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Emittance Reduction of RF Photoinjector Generated Electron Beams by Transverse Laser Beam Shaping

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Abstract. Laser pulse shaping is one of the key elements to generate low emittance electron beams with RF photoinjectors. Ultimately high performance can be achieved with ellipsoidal laser pulses, but 3-dimensional shaping is challenging. High beam quality can also be reached by simple transverse pulse shaping, which has demonstrated improved beam emittance compared to a transversely uniform laser in the 'pancake' photoemission regime. In this contribution we present the truncation of a Gaussian laser at a radius of approximately one sigma in the intermediate (electron bunch length directly after emission about the same as radius) photoemission regime with high acceleration gradients (up to 60 MV/m). This type of electron bunch is used e.g. at the European XFEL and FLASH free electron lasers at DESY, Hamburg site and is being investigated in detail at the Photoinjector Test facility at DESY in Zeuthen (PITZ). Here we present ray-tracing simulations and experimental data of a laser beamline upgrade enabling variable transverse truncation. Initial projected emittance measurements taken with help of this setup are shown, as well as supporting beam dynamics simulations. Additional simulations show the potential for substantial reduction of slice emittance at PITZ.

1. Introduction

Short pulse laser systems are driving RF photoinjectors and as a standard, the transverse shape of their laser pulses can be approximated very well with a Gaussian distribution. Simulations have shown that the emittance of resulting electron bunches can be decreased when utilizing laser pulses with a flat-top transverse intensity distribution instead [1]. Typically this is realized by cutting out the central part of the Gaussian distribution with an aperture along the transport beamline, resulting in a well-approximated flat-top but with high pulse energy loss, typically one order of magnitude.

In an investigation at LCLS-I it was shown that it can be advantageous to use a transverse distribution between Gaussian and flat-top, a truncated Gaussian [2]. In experiment a projected emittance reduction of about 25% was demonstrated when truncating the Gaussian at one sigma (in this case the intensity at the edge is about 60% of the intensity in the centre). This was corroborated by slice emittance simulations.

While LCLS-I runs in the 'pancake' photoemission regime with 3 ps (FWHM) laser pulses, DESY's Photoinjector Test facility at DESY in Zeuthen (PITZ) usually runs in the intermediate regime. One of the main working areas at PITZ is the generation of highly brilliant electron beams

with the help of laser pulse shaping [3]. The current standard condition at PITZ is a flat-top transverse profile, but it was shown in simulation [4] that under certain conditions the use of a truncated Gaussian transverse profile leads to an emittance reduction up to 15%.

An additional aspect is the linearization of the transverse space charge. This is done ideally with a parabolic radial distribution [5], but a Gaussian, truncated at about one sigma is a very good approximation of this condition. Therefore we decided to investigate this pulse shaping technique in experiment and simulation at PITZ.

2. Investigations at PITZ

2.1. Experimental preparation: zoom telescope

The pulses of the PITZ photocathode laser are transported from the laser output to the photocathode with a double image relay [4]. The first imaging system is a Keplerian telescope consisting of three lenses; the distance between object and image plane is about 14 m and it has a magnification of about 10. This magnification factor is optimized for generating a transverse flat-top shape of about 0.5 to 1.5 mm diameter by cutting out the central part of the Gaussian distribution provided by the laser with a variable iris placed in the image plane. The laser pulses are then imaged onto the photocathode with a second Keplerian telescope, this time a simple two lens 4f system with a total length of 22 m and a magnification of 1. This imaging system had to be adjusted for this investigation since the plan was to look at varying bunch charge and optimize truncation settings. This made it necessary to be able to control the laser spot size on the variable iris by adjusting the magnification of the first image relay. In order to minimize the construction effort and have the possibility to revert to the original setup it was decided to keep the original three lens setup unchanged and add a zoom telescope. This zoom telescope was supposed to be placed soon after the first original lens to utilize available space on the laser optical table. The targeted range of bunch charge for the emittance measurements was from 20 pC to 2 nC and with the additional requirement that it should be possible to illuminate the whole photocathode, the magnification of the imaging system to the variable iris has to cover the range of 2.5 up to 20. One additional requirement is that the imaging system should work not only for the currently used UV wavelength of 257 nm, but also for green light at 515 nm for future upgrade once photocathodes are available for this wavelength range.

Ray-tracing simulations were conducted with the commercial OpticStudio® software from Zemax and it was found that adding a Galilean zoom telescope with three lenses enables to cover the needed range of magnifications with close to diffraction limited performance. The simulation result for magnification 20 is shown in Fig. 1.
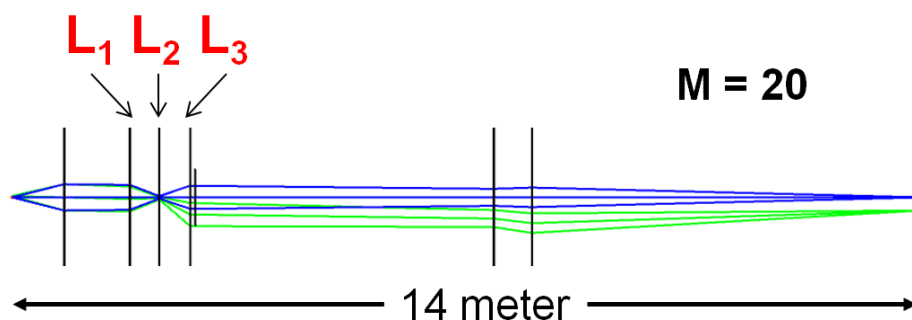

Figure 1. Ray-tracing simulation of the transport beamline from the laser output to the variable iris for beam shaping. The zoom telescope is adjusted for a magnification M = 20.

The original three lenses are the one on the outer left in Fig. 1 and the two larger lenses in the middle with diameters of 25 mm and 50 mm, respectively. Two optical fields were simulated, representing on-axis and off-axis fields within the laser beam. The magnification M is calculated as

the ratio of transverse distance to the axis at the image plane and at the object plane. The image quality was estimated with the simulated RMS spot radius of both the on-axis and off-axis beams.
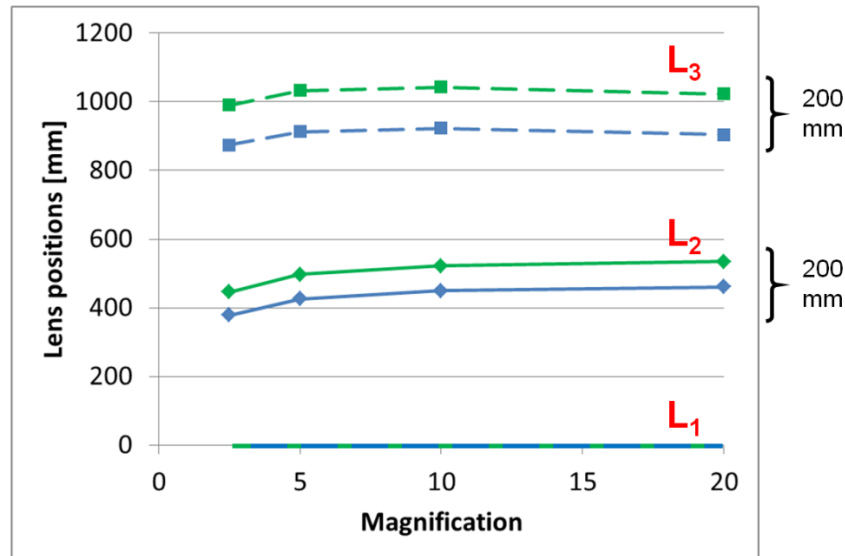

Figure 2. Simulated moving range of the telescope lenses for the required range of magnification. Lens one is fixed and the simulated positions for lenses two and three are depicted in blue ($\lambda = 257$ nm) and green ($\lambda = 515$ nm).

Another important aspect which was optimized during simulations is the required moving range of the lenses which should be as small as possible. Results are shown in Fig. 2 for both wavelengths. The position of the first lens was fixed, so only two lenses have to be moved to adjust the magnification. Looking at both wavelengths separately, each lens has to be moved by less than 100 mm to cover the whole range. The main difference of lens movement for UV and green wavelengths is an offset caused by the difference in index of refraction of the lens material for the two wavelengths. A setup covering the full moving range for both wavelengths can be realized by mounting lenses two and three each on a moving stage with a range of 200 mm.

The optical setup was built and put into operation with the zoom telescope as shown in Fig. 3.
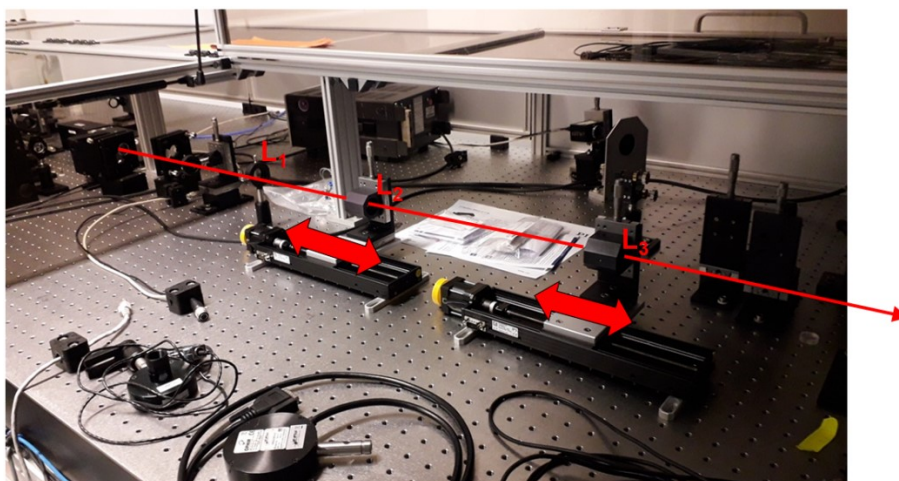

Figure 3. Setup of zoom telescope.

Resulting transverse beam shapes can be seen in Fig. 4. These pictures were taken with a virtual cathode camera which is mounted at the same optical distance as the photocathode.
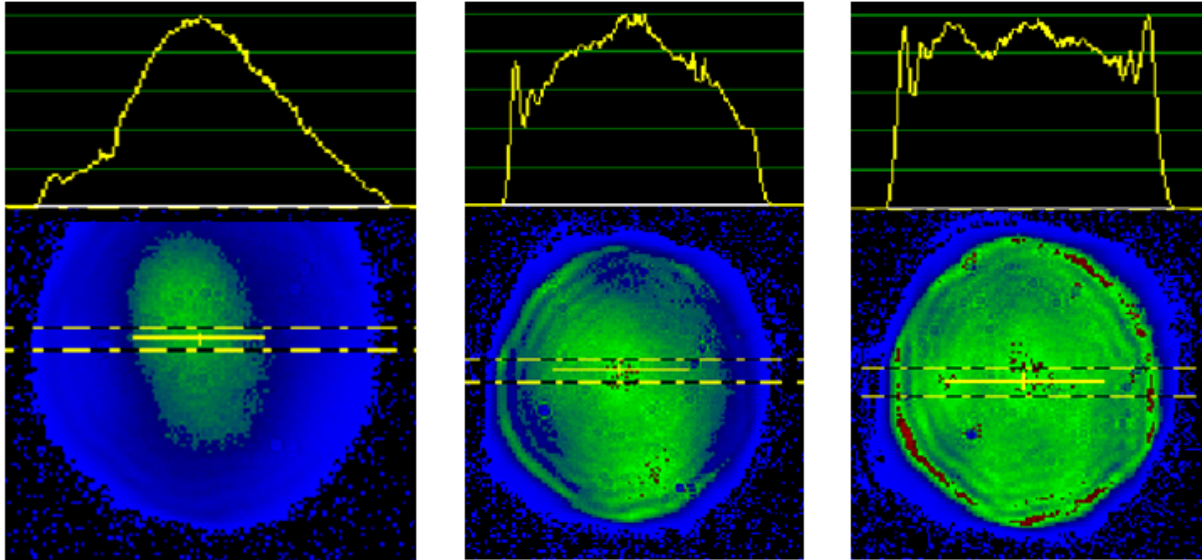

Figure 4. Laser transverse intensity distribution captured at the photocathode plane for a variable iris diameter of 1 mm and different transport beamline magnifications: M = 1.7 (left); M = 3.3 (middle); M = 5 (right). The top pictures show the projection of a horizontal section along the centre line.

The measurements in Fig. 4 demonstrate the full range of possible transverse shapes with this setup. For small magnifications (M = 1.7 ≡ 2σ cut) the laser intensity is barely cut and has the almost Gaussian shape coming from the laser (the laser used for these measurements is not purely single mode transversally). For medium magnifications (M = 3.3 ≡ 1σ cut) truncated Gaussian shapes can be generated, while for large magnifications (M = 5 ≡ 2/3σ cut) the resulting shape is close to a flat-top. Note the ring structure in the middle and right distributions, resulting from diffraction at the hard edges of the variable iris and subsequent cut of the high spatial frequencies at apertures of intermediate optics.

2.2. Experiments and Simulations

First projected emittance measurements utilizing the upgraded setup were conducted with the PITZ accelerator with the slit-scan technique [1]. The temporal profile of the photocathode laser was set to a Gaussian with ~6 ps FWHM. The diameter of the variable iris in the beamline was set to 1 mm as in Fig. 4 and the bunch charge was fixed at 250 pC. The beam momentum out of the gun was ~6.3 MeV/c (the acceleration gradient at the photocathode is then ~57 MV/m) and the momentum after the booster was ~19.5 MeV/c. Both accelerating cavity phases were set to achieve maximum mean momentum gain. Gun quadrupoles [6] were not applied. Projected emittance was measured at that position along the accelerator where the smallest emittance is expected. The same parameters were also fed into an ASTRA [7] simulation for comparison. The results are shown in Fig. 5.
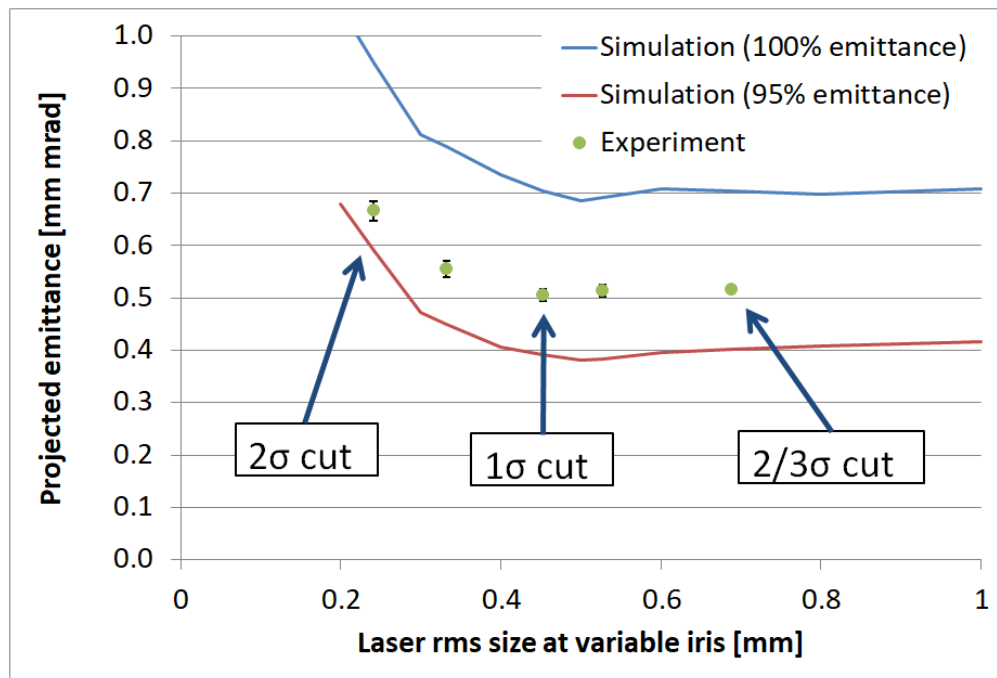
Figure 5. Emittance with transversally truncated Gaussian profiles. Shown are experimental results and simulations for two different phase space cuts (more details in the text).

Simulation and experiment show the same trend: for a large laser transverse size (large magnification) the resulting distribution at the photocathode is a flat-top, setting an emittance baseline. With decreasing laser size we get into the realm of truncated Gaussians, which indeed results in a small reduction of the projected emittance. Further reduction of laser transverse size leads to an emittance increase, which is expected when using a Gaussian transverse distribution. Two simulation curves are shown: the blue curve is the pure simulation result, while the red curve is an adjustment towards the experimental circumstances by including only the 95% of particles closest to the centre of the simulated phase space when calculating the projected emittance. This comes closer to the experimental results since in the slit scan it is difficult to measure low-charge beamlets, resulting in a loss of low-intensity signal at the edges.

3. Outlook, Conclusion

The main result, accordantly shown in simulation and experiment, is that a truncated Gaussian transverse profile of the photocathode laser has an advantage compared to a flat-top at PITZ. The projected emittance shows a shallow minimum when the distribution is cut around one sigma. With parameters chosen for this initial experiment this reduction is only a few percent, but even that is an advantage compared to the flat-top in terms of efficiency since with the reduced cutting the laser pulse energy transported to the photocathode is 6.5 times higher compared to the standard PITZ flat-top setup. The situation is even more interesting for optimized parameters: we conducted ASTRA simulations of slice emittance with an example shown in Fig. 6. It can be seen that a reduction of the slice emittance of up to 23% in the central slices can be achieved.
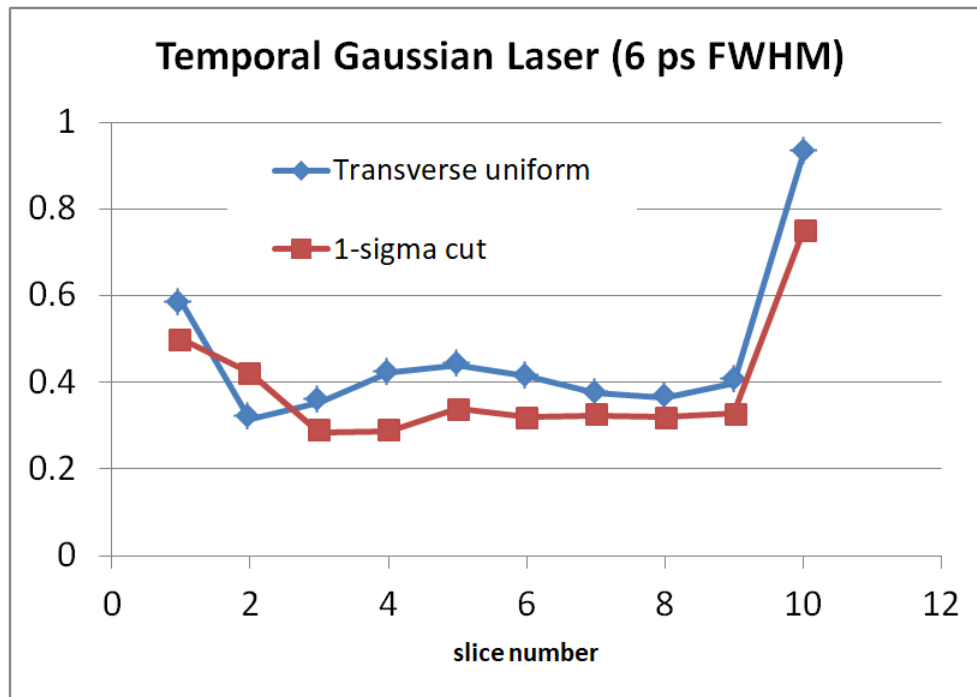
Figure 6. Slice emittance simulations when using laser pulses with a transverse uniform and truncated Gaussian profile.

In summary it can be stated that using transversally truncated laser pulses for generating electron bunches in an RF photoinjector can have advantages in term of emittance and efficiency compared to flat-top pulses.

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