# Physical design of FEL injector based on the performance-enhanced EC-ITC RF gun

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**Abstract:** To meet the requirements of high performance THz-FEL (Free Electron Laser), a compact scheme of FEL injector was proposed. A thermionic cathode was chosen to emit electrons instead of a photo-cathode with its complex structure and high cost. The effective bunch charge was improved to ∼200 pC by adopting an enhanced EC-ITC (External Cathode Independently Tunable Cells) RF gun to extract micro-bunches; back bombardment effects were almost eliminated as well. Constant gradient accelerator structures were designed to improve energy to ∼14 MeV, while the focusing system was applied for emittance suppressing and bunch state maintenance. The physical design and beam dynamics of the key components for the FEL injector were analyzed. Furthermore, start-to-end simulations with multi-pulses were performed using homemade MATLAB and Parmela. The results show that continual high brightness electron bunches with a low energy spread and emittance could be obtained stably.

**Key words:** RF gun, EC-ITC, beam dynamics, LINAC, FEL injector

**PACS:** 29.25.Bx, 41.85.Ar, 29.20.Ej **DOI:** 10.1088/1674-1137/38/1/018101

## 1 Introduction

Nowadays, high quality electron beam sources have been focused on due to the rapid development of FEL facilities. As a key component, the RF gun has been used widely because of its high electric field strength. Comparing with the expensive and complicated photocathode RF gun, the thermionic RF gun with its compact and simple structure generates short bunches relying on the self-bunching effect of electrons in RF standing-wave fields. According to the research of many institutions recently, the thermionic RF gun still has the potential of generating high brightness bunches and compressing bunch length to have a sufficient peak current to drive a FEL [1, 2].

In order to take advantage of the structure compactness and high performance potentials of the thermionic RF gun, Tsinghua University (THU) and the Chinese Academy of Engineering Physics (CAEP) have achieved outstanding results by shortening the first cavity and adjusting the electric field strength ratio of multi-cavities [3, 4]. Refs. [5–7] proposed a preliminary concept of an ITC RF gun with a much simpler structure, which has two independent cavities without $\alpha$-magnets, while feed-in powers and phases could be adjusted independently. An improvement method using an external cathode instead of an embed one has been performed in the National Synchrotron Radiation Laboratory (NSRL), which almost eliminated the back bombardment effect by reducing the electric field influences on the cathode surface; the effective bunch charge has been increased from tens of pC to ∼130 pC within 4.5 ps FWHM (Full Width at Half Maximum) length, while the energy spread (FWHM) is only ∼0.2% [8–10]. However, the main performance of the EC-ITC RF gun, especially the effective bunch charge, are hard to increase due to the space charge effect of the high current electron beam.

To meet the strict requirements of high performance THz-FEL in Huazhong University of Science and Technology (HUST), the effective bunch charge within 5 ps length (FWHM) must be increased to ∼200 pC with a low energy spread and low transverse emittance [11, 12]. By adjusting the structure and RF parameters, the properties of the EC-ITC RF gun have been enhanced. Combining an equal gradient travelling-wave accelerator and a focusing system consisting of a short magnetic lens and solenoids, the design scheme of a compact high brightness FEL injector is proposed and shown in Fig. 1, which is mainly comprised of an EC-ITC RF gun, a traveling-wave accelerator and a focusing system, while the specific design targets are listed in Table 1.

To obtain the high quality bunches described above,

Received 22 March 2013

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the components must cooperate with each other closely. Short high brightness micro-pulses are bunched from the DC beam provided by a grided electron gun and extracted by ITC standing-wave cavities, which then enter into the travelling-wave accelerator for a ~14 MeV energy gain, while the attached short magnetic lens and solenoids are applied to compress the bunch size further.

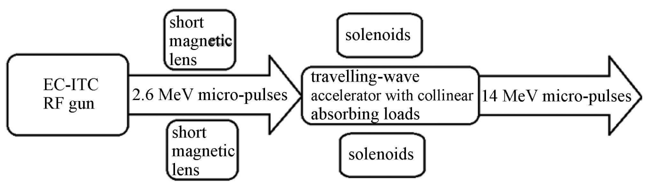


Fig. 1. Schematic of FEL injector.

Table 1. Specific targets of FEL injector.

| parameter | value |
|---|---|
| beam energy/MeV | ~14 |
| micro-pulse width (FWHM)/ps | ~5 |
| Micro-pulse charge/pC | 200–300 |
| energy spread (rms) (%) | 0.5 |
| transverse normalized emittance (rms)/(πmm·mrad) | 6.5 |
| micro-pulse repetition rate/MHz | 2856 |
| macro-pulse width/μs | 2–6 |
| macro-pulse repetition rate/Hz | 10–50 |

## 2 Performance-enhanced EC-ITC RF gun

Considering the beam quality of the micro-pulse might deteriorate when it transmits from the EC-ITC RF gun to the drift tube and travelling-wave accelerator due to the space charge effect of a high current beam, it is necessary to improve the design targets of the RF gun to guarantee high quality extracted bunches. As mentioned in the last section, the RF gun structures adopted by Refs. [8–10] could generate short bunches with a low energy spread and low transverse emittance, but the effective bunch charge was too low to drive the FEL. To solve this issue, the grided electron gun with double anodes is preferred to provide the DC beam instead of the diode electron gun, standing-wave cavity dimensions are optimized and RF parameters are tuned independently as well. As a result, EC-ITC RF gun performances are enhanced substantially; Fig. 2 demonstrates the schematic of the structures.

Cathode-grid assembly with model number Y646 produced by EIMAC Corp. is chosen to emit electrons, while double anodes are adopted to lengthen the gunshot range to ~40 mm and compress the waist radius to ~1 mm. By adjusting the dimensions and anode voltages using Poisson and Parmela [13, 14] codes with ring-based algorithms, the beam envelope shown in Fig. 3 is obtained, with 15 keV kinetic energy, 5 A/cm$^2$ current intensity and 6 πmm·mrad transverse emittance (rms).

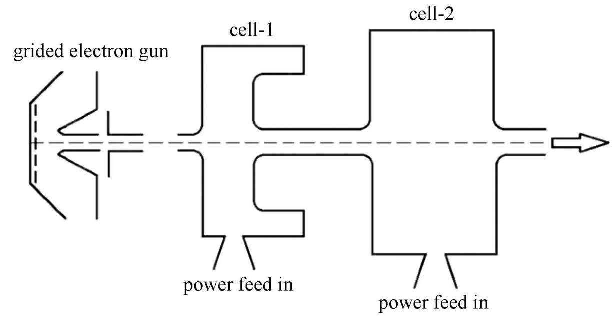


Fig. 2. Schematic of EC-ITC RF gun.

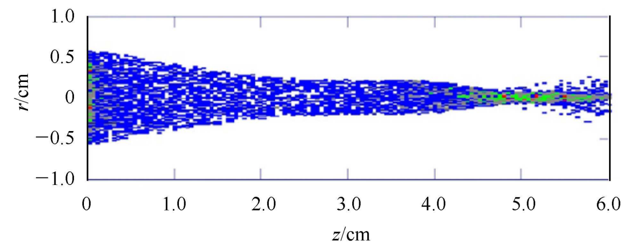


Fig. 3. Beam envelope extracted from grided electron gun.

The DC beam extracted from the grided electron gun enters into ITC cavities. Over 45% of the particles are caught by the fist cavity and bunched into 3 ps length (FWHM), while the second cavity increases the bunch energy to 2.6 MeV and compresses the length even more. The maximum electric field strength on the axis of the cavities provided by Superfish is illustrated in Fig. 4 and the output bunch states of both cells calculated by Parmela are shown in Fig. 5, with beam dynamic results listed in Table 2 in detail.

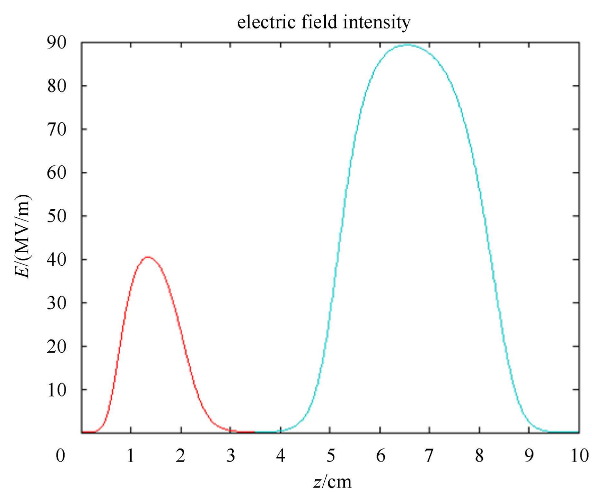


Fig. 4. Electric field strength on beam axis of EC-ITC cavities.

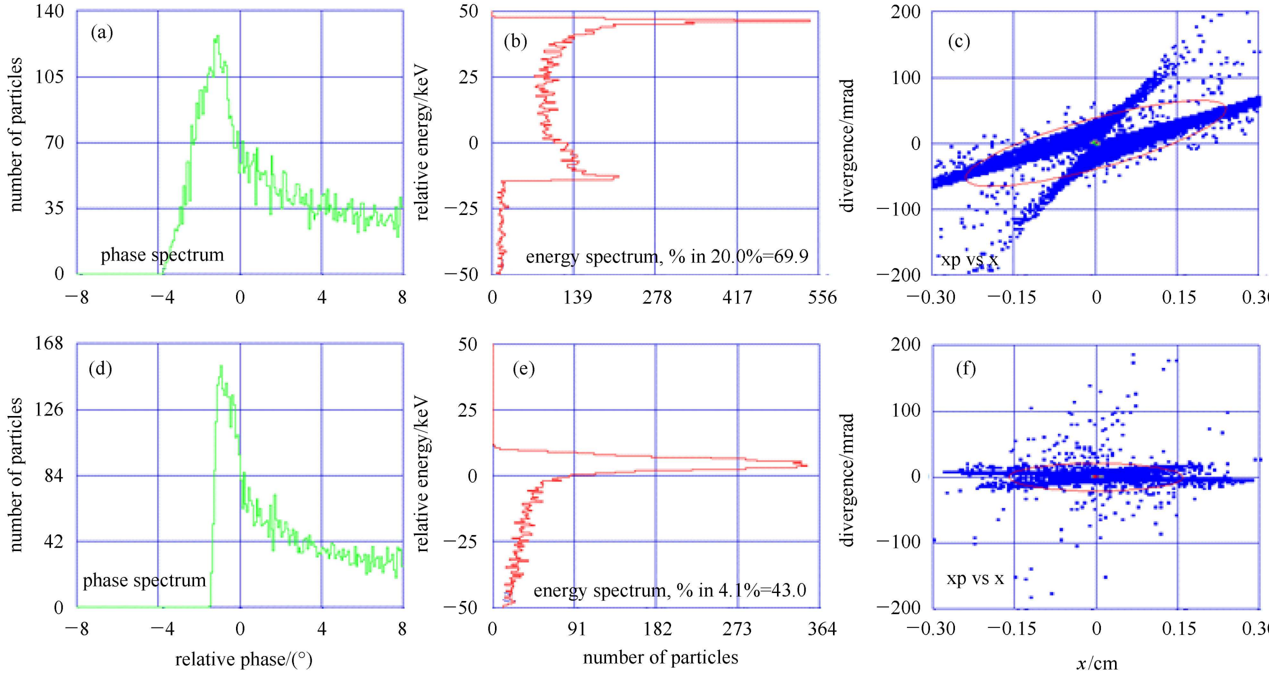


Fig. 5. Output bunch states of EC-ITC RF gun. (a) Phase spectrum of bunch extracted from Cell-1, (b) energy spectrum of bunch extracted from Cell-1. (c) transverse phase spaces at exit of Cell-1, (d) energy spectrum of bunch extracted from Cell-2, (e) energy spectrum of bunch extracted from Cell-2 and (f) transverse phase spaces at exit of Cell-2.

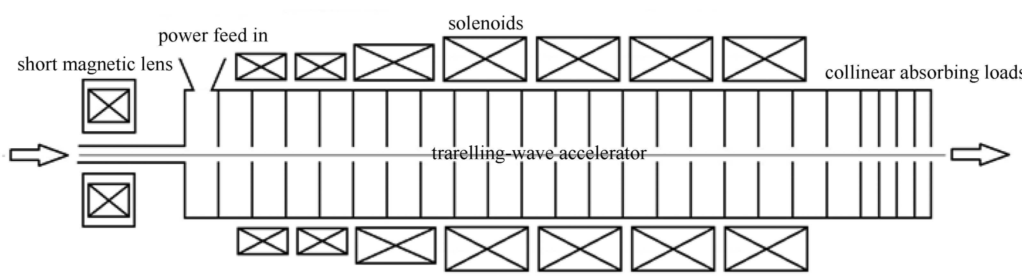


Fig. 6. Focusing system and LINAC.

Table 2. Output bunch properties of EC-ITC RF gun.

| parameter | target |
|---|---|
| bunch energy/MeV | 2.6 |
| Micro-pulse width (FWHM)/ps | ∼1.5 |
| Micro-pulse effective charge/pC | 201 |
| energy spread (FWHM)(%) | 0.27 |
| energy spread (rms)(%) | 0.28 |
| transverse emittance (rms)/($\pi$mm·mrad) | 6.5 |
| Macro-pulse current/A | 0.574 |
| bunch radius/mm | 2.8 |

Obviously, the performance-enhanced EC-ITC RF gun has transferred the DC beam into micro-pulses with a 1.5 ps width (FWHM) and improved the effective bunch charge to ∼200 pC. Furthermore, both energy spread and transverse emittance are small enough to meet overall targets as well.

## 3 Focusing system

Main properties of pulsed short bunches with below 3 MeV energy and over 100 A current intensity, such as length, radius and transverse emittance, will deteriorate in the transmitting progress due to the space charge effect. For the sake of bunch maintenance and improvement, focusing the magnetic field is designed generally to attach with the drift tube and the travelling-wave accelerator, shown in Fig. 6. Taking into account the compactness, the focusing system consists of a short magnetic lens and solenoids. The former is out of the drift tube between the EC-ITC RF gun and the travelling-wave accelerator, so that high magnetic strengths can be obtained in the center while the attenuations to the sides are fast enough to avoid affecting the orbits of low energy electrons near cathode. In addition, solenoids composed of current tunable coils could restrain a weak space charge force and radial defocusing in the accelerator to ensure high brightness bunches would be extracted stably.

Magnetic field distributions of the focusing system near beam axis designed by Poisson are given by Fig. 7. Beam dynamic results indicate that the FEL injector will generate micro-pulses with small stable dimensions when the peak magnetic field strengths of the short magnetic lens and solenoids reach 1600 Gauss and 2000 Gauss, respectively.

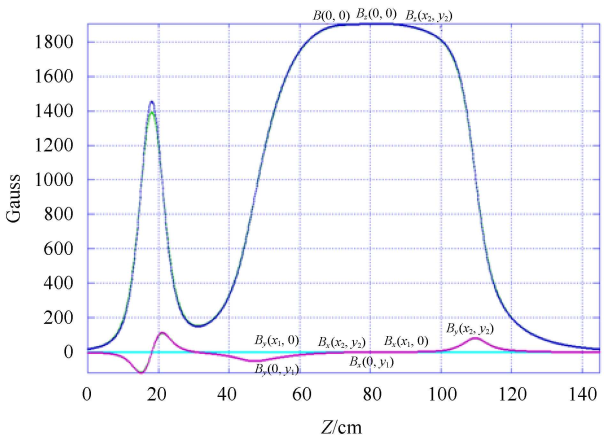


Fig. 7. Magnetic field generated by focusing system.

## 4 Travelling-wave accelerator

To make the micro-pulse energy reach ~14 MeV, the travelling-wave accelerator is designed and it consists of one power fed-in cavity, 19 normal accelerating cells with 2π/3 mode and four collinear absorbing loads. By coating the wave-absorbing materials on the cavity inner surfaces, collinear absorbing loads are used to avoid asymmetric fields caused by the single coupling cavity and reduce the main focusing magnet size in order to realize structure compactness.

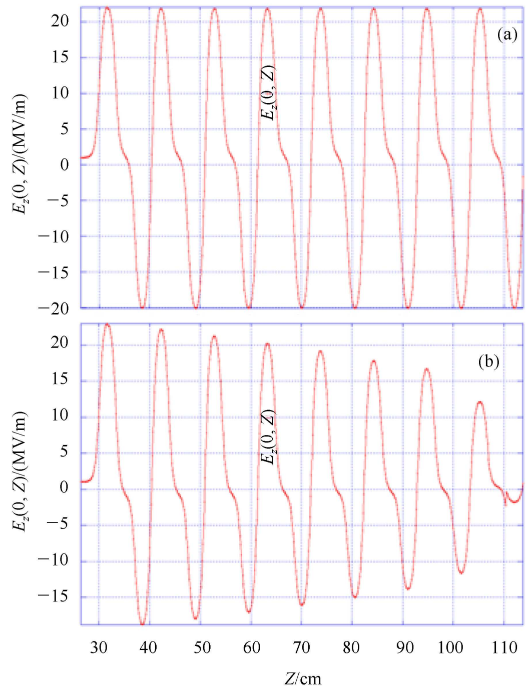


Fig. 8. Electric field distributions on axis of LINAC. (a) Constant gradient accelerating field, (b) accelerating field with beam load.

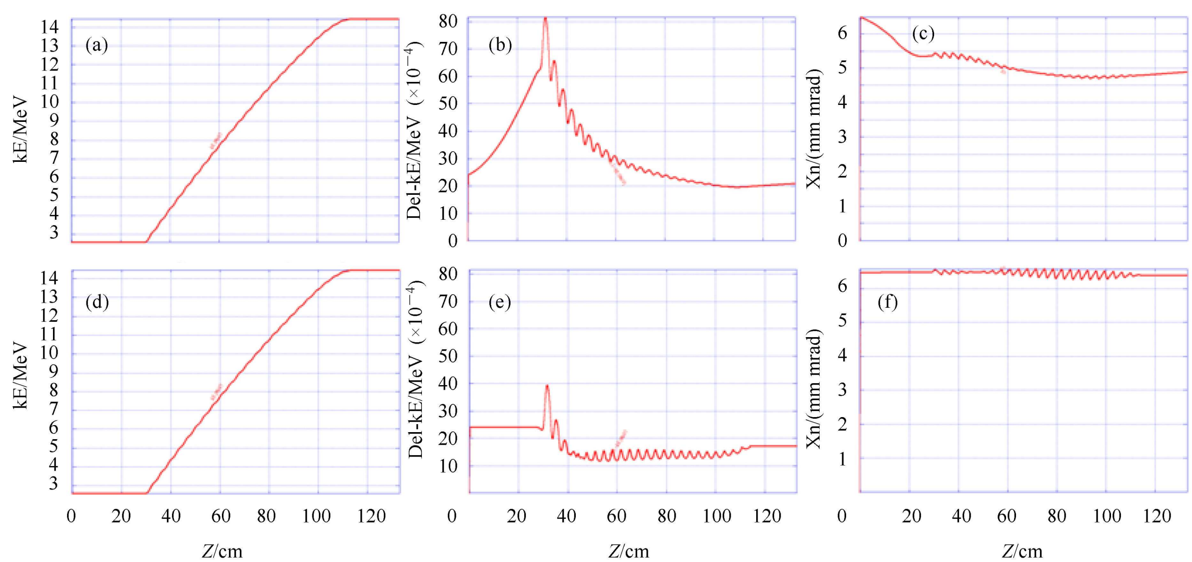


Fig. 9. Bunch property variations in drift tube and LINAC. (a) Kinetic energy variations with space charge force, (b) energy spread variations with space charge force, (c) transverse emittance variations with space charge force, (d) kinetic energy variations without space charge force, (e) energy spread variations without space charge force and (f) transverse emittance variations without space charge force.

After entering into the accelerator, the electron beam could gain energy from the travelling-wave fields illustrated in Fig. 8, so maximum gain could be obtained by tuning accelerating phases. Bunch property variations both with and without space charge force in the drift tube and accelerator calculated by Parmela are shown in Fig. 9. Apparently, energy gain curves are the same. However, compared to slight fluctuations of the energy spread and transverse emittance without space charge force, the calculating results considering space charge

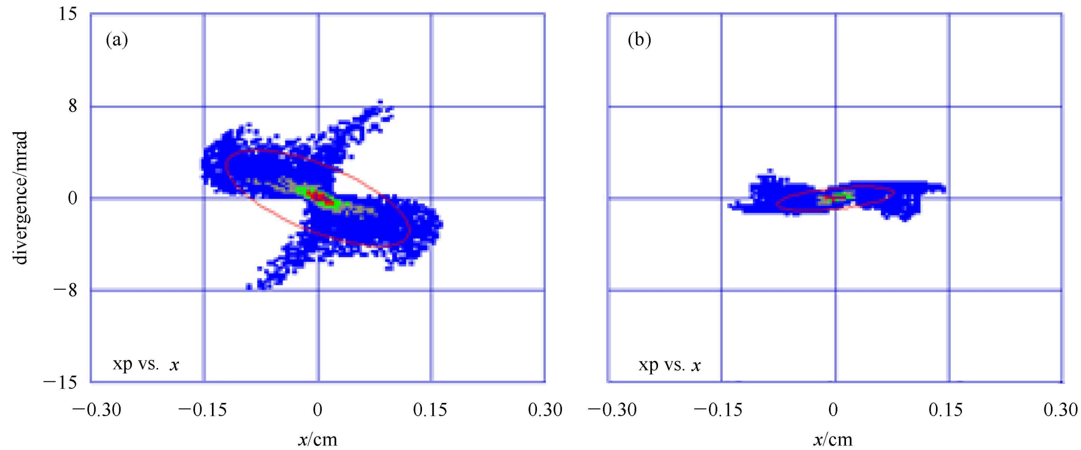


Fig. 10. Transverse phase spaces at exits of drift tube and LINAC. (a) Transverse phase space at exit of drift tube; (b) Transverse phase space at exit of LINAC.

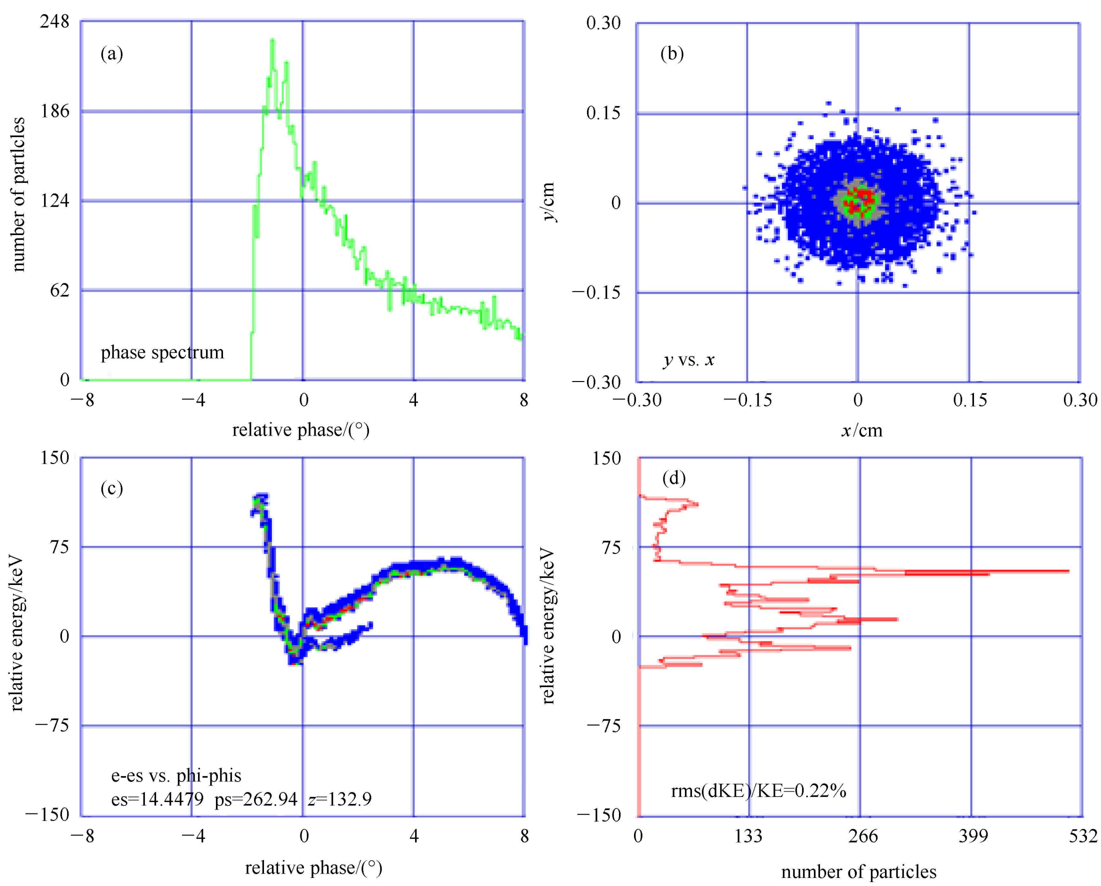


Fig. 11. Output bunch states of LINAC with space charge force. (a) Phase spectrum of bunch generated by injector; (b) Transverse spot of bunch generated by injector; (c) Energy-phase of bunch generated by injector; (d) Energy spectrum of bunch generated by injector.

effect deteriorated first, then tend to stabilize in the latter half of the accelerator because the space charge effect could be ignored when the bunch gets close to relativistic velocity.

Table 3. Output bunch properties of LINAC.

| parameter | target |
|---|---|
| bunch energy/MeV | 14.4 |
| Micro-pulse width (FWHM)/ps | ~4 |
| Micro-pulse effective charge/pC | 201 |
| energy spread (rms) (%) | 0.22 |
| transverse emittance (rms)/($\pi$mm·mrad) | 4.8 |
| Macro-pulse current/A | 0.574 |
| bunch spot radius/mm | 0.9 |

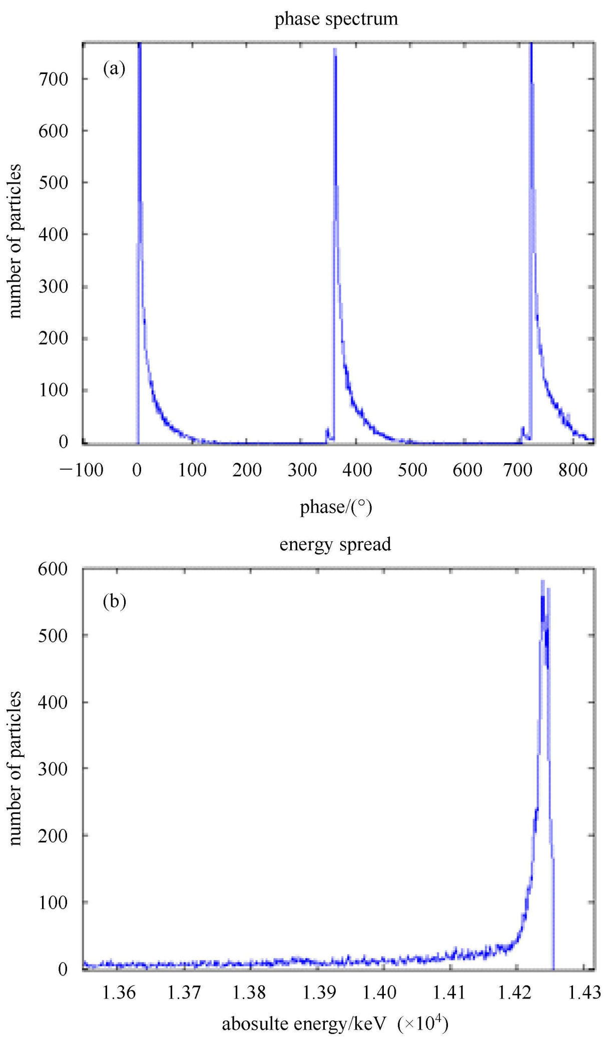


Fig. 12. Phase and energy spectra of three micro-pulses with continual DC beam input. (a) Phase spectra of three micro-pulses and (b) energy spectra of three micro-pulses.

For comparison, the transverse phase spaces at the ends of the drift tube and LINAC are given by Fig. 10. Micro-pulse states extracted from the travelling-wave accelerator are shown in Fig. 11, while Table 3 gives specific performances. The results show that the main parameters, such as energy spread and transverse emittance, are better than before, except the bunch has been lengthen to ~4 ps.

## 5 Multi-pulse simulations

For the sake of the performance stability of THz-FEL, it is vital for the FEL injector to provide high quality micro-pulses continually. Since explicit properties cannot be given directly by Parmela with only one reference particle used, a homemade MATLAB code based on it has been written to analyze the multi-pulse situation, which computes the space charge force by Lorentz-transforming the particles' positions and field maps into the average rest frame of the beam forces between electrons in rest frame, then applies static forces to various rings of the cylindrical map assuming a constant charge density inside a ring [15].

DC beams of three RF periods from the grided electron gun enter into ITC cavities and the following accelerator continually, then micro-pulses are extracted by the FEL injector, with the phase and energy spectra as shown in Fig. 12.

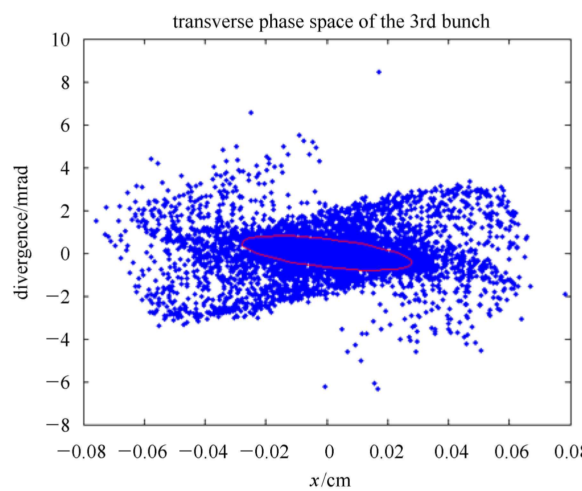


Fig. 13. Transverse phase space of the third bunch.

Table 4 gives the main properties of each bunch separately. Apparently, all of them meet THz-FEL requirements. Furthermore, because of the longitudinal space charge effect and the influences of former beam tails, the third bunch with a transverse phase space shown as in Fig. 13, has got stable properties and should be used to measure injector performances. In short, continual stable high quality micro-pulses are obtained using this type of FEL injector.

Table 4. Main properties of each bunch with 3-pulses input.

| parameter | the 1st bunch | the 2nd bunch | the 3rd bunch |
|---|---|---|---|
| effective electric charge of bunch head/pC | 210 | 228 | 233 |
| energy spread (rms) of effective bunch head (%) | 0.11 | 0.08 | 0.09 |
| transverse normalized emittance (rms)/($\pi$mm·mrad) | 10.8 | 9.0 | 6.9 |
| bunch length(FWHM)/ps | 3.5 | 5 | 3 |

## 6 Conclusion

The performance-enhanced EC-ITC RF gun has many outstanding merits, such as a simple structure, low cost and ability of generating high brightness pulsed bunches from DC beam by adjusting fed-in powers and phases independently. The effective bunch charge is over 200 pC within ~1.5 ps micro-pulse width (FWHM), while the energy spread (FWHM) is only ~0.3% and the transverse emittance (rms) is less than 7 $\pi$mm·mrad. The following travelling-wave accelerator with collinear absorbing loads could improve bunch energy to ~14 MeV and compress the bunch spot radius to 0.9 mm, combined with a focusing system. In the latter half of the accelerator, bunches get so close to light velocity that the space charge force could be ignored and each property of micro-pulses remain stable with 0.22% energy spread (rms) and 4.8 $\pi$mm·mrad transverse emittance (rms). Consequently, analysis results indicate that high quality micro-pulses suitable for THz-FEL could be generated by this type of FEL injector stably.

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