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FIRST LASING OF THE THz SASE FEL AT PITZ*

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Abstract

The Photo Injector Test Facility at DESY in Zeuthen (PITZ) develops a prototype of an accelerator-based high-power tunable THz source for pump-probe experiments at the European XFEL. The PITZ injector is also the site for the development and preparation of the high-brightness electron source for the main linac of the European XFEL and has the same pulse train structure as the X-ray photon source of the XFEL. For the proof-of-principle experiments on high-power THz generation an LCLS- I undulator (on loan from SLAC) is installed in the tunnel annex downstream of the existing accelerator. The extension of the beam line consists of a bunch compressor and a collimation system in the main PITZ tunnel, as well as a matching section, the undulator and the THz diagnostic setup in the tunnel annex. A Self-Amplified Spontaneous Emission (SASE) FEL is used to generate the THz pulses. High radiation power can be achieved by utilizing high charge (up to several nC) electron bunches from the PITZ photo injector. A beam energy of ~17 MeV is used to generate THz radiation with a centre wavelength of 100 µm. The transport of this space charge dominated electron beam and its thorough matching into the planar LCLS-I undulator with a strong vertical focusing is one of the project challenges. The installation of the first THz beamline setup was finished in summer 2022 and commissioning with electron beam started. A specially developed procedure for a high charge beam matching into the undulator was successfully tested resulting in a first THz pulse generation. The start-up THz diagnostics is based on pyrodetectors. First measurements of the THz generation from 1 nC, 2 nC and 3 nC bunches have been taken, the statistics properties analysis corresponds to the expected SASE performance. The gain curve for the 3 nC case reflects the onset of saturation regime.

INTRODUCTION

The Photo Injector Test Facility at DESY in Zeuthen (PITZ) currently develops a prototype for a high-power tunable accelerator-based THz source for pump-probe experiments at the European XFEL [1]. A promising concept to provide THz pulses with a pulse repetition rate identical to that of the X-ray pulses is to generate them using the PITZ photo injector. Because PITZ develops the high-brightness electron source for the European XFEL, properties of the photo injector are fully compatible with the XFEL one, especially both injectors maintain the same pulse train structure. To generate a high-power THz pulses a SASE FEL is considered as a main mechanism. One of the key parameters for the THz SASE FEL high performance is a high beam peak current of up to 200 A. The PITZ RF-gun with a Cs_2Te photocathodes is capable of generating electron bunches with charges of up to several nC (up to 5nC), making it suitable for the proof-of-principle experiments on the high-gain THz SASE FEL. The THz beamline has been designed and implemented as an extension of the existing PITZ linac in the tunnel annex [2]. A planar LCLS-I undulator (on-loan from SLAC) is used to generate the THz radiation. The undulator parameters (period of 3 cm and undulator parameter of ~3.5) demand an electron beam energy of ~17 MeV for the centre radiation wavelength of ~100 µm. The strong magnetic field with a horizontal gradient requires a thorough beam matching. Another challenge is the narrow vacuum chamber (height 5 mm, width 11 mm, and length ~3.5 m), which makes matching and transport of the space charge dominated electron beams a complicated task.

The THz beamline was successfully commissioned [3] with 100 pC beams, then high-charge transport and matching started. A special procedure was developed and experimentally tested before at the existing part of the PITZ linac [4] and then successfully applied at the newly installed THz beamline. The first THz SASE FEL lasing was first detected with 1 nC bunch charge, then the bunch charge was stepwise increased to 3 nC. The gain curves were measured for 1 nC, 2 nC, and 3 nC.

THz BEAMLINE

The previously existing PITZ beamline was extended by a bunch compressor and a collimator system in the first tunnel and a matching system, the LCLS-I undulator and THz diagnostics in the second tunnel annex (second PITZ tunnel) downstream of the existing accelerator [2]. The current THz beamline in the tunnel annex is shown in Fig. 1. The THz radiation is measured using pyrodetectors at two stations after the undulator [3]. To measure gain

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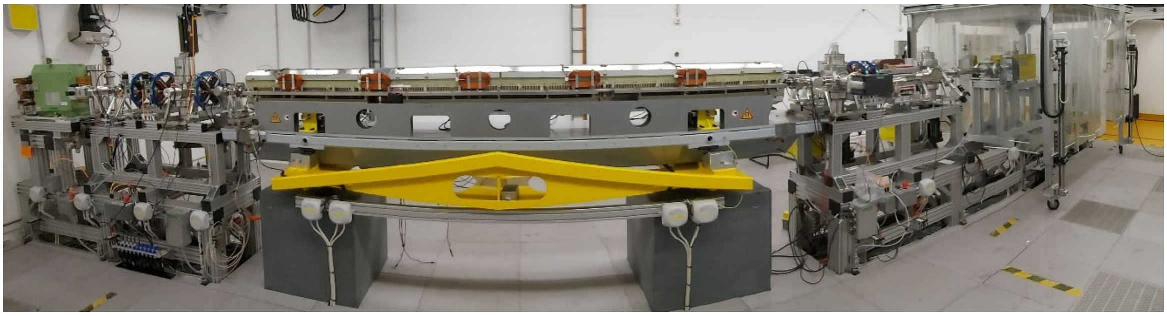

Figure 1: PITZ tunnel annex with installed THz beamline. The electron beam direction is from left to right. Five steering coils are distributed along the undulator to enable gain curve measurements.

curves a set of air coils evenly distributed along the undulator (Fig. 1) is used. They allow to kick an electron bunch away from the nominal trajectory in the undulator to measure the THz pulse energy radiated until the kick location (active undulator length).

ELECTRON BEAM MATCHING

A high-charge electron beam is generated at the PITZ gun (prototype Gun5.1 [5]), the gun gradient is tuned to yield a beam mean momentum of ~6.3 MeV/c at the phase of maximum acceleration. The bunch charge of 1, 2, and 3 nC was obtained by adjustment of the laser spot size at the cathode and the photocathode laser pulse energy. The final beam momentum of 16.5-17 MeV/c was achieved by tuning the gradient and the phase of the CDS booster. The booster phase was chosen to be ~20 deg off-crest, which roughly corresponds to the minimum projected energy spread at the undulator entrance. Main linac and electron beam parameters are summarized in [3].

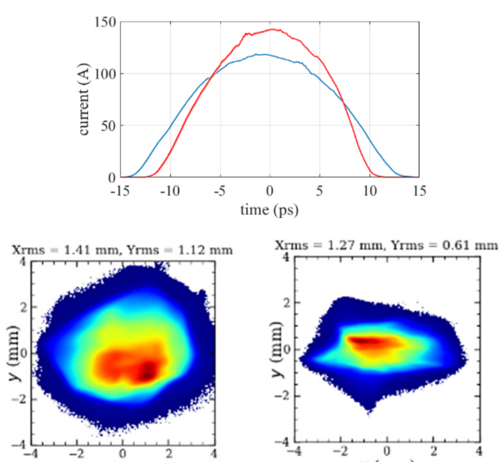

Figure 2: Top: electron bunch current profile, measured by TDS, two curves correspond to two various slopes of the deflecting RF field used for measurements. Bottom: electron beam transverse distribution at the YAG screen before (left) and after (right) undulator for 2 nC bunch.

For the space charge dominated beam transport through the PITZ linac was realized by use of two quadrupole triplets. The third quadrupole triplet is located in the tunnel annex and was utilized for thorough matching of the electron beam into the undulator. The beam current profile was measured by making use of the transverse deflecting system (TDS), the measured beam current profile for 2 nC bunches is shown in Fig. 2 (top plot). The beam matching was realized by subsequent transverse distribution measurements at YAG screens along the beamline. An example of beam characterization is shown in Fig. 2 (bottom plots). The charge was measured with Faraday Cup and integrating current transformer (Bergoz ICT), the charge jitter is estimated to be lower that 1.8% and at larger extent is due to the electronic noise.

THz MEASUREMENTS

The THz radiation is measured by pyroelectric detectors located on the top of dedicated screen stations HIGH3.Scr2 and HIGH3.Scr3. Cylindrical adapters with a conic internal surface for the radiation collection are mounted on the top of a flange with a diamond window. This setup is shown in Fig. 3 (left). Station HIGH3.Scr2 is equipped with a movable THz toroidal mirror with a 5 mm diameter hole for further electron beam transport, and station HIGH3.Scr3 is a solid mirror without a hole for transport of the complete THz radiation to the detector. Losses from the HIGH3.Scr2 mirror due to the hole are roughly estimated to be at least 30%. Typical waveform of the pyroelectric detector signal is shown in Fig. 3 (right).

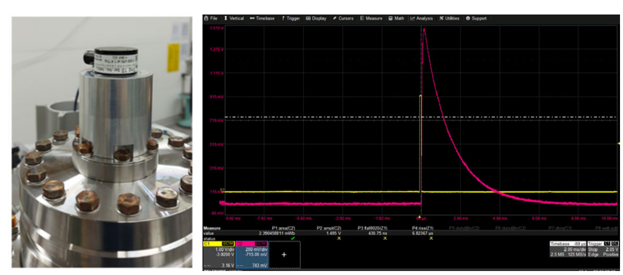

Figure 3: Left: pyroelectric detector on top of conic adapter. Right: typical scope signal from the pyroelectric detector (pink curve).

GAIN CURVES AND SASE STATISTICS

After optimizing the THz radiation signal by making use of many shots averaging and setting the correct electron beam transport, the corresponding gain curve is supposed to be measured. The gain curve measurements procedure is based on application of the short steering coils (see 5 coils on the side of the undulator in Fig. 1). Starting with the last

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coil, all coils one after another are set to a current of +3 A which is supposed to kick the beam from the lasing trajectory (in fact, the beam is dumped on the wall of the vacuum chamber). The measured THz pulse energy using 500-shots statistics along the undulator is shown in Fig. 4 for three values of the bunch charge. The last (rightmost) two points of each curve represent measurements of a single pulse, and the error bars reflect rms fluctuations of the detector signal amplitude. Other points use more pulses in a 1 MHz pulse train, so the pyrodetector shows a better signal-to-noise ratio. The backward propagation of the exponential range of the gain curves leads to an initial signal of a pJ level, which is in basic agreement with expectation for the shot noise at this wavelength. The estimated FEL gain of $\sim 10^6$ indicates a high gain THz SASE FEL, which is a quite remarkable result for this radiation wavelength range.

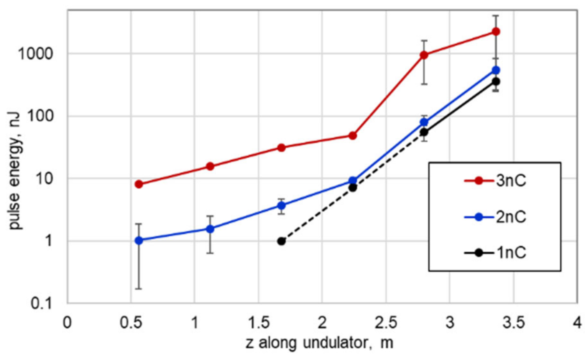

Figure 4: Gain curves for 1, 2 and 3 nC.

Probability distribution of the radiation pulse energy from SASE FEL operating in the high gain linear regime follows gamma distribution [6]:

$$\rho(W) \propto \frac{M^M}{\Gamma(M)} \left(\frac{W}{\langle W \rangle}\right)^{M-1} \frac{1}{\langle W \rangle} \exp\left[-M \frac{W}{\langle W \rangle}\right], \quad (1)$$

where $M = \frac{\langle W \rangle^2}{\sigma_W^2}$ is number of modes in the radiation pulse. Relevant probability distributions for second-to-last point for the 3 nC gain curve is presented in Fig. 5. It can be seen that the probability distribution of the radiation pulse energy indeed follows that of the high gain SASE-FEL in linear regime. A reduction of the gain curve slope indicates the onset of the saturation regime.

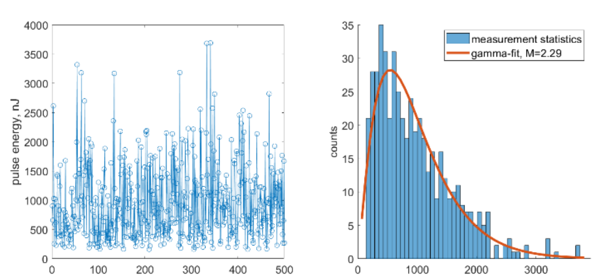

Figure 5: Single pulse radiation measurements (left) and probability distribution of the radiation pulse energy (right). Bunch charge is 3 nC, active undulator length is 2.8 m, average pulse energy is $\langle W \rangle = 0.96$ μJ, the rms spread $\sigma_W = 0.64$ μJ. Red curve is gamma distribution with M=2.29.

CONCLUSION AND OUTLOOK

The first lasing of the high-gain THz SASE FEL at the Photo Injector Test facility at DESY in Zeuthen has been achieved. This is an important milestone in the development on an accelerator-based high-power tunable THz source for pump-probe experiments at the European XFEL. Gain curves for the THz SASE FEL at the wavelength of 100 μm for a bunch charge of up to 3 nC were measured. Statistical properties of the pulse energy fluctuations demonstrate features of the high-gain SASE FEL linear regime. The onset of THz pulse energy saturation has been observed for the 3 nC case. Detailed studies of the properties of the generated THz pulses, as well as steps to optimize the high-power THz source performance are in progress.

ACKNOWLEDGEMENTS

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REFERENCES

[1] E.A. Schneidmiller, M.V. Yurkov, M. Krasilnikov, and F. Stephan, “Tunable IR/THz source for pump probe experiments at the European XFEL”, in *Proc. 34th Int. Free Electron Laser Conf. (FEL’12)*, Nara, Japan, August 2012, paper WEPD55, pp. 503-505.

[2] T. Weilbach *et al.*, "Status of the THz@PITZ Project – The proof-of-principle experiment on a THz SASE FEL at the PITZ facility", in *Proc. 13th Int. Particle Accelerator Conf. (IPAC’22)*, Bangkok, Thailand, Jun. 2022, pp. 1033-1036. doi:10.18429/JACoW-IPAC2022-TUPOPT016

[3] P. Boonpornprasert et al., “First commissioning of the proof-of-principle experiment on a THz SASE FEL at the PITZ facility”, presented at FEL’22, Trieste, Italy, August 2022, paper MOP19, this conference.

[4] X. Li *et al.*, “Matching of a Space-Charge Dominated Beam into the Undulator of the THz SASE FEL at PITZ”, in *Proc. IPAC'21*, Campinas, Brazil, May 2021, pp. 3244-3247. doi:10.18429/JACoW-IPAC2021-WEPAB257

[5] M. Krasilnikov *et al.,* “RF Performance of a new generation L-band RF gun at PITZ”, presented at FEL’22, Trieste, Italy, August 2022, paper TUP03, this conference.

[6] E.L. Saldin, E.A. Schneidmiller, and M.V. Yurkov, “Statistical properties of radiation from VUV and X-ray free electron laser”, *Opt. Commun.*, vol. 148, p. 383, March 1998. doi:10.1016/S0030-4018(97)00670-6