# Numerical modeling of a high power terahertz source in Shanghai*

DAI Jin-Hua(戴进华)[1,2] DENG Hai-Xiao(邓海啸)[1;1)] DAI Zhi-Min(戴志敏)[1]

[1] Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai 201800, China
[2] Graduate University of Chinese Academy of Sciences, Beijing 100049, China

**Abstract:** On the basis of an energy-recovery linac, a terahertz source with a potential for kilowatts of average power is proposed in Shanghai, which will serve as an effective tool for material and biological sciences. In this paper, the physical design of two free electron laser (FEL) oscillators, in a frequency range of 2–10 THz and 0.5–2 THz respectively, are presented. By using three-dimensional, time-dependent numerical modeling of GENESIS in combination with a paraxial optical propagation code, the THz oscillator performance, the detuning effects, and the tolerance requirements on the electron beam, the undulator field and the cavity alignment are given.

**Key words:** THz, oscillator, FEL, cavity alignment

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## 1 Introduction

THz wave is a frontier area for research in physics, chemistry, medicine, and material and biological sciences. THz sources of high quality have been scarce, but this gap has recently begun to be filled by a wide range of new technologies. THz wave is now available in both a continuous wave (CW) and a pulsed form, down to single-cycles or less, with the peak powers up to MW. THz sources have led to new technology in many areas, as scientists are aware of the opportunities for research progress in their fields using a THz wave. Among all the THz sources, a free electron laser (FEL), based on an energy-recovery linac (ERL) is of great interest. The advantage of FEL is the promising prospect in high peak power, high average power and flexible wavelength tuning. At present, the Novo-FEL at BINP Russia is the most powerful THz source in the world, with a record of 0.5 kW average power [1]. Recently, on the basis of a FEL oscillator, an ERL-based THz source with a potential for kilowatts of average power is proposed in Shanghai, China.

The 500 keV electron bunch extracted from a 250 MHz VHF gun is boosted to 2 MeV at the exit of the injector. The electron beam is accelerated to 20 MeV by two 5-cell, 500 MHz superconductive radiofrequency (SRF) modules in the ring and transported through the THz oscillator where the kinetic energy of the electron beam is transferred to the THz radiation. The return electron bunch passes the SRF module again with a decelerating phase for energy recovery, and then is dumped. In order to achieve an average output power of 1 kW, the average beam current is expected to be 20 mA. The parameters of the electron beam and the details of THz oscillator are summarized in Table 1. To cover the band of 0.5–10 THz, two FEL oscillators are supposed. These are a 2–10 THz FEL oscillator with a 20 MeV electron beam and a 0.5–2 THz with a 10 MeV electron beam, respectively.

This paper will present the physical optimization and numerical simulation of two FEL oscillators in the range of 2–10 THz and 0.5–2 THz, respectively. The numerical modeling has been carried out using a three-dimensional, time-dependent FEL code GENESIS [2] in combination with a paraxial optical propagation code (OPC) [3]. In this paper, taking 10 THz as a typical radiation wavelength, we first describe the physical design and optimization, time-dependent simulation, and tolerance performance of

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1) E-mail: denghaixiao@sinap.ac.cn
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the 2–10 THz oscillator in Sections 2, 3 and 4. The primary results of the 0.5–2 THz oscillator is illustrated in Sec. 5. Finally, we present our conclusions in Sec. 6.

Table 1. Main parameters of the Shanghai THz source.

| THz frequency | 0.5–2 THz | 2–10 THz |
|---|---|---|
| beam energy | 10 MeV | 20 MeV |
| beam transverse emittance | 10 μm·rad | 10 μm·rad |
| beam energy spread | 0.2% | 0.2% |
| bunch charge | 240 pC | 240 pC |
| bunch length FWHM | 16 ps | 8 ps |
| micro pulse repetition | 83.33 MHz | 83.33 MHz |
| undulator type | Helical | Planar |
| undulator period length | 100 mm | 60 mm |
| undulator periods number | 30 | 30 |
| cavity length | 18 m | 18 m |
| mirror radius of curvature | 9.2502 m | 9.1160 m |
| cavity stability $g^2$ | 0.89 | 0.95 |
| mirror radius | 120 mm | 50 mm |
| out-coupling hole radius | 9.0 mm | 5.5 mm |
| average output power | ~1 kW | ~1 kW |

## 2 THz oscillator design and optimization

The goal of FEL oscillator design and optimization is maximum gain and optimum output power. The cavity is of a symmetric near-concentric design with a length of 18 m. The reasons for such a long cavity length are that, on one hand, it is helpful for expanding the radiation size of 10 kW order intra-cavity power on the cavity mirror, and on the other hand, a long cavity length would allow the FEL oscillator to start up when the repetition rate of the quasi-CW electron bunch decreases from 83.33 MHz to 41.67, 16.67 and even 8.33 MHz.

The cavity mirror radius of curvature is designed to be 9.1160 m, which results in a Rayleigh length of 1.0 m and a cavity stability parameter of 0.95. The 10 THz optical mode radius at the undulator centre is about 3.09 mm. At this location the matched electron beam radii are 0.45 mm in the horizontal direction and 0.24 mm in the vertical direction. It means that the transverse coupling between the electron and the radiation, and thus the FEL oscillator performance is not sensitive to the electron beam jitter in the transverse position, which is well demonstrated in the following tolerance studies. The 10 THz radiation radius on the cavity mirror surface, assuming the fundamental transverse mode is 28.6 mm compared with a mirror aperture radius of about 50 mm. It is large enough to ensure that the diffraction losses from the fundamental mode are negligible. All high order modes suffer more diffraction loss due to a wider transverse mode size, thus, limiting the mirror aperture is a crude method to control the transverse lasing mode.

The proposed working point of the cavity geometry shows a single-pass FEL gain larger than 50%. In order to obtain an optimum output power, we keep the mirror radius of curvature constant and change the radius of the out-coupling hole on the upstream mirror. Fig. 1 shows the effect of varying the radius of the out-coupling hole on the output power at saturation. This work was carried out using GENESIS and OPC in a steady-state mode. The results show that a coupling hole with a radius of 5.5 mm is near optimum in terms of the output peak power, giving an 11% out-coupling fraction. The optimal peak power is about 5 MW, which agrees exactly with the theoretical power efficiency of the FEL low-gain oscillator.

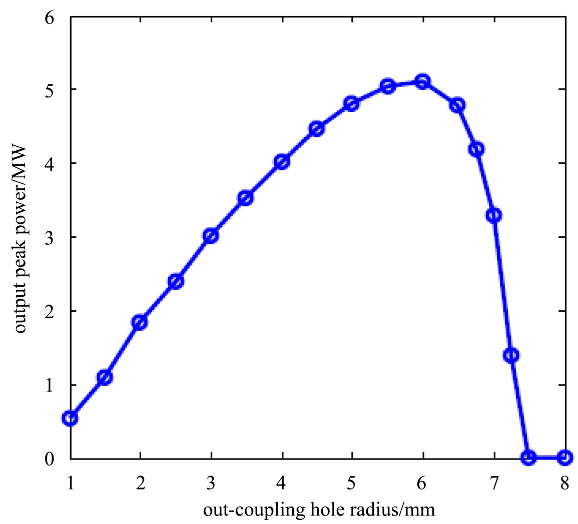


Fig. 1. The output peak power as a function of the radius of the out-coupling hole for the 10 THz oscillator.

## 3 Time-dependent simulation

The time-dependent simulation allows one to further model the effects of cavity length detuning, temporal and spectral performances of the THz oscillator. Using the GENESIS time-dependent method, we are however, limited to detune the cavity length only to half-integer multiples of the THz wavelength [4]. Thus, an external MATLAB script is used for coupling GENESIS and OPC, where the temporal distribution of the electron beam can be detuned by an arbitrary step with respect to the THz radiation after each FEL round trip. In this case, we are able to model the fine detuning of the cavity length.

Figure 2 plots the cavity length detuning curve of the 10 THz oscillator. The average output power of 10 THz radiation exceeds 2 kW with an optimal detuning length of 15 μm. If the cavity length is effectively detuned, the evolution of the single pulse energy of the 10 THz oscillator is shown in Fig. 3. This indicates that the output pulse energy is 25.7 μJ after 200 roundtrips.

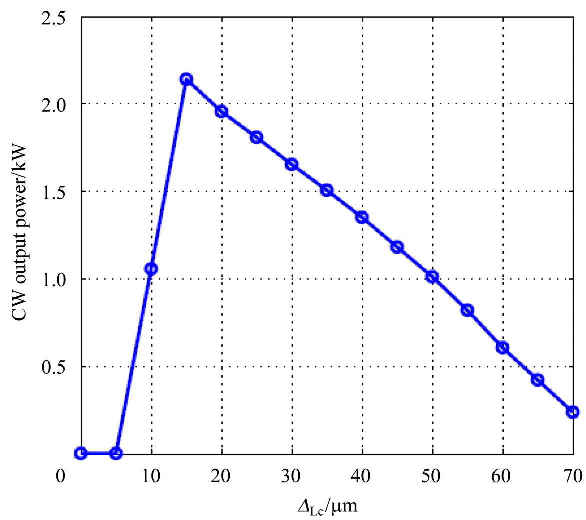


Fig. 2. The detuning effect of the cavity length of 10 THz FEL.

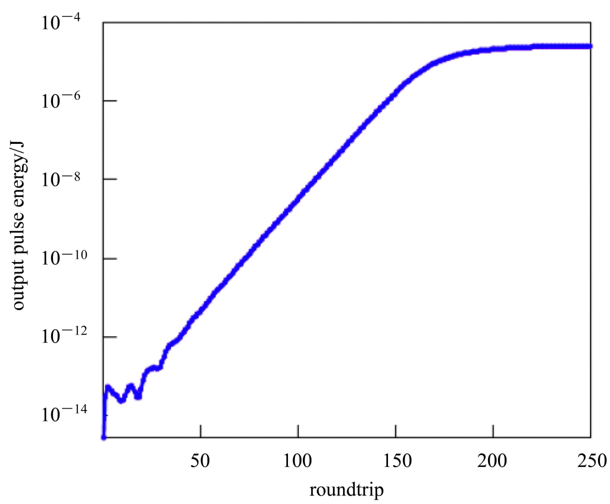


Fig. 3. The output pulse energy growth of the 10 THz radiation.

Figure 4 shows the temporal and spectral distribution of the 10 THz output radiation at saturation with the optimal detuning length. The peak power of the 10 THz radiation pulse is 5.3 MW. Fig. 4 demonstrates a temporal FWHM width of 4.4 ps and a spectral FWHM bandwidth of 1.5%. This corresponds to a time bandwidth product of 0.66, which is close to the Fourier transform limit of 0.44 for a Gaussian pulse profile.

The main effect on the electron beam due to the FEL interaction is an induced energy spread. For the 20 MeV electron beam with an rms input energy spread of 0.2%, the rms energy spread increases to 1.3% due to the FEL interaction. Thus the exhaust energy acceptance of the beam transport return arc should be up to 8%.

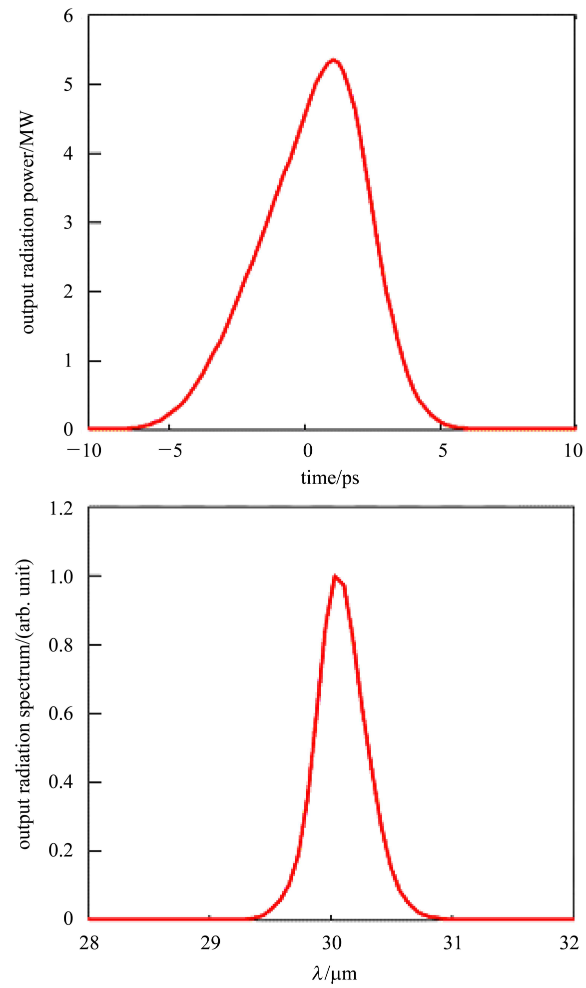


Fig. 4. The saturated output of the 10 THz radiation pulse in time and spectral domain, where the optimal detuning is assumed.

## 4 Sensitivity to parameter variations

The influence of the energy spread, the undulator field error and the cavity mirror misalignments to 10 THz FEL oscillator, especially the saturated FEL output power is checked in this section. For the low-gain THz oscillator, transverse emittance of the electron beam is not an issue. However, the energy spread is crucial. If the initial energy spread increases to 3 times the nominal value 0.2%, the output power decreases monotonically to 8% of that produced by an electron beam with nominal parameters. In order to assure that the THz output power could be up to 1 kW, the beam energy spread should be less than 0.4%.

Undulator field errors contribute to the aberration of the beam trajectory and mismatch of the FEL resonance. Fig. 5 shows the effect of undulator errors to the FEL output power. The square line represents the case in which the undulator errors are correlated to minimize the first and second field integral; e. g. a 10% undulator field error just induces a maximum aberration of 180 μm. This means that the undulator error only contributes to the mismatch of the FEL resonance and the tolerance of the undulator error is pretty relaxed in this case. The circular curve indicates the random undulator error case in which the beam trajectory is not artificially controlled; e. g. a 1% rms undulator field error induces a maximum aberration of 2 mm. In this case, the tolerance of the rms undulator field error should be less than 1%. Moreover, since the 10 THz optical mode size is much larger than the electron beam in the undulator, the FEL performance is not sensitive to the beam centroid offset.

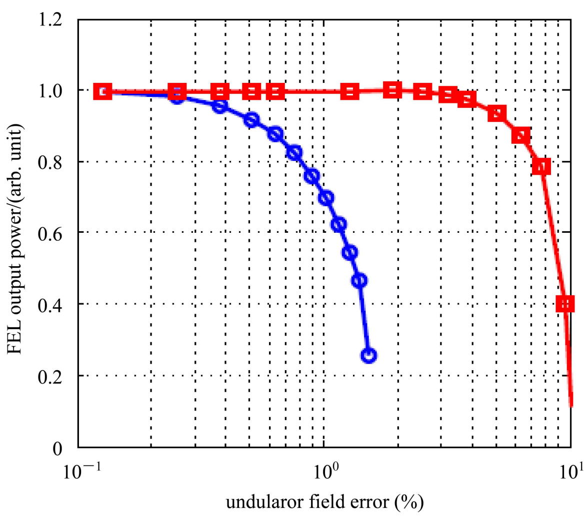


Fig. 5. The normalized output power vs. the undulator error.

The direct effect of the cavity misalignments is the disruption of the routine propagation of the optical mode. This would result in the degradation of the transverse coupling between the electrons and the THz radiation, the increase of the loss in cavity and change of the out-coupling efficiency. Thus, the alignment of the cavity mirror is of great importance for high power THz oscillators. Fig. 6 illustrates the dependence of the FEL output power on the cavity position misalignment. The square shows the downstream mirror position offset, which indicates that the offset of the downstream mirror should be less than 0.3 mm for an optimal output. The upstream mirror offset, represented by the circular line, shows a similar tendency to the downstream one. What needs to be stressed here is that, the output coupling hole is at the upstream mirror center. A small offset of the upstream mirror will induce an out-coupling position shift with respect to the optical axis of the fundamental mode. Consequently, the disruption of the fundamental optical mode by the output-coupling is less serious, and thus the output efficiency is enhanced when compared with a center hole coupling. This is the reason why the output power in the case with upstream mirror offset is a little bit higher than that of with downstream mirror offset. The diamond shows the case in which the positions of the two mirrors are simultaneously shifted in an opposite direction. The requirement of a 0.1 mm order mirror alignment can be easily accomplished by using a dedicated He-Ne laser.

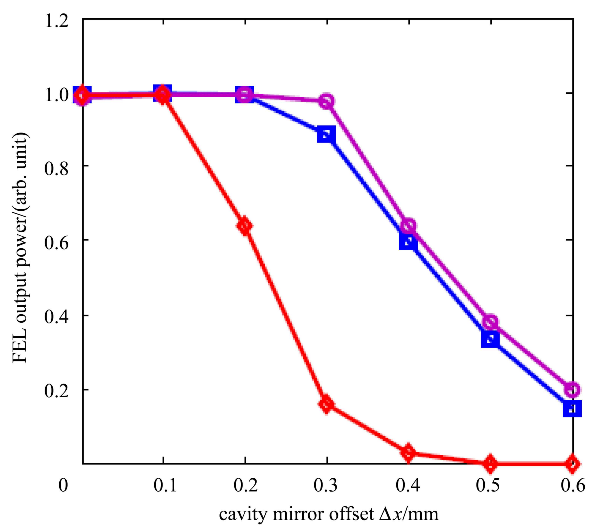


Fig. 6. The normalized output power vs. the cavity mirror offset.

The theory of the optical cavity predicts that the cavity mirror angular tolerance should be far less than 78 μrad. Simulation suggests that the mirror angular misalignment should be well controlled in the range of 0–50 μrad, which is consistent with the theoretical estimate.

## 5 Performance of the 0.5–2 THz oscillator

The design strategy of the 0.5–2 THz mode is similar with the 2–10 THz one, except that a helical undulator is employed to compensate the gain degradation caused by the strong slippage effects in the long wavelength region. Fig. 7 illustrates the cavity length detuning curve of the 1 THz oscillator. Within a 100 μm range of the cavity detuning, the average power of the 1 THz radiation is above 1 kW. The average output power reaches 1.47 kW with a detuning length of 50 μm, where a 17.7 μJ output pulse energy after 270 roundtrips is modeled. In operation, this should be based on experiments to determine the specific detuning to acquire the maximum output power.

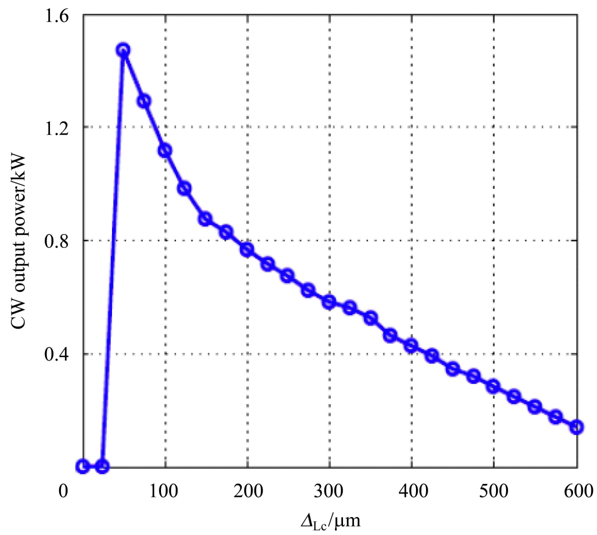


Fig. 7. The detuning effect of the cavity length of the 1 THz FEL.

Figure 8 shows the temporal and spectral distribution of the 1 THz output radiation at saturation with the optimal detuning length. The peak power of the 1 THz radiation pulse is 1.4 MW. Fig. 8 presents a temporal FWHM width of 10.2 ps and a spectral FWHM bandwidth of 4.83%. This corresponds to a time bandwidth product of 0.49, which is almost the Fourier transform limit of 0.44 for a Gaussian pulse profile.

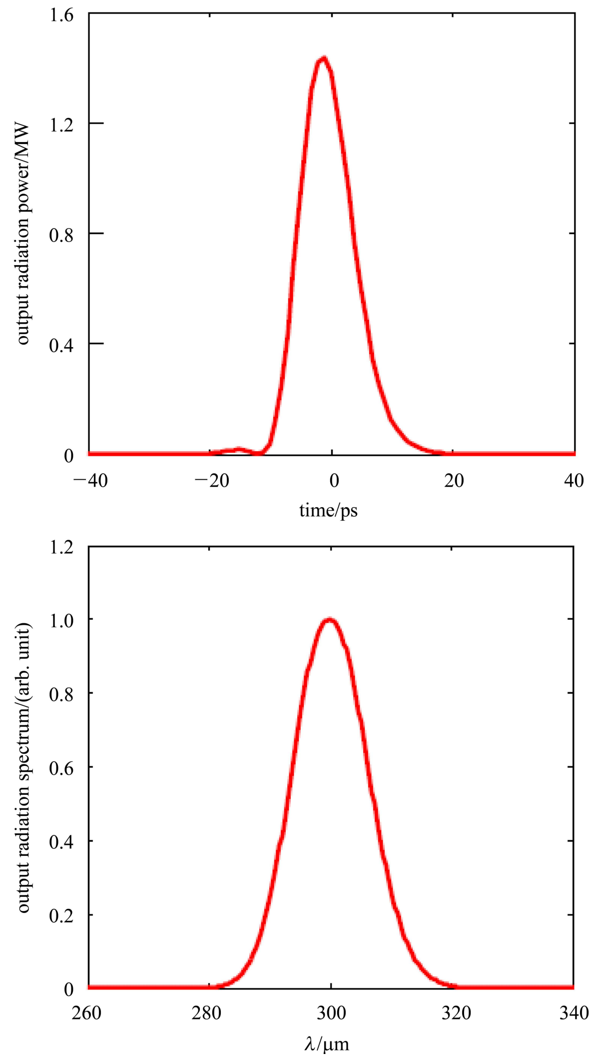


Fig. 8. The saturated output 1 THz radiation pulse in time and spectral domain, where the optimal detuning is assumed.

## 6 Conclusions

The ERL-based, low-gain FEL oscillator is the most attractive scheme to generate high power radiation, on the basis of which, a high power THz source with quasi CW output power of about 1 kW was proposed in Shanghai. The physical design and full three dimensional numerical modeling have been carried out. The results shows that, with a 20 MeV, 20 mA electron beam, coherent radiations with a peak power of megawatts and with an average power of kilowatts can be achieved in the frequency range of 0.5–10 THz.

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