ISBN: 978-3-95450-248-6 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2025-TUPS019

# BEAM DYNAMICS OPTIMIZATION FOR A HIGH-BRIGHTNESS PHOTO INJECTOR WITH VARIOUS PHOTOCATHODE LASER PULSE SHAPES

S. Zeeshan*, M. Krasilnikov, X.-K Li
Deutsches Elektronen-Synchrotron DESY, Platanenallee, Zeuthen, Germany
D. Bazyl, I. Zagorodnov
Deutsches Elektronen-Synchrotron DESY, Notkestraße, Hamburg, Germany



*Abstract*

At PITZ, a comprehensive study is conducted to analyse the factors influencing emittance growth in the European XFEL (EuXFEL) continuous wave (CW) setup. Emittance growth due to space charge effects can be mitigated using advanced photocathode laser pulse shapes. To optimize beam quality, multi-objective optimization studies using ASTRA are performed, focusing not only on minimizing emittance but also on maximizing beam brightness for various laser temporal profiles and durations. The optimization is initially carried out for the CW superconducting radio-frequency (SRF) injector section planned for EuXFEL. The optimized cases are then further tracked through start-to-end (S2E) simulations to evaluate their behaviour in the compression stages of EuXFEL. A comparative analysis of gaussian, flattop, ellipsoidal, and inverted parabolic laser profiles is presented, assessing their efficiency not only in terms of emittance but also in 4D and 6D brightness. Finally, the results of the optimized photoinjector setup and the beam properties after the final bunch compression are presented.

## INTRODUCTION

High gain short wavelength FELs like European XFEL [1] and FLASH [2] generate high brilliance coherent laser light and require high brightness electron beams. The requirements of lower emittance at high peak currents for maximum brightness can be achieved through photo-cathode laser pulse shaping. The longitudinal shape of photocathode laser can be used to control the space charge induced emittance growth and can also affects the compression process later in the chicane bunch compressors. Proper shaping of the photocathode laser pulse ensures an electron bunch distribution in 6D phase space that not only minimizes transverse emittance but also enables smooth multistage compression, essential for efficient XFEL lasing.

Typical laser pulses with a gaussian temporal profile serve as a reference for investigating how photocathode laser pulse shaping influences electron beam performance. The flattop profiles as compared to gaussian have proven to reduce the emittance numbers under similar conditions [3,4]. The ideal distribution for high-brightness charged particle acceleration is uniformly filled 3D ellipsoid that has space charge fields with a linear dependence on the position within the distribution and is therefore resistant to space charge induced emittance growth [5, 6]. The realization of 3D ellipsoidal laser pulses is highly complex, which makes it necessary to explore alternative, more feasible pulse shapes. The investigation of different laser shapes is not only crucial within the photo injector, but also in conjunction with the subsequent beam acceleration and bunch compression to optimize the final beam brightness before entering the undulators. The European XFEL aims for CW operation as an upgrade using a superconducting (SC) RF photo injector [7]. A detailed study has been done on the injector optimization with a SC gun of the EuXFEL, the corresponding start-to-end simulation calculations for the beam transport to the undulators and FEL simulations on the X-ray intensities for the achievable photon energies have also been carried out [8]. After several modifications to the CW photoinjector layout, including modifications to the position of the gun solenoid, the first accelerating cryomodule (A1) was moved from 4 m to 6 m downstream. This change was guided by the optimization of the photoinjector for the temporal flattop profile of the photocathode laser pulse [8].

The Photo Injector Test facility at DESY in Zeuthen (PITZ) develops normal-conducting RF guns for the European XFEL. The facility was also used for the experimental characterization of beam dynamics under CW gun conditions [9]. Beam dynamics studies comparing the performance of different laser pulse shapes have been performed at PITZ using the optimized EuXFEL CW photo injector setup. In this paper we present the emittance optimization studies at the injector of EuXFEL for longitudinal gaussian (G) with transverse radial uniform (RU), longitudinal flattop (FT) with transverse truncated gaussian (TG), 3D ellipsoidal (3D EL) and longitudinal inverted parabolic (IP) with transverse TG profiles. In the second part the optimized cases are further tracked for the S2E simulations and the effect of bunch compressors will be studied. Multistage bunch compression involves the mixing of longitudinal beam slices, making local beam parameters such as slice emittance energy spread from the photoinjector critical to the beam's performance after compression [10]. The shape of the photocathode laser influences the distribution of the slice parameters within the bunch, so the introduction of 4D and 6D brightness is an obvious option. The 4D brightness, is proportional to the peak current divided by 4D transverse phase space volume that is the product of the transverse emittance $B_{4D} = \frac{2I_{peak}}{\epsilon_x \epsilon_y}$; The 6D brightness [11], includes along with transverse emittance the normalized longitudinal emittance or the uncorrelated slice energy spread $\delta$E; $B_{6D} = \frac{2I_{peak}}{\epsilon_x \epsilon_y \delta E}$. In order to consider temporal distributions (form factors) of beam parameters

* sumaira.zeeshan@desy.de

ISBN: 978-3-95450-248-6 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2025-TUPS019

using corresponding local values averaged over the longitudinal core of the beam the brightness can be defined as:

$$B_{4D} = \frac{1}{T}\int_{-T/2}^{T/2} \frac{I(t)}{\epsilon_x(t)\epsilon_y(t)}dt \tag{1}$$

$$B_{6D} = \frac{1}{T}\int_{-T/2}^{T/2} \frac{I(t)}{\epsilon_x(t)\epsilon_y(t)\delta E(t)}dt \tag{2}$$

We will compare the results for the emittance and the brightness at the end of the injector with these four distributions, considering the entire bunch with T $\rightarrow \infty$ . A temporal core of $\pm\sigma$ is used for the results of the S2E simulations (T = $2\sigma_t$).

### *Beam Dynamic Optimization in Injector*

The beam dynamics optimization of the EuXFEL is done first for the injector section. CW injector with the length of 20 m consists of the DESY SRF L-band gun, superconducting focusing solenoid and one accelerating module (A1) which is formed by eight 9-cell 1.3 GHz SRF TESLA cavities. The control parameters are the longitudinal pulse duration and transverse size of the photo-cathode laser, the solenoid strength, gun and booster phases. The fixed parameters used for the optimization are given in Table 1.

Table 1: Main Parameters During Optimization

| Parameters | Values | Parameters | Values |
|---|---|---|---|
| $E_{cath}$ | 55MV/m | Bunch Char | 100 pC |
| A1:$E_p$(1$^{st}$ 1/2) | 32MV/m | Ther emit. | 1 µm/mm |
| A1:$E_p$(2$^{nd}$ 1/2) | 32MV/m | Opt. at | 20 m |

The position of the A1 module and of the solenoid is fixed as a result of earlier optimization done with FT longitudinal profile of photocathode laser [8]. In this optimization, a multiobjective optimizer based on an evolutionary algorithm [12] is used together with a beam dynamics simulation program Astra [13] to find optimal solutions at the exit of the injector. The goal of the optimization is to minimize transverse emittance and the longitudinal length of bunches at the injector exit (20 m). Figure 1 shows the Pareto front

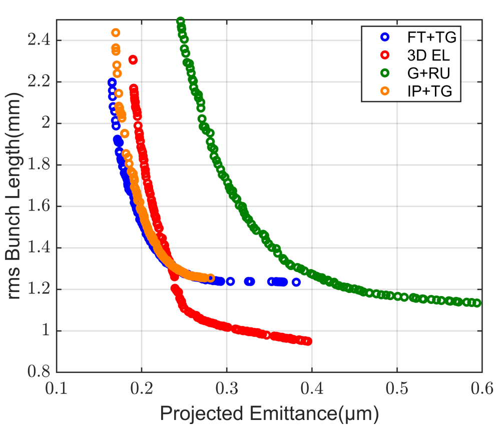


Figure 1: MOGA optimizations for G+RU, FT+TG, 3D EL, IP+TG longitudinal profiles of photocathode laser.

from the Multi Objective Genetic Algorithm (MOGA) optimization for the different laser configurations. Considering that 2 mm of e bunch length achieves the 5 kA peak currents and is sufficient to be compressed, the best cases for the 2 mm electron bunch length are summarised in Table 2. For 2 mm rms electron bunch length the best emittance is achieved from flattop laser profile; emittance from IP+TG and 3D EL are also close. Implementation of the FT laser yield slightly lower emittance values as compared to the 3D EL profile. However, 3D EL laser profile allows to reach higher peak current (i.e bunch length) while maintaining the same emittance values. For the FEL performance the peak currents play a major role in defining the brightness of the beam. The best cases for the 2 mm electron bunch length are summarised in Table 2. The lowest projected emittance is achieved for FT+TG photoinjector laser profile. IP+TG also emerged as a candidate to achieve better emittance. It is to be noted that the injector setup, specially the position of the A1 module, is optimized for flattop longitudinal profile of the photocathode laser and can be the reason of FT generating better emittance numbers as compared to EL. However, we did some initial studies including the A1 module position as variable with G, FT and EL; showed different optimized positions for FT and EL. This paper uses the practically finalised position of the A1 module for the FT.

Table 2: The Optimized Values for 4 Laser Pulse Shapes at 2 mm of Electron (RMS) Bunch Length

| Laser Shapes | FT+TG | EL | G+RU | IP+TG |
|---|---|---|---|---|
| Proj. emit | 0.17 | 0.19 | 0.26 | 0.18 |
| Long emit | 395 | 506 | 610 | 471 |
| Energy spread | 0.36 | 0.27 | 0.56 | 0.76 |
| Avr. 4D Brit | 1708 | 1983 | 1231 | 2020 |

The energy spread is lowest for the 3D EL distribution. The highest brightness achieved is for the IP+TG case and ellipsoidal is showing comparable numbers. The lower energy spread of electron bunch can be advantageous for the improved gain, narrow bandwidth and stable lasing process. However very small energy spread can lead to microbunching instabilities during compression stages and CSR induced energy spread leading to FEL performance degradation. The small energy spread beam is more sensitive to energy chirps, wake field and collective effects. Slice emittance and beam current for the optimized cases for 2 mm rms bunch length are plotted in Fig. 2. The peak/central charge within the electron bunch is highest for ellipsoidal and lowest for flattop and central slice emittance is lowest for the flattop and highest for the gaussian. However, the charge and emittance distributions are very smooth and uniformly filled in the bunch for the ellipsoidal distribution. The phase space of the four laser shapes is shown in Fig. 3 for the 2 mm rms electron bunch length. The beam halo is minimum for the 3D EL shaped photocathode laser generated electron beam. However, the phase space reveals a larger beam size for the 3D EL shape compared to other pulse profiles, which results from the A1 position being optimized for flattop pulses.

ISBN: 978-3-95450-248-6 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2025-TUPS019

Optimizing the A1 position for 3D EL pulses shifts the optimal position by an additional 3 meters, a change that is considered impractical and is therefore not presented here.

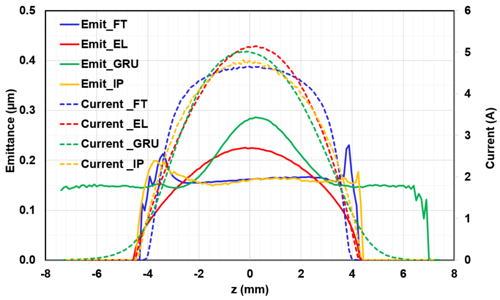


Figure 2: Slice emittance and beam current for 2 mm of electron (rms) bunch length simulated at z = 20 m.

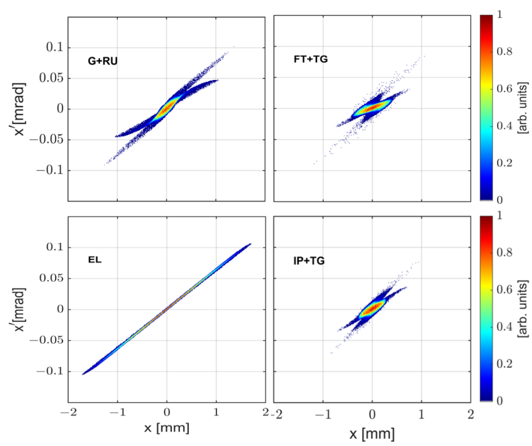


Figure 3: Transverse phase space for 2 mm rms bunch length generated by four laser pulse shapes at 20 m.

### *Start to End Simulations*

The inverted parabolic laser profile has emerged as a promising shape for lower emittance and high brightness and is technically less challenging as compared to ellipsoidal. To see the effect of laser shaping in the bunch compression and analyse the advantage of low emittance and energy spread under compression stages the start to end simulations under collective effects are performed. The optimized parameters at the end of the injector for IP in comparison with FT and G are further tracked in the EuXFEL setup. The goal at the FEL entrance is to have maximum brightness as it will lead to the better FEL performance. The propagation of the electron beam generated from these three lasers is studied under the collective effects of wakefield, space charge and CSR, all performed by the Ocelot code [14]. Photo injector setups optimized at z=20 m (after the first accelerating module, A1) were used for S2E simulations, including multi-stage compression. However, beam monitors at z = 5.24 m were utilized, as the A1 RF parameters were also considered in the bunch compression optimization. The CW mode EuXFEL beamline has three bunch compressors BC0, BC1 and BC2. The beam energy at each BC is 130 MeV,0.6 GeV and 1.45 2 GeV respectively [8]. The longitudinal profiles of the beam and the current at the end of BC2 are shown in Fig. 4 and all final parameters in Table 3. Initial compression factors of 3, 7.5 were applied to BC0 and BC1, while BC2 was tuned to achieve a final peak current of 5 kA. The three-stage compression was iteratively optimized by simultaneously adjusting the RF parameters of the linacs to achieve the desired longitudinal phase space characteristics. The final energy spread of 2 MeV is obtained by tuning the laser heater at the injection section. The estimation of the final energy spread is obtained in the micro bunching studies [10].

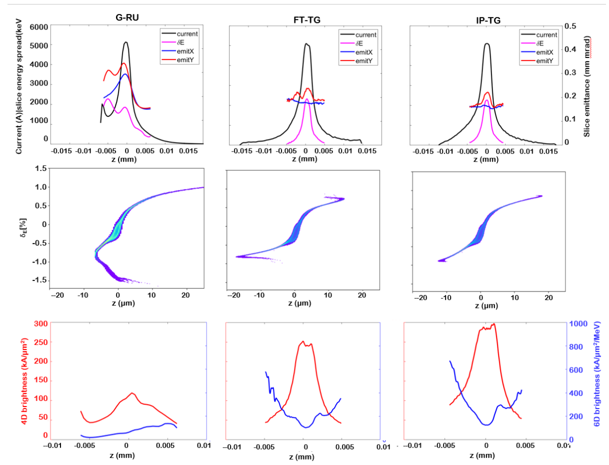


Figure 4: Major parameters, beam current, slice emittance and slice energy spread after the BC2 are shown for the three laser profiles,G+RU, FT+TG and IP+TG (left to right columns) in the 1st row; the 2nd row shows the longitudinal phase space and 3rd row shows 4D and 6D brightness plots.

Table 3: The Beam Parameters After 3 Stages of Compression

| | G+RU | FT+TG | IP+TG |
|---|---|---|---|
| $I_{peak}$ (kA) | 5.1 | 5.1 | 5.1 |
| em$X_{(z=0)}$ (mm mrad) | 0.33 | 0.19 | 0.18 |
| em$Y_{(z=0)}$ (mm mrad) | 0.29 | 0.24 | 0.22 |
| $dE_{z=0}$ (MeV) | 1.8 | 2.2 | 2.2 |
| $< B_{4D} >$ (kA/µm$^2$) | 75.9 | 125 | 170 |
| $< B_{6D} >$ (kA/µm$^2$/MeV) | 75.3 | 245 | 303 |

## SUMMARY

Beam dynamics simulations for the CW SRF injector for the European XFL have been carried out. A comparison of four photocathode laser pulse shapes for the photoinjector is presented in terms of brightness and emittance optimization. The injector optimizations showed that flattop longitudinal profile with truncated gaussian as transverse distribution yields the best emittance at the injector. The laser pulses with inverted parabolic temporal profile and transverse truncated gaussian distribution is promising not only at the injector but also at the end of BC2 as a result of start to end simulations. It can be considered a better brightness achieving shape as compared to flattop and comparable to ellipsoidal considering less technically challenging to achieve.

ISBN: 978-3-95450-248-6 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2025-TUPS019

## REFERENCES

[1] M. Altarelli *et al.*, "XFEL The European X-Ray Free- Electron Laser Technical Design Report", DESY, Hamburg, Germany, Rep. DESY 2006-097, Jul. 2006.

[2] W. Ackermann *et al.*, "Operation of a free-electron laser from the extreme ultraviolet to the water window", *Nat. Photonics*, vol. 1, pp. 336—342, Jun. 2007. doi:10.1038/nphoton.2007.76

[3] M. Krasilnikov *et al.*, "Experimentally minimized beam emittance from anL-band photoinjector", *Phys. Rev. Spec. Top. Accel Beams*, vol. 15, p. 100701, Oct. 2012. doi:10.1103/physrevstab.15.100701

[4] J. Yang *et al.*,"Low-emittance electron-beam generation with laser pulse shaping in photocathode radio-frequency gun", *J. Appl. Phys.*, vol. 92, pp. 1608—1612, Aug. 2002. doi:10.1063/1.1487457

[5] G. Ha *et al.*, "Bunch shaping in electron linear accelerators", *Rev. Mod. Phys.*, vol. 94, p. 025006, May 2022. doi:10.1103/revmodphys.94.025006

[6] O. J. Luiten *et al.*, "How to Realize Uniform Three-Dimensional Ellipsoidal Electron Bunches", *Phys. Rev. Lett.*, vol. 93, p. 094802, Aug. 2004. doi:10.1103/physrevlett.93.094802

[7] R. Brinkmann *et al.*, "Prospects for CW Operation of the European XFEL in Hard X-ray Regime", in *Proc. FEL'14*, Basel, Switzerland, Aug. 2014, paper MOP067, pp. 210–214.

[8] D. Bazyl *et al.*, "CW Operation of the European XFEL: SC-Gun Injector Optimization, S2E Calculations and SASE Performance", DESY, Hamburg, Germany, Rep. DESY 21-138, arXiv:2111.01756, Nov. 2021. doi:10.48550/arXiv.2111.01756

[9] M. Krasilnikov *et al.*, "PITZ Experimental Optimization for the Aimed Cathode Gradient of a Superconducting CW RF Gun", in *Proc. FEL'19*, Hamburg, Germany, Aug. 2019, pp. 440–443. doi:10.18429/JACoW-FEL2019-WEP051

[10] I. Zagorodnov *et al.*, "Semianalytical Modeling of Multistage Bunch Compression with Collective Effects", *Phys. Rev. Spec. Top. Accel Beams*, vol. 14, p. 014403, Jan. 2011. doi:10.1103/PhysRevSTAB.14.014403

[11] H. Qian *et al.*, "Slice energy spread measurement in the low energy photoinjector", *Phys. Rev. Accel. Beams*, vol. 25, p. 083401, Aug. 2022. doi:10.1103/physrevaccelbeams.25.083401

[12] J. Blank and K. Deb, "Pymoo: Multi-Objective Optimization in Python", *IEEE Access*, vol. 8, pp. 89497—89509, Apr. 2020. doi:10.1109/ACCESS.2020.2990567

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

[14] Ocelot code, https://ocelot.readthedocs.io/en/latest/index.html