Nuclear Science and Techniques **20** (2009) 321–324

Simulation of coherent spontaneous emission in a FEL with a groove guide

LUO Feng[1,2,*] BEI Hua[1,2] LIN Xuling[1,2] DAI Zhimin[1]

[1] *Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai 201800, China*

[2] *Graduate School of Chinese Academy of Sciences, Beijing 100049, China*

Abstract Based on a femtosecond linear accelerator, here we present a study of the use of a groove guide as the FEL interaction structure for high power FEL experiment. The transmission and attenuation characteristics of the dominant mode in the groove guide are discussed. And the coherent spontaneous emission in the FEL is simulated by Gover theory.

Key words Free electron laser, Groove guide, Coherent radiation

1 Introduction

In a free electron laser (FEL), relativistic electron beams passing through a transverse periodic magnetic field generate coherent electromagnetic radiations. For an FEL operation in THz wave band, the “slippage”, i.e. the lack of overlapping between the wave packet and the electron bunch due to their different velocities, strongly affects the effective interaction, especially for the short electron bunches produced by the RF accelerator.

However, in a waveguide, the possibility of controlling the group velocity by varying the transverse dimensions may reduce the slippage[1]. Besides, at long wavelength the use of waveguide is an effective way to confine the diffraction loss. The theory of waveguide FEL[1–3] has been well investigated and several experiments have been performed successfully[4,5].

The aim of this paper is to show the use of groove guide[6]: a low loss, low dispersion and single mode transmission waveguide in the short millimeter and submillimeter wave bands, as a new optical cavity in an FEL experiment. The transmission characteristics of groove guide are described, and the spontaneous radiation in the FEL is simulated based on Gover theory[7,8].

2 Groove guide

A groove guide is made of two parallel metallic plates with a groove, of any possible shape in the central region of the transverse section, from rectangular groove guide[6], circular groove guide[9], to V-shaped groove guide[10]. Unlike conventional waveguides, the groove guide supports single mode propagation even with larger dimensions than the wavelength. This is important for our THz wave band FEL operation. Among the three kinds of groove guides in similar dimensions, the V-shaped groove guide has the lowest loss[11]. The circular groove guide, proposed by Yang H S, *et al*[9], takes the second place, but it is the best for confining most of the electromagnetic field in the central groove region, being in favor of the effective interaction between electrons and radiation wave, hence our choice of the circular groove guide.

A cross section of the groove guide in this study is shown in Fig.1. The radius is a for the groove region designated as A. The two side regions designated as B are defined by the two parallel plates separated by $2d$. The overall transverse dimension is $2h$. The two sides of the guide are laid open for the high order modes to radiate out of the guide. Here we just discuss the fundamental mode in the circular groove guide. We take cylindrical coordinates system in Region A and

* Corresponding author. *E-mail address:* luofeng@sinap.ac.cn

Received date: 2009-06-05

rectangular coordinates system in Region B. Considering the conductor boundary conditions, Eqs.(1) and (2) can be derived for the H_z components in Regions A and B,

$$H_{zA}=\sum A_p k_c^2 J_p(k_c\rho)\sin(p\alpha) \quad (p=1,3,\ldots) \tag{1}$$

$$H_{zBr}=[\sum A_r k_c^2 \sin(k_{yr}y)]\exp[-k_{xy}(x-x_0)] \quad (r=1,3,\ldots) \tag{2}$$

where A_p and B_r are the amplitude coefficients of field components in Regions A and B, respectively; k_c is the cutoff wave number; and k_{xy} are wave numbers in y and x direction respectively in Region B; J_p is the p^{th} order Bessel function; x_0 is the value of X direction at the arc boundary between Regions A and B.

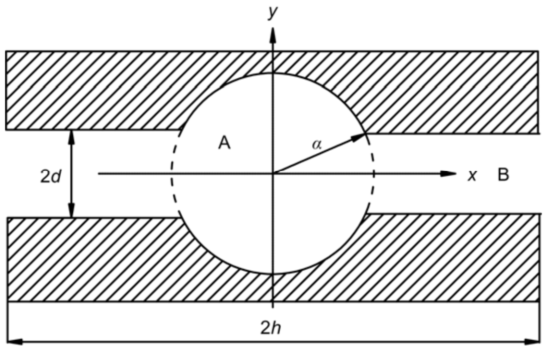

Fig.1 Cross section of the circular groove guide.

Fig.2 shows the electric field distribution of the dominant mode in the groove guide simulated by the CST software. From Fig.2, it is evident that the electric field is mainly confined in the central part and its vector direction is mainly parallel to the X-axis.

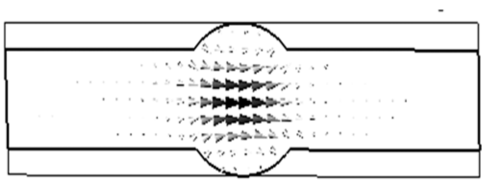

Fig.2 Vector graphe of electric field in the guide.

Transmission characteristics of the circular groove guide have been described in literatures[9,12]. For a proper design of the guide, we are interested in studying power-handling and attenuation properties of the guide, using equations derived in Ref.[9]. In order to improve the calculation precision, we adopt the third-order approximation[12] of the field, i.e. take 1, 3 and 5 in Eqs. (1) and (2) for both p and r.

Fig.3a shows the variation of $P_A/(P_A+P_B)$ with d/a, which represents the guide's ability to confine energy in the central groove region, with P_A and P_B being the power transmitted through the Regions A and B, respectively. The attenuation property (in Np/m) of the guide could be described by

$$\alpha=(W_A+W_B+W_R)/[2(P_A+P_B)] \tag{3}$$

where W_A and W_B are the conductor loss of the guide in Regions A and B, respectively, and W_R is the power leakage through the two open sides. Fig.3b shows the variation of the attenuation constant α with d/a for frequency wave of 400 GHz and for copper waveguide. From Fig.3a, $P_A/(P_A+P_B)$ decreases monotonously with increasing d/a ratio. From Fig.3b, low attenuation can be obtained by proper choice of the d/a ratio.

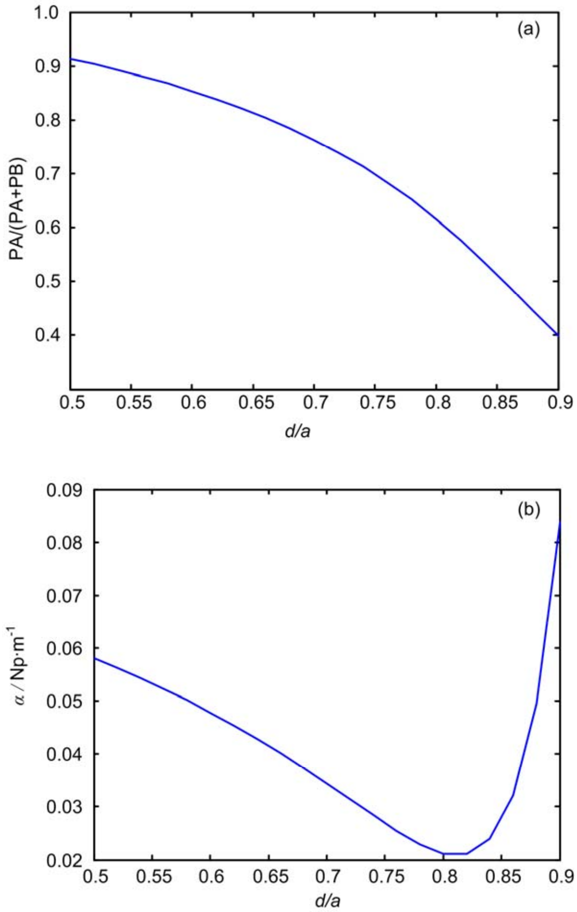

Fig.3 Power transmission (a) and attenuation (b) of the waveguide of different d/a ratios (a=2.6 mm).

Considering the spot size of electron beam at the undulator entrance, and to have the guide in dimensions suitable for our near zero slippage operation[1] of the FEL, we choose a=2.6 mm. The latter point can be explained by the guide's dispersion effect on resonant frequency of the FEL. This will be discussed in Section 3. And for common application of the guide, the d/a ratio is chosen as 0.65, at which the guide has both moderate power capacity and attenuation property. This can be seen from Fig.3.

3 Simulation of the spontaneous emission

In a waveguide FEL, the two resonant frequencies are given by[2,3]

$$\omega_{\pm} = c\beta_z\gamma_z^2 k_u\left\{1 \pm \beta_z\left[1-\left(\frac{k_c}{\beta_z\gamma_z k_u}\right)^2\right]^{1/2}\right\} \tag{4}$$

where β_z is the electron's longitudinal velocity v_z normalized by the light velocity c, γ_z is the relativistic factor, k_c is the cutoff wave number of the waveguide mode, and k_u is the undulator wave number.

For the higher frequency solution, the radiation group velocity is larger than the electron velocity, and *vice versa* for the lower frequency solution. This results in two wave packets propagating ahead and behind the electron beam with slippage time t_{s1} and, t_{s2}, respectively.

$$t_{s1,2} = L/v_z - L/v_{g1,2} \tag{5}$$

where $v_{g1,2}$ are group velocities of the wave packets ω_+ and ω_-, L is the interaction length. On the other hand, Eq.(4) indicates that, there is only one resonant frequency at $k_u=k_c/(\beta_z\gamma_z)$, hence the so-called "zero slippage" condition, where the group velocity of the wave packet equals the beam velocity. Our simulation parameters are listed in Table 1.

Fig.4 shows the solution of the resonant Eq.(4) as a function of the electron beam energy with the data in Table 1. The 250 fs pulse width (FWHM) of electron bunch is much shorter than the resonant wavelength. So the individual electrons emit radiation almost in the same phase, resulting in the coherent radiation[13]. Short pulse coherent radiation has been investigated in details by Gover *et al*[8]. Using their conclusions with our parameters in Table 1, the single pass spectral energy emission for single electron bunch is

$$\frac{\mathrm{d}W}{\mathrm{d}\omega} = \frac{N^2e^2Z}{16\pi}\left(\frac{eB_u}{\beta_z\gamma mc}\right)^2\frac{L^2}{k_u^2A_{em}}\times \operatorname{sinc}^2(\theta L/2)\left|M_b(\omega)\right|^2 \tag{6}$$

where $\theta=\omega/v_z-k_z(\omega)-k_u$ is the usual definition of the FEL detuning parameter, $A_{em}=P/[|E_\perp(0,0)|^2/(2Z)]$ is the effective mode area, N is the total number of electrons in the bunched beam, Z is the mode impedance, B_u is the magnetic field amplitude of the undulator, e is the electron charge, m is the electric mass, $k_z(\omega)$ is the axial wave number of the waveguide mode, P is the normalization power, $E_\perp(0,0)$ is the electric field amplitude on Y axis, and the microbunch form factor $M_b(\omega)$ is the Fourier transform of the microbunch current waveform,

$$M_b(\omega) = \int_{-\infty}^{+\infty} f(t)e^{i\omega t}\mathrm{d}t \tag{7}$$

Table1 Simulation parameters

Electron beam	Parameters
Beam energy / MeV	24–30
Micro-bunch peak current / A	100
Micro-bunch duration (FWHM) / fs	250
Undulator	Parameters
Period / cm	10
Number of periods	5
Peak magnetic field / T	0.59
Circular groove guide	Parameters
Radius of central groove / mm	2.6
Overall width / mm	20
d/a	0.65

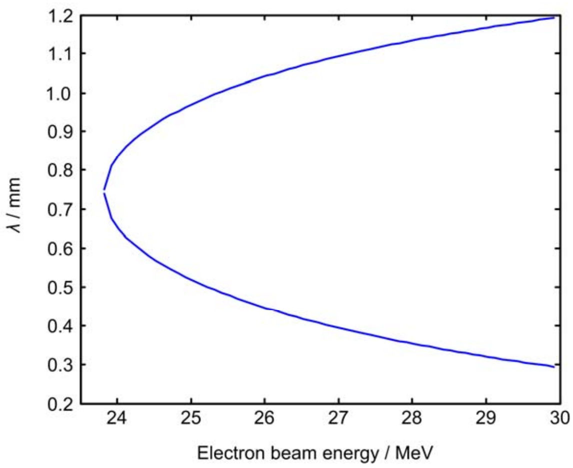

Fig.4 Resonant wavelength versus beam energy.

Assuming a Gaussian electron beam bunch distribution $f(t)=[\exp(-t^2/t_b^2)]/(\pi^{1/2}t_b)$, one has $M_b(\omega) = \exp(-\omega^2t_b^2/4)$. Fig.5 shows the energy spectra calculated by Eq.(6) for electron beams of different energies. Two peaks can be observed corresponding to the two resonant frequencies. This figure indicates that we can just achieve near zero slippage operation by varying the beam energy.

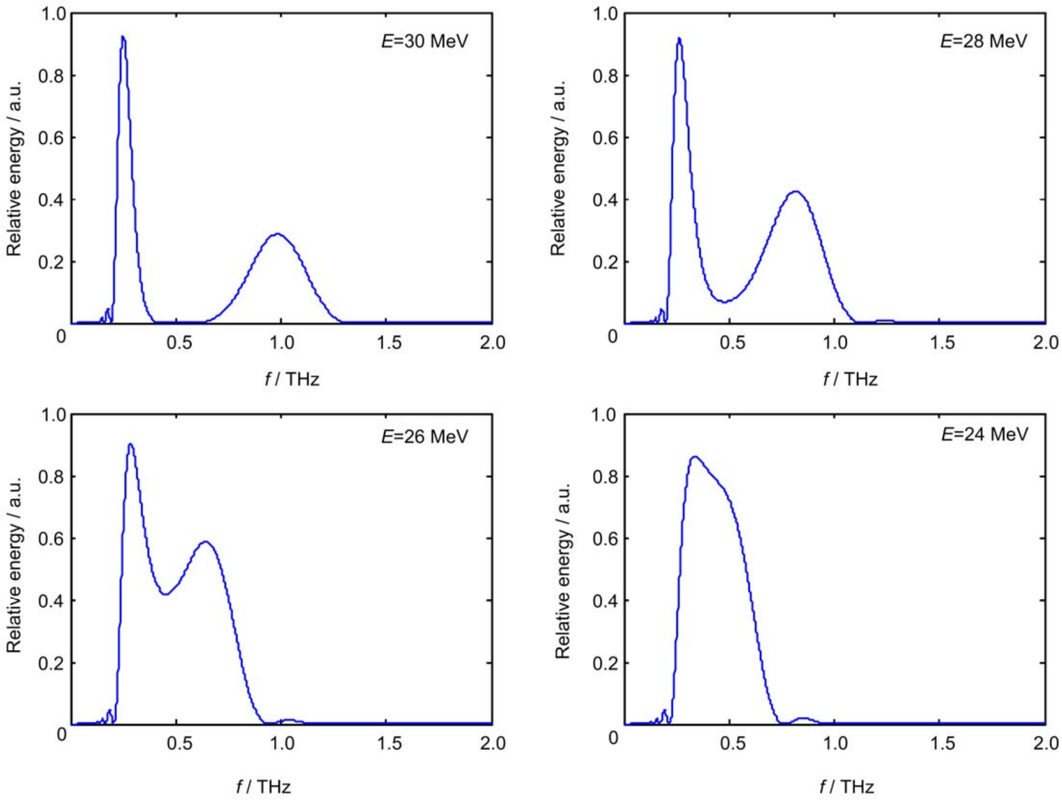

Fig.5 Energy spectra for electron beams of different energies.

The total emission energy can be obtained by integrating Eq.(6). We only calculate the near zero slippage condition. The relevant total emitted energy for 25 MeV electron beam is about 2.55 μJ. And the average power within the macropulse is about 7.3 kW.

4 Conclusion

A groove guide in far infrared FEL, with its low loss and single mode transmission characteristics, is very attractive. FEL with a waveguide can effectively solve the problem of the slippage. The simulation results obtained in this study is of help for high power THz FEL oscillator experiment.

References

1 Ride S K, Pantell R H, Feinstein J. Appl Phys Lett, 1990, **57:** 1283–1285.

2 Doria A, Gallerano G P, Renieri A. Opt Commun, 1991, **80:** 417–424.

3 Bartolini R, Doria A, Gallerano G P, *et al*. Nucl Instrum Methods: Phys Res, Sect A, 1991, **304:** 417–420.

4 Ciocci F, Bartolini R, Doria A, *et al*. Phys Rev Lett, 1993, **70:** 928–931.

5 Asakawa M, Sakamoto N, Inoue N, *et al.* Apll Phys Lett, 1994, **64:** 1601–1603.

6 Choi Y M, Douglas J H. Infrared and Millimeter Waves, 1984, **11:** chapter 3.

7 Gover A. Phys Rev ST Accel Beam, 2005, **8:** 030701.

8 Gover A, Dyunim E, *et al*. Phys Rev ST Accel Beam, 2005, **8:** 030702.

9 Yang H S, Ma J L, Lu Z Z. IEEE Trans Microwave Theory Tech, 1995, **43:** 324–329.

10 Choi Y M. Int J of Infrared and Millimeter Waves, 1988, **9:** 635–646.

11 Xu S J, Zhang Y J. Int J of Infrared and Millimeter Waves, 1993, **14:** 1055–1068.

12 Yang H S, Liu Y. IEEE Microwave and Wireless Components Letters, 2002, **12:** 57–59.

13 Doria A, Bartolini R, *et al*. IEEE J Quantum Electron, 1993, **29:** 1428–1436.