# OPTIMIZATION OF THE TRANSVERSE PROJECTED EMITTANCE OF THE ELECTRON BEAM AT PITZ

G. Vashchenko*, G. Asova†, M. Gross, L. Hakobyan, I. Isaev, Y. Ivanisenko, M. Khojoyan‡, M. Krasilnikov, M. Mahgoub, D. Malyutin, A. Oppelt, M. Otevrel, B. Petrosyan, S. Rimjaem§, A. Shapovalov, F. Stephan, DESY, 15738 Zeuthen, Germany
D. Richter, HZB, 14109 Berlin, Germany

*Abstract*

High brightness electron sources for linac based free-electron lasers operating at short wavelength such as the Free-Electron Laser in Hamburg at DESY, Hamburg Site (FLASH) and the European X-Ray Laser Project XFEL (European XFEL) are characterized and optimized at the Photo Injector Test Facility at DESY, Zeuthen Site (PITZ). One of the most important parameters influencing the FEL process is the normalized transverse projected emittance of the electron beam. The major part of the experimental program at PITZ is devoted to its optimization. Detailed simulations of the present facility setup are performed for a $1\,\mathrm{nC}$ bunch charge in order to optimize the transverse projected emittance of the electron beam. Cathode laser pulse length and transverse spot size at the photo cathode, gun and booster accelerating gradients and their launching phases as well as the main solenoid current are optimized. Simulations results together with experimental data are presented.

## INTRODUCTION

Linac based free electron lasers like FLASH [1] and the European XFEL [2], developed to produce high brilliance coherent laser light with wavelength down to nanometers and below, require high quality electron beams with high peak current, small relative energy spread and transverse slice emittance. For the production of the laser light at such FELs the Self Amplified Spontaneous Emission (SASE) process in the undulator is used. Aforementioned parameters of the electron beam define minimum achievable wavelength and brilliance of the emitted laser radiation obtained during the lasing process [3]. Such characteristics like peak current of the electron beam and its energy spread can be improved during the electron beam transport from the gun towards the undulator, while the minimum emittance value of the electron beam at the undulator entrance is a property which is already determined at the output of the photo injector and usually only degrades after the electron beam leaves the photo injector. The research program at PITZ is devoted to the characterization and optimization of the photo injectors which will be used at FLASH and the European XFEL. The description of the PITZ facility setup used for measurements and simulations can be found in [4]. The emittance of the electron beam in the PITZ photo injector is a quantity which depends on several machine parameters such as laser transverse and temporal profiles, gun and booster on-axis peak fields and their launching phases with respect to maximum mean momentum gain phase, hereinafter w.r.t MMMG phase as well as the focusing current of the main solenoid. A detailed set of the simulations was done in order to study the emittance dependence on the aforementioned machine parameters and will be presented together with experimental data obtained during the run period January-June 2011.

* Grygorii.Vashchenko@desy.de
† On leave from INRNE, Sofia, Bulgaria
‡ On leave from ANSL, Yerevan, Armenia
§ Currently at Chiang Mai University, Chiang Mai, Thailand

## BEAM DYNAMICS SIMULATIONS AND EXPERIMENTAL RESULTS

A Space charge TRacking Algorithm (ASTRA) code was used for the simulations [5]. The range of parameters used for the emittance simulations is presented in Table.1. The booster launching phase was kept constant during the simulations since the emittance dependence on this parameter is negligible [6]. The normalized transverse projected emittance, hereinafter emittance, of the electron beam was measured at EMSY1 (see [4]), placed directly behind the booster cavity, by using the well established single slit scan technique [4, 7].

### *Emittance dependence on the gun on-axis peak field*

The emittance dependence on the gun on-axis peak field was studied for a fixed laser pulse length with $\mathrm{FWHM} = 21.5\,\mathrm{ps}$ corresponding to an average value measured during the last run period. Other parameters like gun launching phase, main solenoid current, booster on-axis peak field were varied in order to get the minimum emittance values for each gun on-axis peak field. Results of the simulations are presented in Fig.1. An exponential decay fit is applied to the simulation data.

The values of the rms laser spot size on the cathode for which minimum emittance value was found for a given gun on-axis peak field are presented in Fig.2. An allometric fit is applied to the simulation data. Values of the gun launching phase at which minimum emittance value was found for a given gun on-axis peak field are presented in Fig.3. We can consider some weak trend on the phase to the negative direction meaning relative growth of the space-charge induced emittance compared to the RF-induced emittance as the electron beam more compressed for the positive phases. The focusing strength of the main solenoid current deliver-

| Parameter | Range | Step | Unit |
|---|---|---|---|
| Flat-top laser temporal profile, FWHM | [20; 44] | 1 | ps |
| Flat top laser temporal profile, rise/fall times | 2 | - | ps |
| Uniform laser transverse profile, rms, $\sigma$ | [0.2; 0.6] | 0.01 | mm |
| Gun on-axis peak field, $E_{gun}$ | [44; 61] | 1 | MV/m |
| Gun launching phase w.r.t. MMMG phase, $\phi_{gun}$ | [-10; 10] | 0.5 | deg |
| Main solenoid current, $I_{main}$ | [280; 400] | 1 | A |
| Booster on-axis peak field, $E_{booster}$ | [0; 25] | 1 | MV/m |
| Booster launching phase w.r.t. MMMG phase, $\phi_{booster}$ | 0 | - | deg |

Table 1: PITZ setup parameters used in the emittance simulations with 1 nC bunch charge.

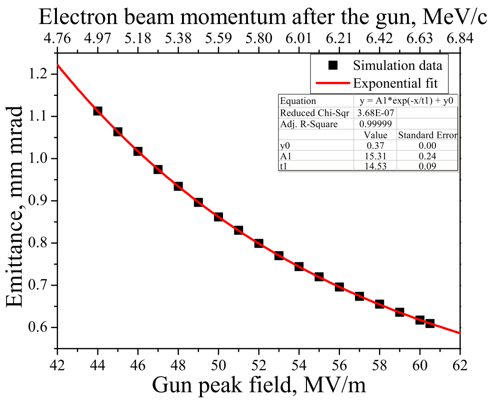


Figure 1: Emittance dependence on the gun on-axis peak field.

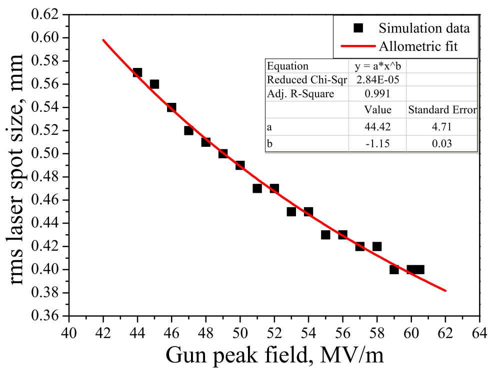


Figure 2: rms laser spot size on the cathode dependence on the gun on-axis peak field.

ing minimum emittance values has a linear dependence on the gun on-axis peak field and is presented in Fig.4 . The dependence of the booster on-axis peak field on the gun on-axis peak field is presented in Fig.5. The optimum booster on-axis peak field value fluctuates around $17.75\,\mathrm{MeV/c}$. It can be assumed that the optimum booster on-axis peak field value is not changing while varying the gun on-axis peak field and its fluctuation obtained in simulations is caused by too rough steps on the other parameters during their optimization.

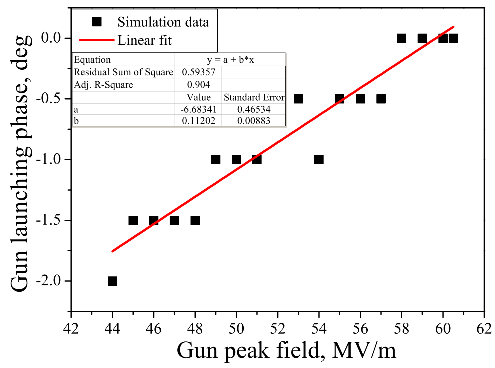


Figure 3: Gun launching phase dependence on the gun on-axis peak field.

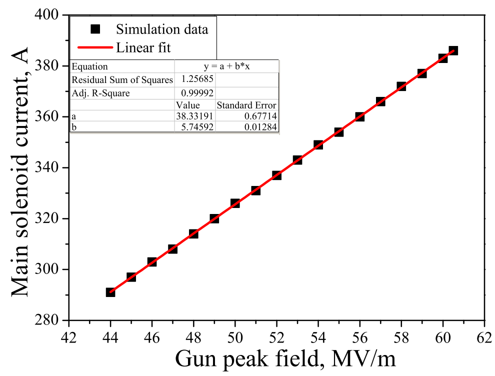


Figure 4: Main solenoid current dependence on the gun on-axis peak field.

### *Emittance dependence on various parameters for a fixed gun on-axis peak field value*

The emittance dependence on the various machine parameters for a fixed gun on-axis peak field of $E_{gun} = 60.58\,\mathrm{MV/m}$ was studied in more details. This value was chosen to fit the average electron beam momentum at MMMG phase measured during the last run period of $< p_z >= 6.68\,\mathrm{MeV/c}$. A laser temporal profile was used with parameters like described in the previous subsection. The absolute minimum emittance value of $\varepsilon = 0.61\,\mathrm{mm\,mrad}$ was found during the simulations for the rms laser spot size on the cathode $\sigma = 0.4\,\mathrm{mm}$, gun launching phase $\phi_{gun} = 0\,\mathrm{deg}$, main solenoid cur-

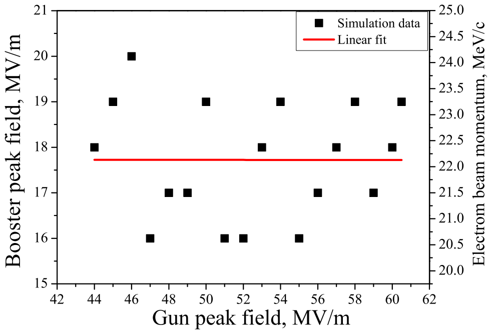


Figure 5: Booster on-axis peak field dependence on the gun on-axis peak field.

rent $\mathrm{I_{main}} = 386\,\mathrm{A}$ and booster on-axis peak field $\mathrm{E_{booster}} = 19\,\mathrm{MeV/c}$. During experimental investigations a minimum emittance value of $\varepsilon = 0.66 \pm 0.05\,\mathrm{mm\,mrad}$ was found for $\sigma = 0.3\,\mathrm{mm}$, $\phi_{\mathrm{gun}} = 6\,\mathrm{deg}$, $\mathrm{I_{main}} = 396\,\mathrm{A}$ and $\mathrm{E_{booster}} = 20.5\,\mathrm{MeV/c}$. The strong discrepancy of $0.1\,\mathrm{mm}$ between simulated and measured optimum rms laser spot size at the cathode, as well as $6\,\mathrm{deg}$ difference in gun launching phase and $10\,\mathrm{A}$ difference in the optimum main solenoid current, can be caused by neglecting the enhanced electron emission from the cathode in the RF field during the simulations as described in [8]. In addition the transverse and longitudinal distributions of the cathode laser used in the experiment are not perfect as compare to distributions used for simulations [9]. On the following Figs. 6 - 9 the emittance dependencies on different parameters are presented by three curves. Connected red filled squares represent emittance values on one of the parameters listed above while the rest are fixed to the values at which the absolute minimum emittance was found as described above. Connected black filled squares represent emittance values on the parameters listed above while tuning the rest of the parameters as well. Blue filled circles represent experimental data obtained during the last run period with the statistical errors where additional statistical measurement was done. The emittance dependence on the rms laser spot size on the cathode is shown in Fig.6 in terms of detuning from the rms laser spot size value delivering the minimum emittance. It can be seen that the emittance values for both simulation curves coincide in the range $[-5;\,10]\,\%$ which corresponds to $[0.38;\,0.43]\,\mathrm{mm}$ in terms of rms laser spot size at the cathode and means that the rest of the optimized parameters are not changed in this range. The emittance growth on the left side from the optimum emittance value is caused by approaching space-charge limited extraction of the electrons from the cathode, while on the right side the contribution of the thermal emittance is increasing. The usual accuracy of setting the rms laser spot size on the cathode during experiments at PITZ is about $5\,\mu\mathrm{m}$ that means less than $1\,\%$ possible systematic uncertainty in the measured emittance value.

The emittance dependence on the gun launching phase is shown in Fig.7. The rest of the parameters stay con-

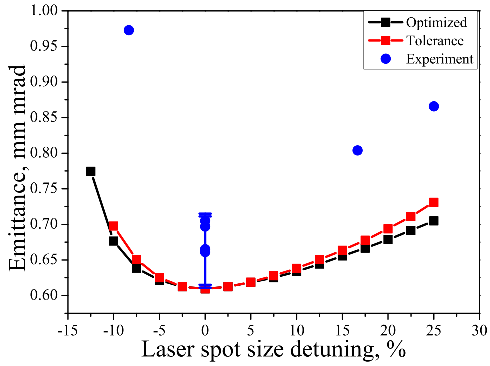


Figure 6: Emittance dependence on the rms laser spot size on the cathode for $\mathrm{E_{gun}} = 60.58\,\mathrm{MV/m}$.

stant within the phase range of $[-2;\,2]\,\mathrm{deg}$. The emittance growth on the right side from the optimum emittance value is caused by an increasing of the RF-induced emittance due to the stretching of the electron beam. For negative phases the beam compresses and space-charge forces dominate. The usual accuracy of the the gun launching phase determination at PITZ using LEDA (see [4]) is about $1\,\mathrm{deg}$ which gives a possible systematic uncertainty of about $3\,\%$ in the measured emittance value. The abscissa axis for the experimental data is shifted by $-6\,\mathrm{deg}$ for convenience.

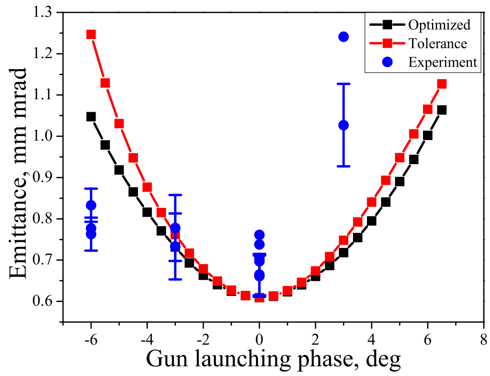


Figure 7: Emittance dependence on the gun launching phase for $\mathrm{E_{gun}} = 60.58\,\mathrm{MV/m}$.

The emittance dependence on the main solenoid current is shown in Fig.8 in terms of detuning from the main solenoid current value delivering the minimum emittance. Deviation of the solenoid current by $1\,\mathrm{A}$ from the optimum value corresponds to $0.25\,\%$ in terms of detuning, usual for experimental studies at PITZ, and gives a 1.7% increase of the emittance while optimizing other parameters and 4% if they stay the same as for the optimum emittance value.

The emittance dependence on the booster on-axis peak field is shown in Fig.9. The emittance stays rather flat in a wide range of booster on-axis peak fields $[14;\,23]\,\mathrm{MV/m}$ which corresponds to $[19;\,27.5]\,\mathrm{MeV/c}$ in terms of electron beam momentum. Moreover, the other machine parameters delivering minimum emittance stay constant in this range. The usual accuracy of the electron beam mean

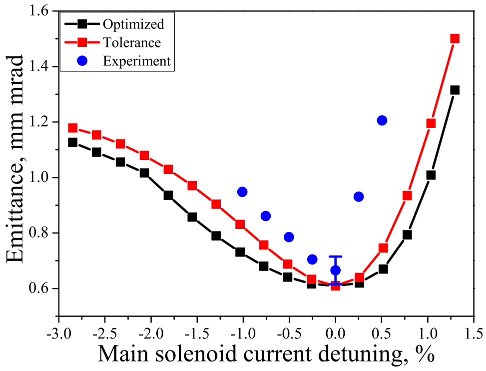


Figure 8: Emittance dependence on the main solenoid current for $E_{gun} = 60.58\,\mathrm{MV/m}$.

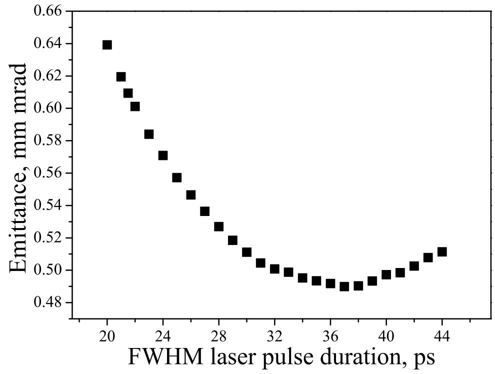


Figure 10: Emittance dependence on the laser pulse duration for $E_{gun} = 60.58\,\mathrm{MV/m}$.

momentum measurement at PITZ using HEDA1 (see [4]) is better than $100\,\mathrm{KeV/c}$. In such a way the possible influence of the booster on-axis peak field detuning during experiments is negligible. The gun launching phase was not optimized during this measurement. Nevertheless, simulation and measurement data have well comparable trends.

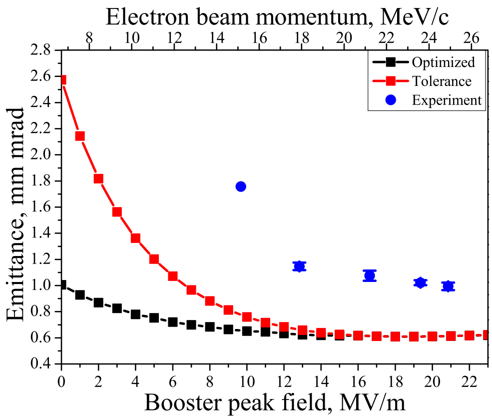


Figure 9: Emittance dependence on the booster on-axis peak field for $E_{gun} = 60.58\,\mathrm{MV/m}$.

The emittance dependence on the cathode laser pulse duration is shown in Fig.10. The minimum emittance value of $0.49\,\mathrm{mm\,mrad}$ was found for a laser pulse length of $\mathrm{FWHM} = 37\,\mathrm{ps}$ which is quite far from the usual $22\,\mathrm{ps}$ used at PITZ and designed for the European XFEL [2]. Despite on the $20\%$ emittance reduction for $\mathrm{FWHM} = 37\,\mathrm{ps}$, it has to be taken into account that the peak current reduces by $30\%$ in this case that has negative effect on the brilliance of the FEL radiation.

## SUMMARY

Detailed simulations of the PITZ photo injector were performed in order to optimize the electron beam emittance for a bunch charge of $1\,\mathrm{nC}$. The minimum emittance value of $0.61\,\mathrm{mm\,mrad}$ obtained during the simulations is well comparable with the experimentally measured $0.66 \pm 0.05\,\mathrm{mm\,mrad}$. The strong discrepancy between machine parameters delivering minimum emittance in simulations and measurements can be caused by the enhanced electron emission from the cathode surface in the presence of an RF field which was not taken into account during the simulations. Cathode laser pulses distributions imperfections compare to the distributions used in simulations have an impact as well. The systematic error caused by detuning of such machine parameters like main solenoid current, gun launching phase, rms laser spot size on the cathode and booster on-axis peak field during experiments is estimated at the level of $10\%$. Simulation studies of the electron beam emittance for other bunch charges ($250\,\mathrm{pC}$, $100\,\mathrm{pC}$, $20\,\mathrm{pC}$) having interest for the FEL community are ongoing.

## REFERENCES


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

[2] M. Altarelli et al. (Eds.), "XFEL The European X-Ray Free-Electron Laser Technical Design Report," DESY 2006-097, DESY, Hamburg, July (2006).

[3] P. Schmüser et al., *Ultraviolet and Soft X-Ray Free-Electron Lasers: Introduction to Physical Principles, Experimental Results, Technological Challenges*, (Berlin: Springer, 2007), 207

[4] S. Rimjaem et al., Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 671 (2012) 62

[5] K. Flöttmann, ASTRA particle tracking code, `http://www.desy.de/~mpyflo`

[6] G. Vashchenko et al., "Emittance optimization for different bunch charges with upgraded setup at PITZ," IPAC2011, San Sebastian, September 2011, THPC115, p. 3155, `http://www.JACoW.org`

[7] F. Stephan et al., Phys. Rev. ST Accel. Beams 13 (2010) 20704.

[8] M. Krasilnikov et al., "Setting a new benchmark for experimentally optimizing photo injector performance," submitted to Phys. Rev. ST Accel. Beams.

[9] M. Gross et al., "Laser pulse train management with an acousto-optic modulator," MOPD61, these proceedings.