BEAM DYNAMICS IN RF GUN WITH PLASMA CATHODE

I.V. Khodak, V.A. Kushnir, V.V. Mitrochenko, A.N. Opanasenko
National Science Center “Kharkov Institute of Physics and Technology”, Kharkov, Ukraine
E-mail: khiv@kipt.kharkov.ua

Radiofrequency (RF) guns with a plasma cathode are comparably simple sources of intense electron beam of nanosecond pulse duration. The plasma cathode is produced either due to the surface high-permittivity dielectric flashover triggered by an external voltage source or due to RF discharge. Numerical simulation results of self-consistent transient electron beam dynamics in S-band RF gun with the plasma cathode are described in the paper.

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INTRODUCTION

Radiofrequency (RF) sources for electron linacs tend to generate beams with unique parameters. The main advantage of these sources is the beam of series dense bunches of particles with low emittance. Therefore RF guns are found their wide application mainly in accelerators with high-brightness beams that are used for x-rays and gamma rays generation, in free electron lasers particularly. Resonance systems of RF guns are composed of one or few coupled RF cavities. Beam parameters depend on the amplitude and on-axis accelerating electric field distribution. An RF gun cathode with definite emission determines the greatest difference in a particle dynamics and beam generation in RF guns. RF guns with thermionic and photoemission cathodes have got the maximum spread in accelerator technique. High-brightness beam generation in such devices is well researched. Meanwhile, RF guns generating powerful pulsed electron beams may be paid of great applied interest. These are the plasma cathode RF guns that may be comparably simple sources of intense electron beam of nanosecond pulse duration. The plasma cathode is produced either due to the surface high-permittivity dielectric flashover triggered by an external voltage source [1] or due to RF discharge [2]. According to the results of the first experiments executed in NSC KIPT, electron beam with a 0.5 MeV energy, 11 A pulsed current and 50 ns pulse duration was generated by S-band single cavity RF gun. Beam parameters at the gun extraction are determined mainly by the energy stored in the gun resonance system that is decreased significantly during the current pulse. Beam dynamics research is evidently reduced to the self-consistent problem solution in this case. The paper describes results of the self-consistent beam dynamics research by the numerical simulation technique.

RF GUN

Single cavity RF gun with the external pulsed voltage source driven plasma cathode was chosen for the particle dynamics research. The gun resonance system includes S-band (f_0=2797 MHz) E_{010} cavity that is fed through a waveguide by the klystron RF amplifier operating in self-excited mode. The quality factor and oscillation rise time of the cavity are Q=1.2·10^4 и $Q/\pi f_0$=1.4 μs respectively. The face side of the cavity has the plasma cathode mounted on. Plasma in the cathode is developed due to the surface dielectric flashover triggered by an external pulsed voltage. The gun design is described in detail by the reference [3]. The cathode design is rough drawn on the Fig. 1.

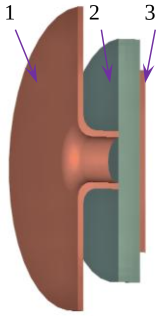


Fig. 1. Plasma cathode design (sectional view)

The base element of the plasma cathode is the ferroelectric $BaTiO_3$ (ε=2150) disk 2 with diameter 10 mm. The rear side of the disk is deposited by the metallic electrode 3 for the triggering pulse U_{tr} to be supplied from external pulsed generator. The triggering pulse amplitude and polarity can be varied. The front side of the disc contacts with metallic electrode 1 that has been grounded in operation. This circular electrode is patterned by the on-axis pinhole that is extruded to cylindrical channel with diameter of 1 mm and length of 1.5 mm. The end face of the channel has the sharped ridge that is in a contact with the ferroelectric disc. Plasma is developed due to discharge in this contact while the triggering voltage pulse is applied. Physics of this phenomenon is researched in depth, see for instance [1]. After the developing, plasma is expanded through the cylindrical channel and reaches the gun cavity. Electrons are emitted from plasma surface and are accelerated by the cavity field.

SIMULATION TECHNIQUE

Electron emission from plasma and post-acceleration by electric field with strength of tens megavolt per meter is transient during all stages of beam shaping in RF gun. Therefore, the overall transient intense beam dynamics can be researched numerically only. Self-consistent transient beam dynamics in this case was simulated using the computer code developed in NSC KIPT [4, 5] and based on application PARMELA [6] and SUPERFISH [7] codes.

According to the algorithm of the developed code the slow-varying complex amplitudes C_{r} of electric $\vec{E}(t,\vec{r})$ and magnetic $\vec{H}(t,\vec{r})$ fields of standing wave cavities are evaluated from the difference equation:

$$\frac{C_r^{(n+1)}-C_r^{(n)}}{\Delta t}+\left(i(\omega_0-\omega_r)+\frac{\omega_r(1+\beta)}{2Q_r}\right)C_r^{(n)}= \qquad ,(1)$$

$$\frac{\omega_r}{Q_rE_0}\sqrt{\frac{Z_{sh}\beta P_{r0}^{(n)}}{d}}e^{i(\varphi_r+\pi/2)}+\frac{Z_{sh}\omega_r q}{Q_rE_0}\sum_{k=1}\overline{\vec{v}_k(n\Delta t)\vec{E}_r(\vec{r}_k(n\Delta t))e^{i\omega t}}$$

where ω_r is the resonant frequency of the cavity, Q_r is the unloaded quality factor, Z_{sh} is the shunt impedance per unit length, d is the cavity length, E_0 is the mean amplitude of the on-axis electric field, v_k is the particle velocity, β is the coupling factor for a cavity with a feeder, φ_r is the phase shift, and $P_{r0}^{(n)}$ is the incident RF power at the given time step. The overbar in Eq. (1) represents time averaging.

The developed code consists of two blocks. The first block solves the task of a cavity excitation by a beam and by external RF source simultaneously computing field amplitude and phase in the instant temporal step Δt. The second block is the PARMELA code which solves motion equations in the field with instant amplitude and phase and with space charge forces taken into account. To keep a physical sense of the obtained results, the temporal step Δt should be longer than the time-of-flight of particles through the simulated longitudinal segment Δz.

The self-consistent dynamics simulation code accepts the following initial data:

- parameters of a RF gun resonance structure including axial electric field distribution;
- initial energy and spatial distribution.

Accelerating field distribution and values of ω_r, Q and Z_{sh} were computed using SUPERFISH code. As for initial array of particles arranging, there were made the following assumptions for the simulation:

- drift velocity of plasma ions is one order of magnitude less then drift velocity of electrons and the beam shaping is finished to moment when plasma ions begin affect the field distribution in the gun cavity;
- emission from plasma surface in vacuum is thermionic. Analysis of this process with Maxwell-Boltzmann distribution law taken into account evaluates the following expression for calculation of the electron emission current density from plasma surface [8]:

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

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

- velocity of electrons (~10^8 cm/s) leaving plasma is two order of magnitude higher then plasma sheath expansion velocity over the emission surface (~10^6 cm/s). Plasma sheath moves on a distance less than 50 μm during the current pulse duration (~40...60 ns). Therefore, electron emission from plasma surface was considered as quasi-steady process in the particle dynamics simulation.
- the triggering pulse duration is much higher than RF field oscillation period and much less than oscillation rise time of the cavity ($c/f_0 \ll \tau_и \ll Q/\pi f_0$).
- the alternating of the triggering pulse polarity was simulated by applying additional longitudinal momentum of electrons in the initial distribution so that electrons were accelerated for the $U_{tr}>0$.

SIMULATION RESULTS

During the simulation we studied temporal and spatial performances of RF gun exit electron beam depending on plasma density, on the triggering pulse amplitude and polarity and on the cavity field magnitude. The triggering pulse duration is 60 ns and it is applied to the cathode rare electrode after 2.25 μs of the RF power pulse supplying. This time moment corresponds to the maximum accelerating field value. RF power pulse envelopes featured for the RF gun operation are shown on Figs. 2 and 3.

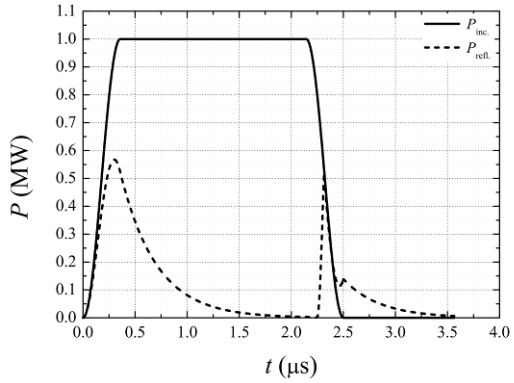


Fig. 2. Pulses of incident and reflected RF power (beam current pulse is 10 A)

RF power is reflected significantly in the moment of the triggering pulse applying and the RF field amplitude in the gun cavity is decreased and its phase is changed at the moment of the beam current pulse raising (Fig. 3). Such RF field behavior is the result of the sum of radiation field of accelerated particles and of the cavity stored field before the beam current pulse raising.

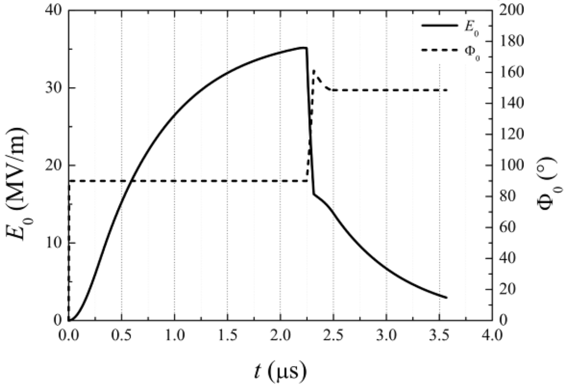


Fig. 3. Amplitude and phase of the cavity field (beam current pulse is 10 A)

The current pulse shape and amplitude at the RF gun exit depends on plasma density significantly and on accelerating field magnitude while the triggering pulse is applied (Fig. 4).

As one can see, the beam current is increased and its pulse duration is decreased while the growth of plasma density. The last fact is defined by the relation of the cavity stored energy and of the energy transferred to the electron beam. The main parameter defining quality of the beam at plasma cathode RF gun exit (emittance and energy spread) is space charge forces. So, the Fig. 5 shows beam normalized emittance dependences at the gun exit vs. plasma density for different values of the triggering voltage and accelerating field value of 36 MV/m.

Space charge forces effect is confirmed by the fact that beam emittance value is decreased while the accelerating electric field strength is increased. Fig. 6 illustrates this dependence for the alternate triggering pulse voltage values. The emittance increase for E>36 MV/m is interpreted by the effect of nonlinear transverse components of RF fields.

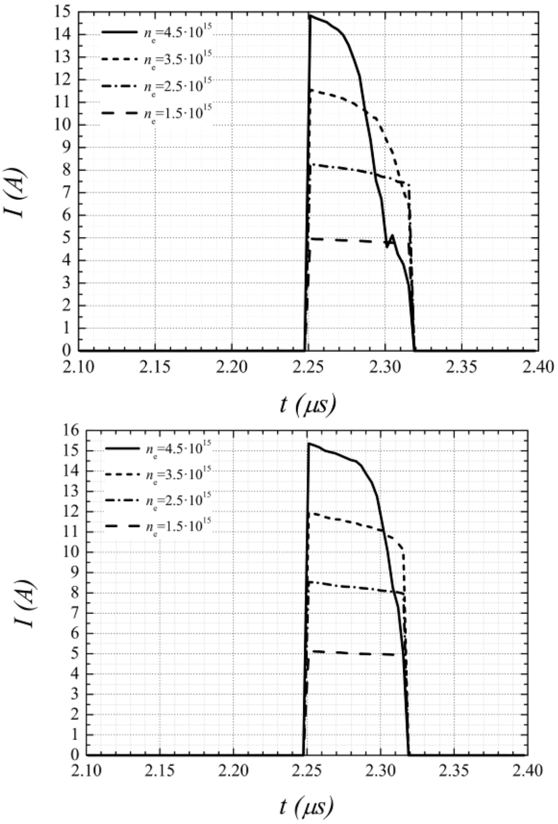


Fig. 4. Beam current pulse at the gun exit for U_{tr} =-2.5 kV. Accelerating field magnitude is E=36 MV/m (top) and is E=44 MV/m (bottom)

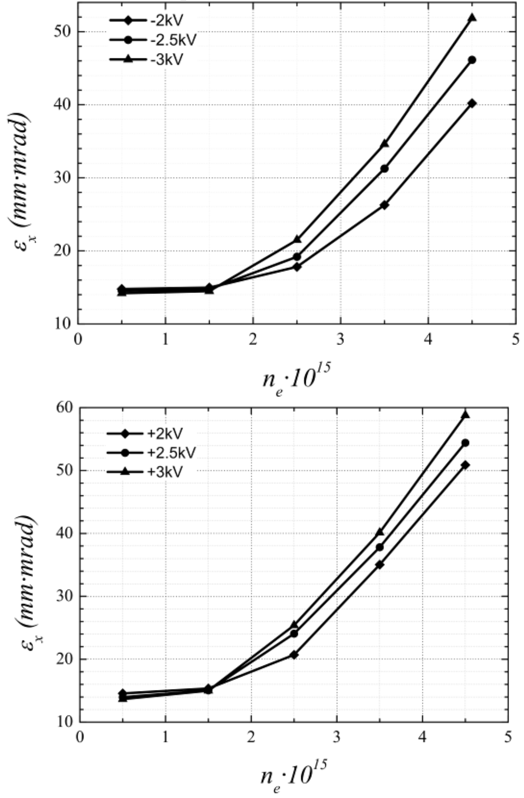


Fig. 5. Emittance vs. plasma density for negative U_{tr} (top) and positive U_{tr} (bottom) and for E=36 MV/m

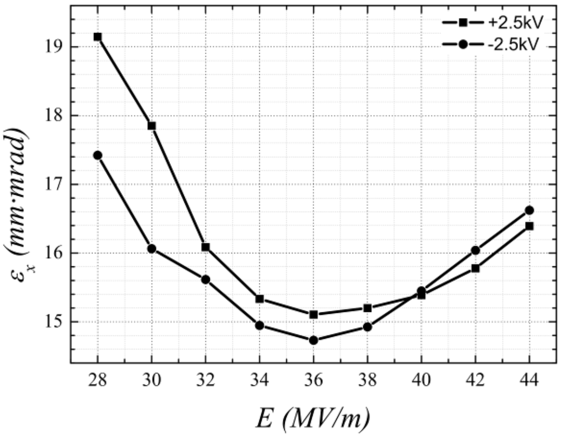
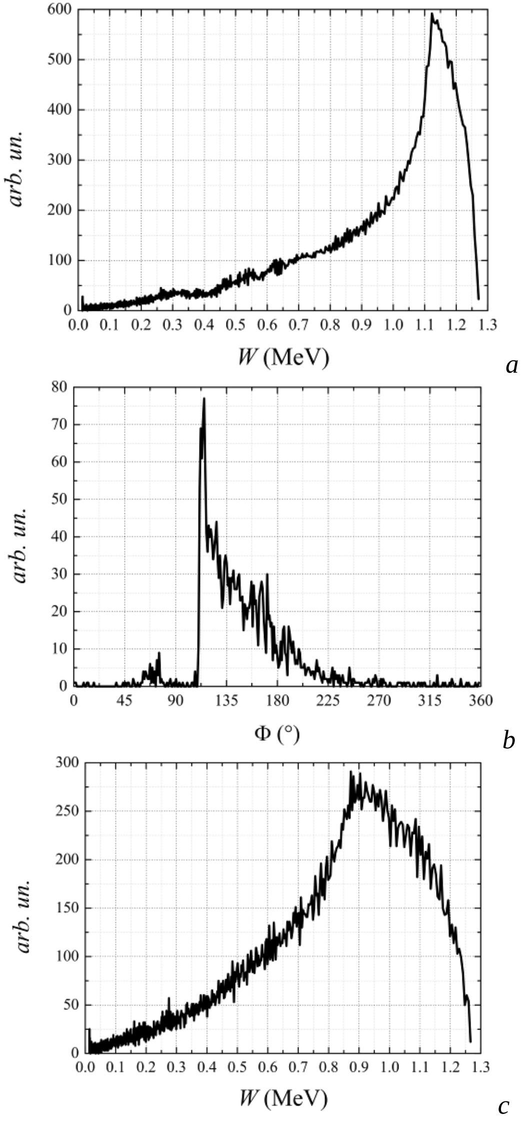


Fig. 6. Dependencies obtained for plasma density value n_e = 1.5·10^{15}

As it follows from the Fig. 6 the beam emittance value is decreased in half for the field strength range from 28 to 44 MV/m whereas, the beam current is also increased. Space charge forces are determinative for the evaluation of the electron beam energy performances. As it follows from the simulation results (Fig. 7) there is the electron repulsion due to space charge forces that prevents electron phase bunching and causes energy spread increasing.



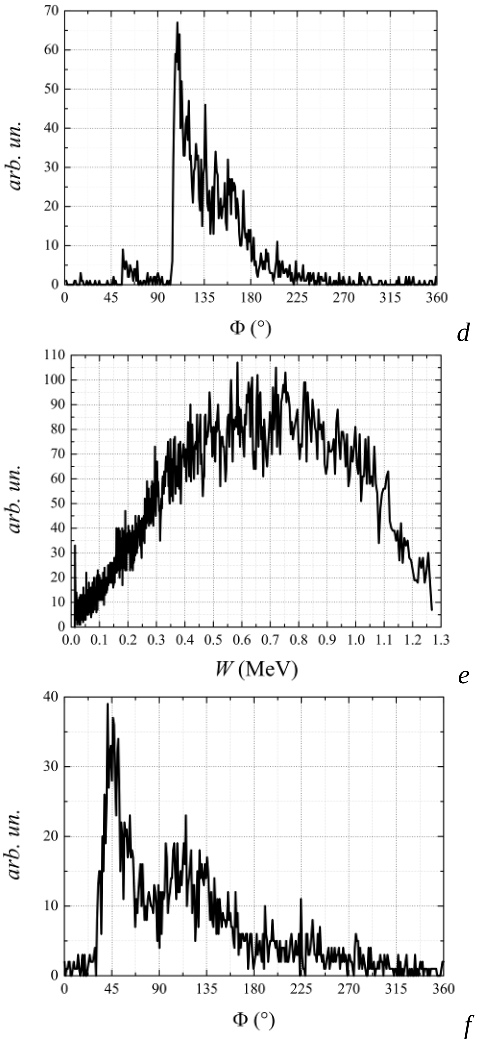


Fig. 7. Electron energy and phase distributions at the gun exit for plasma density values $0.5{\cdot}10^{15}$ (a, b); $1.5{\cdot}10^{15}$(c, d) and $4.5{\cdot}10^{15}$ (e, f) and E=36 MV/m

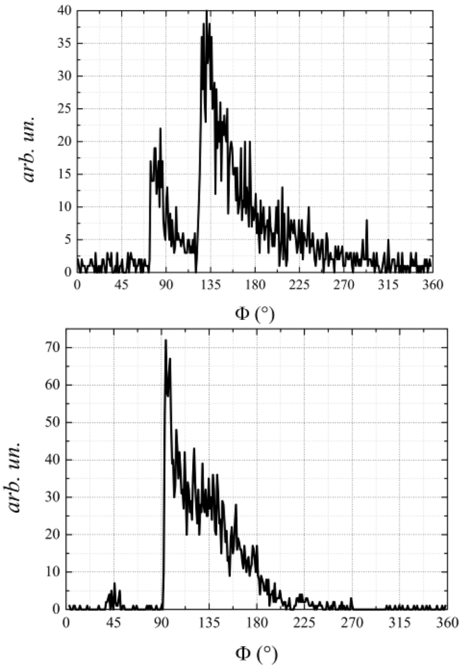


Fig. 8. Phase electron distribution at the gun exit for the plasma density value of $1.5{\cdot}10^{15}$ and for electric field strength E=20 MV/m (top) and E=64 MV/m (bottom)

The effect of space charge forces on phase length of electron bunches is decreased with the accelerating electric field strength increasing. So, Fig. 8 shows phase spreads for the plasma density value of $1.5{\cdot}10^{15}$.

Beam shaping and beam performances in the RF gun with plasma cathode are also depend on the triggering pulse polarity. For the positive triggering pulse polarity beam current and emittance values are higher than for the negative triggering pulse polarity for any plasma density. Besides, for $U_{\mathrm{tr}}>0$ the average beam energy is lower than for $U_{\mathrm{tr}}<0$. The simulated dependences fit well experimental data described in reference [3]. It should be noted, the effect of a triggering pulse polarity and value on the beam shaping in the near cathode region should be more studied in future.

Fig. 9 shows dependences of the beam pulse current at RF gun exit on accelerating field strength for different plasma density values.

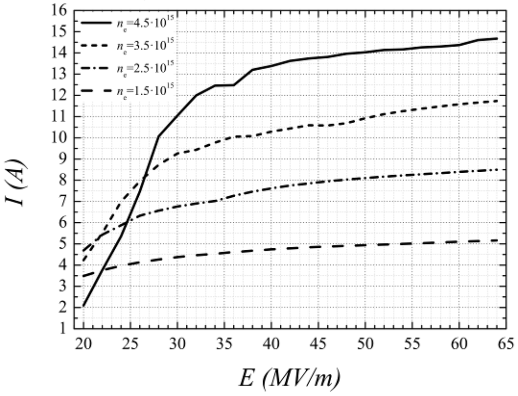


Fig. 9. Beam pulse current vs. accelerating field strength for different plasma density values

The obtained dependences feature the current of a vacuum diode in a space charge mode operation. Emission is limited by space charge for low field strength values and for higher field strength values the current is increased due to increasing of emission current density according to the expression (2).

CONCLUSIONS

Numerical simulation defined main spatial and energy beam performance dependences at the plasma cathode RF gun exit vs. plasma density and electric field strength. It was established that the main determined factor of these performances is space charge forces. The accelerating electric field strength should be increased to get more beam quality. Simulation results fit well experimental data obtained before. This gives ground to state that the used numerical simulation technique fits electron beam shaping in the plasma cathode RF gun adequately.

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ДИНАМИКА ПУЧКА В ВЫСОКОЧАСТОТНОЙ ПУШКЕ С ПЛАЗМЕННЫМ КАТОДОМ

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

Высокочастотные пушки (ВЧ) с плазменным катодом являются сравнительно простыми источниками интенсивного импульсного электронного пучка наносекундной длительности. Плазменный катод образуется либо вследствие разряда, управляемого внешним источником напряжения, по поверхности диэлектрика с большой диэлектрической проницаемостью, либо вследствие СВЧ-разряда. В работе приводятся результаты численного моделирования самосогласованной нестационарной динамики электронного пучка в ВЧ-пушке 10-см диапазона с плазменным катодом.

ДИНАМІКА ПУЧКА У ВИСОКОЧАСТОТНІЙ ГАРМАТІ З ПЛАЗМОВИМ КАТОДОМ

І.В. Ходак, В.А. Кушнір, В.В. Митроченко, А.М. Опанасенко

Високочастотні гармати (ВЧ) з плазмовим катодом є порівняно простими джерелами інтенсивного імпульсного електронного пучка наносекундної тривалості. Плазмовий катод утворюється або внаслідок розряду, керованого зовнішнім джерелом напруги, по поверхні діелектрика з великою діелектричною проникністю, або внаслідок НВЧ-розряду. У роботі наводяться результати числового моделювання самоузгодженої нестаціонарної динаміки електронного пучка у ВЧ-гарматі 10 см діапазону з плазмовим катодом.