ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-WEPAB257

MATCHING OF A SPACE-CHARGE DOMINATED BEAM INTO THE UNDULATOR OF THE THz SASE FEL AT PITZ*

X. -K. Li†, Z. Aboulbanine, G. Adhikari, N. Aftab, Z. Amirkhanyan, P. Boonpornprasert, M. -E Castro-Carballo, N. Chaisueb, G. Georgiev, J. Good, M. Gross, C. Koschitzki, M. Krasilnikov, O. Lishilin, A. Lueangaramwong, D. Melkumyan, R. Niemczyk, A. Oppelt, H. Qian, G. Shu, F. Stephan, G. Vashchenko, T. Weilbach, DESY, Zeuthen, Germany

Abstract

The Photo Injector Test facility at DESY in Zeuthen (PITZ) is developing a THz SASE FEL as a prototype high repetition rate source for THz-pumped, X-ray-probed experiments at the European XFEL. For the generation of THz pulses of mJ-level energy from SASE, an electron beam with a high charge (up to 4 nC) and high peak current (~200 A) will be injected into an LCLS-I undulator, which is currently being installed at the end of the photo-injector. The narrow vacuum chamber (11x5 mm) between the magnetic poles and the strong vertical focusing from the undulator, as well as the lack of beam diagnostics, have made it a challenge to match the space-charge dominated beam into the undulator without beam loss during the following transport. In this paper, boundary conditions of a matched electron beam will be discussed and the simulation and experimental study on our matching strategy will be presented.

INTRODUCTION

Pump-probe experiments play an important role at the European X-ray free-electron laser facility (EuXFEL) in research frontiers in biology, chemistry and condensed matters, etc. Among them are the THz-pumped and X-ray-probed experiments, where a tunable THz pulse is used to excite a sample and the following X-ray pulse to detect its dynamics [1]. A potential solution to the THz pump source is to install a THz undulator driven by an independent PITZ-like photo-injector [2] near the user hall, which takes advantage of the identical bunch train structure of PITZ-like injector (thus the THz pulses) as the X-ray pulses. For this purpose, a proof-of-principle experiment is undergoing at PITZ, with the existing beamline extended with an LCLS-I undulator.

Previous simulations have shown the capability of producing THz pulses with milli-Joule level energy in the SASE regime [3–5]. However, it requires a high bunch charge (up to 4 nC) and high peak current (~200 A) for the electron beam. While its momentum is only 17-22 MeV/c (corresponding to a resonant FEL pulse wavelength of 60-100 μm), the electron beam is strongly space-charge dominated. In this paper, one of the key issues in the proof-of-principle experiment, the matching of the space-charge dominated beam into the undulator, is discussed, using the limited beam momentum of 22 MeV/c at the bunch charge of 4 nC and the peak current of 200 A. It will be demonstrated later that the transverse phase space of the electron bunch must be properly tuned before the undulator, in order to avoid beam loss to the vacuum chamber in the undulator. However, due to the space charge effects, the transverse phase space downstream could not be predicted from the measured phase space upstream and the beamline optics after the measurement. Besides, the limited space also makes it impossible to measure the transverse phase space directly at the undulator entrance. Therefore, a matching strategy using only two screen stations together with prepared particle tracking results is proposed and verified with simulations and experiments.

BOUNDARY CONDITIONS OF THE ELECTRON BEAM

The flat vacuum chamber (11-mm-wide and 5-mm-high) between the magnetic poles in the LCLS-I undulator assumes the beam size should be bigger in the horizontal plane than in the vertical plane. Meanwhile, in order to cancel the growth of beam size due to the expelling space charge forces, a converging beam is foreseen in the horizontal plane. And to match the strong vertical focusing forces from the undulator, a converging beam is also foreseen in the vertical plane. Therefore, a strong *x*-*y* asymmetry should be provided in terms of beam sizes as well as in terms of divergencies (or Twiss parameters). To produce such a beam, a quadrupole triplet is to be installed right before the undulator.

In order to investigate what kind of transverse distribution is suitable for the electron beam to transport safely through the undulator, the distribution was scanned and for each point the beam was tracked until the undulator exit using ASTRA [6]. Goal functions were defined as $F_x = |\sigma_x - \sigma_x^0|$ in the horizontal plane and $F_y = \langle\sigma_y\rangle$ in the vertical plane, where σ_x and σ_y are the horizontal and vertical beam size, respectively, the superscript 0 denotes the parameters at the undulator entrance. F_x is minimized if the beam size at the exit is close or equal to the initial beam size, which will allow an overall large beam size in the horizontal plane, thus relaxing the space charge effects. And F_y is to minimize the average beam size, since the chamber is smaller vertically. It is found that the horizontal beam size is mainly dependent on the space charge effects and the vertical beam size is dominated by the focusing forces from the undulator magnetic fields, allowing to scan the horizontal and vertical beam distribution independently.

The goal functions are shown as functions of the RMS beam size and the covariance in Fig. 1. A good choice would allow a relatively large tuning tolerance for all the scanned

* Supported by the European XFEL research and development program
† xiangkun.li@desy.de

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-WEPAB257

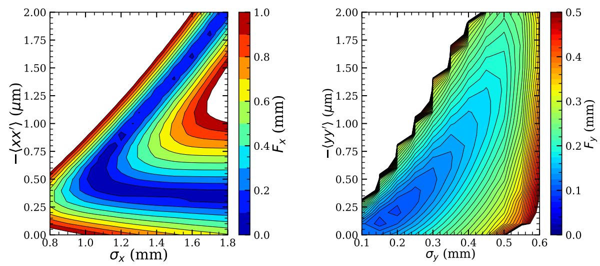

Figure 1: The goal function dependence on the initial beam parameters in horizontal plane (left) and vertical plane (right), with the normalized emittance of 4 mm mrad.

parameters, as listed in Table. 1. In Fig. 2, it shows how the beam envelope evolves in the undulator when keeping the RMS beam size and changing the covariance. In both planes, the covariance must not be too small or too large, otherwise the beam will be lost in the middle of the undulator.

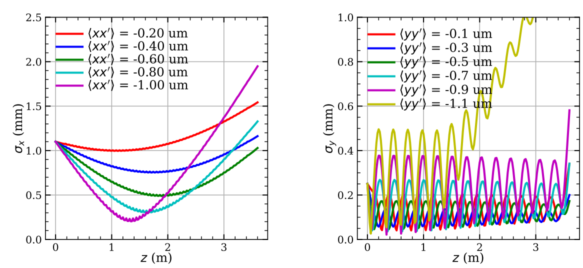

Figure 2: Beam transport along the undulator in horizontal plane (left) and vertical plane (right) when keeping the RMS beam size and changing the covariance.

In the above simulations, a constant normalized beam emittance of 4 mm mrad has been assumed. Further studies have shown that the density plots in Fig. 1 still hold even though doubling the beam emittance.

MATCHING STRATEGY

Matching Concept

In order to control the transverse phase space of the electron beam, a quadrupole triplet is to be installed in front of the undulator. However, the absence of phase space diagnostics around the undulator makes it difficult to tell if the beam arrives with the proper distribution. Besides, due to the installation of new components (i.e., collimator, BPMs, steerers, chicane dipoles and so on) [7, 8], there is not much space left in the extension beamline. As a result, only two far apart screen stations are available before the undulator, labeled as High2.Scr3 and High3.Scr1 in Fig. 3.

With the two screen stations, a matching strategy has been proposed as follows. Firstly, the simulation results in the previous section have suggested that once the beam size and covariance in the transverse plane are well chosen, the beam could transport safely in the undulator fields. That is,

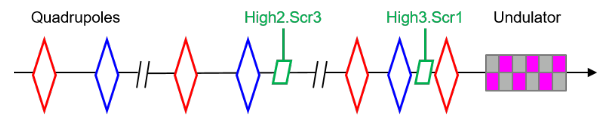

Figure 3: Layout of beamline around the undulator.

four parameters are enough to define the transverse space space. Then, the quadrupole triplet in front of the undulator is tuned in such a way that the beam is symmetric or round before entering the first quadrupole. Such a triplet setting could be easily found by tracking the beam backward from the undulator entrance, as shown in Fig. 4, where the beam covariances have been reversed to make the electron bunch diverging at the starting position. With the round beam, the four parameters after the triplet are turned into two parameters before the triplet. The two parameters could be the beam size and covariance at a given position, and could also be the beam size at two locations. In other words, they could be the beam size at the two screen stations in Fig. 3. Note that the screen High3.Scr1 is inside the triplet, the beam size there has to be obtained by extrapolation. Next, the upstream quads before High2.Scr3 are tuned to make the measured beam size match the wanted beam size at both screens. And once the matching point is found, the gradients of the triplet are set according to backward simulations, and finally the electron beam will arrive at the undualtor with the proper phase space distribution. It should also be noted that a round beam in front of the triplet does not mean the phase space is identical in both horizontal and vertical planes, due to the asymmetric space charge effects in the quadrupoles.

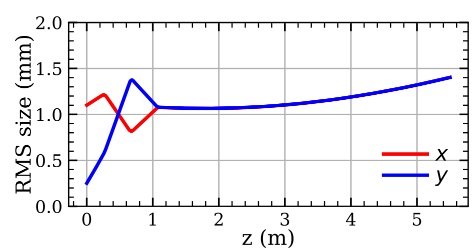

Figure 4: Backward tracking of the electron bunch starting from the undulator entrance ($z = 0$).

Simulations

In the backward tracking, the focusing of the quadrupole triplet has been scanned, with the gradients tuned for a round beam upstream, as shown in Fig. 4. The RMS beam size at the two screen stations (i.e., HIGH2.SCR3 and HIGH3.SCR1 in Fig. 3) is plotted against each other, as shown by the red curve on the left side in Fig. 5.

Meanwhile, simulations starting from the photocathode have been performed with the electron beam being transported to the entrance of the first quadrupole involved in the matching procedure. From there, the focusing of the quadrupoles has also been scanned, with the gradients tuned

12th Int. Particle Acc. Conf. IPAC2021, Campinas, SP, Brazil JACoW Publishing
ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-WEPAB257

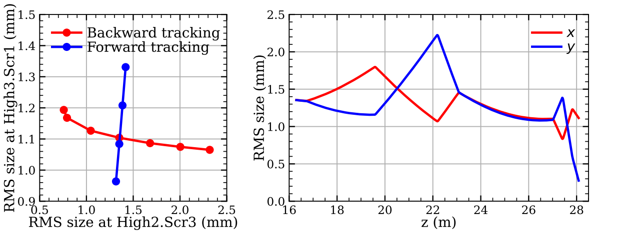

Figure 5: Matching procedure (left) and transport of the electron bunch under the matching condition (right).

to allow a round beam transport after them. The RMS beam size at HIGH2.SCR3 and HIGH3.SCR1 is plotted against each other, as shown by the blue curve on the left side in Fig. 5. The matching condition is then given by the intersection point, which determines the gradients of all the quadrupoles. Under the matching condition, the beam has been tracked until the undulator entrance, as shown on the right side in Fig. 5. In Table. 1 the designed and simulated parameters were compared, agreeing well with each other.

Table 1: Summary of the Beam Parameters at the Undulator Entrance

Parameter	Designed	Simulated	Measured	Unit
σ_x	1.10	1.11	1.15	mm
$\langle xx' \rangle$	-0.50	-0.51	N.A.	µm
σ_y	0.25	0.28	0.27	mm
$\langle yy' \rangle$	-0.30	-0.31	N.A	µm

EXPERIMENTAL DEMONSTRATION OF MATCHING STRATEGY

While the construction work of the extension beamline is ongoing, the existing beamline at PITZ has been employed to demonstrate the validity of the matching procedure. It was carried out with six quadrupoles, three of them far from each other to represent the quadrupoles for tuning the incoming electron beam and the other three very close to each other to represent the quadrupole triplet before the undulator for tuning electron beam distribution at the virtual undulator entrance, as shown in Fig. 6. Before the experiment, simulations similar to the previous section have been performed with such a beamline, with the beam sizes at the two screens obtained from backward tracking to be compared to experimental results. The intersection point of the red and blue curves, both of which were from simulations, on the left side in Fig. 7 clearly shows there was a matching point.

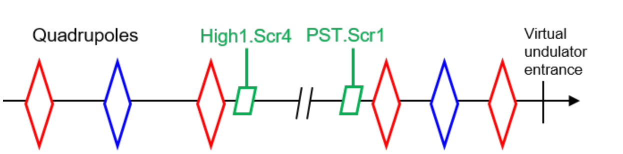

Figure 6: Layout of the beamline used in the experiment.

For the experiment, the round beam transport has been achieved by tuning the first quadrupole triplet in the following steps. Firstly, two screen stations after the triplet are chosen to monitor the beam distribution. Then, the first quadrupole is set to a given current. Next, the strength of the second quadrupole (with an opposite polarity to the first one) is increased gradually while monitoring the beam distribution at the first screen station, until a round beam is observed. After that, the strength of the third quadrupole (with the same polarity as the first one) is increased gradually while monitoring the beam distribution at the second screen station, until a round beam is observed. After tuning the second and third quadrupoles alternately several times, a round beam transport after the triplet will be reached.

The current of the first quadrupole has been scanned experimentally to get the beam size at both screens, as shown by the green curve on the left side in Fig. 7. It is found that the measured curve has shifted from the simulated one. The possible reason is that the phase space of the electron beam before the first triplet is different in the simulation and in the experiment, e.g., due to the imperfections of laser and the RF fields in the experiment. From the intersection point, the currents of all the six quadrupoles could be derived and the resulting beam transport was measured, as shown on the right side in Fig. 7. The horizontal and vertical beam size at the virtual undulator entrance (z = 13.8 m) have also been compared to the designed ones in Table. 1. Although the covariance is not available in the table, one can tell from the overlapping beam envelops afterwards that it agreed well between simulations and measurements.

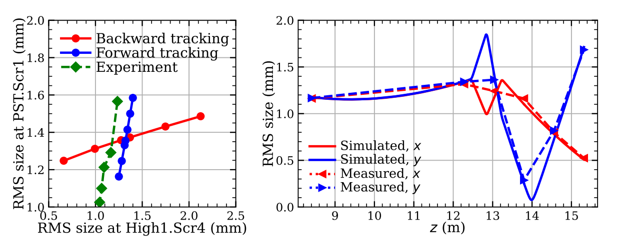

Figure 7: Matching procedure (left) and transport of the electron bunch under the matching condition (right).

CONCLUSION

In this paper, we introduced and demonstrated the strategy for matching the space-charge dominated electron beam into the LCLS-I undulator, which is part of the THz SASE FEL at PITZ. The electron beam is strongly space-charge dominated, therefore the beam transport could not be predicted using measured phase space upstream and transfer matrix of the beamline. With knowledge of a matched beam around the undulator obtained from the backward tracking in advance, the matching procedure has been shown effective and easy to realize by both simulations with the real beamline around the undulator and experiments performed in the existing beamline.

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-WEPAB257

REFERENCES

[1] P. Zalden *et al.*, "Terahertz Science at European XFEL", XFEL.EU, Schenefeld, Germany, Rep. TN-2018-001-01.0, Apr. 2018.

[2] E. Schneidmiller *et al.*, "Tunable IR/THz source for pump probe experiment at European XFEL", in *Proc. (FEL'12)*, Nara, Japan, Aug. 2012, paper WEPD55, pp. 503-506.

[3] P. Boonpornprasert, M. Krasilnikov, and F. Stephan, "Calculations for a THz SASE FEL based on the measured electron beam parameters at PITZ", in Proc. FEL'17, Santa Fe, NM, USA, Aug. 2017, pp. 419-421.

[4] M. Krasilnikov, P. Boonpornprasert, H.-D. Nuhn, E. Schneidmiller, F. Stephan, and M. V. Yurkov, "Start-to-End Simulations of THz SASE FEL Proof-of-Principle Experiment at PITZ", in *Proc. 13th International Computational Accelerator Physics Conference (ICAP'18)*, Key West, Florida, USA, Oct. 2018, pp. 246–252. doi:10.18429/JACoW-ICAP2018-TUPAF23

[5] X.-K. Li *et al*, "Design studies of a proof-of-principle experiment on THz SASE FEL at PITZ", *Journal of Physics: Conference Series*, vol. 1350, p. 012036, Nov. 2019. doi:10.1088/1742-6596/1350/1/012036

[6] K. Flottmann, ASTRA particle tracking code, http://www.desy.de/~mpyflo/.

[7] A. Lueangaramwong *et al.*, "Numerical Study of Beam Dynamics in PITZ Bunch Compressor", presented at the 12th Int. Particle Accelerator Conf. (IPAC'21), Campinas, Brazil, May 2021, paper WEPAB274, this conference.

[8] T. Weilbach *et al.*, "Beam Line Design and Instrumentation for THz@PITZ - the Proof-of-Principle Experiment on a THz SASE FEL at the PITZ Facility", presented at the 12th Int. Particle Accelerator Conf. (IPAC'21), Campinas, Brazil, May 2021, paper TUPAB071, this conference.