APPLICATION OF DRIVEN PLASMA CATHODE IN RF ELECTRON GUN

I.V. Khodak, V.A. Kushnir

National Science Center "Kharkov Institute of Physics and Technology", Ukraine
e-mail: khiv@kipt.kharkov.ua

The results of the experimental research of generation of pulsed electron beam in S-band RF gun with driven plasma cathode are described. There has been designed experimental sample of the cathode based on ferroelectric ceramics. It has been obtained at RF gun output electron beam with particle energy ≅500 keV, pulsed peak current of 3 A and pulse duration of 50 ns.

PACS: 29.25.BX, 41.75.FR, 52.25.Mq, 52.80.PI

1. INTRODUCTION

The main advantage feature of RF guns is their ability to generate intense and high brightness electron beams. This is possible due to employing of thermionic cathodes with emission current density of 10 A/cm^2 or photocathodes with emission current density up to 10^2 A/cm^2 within a laser pulse duration of 10^{-8}…10^{-11} s. The value of accelerating field strength in the gun cavity of ~10^7 V/m makes it possible to obtain the beam particle energy over 10^6 eV at RF gun output. In this context, RF guns may generate electron beams with a peak current up to 1 kA and charge over 1 nC. These features make RF guns to be stand out particularly in compactness unlike conventional DC pulsed electron guns. Therewith, technologies and equipment accompanying operation of photoemission RF guns are quite complicated and expensive to expand their application fields.

The range of pulsed current amplitudes of few amperes with pulse duration of few tens of nanoseconds may be also produced in RF guns within the application of plasma cathodes based on solid dielectrics [1-3]. Electrons in the cathodes are emitted from plasma sheath of a surface flashover excited by driving voltage pulse. As it has been shown in numerous experiments with pulsed guns [2], the emission current density of the plasma cathodes may be over 100 A/cm^2 with the nanosecond range of the pulse current duration. High peak current can be extracted from RF gun due to bunched beam structure and features of electron emission from plasma in high strength RF field. Electrons extracted from a plasma cathode are accelerated due to the RF field energy stored in the cavity of the gun. Such cathodes don't need heating and pre-activation process before operation, and may be handled and operated in vacuum of 10^{-4}…10^{-5} torr. Application of plasma cathodes in RF gun [4] also potentiates the gun operation with the pulse repetition frequency of 10…10^2 Hz. These advantages make RF guns with plasma cathodes competitive electron sources.

Results of the experimental research of RF gun operation with plasma cathode are reviewed in the present paper. Plasma cathode is made from ferroelectric ceramics. The cathode is driven by external source of pulsed low voltage.

2. EXPERIMENTAL ARRANGEMENT

All experimental research has been carried out on the special test set-up that permits to measure parameters of electron beams with particle energy from tens of keV to 1 MeV. Fig. 1 illustrates the layout of main measuring equipment that has been used in the experiments.

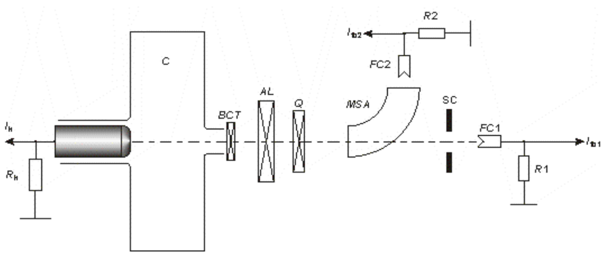


Fig. 1. *Measuring equipment layout*

The researched cathode having been mounted in the single-cavity S-band RF gun *C*. The cathode holder has the plug-in to supply the cathode by the trigger pulse. The pulsed output current having been measured by beam current transformer *BCT* having time resolution of 5 ns. The magnetic lens *AL* and quadrupole *Q* supplied beam transport. Electron energy of the beam having been measured using magnetic analyzer *MSA* and Faraday cup *FC2*. The beam profile having been measured by driving slits *SC* and Faraday cup *FC1*. The gun was fed by klystron RF amplifier operating in self-excited mode with operating frequency of 2797.15 MHz. Tunable directional coupler in the feeding waveguide supplied the gun feeding power P_c in the range 0.1…1 MW. The pulse duration of the feeding power was 1.8 μs. The axial electric field strength in the RF gun is determined by the following expression:

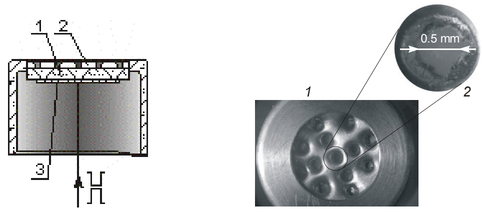
$$E(V/m) = 470\sqrt{P_c(W)Q_0}\ ,$$

where Q_0 is unloaded quality factor of the gun cavity.

The RF gun design has the optical input port which has been used in the experiments to observe a plasma glow on the surface of the cathode. Distribution of the plasma glow has been registered by digital photo camera.

3. PLASMA CATHODE DESCRIPTION

The plasma cathode has been designed using ferroelectric ceramics because of its feature of "strong" electron emission characterized as plasma-assisted emission with the emission current density of 100 A/cm^2. As to conventional ferroelectric cathodes [2], the designed cathode includes the ferroelectric disk 1 (Fig. 2), the patterned electrode 2 being in contact with the disk in front side and the solid electrode 3 deposited on the rear side. The material of the disk with ≅0.8 cm^2 area and 0.5 mm thickness is $BaTiO_3$ with permittivity $\varepsilon_r \cong 2000$.



a) *b)*

Fig. 2. *Ferroelectric cathode*

Special design of the patterned electrode implements the principle of the spatial separation of plasma development and electron acceleration in the gun cavity (Fig. 2 (*b*, 1)). According to the principle the developed plasma is localized in small-sized cylindrical-shaped apertures of the patterned electrode. The size of the aperture defines the value of the RF electric field strength over the ferroelectric surface. This value would be few orders of magnitude lower than the threshold magnitude of the self-excited and uncontrolled flashover [4]. According to calculations using the SUPERFISH code [5] the ratio of the electric field strengths over the ferroelectric surface and in the gun cavity is 10^4 for the accepted patterned electrode design.

The one of the origin of the conventional surface flashover in ferroelectric cathodes is the region of triple junctions like for any dielectrics [6]. The face end of apertures being in contact with ferroelectric surface has been made of tapered shape to increase the electric field strength in the region of triple junctions. According to the results of computing of static electric field distribution, the strength of the field in the gap of 10^{-6} m between surfaces of the ceramics ($\varepsilon = 2000$) and tapered aperture is $\sim 1{\cdot}10^9$ V/m within the applied voltage value of 1 kV (Fig. 3). The value of the gap length has been taken as average gap featuring the surface roughness.

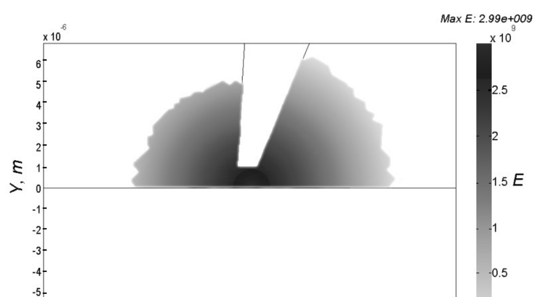


Fig. 3. *Electric field in the 1 μm gap*

The order of the obtained electric field strength is the same as the order of the threshold electric field E_k of the vacuum discharge development [7].

4. RESULTS OF THE RESEARCH

Following the electric field strength of ∝1 MV/m featuring the voltage applied for the flashover initiation in the most of ferroelectrics [8], there was used external pulsed voltage source adjustable in the range of 0.1…1.5 κV. The duration of the driving pulse was of 1 μs with rise time of 0.4 μs. The patterned electrode has been grounded, and the rear electrode has been supplied by trigger pulse $U_{tr.}$ of both positive and negative polarity.

Before the trigger pulse to be applied the gun output current was null in the range of the electric field strength from minimum to 40 MV/m. Within the applying of $U_{tr.}$, the discharge initiation time corresponded to the rise time of the $U_{tr.}$ within the accuracy of measurement limits.

For the positive polarity of $U_{tr.}$, the output current realized at $U_{tr.}$=1000 V was of 3 A in peak magnitude and had the shape shown on Fig. 4(*a*). Such electron beam is featured by particle energy of ≅500 keV in the maximum of the energy distribution. There was observed discharge glow only in the central aperture of the patterned electrode during the positive $U_{tr.}$.

For the negative polarity of $U_{tr.}$, the output current realized at $U_{tr.}$=600 V, and particle energy in this case is ≅300 keV for each pulse of the current shape (Fig. 4(*b*)). In this case the discharge glow was ob-served in each aperture of the patterned electrode. Thus, one may assume that each current pulse corresponds to the electron emission from apertures in the patterned electrode. Moreover, as it follows from Fig. 4(*b*) electrons are emitted also after the amplitude of $U_{tr.}$ becomes of zero value. The most evidently, the source of $U_{tr.}$ is shunted by the excited plasma which enhanced through the apertures into the gun cavity being the source of electrons.

a) *b)*

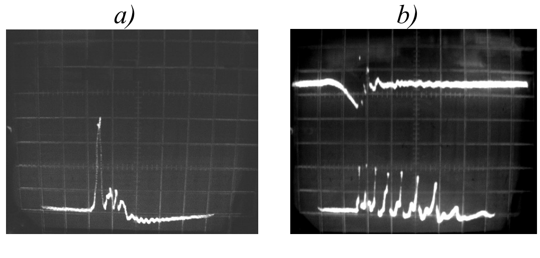


Fig. 4. *Oscilloscope traces: a) the gun current* (0.74 *A/div.*), *time sweep is 200 ns/div; b) top trace is trigger pulse, bottom trace is the gun current* (0.74 *A/div.*), *time sweep is 200 ns/div*

The width of the measured energy spectrum (FWHM) wasn't higher of 10 % in any polarity of $U_{tr.}$. However, the electron energy is differed considerably for different polarity of $U_{tr.}$ under equal magnitude of the electric field strength (500 keV for $U_{tr.}$>0 and 300 keV for $U_{tr.}$<0). The one of interpretations of the difference is the hypothesis that parameters of the initially excited plasma and emitted electrons are quite different for each polarity of $U_{tr.}$. These parameters have effect on dynamics of beam particles in the gun cavity and their energy distribution at the gun output.

The amplitude of the pulse current was varied at the gun output within variation of the driving pulse amplitude of any polarity. It is most probably that the origin of this variation is the variation of performances of the initially excited plasma and emitted electrons as well as in previous case.

The electric field strength hasn't been changed considerably during the discharge duration and after up to the end of the RF feeding pulse. This indicates that dimensions and density of the plasma wasn't of enough magnitude to detune the gun cavity considerably.

The transverse beam size (FWHM) measured for positive polarity $U_{tr.}$ on the distance of 1.5 m from the gun output is 5.3 mm (Fig. 5).

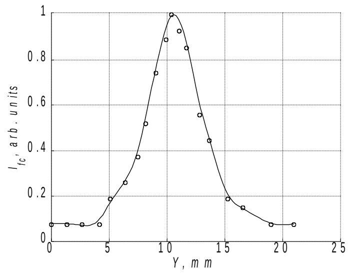


Fig. 5. *The measured beam profile*

Beam parameters were stable during the RF gun operation with the pulse repetition frequency up to 10 Hz and with any polarity of $U_{tr.}$.

It should be noted that within the phase length of electron bunch in RF gun of $\Delta\varphi$ the peak current value in the bunch is $I_{pb}=I_p\cdot(2\cdot\pi)/\Delta\varphi$. Therefore, within the application of special equipment for the bunch phase length compression [9] the magnitude of the peak current in the bunch may be of 10^2-10^3 A.

5. CONCLUSIONS

RF electron guns with ferroelectric plasma cathodes can generate electron beams with pulsed current of few amperes and pulse duration of few tens of nanoseconds. Application of driven plasma cathode permits the RF gun output current to be stable within time and amplitude. Such RF guns can be used as injectors in linear resonance electron accelerators with nanosecond current pulse duration. Different modes of plasma ferroelectric cathode operation in RF gun found such RF electron source to be applied for generation of electron beam of both single pulse and multiple pulses within the one RF feeding pulse.

ACKNOWLEDGMENT

The authors are exceedingly grateful to the staff of R&D "Accelerator" of NSC KIPT for their help throughout the experiment period.

REFERENCES

1. V.S. Balagura, B.G. Safronov, S.A. Chereshchikov. Short-pulse electron guns with unheated cathodes for linacs // *Problems of Atomic Science and Technology. Series: Nuclear Physics Investigations (Theory and Experiment)*. 1992, №4(25), p. 48-51 (in Russian).
2. G. Rosenman, D. Shur, Ya. E. Krasik and A. Dunaevsky Electron emission from ferroelectrics // *J. Appl. Phys.* 2000, v. 88, p. 6109-6161.
3. N.I. Aizatskii, E.Z. Biller, I.V. Khodak et al. Metal–insulator cathode in an rf electron gun // *Technical Physics Letters (An English translation of Russian journal "Pis'ma v Zhurnal Tekhnicheskoi Fiziki")*. 1998, v. 24, № 10, p. 762-763.
4. I.V. Khodak, V.A. Kushnir. *Performances of the beam generated by metal-dielectric cathodes in RF electron guns*. Proc. of the EPAC'04, 2004, Lucerne Switzerland, MOPLT101.
5. J.H. Billen, L.M. Young. *POISSON/SUPERFISH on PC compatibles.* Proc. of the PAC'93, 1993, Washington USA, p.790-792.
6. G. A. Mesyatz. *Ectons. Part 2.* Ekaterinburg: "Nauka", 1994, 184 p. (in Russian).
7. G. A. Mesyatz. *Ectons. Part 1.* Ekaterinburg: "Nauka", 1994, p. 60-62 (in Russian).
8. D. Shur, G. Rosenman. Two modes of plasma-assisted electron emission from ferroelectric ceramics // *J. Phys. D: Appl. Phys*. 1999, v. 32, p. L29–L33.
9. M. Borland, J. Lewellen, S. Milton. *A highly flexible bunch compressor for the APS leutl FEL*. Proc. XX International Linac Conference, 2000, Monterey, USA, p. 863-865.

ПРИМЕНЕНИЕ УПРАВЛЯЕМОГО ПЛАЗМЕННОГО КАТОДА В ВЫСОКОЧАСТОТНОЙ ЭЛЕКТРОННОЙ ПУШКЕ

И.В. Ходак, В.А. Кушнир

Описаны результаты экспериментального исследования генерации импульсного электронного пучка в ВЧ-пушке S-диапазона с управляемым плазменным катодом. Был разработан опытный образец катода на основе ферроэлектрической керамики. На выходе ВЧ-пушки был получен электронный пучок с энергией частиц ≅500 кэВ, импульсным током 3 А и длительностью импульса 50 нс.

ЗАСТОСУВАННЯ КЕРОВАНОГО ПЛАЗМОВОГО КАТОДА У ВИСОКОЧАСТОТНІЙ ЕЛЕКТРОННІЙ ГАРМАТІ

І.В. Ходак, В.А. Кушнір

Описано результати експериментального дослідження генерації імпульсного електронного пучка у ВЧ-гарматі S-діапазону з керованим плазмовим катодом. Було розроблено дослідний зразок катода на основі

ферроелектричної кераміки. На виході НВЧ-гармати було отримано електронний пучок з енергією часток ≅ 500 кеВ, імпульсним струмом 3 А і тривалістю імпульсу 50 нс.