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CONCEPTUAL DESIGN OF A HIGH-PERFORMANCE INJECTOR BASED ON RF-GATED GRIDDED THERMIONIC GUN FOR THz FEL

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Abstract

Free-Electron Laser (FEL) has higher requirements on electron beam properties, for example, low transverse emittance, small energy spread, short bunch length and high peak current. Taking compactness and economy into account, we aim to design a high-performance linear accelerator based on a RF-gated gridded thermionic electron gun, which will be used as the injector of the oscillator-type THz FEL facility at Huazhong University of Science and Technology of China [1]. The RF-gated grid will be modulated with the fundamental and 3rd harmonic microwave of the LINAC frequency, which will be very helpful to get high electron capture efficiency and short bunch length. Concerning velocity bunching effect in the LINAC, electron bunch with good symmetry of current profile and bunch length less than 10 ps can be obtained at the exit of the injector. In this paper, design and beam dynamics simulation for the high-performance injector are presented.

INTRODUCTION

Free electron laser has strict limits on the beam parameters produced from the injector. In the initial stage of acceleration, the longitudinal motion of electrons is the most complicated, and the beam performance is of vital importance to the final beam performance parameters of the entire accelerator. In order to meet the requirements of simple and compact structure without reducing the beam quality and accomplish beam lossless transmission, a high-performance electron injector is especially needed. Beam quality, capture efficiency, gain, device stability, etc. are factors to consider. Conceptual design of a compact high-performance injector based on a RF-gated gridded thermionic gun [2] is proposed. The schematic diagram of the injector is shown in Fig. 1.

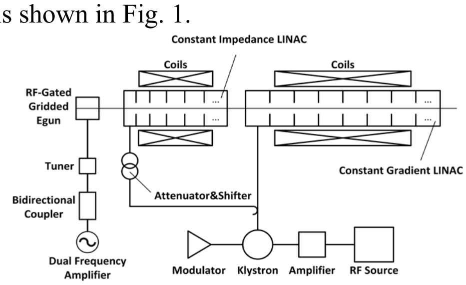

Figure 1: Schematic diagram of the THz FEL injector based on a RF-gated gridded electron gun.

The entire system will consist of a RF-gated gridded electron gun, a constant impedance travelling wave structure for bunching, a constant gradient travelling wave structure for acceleration. Comparing with the general system, this system eliminates the independently bunching cavity, and the beam bunch can be compressed directly with the electron gun which is regulated by a very low microwave power [3]. While retaining the advantages of the DC gun, it also avoids a series of negative effects of excessive length of bunch. The bunch is directly injected into the accelerating section from the gun, which can improve the capture efficiency of the electrons. The compressed electron bunch is further bunched in the LINAC section and the maximum energy can reach 15 MeV. After parameters optimization, electron beam with emittance of less than 20mm·mrad, energy spread of less than 0.8% and bunch length of less than 10 ps can be obtained, which will meet the requirements from THz FEL performance.

RF-GATED GRIDDED EGUN DESIGN

DC Thermionic Electron Gun

DC thermionic electron gun is main composed of a cathode, a focusing gate and an anode. Electrons emitted from the cathode are drawn through a DC high voltage between the anode and the cathode and are focused with a shaped focus pole [4].

Simulation results are shown in Fig. 2. At 8 cm downstream of the electron gun, 50 keV/1.0 A beam spot size less than 4 mm.

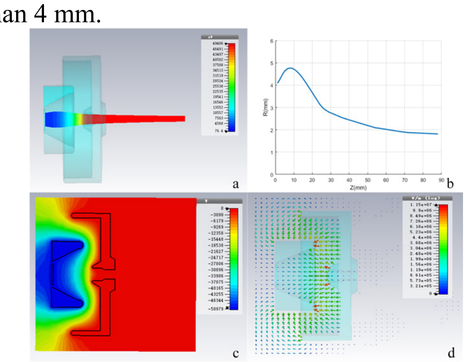

Figure 2: a. 3D model of the DC gun with trajectory. b. Envelope of the beam. c. Potential distribution. d. Electric field distribution.

RF-Gated Gridded Egun

Different from a DC high voltage Egun, the RF-gated gridded Egun has a microwave cavity which is formed between cathode and grid, as shown in Fig. 3. The cavity works in TM010 and TM020 modes with frequencies correspond to 952 MHz and 2856 MHz respectively. The two-mode axial field is used to extract electrons from the cathode across the grid.

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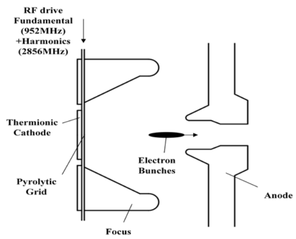

Figure 3: Diagram of RF-gated gridded Egun.

The internal field of the resonator cavity is shown in Fig. 4. The RF dual-frequency field and the grid negative bias jointly control the cathode electron extraction. Electrons can only be extracted at a suitable phase to obtain shorter bunch. The DC negative bias limits the electron bunch length of the fundamental and the 3rd harmonic, while filling every bucket [5].

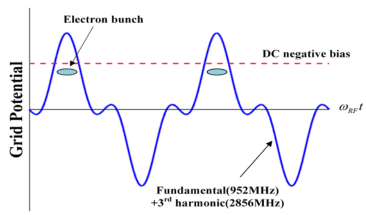

Figure 4: Microwave field and DC bias.

When the fundamental and the 3rd harmonic microwave power are fed in gate, the expression of the longitudinal electric field on the cathode surface is as follows:

$$E_z = E_{z,DC} + E_{z,1}\sin(\omega t) + E_{z,3}\sin(3\omega t + \delta) \quad (1)$$

Where $E_{z,DC}$ is the longitudinal electric field; $E_{z,1}$ represents the fundamental peak field; $E_{z,3}$ is the 3rd harmonic field; ω is the angular frequency of 952MHz.

Dual-frequency Cavity Design

The Dual-frequency cavity is modelled with SUPERFISH code. Because the grid hole is relatively tiny in the model, the microwave power will be cut off in the hole. Thus, the cathode-grid portion can be seen as a cavity. The main factors [6] considered in the design include cavity structure, cathode-grid distance, grid structure, etc. Results of the simulation are shown in Fig. 5. The superposition of the two electric fields is to simulate the fundamental and 3rd harmonic field between the cathode and gate.

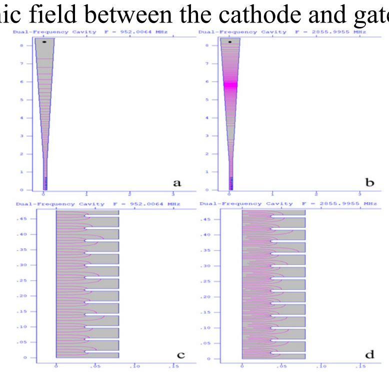

Figure 5: a, b are the electric fields of TM010, TM020 mode respectively in cavity. c, d are the Electric fields of TM010, TM020 mode respectively at the grid.

Simulation of the RF-Gated Gun

When voltage applied on the cathode and the anode are -50 kV and 0 kV respectively, current of electron beam emitted from cathode is 1.0 A and macro-bunch length is 1.05ns during the whole 952 MHz period. The peak field strength of the fundamental and 3rd harmonic is 1.5 MV/m, while the amplitude of the 3rd harmonic is taken to be half that of the fundamental. The model of RF-gated gridded electron gun with POISSON is shown as Fig. 6.

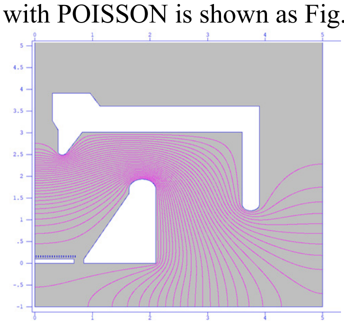

Figure 6: Model of RF-gated gridded gun.

PARMELA code has been used to simulate the beam emission process in the case with dual-frequency modulation. RF-gated gridded electron gun without dual-frequency modulation can be regarded as a general DC high voltage electron gun, from which the beam emission is continuous. When the beam is modulated by the microwave field, the continuous beam is bunched. The simulation results with PARMELA code are shown in the Fig. 7.

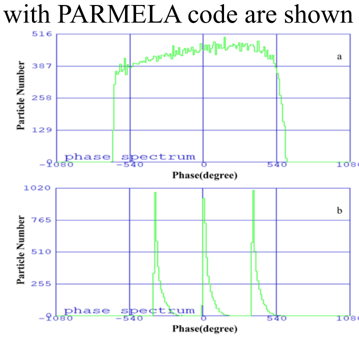

Figure 7: (Up) current profile at exit of the DC gun. (Down) current profile at exit of the RF-gated gridded gun.

The main comparative parameters between the DC gun and RF-gated gun as Table 1 showed and the results of 2 cm downstream of both guns are showed in Fig. 8.

Table 1: Parameters Comparison Between DC Gun and RF-Gated Gridded Gun

Parameters	**DC gun**	**RF-gated gun**
Average energy / keV	50	50
Bunch length / ps	>1050	~68
Energy spread(rms) / %	1.15	1.77
Transverse emittance(rms) / πmm·mrad	2.1	5.195
Beam spot diameter / mm	3.6	3.0
Bunch charge / nC	1	>0.2

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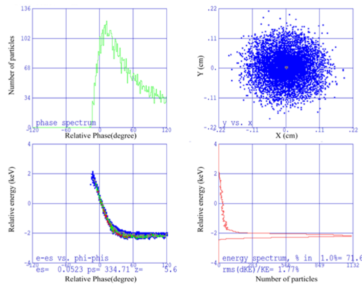

Figure 8: Current profile, transverse beam size, longitudinal phase space and Energy spectrum for RF-gated gridded gun.

LINAC DESIGN

Beam bunch from the electron gun can be compressed into dozens of ps level. Therefore, it is not necessary to increase the capture efficiency by increasing the length of the bunching section. The total length of the LINAC can be further shortened to meet the requirements of compactness.

Constant impedance traveling wave structure is used for the bunching section and constant gradient traveling wave structure is used for the accelerating section [7].

Velocity bunching occurs during the acceleration of electrons from low energy to near speed of light. According to the principle of auto phasing, particles close to the synchronized phase can finally be concentrated into a small phase width Δφ near the equilibrium phase. During the accelerating process, the phase velocity of the electron changes greatly so that the length of the accelerating cell should change correspondingly. Six kinds of phase velocities of 0.56, 0.68, 0.82, 0.90, 0.92 and 0.999 have been used for a total of nine traveling wave cells with 2π/3 mode. The input power for this 0.2777 m length section is 5 MW. Variation of power and field strength along the velocity bunching section are shown in Fig. 9. During the calculation, beam loading effect has been taken into account [8].

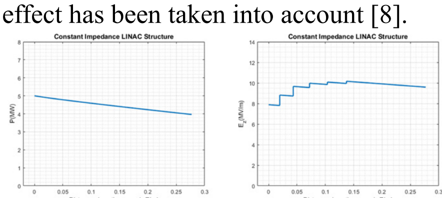

Figure 9: RF power and field strength along the bunching section.

The accelerating section has a 0.8047 m length traveling wave constant gradient structure, which consists of 23 normal accelerating cells with 2π/3 mode. Variation of power and field strength along the axis in the accelerating section are shown in Fig. 10.

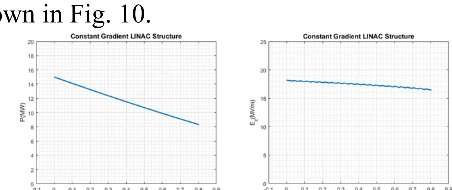

Figure 10: RF power and field strength along the accelerating section.

Calculation results show that the capture efficiency of the electron beam with the RF-gated gridded gun can reach 100%. The beam energy gain γ is 32.16, as shown in Fig.11. The energy spread of less than 1.12% and bunch length of 8 ps at exit of the LINAC have been obtained.

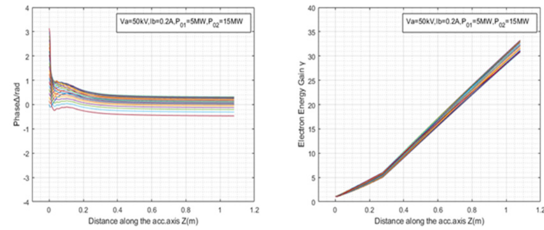

Figure 11: Beam phase trajectory and energy gain.

BEAM DYNAMICS SIMULATION

Beam dynamics for the injector is simulated by means of using PARMELA code. According to the results showed in Fig.12, the beam parameters at entry and exit of the LINAC is listed in Table 2.

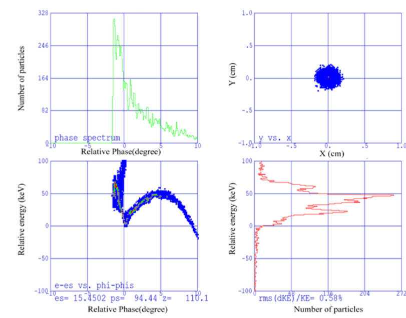

Figure 12: Current profile, transverse beam size, longitudinal phase space and Energy spectrum at exit of the LINAC.

Table 2: Main Beam Parameters of the LINAC

Parameters	Input	Output
Average energy / MeV	0.05	15.49
Bunch length / ps	~68	~3.6
Energy spread(rms) / %	1.77	0.58
Transverse emittance(rms) / πmm·mrad	5.195	6.261
Beam spot diameter / mm	3.0	3.2
Bunch charge / pC	>200	>200
Capture efficiency / %	\	98.07
Macro-pulse current / A	0.2	~0.2

CONCLUSION

This paper presents the preliminary physical design of a high-performance electron injector based on RF-gated gridded thermionic electron gun. Through simulation and parameters analysis, the RF-gated gridded thermionic electron gun can compress bunch length as expected. The electron beam properties can meet requirements of THz FEL based on optimizing the parameters of velocity bunching and accelerating section.

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