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Effect of Control of a Fast-Electron Beam using a Ceramic Channel

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Abstract—The possibility of controlling charged-particle beams by the use of dielectric channels (guiding) is an urgent task because of the potential of developing inexpensive autonomous controlling and focusing devices. At present, experiments with the use of ions with an energy on the order of MeV are intended for the application of radiation with a spot size of about one micrometer for material analysis, surface modification, and cell surgery. In the case of using electron beams, such a possibility is still under study. In this work, the possibility of controlling a beam of accelerated electrons by using a ceramic channel in the case of its inclination both in the vertical and in horizontal planes is demonstrated. Data about the control are obtained for the channel after irradiation of both its end faces for no less than 5 h. After such treatment, an inhomogeneous carbon-containing deposit is formed on the interior surface of the channel near its end faces. It is demonstrated that the formed deposit has no influence on the guiding properties of the channel.

Keywords: electron beam, dielectric channel, characteristic radiation, time dependence, control effect, carbon-containing layer, X-ray radiation, beam deviation, high-speed electrons, geometric transmission angle, visualization of the electron beam, scintillator, ceramics

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INTRODUCTION

The effect of controlling electron beams with an energy up to 10 keV by dielectric channels have been actively investigated since 2007 [1, 2]. At present, there is a large amount of experimental data on investigating the grazing interaction of electrons with an energy up to 20 keV with dielectric surfaces [3–10]. However, to date, there is no unambiguous answer to the question of the mechanism of such an interaction: whether the control effect is a consequence of the scattering of electrons at surface atoms, or whether self-consistent dynamic charge distribution on the surface of the dielectric sample acts as a determining factor as in the case of ions [11–13]. It is evident that some time is needed for the formation of surface distribution on the internal walls of a channel upon a beam of electrons entering it. The formed self-consistent distribution is able to provide the contactless passage of a part of electrons of the beam through the channel, as is evidenced by, for example, the results [1, 3, 6] of measurement of the time dependences of transmission of the investigated channels. However, it was demonstrated in [2, 4, 5] that transmission of the investigated channels started instantaneously. This led the authors to the conclusion that the scattering of electrons at atoms of the surface layer of a dielectric is the main mechanism of the control effect.

Another important point when studying the effect of controlling electrons with dielectric surfaces is the type of the dependence of transmission of the dielectric channels on the magnitude of the incident current strength. This problem is important for describing the surface conductivity of a dielectric upon the impact of a grazing electron beam on it. The absence of an explicit dependence of the angle of deviation of electrons with an energy of 10 keV on a dielectric single plate on the magnitude of the intensity of the incident beam current was demonstrated in [14]; however, such an investigation has not been carried out for a dielectric channel.

Comprehensive research of the process of the propagation of electrons with an energy of 10 keV through a ceramic (zirconium oxide) macrocapillary was carried out earlier [15]. The dependences of the channel throughput on time and the value of the intensity of the incident current in the geometry in which the axis of the channel is parallel to the axis of the incident beam were measured. This work follows in the footsteps of the performed experiment [15]; it investigates the presence of the guiding effect for a

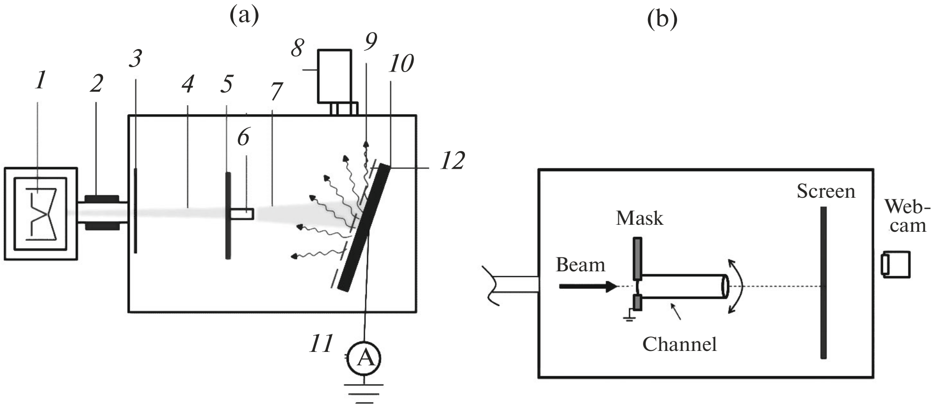

Fig. 1. Experimental schematic: (a) measurement of time and current dependence of a beam incident on the channel [15]: *1*—electron-beam gun, *2*—electromagnetic lens system, *3*—collimator with a diameter of 1 mm, *4*—beam of accelerated electrons, *5*—holder with an electrically grounded mask, *6*—investigated sample, *7*—beam of electrons transmitted through the sample, *8*—X-ray detector, *9*—radiation generated at getting of electrons to copper plate, *10*—copper plate, *11*—ammeter, *12*—brass mesh under a voltage of 400 V; (b) investigation of the effect of electron-beam control.

channel exposed to many-hours-long irradiation by a beam of electrons with an energy of 10 keV at both end faces.

EXPERIMENTAL

A pilot experimental unit for investigating the processes of interaction of ionizing radiation with a substance, whose detailed description is given in [16], was used in this work. The experimental scheme is shown in Fig. 1. The experiment for investigating the time dependence of transmission of the electron beam by a dielectric channel was primarily carried out [15] (Fig. 1a). The electron beam is generated by an electron-beam gun *1* and passes through a system of electromagnetic lenses *2* and a collimator *3* of 1 mm in diameter. The formed beam *4* with an angular spread of less than 0.35° is incident on the input of the investigated channel *6*, mounted in the holder *5*. The length of the channel is 20 mm and the inside diameter is 1.5 mm. The channel inlet is closed by a grounded metal mask with a millimeter aperture at the input of the sample. The mask helps to shield the end face of the channel from irradiation by electrons of the beam and prevents blocking of the channel. An additional through aperture with a diameter of 1 mm was provided in the mask for measurement of the current of the initial beam incident on the channel. It is important in the experiment to determine the energy state of electrons transmitted through the channel, in particular, to estimate the fraction of electrons whose energy loss is less than 1 keV, i.e., 10% of the initial energy of the beam electrons. Estimation was carried out by the method suggested by the authors described in detail in [17]. The principle of the method lies in the comparison of the spectra of emission generated in the metal target upon its exposure to an incident and transmitted beam of electrons *7*, which is generated in the metal (copper) plate *10* upon its exposure to electrons. The spectrum consists of a smooth curve of bremsstrahlung radiation and quasimonochromatic characteristic X-ray peaks, the most important of which are the lines at energies of 8.04 (CuK_α) and 8.9 keV (CuK_β). It should be noted that both *K* lines of copper can be generated upon the incidence of electrons with an energy of more than 8.99 keV on the copper target. This property defines the fraction of electrons whose energy loss is less than 1.01 keV of the initial energy 10 keV. The estimation was made on the basis of comparison of the ratio of events related to the characteristic peaks of *K* lines of copper, to the total number of events. In the case of a monochromatic beam, this ratio remains constant to a good approximation. However, if a part of the electrons loses its energy, the number of events concerning the characteristic lines of copper, decreases, which leads to a decrease in the corresponding ratio. The spectrum of the emission generated in the plate was measured with use of an XR-100SDD solid-state semiconductor detector *8*. Simultaneously the intensity of the current of the transmitted or direct beam was measured by a Keithley 6482 picoammeter *11*. To suppress the secondary-electron yield from the copper plate, a brass mesh *12* was mounted just before it, to which a voltage of 400 V was applied. The residual pressure in the chamber was ~10^{-6} torr.

The typical spectrum generated in the copper plate upon the incidence of electrons with an energy of 10 keV is demonstrated in Fig. 2. The algorithm for carrying out the experiment [15], in which the channel is exposed to irradiation by an electron beam, is important: measurement of the current intensity of the beam passing through the through aperture of the mask, simultaneous taking of the radiation spectrum, generated in the copper plate, over 5 min; the sample –

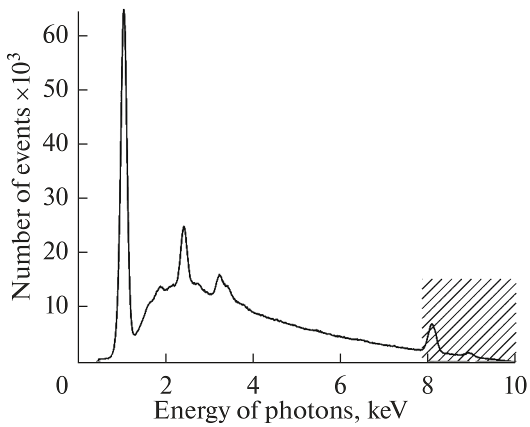

Fig. 2. Typical spectrum generated upon the incidence of electrons of the initial beam (energy of 10 keV) onto the copper plate. The shaded region of the spectrum contains events corresponding to CuK_{α} and CuK_{β} lines.

ceramic channel was set below the beam using a linear translator, the sample then was irradiated for 2 min, after that the incident beam was blocked for sample discharging for 2–5 min. Such charging of the channel with breaks was repeated six to eight times depending on the dynamics of the propagation of electrons through the channel. During irradiation of the ceramic channel, the current intensity of transmitted electrons, and the corresponding spectrum, were measured to estimate their energy loss.

Measurements according to the algorithm described above were carried out for various currents of the incident beam: from ~50 to ~250 nA. The total time of irradiation was more than 5 h. The results of experiments carried out according to the described schedule are demonstrated in [15]. The main conclusions made upon analysis of the obtained data are the following. The channel is "blocked" for several minutes; at the same time, upon an increase in the current intensity of the beam, entering the channel, the fraction of electrons transmitted through the channel decreases.

However, in the discussed work, the technical result is very interesting, in particular the generation of a dark deposit on the interior surface of the channel near its inlet. The presence of inhomogeneously distributed spots on the interior surface of the channel was confirmed by the methods of electron microscopy (Fig. 3b), and it was established that the carbon concentration in the spots is more than three times the concentration at an arbitrary point of the interior surface. The deposit could be generated from residual gases, carbon-containing elements of the sample holder and any possible greasy or other organic contaminant. The question arises as to whether it is possible to have a profound effect on the transmission of the channel by the formation of a similar layer also near its outlet end face. The channel was turned so that the outlet unirradiated end face became inlet, while the irradiated end face (with traces of the carbon film) became the outlet. The channel was discharged for almost one day (19 h) due to carrying out necessary maintenance, and then, as well as in the initial case, was irradiated by a direct beam for 5 h. For the turned position of the channel, the measurements, similar to the forward position, were carried out at several magnitudes of intensity of the incident current.

The results of the experiment demonstrated that, with an increase in the intensity of the current of the direct beam, propagation increases until a certain maximum and then begins to decrease. The maximum was achieved within the range of 50–120 nA. Moreover, at a current of about 50 nA, the turned channel was not "blocked" in contrast with the initial position when only the inlet part of the channel was irradiated (Fig. 3a). The explicit dependence of channel transmission on time argues in favor of the assumption that

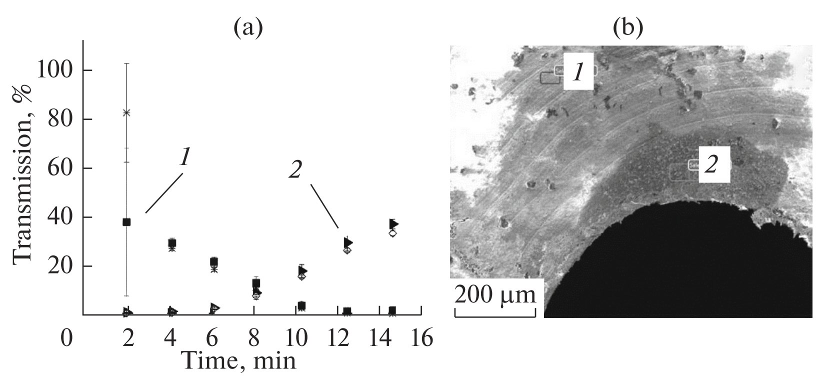

Fig. 3. Time-dependence plot of transmission of the channel in the forward (*1*) and turned (*2*) positions (a): solid squares and triangles are the ratio of transmitted electrons; asterisks and diamond symbols are the ratio of electrons, whose energy loss is less than 1 keV. Calculation carried out with reference to the current incident in the channel ~50 nA. Photograph of the inlet part of the channel (interior part close to the end face) (b): (*1*) arbitrary area of the channel where the carbon-containing deposit was not observed; (*2*) area of the spot (carbon-containing deposit).

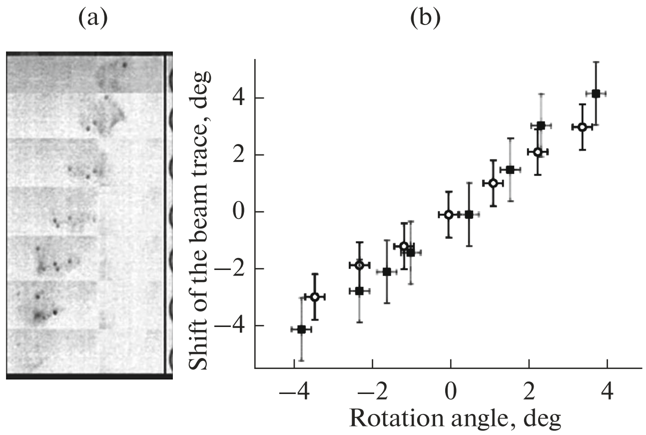

Fig. 4. Series of photographs (the color is inverted) demonstrating a shift in the trace of the transmitted electron beam in reference to that of the direct beam depending on the rotation angle of the channel about the vertical axis (a) and plots of the respective dependences (b): empty circles denote about the vertical axis; solid squares denote about the horizontal axis. The black vertical line in the photographs demonstrates the position of the direct beam which is used as the reference point.

a charge distribution is formed on the internal walls of the channel, which can be caused by the control effect.

If it is supposed that the spots of the deposit are those of a carbon-containing deposit, similar to carbon black, their conductivity will be higher than the surface conductivity of ceramics. It should be pointed out that the measurements were carried out in the geometry when the axis of the channel was parallel to the axis of the incident beam, and after many-hours-long irradiation of the channel from both end faces transmission of the channel vastly improved.

From there, the need for verification of occurrence of the effect of electron-beam manipulation, by the irradiated ceramic channel, arises. To confirm the controlling ability of an irradiated channel, an experiment in visualizing the guiding effect upon a variation in the angle of slope of the channel with reference to the incident beam axis was carried out. The experimental scheme is given in Fig. 1b. The electron beam (the current is about 50 nA) was incident on the channel and irradiated it for several minutes, which was necessary for stabilization of its transmission. The electrons transmitted through the channel were incident on a glass screen with a deposited scale marking of 10 × 10 mm. The glass was coated with a semi-transparent silver layer and electrically grounded. The powder of the scintillator was also deposited onto the metallized area making it possible to visualize the change in the position of the trace of the beam on the screen upon rotation of the channel. The beam trace on the screen was recorded by a webcam positioned at the vacuum viewport outside of the chamber (Fig. 1b). Then the channel was rotated about the incident-beam axis for some angles about the horizontal or vertical axis (the axes pass through the fixed inlet of the channel), and photographs were taken again. Then, the obtained images were stacked into an integrated series (Fig. 4a) and the position of the trace of the transmitted beam was compared with that of the direct beam, transmitted through the through aperture.

RESULTS AND DISCUSSION

The results of the experiment on visualizing the control effect are given in Fig. 3. It is evident that the channel controls the electron beam both horizontally and vertically within the geometric angle of transmission of the channel (±3.6°). The geometric transmission angle was calculated bearing in mind the following parameters: inlet aperture of 1 mm, outlet aperture of 1.5 mm, and the channel length of 20 mm.

It is evident from the photographs that the position of the trace of the direct beam does not coincide with the "zero" position of the trace. It can be explained by the fact that the spots of the carbon-containing deposit near the outlet aperture of the channel are distributed so that the inhomogeneously charged outlet of the channel additionally deflects the beam as a whole. Because of this, the "zero" position of the channel was selected for our purpose after plotting the graph, oriented on the symmetry of the angular shift of the trace of the transmitted beam. A similar situation takes place also in the case of rotation of the channel about the horizontal axis (a photograph is not shown).

Generally, it is evident from Fig. 4 that the beam follows the turn of the channel at a ratio of almost one-to-one, i.e., the guiding effect takes place [11], in spite of the fact that the channel was many-hours-long irradiated at both end faces. This fact is important both from the practical and theoretical points of view, because, at present, the possibility of controlling beams of charged particles by capillaries made of materials containing carbon in their composition (polysulfone bio-compatible fibers [10], PET membranes [18–20]) is attracting special attention. Again, it is necessary to take into account the presence of possible carbon-containing contaminations in vacuum chambers upon carrying out similar experiments. The formation of a carbon-containing deposit can become a factor promoting a change in the surface conductivity of capillaries, and whereby explain the instability of the transmission of beams of charged particles through dielectric channels.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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