RECENT PROGRESS OF THz SOURCE AT THE SXFEL

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Abstract

Coherent, wide-tunable frequency and high intensity terahertz (THz) source is under preparation at the Shanghai Soft X-ray free-electron laser facility (SXFEL). The electron bunches modulated by frequency beating light can generate coherent, wide-tunable, high intensity THz radiation from 0.1 to 30 THz through wigglers. The electromagnetic wiggler with peak magnetic field up to 1.75 T is adopted and the parameters of the wiggler are optimized to ensure the generation of strong field THz radiation. Due to the limitation of layout space of the SXFEL, the length of wiggler is limited within 5 meters. By properly increasing the charge of the electron beam, the THz pulse energy can be kept at sub mJ level under the proposed different parameters of the wiggler. In this article, we will present the possible layout of THz source on the SXFEL and the S2E simulation of THz radiation of sub mJ magnitude within the 5-meter wiggler.

INTRODUCTION

The frequency of terahertz (THz) wave is between microwave and visible light about 0.1 THz to 10 THz, corresponding wavelength from 3 mm to 30 microns. For a long time, the research of THz wave is difficult due to the lack of suitable THz source and detector for THz light, forming the “THz Gap”. However, THz radiation is widely used in industrial applications such as security inspection, wireless communication and so on. More importantly, THz radiation plays an indispensable role in scientific applications such as information science, life science and superconducting materials [1, 2]. Free-electron laser (FEL) facilities are generally based on electronic linear accelerators, which have the natural advantage of producing high intensity THz radiation in a wide frequency range. Therefore, all large FEL facilities in the world, for example FLASH [3, 4], LCLS-II [5] and so on, have high intensity THz radiation sources or actively plan to arrange THz radiation sources.

The total length of SXFEL is 532 meters, and the energy of the electron beam with a charge of 500 pC can be increased to 1.5 GeV through three main acceleration stages. It mainly includes two undulator lines, one running in SASE mode and the other running in seeding mode. In the previous work [6], we calculated the 15µm THz radiation with a peak power of 2.41 GW through the 15-meter wiggler. In addition, it proved that the modulation of THz wavelength on the electron beam did not weaken the SASE radiation of X-ray, and instead enhanced the X-ray radiation due to the increase of local current intensity. However, it is unacceptable to add a 15-meter wiggler at the end of SASE line of SXFEL. Therefore, the amount of electron beam charge generated by SXFEL injector can be appropriately increase from 500 pC to 1 nC to shorten the gain length of the THz radiation. The S2E simulation shows that THz radiation with pulse energy up to 0.5 mJ can be realized within an acceptable range of 5 meters.

THE LAYOUT

The basic layout of the THz source at the SXFEL facility is shown in Fig. 1. The top line shows the linac which consists of a photocathode rf gun, a laser heater (LH) system, an X-band linearizer, a bunch compressor (BC), S-band and C-band accelerating structures, a transverse deflecting structure (TDS), and a dipole for beam dump. The bottom line shows the radiator system which consists of X-ray undulator and THz wiggler, and the FEL pulses can be detected by diagnostic stations. An electron beam with a length of about 10 ps is first generated by an electron gun, and then accelerated to 125 MeV through S-band accelerating structure. The laser heater heats the electron beam to suppress microbunching instability, and then the electron beam is compressed through a magnetic compression section to about 1 ps in length. Finally, the electron beam with an energy of about 1.5 GeV is obtained through C-band accelerating structure. The frequency beating light modulates the electron beam in the modulator, making the electron beam carry THz information, and then the electron beam is compressed through a magnetic compression section to about 1 ps in length. The modulated electron beam first generates X-ray through the X-ray undulator, and then generates intense THz radiation through the THz wiggler. The X-ray and THz radiation have good natural synchronisation and are sent to the experimental hall through beam line. The beam line and basic layout of the experimental hall are shown in Fig. 2.

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The length of THz experimental hall is about 20 meters and mainly includes three experimental stations. The end station 1 can carry out biochemical reaction kinetics experiment on picosecond time scale. The end station 2 can conduct broadband THz absorption spectrum experiments, and the end station 3 can observe the motility evolution of biomolecules on micro scale. The frequency of the seed light is determined by [7]:

\[ f \approx \frac{|\alpha|}{\pi} \tau. \]  

Here $|\alpha|$ is the chirp parameter and $\tau$ is the time delay between the two light pulses. The chirp parameter is controlled by a grating pair, and the time delay of the two light pulses is introduced by a Michelson interferometer. More details are in our previous work [6]. By adjusting chirp parameter $|\alpha|$, time delay $\tau$, and adopting harmonic radiation, a wide range of continuous tuning of THz frequencies from 0.1 THz to 30 THz can be achieved. Due to space constraints of the SXFEL, only 5-meter THz wiggler are allowed to be placed at the end of the X-ray undulator. On the premise of ensuring THz pulse with pulse energy of sub mJ magnitude, the parameters of the wiggler are important for this scheme. The resonance condition can be expressed as:

\[ \lambda_s = \frac{\lambda_w}{2\pi^2} (1 + \frac{K^2}{2}), \]  

Where $\lambda_s$ is the radiation wavelength and $\lambda_w$ is the wiggler period. $K$ is the dimensionless wiggler deflection parameter and can be expressed by a practical engineering equation as:

\[ K = 0.934\lambda_w[c]B_p[T]. \]

The $B_p$ is the maximum magnetic field and cannot actually exceed 2.5 T for a room-temperature wiggler. An electromagnetic wiggler with a peak magnetic field of 1.75 T is adopted in our THz source. According to Eq. (2) and Eq. (3), the period of the wiggler is selected as 0.28 m to preferentially cover frequency from 5 THz to 15 THz. In addition, the period of the wiggler can be switched to 0.56 m by changing the power supply.

**SIMULATION AND OPTIMIZATION**

In order to determine and optimize the parameters of the 5-meter THz wiggler while ensuring the generation of THz pulses of sub mJ magnitude, the typical parameters of the SXFEL are used as shown in Table 1. The entire S2E simulation process uses the code of ASTRA [8], FALCON [9], ELEGANT [10] and GENESIS 1.3 [11].

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser wavelength</td>
<td>800 nm</td>
</tr>
<tr>
<td>Laser pulse width</td>
<td>100 fs</td>
</tr>
<tr>
<td>Laser peak power</td>
<td>7 MW</td>
</tr>
<tr>
<td>Electron beam energy</td>
<td>1.4 GeV</td>
</tr>
<tr>
<td>Energy spread (slice)</td>
<td>0.02 %</td>
</tr>
<tr>
<td>Bunch length</td>
<td>270 µm</td>
</tr>
<tr>
<td>Bunch charge</td>
<td>1 nC</td>
</tr>
<tr>
<td>Undulator period</td>
<td>1.6 cm</td>
</tr>
<tr>
<td>Wiggler period</td>
<td>28 cm/56 cm</td>
</tr>
</tbody>
</table>

Using the classic parameters of the SXFEL, we scanned the THz spectrum range that can be covered as shown in Fig. 3.
Figure 3: The evolutions of THz frequency with electron beam energy (the left) and effective magnetic field (the right).

From Fig. 3, the range from 5 to 15 THz that we are most concerned about is effectively covered. In addition, when the period becomes 0.56 m by changing the power supply, it can be dedicated to low-frequency THz radiation.

By appropriately increasing the charge amount of the electron beam, the current intensity of the modulated electron beam can reach $10^{96}$ A. Such a high current intensity greatly reduces the gain length, not only enhancing X-ray radiation, but also ensuring THz radiation within a 5-meter wiggler. The modulated electron beam is first sent into undulators with the period length of 1.6 cm and the dimensionless undulator parameter $K$ of 1.34 to generate X-ray radiation at 2 nm. Then the THz radiation at 15 µm (20 THz) is generated through wigglers with the period of 28 cm and the dimensionless undulator parameter $K$ of 38.69. The peak power evolutions of X-ray and THz radiation are shown in Fig. 4. The X-ray radiation is saturated at 11 m and has a peak power of 3.61 GW. In addition, from the evolutions of the peak power and bunching factor of the THz radiation, it can be seen that the THz radiation has not yet reached saturation within 5-meter wiggler. However, due to the very large peak current intensity, the peak power of the THz radiation can reach 0.58 GW. The pulse energy of the THz radiation is 0.50 mJ, which can provide strong electric field of 1.38 MV/cm.

Figure 4: The peak power evolutions of the X-ray radiation (the left) and the THz radiation (the right).

The spectrum and the transverse intensity of the THz radiation at 15 µm are shown in Fig. 5. Due to numerical simulation errors, the center point of the spectrum shifted from 15 µm to 14.52 µm, and the FWHM of the spectral bandwidth was 1 µm. The THz radiation has a Gaussian like distribution in the lateral distribution, with a radiation size of approximately 2 mm. Without considering the limitation of the wiggler designed by our facility, the estimated THz pulse energy of different light beams relative to the radiation frequency is shown in Fig. 6.

Figure 5: The THz radiation spectrum at 15 µm (the left) and the transverse intensity (the right).

Figure 6: The estimated THz pulse energy of frequency from 10 THz to 30 THz.

From Fig. 6, the pulse energy of THz radiation remains at the sub mJ level. For THz radiation at lower frequencies, it may be more convenient to use methods of compressing the electron beam or coherent transition radiation (CTR).

CONCLUSION

In this article, we introduce the recent progress in building advanced THz sources at the SXFEL, as well as the basic layout of beam lines and experimental stations. In addition, we selected the parameters of the wiggler and performed S2E simulation based on the wiggler. The results show that the electron beam with a charge of 1 nC after being modulated by the frequency beating light can achieve THz radiation of sub mJ magnitude within 5-meter wiggler. This intensity of THz radiation can provide an electric field of MV/cm, which can meet the needs of most advanced intense THz experiments [12]. For lower frequency such as below 10 THz, generating THz radiation through compressing electron beam or CTR is more suitable for our THz source.

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REFERENCES


