Formation and Focusing of Electron Beams in Electron-Optical System with the Plasma Emitter in a Magnetic Field

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Abstract – At the result of electron beam formation and focusing in the electron-optical system with plasma emitter in a magnetic field are presented. A magnetic field is produced by the constant magnet of the electron emitter discharge chamber, which is necessary for discharge initiation.

There are presented the calculations results of a magnetic field configuration and quantity of formation areas, acceleration and transportation of electrons. It is shown that a magnetic field configuration and quantity in these areas can change essentially by a select of an electrodes material the forming a magnetic circuit. It allows implementing without a special additional field source situations with a various degree of a shielding the plasma emitter from a magnetic field. It is shown that making of the quasi-homogeneous magnetic field in the electron source acceleration gap is possible to refine considerably beam focusing at the plasma emitter systems.

1. Introduction

Long-term research of electron sources with plasma emitter based on a hollow-cathode reflected discharge [1] is investigated at plasma emission electronics laboratory of Tomsk State University of Control Systems and Radio electronics (TSUSCR). The increase in demand for these sources from the industry and the scientific organizations became a real stimulus for the research. Studying possibility of reception hyperfine (with a power density over 106 W/cm²) continuous electron beams is one of the important scientific problems of sources with plasma emitter improvement.

It is considered that reception of hyperfine strongly focused beams is impeded by high electron temperature in plasma. However there are many others specific factors to the plasma emitter, which is need to be studied. One of these factors is a magnetic field with a reflective discharge in it. This field is concentrated at the discharge chamber. But there is also exists a leakage field, which is closed through backlashes between magnetic parts of source construction. This field can appear in the space out of the discharge chamber where the charged particles move. Besides, the hollow cathode and emitter electrode do not form the closed magnetic circuit as usual. Therefore, the field pattern and quantity out of the discharge chamber also depend on material and shape of electrodes or their magnetic insertions. Entering to electron-optical system magnetic field changes the electron beam formation conditions. Therefore, on the one part, it is necessary to attenuate defocusing action of this field to a beam. On the other part, it is possible to form a magnetic field in electron-optical system which allows refining focusing.

The report is devoted to research of these questions.

2. The scheme of electron source with plasma emitter

The scheme of electron source on a base of hollow-cathode reflected discharge in a magnetic field is presented in Fig. 1.

Fig. 1. The scheme of electron source with plasma emitter: 1 – hollow cathode; 2 – anode; 3 – permanent magnet; 4 – emitter electrode; 5 – aggregate accelerating electrode; 6 – focusing lens

The discharge in such source is the plasma generator. Emission of electrons is carried out from a plasma surface through a whole (channel) of one of the discharge chamber electrodes of the discharge chamber [2]. The discharge chamber is formed by hollow cathode 1, cylindrical anode 2, and emitter electrode 4.

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with the emission channel executed on its axis. The emitting surface is formed inside the channel as usual. Magnetic field order of 0.1 T is created by constant magnet 3 and pressure about 3–10 Pa is supported by gas flow at the discharge chamber for ignition and existence of the discharge. The hollow cathode and the emitter electrode are made of magnetic material and are magnetic circuit part. The magnet and pole pieces are intended for concentration of a magnetic field inside the discharge chamber.

There are four typical regions in electron-optical system with plasma emitter. The first one is primary formation of the electron beam area, the second is acceleration field (an accelerating gap), the third – transportation region (drift space), the fourth – focusing region (focusing system).

The primary formation of the electron beam area includes plasma emitting surface and electric field close to it surface.

The acceleration region is a region between emitter electrode 4 and accelerating electrode 5 where the high-voltage electric field is concentrated.

The transportation region (drift space) is the equipotential space behind accelerating electrode 5.

The focusing regions a part of transportation region where the magnetic field of focusing lens 6 is localized as usual.

As is known parameters of the focused beams depend on a magnetic field in electron-optical system [3]. This field can have material effect to character of electrons moving inside the beam. If value of lateral component magnetic induction is large at the beam-forming region the electron beam can be broaden. Beam broadening leads to current loss to electrodes and their heating. The magnetic field can restrict the electron beam lateral dimension. It can be released longitudinal magnetic field making.

The selection of research method is an important moment at studying of magnetic field configuration and distribution. Using of various detectors is limited by their rather big sizes. Besides, many of them do not allow diagnosing a field concerning magnetic materials. There is another method based on magnetic field modeling and calculation by means of special computer programs, it looks more effective. At the present report calculations are made using the program Femm [4]. This program allows creating model of a plane-parallel or axisymmetric magnetic field distribution, and also construct the field distribution pattern and to calculate its basic characteristics.

3. Magnetic field calculation in electron-optical system with plasma emitter

Magnetic field distribution to the parts of electron source with plasma emitter standard construction is presented in Fig. 2. The geometry and material of electrodes with the source body are considered in calculations. Elements of source construction are made of nonmagnetic materials (except for anode 2 and accelerating electrode 5), they are not shown in the figures.

From Fig. 2, a is evidently that hollow cathode 1, magnet 3, emitter electrode 4, and source case 6 form together the complex magnetic circuit.

There is a magnetic field in the discharge chamber, primary formation, acceleration and transportation of an electron beam regions. In Fig. 2, b is described the magnetic field distribution pattern in discussed regions for random magnetic circuit in more details way.

Calculations show the resources to change the constant magnetic field configuration and quantity in regions of electron-optical system. This modification occurs by selection of source electrode materials forming a magnetic circuit. It makes possible to create various motion electrons conditions in electron-optical system without application of additional magnetic field sources. Source of magnetic field is the constant magnet of the discharge chamber. Particularly, it is possible to research character of motion electrons in electron-optical system, with the difference in degree of emitter shielding and magnetic field.

Field induction at emitter $B_e$ to field induction $B$ in transportation region of electron-optical system ratio forms the emitter shielding degree. It is accepted in the literature [5, 6]. Results of these researches can help to optimize both conditions of electron beam
formation in the acceleration region and input electron beam to magnetic field region of the basic focusing lens.

The calculated magnetic field distributions and modulus of magnetic flux density curve along coordinate $z|B| = f(z)$ (along the electron-optical system axis) are given in Fig. 3.

The electrodes configuration which is forming electron-optical system is the same in calculations. At each set of calculations there was changed only material emitter electrode or its segment. The magnetic field pattern is presented in Fig. 3, a. This pattern characterizes the model with emitter electrode completely made of a ferromagnetic. In Fig. 3, b, c are shown distributions of field and dependence $|B| = f(z)$ on composite emitter electrode. Fig. 3b – the main part of electrode is made of nonmagnetic material. There is a magnetic insertion in paraxial part of electrode. The insertion allows concentrating the field in the primary formation and acceleration field of electron beam.

The emitter electrode field, which distribution is shown in Fig. 3, a is made of a magnetic material with nonmagnetic paraxial insertion.

Distributions show possibility to organize electron-optical system with completely shielding (Fig. 3, a), partially shielding (Fig. 3, b) and not shielding (Fig. 3, c) emitter for magnetic field. It is necessary to note that the notion of shielding can depend on electron source operating mode for system with plasma emitter. Condition $B_e/B = 0$ (full emitter shielding for magnetic field) is carried out with the forming of emitting plasma surface aggregate in the emission channel depth for a variant shown in Fig. 3, a. However, in the same situation with moving of emitting surface to outlet from the emission channel the variant with a partial emitter shielding ($0 < B_e/B < 1$) takes place. Quantity of a magnetic induction is constant in the acceleration region. The magnetic field is homogeneous. Magnetic field lines are parallel an axis.

The variant with a partial emitter shielding is presented in Fig. 3, b. The shielding degrees depend on emitting surface position in the channel. It is important that, the variant of the Fig. 3, a in comparison with the magnetic induction in primary formation and acceleration regions is 6–10 times more.

Presented in Fig. 3, c calculations show the possibility of making electron-optical system with unshielded emitter ($B_e/B = 1$). Quantity of a magnetic induction is constant at the acceleration area. The magnetic field is homogeneous. Magnetic field lines are parallel an axis.

Thus, calculation results show possibility to realize the situations with various degrees of shielding the plasma emitter from a magnetic field in electron-optical system with plasma emitter. It can be realized by only changing the magnetic field distribution of the reflective discharge.

4. Electron beam formation and focusing at a various degrees of a emitter shielding

To check the influence of various degrees of emitter shielding for a magnetic field and also quantities of this field on electron beam parameters some experiments were made.

Constant parameters in experiment were supported a beam current (20 mA), gas flow (20 cm$^3$/h) and position of region with minimal focused beam diameter.

![Fig. 3. The magnetic field distribution in electron-optical system with plasma emitter at $|B|_{max}$ mT: a – 10.3; b – 60.8; c – 10. Numbering of elements is the same as it Fig. 2](image-url)
The position of emitting surface in the emission channel was changing by accelerating voltage. Beam diameter was measured by a double rotating probe [7]. Beam current density distributions were calculated according to probe characteristics.

The typical view of oscillograms of a probe current (zondograms) is presented in Fig. 4.

Recalculation of probe current distribution to radial beam current density distribution is made by means of Abel’s integrated transformation [8].

Radial current density distributions of focused beam are presented in Fig. 5.

There are current density distributions on Fig. 5, a. These distributions are obtained at accelerating voltage 10 kV. Such accelerating voltage allows carry out variants with emitter shielding for a magnetic field, when emitting surface is in the emission channel close to its boundary. Current density distributions (Fig. 5, b) are obtained at accelerating voltage 20 kV. These distributions characterize the cases when an emitting surface is in depth of the emission channel.

Figure 5 implies the magnetic field configuration and quantity change the condition of electron beam formation and it’s focusing in electron-optical system.

In electron-optical system with not shielding plasma emitter magnetic field activity is shown in effective restriction of the traversal beam dimensions when it accelerates and moves. Figs. 5, a and b illustrate these dependences. The beam current density is maximum. Density distribution is more homogeneous for beam cross-section. 

Presented by curves 2 distributions are on the same figures correspond to a partial emitter shielding to high magnetic field (|B|\text{max} = 60.8 mT). Significant influence on electrons trajectory is taken by lateral component magnetic induction at low accelerating voltage. The beam lateral dimension increases. Current density distribution becomes more flat (Fig. 5, a). Influence of a lateral component magnetic field affects less. Current density distribution gets the wedge shape (Fig. 5, b).

Conclusion

Thus, efforts allow drawing the conclusions:

1. At any construction of electron source with plasma emitter the reflective discharge magnetic field penetrates into beam formation area. The configuration and quantity of this field can be controlled by selection of various combinations magnetic materials. From these materials the source electrodes are made.
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Such control doesn’t seriously effect on discharge stability and parameters.

2. The reflective discharge magnetic field can effectively restrict the traversal beam dimensions during its formation and transportation. Such effect is possible in electron-optical system with not shielding emitter for a magnetic field.

3. Aggregate effect of a reflective discharge magnetic field in electron beam formation and transportation regions and the field of basic focusing lens can be similar to activity of the two-lens magnetic focusing system.

References