# INVESTIGATIONS ON THE IMPACT OF MODULATIONS OF THE TRANSVERSE LASER PROFILE ON THE TRANSVERSE EMITTANCE AT PITZ

M. Hänel*, M. Krasilnikov, F. Stephan, DESY, Zeuthen, Germany

### *Abstract*

The Photoinjector Test Facility at DESY, Zeuthen site (PITZ), was established to develop and optimize electron bunch sources for superconducting linac-based free electron lasers like FLASH or the future European XFEL. The successful operation of such FELs requires electron bunches of very low normalized transverse emittance of the order of 1 mm mrad at a charge of 1 nC. One key issue for obtaining low-emittance electron bunches is the possibility to influence the electron bunch properties by varying the photocathode laser pulse characteristics. This contribution focuses on the discussion of deviations from the optimum transverse shape of a circular flat-top. Different types of modulations are added to the flat-top and the resulting change in transverse emittance will be discussed based on beam dynamics simulations.

## INTRODUCTION

Temporal and transverse photocathode laser pulse shaping is a key issue of generating ultra-low emittance electron bunches in an rf photoelectron source using cathodes with a response time much shorter than the laser pulse duration. Besides the ellipsoidal electron bunch shape [1] which requires very special laser systems [2] or acceleration schemes [3], it is believed that a very good laser pulse shape for generating low emittance bunches is a temporal flat-top with short rise- and fall-times together with a circular flat-top transverse profile (*beer can*-shape). The temporal laser pulse shape is usually produced by employing an appropriate laser pulse shaper, e.g. a birefringent filter network [4], while the transverse flat-top can be generated by cutting-off the tail parts of a magnified transverse Gaussian shape using a circular aperture and a subsequent imaging of the remaining, almost flat-top center part onto the photocathode.

While the optimum transverse laser spot size is a compromise between cathode emittance and space charge forces, the influence of deviations from the perfect circular flat-top shape of the emitted electrons on the bunch emittance is presented in this paper. These deviations in the transverse electron density distribution can be due to two reasons: firstly, the transverse shape of the laser pulse used for extraction of the electrons is not a circular flat-top and secondly, the photocathodes quantum efficiency is not homogeneous across the surface. Similar investigations were done at ENEA (Frascati) for a different setup using another simulation code [5, 6]. During the simulations presented in this paper, the temporal shape of the laser pulse was chosen to be a flat-top with 20 ps duration (FWHM) and 2 ps rise- and fall-times and the bunch charge was 1 nC throughout these investigations. It will be shown that a single maximum in the center results in the lowest transverse emittance.

The first section describes the machine setup that was assumed for the simulations. The second section introduces the mathematical models of the deviations added to the transverse flat-top while in the last part the results are discussed.

## SIMULATION PARAMETERS

The setup consist of a 1.6-cell gun cavity operated at 1.3 GHz and a maximum electric field at the cathode of 60 MV/m. The electron bunch is emitted by a cathode assumed to have zero response time. The initial kinetic energy of the electrons is set to 0.55 eV. A solenoid magnet located 27.6 cm downstream of the cathode focuses the electron bunch and allows for emittance compensation. Its field at the cathode is compensated by a bucking solenoid.

With the described setup, simulation were done using the particle-in-cell (PIC) code ASTRA [7]. Here, the electron bunch density distribution at emission is defined by an initial particle distribution. This distribution was modified on purpose to model the transverse inhomogeinities.

Before the simulations were done for the various transverse imperfections, the machine parameters were found which produce the smallest emittance for a flat-top transverse distribution. The lowest transverse emittance of 0.86 mm mrad was found at 3.24 m downstream of the photocathode and the corresponding values of the machine parameters are summarized in Table 1. For this case, the evolution of the transverse emittance as well as the transverse beam size are depicted in Figure 1. Note, that the actual values differ from those obtained in simulations which include a further accelerating cavity.

Table 1: Machine Parameters for Lowest Emittance

| **parameter** | **value** |
|---|---|
| gun phase w.r.t. phase of max. mean mom. gain | 0 degrees |
| solenoid peak field | 234 mT |
| laser spot diameter | 1.9 mm |

In the simulations, one million macroparticles were used to model the electron bunch. This number was a compromise between computation speed and optimal modeling of the modulations introduced on the transverse laser profile

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[*] corresponding author: marc.haenel@desy.de

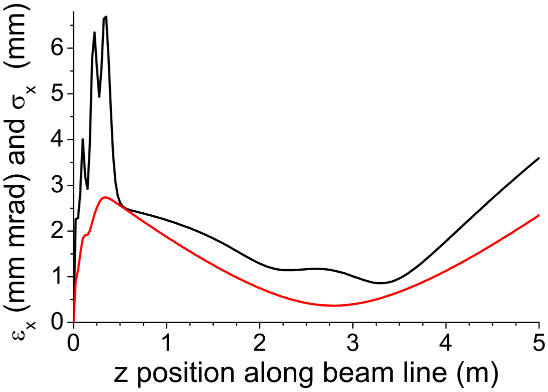

Figure 1: Evolution of transverse emittance (black line) and beam size (red line) for the optimum case.

which require a large number of grid cells and therefore a large number of macroparticles.

Since some of the modulations introduced on the transverse distribution are not cylindrically symmetric, a three-dimensional grid routine must be used instead of the default two-dimensional one. However, the used computer code does not support modeling the emission from the cathode using the 3D-algorithm. For this reason, a compromise was found by tracking the electron bunches using the 2D-algorithm until the cathode effects like mirror charge can be neglected. This occurs approx. 7.5 cm downstream of the cathode. Subsequently, the simulation was continued using the 3D-routine.

Using this procedure, the different cathode distribution modulation types and depths were tracked up to the reference position at 3.24 m at which the transverse emittance was evaluated and compared to the one obtained for the *beer can*-shape.

Since the pure 2D-tracking for the cylindrically symmetric distributions and the mixed tracking for the others result in slightly different emittance values, the results are given as emittance change relative to the value obtained for the perfect flat-top in each case.

## MODULATION TYPES

In the simulations, the modulations were added to the actual transverse profile by adjusting the charge of the macroparticles in the initial particle distribution according to the applied model. The modulation types which were added to the circular flat-top transverse distribution can be divided into radially symmetric (equation 1) and non-radially symmetric distributions (equations 2 and 3). The charge-scaling formulae are summarized in the following equations.

$$q^* = q \cdot [1 + d \cdot \cos(k \cdot r)] \tag{1}$$

$$q^* = q \cdot [1 + d \cdot \cos(kx)]\,[1 + d \cdot \cos(ky)] \tag{2}$$

$$q^* = q \cdot [1 + d \cdot \sin(kx)]\,[1 + d \cdot \sin(ky)] \tag{3}$$

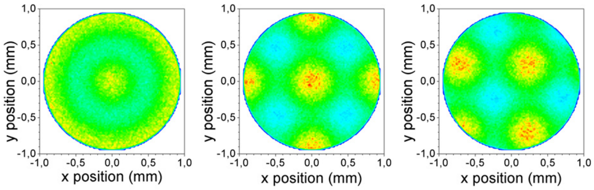

Figure 2: Transverse distributions used in the simulations: equation 1 (left), equation 2 (center) and equation 3 (right). In each graph, the distributions for $f_s$=1.0 and $d$=0.3 are displayed.

In these equations, $q$ is the initial charge of the macroparticle, $d$ describes the modulation depth, $r = \sqrt{x^2 + y^2}$ is the distance from the center and $k$ is wavenumber defined by $k = f_s \cdot 2\pi/D$ with $f_s$ being the number of full transverse modulations and $D = 1.9\,\mathrm{mm}$ the diameter of the transverse distribution. In Figure 2 the corresponding shapes are displayed.

For the case of equations 1 (left in Figure 2) and 2 (middle in Figure 2), negative modulation depths result in different distributions and are therefore treated independently. After applying formulae 1-3 the overall bunch charge was rescaled to 1 nC.

The simulations were performed for $f_s$ = 0.5, 1.0, 2.0 and 3.0 full oscillations as well as for modulation depths of $d$ = 0.05, 0.1, 0.2, 0.3 and 0.5.

## SIMULATION RESULTS AND DISCUSSION

In Figures 3 - 7 the results of the simulations are shown. In each graph, the different numbers of oscillations are displayed with different colors: $f_s$ = 0.5 (black), $f_s$ = 1.0 (green), $f_s$ = 2.0 (blue) and $f_s$ = 3.0 (red).

The main results are:

- The larger the number of oscillations, the lower is their impact on the transverse emittance.
- The larger the modulation depth, the stronger is the detrimental effect on the transverse emittance. This is true for all cases except those modulation models which introduce a single maximum in the center of the transverse distribution. Here, a minimum of the transverse emittance can be observed for modulation depths between 0.2 and 0.3.
- For a large number of oscillations, the emittance increase becomes similar for analog shapes (model 1 for $d < 0$ and $d > 0$; model 2 and 3)
- The largest increase of transverse emittance can be found for model 3 which imposes a modulation where the geometric center and the center of mass do not coincide.

The circular flat-top was chosen because it generates linear radial space-charge forces $F_r(r) \propto r$ (for the case of an infinitely long cylinder) which can be compensated using a linear lens like a solenoid. Here, it was shown that a single maximum in the center of the transverse distribution can deliver a transverse emittance which is approx. 15 % smaller than for the *beer-can* shape. There are two reasons. Firstly, this distribution has the same diameter as the original circular flat-top but a smaller rms beam size $\sigma_x$, which results in a reduced cathode emittance. This contribution can be estimated using the formula

$$\varepsilon_{\text{cath}} = \sigma_x \cdot \sqrt{\frac{2E_{\text{kin}}}{3m_0c^2}} \tag{4}$$

which was derived in [8]. Here, $E_{\text{kin}} = 0.55\,\text{eV}$ is the initial kinetic energy of the electrons, $m_0$ is the electrons rest mass and $c$ is the speed of light. Using the rms beam size of the transverse distribution producing the smallest emittance, the cathode emittance amounts to 0.388 mm mrad compared to 0.402 mm mrad for the flat-top case. Secondly, the fact that the radial space charge forces have a nonlinear component is over-compensated by the fact that more charge is located near the center which causes a reduction of the total emittance.

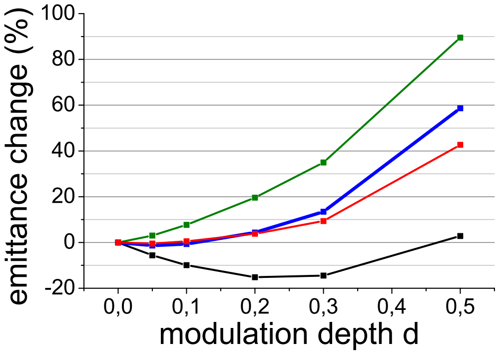

Figure 3: Simulation results for model (1) and $d > 0$.

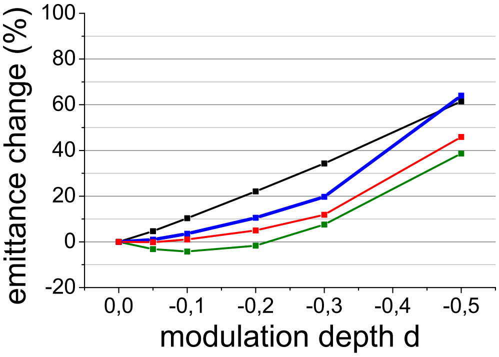

Figure 4: Simulation results for model (1) and $d < 0$.

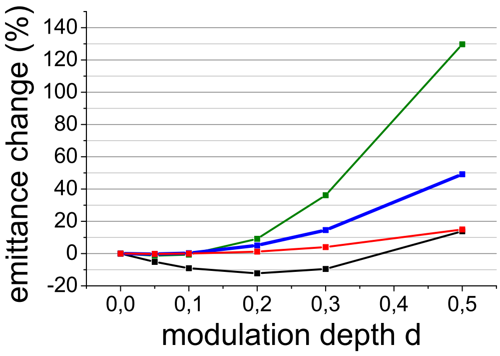

Figure 5: Simulation results for model (2) and $d > 0$.

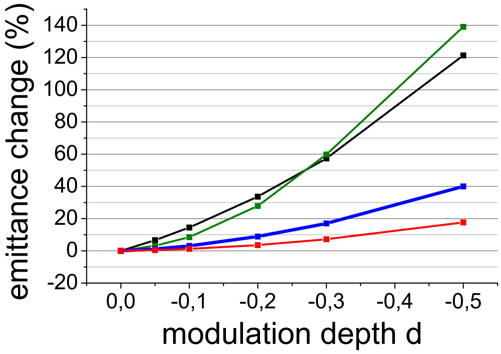

Figure 6: Simulation results for model (2) and $d < 0$.

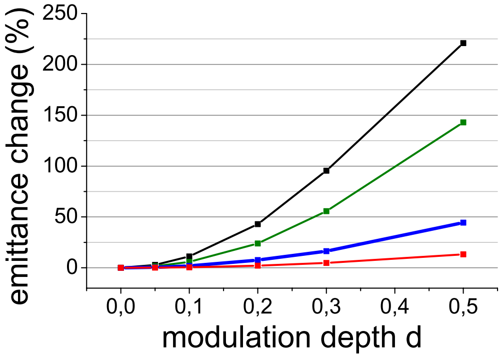

Figure 7: Simulation results for model (3).

## SUMMARY AND OUTLOOK

In this paper, it was shown how deviations from the circular flat-top transverse distribution influence the transverse emittance. It was found that a single maximum in the center of the transverse distribution can result in an emittance reduction of approx. 15 %. These results must be confirmed by dedicated experimental investigations. Furthermore, the studies should be extended to cover small bunch charges to achieve a full knowledge about tolerable imperfections depending on the space charge density.

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