THERMIONIC RF GUN WITH HIGH-TEMPERATURE METALLIC CATHODE

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Abstract

The paper describes 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 and high beam quality to be saved simultaneously. 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.

1 INTRODUCTION

The main trend in the development of RF guns intends the generation of intensive beams with small emittance. Thermionic RF guns have got enough of applications among others RF guns [1,2]. The main their disadvantage is beam parameter variations during the pulse caused by back electron bombardment. 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 for the pulse duration of 2−10 μs and pulse repetition rate of 1-25 Hz. This situation, on the one hand, 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 the cathode temperature variation. Schottky effect has also negative effect on beam parameters (mainly on emittance). It is obviously that the influence of mentioned above factors on beam parameters is reduced with the growth of the cathode work function and its operating temperature (heating-up power). 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 ($\sim 10^{-3}$-10^{-2} A) pulse current and high pulse repetition rate ($\sim 10^2$ 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 crystal [3].

The purpose of the work is the development of thermionic RF gun with suitable beam parameters without 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, normalised emittance is not higher of 30 mm·mrad, electron energy is not less of 300 keV, pulse repetition rate is up to 300 Hz. The gun design has to provide the possibility of the output current variation in a wide range.

2 CALCULATIONS AND PHYSICAL PRINCIPLE OF THE DESIGN

Application of high temperature metallic emitter made from thin plate is the main concept of the design. 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 to provide enough electron emission from the emitter region of small sizes. The tantalum having work function of $\varphi = 4.12$ eV was chosen to be the emitter. The plate thickness is 300 μm. According to beam dynamics in RF guns [4], the emission current from the cathode has to be no lower of 100 mA in order to extract the pulse current of 50 mA at RF gun output. Therefore the emission current density from acceptable emitting cathode surface has to be $\approx$ 15-20 mA/mm^2 without Schottky effect taken into account. The temperature corresponding to the required emission current was computed by solving of the heat conduction equation with boundary conditions taking into account radiant heat transfer. The emissivity factor of the material was taken equal to 1 to estimate maximum temperature.

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 the emitter temperature should be ~2400°K to extract the emission current of the above value. 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.

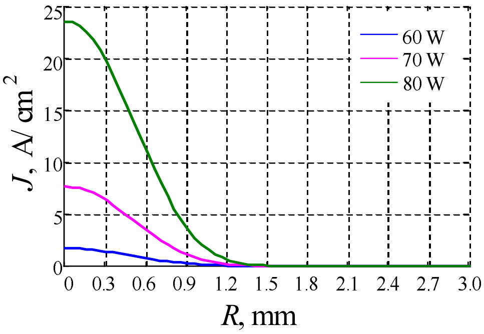

Fig. 1. Current density distribution on the emitter surface

These distributions were computed in the approximation of uniform axial particle distribution. 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 is released at 70 W heating-up power.

It follows from the computation 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 heating-up gun 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 $0.187\cdot10^{-6}$ A/V$^{3/2}$ that permits to produce electron beam with current of 30.7 mA at the anode voltage of 3 kV that corresponds to the required heating-up power of the RF gun tantalum emitter. Results of the heating-up gun design and development are referred explicitly in [6].

The beam dynamics in the RF gun [7] was simulated using PARMELA code [8]. Beam current, beam emittance and back electron power at RF gun output was 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.

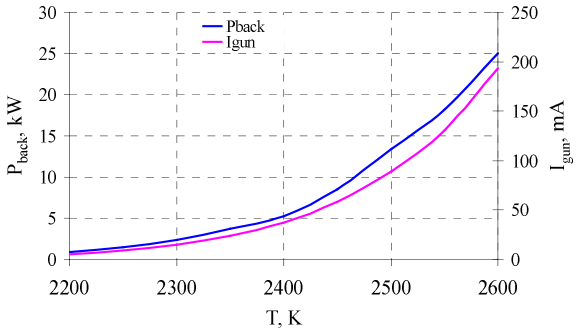

Fig. 2. Back electron pulsed power and the RF gun output current vs the metallic emitter temperature

The inpulse emission current growth caused by back electrons is not higher of 20° that is fully accepted. As for average temperature growth, the current growth on 20 % at the metallic emitter temperature of 2400°K and pulse duration of 3 µs 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 the current growth. The appropriated servo control system can be applied for this purpose.

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 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 transverse pulses of emitted particles. Minimum transverse normalised emittance of the beam on the cathode was estimated according to the expression:

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

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 that 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 normalised beam emittance is 30 mm·mrad for 90% of particles at the 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 RF gun cavity causes the emittance decreasing. Therewith, the current at the gun output is increased insignificantly with the input power increasing.

3. EXPERIMENTAL RESULTS

The heating-up gun was mounted on the special test set-up and pilot studied before to be installed in the RF gun. There was obtained the gun current of 27 mA under anode voltage of 2.6 kV. The temperature of the tantalum emitter surface localised by the beam of the heating-up gun was ~2350°K. Size of the 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 (purple) and temperature (blue) on the emitter heating-up power.

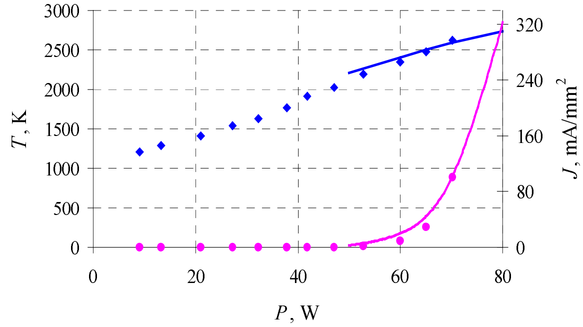

Fig. 3. Computed (lines) and experimental (dot) performances of the tantalum emitter

After pilot tests the cathode assembly with tantalum emitter was mounted in the RF gun being the injector of the linear electron accelerator Laser Injector Complex (LIC) [9]. There was used both moving single wire secondary emission monitor and the system of moving slotted collimators to measure transverse particle distribution. The beam current was defined in different points of the linac by beam current transformers and by

Faraday cups. Beam emittance was defined using the three-gradient method.

The metallic emitter heating up to operating temperature causes the eigenfrequency shift on 700 kHz in the RF gun resonance system. This fact was taken into account to tune RF gun on the operating frequency. 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. Typical oscillograms of the current both at the RF gun and the accelerator outputs are shown on Fig. 4.

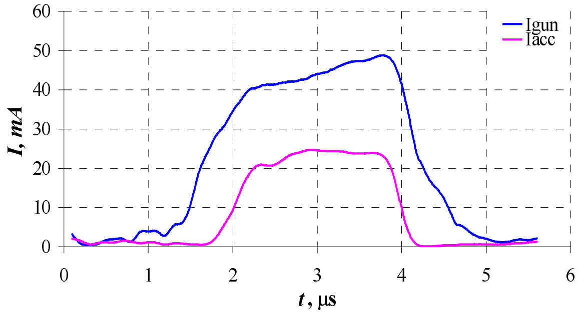

Fig. 4. Current pulses at the RF gun output (I_{gun}) and at the linac output ($I_{acc.}$)

Accelerating waveguide of the linac LIC captures particles with energy of over definite value into acceleration [10]. This fact can be applied to define indirectly the energy of particles. 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 particles injected 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 $2\sigma_x=1.8\pm0.2$ mm without applying additional focusing elements. Fig. 5 illustrates dependences of transverse beam sizes on the quadrupole lens current during emittance measurements in different time intervals of the pulse.

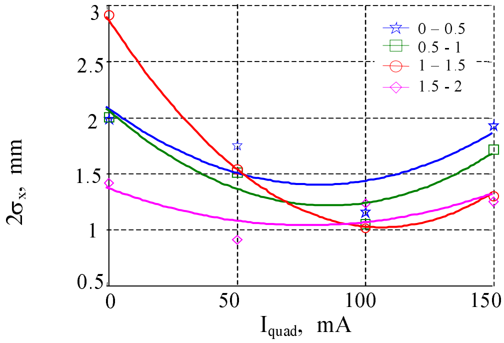

Fig. 5. Transverse beam sizes (2σ) vs quadrupole lens current

One can see that spatial beam performances have time inhomogeneity what is explained by transient behaviour in RF gun cavity and in the accelerating waveguide. The measured normalised rms emittance is 42 mm·mrad and 25 mm·mrad at $\gamma=25$ in time of 1 µs and 2 µs respectively. There were not observed significant variations in the shape and magnitude of the current pulse at the RF gun output during the operation in the repetition frequency range of 1-50 Hz.

4. CONCLUSION

Thus, main results obtained in present work are:

– the concept of thermionic RF gun design without disadvantages connected with cathode back electron bombardment was proposed;

– the cathode assembly with an extra electron heating-up was developed for the RF gun.

– thermionic RF gun with high-temperature metallic cathode was developed and researched experimentally.

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