Design of an electron gun for terahertz radiation source*

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Abstract: An EC-ITC (External-Cathode Independently Tunable Cells) RF gun was employed with the aim of obtaining short-pulse bunches with high peak current for a terahertz radiation source. A gridded DC gun plays a key role as the external injecting electron source of the ITC RF gun, the performance of which determines the beam quality in the injector and transport line. In order to make the beam well compressed in the ITC RF gun, the energy of the electrons acquired from the gridded DC gun should be 15 keV at most. A proper structure of the gridded gun with double-anode is shown to overcome the strong space- charge force on the cathode, which is able to generate 6 μs beam with 4.5 A current successfully.

Key words: gridded DC gun, RF gun, EC-ITC

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1 Introduction

The Terahertz wave, which is electromagnetic radiation between far infrared wave and microwave, has very important academic and application values. Compared to other Terahertz sources, FEL is the best ways to get maximum power output. In this paper, a high-quality electron gun is studied to serve as a compact FEL Terahertz radiation source [1].

Although photocathode RF guns have been widely developed as electron sources for FELs, thermionic RF guns are expected to have the potential to generate high brightness and short-pulse electron beams [2]. A thermionic RF gun with two independently tunable cells (ITC) has been developed in the National Synchrotron Radiation Laboratory for several years, of which the cells are power fed independently. The external injecting ITC RF gun can generate beam bunches of superior characteristics by setting appropriate feeding powers and phases of the two cells instead of using alpha-magnets. The external injecting structure can increase beam current, and decrease the energy spread and the negative effect of back bombardment to the cathode.

In order to obtain a beam pulse with sharp rising edge and falling edge, a 15 keV gridded DC gun has been designed. The electrodes were properly distributed to generate a 4.5 A beam current.

2 The external-cathode structure

As the power into the cells is fed independently, the ITC RF gun can capture the beam and compress the bunches well by setting the appropriate feeding power and launch phases separately, instead of using α-magnet or a complicated laser drive system [3]. In addition, simulation results shows that the external cathode structure shown in Fig. 1 can increase the captured beam current and decrease the energy spread further than the common structure with cathode inside the cavity. A part of the backwards travelling electrons are lost on the aperture,

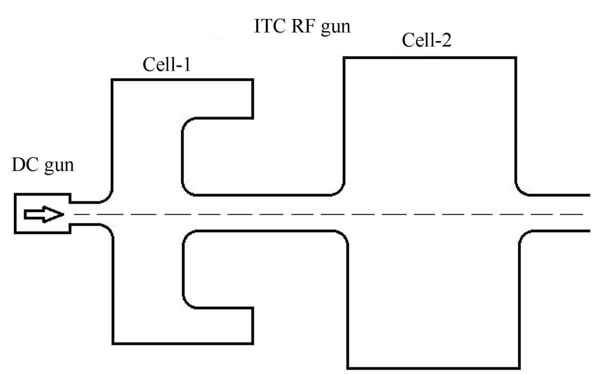

Fig. 1. Layout of the external injecting ITC RF gun.

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the rest are decelerated in the DC gun, so the negative effect of back bombardment to the cathode is nearly eliminated [4, 5].

3 The 15 keV gridded DC gun

3.1 Emitter

Considering the emission capability, the EIMAC Y646E cathode-grid assembly was chosen as the electron source. The stability and long life of this kind of cathode-grid assembly have been proved in testing and operation. The area of the emitting surface is 1 cm^2.

3.2 The double-anode gun model

In order to inject the 4.5 A beam into the ITC RF gun without hitting the wall of the cavity, the transverse beam size should be very small (<1.5 mm). Thus, a gun of high perveance, high compression ratio and long shot distance should be designed. We have used a special geometry with intermediate electrode, which is also called a double-anode structure, to satisfy the strict requirements.

Due to the strong longitudinal space-charge force of 4.5 A beam exerted on the emission surface, the electric field strength should be large enough to extract the beam from the cathode-grid assembly. The beam from a flat emission surface also needs sufficient focusing force to get compressed transversely. Furthermore, the 15 keV/4.5 A beam is easy to diverge in drift space. To sum up, the Pierce-type diode structure is very hard to use to emit a 15 keV/4.5 A beam into the ITC RF gun.

In order to enhance the electric field strength on the emission surface and the transverse focusing force, we add an intermediate electrode to accelerate the electrons to higher energy, and the electrons will then be decelerated to 15 keV between intermediate electrode and the anode. In this way, the beam is focused twice in the gun. The focusing principle is shown in Fig. 2, in which the dotted lines represent the equipotential lines and the red arrowed lines represent the electric field lines.

The emitter is connected with a −15 kV power supply and the anode is grounded. In principle, a stronger transverse focusing force will be obtained if a higher voltage is connected with the intermediate electrode. Considering the limited space, too large a ceramic for high voltage is not recommended. Thus, 20 kV on the intermediate electrode is a compromise of beam quality and compact structure. The angle of the focusing electrode, the nose of focusing electrode and intermediate electrode, the shape of the anode, and the distance between every two electrodes are all optimized to get a high-quality laminar beam and to avoid breakdown. The electric field

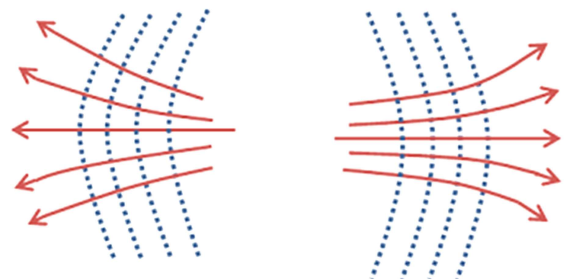

Fig. 2. (color online) Focusing principle in acceleration (left) and deceleration (right).

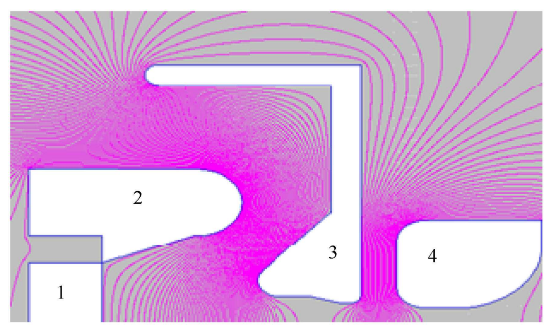

Fig. 3. (color online) Model of 15 keV DC gun. From 1 to 4, the electrodes are emitter, focusing electrode, intermediate electrode and anode.

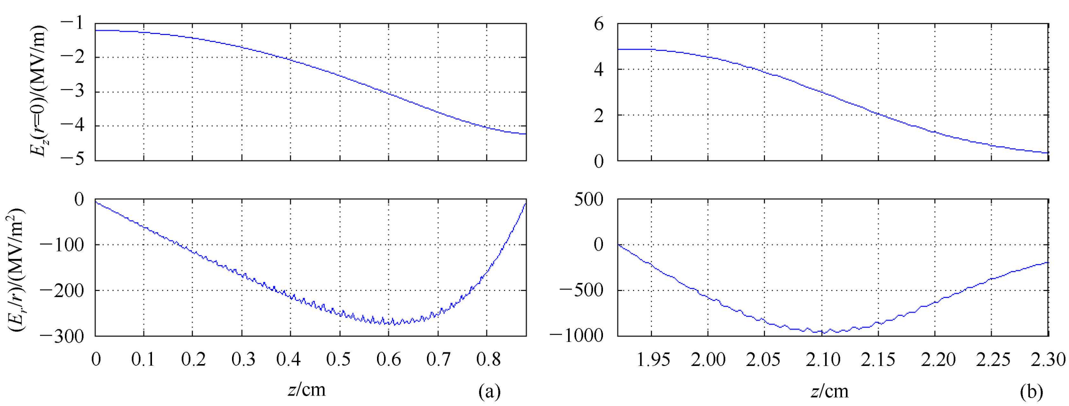

Fig. 4. (color online) E_z on the axis and E_r/r in acceleration process (a) and deceleration process (b).

distribution is calculated by Poisson code [6], as shown in Fig. 3, in which the red solid lines are the equipotential lines. The cathode-grid assembly is represented by the emitter in this model, and the anode is a combination of real anode and a part of the first cell of the ITC RF gun.

The transverse electric field can be expressed as [7]:

$$E_r(r,z)\approx-\left(\frac{r}{2}\right)\left[\frac{\partial E_z(0,z)}{\partial z}\right]=-\left(\frac{r}{2}\right)E_z', \qquad (1)$$

where E_z is the longitudinal electric field on the axis. As shown in Fig. 4, E_z and E_r/r in the accelerating and decelerating process.

3.3 Simulations of the DC gun

The DC gun was modeled with OPERA-3D [8], of which the SCALA module analyses electrostatic fields taking into account the effects of space charge created by beams of charged particles. In this model, the emitter and focusing electrode are connected with −15 kV and 20 kV power supplies separately. Considering the strong space-charge force of low-energy and high-density beam, the grounded anode is amounted together with a part of the first cell of ITC RF gun to decrease the distance in the anode hole. The initial condition is set as that 4.5 A beam with 150 eV extracted from the emission surface.

The simulation results in Fig. 5 show that the 15 keV/4.5 A beam can be injected into the ITC RF gun sucessfully. The trajectory shows that the beam is focused at the entrance of the anode again to supress the divergence. The focusing strength is modulated through optimizing the shape of the anode to avoid over focus and under focus. Briefly, the beam is shaped well in the accelerating process and contained in the decelerating process.

The maximum electric field strength is 12.7 MV/m on the nose of intermediate electrode, and experiments show that breakdown threshold is 15 MV/m in DC case [9]. In operation, the emitter will be connected with 15 kV pulsed power supply, which can reduce the possibility of breaking down.

The simulation results are also testified by CST Particle Studio [10]. The evaluation of electron motion in Fig. 6 is almost the same as the trajectory from OPERA-3D. The normalized RMS emittance at the exit of the 15 keV gridded DC gun is 6.62 mm·mrad.

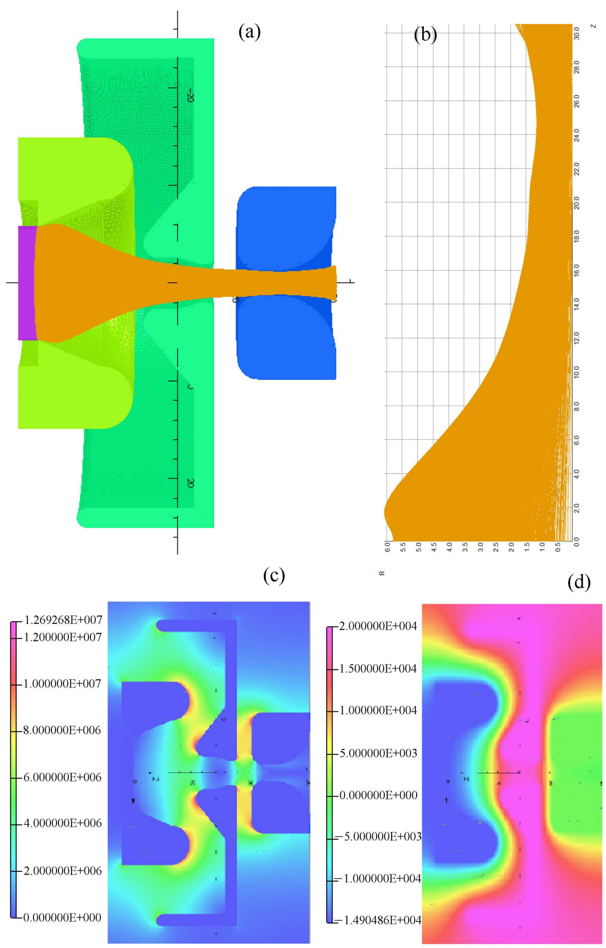

Fig. 5. (color online) (a) 3D model with trajectory; (b) Beam trajectory; (c) Electric field strength distribution; (d) Potential distribution.

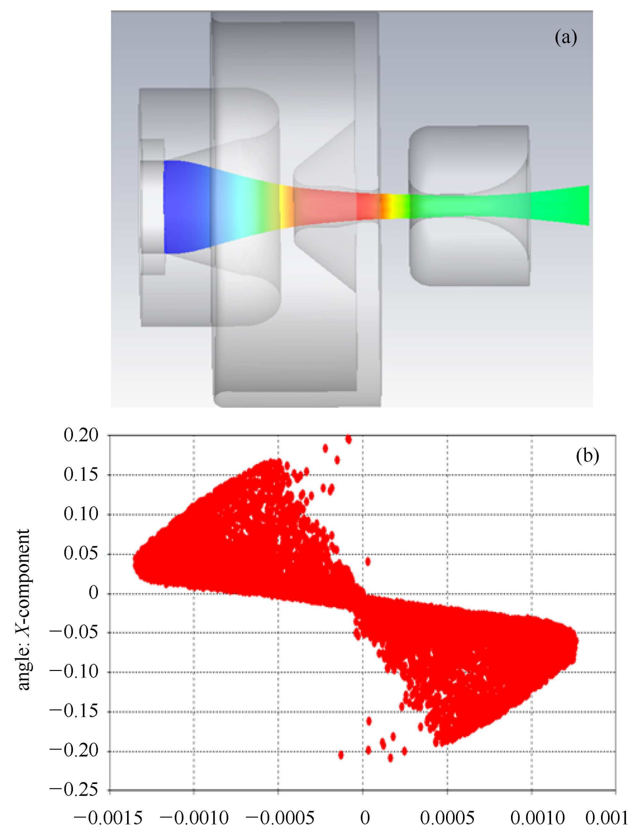

Fig. 6. (color online) Beam trajectory in the 3D model (a) and phase space (b) from CST.

3.4 The ITC RF gun

The beam from 15 kV DC gun is captured and bunched in the first cell of ITC, and then the beam bunches are compressed and accelerated to 2.6 MeV in the second cell. The two cells are power fed independently and achieve resonance at 2856 MHz. The magnitude of electric field strength along the axis in the cavities is calculated by Superfish code [6] in the Fig. 7, while the expected properties of the output bunch are listed in Table 1.

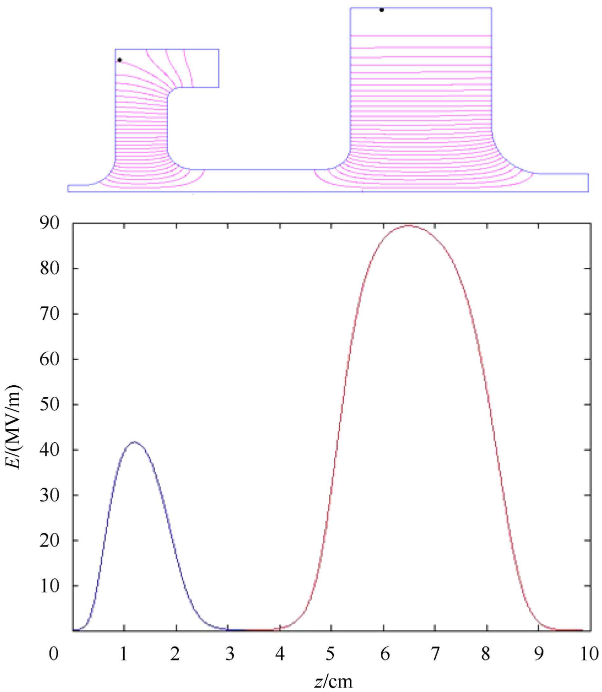

Fig. 7. (color online) Superfish model of the ITC RF gun and magnitude of electric field on axis.

Table 1. Expected properties of output bunch of ITC RF gun.

parameters	values
transverse emittance/(mm·mrad)	<10
energy spread (FWHM)	<0.50%
micro-pulse length (FWHM)/ps	1–10
micro-pulse effective charge/pC	200–300

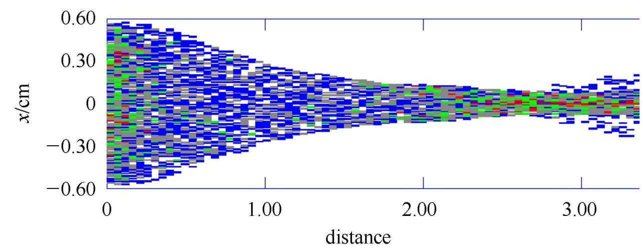

Fig. 8. Bean envelope of DC gun as initial distribution for tracking.

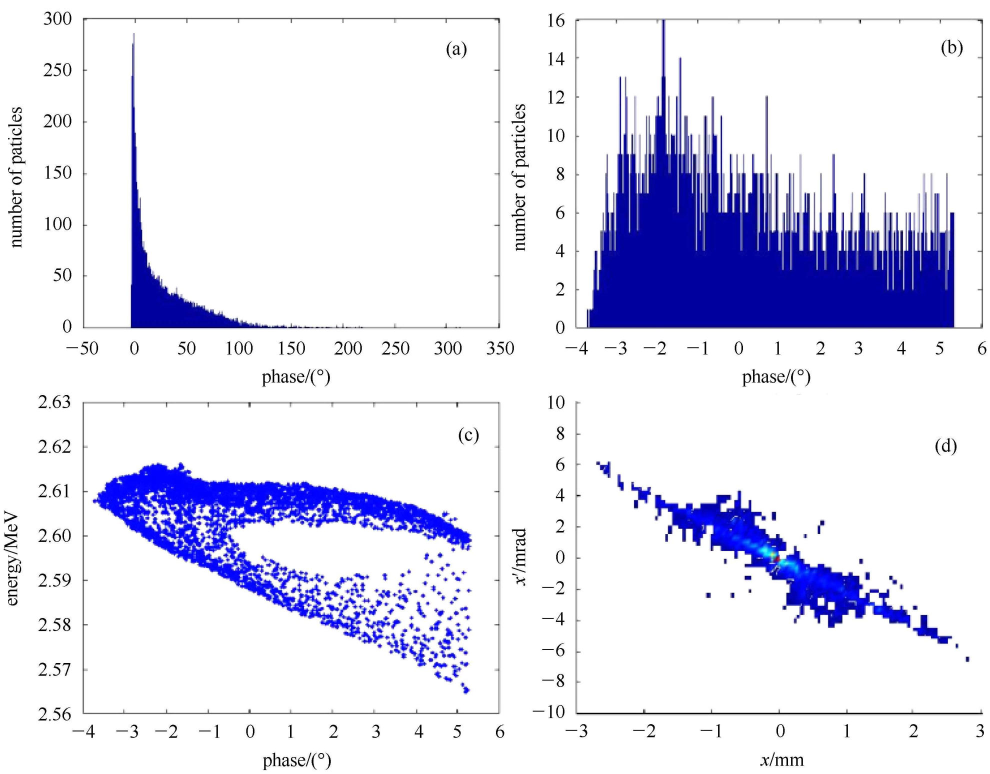

Fig. 9. (color online) (a) Phase spectrum (output); (b) Phase spectrum (effective part); (c) Energy vs. phase (effective part); (d) Phase space (effective part).

4 Particle-dynamics simulation

Dynamics computation from the DC gun to the ITC RF gun was executed with PARMELA code [11]. The initial distribution was generated by PARMELA according to the simulation results from OPERA and CST, as shown in Fig. 8. The peak electric field on the axis is 41 MV/m in the first cell and 90 MV/m in the second cell.

Table 2. Properties of output bunch.

parameters	values
beam radius/mm	2.8
beam energy/MeV	2.6
transverse emittance/(mm·mrad)	9
energy spread (FWHM)	0.30%
micro-pulse length (FWHM)/ps	3.8
micro-pulse effective charge/pC	210

The performance of the output is characterized with the parameters of the effective part (the head) of the bunch, of which the length is ~10 ps. The results of dynamics computation at the exit of the ITC RF gun are shown in Fig. 9 and Table 2.

5 Conclusion

A new-type gridded DC gun of high perveance, high compression ratio and long shot distance was designed for ITC RF gun. The gun is currently being manufactured by EAST China Institute of Optics and Electronics. The simulation results show that the external-cathode RF gun can generate a high-quality beam to satisfy the strict requirements of terahertz source. The effective bunch charge is over 200 pC with ~4 ps micro-pulse width (FWHM), while energy spread (FWHM) is ~0.3% and the transverse normalized RMS emittance is less than 10 mm·mrad.

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