

# PERFORMANCES OF THE BEAM GENERATED BY METAL-DIELECTRIC CATHODE IN RF ELECTRON GUNS

I.V. Khodak, V.A. Kushnir

NSC 'KIPT', 1, Academicheskaya St., 61108 Kharkov, Ukraine

## Abstract

Metal-dielectric (MD) cathodes may generate intense electron beam with nanosecond current pulse duration. Electrons are extracted from a plasma sheath developed due to dielectric surface flashover in vacuum. The paper describes results of the experimental research of RF electron gun operation with MD cathodes of different design. Parameters of the beam generated by the single-cavity RF gun are referred in. The results are compared with results obtained before in the 1.5-cavity RF gun. First experimental results of a ferroelectric (FE) cathode operation in RF gun are reviewed in the paper.

## INTRODUCTION

RF guns generating intense and high brightness electron beams employ thermionic cathodes with emission current density of  $10 \text{ A/cm}^2$  or photocathodes with emission current density up to  $10^2 \text{ A/cm}^2$  within a laser pulse duration of  $10^{-8}$ – $10^{-11}$  s. The high value of accelerating field strength makes it possible to obtain the beam particle energy over  $10^6$  eV at RF gun output. This feature makes RF guns to be stand out particularly in compactness unlike conventional DC pulsed electron guns. RF guns may generate electron beams with a peak current up to 1 kA and charge over 1 nC.

In our opinion the beam with such parameters may also be obtained in RF guns with plasma cathodes including MD cathodes [1,2] and FE cathodes [3-5]. Electrons in the cathodes are emitted from plasma sheath developed on a dielectric surface. As it has been shown in numerous experiments with pulsed guns, the emission current density of the plasma cathodes may be over  $100 \text{ A/cm}^2$  with the nanosecond range of the pulse current duration.

To generate intense electron beam in RF gun we have applied uncontrolled MD cathodes of various design. Moreover, for the first time we have applied in RF gun FE cathode driven by external source of pulsed voltage. Results of the experiments are reviewed in the paper.

## EXPERIMENTAL ARRANGEMENT

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

Researched cathodes having been mounted in the single-cavity S-band RF gun *C*. The cathode holder has the plug-in for measurement of the current  $I_k$  of the coaxial cathode. This plug-in has been also used for the FE cathode to be supplied by trigger pulse.

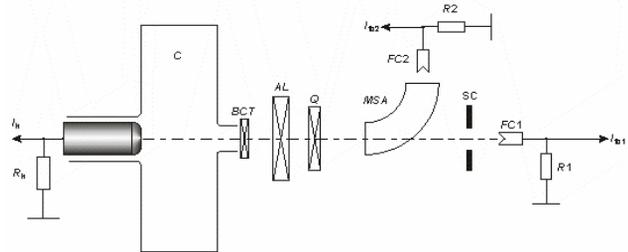


Figure 1: Measuring equipment layout

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  $\mu\text{s}$ . The axial electric field strength 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 cathodes. Distribution of the plasma glow has been registered by digital photo camera.

## EXPERIMENTAL RESULTS

### RF gun with metal-dielectric cathode

MD cathodes of two designs have been used. The first design was the coaxial with one or few dielectric cylinders separated by metal cylinders [1]. The second design was a flat dielectric being in contact with metallic wire grid. The main feature of the cathodes is the excitation of plasma by RF electric field of the gun. The plasma excitation moment is defined by many factors including electric field strength, roughness of a dielectric surface, distribution of static charges, and so on. In this context these cathodes may be classified as uncontrolled plasma cathodes.

We have reported before about research of single coaxial MD cathode in 1.5-cell RF gun [6]. On purpose of possible beam current increasing there has been designed and fabricated double coaxial structure of the cathode (Fig. 2). Within the cathode two quartz cylinders *4* are

separated inside and surrounded outside by thin copper cylinders 3. Copper cylinders are connected to each other and grounded through the measuring resistance  $R_k$ .

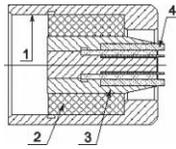


Figure 2: The cross-section of the double coaxial cathode

According to calculations using the SUPERFISH code [7], the electric field strength near the metallic surfaces is different due to different radial distance from the axis and also due to different amount of dielectric components of the junction inside and outside the structure. Besides, the variation of face end shapes of outer copper cylinders permitted to change the electric field strength.

As well as in the case of the single coaxial MD cathode, the pulsed current  $I_k$  from the metallic component follows field emission law in prebreakdown period. The maximum value of the  $I_k$  was 0.4 A in these experiments. The increasing of the electric field strength in the gun cavity over the threshold value excited discharge that caused jump-like increasing of the current  $I_k$  by a factor of  $10^2$  and the beam emergence at RF gun output. The cathode displacing as to face end of the gun cavity has varied the threshold electric field strength. Simultaneously, this adjustment also varied amplitude of the gun output current. In experiments, the maximum value of the gun output current was 2.5 A with the current pulse duration of 50 ns. During the current pulse duration the electric field strength felt down to zero value and didn't restored up to the end of the RF pulse (2  $\mu$ s). Taking into account the current  $I_k$  that still has been lasted (Fig. 3) this fact indicates the plasma enhancement in the gun cavity.

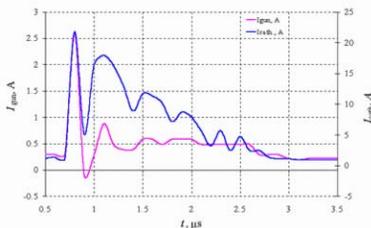


Figure 3: Measured currents

The study of the optical radiation has shown that plasma developed on inner and middle surfaces of the MD junction. This fact is confirmed by brighter points in these places (Fig. 4). Less intense glow of cylindrical shape permits to assume that plasma is enhanced over total cylindrical surface near the junction line.

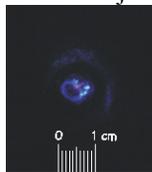


Figure 4: Discharge glow on the double coaxial cathode

Plasma is developed and enhanced along the direction of particle motion in a coaxial cathode. This is equivalent to the particle injection into the gun cavity with temporal and spatial performances being varied during the current pulse duration. Evidently, this causes the degradation of averaged parameters of the output beam.

Application of a planar MD cathode may eliminate this situation. The plane of electron emission is orthogonal to the direction of particle motion in this case. Dielectric disk of 10 mm in diameter has been used in the planar cathode. The disk was in contact with wire grid having 1 mm square cells. The source of the emitted electrons in this case was plasma of RF discharge developed in contact points of the grid and dielectric. Measured parameters of electron beam in RF gun with such cathode and also with two coaxial cathodes are summarized in Table 1. The given magnitudes of the electric field strength correspond to the average axial field values being the discharge threshold.

RF gun operation with coaxial cathodes at repetition frequency up to 10 Hz has shown the increasing of pulsed output current against to operation in the single pulse mode. This indicates that the flashover exciting and parameters of the developed plasma have dependence on static charges on the dielectric surface.

Table1: Beam parameters of RF gun with MD cathodes

Cathode type	Gun type	$E_s$ , MV/m	$I$ , A	$t$ , ns	$W$ , keV
Coaxial	1.5 cell	25	4	40	>300
Double coaxial	Single cell	12	2.5	50	200
Flat	Single cell	24	2	100	250

As it follows from experiments (see the table), the increasing of dielectric and metal surfaces being in contact caused the decreasing of the threshold value of the electric field strength in coaxial cathodes. According to the particle beam dynamics in RF guns [8], the electric field strength in this case is not enough for the effective capture of electrons and their acceleration. It should be noted also that the flashover exciting by RF field causes time instability of the current pulse and particle energy at RF gun output. The instability is increased considerably if the flashover is excited by the electric field strength corresponding to the flat top of the pulse. These facts make to be important to design methods of the control of the flashover initiation time against to the RF field pulse duration.

### RF gun with ferroelectric plasma cathode

As to conventional FE cathodes, the applied in RF gun cathode includes FE disk ( $BaTiO_3$ ,  $\epsilon \approx 2000$ , thickness is 0.5 mm), patterned front electrode and solid rear electrode. The layout and general view of the cathode are illustrated on Fig. 5. The flashover has been excited by an external pulsed voltage source adjustable in the range of 0.1-1.5 kV and having pulse duration of 1  $\mu$ s with rise time of 0.4  $\mu$ s. The special design of the patterned electrode (Fig. 5 (a)) implements the principle of the spatial separation of plasma development and electron

acceleration. According to the principle the developed plasma is localized in small-sized cylindrical-shaped apertures of the patterned electrode.

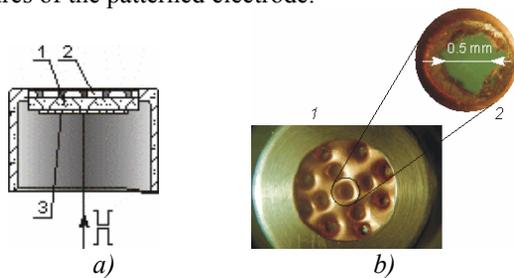


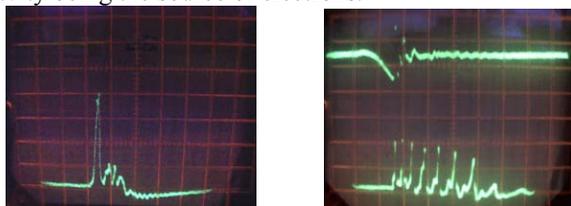
Figure 5: Ferroelectric cathode

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. 6(a). Such electron beam is featured by particle energy of  $\approx 500$  keV in the maximum of 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  $\approx 300$  keV for each pulse of the current shape (Fig. 6(b)). In this case the discharge glow was observed 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. Besides, as it follows from Fig. 6(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) 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.

Figure. 6 Oscilloscope traces

The width of 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. The one of interpretations of the difference is the hypothesis that parameters of the excited plasma and

emitted electrons are quite different for each polarity of  $U_{tr}$ .

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.

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

## CONCLUSION

RF electron guns with MD and FE plasma cathodes can generate electron beams with pulsed current of few amperes and pulse duration of few tens of nanoseconds. Application of driven FE cathodes permits the RF gun output current to be stable within time and amplitude. Such RF guns can be used as injectors in linear electron accelerators with nanosecond current pulse duration.

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