PRELIMINARY STUDY OF TERAHERTZ FREE-ELECTRON LASER OSCILLATOR BASED ON ELECTROSTATIC ACCELERATOR*

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Abstract

Since the terahertz radiation sources provide wide applications in medical science, material science and industrial, a compact, wavelength tunable and high-power THz source attracted much attention in many laboratories [1]. In this paper, we give a primary study of a compact electrostatic accelerator driven THz FEL (EA-THz) and its basic design parameters. The feasibility study is carried out using FELO code [2]. The initial results show that such EA-FEL will be a promising compact and powerful THz source.

INTRODUCTION

FEL is one of the best methods to realize the powerful THz source, which can not only produce high power, but also obtain coherent and tunable wavelength. However, the conventional FEL facilities, based on normal conducting linacs, are not able to work in CW mode. EA-FEL can achieve high average power, better energy-conversion efficiency and spectral purity. Some EA-FEL devices have been successfully developed and commissioned world-widely in many laboratories. UCSB-FEL employed a 6MeV Pelletron accelerator and obtained 2.5 mm to 30 μm FEL [3]. Israel FEL based on a 6MeV EN tandem acceleration can produce average power of 1kW in the range of 70-130 GHz [4]. Recently, we proposed a high power CW MM-THz wave source based on EA-FEL [5].

Within the principle of FEL oscillator, the main parameters of electron beam, undulator and the optical cavity are given in this paper. And the performance of this scheme is investigated with FELO code.

STUDY OF EA-FEL OSCILLATOR

The concept of THz EA-FEL source works as a FEL oscillator with a recycled current device. The simple schema of an EA-FEL oscillator is shown in Figure 1.

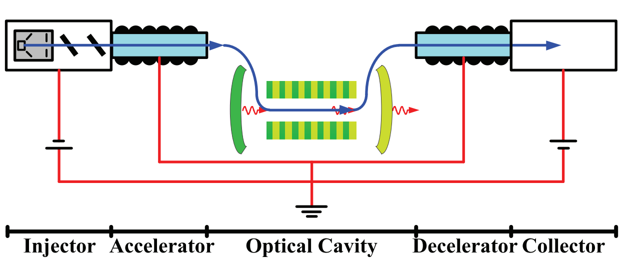

Figure 1: Conceptual design of an EA-FEL.

As shown in Figure 1, it consists of a DC gun, an accelerator producing a sequence of electron beam, a resonator generating radiation, a deceleration and a collector collecting the decelerated electrons to achieve energy retrieval.

To start oscillation, the single pass gain must exceed the cavity loss. The maximum gain of such an oscillator is [6],

$$G = 0.85\left(g_0 F_{inh} F_c F_f\right) + 0.19\left(g_0 F_{inh} F_c F_f\right)^2 + 4.12*10^{-3}\left(g_0 F_{inh} F_c F_f\right)^3 \qquad (1)$$

where $g_0 = \frac{16\pi\lambda_s L_u N_u^2 \xi f_B^2 J_e}{I_A \gamma}$ is small signal gain, $F_{inh} = \frac{1}{1+1.7\mu_e^2} \times \frac{1}{1+\mu_y^2}$ is an inhomogeneous broadening factor accounting for beam energy spread and the normalized emittance, $F_c = \left(1+\frac{N_u \lambda_s}{3 l_e}\right)^{-1}$ is a correction factor caused by the gain reduction due to the relative slippage between electron and radiation pulse, $F_f = \left(1+\frac{\overline{w}^2}{4 r_b^2}\right)^{-1}$ is a filling factor which is used to account for the transverse overlap between electron beam and optical mode. Due to the space limitations, the readers are advised to refer to [6] for notations in Eq. (1).

It implies that energy spread ($g_0 \propto \delta^{-1}$), normalized emittance ($g_0 \propto \varepsilon_n^{-1}$) and beam current ($g_0 \propto J_e$) impact on the FEL oscillator performance. The EA-FEL could have a very high quality electron beam, like the one in UCSB, which has low emittance (10mm-mrad), small energy spread (0.01%) and large current (2A).

Also, it means that the length ($g_0 \propto L_u N_u^2$) and on-axis field strength ($g_0 \propto \xi$) of the undulator is very important for the oscillator. It is desirable to minimize the length of an undulator for a compact EA-FEL oscillator. A Halbach type undulator ($\lambda_u \geq 2cm$ and gap$\geq 3mm$) made of permanent magnet (NdFeB) is adopted in EA-FEL, which is easily operational and has large residual magnetism. We set the undulator period length of 2cm and period number of 50. The output wavelength of the FEL radiation is given by,

$$\lambda_s = \frac{\lambda_u}{2\gamma^2}\left(1+\frac{K^2}{2}\right) \qquad (2)$$

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where K=93.4×B[T]×λ_u[m] is the undulator strength parameter. The simulation of Halbach undulator has been carried out with RADIA [7].The relationship between maximum field strength and undulator gap is shown in Figure 2. Table 1 shows the variation of radiation wavelength caused by different electron beam energy and gap.

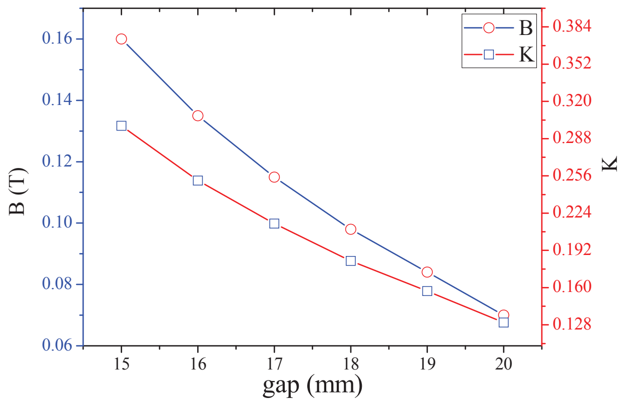

Figure 2: Maximum field strength and K versus gap.

Table 1: The variation of radiation wavelength caused by different electron beam energy and gap

Wavelength [μm] / Gap[mm]	E=3MeV	E=4MeV	E=5MeV	E=6MeV
15	303	170	108	76
16	299	168	108	75
17	297	167	107	74
18	295	166	106	74
19	294	165	106	73
20	293	165	105	73

Table 2: Parameters of Accelerator and Undulator

Parameters	Value
Beam Energy	3-5MeV
Current	2A
Energy spread	0.01%
Emittance	10mm-mrad
Period	0.02m
Period Number	50
gap	15mm
K	0.3
B	0.135T
wavelength	108-299μm

It implied the lager gap can cause the decrease of the maximum field strength, K, as seen in Figure 2. From Table 1, the wide tunability from 108 to 303 μm can be achieved when the gap is fixed to 15 mm. The basic design parameters of EA-FEL are shown in Table 2.

The optical cavity is the most important part in a FEL oscillator, because it offers an optical positive feedback and controls the characters of laser. Typically, to prevent the effect of lethargy, it is necessary to give a detuning of the cavity length to determine the cavity parameters. However, such detuning is not necessary for the CW mode EA-FEL. In practical applications, the cavity length is long for the requirement of dipoles and quadrupoles within the cavity. Thus, the design must take the compactness and actual situation into account. We choose the optical cavity with 2 meters long, which has two symmetric spherical mirrors ($r1=r2$) with an on-axis hole. The Rayleigh length is,

$$l_{ZR} = \frac{1}{2}\sqrt{L_c\left(2r - L_c\right)} \qquad (2)$$

where L_c is the cavity length and r is the radii of curvature. The optical cavity stability condition for a symmetric cavity is needs $0<g^2<1$, where $g=1-L_c/r$. The Rayleigh length affects the filling factor F_f, thus the choice of the radii of curvature involves a compromise between performance and stability. When electron beam Energy is 3MeV, the maximum gain and the output coupling varying with the radii of curvature are shown in Figure 3. The characteristics of the optical cavity are listed in Table 3.The result of FELO simulation shows the maximum single pass gain is about 6.2% which is in good agreement with the results obtained by analytical calculation. The EA-FEL oscillator, which has the gain slightly in excess of the losses, will start up after hundreds of passes.

Table 3: Characteristics of Optical Cavity

Parameters	Value
Length	2m
Rayleigh length	0.283m
g^2-parameter	0.73
Mirror type	Cu coated
Mirror curvature	1.08m
Reflection coefficient	0.99
Alignment tolerances	1.68mrad
Maximum gain	6.21%
Outcoupling fraction	1.21%

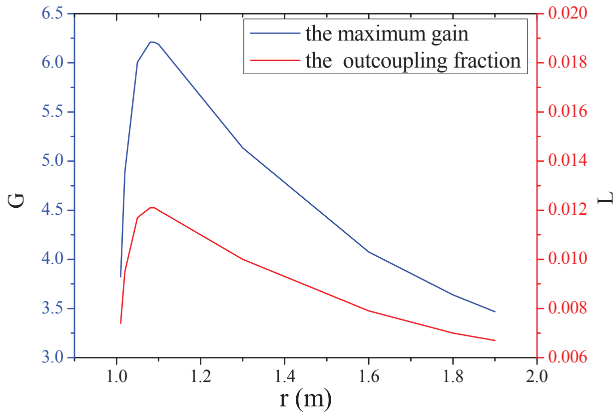

Figure 3: Maximum gain and the loss of output coupling versus the radii of curvature.

SUMMARY

A primary study of a Terahertz FEL oscillator based on electrostatic accelerator is presented in this paper. The design obtains a compact and tunable FEL device. The simulation of EA-FEL oscillator will be carried out to optimize the conversion efficiency describing electron beam power into FEL power. In order to reduce the passive losses, we are considering the use of waveguide resonator in the future.

REFERENCES

[1] G. P. Gallerano et al. "overview of terahertz radiation sources". Proceeding of FEL 2004, pp. 216-221.

[2] B. W. J. McNeil, G. R. M. Robb, "FELO: A one dimensional time-dependent FEL oscillator code". Proceeding of FEL 2006, pp.59-60.

[3] http://sbfel3.ucsb.edu/.

[4] J. S. Sokolowski et al. "First lasing of the Israeli tandem electrostatic accelerator free electron laser". Particle accelerator conference1997, pp. 906-908.

[5] Faya Wang et al. "A high power CW MM-THz wave source based on electrostatic accelerator FEL". Proceeding of FEL 2010, pp. 222-225.

[6] 4GLS Conceptual Design Report, Council for the Central Laboratory of the Research Councils, UK, http://www.4gls.ac.uk/documents.htm#CDR (2006).

[7] http://www.esrf.eu/Accelerators/Groups/InsertionDevices/Software/Radia.