# OPTIMIZATION OF THE PITZ PHOTO INJECTOR TOWARDS THE BEST ACHIEVABLE BEAM QUALITY*

M. Khojoyan #, M. Krasilnikov, F. Stephan, G. Vashchenko, DESY Zeuthen, Zeuthen, Germany

*Abstract*

Uniform 3D ellipsoids are proven to be the best distributions for high brightness charged particle beam applications due to the linear dependence of the space charge fields on the position within the distribution [1]. Such electron bunches have lower emittance and are less sensitive to the machine settings and, therefore, should allow more reliable operation, which is one of the key requirements for single-pass free-electron lasers (FELs). The Photo Injector test facility at DESY, Zeuthen site (PITZ) is optimizing high brightness electron sources for linac based FELs such as the European XFEL. Recent measurements at PITZ using a photocathode laser with a flat-top temporal profile have revealed record low transverse emittance values at different bunch charges [2]. As a next step towards the further improvement of the high quality beams, a cathode laser system, capable of producing quasi-3D ellipsoidal bunches is intended to be used at PITZ. In this work the beam dynamics optimization results for various bunch charges and for flat-top and 3D ellipsoidal cathode laser shapes are presented. For each working point the relative emittance growth is estimated due to possible deviations of the machine parameters.

## INTRODUCTION

The Photo Injector test facility at DESY, Zeuthen site (PITZ) is one of the leading laboratories on generation and optimization of high brightness electron bunches of different charges for free-electron laser (FEL) machines such as FLASH [3] and the European XFEL [4]. At PITZ electron beams of excellent quality are created utilizing the photo effect and are accelerated in an L-band RF gun up to several MeV energies. A pair of solenoid coils surrounding the gun is used for beam transverse focusing meanwhile providing zero remnant magnetic fields at the cathode. The final as high as 25 MeV beam energy is reached after passing through a second accelerating structure. The electron beam transverse properties are usually measured with the help of the emittance measurement systems (EMSY), where a single slit scan technique [5] is used to measure the electron beam emittance. Additionally, there are many diagnostics available for full characterization of high brightness electron beams. A more detailed description of the PITZ setup can be found elsewhere [6].

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#martin.khojoyan@desy.de

Optimization of the photocathode laser shape is one of the key issues on generating high quality bunches. Recent measurements performed at PITZ by applying a nominal flat-top longitudinal laser shape have revealed unprecedented transverse emittance values for different bunch charges [2]. To further improve the achievable beam quality a laser system capable of producing quasi-3D ellipsoidal laser pulses is under development at the Institute of Applied Physics (IAP, Nizhny Novgorod). The project is being realized in the frame of a joint German-Russian research activity including the Joint Institute of Nuclear Research (JINR, Dubna) and PITZ (DESY).

In this contribution, an optimization of the transverse beam emittance is performed for different bunch charges comparing a cylindrical (flat-top temporal profile) and 3D ellipsoidal cathode laser distributions. A new linac setup with shifted (optimized) positions of the second accelerating cavity and the first emittance measurement system (EMSY1) is used in the simulations. The tolerance studies are performed for each optimized machine setup to predict the transverse emittance dilution due to possible mismatch of the machine parameters during the experiments. Finally, the influence of possible imperfections coming from the 3D laser shape on the electron beam emittance is estimated for different bunch charges.

## SIMULATION SETUP FOR EMITTTANCE OPTIMIZATION

The ASTRA [7] simulation code has been used to optimize the electron beam quality at various bunch charges assuming flat-top and 3D ellipsoidal cathode laser pulse shapes. Previously performed studies have revealed a much better injector performance of a 1 nC electron beam for the 3D ellipsoidal laser profile with a shifted position (40 cm closer to the gun) of the second accelerating cavity as compared to the current setup [8]. In this work the position of the first emittance measurement system (EMSY1) is shifted accordingly by ~ 45 cm upstream towards the cathode. The simulation setup is shown in Fig. 1. The following values of machine parameters were used during the optimization. A flat-top temporal laser shape with fixed FWHM length of 21.5 ps and 2 ps rise and fall times was considered in simulations for different charges. The transverse laser profile was assumed to be homogeneous. For each bunch charge the longitudinal size of the 3D ellipsoidal laser was tuned accordingly to get the same electron bunch rms length at EMSY1 (Z=5.28 m) as it is for the flat-top case. The gun

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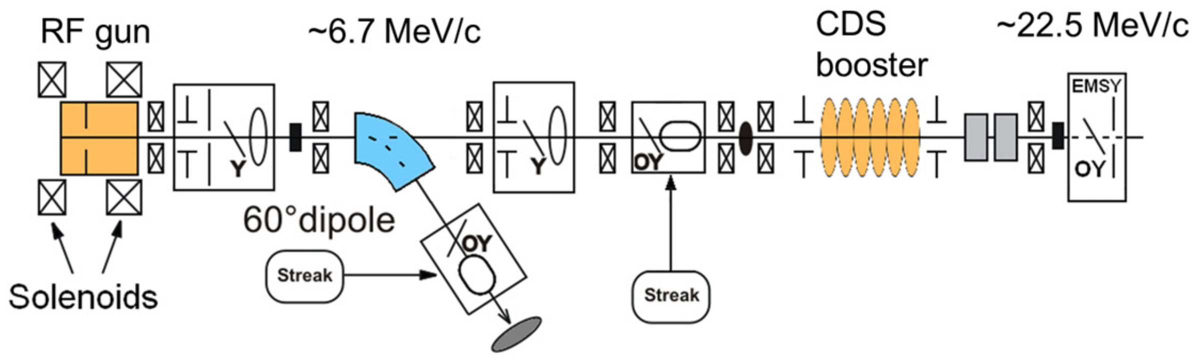


Figure 1: Part of the PITZ setup used in simulations for the emittance optimization. Starting position of the CDS booster is at Z=2.675 m and the first emittance measurement screen is located at 5.28 m downstream the cathode.

peak electric field at the cathode was kept constant to a value that corresponds to ~ 6.7 MeV/c beam momentum at the phase of maximum acceleration. The accelerating field gradient in the booster was 18 MV/m yielding to ~ 22.5 MeV/c final beam momentum. For different bunch charges (from 20 pC to 1 nC) the transverse normalized rms emittance was optimized at the position of EMSY1 by simultaneously tuning the laser rms spot size, gun phase and the main solenoid current. The obtained results are shown in Fig. 2, where the normalized rms projected emittance as a function of bunch charge is shown for flat-top (blue dots) and 3D ellipsoidal (red dots) cathode laser profiles. As seen from the plot, there is ~ 30-35 % improvement in transverse emittance for the case of 3D ellipsoidal laser profile in a wide range of bunch charges. It should be mentioned that this dependence was obtained for fixed laser pulse length and fixed beam energy and can be modified after retuning of the above mentioned parameters.

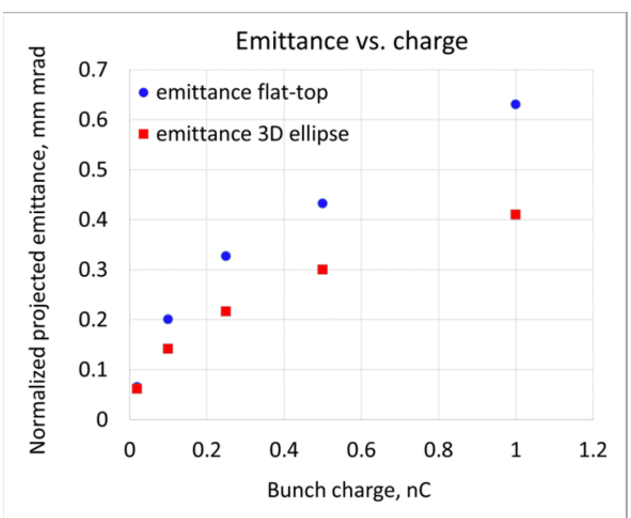


Figure 2: Electron beam transverse emittance as a function of bunch charge for flat-top and 3D ellipsoidal laser profiles.

## EMITTANCE DILUTION DUE TO VARIOUS IMPERFECTIONS

Different sources of emittance dilution during the experimental measurements are described in the following sections.

### *Jitter of Optimized Machine Parameters*

During the experiments one of the possible sources of emittance growth is a deviation / jitter of optimized machine parameters from their optimal values. In this section, the influence of the jitter of various machine parameters on the transverse emittance is estimated for different charges. At each working point the maximum possible deviations of three parameters, namely main solenoid current (± 0.5 A), laser rms spot size on the cathode (± 10 µm) and the gun phase (± 1 deg) were considered as a possible source of emittance overestimation during the experiments. The first parameter justifies the step of the solenoid scan during the emittance measurements. The second parameter is chosen taking into account the measurement precision of the laser spot size on the virtual cathode. The third parameter is taken with safety margins combining the impacts of gun phase jitter and limited accuracy of momentum measurements. For each bunch charge and cathode laser profile the above mentioned parameters were simultaneously scanned in the specified ranges. The difference between the highest emittance value obtained from the scan and the initial emittance value without any jitter considerations was assumed to be the possible influence of the jitter of machine parameters on the emittance. The result is summarized in Tab. 1, where the relative emittance growth caused by the jitter of optimized machine parameters is shown for various bunch charges and two laser profiles. One can notice a rather strong jitter influence on the emittance for the flat-top laser profile at low charges. A possible explanation can be that the absolute optimum emittance predicted from the simulations at such low charges is not obtained at high beam energies (22.5 MeV/c beam momentum as fixed in our simulations) but at fairly low energies [9]. More



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detailed studies are still needed for a better understanding of beam physics at such low charges. For other bunch charges the estimated error on the emittance is less than 10 % for both laser shapes. In addition, less sensitivity on machine parameters was observed for 3D ellipsoidal laser profile as compared to the flat-top case.

Table 1: Summary of Beam Tolerance Studies for Two Laser Profiles. The values in the table represent the emittance overestimation due to the possible jitter of optimized machine parameters: main solenoid current (± 0.5 A), laser rms spot size (± 10 μm) and gun phase (± 1 deg).

| Charge / laser profile | Estimated error on the emittance, % |
|---|---|
| 20pC / flat-top | 21 |
| 20 pC / 3D ellipse | 9 |
| 100 pC / flat-top | 17 |
| 100 pC / 3D ellipse | 5.5 |
| 250 pC / flat-top | 5 |
| 250 pC / 3D ellipse | 4.5 |
| 500 pC / flat-top | 6 |
| 500 pC / 3D ellipse | 4 |
| 1 nC / flat-top | 5.5 |
| 1 nC / 3D ellipse | 5 |

### *Non-perfectness of the 3D Laser Shape*

Another possible source of emittance dilution is the imperfections of the quasi-3D ellipsoidal laser shape, which was observed lately during the tests at IAP [10]. In order to study how a non-perfect ellipsoidal cathode laser shape (spatial and temporal imperfections in 3D laser shape) impacts on the electron beam transverse emittance, a modelling of the non-perfect 3D laser shape has been implemented into the beam dynamics simulations. For that purpose, temporal ($\delta_t$) and radial ($\delta_r$) border sharpness parameters have been introduced into the laser intensity distribution, describing the fraction of spatial and temporal distortions with respect to the perfect 3D shape [11]. Figure 3 depicts the intensity distribution of a perfect 3D laser pulse (a), likewise the distribution which is modified due to bounded sharpness of ellipsoid edges (b). The transverse emittance growth was estimated at the position of EMSY1 for different values of border sharpness parameters and for different bunch charges. In Fig. 4, the transverse emittance is given as a function of border sharpness parameter. In this example, the case of the 1 nC bunch charge is shown. It can be concluded, that overall 30 % spatial and temporal distortions in the 3D ellipsoidal shape yield to a transverse emittance growth, where the resulting emittance value is comparable to the optimized emittance value for the flat-top laser profile. Similar results were obtained for other charges as well.

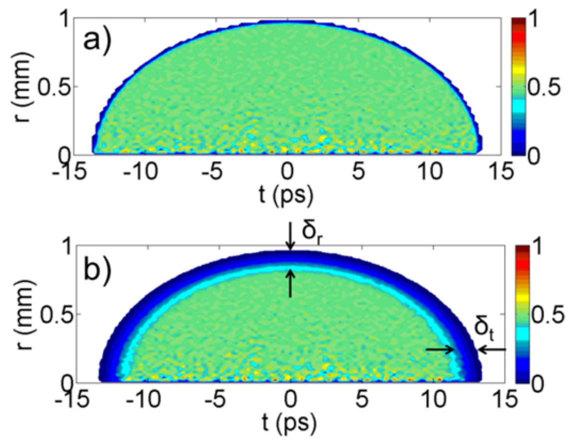


Figure 3: An example from border sharpness modelling in ASTRA. a) Intensity distribution of a perfect 3D shape, b) 20 % distortion in temporal and radial directions. The range of the intensity values (0 --> the lowest, 1 --> the highest) is shown by colour bars on the right part of each figure.

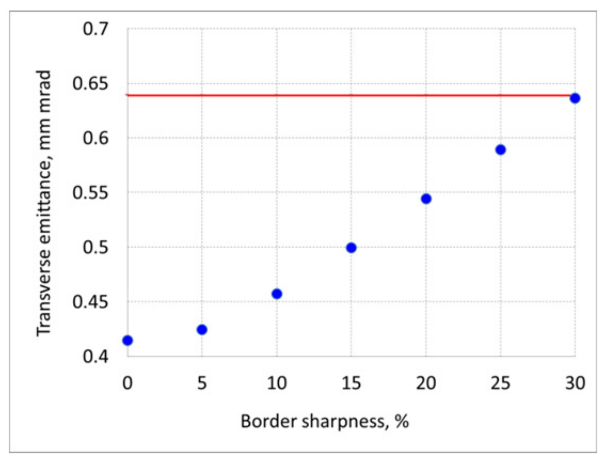


Figure 4: Transverse emittance at EMSY1 as a function of border sharpness parameter ($\delta_t$=$\delta_r$=$\delta$) for 1 nC bunch charge (blue dots). The red line on the graph emphasizes the optimized transverse emittance value for the case of the flat-top temporal laser profile at the same charge.

## CONCLUSION

A transverse emittance optimization has been performed for different bunch charges with a modified PITZ setup, including shifted (optimized) positions of the second accelerating cavity and the first emittance measurement station. 30-35 % improvement in transverse emittance was obtained for almost all charges when using quasi 3D ellipsoidal laser pulses with respect to flat-top laser pulses. The alteration of the electron beam quality, namely the dilution of the beam transverse emittance was



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estimated taking into account two possible sources of systematic errors: the impact of possible deviation of the optimized machine parameters from their optimal values during the experiments and the non-perfectness of the 3D ellipsoidal cathode laser shape. The studies for the first case have revealed < 10 % emittance overestimation for different laser profiles and for charges higher than 100 pC. Much less sensitivity of the transverse emittance depending on the 3D ellipsoidal cathode laser shape imperfections has been obtained with the new linac setup. More extended investigations are necessary to study the precision of the emittance measurements while operating at low bunch charges.

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