EMITTANCE MEASUREMENTS OF THE ELECTRON BEAM AT PITZ FOR THE COMMISSIONING PHASE OF THE EUROPEAN XFEL

G. Vashchenko*, G. Asova†, M. Bakr‡, P. Boonpornprasert, J. D. Good, M. Gross, C. Hernandez-Garcia§, H. Huck, I. Isaev, D. Kalantaryan, G. Kourkafas, M. Krasilnikov, D. Malyutin, D. Melkumyan, A. Oppelt, M. Otevrel, Y. Renier, T. Rublack, F. Stephan, Q. Zhao¶, Deutsches Elektronen-Synchrotron, Zeuthen site, Zeuthen, Germany
O. Lishilin, G. Pathak, Hamburg University, Hamburg, Germany

Abstract

For the operation of free electron lasers (FELs) like the European XFEL and FLASH located at DESY, Hamburg Site, high quality electron beams are required already from the source. The Photo Injector Test facility at DESY, Zeuthen Site (PITZ), was established to develop, characterize and optimize electron sources for such FELs. Last year the work at PITZ focused on the optimization of a photo injector operated very close to the startup parameters of the European XFEL. This implies photocathode laser pulses with a Gaussian temporal profile of about 11 – 12 ps FWHM to drive the photo gun operated at a gradient of about 53 MV/m. Significant effort was spent on the electron beam characterization and optimization for various bunch charges. Emittance measurements were performed as a function of major accelerator parameters such as main solenoid current, laser spot size on the cathode and the gun launching phase. The requirement on the beam emittance for a bunch charge of 500 pC for the European XFEL commissioning phase has been demonstrated. Results of these studies accompanied with the corresponding simulations are presented in this paper.

INTRODUCTION

Free electron lasers like the European XFEL and FLASH require high quality electron beams already from the photo injector [1, 2]. The commissioning phase of the European XFEL injector section is planned to start end of 2015. For the commissioning phase there are reduced requirements on the operation conditions and electron beam quality as compared to the nominal ones in order to simplify the commissioning phase and operate the machine at most stable, reliable and robust conditions. Namely, it is planned to use a gun gradient reduced from 60 MV/m to 53 MV/m which corresponds to a reduced electron beam momentum after the gun from about 6.7 MeV/c to 6.1 MeV/c. The photocathode laser system used for the commissioning phase will produce transversally uniform pulses which correspond to the nominal operation, while the temporal profile will be Gaussian with a full width at half maximum (FWHM) of about 13 ps as compared to the nominal flat-top profile with an FWHM of 20 ps and rise/fall times of 2 ps. Various electron beam charges (0.1 – 1 nC) with corresponding electron beam quality are planned to be used for the nominal operation of the European XFEL [3]. For SASE (Self Amplified Spontaneous Emission) commissioning it is currently planned to use a bunch charge of 500 pC, which is in the middle of the nominal charge range. For this charge the requirement on the normalized transverse slice emittance during the commissioning phase is 1 mm mrad at the undulator section.

The possibility to run the European XFEL photo injector with the aforementioned parameters was validated at the Photo Injector Test facility at DESY, Zeuthen site (PITZ), which serves as an injector test-bed for FLASH and the European XFEL. A schematic layout of PITZ is presented in Fig. 1. Conditioning and characterization of the normal conducting L-band RF gun cavities is performed at PITZ for their further usage at the European XFEL and FLASH. The photoelectrons are produced with a Cs_2Te semiconductor photocathode. UV laser pulses which are transversely uniform and temporally Gaussian, with an estimated FWHM of about 11 – 12 ps, are currently used. The produced photoelectrons are accelerated in the gun cavity and are focused with the main solenoid installed at the exit of the gun. The bucking solenoid installed upstream the cavity is used to compensate the field of the main solenoid at the cathode plane in order to avoid initial angular momentum in the electron beam which spoils the electron beam quality. During the last run period the RF gun was operated at a maximum on-axis peak field of about 53 MV/m and 640 μs RF pulse length as required for the commissioning phase of the European XFEL. Several diagnostic devices are installed downstream the gun for the electron beam characterization (see Fig. 1). Further beam acceleration is done using a normal conducting L-band Cut Disk Structure (CDS) booster cavity which can increase the momentum of the electron beam up to about 22 MeV/c. The first Emittance Measurement SYstem (EMSY1) is installed directly at the exit of the CDS booster at about 5.3 m downstream the cathode. The transverse projected normalized emittance of the electron beam is measured using the conventional slit scan method based on a direct measurement of the electron beam size and angular spread [4]. More details about the PITZ setup can be found elsewhere [4–6].

* Grygorii.Vashchenko@desy.de
† on leave from INRNE-BAS, 1784 Sofia, Bulgaria
‡ on leave from Assiut University, 71515 Assiut, Arab Republic of Egypt
§ on leave from JLab, Newport News, VA 23606, USA
¶ on leave from IMP/CAS, 730000 Lanzhou, China

ISBN 978-3-95450-134-2

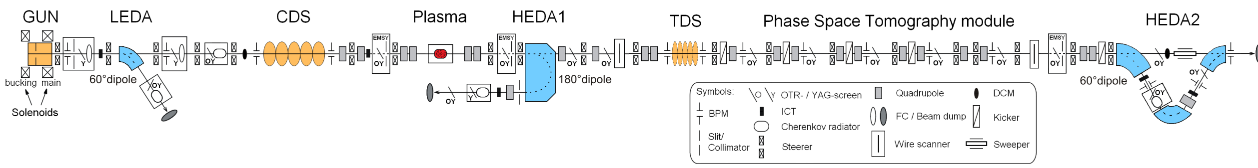
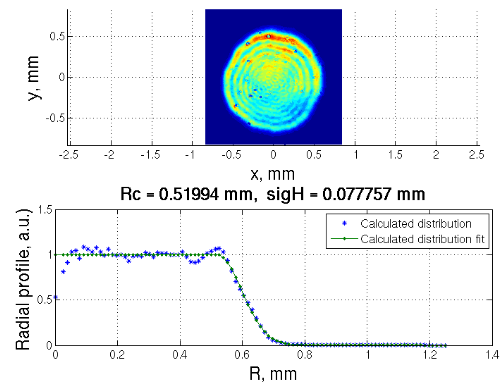


Figure 1: Schematic layout of the Photo Injector Test facility at DESY, Zeuthen site (PITZ).

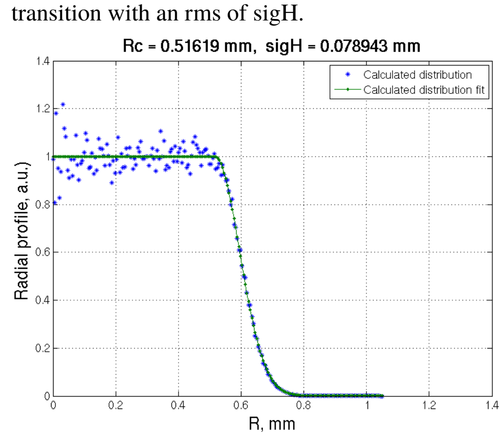
BEAM DYNAMICS SIMULATIONS WITH REALISTIC TRANSVERSE LASER PROFILE

A Space charge TRacking Algorithm (ASTRA) code was used to perform beam dynamics simulations [7]. Electron beams of 1 nC, 500 pC, 250 pC and 100 pC were used in simulations as well as during the measurements. The gun on-axis peak field at the cathode was fixed to 53.25 MV/m based on the matching of the electron beam momentum of about 6.1 MeV/c measured experimentally and found during the simulations for the gun launching phase which provides the Maximum Mean Momentum Gain (MMMG). The CDS booster on-axis peak field was tuned in the same manner and resulted in 17.1 MV/m in order to achieve the electron beam momentum of about 21.0 MeV/c at MMMG phase as during the experimental measurements. The CDS booster launching phase was fixed to MMMG phase for simulations and measurements as it has a minor impact on the quality of the electron beam in a wide range [8]. Laser pulses with a Gaussian temporal profile and an FWHM of about 12 ps were used during the simulations as well as for measurements. The main solenoid current, gun launching phase and laser spot size on the cathode were used as input parameters for the multi-parameter optimization.

The transverse laser profile used in the simulation was generated using two different approaches. In the first, conventional approach the uniform transverse profiles of different sizes were used like in previous simulations [4–6] where the laser spot size was a parameter of optimization and was assumed to fit to the experiment. In a second more sophisticated approach, in order to better match the real laser transverse distribution at the cathode measured with the help of a CCD camera installed at an equivalent position, the transverse laser profile was generated as follows. At first, the measured laser transverse distribution is analyzed and converted to a radial profile by integrating over the azimuthal angle in 2π as shown in Fig 2a. The obtained radial profile can be split in two parts: the core part with a uniform distribution and the halo part with a Gaussian transition as shown in Fig. 2a. By fitting the experimental data with the corresponding model the radius of the uniform part Rc and the rms size of the Gaussian transition sigH are found. Using these values the corresponding cathode distribution, which will be used for simulations as shown in Fig. 2b, is generated. A small discrepancy between the values of Rc and sigH in Fig. 2a and 2b is caused by limited statistics during the generation of the initial cathode distribution for ASTRA: only $2 \cdot 10^5$ particles were generated in this case. More details on the generation of such distributions and their influence on beam dynamics can be found in [9]. When using a uniform



(a) Example of an analysis of a real laser transverse profile and generation of its radial profile. The generated radial profile is fitted with a multi curve: an uniform distribution with radius Rc and a Gaussian transition with an rms of sigH.



(b) Example of an ASTRA distribution (radial profile) generated with parameters found in the upper figure. Radial profile is fitted with the model described above and the fit parameters found are in a good agreement.

Figure 2: Example of generating an ASTRA input laser distribution with a realistic laser profile.

laser transverse distribution the beam dynamics simulations are quasi-continuous, while by using a more realistic distribution, as in the second approach, the beam dynamics simulations are performed only for the ceratin experimental conditions. Simulation results with both approaches for var-

ISBN 978-3-95450-134-2

ious electron beam charges are presented in the following section together with experimental data.

EMITTANCE SIMULATIONS AND MEASUREMENT RESULTS

Emittance dependencies on the main solenoid current, gun launching phase and rms laser spot size on the cathode were measured for various electron beam charges. At first, for a fixed electron beam charge the emittance dependence on the laser spot size on the cathode was measured at the MMMG gun launching phase as a phase which expects to deliver the minimum emittance [4]. For each laser spot size a solenoid scan was done in order to minimize the emittance and for the main solenoid current delivering the best emittance several statistical measurements were performed. The results of such measurements for 500 pC electron beams are presented in Fig. 3 together with simulation results. As

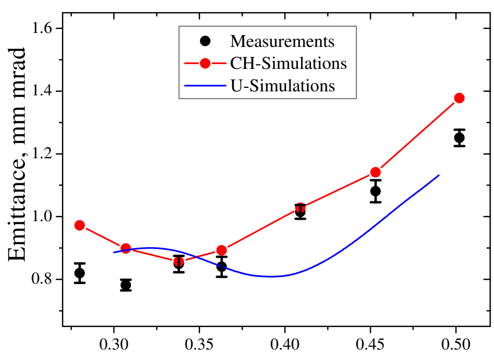


Figure 3: Emittance dependence on the rms laser spot size on the cathode for an electron beam with 500 pC bunch charge. Statistical error bars are shown in experimental measurements. "CH-" states for simulations with realistic transverse laser profile while "U-" for the simulations with uniform laser transverse profile, see text.

it can be seen from Fig. 3 for rms laser spot sizes of less than 0.37 mm the emittance dependence is weak and taking into account the systematic errors during the measurements, which are estimated to be about 10 % (see [4]), the laser spot size delivering the best emittance value cannot be conclusively determined. Taking into account that the slice emittance would be smaller than the projected one and that the emittance increase from the injector to the undulator section is small, it can be concluded that the requirement for the commissioning phase of the European XFEL on the emittance of less than 1 mm mrad for an electron bunch charge of 500 pC is fulfilled within good margins.

The red dotted curve in Fig. 3 represents the simulations with a realistic transverse profile which includes core and halo parts as described in the previous section, while the blue curve shows the simulations with an uniform profile. It can be seen that inclusion of the realistic transverse laser profiles in the simulation delivers better agreement to measurements not only by the obtained emittance values but also by better agreement for the machine parameters delivering the minimum emittance value. Additionally, as can be seen in Fig. 3, in the simulations with the uniform transverse laser distribution it is not possible to extract the desired charge for rms laser spot sizes on the cathode of less than 0.3 mm due to space-charge limitations at the cathode, while for the measurements it is limited at about 0.28 mm.

For the rms laser spot of about 0.31 mm, which delivered the smallest measured emittance during the laser spot size scan, the dependance of emittance on gun launching phase was measured as presented in Fig. 4. As well as in

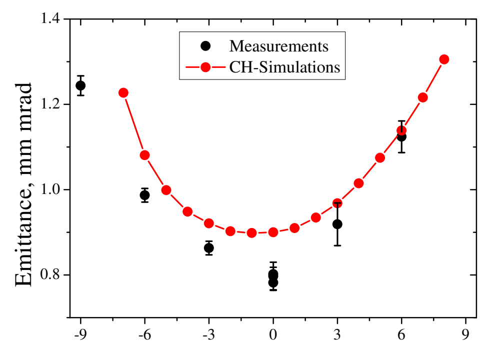


Figure 4: Emittance dependence on the gun launching phase for an electron beam with 500 pC bunch charge and rms laser spot size of 0.31 mm. Statistical error bars are shown in experimental measurements.

the previously described measurements for each gun phase the main solenoid current was scanned in order to find the minimum emittance for each gun launching phase and for the solenoid current delivering the minimum emittance value several statistical measurements were performed. Again a comparable trend between the measurements and simulations is observed. Additionally, one has to point out the emittance measurements at MMMG phase which are represented by three tightly positioned points in Fig. 4. These measurements were done at the same machine conditions. Between these measurements the machine conditions were changed to perform different studies. As in total four days passed between the first and the last measurement it can be concluded that the machine stability and reproducibility is very good at least within this short period.

A summary plot of the emittance for different electron beam charges is shown in Fig. 5 for parameters corresponding to the commissioning phase as well as for nominal conditions of the European XFEL [4, 6]. As it can be seen from Fig. 5 and was expected in advance the obtained emittance values for the machine operating at the parameters close to those for the commissioning phase of the European XFEL are systematically higher than for the nominal conditions but will allow a stable and robust first commissioning of the European XFEL.

ISBN 978-3-95450-134-2

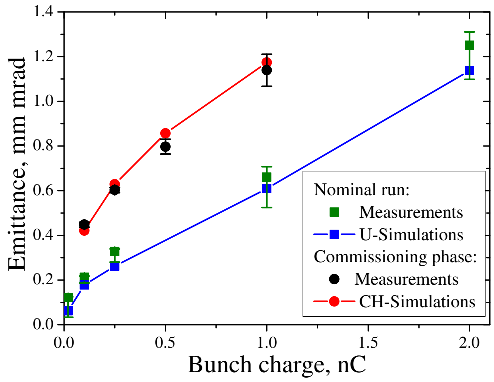


Figure 5: Emittance dependence on electron bunch charge for different stages of the European XFEL.

SUMMARY AND OUTLOOK

Operation of the PITZ photo injector at parameters very close to the ones planned for the commissioning phase of the European XFEL has revealed that the requirement on electron beam quality in terms of emittance is well fulfilled and that the RF gun is operated reliably. Beam dynamics simulations with improved modeling of the transverse laser distribution were performed and yield a better agreement between the simulated and measured data as a function of machine parameters. On the way to further improve the electron beam quality beyond the nominal European XFEL parameter set, the commissioning of a new type of photocathode laser system, capable of producing 3D-ellipsoidal laser pulses, has started at PITZ [10, 11]. In addition to the already existing very flexible photocathode laser system [12] this should allow to ultimately optimize the electron beam parameters.

REFERENCES

[1] W. Ackermann et al., Nature Photon. 1, 336 (2007).

[2] M. Altarelli et al., DESY Hamburg Report No. DESY 2006-097, 2007.

[3] W. Decking et al., "European XFEL construction status", FEL2014, Basel, Switzerland, August 2014, WEB03, p. 623.

[4] G. Vashchenko, *Transverse phase space studies with the new CDS booster cavity at PITZ.* PhD thesis. DESY-THESIS-2013-043, 2013.

[5] F. Stephan et al., Phys. Rev. ST Accel. Beams 13, 020704 (2010).

[6] M. Krasilnikov et al., Phys. Rev. ST Accel. Beams 15, 100701 (2012).

[7] K. Floetmann, A Space charge TRacking Algorithm, `http://www.desy.de/~mpyflo`.

[8] G. Vashchenko et al., "Emittance optimization for different bunch charges with upgraded setup at PITZ", IPAC2011, San Sebastian, Spain, September 2011, THPC115, p. 3155.

[9] C. Hernandez-Garcia et al., "Studies on charge production from Cs_2Te photocathodes in the PITZ L-band normal conducting radio frequency photo injector", in preparation, to be submitted to Phys. Rev. ST Accel. Beams.

[10] M. Khojoyan et al., "Optimization of the PITZ photo injector towards the best achievable beam quality", FEL2014, Basel, Switzerland, August 2014, THP006, p. 685.

[11] J. Good., "New ellipsoidal laser at the upgraded PITZ facility", *These Proceedings*, TUP034, FEL2015, Daejeon, Korea (2015).

[12] I. Will and G. Klemz, Optics Express 16, 14922 (2008).

ISBN 978-3-95450-134-2