

RF Design for the Linac Coherent Light Source (LCLS) Injector*

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Abstract

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Abstract

The Linac Coherent Light Source (LCLS) will be the world's first x-ray free electron laser, and the successful operation of this very short-wavelength FEL will require excellent beam quality from its electron source. Therefore a critical component is the RF photocathode injector. This paper describes the design issues of the LCLS RF gun and accelerator structures. The injector consists of a 1.6 cell s-band gun followed by two 3-meter SLAC sections. The gun and the first RF section will have dual RF feeds both to eliminate transverse RF kicks and to reduce the pulsed heating of the coupling ports. In addition, the input coupler cavities will be specially shaped to greatly reduce the RF quadrupole fields. RF designs for the gun and the first accelerator section are now complete. The work includes the gun's new dual coupler and full cell shape as well as the dimensions of the L0-1 dual RF feed and coupling cell. Engineering has begun on the L0-1 structure. These and other aspects of the gun and RF structure design will be discussed.

GENERAL DESCRIPTION OF THE INJECTOR

The Linac Coherent Light Source (LCLS) is a SASE free electron laser using the last 1/3 of the SLAC two mile linac to produce 1.5 to 15 angstrom x-rays in a 120 meter long undulator for use in a variety of x-ray science experiments[1]. In order to satisfy the demanding electron beam requirements, a new 135MeV photo-injector shown in Figure 1 will be built in an existing, off-axis vault at the 2/3 point of the main linac. The injector accelerator consists of a modified BNL/SLAC/UCLA 1.6 cell S-band gun followed by two 3-meter long SLAC accelerator sections. The 6MeV beam from the gun is matched into the first accelerator section and accelerated to 135MeV before injection onto the main linac axis with a 35degree bend [2]. Several modifications to the rf gun, linac and beamline as well as the inclusion of several diagnostics have been incorporated into the injector design to achieve the required 1.2micron projected and less than 1micron slice emittance at a charge of 1nC.

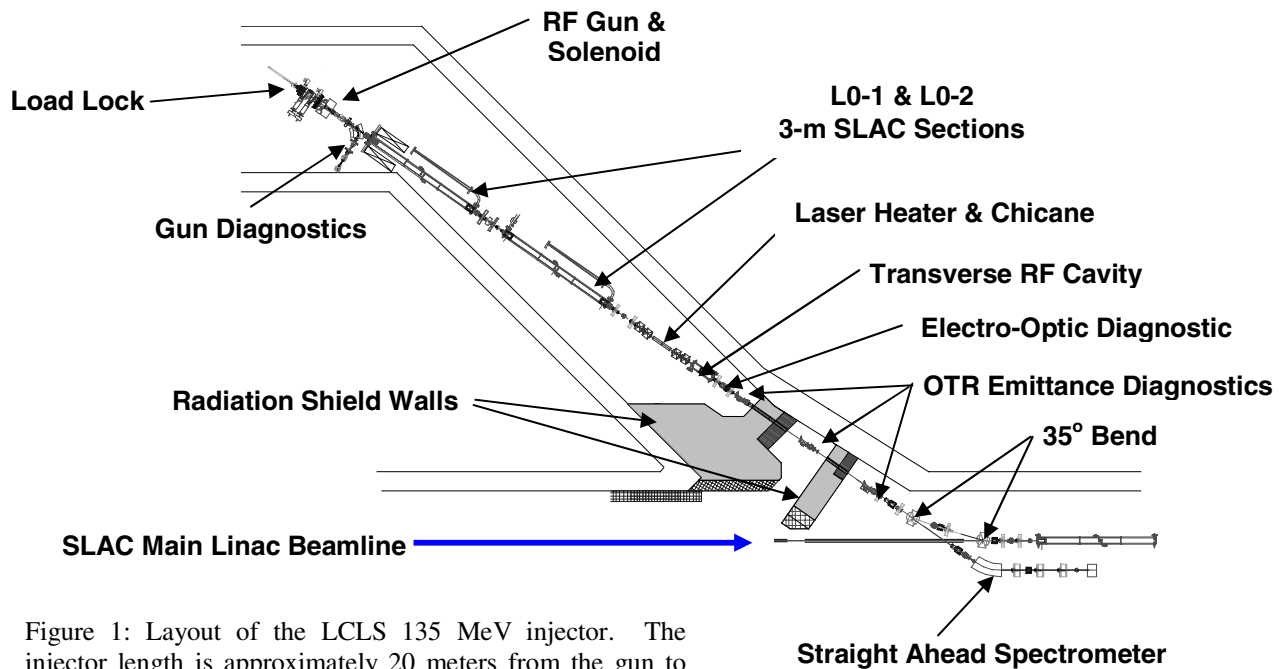


Figure 1: Layout of the LCLS 135 MeV injector. The injector length is approximately 20 meters from the gun to the straight ahead spectrometer.

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Recently an inverse free electron laser, e.g. laser heater [3], has been included in the injector to increase the uncorrelated energy spread which suppresses the coherent synchrotron radiation and longitudinal space charge instabilities in the main accelerator and bunch compressors [4].

This paper describes the RF design of the gun and accelerator structures.

RF GUN DESIGN ISSUES

The design of the BNL/SLAC/UCLA s-band gun is being studied to meet the demanding beam requirements for LCLS. In general, the issues can be divided into two types: thermal effects and RF field quality.

Gun Thermal Design

The need for 120 Hz operation of this gun necessitates a careful analysis of both the average and pulsed heating thermal effects. ANSYS modeling of the gun was done to obtain the average temperature and stress distributions at 120 Hz. The gun temperature distribution is shown in Figure 2 for the gun operating at 3.7kW of average power (120Hz, 3microsecond/pulse and 130MV/m peak cathode field).

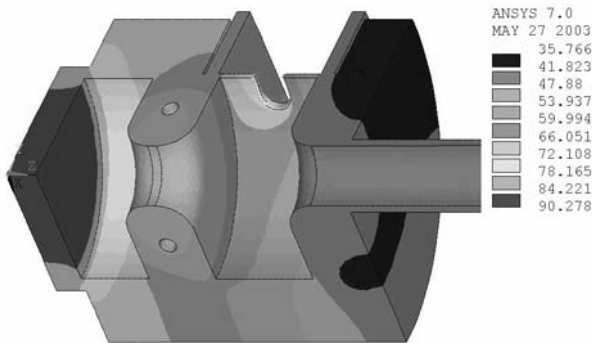


Figure 2: Equilibrium gun body temperature distribution of the BNL/SLAC/UCLA gun operating at 3.7kW of average power with an inlet water temperature of 20 degrees C and a flow velocity of 16 fps. The temperatures are given in degrees C.

The gun's bulk distortion between ambient and operating temperatures shown in Figure 2 shifts the pi-mode resonant frequency downward 1750 kHz. Additional cooling and adjusting the water temperature to keep the gun body temperature at 30 degrees C lowered the pi-mode shift to an acceptable 100 kHz. This was for 4 kW average RF power and 13.9 degrees C inlet water. [5] Therefore in the LCLS injector, the gun frequency will be kept constant by regulating the gun temperature via the cooling water.

The mechanical stress distribution due to the average thermal load is shown in Figure 3. The location of greatest stress is around the hole which couples the RF from the waveguide into the full cell. The maximum static stress here is 14 ksi, which far exceeds the accepted maximum of 3-5 ksi for brazed copper.[5] In addition,

this is also the location of the largest dynamic stress due to pulsed heating. The temperature rise per pulse is computed to be 137 degrees C for the original BNL/SLAC/UCLA gun.

Both the static and dynamic stresses around the coupling apertures are too large and would drastically shorten the gun lifetime at continuous 120Hz operation. Therefore a new coupling-hole was designed with a pulse temperature rise of 41 degrees C, well below 50 degrees C which is considered acceptable for the NLC x-band structures [6]. Further analysis is required to confirm the bulk stress is similarly reduced.

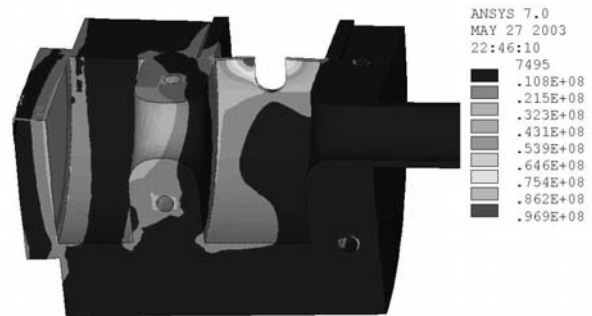


Figure 3: Mechanical stresses at 120 Hz operation. The von Mises stress is given in Pascals.

RF Gun Dual Feed and Racetrack Design

The electron source for the injector is the 1.6 cell, s-band gun which will be modified to have dual RF feeds and a racetrack shape for the full cell. The dual feed is motivated by the desire to reduce the time-dependent dipole field perturbation introduced by a single feed. In the conventional BNL/SLAC/UCLA gun, the dipole field from the single feed is compensated with another un-powered, symmetric port opposite the power feed. In addition, for the standard gun, the RF is coupled into the cell using θ -coupling which also reduces the dipole field [7]. However, even with the symmetric port and θ -coupling, there remains a dipole kick due to the power flowing into the cavity which dual feed eliminates.

Although the dual RF feed eliminates the dipole fields, it increases the full cell quadrupole field. To study this effect the 3-D fields were computed using the parallel code S3P developed by the Advanced Computation Department of SLAC. These fully 3-D fields were used to obtain the gun quadrupole strength as plotted in Figure 4. The original full cell cylindrical shape has a large quadrupole strength which for a normalized electron energy of 10 (5MeV) would have a quadrupole focal length of approximately 300 cm. Although this is 20-times weaker than the gun's strong focusing (focal length of approximately 15 cm) due to the rotationally symmetric radial fields at the ends of the cells, it generates an asymmetric beam and emittance growth.

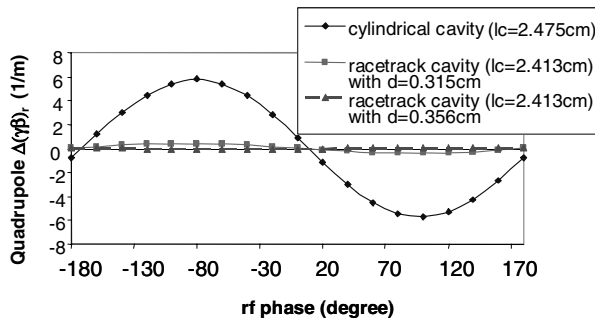


Figure 4: RF quadrupole kicks $(\gamma\beta)_r$ in the full cell with cylindrical and racetrack shapes.

In order to eliminate the quadrupole fields the full cell is made slightly elliptical with the long axis perpendicular to the dual feed axis. The ideal elliptical shape is well represented by offsetting two cylinders a distance d as shown in Figure 5. The cylinder offset distance d is adjusted to eliminate the quadrupole field.

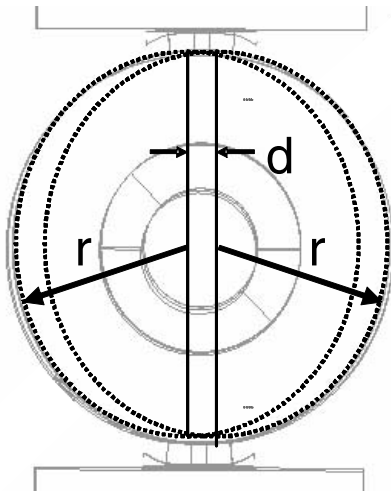


Figure 5: Racetrack shape of the full cell which cancels the quadrupole field of the dual RF coupling holes. The waveguide is above and below the cell. The optimal full cell dimensions are $r = 4.061\text{cm}$ cylinders offset a distance $d=0.340\text{cm}$.

Other Gun Field Quality Issues

In addition to rotational field asymmetries, there are also fields which depend upon the radius that are both chromatic and geometric. One chromatic effect is shown in Figure 6, where the difference between the off-axis and on-axis longitudinal fields is plotted vs. z for radii of 1, 3 and 5mm. This radial field dependence is significant, for example, integrating an electron from rest along a trajectory at $r=1\text{mm}$ has 2.7keV lower kinetic energy than the on axis electron. This energy spread contributes to the uncorrelated slice energy spread although initially it has a radius-energy correlation in the gun.

It is interesting to note that the measured uncorrelated energy spread is a few keV[8], suggesting that a significant portion of the uncorrelated energy spread is due to the radial-dependence of the RF field and not only to the space charge field.

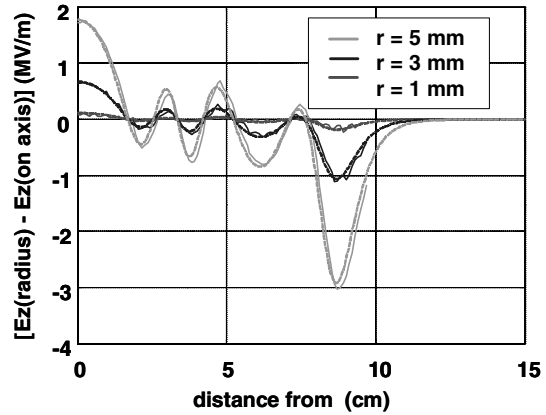


Figure 6: The difference of the off-axis and on-axis longitudinal electric field along lines of constant radii, $E_z(r,z) - E_z(r=0,z)$ for $R=1,3$ and 5 mm. Solid curves: S3P (3D), dashed curves: Superfish (2D).

The dependence of the radial electric field upon distance from the axis is shown in Figure 7. These radial fields have a linear dependence upon radius, indicating little spherical aberration.

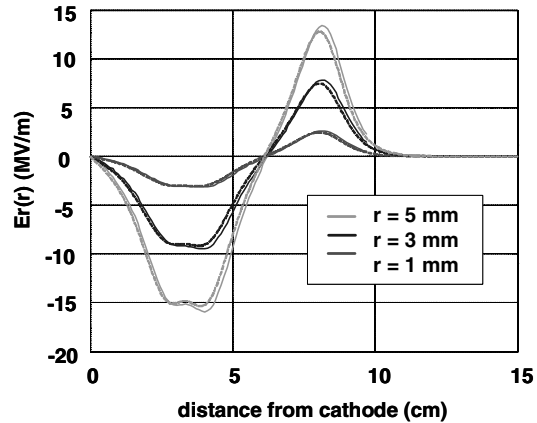


Figure 7: The radial electric field along lines of constant radii: 1, 3 and 5 mm. Solid curves: S3P (3D), dashed curves: Superfish (2D).

L0-1 STRUCTURE RF DESIGN

The 3-meter SLAC RF structures have known dipole fields in both the input and output coupler cells due to the single-side feeds. In the original design the coupler cells were offset transverse to the structure axis to compensate for the amplitude part of the field, however the phase or power flow term could not be canceled.[9] Our analysis for the LCLS injector shows the remaining dipole and quadrupole fields lead to unacceptable emittance growth. Therefore the coupler cell of L0-1 has been redesigned to have a dual feed and a racetrack shape as shown in Figure 8.[10]

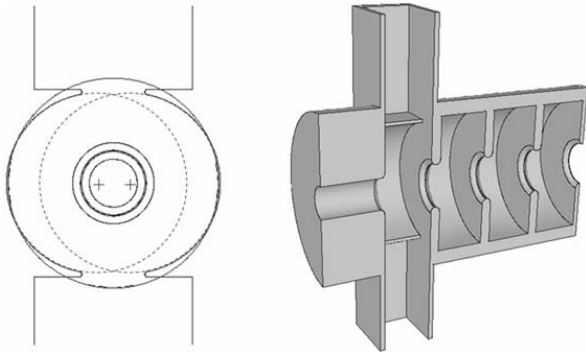


Figure 8: The L0-1 structure coupler cell with dual RF feed and racetrack shape. The optimal distance between the cylinder centers is 13 mm.

The integrated quadrupole kick as a function of RF phase (crest at 0 degrees) is given in Figure 9 for four coupler configurations. The original single feed and the cylindrical dual feeds both have approximately the same quadrupole kick. Both a cross dual feed and the racetrack shape are effective at canceling the quadrupole field. We have chosen the racetrack design for ease of fabrication and because it introduces no additional penetrations in the cell walls.

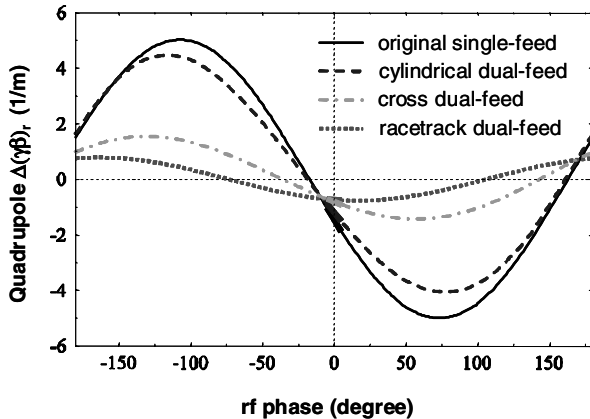


Figure 9: Change in transverse momentum as a function of RF phase for various coupler cell geometries.

It is useful to compare the angular kicks with the natural divergence of the beam. For an emittance of 1 micron, assume the beam is at a waist of radius 1 mm (rms). The beam divergence is then

$$\sigma_x = \frac{\epsilon_n}{\beta\gamma\sigma_x} = 100 \text{ micro-radians}$$

Table I gives the head-tail kick for a 10 degree (~10ps) long bunch traveling through the L0-1 input coupler cell. The head-tail angle for the original SLAC coupler is 78 micro-radians per mm. As this is nearly the same as the beam's natural divergence, the coupler field will increase the projected emittance. The racetrack dual feed quadrupole field is 20 times smaller, producing negligible emittance growth

Table I: Comparison of the original SLAC input coupler with three dual feed coupler designs. Quadrupole head-tail kick, $\Delta(\perp\beta\gamma)/m$, is given for a 10 degree bunch at 5MeV.

	$\Delta(\perp\beta\gamma)/m$	Head-tail angle $\Delta\theta$ (rad/m)
SLAC Single feed	0.78	0.078
Symmetric dual	0.63	0.063
Race-track dual	0.04	0.004
Cross Dual	0.20	0.020

SUMMARY AND CONCLUSIONS

A thermal analysis for the 120 Hz gun was performed and the region of greatest heating and stress was determined to be the RF coupling apertures in the full cell. New apertures were designed with thicker copper and larger radii to reduce the pulse temperature rise to 41 degrees C/pulse. This is considered acceptable based upon NLC structure studies. The bulk thermal distortions will be controlled by regulating the gun coolant to keep the gun body at a constant temperature.

The designs of the RF gun and first accelerator section were studied and found to have larger RF kicks than acceptable for LCLS beam requirements. The RF coupling cells for the gun and the L0-1 structure were redesigned to have both dual feeds and racetrack shapes. The dual feed eliminates the dipole fields and the racetrack shape cancels the quadrupole fields.

The RF design of L0-1 is finished and the engineering of the dual feed accelerator structure has begun. The gun design is nearing completion.

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