

SIMULATION FOR THZ COHERENT UNDULATOR RADIATION FROM COMBINATION OF VELOCITY BUNCHINGS

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Abstract

We study the effect of a combination of velocity bunchings and its application to THz coherent undulator radiation at LEBRA, Nihon U. by simulations. The velocity bunching is a technique that is commonly used to make the bunch length shorter at lower energies. However, since one velocity bunching has a correlation between bunch energy and length, we may not have so much room to change energies to obtain different coherent radiation wavelengths. Hence we propose a combination of velocity bunchings that relaxes the restrictive correlation.

We have three 4 m traveling-wave accelerator tubes at LEBRA, Nihon U. The undulator is installed after the acceleration tubes and 2×45 degree bending magnets. Since the design of current undulator requires less than 25 MeV beam energy to obtain the radiation in THz region, the velocity bunching is reasonable for coherent radiation. We show the simulation results of a combination of velocity bunchings of the three tubes and the magnetic bunching at bending magnets, suitable for coherent undulator radiation.

INTRODUCTION

Thanks to the recent advances of spectroscopy, the light source of terahertz (THz) region became an exciting frontier. The THz source has a great potential to open up a new direction of material research at milli-electron volt (meV) region, including the physics related to intermolecular forces (see e.g. [1]).

The accelerator technologies are now mature so that the electron bunch can be compressed suitable for generating bright THz radiation. When the bunch length is shorter than the wavelength of generated radiation, the phases of each photon are no longer random, resulting in the coherent radiation whose power is proportional to the square of the peak current. Here we focus on one of the method of bunch length compression, called the "velocity bunching".

When the electrons of few mega-electron volts (MeV), that are slightly slower than the speed of light, enter in a traveling wave tube, the different acceleration gradient between head and tail of the bunch are applied given the suitable phase of microwave acceleration. If the tail particles are accelerated more than head particles, there is a crossover point where the bunch length is compressed. However, when we apply this method by using one traveling wave tube, i.e. the ordinary velocity bunching, we encounter the correlation between the minimum bunch length and the energy of electrons. The energy of electrons crucially affects the wavelength of resulting radiation, and there may not be large room to select

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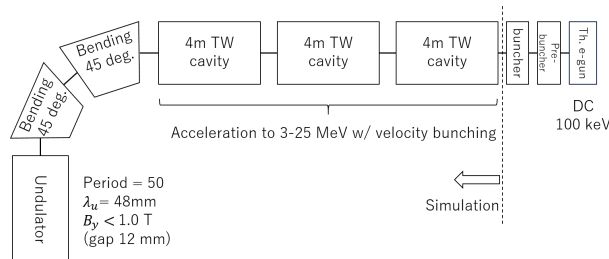


Figure 1: The sketch of LEBRA beam line. Quadrupole magnets are not displayed.

the wavelength upon users' requests. So we introduce the "combination of velocity bunchings" by using some traveling wave tubes instead of one, relaxing the correlation and introducing a freedom of choices of radiation wavelength but keeping the bunch length shorter. Although the parameter space is enlarged by the introduction of some number of tubes used both for accelerations and decelerations, the recent computing techniques including parallel computations help to find the good parameter region efficiently. Note that some results of the combination of velocity bunchings were reported in [2] (written in Japanese).

In this presentation, we show the simulation results of the combination of velocity bunchings as well as the optimization of the undulator coherent radiation as an application. At the LEBRA facility, the undulator is currently used for the generation of infrared rays as the oscillator free-electron laser (FEL). However, we can consider the generation of THz undulator radiation when the electron energy is less than 25 MeV. Since the undulator is installed after the 2×45 degree bends as in Fig. 1, we also think of the magnetic compression at the bending section. The magnetic compression requires the enough bunch energy spread to have path length differences. Since the combination of the velocity bunchings accompanies the energy spread, they are a good match.

It is worth commenting that the ordinary velocity bunching has been used in many places for the bunch compression, including the application to the generation of coherent undulator radiation [3]. Here we clarify the further potential of velocity bunching scheme by introducing the combination of its multiples. The proposed scenario may be useful for both the existed facilities and future accelerators.

ORDINARY VELOCITY BUNCHING

First, we start with the ordinary velocity bunching. Since electrons of few MeV are affected by the space charge force, it is important to estimate their behavior. We use the simulation code, "ASTRA" [4] which has an advantage to deal with the space charge effect accordingly. In our simulation,

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we assume an initial condition given in Table 1 and set at the simulation starting point of Fig. 1 for a better understanding. The parameters here are reasonable at LEBRA. Note that the structure of the buncher is not cyclic and the simulation of this part requires other codes than ASTRA.

Table 1: A Set of Parameters for Electron Initial Distribution

Q	E_k	$\Delta E/E$
40 pC	5 MeV	0.5 %
σ_z	$\sigma_{x,y}$	$\varepsilon_{n,x,y}$
5 ps	3 mm	20 π mrad mm

We perform the simulation given various gradients of the first tube by scanning the phase of acceleration. The resultant bunch length and energy at the exit of the first tube are illustrated in Fig. 2. We clearly see the correlation between the bunch length and the gained energy. Thus if we aim to obtain the minimized bunch length, we do not have so many choices of the bunch energy, which crucially affects the undulator radiation wavelength. At LEBRA, the same klystron supplies the microwave not only for the first acceleration tube, but also for the pre-buncher and buncher. So the condition for electron beam would be tight when we decrease the power of microwave to have the minimized bunch length.

COMBINATION OF VELOCITY BUNCHINGS

Next, we proceed to the combination of velocity bunchings. We use the three traveling wave acceleration tubes installed at LEBRA instead of one, and perform the ASTRA simulation with the initial condition in Table 1. By optimizing the acceleration phases, we can find suitable choices for the combination of velocity bunchings.

Here we introduce the bunch factor $B = e^{-\omega_r^2 \sigma_z^2 / 2}$ that characterizes the coherent radiation, where ω_r is the angular frequency of radiation, and σ_z is the RMS bunch length in units of picoseconds. The radiation power is approximated by $P = ((1 - B^2)N_e + B^2 N_e^2) P_0$ in ideal conditions, where P_0 is the radiation power obtained by a single electron, and N_e is the number of electrons. So, when B gets closer to one, the total power is non-linearly enhanced, resulting in

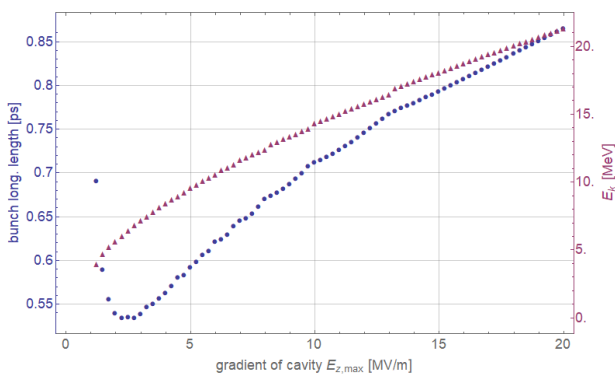


Figure 2: The gradient scan for minimum bunch length (blue circle) and its mean energy (red triangle). Each point is optimized by the phase scan.

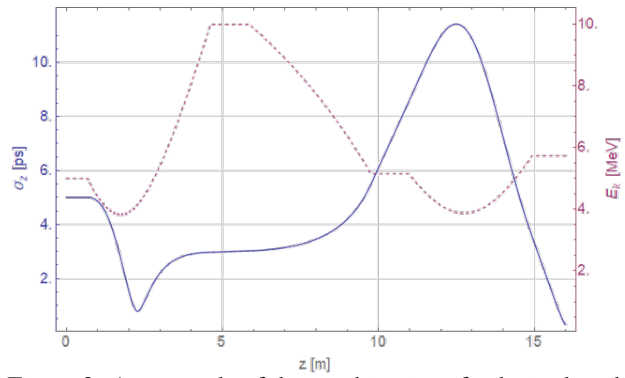


Figure 3: An example of the combination of velocity bunchings by three tubes at LINAC sector. The blue solid line represents the bunch length against longitudinal distance, while the red dashed line shows the mean energy of a bunch.

the coherent high-power radiation. The power estimation with the detail will be estimated afterwards.

We illustrate an example of the combination of velocity bunchings in Fig. 3, where we temporarily expect the bunch length minimized after the three tubes to compare with the result in previous sections, and the transverse beam sizes are controlled appropriately. The minimum bunch length reaches 0.3 picoseconds, and this corresponds to $B = 0.62$ at the radiation frequency $f_r = 0.52$ THz or $E_k = 5.7$ MeV, assuming LEBRA undulator parameters. Hence the bunch length becomes short enough for the coherent radiation. Compared with the result by the ordinary velocity bunching in Fig. 2, the bunch compression here works better. In addition to the acceleration, the deceleration plays the important role of the strong compression. The combination of velocity bunchings enhances not only the range of applications, but also the bunching effect itself. Note that there are also the other sets of parameters good for the coherent radiation at different wavelengths, which are not displayed here.

MAGNETIC BUNCHING

The undulator is installed after the 2×45 degree bending section at LEBRA. In the bending magnet, the outside electrons travel longer distance than the inside, and such the difference is converted into bunch length after the bending section, known as "magnetic bunching". The magnetic bunching is a good match for the combination of velocity bunchings since the velocity bunching can generate the energy spread required by the magnetic bunching.

Given the set of parameters obtained from the simulation of the combination of velocity bunchings, we optimize its trajectory at the bending section. Here we use the "SAD" code [5] which has an advantage to efficient optimization of many magnets for the suitable trajectory. In Fig. 4, the magnetic strength of quadrupole magnets are optimized such that the electron beam becomes achromatic and the magnetic bunching effect is maximized. We also have a slit in-between that removes some electrons spread along a transverse direction (x) so that the bunch energy spread can be decreased properly. We will see how the slit width affects for the undulator radiation in the next section.

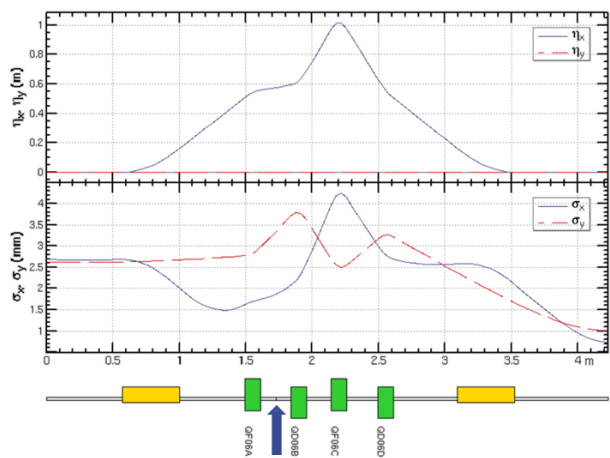


Figure 4: An achromatic optimization at bending sector. The slit is installed at the blue arrow point. The yellow boxes represent the bending magnets, while the green boxes show quadrupole magnets.

UNDULATOR RADIATION

In this section we show the simulation result of the undulator radiation referring the electron beam parameters under the optimization schemes explained in the previous sections. Now the electron beam is optimized for the undulator radiation. We use the simulation code, "GENESIS 1.3" which can deal with the time-dependent three-dimensional dynamics of electron bunch and estimate the resulting radiation at the undulator accordingly [6].

Plugging the optimized electron bunch profiles from ASTRA and SAD into the GENESIS 1.3 simulation, we can estimate the peak radiation power given the radiation wavelength as in Fig. 5. Here we illustrate the peak radiation power at $f_r = 0.48$ THz varying the slit width, as well as bunch energy spread, peak current, and bunch factor, as an example. By decreasing the slit width, the electrons away from the coherent condition are removed appropriately. Hence the bunch factor increases while the peak current decreases. At the balance points ($x = 6 - 10$ mm), we see that the peak radiation power is maximized where the coherent undulator radiation is generated. Although the value of peak power is not large due to the low peak current, we can expect the non-linear enhancement of the peak power once the bunch charge increases.

DISCUSSION

We proposed the "combination of velocity bunchings" which is a method to strengthen the electron bunch minimization with keeping the wide application range of parameters. As an application, we showed the estimation of the coherent THz radiation at LEBRA undulator. The wide range of application ensures that the radiation wavelength can be adjusted upon requests while keeping the coherent condition. Although the searching condition in the large parameter space may not be so easy, this is the age where we can handle with the help of the recent powerful computer technologies.

In the result of the undulator radiation, the peak current of the electron bunch is not large. This is due to the fact that

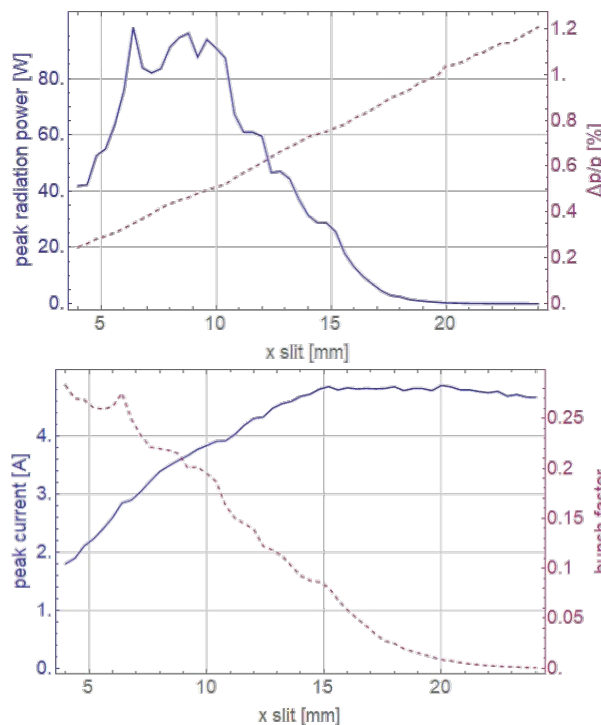


Figure 5: A simulation result of undulator radiation varying the slit width, including the peak radiation power at $f_r = 0.48$ THz (blue line at the upper Figure), bunch energy spread (red dashed line at the upper Figure), peak current (blue line at the bottom Figure), and bunch factor (red dashed line at the bottom Figure).

we started with the conservative initial condition (Table 1) where $Q = 40$ pC, just for simplicity. However, at the LEBRA, we have the burst operation mode of the thermionic electron gun where the peak current is increased more than ten times than normal full bunch mode. So we are planning to improve the simulation with increasing charge of electron bunch. When the charge increases, the space charge effect may be more serious. Hence we will incorporate the SAD optimization feed forward system into the ASTRA simulation to optimize the combination of velocity bunchings.

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