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STUDY ON LASER MODULATOR FOR ELECTRON BEAM DENSITY MODULATION

Koichi Kan†, Masao Gohdo, Jinfeng Yang, Yoichi Yoshida
The Institute of Scientific and Industrial Research (ISIR), Osaka University, Osaka, Japan

Abstract

Ultrashort electron beams are essential for light sources and time-resolved measurements. Laser modulation using an undulator and pulsed near infrared light is expected for attosecond density modulation of electron beam. In this study, simulation of laser modulation using undulator with period length of 6.6 mm and optical pulse with a wavelength of 800 nm was performed by ELEGANT code. Simulation results of laser modulation for electron beam with an energy of 32.5 MeV will be presented from a view point of the density modulation.

INTRODUCTION

Short electron bunches with durations from femtoseconds to picoseconds are useful for not only generation of light from X-ray [1] to terahertz (THz) range [2] but also time-resolved studies of ultrafast phenomena and reactions including ultrafast electron diffraction (UED) [3] and pulse radiolysis [4-6]. Femtosecond electron beam generated by photocathode-based linac is one of candidates for the time-resolved measurements. In ISIR, Osaka University, magnetic bunch compression of electron beam has been performed for pulse radiolysis and electron beam irradiation experiments. To improve the time resolution of pulse radiolysis, femtosecond electron beam is essential. In the previous scheme, femtosecond ultraviolet (UV) pulse was injected on the photocathode. Generated electron beam was accelerated and modulated in energy using a linac. The accelerated electron beam of ~30 MeV was compressed to femtosecond electron beam using an achromatic-arc-type compressor. Optimization of electron beam generation and compression lead to bunch length of 20 fs analysed using a Michelson-type interferometer [7].

Laser modulation for shorter single bunch or bunch train is expected for electron beam manipulation technique. Laser modulation increases slice energy spread of electron bunch using interaction between electron beam and laser in an undulator, that is, periodic magnetic field. In typical cases, single pulse of laser is used for electron beam modulation. Such laser modulation technique is used for stabilization of X-ray pulse energy in X-ray free electron lasers [8]. Temporally modulated laser are also used sometimes for other applications in laser modulation because the increase of slice energy spread depends on laser intensity. Superposed laser pulse using a Michelson-type interferometer enhances beating according to chirp of the laser pulse when separated laser pulses are superposed with adequate time delay. Temporally modulated laser pulse in intensity is used as chirped pulse beating for THz generation using a photoconductive antenna [9] which is a laser-based THz generation device. In circular accelerator, THz generation was demonstrated using laser modulation with chirped pulse beating [10]. High power THz generation using photocathode-based accelerator and THz laser modulation was also proposed [11, 12]. Temporally modulated laser pulse is enabled by femtosecond lasers which cover THz frequency due to the pulse width. The efficiency of laser modulation depends on electron beam, laser, and undulator. For electron beam, beam energy and energy spread are key parameters because resonant wavelength using the undulator as a light source should be set to the laser wavelength. Resonant wavelength is adjusted by undulator period length and K parameter. For laser, wavelength and peak power effect on laser modulation. Undulator period number and laser peak power lead to the interaction number and amount in the laser modulation. Finally, beam transport at the downstream of the laser modulator has influence in R_{56} of transfer matrix which rotate phase-space distribution due to the slice energy spread increase. Thus, several parameters have to be optimized for laser modulation.

In this study, simulation of laser modulation for electron density modulation was performed. Femtosecond electron beam with energy of 32.5 MeV, charge of 2 pC, and bunch length of 9 fs in rms was calculated for the laser modulation. A femtosecond laser with wavelength of 800 nm and peak power of 4 GW corresponding to 0.4 mJ / 100 fs was considered for attosecond electron beam density modulation.

SIMULATION OF LASER MODULATION

To optimize laser modulation, resonant wavelength in the undulator for light source usage should be tuned to the femtosecond laser wavelength. Higher-order interaction using undulator and laser can be also supported. In an undulator with linear polarization in x axis, magnetic field of the undulator in y axis B_U for electrons traveling along z axis is expressed as

$$B_U = B_0 sin\frac{2\pi}{\lambda_U}z, \tag{1}$$

where B_0 and λ_U denote amplitude of magnetic field and period length, respectively. Fundamental resonant wavelength λ_L is expressed as

$$\lambda_L = \frac{\lambda_U}{2\gamma^2}\left(1+\frac{K^2}{2}\right), \tag{2}$$

$$K = \frac{eB_0\lambda_U}{2\pi mc}, \tag{3}$$

† koichi81@sanken.osaka-u.ac.jp

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where K denote undulator parameter which depends on magnetic field. γ, m, and c are Lorentz factor of electron, electron rest mass, and speed of light in vacuum, respectively.

The fundamental resonant wavelength of 800 nm was considered in this study for electron beam of 32.5 MeV and existing femtosecond laser with wavelength of 800 nm. As the result, K and B_0 were calculated as 0.15 and 0.25 T, respectively, at λ_U = 6.6 mm for the wavelength.

Figure 1 shows the diagram of simulation for laser modulation. Beam tracking simulation code of ELEGANT was used. Table 1 shows simulation parameters. Conditions of undulator field of B_0 and drift space length z_0 were optimized. Macro-particles of 10,000 was transported through the undulator. Normalized time profile as a function of time $f(t)$ was calculated using six phase-space coordinates after the transportation. Bunching factor $F(\omega)$ was calculated as

$$F(\omega) = \left|\int_{-\infty}^{\infty} f(t) e^{-i\omega t} dt\right|. \tag{4}$$

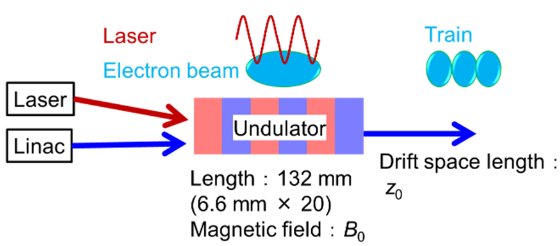

Figure 1: Diagram of simulation.

Table 1: Simulation Parameters

Item	**Parameter**
Electron beam	32.5 MeV, 9 fs rms, 2 pC, dE/E 0.1%, ε_n 0.1 mm-mrad
Undulator	Period of 6.6 mm, number of 20
Laser	Wavelength of 800 nm, peak power of 4 GW (0.4 mJ, 100 fs)

SIMULATION RESULTS OF BUNCHING FACTOR

Figure 2 shows simulation results of bunching factor with changing of B_0 and z_0. Figure 2 (a) shows phase-space distribution and time profile in conditions of B_0 = 0.25 T and z_0 = 150 mm. Slope of the phase-space distribution effect on modulation depth of laser modulation in time profile. Figure 2 (b) shows bunching factor calculated using Eq. (4). Fundamental frequency component of 0.37 THz which correspond to 808 nm was confirmed as a peak according to the similarity to the laser wavelength. Second higher-order modulation was also confirmed as a peak of 0.74 PHz. Periodic delta functions in time profile lead to higher-order components in a frequency spectrum. Thus, shortened bunch length are also occurred in micro bunches. Figure 2 (c) shows optimization of bunching factor near 0.37 PHz with changing B_0 and z_0.

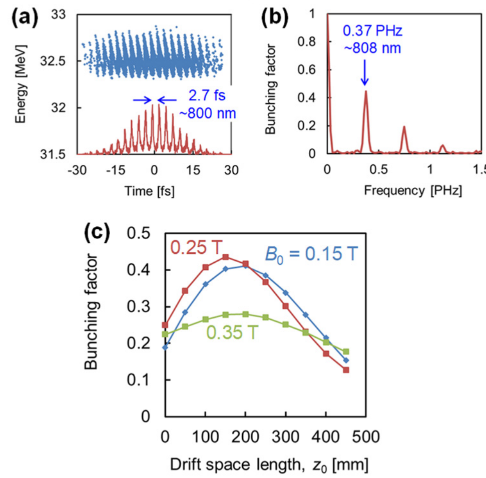

Figure 2: (a) Longitudinal phase-space distribution and time profile after laser modulation with conditions of B0 = 0.25 T, z0 = 150 mm. (b) Bunching factor. (c) Bunching factor at ~0.37 PHz as a function of z0. Three different cases of B0 are shown.

Amplitude of magnetic field changes slice energy spread increase. As expected from the resonant wavelength and magnetic field using Eq. (2), bunching factor was maximized at B_0 = 0.25 T. The drift space length adjusts the rotation of phase-space distribution after the laser modulation, that is, a momentum compaction factor, resulting in maximized bunching factor in different drift space length according to the energy spread. Maximum of the bunching was obtained to be 0.44 at optimized conditions of B_0 = 0.25 T and z_0 = 150 mm.

ANALYSIS OF BUNCH TRAIN

Figure 3 shows an example of analysis of bunch train. Multi-peak fit of Gaussian was used. Micro-bunch length in rms was ~300 as using average of middle 8 pulses. Detailed analysis of bunching factor and micro-bunch length will be performed.

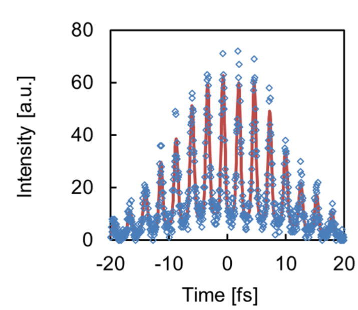

Figure 3: Analysis of micro-bunch train. Time profile at a condition of z_0 = 150 mm is shown with multi-peak fit (solid line).

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CONCLUSION

Simulation study on laser modulator for electron beam density modulation for attosecond bunch train generation. Conditions of period length of 6.6 mm, magnetic field of 0.25 T, and drift space length of 150 mm maximized bunching factor to 0.44. In the future, the undulator for the laser modulation will be produced and higher-order interaction using an undulator with fundamental resonant wavelength of 2400 nm will be also considered.

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