DESIGN SUTDY OF A HIGH-INTNEISITY, LOW-ENERGY ELECTRON GUN

Quan Zhang†, Tongning Hu, Kuanjun Fan, Kaifeng Liu, Zhiyuan Mei
State Key Laboratory of Advanced Electromagnetic Engineering and Technology, School of Electrical and Electronic Engineering, Huazhong University of Science and Technology

Abstract

An independently-tunable-cells thermionic RF gun (ITC-RF gun) is adopted in a compact FEL-THz facility due to its compactness, low-cost and high intensity. An electron gun is required to generate maximum beam current of 3.2 A at low energy of 15keV for the ITC-RF gun, which creates difficulties for the design of electron gun because of the strong space charge effect. A double-anode gridded gun structure is adopted that controls the beam current easily while maintains the energy dispersion less than 0.5%, with high perveance and high compression ratio. CST code has been used extensively for design optimization, which includes electrode shape, influences of grid, installation errors. A measurement scheme is also proposed for key parameters verification. Beam current, emittance and energy dispersion can be measured.

INTRODUCTION

THz radiation sources open a wide range of applications in science and technology. In some applications, the power of the THz radiation is crucial [1]. However, THz sources with high power are currently restricted to large facilities. A compact FEL-THz facility with power of 1 Watt is being developed at Huazhong University of Science and Technology (HUST).

To meet the stringent requirements on electron beam, photocathode electron guns are widely used to provide high quality electron beams for FEL-THz facilities. However, the high cost, large size and complicated structure restrict their applications in compact FEL-THz facilities. An independently-tunable-cells thermionic RF gun (ITC-RF gun) is adopted in our FEL-THz facility due to its compactness, low-cost and high intensity. The structure of an ITC-RF gun is shown in Figure 1, which consists of a high voltage DC electron gun as an electron source followed by two independently tunable cells. The injection beam current is required as high as 3.2 A. The acceptable injection beam energy for the independently tunable RF cell-1 is restricted to be 15keV at most [2]. Thus, the resultant perveance, one of the most important characteristics of an electron gun, is relatively high. It can be giving in following equation [3]:

$$P = \frac{I}{V_a^{3/2}} = \frac{3.2A}{(15000V)^{3/2}} = 1.74\mu P_{erv} \qquad (1)$$

Where I is the beam current and V_a is the anode potential with respect to the cathode. The high perveance makes the DC electron gun design becomes difficult and results in poor beam quality.

* Work supported by the Fundamental Research Funds for the Central Universities (2016YXMS280)
† email address: zhangquanhust@hust.edu.cn

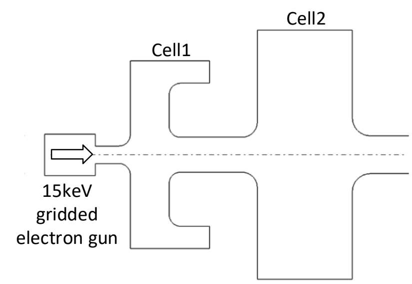


Figure 1: Schematic of Independently-tunable-cells thermionic RF gun (ITC-RF gun)

Currently, a diode gun is being used in the FEL-THz facility [4]. However, its performance is undesirable due to the restrictions of high voltage pulse between anode and cathode. Since it is hard for high voltage modulators to produce ideal pulses with very sharp rising/falling edge and low voltage fluctuation, high voltage pulses result in large energy dispersion for diode guns. Limited by lifetime of the emitter, the diode gun also has a disadvantage of short life.

In this paper, a 15keV gridded DC gun with double anode structure is designed, which can generate a better beam quality than that of the diode gun [5]. The new design has advantages of easy beam current control, low energy dispersion of 0.5%, high perveance, high compression ratio, long life and low requirements for high voltage source.

DESIGN OF ELECTRON GUN

Double Anode Gridded Electron Gun

The structure of the double anode gridded electron gun is shown in Figure 2, which consists of four parts, emitter, focus electrode, intermediate electrode and anode. The emitter is made of an EIMAC-Y646E cathode-grid assembly, which has characteristics of stable performance, long life time, maximum current of 10A. High quality beam pulses with very sharp rising/falling edge can be generated easily by adding 0~200V extracting pulsed voltage on the cathode-grid. The energy dispersion can be reduced significantly comparing with diode guns.

Double anode structure [2] is adopted to enhance the maximum beam current while keeping beam energy constant by increasing extraction voltage. The potential of the emitter and focus electrode is -15kV, the intermediate electrode can be applied a high voltage up to 23kV, and the anode is grounded. Based on the requirements of RF cells, the basic design parameters of the electron gun are shown in Tab.1.

ISBN 978-3-95450-182-3

Optimal Design of the Electron Gun

The electron gun is designed with high intensity (Max. $90A \cdot cm^{-2}$) but with low energy(15keV) , that results in very strong space charge effects. This creates difficulties for the beam compression within the electron gun. High perveance results in high electric field which will increase the risk of breakdown. Geometry of electrodes should be designed iteratively to satisfy design requirements.

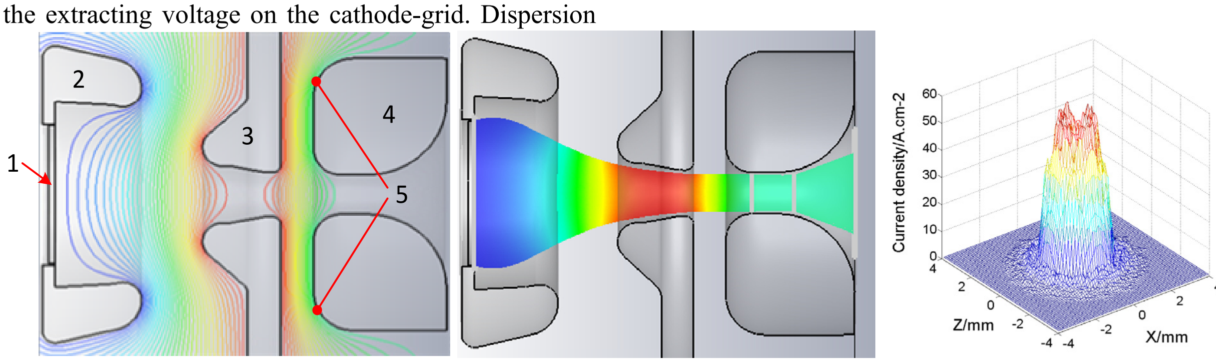
Particle Tracking of CST is used for simulation, with space charge effect being considered. Since the scale of grid is very small comparing with that of electron gun, cathode-grid assembly is simulated separately. The separated simulation results are integrated to the entire simulation of electron gun. Figure 2 shows the simulation results by CST.

The grid of the cathode-grid assembly acts like a lens which leads to emittance increase of the beam. Cathode-grid assembly has a thermal emittance of about 1.3mm · mrad, and the interception ratio of the grid is about 15%. Precision requirements for electron gun manufacture and assembling are necessary. Essential parameters of electron gun are changed slightly to simulate manufacture and assembling errors. The final simulation results demonstrate that the maximum manufacture and assembling errors for key sizes are no more than 50μm.

Comparison of design parameters and simulation results are shown is Table 1. The maximum beam current is 3.27A, and beam energy is slightly larger than 15keV due to the extracting voltage on the cathode-grid. Dispersion of energy is 1.2‰ (RMS), which is pretty small. The maximum electric field is 12.66MV/m, occurring at the edge of anode, it can be seen from Figure 2. The strength of the electric field has a low possibility of breakdown if the surface processing is good. Normalized emittance of the electron gun is 61.6mm·mrad, that is very high for an electron gun. Since cells of ITC-RF gun focus the beam exported from the DC gun, acceptable emittance for the ITC-RF gun is relatively high.

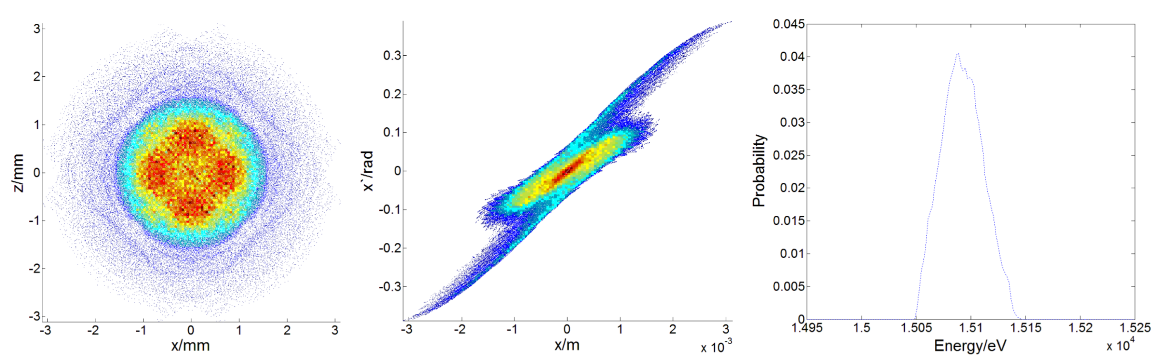
Table 1: Comparison of Design Parameters and Simulation Results

Parameter	**Design value**	**Simulation results**
Beam current /A	>3.2	3.27A
Beam energy /keV	15	15.06~15.16
Perveance /μP	>1.74	1.78
Beam waist/mm	<1.4	1.35
Compression ratio	>16.2	17.5
Range /mm	>13	13.4
Normalized emittance /mm·mrad	<70	61.6
Dispersion of energy （RMS）	<0.5%	1.2‰
Maximum electric field (MV/m)	13	12.66



(a (b) (c)

Figure 2: Simulation results of CST. (a) Equipotential line, 1 emitter, 2 focus electrode, 3 intermediate electrode, 4 anode, the maximum electric field occurs at 5; (b) Beam envelop; (c) Current density at the exit.



(a) (b) (c)

Figure 3: Beam at the exit. (a) Cross section; (b) Phase space; (c) Energy spectrum.

Figure 3 indicates cross section, space phase, energy spectrum of the beam at the exit of electron gun. As shown, particles get denser approaching the center, and the shape of contour lines present to be square. Since the holes of the grid are square and contour lines present to be circle in the case of no girds, square contour lines can be explained by square grid holes.

MEASURE OF KEY PARAMETERS

A test bench is proposed that can measure the key characteristics of the gun. Figure 4 shows the scheme of the test bench, which can measure beam current, emittance and energy dispersion.

Measurement of Beam Current

FCT122 (fast current transformer) of Bergoz is used to measure beam current. Secondary coil can induce beam current when beam goes through FCT.

Measurement of Emittance

Multi-screen method is adopted for measurement of beam emittance; a CCD camera and a fluorescent screen is used [6]. According the equation of multi-screen method, transverse normalized emittance of x direction can be expressed as the following:

$$\varepsilon_x = \beta\gamma\sqrt{\det(\sigma)} = \beta\gamma\sqrt{\sigma_{11}\sigma_{22} - \sigma_{12}^2} \tag{2}$$

Measurement of Energy Dispersion

An energy analyzer is designed in this paper [7], principle of measurement is shown in Figure 4. Decelerating grid connects a negative high voltage, which produces a decelerating electric field. Particles will be decelerated in energy analyzer, only particles with an energy higher than decelerating voltage can go through the decelerating grid and be collected by the collector. Energy spectrum can be obtained by adjusting decelerating voltage. Space charge effect brings about great energy dispersion within the energy analyzer. A beam scraper is used to intercept most particles. Less than 10mA can enter the energy analyzer, energy dispersion caused by space charge effect decreases significantly. Figure 5 indicates the simulation results of the energy analyzer, which has an energy resolution higher than 20eV(RMS).

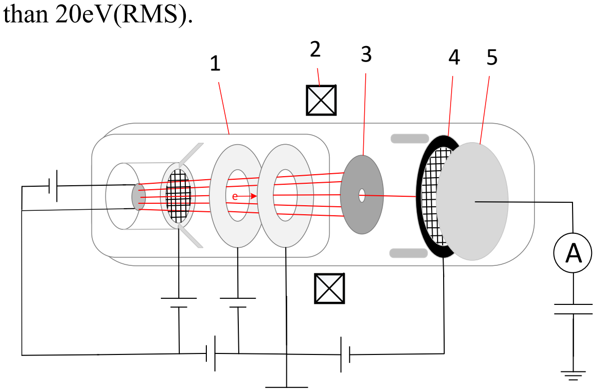


Figure 4: Schematic of test bench. 1 electron gun; 2 FCT; 3 beam scraper; 4 decelerating grid; 5 collector.

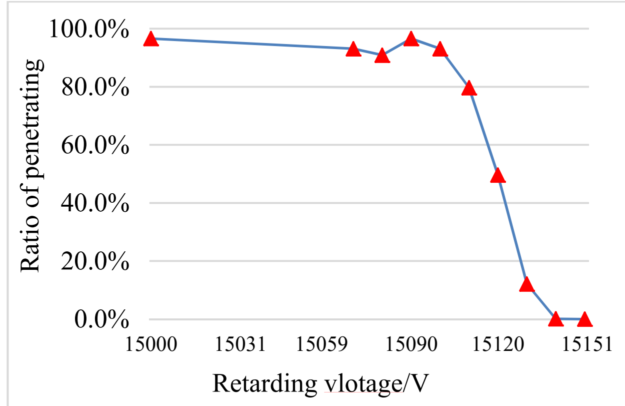


Figure 5: Simulation result of analyzer (by CST).

CONCLUSION

A high intensity, low energy electron gun is designed in this paper for ITC-RF gun in FEL-THz facility. It is a gridded electron gun with double anode structure. Design parameters are satisfied. A measurement scheme for key parameters is proposed in this paper, a beam scraper is developed to decrease space charge effect in the measurement of energy dispersion. Simulation results achieve the expected effect.

ACKNOWLEDGMENT

The work gain supports from National Synchrotron Radiation Laboratory, University of Science and Technology of China. The author would like to thanks Li Ji, PEI Yuan-Ji, Y.L Hong and S.W. Hu for consultations and advice.

REFERENCES

[1] Y. U. Jeong, *et al*,. High power table-top THz free electron laser and its application, 34th International Conference on Infrared, Millimeter, and Terahertz Waves.

[2] Li Ji, Pei Yuan-Ji, *et al*., "Design of an electron gun for terahertz radiation source", *Chinese Physics C*, Vol. 38, No. 4 (2014) 047004.

[3] Stanley Humphries, "Charged Particle Beams", *Atomic Energy Press*, 1999.

[4] Hu T, Pei Y, Tan P, *et al.,* "Beam Diagnostic of the LINAC for the Compact High-Performance THz-FEL", *Proceedings of IPAC'15*, VA, USA.

[5] HU Tong-ning, CHEN Qu-shan, PEI Yuan-ji*, et al*., "Physical design of FEL injector based on the performance-enhanced EC-ITC RF gun[J]", *Chinese Physics C*, 2014, 38(1):79-85.

[6] Peter Forck, "Lecture Notes on Beam, Instrumentation and Diagnostics",Juas 2011, http://www-bd.gsi.de/conf/juas/juas_script.pdf

[7] Y.Cui, Y.Zou, "Design and operation of a retarding field energy analyzer with variable focusing for space-charge-dominated electron beams", *Review of Scientific Instrument*, 2004.

ISBN 978-3-95450-182-3