LCLS DRIVE LASER SHAPING EXPERIMENTS*

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Abstract

The effect of the drive laser transverse shape upon the electron beam emittance and FEL performance at 1.5 Ångstroms was studied at 250 pC for the Linac Coherent Light Source X-Ray FEL. Rectangular grids and radial symmetric shapes were imaged onto the cathode and the emittance and FEL output were measured. Each pattern was truncated by a 1.2 mm diameter iris. The projected and time-sliced emittances as well as the electron bunch shape were measured at 135 MeV using a one micron thick optical transition radiation foil and a transverse RF deflecting cavity. The beam was then compressed and accelerated to 13.63 GeV and transported through the undulator. In our initial measurements, the 1.5 Ångstrom FEL pulse energy was determined from the energy loss of the electron beam. Future experiments will use an x-ray calorimeter. The gain length was obtained by measuring the FEL output along the undulator by deflecting the electron beam off the optical axis sequentially along the undulator. These emittances and the FEL performance are compared with the nominal uniform transverse shape. The results indicate that the more uniform the laser profile, the lower the emittance. A simple beamlet model is presented which quantitatively supports our results.

INTRODUCTION

The beam quality from a photocathode RF gun is strongly dependent upon the transverse and longitudinal shape of the drive laser pulse. Previous theoretical and experimental studies indicate that one best shape is a uniformly filled cylinder with sharp edges, while more other work argues for a three dimensional ellipsoidal shape. The LCLS baseline design specifies the cylindrical shape. However since shaping the laser pulse is a technical challenge, it is important to study experimentally the effect of laser shape on beam emittance.

The LCLS x-ray free electron laser provides an excellent facility for performing these studies. Its injector includes not only state-of-the-art, well-characterized drive laser and photocathode RF gun but also has electron diagnostics for measuring the projected and slice emittance, and the longitudinal shape of the bunch. After characterization in the injector, the beam can then be accelerated and compressed and sent to the undulator where the corresponding lasing performance can be measured.

DESCRIPTION OF THE EXPERIMENT

In these experiments, the projected and slice emittances produced by seven different transverse laser shapes were compared. The longitudinal shape of the laser was the same in all cases. The transverse shapes are shown in Fig. 1 were by the virtual cathode camera. The distributions were truncated by an iris producing a 1.2 mm diameter laser spot on the cathode.

The projected emittances were measured at 135 MeV using the quadrupole scan technique with an OTR foil and a digital camera. A transverse cavity also at 135 MeV deflected the beam vertically on this same OTR foil which combined with the quadrupole scan gives the slice emittance [1].

After the measurements at 135 MeV, the beam was compressed longitudinally and accelerated to 13.63 GeV and transported through the undulator. Various degrees of FEL lasing were observed, which depended significantly upon the laser shape. The electron energy loss was measured after the undulator to determine the FEL energy extraction. The gain length was determined by measuring this energy loss as a function of the effective undulator length when the electron beam was steered off the optical axis. Further details of these measurement techniques are given in another contribution to these proceedings [2].

THE EXPERIMENTAL RESULTS

Nominal FEL Operation

The beam parameters for nominal LCLS operation are listed in Table 1. The slice emittance is for the central slice and the FEL gain length and energy loss are representative values at the time of these measurements. These results have shown continuous improvement as the commissioning effort has explored various undulator taper configurations and electron bunch compressions.

Table 1: Nominal LCLS Beam and FEL Parameters

Parameter	Measured Value
Bunch Charge	250 pC
Projected Emittance (x-plane)	0.44 microns (rms)
Projected Emittance (y-plane)	0.46 microns (rms)
Slice Emittance (x-plane)	0.39 microns (rms)
Bunch Length	697.6 microns (rms)
Gain Length	3.7 meters
Electron Energy Loss	6.4 MeV

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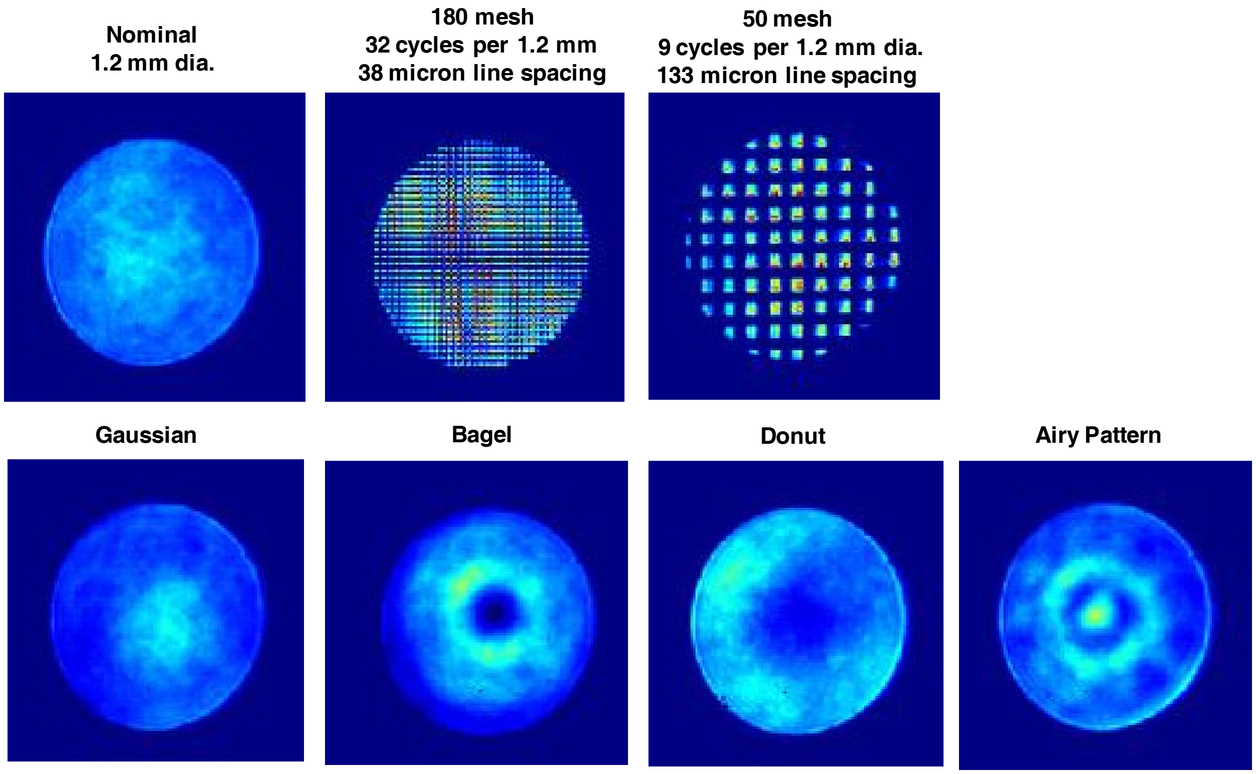

Figure 1: (color) The seven laser shapes used in the electron beam and FEL lasing studies. The edge diameter of all the shapes is 1.2 mm.

The Seven Laser Shapes

False-color images of the laser shapes studied are shown in Fig. 1. Two styles of shapes were explored: two rectangular mesh and four axial symmetric circular shapes. Compared to the laser spot, the two mesh patterns have high spatial frequencies: ~32 cycles and 9 cycles over the 1.2 mm diameter. Four of the laser shapes have radial symmetry with low spatial frequency. They explore the emittance growth due to Gaussian, a steep central hole (bagel), a gradual central hole (donut) and an Airy diffraction pattern.

Summary of Experimental Results

The measurements of the projected emittance, the FEL gain length and the electron energy loss are compared with the nominal values in Fig. 2. In all cases the FEL performance, as determined from the energy loss, is lower for any shape other than the nominal flat top.

The measured gain length as a function of the projected emittance is shown in Figure 3. In general the center slice emittance is approximately 10% lower than the projected.

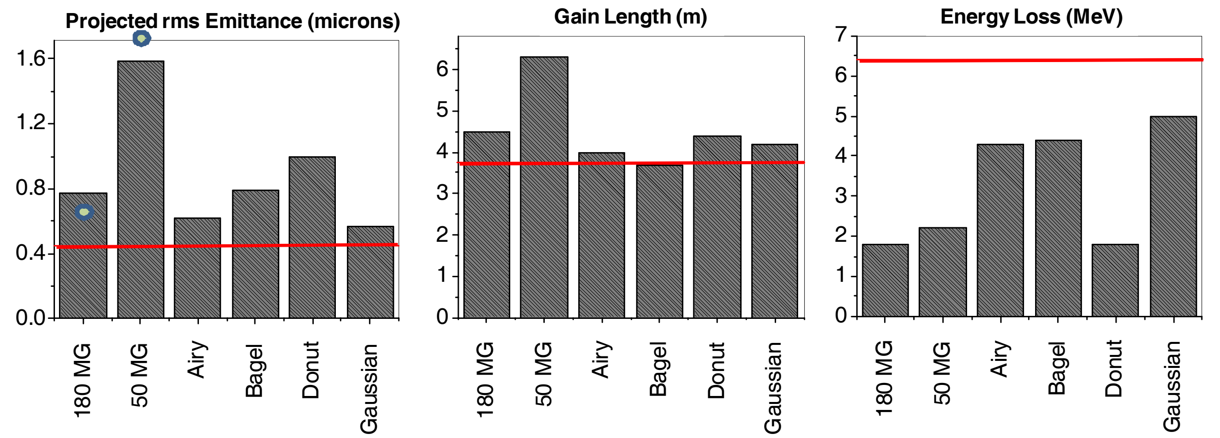

Figure 2: (color) The projected emittance, the gain length and the electron energy loss due to lasing for the six laser shapes shown in Fig. 1. The lines indicate the nominal values. The two circles are the emittances for 50 and 180 mesh grids (left plot) given by Eqn. 5 summed in quadrature with the nominal emittance.

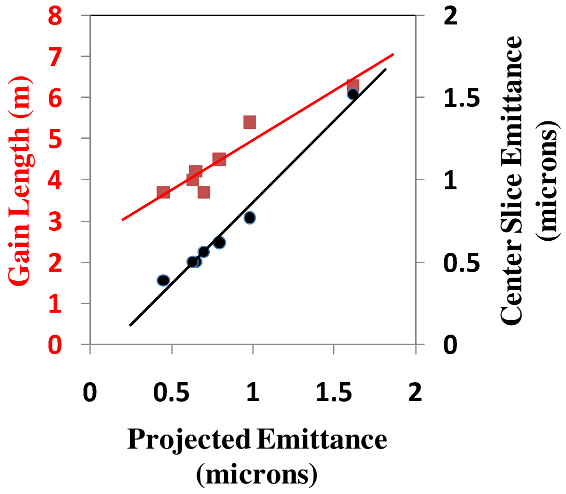

Figure 3: (color) The gain length and the center slice emittance plotted as functions of the projected emittance at 135 MeV. The slope of the gain length is 2.4 m/micron and the slice emittance fit has a slope of 0.995.

DATA ANALYSIS

There has been considerable theoretical and experimental work related to the emittance growth of non-stationary beams using the concept of free energy [3,4]. In these studies the emittance growth is related to the energy difference between the non-stable initial beam and the final stationary beam configurations. The initially correlated beam distribution becomes thermal or random via non-linear forces to an uncorrelated emittance growth.

An intuitive view of the electron motion for non-uniform laser profiles would be to consider first how individual beamlets expand for the rectangular mesh. The mutual repulsion of the electrons will cause the beamlet to expand in the radial direction from its center. The expanding beamlets at some point begin to overlap producing a more uniform charge distribution and reduce the space charge force. As the beamlets merge to a nearly uniform electron distribution, the space charge force driving the expansion becomes small and the transverse acceleration comes to an end. The radial velocities acquired from the acceleration before the beamlet merger remain, becoming the emittance growth due to the laser non-uniformity. In addition to the asymptotic emittance growth of the merging beamlets, there is also a reduction of the transverse space charge force as the beam becomes relativistic. Hence once the beamlets completely overlap and the beam becomes relativistic, the emittance growth due to the laser non-uniformity ends. This growth occurs dominantly near the cathode, typically during the first 10's of picoseconds of the bunch's acceleration from rest, and within a centimeter from the cathode.

This rapid emittance growth can be quantified for the rectangular mesh patterns by writing the radial electric field due to an infinitely long line of charge. Consider first the field on an electron at the radial edge of a beamlet given by [5],

$$E_r = \frac{\rho_l}{2\pi\varepsilon_0 r} \qquad [1]$$

Here ρ_l is the line charge density of a beamlet. For an initial beamlet radius, r_0, a bunch length, l_b, and a full laser beam radius, R, and a total bunch charge, Q, and a center-to-center beamlet spacing of $4r_0$, the radial electric field of a single beamlet for $r \geq r_0$ can be written as

$$E_r = \frac{8Qr_0^2}{\pi^2\varepsilon_0 R^2 l_b r} \qquad [2]$$

Inserting the values for the 50 mesh case: $r_0 = 33$ microns, $l_b = 2$ mm (6.7 ps(fwhm)), $Q = 250$ pC, $R = 0.6$ mm; an electron at the radial edge of a beamlet, $r = r_0$, experiences ~1 MV/m radial electric field.

While the precise calculation of the emittance using a particle simulation code is beyond the scope (and length) of this paper, a useful relation for the emittance can be obtained from this radial field. Integrating Eqn. [2] over a radial distance from r_0 to ar_0 gives the transverse energy gain of this edge electron,

$$\frac{p_r^2}{2m} = \frac{8Qer_0^2}{\pi^2\varepsilon_0 R^2 l_b}\ln a \qquad [3]$$

Since the beamlets are identical and small compared to the 1.2 mm ($4\sigma_x$) diameter laser spot, each can be considered a "point" source with the same rms divergence. Therefore we assume there is no position-divergence correlation on a scale larger than a beamlet diameter and the normalized emittance can be written as,

$$\varepsilon_n = \sigma_x \frac{\sqrt{\langle p_x^2 \rangle}}{mc}. \qquad [4]$$

Next we make the reasonable assumption that $\langle p_x^2 \rangle \approx p_r^2/4$, and find the emittance due to an evenly spaced rectangular array of beamlets is

$$\varepsilon_{n,mesh} = \sigma_x \frac{2r_0}{\pi R}\sqrt{\frac{Qe\ln a}{mc^2\varepsilon_0 l_b}} \qquad [5]$$

The circles in Fig. 2 are theoretical emittances for 50 and 180 meshes given by the square root of the sum of Eqn. 5 emittance squared and the nominal emittance squared. There is reasonable agreement with the data. A similar analysis can be done for the radial laser distributions.

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