A SIMULATION FOR BRIGHT THZ LIGHT SOURCE FROM WIGGLER RADIATION AT KEK LUCX

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Abstract

We study a bright THz light source generated by a wiggler radiation at KEK LUCX THz experiment, where an injected four pre-micro-bunched electron beam with few hundreds femto-seconds separation plays a crucial role. The energy of pre-bunched beam reaches few MeV at an S-band 3.6 cell RF Gun, and hence the space-charge effect is not negligible. We simulate the beam optics by ASTRA code, a charged beam optics simulator with space-charge effect, and then the resultant particle distribution is passed to GENESIS, a FEL simulator to deal with the wiggler radiation. We also present an experimental result at KEK LUCX. The major advantage of this system is a compactness of total setup that is expected to generate a MW class peak power THz beam by the coherent radiation.

INTRODUCTION

The light source of terahertz (THz) region became an attractive frontier recent years owing to several major technical advances. The THz sources have a great potential to sense a material characteristics that can not be found with the other frequency bands (see e.g. [1]). A megawatt bright source can be generated by the help of RF accelerator and wiggler/undulator coherent radiation.

We use a THz-pulse-train photo injector where a RF-gun (S-band) accelerates a micro-bunched electron pulse train with THz separations up to few MeV, and then the pulse train enters into a wiggler after an optics system [2]. Usually, a free-electron laser (FEL) consists of long and multiple of undulators/wigglers since the micro-bunching is processed along undulators/wigglers by interactions with electromagnetic fields. In our system, the pre-micro-bunched structure of bunch train already has a high bunching factor that sources a high power electromagnetic radiation within a short distance. Hence our system is compact and costs reasonable.

The THz-pulse-train photo injector is realized in LUCX (Laser Undulator Compact X-ray project) at KEK with a pulse gun laser system [3]. Currently, the pulse laser system admits a electron train with up to four micro-bunches, where the micro-bunch length would be 50 femto-seconds (fs) at photo-cathode, and distances can be few hundreds fs. Figure 1 illustrates a rough schematic picture of LUCX alignment, where sizes and distances are not accurate for a simple illustration. Due to lack of space and coexistence with the other experiments, the wiggler is installed after the bending magnet. Since the profile of micro-bunched train after the bend is not desirable for the THz wiggler coherent radiation as we will explain later, we will first perform the FEL simulation assuming that the wiggler is installed at the virtual wiggler place in Fig. 1, where the other experiment takes place. Then we will present an experimental result at the actual wiggler place with simulation data.

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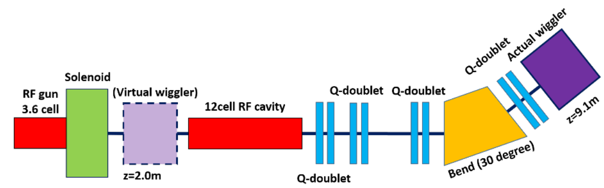

Figure 1: A rough sketch of LUCX beam alignment. The virtual wiggler is for simulation while the actual wiggler is for experiment. We explain the detail reason in context.

FEL SIMULATION OF VIRTUAL WIGGLER

In this section, we present the simulation result of FEL as well as particle tracking, assuming that the wiggler is at the virtual place in Fig. 1. The particle tracking includes the space-charge force that is not negligible and affects particle distributions seriously for energy up to few MeV.

ASTRA Simulation

We use a free code, ASTRA [4] for the particle space-charge tracking. We prepare an initial distribution at the cathode, consisting of a bunch train with four micro-bunches, as in Table 1. This setup is motivated by the realistic situation at KEK LUCX.

Table 1: A micro-bunch distribution at cathode. Each micro-bunch is separated by $d_{\rm sep}$. The emittance is normalized.

Q	σ_t	$\sigma_{x,y}$	$\varepsilon_{x,y}$	$d_{\rm sep}$
60 pC	50 fs	0.5 mm	1 π mrad mm	900 fs

The micro-bunched train is then accelerated by the 3.6-cell S-band RF gun to $E = 10.2$ MeV with 97 MV/m. The phase of RF cavity is chosen such that the peak bunching factor is high enough around 1 THz. The maximum solenoid field value is set at 0.273 T to minimize the transverse size. In Fig. 2, we illustrate the optimization for the wiggler radiation.

The resultant distribution at the entrance of wiggler is illustrated in the upper side of Fig. 3. The space-charge force affects the distribution as seen clearly. Now the beam size and normalized emittance become $\sigma_x \sim 0.197$ mm, $\sigma_y \sim 0.197$ mm, $\varepsilon_x \sim 1.99\,\pi$ mrad mm, $\varepsilon_y \sim 1.99\,\pi$ mrad

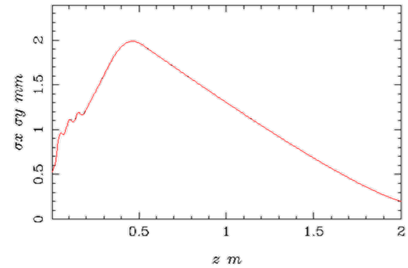

Figure 2: An optimization for wiggler radiation around z=2m.

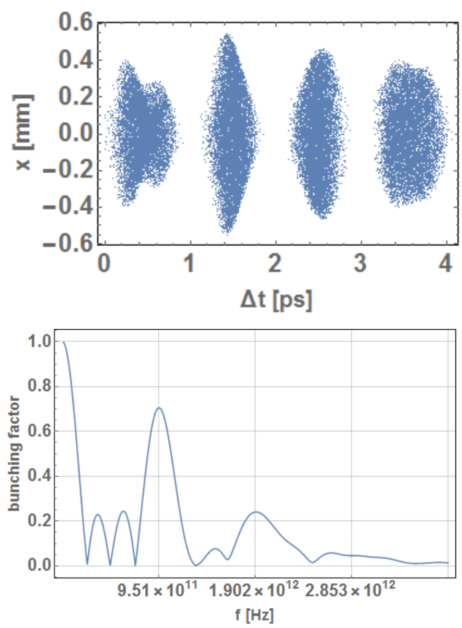

Figure 3: A distribution at the entrance of virtual wiggler (upper) and its bunching factor against frequencies (lower).

mm, and the energy spread is $\Delta\gamma/\gamma \sim 0.517\%$ due to the choice of late phase. We also estimate the bunching factor of this distribution against frequencies in the lower side of Fig. 3. The bunching factor peaks at 0.951 THz with the value 0.706, which is a good initial condition for wiggler radiation as we will see in next section.

GENESIS 1.3 Simulation

Next we use a free time-dependent three-dimensional FEL simulation code, GENESIS 1.3 (version 3) [5] for the wiggler radiation, especially using the distribution generated by ASTRA (Fig. 3) as an input. Our wiggler is an edge-focusing planar wiggler with a strong field gradient for transverse focusing, and the generated magnetic field agrees well with the calculated data [6]. We use a set of parameters required for FEL simulation when the magnetic gap distance is set to be 30 mm as in Table 2. Here $K = eB_0\lambda_w/(2\sqrt{2}\pi m_e c)$ is the undulator/wiggler parameter with peak magnetic field B_0, λ_w is the period length, and N_{period} is the number of periods. The normalized natural focusing parameters of undulator/wiggler k_x, k_y ($k_x + k_y = 1$) depend on energy due to the edge-focusing effect. The values in Table 2 are estimated at $\gamma \sim 20.0$ of the simulated ASTRA distribution using the formulas in [6].

Table 2: A set of parameter at 30 mm magnetic gap of the edge focusing wiggler. The normalized natural focusing parameters k_x, k_y are given at $\gamma \sim 20.0$.

K	λ_w	N_{period}	k_x	k_y
1.71	60 mm	5	0.357	0.643

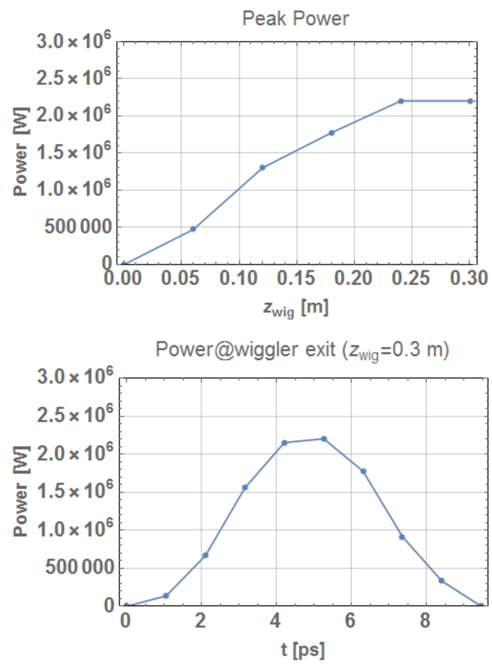

Figure 4: A time-dependent FEL simulation of wiggler. The upper side illustrates the peak power at each magnetic period, while the lower side displays the power gain at wiggler exit over the simulated time period.

In fact, it is not easy to make GENESIS 1.3 read the external micro-bunched distribution directly due to its internal processes, especially the bunching factor is not reproduced correctly. Therefore, we have to reconstruct the distribution in the particle dump format of GENESIS 1.3 by a code, that is HDF5 file format in version 3. Using the reconstructed data in GENESIS dump format with a suitable assignment of slices for the calculation, the bunching factor of pre-bunched distribution can be used as an initial input.

To prepare the data in dump format, we need to specify the wavelength of radiation which determines the slice length and time period of simulation. The FEL coherent radiation wavelength is given by

$$\lambda = \frac{\lambda_w}{2\gamma^2}\left(1 + K^2\right) \tag{1}$$

at a weak electric field limit. At the wavelength λ, the energy loss of electron beam is accumulated over wiggler periods, resulting in a significant radiation amplitude enhancement. We set the radiation wavelength $\lambda \sim 0.315$ mm, corresponding to the peak point of bunching factor, where Ep.(1) suggests $\gamma \sim 19.3$. Although the energy of distribution we use is slightly higher, the actual coherent condition depends on many details, including a transverse betatron motion and a strong radiation field that shift the condition slightly.

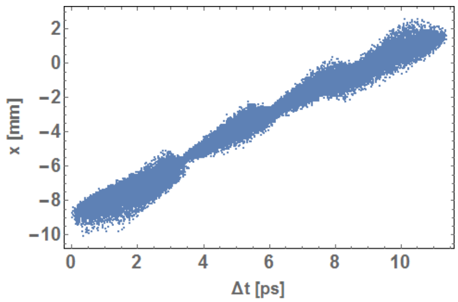

Figure 5: A distribution at the entrance of actual wiggler.

The result of GENESIS 1.3 FEL simulation is shown in Fig. 4. The peak power reaches 2.20 MW at the end of wiggler despite the short distance, because of the coherent radiation by the pre-bunched distribution. The lower plot of Fig. 4 illustrates the power at wiggler exit over the simulated time period. It is clearly seen that slippages of radiation are accumulated over four micro-bunches separated each other by the distance around λ. Hence we conclude that a MW class power compact THz radiation source based on the short edge-focusing wiggler can be realized at KEK LUCX.

EXPERIMENT WITH ACTUAL WIGGLER

In this section, we show the result of experiment at the actual wiggler place in Fig. 1. First we present an ASTRA simulation result to get a better understanding. In order to minimize space-charge influence, we have set the following micro-bunch distribution at cathode: Q = 15 pC, d_{sep} = 2.5 pico-seconds (ps), and the other is same as in Table 1. The reason why we have the large separation is in the following. When a micro-bunch goes through the bending magnet (30 degree), the outer side of bunch edge delays than the inner side due to different path lengths, resulting in a tilted distribution on $x - z$ plane. Then, focuses by bending and quadrupole magnets are likely to spoil the pre-bunched structure due to its space charge effect. Thus we have the enough separation and the gun phase is chosen such that the separation holds sacrificing the energy spread. Here the energy is set around the coherent value from Eq.(1) which is at $\gamma \sim 12.5$, and hence the 12-cell cavity is off . The resultant distribution at the entrance of wiggler is illustrated in Fig. 5. The bunching factor around the frequency range of interest (0.3-0.5 THz) is no longer high, but still has a value 0.165, and hence we would expect some enhanced signals.

In the experiment, we scan the wiggler radiation by changing a light path of fs laser system, and also by an interferometer. We use a Schottky Barrier Diode with sensitivity range of 320-480 GHz. The upper side of Fig. 6 illustrates the radiation by changing the light path corresponding to changes of a relative separation of two micro-bunch pairs. The last arrow point after two bunches overlaps is around the region of 2.5 ps separation each. At this point, we perform the interferometer scan as in the lower plot of Fig. 6. We can easily see that the signal peaks at 0.4 THz. Although the actual separations may not be exactly at 2.5 ps, the mixture of other conditions ends up with this result. Thus we conclude that the enhanced signal around the last arrow point is related with the coherent radiation by four micro-bunches.

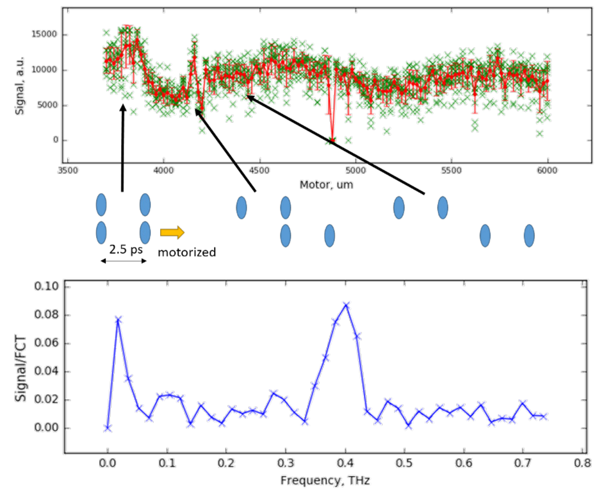

Figure 6: An experimental result of wiggler radiation.

DISCUSSION

We presented the simulation of wiggler radiation under the assumptions well motivated by the current KEK LUCX setup. The simulation result strongly suggests that a MW class power of THz light source is available at the compact and reasonable facility. Although our wiggler period is long, a wider range THz light source can be realized with a short period undulator/wiggler λ_w < 10 mm within the energy reach of RF gun. It is not difficult to enhance the power by a slight upgrade, e.g. larger number of periods of wiggler with more micro-bunches, or an increase of current. We also showed the experimental result. Although the micro-bunch profile after the bend is not desirable for the coherent radiation, we observed the enhancement of signal around the region of interest. We believe that these results encourage further wiggler studies using the pre-bunched electron beam.

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