DEVELOPMENT OF THz LIGHT SOURCE USING PRE-BUNCHED FEL

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Abstract

A project of pre-bunched FEL as a Terahertz (THz) light source using short electron bunches less than 100 femtosecond has been progressed at Laboratory of Nuclear Science, Tohoku University. We expect FEL with shorter electron bunch generates different characteristics of light pulse from conventional FELs with long electron bunch. By choosing appropriate initial electron phases (bunch length is less than wavelength of FEL), the FEL gain will be higher. We have developed a numerical simulation code by solving 1-D equations. We report on time structures of FEL field and trajectory of electron in separatrix.

INTRODUCTION

The THz light (wavelength between 3μm – 1mm) is located in a spectrum region between microwave and infrared light. Since these wavelength regions correspond to energy level of vibration, rotation and absorption in molecules, various scientific applications in the fields of molecular science and bio-medical science are expected.

An FEL project of high intensity THz light source based on accelerator has been progressed at Laboratory of Nuclear Science, Tohoku University. The most noticeable feature of the project is use of very short electron beam whose bunch length is less than 100 fs. As for conventional FELs, it is general to use long electron bunches compared with wavelength of FEL. Research of the FEL interaction with the electrons having bunch length less than FEL wavelength seems to be interesting. Since electron bunch length is less than wavelength of FEL, we can choose initial phases of electron in separatrix. By choosing appropriate initial phase, field gain is expected to be higher.

We report on time structures of FEL field and time evolutions of phase space derived from numerical simulation using 1-D FEL equations.

A PROJECT OF PRE-BUNCHED FEL

Here we define “Pre-bunched FEL” is an FEL driven by shorter electron bunches less than FEL wavelength. To generate THz light with the pre-bunched FEL, very short electron beam whose bunch length is less than 100 fs is needed. In order to produce such short bunch, we have developed an Independent Tuneable Cells RF gun (ITC RF gun) and a bunch compressor employing an α-magnet. The THz light source is composed of ITC RF gun, a bunch compressor, accelerator and an FEL device. Before entering the undulator section, the electron beam energy reaches 12 MeV, the normalized emittance is ~ 2 πmm mrad, and the bunch length is less than 100 fs (pre-bunched).

ITC RF gun

ITC RF gun has two independent cavities. Each cavity has independent RF input port. By changing RF input power and phase independently, we can manipulate longitudinal phase space to be optimum for the bunch compressor [1].

Bunch Compressor

We have planed a bunch compressor equipped α–magnet. Since the electron trajectory in the α-magnet is relatively short, space charge effects will be minimized and the whole system can be compact.

DETAILS OF SIMULATION

Parameter

Parameters for the numerical simulation are listed in Table 1. The electron beam is assumed to be a rectangular shape (uniform distribution in the space), and the bunch length is employed to be 100 fs. In the calculations, the bunch length of the electron beam is supposed to be one-third of the resonant wavelength (λr).

Table 1: Parameters

Electron kinetic energy	E=12 [MeV] (Δ E = 0)
Undulator period	λ = 0.08 [m]
Number of undulator period	N = 20
Peak magnetic field	B = 0.3 [T]
Resonance wavelength	λ r = 256 [μm]
Total bunch charge	Q = 20 [pC]
Normalized emittance	ε ~ 2 [π mm mrad]
Peak current	I = 80 [A]
FEL parameter	$\rho \sim e^{-3}$
Electron bunch length	L= λr/3 [μm]

Simulation code

The code calculates FEL interaction between the electric field and the electrons with finite bunch length by solving 1-D FEL equations with Euler method. We set several assumptions and conditions as follows:

- Variation of the field is not so large within one wavelength. (We use slowly varying envelope approximation)
- The calculations are varid for the resonant wavelength (λr).

- Because of slippage effect, the length of stored light pulse is assumed to be (N+L)λr. N is the number of the undulator and L is the electron bunch length in λr unit.
- Mirror loss (R) is not considered. Initial field envelope at n+1 turn is A_0 (n+1) = A (n) (at the undulator exit).
- Initial value of field envelope at 1-st turn (A_0) is arbitrarily chosen. (the simulation assumes that seed light is laser field).
  The calculations are NOT started from spontaneous radiation.

Under these assumptions, electric field envelope, electron energy and phase are calculated.

FEL equations

The calculation is based on following 1-D FEL equations [2,3].Electric field envelope is calculated by

$$\frac{\partial a(\zeta,\tau)}{\partial \tau} = ij_e(\zeta)\left\langle \exp^{-i\psi_i(\tau)} \right\rangle \quad (1)$$

Right term in Eq. (1) is defined as bunching factor which is calculated by averaging over electron phases within an optical wavelength.

Electrons phase and energy are calculated by so-called pendulum equations

$$\frac{d\mu_i}{d\tau} = \mathrm{Re}\left[ia(\zeta_i,\tau)\exp^{-i\psi_i(\tau)}\right] \quad (2)$$

$$\frac{d\psi_i}{d\tau} = -\mu_i(\psi) \quad (3)$$

SIMULATION RESULTS

In this section we describe results of the simulation i.e., pulse structure of FEL field and electron phase space in separatrix. In addition, we show the results of 1-pass gain and field amplitude with various electron initial phases. Since the electron bunch length is shorter than optical wavelength, the electrons have particular phases in separatrix at the undulator entrance. We have examined initial phase dependences of field amplification.

1-pass field gain

Figure 1 shows 1-pass gains of FEL field. Electron bunch length λr and λr/3 with various initial phases were calculated. In the case of the bunch length λr/3, the field gain is higher than the bunch length λr despite using the same peak current (FEL parameter is identical).

It also shows that 1-pass gain of short electron bunch is subject to turn number.

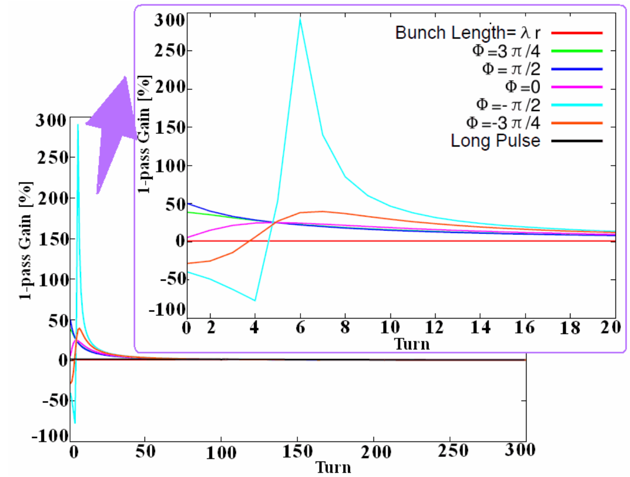

Figure 2 : 1-pass gain of FEL field

Pulse structure (after 300 turns)

Figure 2 shows time structures of FEL pulse after 300 turns. The upper is for the bunch length of one third of λ_r. The lower is for the bunch length of 1 wavelength (λ_r) with the uniform initial phase distribution. From the result, the remarkable difference between two cases is that in the case of electron bunch length of λr/3, the light pulse has a strong forward peak and no lethargy effect. Although at the beginning of the turns(≦20-th turns), both phase regions (gain and loss) exist, any initial phases become to have a positive gain as turn number increasing. For bunch length of λr, the light pulse has a weak backward peak with bunching of electrons, which is namely lethargy effect.

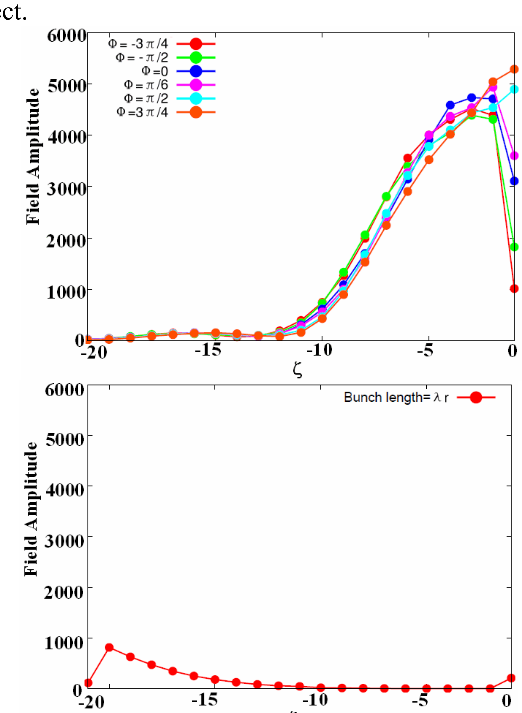

Figure 2 : Pulse structure of FEL filed after 300 turn. The upper is bunch length of λr/3 calculated with various electron initial phases. The lower is bunch length of λr

Phase space (after 300 turns)

We calculated time evolutions of the longitudinal phase space from the undulator entrance (τ= 0) to the undulator exit (τ=1) at 300-th turns. In FEL interactions with short electron bunches, electrons no longer rotate in separatrix. For electron bunch length of λr, despite the deviation from separatrix, electrons still behave like a ponderamotive movement. (Fig.3 upper) However, electron bunch length of λr/3 is quite different from electron bunch length of λr. The trajectory of the electrons widely deviate from separatrix and move along boundary of separatrix. Consequently every electron loses energy. Such electron movement in the phase space does not change so much for various initial phases (Fig. 3 lower) .

Most interesting feature of electron bunch length of λr/3 case can be seen in phase shift of electrons in separatrix at the undulator entrance. Figure 4 shows whichever initial phases we choose, electron average phase in separatrix at the undulator entrance (ϕ) is rapidly approaching to π / 2. This effect is particular to the case of electrons whose bunch length is less than FEL wavelength. It is considered to be one of the distinctive pulse structures: forward peak and no lethargy effect.

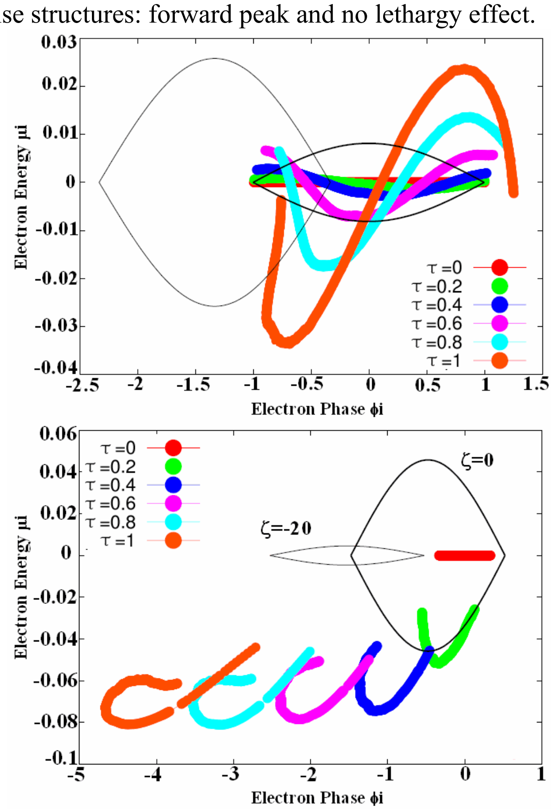

Figure 3: Time evolutions of phase space at the 300-th turns. The upper is for bunch length λr, the lower is for bunch length λr/3 with electron initial phase, ϕc=0. Black solid lines are separatrix at the undulator entrance, τ=0 (thick line) and at the undulator exit, τ=1 (thin line). Electron phase spaces are plotted at τ=0 , 0.2 , 0.4 , 0.6 , 0.8 and 1.

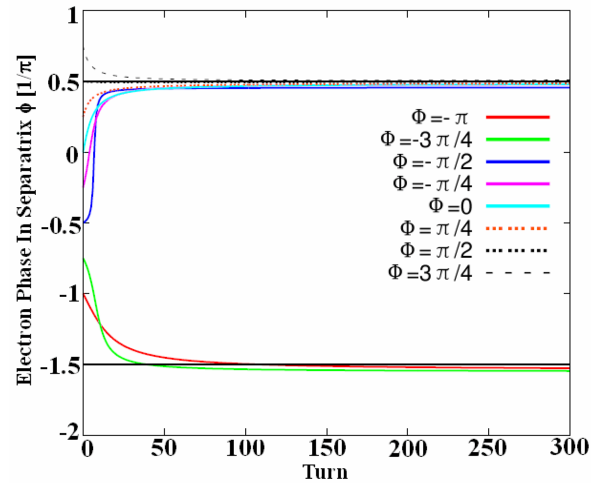

Figure 4: Electron averaged phase shifts in separatrix plotted as a function of turn number (bunch length = λr).

Field amplitude with various initial phases

Figure 5 shows integrated intensities of FEL pulses after 300 turns for various initial phases. At the first turn (Fig. 5 upper), there are both gain phase and loss phase regions, which is consistent with energy shift of electrons in separatrix of the long pulse assumption. The shape shifts as turn number increase (Fig. 5 bottom). Around 20-th turns, the FEL field has a positive gain at all initial phases. Figure 5 also shows that for electron bunch length λr with the same peak current. Compared with the electron bunch length of λr/3 case, amplification of FEL field is much smaller.

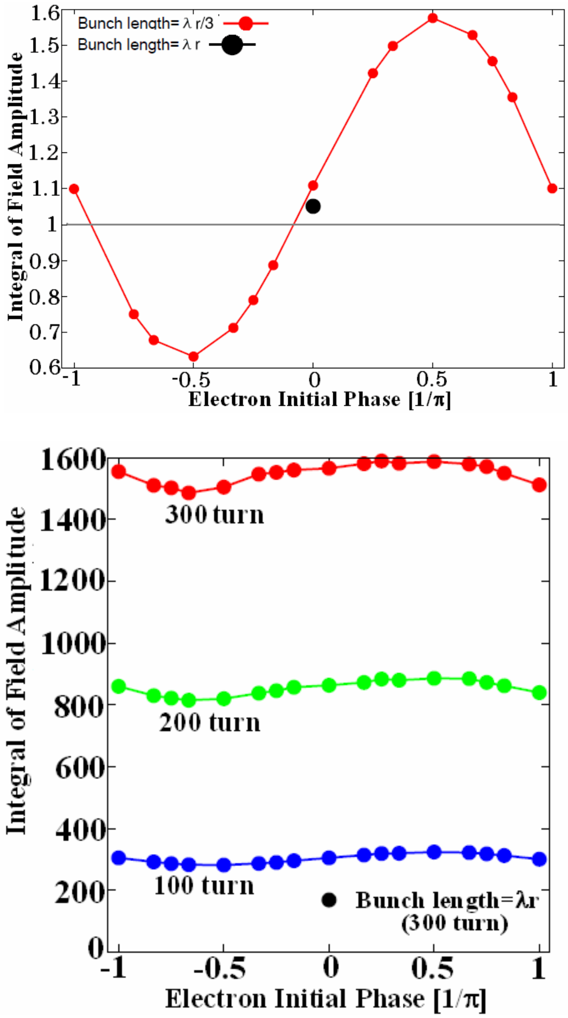

Figure 5: Initial electron phase dependences of the intensity of amplified FEL field after n-th turns. The upper is for after 1-st turn, the lower is for after 100-th ,200-th and 300-th turns.

SUMMARY

A project of pre-bunched FEL as a high intensity THz light source using very short electron bunch less than 100 fs has been progressed.

From the simulations, we obtained interesting features of FEL interaction with electrons having bunch length less than FEL wave length. The most remarkable point is electron phases in sepataratrix rapidly shift to π/2 [4]. It is the distinguish characteristic of pulse structure of the pre-bunched FEL. The light pulse has a forward peak, no lethargy effect and higher gain.

The calculations, however, contain several problems. First of all, the effect of coherent radiation is not included in the calculation. Since electron bunch length is shorter than wavelength of FEL, the effect of coherent radiation cannot be neglected. Phase between every coherent radiation and stored field is important subject. Secondly, the validity of FEL equations should be reconsidered. We found when we apply FEL equations to small initial electric field and large bunching factor, the energy conservation is not satisfied. Thirdly, definition of bunching factor is not clear if it is extended to the case of very short electron beam. For example, the region for averaging the electron phases and the partition of electron distribution are ambiguous. Further discussion on the physical meaning of bunching factor and approximation process of FEL equations is highly desired. To apply calculations employing coherent radiation as a seed light, more fundamental equations based on Maxwell's equation which can be applied for such conditions is indispensable.

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