12.3;05.6;06.4

Investigation of the parameters of a self-focused electron beam outputted behind the anode of a vacuum diode

© V.I. Oleshko, V.V. Nguyen

Tomsk Polytechnic University, Tomsk, Russia
E-mail: oleshko@tpu.ru

Received October 14, 2021
Revised October 29, 2021
Accepted October 29, 2021

The parameters of a high-current electron beam extracted from the self-focusing zone through a hole in the anode into a vacuum chamber are investigated. The beam parameters were determined from the measurement of the spatial distribution of destruction and glow arising in polymethyl methacrylate samples installed at different distances from the anode (electron beam autographs). The formation of two electron beams — a self-focused with a high energy density, propagating along the axis of the cone facing the base to the anode with an apex angle of $\sim 7^\circ$ and a high-energy beam of low density, propagating in a hollow truncated cone and surrounding self-focused, was found. The oscillograms of the current and the energy of the electron beams were measured.

Keywords: vacuum diode, electron beam, filamentation, self-focusing, polymethyl methacrylate, destruction, glow, high current pulsed electron beam

DOI: 10.21883/0000000000

The study of cumulation of energy of high-current electron beams in vacuum and plasma diodes is relevant to a number of academic and applied research fields [1–5]. These studies are stimulated by the general scientific interest in the investigation of behavior of condensed media at high energy densities and the retrieval of new data on the physical nature of such phenomena (the mechanisms of which have not yet been determined conclusively) as filamentation and self-focusing of electron beams in diodes with an explosive-emission cathode. The lack of a consistent theory of filamentation and self-focusing of electron beams in vacuum and gas diodes of high-current electron accelerators with different parameters stimulated experimental investigations performed based on different model approximations [1,4,6–11].

The phenomena of filamentation and self-focusing of high-current electron beams in a vacuum diode of a high-current electron accelerator with a GIN-600 generator have been studied earlier in [9,12]. The formation of a multitude of high-density electron microbeams concentrating into a central self-focusing spot at the anode has been reported. The volumetric energy density in the self-focusing spot at the copper anode was so high ($\sim 10^9$ J/m^3) that it induced evaporation of the anode material, development of a shock wave, and spallation of the back surface of the copper target.

It is essential for fundamental and applied research into the process of interaction between high-power electron beams with condensed media to output a self-focused electron beam behind the anode of a vacuum diode and maximize the energy density at a given distance from the anode.

The aim of the present study is to retrieve data on the spatial, temporal, and energy parameters of a self-focused high-current electron beam (SFHCEB) output behind the anode of a vacuum diode.

Experiments were performed at a pulsed electron accelerator with a GIN-600 generator. A vacuum diode under a pressure of $\sim 10^{-2}$ Torr was connected to it. The maximum energy of electrons in the beam spectrum was $T \sim 350$ keV, and the half-amplitude duration of beam current pulses varied from 2 to 15 ns. The maximum beam current was $I_{\max} \approx 2$ kA. The vacuum diode had a sleeve brass cathode with radius $R = 3$ mm and a planar anode with a thickness of ~ 0.5 mm. Aspect ratio $g = R/d_{CA}$ (R is the cathode radius and d_{CA} is the cathode–anode gap) varied within the range of $0.8-1.2$.

The electron beam was output from the self-focusing region through an aperture with a diameter of ~ 1.5 mm in the copper anode and propagated within a cylindrical vacuum chamber 23 mm in diameter and 15 mm in length. The spatial structure of the beam was determined based on the patterns of destruction (beam autographs) of samples made from poly(methyl methacrylate) (PMMA) and copper and the glow of PMMA and scintillators installed at different distances L from the back surface of the anode. The patterns of destruction of metals and dielectrics irradiated with a single pulse and the glow of dielectrics at the moment of pulsed excitation were recorded with a SONY DSLR-A500 digital single-lens reflex camera via an MBS-10 microscope and with a μVizo-101 transmitting-type microvisor. The electron beam current was measured using a collector composed of a metal cone that formed a line with a wave impedance of 50 Ω with the case. This collector was installed behind aluminum foil that separated the vacuum diode from atmospheric air. A DPO 3034 (300 MHz) digital oscilloscope was used to record signals from the collector. The oscilloscope was triggered on a synchronization pulse

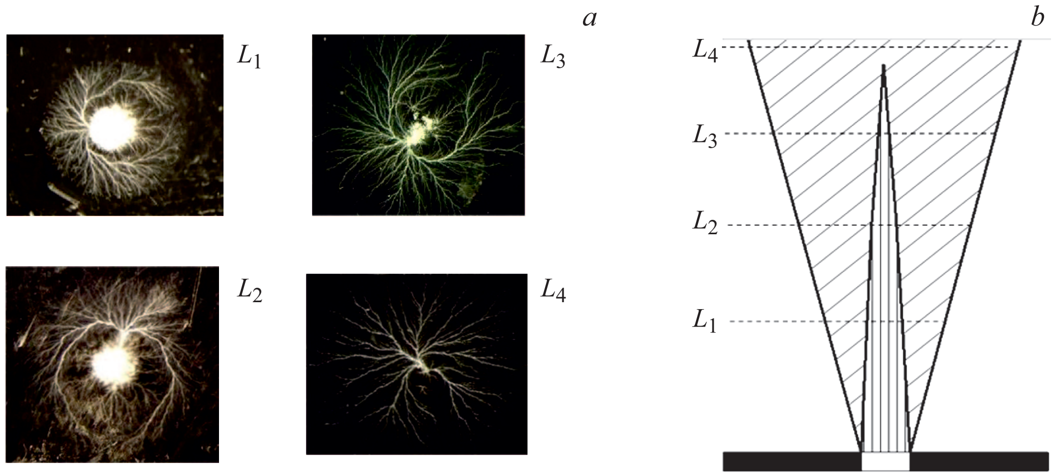

Figure 1. *a* — photographic images of PMMA destruction patterns produced by an electron beam output behind the anode of a vacuum diode at distance $L_1 = 4$ mm, $L_2 = 6$ mm, $L_3 = 9$ mm, or $L_4 = 13$ mm from the anode; *b* — spatial structure of electron beams output behind the anode of a vacuum diode. $d_{CA} = 3.5$ mm, $Ø_A = 1.5$ mm, and $Ø_C = 6$ mm.

from the accelerator. The temporal resolution of the detection system was ~ 2 ns. PMMA was chosen to be used for diagnostics of an electron beam based on its glow and residual micropatterns of destruction, since this dielectric material features low density, high transparency, and a well-known morphology of destruction in the form of Lichtenberg figures (electrical discharge trees) that are produced under irradiation with electron beams of various density, duration, and energy [13]. The energy of electrons in the beam was measured based on the depth of occurrence of destruction micropatterns produced by the electron beam in PMMA and based on the absorption of electrons in thin aluminum foils. The transition to the evaporation regime was monitored by the traces of erosion on the surface of irradiated targets and by the glow spectra of erosion plasma.

Figure 1, *a* presents the beam autographs in PMMA obtained at different distances L from the anode at $d_{CA} = 3.5$ mm and diameter $Ø_A = 1.5$ mm of the aperture in the anode. It is evident that two types of destruction patterns are produced due to the nonuniformity of distribution of the current density over the beam diameter. Ensembles of microbubbles with diameters ranging from 10 to 50 μm formed in the central regions of irradiated targets. Apparently, these bubbles were produced due to explosive boiling of the polymer heated by the SFHCEB. The spatial structure, the size, and the shape of microbubbles in PMMA subjected to irradiation with a high-current electron beam in the filamentation and self-focusing regime have already been examined in [12]. A thin ($\sim 10\,\mu$m) aluminum foil was used as the anode in this study.

Volumetric electrical discharges were observed around the boiling region. They were detected in the form of annular structures within a single excitation pulse both in destruction (Fig. 1, *a*) and in glow measurements. As L increased, the diameter of the central destruction region decreased; at $L = 13$ mm, only one type of destruction patterns (electrical breakdown channels) was observed (Fig. 1, *a*). Conspicuous is the fact that the annular discharge structure was not observed after SFHCEB dispersion; instead, a homogeneous Lichtenberg figure was formed. This is attributable to the Coulomb repulsion of charged particles in a peripheral electron beam and their movement in the radial direction. It follows from the comparison of photographic images of PMMA destruction and glow that the electrical discharge figures recorded in destruction and glow measurements were identical. The only difference between these images is that volumetric destruction in the form of microbubbles is not detected in glow measurements. This may be attributed both to the difference in temperature between cooler PMMA in the central region of SFHCEB irradiation and the hotter plasma in electrical breakdown channels and to the fact that the process of polymer boiling lags behind the evolution of electrical discharges. The depth of occurrence of microbubbles and electrical breakdown channels measured from the irradiated surface is 20–70 and 350–450 μm. These values correspond to an average energy of electrons in the SFHCEB and the peripheral beam of ~ 70 and ~ 220 keV, respectively.

When the cathode–anode gap was reduced to $d_{CA} = 2.5$ mm, the energy density of the central SFHCEB increased. This is verified by the formation of erosion spots on metal targets and deep craters in PMMA (with ejection of ablation products and formation of polymer threads on the irradiated surface).

The peripheral high-energy high-current electron beam (HEHCEB) revealed by the electrical breakdown channels in PMMA and by the glow of scintillators does not manifest itself in any way on metal targets, since its energy density is low. The spatial structure of two electron beams reconstructed by examining the morphology of PMMA destruction patterns is presented in Fig. 1, *b*.

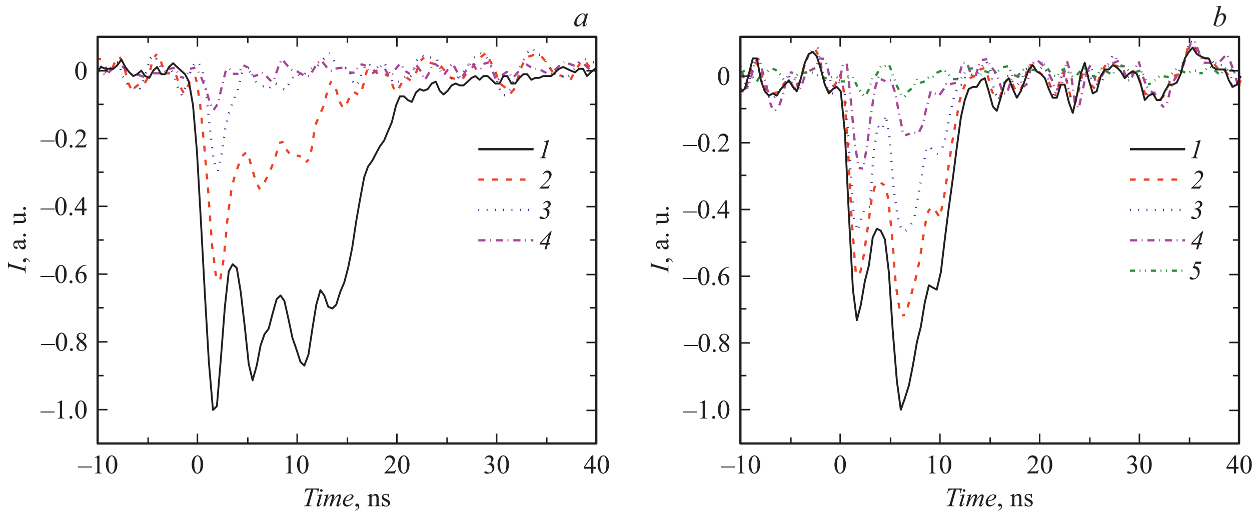

Figure 2. Oscilloscope records of current of the electron beam, which was output behind the anode of a vacuum diode, after its propagation through absorbing aluminum foils with a thickness of 30 (*1*), 80 (*2*), 130 (*3*), 230 (*4*), and 280 μm (*5*). *a* — SFHCEB current, *b* — HEHCEB current. $d_{CA} = 3.5$ mm, $\text{Ø}_A = 1.5$ mm, and $\text{Ø}_C = 6$ mm.

The data on temporal and energy parameters of SFHCEB and HEHCEB were extracted from the oscilloscope records of current. Apertures were installed at distance L to separate electron beams and isolate the central self-focused beam or the peripheral beam. Several maxima are seen clearly in the oscilloscope records of current of SFHCEB (Fig. 2, *a*) and HEHCEB (Fig. 2, *b*) transmitted through absorbing aluminum foils of various thickness. These maxima emerge due to a mismatch between the diode and the forming line. It follows from the comparison of two oscilloscope records (Figs. 2, *a* and *b*) that the SFHCEB current pulse is longer than the HEHCEB current pulse. The energies of SFHCEB and HEHCEB electrons also differ. It can be seen that the fourth SFHCEB current peak (Fig. 2, *a*) is almost completely absorbed by aluminum foil with a thickness of $\sim 80\,\mu$m, while the amplitudes of the second and the third current pulses decrease by a factor of more than 2. This implies that the majority of SFHCEB electrons have an energy of ~ 100 keV. As for HEHCEB, the oscilloscope records in Fig. 2, *b* demonstrate that all three current pulses remain when the total thickness of absorbing aluminum foil is $\sim 280\,\mu$m. This corresponds the maximum energy of electrons of ~ 290 keV.

Thus, two electron beams with different parameters are detected in the region behind the anode. The first one (SFHCEB with an energy density sufficient for evaporation of metal and dielectric targets and an average energy of electrons in the spectrum of ~ 100 keV) propagates in a cone with its base facing the anode (Fig. 1, *b*) and an apex angle of $\sim 7°$. The second beam (HEHCEB with an energy density exceeding the threshold needed to initiate electrical breakdown in PMMA ($\geqslant 0.2\,\text{J/cm}^2$) and the maximum energy of electrons in the spectrum of ~ 290 keV) propagates in a centrally symmetric fashion with respect to SFHCEB in a hollow truncated cone with its base facing away from the anode and an apex angle of $\sim 22°$ (Fig. 1, *b*). The length of SFHCEB transport in a vacuum chamber 15 mm in length and 23 mm in diameter at $d_{CA} = 2.5$ mm and at anode aperture diameter $\text{Ø}_A = 1.5$ mm is $L \sim 10$ mm. The spatial structure of SFHCEB and HEHCEB presented in Fig. 1, *b* likely forms as a result of interaction of the electromagnetic fields of two beams between themselves and with the vacuum chamber walls. One factor probably contributing to the SFHCEB dispersion is the development of instabilities of various kinds.

Funding

This study was performed as part of the development program of the Tomsk Polytechnic University.

Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] D.D. Hinshelwood, R.J. Allen, R.J. Commisso, G. Cooperstein, B.M. Huhman, D. Mosher, D.P. Murphy, P.F. Ottinger, J.W. Schumer, S.B. Swanekamp, S.J. Stephanakis, B.V. Weber, F.C. Young, I. Crotch, J. O'Malley, J.R. Threadgold, IEEE Trans. Plasma Sci., **35** (3), 565 (2007). DOI: 10.1109/TPS.2007.895227

[2] V.E. Fortov, *Fizika vysokikh plotnostei energii* (Fizmatlit, M., 2013) (in Russian).

[3] B.A. Demidov, V.P. Efremov, V.A. Petrov, A.N. Mescheryakov, J. Synch. Investig., **3** (5), 673 (2009). DOI: 10.1134/S1027451009050036

[4] E.E. Tarumov, *Generatsiya i fokusirovka sil'notochnykh relyativistskikh elektronnykh puchkov* (Energoatomizdat, M., 1990) (in Russian).
[5] V.I. Oleshko, *Porogovye protsessy v tverdykh telakh pri vzaimodeistvii s sil'notochnymi elektronnymi puchkami,* Doctoral Dissertation in Mathematics and Physics (Tomsk. Politekh. Univ., Tomsk, 2009) (in Russian).
[6] S. Anishchenko, V. Baryshevsky, N. Belous, A. Gurinovich, E. Gurinovich, E. Gurnevich, P. Molchano, IEEE Trans. Plasma Sci., **45** (10), 2739 (2017). DOI: 10.1109/TPS.2017.2707591
[7] V.I. Baryshnikov, V.L. Paperny, Phys. Plasmas., **25** (8), 083106 (2018). DOI: 10.1088/1361-6463/aa85c4
[8] M.I. Lomaev, V.F. Tarasenko, A.V. Dyatlov, Russ. Phys. J., **62** (6), 996 (2019). DOI: 10.17223/00213411/62/6/68.
[9] V.I. Oleshko, V.F. Tarasenko, A.G. Burachenko, V.V. Nguyen, Tech. Phys. Lett., **45** (4), 309 (2019). DOI: 10.1134/S1063785019040023.
[10] G.A. Mesyats, V.G. Shpak, Pis'ma Zh. Tekh. Fiz., **3** (14), 708 (1977).
[11] A.A. Zherlitsyn, B.M. Koval'chuk, N.N. Pedin, Tech. Phys., **59** (4), 600 (2014). DOI: 10.1134/S1063784214040276.
[12] V. Oleshko, A. Yakovlev, V. Tarasenko, V. Nguyen, in *Proc. 2020 7th Int. Congress on energy fluxes and radiation effects (EFRE)* (IEEE, 2020), p. 906. DOI: 10.1109/EFRE47760.2020.9242003
[13] A.I. Akishin, *Kosmicheskoe materialovedenie* (Nauchno-Issled. Inst. Yad. Fiz. Mosk. Gos. Univ., M., 2007) (in Russian).