SIMULATION AND OPTIMIZATION RESEARCH OF A THz FREE-ELECTRON LASER OSCILLATOR

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Abstract

A primary design of a compact Terahertz Free-electron lase oscillator is presented, which is consisted of an independently tuneable cell thermonic RF gun (ITC-RF Gun), a RF linac, a planar undulator and an near concentric optical cavity composed of symmetrical spherical mirrors with an on-axis outcouple hole. Without α-magnet and other bunch compressor, the size of this machine is decreased sharply. The effects of the electron beam parameters and undulator parameters on THz radiation of free-electron laser oscilaltor are discussed. It is found that the influence of energy spread is pronounced and the influence of emittance is neglectable. Large current is required to got saturation in several μs. Then the optimized beam parameters and basic design parameters are summarized.

INTRODUCTION

Compact Terahertz radiation source based on free-electron laser oscillator (FEL-THz oscillator) has been the research highlight due to its unique advantages including coherent and tunable wavelength, high efficiency and high power (peak and average)[1].

In this paper, we present the concept design of a compact FEL-THz. Aiming to optimize the electron beam parameters in the practical available level to produce the expected FEL performance, the effects of electron beam quality on THz radiation are discussed, and main parameters to enable the FEL-THz source to satisfy its output requirements are summarized by analytical calculations and numerical simulations.

CONCEPT DESIGN OF COMPACT THZ FEL OSCILLATOR

A compact terahertz free-electron laser oscillator is under development at Huazhong University of science and technology, which is considered to produce 100-300μm terahertz radiation. The concept design of the compact THz FEL oscillator is composed of an independently tunable cell thermonic RF gun (ITC-RF Gun), a RF linac, a planar undulator and an near concentric waveguided optical cavity composed of symmetrical spherical mirrors with an on-axis outcouple hole. Without α-magnet and other bunch compressor, the size of this machine is decreased sharply. Figure 1 is the basic schematic illustration of the concept machine. The basic design parameters are specified in Table I.

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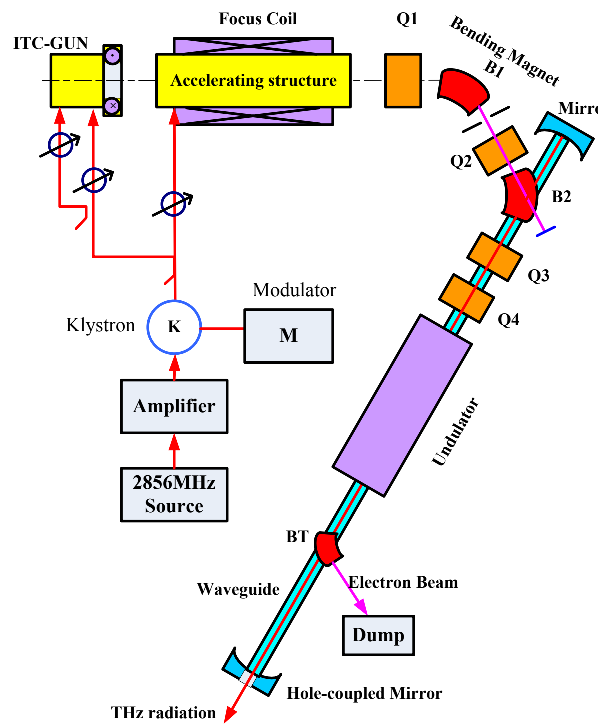

Figure 1: Layout of the compact THz FEL oscillator.

Table 1: Design Parameters of the THz-FEL Oscillator

Parameters	Value
Beam Energy	6-10MeV
RF frequency	2856MHz
pulse width	4μs
Undulator Period Lu	0.05m
Number of periods Nu	25
Undulator parameter	1
Wavelength λ	300-100μm
Resonator length L_R	2.8887m
Reflection coefficience	> 0.98 (Cu coated)
Aperture of outcouple hole	2mm
Gap of waveguide	10mm
ROC of mirrors	1.4632

SIMULATION AND OPTIMIZATION

The strength of coupling between a pulse of electron beam and a terahertz radiation field in a planar undulator is most conveniently parameterized by the small coefficient g0 [2]. To meet the start-oscillation conditions, g0 should be large enough so that the single pass signal gain exceeds the cavity loss. The simplified small gain formula (1) shows the electron beam parameters that can be varied to optimise terahertz radiation power

$$g_0 = \frac{16\pi\lambda L_u N_u^2 \xi f_B^2 J_e}{I_A \gamma} \qquad (1)$$

Where Lu is the undulator length, Nu is the number of the undulator periods, λ is the wavelength of terahertz radiation, $J_e = I_{pk} / 2\pi r_b^2$ is the electron beam current density and I_A is the Alfven current.

The undulator must have a certain minimum length and the on-axis field strength of the undulator must be sufficiently strong, since $g_0 \propto L_u N_u^2$. Also it is necessary to decrease the size of the undulator for a compact THz FEL oscillator, then an optimisation design of a short and strong field undulator is necessary.

It also implies that the electron beam quality is very important and has negatively impact on the THz radiation performance.

The single pass gain in such a system is low. This means the number of passes required to reach saturation is typically in the hundreds, over which time the radiation pulse is store within the cavity and amplified pass by pass. So it is a multi-dimensional optimisation problem to choose reasonable parameters to maximise the small signal gain parameter. To this end, the influence of energy spread, normalized emittance, bunch charge and RMS bunch length on FEL-THz radiation is investigated with numerical simulations using the FELO code, which is a 1D FEL oscillator simulation code that is capable of treating FEL oscillators in time-dependent regimes [3].

Emittance

The effect of normalized emittance on FEL THz radiation is given by numerical simulation. Fig.2 plots the single pass gain (normalized with respect to the gain assuming zero emittance) as a function of relative emittance. It is seen that the gain will continue to increase as the emittance is reduced, and then the gain becomes independent of the emittance at the point of 100 mm-mrad, where the electron beam size becomes significantly smaller than the optical mode size. So we set normalized emittance value as 10mm-mrad to meet the practical available level.

Energy Spread

Fig.3 shows the single pass gain of the FEL-THz source, normalized with respect to the gain in the cold-beam limit and plotted as a function of relative RMS energy spread. An energy spread of 0.5% degrades the gain to ~0.55 of the gain in the cold-beam limit, whereas an energy spread of 0.3% degrades the gain to ~0.8 of that at the cold beam limit. The maximum pulse intensity as a function of pass number for different energy spreads is shown in Fig.4. It also shows that the relative RMS energy spread should be less than ~0.3% which is readily achievable and thus specified as the nominal value.

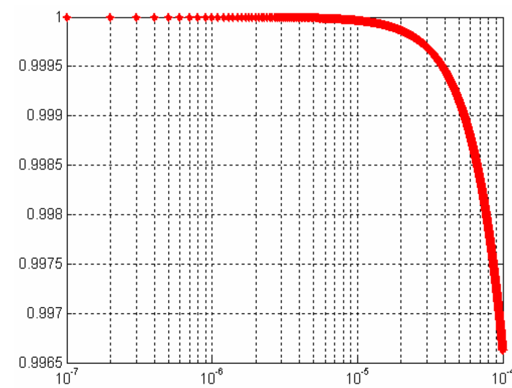

Figure 2: Single pass gain (normalized with respect to the gain at the 1D limit) of the THz FEL oscillator at 300μm.

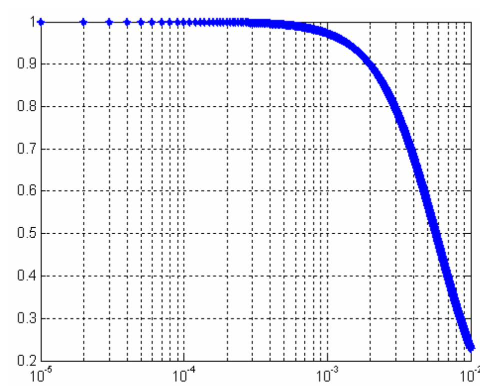

Figure 3: Single pass gain normalized with respect to the gain vs. relative RMS energy spread.

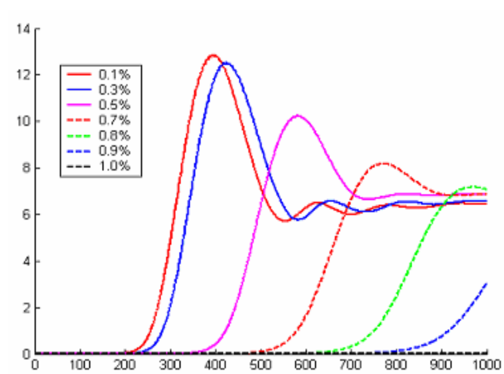

Figure 4: Normalized max. pulse intensity vs. pass number for different energy spread from 0.1% to 1.0%.

Bunch Charge and Bunch Length

The dynamics of a short pulse FEL oscillator is strongly affected by the fact that the group velocity of the optical pulse is larger than electron bunch and the slippage should be considered. To study the effect of RMS bunch length varying from, 5ps to 50ps, the bunch charge Q=200pC is held constant. The results of the simulations are illustrated in Fig.5 which shows that for a large bunch length, the maximum pulse intensity increases and more pass number is required to realize saturation. So RMS bunch length of 20ps is proposed.

The charge in the bunch should be high enough to give a sufficiently high peak current in the long bunch. Assuming the mirror reflectivity is 95%, emittance is 10mm-mrad, energy spread is 0.3%, the number of passes needed to reach saturation as a function of bunch charge is plotted in Fig. 6. Since the macropulse length of electron gun is normally 4~10μs, adequate current is required to reach saturation in few microseconds. As shown in the Fig.6, at least 500pC Charge is needed to reach saturation in 4μs.

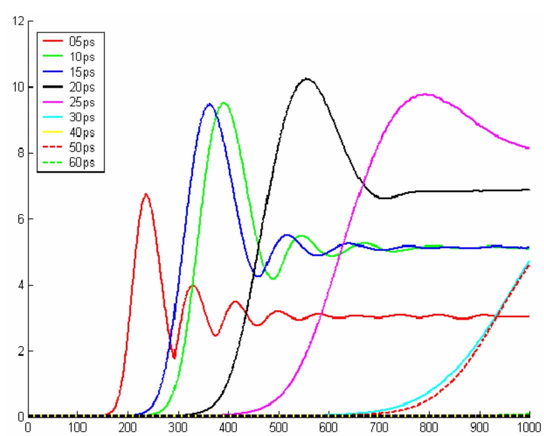

Figure 5: Normalized max. pulse intensity vs. pass number for different RMS bunch length varying from 5ps to 50ps.

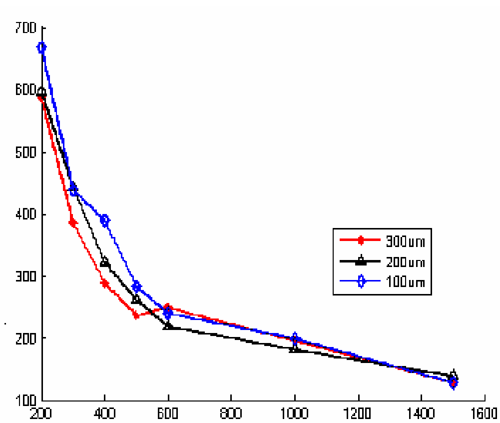

Figure 6: Pass number needed to reach saturations as a function of bunch.

CONCLUSION

A primary design of a FEL-THz source to emit 300μm THz radiation is presented in this paper. The improvements in RF-gun technology helps to make a compact high power FEL-THz source.

The electron beam quality is very important and has negatively impact on the THz radiation performance; hence, it is important to predict the character and magnitude of the effects and to be able to optimize the design of a FEL-THz oscillator. It is found that the influence of energy spread is pronounced and the influence of emittance is neglectable at readily achievable level. The charge in the bunch should be high enough to give a sufficiently high peak current in the long bunch. Considering the influence of the electron beam quality on THz radiation, the optimized beam parameters are summarized in Table II.

Table II: Proposed Electron Beam Parameters of the Designed Compact THz FEL Oscillator

Parameters	**Value**
Normalized emittance	10mm-mrad
Relative energy spread	0.3%
Bunch Charge	500pC
RMS Bunch Length	20ps

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