HIGH-CURRENT HOLLOW BEAM DYNAMICS IN RF ELECTRON GUNS

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RF electron guns with a metal-dielectric cathode are able to generate intense beams with nanosecond current pulse duration. The plasma developed during the dielectric surface flashover in vacuum is the source of particles of the cathode. Results of the computer simulation of dynamics of the beam of particles that are emitted from the surface of metal-dielectric cathode of a ring geometry are reported. The average emission current value on the cathode in the RF field is about few tens of amperes. Beam parameters obtained experimentally at the two-cell RF gun output are referred in the paper.

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1. INTRODUCTION

Metal-dielectric (MD) cathodes can be applied in S-band RF guns for intense electron beam generation [1]. The beam current pulse, in this case, has the duration of few tens nanoseconds and the amplitude of few amperes. It is known that beam parameters at the RF gun output are mainly defined by the axial electric field distribution [2]. Plasma spots developing during the dielectric surface flashover in vacuum also have influence on particle dynamics in the RF gun with a MD cathode. The cathode should be made of a ring configuration to obtain the large area for the flashover development and homogeneous electric field distribution alongside the emitting surface simultaneously. Besides, the effect of space charge forces will be overcame fractionally, that is especially important during the initial stage of the acceleration, if the electron flow will have the hollow configuration and the amplitude of the electric field applied to the cathode will be high enough. Positive ions are emitted during the negative alternation of RF field. The drift of ions with the velocity that is much lower of the velocity of electrons facilitates the neutralization of the beam space charge fractionally too. Conditions of the beam formation with the most optimal parameters are reviewed in the report in the approximation of the steady state of the flashover. Electron dynamics was computer simulated taking into account the presence of some ions that are representative for absorbed gases and erosion products of a dielectric.

2. PRESUPPOSITIONS IN THE PARTICLE EMISSION

Beam formation from plasma in RF field is unsteady during all stages of the surface flashover development and maintaining. To estimate beam parameters let's take into account the condition of the discharge steady state in the defined time moment corresponding to the total plasma filling of the discharge interval in the approximation of the defined electric field strength. The threshold behavior of the current found in [1] permits to do this.

The study of RF breakdown in the accelerating structures [3] and of a dielectric surface flashover in vacuum [4] shows that properties and stages of plasma development in intense RF fields are similar in many cases with properties of cathode plasma in a pulse electric field [5]. The material of a cathode defines the ionization ratio of plasma which equals to 50% for copper. However, the ion current doesn't depend on the material and its fraction is 8...10% of the total emission current. The density of the current of electrons emitted from the plasma sheath on the hypothesis that electron distribution in plasma spot follows Maxwell-Boltzmann statistics is defined as following [5]:

$$j = en_e\left(\frac{kT_e}{2\pi\, m_e}\right)^{1/2}\exp\left(\frac{\sqrt{e^3E}}{kT_e}\right), \qquad (1)$$

where e is electron charge, m_e is electron mass; T_e is plasma temperature; n_e is plasma density; E is electric field strength; k is Boltzmann constant.

The current density as a function of RF field strength can be ignored for values of the field strength featured for RF guns. Thus, estimations show that the value of the exponential function in Eq. (1) is close to unity for values of electric field strength of 30...45 MV/m and for plasma temperature of ~4 eV. The current of electrons having the density featured in the RF field (10^{15}...10^{16} cm^{-3}) is defined by thermal electron energy.

The velocity of electrons leaving plasma is of two order of magnitude higher (~10^8 cm/s) than the velocity of the expansion of a plasma spot (~10^6 cm/s). During the representative time of the current pulse duration (~ 30...40 ns) the plasma spot is expanded on a distance length of less than 50 μm. Hence, the electron emission relatively the plasma spot can be considered as quasi-stationary process.

The analysis of the density distribution of micro-points over the emitting surface carried out using properties of field emitters and featured value of the emission current from plasma obtained from Eq. (1) permits to assume that the plasma spot covers the total emitting surface of the ring configuration. To see this, let us take the featured value of the square of the one micro-point of ~10^{-8} mm^2. Then the total number of micro-points on the ring of infinitely thin thickness and of 5 mm in diameter will be ~3000 per 1 mm of the surface. Because of the velocity of electron scattering is ~10^8 cm/s the plasma will developed and hence, the electron will emitted, throughout the whole ring surface.

3. BEAM DYNAMICS

The particle dynamics was computer simulated using the PARMELA code [6] which permits to take into account the space-charge neutralization in the beam by generation of additional array of mass-similar macroparticles of opposite charge. There was developed the additional program which generates array of macro-particles using random distribution in two-dimensional hollow configuration taking into account the above considered current density dependence.

Beam dynamics was simulated in the one and half S-band RF gun [7]. The feature of the gun design is the possibility to change electric field distribution by varying the relation between amplitudes of axial electric field in the first cavity and the same quantity in the second cavity η with the frequency of ‘π’ oscillating mode kept changeless. The axial electric field distribution has been calculated using the SUPERFISH code [8] in the gun geometry shown in the Fig.1.

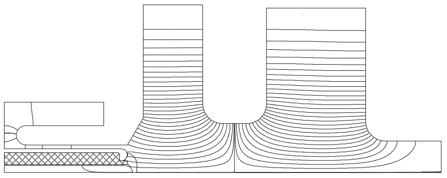


Fig.1. RF gun SUPERFISH geometry

The magnitude of η has been chosen in the range 0.7...1.2 for calculations of the electric field distribution. The maximum value of the axial electric field, in this case, is not higher than 48 MV/m for the feeding the RF power of 1 MW.

According to preliminary estimations made taking into account Eq. 1 and the solution of self-consistent problem using the method proposed in [9] the maximum value of the emission current of particles which can be accelerated in the gun with the field of the above strength is about 30 A. To avoid the critical electric field reducing due to the current loading the value of the emission current was chosen equal to 20 A. The fraction of 10% of this current is the ion current. The array of ions included light hydrogen ions and heavy carbon ions as the most prevailing components of residual gases and products of the erosion of polymer based dielectrics.

The simulation shows that the electric field distribution as a function of η affects mainly on the beam emittance depending on outer R_o and inner R_i radii of the emitting region. Thus, for equal R_o values and following the condition of $2R_i<R_o$ the beam emittance does not vary in fact and has decreasing behavior for the condition $2R_i>R_o$. In the first case the normalized emittance is ≈40 mm·mrad for R_o=1.5 mm and R_i=0.5 mm. In the second case for R_o=1.5 mm and R_i=1 mm the emittance depends on different electric field distributions (Fig.2, curve 1). There is also the dependence of the beam cross-section here (curve 2).

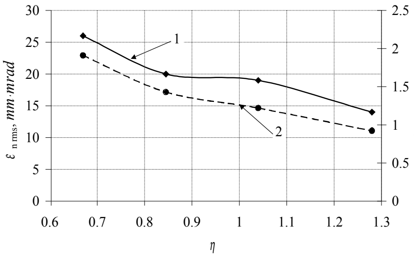


Fig.2. Emittance and cross-section vs η

For the decreasing of dimensions of R_o and R_i the emittance value is magnified significantly and has an increasing behavior versus increasing of the value η. The phase spread of the beam in this case has also increasing behavior versus increasing η. The analysis of trajectories in this situation shows that particles are overfocused that is caused by the increasing of the radial electric field component alongside the emitting surface. This is connected with the amplification of the self-electrostatic field of the ion cloud developed due to the polarized drift. The strength of the ion field added to the strength of the electric component of RF field during the positive half-period sets the electric field strength near the emitting surface increased. The similar field increasing is also caused by increasing of the plasma density. The growth of the electric field of ions reduces the capture factor due to decelerating the major part of electrons and accelerating them in the backward direction. This situation is shown in Fig.3 for the electron density higher then 10^{16} cm^{-3}.

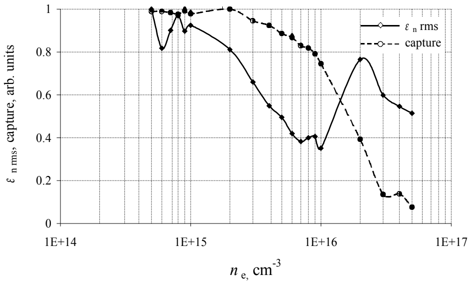
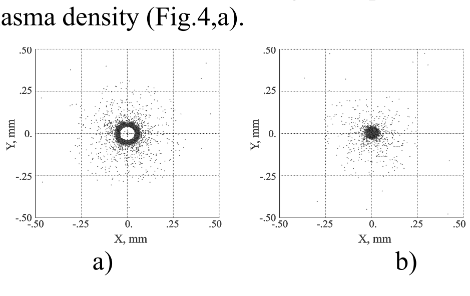


Fig.3. Emittance and capture vs electron density

Electric field of ions makes the electron focusing stronger by radial forces alongside the plasma sheath during the positive RF field half-period. During the negative RF field the half-period electric field of ions prevents electron radial scattering alongside the plasma sheath. Both these actions simultaneously provide the beam to be evident hollow at the gun output for the definite plasma density (Fig.4,a).



a) b)

Fig.4. Beam cross-section (a - η=0.67, b - η=1.28)

The affect of the electric field of ions can be reduced by changing the electric field configuration with the increased electric field strength in the first cavity relative to the second cavity. The beam cross-section in this case is solid (Fig.4,b).

In the range of chosen values of η the phase energy spread of the beam is in fact unvaried and is of ≈45°. The beam current density at the gun output is increased from 4 to 5 A. The energy spread has the decreasing behavior versus increasing of η. The typical energy spread of the beam at the gun output for η=1.28 is shown in Fig.5. The average beam energy in this case is 1.2 MeV and the energy spread is 33% for 70% of particles. These values of phase and energy spread are typical for thermionic RF guns [7].

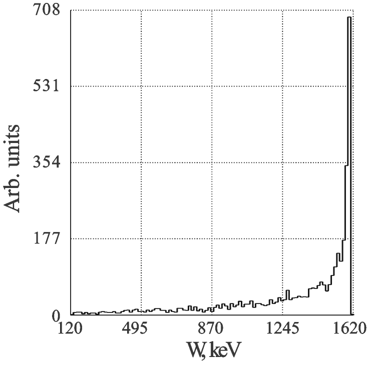


Fig.5. Energy spread of the hollow beam

The beam current value obtained by simulation is in a good conformity with the results obtained in experimental investigations of this RF gun operation with the MD cathode [1]. For the RF field strength in the gun cavity of 25...30 MV/m there was obtained a stable beam current with the amplitude of ≈4.5 A and with the current pulse duration of 30...40 ns.

4. CONCLUSIONS

After the research of the dynamics of the high-current hollow beam in the RF gun there was established that the electric field of ions affects considerably on the beam configuration and its parameters. The hollow or solid beam configuration can be obtained at the RF gun output depending on the plasma density or relation between electric field amplitudes in the gun cavities. Electron beam with both hollow and solid configurations have parameters that are compared with beam parameters of thermionic RF guns.

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ДИНАМИКА СИЛЬНОТОЧНОГО ПОЛОГО ПУЧКА ЭЛЕКТРОНОВ В ВЫСОКОЧАСТОТНЫХ ПУШКАХ

В.А. Кушнир, В.В. Митроченко, И.В. Ходак

ВЧ электронные пушки с металлодиэлектрическим катодом позволяют формировать интенсивные пучки с наносекундной длительностью импульса тока. Источником частиц в таком катоде является плазма, образующаяся в результате поверхностного разряда по диэлектрику в вакууме. В работе приводятся результаты численного моделирования динамики пучка частиц, эмитируемых с поверхности металлодиэлектрического катода кольцевой структуры. Среднее значение эмиссионного тока с катода в высокочастотном поле составляет десятки ампер. Приводятся параметры пучка, полученные экспериментально на выходе двухрезонаторной ВЧ пушки.

ДИНАМІКА ПОЛОГО ПУЧКА ЕЛЕКТРОНІВ З ВИСОКИМ СТРУМОМ У ВИСОКОЧАСТОТНИХ ГАРМАТАХ

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ВЧ електронні гармати з металодіелектричним катодом дозволяють формувати інтенсивні пучки з наносекундною тривалістю імпульсу струму. Джерелом частинок у такому катоді є плазма, яка створюється в результаті поверхневого розряду по діелектрику у вакуумі. В роботі приводяться результати чисельного моделювання динаміки пучка частинок, що емітуються з поверхні металодіелектричного катоду кільцевої структури. Середнє значення емісійного струму з катоду у високочастотному полі дорівнює десяткам ампер. Приводяться параметри пучка, отримані експериментально на виході дворезонаторної ВЧ-гармати.