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.

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Measured Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bunch Charge</td>
<td>250 pC</td>
</tr>
<tr>
<td>Projected Emittance (x-plane)</td>
<td>0.44 microns (rms)</td>
</tr>
<tr>
<td>Projected Emittance (y-plane)</td>
<td>0.46 microns (rms)</td>
</tr>
<tr>
<td>Slice Emittance (x-plane)</td>
<td>0.39 microns (rms)</td>
</tr>
<tr>
<td>Bunch Length</td>
<td>697.6 microns (rms)</td>
</tr>
<tr>
<td>Gain Length</td>
<td>3.7 meters</td>
</tr>
<tr>
<td>Electron Energy Loss</td>
<td>6.4 MeV</td>
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</tbody>
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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.
First, consider the field on an electron at the radial edge of a beamlet given by [5],

\[ E_r = \frac{\rho_l}{2\pi\varepsilon_0 r} \]  \[\text{(1)}\]

Here \( \rho_l \) 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

\[ E_r = \frac{8Qr_0^2}{\pi^2\varepsilon_0 R^2 l_b r} \]  \[\text{(2)}\]

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,

\[ \frac{p_r^2}{2m} = \frac{8Qe\varepsilon_0^2}{\pi^2\varepsilon_0 R^2 l_b} \ln a \]  \[\text{(3)}\]

Since the beamlets are identical and small compared to the 1.2 mm (4\( \sigma_r \)) 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,

\[ \varepsilon_n = \sigma_x \frac{\sqrt{\langle p_x^2 \rangle}}{mc}. \]  \[\text{(4)}\]

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

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

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.

+REFERENCES