CONSIDERATION ON TERAHERTZ FEL USING PRE-BUNCHED ELECTRONS SHORTER THAN THE WAVELENGTH*

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Abstract

Interaction between optical field and electron pulse, whose bunch length is much shorter than a wavelength (pre-bunched beam), has been studied by developing a simulation code based on 1-D FEL equations for oscillator configuration. Since coherent spontaneous (CSR) radiation dominates in early stage of the oscillation, we have not applied shot-noise electron population in an optical potential. Start-up of lasing is very much faster because of CSR, and the FEL interaction at head of the optical pulse becomes significant, so that the pulse width gets shorter. It is just the contrary of lethargy effect occurred at zero-detuning with the long electron pulse. In addition saturation mechanism seems to be different from that with the long electron pulse and saturated peak power is very much higher than that of conventional FELs. As a whole the FEL with pre-bunched beam is very much attractive for future light source particularly in terahertz (THz) wavelength region because of unique properties of the optical pulse evolution.

INTRODUCTION

To evaluate fundamental characteristics of conventional FELs, we assume an electron pulse sufficiently longer than the FEL wavelength in general (long pulse approximation). In the process of microbunching, the optical pulse gains the power exponentially. Taking finite bunch length into account, head of the optical pulse does not grow as much as tail part of it due to slippage. Consequently if there is no detuning for an optical cavity, the electrons are no longer able to be microbunched because of no power growth at head of the optical pulse, which is well known as lethargy effect.

Recent progress of the linac technology enables us to utilize high brilliant beam in 6-dimensional phase space. Accordingly the electron bunch length reaches sub-picosecond that is, for instance, much shorter than the wavelength of THz radiation. We have studied a THz FEL employing such pre-bunched beam by applying 1-D FEL equations [1]. Since bunching factor of ~ 100 fs bunch length is already close to unity in the optical potential of THz radiation, non-linear power amplification is expected to occur. Bunching factor is applied to long pulse approximation basically, so that we have to discuss the pre-bunched FEL carefully. The study has been focused on which power evolution of the optical pulse and saturation mechanism of the pre-bunched FEL in oscillator configuration.

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SOURCE APPARATUS

An accelerator-based THz radiation source has been developed at Tohoku University. The THz source may consist with an advanced linac oriented to producing extreme short electron pulses and an isochronous ring for preserving short bunch length during circulation [2]. We have developed an Independent Tuneable Cells (ITC) RF gun in order to manipulate the longitudinal phase space for bunch compression by changing input powers and relative phase between two cells independently [3]. Scheme of bunch compression toward the bunch length less than 100 fs is presented elsewhere [4].

Along with the coherent THz radiation source, we have investigated possibility of pre-bunched THz FEL driven by electrons of which the bunch length is much shorter than the wavelength. Of interest in this pre-bunched FEL is the phase space evolution of the pre-bunched beam in the separatrix of the optical pulse. Accordingly, to exclude complicate transaction for waveguide mode and unessential physics, we have employed open resonator model in free-space assured by a large gap undulator. As shown in Table 1, we presume that the undulator period and the peak magnetic field are 8 cm and 0.3 T. Using permanent magnet widely used such as Nd-Fe-Bo or Sm-Co, a magnetic gap would be ~ 6 cm that may secure enough room for free-space against THz frequency region in an optical cavity. Employing a beam energy of 12 MeV, the resonant wavelength is 254 μm (1.2 THz). Simulation study so far has proven the accelerator system can provide a bunch charge of 20 pC for 100 fs bunch length, in which case the FEL parameter becomes 0.0043.

SIMULATION OF PRE-BUNCHED FEL

Field envelope of radiation and bunching factor

Based on the 1 dimensional wave equation for the FEL interaction, the field envelope of the radiation $\underline{E}_L$ is

Table 1: Undulator and beam parameters

Undulator period	λ_w	0.08 m
Number of period	N_w	20
Peak magnetic field	B_w	0.3 T
Resonant wavelength	λ_r	254 μm
Beam energy	γ	23.5 (12 MeV)
Total beam current	Q	20 pC
Normalized emittance	ε_n	~ 2 π mm mrad
Peak current	I	80 A
FEL parameter	ρ	4.3E-3

described as

$$\left(\frac{\partial}{\partial z}+\frac{1}{c}\frac{\partial}{\partial t}\right)\underline{E}_L e^{i\phi L} = i\,\frac{e a_w}{2\varepsilon_0\gamma_r}\left[J_0(\xi)-J_1(\xi)\right]\frac{N}{V}\left\langle e^{-i\psi_i}\right\rangle \quad , \tag{1}$$

where a_w, γ_r and J are the undulator parameter (diffraction parameter), the resonant energy of the electron and the Bessel function, respectively. We note in eq. (1) that if we chose the unit volume V for one wavelength in the z-direction, $\left\langle e^{-i\psi_i}\right\rangle$ is like a form factor of electron phase averaging over the optical wavelength. That is so-called the bunching factor. Eq. (1) is obviously valid for which the field envelope is not steeply varied (slowly varying envelope approximation; SVEA).

Micro-bunching is occurred in process of FEL interaction in general. It is apparent that there would be no field evolution because of zero bunching factor, if the initial electron distribution is completely uniform. Therefore a shot-noise in the electron population is required for the start-up. In the pre-bunched FEL, the bunching factor is already significantly large at a beginning of the interaction. This means CSR is dominant in the early stage of the FEL oscillation, which is clearly described in eq. (1).

Bunching factor for shorter bunch length

For a code for pre-bunched FEL, we have employed non-dimensional FEL equations

$$\frac{\partial}{\partial\tau}\underline{a}(\varsigma,\tau) = i j_e(\varsigma)\left\langle e^{-i\psi_i}\right\rangle_{|\varsigma=\varsigma_i(\tau)}, \tag{2}$$

$$\frac{\partial}{\partial\tau}\mu_i(\tau) = \mathrm{Re}\left[i\,\underline{a}(\varsigma,\tau)\right]e^{i\psi_i(\tau)}, \tag{3}$$

$$\frac{\partial}{\partial\tau}\psi_i(\tau) = \mu_i(\tau) \tag{4}$$

and

$$\frac{\partial}{\partial\tau}\varsigma_i(\tau) = -1, \tag{5}$$

where $\underline{a}$, μ_i, ψ_i and ς_i are the field envelope amplitude, the relative electron energy, the electron phase and electron position respect to the FEL field, respectively [5]. Symbols τ and j_e are normalized time and non-dimensional beam current, respectively.

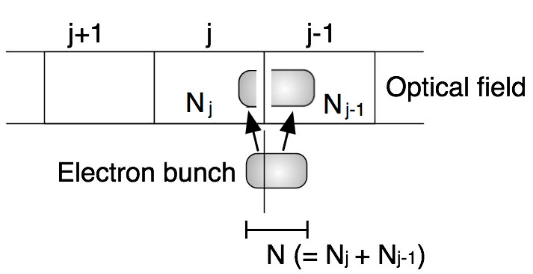

Figure 1: Partition of the electron bunch for calculating the bunching factor in each slice of the optical field.

In the long pulse approximation, slippage effect is not required for evaluation of the FEL, and evolution of only one optical potential is sufficient to calculate. However, for the pre-bunched FEL, we have to take slippage into account correctly and number of optical potentials prepared in the calculation is at least equal to that of undulator periods.

In the calculation, we have employed a smaller time step $\Delta\tau$ for integration of the FEL equations as $\tau/N_w/m$. We confirmed that there was no significant difference in results for $m>20$, so that we have used $m=24$ for actual calculation. A particular case in such calculation is indicated in Fig. 1. We considered that the electron distribution has to be distributed into two slices for the bunch across separatrix.

SIMULATION RESULTS

In the simulation study, rectangular distribution is employed for the electron bunch and the length of $\lambda_r/3$ is assumed as the pre-bunched beam. Number of slices for the optical field ζ is $21(=N_w+1)$. Note we have not taken detuning length into account throughout this study because lethargy effect is not occurred in the pre-bunched FEL as mentioned later.

In the following, no detuning length for the optical cavity is included in the simulation

Evolution of field amplitude in early stage

Figure 2 shows the field amplitudes $\underline{a}(\varsigma)$ after 1, 5, 10 and 20 round trips. In addition to that temporal structure of optical pulse is almost flat, one notices the amplitude is linearly growing turn by turn.

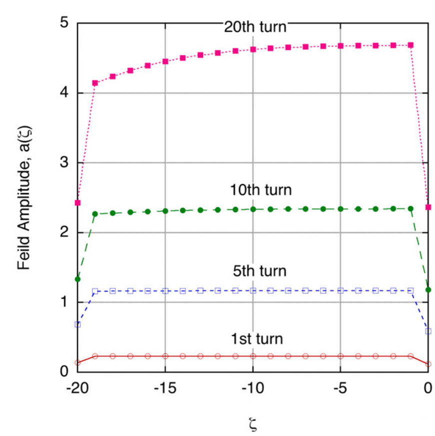

Figure 2: Evolution of the field amplitude at the beginning of lasing. Up to ~ 20 turns, the amplitude grows linearly.

This means the electric field of the radiation is piling up each turn. In other words the CSR dominates in the interaction. However at the 20th round-trip, temporal structure deviates from the flat distribution. That is the FEL interaction begins to compete with.

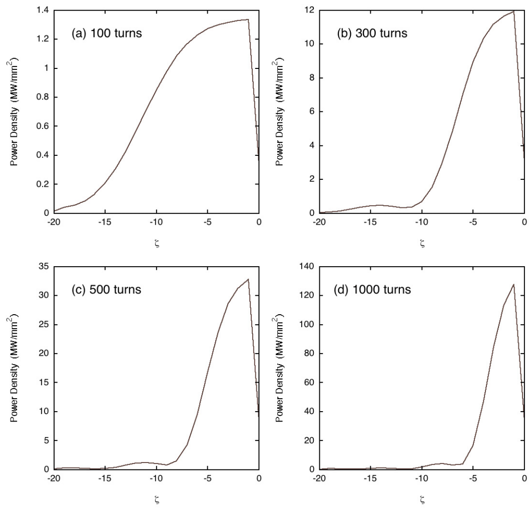

Figure 3: Evolution of the field amplitude at the turns of 100(a), 300(b), 500(c) and 1000(d), respectively.

Evolution of field amplitude in late stage

After the FEL interaction surpasses the pile-up of CSR, shape of the optical pulse becomes forward peak as shown in Fig. 3. At the 1000 turns, only the 1st slice is getting vigorous. It is very interesting because several-cycle optical pulse with a high electric field would be produced by the FEL oscillation.

Mechanism of rapid growth of the head slices is found in Fig. 4. The bunch quickly looses the energy in the optical potential after entering the undulator, and goes out from the optimum phase so that growth late of the optical potential behind is slower than head. After considerable difference of the field amplitude is formed, the bunch is thrown out of the separatrix by the FEL interaction in the head slices.

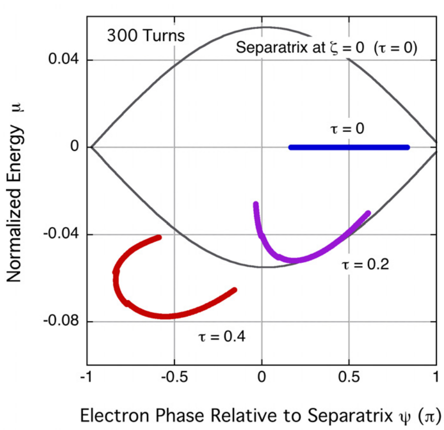

Figure 4: The phase space evolution at 300th round-trip. The bunch phase relative to the 1st slice of optical potential is around $\pi/2$ at the entrance of the undulator. At $\tau = 0.4$, the bunch is passing through the 8th slice because the number of undulator period is 20. As shown in Fig. 3(b), the separatrix of the 8th potential is much smaller so that the bunch is no longer inside of the separatrix.

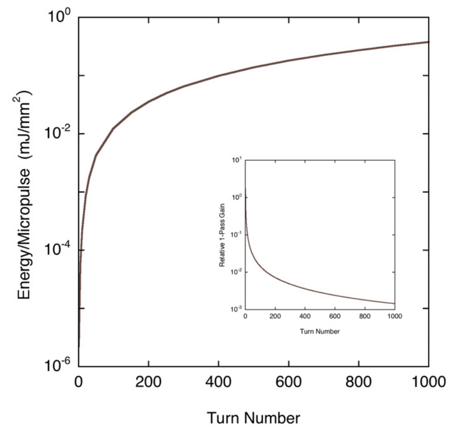

Figure 5: Evolution of micropulse energy plotted as a function of the turn number. Insert shows relative one-pass gain.

However such steep variation of the amplitude in an optical pulse suggests an issue whether SVEA is still valid or not. This may be crucial subject for understanding the pre-bunched FEL.

We noted that the electron phase relative to the 1st slice of the optical pulse becomes to $\pi/2$ after several tens round trips where the instantaneous gain is the highest. This phenomenon was also found in calculations of which seed optical fields were applied for initial stage with various phase relative to the electron. We have supposed CSR establishes the phase of the optical field, which is taken over by the FEL interaction.

Growth and saturation

Growth of the micropulse energy is shown in Fig. 5. As one notice from Fig. 4, saturation mechanism of the pre-bunched FEL is supposed to be completely different from conventional FELs. Even at 1000 turns, there is no sign of power saturation. As shown in an insert of Fig. 5, though the gain drops gradually it somewhat remains.

SUMMARY

An oscillator THz FEL driven by the electron bunch much shorter than resonant wavelength has been studied. We presume the line charge whose longitudinal length is one third of the THz wavelength, which corresponds to a bunch length of 100 fs with Gaussian distribution.

For applying the pre-bunched FEL to actual experiment, we have to take 3-dimensional effects for filling factor and diffraction loss into account because diffraction properties are significant in the long wavelength regime particularly. A 3-D code GENESIS would be possible tool to evaluate 3-D effects in the optical cavity [6]. However the code does not care the bunch length less than wavelength, so that proper initial phase distribution of the electrons cannot be prepared as it is.

Furthermore validity of SVEA for the pre-bunched FEL is also important but interesting problem.

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