Beam dynamics simulations of the injector for a compact THz source*

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Abstract: Terahertz radiation has broad application prospects due to its ability to penetrate deep into many organic materials without the damage caused by ionizing radiations. A free electron laser (FEL)-based THz source is the best choice to produce high-power radiation. In this paper, a 14 MeV injector is introduced for generating high-quality beam for FEL, is composed of an EC-ITC RF gun, compensating coils and a travelling-wave structure. Beam dynamics simulations have been done with ASTRA code to verify the design and to optimize parameters. Simulations of the operating mode at 6 MeV have also been executed.

Key words: EC-ITC RF gun, compensating coils, travelling-wave structure, start-to-end simulation

PACS: 29.27.-a, 41.85.-p **DOI:** 10.1088/1674-1137/38/8/088103

1 Introduction

Terahertz radiation has very important academic and application value and in the long term, compact THz sources have broader application prospects. Compared to other Terahertz sources, free electron lasers (FELs) are the best way to get maximum power output [1]. HUST (Huazhong University of Science and Technology) and NSRL (National Synchrotron Radiation Laboratory) / USTC (University of Science and Technology) have jointly proposed a compact THz radiation source based on FEL, which is under construction now. The layout of the whole facility is as shown in Fig. 1 [2].

THz sources require a high-quality electron source, and a photocathode RF gun is the best choice [3]. The complicated laser drive system and low quantum efficiency of photocathode RF guns, however, means the thermionic RF gun also has broad application prospects. NSRL has for some years developed a thermionic RF gun with two independently tunable cells (ITC) and external-cathode (EC) structure for years, called the EC-ITC RF gun. The EC-ITC RF gun can generate beam bunches with superior characteristics for THz sources [4].

The beam from the EC-ITC RF gun is accelerated to 6–14 MeV in the constant gradient traveling-wave structure, and then transported to the undulator through the transport line. A short magnetic lens and a solenoid were designed to compensate for the emittance growth in the injector. The main parameters of the injector are shown in Table 1.

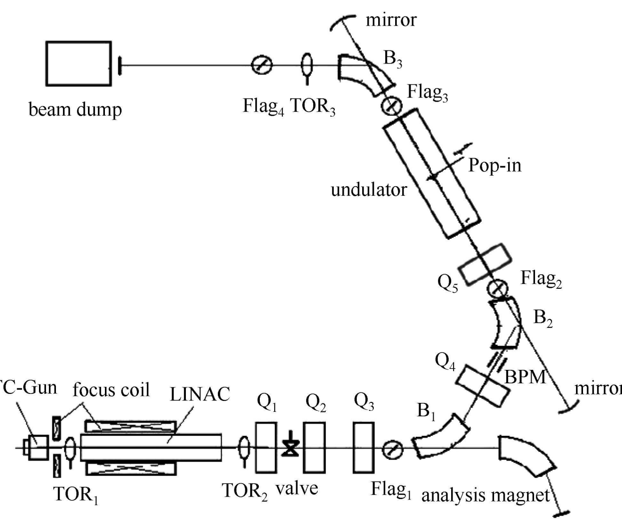

Fig. 1. Layout of the THz source facility.

Received 31 October 2013
* Supported by NSFC (10875116)
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Table 1. Expected properties of output beam from the injector.

parameters	values
beam energy (effective part)/MeV	6–14
beam current (micro pulse)/A	>30
micro-pulse length (FWHM)/ps	1–10
energy spread (effective part) at 14 MeV(%)	<0.3
energy spread (effective part) at 6 MeV(%)	<0.5
transverse emittance (effective part)/(mm·mrad)	<16
beam length (effective part)/ps	<10
micro-pulse effective charge	>200

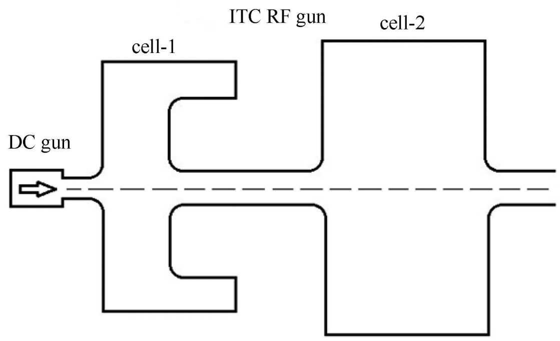

Fig. 2. Layout of the external injecting ITC RF gun.

2 The 14 MeV injector

2.1 EC-ITC RF gun

The ITC RF gun can compress the bunch well and get expected beam quality by setting the appropriate feeding power and launch phases separately, instead of using an α-magnet or complicated laser drive system. In addition,

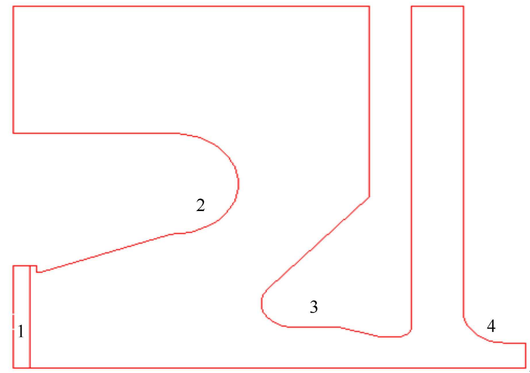

Fig. 3. Model of 15 keV DC gun. From 1 to 4, the electrodes are emitter, focusing electrode, intermediate electrode and anode.

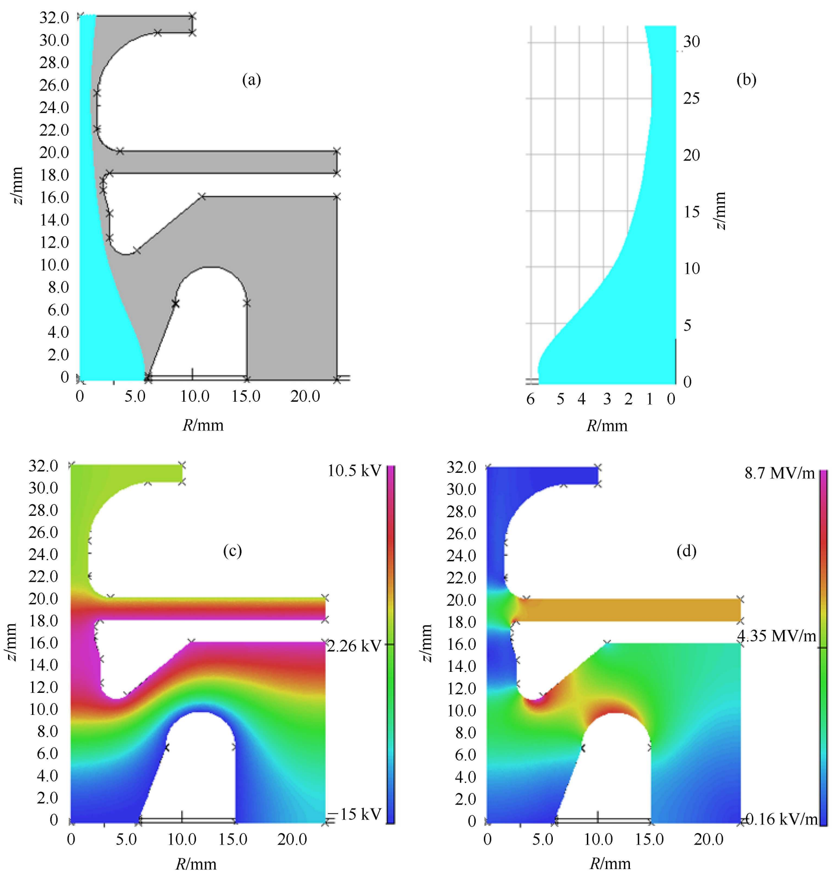

Fig. 4. (a) OPERA model with trajectory; (b) beam trajectory; (c) potential distribution; (d) electric field strength distribution.

the EC structure we use can increase the captured beam current and decrease the energy spread more than the common structure with cathode inside the cavity. The negative effect of back bombardment to the cathode is almost eliminated [5, 6]. The layout of the EC-ITC RF gun is shown in Fig. 2.

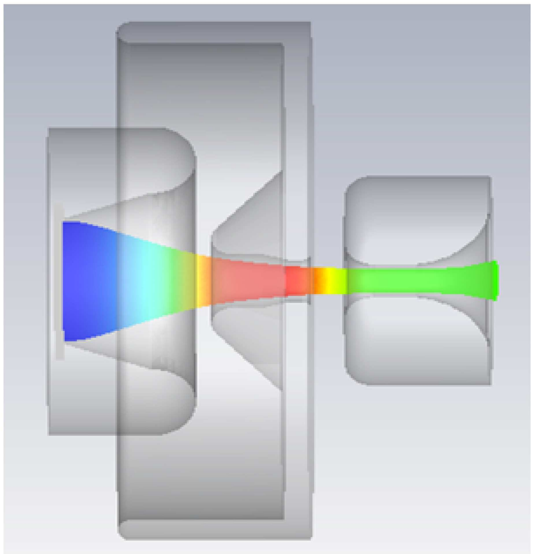

Fig. 5. Beam trajectory in the 3D model from CST.

2.1.1 15 keV gridded DC gun

A 15 keV gridded DC gun was designed to provide a pulsed beam. In the preliminary design, a special geometry with an intermediate electrode, known as a double-anode structure, shown in Fig. 3, was used to provide 4.5 A beam current [7]. In order to enhance the electric field strength on the emitting surface and the transverse focusing force, an intermediate electrode was added to accelerate the electrons to higher energy, and the electrons will then be decelerated to ~15 keV between theintermediate electrode and the anode.

After optimization, the lower–current beam injected into the ITC RF gun can also satisfy the requirements of beam quality at the injector exit. This structure makes it possible to provide laminar beam at different currents in a certain range through adjusting the high voltage on

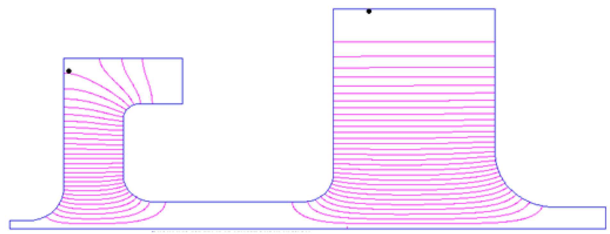

Fig. 6. Superfish model of the ITC RF gun.

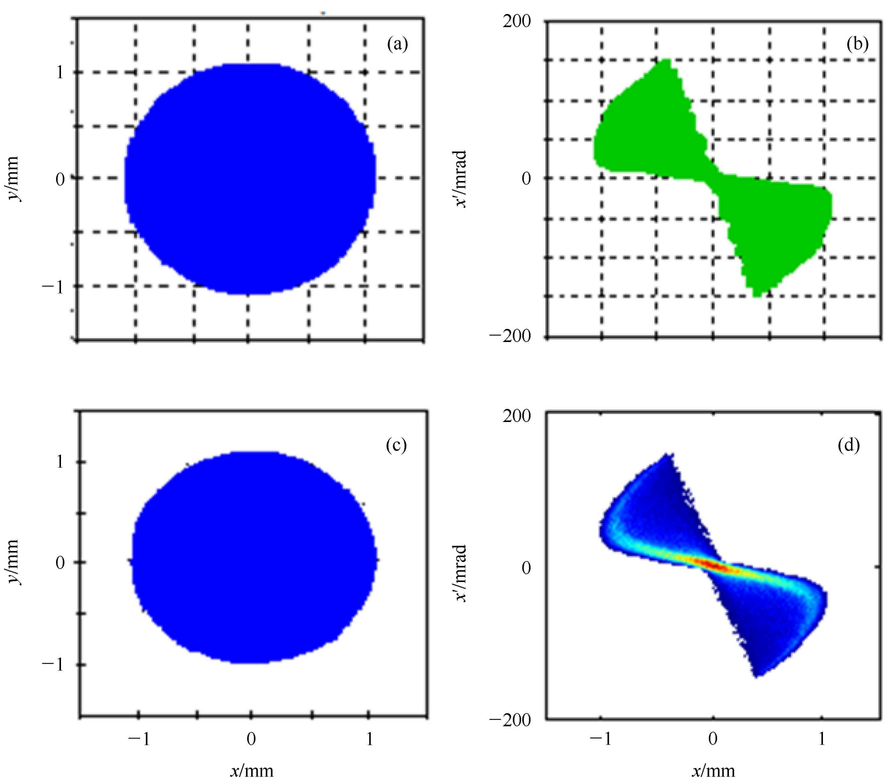

Fig. 7. (a) Transverse size of the beam at the exit of DC gun from CST; (b) Transverse phase space of the beam at the exit of DC gun from CST; (c) Transverse size of the beam for dynamic simulation; (d) Transverse phase space of the beam for dynamic simulation.

the intermediate electrode. In this paper, the beam current we need is 2.45 A. The OPERA [8] model of the gun is shown in Fig. 4. The maximum electric field in the gun is 8.7 MV/m, which is lower than the breakdown threshold.

The simulation results were verified with CST Particle Studio [9]. The trajectory of the electrons in Fig. 5 is nearly the same as that obtained from OPERA.

2.1.2 ITC RF gun

The beam from the 15 keV DC gun is captured and bunched in the first ITC cell, and then the beam bunches are compressed and accelerated to ~2.3 MeV in the second cell. The two cells are powered independently and achieve resonance at 2856 MHz. They are modeled with Superfish code [10] as shown in Fig. 6.

Dynamics simulations from the exit of the DC gun to the entrance of the beam transport line were executed with ASTRA code [11]. The initial distribution was generated according to the simulation results from OPERA and CST, as shown in Fig. 7.

Since the ITC RF gun consists of two independently tunable cells, the parameters of the two cells, including peak electric fields and phases, need to be optimized to match. In Fig. 8, the peak field electric fields on the axis are 42 MV/m in the first cell and 90 MV/m in the second cell.

Due to the advantages of the ITC RF gun, we can provide the expected bunches at different launching phases by matching the setting phases of cells one two. Optimizations have been made to get the best output. The particle distributions at the entrance of the travelling-wave structure are shown in Fig. 9.

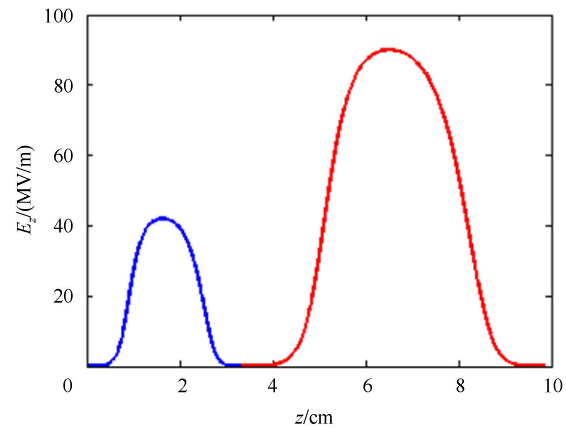

Fig. 8. Magnitude of electric field on axis.

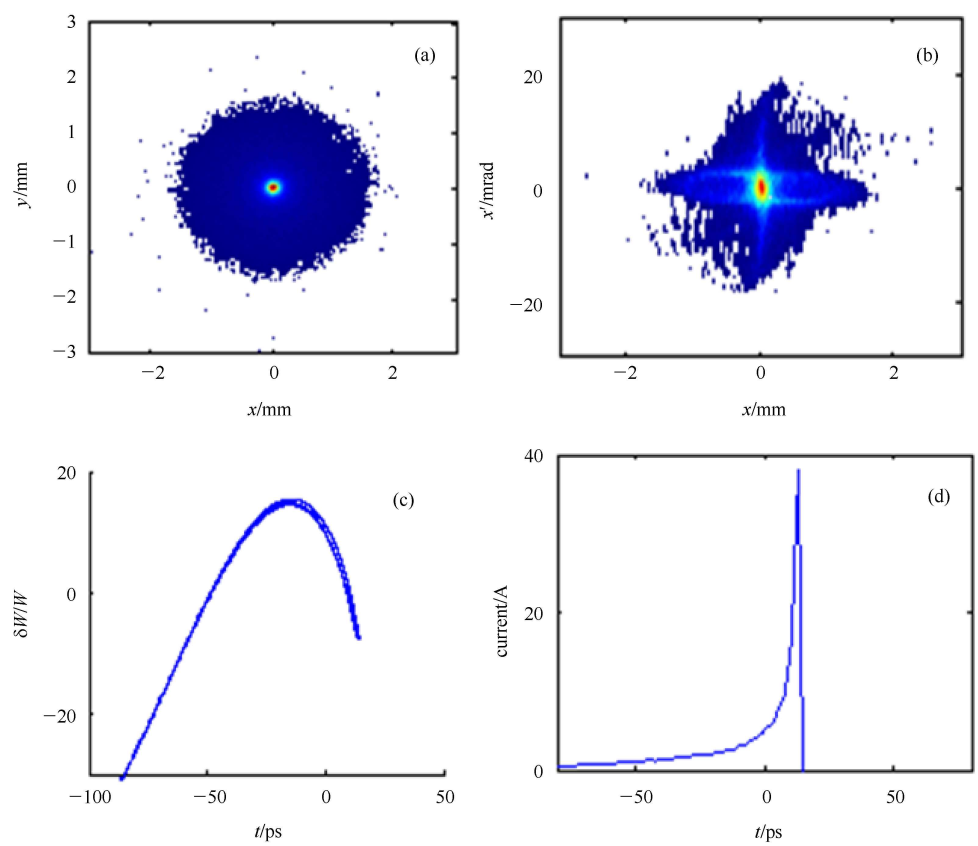

Fig. 9. Particle distribution at the TWS entrance. (a) Transverse size; (b) Transverse phase space; (c) Longitudinal phase space; (d) Longitudinal distribution.

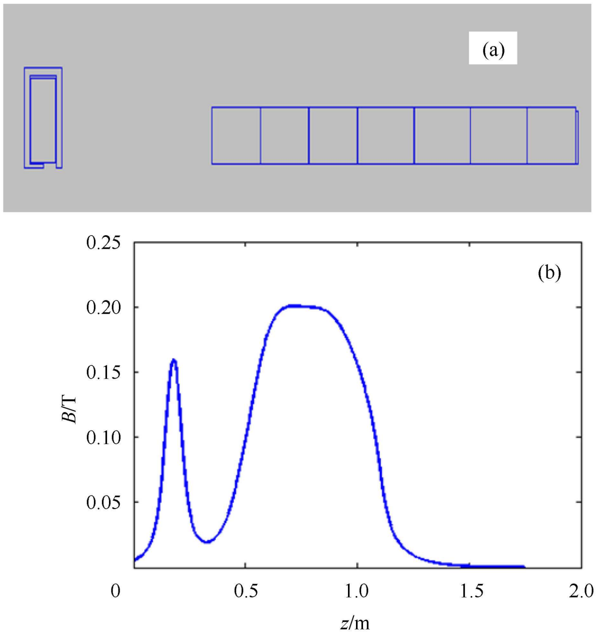

Fig. 10. (a) Model of short magnetic lens and solenoids; (b) Optimized magnetic field on the axis (14 MeV).

2.2 Compensating coils

In order to compensate for the emittance growth and focus the bunch, a short lens and a solenoid were designed [12]. The center of the short lens is 192 mm downstream from the cathode. The magnetic field is optimized cell by cell to get the best beam quality. The model of the compensating coils and the field distribution are shown in Fig. 10.

2.3 The travelling-wave structure (TWS)

The constant gradient travelling-wave structure consists of one input coupler, 19 accelerating cells with $2\pi/3$ mode and 4 collinear absorbing loads consist of a coating of wave-absorbing materials on cavity inner surfaces.

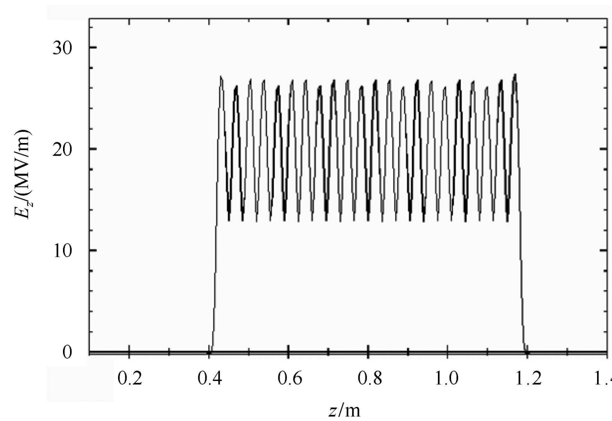

Fig. 11. Electric field on the axis in the TWS.

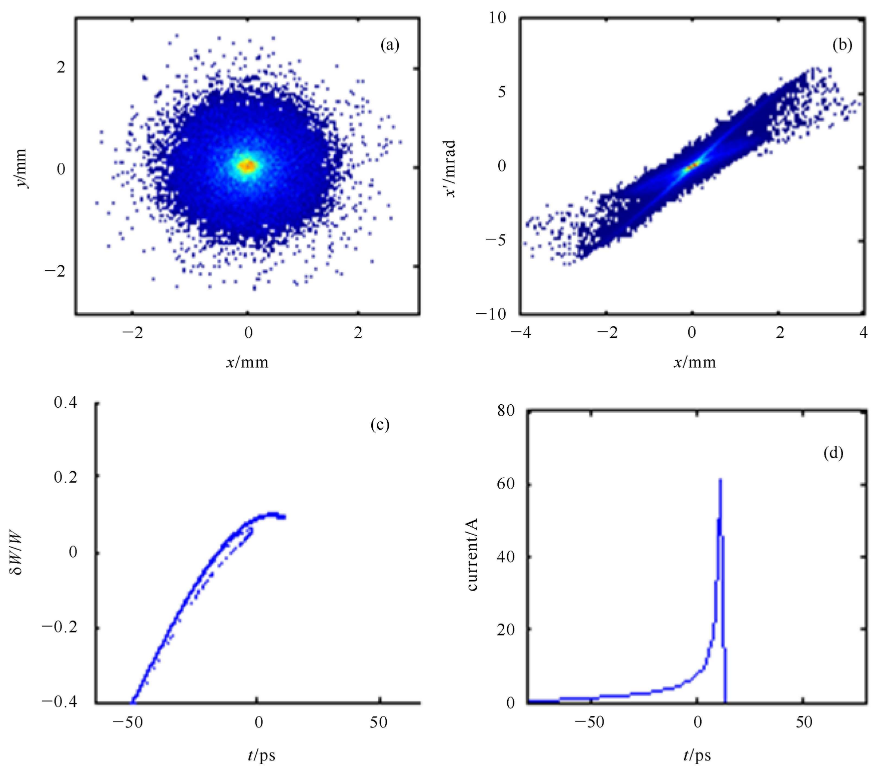

Fig. 12. Particle distributions at the injector exit. (a) Transverse size; (b) Transverse phase space; (c) Longitudinal phase space; (d) Longitudinal distribution.

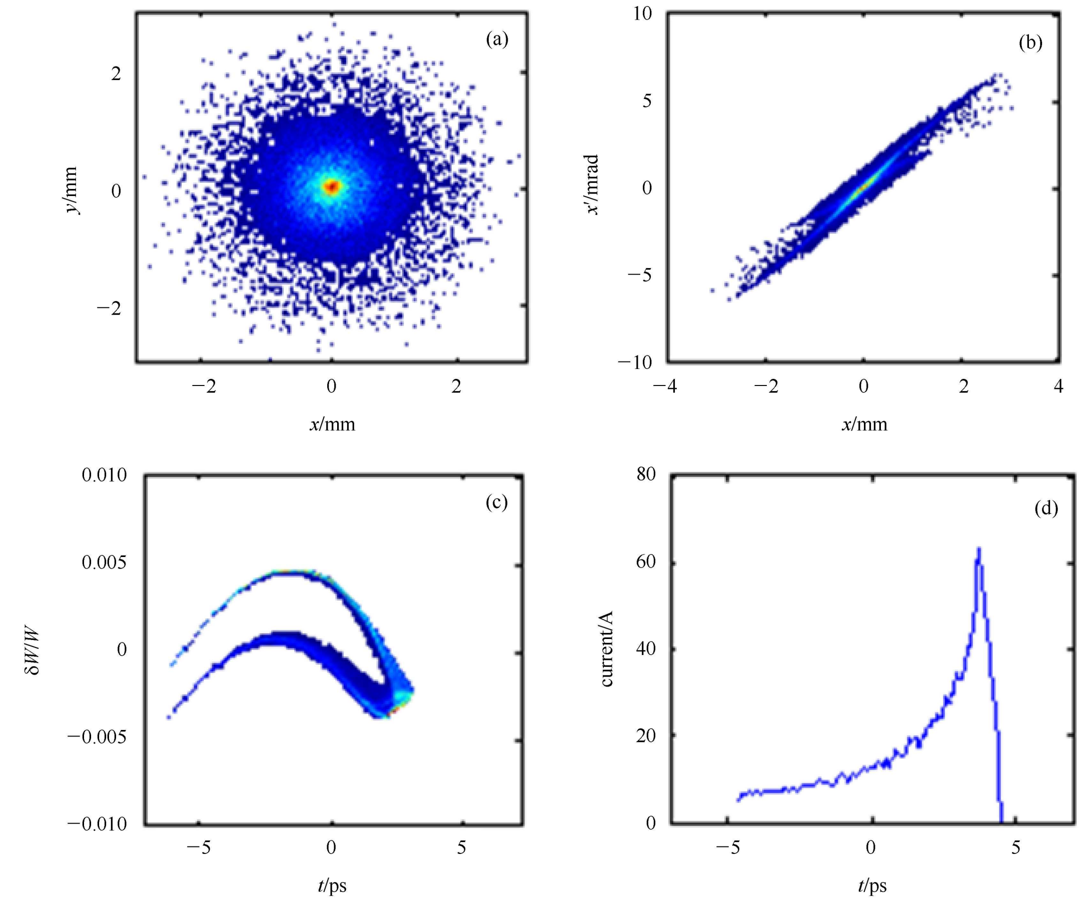

Fig. 13. Particle distributions of the effective part of the bunch. (a) Transverse size; (b) Transverse phase space; (c) Longitudinal phase space; (d) Longitudinal distribution.

In this simulation, the travelling-wave structure is represented by an input coupler, 21 travelling-wave cells and an output coupler. The maximum field on the axis plotted in Fig. 11 is 27.65 MV/m, and the beam loading effect is also considered with ASTRA code. Particle distributions 90 mm downstream of the injector are shown in Fig. 12.

Table 2. Properties of output beam from the injector (14 MeV).

parameters	values
beam energy (effective part)/MeV	13.91
beam current (micro pulse)/A	60
micro-pulse length (FWHM)/ps	3.8
energy spread (effective part)(%)	0.26
transverse emittance (effective part)/(mm·mrad)	14.84
beam length (effective part)/ps	9
micro-pulse effective charge	202

2.4 Analysis of simulation results

The output performance is characterized by the parameters of the effective part (the head) of the bunch, of which the RMS energy spread should be less than 0.3% within 10 ps. The effective part determines the quality of the THz radiation in the undulator, of which the charge should be more than 200 pC. Moreover, the emittance of the effective part should be less than 16 mm·mrad.

Particle distributions of the effective part are given in Fig. 13. As described in Table 2, the emittance energy spread and charge of the effective part can satisfy the strict requirements for THz radiation. The emittance is 14.84 mm·mrad, and the energy spread is 0.26%.

3 The 6 MeV operating mode

It is expected that the injector can provide the beam bunch with energies in the range of 6 MeV to 14 MeV. Thus, the injector at 6 MeV mode has also been simulated and optimized.

In this mode, the properties of the beam from the EC-ITC RF gun should be the same as those in the 14 MeV mode. The magnetic field has been adjusted to fit the 6 MeV case, as depicted in Fig. 14. In order to accelerate the bunch to 6 MeV, the maximum field in the travelling-wave structure should be 12.65 MV/m. The

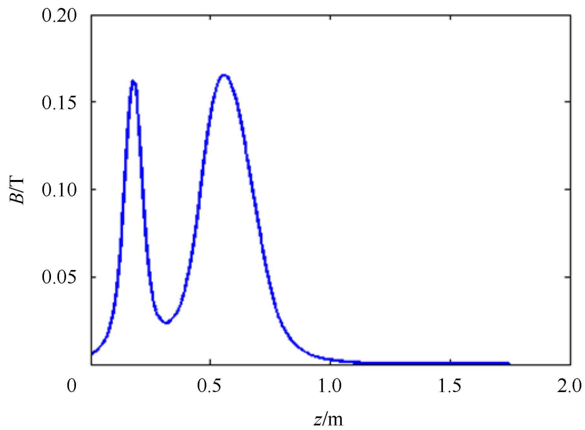

Fig. 14. Optimized magnetic field on the axis (6 MeV).

beam distributions of the effective part at the injector exit are shown in Fig. 15.

The parameters in Table 3 show that the output beam of the injector achieves the anticipated target. When operating in this mode, the emittance is 14.2 mm·mrad and the energy spread is 0.449%.

Table 3. Properties of output beam from the injector (6 MeV).

parameters	values
beam energy (effective part)/MeV	5.98
beam current (micro pulse)/A	50
micro-pulse length (FWHM)/ps	5.71
energy spread (effective part)(%)	0.45
transverse emittance (effective part)/(mm·mrad)	14.2
neam length (effective part)/ps	9
micro-pulse effective charge	201

4 Multi-bunch simulations

Muti-bunch simulations have been executed to study the bunch interactions. Taking the 14 MeV case as an example, we can see that tail of the bunch ahead becomes a part of the head part of the next bunch, as shown in Fig. 16 This phenomenon will cause the emittance growth and energy spread growth of the next bunch. Nevertheless, the analysis results show that the effective part is still

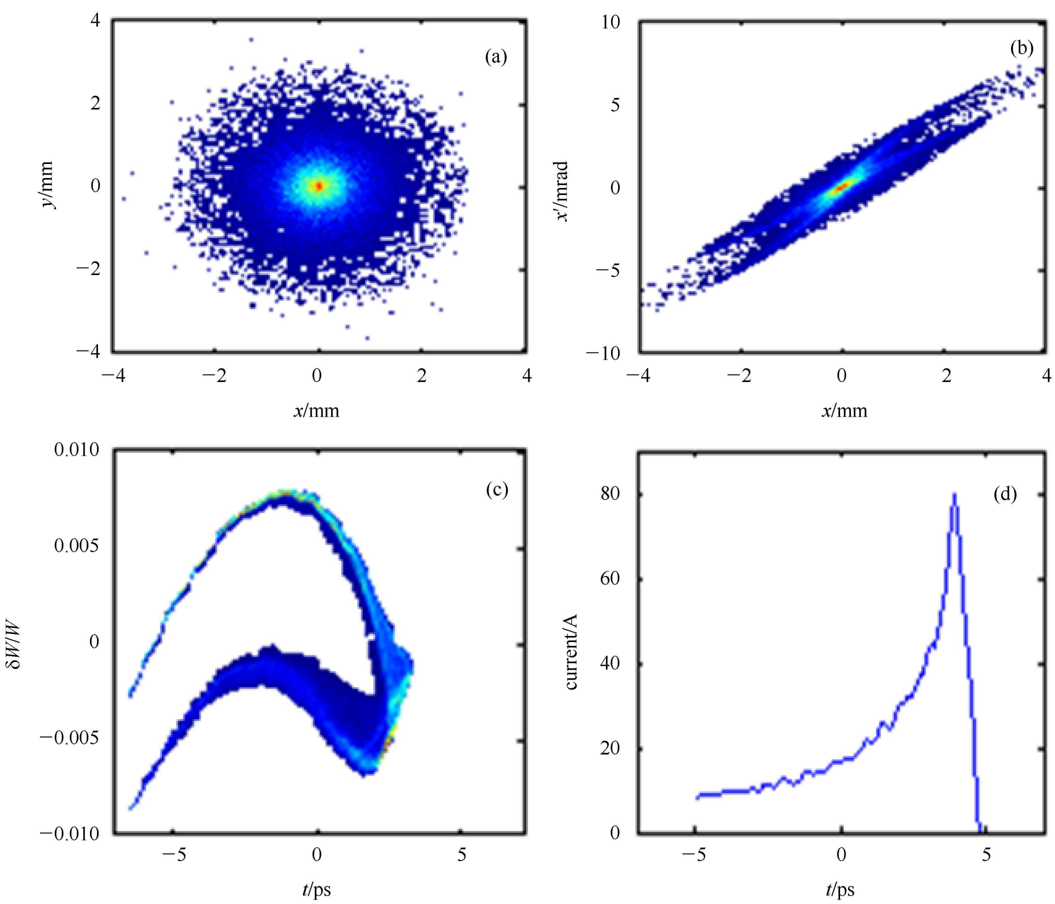

Fig. 15. Particle distributions of the effective part of the bunch (6 MeV). (a) Transverse size; (b) Transverse phase space; (c) Longitudinal phase space; (d) Longitudinal distribution.

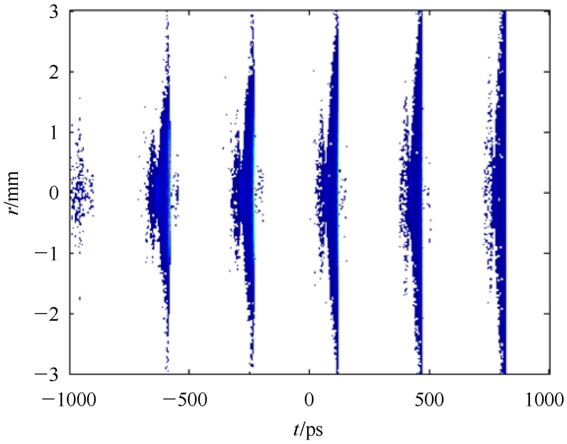

Fig. 16. Longitudinal distribution of multi-bunch case.

high-quality, with the emittance less than 16 mm·mrad with more than 200 pC charge. This phenomenon also occurs in the 6 MeV mode.

5 Conclusion

This paper has described the injector for a compact THz radiation source. Beam dynamics simulations have been done to check the proposed design. Laminar beams at different current values in a certain range can be provided by the 15 keV gridded DC gun. The EC-ITC RF gun can generate the desired output through various combinations of phases in the first and second cell. The output beam from the travelling-wave structure can satisfy the requirements of THz source. The effective charge is more than 200 pC, and the normalized RMS emittance is less than 15 mm·mrad. The energy spread is less than 0.3% at 14 MeV, and less than 0.5% at 6 MeV.

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