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EXPERIMENTAL STUDIES WITH SPATIAL GAUSSIAN-CUT LASER FOR THE LCLS PHOTOCATHODE GUN*

F. Zhou+, A. Brachmann, P. Emma, S. Gilevich, and Z. Huang

SLAC National Accelerator Laboratory, 2575 Sand Hill Road, Menlo Park, CA 94025, USA

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+ zhoufeng@slac.stanford.edu

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Abstract

To simplify the LCLS operation and further enhance the injector performances, we are evaluating the various parameters including the photocathode drive laser system. Extensive simulations show that both the projected and time-sliced emittances with spatial Gaussian profiles having reasonable tail-cut are better than those with uniform one. The simulated results are also supported by theoretical analyses. In the LCLS, the spatial uniform or Gaussian-cut laser profiles are conveniently obtained by adjusting the optics of the telescope upstream of an iris, used to define laser size on the cathode. Preliminary beam studies at the LCLS injector show that both the projected and time-sliced emittances with spatial Gaussian-cut laser are almost as good as, although not better than, those with uniform one. In addition, the laser transmission through the iris with the Gaussian-cut profile is twice with uniform one, which can significantly ease LCLS copper cathode/laser operations and thus improve the LCLS operation efficiency. More beam studies are planned to measure FEL performances with the Gaussian-cut in comparison with the uniform one. All simulations and measurements are presented in the paper.

OVERVIEW

The drive laser requirements are usually set to very stringent conditions for the planned X-ray Free Electron Laser (FEL) projects, such as temporal and spatial profiles required to be uniform, to achieve an ultra-high brightness electron beam from photocathode RF gun system. To get a uniform temporal profile, laser beams mostly have to be stacked to get for a few ps pulse length, which certainly make laser system complicated and thus probably unreliable. The LCLS was to stack 3 ps S-polarization and P-polarization Gaussian laser beams to obtain about 6.5 ps final temporal uniform laser beam shining on the cathode. To get a uniform spatial laser profile, the telescope optics upstream of an iris, used to define laser size on the cathode, has to be properly adjusted with severely sacrificing drive laser transmission through the small iris. The LCLS is making efforts to simplify the drive laser systems without compromising high brightness electron beam performances. In spring of 2010, one of two stacked lasers was removed. Since then only single laser with ~3 ps Gaussian distribution is being used for the routine operations, which generates similar or even better electron beam in comparison with 6.5 ps stacked uniform laser beam [1]. In late of 2010, the extensive simulations indicated that the emittance could be further improved with spatial Gaussian-cut drive laser distribution rather than spatial uniform one. It is well-known that to obtain a uniform laser on the cathode the telescope upstream of the iris has to make laser beam much bigger than the iris size and thus most part of laser beam has been cut away through the small iris. However, to generate a Gaussian-cut laser beam the telescope only needs to make the laser size comparable to the iris size so a larger laser transmission through the iris is expected. The spatial Gaussian-cut may have advantages of easing the LCLS copper cathode/laser operations as well as a better emittance.

This paper will present extensive simulations using ImpactT code [2], theoretical analyses, and preliminary experimental results at the LCLS injector.

SIMULATIONS AND THEORY

A fully 3D code, ImpactT, is used to track particles taking into account space charge forces, short range wakefields and some other effects. All parameters applied in the simulations except spatial profiles are the same as the ones operated in the LCLS, such as 3 ps FWHM of temporal Gaussian laser, 115 MV/m of gun gradient on the cathode, 30° of laser launch phase from zero-crossing, and 250 pC of bunch charge.

Simulated Projected and Slice Emittances

The edge-to-edge laser beam size on the cathode is set to 1.2 mm for 250 pC bunch charge in the LCLS practical operations to acquire an optimum emittance. In preparing all spatial laser distributions for the simulations, all of them are truncated at the iris radius, 0.6 mm, same as LCLS realistic parameter. We start with pure Gaussian distributions but with different rms size σ_x (same for σ_y) values to generate uniform and Gaussian-cut distributions on the cathode. For example, for generation of a spatial uniform beam, a Gaussian beam with much larger rms size than iris radius - 0.6 mm, 6.0 mm for example, is chosen. Gaussian distributions with smaller rms sizes comparable to the iris radius, from 0.3 mm to 0.6 mm, truncated at ±0.6 mm are used to generate different spatial Gaussian-cut laser beams. Figure 1 shows the spatial laser profiles (line-out intensity) used in the ImpactT simulations, where σ_x=6.0 mm means for spatial uniform profile while σ_x=0.3-0.6 means for different Gaussian-cut profile. The projected and time-sliced emittances at 135 MeV of beam energy are simulated with 250 pC of bunch charge, as shown in Figure 2. It is shown that both projected and time-sliced emittances with σ_x=0.4 mm are better than the ones with the uniform distribution.

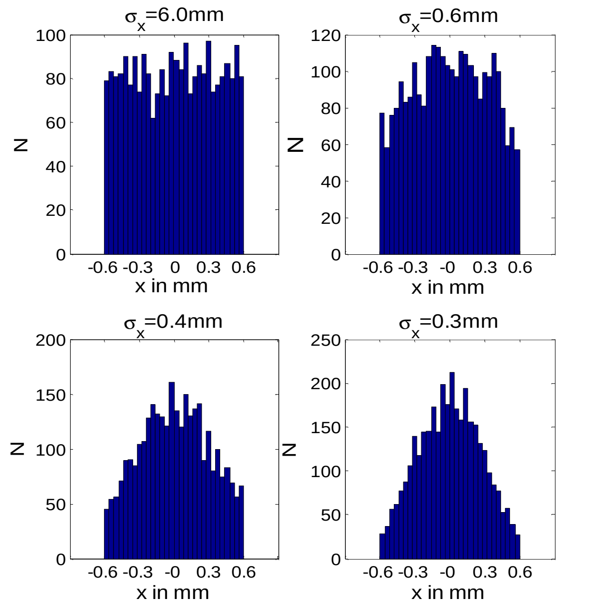

Figure 1: Different spatial laser distributions (line-out intensity shown) used in the simulations for emittance comparisons: spatial uniform laser beam (σ_x=6.0 mm) and different spatial Gaussian-cut laser beams (σ_x=0.3 - 0.6 mm).

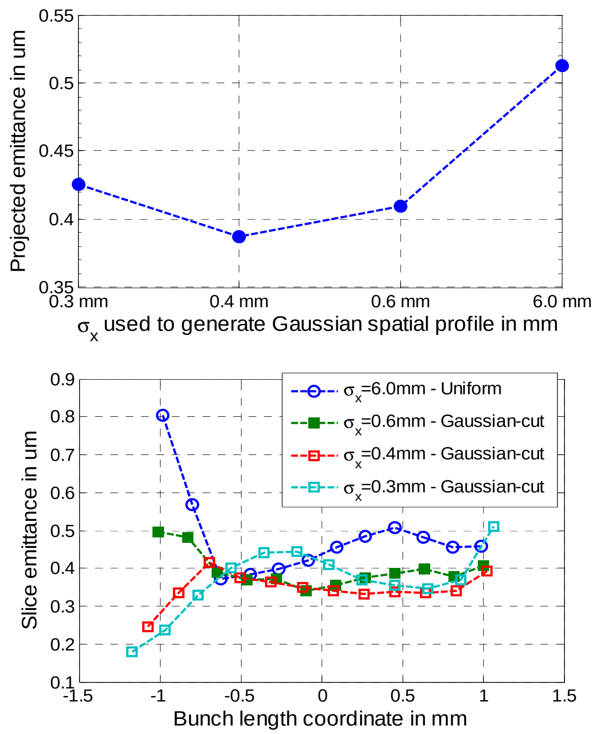

Figure 2: Projected (top) and time-sliced (bottom) emittances with the uniform beam (σ_x=6.0 mm) and different Gaussian-cuts (σ_x=0.3 - 0.6 mm) at 250 pC of bunch charge.

Theoretical Explanation

The long-standing conclusion – spatial uniform laser beam on the cathode is the best for emittance – is well accepted by the community. Our conclusion from the simulations is obvious in contradiction with the statement. A simple analytical model is developed to qualitatively explain our observations from the simulations. We can consider the distributions in x, y, and z planes as Gaussians for all of the simulated spatial distributions. The charge density ρ for the truncated Gaussian profile is:

$$\rho = \frac{Q}{(2\pi)^{3/2}\sigma_x^2\,\mathrm{Erf}(r/(\sqrt{2}\sigma_x))^2\sigma_z}e^{-\frac{x^2+y^2}{2\sigma_x^2}-\frac{z^2}{2\sigma_z^2}} \qquad (1)$$

where Q is the total charge, σ_x and σ_z are the rms beam sizes in transverse and longitudinal planes, and ρ=0 for $|x|>r$ or $|y|>r$ due to the transverse truncation (approximated by a square iris). The solution of the electrostatic potential ϕ is:

$$\phi(x,y,z) = \frac{1}{4\pi\varepsilon_0}\int\frac{\rho(x',y',z')dx'dy'dz'}{\left[(x-x')^2+(y-y')^2+(z-z')^2\right]^{1/2}} \qquad (2)$$

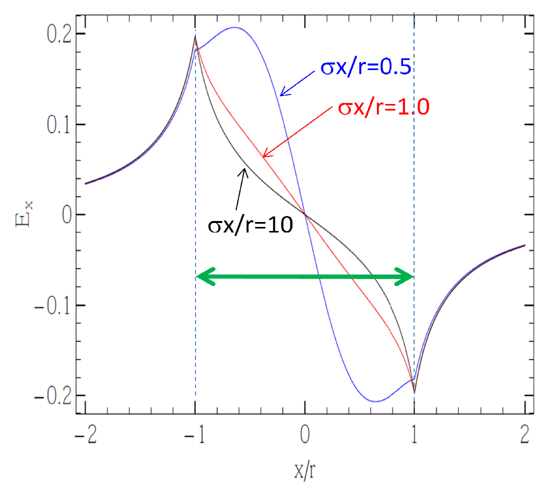

Figure 3: Transverse space charge force vs. x/r. The black one is for spatial uniform beam and, the red and blue are for different spatial Gaussian-cut profiles. The transverse space charge force in the red one is the most linear.

Following Ref. [3], the transverse space charge field derived from the above electrostatic potential can be expressed as a one-dimensional integral. The bunch is pancake-like with large aspect ratio x/z when it is immediately released from the cathode. The transverse space charge force E_x near the cathode is calculated for σ_z/r=0.1 as shown in Figure 3. The interested x (same for y) range of the numerical integration for our problems is from -r to r, where r is iris radius, 0.6 mm, i.e., all spatial distributions are truncated at ±0.6 mm, same as in the simulations. In the Figure, the black curve with σ_x/r=10 (i.e., σ_x=6.0 mm) is for the spatial uniform beam while the red one is for Gaussian-cut with σ_x=0.6 mm and the blue one is for Gaussian-cut with σ_x=0.3 mm. It is shown that the transverse space charge force of the Gaussian-cut distribution with σ_x=~0.6 mm is the most linear among uniform and all Gaussian-cuts, which may result in a better transverse emittance. This analysis, although highly simplified and assuming a square transverse iris instead of a round one, provides a qualitatively understanding of the simulation results.

PRELIMINARY EXPERIMENTAL RESULTS

A beam experiment was performed at the LCLS injector to compare the projected and slice emittances using regular spatial uniform and Gaussian-cut laser beams on the cathode. Figure 4 shows the drive laser profiles (uniform and a Gaussian-cut) on the iris. The laser transmission through the iris for the uniform case (upper) is only half the one with the Gaussian-cut (bottom). Therefore, the needed laser power for the Gaussian-cut is only half the uniform case, which definitely eases the copper cathode operations.

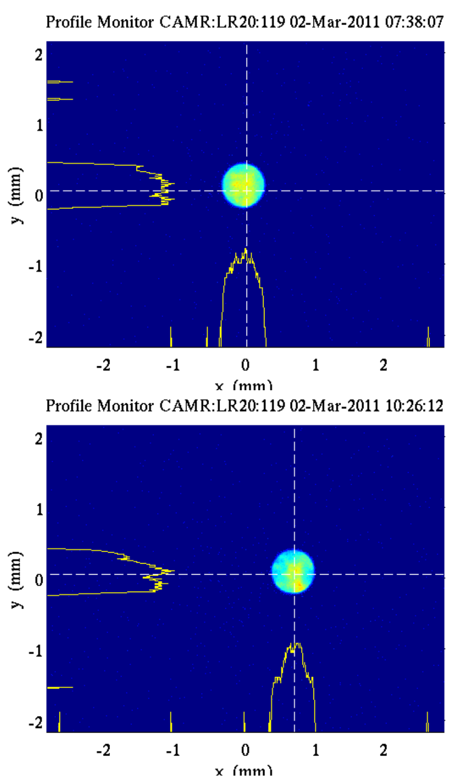

Figure 4: Regular uniform laser (upper) and Gaussian-cut profiles on the cathode (bottom)

The projected emittances for both cases are optimized through scanning main solenoid, small quadrupoles in the gun, etc. The projected emittance with 250 pC charge is measured at OTR2 [4] with 135 MeV of electron beam energy, as shown in Figure 5. Note that all projected and slice emittance measurements are taken with laser heater off. It is shown that the projected emittance is ~0.43 μm with the Gaussian-cut distribution, very close to 0.41 μm with the regular uniform case. After projected emittance measurements for each case, we immediately turn on the transverse cavity to measure slice emittance in x-plane at the energy. All slice emittances for both cases are measured, as shown in Figure 6. It is shown that the middle slice of the Gaussian-cut is 0.37 μm compared with 0.33 μm of uniform case. It is found in the figure that all slice emittance with the Gaussian-cut is 5%-10% larger than that with uniform case. Simulations show that asymmetry rather than symmetrical Gaussian-cut profile may wash out the emittance improvement. In the practical operations, it is hard to maintain Gaussian-cut profile to symmetry. Thus it may be one of the reasons why we did not get the emittance improvements. In addition, the emittance difference is within the measurement errors, and also only one shot measurement for each case is made. Nevertheless, the emittance with the Gaussian-cut is still very good for FEL although not better than that with the uniform case.

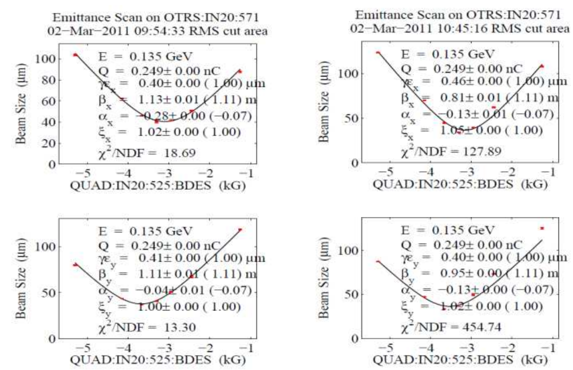

Figure 5: Measured projected emittance at 250 pC: regular uniform (left) and Gaussian-cut (right).

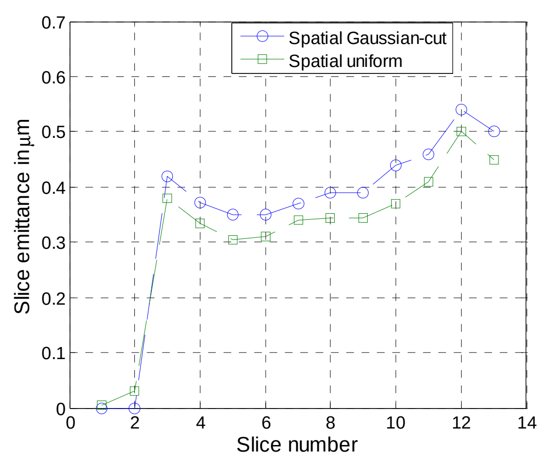

Figure 6: Comparison of the measured slice emittances for uniform and the Gaussian-cut distributions at 250 pC

SUMMARY AND FUTURE WORK

Extensive simulations show that the emittance can be improved with certain spatial Gaussian-cut distribution rather than spatially uniform beam. The analytical analyses show that the transverse space charge force with certain Gaussian-cut distribution is more linear than the uniform one. The preliminary experiment performed at the LCLS injector show that the projected and slice emittances with the Gaussian-cut distribution are as good as, although not better than, that with uniform one. Asymmetry rather than symmetry Gaussian-cut profile in the practical operations is probably one of reasons to wash out the emittance improvement. The laser transmission through the iris with the Gaussian-cut distribution is double that with the uniform one, which definitely eases the LCLS laser/cathode operations and improve the overall operation efficiency. Future work is to compare FEL performances between spatial uniform and Gaussian-cut beams.

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