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CHARACTERIZATION OF LOW EMITTANCE ELECTRON BEAMS GENERATED BY TRANSVERSE LASER BEAM SHAPING

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Abstract

Linac based X-ray free electron lasers demand a high beam quality from the electron source, therefore RF photoinjectors are used to generate the electron bunches for state-of-the-art beam brightness. One important figure of merit for these injectors is the transverse emittance of the generated electron beam, which can be minimized by shaping the photocathode laser pulses. Best performance can be achieved with ellipsoidal laser pulses, but 3D shaping is technically challenging. Typically, a quasi-uniform transverse laser profile is truncated from the Gaussian profile generated by the laser with an aperture to reduce the transverse nonlinear space charge forces. This is investigated in detail by optimizing the laser transverse profile at the Photoinjector Test facility at DESY in Zeuthen (PITZ), where photoinjector R&D is conducted for the European XFEL and FLASH free electron lasers at DESY in Hamburg. In this contribution we present experimental results at high acceleration gradients (up to 60 MV/m) for both 250 pC and 500 pC. For a bunch charge of 500 pC an emittance reduction of about 30% compared to the commonly used transverse flat-top laser distribution was achieved.

INTRODUCTION

Free electron lasers (FELs) are attractive light sources by the ability to provide highly brilliant pulses at very short wavelengths down into the hard x-ray regime [1, 2]. The light is generated in undulators which are driven by electron bunches. One key parameter here is the transverse emittance of these bunches, which for the FELs at the photon energy frontier makes it necessary to generate them with a photoinjector driven linear accelerator [1, 2]. The shape of the electron bunches is defined initially by the intensity distribution of the photoinjector laser pulse, which can be approximated very well with a Gaussian distribution in time as well as transversely, as generated by the laser. While the longitudinal distribution is kept Gaussian as a standard, it was found early on that the electron bunch emittance can be easily lowered substantially by using a flat-top profile transversely [3]. Usually this is done by cutting out the central part of the transverse Gauss distribution with a beam shaping aperture (BSA) along the transport beamline from the laser to the photocathode. While this is a simple and robust setup, giving the freedom of generating flat-top distributions over a range of diameters, it is very lossy with a typical efficiency of around 10%.

In investigations at the LCLS-I facility [4] and at PAL-XFEL [5] it was shown that it can be advantageous to use a transverse distribution between Gaussian and flat-top, a truncated Gaussian. This kind of laser shaping was also studied at FLASH (DESY, Hamburg site) [6] with positive results. The technique is now routinely applied at these and other FEL facilities. As a byproduct, the transmission efficiency of truncated Gaussian shaping is increased compared to flat-top shaping because the laser distribution is cut further away from the center.

Here we present an experimental investigation in continuation of the work presented in [7]. This was conducted at the Photoinjector Test facility at DESY in Zeuthen (PITZ). Measurements were conducted for two typical FEL working points (bunch charge 250 pC and 500 pC) as described in the following.

MEASUREMENTS

Setup

The experiments were conducted at PITZ with parameters which are typical for operation of a FEL photoinjector, e.g. at the European XFEL. Projected emittance measurements were conducted with the slit-scan technique [3]. The temporal profile of the photocathode laser was set to a Gaussian with ~6 ps FWHM; the wavelength of the laser was 257 nm. 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 final beam momentum after a booster was ~19.5 MeV/c. Both accelerating cavity phases were set to achieve maximum mean momentum gain. Projected emittance was measured at that position along the accelerator where the smallest emittance is expected.

To enable systematic studies, the transverse laser distribution on the photocathode has to be flexibly controllable. The key point here is the transverse size of the Gaussian shaped laser beam at the BSA position: The size of the BSA is set to the optimum (lowest projected emittance) which was determined with the standard flat-top setup. Then the laser transverse size has to be adjusted to achieve truncation to varying degrees. To enable this function a zoom telescope was implemented in the PITZ laser beamline [7]. On top of that a mode cleaner was installed to improve the laser beam quality. The mode cleaner consists of two lenses with a focal length of 250 mm, installed at a distance of 500 mm in a 4f configuration. In the focal point between the lenses a pinhole with a diameter of 75 µm was installed to filter out higher order transverse modes and transmit the

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Gaussian shaped fundamental mode. The mode cleaner was installed at the beginning of the transport beamline to the BSA where the laser beam is approximately collimated.

The amount of truncation of the Gaussian distribution can be expressed either in term of multiples of standard variation σ or as edge intensity normalized to the central intensity. An overview of the range used in our experiments is given in Fig. 1.

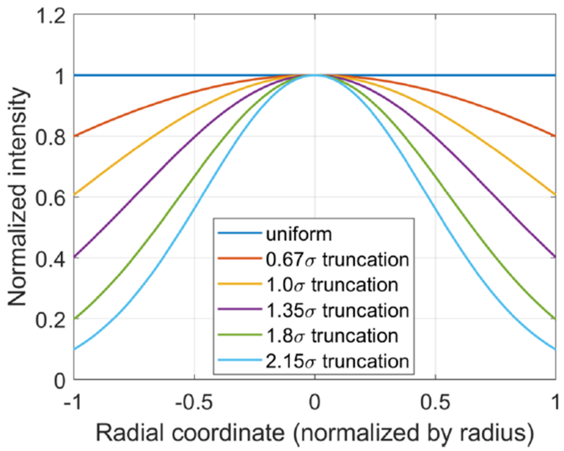

Figure 1: Visualization of Truncated Gaussian distributions used in the measurements.

Some examples of measured truncated Gaussian laser distributions are shown in Fig. 2. For a fixed BSA size of 1.3mm diameter the laser mode size at the BSA position was adjusted with the zoom telescope to achieve truncations at 1σ (a), 1.35σ (b) and 1.8σ (c). Also given in the figure are the laser intensities at the edge of the distribution as compared to the intensity at the center. These measurements were conducted with a CCD camera which is installed at the same optical distance from the BSA as the photocathode (virtual cathode camera). Slight asymmetries in the shapes are caused by remaining higher-order laser modes and imperfect laser beam transport.

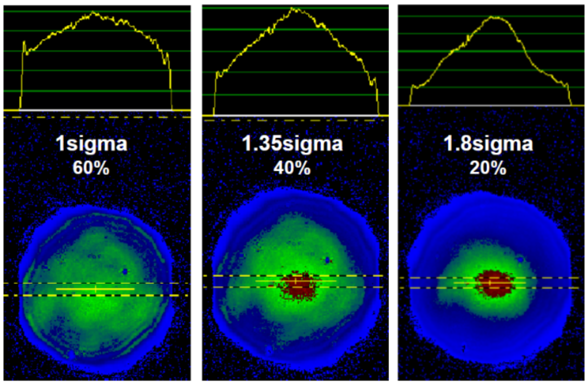

Figure 2: Transverse laser distributions and horizontal projections around the centre line at the virtual cathode position for varying truncation rates.

Projected Emittance (250 pC)

The first working point which was characterized was a bunch charge of 250 pC. The diameter of the BSA in the beamline was set to the flat-top emittance optimum of 1 mm. Results are shown in Fig. 3 as normalized XY-Emittance ε_{xy}, which is calculated from the measured X- and Y-emittances as $\varepsilon_{xy} = \sqrt{\varepsilon_x \cdot \varepsilon_y}$. The rate of Gaussian truncation is given as ratio of intensities at the edge of the distribution to the center. The standard condition of a transverse flat-top is therefore a normalized intensity of 1.

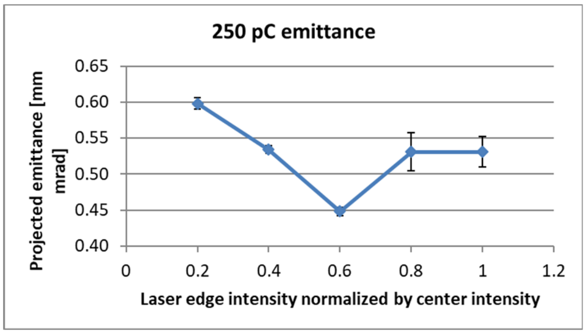

Figure 3: Measured projected emittance vs. truncation with a bunch charge of 250 pC as characterized by the normalized edge intensity.

Starting from a normalized edge intensity of 0.2 which is close to an untruncated Gaussian the emittance decreases with stronger truncation up to a minimal value of ~0.45 mm mrad for an edge intensity of 0.6. This value corresponds to a 1σ-truncation which was found as an optimum earlier [4, 5]. For even higher edge intensities towards the flat-top case the emittance increases, but stays below the near-Gaussian case. The emittance reduction from flat-top to the optimal case is 15%. As a side effect the loss of laser pulse energy is lower for the optimum truncated Gaussian case compared to the flat-top since a higher fraction of the laser pulse generated by the photocathode laser is passing the BSA. In this case, assuming a Gauss distribution with a FWHM of 3mm which is used as a standard to generate flat-top distributions at PITZ (this equals a 0.4σ truncation), the available pulse energy is increased by a factor of 4.8.

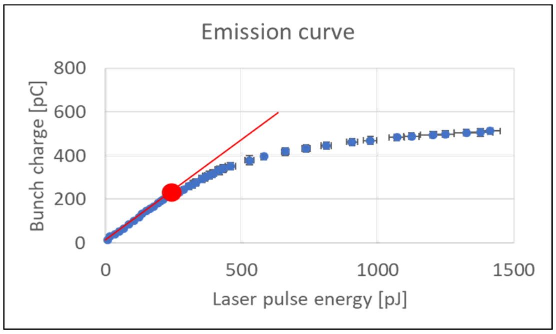

Figure 4: Emission curve for a 1 mm BSA size at optimal Gaussian truncation (60% edge intensity). The red trend line is visualizing the low charge, linear region. The red dot indicates the working point.

In order to judge the influence of the space charge force, an emission curve (charge generated at the photocathode vs. incoming laser pulse energy) was recorded [8] for the point of minimal emittance (60% edge intensity) as shown in Fig. 4.

The 250 pC working point is at the upper edge of the linear emission region, which means that the emittance is mostly driven by the emission from the photocathode while space charge influence is small.

Projected Emittance (500 pC)

The second working point which was characterized was a bunch charge of 500 pC. As before we used the BSA for the flat-top emittance optimum, in this case a BSA diameter of 1.3 mm. Results are shown in Fig. 5 as normalized XY-Emittance ε_{xy}.

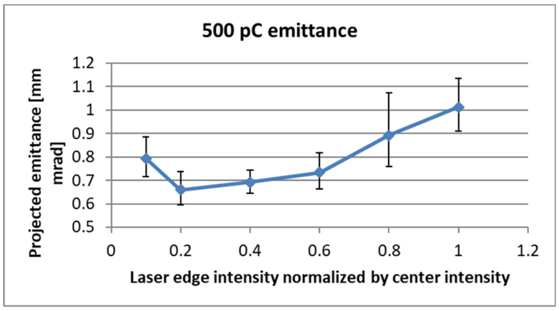

Figure 5: Measured projected emittance vs. truncation with a bunch charge of 500 pC as characterized by the normalized edge intensity.

As was the case for the lower bunch charge a truncated Gaussian shape yields the lowest emittance, but for 500 pC bunch charge the optimum (normalized edge intensity of 0.2) is much closer to the pure Gaussian distribution. From there the emittance increases strongly towards the pure Gaussian distribution which cannot be measured in a fair comparison since the BSA always cuts off a part of the Gaussian distribution. It is also very difficult to make valid measurements below an edge intensity of 0.1 since the accurate determination of edge intensity gets increasingly difficult. The emittance decrease from flat-top to optimal truncated Gaussian is 34% in this case. Since the optimum is so close to the pure Gaussian, the laser pulse energy transmission efficiency increase is very high with a factor of 9.

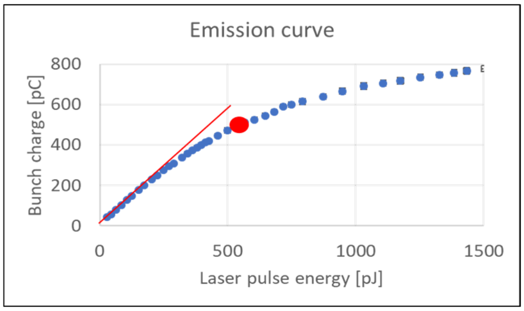

Figure 6: Emission curve for a 1.3 mm BSA size at optimal Gaussian truncation (20% edge intensity). The red trend line is visualizing the low charge, linear region. The red dot indicates the working point.

As before an emission curve was measured for the point of minimal emittance (20% edge intensity in this case) as shown in Fig. 6. This case is different compared to 250 pC insofar as the working point is clearly beyond the linear part of the emission curve in the transition regime between linear and saturated (space charge dominated) emission. This could be an explanation of the difference in optimal truncation ratio and emittance reduction for the bunch charges characterized here.

CONCLUSION

Projected transverse emittance measurements were presented in this contribution. Two working points with bunch charges of 250 pC and 500 pC were characterized and it was found that emittance can be reduced by 15% and 34%, respectively when using a truncated Gaussian photocathode laser profile instead of a flat-top profile. As a side effect the available laser pulse energy is increased significantly when using a beam shaping aperture to define the transverse profile. Additionally, emission curves were taken for both working points.

ACKNOWLEDGMENTS

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