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THZ-PUMP AND UV-PROBE SCHEME BASED ON STORAGE RING*

Haoran Zhang, Wenxing Wang, Shiming Jiang, Zhigang He†,
National Synchrotron Radiation Laboratory,
University of Science and Technology of China, Hefei, China

Abstract

We propose a THz-pump and UV-probe scheme based on storage ring for ultra-fast dynamics experiment. In which, two sequential laser pulses, one of which has a periodic intensity envelope, simultaneously interact with different parts of the long electron beam in a modulator. After a chicane, the part that interacts with the periodic pulse will be moudulated at THz domain and radiate through a bend magnet. Another part that interacts with normal laser will be modulated at UV domain and radiate at a radiator, which based on high-harmonic generation. The electron beam can be utilized circularly in the storage ring, which will increase its average power. The feasibility of this THz-pump and UV-probe scheme is verified in both theory and simulation.

INTRODUCTION

The pump-probe experiment is a powerful tool for studying ultrafast science. It provides a completely new method for exploring matter. Its general principle is as follows: the sample interacts with a strong pump pulse to produce excitation or changes in properties, which will be detected by subsequent probe pulse. By adjusting the time interval between the pump and the probe, it will be revealed that the process of exciting over time. Pump and probe experiments can track ultra-fast dynamics of matter in a non-equilibrium state in real time. Such phenomenas can be induced by intense THz pulses which include a variety of transient processes: material phase transitions [1], quantum optics [2], electron decay [3, 4], molecular motion [5, 6] and magnetic field dynamics [7]. Then, through ultraviolet (UV) spectroscopy, such as angle-resolved photoemission spectroscopy (ARPES), it can be probed that the dynamics processes [8, 9].

In this paper, we propose a scheme of THz-pump and UV-probe experiment based on the storage ring. As shown in Fig. 1, a chirp-beating-pulse follows a conventional laser pulse, enters the modulator and interacts with the electron beam from the storage ring in different regions. Then, after the first chicane (C1), the part that interacts with the chirp-beating-pulse bunch at THz domain and radiate in a bend magnet. After the second chicane (C2), another part bunch at short wavelength and generate UV pulse in the radiator.

PRINCIPLE

A sinusoidal-envelope laser-induced method is used to generate narrow-band THz radiation [10], mainly including a modulation section and a dispersion section.

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† Email: hezhg@ustc.edu.cn

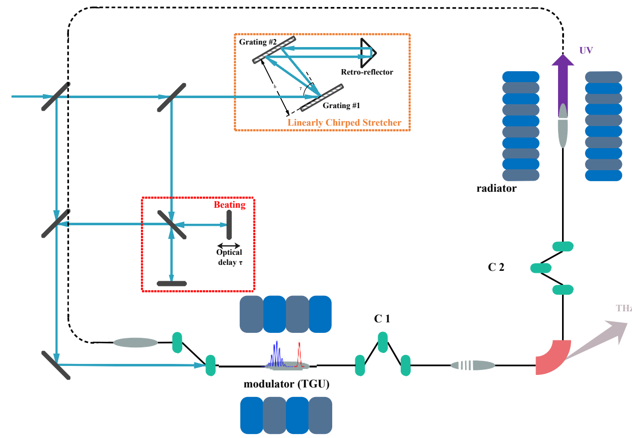

Figure 1: Principle of the experiment.

The beam is modulated by a laser with a quasi-sinusoidal envelope. The laser can be obtained by beating frequency pulse [11]and its amplitude distribution is:

$$a(z) = \omega_0 e^{-(\frac{z^2}{4\sigma_L^2})} \cos(\frac{k_m}{2} z + \phi) \quad (1)$$

Where ω_0 is normalized modulation amplitude and k_m is normalized modulation wave number.

A normal beam (Fig. 2a) is modulated by the modulator to generate periodic energy modulation in the phase space (Fig. 2b), but the bunch density distribution is unchanged. The energy modulation is converted to density modulation by the first chicane (since the previous dogleg is mainly used for short-wavelength modulation, the influence can be ignored here), and the electron beam is tilted in the phase space (Fig. 2c), thus producing a periodic distribution over the density distribution. Here is an approximation of the spectrum of the beam after density modulation:

$$\tilde{\rho}(k) \approx e^{-[(r_{51}^2+r_{52}^2+r_{56}^2)/2]k^2} \int_{-\infty}^{+\infty} e^{-ikz} \frac{e^{-(z^2/2)}}{\sqrt{2\pi}} J_0[kr_{56}a(z)]\mathrm{d}z \quad (2)$$

Where r_{ij} is the normalization coefficient of the dispersion segment transmission matrix.

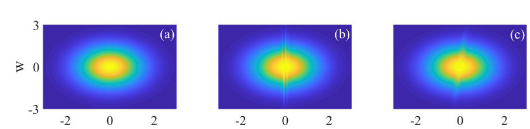

Figure 2: Theoretical calculation of phase space of bunch. (a) phase space with gaussian distribution; (b) phase space with energy modulation; (c) phase space with dispersion.

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The method of Phase-merging Hammonic Generation (PEHG) [12] is used to generate short wavelength pulse. A transversal dispersion is introduced by the dogleg, followed by a phase merging effect in the transverse gradient undulator (TGU). The relationship between transverse dispersion and transverse gradient is:

$$\alpha\eta = -\frac{4\gamma^3(n + 0.81n^{1/3})}{nAk_s L_m K_0^2 \sigma_\gamma} \tag{3}$$

Where α is the transverse gradient of the undulator, η is the transverse dispersion of a dogleg, n is the harmonic number, A is the energy moudulated amplitude, k_s is the wave number, L_m is the modulator length, K_0 is the modulator center K value, σ_γ is the energy spread. It can achieve higher bunching factors on higher harmonics. For the n_{th} harmonic, when larger A and η or smaller horizontal size σ_x are used, the bunching factor can be approximated as follows:

$$b_n \approx 0.67/n^{1/3} \tag{4}$$

Where b_n is the bunching factor of the n_{th} harmonic.

SIMULATION

Using the bunch parameters (see Table 1) of Hefei Light Source (HLS), we have done time-dependent simulations. The energy modulation and radiation was performed by the Genesis [13], and Elegant [14] was used to evaluate the phase space in the dogleg and chicane.

Table 1: Parameter of HLS for Simulation

Bunch	
E_0	800 MeV
σ_γ	1×10^{-3}
I_{peak}	25 A
Moudulator	
N	10
λ_u	0.08 m
K_0	9.8
Radiator	
N	50
λ_u	0.05 m
K	2.4

Here, an 800 nm laser with a beating frequency of 1 THz is used as the seed laser. Its power distribution is shown in Fig. 3. The energy modulation amplitude is related to the seed laser power and the modulation length. Only the modulation part is calculated (Fig. 4), and its energy modulation amplitude is about A = 2.2. Where only the longitudinal position and energy correlation terms is considered, R_{56} = 19.8 mm, the final spectrum is shown in Fig. 4, and the bunching factor is 0.2 at 1 THz. Assuming that the bunch is focused at a small spot and the frequency is truncated due to the finite size of the target, the THz radiation

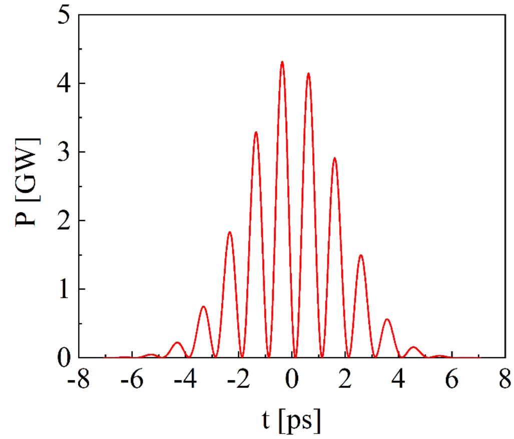

Figure 3: Power distribution of the chirp-beating pulse.

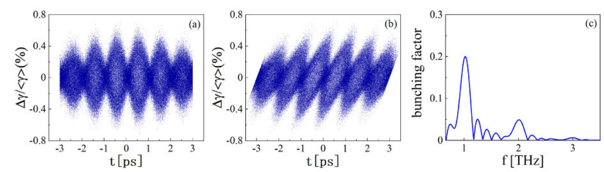

Figure 4: Longitudinal phase space distributions at the exits of the modulator (TGU) (a) and the first dispersion section(chicane1) (b) and the corresponding spectrum(c).

energy in the bend magnet can be evaluated by:

$$E_{THz} = N_e^2 b^2 \frac{dW_1}{d\omega} \delta\omega \tag{5}$$

Where b is the bunching factor, N_e is the number of electrons of coherent radiation, $\frac{dW_1}{d\omega}$ is the power spectrum of a single particle, and $\delta\omega$ is the linewidth. For the above parameter, when the charge is 1 nC, the bandwidth is 0.1%, the pulse energy is 0.15 μJ.

The bunch from the ring gain a transverse dispersion through a dogleg before entering the modulator, $\eta = 0.192$. The gradient parameter of the TGU is $\alpha = -31.1414$. The beam undergoes energy modulation in the modulator and produces phase merging as shown in Fig. 5a.The length of the 800 nm seed laser is σ_t = 100 fs and the maximum energy modulation amplitude $A = 5$. Since the first dispersion segment is used for bunching of THz domain and does not satisfy the short wavelength condition, it is necessary to add another chicane (C2) to compensate the dispersion, so that it bunching in the short wavelength. Its total dispersion parameter R_{56} = −0.0093 mm. When the harmonic number n = 20, the bunching factor b = 0.176 (Fig. 5c). Its radiation in the radiator is shown in Fig. 6. It is shown that the initially steep quadratic power growth in Fig. 6a. The radiation reaches the saturation quickly and the output peak power is about 32kW (~10^9photos/pulse). Due to the harmonic pulse shortening effect, the output pulse durations is about 40 fs (rms). Further, It can have a better performance in other storage rings with better bunch parameters.

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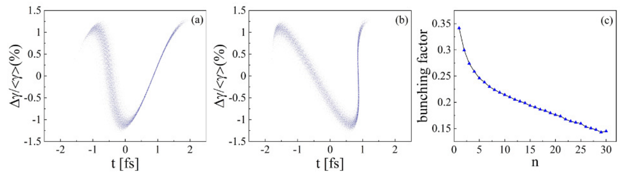

Figure 5: Longitudinal phase space distributions at the exits of the modulator (TGU) (a) and the first dispersion section (C1) (b) and the corresponding bunching factor for n_{th} harmonic (c). One electron slice ($= \lambda_s = 800\,\mathrm{nm}$) has been highlighted to show the principle.

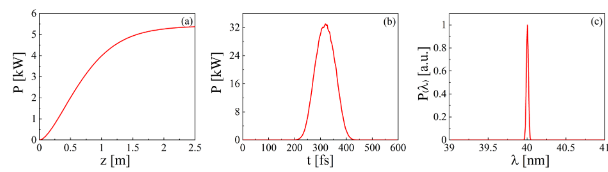

Figure 6: The UV radiation performance. (a) Power growth with the radiator distance; (b) Output radiation pulse; (c) Spectra at the exit of the radiator.

DISCUSSION

Both the pump and probe pulse wavelength can be tuned within a certain range. The wavelength of the THz pulse is determined by the amplitude modulation frequency of the seed laser, which is determined by the time delay in the Michelson interferometer. For UV pulse, the wavelength can be tuned through the OPA technique. Since the higher harmonics are selected, a small wavelength adjustment in the OPA can also cause the final UV pulse to vary over a wide range. The radiant energy can be mainly increased by increasing the bunching factor and the peak current of the bunch. For both types of radiation, the bunching factor can be increased by improving the seed laser energy. However it is subject to the requirements of energy spread proportional to laser energy. Therefore, it has also been proposed to obtain higher bunching beam with lower energy laser [15, 16].

SUMMARY

A new scheme based on storage ring is proposed to generate adjustable narrowband THz-pump pulses and UV-probe pulses. Their wavelengths are adjustable, the bandwidth of THz can be changed by changing the envelope period of the beating seed laser, and for UV light, the length of the seed laser can be reduced to improve the time resolution. Furthermore, it is a key term to explore the damping process of the bunch in the ring which is also the following work.

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