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START TO END SIMULATION FOR A COMPACT THz-FEL *

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Abstract

An oscillator type terahertz free electron laser (THz-FEL) is under construction at Huazhong University of Science and Technology (HUST). The designed electron beam energy ranges from 8 MeV to 14 MeV, and the radiation frequency ranges from 3 THz to 10 THz. FEL requires high quality electron beams of emittance, energy spread, bunch charge etc. To know the overall facility performance, a start-to-end simulation (from electron gun to the end of the oscillator) of the THz-FEL is performed. The simulation of the electron gun to the exit of the linac is performed using PARMELA, where the effect of space charge effects is considered. In addition, the effect of beam loading effect is considered for the linac. The transport line is matched and simulated using ELEGANT. GENESIS 1.3 and OPC is used for the lasing process. Results of the simulation are presented and discussed in this paper.

INTRODUCTION

Terahertz (THz) radiation has attracted more and more attention because it holds the promise of enabling various new scientific and industrial applications. Due to the advantages of high output power, continuously adjustable wavelength, etc, terahertz free electron laser (THz-FEL) has received wide attention and research [1–3]. Huazhong University of Science and Technology (HUST) has constructed a compact oscillator type THz-FEL facility. It mainly consists of an injector and laser. The injector provides the required electron beam, which mainly includes EC-ITC (external cathode and independently tunable cavities) RF (radio frequency) gun, an S-band traveling wave (TW) linac and a double bend achromatic transport line. The laser consists of a pure permanent magnet type undulator and an optical resonant cavity [4]. The layout of HUST THz-FEL is depicted in Fig. 1.

Start-to-end simulation is an important method to understand the performance of FEL. It can take nonlinear effects into account and provide guidance for FEL design and optimization. To know the overall facility performance, a start-to-end simulation is performed. PARMELA is used to simulate the electron gun and linac, where the space charge effect is considered. ELEGANT is used to match and simulate the transport line. GENESIS 1.3 is used to simulate the interaction of the electron bunch with the radiation field in the undulator. And OPC is used to simulate the propagation of the radiation field in the optical cavity. In the paper, taking the beam energy of 14 MeV as an example, the parameters of bunch at the entrance of the undulator is obtained and the performance of the radiation field is analyzed.

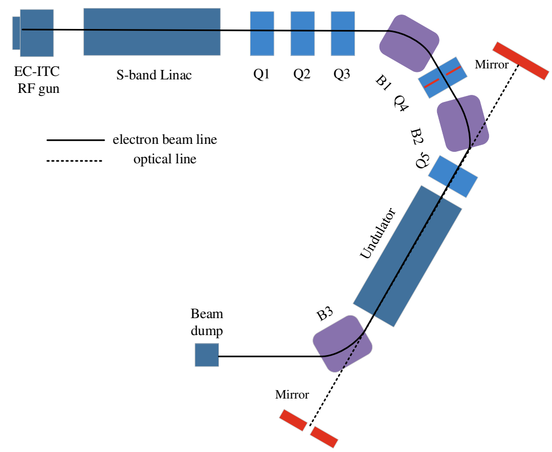

Figure 1: The layout of HUST THz-FEL.

MACHINE LAYOUT AND SET UP

The EC-ITC gun is composed of a thermionic cathode and two independently tunable cavities. The electrons are extracted from the thermionic cathode by using a high voltage of 15 kV and then injected into two cascaded, but independent tuning standing wave cells [5]. The two standing wave cells (C1 and C2) bunch the electron pulses into multiple electron bunches with an interval of 350 ps and accelerate the bunches to 2.6 MeV. The maximum gradients of C1 and C2 are 40 MV/m and 89 MV/m, respectively. The bunch at the exit of the electron gun has a long tail, which results in beam loss during acceleration and transport processes.

The TW linac operates at 2856 MHz and can accelerates the bunch from 2.6 MeV to 8-14 MeV to meet the requirements of the lasing frequency varying from 3 to 10 THz. Instead of using the typical coupling output structure at the end, it employs coaxial load absorbing cells [6]. The total length of the linac is 875 mm, and there are 24 cells in all, of which the last 4 cells are coaxial load absorbing cells. Since the electron bunch has a long tail, the tail particles will absorb microwave power when they enter the linac. Therefore, careful analysis of the beam loading effect is required to obtain the acceleratng gradient of each cell.

The transport line transports the bunch from the exit of the linac to the entrance of the undulator and makes the bunch with suitable Twiss parameters at the entrance of the undulator. The bunch has a long tail, and the tail particles belongs to useless particles. Therefore, an x-directional slit

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with an aperture of 3 mm is placed in the middle of Q4 to remove the trail particles.

An undulator and optical cavity make up the laser. The radiation field is coupled to the output through a hole with a radius of 1 mm in downstream mirror. HUST THz-FEL is a low gain FEL with 30 undulator periods and a total optical cavity length of 2.887 m. Table 1 presents the parameters of the laser.

Table 1: Laser Parameters

Parameter	value
Undulator parameter K	1
Undulator period λ_u	32 mm
Number of Undulator periods N	30
Optical cavity length L	2.887 m
Radius of curvature of mirror r	1.473 m
Reflectivity of output cavity mirror R	0.95
Radius of Coupling hole	1 mm

START TO END SIMULATION

Injector

For the simulation of the injector, the longitudinal distribution of the bunch at the entrance of the linac needs to be obtained first for the analysis of the beam loading effect. We has proposed an algorithm called macro-particle tracking (MPT) to analyze beam loading effects with long tail bunch [7]. When the linac input power is 14 MW, the bunch can be accelerated to 14 MeV. The accelerating gradient of each cell is obtained by analysis of beam loading effect, and the maximum accelerating gradient is 19.4 MV/m. ELEGANT is used to match the dispersion and Twiss parameters of the transport line. The Twiss parameters at the entrance of the undulator are determined according to the requirement that the beam waist is located at the center of the undulator [8], which is $\alpha_x = 1.0$, $\beta_x = 1.2$, $\alpha_y = 0.55$, $\beta_y = 0.26$.

The variation of bunch charge and energy spread from the electron gun to the entrance of the undulator is shown in Fig. 2. It can be seen that there is a beam loss throughout the injection process, which is caused by the long tail of the bunch. The initial thermionic cathode emits electrons with a charge of 875 pC, leaving only 174 pC at the entrance of the undulator. Since the bunch has a long tail, only the head particles are considered for the statistical parameters. Particles with a longitudinal position less than 15 ps are defined as the head of the bunch, which is mainly determined by the bunch length at the entrance of the undulator. There are two more obvious changes in energy spread curve. The first one appears at the linac, mainly due to the effect of the longitudinal electric field. The second one appears in the dispersion region. The sudden increase in energy spread is due to the increase in the number of head particles caused by the compression of the bunch length. The reduction of energy spread is mainly because particles with large transverse positions are lost. Table 2 presents the bunch parameters at the entrance of the undulator.

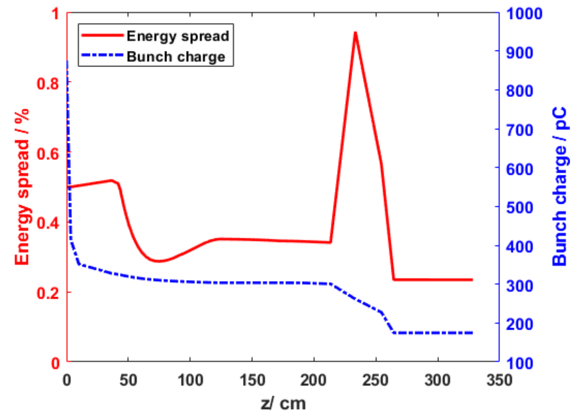

Figure 2: The variation of bunch charge and energy spread from the electron gun to the entrance of undulator

Table 2: Bunch Parameters at the Entrance of Undulator

Parameter	value
Beam energy E	14 MeV
peak current I_p	11.8 A
Energy spread δ_E	0.24 %
Bunch charge Q	174 pC
Bunch length σ_t	4 ps
Normalized emittance in x ε_{xn}	11.05 mm mrad
Normalized emittance in y ε_{yn}	10.51 mm mrad

Laser

GENESIS 1.3 combined with OPC allows the simulation of a three-dimensionals free electron laser oscillator. We have performed time-dependent simulation of the FEL oscillator using these two software. For oscillator type FEL, cavity length detuning is an important parameter. Since GENESIS 1.3 can only set the cavity length detuning to an integer multiple of half wavelength, we use OPC to vary the relative position of the radiation field and the electron bunch to obtain an arbitrary cavity length detuning.

The frequency of radiation field is 10 THz when the beam energy is 14 MeV. Taking the cavity length detuning of 20 µm as an example, the variation of peak power in the optical cavity and output peak power with the number of cavity passes are shown in Fig. 3. When saturation is reached, the peak power in the cavity is 12.8 MW, but the output power through the hole is only 0.28 MW. Only 2.2% of power in the optical cavity is coupled to output through the hole. When saturation is reached, the micro-pulse energy of radiation field is 2.2 µJ. The electron macro-pulse width is 4 µs, and the electron micro-pulse repetition frequency is 2856 MHz. The macro-pulse energy of radiation field is 3 mJ. Fig. 4 demonstrates the power distribution and spectrum of the radiation field at the 20th and 200th cavity passes. In the initial few passes, there are many frequencies of radiation field in the optical cavity, and as the radiation field gradually increases, there is finally only one major frequency in the optical cavity. At saturation, the longitudinal phase space at the exit of undulator is shown in Fig. 5. Electrons exhibit significant rotation in longitudinal phase space.

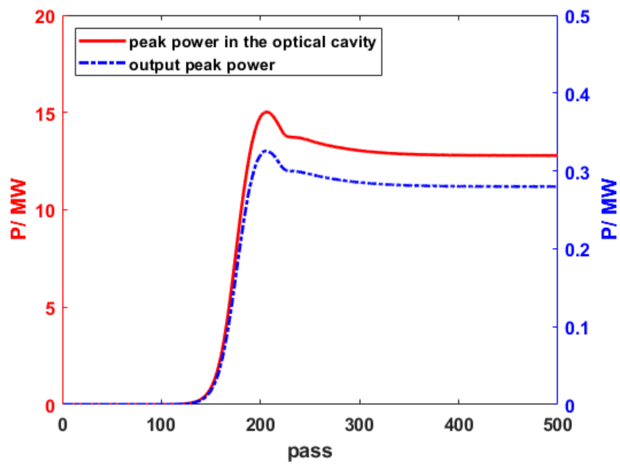

Figure 3: The variation of peak power with number of cavity passes.

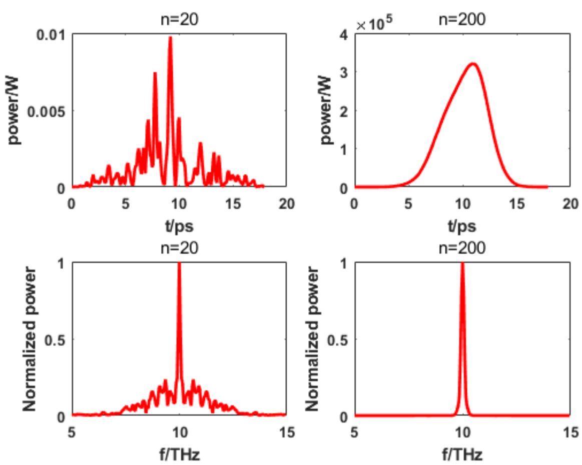

Figure 4: Time and frequency diagram at different cavity passes.

DISCUSSION AND CONCLUSION

In this paper, a start-to-end simulation of the HUST THz-FEL facility is performed using a 14 MeV electron beam energy and a 10 THz radiation frequency as an example. For the injector, PARMELA and ELEGANT are used for simulation, where space charge effects and beam loading effects are considered. The parameters of the electron bunch at the entrance of the undulator are obtained. For the laser, a 3D time-dependent simulation of the FEL oscillator is accomplished by using GENESIS 1.3 and OPC. The results show that when the radiation frequency is 10 THz and the

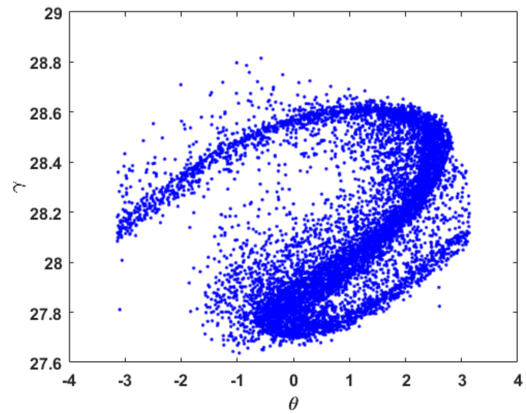

Figure 5: Electron longitudinal phase space at the exit of undulator.

cavity length detuning is 20 µm, the macro-pulse energy of the radiation field is 3 mJ.

In this paper, the radiation performance at 10 THz frequency is preliminary simulated. The optimization of cavity length detuning and the verification of results will be reported in the future paper. In addition, the designed values of HUST THz-FEL radiation frequency are from 3 to 10 THz, but here we only report the case of 10 THz. Different radiation frequency will present different radiation performance, and the simulation results of S2E at different frequency will also be reported in future papers.

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