J. Nano- Electron. Phys.
3 (2011) No3, P. 67-79

PACS numbers: 41.85.Ct, 29.27.Eg, 42.60.Jf

INTENSE ELECTRON BEAM FORMATION AND ANALYSIS METHODS IN STATIC ELECTROMAGNETIC FIELDS (REVIEW)

G.S. Vorobyov, I.V. Barsuk, A.A. Drozdenko

Sumy State University,
2, Rimsky-Korsakov Str., 40007 Sumy, Ukraine
E-mail: vp@sumdu.edu.ua

In this review basic principles of the electron beam formation in static electric and magnetic fields are reported. Traditional and new perspective designs of electron-optical systems and magnetic systems are also considered. Questions of charged-particle beam focusing and transport on the level of modern technologies are being analyzed and their theoretical and experimental parameter research methods are examined as well.

Keywords: *CHARGED PARTICLE BEAMS, CURRENT DENSITY DISTRIBUTION, ELECTROMAGNETIC FIELD, ELECTRON, ELECTRON GUN.*

(Received 17 March 2011, in final form 28 October 2011, online 05 November 2011)

1. INTRODUCTION

Currently, charged particle beams of different intensity levels have found wide application in material diagnostics (betatrons, linear accelerators, microtrons), in defectoscopy and at the non-destructive testing of product quality [1, 2], became an effective tool in industrial process installations for dimensional and thermal treatment of different materials: cutting, welding, metal fusion and spraying, coating deposition and modification, production of new structures, polymerization of plastics, etc. Moreover, intense extensive electron beams (EB) are the main working element of numerous and various in types vacuum microwave devices, where they transform the external power source energy to the high-frequency oscillation energy: klystrons, magnetrons, backward-wave tubes (BWT), traveling-wave tubes (TWT), diffraction radiation generators (DRG), etc [3, 4, 5]. For parameter optimization in such devices besides the output characteristics one needs information concerning spatial configuration and microstructure of the EB itself, i.e. about current density distribution, transverse and longitudinal components of electron velocity in any beam cross-section. This information is especially important when constructing electron devices with extensive intense beams of sufficiently high energies.

At the present time, information concerning the beam parameters can be obtained by experimental or theoretical analysis. Experimental investigations of beams [6, 7] show that efficiency of application of different measurement methods of their parameters depend largely on the specificity of the devices, in which they are applied. However, application of the experimental methods is considerably expensive process; therefore on the stage of the initial study of characteristics of specific EB it is reasonable to analyze EB numerically. Thus, theoretical investigation methods of EB characteristics allow to quickly determine geometry and key parameters of the beam without experiment, however, proximity of the design models forces to consider the obtained information only as the preliminary one. Thus, development of both the experimental and theoretical investigation methods of EB is the actual question.

The aim of the present paper is the short review of traditional and modern directions in the development of electron-optical systems (EOS), as well as the analysis of main experimental and theoretical investigation methods of static parameters of extensive EB and choice on this basis of the most optimal solutions for their application. In conformity with this fact the main attention is devoted to the experimental diagnostic techniques of beam microstructure of the power from units of W/cm^2 to hundreds kW/cm^2, and to the theoretical methods of field calculation and analysis of the electron motion taking into account different factors and parameters, which significantly influence the EB configuration and characteristics.

2. GENERAL PRINCIPLES OF THE FORMATION AND FOCUSING OF CHARGED PARTICLE BEAMS IN LONGITUDINAL STATIC FIELDS

2.1 Traditional directions in the development of electron guns and beam formation systems

In general case, structure of EOS can be represented by way of two functional assemblies. The first assembly is the electron gun, which forms an electron beam for the specified values of perveance, emittance, and configuration. The second unit is the focusing system, whose main problem is the transportation of the beam of specified geometry, formed earlier, from the electron gun to the collector with minimal current fall-out on electrodes [8]. The main types of classical electron guns and their modifications are represented in Fig. 1.

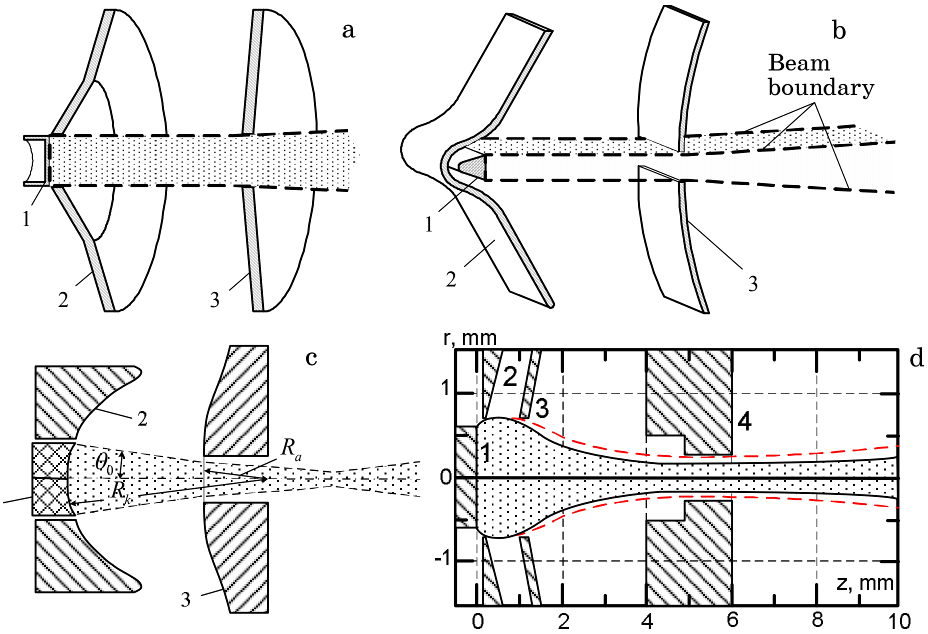

Fig. 1 – *Examples of the designs of classical electron guns: Pierce guns (a, b); Treneva gun (c); typical modification of electrodes of axially-symmetrical electron gun (d)*

Pierce gun was historically first developed for the formation of straight electron beams of simple configuration (Fig. 1a, b), which consisted of the hot cathode 1, cathode electrode 2, anode 3 with a central hole. Pierce guns were widely spread with the use of different types of cathodes, namely, thermoemission, photoemission, and field-emission [9, 10].

We have also to note the electron guns developed by Treneva S.N., who has taken as the basis the spherical gun consisting of the cathode 1, focusing electrode 2, and anode 3 (Fig. 1c). Treneva gun was aimed for the formation of wedge-shaped and cone-shaped convergent electron beams.

As a rule, axially-symmetrical EB is formed by three-electrode gun with convergent optics; then it is introduced into electrodynamic system, where it is focused by periodic magnetic field. In Fig. 1d we represent the typical configuration of electrodes of the axially-symmetrical system consisting of the following elements: hot cathode 1, focusing electrode 2, first anode 3, second anode 4. Guns of such type allow to form EB with the diameter in crossover of the order of 0,1-0,25 mm, beam current 1-25 μA at accelerating voltages 1000-6000 V [11].

Along with the axially-symmetrical EB, ribbon beams also have found a wide application in electron microwave devices of BWT and DRG types [12]. Two-electrode diode gun modified based on the system in Fig. 1b for the use in the electric vacuum devices (EVD) of millimeter wave range is one of the typical systems, which form a ribbon beam. Such guns allow to form ribbon electron beams with the width 3-10 mm and thickness 0,1-0,25 mm, beam current 10-200 μA at accelerating voltages 1000-5000 V [12].

2.2 New directions in the development of electron guns

2.2.1. Single-beam EOS

Efforts to improve the microparameters of ribbon EB, as well as their miniaturization, led to the appearance of new development of slit cathode in IRE NAN of Ukraine. It was proposed to use a non-uniform electric field for the formation of EB in diode electron guns with magnetic flow restriction that was realized in original EOS of the type of injector magnetron gun [13].

The proposed principle consists in the use of considerably non-uniform electric field for the emission current withdrawal from cathode and further electron flow formation in the cathode-anode spacing for the EOS placed in the magnetic field closed to the uniform one. The use of L-cathode of "slit" type schematically represented in Fig. 2a allows to form EB with high current density at the thickness of tenth and hundredth millimeter.

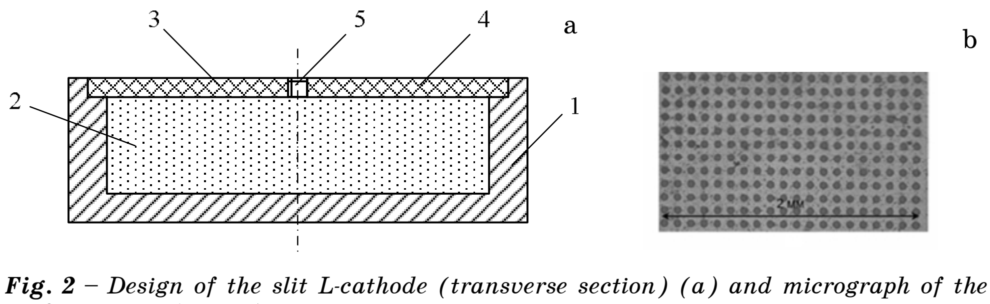

***Fig. 2** – Design of the slit L-cathode (transverse section) (a) and micrograph of the FEC array surface (b)*

Cathode consists of the cylindrical vessel (cup) 1 filled by the substance reserves 2, which provide the reduction of the work function from cathode surface. During mechanical compression of semicylinders done along their perimeter, a specific slit structure 5 is formed on the area of their junction.

Approval of electron guns with L-cathodes of constant activation, whose transverse size is not less than 0,05 mm at the emission density of 10 A/cm^2 used in DRG of the range of 65-80 Hz has shown their high efficiency [14].

Production of EOS based on the matrices of field emission cathodes (FEC) (Fig. 2b) is the modern direction at the present time. Such systems have a number of advantages in comparison with thermal emission analogues, since they expend substantially less energy, are almost inertialess, have narrower energy spectrum of emitted electrons [15, 16].

Besides of FEC based on carbon nanotubes, field emission cathodes on the basis of thin polymer coatings [17] and special semiconductor films [18] are also prospective. In a number of publications it is reported about the increase in the emission current of silicon, molybdenum, and tungsten tips during their coating by diamond-like films [19].

2.2.2. Multibeam EOS

Microwave devices of the millimeter-wave band (TWT, klystrons) with high output power level are widely used in the transmitting equipment of communication systems, radars, and tools of radio counter-measures. Therefore, a special attention is devoted to the development and improvement of EOS in such devices [20, 21].

In this respect microwave amplifier designs, which use low-voltage multibeam electron beam [21] with curvilinear beam axes and multiple-row cathode arrangement are compared favorably.

The given idea was proposed and realized in modification of multibeam electron gun with single-row cathode arrangement, which forms curvilinear electron beams with 90° deflection of their axes using electrostatic field [22] that allowed to improve the technological effectiveness and manufacturing accuracy of the gun and exclude a complex electron beam rotation system accompanied by the magnetic field as well.

Typical multibeam radial gun consists of 8 individual cathode assemblies, anode, and reflector. Total shielding from the magnetic field generated in the floating channels is the essential operating condition of such gun. Configuration of electrodes of one gun cell is shown in Fig. 3.

Each cathode assembly consists of the spherical cathode 1 surrounded by cylindrical focusing electrode 2 under the cathode potential. Anode inlet is the cylindrical tube 3, whose axis coincides with the common symmetry axis of the gun. Tube butt is closed by cathode pole tip 4 in the form of a disc with holes. There are reflector 5 and ring electrode 6 in the anode cavity, between which electrostatic field is generated. This field deflects the electron beams by 90° and provides their optimal entry to the floating channels. To eliminate beam "spreading" along the azimuth direction and decrease the electron velocity spread, deflecting electrode 5 should have additional hills 7.

The described modification of multibeam electron gun with curvilinear electron beams and electrostatic beam deflection by 90° is compared favorably by the design simplicity and possibility to provide the beam compression on the level of single-beam guns.

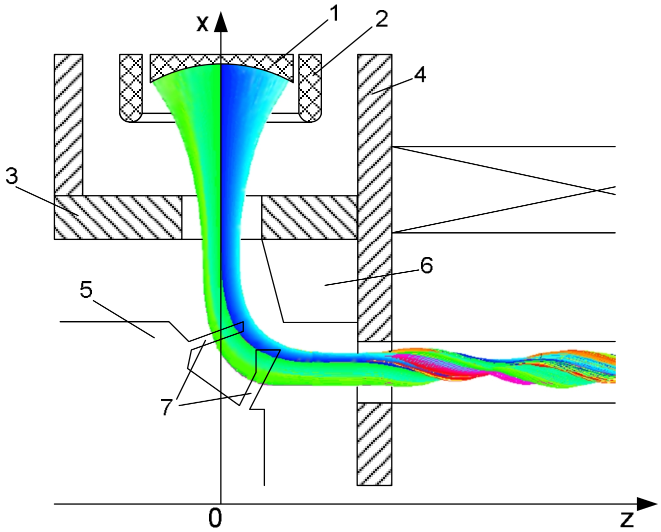

Fig. 3 – *Electrode configuration of one cell of the multibeam radial electron gun*

Radically new possibilities for constructing power low-voltage microwave amplifiers are opened while using several multibeam electron guns located along the chains of coupled multigap resonators [21].

2.3 Magnetic focusing systems

The main problem of an electron beam at the EOS outlet is its tracking in space of the interaction with microwave fields of the specified electrodynamic system. For this purpose one uses different magnetic focusing systems (MFS). The simplest MFS with electron flow focusing by the uniform magnetic field was first investigated and applied for the focusing of extensive axially-symmetrical and ribbon flows in the forties-fifties of the last century [23].

Multireverse MFS are widely spread now [20]. Application of the reverse systems of magnetic focusing is found to be reasonable for the design of the power traveling-wave devices in the millimeter wave range. In such devices, as a rule, the chains of coupled resonators divided into cascades are used as the slowing system (SS). In this case focusing reverse system is made of the sections conjugated with SS sections. Such matching of focusing and slowing systems allows to maximally optimize the design and substantially decrease the EVD dimensions.

Periodic focusing is widely used in EVD with extensive interaction.

Applying in multibeam TWT the electron beam focusing by the uniform magnetic field, which is realized by the system of constant magnets, it is possible to obtain satisfactory mass-dimensional characteristics of the lamps themselves only at their small length that does not allow to obtain high amplification. In connection with this, new area of power amplifier production in the form of a chain of two TWT: the preliminary ordinary TWT with focusing by periodic magnetic field and the output single-section "transparent" TWT with beam focusing by the constant magnetic field [24]. Together with this, search of other alternative and more acceptable focusing techniques of multibeam electron flows in diminutive multibeam TWT and amplifier klystrons of the millimeter wave range led to the appearance of TWT EOS design with multibeam electron flow focusing by the field of single-reverse magnetic system on the constant longitudinally magnetized magnets [25].

Scientists from the research institute "Orion" (Ukraine) has developed and introduced into production the multibeam sectioned TWT with high amplification and electron beam focusing by the periodic magnetic field that allows to comprehensively solve the problem of the decrease in the mass-dimensional characteristics and, consequently, the TWT length as the amplification is increased [26, 27].

3. ANALYSIS TECHNIQUES OF THE CHARGED PARTICLE BEAM PARAMETERS

Acquisition of information about the EB parameters by theoretical methods is based on the analysis of the trajectories of electrons and their energies, velocity components, spatial coordinates and other parameters directly connected with the particles. Calculation of the particle trajectories in uniform fields is not difficult; however, in real fields the trajectory modeling is considerably complicated. Before we study the particle motion in the fields with complex configuration, it is necessary to obtain information concerning the spatial field distribution for the specified electrode geometry. Traditionally, theoretical methods for the determination of the field distribution and trajectories of electrons can be divided into analytical and numerical ones [28, 29].

The case when one can obtain the exact expression for the description of the potentials or field strengths is the perfect one. However, it is possible only for the elementarily prime EOS. In real situations, while considering an arbitrary scalar electrostatic or magnetic potential $u(\vec{r})$ as a function of spatial coordinates it is often convenient to represent it in the form of the Fourier series [30].

After determination of the electric and magnetic fields, it is necessary to calculate the motion trajectories by different analytical or numerical solution methods. In the most cases, in connection with the development of computational engineering, the use of the numerical methods is an optimal solution.

3.1 Numerical analysis methods of the charged particle beams

Now we briefly consider the most popular at present numerical methods of the electrostatic field calculation.

The ***finite difference method*** is based on the discretization of the Laplace equation. As a result, continuous differential equation is replaced by the system of algebraic equations, which can be easily solved.

In order to start the calculation it is necessary to cover a whole region by the discrete mesh (design lattice). System discretization method is not uniquely defined, since one can freely choose mesh according to the current problem, and the finite cell width can be variable. Obviously, calculation accuracy and computation speed depend on the cell shape and size. Having constructed the computational mesh and written equations for all nodes, it is possible to start the numerical solution of the system of linear algebraic equations by direct or iterative techniques [8, 30]. Finite difference method is used in modern software packages QuickWave-3D (Concerto), Fidelity, XFDTD, CST Microwave Studio, etc.

The ***finite element method*** is based on the use of the computational mesh consisting of triangular elements of variable size covering the whole region, for which it is necessary to find the solution of partial differential equation. Then the approximate variation of the potential Δu on each such element is connected with the location of the angular nodes, and the functional (integrated quantity defined on the set of functions) is constructed, whose minimization over the potential values in the triangle nodes is equivalent to the solution of partial differential equation. The finite difference procedure approximates the problem solution in the form of partial differential equation, while the finite element method solves the same problem on the basis of the variational approach.

The apparent advantage of the finite element method over the finite difference method is the simplicity of the statement of the boundary conditions and consideration of complex electrode or pole configurations conditioned by the possibility to arbitrarily change both the element shape and density adjusting their edges to the boundaries and increasing the accuracy on the critical regions. The obvious disadvantage of the finite element method is its relatively low accuracy (especially in the critical region adjacent to the axis) and the calculating speed.

Choice between two methods should depend on the certain problem. It is obvious that the finite element method is more appropriate for non-linear magnetic problems, while one should give preference to the finite difference method in the calculation of electrostatic fields. However, both methods are efficient for the closed systems only. If focusing or deflecting element is not surrounded by the shield, great mistakes appear in the calculations.

The most popular packages of electromagnetic simulation based on the finite element method are HFSS, Multiphysics, and FEMLAB.

The ***charge density method*** (***integral method***) is based on the fact that static field is ejected from any region occupied by conductor. Charges are distributed over the surfaces of all conductors in such a way that all of them become equipotential. If potentials of conductors (electrodes) are generated outside, this is equivalent to the certain charge distributions on electrodes. One can consider that these charges are the sources of electrostatic potential distribution in space surrounded electrodes including the potentials of the electrodes themselves. If replace the potentials of electrodes by these surface charge distributions on electrodes, it is not difficult to calculate the potential in any point based on the field superposition principle without recourse to the use of complex computational meshes as well as in the finite element or finite difference methods. The charge density method allows to calculate exactly the potential distribution on the axis and does not require the closed boundaries in contrast to the methods considered before, and it is also can be applied for the calculation of magnetic fields under the condition of the possibility to use the scalar magnetic potential [31, 32].

The ***finite integration technique*** (***FIT***) was first proposed by Weiland in 1977 [33]. Currently the given algorithm in different modifications is widely used in acoustics, dynamical theory of elasticity, at modeling of electromagnetic fields, piezoelectric effects, etc. In contrast to the most of numerical algorithms, FIT is based on the use of the system of Maxwell equations not in the differential but in the integral form. Discretization of the equations is realized by the two-grid scheme: apart from the main grid covering the calculation region, the secondary grid located orthogonal to the main one is formed. Mechanism of discretization of the Maxwell equations consists in the sequential replacement of analytical curl and divergence operators by their discrete analogues that allows to form the system of the so-called Maxwell finite-difference equations [34]. We have to note that discrete operators contain the topological information solely and preserve the most important properties of the vector field within the studied space.

The FIT stands out because of the universality, since it can be realized both in the time and frequency domains. Moreover, the given method does not impose any constraints on the type of the used grid of space discretization: along with the structured grid, unorthogonal grids are maintained in the Cartesian coordinate system that allows to carry out the modeling of three-dimensional configurations of the systems of any complexity. Numerical FIT algorithm was successfully realized in software packages CST MAFIA and CST Studio Suite

After numerical calculation of electric and magnetic fields it is possible to perform the trajectory analysis of electron motion. Particle trajectories in the general case are fully defined by the system of second-order differential equations of the following form:

$$\frac{d^2y}{dz^2} = f(z, y, y'), \tag{1}$$

where y' is the differentiation over the independent variable z; f is the arbitrary function of three variables defined by the certain form of differential equation and dependent on the potential distribution and magnetic induction of focusing fields.

The simplest way to solve such equations is the use of the Euler method [30]. Unfortunately, accuracy of this method is unsatisfactory. Therefore, one-step and multistep approximation methods have found wider application in numerical solution of the equation (1).

One-step methods use information about the function $f(z, y, y')$ inside the interval, where the solution is searched. These methods require calculation of the function values not only in the boundary points of the interval, but in the points inside the interval. The most widespread specimen from this class of methods is the explicit one-step Runge-Kutt algorithm, which uses expansion in the Taylor series. However, from the point of view of response speed, the rational extrapolation Stoer-Bulirsh method and the Everhart method [35] are more efficient.

Multistep methods are based on the use of information about the function $f(z, y, y')$ in more than one grid point. Obviously, while using this information one can expect both the increase in the speed and improvement in the accuracy of the computational procedure. The most well-known alternative methods of this class are the Adams-Milton algorithm based on the predictor-collector method and the Numerov method (it is often mentioned as the Fox-Goodwin method). The disadvantage of such methods is the following: they need extrapolation based on some values of supporting points obtained before, and this implies the use of some one-step method for the beginning of the computational cycle. Moreover, if it is necessary to change the step value, one should execute the initial procedure again. Thus, use of multistep methods can be much more complicated in comparison with simple one-step methods.

3.2 Experimental measurement methods of the beam parameters

Currently, review [7] is more complete among the classical experimental investigation methods of the electron beam configuration and microstructure. New developments, which led not only to the considerable technological refinement but to the landmark solutions of the charge particle beam investigation problems [6, 36, 37], have appeared during the time elapsed after the mentioned review publication.

In accordance with the approach to the measurement of the beam parameters, all investigation methods can be divided into two groups: direct and indirect ones. The first group of the methods is based on the measurement of the EB characteristics, namely, current, current density, energy, velocity distribution, etc. Indirect methods are based on the detection and analysis of the EB electric and magnetic fields or different effects occurring during the interaction between electrons and environment or objects located along the EB path.

Direct methods are collector ones in essence, since they are based on the EB absorption (completely or partially) by collector of the measuring device placed on the EB path. The given methods are subdivided into the methods, which do not require spatial EB resolution, and the methods with the beam resolution into separate elements. The following direct methods have found the widest application in the EB analysis technique: probe method, traveling collector technique with small hole, and slot-screen method [7].

Indirect methods can be both the contact and contactless. Contact methods are connected with the effects appearing during interaction between EB and substance: radiation methods – gas glow, optical radiation of the excited semiconductor, thermal radiation of metal plate; and radiationless methods based on the measurements of the electrical and mechanical properties of the target (method of the induced conduction of semiconductor and shock acoustic waves in target). Indirect contactless methods can be divided into the radiation (the Vavilov-Cherenkov effect; synchronous, slowing-down and transient radiations) and the field ones (cavity methods, pilot beam methods). Methods of detection and analysis of the slowing-down and transient radiations, pilot beam methods have become widespread among the mentioned EB diagnostic techniques.

Now we consider in detail the most known direct and indirect methods of experimental investigation of EB parameters in the O-type microwave devices.

Probe methods. Wire probes of different configurations have found wide application in the investigation of the current density distribution and EB contour [7]. Scanning probes with total extraction of the beam current [38] are used up to now. However, significant disadvantages of this method, such as complexity of information handling, impossibility to measure the beam structure in the floating channel of the microwave device and poor accuracy, have considerably restricted its application range.

Traveling collector technique with small hole. The essence of the given method consists in the sequential resolution (using traveling hole) of the EB cross-section into small elements and in the current measurement of these elements. The obtained dependence of the current passed through the hole on the hole location (coordinates of the hole center) will determine the current density distribution function along the direction of the hole travel with some error. In such a way one can find the following quantities: current density distributions in different EB cross-sections, dimensions of these cross-sections, change in these dimensions along the beam length, emittance, etc.

However, while determining the absolute value of the current density, the significant errors connected with the finite sizes of the diaphragm (aperture error), instrument accuracy, and diaphragm distortion as well take place. In the measurements of the beam parameters of small diameter (0,5-1 mm) with the maximum density in the diaphragm center with the hole diameter of 0,1 mm the error can not exceed 15%.

Method of detection of the residual gas optical radiation. Ionization gas glow is widely used for the control of the current, dimensions, profile, and emittance of electron and proton beams of the power radiation sources [39].

While measuring the particle beam parameters using ionization gas glow one should pay special attention to the geometry of the experiment. It is necessary to take measures for the removal of light background of the injector cathode, to shield the glow induced by the impacts of the particles with the surfaces of volume, from which the radiation is extracted, and to decrease the number of back-scattered electrons as well. To this purpose light radiation is collimated by diaphragms. Measurement error of the beam current by this method depends on the receiving, amplifying, and detecting equipment and is equal to 5-10%.

Method of detection of the transient radiation on target. Experimental investigations of the EB with transverse dimensions of the order of 0,1 mm and specific powers of tens and hundreds of kW/cm^2 have shown that for such beams it is problematic to use diaphragms with small inlet. This fact has stimulated the development of the method based on the use of the phenomenon of transient optical radiation arising when electrons fall on a metal target and realized in certain measuring circuits of the ribbon and axially-symmetric [36] EB parameters.

In the experimental investigation the following properties of the transient radiation [40] are determined:

– direct proportionality of the radiation intensity to the bombarding electron energy in the energy range from 30 eV to 100 keV; obtained values of the intensity agree well with the calculated ones based on the linear energy recalculation from 80 eV to 100 keV;

– uniformity in structure over the whole surface of the metal exposed to electron bombardment;

– radiation spectrum is continuous in the observed wavelength range from 400 nm to 600 nm;

– radiation sources are localized on the metal surface in the region of the electron fall;

– radiation intensity does not depend on the residual gas pressure in the operating pressure range;

– radiation intensity distribution is determined by the current density distribution in transverse section of an incident (on target) beam;

– dependence of the transient radiation intensity on the EB current density has linear behavior at the fixed accelerating voltage;

– transient radiation is completely polarized, and this can be used for the radiation selection.

Described properties of transient radiation form the basis of the determination method of geometry, distribution behavior, and current density in the EB transverse section [36, 40, 41]. The given method has obtained further development in the works [42, 43].

Estimation of the power limits of the studied EB (from units of W/cm^2 to 100 kW/cm^2 and more) points out also on the possibility of application of the transient radiation method in diagnostics of high-intensity beams used in the process installations and for physical investigations.

4. CONCLUSIONS

Miniaturization of modern electron devices as well as the increase of demands for their microparameters and output characteristics have promoted the appearance of new and development of the existed types of emission surfaces, developments of electron guns and designs of focusing systems.

Upgrading of the thermal emission cathode parameters led to the creation of a new model of "slit" cathode, which allows to form EB with high current density at the thickness of tenth and hundredth millimeter. Formation of EOS on the basis of cold FEC is actively developing. Created on their basis FEC matrices allow to obtain uniform in area and time-stable electron emission at small values of the electric field strength. FEC based on thin polymer coatings, semiconductor films, silicon and molybdenum structures coated by diamond-like films demonstrate high efficiency.

Search of an optimal combination of the mass-dimensional parameters and output power of microwave devices led to the appearance of different modifications of their electron guns and focusing systems. Multibeam systems with curvilinear beam axes, as well as EOS consisting of some multibeam electron guns, which can provide high output power at small current density, are rather promising for the construction of power low-voltage microwave amplifiers. Multireverse and periodic MFS are widely spread among the focusing systems. Also, we have to note the development of the power amplifiers in the form of a chain of two TWT with focusing by periodic and constant magnetic fields.

Analysis of the main experimental investigation methods of the EB parameters has shown that efficiency of their application depends largely on the peculiarities of the studied systems. In spite of their variety, the transient radiation method is considered to be the promising one. Numerical analysis methods of charge particle beams obtain more development when constructing EOS taking into account the preliminary data about EB microstructure and parameters. Their comparative analysis in the problems of field and particle trajectory calculation allows to conclude that at the corresponding choice of the system of equations, order of method, integration step, and mesh length, high precision of calculation can be achieved by any of the stated methods.

REFERENCES

1. P.V. Logatchov, P.A. Bak, A.A. Starostenko, N.S. Dikansky, Ye.A. Gusev, A.R. Frolov, D.A. Malutin, *Particle Accelerator Conference. Proceedings of the 2004*, 355 (2004).
2. P.V. Logatchov, D.A. Malyutin, A.A. Starostenko, *Particle Accelerator Conference. Proceedings of the 2006*, 40 (2006).
3. D.I. Trubetskov, A.E. Khramov, *Lektsii po sverhvysokochastotnoy elektronike dlya fizikov. T.2* (M.: Fizmatlit: 2004).
4. A.A. Shmatko, *Elektronno-volnovye sistemy millimetrovogo diapazona. T.1* (Kharkov: KhNU im. V.N. Karazina: 2008).
5. *Vakuumnaya SVCh elektronika: Sbornik obzorov* (Red. M.I. Petelin) (Nizhniy Novgorod: IPF RAN: 2002).

6. G.S. Vorobyov, A.A. Drozdenko, K.A. Pushkarev, I.V. Barsuk, *Kompressornoe i energeticheskoe mashinostroenie* No3(9), 79 (2007).
7. G.I. Aleksandrov, B.M. Zamorozkov, A.Yu Kalinin, et al., *Ser. 1. Elektronika SVCh* 8(108) (1973).
8. S.I Molokovskiy, A.D. Sushkov, *Intensivnye elektronnye i ionnye puchki* (M.: Energoatomizdat: 1991).
9. T. Srinivasan-Rao, J. Fischer, T. Tsang, *J. Appl. Phys.* **77**, 1275 (1995).
10. I.A. Svetlikina, A.V. Ivanova, O.F. Kuznetsova, *Ser. 1. Elektronika SVCh* No19 (1988).
11. E.V. Belousov, G.S. Vorobjov, V.G. Korzh, K.A. Pushkarev, A.I. Ruban, *Visnyk SumDU. Seriya Fizyka, matematyka, mekhanika* No1(7), 73 (1997).
12. *Generatory difraktsionnogo izlucheniya* (Red. V.P. Shestopalov) (K.: Nauk. dumka: 1991).
13. A.N. Averin, E.V. Belousov, V.G. Korzh, A.S. Tischenko, L.V. Udyanskaya, *A.s. 486600 SU 1762675 A1, H01 J 23/06* (1992).
14. E.V. Belousov, V.V. Zavertannyi, A.V. Nesterenko, *Radiofizika i elektronika* **11**, 275 (2006).
15. N.N. Dzbanovskii, P.V. Minakov, A.A. Pilevskii, A.T. Rakhimov, B.V. Seleznev, N.V. Suetin, A.Yu. Yur'ev, *Tech. Phys.* **50**, 1360 (2005).
16. G.S. Bocharov, A.V. Eletskii, *Tech. Phys.* **50**, 944 (2005).
17. A.N. Ionov, E.O. Popov, V.M. Svetlichnyi, A.A. Pashkevich, *Tech. Phys. Lett.* **30**, 566 (2004).
18. N.V. Egorov, L.I. Antonova, S.R. Antonov, D.V. Zhukov, L.-C. Chao, *Tech. Phys.* **54**, 916 (2009).
19. S.A. Pshenichnyuk, Yu.M. Yumaguzin, *Tech. Phys.* **49**, 623 (2004).
20. L.V. Kasatkin, V.P. Rukin, V.D. Eremka, V.D. Naumenko, G.N. Rapoport, and V.S. Miroshnichenko, *Elektrovakuumnye pribory diapazona millimetrovyh voln* (Sevastopol: veber: 2007).
21. N.I. Sinitsyn, Yu.F. Zakharchenko, Yu.V. Gulyaev, *Zhurnal Radioelektroniki* No10 (2009).
22. A.V. Galdetskiy, I.I. Golenitskij, N.G. Dukhina, L.A. Saprynskaja, *17th International Crimean Conference – Microwave and Telecommunication Technology (CRIMICO-2007)*, art. no. 4368658, 133 (2007).
23. I.V. Alyamovskii, *Radiotekhnika i elektronika* **4**, 841 (1959).
24. B.V. Sazonov, A.S. Pobedonostsev, *Elektronnaya tekhnika. Seriya SVCh-tekhnika* No2, 5 (2003).
25. A.V. Galdetskiy, I.I. Golenitskij, N.G. Dukhina, E.G. Kanevskij, L.A. Saprynskaja, *18th International Crimean Conference – Microwave and Telecommunication Technology (CRIMICO-2008)*, art. no. 4676344, 187 (2008).
26. I.A. Danovich, V.A. Perekupko, *TP SVCh: Elektrovakuumnye pribory* No1, 7 (2009).
27. S.P. Rakitin, *Prikladnaya radioelektronika* **3**, 2 (2004).
28. V.P. Il'in, *Chislennye metody resheniya zadach elektrofiziki* (M.: Nauka. Fizmatlit: 1985).
29. I.V. Melnik, *Izv. vuzov. Radioelektronika* 48, 61 (2005).
30. M. Szilagyi, Electron and ion optics (M.: Mir: 1990).
31. I.O. Arushanyan, *Chislennoe reshenie integral'nyh uravneniy metodom kvadratur: posobie dlya praktikuma na EVM* (M.: MGU: 2002).
32. A.D. Polyanin, A.I. Zhurov, V.F. Zaitsev, *Metody resheniya nelineinyh uravneniy matematicheskoy fiziki i mekhaniki* (M.: Fizmatlit: 2005).
33. T. Weiland, *Electron. Commun. (AEU)* **31**, 3 (1977).
34. M. Clemens, T. Weiland, *Progr. Electromagn. Res.* **32**, 65 (2001).
35. E. Everhart, *Celestial Mech.* **10**, 35 (1974).

36. E.V. Belousov, G.S. Vorobjov, V.G. Korzh, K.A. Pushkarev, V.Ya. Chaban, *Patent 2008737 CI RF, MKI H01J–9/42, G01T1/29, Byull. RF "Izobreteniya"* No4, 160 (1994).
37. Yu.O. Averkov, *Tech. Phys.* **50**, 1058 (2005).
38. M.A. Alsaed Ali, *Elektronnyi zhurnal "Issledovano v Rosii"* (http://zhurnal.ape.relarn.ru/articles/2001/020.pdf).
39. A.S. Artemov, G.F. Astrakharchik, Yu.K. Baigachev, A.K. Gevorkov, *Tech. Phys.* **45**, 116 (2000).
40. I.M. Balaklitskii, E.V. Belousov, V.G. Korzh, *Izv. vuzov. Radioelektronika* **25**, 38 (1982).
41. A.F. Sharafutdinov, G.A. Naumenko, A.P. Potylitsyn, B.N. Kalinin, G.A. Saruev, *Izvestiya Tomskogo politekhnicheskogo universiteta* **307**, 15 (2004).
42. G.S. Vorobjov, A.A. Drozdenko, D.A. Nagorniy, A.A. Rybalko, *Radioelectronics and Communications Systems* **51**, 364 (2008).
43. G.S. Vorob'ev, A.A. Drozdenko, D.A. Nagornyi, *Instrum. Exp. Tech.* **52**, 104 (2009).