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Distribution in the material of the absorbed energy of a space-limited beam flow of high-energy electrons

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Abstract. This article describes the numerical simulation of the energy loss of a high-energy electron flow in matter using the Casino program. The simulation results are confirmed experimentally. Materials MgF_2, YAG, $MgAl_2O_4$, $BaMgF_4$ were chosen for calculation.
Keywords. ceramics, radiation synthesis, high-energy electron flow.

1. Introduction

High-energy electron flows are widely used for the synthesis of materials, modification of their properties, and surface treatment. The advantages of their use in radiation technologies are the high efficiency of flow generation, the simplicity of flow control in space, time, and electron energies. The advantages are the possibility of simple protection from radiation flows, the absence of residual activity.

Low (up to tens of keV, LEE) and medium (up to hundreds of keV) electron flows have found the greatest distribution for radiation technologies. Technologies are being developed using electron flows with energies up to units of MeV. Low-energy electron flows are used to heat targets, crucibles for synthesis, sputtering of materials, etc. Using medium-energy flows, effective processes of film formation, modification of surface properties, etc. are carried out [1–4].

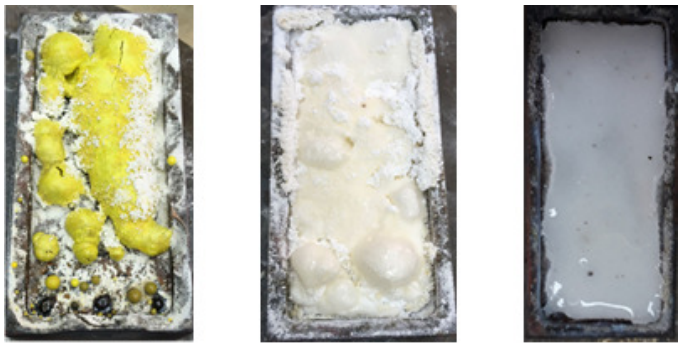
Of particular interest for radiation technologies is the use of electrons with energies of 1–3 MeV. With their use, it is possible to process bulk materials with a thickness of several mm. The possibility of synthesizing refractory ceramics based on metal oxides and fluorides has already been shown [5–7].

It has been established that the synthesis of $Y_3Al_5O_{12}$:Ce ceramics from the initial Y, Al, and Ce oxide powders with melting points T_{melt} of 2410, 2040, and 2400°C, respectively, is realized under the action of electrons with an energy of 1.4 MeV with a flux power density P of 15–23 kW/cm^2, while steel T_{melt} = 1560°C melts when exposed to a flow P > 23 kW/cm^2. The synthesis of ceramics based on metal oxides and fluorides is realized under the same irradiation regimes, although the T_{melt} of metal fluorides is much lower (1263°C MgF_2, 1368°C BaF_2). It is assumed that in dielectric materials, ionization processes and the density of electronic excitations play a dominant role in synthesis processes with a change in phase composition and morphology. In this regard, it became necessary to analyze the distribution of energy losses of the electron flow in a substance under the synthesis conditions used.

2. Radiation synthesis of ceramics

To date, the synthesis of ceramics with a new structure and composition ($Y_3Al_5O_{12}$:Gd,Ce, $MgAl_2O_4$, $BaMgF_4$) has been realized; the same structure and new composition (MgF_2:W, BaF_2:W) from feedstock with high melting points from 1253 to 2825°C. Synthesis was carried out by direct action by direct action on the mixture of an electron beam with an energy of 1.4 MeV and a power density of 13–25 kW/cm^2 at the ELV-6 accelerator of the INP named after. Budker SB RAS. The mixture was a mixture of powders in a stoichiometric ratio to obtain a given phase and had a bulk density of 1 to 2 g/cm^3 (YAG density – 4.56 g/cm^3; MgF_2 – 3.18 g/cm^3). For synthesis, the charge was poured into a 7 mm deep recess in a massive copper crucible with dimensions of

110×50×40 mm^3. The electron beam was taken out into the open atmosphere through a differential pumping system and directed to the target – the surface of the crucible with the charge. The cross section diameter c 0.5 of the maximum intensity of the Gaussian conical beam near the crucible surface was 7.5 mm. To irradiate the entire surface of the charge in the crucible, the beam was scanned across the crucible at a frequency of 50 Hz and an amplitude of 50 mm. The entire crucible was moved in the direction perpendicular to the beam scanning plane at a speed of 1 cm/s. Thus, each elementary section of the charge surface was exposed to a series of rising-falling pulses of the electron flow with a duration of 2 ms and a period of 10 ms. Under such regimes, and for every 1 cm^2 of the surface of the irradiated charge volume, there is an absorbed energy equal to 0.25 of the flow energy per 1 s.



(a) (b) (c)

Fig.1. Photographs of synthesized $Y_3Al_5O_{12}$:Ce (a), MgAl2O4 (b), and MgF_2 (c) samples.

Photographs of ceramic samples in crucibles are shown in Fig.1 as an example. During synthesis in a crucible, a series of drop-shaped ceramic samples of irregular shape and sizes up to 30×20×5 mm^3 or plates with dimensions up to 40×100 mm^2 are formed. We draw attention to the fact that often the original charge remains above the surface of the samples.

It is shown that synthesis is realized only due to radiation energy, only from charge materials, without additives and other materials that facilitate synthesis, with high mixing efficiency, in less than 1 s.

3. Loss of energy of the electron flow

Using the Casino v2.51 program, numerical simulation of energy losses by electrons during the passage through MgF_2 $MgAl_2O_4$, $BaMgF_4$ and YAG by Monte Carlo methods was performed under the following conditions: electron energy 1.4 – 2.5 MeV; beam diameter – 7.5 mm; YAG density – 4.56 g/cm^3; MgF_2 – 3.18 g/cm^3, $MgAl_2O_4$ – 3.61 g/cm^3, $BaMgF_4$ – 4.3 g/cm^3. The results of calculations for the passage of 10.000 electrons using $BaMgF_4$ as an example are shown in Fig.2. In the experiments, the synthesis was carried out by the action of an electron beam on a mixture of stoichiometric powders. Therefore, the depth of the electron path is given for the bulk density of the mixture of MgF_2 and BaF_2 2 g/cm^3. The insets at the top show the characteristic trajectories of electrons as they pass through matter and the depth distribution of the absorbed energy.

As follows from the results presented in Fig.2, when an electron beam, limited in cross section, passes through the substance, redistribution of energy losses takes place. Part of the energy is transferred to matter outside the beam-confining hole. Part of the energy is redistributed towards the center of the beam during its passage. Due to this, the energy loss density along the beam axis exceeds the peripheral one. The energy loss of the electron flow grows up to a certain depth, then decreases. The result of these effects is the following redistribution of energy losses in matter. The largest fraction of energy losses falls on the region remote from the surface and concentrated along

the beam axis. The curves in the figure show areas of energy loss of equal magnitude in relative units. For clarity, the area of matter with maximum losses is marked with a solid fill. For a mixture of MgF_2 and BaF_2 with a bulk density of 2 g/cm^3, prepared for the synthesis of $BaMgF_4$, about 0.5 of the total energy is absorbed in a region 4.0 mm in diameter in a cross section perpendicular to the direction of electron incidence and at a path depth of 0.9 to 1.7 mm from the surface. The energy loss density in the central part is at least 5 times higher than the volume average. Completely similar effects of energy redistribution also take place for other studied compositions. There is only a difference in quantitative characteristics.

Thus, energy losses in a substance under the action of a limited electron flow are redistributed in such a way that the main fraction is concentrated inside the irradiated substance along the beam axis.

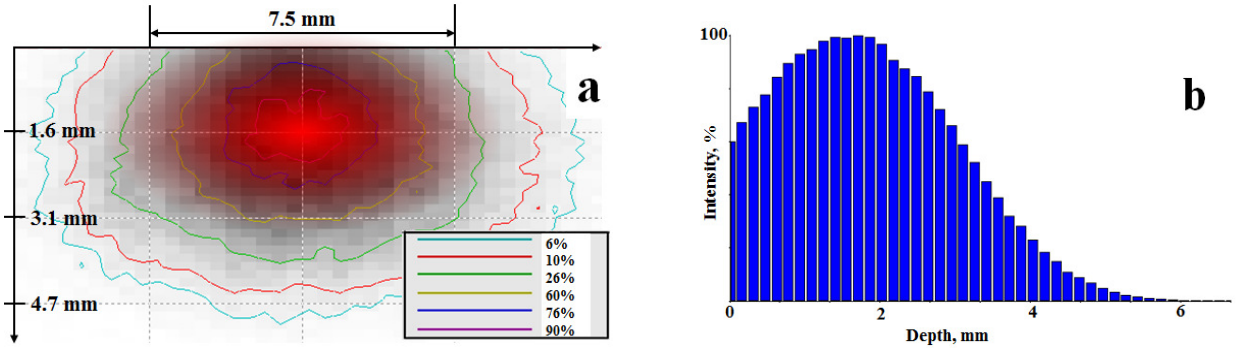


Fig.2. The result of the calculation of the electron range.

Calculations were made of the energy losses of the flow of electrons of different energies in the range provided by the ELV-6 accelerator of the INP. Budker SB RAS in the materials under study. The results of calculating the effective depth of free path in "mm" and "g/cm^2" of electrons of different energies in the materials under study are given in Table 1. In the same place, for comparison, the value of the depth of run in the charge prepared for the synthesis of $BaMgF_4$ ceramics is given.

Table 1. Electron range in the investigated ceramic materials

Material	**Density, g/sm3**	**Run depth**		
		1.4 MeV	**2 MeV**	**2.5 MeV**
MgF_2	3.18	2.6mm (0.83g/cm^2)	3.7mm (1.18g/cm^2)	4.7mm (1.49g/cm^2)
YAG	4.56	1.7mm (0.78g/cm^2)	2.5mm (1.14g/cm^2)	3.2mm (1.46g/cm^2)
$MgAl_2O_4$	3.56	2.2mm (0.78g/cm^2)	3.3mm (1.14g/cm^2)	4.1mm (1.46g/cm^2)
$BaMgF_4$	4.3	1.9mm (0.81g/cm^2)	3.1mm (1.33g/cm^2)	3.9mm (1.67g/cm^2)
$BaMgF_4$, mixture	1.4	5.9mm (0.81g/cm^2)		

The depth of the path of electrons in a substance depends on their energy, the geometric depth depends on the bulk density. In the studied range of irradiation conditions, the specific energy losses per unit depth of free path depend weakly on the electron energy. The volume of the region of matter in which energy is absorbed grows in proportion to the energy of the electrons for the regimes under consideration.

The following should be noted. In a real synthesis situation, the beam has a Gaussian shape, along the entry axis the beam density is much higher than at the periphery. Therefore, the described effect of the concentration of absorbed energy along the axis of beam passage in matter in a real situation should be even more pronounced.

4. Experimental results

To establish the role of the redistribution of the energy of the electron flux in space, a series of works was carried out on the synthesis of ceramic samples based on YAG and MgF_2. The synthesis was realized in the "without scanning" mode. The crucible with the charge, prepared by the standard method, was placed on a table under the accelerator exit window under constant conditions for the selected irradiation regimes. The irradiation conditions changed: scanning was turned off, the electron beam was placed in front of the crucible at the middle of its width. Then the crucible moved at a speed of 1 cm/s relative to the beam. In this mode, the electron beam crossed the entire crucible along its length and turned off. The beam power was set such that the amount of energy absorbed during the exposure to the electron flow was equal to that used for synthesis, i.e., equal to 0.25 of the power of the flow in the scanning mode. The total time of the action of the electron flow on the mixture was 10 s, as in the scanning mode.

After pulling the crucible under the beam, a trace appeared on the charge from the result of radiation exposure, and ceramics were formed. Examples of the result of Al_2O_3(43%) + Y_2O_3 (56%), Ce_2O_3 (1%) exposure to the charge are shown in Fig.3. A Y_3 Al_5O_{12}:Ce ceramic band of characteristic yellow color was formed along the crucible. The photographs show ceramic strips obtained under exposure to flows of 7, 5, 4, 3, 2.5 kW, corresponding to flows with a power of 26, 20, 16, 12, 10 kW in the scanning mode.

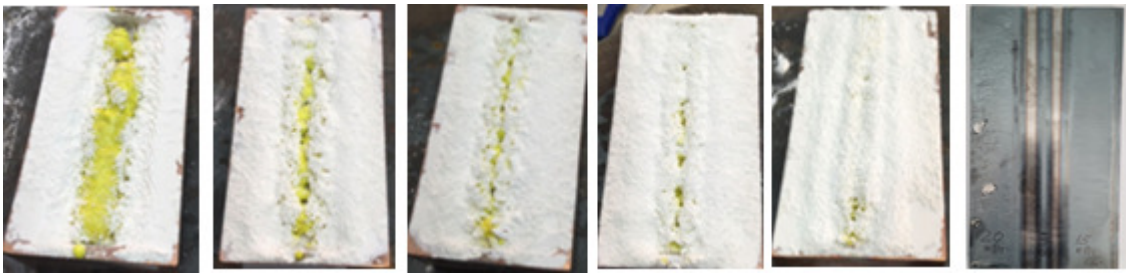


Fig.3. Photographs of ceramic samples in crucibles, synthesized under the influence of flows of 7, 5, 4, 3, 2.5 kW. Here are also photographs of the traces of processing of a steel plate with dimensions of 250×140 mm^2 under the same irradiation conditions.

In the range of the same regimes of radiation treatment, only thin oxidized traces of melting appear on the steel surface.

As can be seen from the presented results, ceramics were formed under the influence of flows from 7 to 2.5 kW. The results of photoluminescence measurements showed that the spectra of ceramic samples obtained under all indicated irradiation regimes have the same form, which indicates the completion of the synthesis process. However, with a decrease in the flow power, the cross-sectional area of the obtained sample decreases, and the thickness of the charge layer above the ceramic strip increases. At a high flow power, a sample is formed in the form of a continuous rod, and at a low flow power, a thin interrupted one is formed.

Quite similar results were obtained in studying the dependence of the efficiency of synthesis of ceramics based on MgF_2 on the flow rate. Under the influence of flows of 5, 4, 3, 2 kW, ceramic strips were formed in the crucible, differing in thickness and shape. The track of ceramics, obtained under the action of a flow with a power of 2 kW, is partially covered with a charge.

The results obtained clearly confirm the existence of a high energy loss density of the electron flux and, accordingly, the absorbed energy in a region of matter spatially remote from the surface and concentrated along the beam axis.

5. Discussion

Investigations are carried out by numerical simulation of the energy losses of a high-energy electron flow in matter. When passing through a substance, there is an increase in energy losses and then a decrease. In the case when the electron beam has a limited size in the cross section, comparable to the depth of run, the redistribution of energy losses in the direction transverse to the flow propagation becomes noticeable. This pattern is well expressed when a substance is exposed to electron flows with energies of 1–5 MeV, which are often used for synthesis, deep modification of the properties of materials. The redistribution of energy losses in matter can affect the totality of ongoing processes under the influence of high-power flows and short exposure time. This effect should manifest itself in materials with a low rate of post-radiation processes, which cause energy equalization over the entire irradiated volume. In dielectrics, the dissipation of absorbed energy passes through the stages of relaxation of electronic excitations, their decay, and the evolution of the created primary imperfection. Ionization in metals in a short time ends with the transfer of energy to the lattice, heating. The thermal conductivity of metals is an order of magnitude higher than that of dielectrics, and two orders of magnitude higher than that of dielectric powders. Therefore, the effect of non-uniform spatial distribution is well manifested in dielectrics, dielectric powders and is not manifested in metals.

Thus, the impact on dielectric materials of electron beams with a cross-sectional diameter comparable to the depth of the electron path leads to the creation of an inhomogeneity in the distribution of absorbed energy. In local areas of matter at a depth of about 0.3 of the electron path length, a high density of excitations is created, which is many times higher than the average one. In this region, the realization of synthesis is most probable. The inhomogeneity of the distribution of the absorbed energy in the substance is formed during the exposure of the beam, less than 1 s under the conditions used by us. During this time, in dielectric media, in dielectric powders, mass and energy transfer is unlikely. The fusion reaction with the highest probability is realized in the central region of high energy losses and only then propagates further.

It should be emphasized that the existence of a nonuniform distribution of energy losses in materials exposed to high-energy electron beams makes it difficult to establish the thresholds for synthesis. The energy loss gradients depend on the ratio between the beam size and the depth of the electron path.

6. Conclusion

The study showed that high-energy electron flows during the passage of matter are absorbed mainly in the middle along the beam. This was shown by numerical calculation methods and experimental methods. According to experiments, the impact of high-energy electron flows on different substances in a short time, in particular, metals and dielectrics, is very different. In a metal, the energy of electrons is transferred faster to the lattice compared to a dielectric.

7. References

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