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# BEYOND UNIFORM ELLIPSOIDAL LASER SHAPING FOR BEAM BRIGHTNESS IMPROVEMENTS AT PITZ

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*Abstract*

In the last decades, photoinjector brightness has improved significantly, driven by the needs of free electron lasers and many other applications. One of the key elements is photocathode laser shaping for reducing emittance growth from nonlinear space charge forces. At the photoinjector test facility at DESY in Zeuthen (PITZ), a uniform flattop laser was used to achieve record low emittance for a bunch charge from 20 pC to 2 nC. Due to the ideal 3D space charge force linearization in ellipsoidal electron bunches, uniform ellipsoidal photocathode laser shaping were proposed to improve beam emittance up to 33% for 1 nC beam at PITZ. In this paper, we will show even further transverse emittance improvements in simulations for both flattop and ellipsoidal laser pulses with parabolic radial distribution, versus uniform distributions. The laser shaping effects on longitudinal phase space are also discussed.


## INTRODUCTION

Photoinjector development has seen great achievements in the past decades, enabling the success of X-ray free electron lasers (XFEL) and many other applications with high brightness electron sources. Besides high gradient gun and low thermal emittance cathode development, another key in improving photoinjector beam peak brightness is photocathode laser shaping for reducing emittance growth from nonlinear space charge forces. A temporal flattop laser pulse with uniform spatial distribution has been deployed at different photoinjectors to improve transverse beam emittance [1-3]. At the photoinjector test facility at DESY in Zeuthen (PITZ), a uniform flattop photocathode laser was used to achieve record low emittance for a bunch charge from 20 pC to 2 nC, fulfilling the nominal emittance specification of European XFEL injector.

Further improvement of state of the art photoinjector beam brightness is still wished by XFEL applications [4]. Besides going towards low bunch charge (<100 pC) for ultralow emittance (<0.1 µm.rad), there is also a wish for improving high bunch charge (>0.5 nC) beam brightness for high flux FELs. For high bunch charge in a high gradient pulsed gun, or even low bunch charge in a low gradient CW gun, the beam is more vulnerable to the space charge effects, and uniform ellipsoidal photocathode laser shaping is proposed to further reduce the nonlinear space charge effect beyond uniform flattop laser shaping [5-7]. The argument is that an ellipsoidal bunch with a uniform density has 3D linearized space charge forces. Simulations based on the PITZ photoinjector have shown ~33% emittance reduction between uniform ellipsoidal laser pulses and uniform flattop laser pulses for 1 nC bunch charge with ~50 A peak current [5]. Simulations based on LCLS-II CW injector have also shown ~33% emittance reduction with uniform ellipsoidal laser pulses for 100 pC bunch charge with 20 A peak current [6].

Compared to flattop laser shaping, uniform ellipsoidal laser shaping is more complicated due to the required 3D spatiotemporal control of the laser distribution. Generation of ellipsoidal photocathode laser pulses was first conceptually tested at ANL based on chromatic aberration of a dispersive lens, and is now under investigation at PITZ utilizing the Fourier masking technique [8, 9]. Besides 3D laser shaping, ellipsoidal electron beam was also demonstrated in blowout photoemission with longitudinal or transverse laser shaping only, but the optimum bunch charge is limited (~ pC) [10, 11].

In this paper, we will first revisit the photoinjector simulation with uniform flattop and unifom ellipsoidal laser based on the PITZ injector. Then flattop and ellipsoidal laser pulses with parabolic spatial shaping instead of 3D uniform distribution is proposed to further improve photoinjector beam brightness, and their effects on both transverse and longitudinal phase spaces are discussed with simulation results.

## PITZ PHOTOINJECTOR SIMULATION

The PITZ gun is an L-band normal conducting gun for driving SC linac based FELs in pulsed mode. It features both high gradient (60 MV/m) and long RF pulse length (650 µs). A $Cs_2Te$ cathode is used to generate photoelectron bunch trains at 10 Hz. To characterize the gun and optimize beam emittance, the PITZ facility was established at DESY for FLASH and European XFEL, see Fig. 1. The maximum beam momentum after the booster is ~25 MeV/c, and the space charge effect is still not fully negligible for high bunch charge cases, so transverse projected emittance is measured with slit scan technique at ~0.9 m downstream the booster exit.

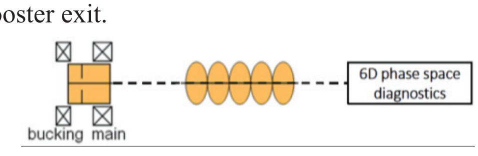


Figure 1: PITZ photoinjector layout.

In this paper, a MOGA tool developed at LBNL is used to drive ASTRA simulations for photoinjector optimization [12]. 10000 macro particles are used in MOGA simulations, and interesting solutions are refined with 200000 macro particles in ASTRA for detailed analysis. The PITZ injector layout is used as an example for investigating laser shaping effects on transverse emittance. The gun is set to 60 MV/m at maximum energy gain phase. The booster is set to maximum energy gain phase. The flattop laser is set to 22 ps FWHM with 2 ps edges, and the ellipsoidal laser is set

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to 19.3 ps FWHM to match the rms bunch length with flattop laser case. The cathode thermal emittance is set to 0.85 µm.rad/mm. The laser radius, booster amplitude and solenoid focusing are varied to optimize transverse emittance at slit scan location.

## UNIFORM FLATTOP VS UNIFORM ELLIPSOIDAL LASER PULSE

The PITZ injector emittance was experimentally optimized with both Gaussian and uniform flattop laser pulses, and simulations show uniform ellipsoidal laser pulses could reduce the projected emittance by ~33% at 1 nC bunch charge [5]. Sliced bunch parameters are shown in Fig. 2 and Fig. 3. Figure 2 shows transverse slice emittance growth from the cathode to the measurement location. For the uniform ellipsoidal laser case there is still slice emittance growth at central slices close to the thermal emittance level, and the final slice emittances of the central slices are even higher than the projected emittance. Figure 3 shows the longitudinal phase space comparison after linear and quadratic energy chirp removal by post processing. Direct longitudinal phase space comparison without post processing shows similar longitudinal emittance between the two laser shapes, which is misleading. The similar longitudinal emittances are due to similar RMS bunch length and similar uncorrelated energy spread which is dominated by the RF curvature. After linear and quadratic energy chirp removal, the reduction of higher order (H.O.) energy spread reveals the advantage of ellipsoidal laser shaping on longitudinal phase space linearization.

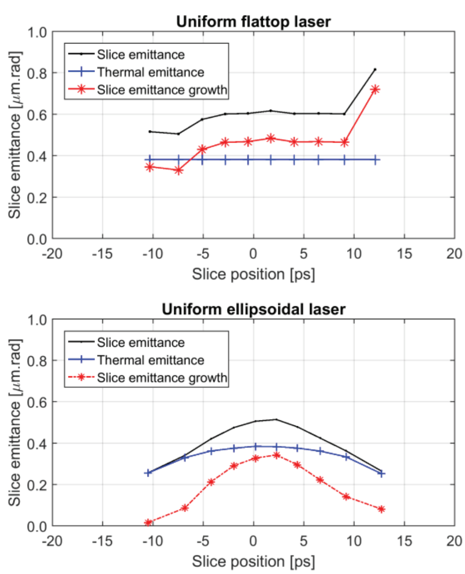


Figure 2: Slice emittance comparison between uniform flattop laser and uniform ellipsoidal laser (each slice contains equal charge).

With uniform ellipsoidal laser shaping, 3D space charge force linearization is expected, but emittance growth in the central slices is still not understood. One suspect is that the slice emittance growth happens during photoemission when part of the ellipsoidal beam is emitted and the transverse space charge force is not linear. To investigate this, the slice emittance near the cathode is shown in Fig. 4. Simulations show central slices keep the thermal emittance at 5 cm from cathode, so the final central slice emittance growth does not happen in the emission process.

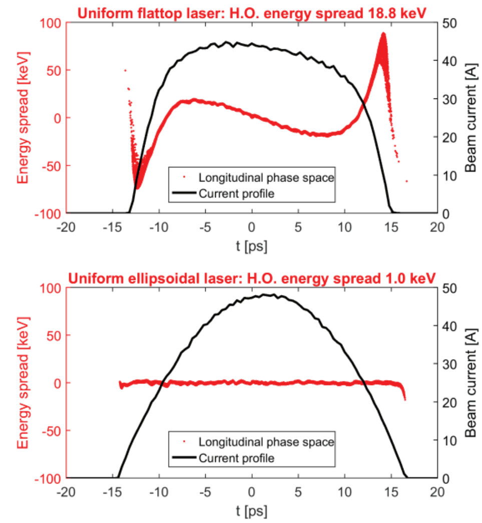


Figure 3: Longitudinal phase space comparison between uniform flattop laser and uniform ellipsoidal laser. 1st and 2nd order energy chirps are removed numerically, leaving only higher order (H.O.) energy spread.

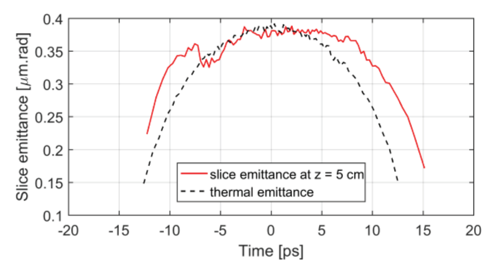


Figure 4: Slice emittance near cathode region for uniform ellipsoidal laser case.

## PARABOLIC SPATIAL LASER SHAPING

Besides uniform flattop and uniform ellipsoidal laser pulses, a laser pulse with a special parabolic radial distribution was also proposed to linearize transverse space charge forces to the 3rd order [13].

$$I(r) = I_0\left(1-\frac{r^2}{3R^2}\right). \tag{1}$$

r is the distance from beam center, $R$ is the radius of the beam, $I_0$ is the peak beam intensity. Such a spatial distribution can be approximated by truncating Gaussian distribution at 0.9 sigma, see Fig. 5. The truncated Gaussian laser spatial shaping has been found at DESY and LCLS injectors in the 'pancake' photoemission regime,

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improving transverse emittance compared to uniform transverse distribution [14 - 16].

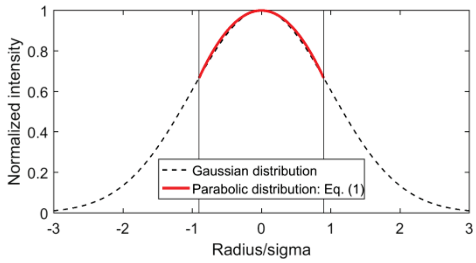


Figure 5: Parabolic Laser spatial intensity approximation by truncating Gaussian distribution at 0.9 sigma.

Laser spatial shaping with truncated Gaussian distribution was applied (in simulation) to the PITZ injector in the 'cigar' photoemission regime for both flattop laser pulses and ellipsoidal laser pulses. For flattop laser, the Gaussian truncation can be varied from 0.5 sigma to 1.5 sigma in the optmizer. The modulated ellipsoidal laser pulse shape is cut from a hard-edge flattop laser with truncated Gaussian transverse distribution, as shown in Fig. 6. Both the flattop case and ellipsoidal case have the same full temporal width as used in the previous simulations.

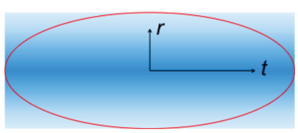


Figure 6: Illustration of modulated ellipsoidal laser pulse cut from a flattop laser pulse with transverse modulation.

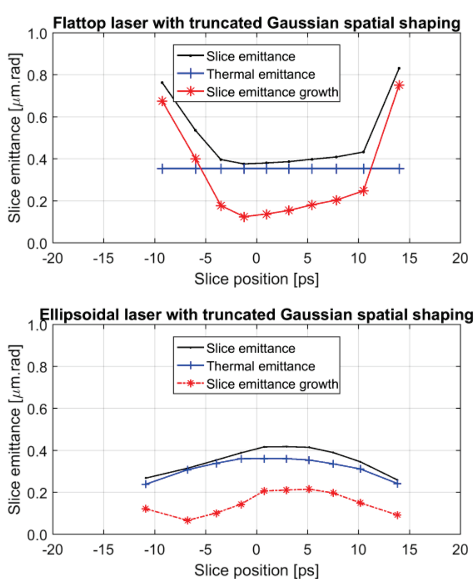


Figure 7: Slice emittance of flattop and ellipsoidal cases after truncated Gaussian spatial shaping is applied.

The optimized solutions for both distributions at 1 nC are shown in Fig. 7, and the comparisons between a uniform transverse distribution and a truncated Gaussian distribution are shown in Table 1. The optimum Gaussian truncations found from numerical simulations are 1 sigma cut for flattop laser and 0.9 sigma for ellipsoidal laser at a bunch charge of 1 nC, which are almost the same as theoretical predictions. Parabolic radial shaping improves the slice emittance by ~30% for the flattop laser case and by ~14% for the ellipsoidal laser case. Now the emittances of the central slices are almost the same as the thermal emittance for both lasers.

Table 1: Simulation comparison between lasers with uniform transverse distribution and truncated Gaussian distribution at 1 nC ($\langle\varepsilon_{slice}\rangle$ is the average emittance of the central 8 slices).

| | Flat-U | Flat-G | Ellip-U | Ellip-G | Unit |
|---|---|---|---|---|---|
| $\varepsilon_{100\%}$ | 0.65 | 0.46 | 0.42 | 0.38 | µm |
| $\varepsilon_{95\%}$ | 0.45 | 0.35 | 0.32 | 0.31 | µm |
| $\langle\varepsilon_{slice}\rangle$ | 0.59 | 0.41 | 0.44 | 0.38 | µm |
| $\delta E_{H.O.}$ | 18.8 | 15.5 | 1.0 | 1.6 | keV |

After parabolic radial shaping, the transverse emittance of the flattop laser case approaches that of ellipsoidal laser pulse, but the higher order energy spread is still one order of magnitude worse. Smaller higher order energy spread, i.e. a more linearized longitudinal phase space, will help longitudinal beam dynamics optimization in the main linac for XFEL applications. Radial parabolic distributions not only improve transverse emittance of both flattop and ellipsoidal laser pulse shapes, but also increase the laser shaping efficiencies.

## CONCLUSION

In this paper, the PITZ photoinjector is used as a case study to further investigate laser spatial shaping for high bunch charge cases (~1 nC). With radial parabolic distribution approximated by Gaussian truncation at ~ 1 sigma, the slice emittance further improves by ~30% for the flattop laser case, and by ~14% for the ellipsoidal laser case, which makes the slice emittance almost the same as thermal emittance in the central slices. Such a radial laser shaping not only improves transverse emittance, but should also increase laser shaping efficiencies. With parabolic spatial shaping, the advantage of ellipsoidal laser on transverse emittance is reduced compared to the flattop laser, but the longitudinal phase space linearization is still one order of magnitude better.

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