7.1 Radio Frequency Systems

The installed complement of S-band klystrons in the SLAC linac, from sector-21 through sector-30, are capable of accelerating the LCLS beam to the required energy of 14.35 GeV. This includes 6% overhead to allow for klystron failures and maintenance. Precise control of rf phase and amplitude is required to manipulate the longitudinal phase space of the beam to produce the desired short bunch at the end of the linac. Specifically, the linac rf is used to introduce \( f_z \) correlations for bunch compression and to compensate for wakefields generated by the accelerating structures. This process is supplemented with an additional, higher-harmonic X-band accelerating structure installed ahead of the first bunch compressor. The success of the bunch compression and wakefield compensation schemes requires very tight tolerances for phase and amplitude control of the linac, as described earlier in this chapter.

The jitter tolerance specifies the pulse-to-pulse variation that is acceptable in the linac phase and amplitude parameters and still maintains the desired peak current and energy at the entrance to the undulator. Pulse-to-pulse random variations cannot be corrected by feedback and therefore place upper limits on the phase and amplitude noise level of individual components such as klystrons. Longer-term drifts, ranging from several seconds to several hours, can be corrected by feedback systems. It is assumed that beam-based diagnostics of relative bunch length and relative energy will be developed with sufficient accuracy to provide feedback for the rf phase and amplitude to control variations slower than \( \approx 0.5 \) Hz.

Some modifications and improvements to the SLAC linac rf system are necessary to meet the tighter tolerances for LCLS operation. The changes must remain compatible with the other SLAC linac functions, chief among which is its role as the injector for the PEP II B-Factory. The rf controls and timing system must coexist with the PEP II injection cycles as well as allow the linac to be switched back to alternate beams for end-station experiments.

Although beam-based feedback will be the final mechanism to stabilize rf phase and amplitude, there are several reasons for keeping the low level rf distribution system as stable as possible. Some development work on feedback tuning algorithms is to be expected before subsystems can be cascaded together. Any extension in the duration over which the beam remains stable and within tolerance makes the task of tuning easier, both during the period of commissioning the accelerator and subsequent operation.

7.1.1 RF Distribution in the Injector and Linac

The major components of the rf system, starting with the gun laser, through the linac and bunch compressors, are shown schematically in Figure 7.1-1. The laser is included in this description since the laser oscillator mode-lock frequency and timing stability are critical to the layout of the low-level rf systems and the phase stability of the beam. Figure 7.1-1 shows that there is some rearrangement of the klystrons as a result of the LCLS installation in the SLAC linac, but no new S-band klystron stations, with their associated modulators need be added.
This assumes that two of the present klystrons in sector-20, downstream of the positron production area used by PEP II, can be used to power the LCLS injector instead. The loss of a total of three klystrons, plus various section modifications as described in Error! Reference source not found., still allows alternate beams to run through the linac for end-station experiments. The only impact is a slightly reduced (~2%) voltage overhead for such beams.

![INSTALLED KLYSTRON COMPLEMENT](image)

**Figure 7.1-1.** Allocation of major components of the LCLS rf system.

The rf-gun and each of the two booster accelerating sections in the L0 linac are powered by individual klystrons. This is to allow vernier control of the phase and amplitude of the individual sections, which is necessary for both diagnosing and optimizing the performance of the injector at different bunch charges. A single klystron is sufficient to provide power to these sections, but this requires high-power phase shifters and attenuators to be used. Individual klystrons allow the phase and amplitude to be controlled at low power levels, with existing technology, where electronically controlled devices can provide the necessary fine resolution, pulse-to-pulse response, and reproducibility.

The L1 accelerator is made up of three SLAC accelerating sections powered by one klystron. A standard SLAC accelerating section consists of four 3-meter long structures with power divided equally from one klystron. In L1, the first two sections are shortened by 20 cm to accommodate extra quadrupole/corrector/BPM packages, and the power is divided to give 50% in the first structure and 25% in the other two. The higher gradient in the first structure is slightly advantageous from a beam dynamics point of view.

A short section of X-band accelerating operating at 11.424 GHz structure provides 4th harmonic corrections to the energy profile of the bunch before it passes through the first bunch compressor chicane. The section requires a modest power source to operate at 37 MV/m over a length of 0.6 m to generate the needed 22 MV of X-band rf.

The klystrons in the injector and L1 must operate unsaturated to provide for feedback control of the amplitude. A typical operating point would be 5% below the maximum power output of the klystron to allow enough overhead for feedback operation.
The L2 accelerating sections are powered by 26 klystrons plus 2 in standby as maintenance spares. The majority of these klystrons can be operated in saturation, with no amplitude control, and having global phase control. Two klystrons near the end of L2 will be operated unsaturated to provide for feedback control of the amplitude. Only one of these two klystrons will be in ‘feedback’ mode at any one time, with the other reserved as a spare, or as a standard saturated klystron. The feedback klystron will have its phase on-crest to decouple phase and amplitude control. The average phase of L2 will be controlled by feedback adjustment of the phase of the last full sector in L2 (sector-23). This provides a finer resolution control of the average phase with only one of the four sectors varied and yet provides adequate dynamic range. Using the last sector will have the least impact on the energy profile and hence the focusing lattice in L2.

The L3 accelerating section is powered by 45 klystrons plus 3 klystrons in standby as maintenance spares. The majority of these klystrons can be operated in saturation, with no amplitude control, and having global phase control. Two klystrons near the end of L3 will also operate in unsaturated mode to provide for feedback control of the amplitude. The phase for the entire L3 linac will also be controlled by feedback using two or more sectors of L3.

An additional S-band klystron running unsaturated, with independent amplitude and phase control, will power the rf deflecting structure at the 25-5A location in the L3 linac.

7.1.2 Layout and Performance of the Present SLAC Linac RF

The SLAC linac is divided into 30 sectors, of which the LCLS will utilize sectors 21 through 30. The rf distribution for two adjacent, nominal sectors is shown in Figure 7.1-2, showing how the rf power is derived for each sector and distributed to each of the eight klystrons in the sector. A 476-MHz master oscillator located in sector-0 of the linac transmits low-level power along a phase stabilized Main Drive Line (MDL). An interferometer controls the overall phase length of the MDL to compensate for temperature related diurnal phase variations, an example of which is shown in Figure 7.1-3. At each sector boundary a ×6-multiplier is coupled to the MDL and provides 2856-MHz power for the sector phase reference line and the sub-booster driving 8 klystrons. The sector drive line and the Phase Reference Line (PRL) run the length of one sector and are temperature stabilized over most (but not all) of their length. A ‘head-tail’ phase detector monitors the phase error between adjacent sectors. Phase errors of the order of several degrees between adjacent sectors are typical in the present distribution system, as shown in Figure 7.1-4, and are the result of imperfect compensation of temperature discrepancies and other various sources.
Figure 7.1-2.  Schematic of two adjacent nominal sectors showing distribution of rf power to the klystrons.

Figure 7.1-3  Measurement of phase variations seen along the linac main drive line over a period of several days.
Figure 7.1-4. Measurement of the phase variations between two adjacent linac sectors over a period of several days.

The control loops for each klystron are shown in greater detail in Figure 7.1-5. The phase variation measured locally at individual klystrons is less pronounced than the errors for the sector drive line.

Figure 7.1-5 Drive power and control loops for a typical linac klystron.
Measurements at the Phase and Amplitude Detector (PAD), in Figure 7.1-6, show typically less than 1° S-band rms phase variation over several minutes. On a 17-second time scale, the pulse-to-pulse phase variation of a single klystron measured at its PAD, shown in Figure 7.1-7, is stable to within 0.07° rms. This data is typical of a sample of 73 operating klystrons that were scanned during a period when the outside temperature was stable. The pulse-to-pulse amplitude stability over 2 seconds is 0.06% rms, measured at the PAD, as shown in Figure 7.1-8.
Analysis of the performance of the present linac shows that individual SLAC klystrons, selected for superior stability, can meet LCLS pulse-to-pulse jitter tolerances over a short (~2 second) time scale. Some improvements are planned for the rf distribution and control system. These will facilitate beam-based feedback control to be applied to the LCLS linac sections. Individual phase and amplitude control of individual klystrons will be implemented for parts of the linac as well as global sector controls. The phase gymnastics for PEP II injection need to be decoupled from the LCLS rf distribution while preserving compatibility with the present timing control system. These changes are described in the following section.

### 7.1.3 Improvements to the RF System

Improvements are being planned for the SLAC linac rf and control systems and should be implemented before LCLS commissioning. The requirements of the subsystems and individual components are reviewed in this section in order that the rf system as whole can function within the tolerance specifications for the LCLS, as opposed to the isolated performance of single klystrons. The reliability of the components is also considered here, since the operating criteria for acceptable noise or drift of components becomes much narrower for LCLS than it has been in the past.

**Sub-boosters**

The present linac uses one klystron sub-booster per sector to provide 60 kW of drive power divided into 8 klystrons. Low power phase control is therefore only done at the input side to the sub-booster klystron and hence changes the phase of all 8 klystrons. The high power mechanical phase shifters on the individual klystrons are only capable of coarser, 0.125° steps. Also they were not designed for pulse-to-pulse operation, typically making a few tens of phase correction per day in present linac operation. For comparison, the low-power phase shifter at
the input to the sub-booster klystron is electronically controlled and its resolution is within the required tolerances.

The three klystrons in the injector, the L1-linac klystron, and the four feedback control klystrons in the L2 and L3 linacs, as well as the special X-band and rf deflector klystrons, will require individual sub-boosters. This allows low-power phase shifters to be used at each individual klystron, on the input side to its sub-booster, to enable the necessary pulse-to-pulse fine resolution phase control.

The power requirement for individual sub-boosters can be met with solid-state amplifiers. These solid-state-sub-boosters (SSSBs) have the additional advantages of lower noise level and greater reliability than the present klystron sub-boosters.

**Phase and Amplitude Control Units**

Klystrons that are equipped with the new SSSBs and low-power phase shifters will require some revisions to their control systems, as shown in Figure 7.1-9. The existing Phase and Amplitude Detecting units (PADs) meet the LCLS specifications.

![Control system components at each klystron station.](image)

The Isolator-Phase-shifter-Attenuator chassis (IPA) contains the high-power mechanical phase shifter. The new SSSB will have an integral low power phase shifter and high power attenuator, both of which will be capable of pulse-to-pulse corrections. In these stations the IPA chassis will no longer be required.
The Modulator-Klystron Support Unit (MKSU), which contains the drive hardware for the IPA, will need to be modified to accommodate the additional drivers for a low-power phase shifter and high power attenuator.

A new Parallel Input/Output Processor (PIOP) for the CAMAC control of the MKSU will be designed to accommodate the higher resolution and characteristics of the low-power phase shifter. The new PIOP will also incorporate software to allow for pulse-to-pulse feedback and more diagnostics. The existing PIOP is based on obsolete hardware and cannot be upgraded without extensive redesign work.

**Master Oscillator**

The present Main Drive Line (MDL) transmits 476 MHz along the linac from sector-0 where it is derived from an 8.5-MHz clock frequency. The 8.5-MHz coincides with the revolution frequency of the Damping Rings. The frequency shifts on the MDL for the purposes of PEP II injection are not compatible with the fixed frequency, mode-locked laser of the LCLS photoinjector.

A second master oscillator will instead be housed at the LCLS injector, as shown in Figure 7.1-10. This new master oscillator will be phase locked to the MDL to allow for straight ahead beams being run down the LCLS portion of the linac for end station experiments. The master oscillator will be based on an ovenized crystal oscillator VCO. The crystal frequency will be chosen to be compatible with the mode-lock frequency of the laser and be a sub-harmonic of 2856 MHz.

![Figure 7.1-10. Timing and rf distribution in sector-0 and sector-20 of the linac.](image)

The mode-lock frequency of the laser should be as close as possible to 80 MHz, plus or minus one or two MHz deviation at most. This is dictated by the operating range of commercially available lasers that have the best stability properties at the desired wavelength and power for LCLS operation. Our present conceptual design uses 79.33 MHz for the mode-lock frequency, which is the 36th sub-harmonic of 2856 MHz.
For comparison, the Damping Ring 8.5-MHz revolution frequency is the 336th sub-
harmonic of 2856-MHz. The sector-0 master oscillator VCO and the LCLS VCO frequencies
are therefore in the ratio of 6:7.

For instrumentation and diagnostics associated with the laser it is convenient to have a
phase-locked reference signal close in frequency to 10 MHz. The crystal for the VCO will
therefore either be tuned to 9.916 MHz and use a ×8-multiplier to obtain the 79.33 MHz, or the
crystal will operate at 79.33 MHz and a ÷ 8-module will supply the diagnostic reference signal.

The gun, the L0, and the L1 klystrons are all located very close to the LCLS master
oscillator and will use this stable 2856-MHz reference as their drive signal. These are the
systems with the most stringent phase tolerances and so will share a single, local phase
reference.

**Timing System**

The present linac timing system is based on 360-Hz fiducials superimposed on the 476-
MHz MDL frequency. Its purpose is to synchronize the beam at the damping ring’s 8.5-MHz
revolution frequency, and hence the 2856 MHz in the linac, with the phase zero-crossing of the
360 Hz power grid. This feature is to be preserved in the LCLS linac because of shared
hardware with the PEP II system.

In order for the LCLS to operate, the fiducial generator must also supply pulses that are
synchronized to the zero crossing of the 79.33 MHz laser mode-lock frequency. This requires a
new 79.33 MHz connection from the LCLS VCO to the fiducial generator at the sector-0
master oscillator.

The linac can operate at a maximum of 120 Hz repetition rate, so there are 3 possible “time
slots” for it to be synchronized to within the 360-Hz line power cycle. The LCLS beam can
therefore run on a different time slot from the PEP II beam. Beam codes in the timing system
will allow PEP II beams to be read out on one time slot and LCLS beams on another. This will
allow the same control system hardware, such as the micro-processors, BPMs, etc., to be
shared between PEP II and LCLS.

**Synchronization Pulses for Experiments**

As indicated in Fig. 7.7-10, a new 2856-MHz phase reference line is planned to provide the
LCLS scientific experiments with synchronization pulses. It will take advantage of fiber optic
technology to avoid attenuation over the longer distance. Furthermore, only a single fiber is
required along the length of the linac, without multiple receivers or couplers enroute. A
distribution system for the synchronization pulses is planned in the experimental halls.

**Beam Diagnostics**

Our assumption is that measurements of relative bunch length at 1-10 Hz will become
available for feedback control of the rf phase. These will be based on CSR detectors and/or
cavity spectral power monitors. These are less well developed than diagnostics for beam energy
using BPMs. The bunch length monitors will be calibrated against the absolute bunch length measurement from the rf deflecting cavity and the zero-phasing technique (see Section Error! Reference source not found.).

Direct measurement of the beam phase with respect to the linac rf would be desirable from the point of view of feedback control. However, the thermal sources of phase drift that need to be compensated in the rf distribution system are equally likely to disturb the phase measurement at the 0.1° S-band level required here. A technique of measuring the phase of the beam-induced signal in the accelerating structures relative to the drive rf will be further studied. One accelerating structure per klystron is typically equipped with an output coupler on its load, where such measurements can be made. It is not clear whether the signal measured at just one structure is representative of the average phase of all four structures driven by the same klystron. Each sector is also equipped with a S-band beam phase monitor that can also provide some information of the average beam phase with respect to that sector. Both these techniques will be studied as future options for phase monitoring and control. This may be a suitable technique for long-term phase control at the 1-deg level in the L3-linac where, with no following bunch compressor, there are no other phase diagnostics.

Reliability

Critical klystrons at the gun, L0 and L1 linacs need to be specifically chosen from the complement of SLAC klystrons in order to meet the stability requirements. This sorting technique is presently used in the existing SLAC linac for critical locations in the particle sources and bunch compressors.