DOI 10.1007/s10717-024-00705-x
Glass and Ceramics, Vol. 81, Nos. 7 – 8, November, 2024 (Russian Original, Nos. 7 – 8, July – August, 2024)

UDC 537.533.79

STUDY OF THE POSSIBILITY OF A STABLE INCREASE IN THE ELECTRON BEAM CURRENT DENSITY USING A TAPERED GLASS CHANNEL

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Translated from *Steklo i Keramika*, No. 8, pp. 28 – 34, August, 2024.

Original article submitted July 13, 2024.

The possibility of increasing the current density of a charged particle beam (focusing) by means of tapered glass channels without the use of external energy sources is actively translated into action today for positively charged ions. For electron beams, this possibility is not realized due to the lack of experimental data on the sliding interaction between electron beams and a dielectric surface. It is necessary to examine the compression of an electron beam by tapered capillaries depending on their geometrical parameters, as well as to study the temporal characteristics of the focusing process. In this work, the authors experimentally studied the compression of a 10 keV electron beam using a 15-mm-long tapered glass channel with an inlet-to-outlet inside diameter ratio of 1.15 mm/0.30 mm. The beam current density is shown to increase at the outlet of the capillary with the specified parameters by up to a factor of 2.7 for the position where the channel axis is parallel to that of the initial beam. This density increase is estimated for electrons that have lost no more than 1 keV of initial energy. It is also shown that the process of electron transmission by a tapered capillary is stable regardless of the orientation of the capillary with respect to the direction of the initial beam.

Keywords: glass capillary, accelerated electrons, dielectric surface, focusing, dielectric channels.

INTRODUCTION

The contactless propagation of a beam of positively charged particles through dielectric nanochannels was first described for multicharged Ne^{7+} ions in 2002 [1]. Subsequently, this effect found a practical application in controlling and focusing the beams of positively charged ions with tapered glass channels [2, 3]. The term “focusing” is used to refer to the process of increasing the current density of a beam of charged particles that have passed through the channel, as compared to the current density of the incident beam. The realization of this possibility for electron beams [4] is hampered by other mechanisms of interaction between electrons and dielectric surfaces [5]. Tapered dielectric channels provide a means to significantly increase electron beam density [6, 7]; however, the process of electron passage through the channel and, therefore, focusing proves to be unstable and difficult to reproduce in some cases [8 – 10].

According to the generally accepted model of sliding interaction between charged particles and dielectric surfaces, once particles hit the surface, they make it similarly charged until the charge distribution creates a field sufficient to prevent charged particles from reaching the surface—a repulsive field. In this case, the surface charge distribution is self-consistent in character: the processes of charge deposition and dissipation from the surface are in dynamic equilibrium, with only a small fraction of charged particles in the beam used for charging the surface; the main part of the beam travels along the surface without direct interaction with it [6]. However, for electrons, this situation is complicated by the fact that the electron has a much smaller mass than the positive ion; therefore, it reacts more strongly to external electromagnetic fields. In addition, the interaction of electrons with the dielectric surface causes secondary electron emission, which can lead to the formation of positively charged regions on the surface and in the near-surface layer [11].

The study examined the process of increasing the current density of a 10 keV electron beam by means of a tapered glass channel in terms of reproducibility and temporal stability. We also performed experiments using two identical spe-

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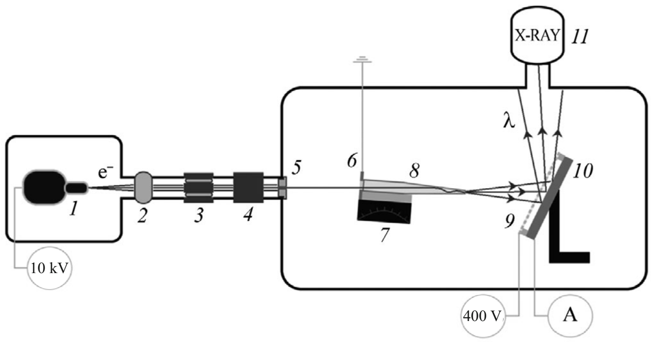


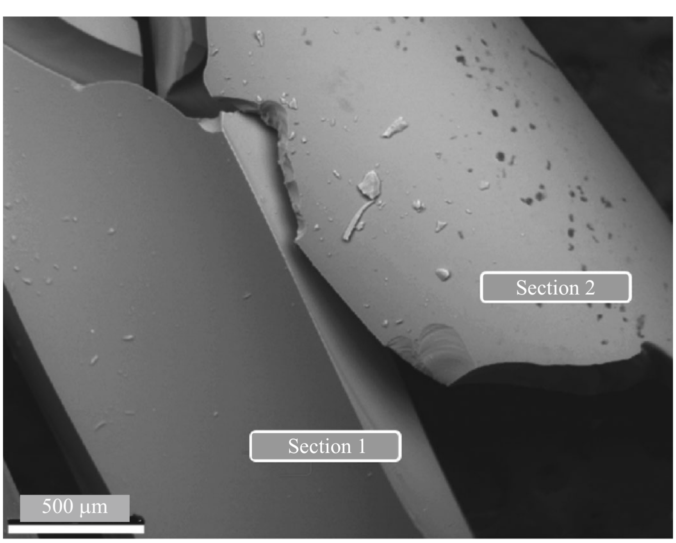
Fig. 1. Schematic of the experiment: *1*) electron gun; *2 – 4*) electromagnetic beamforming system; *5*) 1 mm collimator; *6*) grounded metal mask with a 0.9 mm opening; *7*) goniometer; *8*) tapered glass capillary; *9*) bass mesh under a negative voltage of 400 V; *10*) copper shield connected to a Keithley 6482 ammeter; *11*) XR100SDD detector.

cimens made of the same brand of glass (length of 15 mm; inlet/outlet inside diameter ratio of 1.15 mm/0.30 mm). The study shows good reproducibility and sufficiently high stability of electron transmission through the channel with the maximum increase in the output beam density by a factor of 2.7.

EXPERIMENT

The studies were conducted using the setup described in detail in [12]. A schematic of the experiment is shown in Fig. 1. An electron beam was generated by the hot cathode of an electron gun *1*, shaped, and directed into the target chamber by an electromagnetic system *2* – *4*. A collimator with an aperture of 1 mm *5* was installed at the target chamber inlet. The electron beam was incident on the inlet of a specimen *8* mounted in the holder of a non-magnetic goniometer *7*; the end of the specimen was closed by a grounded metal mask *6* having an opening of approx. 0.7 mm. Part of the electrons that had traveled through the channel reached a copper plate *10* having a brass mesh *9* (under a negative voltage of 400 V) secured in front of it to prevent secondary electrons from escaping the plate. The current from the plate was measured using a Keithley 6482 picoammeter. The radiation emitted as electrons hit the copper plate was detected using of an XR100SDD *11*. An analysis of the measured spectra provided an estimate of the fraction of electrons that travelled through the capillary without significant energy losses.

The present work used two identical specimens made of the same glass, whose composition is shown in Fig. 2. The elemental composition of glass was analyzed via energy-dispersive x-ray spectroscopy using an FEI Quanta 600 FEG scanning electron microscope. The specimens constituted tapered channels measuring 15 mm in length (cylindrical part — 10.0 ± 0.5 mm; tapering part — 5.0 ± 0.5 mm). The other parameters are as follows: inlet inside diameter of the specimens — 1.15 ± 0.05 mm; the mask opening at the channel inlet — 0.9 ± 0.1 mm; the outlet inside diameter of both specimens — 0.30 ± 0.05 mm; geometric transmission angle of the glass specimens — ± 2.5°. In order to determine the reference position, where the axis of the channel is parallel to that of the incident beam, a grounded cylindrical metal capillary measuring 34 mm in length and having an inside diameter of 0.9 mm was used. The reference position was defined as the arithmetic mean of limiting inclination angles of the metal tube, at which the beam is completely overlapped with respect to the incident beam axis in the horizontal and vertical planes.



a

Element	Weight %	MDL	Atomic %	Error %
			Area 1 | Selected Area 1	
O K	50.66	0.10	64.52	10.17
Na K	10.74	0.08	9.52	9.95
Mg K	1.50	0.05	1.26	10.53
Al K	2.29	0.04	1.73	9.11
Si K	27.21	0.03	19.74	7.20
K K	2.27	0.03	1.19	5.15
Ca K	3.49	0.04	1.77	4.16
Ba L	1.84	0.11	0.27	7.26
			Area 1 | Selected Area 2	
O K	50.83	0.07	64.43	10.06
Na K	11.24	0.06	9.91	9.77
Mg K	1.59	0.04	1.33	9.95
Al K	2.30	0.03	1.73	8.77
Si K	27.29	0.02	19.71	7.13
K K	2.12	0.02	1.10	4.76
Ca K	3.08	0.03	1.56	3.95
Ba L	1.54	0.07	0.23	6.07

b

Fig. 2. Elemental composition of glass: *a*) analyzed surface of the split specimen; Section 1 — inner (irradiated) surface; Section 2 — outer (unirradiated) surface; *b*) elemental composition of glass.

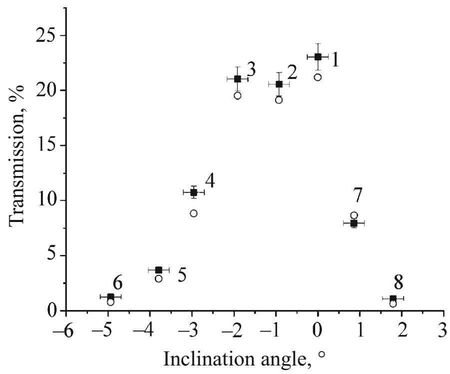


Fig. 3. Dependence between the fraction of the electron beam that travels through the tapered channel on the inclination angle of the channel with respect to the reference position: ■) fraction of all electrons that pass through the channel; ○) electrons that pass through the channel without significant energy losses; numbers on the graph denote the order in which the measurements are performed.

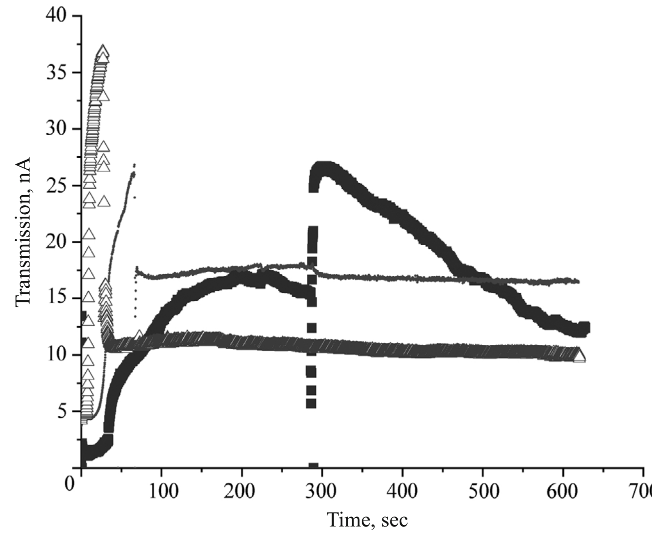


Fig. 4. Time dependence of the tapered channel transmission at different inclination angles of the channel: ■) reference channel position; ○) inclination angle of 1.9°; △) inclination angle of 2.9°.

The first experiment was performed for an uncontaminated channel (i.e., a specimen that was not exposed to electron beam irradiation). The transmission of an electron beam by a glass channel was studied for several inclination angles of the capillary with respect to the incident beam, which had the following initial characteristics: electron energy — 10 keV; current measured at the outlet of the metal tube in the reference position — 70 nA. The total duration of the experiment (irradiation of the specimen) was approx. 3.5 h. The measurement results are presented in Fig. 3. All calculations were performed for an electron beam that had passed through a metal tube in a position parallel to the incident beam axis. The channel inclination angles were varied without a break for surface charge relaxation. The graph shows the results of measuring both the total electron current, without taking energy losses into account (black squares), and the fraction of electrons that passed through the channel with energy losses of less than 1 keV (white circles). In addition, the time dependence of the total fraction of electrons that had traveled through the channel was measured for several inclination angles with the highest channel transmission.

The measurement results are presented in Fig. 4. The energy state was assessed by analyzing the spectra of x-ray radiation generated in the interaction of electrons with the copper plate surface. The spectra were compared for electrons of the initial 10 keV beam and for electrons that had passed through the channel (i.e., interacted with the dielectric surface). A detailed description of the assessment method is given in [13]. The spectrum accumulation time in all presented experiments was 10 min.

Similar to the experiment described above, the transmission of a beam by a tapered glass channel was studied for different inclination angles with respect to the incident electron beam, which had the following initial characteristics: electron energy — 10 keV; current measured at the outlet of the metal tube in the reference position — 103 nA. The time dependence shows that with "reference" beam incidence on the channel, the stabilization of charge distribution on its walls takes a considerable time (about 10 min). For non-reference beam incidence on the channel, the stabilization time decreases with increasing inclination angle. Once the charge is distributed on the channel inner walls, the capillary provides a fairly stable electron transmission for several minutes. This parameter is important in determining the optimal mode of tapered channel operation and further possible applications of the resulting focusing effect.

The second series of experiments was performed in order to determine the inclination angle of the already-irradiated tapered channel that corresponds to the maximum transmission; thus, measurements were made for the transmitted current at several capillary inclination angles where the transmission was highest (Fig. 5*a*). The same specimen as in the previous experiment was used.

The dependence was found to be narrower and shifted relative to the reference position by nearly 2°. However, it can be seen from the figure that the maximum transmission and, therefore, the focusing are almost identical to the corresponding data for the unirradiated specimen.

The maximum transmission was observed at an angle much greater than that in the reference position. Of note is that the fraction of transmitted electrons remained at the same level as in the previous experiment.

In order to verify the results obtained in the first experiment, the third series of measurements was performed using a new unirradiated specimen having similar parameters: length — 15 mm; inlet/outlet inside diameters — 1.15 mm/0.30 mm. The beam current strength was 39 nA. The unirradiated specimen in the reference position exhibited unstable beam transmission; this fact can be attributed to channel contamination, which disappeared after sufficient irradiation. The total irradiation time amounted to 2 h. Fol-

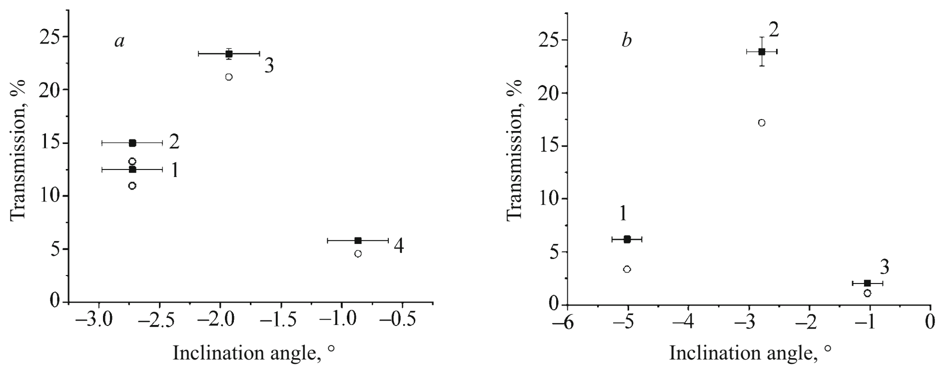


Fig. 5. Dependence between the fraction of the electron beam that travels through the irradiated tapered channels and the inclination angle of channels with respect to the reference position: ■) fraction of all electrons that pass through the channel; ○) electrons that pass through the channel without significant energy losses; the numbers on the graph denote the order in which the measurements are performed; *a*) specimen preirradiated for over 3.5 h; *b*) specimen preirradiated for about 2 h.

lowing an abrupt change in the channel angle (point 1 in Fig. 5*b*), the transmission was stabilized and increased with further changes in the inclination angle. The obtained dependence between electron transmission through the channel and the channel inclination angle is presented in Fig. 5*b*. As in the case of the second experiment with the irradiated specimen, the dependence is narrower than in the first experiment using the uncontaminated capillary. However, the maximum transmission, regardless of the energy state of transmitted electrons, remains at the same level.

A comparison of the results obtained in the described experiments revealed some peculiarities of the process.

RESULTS AND DISCUSSION

Figure 6 shows the result of comparing the ability of a tapered channel having an output inside diameter of 0.3 mm to focus a 10 keV electron beam for three series of experiments.

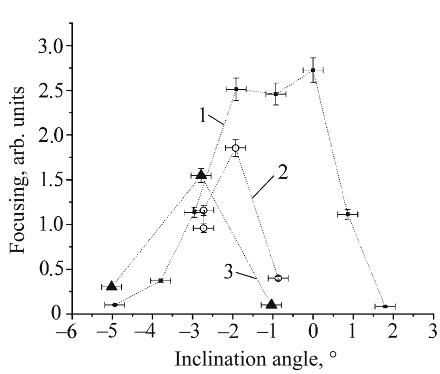


Fig. 6. Dependence between the compression of a beam of electrons that travels through the channel virtually without contact and the channel inclination angle relative to the reference position for the three series of measurements: ■) unirradiated specimen (Experiment 1); ○) irradiated specimen (Experiment 2, irradiation time of 4 h); ▲) irradiated specimen (Experiment 3, irradiation time of 2 h).

The first series of experiments involved working with an unirradiated specimen, whereas the other two experiments used irradiated specimens (approx. 3.5 and 2.0 h, respectively). Noteworthy is that these results are obtained for electrons that lost energy of 1 keV or less. The obtained data indicate that the initially uncontaminated capillary compresses the beam most effectively (by up to 2.7 times), with the maximum transmission realized at inclination angles close to those where the initial electron beam propagates in the original direction.

For irradiated specimens, no time dependence was measured. However, the obtained data indicate that their focusing ability is significantly reduced with respect to the electrons that retain their initial energy state. This fact can be attributed to the radiation defect accumulation in the glass (formation of color centers), as well as to the order in which the measurements were performed.

CONCLUSIONS

In this work, we report the results of an experimental study into the ability of a 15 mm long tapered glass channel having an inlet/outlet inside diameter ratio of 1.0 mm/0.3 mm to focus a 10 keV electron beam. Three series of measurements using two identical channels were performed. The first two series studied one specimen. The third series of measurements presents data on the second identical specimen.

The maximum increase in the output beam current density was observed for the unirradiated channel with the specified parameters, reaching up to 2.7 times for the position where the channel axis is parallel to that of the incident beam. In this case, the electrons of the transmitted beam lose no more than 1 keV of their initial energy. The time required for stabilization of the output current did not exceed 10 min, decreasing with changes in the inclination angle of the channel relative to the reference position.

The work was financially supported by a Program of the Ministry of Education and Science of the Russian Federation for higher education establishments, project No. FZWG-2020-0032 (2019-1569).

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