap had one variation. In Fig. 6, the results of two shots with a narrow coupling window are presented; they show that the frequency became lower. However, other parameters of the microwave pulses remained the same. Namely, at $d_{AK} = 19$ mm, the waveform of the microwave signal is very similar to that in Fig. 5 and at $d_{AK} =$ 22 mm, the same delay is observed as at the higher operating frequency [16]. Hence, the explanation that the generation is delayed by the influence of electrons returning back into the cavity from the diode has not been confirmed.

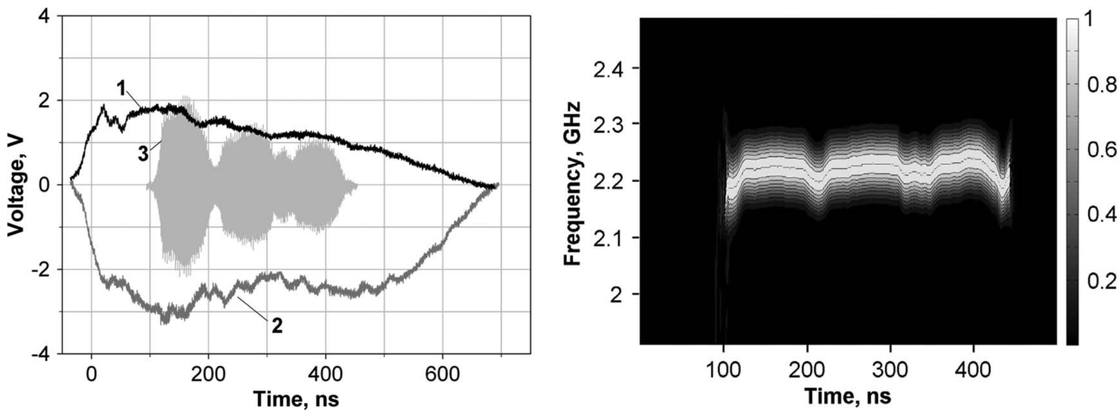

Fig. 5. Left: Accelerating voltage (1, 200 kV/div.), diode current measured by the RC (2, 5 kA/div.), and RF voltage from the B-dot probe (3). Right: Time variation of the radiation spectrum (the RF voltage Fourier transform within the 30-ns time window being shifted by a 1-ns time step). Cathode of [16], $d_{AK} =$ 19 mm, cavity geometry of [16].

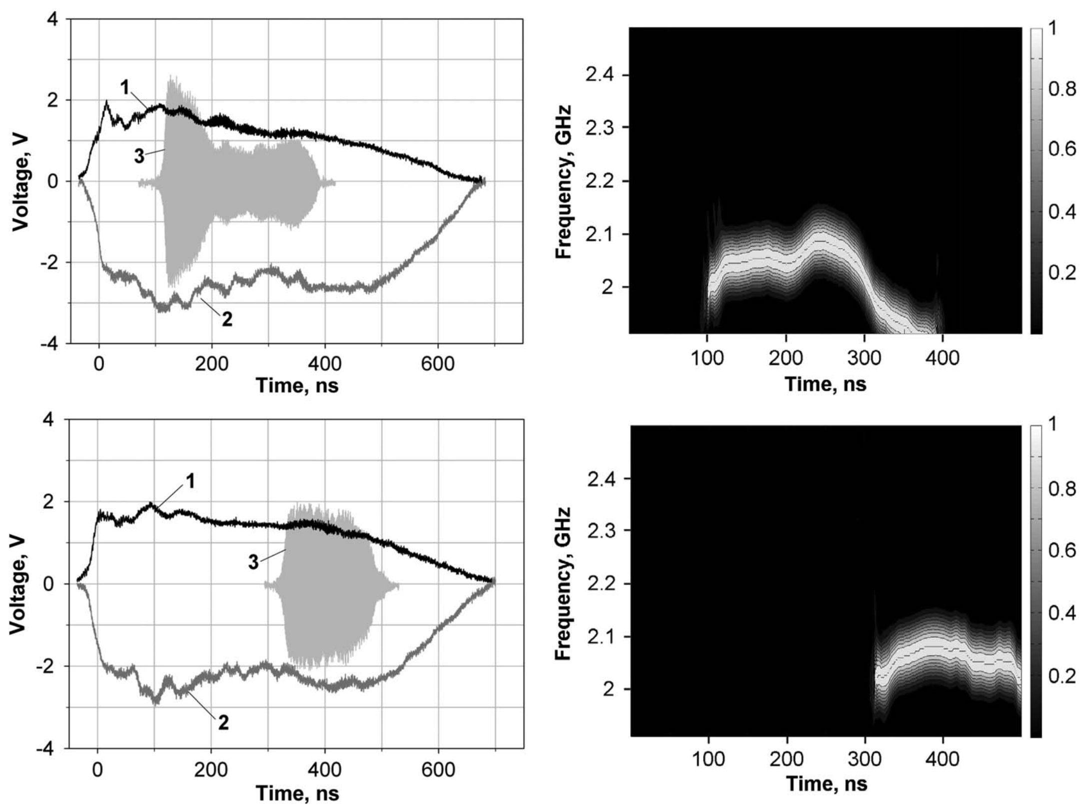

Fig. 6. Shots with the cathode of [16] at the modified geometry of the cavity providing a lower operation frequency. Top: $d_{AK} = 19$ mm. Bottom: $d_{AK} =$ 22 mm. Left: Accelerating voltage (1, 200 kV/div.), diode current (2, 5 kA/div.), and RF voltage from the B-dot probe (3). Right: Time variation of the radiation spectrum.

Furthermore, it can be noticed in Fig. 6 that the diode voltage and current obtained at different AK gaps are almost identical. This means that making the cathode emitting surface slightly convex (see Fig. 4) is not sufficient to compensate the edge effect, i.e., a substantial part of the electron current is emitted from the cathode edge. The latter leads to beam radial divergence and, respectively, increasing electrons losses on the way toward the vircator cavity with an increasing AK gap. Moreover, the beam current entering the vircator can become lower than the limiting current required for the VC formation. As a result, the microwave generation does not occur.

The modified design of the velvet cathode (Fig. 4, left) was therefore implemented. The improved cathode has a smaller diameter (66 mm instead of 76 mm), and the slightly convex velvet surface is surrounded by an aluminum screening electrode. This approach had been proven earlier to work well at accelerating voltages $\leq$300 kV [3], [4]. In the case of 400–600 kV voltages at an average electric field of up to 300 kV/cm, explosive emission plasma forms at the screening electrode, and the fast expansion of the plasma results in the diode closing. To avoid this, the surface of the screening electrode was coated with Al_2O_3 ceramics of $\sim$100 μm thickness. To confirm the improvement, experiments were carried out with the planar

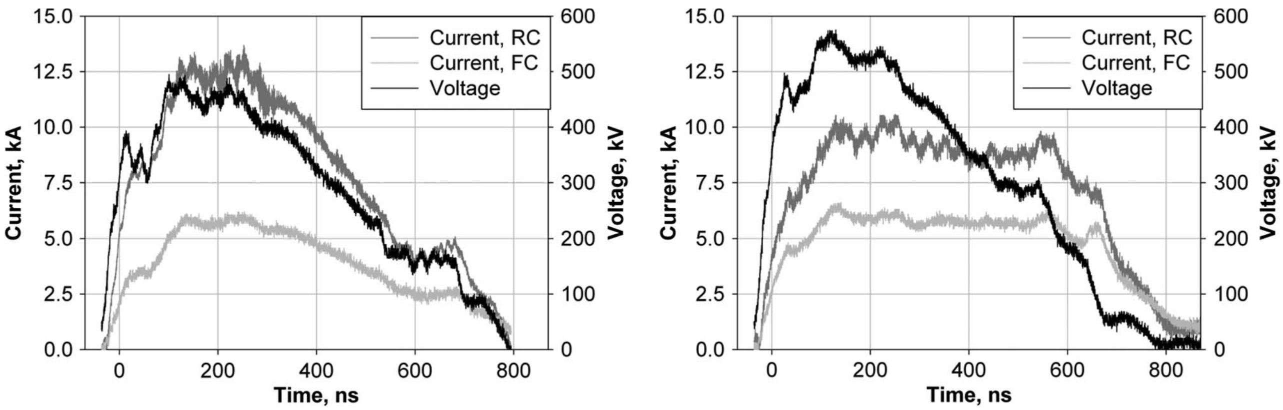

Fig. 7. Pulses of the diode voltage, total diode current, and current delivered to the FC behind the grid anode of the planar diode with the cathode of [16] (left) and improved cathode (right). $d_{AK} = 20$ mm.

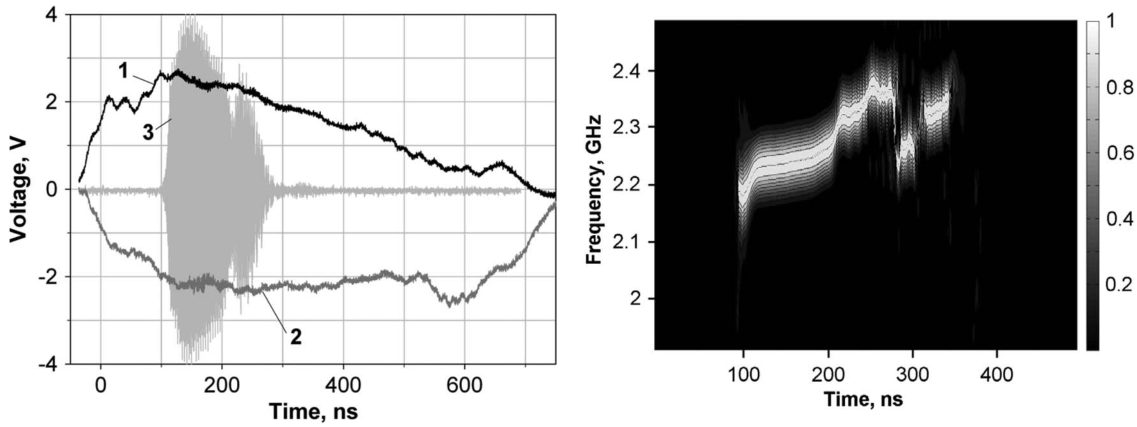

Fig. 8. Left: Accelerating voltage (1, 200 kV/div.), diode current (2, 5 kA/div.), and RF voltage from the B-dot probe (3). Right: Time variation of the radiation spectrum. Improved velvet cathode, $d_{AK} = 19$ mm, cavity geometry of [16].

diode and the same anode grid as that used in the vircator. The vircator geometry was modeled using a diaphragm of ∅80 mm (equal to the vircator opening) at the anode grid and an FC with a collector of ∅100 mm, the same diameter as that of the vircator foil. The FC was placed ∼1 cm behind the grid, the same distance as that between the grid and the foil in the vircator. The goal was to compare the current measured by the FC and the full diode current, which was measured by the RC.

The experiments have shown that the current losses with the cathode of [16] are, indeed, inadmissibly big. In the left plot of Fig. 7, typical voltage and current pulses obtained at $d_{AK} = 20$ mm are shown. It is seen that the current injected into the vircator cavity is only ∼45% of the diode current. For $d_{AK} = 24$ mm, the ratio of the FC to RC currents becomes as low as ∼30%. Meanwhile, for the modified cathode (the right plot of Fig. 7), the ratio of the FC to RC currents is about 70%, which is close to the grid transparency and remains practically unchanged when the AK gap is increased. The decrease in the current losses (due to suppression of the edge effect) leads to an increase in the diode voltage, with a respective increase in the impedance value, and to a dramatic increase in the microwave power generated by the vircator. The results of the shot with the modified cathode in the same conditions as for the shot in Fig. 5, except for the change in the cathode, are presented in Fig. 8. Comparing the RF voltage pulses in Figs. 5 and 8, one can see that with the improved cathode, the output radiation power is ∼3.5 times higher. The estimated value of the peak power in this case is above 200 MW. and the generation efficiency of ∼5% is the same as that obtained in earlier research [10], [14], [15], [17]. At the same time, the microwave pulse duration is seen to be limited (the full length is ∼200 ns) because of the formation of the foil plasma [18]. Further, all the results presented are obtained with the improved cathode and with the FC registering the current of electrons traversing the vircator cavity.

III. Microwave Generation Delay

In experiments [16], the value of the AK gap was identified as a factor that determines the delay in the start time of the microwave generation. Unlike in [16], the present studies of the delay were carried out at different fixed AK gaps with a varied (37—30 kV) generator charging voltage. Typical results showing the dependence of the vircator operation on the diode voltage are shown in Fig. 9 for $d_{AK} = 20$ mm. The cavity geometry for these results was the same as in [16]. It is seen that the value of the accelerating voltage affects the microwave generation process, namely, the generation delay increases with decreasing diode voltage. It is important to note that the radiation frequency, as one can see from the right plots

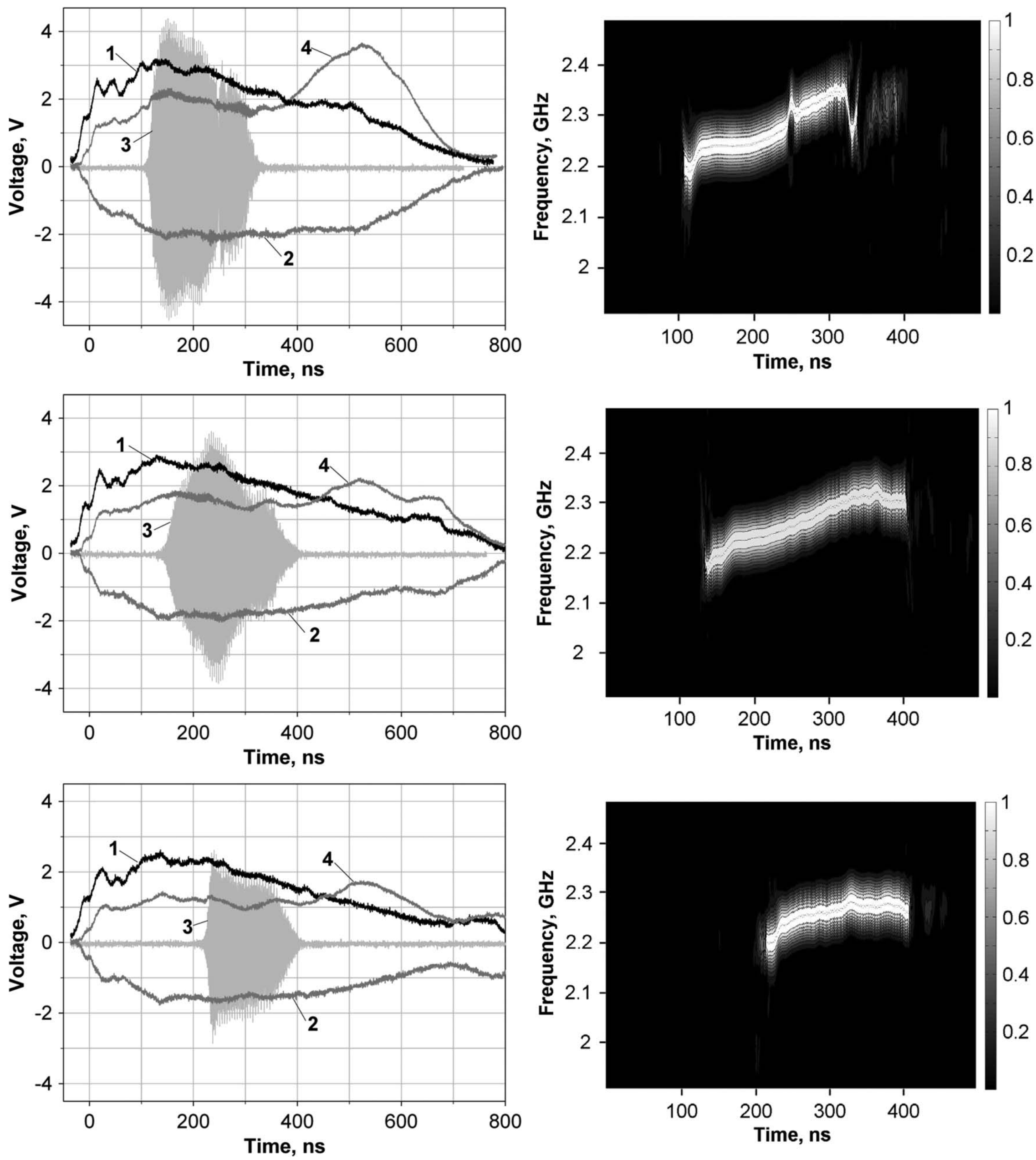

Fig. 9. Left: Accelerating voltage (1, 200 kV/div.), diode current (2, 5 kA/div.), RF voltage from the B-dot probe (3), and current traversing the cavity (4, 1 kA/div.). Right: Time variation of the radiation spectrum. Shots with the cavity geometry of [16] for $d_{AK} = 20$ mm and different charging voltages U_{ch} of the generator primary storage. From top to bottom, $U_{ch} = 37$, 34, and 30 kV.

of Fig. 9, practically does not change with the variation of the accelerating voltage. The radiation power naturally tends to decrease with decreasing electron beam power, but the generation efficiency weakly depends on it. As the accelerating voltage decreases, the microwave generation starts later, and also terminates later because a smaller beam energy is deposited into the foil. There are, nevertheless, some optima in terms of the microwave pulse full and FWHM durations; the maximum in the FWHM duration is achieved at a slightly higher charging voltage, i.e., accelerating voltage, than that in the full duration. At other values of AK gap, all the aforementioned tendencies are similar. With a larger AK gap, a higher diode voltage is required to avoid the generation delay; with a smaller gap, a lower voltage is sufficient for the generation to start even at the stage of the voltage rise. The latter is shown in Fig. 10 (top), where the data corresponding to the shot with $d_{AK} =$ 15 mm are shown. The waveform of the microwave pulse in this case is close to rectangular and the frequency is stable, but the peak power is low, and the pulse duration is rather short. For comparison, in Fig. 10 (bottom), the data corresponding to the shot with $d_{AK} = 19$ mm at the same charging voltage (i.e., lower diode current but higher accelerating voltage) are shown. At these parameters, the longest FWHM duration of the generated microwave pulse ($\sim$180 ns) was achieved. The frequency drift during the pulse in this case is more noticeable.

One can conclude from these results that the factor that determines the microwave generation delay is not the size of the AK gap, but rather the magnitude of the electron beam

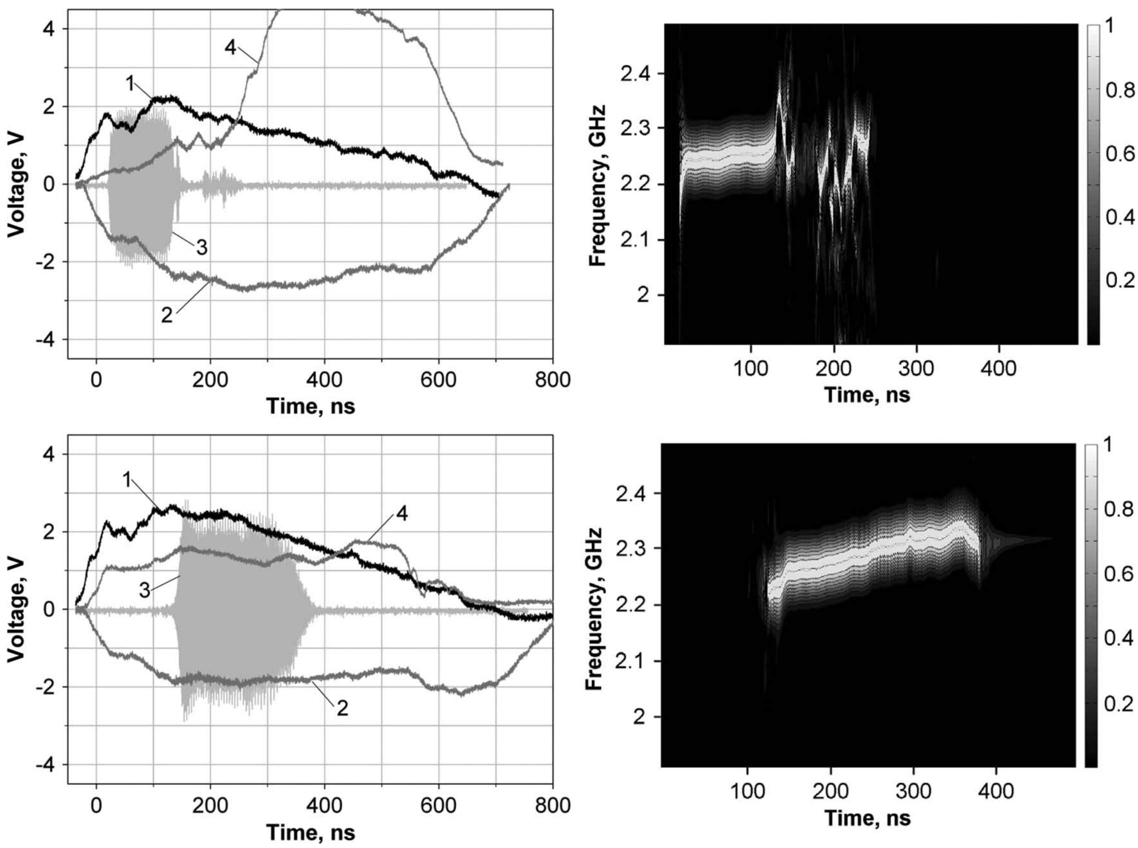

Fig. 10. Left: Accelerating voltage (1, 200 kV/div.), diode current (2, 5 kA/div.), RF voltage from the B-dot probe (3), and current traversing the cavity (4, 1 kA/div.). Right: Time variation of the radiation spectrum. Shots with the cavity geometry of [16] for $U_{ch} = 33$ kV at $d_{AK} = 15$ mm (top) and $d_{AK} = 19$ mm (bottom).

current. Insufficient current causes the absence of generation; at the same time, this does not mean that the VC is not formed. As seen in Figs. 9 and 10, the current transmitted through the cavity prior to the beginning of the microwave pulse is 1–2 kA, whereas the total diode current is 7–10 kA. If the VC is not formed, current losses on the way to the FC are determined only by the anode and output grids and the radial divergence, which is known from the preliminary experiments, so that the current delivered to the FC would be ~50% of the total diode current. Therefore, the current traversing the cavity is always substantially less than the current injected into the second gap of the cavity. In addition, the waveforms of the transmitted currents exhibit no jumps preceding the microwave pulses. Hence, reflected electrons are present, i.e., the VC exists, although the microwave generation does not take place. Thus, one can conclude that the current required for the generation to start exceeds the current at which the VC is formed. We will discuss this issue in Section IV.

The evolution of the current transmitted through the cavity illustrates very well the reason for the termination of generation: neutralization of the VC space charge by ions emitted from the plasma formed at the surface of the foil. In addition to the data presented for the fixed AK gap and charging voltage in [18], the curves numbered 4 in Figs. 9 and 10 show the difference in the transmitted currents when the diode voltage and current are varied. One can see that the transmitted current increases more when a larger beam energy is deposited into the foil, indicating a more intense plasma production. The increase is particularly big for the short AK gap (top left plot of Fig. 10) because the factor of higher current is added here to the factor of lower electron energy and, respectively, bigger energy losses in the foil. Let us note that in shots that yielded a small increase in the transmitted current after the ending of the generation, as, for instance, in the bottom left plot in Fig. 9, the 7.6 μm aluminum foil even remained undamaged.

In addition to the measuring the current traversing the vircator cavity, in experiments, collimated FCs (CFCs) were used to evaluate the radial profile of the transmitted current density and to shed light on the possible influence of beam pinching on the microwave generation. An array of three CFCs with collimation holes 1 mm in diameter was placed at a distance of ~1 cm behind the output grid. The CFCs were located at radii of 5, 17, and 30 mm off the axis of the cathode. The CFC current waveforms along with the waveforms of the diode voltage and current and microwaves are shown in Fig. 11 for the case when a substantial generation delay was obtained. It is seen that at the beam periphery (curve 6), the current density begins to decrease long before the microwave generation starts. This decrease continues during the entire microwave pulse, whereas the signals from CFCs located closer to the axis (curves 4 and 5) exhibit drastic increases after the maximum microwave power is attained. Thus, the effect of pinching in the beam self-magnetic field observed earlier by light emission imaging [18] is confirmed in these measurements. Nevertheless, at the moment when the generation starts, the pinching is not so significant as to be considered to promote the generation.

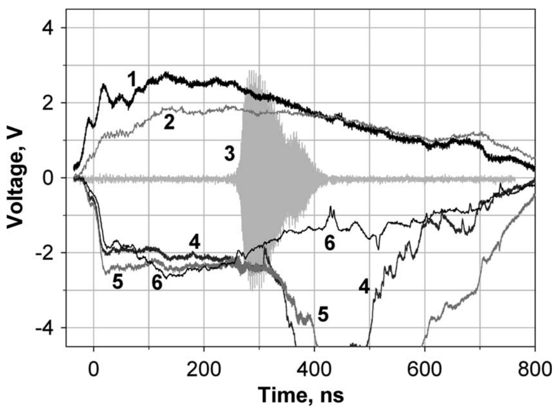

Fig. 11. Accelerating voltage (1, 200 kV/div.), diode current (2, 5 kA/div.), and RF voltage (3) along with the signals from the collimated FCs placed 1 cm behind the vircator cavity at: 4–5 mm off axis; 5–17 mm off axis; 6–30 mm off axis. $d_{AK} = 20$ mm, $U_{ch} = 32$ kV.

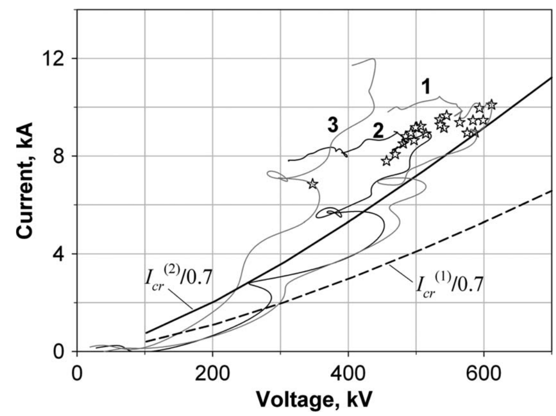

Fig. 12. Beginning of the microwave generation on the current-voltage plane. Stars correspond to instantaneous values of the accelerating voltage and diode current at the moment when the microwave pulse power reaches 10% of its maximum. The shots processed were made with the fixed cavity geometry at different charging voltages for the AK gaps of 21, 20, 19, and 15 mm. Also, shown are experimental I–V trajectories for the shots with $d_{AK} = 21$ mm, $U_{ch} = 37$ kV (curve 1), $d_{AK} = 19$ mm, $U_{ch} = 32$ kV (curve 2), and $d_{AK} = 15$ mm, $U_{ch} = 33$ kV (curve 3) and critical currents versus accelerating voltage according to the 1-D theory [13]. The second (solid curve) and first (dashed curve) critical currents are calculated for an equipotential gap 6 cm in length, electron beam radius of 3.3 cm and reduced to the diode currents.

IV. Generation Starting Current: Discussion

To gain a better understanding of the results of the present studies, it is important to analyze the instantaneous values of the voltage and current at the moment of the start of the microwave generation, rather than the values of the generation delay. Plotting the said instantaneous values as points on the current-voltage plane would give the dependence of the generation starting current on the accelerating voltage. In order to obtain this dependence, we have processed recorded data from the 22 shots made when the geometry of the vircator cavity was fixed (the same as in [16]) at different AK gaps and charging voltages. The time at which the microwave power reaches 10% of the peak power was considered as the start of the generation. The values of diode voltage and current corresponding to this moment were then determined. The results are shown as stars in Fig. 12. Note that stars do not designate the value of the current entering the vircator cavity, which is estimated to be $\sim$70% of the current corresponding to a star position.

The stars shown in Fig. 12 form a clearly expressed monotonic curve, which characterizes the microwave generation starting current for the given cavity geometry. This is additionally illustrated by I–V trajectories for three specific shots (such trajectories are similar for any shot). The plotted trajectories begin from zero point and end at the moment when the microwave pulse is terminated in a given shot. It is seen that all trajectories lie below the starting current curve prior to the beginning of generation, and afterward always go above it. Thus, the obtained starting current curve on the I–V plane determines the maximum admissible diode impedance above which microwave generation does not occur. Therefore, for larger AK gaps, the generation delay is avoided at higher charging voltages, since the diode impedance decreases with increasing voltage. Otherwise, the impedance decreases because of the cathode plasma expansion, which is rather slow for velvet cathodes; it takes time and causes the delay.

Hence, for longer output microwave pulses, the generation starting current should be lower; one can then avoid the delay when a smaller beam energy is deposited into the foil. The question now arises: on what does the starting current depend? Naturally, the starting current relates to the space-charge-limiting current as the microwave generation requires the presence of the VC. It should be noted that the limiting current was lower in the experiments with the cathode of [16] (see Section II) because of lower diode voltage, and the beam current entering the cavity was sufficiently low because of big current losses. These factors, very likely, were the reason for the rather long full duration of the microwave pulse (see Fig. 5).

For double-gap vircators, it was stated in [10] (and later in [17]) that the necessary condition of operation is that the injected beam current exceeds the second critical current $I_{in} > I_{cr}^{(2)}$. The definition of $I_{cr}^{(2)}$ in the 1-D stationary theory [13] is that no current above $I_{cr}^{(2)}$ can pass through an equipotential gap, so that the VC formation is inevitable. Meanwhile, in the 1-D stationary theory, the VC formation is also possible for the beam current $I_{cr}^{(1)} \leq I_{in} \leq I_{cr}^{(2)}$, where $I_{cr}^{(1)}$ is the first critical current [13]. Only below $I_{cr}^{(1)}$, the VC cannot exist and $I_{tr} = I_{in}$. The values of $I_{cr}^{(2)}$ and $I_{cr}^{(1)}$ calculated according to [13] are also shown in Fig. 12 versus the accelerating voltage for a beam injected into the gap. The gap length used in the calculations was the length of the second cavity section, and the currents were obtained assuming that the beam cross-sectional area corresponds to the diameter of the velvet cathode. In addition, the critical currents were reduced to the would-be diode currents using the ratio of $\sim$70% estimated in experiments. Comparing the curves for the critical currents with the position of stars for the starting current and shot trajectories on the I–V plane, one should note that the starting current, indeed, very slightly exceeds $I_{cr}^{(2)}$ and significantly exceeds $I_{cr}^{(1)}$. At the same time, the I–V trajectories lie above the $I_{cr}^{(1)}$ curve (not taking into account the very beginning of the pulses) even before the generation. These data agree with the measurements of the transmitted current that indicates the VC's existence in spite of the absence of microwave generation.

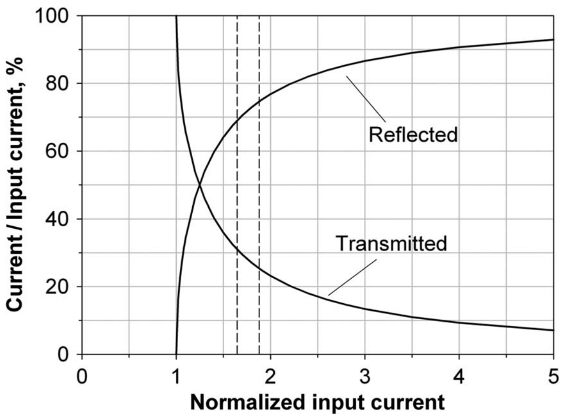

Fig. 13. Percentage of reflected and transmitted currents with respect to the input current according to the 1-D stationary theory for the electron flow with the VC in the equipotential gap. The input current is normalized to $I_{cr}^{(1)}$. Dashed lines indicate the ratios $I_{cr}^{(2)}/I_{cr}^{(1)}$ for 1 MeV (left) and 100 keV (right) kinetic energy of injected electrons.

A possible reason for the absence of generation is that the amount of electrons reflected from the VC is insufficient. Indeed, one can consider the mechanism of microwave generation in the double-gap vircator as similar to that in a reflex klystron: electrons being modulated in a gap return bunched and radiate in the same gap. Unlike in a reflex klystron, there is a VC instead of a reflecting electrode, so that the percentage of electrons returning to the modulating gap is $<100\%$ and depends on I_{in}. Thus, the number of reflected electrons is of importance. One can determine the portion of the beam current reflected from the VC using the 1-D stationary theory [13]. The current transmitted through the gap with the VC is related to the injected current as

$$I_{tr} = I_{in}\left(1 - \sqrt{1 - \frac{2}{4I_{in}/I_{cr}^{(1)} - \sqrt{8I_{in}/I_{cr}^{(1)}+1}+1}}\right). \quad (1)$$

The ratios of the transmitted and reflected current to the injected current, calculated from (1), are plotted in Fig. 13. The interval between the vertical lines here corresponds to typical values of $I_{cr}^{(2)}$, since the ratio $I_{cr}^{(2)}/I_{cr}^{(1)}$ depends on the accelerating voltage. It is seen that, for the beam currents $I_{in} < I_{cr}^{(2)}$, the portion of reflected electrons begins to decrease very fast. So, the condition $I_{in} > I_{cr}^{(2)}$ as a necessary condition for the operation of the double-gap vircator is not simply that the VC is formed but rather that the percentage of reflected electrons sufficient for the generation to start is provided.

The existence of the VC with fewer reflected electrons in the absence of microwave generation was confirmed in the numerical simulations. It is important to note that, for a 1-D monoenergetic electron beam injected into an equipotential gap, the stationary state with the VC cannot be realized in simulations because of the self-oscillations of the VC. In the 2-D geometry, the radial potential well of the beam space charge produces the spread of electron kinetic energy even if the injected beam is monoenergetic; the spread leads to suppression of the self-oscillations [10]. Our simulations were carried out using the 2-D potential version of the PIC-code KARAT [20] for a simplified cylindrical geometry. Namely, a beam 6.6 cm in diameter was injected into a cavity 7 cm in length and 20 cm in diameter separated into two sections (1 cm and 6 cm in length) by a transparent foil. The approach, by not taking into account curl electromagnetic fields, allowed us to focus only on the formation of the quasistationary state with the VC depending on the beam current.

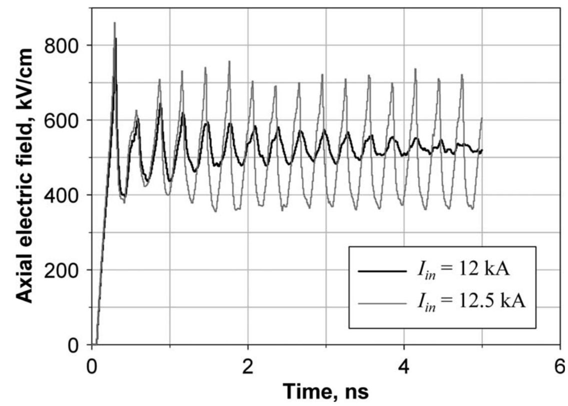

Fig. 14. Axial electric field versus time for different injected currents. The observation point is on the axis, 0.5 cm from the foil in the second section of the cavity. The kinetic energy of injected electrons is 500 keV.

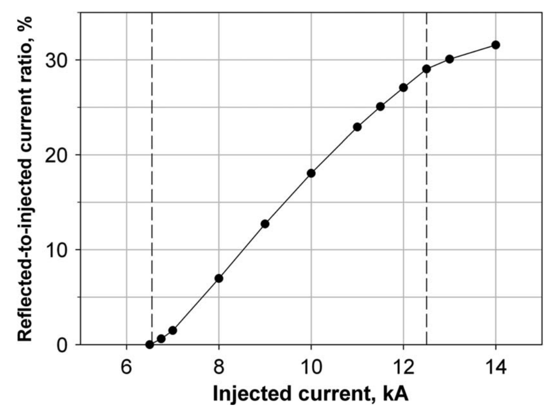

Fig. 15. Percentage of reflected electrons (the difference between the injected current and the current delivered to the cavity back and lateral surfaces averaged over the simulation time) versus injected current. Vertical dashed lines indicate the interval of currents corresponding to a quasistationary state with the VC. The kinetic energy of injected electrons is 500 keV.

Simulation results showed that there is an interval of injected beam currents within which the VC formation and existence is not accompanied by strong oscillations of the electric field in the injection volume. In Fig. 14, the evolution of the field in time is shown for two rather close values of the injected current. It is seen that for the case $I_{in} = 12$ kA, the oscillations are damped in contrast to the case $I_{in} = 12.5$ kA. Meanwhile, the reflected electrons appear at a significantly lower injected current, ≤ 7 kA. The number of reflected electrons in the case of such a quasistationary state with the VC is smaller than in the case of VC self-oscillations (see Fig. 15).

Thus, there is a minimal admissible degree of beam current supercriticality below which microwave generation becomes impossible, in spite of the existence of the VC. It is understood that the amount of reflected electrons is not the only factor that determines the generation starting current. It depends also on the cavity Q-factor, the coupling between the cavity gaps, the coupling to the output antenna, and the RF field transverse structure inside the cavity. Thus, a theory that allows one to calculate the double-gap vircator starting current is needed.

Finally, let us note that the above discussion has not involved any 2-D effects or the possible role of the electron beam pinching. For the latter effect to be of crucial importance for the vircator operation, a beam current of the order of 10 kA seems too low, in contrast to the work [21], in which a beam of ∼100 kA current was employed. Nevertheless, in the geometry of our experiments, the transverse dimension of the electron beam is comparable with the quarter wavelength of the RF wave in the cavity waveguide as well as with the half width of the cavity. Therefore, an increase in electron density around the beam axis, where the RF electric field is close to maximum, can increase energy exchange; this can lower the microwave generation starting current. Thus, taking 2-D effects into consideration, even at moderate beam currents can be important.

V. Conclusion

An S-band (2.0 to 2.3 GHz) double-gap vircator driven by submicrosecond electron beams at moderate accelerating voltages of 400–600 kV was investigated. The vircator operated with the typical efficiency of microwave generation, ∼5%, reported in earlier experiments that employed more powerful beams, so that the peak power of microwave output pulses was up to 200 MW. The radiation frequency depended only on the cavity geometry and was quite stable during the pulse. The issue of limitations on the microwave pulse duration when a velvet cathode, which provides a relatively slow expansion of the cathode plasma, is used has been primarily addressed. In these conditions, the microwave generation is terminated when the electron beam energy deposition into the foil separating the two gaps of the vircator cavity becomes sufficient for plasma to form, and ions from the plasma neutralize the VC. If the energy deposition into the foil is reduced, then a delay in the beginning of the generation appears, so that the microwave pulse is shortened from the opposite end. This delay in microwave generation has been studied in detail.

It has been found that the formal reason for the generation delay is a too high value of diode impedance. Experiments have shown that the delay increases with decreasing diode voltage at a fixed AK gap, as well as with an increasing AK gap at a fixed charging voltage. Like an increased AK gap, a decreased voltage corresponds to a higher impedance of the Child-Langmuir diode. Admissible diode impedance is determined by the experimental dependence of the generation starting current on the accelerating voltage. In addition, it has been found that the beam current required for the microwave generation to start is not the same as the current required for the VC formation. Measurements of the current transmitted through the cavity during the generation delay have indicated that the VC is present in the absence of generation. The actual reason for the generation delay may be in an insufficient amount of electrons reflected from the VC. Simplified numerical simulations have identified the interval of beam currents, within which the VC is formed without self-oscillations. Within this interval, the portion of electrons reflected from the VC is small.

With these two limiting factors for the microwave generation, i.e., termination by the foil plasma ions and delay because of a current lower than the starting current, the maximal output pulse duration achieved was of ∼180 ns FWHM. The maximal full duration of the output pulse was of ∼350 ns, but with a lower and unstable power. It seems unlikely that one can improve on these results with the given vircator cavity. In order to lengthen the microwave output pulse, the generation starting current should be lower to have a lower operating current and to lower the beam energy deposition into the foil. In its turn, the starting current can be decreased by decreasing the space-charge-limiting current, i.e., with a longer second gap of the cavity. Of interest is also an option to decrease an admissible portion of electrons reflected from the VC, by means, for instance, of using a higher Q-factor of the cavity. In this case, the generation starting current would not decrease so much, but a smaller amount of reflected electrons would yield less energy deposited into the foil.

It should be noted that with a longer second cavity gap, the electron beam power need not be decreased, since it is the energy density deposited into the foil that possesses a threshold for the plasma production, and a cathode of a larger area can be implemented. In this case, however, the transverse dimensions of the cavity should be increased too, which inevitably leads to lower operating frequencies. Hence, a double-gap vircator generating the submicrosecond and sub-gigawatt microwave pulses is more realistic at L-band frequencies.

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Anatoli S. Shlapakovski received the M.Sc. degree in physics from Kharkov State University, Kharkov, Ukraine, in 1979, and the Ph.D. degree in particle beam physics from Tomsk Polytechnic University, Tomsk, Russia, in 1987.

In 1980, he joined the Nuclear Physics Institute at Tomsk Polytechnic University, where he worked in the area of high-current charged particle beam physics and high-power microwaves. Since 2009, he has been with the Physics Department, Technion, Haifa, Israel.

Tal Queller received the B.Sc. degree in physics—mathematics from the Technion, Israel Institute of Technology, Haifa, Israel, in 2007, where he is currently working toward the Ph.D. degree with the Plasma and Pulsed Power Laboratory, in the Department of Physics.

He is conducting research on plasma sources and high-power microwave generation at the Plasma and Pulsed Power Laboratory, in the Department of Physics, Technion.

Yuri P. Bliokh received the M.Sc. and Ph.D. degrees in physics and mathematics from Kharkov State University, Kharkov, Ukraine and the D.Sc. degree in physics and mathematics from the Kharkov Institute of Physics and Technology, Kharkov, in 1970, 1977, and 1987, respectively.

From 1970 to 2000, he was with the Kharkov Institute of Physics and Technology. Since 2000, he has been with the Plasma and Microwaves Laboratory, Department of Physics, Technion, Haifa, Israel. His research interests include plasma electronics and stochastic processes in plasma-beam systems.

Yakov E. Krasik received the M.Sc. degree in physics from the Tomsk Potechnical Institute, Tomsk, Russia, in 1976 and the Ph.D. degree in physics from the Joint Institute for Nuclear Research, Dubna, Russia, in 1980.

From 1980 to 1991, he was with the Nuclear Physics Institute, Tomsk and from 1991 to 1996 with the Weizmann Institute of Science, Rehovot, Israel. Since 1997, he has been with the Physics Department, Technion, Haifa, Israel, where he is currently a Professor. His main research interests are related to pulsed current-carrying plasmas.