DESIGN OF SHANGHAI HIGH POWER THZ-FEL SOURCE

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Abstract

An ERL-based THz source with kW average power is proposed in Shanghai, which will serve as an effective tool in material and biological sciences. In this paper, the physical design of two FEL oscillators, in the frequency range of 2~10THz and 0.5~2THz respectively, are given. In the design strategy, three dimensional, time-dependent numerical modelling of GENESIS and paraxial optical propagation code (OPC) are used. The performances of THz oscillator, the detuning effects and the influence of the THz radiation to the electron beam are presented.

INTRODUCTION

Recently, on the basis of ERL-based FEL oscillator, a THz source with kW average power is proposed in Shanghai, China. The layout of the THz source is shown in Figure 1. At the exit of the injector the 500keV electron bunch extracted from a 250MHz VHF gun is boosted to 2MeV. The electron beam is accelerated to 20MeV by 2 5-cell, 500MHz superconductive radiofrequency (SRF) module 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 dumped. In order to achieve an average output power of 1kW, the average beam current is expected to be 20mA. The parameters of the electron beam and the details of THz oscillator are summarized in Table 1. To achieve the goal of the design, covering the band of 0.5~10THz, two FEL oscillators, 2~10THz FEL with 20MeV electron beam and 0.5~2THz with 10MeV electron beam, are proposed.

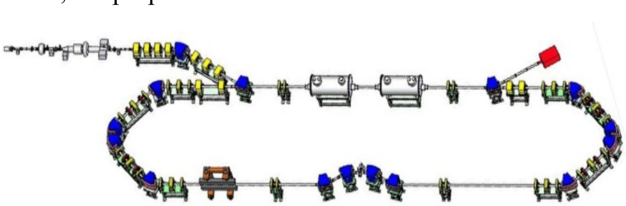

Figure 1: Schematic of Shanghai high power THz source based on ERL-FEL.

This paper presents the design of two FEL oscillators in the range of 2~10THz and 0.5~2THz, respectively. The numerical modelling has been carried out using three dimensional, time-dependent FEL code GENESIS [1] in combination with paraxial optical propagation code (OPC) [2]. In this paper, taking 10THz as a typical radiation wavelength, we first describe the physical design, time-dependent simulation, and the influence of the high power THz to electron beam. The primary results of 0.5~2THz oscillator is illustrated in the last section.

Table 1: Main parameters of the Shanghai THz source.

Parameters	Value	Value
THz frequency	2~10THz	0.5~2THz
Undulator type	Planar	Helical
Undulator period length	60mm	100mm
Undulator periods number	30	30
Beam energy	20MeV	10MeV
Beam transverse emittance	10μm-rad	10μm-rad
Beam energy spread	0.2%	0.2%
Bunch charge	240pC	240pC
Bunch length FWHM	8ps	16ps
Micro pulse repetition	83.33MHz	83.33MHz
Mirror radius of curvature	9.1160m	9.2502m
Mirror radius	50mm	120mm
Cavity length	18m	18m
Cavity stability g^2	0.95	0.89
Out-coupling hole radius	5.5mm	9.0mm
Average output power	~1kW	~1kW

DESIGN AND OPTIMIZATION

The maximum gain and optimum output power are two important factors of the FEL oscillator design and the optimization. So details of the optimization are given in this section first. The cavity is of a symmetric near-concentric design with a length of 18m. Choosing such a long cavity length there are the following factors that, on one hand, it is helpful for expanding the radiation size of 10kW order intra-cavity power on the cavity mirror. 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 83.33MHz to 41.67, 16.67 and even 8.33MHz.

The cavity mirror radius of curvature is designed to be 9.1160m, which results in a Rayleigh length of 1.0m and a cavity stability parameter of 0.95. The 10THz optical mode radius at the undulator centre is about 3.09mm. So the matched electron beam radii are 0.45mm in horizontal and 0.24mm in vertical. It means that the coupling between the electron bunch and the radiation is near-optimal in a large range. The 10THz radiation radius on the upstream mirror surface is 14.3mm, compared to a mirror aperture radius about 50mm. It is large enough to ensure that the diffraction losses from the fundamental mode are minimal.

The proposed working point of the cavity geometry shows a single-pass FEL gain larger than 50%. Figure 2 shows that the max single pass gain is 60%. In order to obtain an optimum output power, we keep the mirror radius of curvature constant and change the values of the out-coupling radii on the upstream mirror. The results show that a coupling hole with radius of 5.5mm is near

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optimum in terms of the output peak power, giving an 11% out-coupling fraction. The optimal peak power is about 5MW, which agrees exactly with the theoretical power efficiency of the FEL low-gain oscillator.

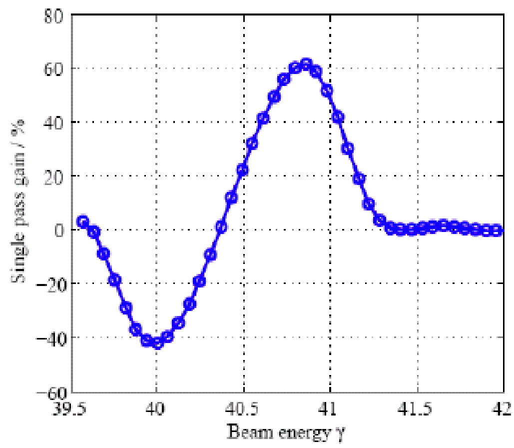

Figure 2: The single pass gain vs. the beam energy for the 10THz oscillator.

TIME-DEPENDENT SIMULATION

The time-dependent simulation allows us to model the effects of cavity length detuning, and the temporal and the spectral performances of THz oscillator in further. Using GENESIS in time-dependent mode allows us to model the effects of the cavity detuning, we are however, limited to detune the cavity only to half-integer multiples of the wavelength [3]. But MATLAB, which can couple the GENESIS and OPC, could be used to increase or decrease the detuning of the electron beam correspondingly, so that we could get the opportune detuning of the cavity.

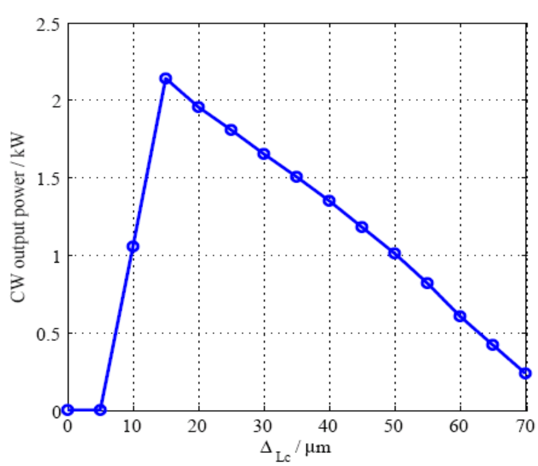

Figure 3: The detuning of the cavity length of 10THz FEL.

Figure 3 plots the cavity length detuning curve of 10THz oscillator. The average output power of 10THz radiation exceeds 2kW with an optimal detuning length of 15μm. If the cavity length is effectively detuned, the evolution of the single pulse energy of the 10THz oscillator is shown in Figure 4. It indicates 25.7μJ output pulse energy after 200 passes.

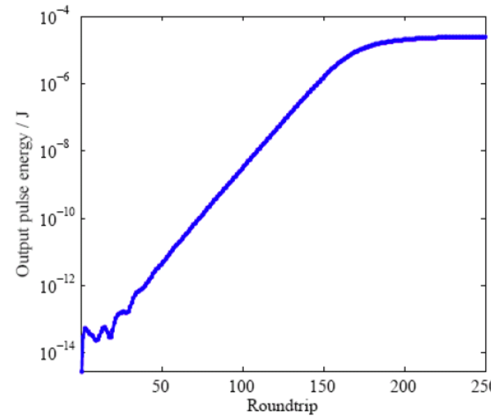

Figure 4: The pulse energy growth of the output 10THz radiation in 2~10THz oscillator.

Figure 5 shows the temporal and spectral distribution of the 10THz output radiation at saturation with the optimal detuning length. The peak power of the 10THz radiation pulse is 5.3MW. Figure 5 demonstrates a temporal FWHM width of 4.4ps and a spectral FWHM bandwidth of 1.5%. This corresponds to a time bandwidth product of 0.66, which is close the Fourier transform limit of 0.44 for a Gaussian pulse profile.

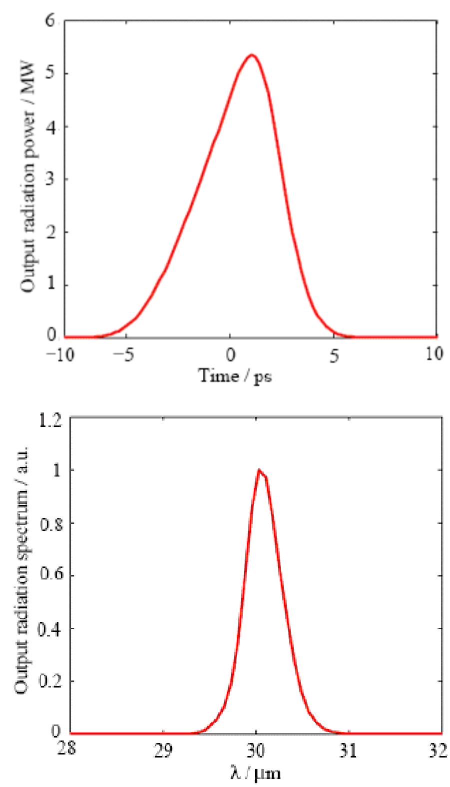

Figure 5: The saturated output 10THz radiation pulse in time and spectral domain with the optimal detuning.

INFLUENCE OF HIGH-POWER THZ TO ELECTRON BEAM

The high power relativity electron beam produces FEL THz radiation and interacts with it through the optical resonator. It makes the change of the electron beam, especially the beam energy including the increase of

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energy spread and the decrease of the centric energy. It will have a direct impact on the recovery efficiency of the whole accelerator and the transmission of the undulator downstream. The main effect on the electron beam due to the FEL interaction is an induced energy spread. Figure 6 shows that for the 20MeV electron beam with a RMS input energy spread of 0.2%, the energy spread increases to 1.3% due to the FEL interaction. Figure 7 shows that the maximal loss of the energy 0.36MeV compared to the energy loss of the maximal output power 0.18MeV, the efficiency of the cavity are 50%. Thus the exhaust energy acceptance of the beam transport return arc should be up to 8%.

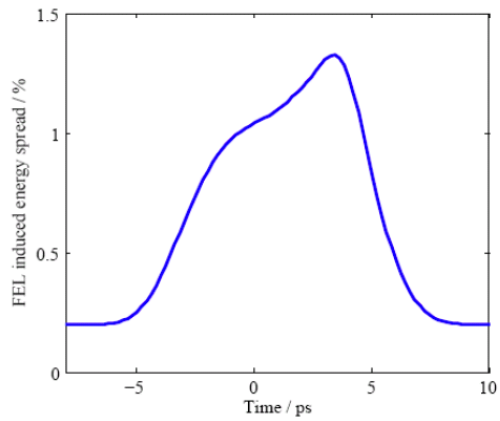

Figure 6: The final energy spread of 10THz oscillator at the saturation.

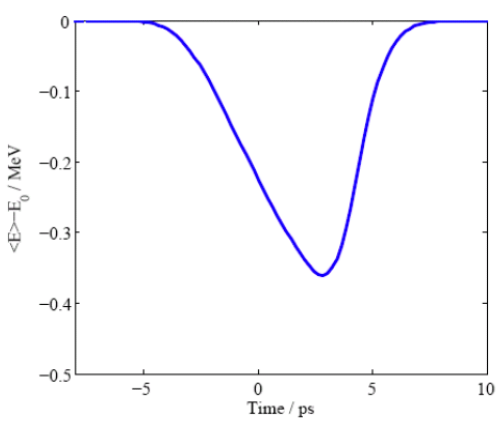

Figure 7: The mean energy of the downstream electron beam of 10 THz at the saturation.

0.5~2THz OSCILLATOR

In the mode of 0.5~2THz, we choose 1THz to design the cavity. In this case, the detuning of the cavity has much greater influences. Figure 8 plots the cavity length detuning curve of 1THz oscillator. When the detuning is 50μm, the radiation average power reached 1.5kW. In real operation, it should be based on the experiments to determine the specific detuning to acquire the maximum output power. Figure 9 shows the evolution of the single pulse energy of the 1THz oscillator in the case of optimal detuning. It indicates 17.7μJ output pulse energy after 270 passes.

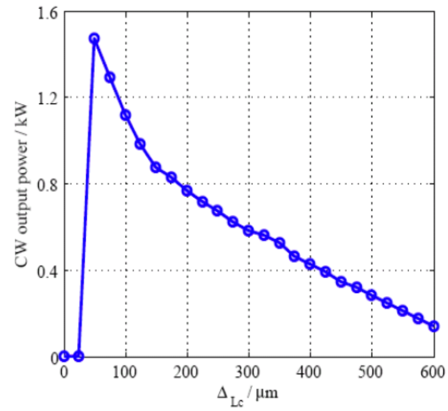

Figure 8: The detuning effect of the cavity length of 1THz FEL. Within a 100μm range of the cavity detuning, the average power of the 1THz radiation is 1kW above.

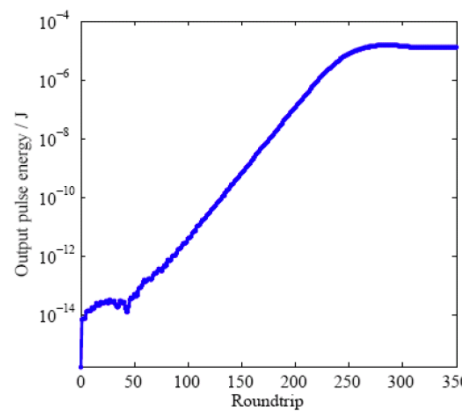

Figure 9: The pulse energy growth of the output 1THz radiation in 0.5~2THz oscillator.

CONCLUSION

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

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