RF ELECTRON GUNS WITH PLASMA-ASSISTED EMISSION CATHODES

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Abstract

One of the ways the pulse charge over 10^2 nC ($\tau_{и}$ ~10^{-8} s) can be achieved in S-band RF guns is the exploitation of cathodes with plasma-assisted electron emission. The cathodes are featured by the emission current density ≥ 10^2 A/cm^2. There are considered in the paper experimentally researched and computer simulated features of the beam formation in RF guns with plasma cathodes having spatially extended emission channel.

INTRODUCTION

Some cathodes for RF guns are featured by the development of plasma layer on a cathode surface. The layer can be produced, for instance, on a metallic cathode surface that is exposed by a laser pulse with power fluence >10^9 W/cm^2 [1]. The electrons emitted directly from a flat cathode surface are accelerated by strong homogeneous RF field in a gun cavity. The similar beam bunching is realized in nanosecond RF guns with metallic and dispenser photocathodes [2, 3] producing emission current density of ~10^2 A/cm^2. In case of electron emission from a longitudinally extended plasma cloud moving in heterogeneous RF field, the beam is bunched in a different way. Just such bunching is realized in RF guns with cathodes including plasma developed due to driven ferroelectric surface flashover [4, 5, 6]. The current density of electron emission in ferroelectric plasma cathode may be up to 10^3 A/cm^2 within the duration of a beam current pulse ~10^{-8} s. The peak charge in a bunch of 3 nC has been achieved in the single-cell RF gun with such cathode [6]. The plasma cathode used in the gun has special design adopted for the operation in RF electric field strength more than 10^7 V/m (Fig. 1). One of the ways the beam current can be increased at RF gun output is the increasing, at the first face, of the transverse cross-section occupied by plasma in the emission channel. At the same time, the increasing of the channel diameter should be followed by the proper lengthening of the channel. This is required to reduce RF electric field strength in the region of the metal-ferroelectric contact lower then the threshold of the self-excited plasma origination [6]. Beam parameters at RF gun output are defined mainly by electron dynamics in pre-cathode region of the gun cavity [7]. Velocities of particles in this region are quite small than velocity of light. Therefore, beam parameters at RF gun output may be differed considerably depending on the position of the emitting plasma front. Peculiarities of beam formation by the ferroelectric plasma cathode in RF gun have been researched experimentally and using computer simulation. The obtained results are considered below.

PLASMA CATHODES IN RF GUN

The designed plasma ferroelectric cathode for RF gun is based on the principle of spatial separation of plasma layer development on the cathode and after-acceleration of electrons [6]. The plasma development in the cathode channel is driven by external voltage pulse applied to the cathode during the pulse of feeding RF power. The rise time of the driving voltage pulse corresponds to maximum electromagnetic energy stored in a gun cavity. Contact of the face end of the channel in the front electrode *1* (it is grounded in the given cathode design) with ferroelectric disk *2* (Fig. 1) is the place of plasma development.

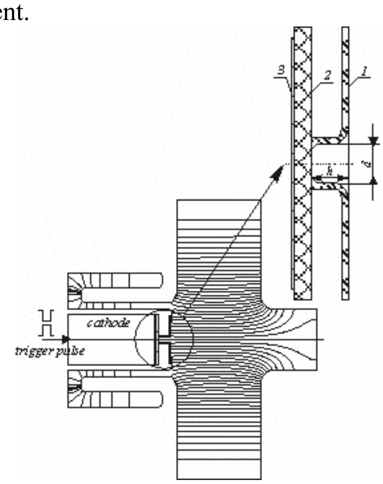

Figure 1: Plasma cathode in RF gun: 1–front electrode, 2–ferroelectric disc, 3–rear electrode.

Electrode *3* deposited on the rear side of the disk supplies the driving pulse voltage amplitude up to 3.5 kV. The disc with area of ≅0.8 cm^2 and thickness 0.5 mm is made from $BaTiO_3$ with $\varepsilon_r = 2150$. It was fabricated for the experiments three front electrodes with different dimensions of the emission channel (Table 1).

Table 1: Cathode specifications

Cathode number	1	2	3
Channel diameter *d*, mm	1.5	3	5
Channel depths *h*, mm	1.5	3.5	5.5

The maximum frequency deviation in the RF gun with cathode 3 is ≅300 kHz that is in the band of the tuning of the gun operating frequency.

EXPERIMENTAL RESEARCH

The beam formation in the single-cell S-band RF gun has been researched in the special facility purposed for pilot tests of injectors for electron linacs. The RF gun and experimental facility is more detailed in [8]. During the experiment, cathodes 1, 2 and 3 (Table 1) have been installed in the RF gun one by one. The driving pulse voltage of +3 kV has been kept unvaried for all three cathodes to produce equal initial plasma density. At maximum possible in experiment RF power of ≅940 kV, the pulse beam current was of maximum value (8.4 A) in RF gun with cathode 1 i.e. with cathode having minimal dimensions of the emission channel. At the same RF power, the pulse beam current in RF gun with cathodes 2 and 3 was 6.2 A and 5.2 A respectively (Table 2). For these beam currents, the pulse charge of the beam in the gun with cathodes 1, 2 and 3 is 505 nC, 560 nC and 625 nC respectively. Temporal parameters of a beam generated by different cathodes were researched for close values of the pulse current that was achieving by setting different RF power in the gun cavity (Table 2).

Table 2: Pulse current and charge of beams

Cathode number	1		2		3
$_{\text{RF cav.}}$, kW	940	400	940	650	940
$_{\text{cav.}}$, MV/m	47	31	47	41	47
$I_{\text{gun.}}$, A	8.4	4.38	6.2	5.09	5.2
Q_{pulse}, nC	505	260	560	460	625

Typical oscillograms of the beam current pulse generated at RF gun output using different cathodes are shown in the Fig. 2. The value t=0 ns corresponds to the beginning of the driving voltage pulse supplying.

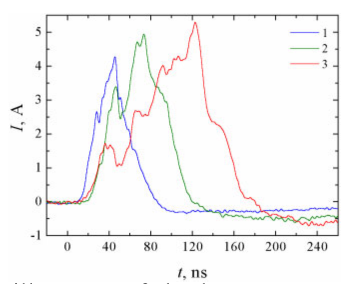

Figure 2: Oscillograms of the beam current pulse in the RF gun with cathodes 1, 2 and 3.

As it follows from the Fig. 2, the rise time of the beam current pulse at RF gun output is increased for longer emission channel in the plasma cathode. Besides, there are oscillations on the pulse rise that are more expressed in case of the cathode 3 with the longest emission channel (Fig. 2, curve 3). It was found the RF electric field strength in the gun cavity is almost invariable during the pulse rise time. However, at maximum pulse current the field strength in the cavity is jump-like decreased (during 10 ns) almost down to zero value. At the same time, the pulse amplitude of the reflected from the gun cavity RF power is increased so fast. These amplitude variations indicate the total RF power reflection from the gun cavity that features interaction of critical or overcritical plasma with electromagnetic wave [9]. It should be noted here that critical plasma density is n_{ec}~10^{11} cm^{-3} for the gun operating frequency f_0=2797.15 MHz.

The obtained experimental result can be interpreted by the next way. It's obviously that the motion of plasma layer in longitudinally extended emission channel should cause the variation of beam parameters at RF gun output during the motion time. The plasma layer having almost ideal conductivity (it's presumed that plasma density is much higher than n_{ec}) may be considered as a virtual cathode. Its displacement relatively the face wall of the gun cavity modifies RF electric field distribution in the cathode channel and in the pre-cathode region of the gun cavity. As far as the time of plasma layer motion in the cathode channel is much higher than the period of RF oscillations, the conditions for the best beam formation may be realized periodically in the gun cavity. This is the reason of the observed oscillations during the beam pulse rise at RF gun output. Insignificant RF field variation and, hence, the negligible detuning of the gun cavity indicates that small bulk plasma is inside the cathode channel. At maximum pulse current value at RF gun output, the plasma is extracted into the gun cavity. This is followed by the cavity detuning and RF power dissipation. According to measured result analysis, one may estimate the velocity of plasma in the cathode channel that is (4±0.7)·10^6 cm/s for the researched cathodes.

As it follows from experimental results, the pulse beam current is decreased within the channel diameter increasing and unvaried average electric field strength (Fig. 3, points *I*). The decreasing may be fitted by square polynomial law. However, it remains unclear and should be treated more carefully. Therewith, the beam current decreasing indicates that the emission current density of the cathode is decreased because of plasma fills the total cross-section of the cathode channel and of corresponding plasma density decreasing. At the same time, the pulse beam charge is increased due longer time interval of plasma moving in the cathode channel.

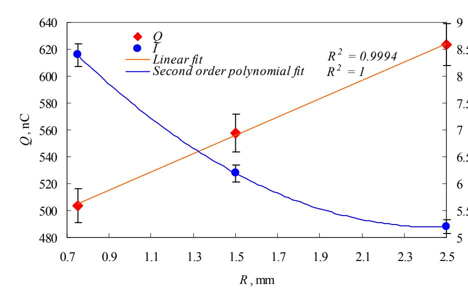

Figure 3: Pulse charge and pulse beam current vs. cathode radius.

BEAM SIMULATION RESULTS

The variation of beam parameters was analysed by the particle dynamics simulation using PARMELA code [10]. It was accepted in the simulation the approximation of preset field and the assumption of ideal conductivity of the emitting plasma layer. The emission current value of the plasma layer was accepted of 30 A for all three cathodes within the average electric field strength of 30 MV/m in the gun cavity. It was presumed in the simulation that the plasma layer occupies the total cross-section of the cathode channel. The motion of plasma layer was simulated by its displacement in the channel.

The obtained by the simulation, dependences of the beam current, of electron energy and of beam emittance at RF gun output for all three cathodes are shown on the Fig. 4. The abscissa value Z=0 cm corresponds to the front electrode plain turned towards the gun cavity.

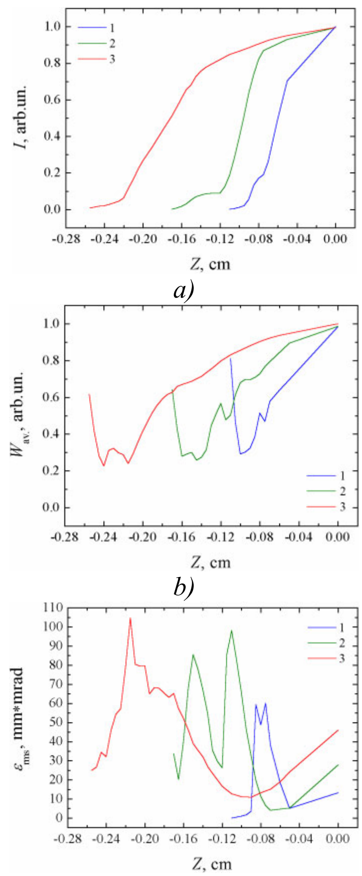

Figure 4: Beam current (*a*), energy (*b*) and emittance (*c*) at the RF gun output with cathodes 1, 2 and 3.

As it follows from the simulation, beam current, electron energy and beam spatial parameters are varied significantly during the plasma expansion in the channel. The particle beam energy is increased rapidly (comparatively to plasma expansion velocity estimated before) and is decreased so rapidly within the definite intervals of the each cathode channel (Fig. 4, *b*). These energy variations are related to the variation of the phase of the particle injection from plasma layer into accelerating electric field of the gun cavity. The number of oscillations is decreased for the shorter cathode channel that corresponds to the experimental results.

As it follows from the Fig. 4*c*, the pulse integrated beam emittance is decreased for the smaller cathode channel diameter. For the emission current accepted in the simulation, this decreasing doesn't depend on the increasing space charge effect due to the current density decreasing. The emittance decreasing is related, first of all, to the decreasing of the initial beam transverse size.

CONCLUSION

The research clarified the affect of the spatially extended emission channel in the plasma ferroelectric cathode on the RF gun beam parameters.

The pulse rise time of the gun beam current is defined by the time of the emitting plasma layer propagation in the cathode channel.

The increasing of the emission channel diameter and its length doesn't increase the pulse current but increases the pulse charge. However, there are significant variations of in-pulse beam parameters in this case.

It is advisable to apply plasma cathode with the emission channel of minimal sizes for the generation of maximum beam pulse current and minimum pulse duration with minimized variations of in-pulse beam parameters. The space charge effect should be taken into account in this case [6].

REFERENCES

[1] X.J. Wang, T. Tsang, H. Kirk et al., Intense electron emission due to picoseconds laser-produced plasmas in high gradient electric field. J.Appl.Phys. 72(3), (1992), 888.

[2] C. Travier, L. Boy, J.N. Cayla et al., CANDELA photo-injector experimental results, http://arxiv.org/abs/acc-phys/9411003 .

[3] N.I. Ayzatsky, E.Z. Biller, V.N. Boriskin et al., Electron resonance high-current accelerator for investigation of collective methods of acceleration. Plasma physics. 20(7,8), (1994), 671. (in Russian).

[4] G. A. Mesyatz, About the nature of electron emission from ferroelectric ceramics, Technical Physics Letters. 20, (1994), 17. (in Russian)

[5] G. Rosenman, D. Shur, Ya. E. Krasik and A. Dunaevsky, Electron emission from ferroelectrics. J.Appl.Phys., 88, (2000), 6109.

[6] I.V. Khodak, V.A. Kushnir, RF gun with ferroelectric cathode. NIM A562(2), (2006), 662.

[7] V.A. Kushnir, V.V. Mitrochenko, Electron Dynamics Investigation in RF Guns, Problems of Atomic Science and Technology. Ser.: Nuclear Physics Research, 3(29,30), (1997), 96 (in Russian).

[8] I.V. Khodak, V.A. Kushnir, V.P. Romas'ko et al., Parameters of electron beam generated by RF gun with ferroelectric cathode, Problems of Atomic Science and Technology. Ser.: Nuclear physics Research, 3, (2006), 66 (in Russian).

[9] I.R. Gekker, Interaction of strong electromagnetic fields with plasma, (Moscow: Atomizdat, 1978). (in Russian).

[10] L.M. Young, PARMELA, Los Alamos LA-UR-96-1835, Ver.3.21 for PC, 2002.