RF ELECTRON GUN WITH DRIVEN PLASMA CATHODE

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Abstract

The paper describes results of the experimental research of generation of intense pulsed electron beam in S-band RF gun with driven plasma cathode. There has been designed experimental sample of the cathode based on ferroelectric ceramics. At the RF gun output the generated electron beam has pulsed current of 6 A, pulse duration of 50-90 ns and particle energy $\cong$500 keV.

INTRODUCTION

The main advantage of RF guns among electron beam sources is the ability to generate high brightness and intense beams. Generally, thermionic and photoemission cathodes are employed in RF gun for this generation. In our opinion, electron beam with pulsed current of few amperes and with pulse duration of few tens nanoseconds may be also generated by RF guns within the application of plasma cathodes based on solid dielectrics [1-3]. The source of electrons in the cathodes is the sheath of plasma which origin is a surface flashover that may be excited by driving voltage pulse. As it has been shown in numerous experimental investigations with pulsed electron DC guns [2], the emission current density of the plasma cathodes may be over 100 A/cm^2, and the pulse current duration can be in the nanosecond range. High peak current can be extracted from RF gun due to bunched beam structure and features of electron emission from plasma in RF field of high strength ($\sim$10^7 V/cm). Electrons extracted from a plasma cathode gain 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 $10^{-4}\ldots10^{-5}$ torr. Application of plasma cathodes in RF gun also potentiates the gun operation with the pulse repetition frequency of $10\ldots10^2$ Hz [3]. Results of the experimental research of S-band RF gun operation with plasma cathode are reviewed in the present paper. Plasma cathode is made from ferroelectric ceramics. The electron emission initiation on the cathode is driven by external source of pulsed voltage.

EXPERIMENT APPROACH

Design Features of Plasma Cathode

The researched plasma cathode driven by external pulse voltage was mounted in the single-cavity S-band RF gun. The base of the cathode is ferroelectric disc *2* (Fig. 1). The front side of the disc contacts with patterned electrode *1*, and the rear side is deposited by solid electrode *3* that supplies trigger pulse on the cathode.
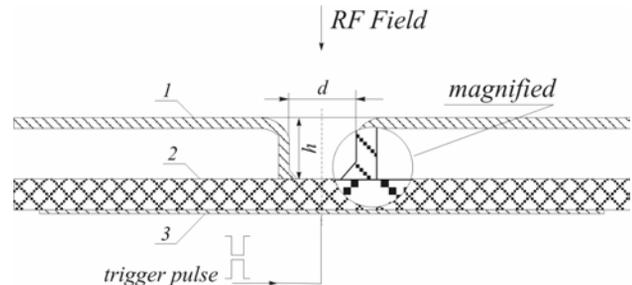
Figure 1: Cross-section of the plasma cathode.

The disc with square size of $\cong$0.8 cm^2 and thickness 0.5 mm is made from $BaTiO_3$ with $\varepsilon = 2150$. The aperture in the patterned electrode is prolonged by cylindrical surface of finite length h making cylindrical cavity. The free end face of the cavity contacts with ferroelectric disc and the opposite open plane is the interface for plasma extraction.

The driving of the surface flashover initiation on the cathode defines the principle of spatial separation of plasma development on the cathode and after-acceleration of electrons [4]. The design of RF gun plasma cathode driven by external pulse voltage was founded by the principle. The design of the cathode follows the conditions outgoing from the superposition of electrostatic field of the cathode and RF field of the gun near the cathode interface. In the first place, the electric RF field strength in the region of triple point junctions should be few orders of magnitude lower of the threshold magnitude of the self-excited and uncontrolled flashover [5]. In the next place, the electrostatic field of the driven voltage should not corrupt considerably the electric RF field distribution near the cathode interface that defines the initial electron dynamics.

The RF field penetrating from the gun cavity into the region of triple point junctions can be attenuated considerably by making radial d and linear h sizes of the cylindrical cavity in the patterned electrode too small. There was computed the axial electric RF field distribution in the interface 'cathode - gun cavity' using SUPERFISH code [6]. According to results of the computing, the attenuation of the electric RF field strength near the surface of the ferroelectric disc is 10^4 times smaller for the cylindrical cavity with sizes $d = 1$ mm and $h = 1$ mm in the patterned electrode.

The end face of the cylindrical cavity contacting with the ferroelectric disc has sharped ridge (Fig. 2). This element permits to implement tangential component of electrostatic field and to induce electric field strength in the region of triple point junctions up to $\sim$10^9 V/m within the driving voltage of 1-3 kV. Thus, there is implemented the mode of 'strong' ferroelectric electron emission in the

cathode [2]. It should be also noted that the ridge has an effect on the electrostatic field distribution in the interface of plasma extraction. According to the results of the computing using POISSON code [6], the ridge with sizes 0.15×0.15 mm decreases values of tangential and radial components of electrostatic field approximately in 2 times (see Table. 1). Values E_z correspond to the axial electric field strength in the extraction interface. Values E_{rmax} correspond to the electric field strength at maximum radius in the extraction interface.

Table 1: Electric RF field strength in the plasma extraction interface of the cathode.

	Without ridge		With ridge	
ε	E_z, kV/cm	E_{rmax}, kV/cm	E_z, kV/cm	E_{rmax}, kV/cm
1	0.51	0.27	0.32	0.165
2000	1.29	0.67	0.7	0.36

Test Set-up Arrangement

The 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. 2 illustrates the layout of main measuring equipment that has been used in the experiments.
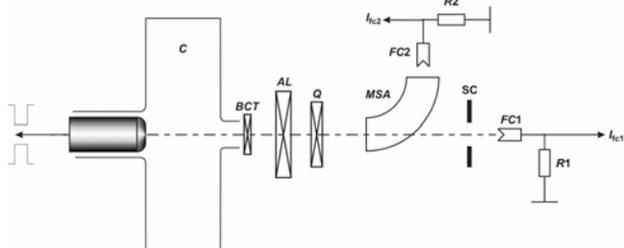
Figure 2: The layout of measuring equipment.

The cathode holder with high voltage connector supplied the cathode with a trigger pulse voltage from external pulse source. The trigger pulse has voltage up to 3 kV amplitude, and its duration is 60 ns. The pulsed output current having been measured by the 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. The pulse RF power P_c feeding the gun is in the range 0.1…1 MW with pulse duration 1.8 μs. The axial electric field strength in the RF gun is determined by the following expression evaluated from resonant perturbation measurements of the field:

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

where Q_0 is unloaded quality factor of the gun cavity.

RESULTS OF THE RESEARCH

There has been the purpose of the research of RF gun operation with plasma cathode to measure parameters of the generated beam current and the identification of featured beam current dependences on electric RF field strength and on driving voltage.

The cathode was fed by trigger pulses U_{tr} both positive and negative polarity during the research. The patterned electrode of the cathode was grounded. Results of measurements of generated beam current has shown up the time difference in the beginning of the current pulse rise at RF gun output and in the duration of this pulse for different polarity of U_{tr}. For the negative polarity of U_{tr} the peak amplitude of the gun output beam current has time delay $\cong$50 ns after the pulse voltage U_{tr} falls to zero value. The duration of the beam current pulse is 50 ns in this case. For the positive polarity of U_{tr} the gun output current runs into the peak value just after the pulse voltage U_{tr} falls to zero value. The duration of the beam current pulse is 90 ns in this case.

The one of interpretations of the observed difference is the confinement of plasma bulk in the cylindrical cavity of the patterned electrode under the negative pulse of U_{tr}. It should be also noted that peak value of the beam current pulse is of the same value both for negative and positive polarity of the pulse U_{tr}.

Results of measurements of the dependence of the output beam current on average electric field strength in the gun cavity are shown on the Fig. 3.
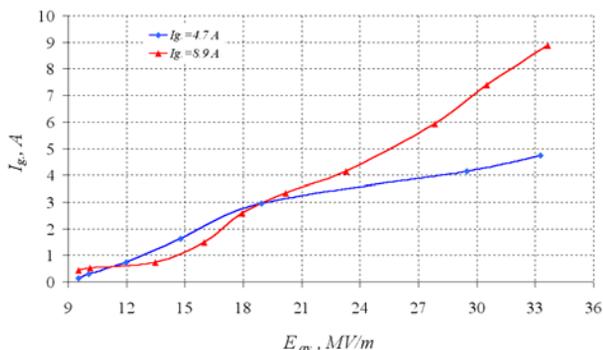
Figure 3: Beam current dependences.

The dependences have been measured for two different maximum values of the gun output current that were set by the voltage value of the pulse U_{tr}. As one can see from the dependences, the mode of RF gun operation with pulse current 4.7 A is close to the mode of space charge saturation similar to DC guns. Comparative analysis of measured results with results of numerical simulation of particle dynamics in the beam using PARMELA code [7] has shown that emission current density is approximately $\approx 9 \cdot 10^2$ A/cm^2 in this case (Fig. 4). The particle energy estimated after the results of the analysis is $\cong$500 keV that fits the experimental investigation of RF gun operation with metal-dielectric cathodes [8].
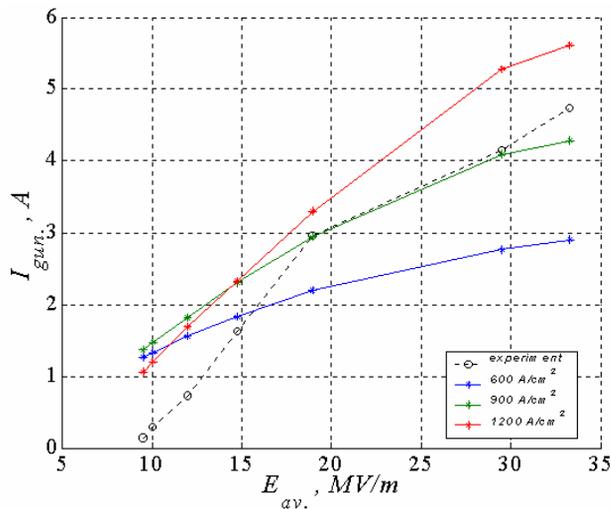
Figure 4: Results of comparative analysis.

The dependence of maximum pulse current of the gun on the average electric field strength in the gun cavity goes like linear function (Fig. 3) for the gun output current more than 4.7 A. This fact permits to assume that there is no saturation of the current transmitted to the gun output under the increasing of the current extracted from plasma within the same range of average electric field strength values. According to the results of the analysis, the saturation of the transmitted current occurs for the average electric field strength more than 35 MV/m, and the gun output current is limited by the particle loss in the gun cavity.

There has been measured the profile of the generated electron beam in two transverse planes during the research. Fig. 6 demonstrates the plane projection of the two-dimensional beam current distribution. The dotted line corresponds to the FWHM level of the distribution. According to results of profile measurements, the beam generated by RF gun with plasma cathode may considered as axially symmetric with 6.5 mm diameter.
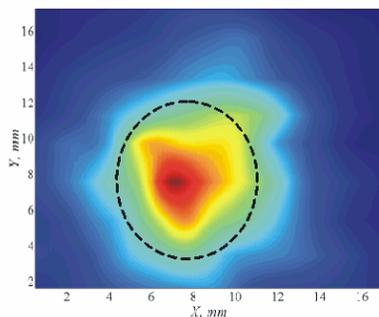
Figure 5: Measured beam profile.

CONCLUSION

It was established in the research that RF guns with plasma cathodes based on ferroelectric ceramics can generate pulse electron beams with pulse current up to 10 A and with pulse duration few tens nanoseconds. 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 $I_b = I_p \cdot (2 \cdot \pi)/\Delta\varphi$. It means that for a bunch phase length about 0.7 rad the peak current in a bunch at RF gun output may be up to 10^2 A with particle energy $\cong 500$ keV.

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