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GENERATION OF TERAHERTZ SYNCHROTRON RADIATION USING LASER-BUNCH SLICING AT HEFEI LIGHT SOURCE*

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Abstract

Hefei Light Source is a second-generation low-energy synchrotron light source. The low energy machine is capable of generating intense Terahertz radiation through coherent synchrotron radiation. To realize this, one method is to shorten the bunch length to the same level of its radiation wavelength, e.g. by adopting low-α lattice. Another method is to modulate the electron bunch to produce micostructure at picosecond scale and intense Terahertz coherent synchrotron radiation can be obtained due to the increase of the bunch form factor. This technique is called the laser bunch slicing method which introduces a laser beam into an undulator to interact with the electron bunches. In this paper we report our work on the simulation of the laser bunch slicing at Hefei Light Source.

INTRODUCTION

Hefei Light Source (HLS) is a second-generation storage ring based light source with an electron beam energy of 800 MeV. It has provided continuous service to users since 1991 and gone through two successful major upgrades started in 1998 and 2010. Some main parameters of the present HLS storage ring are listed in Table 1. Due to its low beam energy, this light source mainly focuses on vacuum ultraviolet (VUV) and infrared region. Since the use of Terahertz (THz) radiation (ranges from 0.1 THz to 3 THz) for scientific research becomes more and more widespread, we decide to develop a THz beamline at HLS to expand its application fields. In a storage ring, intense THz radiation can be generated using coherent synchrotron radiation from a bending magnet. In simple terms, if the length of an electron bunch is comparable with the wavelength of its radiation, the individual electrons in the bunch can emit coherently which produces intense synchrotron radiation. For THz range, the bunch length should be around 1 ps. Usually a low-α lattice is adopted in order to shorten the bunches in the storage ring. To further shorten the bunch length, one can even increase the RF frequency (harmonic number) and voltage. A design of changing the HLS to a dedicated THz light source was presented in [1]. However this method needs to reconstruct the whole machine and dump all the current beamlines. Another method is to introduce a laser pulse to interact with the electron bunch in an undulator which causes energy modulation, and thus generate microstructure in the electron bunch. This technique was firstly adopted for the generation of ultrafast X-ray pulses of synchrotron radiation because the energy-modulated bunch slice will be transversely separated in the dispersion region of the storage ring [2, 3]. Longitudinally the energy modulation can also leads to the change of the bunch intensity distribution, which can be used to produce coherent radiation in THz range.

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Table 1: Main Parameters of the HLS-II Storage Ring.

Parameters	Value
Circumference	66.13 m
Energy	800 MeV
Horizontal Emittance	38 nm·rad
RF frequency	204 MHz
Harmonic number	45
Tune	4.4448/2.3598
Natural chromaticity	−7.4098/−7.1066
Natural bunch length	70.2 ps
Natural energy spread	4.7×10^{-4}

COHERENT SYNCHROTRON RADIATION

The radiation power of a bunch with N electrons can be expressed as

$$P(f) = Np(f) + N(N-1)F(f)p(f), \tag{1}$$

where f is the radiation frequency, $p(f)$ is the incoherent synchrotron radiation power from an individual electron, and $F(f)$ is the form factor. The form factor of an electron bunch can be calculated by a Fourier transformation [4]

$$F(f) = |\int \rho(t)\exp(2\pi i f t)dt|^2, \tag{2}$$

where $\rho(t)$ is the normalized bunch density distribution along longitudinal direction. A bunch with longitudinal Gaussian distribution with can be described as [5]

$$\rho(t) = \frac{1}{\sqrt{2\pi}\sigma_t}\exp(-\frac{(t-t_0)^2}{2\sigma_t^2}), \tag{3}$$

where t_0 is the time parameter of the reference particle and σ_t is used to weigh the bunch length.

For different bunch lengths, the form factors are calculated and plotted in Fig. 1. It shows that the form factor remains 1 in the low frequency range and decays to 0 as the frequency increases. This is because the Fourier transformation of a Gaussian function is also Gaussian with an inverse sigma. The form factor of longer bunches decays at lower frequencies. This implies that shorter bunches can be used to enhance the THz radiation by increasing the corresponding CSR form factor.

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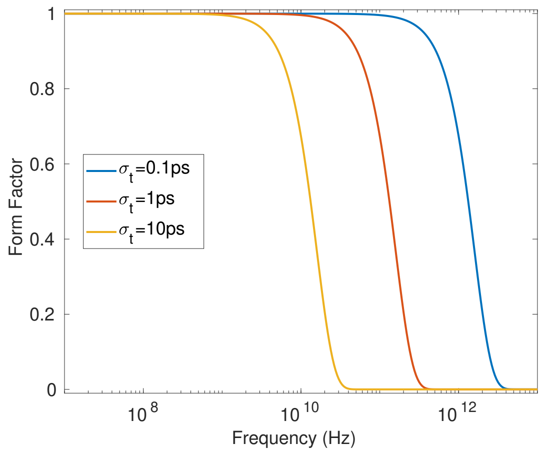

Figure 1: Form factors for Gaussian distributions with different bunch lengths.

LASER BUNCH SLICING METHOD

A laser-bunch interaction in an undulator can be used to modulate the CSR form factor. The interaction is accomplished with energy exchange between laser and bunch slices when the undulator period and the laser wavelength satisfies the resonance condition $\lambda_u = 2\gamma^2\lambda_L/(1+K^2/2)$. The maximum energy exchange occurs when the laser and the bunch have the maximum overlap both longitudinally and transversely. This means the laser waist size should be larger than the beam transverse size and the interaction takes place with a part of electrons in the laser duration. The energy exchange is expressed by [2]

$$A = A_L + A_R + 2\sqrt{A_L A_R \Delta\omega_L/\Delta\omega_R}\cos\phi, \quad (4)$$

where A_L and $\Delta\omega_L$ are the field energy and bandwidth of the laser pulse, and A_R and $\Delta\omega_R$ are the corresponding parameters for undulator radiation. In an undulator, the energy modulation amplitude is approximately

$$\begin{aligned}(\Delta E)^2 &\approx 4\pi\alpha A_L\hbar\omega_L \frac{K^2/2}{1+K^2/2}\frac{\Delta\omega_L}{\Delta\omega_R} \\ &\approx 4\pi\alpha A_L\hbar\omega_L \frac{M_u}{M_L}\end{aligned} \quad (5)$$

with α being the fine structure constant, $\hbar$ the Planck's constant, and M_u, M_L being the undulator periods, number of waves in the laser pulse respectively.

After the laser-bunch interaction, the energy of part the electrons is modulated. After passing through a bending magnet, the energy modulation then results in a modulation of longitudinal density distribution due to the effect of R_{56} as

$$z_1 = z_0 + R_{56}\delta. \quad (6)$$

Finally a small dip in the beam distribution occurs, as if the bunch is "sliced". The sliced bunch distribution would modify its CSR form factor and then enhance the radiation in THz region. This laser-bunch slicing scheme for THz generation has an advantage—it does not require additional lattice modification and the present beamlines are not affected. Also the undulator for laser bunch slicing can be used as an insertion device for normal beamlines.

SIMULATION AND RESULTS

The applicability of the laser-bunch interaction method for THz generation in the HLS storage ring is explored. Some simulation is performed with the accelerator program ELEGANT [6]. The nominal HLS lattice is adopted with an undulator inserted to its long straight section, as shown in Fig. 2. Laser pulse is arranged to interact with the bunch within the undulator. An electron bunch with Gaussian distribution is generated and tracked for one turn. After the bunch passes through the undulator, the bending magnet labeled number 1 is used for distribution modulation and that labeled number 2 is used to generate CSR (see Fig. 2). Some main laser and undulator parameters are listed in Table 2. The parameters are preset to satisfy the resonance condition.

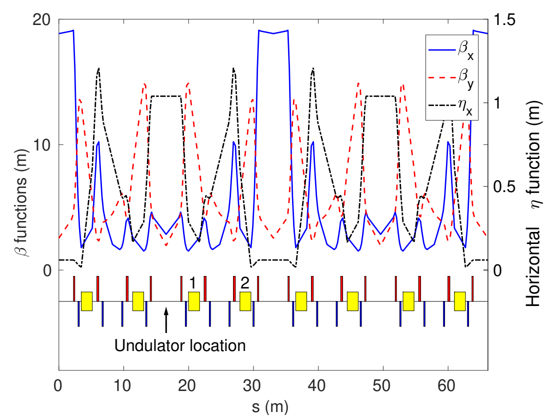

Figure 2: The nominal HLS-II lattice with an undulator inserted for laser bunch slicing.

Table 2: Main Parameters of the Laser and Undulator for Bunch Slicing Simulation.

Parameters	Value
Laser wavelength	800 nm
Laser peak power	3 GW
Laser pulse duration	1 ps
Laser waist size	500 µm
Undulator periods	20
Undulator length	2 m
Undulator K parameter	8.74
RMS beam size at undulator	329 µm/27 µm
R_{56} (from the undulator to the first dipole exit)	0.1695

At the beginning of the simulation, a bunch with gaussian distribution is generated with σ_t =50 ps. After one-turn tracking, the initial bunch distribution, the distribution after the undulator and that after a bending magnet are plotted in both t-δ phase space and the t space, as shown in Fig. 3. We can see that an energy modulation occurs after the bunch passes through the undulator and a small dip appears in the distribution function after the bunch passes through the bending magnet. A detail of the dip with enlarged scale is shown in Fig. 4.

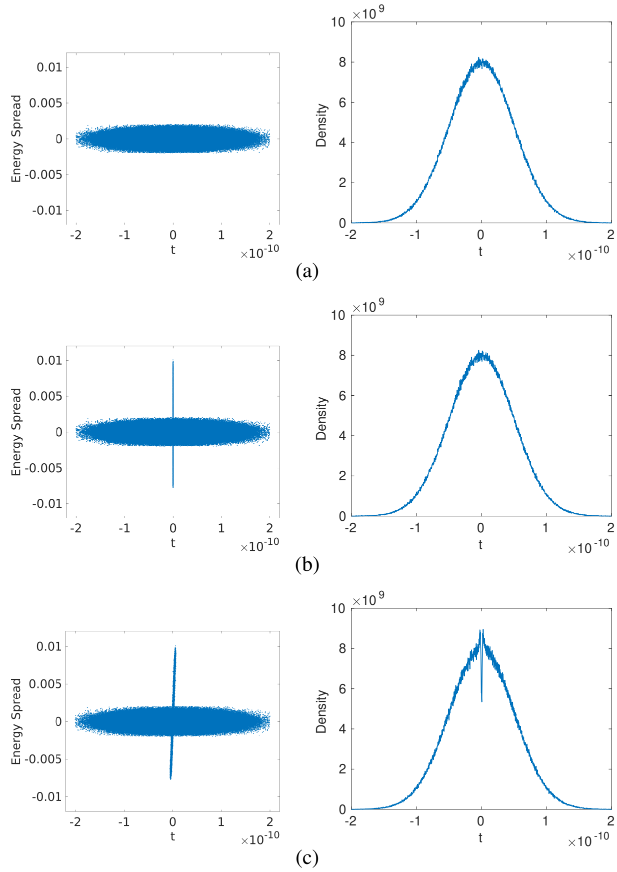

Figure 3: Tracked beam distribution in t-δ space and the corresponding normalized density distribution in time space. (a) Initial beam; (b) After the undulator; (c) After the first bending magnet.

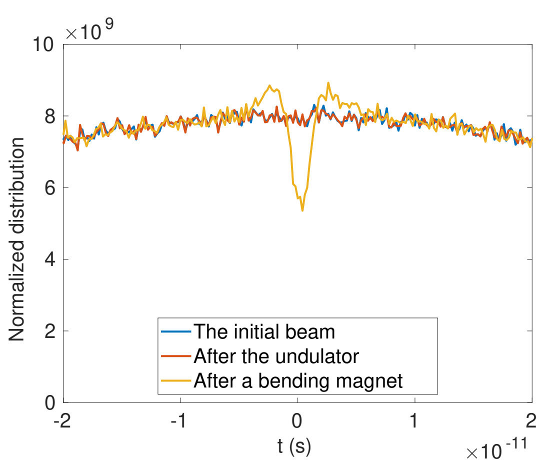

Figure 4: The beam distribution in a smaller range.

The form factor of the bunch with modulated distribution can be calculated using Eq. (2), which is plotted in Fig. 5. The figure shows that after the density modulation in the bending magnet, there is an increase of the form factor in the THz range compared to that without density modulation. Although the absolute value of the form factor is low, the electron number in a normal bunch can be very large, resulting in a considerable contribution to the THz CSR.

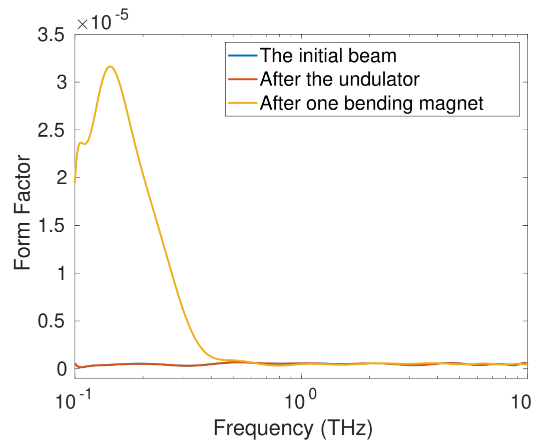

Figure 5: The form factor of the bunch in the laser-bunch slicing simulation within Terahertz range.

SUMMARY

In this paper, the simulation of the laser-bunch slicing method applied for Hefei Light Source for THz radiation generation is presented. An undulator is added at the long straight section where the electron beam interacts with a laser pulse to produce density modification to the bunch. The simulation results show that the CSR form factor in the THz regime is enhanced, which indicates the capability of the bunch slicing method for the HLS storage ring to generate intense THz radiation.

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