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THE EXPERIMENTAL PROGRESS FOR THE STRONG FIELD TERAHERTZ RADIATION AT SXFEL

Kaiqing Zhang[1], Yin Kang[2,3], Cheng Yu[1], Chunlei Li[1], Bin Li[1], Chao Feng[1,†]
[1]Shanghai Advanced Research Institute, Shanghai, China
[2]University of Chinese Academy of Sciences, Beijing, China
[3]Shanghai Institute of Applied Physics, Shanghai, China

Abstract

Strong field Terahertz (THz) light source has been increasingly important for many scientific frontiers, while it is still a challenge to obtain THz radiation with high pulse energy at wide-tunable frequency. In this paper, we introduce an accelerator-based strong filed THz light source to obtain coherent THz radiation with high pulse energy and tunable frequency and X-ray pulse at the same time, which adopts a frequency beating laser pulse modulated electron beam. Here, we present the experimental progress for the strong filed THz radiation at shanghai soft X-ray free-electron laser (SXFEL) facility and show its simulated radiation performance.

INTRODUCTION

Terahertz (THz) radiation, with a frequency from 0.1 THz to several tens of THz, has been increasingly significant for many scientific frontiers, such as THz - triggered chemistry, single shot THz bioimaging and nonlinear physical [1]. The development of strong field THz radiation with a pulse energy on the order of millijoule (mJ) has provided new possibilities for studying various of new scientific phenomenon, such as strong field-novel material interactions, the high-harmonic generation of THz waves, nonlinear THz spectroscopy [2]. In recent years, the so-called THz pump and X-ray probe technique, which exciting the matter with a THz radiation and capturing the dynamic image by X-ray pulse, has been an important technique to measure the basic properties of matters such as magnetization, conductivity and even crystal lattice, or study the dynamic process of matter [3].

One main barrier for the application of strong field THz is lack of THz source with high pulse energy and tunable frequency. Currently, the strong THz radiation is mainly produced by the ultrafast laser [4], laser produced plasma [5] and electron accelerator-based techniques [6]. For the ultrafast laser and laser produced plasma techniques, it cannot generate synchronized high-power X-ray and strong field THz radiation at the same time. The electron accelerator-based technique has been treated as one reliable method to obtain strong field THz radiation, and many electron-accelerator-based THz light source also has been proposed. The electron accelerator can produce THz radiation by several methods: coherent synchrotron radiation (CSR) [7], coherent transition radiation (CTR) [8] and undulator radiation [9]. In recent years, FEL facilities around the world, including LCLS-II, FLASH, European-XFEL and Swiss-FEL have produced high power X-ray and strong-field THz radiation at the same time by adopting an afterburner and compressing the duration of electron beam into one THz period [10]. However, generating THz radiation with a frequency above 10 THz needs to supress the electron beam duration below 100 fs, which can be a challenge for the most existing FEL facilities.

In this paper, we introduce an electron accelerator-based strong field THz radiation technique, which can produce THz radiation with high pulse energy and tunable frequency from 0.1 THz to 40 THz by using a frequency beating laser modulated electron beam. Here, we present the experimental progress, including the frequency beating laser pulse, THz undulator, THz diagnostic line, for the strong THz radiation at shanghai soft X-ray free-electron laser (FEL) (SXFEL) facility. To show the possible performance, simulation results with the basic parameters of SXFEL are also given.

WORKING PRINCIPLE

Figure 1 shows the layout of the introduced THz radiation technique [11, 12]. The working principle can be expressed as following: The electron is firstly produced from a photocathode gun with a beam energy of several keV, and then the beam is accelerated to a beam energy above 1 GeV by the LINAC, and the pulse duration of electron beam is also be supressed by the LINAC. After that, the relativistic electron beam is sent into a modulation section together with a frequency beating laser pulse. Figure 2 shows the layout of the frequency beating laser. An ultrafast laser pulse with an initial pulse length of σ is stretched by a grating pair to generate large frequency chirps, and the laser pulse undergoes a frequency-dependent modulation phase modulation, the phase can be expressed as [13]:

$$\phi(\omega) = \phi(\omega_0) + \tau_0(\omega - \omega_0) + \frac{(\omega-\omega_0)^2}{2\mu} + \cdots,$$

where τ_0 is the group delay at ω_0, μ is the carrier frequency sweep rate (linear chirp rate), $\mu = \frac{d\omega}{dt}$. At the same time, the pulse length of laser pulse is also stretched from σ to σ_n, where σ_n can be calculated by $\sigma_n = \sigma\sqrt{(1+4/\mu^2\sigma^4)}$. And then, a beam splitter is introduced to separate the stretched laser pulse into two pulses, one of them passes through an optical delay line, which will introduce a time delay τ. The laser pulses are recombined, which can form a quasi-sinusoidal chip modulation of the

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† email address: fengc@sari.ac.cn

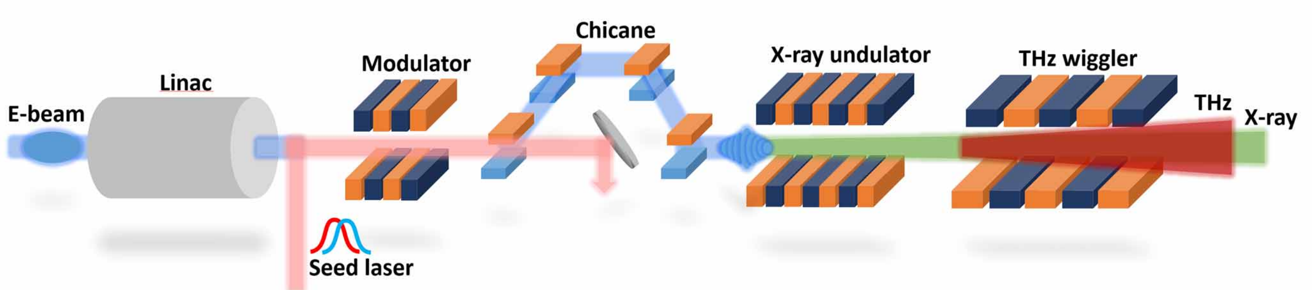


Figure 1: The basic layout of the introduced strong field THz radiation based on the frequency beating laser modulated electron beam.

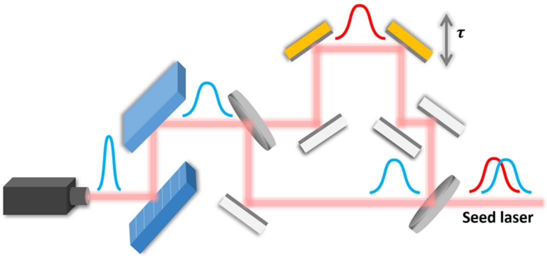


Figure 2: The layout of the frequency beating laser pulse.

light intensity considering that the frequency of the two pulses at every point in the time domain differs by a beating frequency of f, the beating frequency can be expressed by: $f=\frac{\tau}{\pi\sigma\sigma_n}\cong\frac{\mu\tau}{2\pi}$. The frequency beating laser can produce a beating frequency at THz range, and the frequency can be easily adjusted by tuning μ and τ from 0.1 to 40 THz. The frequency beating laser pulse will interact with the electron beam in the magnetic modulator, and imprint the energy modulation at the beating frequency into the beam. The electron beam then passes through a magnetic dispersion section to convert the energy modulation into density modulation at the beating frequency. The modulated electron beam is firstly sent into a undulator with a relative short magnetic period to produce X-ray radiation, and then the beam is sent into a undulator with a much longer magnetic period to THz radiation. By using the proposed technique, synchronized X-ray and THz radiation can be generated at the same time.

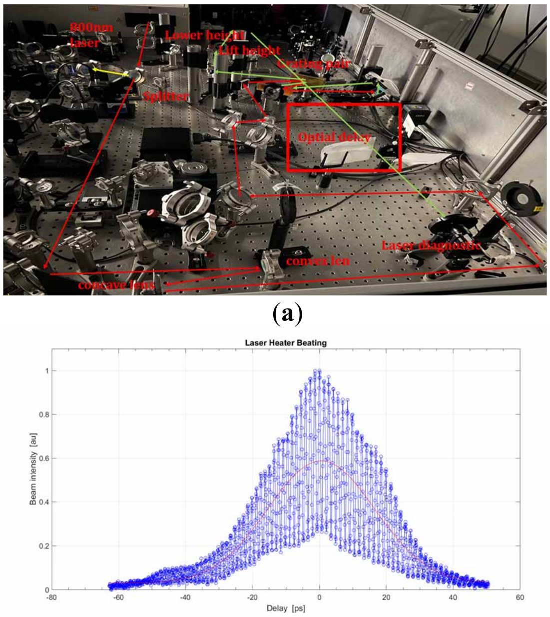
THE EXPERIMENTAL PROGRESS

The experiment of the introduced technique will be carried out at SXFEL. The basic parameters of SXFEL are presented in Table 1. The SXFEL can produce electron beam with a beam energy on the order of GeV, a bunch charge of 500 pC and a bunch length from 0.1 to 7 ps, the electron beam can be used to generate X-ray pulse with a peak power above 1 GW. For the SXFEL, there are two undulator beam line: SBP Line and SUD Line, the experiment will be carried out at the SBP Line. Based on the basic layout of SXFEL, there are two options to modulate the electron beam: the first option is at the laser heater section, the second option is at the existing modulator and dispersion sections before the SBP undulator. To carried out the experiment, frequency beating laser pulse, THz undulator, THz diagnostic line are required. In this section, we will show the experimental progress for the THz radiation at SXFEL.

Table 1: The Basic Parameters of SXFEL

Parameter	Value	Unit
Energy	0.5-1.5	GeV
Bunch Charge	500	pC
Energy spread	0.005%	-
Bunch length	0.1-7	ps
Laser wavelength	800	nm
Laser pulse length	30	fs

As shown in Fig. 2, a frequency beating optical Line is required. Based on the layout of Figure 2, an actual beating frequency optical path has been built together with the laser heater optical path, which has been shown in Fig. 3 (a). To verify the performance of the optical path, the longitudinal profile at the exit of the optical path has been measured, and the results are also shown in the Fig. 3 (b). One can find a frequency beating structure at THz frequency exists along the longitudinal profile.



(a)

(b)

Figure 3: (a) The actual frequency beating optical path and (b) the measured longitudinal profile after the frequency beating optical path.

Besides the frequency beating laser, the THz undulator is also designed and processed. The THz undulator is shown in Fig. 4, and the THz undulator parameters are presented in Table 2. The undulator adopts an electromagnetic undulator with a changeable undulator magnetic period of 280 or 560 mm. The total length of the undulator is about 5m with about 18 magnetic of 280 mm. The THz undulator will be installed before the dump and after the X-ray undulator.

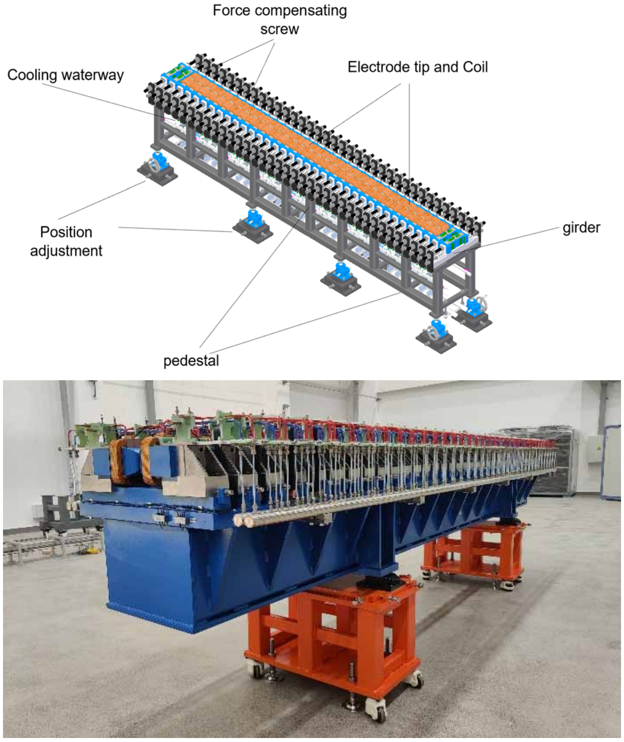


Figure 4: The THz undulator for SXFEL.

Table 2: The Basic Parameters of THz Undulator.

Parameter	Value	Unit
Type	Electromagnetic undulator	-
Period	280/560	mm
Total length	5	m
Efficient peak magnetic field	0.8-1.78	T
$\Delta K/K$	1.4e-4	-
Phase error	<5	degree

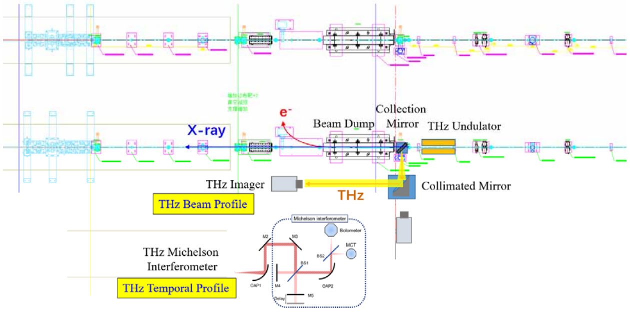


Figure 5: The layout of THz undulator and THz diagnostic line.

After the THz undulator, there will a THz mirror with a 3 mm hole to reflect the THz radiation to the downstream THz diagnostic line and transfer the X-ray to beam line. In the THz diagnostic line, a michelson interferometer will be installed to detect the pulse energy of THz radiation, and THz image and THz temporal profile will also be installed to measure the transverse and temporal image. Figure 5 shows the detail information about the layout of THz diagnostic line at SXFEL.

To show the possible performance of the introduced technique, simulations with the basic parameters of SXFEL facility are also carried out and the simulated results are shown in Fig. 6. According to Fig. 6, one can find that the peak power is about 0.58 GW and the pulse energy is below 1 mJ due to the limitation of THz undulator length.

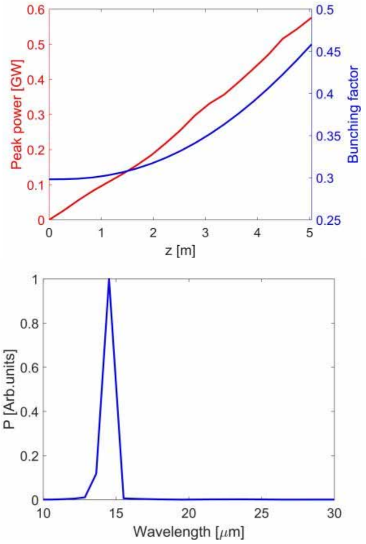


Figure 6 The peak power and bunching factor evolutions along the THz undulator, and the final spectrum of THz radiation.

CONCLUSION

In conclusion, we have introduced the strong field THz radiation technique, which can generate THz radiation with high pulse energy and tunable wavelength by using a frequency beating laser pulse modulated electron beam. The basic working principle and the experimental progress including frequency beating laser, THz undulator and THz diagnostic line are presented. The simulations of the technique are also presented, and the results show that the THz undulator with a total length of 5 m can produce THz radiation with a peak power 0.58 GW and a pulse energy below 1 mJ. The experiment will be carried out at SXFEL in the following years.

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