6.3 rf Photocathode Gun

The design of the LCLS rf photocathode gun is based on the 1.6 cell low-emittance S-band rf photocathode gun (hereafter called the “prototype gun”) that was designed by the BNL/SLAC/UCLA rf gun collaboration for x-ray FEL applications [2]. The parameters for this gun as applied to the LCLS are listed in Table 6.3-1. The prototype gun (BNL Gun III) is now installed at the Brookhaven Accelerator Test Facility (ATF). A modified version is installed at the Gun Test Facility (GTF) at SLAC. Initial measurements at BNL of the gun performance are very encouraging. (See Section 6.2, Summary of Experimental Results.)

Table 6.3-1. LCLS Photoinjector Gun Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cathode material</td>
<td>Cu (or possibly Mg)</td>
</tr>
<tr>
<td>Usable diameter of cathode</td>
<td>12 mm</td>
</tr>
<tr>
<td>Quantum efficiency</td>
<td>&gt;10^{-5} at 260 nm</td>
</tr>
<tr>
<td>Nominal extraction field</td>
<td>120 MV/m</td>
</tr>
<tr>
<td>Beam energy at gun exit</td>
<td>~5.8 MeV</td>
</tr>
<tr>
<td>Energy spread at gun exit</td>
<td>0.2% rms</td>
</tr>
<tr>
<td>rf frequency</td>
<td>2856 MHz</td>
</tr>
<tr>
<td>Bunch repetition rate</td>
<td>120 Hz</td>
</tr>
<tr>
<td>rf pulse duration</td>
<td>3–4 μsec</td>
</tr>
<tr>
<td>rf peak power</td>
<td>15 MW</td>
</tr>
<tr>
<td>Number of cells</td>
<td>1.6</td>
</tr>
<tr>
<td>Length</td>
<td>0.168 m</td>
</tr>
</tbody>
</table>

Definitions and clarifications. The term “rms” after units indicates a 1-σ value; “FWHM” is the full width at half maximum value; and “ptp” indicates the peak-to-peak variation. In this document, the laser is said to produce “pulses,” while the gun produces “bunches.”

The beam energy is quoted for 120 MV/m extraction field and initial phase of ~40° with respect to the rf zero crossing.

6.3.1 Gun Description

The 1.6 cell rf prototype gun design is based on the earlier 1.5 cell gun developed at BNL [20]. To minimize emittance growth due to the $E_z$ component of the TM$_{110}$ mode, the field amplitude in the gun was symmetrized. The original BNL zero-mode-suppressed side-coupling was
replaced. The rf power is now symmetrically coupled into the full cell only, which does not completely suppress the zero mode.

Since there is no direct rf coupling from the waveguide to the half cell, the cell-to-cell coupling between the two cells was improved by increasing the iris size, which also increased the mode separation between the zero- and \( \pi \)-modes. This arrangement allows for more precise field balancing during tuning. To provide more rf focusing and decrease the peak field on the cell-to-cell iris, the half-cell length was slightly increased.

A cross section of the rf prototype gun is shown in Fig. 6.3-1. The rf power is fed symmetrically into the full cell of the rf gun by means of a magic tee and two H bends. The photocathode is located in the geometric center of the end plate of the half-cell. The end plate is removable to facilitate installation of cathode material other than Cu by implantation or by using an insert. As with the original BNL gun, the laser beam can be brought to the cathode either along the axis of the gun or at a grazing incidence through the 72° side port (not shown in the figure).

![Figure 6.3-1](image)

**Figure 6.3-1.** Cross section of rf prototype gun. The rf coupler is the top coupler shown here. The bottom port is for the adjustable short and vacuum pump. The electron beam exits to the right.

Electric field maps for the gun were obtained with SUPERFISH. The \( \pi \)-mode fields are shown in Fig. 6.3-2.
6.3.2 Field Balance

Because of the deleterious effects of space charge on the beam emittance, it is important to accelerate the beam as rapidly as possible within the gun itself. Field balance tuning is accomplished using the observed mode separation measured during cold testing. Emittance versus field balance simulations using PARMELA indicate that there should be no detrimental effects in the photoinjector performance due to field imbalance in the rf gun up to the level of ±25% imbalance. Simulations also indicate that the transverse emittance decreases as the field increases until about 140 MV/m on the cathode surface, at which point a local minimum in the emittance versus solenoidal and cathode field strengths has been observed using PARMELA. See Fig. 6.3-3.

There has been no experience operating a prototype gun above 130 MV/m. However, at the GTF, using a Cu cathode, 120 MV/m has been a rather common operating field, and thus this value has been chosen for the LCLS design. From Fig. 6.3-3, it appears that an emittance reduction of no
more than a few percent could be expected if the technology could be pushed to allow 130 MV/m operation.

### 6.3.3 Symmetrization

The emittance growth due to multipole modes of \( E_z \) (dominated by the dipole mode) in a gun cavity with a conventional asymmetric rf coupler is estimated to contribute >1×10^-6 m to the transverse emittance [21].

The rf field symmetrization of the prototype rf gun will be improved by utilizing a magic tee along with two H bends that symmetrically feed rf power to the full cell of the LCLS 1.6-cell rf gun [22]. A diagnostics port in the magic tee will be provided to monitor rf power asymmetries. Note that during rf power cold tests of the fully symmetrized gun, care must be taken to prevent over coupling of the rf power in the gun. The prototype gun was designed to be slightly over coupled with rf power coupled-in only on one side of the full cell and rf power exponentially decaying in the symmetrizing port. The frequency suppression and rf coupling parameter will be effected by the magic tee and the symmetric rf power feeding of the full cell. Therefore, the prototype coupling hole size for the prototype gun cannot be used for the LCLS gun.

### 6.3.4 120 Hz Operation

The LCLS prototype gun was originally designed for low repetition rates but could be operated up to approximately 40 Hz. The stored energy in the cavity fields is 6.7 J for the LCLS design of 120 MV/m and assuming a \( Q_0 \) of 12000 and a critically coupled cavity as is typically used with the LCLS prototype rf photocathode gun. The LCLS gun requires 10 MW of power from the klystron and has a filling time of almost 700 ns resulting in an average heat load of 2.6 kW at 120 Hz. A slightly modified gun was designed and built by a BNL/KEK/SHI collaboration for operation up to 100 Hz. Thermal analysis showed the primary hot spots were located along the iris between the full and half-cell as well as the center of the cathode [23]. Thus water cooling channels were added in the vicinity of these locations and satisfactory operation at 100 MV/m with a 4 \( \mu \)s wide rf pulse at 50 Hz has been demonstrated at the University of Tokyo at Tokai [24]. At these operating conditions the gun is dissipating roughly 1 kW of power.

Thus, due to excessive heat loading, there is a possibility of damaging a prototype rf gun if it is operated at the desired LCLS 120 Hz repetition rate. There are at least two known solutions to this problem. The first method, already utilized by the BNL/KEK/SHI collaboratin, is to study the energy deposition in the rf gun and provide appropriate cooling at the necessary locations primarily by increasing the cooling channel size and pushing them closer to the iris and cathode surface without compromising structural integrity [23]. Alternatively the thermal load can be reduced by a factor of three to less than the 1 kW already in operation at the University of Tokyo by properly shaping the rf pulse [25]. Simply by using 20 MW of rf power instead of 10 MW to drive the gun, the rf field will build up to the desired value of 120 MV/m in only 800 ns instead of 3 \( \mu \)s with a corresponding reduction in the heat load. Once the desired accelerating voltage is
reached, a fast rf attenuator on the klystron input could be used to stabilize the voltage at the desired value during beam extraction.

6.3.5 Photocathode

The choice of cathode material is a function of several restrictions including gun emittance, laser feasibility, longevity under rf processing or operation and gun cavity construction. The use of a cathode plug or insert in an S-band gun has so far limited the cathode field to about 110 MV/m [26], whereas simulations indicate the transverse emittance drops with increasing field up to about 140 MV/m. However, a loadlock coupled gun which utilizes a back plane replaceable under vacuum should eliminate this restriction. Such a system allows greater flexibility of cathode choice and easy upgrades as improved materials are realized.

A metal photocathode is chosen for the preliminary configuration for several reasons. Since the source is not required to produce a bunch train (multiple microbunches within each pulse), the lower QE of metal cathodes compared to alkali and semiconductor photocathodes is not a major concern. The QE for Cu illuminated with UV light at normal incidence depends on surface preparation, but a QE of $10^{-5}$ at 260 nm in a non-loadlocked gun is achievable [27,28,29]. Much better QE is available from copper installed through a loadlock. (See Fig. 6.3-4.)

![Fig. 6.3-4. Copper QE as a function of wavelength measured with low (22 V) dc bias with the surface untreated after installation.](image)

A gain in QE by a factor of two to four can be achieved by illuminating the cathode at a grazing angle although this is primarily due to the increased absorption of $p$ over $s$ light [30]. At 260 nm, an optical pulse of $\sim500$ µJ on the cathode is required to produce 1 nC of charge when the QE is $10^{-5}$. A laser system to meet this requirement is relatively straightforward to design. (See Section 6.4, Laser System.)

At extremely high photon intensities, the metal surface will begin to disintegrate. Even with such disintegration, the QE of the cathode tends to remain high, presumably due to the
enhancement of field emission along the surface disruptions. However, a large and undesirable increase in dark current accompanies such a surface [31]. The intensities planned for the operation of the LCLS source are well below this regime.

The principal advantages of metal cathodes are that they are easy to fabricate and that the entire end plate of the half cell can be formed in the standard manner of Cu rf cavities, permitting operation at the highest field values. The photoelectric response time of metal cathodes is on the sub-picosecond level, thus imposing no limitation on any desired temporal pulse shaping.

The most recent measurements of QE for grazing incidence using the ATF rf gun gave a value of $4.4 \times 10^{-5}$ for Cu [32]. This value was obtained with a laser injection phase of 90° (where the zero-crossing is defined as 0°) and high gradient to maximize the Schottky effect. The QE for Mg—after careful rf-free laser cleaning—was found to be $5 \times 10^{-3}$ at 266 nm [33]. Since the QE of Mg cathodes is potentially higher than that for Cu for threshold emission, the search for a way to use a Mg cathode with fields on the order of 120 MV/m will continue although a complete spectral response curve is needed for near-threshold, i.e., low thermal emittance, emission for comparison with Cu before laser energy requirements could conceivably be amended.

The QE from a single-crystal $\text{Cu}_{100}$ photocathode was measured in a copy of the prototype gun at UCLA [13]. The QE was found to be $6.2 \times 10^{-5}$ for a field at the cathode at extraction of 90 MV/m. Preliminary results indicate that emission from the single-crystal Cu is quite a bit more uniform than from polycrystalline Cu.

### 6.3.6 Emittance Compensating Solenoid

For emittance compensation, a solenoid with precisely defined field symmetry and positioning will be used at the gun exit. An identical compensation magnet with current flow in the opposite sense will be used to null the magnetic field at the cathode.

The specific solenoid design incorporates several pancake assemblies, each assembly consisting of a pancake coil, a steel flux straightener, a steel flux return, an aluminum alignment tube, a coil spacer, a flux return to coil shim, a ceramic flux straightener spacer, a recessed ceramic yoke-to-flux straightener spacer, and a spacer and compression wave spring. Conventional manufacturing techniques using molded coils will not accommodate the required flux straightener position accuracy therefore the straighteners are positioned independently of the coil positioning. The axial positioning and stability requirement of ±25 µm is met by precisely locating the axis of each of the flux straighteners with respect to the yoke bore by the use of a precision ground aluminum tube. Alignment and survey fiducials will be pinned to the gun side of the steel flux return plate. Precision bronze bushings will be located on either side of the solenoid flux return bore axis. The entire solenoid assembly will be suspended off these two bushings in the solenoid flux return by steel pins. An additional pin in the bottom face of the solenoid gun plate will permit the kinematic location of the gun solenoid assembly. The solenoid will be
pinned to an aluminum cradle, which will be suspended off the floor by struts with thermal expansion coefficient matched to the gun and linac support system.

The physical length of the solenoid is 18.4 cm. A map of the axial magnetic field is shown in Fig. 6.3-5.

This figure is not yet ready.

Figure 6.3-5. Axial magnetic field of the emittance compensation solenoid as a function of distance s along the axis for an excitation current of 300 A.

6.3.7 Vacuum System

After brazing and before final tuning, the rf gun will undergo a 450°C vacuum bakeout in the SLAC Klystron Department's vacuum bakeout facility. This procedure removes excess hydrogen absorbed by the vacuum surfaces of the rf gun during brazing. Ion-NEG pumps (separate or combined) will be located in the rf waveguide near each of the two rf input couplers at the gun (the gun vacuum is separated by the rest of the rf waveguide by rf windows.) and also in the beamline just downstream of the emittance compensating solenoid. Small 20 l/s ion pumps will be used in the waveguide, while a large 220 l/s ion pump will be in the beamline. Together these pumps should provide a pressure of $\leq 5 \times 10^{-10}$ Torr at the gun with the field gradient at 120 MV/m and the rf at 120 Hz. The 220 l/s pump also maintains the vacuum in the diagnostic section following the gun.

A schematic of the gun assembly is shown in Fig. 6.3-6.
Figure 6.3-6. Schematic of gun assembly showing vacuum transfer apparatus for the cathode plug and the bucking coil. The gun is rotated to show the two 72° viewing ports.
6.4 Laser System

The laser system for the electron source is required to deliver a 500 μJ pulse of UV photons to the photocathode at a repetition rate of 120 Hz. To meet the emittance requirements of the source, the laser pulse must have an adjustable pulse length and temporal shape, nominally a flat pulse 10-ps long, and a uniform transverse profile with an adjustable radius, nominally a hard edge at 1.0 mm. Finally, stability is an important operational requirement, and, as discussed in Chapter 7, the timing stability in particular is crucial to meeting the longitudinal emittance requirements of the linac and bunch-compression system. Table 6.4-1 summarizes the laser’s design requirements.

Table 6.4-1. Laser system requirements

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating wavelength</td>
<td>260-280 nm</td>
</tr>
<tr>
<td>Pulse repetition rate</td>
<td>120 Hz</td>
</tr>
<tr>
<td>Number of micropulses per pulse</td>
<td>1</td>
</tr>
<tr>
<td>Pulse energy on cathode</td>
<td>&gt;500 μJ</td>
</tr>
<tr>
<td>Pulse diameter on cathode</td>
<td>2.0 mm FWHM</td>
</tr>
<tr>
<td>Pulse rise time (10-90%)</td>
<td>0.5 ps</td>
</tr>
<tr>
<td>Pulse length</td>
<td>10 ps FWHM</td>
</tr>
<tr>
<td>Longitudinal pulse shape</td>
<td>Various, but nominally uniform</td>
</tr>
<tr>
<td>Transverse pulse shape</td>
<td>Various, but nominally uniform</td>
</tr>
<tr>
<td>Homogeneity on cathode</td>
<td>10% ptp</td>
</tr>
<tr>
<td>Optical energy jitter (in UV)</td>
<td>≤2% rms</td>
</tr>
<tr>
<td>Laser-to-rf phase jitter</td>
<td>≤0.5 ps rms</td>
</tr>
<tr>
<td>Spot diameter jitter at cathode</td>
<td>1% ptp</td>
</tr>
<tr>
<td>Pointing stability</td>
<td>&lt;1% of radius rms</td>
</tr>
</tbody>
</table>

a Definitions and clarifications. The term “rms” after units indicates a 1-σ value; “FWHM” is the full width at half maximum value; and “ptp” indicates the peak-to-peak variation. In this document, the laser is said to produce “pulses,” while the gun produces “bunches.”

b The design will be for 18 mJ of IR energy just after the amplifiers, resulting in at least 500 μJ available at the cathode. For a QE of 10^{-5}, 500 μJ of excitation light at 260 nm at the cathode will produce 1 nC of charge.

c For a uniform, round, transverse cross section, the FWHM = σ(rms) d\sqrt{2π}. Thus a 2.0-mm FWHM section has a radius whose rms sigma is 0.84 mm.

d For a uniform longitudinal cross section, the FWHM = σ(rms)√2. Thus a 10-ps FWHM pulse has an rms sigma of 2.9 ps.
6.4.1 System Description

The titanium-sapphire laser system of Fig. 6.4-1 provides the ultraviolet light pulses for the rf gun. This system is first described briefly; subsequent sections then elaborate on various aspects of the design.

A CW, frequency-doubled, diode-pumped Nd:YAG laser provides highly stable energy in the green (532 nm) to pump the CW mode-locked Ti:sapphire oscillator, which then delivers a stable, continuous train of 12-nJ, 100-fs FWHM pulses that repeat at 79.33 MHz. This frequency, the 32nd subharmonic of the linac’s 2856-MHz rf, locks the timing of the laser pulses to the phase of the rf in the linac and rf gun (and also to lower frequencies used for SLAC timing). The wavelength is tuned to 780 nm, near the peak for Ti:sapphire output. This frequency is tripled to 260 nm after amplification to provide a suitable wavelength for the photocathode of the gun. With some reservations about timing stability (see below), oscillators of this type are commercially available (e.g., the Spectra-Physics Tsunami).

A Pockels cell and polarizer are used to gate single pulses, at 120 Hz, from the 79.33-MHz pulse train. The selected pulses are then amplified by two Ti:sapphire crystals, both configured as 4-pass “bow-tie” amplifiers [34]. Both are pumped by a pair of Q-switched, doubled Nd:YAG lasers that fire in alternation, each producing a 60-Hz train of 3 to 10-ns pulses. Again, we plan to use commercial lasers (such as Coherent’s Infinity or Spectra-Physics’ Quanta-Ray PRO) with an additional feedforward loop to decrease amplitude jitter; this is discussed later in the section on stability. Fourier-relay optics (described below), beginning with a primary aperture between the two amplifiers and continuing to the final optics platform next to the gun, are used to maintain a good transverse mode while efficiently filling the pumped volume of the Ti:sapphire crystals.

In amplifiers for picosecond and especially sub-picosecond pulses, the peak power must be limited to avoid optical damage and nonlinearities. Chirped pulse amplification [35] is used to reduce the peak power in the amplifier. The large bandwidth of the Ti:sapphire oscillator, which enables it to produce the 0.5-ps rise time we want for our shaped pulse, also lets us stretch the pulse to hundreds of picoseconds. In the dispersive region between a pair of gratings, different wavelengths take different optical paths. The resulting space, time, and wavelength correlations are then used to stretch the pulse. After amplification, the process can be reversed to compress the pulse to the original or any greater width. In addition, the oscillator’s large bandwidth allows us to shape the pulse in time by manipulating its Fourier transform under computer control (see below). Fig. 6.4-1 includes the pulse shaper and stretcher after the oscillator and a compressor after the amplifier. An additional low-power compressor after the oscillator is used as a diagnostic for the pulse shaper. It compresses the pulses from the 89-MHz train that are not selected by the Pockels-cell gate. A cross-correlator using a portion of the oscillator light can then probe the resulting pulse shape.
Figure 6.4-1. The drive laser for the rf photocathode electron gun for the LCLS. The thick lines show the main beam path, the closely spaced, dashed lines indicate diagnostic beams, and the widely spaced, dashed lines are pump beams.
After the second amplifier, the transverse shape of the pulse is modified from Gaussian to uniform to better match the requirements for obtaining a low emittance from the gun. Next, two crystals triple the frequency of the light to a wavelength of 260 nm. The flattened pulse also improves efficiency and uniformity in this harmonic-generation process.

Finally, the beam is transported through an evacuated tube to an optics platform next to the gun. Since the Fourier-relay image plane that follows the long transport tube has a spot size that is too small for the photocathode, we magnify the spot, imaging it onto a circular aperture that slightly trims the edge of the beam. This aperture is in turn imaged onto the photocathode, so that the illuminated region of the photocathode is precisely defined without jitter. The imaging includes compensation (discussed below) for the temporal and spatial distortion caused by grazing incidence on the photocathode.

The energy management of the laser system, also indicated in Fig. 6.4-1, is as follows: transmission through the spatial flattener ~50%, through the compressor ~50%, through the frequency tripling stage ~25%, and through the optical transport to the gun ~50%. Consequently, starting with 18 mJ after the second amplifier, the required 500 µJ is delivered to the cathode.

Fig. 6.4-2. The surface building alongside the Klystron Gallery at Sector 20 showing the layout of the laser clean room. The injector vault below is dashed in.
6.4.2 Temporal Pulse Shaping

The spatial and temporal shape of the optical (and thus also the electron) pulse is nominally Gaussian. Simulations indicate that an emittance-compensated beam at the exit of the injector will have a lower transverse emittance if uniform temporal and spatial distributions of charge are extracted at the photocathode. As we follow the beam through the linacs and compressors, present simulations indicate that the bunch length at the entrance to the undulator is more sensitive to timing jitter when the beam starts with a uniform rather than a Gaussian temporal shape. To permit the injector pulse shape to be optimized for the lowest possible emittance, a short X-band accelerating section is introduced just before BC1 to linearize the compression independently of the L0 pulse shape. (See Section 7.2.2, Parameters.) However, since an experimental variation of the pulse shape will be needed to establish the final optimized configuration, the capability to shape (including a uniform shape) the temporal profile of the laser pulse is built into the system.

Temporal shaping of the optical pulse will be accomplished through the well-established technique of frequency-domain pulse shaping [36], which takes advantage of the large bandwidth of ultrafast laser pulses. The bandwidth of a laser pulse is determined by the Fourier transform of its electric field,

$$E(\omega) = \int_{-\infty}^{\infty} dt E(t) e^{i\omega t}.$$  \hspace{1cm} (6.4-1)

For a laser pulse with an intensity envelope

$$I(t) = I_0 e^{-2 \left( \frac{t}{\tau} \right)^2},$$  \hspace{1cm} (6.4-2)

the power spectrum is

$$I(\omega) = I_0 e^{-2 \left( \frac{\omega - \omega_0}{\Delta \omega} \right)^2},$$  \hspace{1cm} (6.4-3)

where $\Delta \omega = 2/\tau$ is the bandwidth of the pulse. The shorter the pulse the larger the spectral bandwidth. The frequency spectrum is dispersed in space between a pair of diffraction gratings separated by a pair of lenses. Relay imaging between the gratings avoids introducing time dispersion in this section. Spatially resolved amplitude and phase masks at the dispersion plane modify the Fourier transform of the laser pulse and permit any pulse shape allowed by the bandwidth to be produced. In principle, we can make a square pulse with a rise time equal to the pulse duration of the original pulse. In Fig. 6.4-1, the gratings and masks for pulse shaping are located between the oscillator and the first amplifier stage. This arrangement reduces the possibility of damage to the pulse shaping optics. The pulse shape will subsequently be modified.

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by the gain properties of the amplifiers and the frequency conversion process. Thus, the Fourier transform produced by the masks and gratings must take these changes into account. To accomplish this, the amplitude and/or phase masks will be made with computer-addressable liquid-crystal optics [37]; linear liquid-crystal arrays designed for this purpose have become commercial [38]. Pulse-shape measurements then allow feedback on the mask configuration, modifying it to produce the desired shape. Thus, the effects of frequency conversion and gain shaping will be readily taken into account, and it will be relatively simple to change the pulse shape if another is found to be advantageous.

6.4.3 Fourier Relay Optics

A technique known as Fourier relay imaging combines relay imaging, in which lenses form an image of an initial aperture at each pass through a subsequent amplifier or harmonic-generation crystal, with the filtering of the beam's spatial Fourier transform. This approach can maintain a clean transverse mode and improve pointing stability, while also achieving better utilization of the pump energy. Initially, the oscillator beam is trimmed in an aperture. At each step a lens of focal length $f_1$ is placed a distance $f_1$ after one of the image planes. The Fourier transform is formed at the focus $f_1$ beyond the lens, where a pinhole removes higher spatial harmonics. A second lens with focal length $f_2$ then recollimates the beam (with magnification $f_2/f_1$) and forms the relay image at a distance $2(f_1 + f_2)$ from the previous image plane. Similar imaging takes place at the harmonic-generation crystals, and finally an image of the aperture is relayed to the photocathode to define the area of photoemission. The relay lenses and pinholes are indicated in Fig. 6.4-1.

6.4.4 Spatial Pulse Shaping

To shape the pulse in space, a position-dependent attenuation will be applied to the beam [39]. Relay imaging must be used after the flattening, to limit diffraction. Since repeated filtering of the spatial Fourier transform would limit the steepness of a flat-top output pulse, Fourier filtering is not incorporated in the imaging after the spatial shaper. Also, flattening is lossy, and so the system must have sufficient gain. On the other hand, harmonic generation can be more efficient with a uniform intensity across the beam.

6.4.5 Frequency Conversion

The 780-nm pulses will be frequency tripled to 260 nm in a pair of frequency conversion crystals using Type-II–Type-II tripling [40]. In this polarization-mismatch scheme, the beam is detuned from optimal conversion in the first crystal in order to allow efficient conversion to the third harmonic in the second. In Type II doubling, the beam is typically incident with a polarization angle of 45° with respect to the e- and o-axes. For polarization mismatch, the beam is polarized at 35° with respect to the o-axis, allowing approximately 50% conversion to the second harmonic. The unconverted fundamental beam is mixed with the converted beam in the second crystal. Frequency conversion efficiencies in excess of 50% to the third harmonic have been
measured with picosecond 1-µm laser pulses. We propose a pair of BBO crystals with phase matching angles of 42° and 54° respectively. The cautious energy estimates of Fig. 6.4-1 assume a day-to-day tripling efficiency of 25%, although twice this efficiency should be achievable.

In general, the intensity and wavelength dependence of frequency conversion can give rise to pulse distortion. However, frequency conversion will maintain the shape of our temporally and spatially uniform pulse (a cylindrical slug), and will allow us to optimize the conversion efficiency. The nonlinearity of the process will also sharpen the edges. On the other hand, an initial non-uniform shape will be distorted during conversion, and this must be accounted for in generating the input pulse shape. In addition, any structure on the pulse—ripples in time or space—can grow during the conversion process, again due to the nonlinearity [41]. This means that the constraints on the spatial and temporal uniformity before conversion will be more severe than those required at the photocathode.

6.4.6 Grazing Incidence

In the rf photocathode guns developed by the Brookhaven-SLAC-UCLA collaboration, the laser can be incident on the photocathode at either normal or near-grazing incidence (72° from the normal). Measurements at SLAC [42] using grazing incidence, in which the UV light was changed from \( p \)-polarized (electric field nearly normal to the surface) to \( s \)-polarized (\( E \) parallel to the surface), have shown 5 to 6 times more photoemission for \( p \). Part of this improvement, a factor of 2.5, is due to the lower reflectivity for \( p \); the balance is attributed to the Schottky effect. Since the reflectivity is intermediate for normal incidence, the emission should be about half when compared to grazing incidence with \( p \) polarization. Similar work at UCLA [43] showed the same effect, but with somewhat lower enhancement due perhaps to lower a rf field in the gun. An additional advantage of grazing incidence is that there is no need to insert a laser mirror directly downstream from the gun, right next to the electron-beam path, where it is a potential obstacle and a source of wakefields. The LCLS gun design allows either method.

However, grazing incidence introduces two geometric difficulties: a circular laser beam incident at a grazing angle illuminates an elliptical spot on the cathode; also, if the spot is millimeters across, the side closer to the laser entry will emit picoseconds earlier than the other side. Corrections for both of these effects are needed to minimize emittance. The elliptical spot is made circular in the last relay of the beam in Fig. 6.4-1, from the final image plane to the cathode. Here, the light reflects from a diffraction grating with a groove spacing and angle of incidence chosen to apply a compensating anamorphic magnification (different horizontally and vertically) and so illuminate a circular area.

A second constraint on the groove spacing and incidence angle provides a simultaneous correction of the time slew by adding a delay that varies across the beam (that is, by tilting the wavefront). By placing the grating in the beam near the final image plane, the time delay is correlated with the position across the cathode. Since gratings are lossy in the ultraviolet, care must be taken to make the beam size on the grating large enough to avoid damage.
6.4.7 Stability of Laser Pulse

Pulse-to-Pulse Timing

If the rms timing jitter of the electron bunch with respect to the rf driving the gun and linac is 1.4 ps measured over a few seconds at 120 Hz, then the energy of the beam in the undulator will vary by 0.1% rms. See Table 7.2-4. However, when all sources of energy jitter are taken into account, the rms timing jitter at L0 must be reduced to the order of 0.9 ps. See Table 7.2-5. A criterion of ≤0.5 ps rms has been adopted for the LCLS photoinjector laser system as indicated in Table 6.4-1.

Almost all of the laser system’s jitter originates in the oscillator. An rms jitter of ≤0.5 ps has been measured on advanced commercial oscillators, such as the Spectra-Physics Tsunami described earlier, or the Time-Bandwidth Products Nd:glass laser used at SLAC’s Gun Test Facility. However, while 0.5-ps performance has been measured, the manufacturers have not made this their standard specification; considerable care is necessary to maintain such performance. These lasers use sealed housings, mechanical stabilization of the optical platform inside, and precise electronics to lock the cavity length to an external rf reference. Careful attention must also be paid to isolating the housing thermally, mechanically, and acoustically on the optical table.

In order to assure both short- and long-term stability, the laser system presented here has its timing stabilized twice. The arrangement is illustrated in Fig. 6.4-3. The first technique is incorporated in the commercial oscillators we are considering. A measurement is made of the laser oscillator’s output phase with respect to rf from the accelerator’s main rf drive line. The phase-error signal, which is first low-pass filtered and then amplified, drives a piezoelectric translation stage holding the end mirror of the laser oscillator. The oscillator incorporates a passive mode-locker (using a Kerr lens or Fabry-Perot saturable absorber), while the length of the oscillator cavity, initially set up to match a subharmonic of the accelerating frequency, is continuously adjusted to lock the phase of subsequent laser pulses to the rf. The bandwidth of the method is estimated to be in the kilohertz range.

Outside the oscillator cavity, the timing is then corrected for long-term drift. A prism is mounted on a piezo stage with a fast motor to provide an optical-trombone delay for the laser pulses. As shown in the figure, this delay is controlled by a similar phase-error to that used for the stage inside the oscillator, but using 2856 MHz for greater sensitivity. It could additionally use the measured phase error of the pulses of electrons or ultraviolet with respect to the rf, as shown in the figure. Both the piezo and motor are computer controlled.
Fig. 6.4-3. Timing stabilization schematic.

**Pulse Duration**

Like timing jitter, the stability of the pulse duration is important for LCLS performance. The pulse duration should fluctuate by no more than the allowable timing jitter. A stable oscillator is again essential. If the bandwidth of the oscillator pulse is wider than that transmitted by the phase and amplitude masks used to shape the pulse in time, so that the masks are illuminated almost uniformly, then fluctuations in the oscillator width have little effect on the final pulse width or shape, which are determined only by the masks and the pulse compressor following the amplifiers.

**Optical Energy**

If the optical energy and thus the charge at the photocathode varies with an rms value of 6% over a period of a few seconds at 120 Hz, the contribution to the peak charge jitter in the undulator will be at the LCLS limit of 12%. See Table 7.2-4. However, when all sources of charge jitter are taken into account, the rms optical energy at the cathode is required to be ≤2%.
See Table 7.2-5. Thus a criterion of ≤2% rms (in the UV) has been adopted as indicated in Table 6.4-1. Harmonic generation compounds the difficulty of this criterion, since 2% stability in the third harmonic requires 0.7% stability in the fundamental. Because it is difficult for a Pockels cell to trim the amplitude of a broadband pulse without affecting its temporal shape, we stabilize the UV energy at the gun by using laser-diode pumping in the oscillator, by carefully controlling the beam mode and its pointing through the amplifiers through Fourier relay imaging, and by stabilizing the amplifier pumping with feedback.

The older generation of Ti:sapphire oscillators, both CW and mode locked, were pumped by green light from argon-ion lasers. In the newer generation, these have been replaced by diode-pumped, frequency-doubled Nd:YVO₄ lasers, which have far lower noise. With 10 W of green, the pumps from both Spectra-Physics (Millennia Xs) and Coherent (Verdi-V10) have a rated noise (above 10 Hz) below 0.04% rms. Most of this performance carries forward to the Ti:sapphire output, although there are some differences in how the manufacturers have tightened their specifications since moving to the new pumps. At our wavelength, we expect an output power of at least 1.2 W with rms noise of 0.1% or less.

To control the amplifier’s pumping, we take advantage of the relatively long upper-state lifetime of Ti:sapphire (3.2 µs, long compared to the few-nanosecond duration of the pump pulse) to hold the total pump energy constant on every pulse. The pump beam has an rms jitter of about 2.2% (for the Infinity delivering 200 mJ of green at 60 Hz) to 3% (for the Quanta-Ray, which can deliver more than 300 mJ and so provides some “headroom”). We pick off and delay 10% (or perhaps 15%) of this beam, enough to correct the jitter, by a 30 ns optical path. This delay gives time to adjust the high voltage on the Pockels-cell of Fig. 6.4-1. Based on a measurement of the energy in the pump pulse, we then add a portion (nominally half) of the delayed light back into the pump path, so that we can trim the pumping of the Ti:sapphire for each pulse by up to ±5%. The pump has a narrow bandwidth, unlike the temporally shaped Ti:sapphire beam, and so it is easily trimmed by the Pockels cell. We do not trim the full pump beam, because at 50% transmission a Pockels cell and polarizer is in the linear part of the control range, while at 95% the curve is flat and nonlinear; a much larger voltage swing would be needed to effect the same change.

To correct for long-term drift in the UV pulse energy as monitored at the gun, a slower software feedback loop will adjust the set point in the faster feedback loop that stabilizes the amplifier pump energy.

Spot Size and Position

To carefully and reproducibly control the distribution of space charge in the gun for optimal emittance, the laser must maintain a 1% variation in the diameter of the laser spot on the photocathode with a centroid location that varies by no more than 1% of the diameter. Position stability can be achieved by trimming the edge of the beam with a circular aperture placed on the final relay-image plane before the gun; this aperture is then imaged onto the photocathode. A
Gaussian beam could still have fluctuations in the position of its centroid within the aperture, but with the uniform pulse shape preferred for LCLS, pointing jitter does not cause any change in cathode illumination (as long as the full beam-trimming aperture is illuminated, despite the jitter).

6.4.8 Laser System Diagnostics

The laser system is designed with an integral diagnostic beam. (See Fig. 6.4-1.) This beam is used to monitor the shot-to-shot amplifier gain and also is used for diagnosing the temporal shape of the UV pulse heading toward the photocathode. To obtain the diagnostic beam (narrowly spaced dashed line in the figure), a Pockels cell and polarizer gate a second oscillator pulse that follows the primary pulse by tens of nanoseconds. The diagnostic pulse makes only one pass through each of the amplifiers. A photodiode measures its energy at each stage to check the gain. The unstretched (100 fs) diagnostic pulse is then cross correlated with the UV output pulse (3–10 ps) to measure the pulse shape.

Cross-correlation Pulse Shape

The advantage of using a diagnostic beam for a cross-correlation measurement of the UV pulse is that the diagnostic beam retains the original 100-fs duration of the seed beam and so provides a comparable temporal resolution. A cross-correlation provides more information than an autocorrelation because the latter cannot distinguish temporal asymmetries. The diagnostic pulse will be chosen to arrive at a cross-correlator at the same time as a fraction of the primary pulse picked off by a beam splitter. There are a number of techniques for measuring the cross-correlation of an infrared and UV pulse. It is anticipated that a single-shot polarization-gating cross-correlator [44] will be used. This will generate a third-order intensity cross-correlation of the 100-fs, 780-nm IR pulse and the 10-ps UV pulse. If the IR pulse is used as the gating pulse, the measured pulse shape is that of the UV pulse with a temporal resolution of approximately 100 fs. The two pulses are incident nearly collinearly on a nonlinear optic. The UV pulse to be detected is incident on a spatially resolving detector through crossed polarizers. In the absence of a gating pulse, no UV light is detected. Between the polarizers there is a Kerr medium, such as a thin piece of fused silica. When the gate pulse is incident on the Kerr medium, it acts as in instantaneous waveplate, which allows the portion of the UV pulse passing through the same space-time location to pass through the crossed polarizers and be detected. By choosing the crossing angle, detector and crystal size, and appropriate probe-beam energy, the pulse duration can be measured with a resolution approaching the 100-fs duration of the gate pulse. In addition, by following the cross-correlator with a spectrometer, we gain frequency resolution. This FROG (frequency-resolved optical gating) technique [45] allows us to determine both the temporal and phase profiles of the beam.

The effect of the pulse shaping on the low-energy IR pulse will also be measured using cross-correlation. In this case, all of the pulses (other than the pulse selected for amplification) from the 79.33-MHz train leaving the shaper and stretcher are selected. After recompression, their shape is measured in the cross-correlator shown in the low-energy area of Fig. 6.4-1. The gating pulse
comes from the diagnostic beam picked off before the shaper and stretcher. Again, we make use of all of the 79.33-MHz train except for the diagnostic pulse. Because both beams entering this cross-correlator are trains (except for the 120 pulses per second selected by the Pockels cells), it can use a simpler swept time delay to scan the overlap of the pulse trains, rather than the single-shot approach of the output cross-correlator, where different time delays occur at different spatial locations.

**Energy**

The energy will be monitored using joulemeter probes in combination with calibrated pick-offs at several points in the system: after each amplifier stage, after each harmonic conversion, and just before the beam enters the rf gun’s vacuum to strike the photocathode. These checks allow simple monitoring of amplifier and harmonic-generation efficiency. Photodiodes will be used at other points where the pulse energy will be low.

**Spatial Shape**

The spatial shape of the beam on the photocathode can be monitored by picking off a fraction of the beam near the window leading into the gun. A CCD (without the usual protective glass cover, since it would block the UV laser light), placed at the pick-off image plane (optically the same distance away as the cathode but physically located outside the high-radiation area using an imaging fiber optic relay) and at the same angle to the beam as the cathode surface, would then image the beam spot. Typical CCDs are 4 to 9 mm wide, a good match for the spot needed on the cathode. For a grazing angle on the cathode, it is preferable to get a CCD on a printed circuit board rather than in a camera body since the body blocks the correct angle. Alternatively, the UV could be incident on a fluorescing surface at the correct angle, and a CCD camera could record the visible glow; however, the response may be somewhat less uniform than that of a direct hit on the CCD. Other CCDs check the beam’s transverse mode after each amplifier and at each harmonic-generation step.

**Stability of Spot Centroid**

The same camera at the gun can measure the stability of the spot centroid on the photocathode. A computer with a digital frame grabber can record the video image, calculate the centroid location, and keep statistics on its stability. For each laser pulse, the centroid can be calculated to better than one pixel, which is typically 8 to 13 $\mu$m, about 1% of the typical 0.9-mm beam radius. The mean and standard deviation can be calculated with even higher accuracy.

**Timing Jitter**

Most of the timing jitter is introduced in the laser oscillator. To measure it, some light is picked off with a fast photodiode just after the oscillator, as shown in Fig. 6.4-3. Such diodes are available with rise times down to 7 ps. Time-domain measurements, using an equivalent-time sampling oscilloscope triggered by the rf of the gun, are limited to 2–3 ps resolution. In the frequency domain, the same photodiode pulse can be the input to a spectrum analyzer. The timing jitter can be determined from the differences of this spectrum at high and low harmonics using
well known techniques [46]. Finally one can mix this diode signal with rf (as already done for the piezo controlling the oscillator’s end mirror). The phase error (DC) can then be measured with an ordinary oscilloscope, studied in a spectrum analyzer to identify possible noise sources with narrow frequencies, and ultimately recorded by the accelerator control system.

A measurement of the laser pulse jitter with respect to the arrival of the electron beam itself is also possible at a BPM or resonant cavity in the beam-line near the gun exit. In a similar fashion the timing jitter of the electron beam itself with the rf can be also estimated as shown in Fig. 6.4-3.
References


[21] D.T. Palmer et al., in Proc. of the 1995 Particle Accelerator Conf. (1995), p. 982. In this reference it is pointed out that the dipole emittance term has been suppressed by an order of magnitude to the level of $0.1 \times 10^{-6}$ m, implying that in the unsymmetrized case the dipole emittance term would be $1 \times 10^{-6}$ m. See also B. Dwersteg et al., “rf gun design for the TESLA VUV free electron laser,” Nucl. Instrum. and Meth. A 393 (1997) 93.


[24] M. Uesaka (U. Tokyo) and M. Kando (JAERI Advanced Photon Research Center), private communication (11/00).


[33] X.-J. Wang et al., “FEL technologies R&D and SASE gain enhancement observation at the BNL ATF,” to be published in the proceedings of the 7th European Particle Accelerator Conference, Vienna, Austria, June 26-30, 2000. Note that the work function for Mg is about 1 eV lower than that for Cu. Thus for excitation at 266 nm, the thermal emittance for Mg may be significantly higher than for Cu.

[34] The gain per pass in Ti:sapphire amplifiers is sufficient to get from 1 nJ to a few mJ in eight (8) passes. For example, see S. Backus et al., Opt. Lett. 20 (1995) 2000.


[38] ShapeShifter spatial light modulator, Meadowlark Optics, Frederick, CO.


[41] For ultrafast laser pulses, the effects of group velocity walkoff and nonlinear phase effects must be considered when designing the conversion stage.


