PHOTON DIAGNOSTICS FOR THE HIGH-GAIN THz FEL AT PITZ*

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Abstract

Research and development of an accelerator-based THz source prototype for pump-probe experiments at the European XFEL are ongoing at the Photo Injector Test Facility at DESY in Zeuthen (PITZ). Proof-of-principle experiments have been performed to generate a high-gain THz Free-electron Laser (FEL) based on the Self-Amplified Spontaneous Emission scheme. The FEL radiation pulses with a central wavelength of about 100 µm (3 THz) and single pulse energy of several tens µm can be generated. In this paper, we present and discuss the photon diagnostic setup for the THz FEL together with examples of diagnostic results, including pulse energy and an FEL gain curve. The upgraded photon diagnostic setup, capable of measuring pulse energy, transverse distribution, and spectral distribution, is expected to be operational in the spring of 2023.

INTRODUCTION

The European XFEL has planned to perform THz pump–X-ray probe experiments at the full bunch repetition rate for users. A promising concept to provide the THz pulses with a pulse repetition rate identical to that of the X-ray pulses is to generate them using an accelerator-based THz source [1, 2]. Proof-of-principle experiments using a Self-Amplified Spontaneous Emission Free-Electron Laser (SASE FEL) to generate THz pulses have been performed at the Photo Injector Test Facility at DESY in Zeuthen (PITZ). A planar LCLS-I undulator (module L143-112000-26 on-loan from SLAC) driven by a high-charge (up to several nC) electron bunches from the PITZ accelerator is used to generate the THz radiation. Recently, the generation of SASE FEL pulses at a central wavelength of 100 µm (a frequency of 3 THz) with single pulse energy of up to several tens µJ has been demonstrated experimentally [3, 4]. Details about optimization of the SASE FEL are presented in [5].

A scheme of the THz beamline at PITZ is shown in Fig. 1. The scheme consists of the undulator, two screen stations named HIGH3.Scr2 and HIGH3.Scr3, a dipole magnet, and a beam dump. HIGH3.Scr2 and HIGH3.Scr3 are located

PHOTON DIAGNOSTIC SETUP

Setup for Pulse Energy Measurement

The THz photon diagnostic setups at HIGH3.Scr2 and HIGH3.Scr3 are identical. Figure 2 shows the drawing of the

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Figure 1: Scheme of the THz beamline at PITZ. Black arrows represent the direction of the electron beam. Red arrows represent the direction of the photon beam.
setup and a photograph of the actual setup in the beamline. The setup consists of a holder, a band-pass filter (BPF), and a THz pyroelectric detector (called shortly as a pyrodetector). The holder for mounting the BPF and the pyrodetector is mounted to the flange of the vacuum window. It is a cylinder made of aluminum alloy with a hollow cone shape inside that focuses the photon beam to the pyrodetector.

The pyrodetector used in the photon diagnostic setup is a room-temperature pyroelectric detector manufactured product model THz10 of SLT Sensor- und Lasertechnik GmbH. A signal voltage preamplifier is used to amplify the output signal from the pyrodetector with an adjustable gain of 10, 10^2, 10^3, and 10^4. The thermal time constant (the relaxation time from the heated state to the ambient state) of this pyrodetector is about 50 ms. Therefore, the detector can measure pulse energy with a repetition rate of 10 Hz which is the normal repetition rate of the RF macropulse at PITZ.

**Examples of Pulse Energy Measurements**

For measurements in this section, the SASE FEL was generated by the electron beam with a bunch charge of 2 nC and an average beam momentum of 17 MeV/c. The pulse energy was measured for three cases: measuring at HIGH3.Scr2, measuring at HIGH3.Scr3 while the HIGH3.Scr2’s mirror is inside the beamline, and measuring at HIGH3.Scr3 while the HIGH3.Scr2’s mirror is outside the beamline. The pulse energy for each case was measured for 500 shots within ~5 minutes. The number of electron bunch per an RF macropulse was limited to 1 to preserve the probability distribution of a single FEL pulse. Note that the BPF was not used during the measurements.

Results of the THz pulse energy measurements are shown in Fig. 3. The measured pulse energies are 16.16±0.82 µJ, 4.94±0.26 µJ, and 22.18±1.03 µJ, for the first, the second and the third cases, respectively. The fluctuation of each case is about 5%, which is lower than the prediction in start-to-end simulations [7]. A possible cause for this discrepancy could be influences of the waveguide walls on the FEL amplification process [8]. Studies and investigations of waveguide effects in the FEL process at PITZ are ongoing.

**FEL GAIN CURVE MEASUREMENT**

A set of steering coils is distributed along the undulator as shown in Fig. 4. They can bend an electron bunch horizontally away from the nominal trajectory in the undulator to measure the THz pulse energy radiated until the bending location. In other words, they can change the active undulator length contributing to the FEL process, which provides an FEL gain curve. The last four coils are more concentrated in the second part of the undulator to provide more points of a gain curve near where saturation is expected to occur.

For measurements in this section, the SASE FEL was generated by the electron beam with a bunch charge of 3 nC and an average beam momentum of 17 MeV/c. The pulse energy was measured at HIGH3.Scr3 while the HIGH3.Scr2’s mirror is outside the beamline. Similar to the previous section, the number of electron bunch per an RF macropulse was limited to 1. However, a BPF with a maximum transmission centered at 100 µm and a bandwidth of ~12 µm (FWHM) was used during the measurements in this section.

Important experimental parameters for the FEL gain curve measurement are summarized in Table 1. Note that the properties of the BPF determine the central wavelength and the spectral bandwidth in the table. The measured FEL gain curve is presented in Fig. 5. The relative fluctuation rates are plotted on the right axis. The measured gain curve shows an increase of six orders of magnitude (10^{-4} – 10^0) within the undulator length of ~2 m. This is an indication of a high-gain FEL. The reduction of energy fluctuations during the FEL amplification process corresponds to the simulation results in [9]. More details about gain curve measurements at PITZ are presented and discussed in [4].
Table 1: Important Experimental Parameters for the FEL Gain Curve Measurement

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bunch charge</td>
<td>3 nC</td>
</tr>
<tr>
<td>RMS bunch length</td>
<td>5.8 ± 0.3 ps</td>
</tr>
<tr>
<td>Peak current</td>
<td>~165 A</td>
</tr>
<tr>
<td>Mean momentum</td>
<td>17 MeV/c</td>
</tr>
<tr>
<td>Projected momentum spread</td>
<td>98 keV/c</td>
</tr>
<tr>
<td>Maximum FEL pulse energy</td>
<td>29.67 ± 5.54 µJ</td>
</tr>
<tr>
<td>Central wavelength</td>
<td>100 µm</td>
</tr>
<tr>
<td>Spectral bandwidth</td>
<td>≤ 12 µm FWHM</td>
</tr>
</tbody>
</table>

All mirrors in the setup have a diameter of 50.8 mm. M2 is a flat mirror located on the top of the diamond window. M3 is an ellipsoidal mirror that focuses the photon beam on the camera. M4 is an ellipsoidal mirror that transports the photon beam to M5. M5 is an off-axis parabolic mirror that collimates the photon beam. M5 and M6 are flat mirrors that are components of a Michelson interferometer.

The BPF, the polarizer, and M3 are mounted on pneumatic actuators. Therefore, they can be moved remotely in and out from the photon path. The camera is mounted on a linear motorized stage, so it can be moved remotely to measure the transverse profiles of the THz pulse at various positions along the photon beam path. M6 is mounted on a linear motorized stage to be used as a movable mirror for the Michelson interferometer. The motorized stage has a moving range of 50 mm. Therefore, the Michelson interferometer can reach a spectral resolution of 0.2 cm⁻¹.

Figure 5: Measured pulse energy and fluctuation as a function of the position along the undulator. The THz FEL pulse was generated by the 3-nC 17-MeV/c electron beam.

Figure 6: Layout of the upgrade photon diagnostic setup at HIGH3.Scr3. The red arrows represent the direction of the photon beam.

**CONCLUSION**

The photon diagnostic setup of the THz FEL at PITZ is described. The setup uses the THz10 pyrodetector to measure THz pulse energy with a repetition rate of 10 Hz. Examples of pulse energy measurements and a gain curve measurement are presented and discussed. The upgraded THz photon diagnostic setup, including the THz camera and the Michelson interferometer, is expected to be operational in the spring of 2023.
REFERENCES


