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STUDY OF INFRARED FREE ELECTRON LASER OSCILLATOR WITH TOHOKU LINAC

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Abstract

The performances of a free electron laser oscillator based on Tohoku Linac are numerically analyzed with a one-dimensional nonlinear theory. It is shown that the FEL can operate in wavelengths of infrared range and a radiation power of several megawatts can be obtained. Some design parameters are discussed. The FEL based on Linac has various applications for its advantages of broad spectral range, picosecond pulses and high peak power.

1. Introduction

Since the first free electron laser (FEL) experiment was achieved, the FEL has developed rapidly in last two decades due to its advantageous characteristics of high power, high efficiency and tunability of frequency[1-4]. In FEL, a simple relationship of the radiation wavelength λ_r with the undulator period λ_u and electron energy factor γ is $\lambda_r=\lambda_u/2\gamma^2$. Thus the wavelength can be tunable by changing the electron energy or undulator period, and the FEL, in principle, can operate in wavelength region of millimeters to X-ray. The FEL based on a linac, therefore, have attracted considerable interest in researches and applications of biology, medical, material and industry because it would be the only source capable of providing picosecond pulses of coherent radiation in the infrared wavelengths. In this paper, a one-dimensional nonlinear simulation mode is used to analyzed the performances of a free electron laser oscillator with the Tohoku Linac. It is shown that the FEL can operate in wavelengths of infrared range and a radiation power of several megawatts can be obtained. Some design parameters are also discussed.

2. FEL Equations

We consider that an electron beam transforms in a planar undulator with constant parameter and exchanges its energy with the radiation fields. For simplifying, we consider one-dimensional case and use the approximate condition of the slowly-varying field amplitude and phase. The longitudinal motion of electrons (averaged over the undulator period) is described by the Lorentz factor γ and the electron phase ψ as[5,6]

$$\frac{d\gamma}{dt}=-\frac{eK}{\gamma_R mc}E_r[J_0(\xi)-J_1(\xi)]\sin(\Psi+\phi_r)\ , \qquad (1)$$

$$\frac{d\Psi}{dt}=2ck_u\frac{\gamma-\gamma_R}{\gamma_R}\ , \qquad (2)$$

where $\xi=\frac{1}{2}\frac{K^2}{1+K^2}$, $k_u=2\pi/\lambda_u$ is the undulator wavenumber, $K=\frac{eB_u\lambda_u}{2\pi mc}$ undulator parameter and γ_R the resonant energy factor given by the relation of $\gamma_R^2=\frac{1+K^2}{2}\frac{\lambda_u}{\lambda_r}$. E_r and ϕ_r describe, respectively, the field amplitude and initial phase with respect to the electron. J_0 and J_1 are the Bessel functions of first kind.

The evolution equation for the radiation field with the electron is described by Maxwell equations, where the moving electrons is used as transverse current density. Assuming the condition of the slowly varying field amplitude and phase approximation, the evolution of radiation field amplitude is governed by the following complex partial differential equation,

$$\left(\frac{\partial}{\partial z}+\frac{1}{c}\frac{\partial}{\partial t}\right)E=-\frac{iKJ_e}{2\varepsilon_0\gamma_R}[J_0(\xi)-J_1(\xi)]\langle\exp(i\psi)\rangle \qquad (3)$$

where $E=E_r\exp(i\phi_r)$ is the complex field. The bracket $\langle\cdots\rangle$ indicates the average over all the electrons in a volume V. J_e describes current density of moving electrons.

The Eqs.(1) and (2) describe the evolution of the electron energy and phase. The Eq. (3) describes the evolution of radiation field amplitude, in space and time, due to the interaction with electron beam. These equations are a set of self-consistent FEL equations from which the general time-dependent, saturated behavior of the radiation field can be described by numerically integrating these motion equations of the electrons and the radiation field.

3. Numerical simulation

We focus our interest in the important case of an free electron laser oscillator with a linac. Because of the limitation of electron beam current in linac, the gain in the FEL is small for single pass of electron pulse and it usually operates as an oscillator. The radiation electromagnetic wave, reflected by the two mirrors, then back to the entrance of the undulator, can be repeatedly amplified. The length of the cavity must be taken to keep the electron bunch and radiation pulse synchronizing when they enter the undulator field. Using the self-consistent one-dimensional FEL theory[5)], the performances of the infrared FEL oscillator with Tohoku Linac are analyzed numerically.

The initial distribution of electrons in a bunch is assumed to have parabolic form in space and random form in energy. According to the operation conditions of Tohoku Linac, an electron beam with energy of 32 MeV, energy spread of 0.5% are taken. The bunch length of 1.2 mm, beam cross area of 2×2 mm^2 and peak bunch current of 10 A are supposed, corresponding to current density of 2.5 10^6 A/m^2. The period and field amplitude of undulator is 4.0 cm and 0.268 T, respectively, so the undulator parameter K approximately equates to unit. The total length of undulator is 240 cm with respect to 60 periods. The cavity length L_c must be chosen to satisfy the synchronization condition $nL_b=2L_c$, where L_b is the distance between two electron bunches. The total reflectance of the cavity is assumed as 98%. The FEL parameters are summarized in Table 1.

Table 1. The parameters of FEL oscillator with Tohoku Linac.

Accelerator	
Type	Linac
Macropulse length	3 μs
Macropulse repetition rate	300 Hz
Micropulse length	3-4 ps
Macropulse repetition rate	2856 MHz
Beam energy	20-60 MeV
Energy spread	0.5%
Emittance	45 mm mrad
Macropulse current	100-200 mA
Average current	150 μA
Wiggler	
Type	Planar permanent
Period	4 cm
Number of periods	60
Wiggler parameter	1 - 2
Wiggler field	0.268 T
Cavity	
Length	3 m
Mirror reflectance, M1	99.9%
M2	98.0%
Coherent Radiation	
Wavelength	10 μm
Power	~ 5 MW

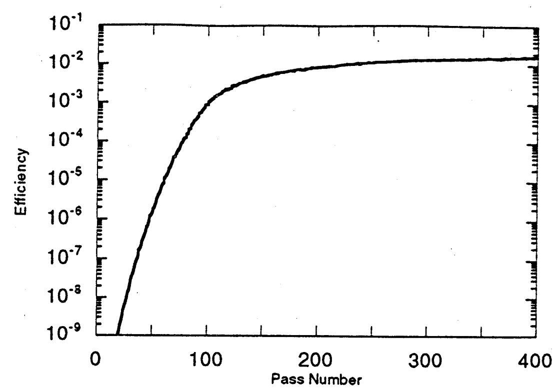

Fig.1 The Efficiency vs. pass number.

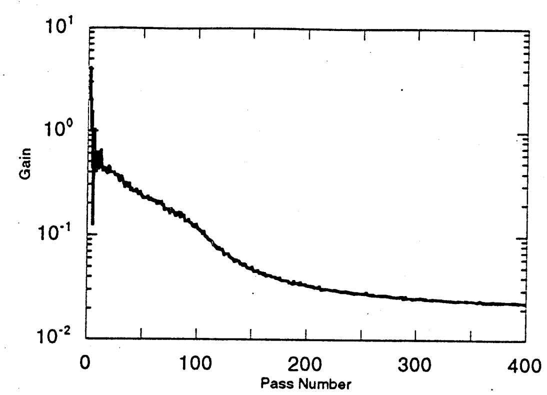

Fig.2 The gain vs. pass number.

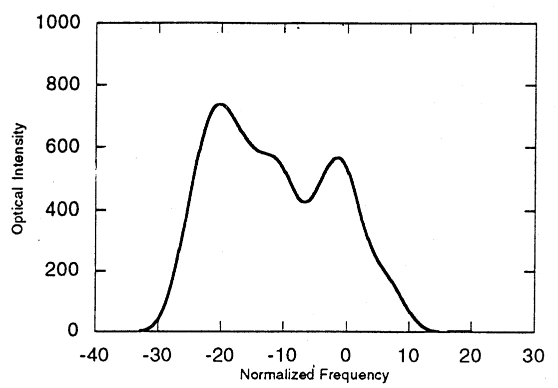

Fig.3 Optical intensity vs. normalized frequency.

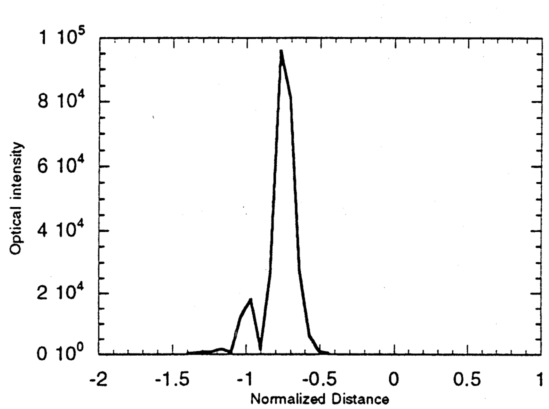

Fig.4 Optical intensity vs. normalized distance.

Some typical numerical simulation results are shown from figure 1 to 3. Figs. 1 and 2 show the relationship of efficiency and gain of radiation field with the oscillation numbers of radiation pulse between the cavities. As shown in Fig.1, the efficiency of FEL oscillator increases exponentially from noise under the pass number of 100. After that it gradually reaches to saturation with a value of one percent. In the case of electron energy of 32 MeV, peak current of 10 A and assuming that the energies loss in electrons are transferred totally to the radiation field, the laser output peak power of several megawatt can be obtained, corresponding to average radiation power of several ten kilowatt. The gain of the FEL oscillator decreases approximately to the total loss of the cavity at saturation, shown in Fig.2.

Fig.3 shows the dependence of optical pulse intensity with the distance of $(z\text{-}ct)/N_u\lambda_R$, where the distance is measured as a relative point in the moving optical field and normalized the slip length $N_u\lambda_R$. From Fig.4 we can see that the optical gain in the front part of the laser pulse are relatively low, where is in the absence of electrons due to the effective of slippage. Thus, in practically, the electron pulses should be put enter the undulator slightly earlier than laser pulses in FEL experiments.

The optical spectrum at saturated regimes is shown in Fig.4, where the frequency, or more precisely wavenumber, is normalized as $N_u\lambda_R(k\text{-}k_R)$. We can see from this figure that the optical pulse gains in a relatively wide spectrum and shifted down far from its resonance value because of the low-energy electrons.

4. Conclusions

Based on above discussion and the operating parameters of Tohoku Linac, it is possible to realize an infrared free electron laser oscillator with this accelerator. The parameters of the FEL are summarized in Table 1. The FEL may be operating in the wavelength of infrared regime and reach to the peak power of several megawatt.

References

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