Experimental Measurement of a Virtual Cathode Velocity

S.D. Polevin, S.Ya. Belomyttsev, A.A. Grishkov, S.A. Kitsanov, I.K. Kurkan, V.V. Ryzhov, and R.V. Tsygankov

Institute of High Current Electronics SB RAS, 2/3, Akademichesky ave., Tomsk, 634055, Russia
Phone: 8(3822) 49-26-52, Fax: 8(3822) 49-21-34, E-mail: polevin@lfe.hcei.tsc.ru

Abstract – The transport of an electron beam in a two-section drift tube with a virtual cathode was studied on a SINUS-7 high-current electron accelerator. An experimental dependence of the virtual cathode velocity on the injection current was obtained for the first time. It was found that as the virtual cathode propagates in the transport system, microwave oscillations are setup due to transient processes involved in transformation of the electron beam into a squeezed state.

1. Introduction

In experiments on electron beam transport in a two-section drift tube of the SINUS-7 high-current electron accelerator [1], a dense electron beam was first obtained for which the relativistic factor is below that for a beam with the limiting current $\gamma_b < \Gamma 1/3$, $\gamma_b = 1 + e\varphi_b/mc^2$, where φ_b is the potential difference between the beam and the cathode, e is the electron charge, m is the electron mass, c is the velocity of light in vacuum, and Γ is the relativistic factor corresponding to the total diode voltage. This state of electron beams is called the "squeezed" state.

The squeezed electron beam and the processes involved in its formation are poorly known. However, the research in this field is necessary for understanding the physics of electron beam transport with a virtual cathode and is promising, e.g., for collective acceleration of positive ions [2, 3] and generation of microwave oscillations using a virtual cathode [4–6].

Theoretical and numerical studies of the squeezed electron beam are described in [7–11]. In [7], it is demonstrated that under certain conditions the virtual cathode formed in a cylindrical two-section drift tube can shift toward the electron injection plane. In [8], theoretical estimates of the virtual cathode velocity in relation to the injection current were obtained for the first time. By and large, there exists a theoretical approach to calculating the ratio of currents and relativistic factors for a beam with a virtual cathode in stationary cases, the virtual cathode velocity in relation to the injection current, and the critical currents at which the electron beam in a two-section drift tube transforms into the squeezed state [8, 10, 11]. The objective of the experiments was to measure the virtual cathode velocity during the electron beam transport.

2. Scheme of experiment

The experiment was performed on a SINUS-7 high-current electron accelerator operating at a diode voltage up to 2 MV, a diode current up to 20 kA, and a current pulse duration of 50 ns. The experimental arrangement is shown in Fig. 1 and is similar to that used in [1] where an electron beam in the squeezed state was found experimentally for the first time. The electron beam was generated in a coaxial vacuum diode with magnetic insulation and was injected into a two-section drift tube via an anode neck. Electrons were emitted from a cylindrical graphite explosive-emission cathode of radius $R_C \approx 9.5$ mm and edge width 0.5 mm. A tubular electron beam was thus formed in a homogeneous longitudinal magnetic field of 15 kOe. The radius and length of the anode neck were 20 mm and 130 mm, respectively. The lengths of the drift tube sections $L_{dr1} \approx 150$ mm, $L_{dr2} \approx 400$ mm were much greater than their radii $R_{A1} \approx 24$ mm, $R_{A2} \approx 41$ mm. The current injected into the drift tube was varied by changing the anode-cathode gap L_{AC}, with the diode voltage kept constant $U \approx -(800 \pm 20)$ kV. The potential difference between the electron beam and the drift tube was measured with capacitive voltage dividers mounted in the central part of each tube section. The beam current was measured using a low-inductance ohmic shunt in the collector circuit. In the narrow section 40 mm away from the faces, there were high-frequency capacitive voltage dividers separated along the axis by $L_{1-2} \approx 70$ mm. The signal-to-signal delay of the dividers was used to measure the virtual cathode velocity.

The vacuum diode current I_D was measured in a series of experiments in which the collector was placed at the end of the anode neck. In this geometry, varying L_{AC} between 100 mm (the cathode is in the anode tube, Fig. 1) and –30 mm (the front edge of the cathode protrudes 30 mm into the anode neck) causes the diode current to vary within $I_{FD} < I_D < I_{FA}$, where $I_{FD} \approx 3.1$ kA, $I_{FA} \approx 7.2$ kA and are the Fedosov currents of coaxial diodes with magnetic insulation for the radii of the anode tube and neck, respectively.

3. Experimental results and numerical simulation

In experiments on electron beam transport in a two-section drift tube with a virtual cathode where the collector was placed at the end of the system (Fig. 1), the injection current was determined taking into account the backscattered current I_{back}: $I_{\text{inj}} = (I_D + I_{\text{out}})/2$, where $I_D = (I_{\text{inj}} + |I_{\text{back}}|)$ and is the experimental value of the diode current with no virtual cathode for a given L_{AC}.

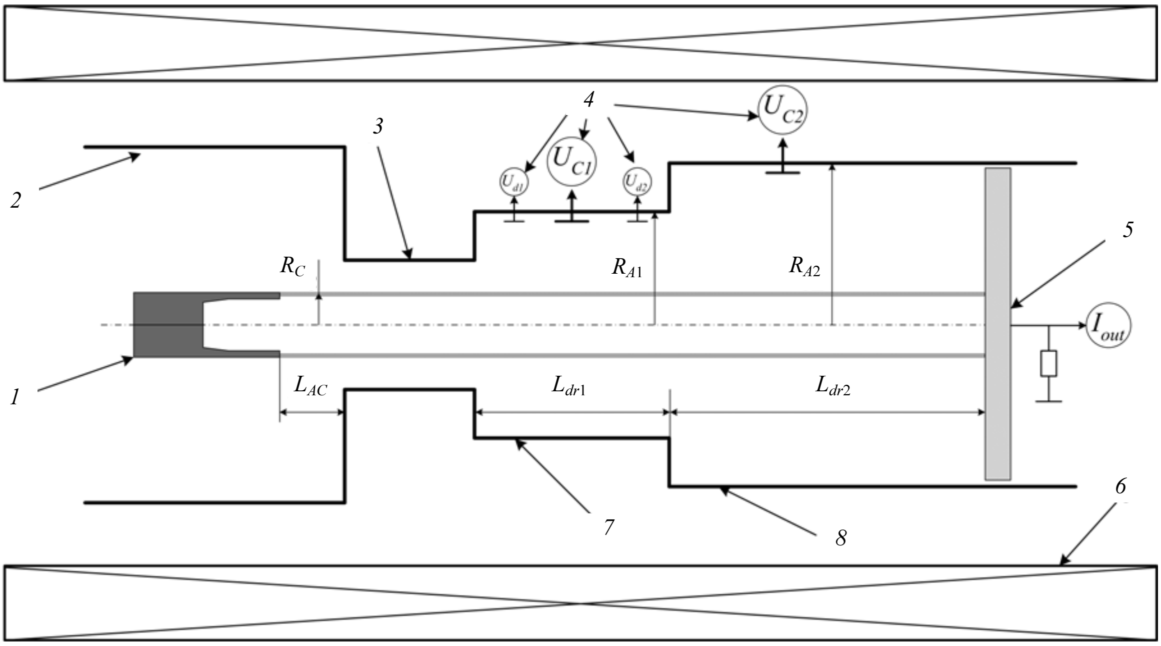

Fig. 1. Schematic of the experimental arrangement: *1* – cathode; *2* – anode tube; *3* – anode neck; *4* – capacitive dividers; *5* – collector; *6* – solenoid; *7*, *8* – sections of the drift tube

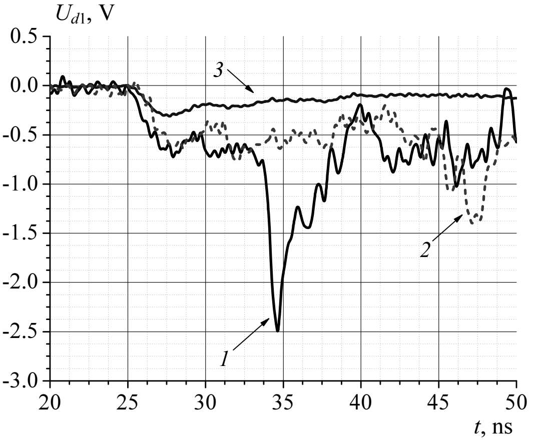

Fig. 2. Typical waveforms of the voltage from the high-frequency capacitive dividers in the narrow section for different anode-cathode gap: –10 mm (*1*); 5 mm (*2*); and 60 mm (*3*)

Figure 2 shows typical oscillograms of the voltage from the high-frequency capacitive voltage dividers for different anode-cathode gaps. Peaks on the oscillograms correspond to the maximum potential due to the virtual cathode formed near the dividers.

For a gap ≤ 5 mm, the injection current is no greater than the transition current I_{Tr} in the narrow section and the virtual cathode starts to shift toward the injection plane as evidenced by a clearly defined peak on the oscillograms for these gaps. On the oscillograms for larger gaps and hence lower injection currents, no peak is observed suggesting that the virtual cathode does not shift toward the injection plane.

Figure 3 shows oscillograms of the voltage from the high-frequency capacitive voltage dividers for a fixed anode-cathode gap. The advance of the signal from the first high-frequency capacitive divider at the initial moment in time corresponds to the passage of the electron beam during the voltage rise time. Further increasing the injection current to a value corresponding to the transition current, the signal from the second divider is ahead of that from the first one. The average virtual cathode velocity was determined from the delay time (τ) between the peaks: $V_{VC} \approx L_{12}/\tau$.

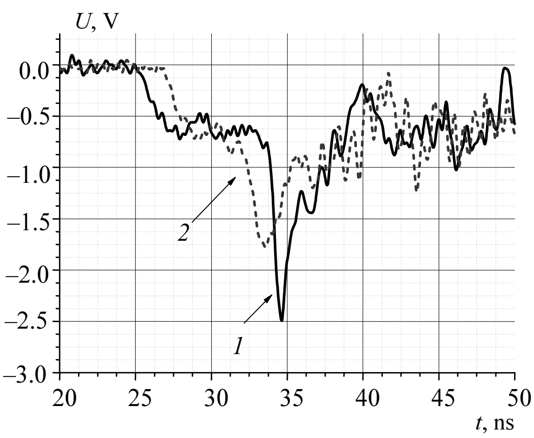

Fig. 3. Waveforms of the voltage from the first (*1*) and second (*2*) high-frequency capacitive voltage dividers for a fixed anode-cathode gap ≈ –10 mm

Figure 4 shows experimental data, numerical solution of e-beam transport equations for a moving virtual cathode, and results of simulation by the PIC code KARAT [13]. The simulation shows that for the injection current Iinj ≈ 6 kA, the virtual cathode is formed during the diode voltage pulse risetime. Like in [1], the result is that low-energy electrons reflected from the virtual cathode are accumulated in the tube, rather than returning back to the cathode, that causes an increase in electron density and a decrease in beam potential. Thus, the effective charge in the drift tube becomes greater than that calculated using the theoretical model that leads to an increase in virtual cathode velocity. This is likely to be the reason for the discordance between the experimental and theoretical values of the virtual cathode velocity in the range of I_{inj} under consideration. Unfortunately, this arrangement does not allow measuring the virtual cathode velocity on "decay" of the squeezed state of the electron beam, since the injection current cannot vary without varying the diode voltage. In the experiment, it is also found that as the virtual cathode propagates in the drift tube, microwave oscillations (with a frequency of ~ 1 GHz) are set up which, according to numerical simulation, are due to transient processes involved in transformation of the electron beam into the squeezed state [14].

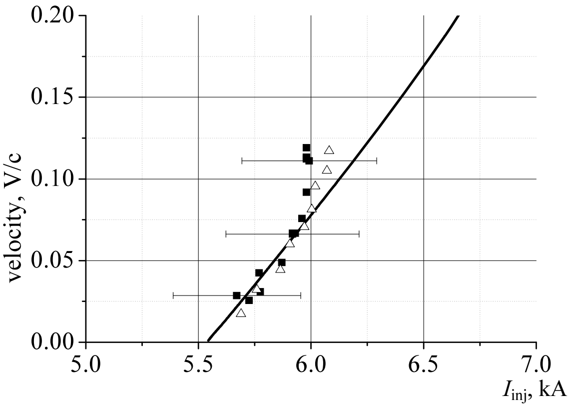

Fig. 4. Virtual cathode velocity vs the injection current: theoretical solution of the e-beam transport equations (solid lines), experiment (■), numerical simulation by the PIC-code KARAT (Δ)

Theoretical studies [8] show that for a thin annular monoenergetic relativistic electron beam transported in a cylindrical drift tube with a virtual cathode, the dependence of the virtual cathode velocity on the injection current is bifurcational. Note that the foregoing experimental values of the virtual cathode velocity agree well with the lower curve of the theoretical dependence of the virtual cathode velocity on the injection current [8].

Thus, the transport of an electron beam in a two-section drift tube with a virtual cathode was studied experimentally. The experimental dependence of the virtual cathode velocity on the injection current was obtained for the first time.

References

[1] S.Ya. Belomyttsev, A.A. Grishkov, S.A. Kitsanov, S.D. Korovin, S.D. Polevin, V.V. Ryzhov, and A.P. Yachnyi, Pis'ma Zh. Tekh. Fiz. **31**, 74 (2005).

[2] Ya.B. Fainberg, *in Proc. of Nucl. Phys. Conf. devoted to the 50-th anniversary of nuclear fission in the USSR*, Part 1, 1983, p. 222.

[3] V.M. Bystritskii and A.N. Didenko, *High-power electron beams*, Moscow, Energoatomizdat, 1984.

[4] A.A. Rukhadze, S.D. Stolbtsev, and V.P. Tarakanov, Radiotekhnika i Electronika **37**, 385 (1992).

[5] B.V. Alyokhin, A.E. Dubinov, V.D. Selemir et al., IEEE Trans. Plasma Sci. **5**, 945 (1994).

[6] A.E. Dubinov and V.D. Selemer, Rus. Zarubezh. Radioelectronics **4**, 54 (1995).

[7] A.M. Ignatov and V.P. Tarakanov, Phys. Plasmas **1**, 741 (1994).

[8] S.Ya. Belomyttsev, A.A. Grishkov, S.D. Korovin, and V.V. Ryzhov, Pis'ma Zh. Tekh. Fiz. **30**, 88 (2004).

[9] A.E. Dubinov and I.E. Efimova, Zh. Tekh. Fiz. **71**, 80 (2001).

[10] S.Ya. Belomyttsev, A.A. Grishkov, S.D. Korovin, and V.V. Ryzhov, Pis'ma Zh. Tekh. Fiz. **29**, 16 (2003).

[11] A.A. Grishkov, S.Ya. Belomyttsev, S.D. Korovin, and V.V. Ryzhov, Pis'ma Zh. Tekh. Fiz. **29**, 46 (2003).

[12] S.D. Korovin and V.V. Rostov, Rus. Fiz. Zh. **12**, 21 (1996).

[13] V.P. Tarakanov, *User's Manual for Code Karat,* BRA, Springfield, 1992.

[14] A.A. Grishkov, V.V. Ryzhov, and S.Ya. Belomyttsev, *in Proc. 14th Symposium on High Current Electronics*, 2006, pp. 42–44.