SIMULATION OF THE LASER ELECTRON INTERACTION FOR FEMTOSECOND BUNCH SLICING ON SOLEIL STORAGE RING

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Abstract

The interaction of an electron bunch with a laser in a wiggler (modulator) to generate a femtosecond slice is simulated for the slicing project on the SOLEIL storage ring, using SLS code which is based on Monte-Carlo method, GENESIS, and ELEGANT. The results from these three codes are consistent with the theoretical values derived from the analytical formulae. The maximum modulated energy of the electron bunch and the number of electrons in the interested energy range are studied for different laser and wiggler parameters. The transport of the 6D distribution of the sliced bunch, from the modulator to the radiators, is simulated using AT (Accelerator Toolbox).

INTRODUCTION

A laser pulse propagating with an electron bunch in the wiggler modulates the energy of the electrons if the resonance condition $\lambda_L=\lambda_w(1+K^2/2)/2\gamma^2$ is satisfied, where λ_L is laser wavelength, λ_w is wiggler period, K is deflection parameter, γ is relativistic energy of the electron.

The modulated electrons by a femtosecond laser pulse can produce in a dipole or an insertion device (radiator) X-Rays with femtosecond temporal structure, which is a powerful tool to approach the atomic motion associated with ultrafast chemical reactions, non-equilibrium phase transitions, surface dynamics, etc.

A FEMTOSLICING facility is designed on the SOLEIL storage ring aiming at providing soft and hard X-rays photons with temporal structure of 100 fs FWHM and a repetition rate up to 10 kHz.

ENERGY MODULATION

The energy modulation of an electron bunch by a laser pulse in the wiggler follows the Lorentz equation which has the approximation as:

$$\frac{d\gamma}{dz} \approx \frac{e}{m_0c^2}\vec{E}(x,y,z)\bullet\vec{\beta} \qquad (1)$$

where z is the longitudinal length along the wiggler, e is the electron charge, m_0c^2 is the rest energy of the electron, $\vec{E}$ is the laser field, $\vec{\beta}$ is the relative velocity of the electron.

For an ideal planar wiggler, only the vertical magnetic field B_y is non-zero:

$$B_y = B_0\cos(k_w z) \qquad (2)$$

B_0 is the peak magnetic field strength, $k_w = 2\pi/\lambda_w$; then the motion of the electron propagating in the ideal wiggler is [1]:

$$\beta_x = -\frac{K}{\gamma}\sin(k_w z), \overline{\beta_z} = 1-\frac{1+K^2/2}{2\gamma^2} \qquad (3)$$

where β_x is the horizontal relative velocity, and $\overline{\beta_z}$ is the average longitudinal relative velocity of the electrons.

Supposing a laser with linear polarization on the horizontal direction, the maximum energy modulation of the electron by the laser pulse in an ideal wiggler is given by [2]:

$$\Delta\gamma_{\max} \approx \frac{2}{m_0c^2}\sqrt{5A_L\alpha\hbar\omega_{0s}}\{JJ\} \qquad (4)$$

where $A_L = (E_0^2/8\pi)(\pi a_0^2/2)\sqrt{2\pi}\sigma_L c$ is the laser pulse energy, E_0 is the amplitude of the laser field, a_0 is the laser waist size, c is speed of light, σ_L is the RMS laser pulse length, α is the fine structure constant, $\hbar$ is the normalized Plank constant, ω_{0s} is the central frequency of the field of the spontaneous emission, $\{JJ\} = J_0(\xi/2) - J_1(\xi/2)$ with $\xi = K^2/(2+K^2)$ and Bessel functions J_0 and J_1.

SIMULATION OF FEMTOSLCING ON SOLEIL RING

Based on Eq. (1), the interaction of a femtosecond laser and an electron bunch in the modulating wiggler (modulator) can be simulated. For the femtoslicing on SOLEIL storage ring, the energy modulation is simulated using a code called SLS code [3] which is based on the Monte-Carlo method. In this code, the fundamental Gaussian mode of the laser wave is used, the electrons in the single bunch are grouped into macro particles which follow Gaussian distribution in the horizontal and vertical direction. Since the order of laser pulse length is femtoseconds and electron bunch length is picoseconds, only the electrons in a tiny slice of the bunch which overlaps with the laser pulse can be modulated, so the longitudinal distribution of the electrons is chosen to be uniform for the computer time saving.

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Generation of the Femto Slice

With 2 mJ laser power and 50 fs FWHM laser pulse length, the generation of the femto slice on SOLEIL storage ring is simulated by SLS code and illustrated in Figure 1. When the laser pulse co-propagates with the electron bunch in the modulator, the interaction between laser and the overlapped electrons generates a "bump" whose size keeps on growing in the energy distribution of the bunch. When the laser is at the exit of the modulator, the sliced "bump" is left behind the laser pulse with a time distance τ_d from its centre to the laser pulse centre, $\tau_d = -\sigma_L N_w / 2N_L c$ [4], where N_w is the number of periods of the modulator and N_L is the optical numbers of the laser.

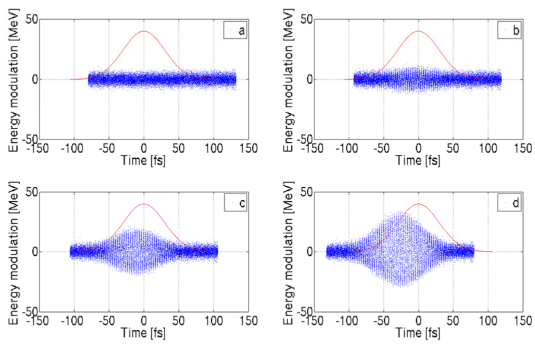

Figure 1: Simulation of the generation of the femto slice. a) Laser pulse at the entrance of modulator. b) Laser pulse at ¼ length of modulator. c) Laser pulse in the middle of modulator. d) laser pulse at the exit of mudulator. The time is the relative distance of the modulated electrons to the centre of the laser pulse.

Figure 2.shows the details of the modulated slice. The energy gain and loss of the modulated electrons are asymmetric; the period of the modulated electrons in the slice corresponds to the laser wavelength of 800 nm.

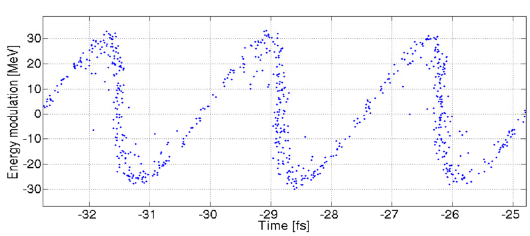

Figure 2: Details of the energy modulation.

Study Versus Laser and Wiggler Parameters

The characteristics of the femto slice are determined by laser and modulator parameters, such as laser pulse energy, laser pulse length, laser wavelength, laser beam quality factor, laser waist size, modulator wavelength, modulator length and peak field strength.

The most relevant characteristics of the femto slice are the maximum modulated beam energy and the number of modulated electrons within the interested energy range. It is easier to separate the femto slice from the core bunch in the following bending magnets with a higher modulated beam energy, and a higher flux of the femtosecond X-Ray requires a larger number of the modulated electron in the interested energy range.

With different laser and modulator parameters shown in Table 1, the maximum modulated energy and the number of modulated electrons are simulated using the SLS code**.**

Table 1: Laser and Wiggler Parameters Used in the Simulaton of Femto Slicing on SOLEIL Ring

Parameter	**Symbol**	**Value**
laser wavelength	λ_L	800 nm
Rayleigh length	z_R	0.547 m
modulator period	λ_W	164 mm
modulator number of period	N_W	20
modulator peak field strength	B_0	1.45 T

Fig. 3 illustrates the dependence of maximum modulated energy on the laser pulse length for different laser pulse energy. In order to get higher modulated energy, a laser device with higher pulse power is required; from 20 to 120 fs, a shorter laser pulse is more effective to modulate the beam energy.

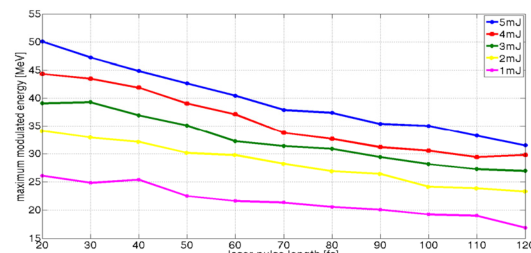

Figure 3: Maximum modulated beam energy versus laser pulse length under different laser pulse energy. The parameters used in the simulation are shown in Table 1

Fig. 4 shows the number of modulated electrons in the energy range from 7 to 21 MeV. With laser pulse length from 20 to 120 fs, laser with pulse power equal to or above 3 mJ modulates the same number of electrons; for the laser with pulse length 50 fs and pulse power 1 mJ, the number of modulated electrons within the interested energy range is about $2.8{*}10^7$ for a bunch with current 10 mA.

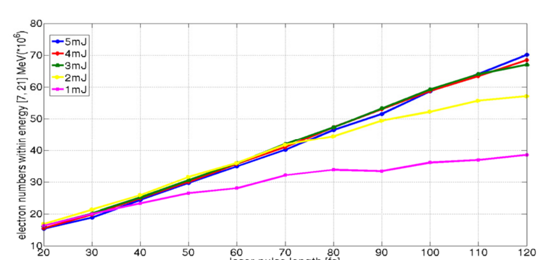

Figure 4: Number of electrons with modulated energy between 7 and 21 MeV versus laser pulse length under different laser pulse energy. The parameters used in the simulation are shown in Table 1.

The results for the laser with fundamental Gaussian mode simulated using SLS code, are compared with the results simulated using GENESIS [5], a reference Free Electron Laser code, and ELEGANT [6] in which the simulation is modelled with Lorentz equation and laser mode up to 4^{th} order, then the simulation results are compared to the one obtained by the analytical formulae given by Eq. (4). The comparison is shown in Fig. 5. The simulation results are larger than the analytical ones since only the horizontal component of the laser field is used in Eq. (4). The simulation results from SLS code and ELEGANT are very close, and they are a little smaller than the result from GENESIS.

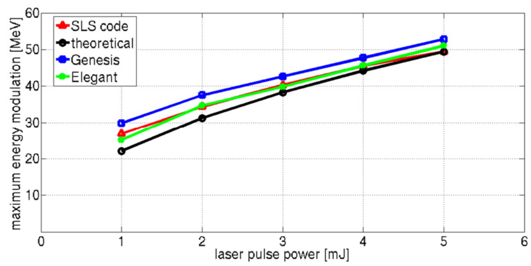

Figure 5: Comparison between the simulation results using SLS code, GENESIS, ELEGANT, and analytical formulae given in Eq.(4).

TRANSFER OF THE FEMTO SLICE

On the FEMTOSLICING facility on SOLEIL storage ring, two beam lines (CRISTAL and TEMPO) utilize the femtosecond X-Ray generated by the modulated femto slice in the radiators. In the radiator, both the modulated electrons in slice and the un-modulated electrons in the core bunch generate radiation, but only the radiation from the electrons in the slice have the femtosecond time structure. So the femto slice must have a clear separation from the core bunch in the horizontal direction.

The transfer of the femto slice on SOLEIL storage ring is simulated using Accelerator Toolbox (AT) [7] under Matlab. The 6D distribution of the electrons in the femto slice is generated by the SLS code, the synchrotron radiation of the electrons in the following bending magnets between the modulator and the radiator are included.

The distributions of the femto slice in the horizontal direction are shown in Fig. 6. At the entrance of the modulator, the electrons in the bunch follow a Gaussian distribution in the horizontal direction and a uniformly longitudinal distribution which are the initial beam status. At the exit of the modulator, the horizontal and longitudinal distributions of the electrons have little change since the laser mainly modulate the electron energy in the modulator. At the end of the radiator before CRISTAL, most electrons are close to the zero closed orbit except the electrons in the femto slice. The dipoles between the modulator and the radiator before beam line CRISTAL separate the electrons in the femto slice from the core bunch with maximum horizontal position 8 mm and minimum − 6 mm. At the end of the radiator before TEMPO, the electrons in the femto slice are separated from the core bunch with the maximum horizontal position 4 mm and minimum − 3 mm.

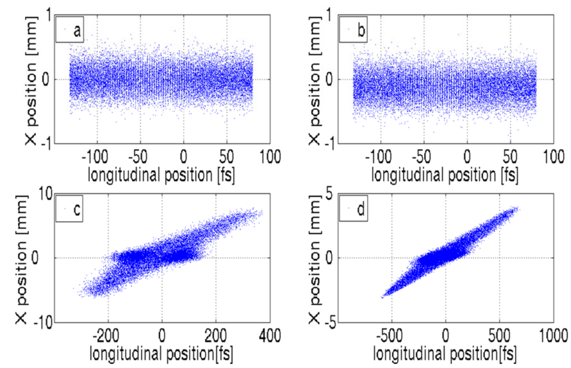

Figure 6: Simulation of the transfer of the femtosecond slice on SOLEIL ring. a) At the entrance of modulator. b) At the exit of modulator. c) At the exit of the radiator before CRISTAL beam line . d) At the exit of the radiator before TEMPO beam line.

CONCLUSIONS

The simulation of the interaction between the electron and a femtosecond laser pulse in a wiggler demonstrates the generation of the femtosecond slice in the electron bunch. The maximum modulated energy and the number of the modulated electrons within the interested energy range are studied for different laser and wiggler parameters. The simulations of the femto slice using different codes are in consistent with the analytical formulae. The simulation of the transfer of the femto slice from the modulating wiggler to the radiators on SOLEIL storage ring illustrates the separation of the femto slice from the core bunch and the distribution of the slice after transfer, which can be further used to calculate the flux of the femtosecond X-Ray.

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