RF ELECTRON GUN WITH METALLIC CATHODE – CALCULATION AND EXPERIMENTAL STUDY

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The present paper is devoted to the RF electron source design for a linear accelerator. In contrary with known RF guns with thermionic cathodes the designed electron source has high temperature metallic cathode. This permits a current pulse repetition rate to be higher significantly with saving high beam quality at the same time. Results of calculations and experimental research both on the special test set-up and in the single section electron accelerator are referred in the paper.

PACS: 29.25.Bx, 41.85.Ar

1. INTRODUCTION

RF guns have been recently very common used in the accelerator technology as sources of high brightness electron beams. The main trend in the development of these devices consists in the intention to obtain intensive beams with small emittance. Guns with thermionic cathodes (TC) have got the most of applications among others RF guns [1, 2]. These sources are trouble-free, have long lifetime and don't require costive satellite equipment. The main disadvantage of RF guns with TC is the variation of beam parameters (current amplitude, particle energy and electron bunch length) caused by back electron bombardment during the pulse. It is known that the pulse power flow of back electrons is higher of 10^5 W for definite emission current values of 1-3 A. The average power due to the bombardment is comparable with filament power for traditionally used pressed, impregnated or LaB_6 cathodes at the pulse duration of 2−10 μs and pulse repetition rate of 1−25 Hz. In this case, the unfailing RF gun operation with mentioned thermionic cathodes is possible in the state of stable action equilibrium of different methods of the cathode surface heating up. This situation, on the one side, doesn't permit to increase average beam current significantly and, from the other hand, doesn't permit to vary beam current pulse magnitude due to cathode temperature variation. The strong emission density dependence on the rf field strength during the accelerating half-period (Schottky effect) has negative effect on beam parameters (mainly on emittance). It is obviously that the influence of mentioned above factors on beam parameters is reduced with a cathode work function growth and its operating temperature (heating-up power) increasing. This can be provided by application of metallic high temperature cathodes. There is wide field of experimental investigations for which accelerated electron beams of high brightness with small ($\sim10^{-3}$ - 10^{-2} A) pulse current and high pulse repetition rate ($\sim10^2$ Hz) are required. For instance, such beams are required for the study of the generation of parametric x-ray radiation caused by interaction of relativistic electrons with crystals [3].

The purpose of present work is the development of RF gun with thermionic cathode with suitable beam parameters that has no mentioned above disadvantages and could be applied for such investigations. Main design beam parameters at the gun output are following: pulse current is up to 50 mA, normalized emittance is not higher of 30 mm·mrad, electron energy is not less of 300 keV, pulse repetition rate is up to 300 Hz.

2. CALCULATIONS AND PHYSICAL PRINCIPLE OF THE DESIGN

The main idea put in the design principle consists in the application of high temperature metallic cathode with electron heating-up as the electron emitter for the RF gun. The emitter is the thin metallic plate. One side of the plate is inside of RF gun cavity, and the other one is bombarded by special shaped electron beam from an extra heating-up electron gun. Material and thickness of the emitter and beam shape of the heating-up electron gun are chosen such that the cathode region with high temperature and providing enough electron emission has a small square. The tantalum having work function of $\varphi = 4.12$ eV was chosen to be the emitter. The plate thickness is 300 μm. According to the existing information about beam dynamics in RF guns [4], the emission current from the cathode has to be no lower of 100 mA in order to obtain the pulse current of 50 mA at the gun output. Therefore the emission current density from acceptable emitting cathode surface has to be ≈ 15 - 20 mA/mm^2 without Schottky effect taken into account. The temperature at which the required emission current can be obtained was computed by solving of the heat conduction equation with boundary conditions taking into account radiant heat transfer.

The temperature distribution in the tantalum emitter having 5 mm in diameter and 300 μm in thickness was computed using numerical methods. It was estimated that emission current of the pointed above value can be produced under emitter temperature of ≈2400°K. Fig. 1 illustrates computed distributions of emission current density for three values of heating-up power of the electron beam of 2.8 mm in diameter. One can see from the figure that the region of the intensive heating-up corresponding to the required emission current values is limited by the circle of 3 mm in diameter and released at 70 W heating-up power.

PROBLEMS OF ATOMIC SCIENCE AND TECHNOLOGY. 2002, № 2.
Series: Nuclear Physics Investigations (40), p. 90-92.

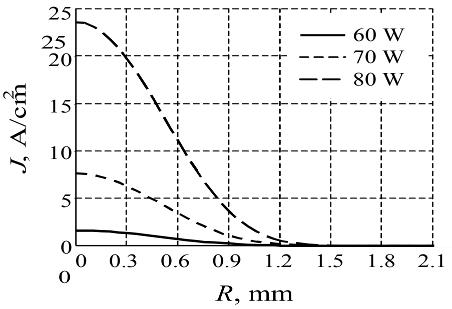

Fig. 1. *Radial distribution of the current density*

It follows from the computation, in particularly, that the maximum temperature and the cathode emission current is of 2500 K and 100 mA respectively for the 70 W heating-up power. On basis of the obtained heating-up power value there were calculated, designed and developed the gun of heating-up and the cathode assembly for the RF gun. The flat impregnated cathode of 2.8 mm in diameter is used in the heating-up gun. Geometry of electron-optic system of the gun was computed using EGUN code [5]. The gun perveance is $0.187 \cdot 10^{-6}$ A/V$^{3/2}$. Results of the heating-up gun design and development are referred explicitly in [6].

The beam dynamics in RF gun was simulated using PARMELA code [7] on the next step of investigations. The RF gun resonance system is essentially two cavities coupled electrically [8]. The operating frequency is 2797.15 MHz. Beam current, beam emittance and back electron power at the RF gun output were defined as a function of the metallic emitter temperature. As it follows from the computation (Fig. 2), the pulsed power of back electrons will be not higher of 15 kW at the emitter temperature of 2200-2550 K and input RF power of 1 MW. The inpulse emission current growth caused by back electrons is not higher of 20°K that is fully accepted. As to touching the average temperature growth, than according to the calculation the current growth on 20% at the metallic emitter temperature can be observed at the pulse repetition rate of 100 Hz (the average power of back electrons is just 4% from the heating-up power). In case of necessity, the corresponding heating-up power decreasing can easy reduce this current growth. The appropriated servo control system can be applied for this purpose.

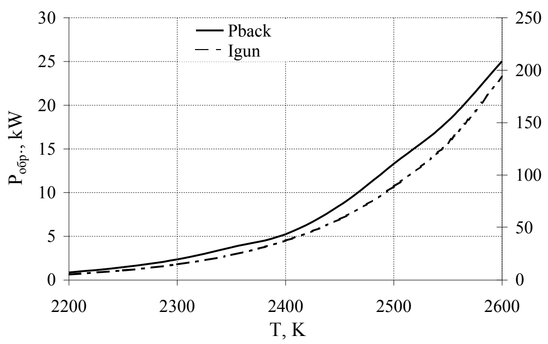

Fig. 2. *Back electron pulsed power and the RF gun output current vs metallic emitter temperature*

The beam emittance computed for fixed RF gun input power value of 1 MW does not depend actually on the metallic emitter temperature. The main source of the emittance growth in the investigated RF gun is RF field in the resonance system. It's known that minimal probably value of beam emittance at the source output is defined by presence of transverse pulses of emitted particles. Let us estimate the minimum transverse normalized emittance of the beam on the cathode that is defined as following:

$$\varepsilon_{nc} = 2\pi \cdot r_c (kT_c/m_0c^2)^{1/2} \text{m} \cdot \text{rad},$$

where r_c – cathode radius, k – Boltzmann's constant, m_0 – electron mass, c – velocity of light. For the total emission current of 100 mA and effective emitter surface of 4.5 mm having the temperature of 2500 K the beam emittance on the cathode is 5.1 mm·mrad. This value is lower significantly of values obtained after beam simulation at the RF gun output. Thus, at the input power value of 1 MW (the electric field strength on the cathode is 26 MV/m) the normalized beam emittance is 30 mm·mrad for 90% of particles and operating temperature of the metallic emitter. Phase length of the electron bunch is 56°, the average particle energy is ≈ 1 MeV and energy spread (FWHM) is 34%. As it follows from the computation the increasing of the electric field in the cavity of investigated RF gun causes the emittance decreasing at its output.

3. EXPERIMENTAL RESULTS

The heating-up gun was mounted on the special test set-up and pilot studied at the anode voltage of 2.6 kV before to be installed in the RF gun. There was obtained the gun current of 27 mA and the temperature of the tantalum emitter surface localized by the beam of the heating-up gun was ~2350°K. Size of this surface was controlled visually of its bright glow and wasn't higher of 3 mm in diameter. Fig. 3 illustrates computed (lines) and experimental (dot) dependences of current density (solid) and temperature (dash) on the emitter heating-up power.

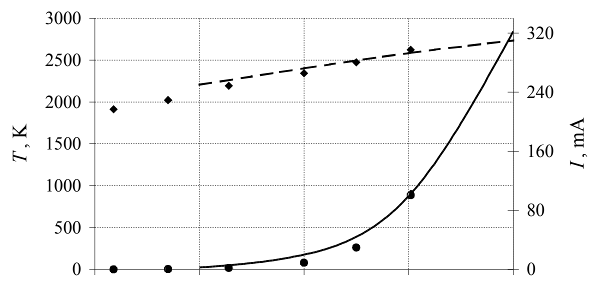

Fig. 3. *Computed (lines) and experimental (dot) performances of the tantalum emitter*

After pilot tests the cathode assembly with tantalum emitter was mounted in the two cell RF gun that is the injector of the linac Laser Injector Complex (LIC) [9]. Electron beam parameters both at the gun output and at the accelerator output were studied in the next step. There were measured the current, spatial distribution of particles and beam emittance using measuring system of the linac. There was used both moving single wire secondary emission monitor and the system of moving slotted collimators to measure transverse particle distribution in. The beam current was defined in different points of the linac by beam current transformers and by Faraday cups. Beam emittance was measured using the three-gradient method.

First experiments have shown that the metallic emitter heating up to operating temperature causes the eigenfrequency shift on 700 kHz in the gun resonance system. This fact was taken into account when RF gun tuning on the operating frequency. During the operation the gun was tuned both by the cathode assembly moving and by using specially provided hardware of the cavity frequency tuning. The cavity of RF gun and accelerating waveguide of the linac LIC were fed by the input power of P_{gun} up to 1 MW and P_{acc} up to 11 MW respectively during experiments. Typical oscillograms of the current at RF gun output and at the accelerator output for P_{gun}=1 ±0.1 MW and P_{acc}=12±1 MW are shown on Fig. 4.

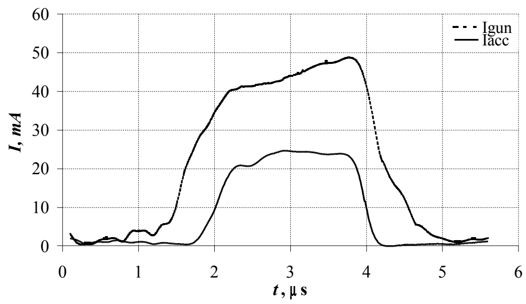

Fig. 4. *Current pulses at the RF gun output (I_{gun}) and at the linac output (I_{acc})*

Accelerating waveguide of the linac LIC [9] accelerates particles by (+1) spatial harmonics having phase velocity equal to c. Therefore particles with energy of over definite value are captured into acceleration [10]. This fact can be applied to define indirectly the energy of particles injected into accelerating waveguide. One can see from the figure that the electron capture factor of the beam is ~50%. There was estimated before that at least 50% of all injected particles into the waveguide have the energy of over 1100 keV. Applied accelerating waveguide has focusing effect on the beam [11]. This permitted to obtain electron beam at the accelerator output with transverse size of $2\sigma_x$=1.8±0.2 mm without applying additional focusing elements. The measured normalized rms emittance is 25 mm·mrad at γ=25.

RF gun operation was tested in different current pulse repetition rates. There was not observed significant variations in the shape and magnitude of the current pulse at RF gun output in the repetition frequency range of 1-50 Hz.

4. CONCLUSIONS

Thus, main results obtained in present work are summarized to following:

– there was proposed the concept of thermionic RF electron gun development having no disadvantages connected with a cathode back electron bombardment;

– there was developed the cathode assembly with high–temperature tantalum cathode with electron heating-up for the RF gun. Purposeful defining of the cathode thickness and the beam shape of the heating-up gun localize electron emission in the small region.

– RF gun with thermionic metallic cathode was researched experimentally. There were measured main beam parameters both at the gun output and at output of the single section linear accelerator.

Developed electron gun will be applied in linear electron accelerators in NSC KIPT for investigations in the field of an electron beam interaction with crystals.

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