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R&D of a Multi-Cavity RF Gun with Thermionic Cathode for BFEL

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In this paper, the design, simulation, and experimentation of a multi-cavity RF gun with a thermionic cathode for BFEL is described. This RF gun consists of 1/2+3 cavities with an on-axis coupling structure operated in the $\pi/2$ mode at 2856 MHz. We shorten the first cavity and add a short drift section between the second and third accelerating cavities, so that the power of back bombardment is decreased significantly and the longitudinal properties are adjusted properly.

Key words: RF gun with thermionic cathode, back bombardment, longitudinal property, current pulse shape.

1. INTRODUCTION

The appearance of free electron lasers (FEL) extends the application area of electron accelerators, and puts forward new research subjects in accelerator physics. To reach the required high quality of electron beams for FEL, high-brightness injectors should be seriously considered. RF guns with thermionic cathode have been widely used in FEL for its high brightness and simplicity. But its performance and application are restricted seriously by the back bombardment effects.

The Beijing Free Electron Laser (BFEL) facility is a Compton regime infrared FEL oscillator [1]. Its electron injector is a single-cavity RF thermionic gun and an α-magnet is used to compress the bunch length. The first saturated oscillation of the BFEL was obtained in 1993. Owing to the back

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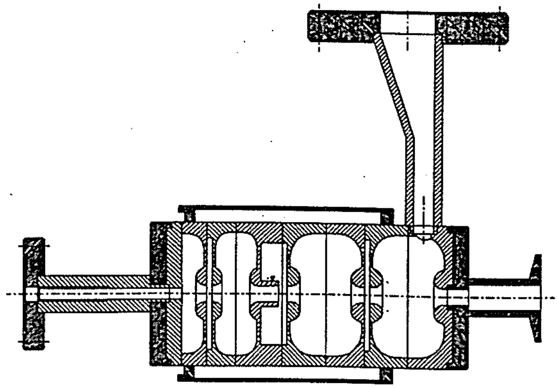

Fig. 1
Cross section of the multi-cavity RF thermionic gun for BFEL.

bombardment effects, the BEFL facility is now operating at the repetition rate of less than 10 pps and pulse width of about 4 μs. The potential of its RF power source with microwave pulses of 6 μs has not been used fully. Here, a novel multi-cavity RF thermionic gun with much fewer back bombardment effects is designed and experimentally tested. It will be used in the BFEL facility to improve its performance.

The structure of the RF gun is shown in Fig. 1. It is an on-axis coupling, bi-period standing wave accelerating structure with four accelerating cells and three coupling cells. The RF power is fed in from the last cavity. It works in a $\pi/2$ mode at the frequency of 2856 MHz. The cathode is made of single crystal LaB_6 with 3-mm diameter, which is installed at the beginning of the first cavity, and heated by a tower-shaped heater made of tungsten filament.

2. PHYSICAL DESIGN

The back bombardment effects of the single-cavity RF thermionic gun of BFEL cause a taper to raise in the current pulse. A typical curve is shown in Fig. 2, which is obtained from the operation of the single-cavity RF thermionic gun of BFEL. Then the beam loading becomes different from micro-bunch to micro-bunch in the micro-pulse, the energy spread among the micro-bunches increases, and the gain of FEL drops. So the back bombardment effects should be considered carefully in designing a RF thermionic gun.

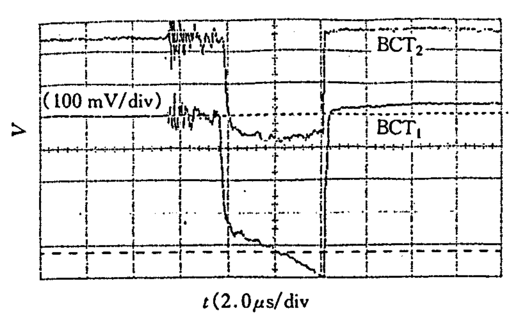

Fig. 2
The macro current pulses with a rising taper.
BCT1 and BCT2 are the wave forms of the current pulses at the exits of the RF gun and the α-magnet.

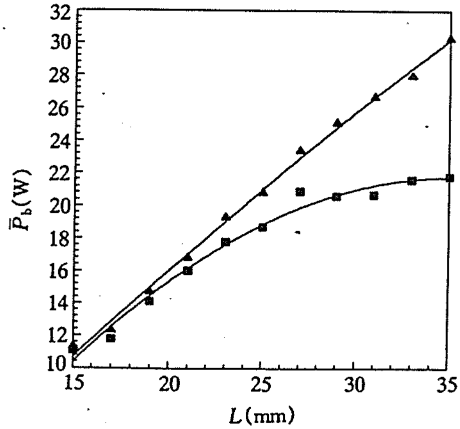

Fig. 3
The average back bombardment power as a function of the cavity length.
▲ for total back bombardment electrons; ■ for the electrons hitting on the cathode.

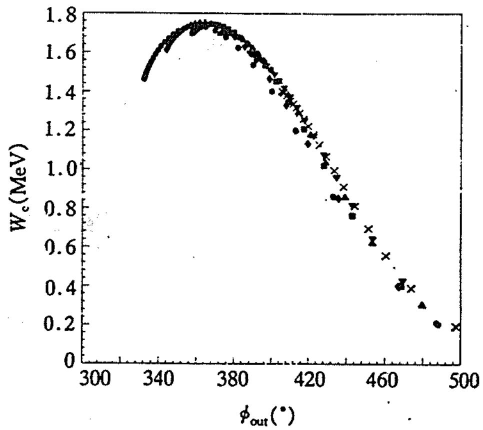

Fig. 4
The W_e-ϕ_{out} curves for different lengths of the drift section between cavities.
● DFT = 0 mm; ◆ DFT = 4 mm; ■ DFT = 8 mm; ▲ DFT = 12 mm; ▼ DFT = 16 mm; × DFT = 20 mm.

Here, a novel multi-cavity RF thermionic gun for BFEL is proposed. The accelerating gap of the first cavity is about 1/3 the length of a full one, so that both the energy and number of the back bombardment electrons can be reduced, and a relatively high accelerating gradient at the surface of the cathode can be kept which is advantageous to obtain high current density and suppress the space charge effects. The average back bombardment power $\bar{P}_b$ as a function of the length L of the cavity is shown in Fig. 3, with the parameters of the cathode and the RF power source remaining unchanged.

The effective accelerating length of the second cavity is about 2/3 of a full one. This design helps to reduce the back bombardment electron number and avoid the overfocusing of the electron bunches caused by the transverse forces of RF fields. The third and fourth cavities are full ones ($\beta \approx 1$), through which beams gain most of the energy.

The phase of the electrons at the head of the bunch gets ahead of the RF phase in the second cavity as the first cavity is shortened. In order to adjust the relative phase between the electron bunch and the RF fields, a drift section is added between the second and the third cavities. It can make the bunch fall behind the RF fields and let the longitudinal property ($W_e - \phi_{out}$) satisfy the bunch compressing requirement of the α-magnet. The curves of electron energy W_e vs. the electron phase at the exit of the RF gun ϕ_{out} for different drift lengths of DFT are shown in Fig. 4.

In addition, a large nose and a large beam aperture are adapted in the design in order to reduce the nonlinear components of the RF fields near the beam axis. The strength of electric field in the first cavity is optimized with consideration of its influence on the longitudinal property of the bunch at the exit of the RF gun, the back bombardment effect, and suppressing the space charge effects and other factors [2].

3. SIMULATIONS

The beam dynamics simulations of the multi-cavity RF thermionic gun are carried out using code HOTGUN [4] and GTL [2]. The simulation conditions are given in the following: parameters of RF power source: input RF power P_{in} = 1.6 MW, RF frequency f_{RF} = 2856 MHz, operating mode $\pi/2$, width of pulse τ = 6 μs, pulse per second F = 50 Hz; parameters of cathode: diameter D = 3 mm, working temperature T_c = 1800 K, current density J_0 = 18.0 A/cm^2 well-distributed on the cathode.

Table 1
The simulation results of the multi-cavity and the single-cavity.

	Parameters	Multi-cavity	Single-cavity
	Average back bombardment power (W)	18.3	99.2
The exit of RF gun	Pulse current (A)	0.74	1.05
	Maximum energy of electron beam (MeV)	1.76	0.96
	ε_x ($\pi \cdot$ mm $\cdot$ mrad)	6.4	4.3
	ε_y ($\pi \cdot$ mm $\cdot$ mrad)	8.4	4.6
The entrance of linac	Pulse current (A)	0.41	0.33
	ε_x ($\pi \cdot$ mm $\cdot$ mrad)	24.4	27.9
	ε_y ($\pi \cdot$ mm $\cdot$ mrad)	9.9	6.8
	Bunch length (ps)	~5	~5

Table 2
Experimental results of the multi-cavity RF thermionic gun for the BFEL.

Experimental results of the multi-cavity RF gun	
Pulses per second (Hz)	12.5
Pulse width (μs)	2.5
Maximum energy of electron beam (MeV)	1.8
Pulse current at gun exit (mA)	800
Pulse current at α-magnet exit (mA)	200
Energy spread between bunches	~2.5%
Energy spread in a bunch	~15%
Taper of the current pulse	< 2%—3%
ε_x ($\pi \cdot$ mm $\cdot$ mrad)	~28
ε_y ($\pi \cdot$ mm $\cdot$ mrad)	~22

The results are shown in Table 1 together with that of the single-cavity RF gun now used in the BFEL. It can be found from Table 1 that back bombardment power is reduced by a factor of 5, the electron energy increases by nearly a factor of 2 at the exit of the RF gun for the newly designed multi-cavity RF gun in comparison with the single-cavity one.

The traces of particles in the RF gun and the beamline of gun-to-linac are shown in Figs. 5 and 6, where D and Q represent the quadrapole and the drift, respectively. Figure 7 gives the particle distribution in the spaces (x, x'), (y, y'), (x, y), and $(\Delta\phi, W_e)$ at the exit of the RF gun, where $\Delta\phi$ is defined as the phase difference between a particle at the exit of the gun and the first one exiting the RF gun.

4. EXPERIMENTAL RESULTS

The multi-cavity RF thermionic gun was measured and tested in the BFEL laboratory. The current pulse and the input RF envelope at 12.5 pps are given in Fig. 8. It can be found from Fig. 8 that there is no taper at the later part of the micro-pulse, which indicates that the back bombardment effects are well suppressed as one expects. The electron energy, energy spectrum, and emittance of electron bunches are measured and shown in Table 2.

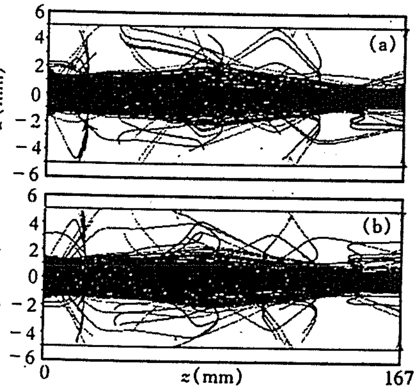

Fig. 5
The traces of particles on x-z and y-z planes in the RF gun.

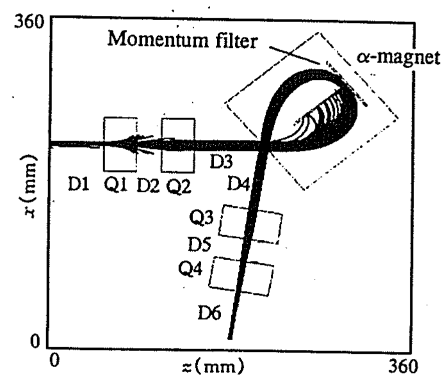

Fig. 6
The traces of particles on x-z plane of the beamline from gun to linac.

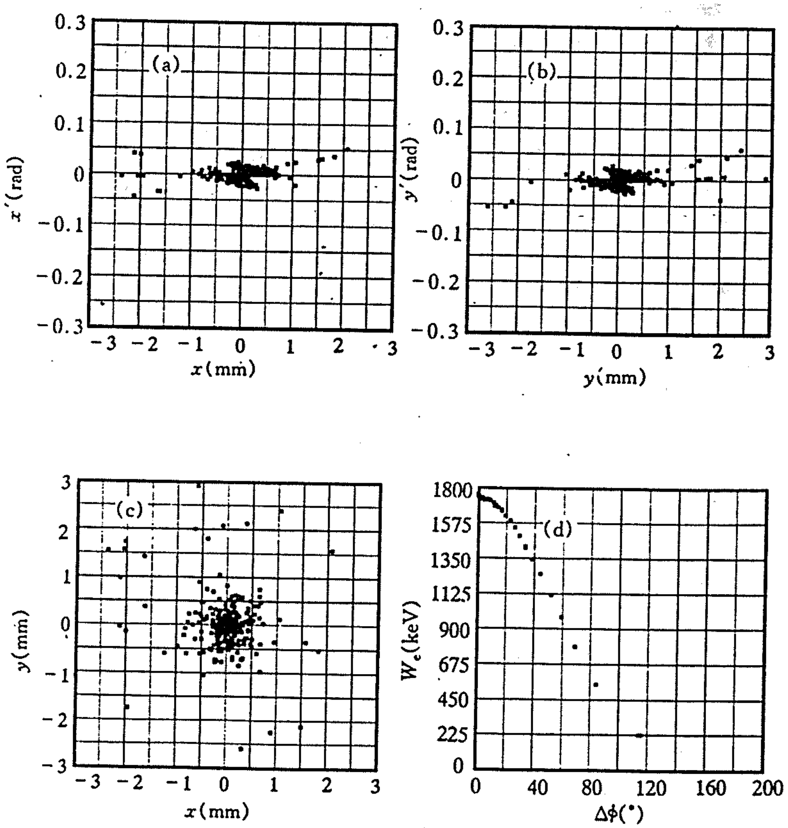

Fig. 7
The space distributions of the bunch at the exit of the RF gun.
(a) (x, x'); (b) (y, y'); (c) (x, y); and (d) $(\Delta\phi, W_e)$.

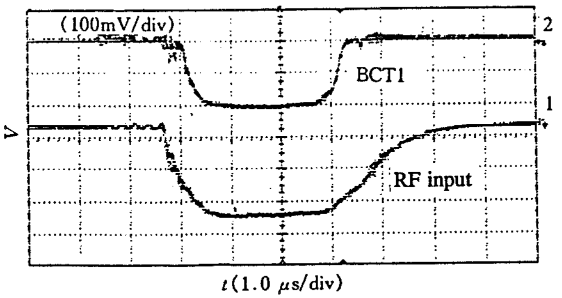

Fig. 8
The measured current pulse at the exit of the RF gun and the envelope of the input RF pulse.

5. CONCLUSIONS

The result of the simulation and experiment was that with the first cavity being shortened the back bombardment effects were reduced greatly and the longitudinal properties of electron bunches at the exit of the RF gun were adjusted properly by introducing a drift section between the cavities. This multi-cavity RF thermionic gun is going to be used in the BFEL facility after further experiments.

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