PARAMETERS OF ELECTRON BEAM GENERATED BY RF GUN WITH FERROELECTRIC CATHODE

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RF guns with thermoemission and photoemission cathodes generate an electron beam pulse current and current pulse duration of $10^{-1}...10^{3}$ A and $10^{-6}...10^{-12}$ s, respectively. It is proposed to apply a ferroelectric cathode in RF gun. S-band RF gun with the cathode has been researched experimentally. Maximum beam pulse current is 9 A with current pulse duration of 40…90 ns and particle energy of 500 keV.

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1. INTRODUCTION

The main advantage of RF guns is the generation of intense and high brightness electron beams. This is possible due to employing of thermionic cathodes with typical emission current density of 10…30 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. RF gun operates in a storage energy mode if the beam current pulse duration τ_b follows the condition: $1<<\tau_b \cdot f_0<<Q_0/\pi \cdot f_0$, where $\cdot f_0$ is the gun operating frequency, Q_0 is unloaded quality factor. According to estimations made in paper [1], S-band photo-RF gun may be the source of nanosecond pulse beam with the maximum charge in a bunch > 10 nC. However, the producing of the charge is limited by high power flow density of laser pulse that is quite close to the cathode damage to be caused.

The alternative way the high charge can be achieved in RF gun is application of the cathodes with plasma-assisted electron emission. The cathodes are featured both by the high emission current density ($\geq 10^2$ A/cm^2) and by the ability to provide the duration of a beam current pulse of few tens nanoseconds. We propose to apply ferroelectric cathodes [2] in RF gun. The emission current density in the cathodes may be up to 10^3 A/cm^2.

The features of the ferroelectric cathode in the context of RF gun and results of the experimental research of S-band RF gun operation with driven ferroelectric cathode are considered in the paper. There are provided and analysed results of operation of experimental sample of the cathode and parameters of generated electron beam.

2. FERROELECTRIC CATHODE FOR RF GUN

An RF gun with ferroelectric cathode follows the conventional RF gun concept. The cathode is featured by the developing of plasma sheath due to conventional dielectric surface flashover in the region of triple point junctions of metal-dielectric structure of the cathode [3]. In the RF gun the flashover may be both self-excited by exposed RF electric field and triggered by external electric field. The self-excited flashover is risen up during the transient of RF gun feeling up by RF power [4]. Therefore, the electric field strength and, hence, the stored energy is not optimal, for instance, to the electron capture ratio. It means that the flashover on a ferroelectric cathode in RF gun should be triggered by the external electric field during the time intervals of RF power pulse duration corresponding to the maximum stored electromagnetic energy.

The design of the driven ferroelectric cathode for the RF gun follows the principle of spatial separation of plasma sheath development on the cathode and after-acceleration of electrons. The base of the cathode is the ferroelectric disc *2* (Fig.1).

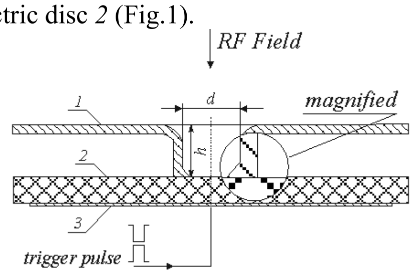

Fig.1. Cross-section of ferroelectric cathode for RF gun

The front side of the disc contacts with the patterned electrode *1*, and the rear side is deposited by the solid electrode *3* that is supplied by a triggering pulse. The disc with area of ≅ 0.8 cm^2 and thickness 0.5 mm is made of $BaTiO_3$ with $\varepsilon_r = 2150$. The aperture in the patterned electrode is prolonged by a cylindrical surface of finite length *h* and diameter *d* making the cut of a cylindrical waveguide. The free end face of the cavity contacts with ferroelectric disc and the opposite end face is the interface for plasma extraction. The RF electric field strength in the waveguide of the patterned electrode decays exponentially. According to results of the computing of the axial RF electric field distribution using SUPERFISH code [5], the attenuation of the RF electric field strength near the surface of the ferroelectric disc is 10^4 times for sizes $d = 1$ mm and $h = 1$ mm. It is much lower of the threshold magnitude of the self-excited and uncontrolled flashover [4]. The end face of the waveguide contacting with the ferroelectric disc has a sharpen ridge (Fig.1). The ridge implements tangential electrostatic field and induces the electric field strength in the region of triple point junctions up to ~10^9 V/m within the driving voltage of 1-3 kV. The computing of electrostatic field distribution using POISSON code [5] has shown up that the ridge with sizes 0.15×0.15 mm decreases tangential and radial electrostatic field two times.

3. EXPERIMENTAL EQUIPMENT

RF gun operation was investigated using a single-cell S-band RF gun with pillbox-like cavity [6]. Some parameters of the gun cavity are summarized in Table.

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RF gun cavity main parameters

Operating frequency, f_0 (MHz)	2797.15
Feeding RF power, P_c (MW)	≤ 1.5
Unloaded Q-factor, Q_0	11000
Coupling coefficient, β	1.05

The maximum axial electric field strength in the gun cavity is determined by the following expression evaluated from resonant perturbation measurements of the field:

$$E(V/m) = 470\sqrt{P_c(W)Q_0}\ . \qquad (2)$$

The gun has been installed in the special facility purposed for pilot tests of injectors for electron linacs. The measuring equipment of the facility permits measuring the parameters of electron beams with particle energy from 10^4 to 10^6 eV. The gun output pulse current was measured by beam current transformer having time resolution of 0.5 ns. Electron energy of the beam was measured using dipole magnetic spectrometer and Faraday cup (FC). The beam profile was measured with a spatial resolution 0.2 mm by actuator-driven slits and FC. The distance between the slits and the gun output is 0.8 m. Beam transport through this beam-line interval is supplied by unit axial lens and unit quadrupole lens. RF power is supplied by klystron RF amplifier operating in self-excited mode with operating frequency of 2797.15 MHz. Tunable directional coupler in the feeding waveguide supplied RF feeding power P_c in 0.08…1 MW range. The RF pulse duration was 2 μs.

The source of the triggering pulse is based on the scheme with transmission line. Its length supplies generation of voltage pulses with flattop duration 60 ns. The magnitude of the pulse voltage may be adjusted in 0.1…3 kV range. The output resistance of the source of ≅ 5 Ohm is matched with 50-Ohm wave impedance of the transmission line by a three-stepped voltage-dividing transformer. The transformer is made from cut-offs of coaxial lines that minimizes the rise time of the pulse down to 10 ns.

4. PARAMETERS OF ELECTRON BEAM

The ferroelectric cathode used in the experiments has one aperture in the patterned electrode. The patterned electrode has been grounded while the rear electrode has been supplied by the triggering pulse U_{tr} both of positive and negative polarity. The generated electron beam had maximum pulse current up to 8.9 A within the both polarity of the pulse U_{tr}. The current pulse duration (FWHM) is different and complies 90 ns for positive U_{tr} and 40 ns for negative U_{tr}. Electron energy in the maximum of energy spread for negative U_{tr} is ≅ 500 keV.

The RF gun output current I_g may be varied by the voltage change of the pulse U_{tr}. Besides this variation, the current I_g also depends on the RF electric field strength. The current I_g is close to saturation in the mode of RF gun operation with U_{tr}=2 kV and E_{av}> 20 MV/m (Fig.2).

However, within the higher voltage U_{tr} the current I_g is not saturated, that can be explained by the virtual cathode existence under electric field up to 35 MV/m. It follows from the dependences there is the high current

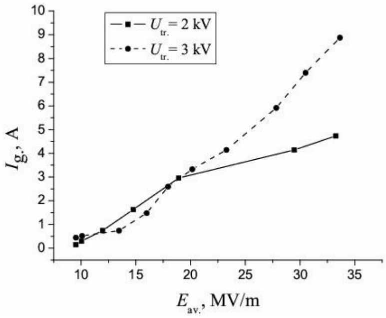

Fig.2. Beam current vs. the electric field strength

density of the emission from the ferroelectric cathode. Comparative analysis of measured results with results of numerical simulation of particle dynamics using PARMELA code [7] has shown that emission current density is approximately ≈9· 10^2 A/cm^2 for the RF gun operation with triggering voltage U_{tr}=-2 kV (Fig.3). The particle energy estimated after the results of the analysis is ≅500 keV that fits the measured results.

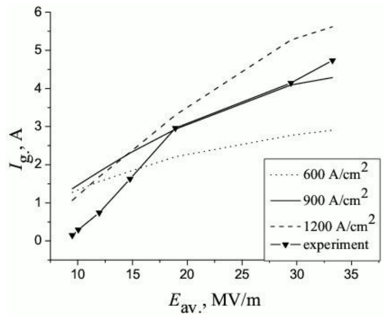

Fig.3. PARMELA simulation and measurements

The beam current pulses I_g are differed by duration, by the time delay of the pulse rising and by the pulse shapes. The positive U_{tr} triggering makes the electrostatic field to be accelerating for electrons during the total time of plasma inducing and enhancement in the waveguide of the patterned electrode. All electrons are extracted into the gun cavity just after the rise time of the pulse U_{tr} and continuously within its duration. The duration of the pulse I_g is 90 ns in this case.

The negative pulse U_{tr} makes the electrostatic field of the cathode to be decelerating for electrons during the same time of plasma inducing and enhancement. There are no extracted electrons that could be accelerated by the RF electric field within the duration of the pulse U_{tr}. The most of electrons are accelerated in this case after the electrostatic field strength becomes lower than RF electric field strength in the plasma extraction interface. As a result, the in-pulse temporal beam current distribution has intervals with flat and sharp slopes differed considerably by the value of the instantaneous current. The duration of the pulse I_g is 50 ns in this case.

The different polarity of the pulse U_{tr} gives rise to different initial transverse and longitudinal momentum spreads of electrons in the plasma extraction interface of the cathode that should cause the difference of spatial and angular parameters of the beam at RF gun output. This statement was validated by the results of the beam profile and beam emittance measurements. Thus, the measured beam profile for the negative U_{tr} has shown up the correlation of the temporal beam structure with the spatial distribution of the beam current. Fig.4 demonstrates the plane projection of the beam deduced from the profile measurements.

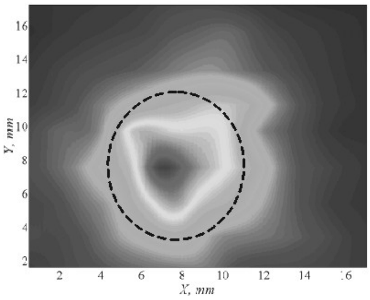

Fig.4. Plane projection of the beam current distribution

It is assumed that particles being inside the dashed line (FWHM level of the distribution) compose the core of the beam with diameter 6.5 mm. The beam emittance was measured using a 'pepper-pot' technique [8]. The measured normalised beam emittance is 20 mm·mrad for 40 % of particles. The normalised beam emittance measured for positive pulse U_{tr} is much larger. There is the large beam size in this case ($\sigma_{x,y}$ (FWHM) =10 mm).

The lifetime (~10^5 shots) of two experimental samples of the cathode during the RF gun operation in a single pulse repetition rate mode was limited by the breakdown of the ferroelectric disk after increasing of the triggering voltage value by design. The same breakdown and lifetime reducing has been observed after the cathode operation without RF field.

5. CONCLUSION

RF guns with the plasma ferroelectric cathode can generate pulse electron beams with pulse current up to 10 A and with pulse duration few tens nanoseconds. The pulse polarity of the cathode is triggered and defines two modes of the beam generation.

Within the phase length of electron bunch in RF gun $\Delta\varphi$ the peak current in a bunch is $I_b=I_p\cdot(2\cdot\pi)/\Delta\varphi$. For a typical bunch length about 0.7 rad the peak current may be up to 10^2 A with particle energy ≅500 keV.

Despite the high plasma electron temperature, the beam emittance is comparable with the same parameter of thermionic RF guns.

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ПАРАМЕТРЫ ЭЛЕКТРОННОГО ПУЧКА, ФОРМИРУЕМОГО ВЧ-ПУШКОЙ С ФЕРРОЭЛЕКТРИЧЕСКИМ КАТОДОМ

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ВЧ-пушки с термо- и фотоэмиссионными катодами генерируют электронные пучки с импульсным током $10^{-1}…10^3$ А и длительностью импульса $10^{-6}…10^{-12}$ с. Предлагается применение в ВЧ-пушке ферроэлектрического катода. ВЧ-пушка S-диапазона с таким катодом была исследована экспериментально. Максимальный импульсный ток пучка составляет 9 А при длительности импульса 40…90 нс и энергии частиц 500 кэВ.

ПАРАМЕТРИ ЕЛЕКТРОННОГО ПУЧКА, ЩО ФОРМУЄТЬСЯ ВЧ-ГАРМАТОЮ З ФЕРРОЕЛЕКТРИЧНИМ КАТОДОМ

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ВЧ-гармати з термо- та фотоемісійними катодами генерують електронні пучки з імпульсним струмом $10^1…10^3$ А і тривалістю імпульсу $10^{-6}…10^{-12}$ с. Пропонується застосування у ВЧ-гарматі фероелектричного катода. ВЧ-гармата S-діапазону з таким катодом була досліджена експериментально. Максимальний імпульсний струм пучка складає 9 А при тривалості імпульсу 40…90 нс та енергії частинок 500 кеВ.