SIMULATION INVESTIGATION OF THE DETUNING CURVE

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Abstract

The detuning curves of free-electron laser oscillators are calculated with the help of our three-dimensional code, which are compared with those from one-dimensional simulations and super-mode theory, and the experiments. The influence of the optical guiding and other three-dimensional effects on the detuning curve is studied. It is found that the length of the detuning curve from three-dimensional simulations is shorter than that from one-dimensional simulations and super-mode theory.

INTRODUCTION

An obstacle to the development of a short pulse free-electron laser (FEL) oscillator is the slippage that occurs between the electron beam and radiation duo to their different velocities, which results in lack of overlapping between the electron and the optical pulses and a reduction in gain, and so is called the laser lethargy effect [1]. This effect can be overcome by slightly shortening the length of the optical cavity from synchronism so to keep the overlapping between the electron and the optical pulses [1, 2]. The FEL power as a function of cavity length, which is named the detuning curve, has been studied abundantly both theoretically and experimentally. The detuning curves are usually calculated by one-dimensional (1D) simulations due to the simplicity and little consumption of the computer time, which in general are good agreement with super-mode theory [3] and experiments. To our knowledge there is almost no detuning curve calculated from three-dimensional (3D) simulations. However, recently it is found that the length of the detuning curve seems to be shorter than possible assuming a one-dimensional super-mode theory when the gain is high in the experiments of an infrared FEL oscillator [4, 5]. On the other hand, the lethargy effects is more severe in a far-infrared FEL such as the CAEP FIR FEL [6] because the slippage length which is proportional to the optical wavelength is large compared to the short electron pulse produced by an RF linac. It is of interesting and necessary to obtain more exact detuning curve from 3D simulations to study it more carefully.

In this paper, the detuning curves of the CAEP FIR FEL [6] and the Jefferson Lab IR Demo FEL [4, 5] are calculated with the help of our 3D code [6-8], which are compared with those from 1D simulations and super-mode theory, and the experiments. The influence of the optical guiding and other three-dimensional effects on the detuning curve is studied. It is found that the length of the detuning curve from 3D simulations is shorter than that from 1D simulations and super-mode theory.

CAEP FIR FEL

Firstly, as usual, the detuning curves are calculated by using our one-dimensional time-dependent code GOFELP [9, 10]. In simulations, the distribution functions of the electrons and optical pulses are assumed as Gaussian. The transverse overlap factor between Gaussian mode of TE_{00} of the optical cavity and the electron beam with a parabolic transverse density profile is considered in the code [11].

In Fig. 1 we show the output power as a function of cavity length with the parameters of CAEP FIR FEL [6] as listed in Table 1. In simulations, the current is adjusted to obtain the same gain as 3D simulations and the loss of the cavity is given the result of 3D simulations. The range of the detuning curve is from about –70 μm to –360 μm and the length is about 290 μm.

Table 1: CAEP FIR FEL Parameters

Electron beam	
Energy (MeV)	6.5
Energy spread (%)	1
Peak current (A)	8
Micro bunch (ps FWHM)	15
Wiggler	
Period (cm)	3
Peak field strength (kG)	3
Number of periods	50
Optical	
Wavelength (μm)	110.7
Cavity length (m)	2.536
Mirror curvature (m)	1.768

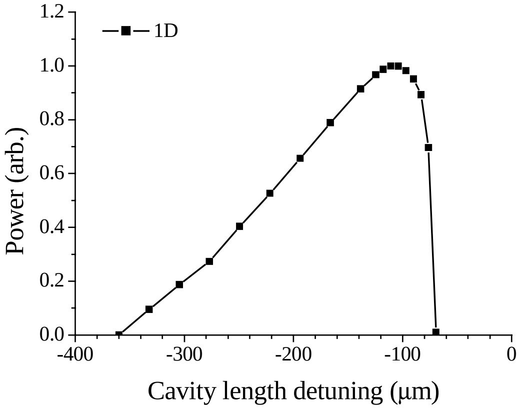

Figure 1: Detuning curve of CAEP FIR FEL from 1D simulations.

Then the detuning curve is calculated by using our 3D code OSIFEL [6-8]. As shown in Fig. 2, the curve has almost same shape as Fig. 1 but moves toward zero point, i.e. synchronism point, which cannot be observed and fixed in experiments. The range of the detuning curve is from about –25 μm to –330 μm and the length is about 300 μm, which approach the result of 1D of 290 μm. The reason is that the gain and loss are almost same in 1D and 3D simulations and the net gain is small [6].

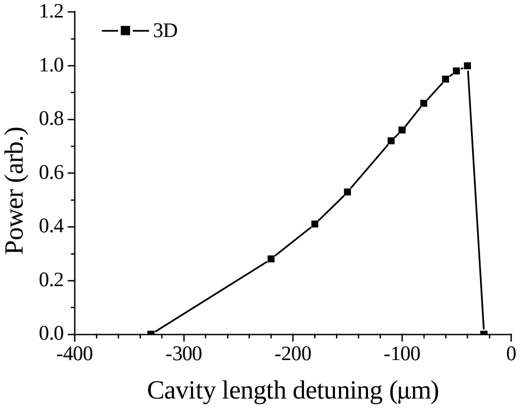

Figure 2: Detuning curve of CAEP FIR FEL from 3D simulations.

JLAB IR DEMO FEL

Fig. 3 shows the detuning curve calculated by using our 1D code with Jlab IR Demo FEL parameters [4, 5] listed in Table 2. In the simulations, the energy spread is zero in order to cut down on the computer time. The range of the detuning curve is from about –0.2 μm to –31 μm and the length is about 30 μm. Note that the curve is very sharp, which is totally different to Fig. 1 and results from experiments [4, 5], due to high small signal gain of more about 150% in the 1D simulations without energy spread.

Table 2: Jlab Demo FEL Parameters Used in Simulations

Electron beam	
Energy (MeV)	47.8
Energy spread (% FWHM)	0.5
Emittance (mm.mrad rms)	8.7
Peak current (A)	58.8
Micro bunch (ps FWHM)	1
Wiggler	
Period (cm)	2.7
Peak field strength (kG)	5.61
Number of periods	40.5
Optical	
Wavelength (μm)	3.1
Cavity length (m)	8.0105
Mirror curvature (m)	4.05
Loss (%)	9.63575

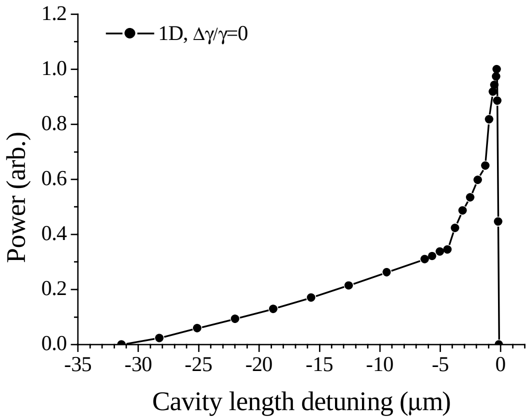

Figure 3: Detuning curve of Jlab IR Demo FEL from 1D simulations without energy spread.

Fig. 4 shows the detuning curve calculated by using our 3D code. The shape of curve becomes gently, not so sharp, since the small signal gain is about 100% in the 3D simulations, which approaches the gain in the experiments. The range of the detuning curve is from about 0 μm to –20 μm and the length is about 20 μm, which is shorter than 30 μm obtained from the 1D simulations without energy spread, but little longer than 16μm of that from the experiments [5] and in good agreement with experiments. The 3D simulations give better results than the 1D calculations and super-mode theory.

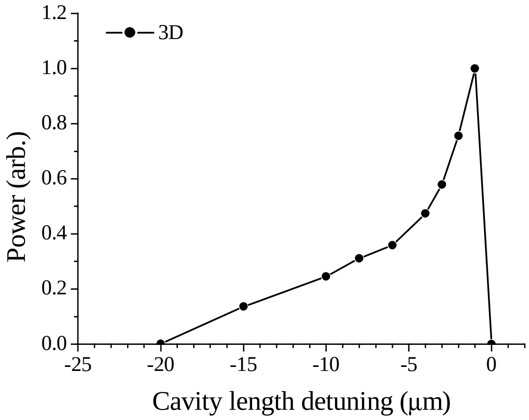

Figure 4: Detuning curve of Jlab IR Demo FEL from 3D simulations.

Then the energy spread of the electron beam is considered in 1D simulations. Fig. 5 shows the detuning curve from the 1D simulation with the energy spread of 0.5%. Fig. 4 and 5 are remarkably similar to each other. The range of the detuning curve is from about 0 μm to –22 μm and the length is about 22 μm, which is little longer than 20 μm that obtained from the 3D simulations and in better agreement with the experiments than the 1D simulations without the energy spread. The small signal gain is about 80%, which is smaller than that from the 3D simulations. The optical guiding effects result in an increase in the gain. Note, however, that the length of detuning curve from the 3D simulations and experiments seems to be shorter than possible assuming a higher gain.

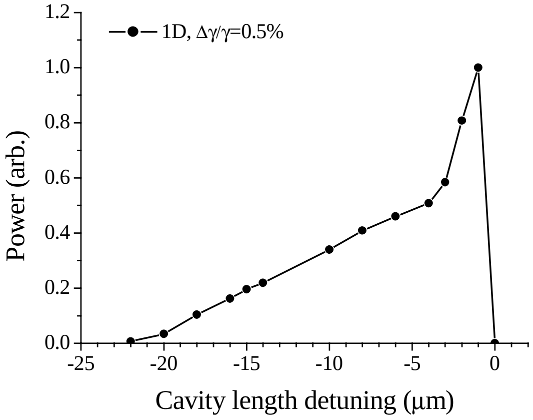

Figure 5: Detuning curve of Jlab IR Demo FEL from 1D simulations with energy spread.

CONCLUSION AND DISCUSSION

In this paper, the detuning curves of the CAEP FIR FEL and the Jefferson Lab IR Demo FEL are calculated with the help of our 3D code, which are compared with those from 1D simulations and the experiments. The influence of the optical guiding and other three-dimensional effects on the detuning curve is studied. It is found that the length of the detuning curve from 3D simulations is shorter than that from 1D simulations when the gain is high and in better agreement with experiments. The 3D non steady-state simulations give better results than the 1D calculations and super-mode theory. The 1D non steady-state simulations with TE_{00} mode and energy spread can give good results due to the facts that the emittance of the electron beam is very small and the optical cavity is a stabile.

The optical guiding effects cause an increase in the gain in the 3D simulations. In general the increase in the gain results in an increase in the length of the detuning curve. It is found, however, that the length of detuning curve from the 3D simulations and experiments seems to be shorter than possible with a higher gain. Does it hint that the optical guiding effects can shorten a detuning curve even though the gain is increased in the case of a high gain FEL oscillator? It is the subject of a future work.

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REFERENCES

[1] H. Al-Abawi et al., Optics Comm. 30 (1979) 235.
[2] W.B. Colson and A. Renieri, J. Phys. Colloq. 44 (1983) 11.
[3] G. Dattoli et al., Nucl. Instr. and Meth. A 285 (1989) 108.
[4] S. Benson et al., Nucl. Instr. and Meth. A 429 (1999) 27.
[5] G.R. Neil et al., Nucl. Instr. and Meth. A 445 (2000) 192.
[6] Xiaojian Shu and Yuanzhang Wang, Nucl. Instr. and Meth. A 483 (2002) 205.
[7] Wang Taichun and Wang Yuanzhang, High Power Laser and Particle Beams, 7 (1995) 25, (in Chinese).
[8] Xiaojian Shu et al., Optical Engineering, 39 (2000) 1543.
[9] Xiaojian Shu, Optics Comm. 105 (1994) 188.
[10]Xiaojian Shu et al., J. Appl. Phys. 77 (1995) 426.
[11]D.C. Quimby et al., IEEE J. Quantum Electron. QE-21 (1985) 979.