The method for determination of electron-beam characteristics in the dense gaseous medium

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Abstract. The work has to do with optimization of vacuum-free material working processes with using the concentrated electron beam. A method for direct experimental determination of primary electrons local characteristics in the dense gaseous medium was proposed. The meter design and the measurement procedure were described. The analytical method for evaluation of the electron beam local parameters in the dense gaseous medium was developed. The method was used for evaluation of kinematic characteristics of detector displacement device.

1. Introduction

The electron beam ejection in the dense gaseous medium (including the air atmosphere) essentially enhances the technological capabilities of an application of electron beams [1]. Vacuum-free realization of such processes, as the surface hardening, the welding, the cutting of metals, raises their productivity in comparison with the vacuum implementation. New possibilities to apply the concentrated energy fluxes of this kind to solving tasks of plasma chemistry, flue gas cleaning of toxic impurities etc are opened up. It is worthy of note, that one of the currently most popular areas of technological vacuum-free application of the electron beams is the hardening of near-surface layers of railway rails aimed at lowering of their wear and an increase of their service life.

The optimization of vacuum-free material working processes with using the concentrated electron beam, which allows one to select an appropriate operational regime and parameters of a generator used, needs a knowledge of such characteristics, as distributions of electron beam current and power densities on the axis and the beam radius. Of equal importance thereat is the proficiency in methods for both analytical, and experimental determination of the magnitudes mentioned. Elaboration of the given methods is the main objective of the present work.

2. The analytical evaluation of electron beam local parameters in the dense gaseous medium

The method for analytical evaluation of the beam current density was described in [2] in the context of the phenomenological model. Using the relationships obtained, we express the power

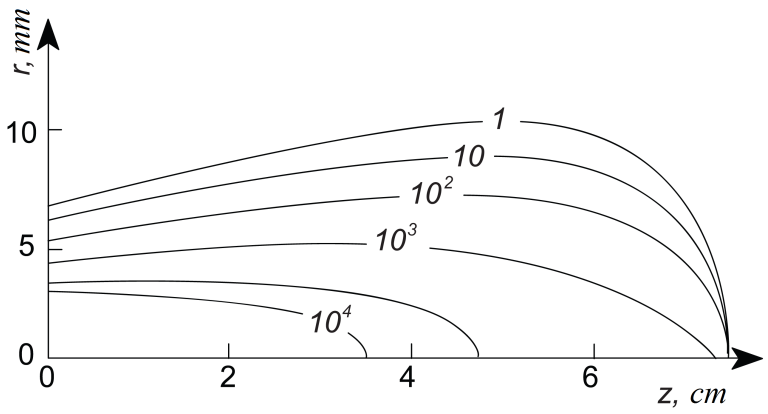

Figure 1. The isodensity lines of the primary electron beam power, W/m^2. The values were obtained for the atmospheric air in the normal conditions, $E_0 = 80$ keV, $r_0 = 2$ mm.

density of the primary electron beam at an arbitrary point at a distance of r from the axis of the beam symmetry and the axial distance z from the beam ejection window through the current density $J(r, z)$ and the mean electron energy at the cross-section $E(z)$:

$$P_{pr}(r, z) = \frac{J(r, z)}{e} E(z) = E(z) \frac{j_0}{e} \exp\left\{ -\frac{z}{a} - \left[\frac{r}{b(z)} \right]^2 \right\},$$

where j_0 is the axial density of the primary electron current at the initial section; a is the magnitude defined by the absorption coefficient; e is the electron charge.

In [2] is shown, that the function $b(z) = r_0 \sqrt{f(z) e^{z/a}}$ refers to the envelope of the beam, which defines, for the given section z, a distance from the beam axis, where the value of the current density is e times less than the axial value, r_0 is the typical radial size of the beam ejection area.

The function $f(z)$ defines the law of degradation of the beam full current, as it recedes from the ejection window, and usually is approximated by the linear dependence $f(z) = 1 - z/L$, where L implies the extrapolated range of electron.

The mean electron energy at the section in hand z [3]:

$$E(z) = \left(E_0^{5/3} - \frac{\rho z}{C} \right)^{3/5},$$

where E_0 is the mean electron energy at the initial section, ρ is the medium density, C is the constant specific for the medium substance.

Presented in Fig. 1 is the pattern of the power density distribution for the primary electron beam on the coordinates r and z.

3. The experimental method for determination of electron-beam local parameters in the dense gaseous medium

For direct experimental measurement of primary beam parameters, the method of moving collector with a small aperture is proposed. It consists in a sequential expansion of the electron beam cross-section (with the help of a moving aperture) into laterally small matrix elements and in measurement of currents of these elements. A so found dependence of the current, passed through the aperture, on a location of this opening (the coordinates of its centre) will define the function of the current density distribution along the line of a travel of the aperture.

It should be recorded, that initially the electron gun generates a monoenergetic electron beam, but because of the passage through the dense gaseous medium a beam spreading in the spectrum takes place. In doing so, the concentration of secondary electrons produced exceeds significantly that of primary electrons ($10^4 \div 10^5$ times), and therefore, the plasma current density is considerably in excess of the primary beam current density. This circumstance results in a difficulty for measurement of the primary electron current and poses the problem to separate fast electrons with typical energies 20 to 80 keV and slow (plasma) electrons with typical energies 1 to 3 eV. As a solution of the problem, a passive separation of the indicated classes of particles may be proposed when using a thin dielectric layer on a basis of the energy dependence of the depth of electron penetration in a substance [3]. In the case the thin dielectric layer fulfils the role of a peculiar filter, allowing the high-energy electrons to easily pass and the low-energy electrons to be confined (to be "cut off").

For the typical energies of the plasma electrons at hand the effective range of electrons in the substance with charge Z and the mass number A is related to the electron energy by the relationship Kanaya-Okayama [4]

$$R_0 = 2.76 \cdot 10^{-6} \cdot \frac{AE^{1.67}}{Z^{0.889}},$$

where the energy is expressed in keV. In the above formula the law of energy loss was chosen in such a manner, that the electron range obtained would provide a most precise approximation to the size of the interaction area in respect to the depth. The magnitude found may be interpreted as the radius of semicircle with the centre at the point of incidence of the beam, which defines the envelope of electrons trajectories. Given in Tables 1 and 2 are the characteristic sizes of the depth of the electron free range in different dielectric (Ta_2O_5, Al_2O_3, TiO_2) and conducting (Al, Cu, W) materials, respectively.

Table 1. The depth of the electron penetration into dielectric material, nm.

E_0, keV	0.4	0.7	1	2	3	4	5
Ta_2O_5	2.5	6.4	11.5	36.7	72.3	116.8	169.6
Al_2O_3	4.0	10.1	18.3	58.3	114.7	185.4	269.1
TiO_2	3.9	10.0	18.1	57.4	113.1	182.8	265.4

Table 2. The depth of the electron penetration into conducting material, μm.

E_0, keV	40	50	60	70	80	90	100
Al	13.4	19.4	26.3	34.0	42.5	51.8	61.7
Cu	4.7	6.8	9.2	11.9	14.8	18.1	21.6
W	2.7	3.9	5.3	6.9	8.6	10.5	12.5

The scheme of the measuring probe and the direction of its motion by scanning procedure are illustrated in Fig. 2. The arrangement of the probe presented makes it possible to measure parameters of beam primary electrons in a wide energy range.

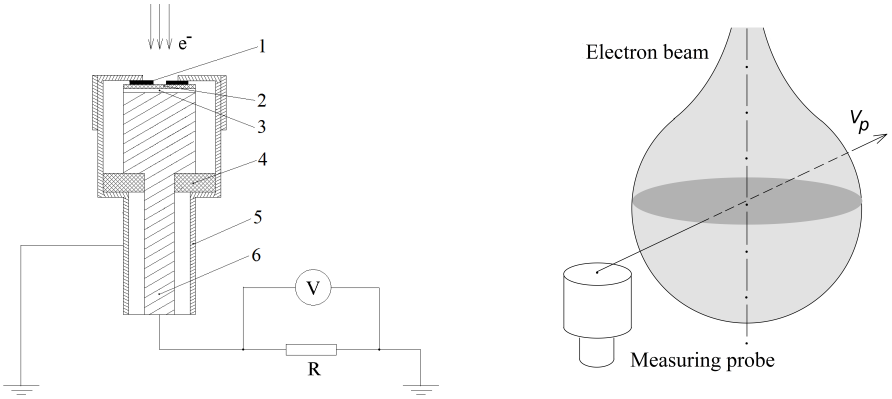

Figure 2. The measuring probe scheme (to the left) and the scheme of the regime of the beam scanning (to the right): *1* — the replaceable metal diaphragm; *2* — the dielectric screen for secondary electrons "cutoff"; *3* — the target (the current collector); *4* — the dielectric washer; *5* — the probe housing; *6* — the inner collector.

The probe is disposed in space, so that its axis is parallel to the beam ejection axis, i.e. the electron flux is chiefly directed on the normal to the probe working area. The motion of the probe is realized at a plane, perpendicular to the beam longitudinal axis. At the incidence of the electron beam to the probe working area the diaphragm *1* "cuts off" the electron beam in its cross-section, i.e. a small area total current component to be measured is selected. Then, the flux passes through the dielectric screen *2*, blocking off the slow secondary electrons, whereupon it strikes the metal target *3* (the current collector). The current collector transfers an arrived charge through the collector *6* to the meter for the following recording and processing.

The filtering out screen *2* and the current collector *3* are structurally a single part in the form of metallic disk, to which a thin coat of the dielectric (e.g., aluminum oxide) was applied. The thickness of the coating layer is about 100 nm. Starting from adaptability to fabrication, the current collector and the collector are made as individual parts, between which a good electric contact should be provided.

4. The evaluation of kinematic characteristics of the detector displacement unit and a measurement error of the method proposed

A rather long thermal action of the electron beam can lead to a fusion of the probe parts and, as a result, to a loss of operability. The most vulnerable (concerning this aspect) part of the probe is the current collector.

To reduce thermal load on the detector construction down to an acceptable level it is worthwhile to use the regime of scanning, when the probe intersects the electron beam with rather a large constant velocity v_p at some distance from the ejection window z.

We estimate the displacement velocity of the probe, necessary that the sensing element of the current collector not fail. As the velocity is perceived to be high, heat conduction and radiation from the surface may be ignored. In the process of measurements the current collector material temperature T is not to exceed the critical temperature T_{max}, at which irreversible phase changes in material start to take place.

Obviously the most stressed thermophysical conditions will come into being with detector moving along a chord, going through the axis of symmetry of the electron beam. We restrict ourselves to integration down this trajectory of motion as an upper bound for current collector heating. The energy, gained by unit area of the current collector at a distance z from the exit

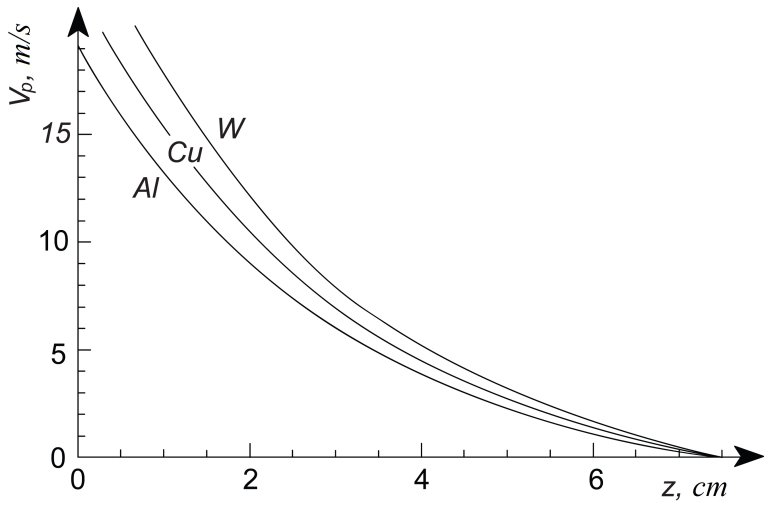

Figure 3. The minimal linear velocity of the probe displacement as a function of the distance between the ejection window of the concentrated electron beam generator and the probe for different materials of the current collector. The values were obtained for the atmospheric air in the normal conditions, the initial electron energy is 80 keV, the beam radius at the initial section 2 mm, the beam full current 60 mA.

section, equals:

$$q(z) = 2\int_0^\infty \frac{j(r,z)}{e} E(z)\frac{dr}{v_p} = \sqrt{\pi}\frac{E(z)}{v_p}\cdot\frac{j(z)}{eb(z)}.$$

The final estimate for determination of the detector minimum velocity appears as follows (Fig. 3):

$$(1-\eta)q(z) \le \rho C_p \Delta T_{max} \Delta z_{ep},$$

or finally

$$v_p \ge \sqrt{\pi}\frac{(1-\eta)E(z)}{\rho C_p \Delta T_{max}\Delta z_{ep}}\cdot\frac{j(z)}{eb(z)},$$

where ρ, C_p are relevant thermophysical constants of the current collector material; Δz_{ep} is the depth of penetration of primary electrons in the current collector material; $\Delta T_{max} \equiv (T_{max} - T)$ is a difference between the maximum allowable and the initial temperatures of the current collector; η is the reflection coefficient of primary electrons from the current collector surface.

For a structure of the "film-on-massive-substrate" type the reflectance η is calculated with using the formula [5]:

$$\eta = \eta_s + \eta_f(D)\left[1 - \frac{\eta_s}{\eta_{f\infty}}\right].$$

In the above expression η_s is the reflectance of electrons from a massive target-substrate, defined by the equation [6]

$$\eta_s(Z,E) = E^{0.1382-0.9211\cdot Z^{-0.5}}\cdot\left(0.1904 - 0.2236\cdot\ln Z + 0.1292\cdot\ln^2 Z - 0.01491\cdot\ln^3 Z\right),$$

where Z is the atomic number of element, E [keV] is the electron energy. This formula is applicable at $5 \le Z \le 80$, $4 \le E(\text{keV}) \le 40$.

The magnitude $\eta_f(D)$ defines the reflectance of the dielectric film with the thickness D [5]

$$\eta_f(D) = \frac{a-1}{a+1}\left[1 - \left(1 - \frac{2a}{a-1}\frac{D}{R_0}\right)\cdot\left(1 - \frac{D}{R_0}\right)^a\right],$$

where R_0 is the range of electron in the film material, $a = 0.045Z$, $10 < Z < 40$, $D \ll R_0$.

The magnitude $\eta_{f\infty}$ is defined as the reflectance from a film of identical composition for a case of its infinite thickness.

When using a material representing a uniform chemical compound out of a few elements, the following rule, allowing for the reflection factors η_i and the mass fractions C_i of components, can be applied:

$$\eta_{tot} = \sum_i \eta_i C_i.$$

As is seen from Fig. 3, aluminum and copper, in regard to a totality of thermophysical characteristics, are more preferential for manufacture of the current collector, than refractory metals (tungsten, tantalum and others), as they require lesser kinematic loads on the detector displacement unit. This is caused by a circumstance, that a characteristic volume of the area of the electrons interaction with a substance for copper and aluminum exceeds substantially that for refractory metals due to a considerable difference between the depths of electron penetration in the materials indicated (Table 2).

The measurement error is a sum of the random and systematic errors. The random error depends on measurement conditions and in most cases it may be minimized at a level no more than 5%. The systematic error, stemming from imperfection of the meter design, may be decreased to aperture error, i.e., an error, correlated with terminal sizes of the analyzing aperture in the diaphragm.

The aperture error depends on the current density distribution at the cross-section of the electron beam and the radius of the diaphragm aperture:

$$\delta_a = \left[1 - \frac{j_{avr\ min}}{j(x,y)}\right]\cdot 100\%,$$

where $j_{avr\ min} = \int_{S_a} j(x,y)dxdy/\pi r_a^2$ is the minimum current density, averaged over the detector diaphragm aperture area. For lowering of this error, it is required to lessen a difference between real and measured values of the current density, which calls for a decrease in the radius of the diaphragm aperture (as compared with the radius of the electron beam).

The least value of the current, that can be measured with a specified accuracy, will be determined by a meter sensitivity [7]. The latter is restricted to the level of fluctuation noises at the meter exit. The sensitivity curves, defined as dependences of the minimum value of the electron beam current density $j_{avr\ min}$ at the plane of the diaphragm aperture, on the radius of the diaphragm aperture are shown in Fig. 4. The curves are given for different values of the magnitude β, equal to the detected signal-to-noise level ratio.

At a prescribed configuration of the detector (i.e., the diameter of the diaphragm aperture) the limiting minimum value of the current density, that the detector is capable of recording, is defined by a curve, relevant to $\beta = 1$ — the case, when the level of desired signal may be compared with the noise level. The indicated minimum value of the current density controls the maximum size of the working area in the direction of the beam ejection axis, i.e. the limiting distance from the ejection window, at which measurements are possible to be conducted. The curve, corresponding to $\beta = 10$, may be considered to be a level of stable detection of a signal. By the removal on the plot in the direction of the curve $\beta = 10$ a transition to a region of the stable detection of signal with reference to the noise level is occuring.

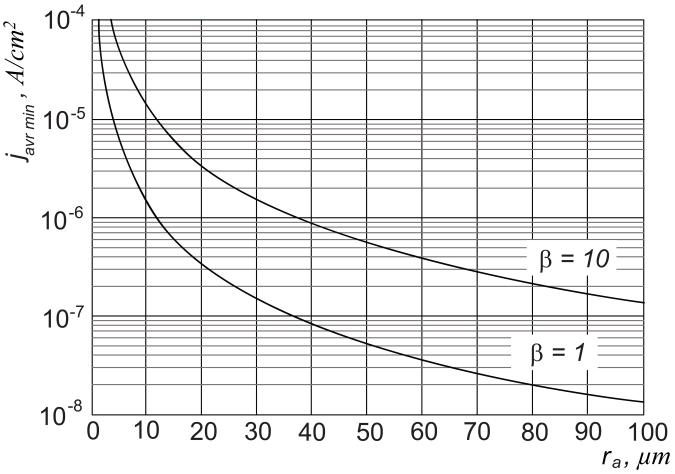

Figure 4. The curves of the meter sensitivity.

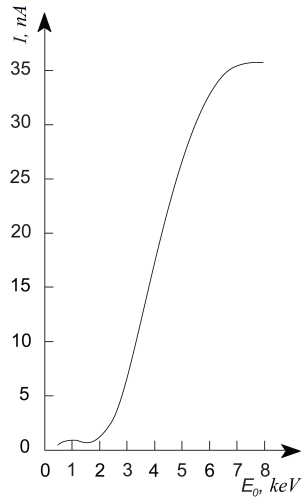

Figure 5. The experimental dependence of the current, passed through the sample with dielectric film, on the electron beam energy.

5. Results and discussion

For verification of functional performance of a current collector prototype with the target, screened with dielectric coating, the experimental investigations were conducted with using the electron source of the scanning electron microscope FEI Quanta 600 FEG.

The samples prepared had a two-layer structure. The copper plates with characteristic dimensions $10 \times 15 \times 2$ mm were used as a substrate. The samples were put through preliminary cleaning of possible impurities and oxides by way of boiling in alcohol, after which the dielectric aluminum oxide Al_2O_3 films with the thickness of about 100 nm were applied to their surface with the atomic layer deposition on the MIR-7 facility.

In the course of the experiment various points of the coating surface were subjected to the action of the electron beam at different values of the accelerating voltage. All samples were in good electric contact with the objective table of the electron microscope vacuum chamber, from which values of the current, passing through the test two-layer sample, were taken. Measurements were conducted with the help of a digital electron picoamperemeter Keithley 6485, connected to the table.

The typical dependence of the current, passed through the sample, on probing electron beam energy is shown in Fig. 5. On the plot presented, a sharp increase in the current with a rise of the accelerating voltage from 2 to 5 kV is clearly defined. This is consistent with the design data, given for aluminum oxide.

Thus, the results of the experimental investigations into dielectric coatings accord well with the calculation results and verify an applicability of this technique for secondary electrons cutoff and feasibility of similar coatings in the structure of the projected meter.

Notice, that the direct measurement of the beam current density is a favourable distinguishing feature of the technique proposed in comparison with similar techniques with a stretched moving collector, as it does not need a subsequent mathematical processing of experimental data base and introduction of supplementary assumptions, implying the axial symmetry of a plasma structure.

6. Conclusions

(i) In the work the analytical method for evaluation of electron beam local parameters in dense gaseous medium was developed and applied. The distribution of the power density for primary electrons on the axis and the radius of the beam was obtained.

(ii) The technique for the direct experimental determination of local characteristics of beam primary electrons in the dense gaseous medium was proposed. The meter design and the measurement procedure with using a passive separation of high-energy and plasma electrons were described. Kinematic characteristics of the detector travel unit were evaluated with using the mathematical model. The error of the technique proposed was estimated.

(iii) The model experimental investigations into separating properties of the dielectric film of aluminum oxide, applied to the copper substrate, at different energies of incident electrons were conducted.

References

[1] Yong-feng D, Rong L, Xian-wei H, Chang T, Rizakhanov R N and Barmin A A 2011 *Journal of Rocket Propulsion* 60–66
[2] Barmin A A and Rizakhanov R N 2007 *Applied physics* 115–118
[3] Schumacher B W 1965 *Electron and Ion Beam Science and Technology* ed Bakish A (John Wiley and Sons)
[4] Goldstein J I, Newbury D E, Echlin P, Joy D C, Fiori C E and Lifshin E 1984 *Scanning Electron Microscopy and X-Ray Microanalysis* (New York and London: Plenum Press)
[5] Saparin G V 1988 *Introduction to scanning electron microscopy* (Moscow: Moscow State University Press)
[6] Hunger H J and Küchler L 1979 *Phys. stat. sol. (a)* **56** K45–K48
[7] Balenkin V I and Ivanov A N 1978 *Methods for analysis of electron beams* (Leningrad: LETI)