Investigation of Beam Alignment Monitor Technologies for the LCLS FEL Undulator†

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Abstract. To maintain gain in the proposed 100 m long linac-driven Linac Coherent Light Source (LCLS) Free Electron Laser (FEL) undulator, the electron and photon beams must propagate colinearly to within ~5 μm rms over distances comparable to the 11.7 m FEL gain length in the 6 mm diameter undulator vacuum chamber. We have considered a variety of intercepting and non-intercepting position monitor technologies to establish and maintain this beam alignment. We present a summary discussion of the applicability and estimated performance of monitors detecting synchrotron radiation, transition and diffraction radiation, fluorescence, photoemission or bremsstrahlung from thin wires, Compton scattering from laser beams, and image currents from the electron beam. We conclude that: 1) non-intercepting rf cavity electron BPMs, together with a beam-based alignment system, are best suited for this application; and 2) insertable, intercepting wire monitors are valuable for rough alignment, for beam size measurements, and for simultaneous measurement of electron and photon beam position by detecting bremsstrahlung from electrons and diffracted x-rays from the photon beam.

INTRODUCTION

The Linac Coherent Light Source (LCLS) will produce intense pulses of coherent x-rays in the 15–1.5 Å range generated by self-amplified spontaneous emission (SASE) from a 4.5–14.4 GeV single-bunch electron beam passing through a 100 m long undulator (1). The pulse repetition rate is 10–120 Hz. LCLS parameters are given in Table 1.

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TABLE 1. LCLS Electron and Photon Beam Parameters

Electron Energy	4.5 GeV	14.4 GeV
Emittance (normal)	2 π mm-mrad	1.5 π mm-mrad
Charge/bunch	1 nC	1 nC
Peak current:	3400 A pk	3400 A pk
Bunches/pulse	1	1
Pulse rep rate	10-120 Hz	10-120 Hz
Bunch radius:	37 μm rms	31 μm rms
Bunch divergence	6.1 μrad	1.7 μrad
Bunch length	20 μm rms	20 μm rms
Photon 1st harmonic	15 Å (0.82 keV)	1.5 Å (8.2 keV)
FEL gain length	3.7 m	11.7 m
FEL peak pwr/pulse	11 GW	9 GW
FEL avg pwr	0.36 W	0.51 W
FEL beam radius	37 μm rms	31 μm rms
FEL divergence	3.2 μrad rms	0.38 μrad rms
FEL peak brightness	1.2×10^{32}	12×10^{32}
FEL avg brightness	0.42×10^{22}	4.2×10^{22}
Spontan.peak pwr/pulse	8.1 GW	81 GW
Spontan. avg pwr	0.27 W	2.7 W
Spontan. beam radius	52 μm rms	33 μm rms
Spontan. beam diverge	6.2 μrad rms	2 μrad rms
Spontan. critical energy	22 keV	200 keV

The undulator has 52 segments, each 1.92 m long, separated by 0.24 m gaps containing vacuum pumps, quadrupoles, and diagnostics (Figure 1). Quadrupoles are equipped with precision transverse movers that are used for beam steering. The undulator gap is 6 mm, and the vacuum chamber within has a 5 mm ID. This chamber dimension will be preserved as much as possible in the gaps between undulator segments to minimize impedance.

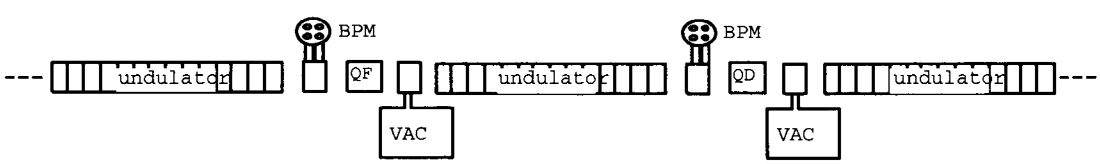

FIGURE 1. The 100 m LCLS undulator consists of 52 magnet sections (1.92 m) separated by 0.24 m gaps containing permanent magnet quadrupoles, vacuum pumping components, and BPMs.

To achieve FEL gain the electron beam must be continuously bathed in the photon beam it creates. For high gain, the two beams must overlap to within ~10% of the transverse beam size in the undulator. The absolute straight line trajectory of the electron beam must be maintained to this degree over distances comparable to an FEL gain length. For the 1.5 Å LCLS photon beam created by the 14.4 GeV electron beam, the overlap requirement and the 11.7 m gain length electron beam straightness tolerance is ~5 μm rms. For the 15 Å, 4.5 GeV case, the 10% overlap is only needed over a 3.7 m gain length.

Several position monitor technologies for aligning the LCLS undulator beams have been considered (2). The choice of beam alignment method determines which BPM types are the most appropriate as discussed in the following section.

BEAM ALIGNMENT METHODS

Techniques considered for achieving LCLS undulator beam alignment include:

1. Using a photon monitor located downstream of the undulator to align spontaneous radiation from individual undulator sections as they are steered in sequence;
2. Using absolutely aligned and stable non-intercepting monitors located in the gaps between undulator sections;
3. Using absolutely aligned insertable intercepting monitors to establish initial alignment and stable non-intercepting monitors to maintain it; and
4. Using non-intercepting monitors and beam-based alignment to establish and maintain absolute beam straightness.

The first method, using sequential steering of undulator radiation from individual sections, was used successfully for the 2m, 24–50 MeV CLIO infrared FEL at LURE (3), but the technique may not be practical for the higher energy and much longer LCLS system due to problems with detecting radiation from downstream undulator sections in the presence of the intense photon beam coming from aligned upstream sections. The method might prove useful as a secondary alignment technique, especially if a system of insertable filters can be used to absorb the upstream photons.

The second and third methods both rely on the ability to install monitors with 5 μm absolute measurement accuracy with respect to a straight line over 11.7 m gain length intervals and maintaining that accuracy over time for 1.5 Å FEL operation. These methods do not seem to be practical given the conclusion from SLAC alignment experts that they can only guarantee 25 μm accuracy over these distances. However they may suffice for 15 Å FEL operation where the gain length is only 3.7 m and the electron beam is not expected to deviate by more than a few microns from magnet errors over this distance. The third method may also work for 1.5 Å FEL operation if the intercepting monitor can simultaneously detect electron and photon beam positions and beam overlap with 5 μm or better relative accuracy; we discuss such a monitor below.

The fourth method employs a powerful beam-based alignment algorithm to achieve absolute beam straightness (1). By recording the readings of roughly aligned

BPMs as a function of beam energy (varied between 4.5 and 14.4 GeV) and by fitting a model of the undulator electron transport optics to those readings, offset errors for quadrupoles, BPMs, and incoming beam trajectory can be calculated and corrected. When this process is repeated 2–3 times (which may take a few hours), simulations indicate that BPM offsets and electron beam straightness in the 100 m long undulator can be established and maintained with better than 5 μm rms accuracy.

We conclude that we will use stable, high-resolution, non-intercepting beam position monitors in the gaps between LCLS undulator sections that can be absolutely aligned to the micron level using a beam-based alignment algorithm. In addition, we will install insertable intercepting monitors that provide an alternate means to measure position and to cross-check beam-based alignment results. As described below, the intercepting monitors will simultaneously measure electron and photon beam position to 5 μm. A spontaneous radiation monitor located downstream of the undulator after the electron beam dump will be available to check photon beam alignment.

MONITOR PERFORMANCE REQUIREMENTS

The LCLS undulator BPM system must be capable of establishing and maintaining electron and photon overlap in both transverse directions to 5 μm rms or better for 1.5 Å FEL operation. While beam-based calibration eliminates the need for micron level installation accuracy, an absolute BPM measurement accuracy of < 50 μm rms over 11.7 m gain length intervals after initial installation is desired to reduce the beam-based calibration time and to achieve FEL gain at low electron energies without that calibration. This specification includes nominal 25 μm absolute accuracy tolerances in alignment over 11.7 m and in knowledge of BPM electrical center location with respect to nearby external fiducials (a few cm away).

Micron resolution and stability is needed only in a bandwidth comparable to thermal drift frequencies (<< 1 Hz, over periods of days), implying that BPM readings from many beam pulses can be averaged for higher resolution. Single shot resolution of order 1 μm for a 1 nC bunch is desired to detect 120 Hz pulse-pulse trajectory instability. A dynamic range of 40 dB is needed for low and high intensity operation. Monitors must be mounted on precision translation stages so that their mechanical alignment can be adjusted and preserved to 1 μm rms with respect to a system of stretched wires running parallel to the undulator (1), similar to the system used for the SLAC FFTB.

The total longitudinal beam impedance of 52 BPMs (one per drift section between undulator segments) must be kept well below a loss factor of 1 kV/pC to keep the correlated energy spread of the electron bunch below 0.1%; otherwise the FEL saturation length would increase beyond 100 m. Insertable BPMs may have much larger impedance since they can be withdrawn for FEL operation. Insertable BPMs must be designed to have minimum impedance when withdrawn.

Intercepting monitors must be able to handle the power densities from both electron and photon beams. Some monitors may only be capable of low intensity operation, having to be withdrawn before operating with the high peak current needed for lasing.

BEAM POSITION MONITOR CANDIDATES

We have investigated several intercepting and non-intercepting beam position monitor technologies that might meet the performance needs for the LCLS undulator.

Intercepting Monitors

Precisely insertable fluorescent screens and crystal wafers, transition radiation monitors, and wire scanners were considered as intercepting electron beam position monitors for the LCLS undulator. The fluorescent and transition radiation monitors can measure horizontal and vertical beam position simultaneously, while the wire scanners require sequential measurements using one wire per plane.

Phosphor screens were eliminated as precision monitors because of the low resolution and dynamic range caused by finite grain size, deposition non-uniformity, and blooming of the phosphor. Fluorescing crystal wafers, such as CsI and YAG, overcome these limitations. YAG crystals in particular have recently been shown to have micron resolution and large dynamic range when visible fluorescence is viewed through a telescope with a CCD camera (4). The problem with using this type of monitor is that both the electron beam and undulator photon beams will excite the crystal, making it difficult to precisely measure position of just one of the beams. This problem might be reduced if the crystal wafer is mounted on the back of a photon-absorbing substrate that passes the electrons, or if absorbing filters (e.g., 100 μm tungsten) can be inserted upstream of the crystal. An alignment fiducial on the crystal holder, viewable by the monitor camera, may be needed for absolute accuracy.

Transition radiation (TR) from a precisely insertable thin foil provides a powerful way to measure beam size and position, especially at wavelengths comparable or longer to the electron bunch length (~30 μm rms) where the transition radiation is coherent. However, the performance of this type of monitor in the LCLS undulator is questionable since undulator radiation at TR wavelengths will be reflected from the foil and will obscure electron beam measurement. Again, this problem might be reduced using insertable tungsten filters upstream of the TR foil.

Wire scanners are used successfully at SLAC to measure micron or smaller rms beam sizes. Those in the FFTB (5) have been used with the same beam intensity as projected for LCLS. Overlap between the electron beam and a precisely positioned carbon wire is detected downstream of the undulator by measuring either bremsstrahlung gamma rays (having a 1/E spectrum extending up to the beam energy) or, in the event that excessive background radiation corrupts this measurement, degraded energy electrons produced by the bremsstrahlung process (in the range of 0.5 to 0.75 of the initial beam energy) that are magnetically deflected from the beam pipe. Radiation-hard Cherenkov detectors with thresholds above 15 MeV have been used to reject background synchrotron radiation having critical energy up to 1.5 MeV. For the LCLS undulator, both gammas and electrons will be detectable, and comparison of their results will give a good indication of systematic errors.

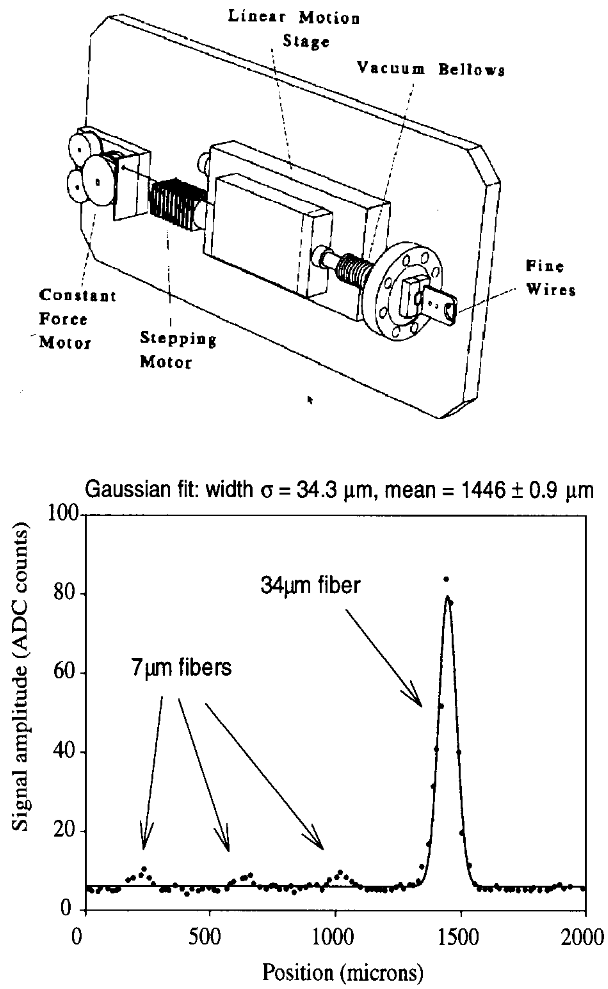

FIGURE 2. Wire scanner with micron resolution beam profile and centroid measurement (SLAC).

By stepping a wire across the beam, pulse by pulse for 10–20 pulses, using a linear motion stage (Figure 2), or by steering the beam across the wire, a profile of the beam can be measured. The beam shape is fitted on line, with a typical uncertainty of 2% of the width, and the center position obtained within 1–2 μm with respect to an external fiducial on the motion stage (Figure 2). Straight-line conventional alignment between stages can only be guaranteed to 25 μm over 11.7 m.

The LCLS beam intensity will be low enough that thinner wires of higher atomic number than carbon could be used without being destroyed. Their advantage is that the thinner the wire, the more accurately its can center be located relative to the fiducial marks outside the vacuum.

A distinct advantage of the carbon wire monitor is that it can be used for simultaneous measurement of electron and undulator photon beam position (Figure 3). While the impinging electron beam generates bremsstrahlung, the undulator photons will diffract from the wire in a powder diffraction pattern. An experiment at SSRL using 7 μm amorphous carbon wire filaments and 1.5 Å x-rays showed that an intensity maximum for Bragg scattering occurs at 25.8°. The energy range for practical Bragg angles is rather limited, though one could use third harmonic radiation when running the beam at lower energies. The energy dispersion caused by diffraction assures that a detector subtending a small angle will acquire x-rays with a narrow energy range.

We conclude that the preferred intercepting monitor for the LCLS is the wire scanner because of its ability to measure both electron and photon position at high operating intensities and because of its proven micron-level performance.

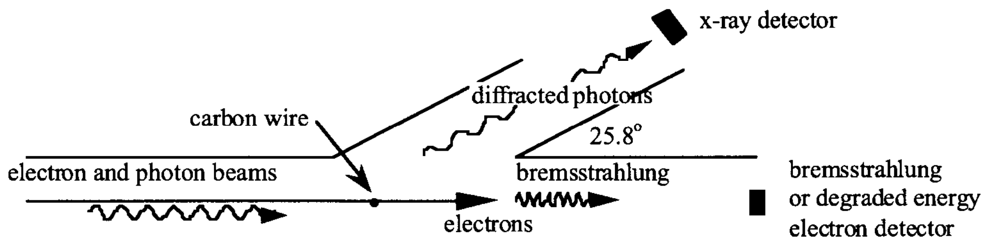

FIGURE 3. Combined electron/photon beam position monitor for one plane. Both beams strike the carbon wire; when they overlap, detectors record maximum signals simultaneously.

Non-Intercepting Monitors

Candidates for non-intercepting position monitors include diffraction radiation monitors, laser wire (or spot) monitor, and more commonly used rf BPMs.

A diffraction radiation (DR) monitor (6) having a 2 mm radius aperture within the 2.5 mm radius undulator vacuum chamber would produce micron wavelength DR (which, like TR, would be coherent at 30 μm or longer) that can be observed with a simple camera system to determine beam size and position. While the measured radiation pattern is sensitive to the transverse displacement of the electron beam from the center of the aperture, a derivation of position sensitivity in both planes has not been completed; it is premature to say this monitor would have the micron position resolution required. Furthermore, the monitor also has a high impedance (~75 V/pC loss factor), implying that only 10 monitors could be inserted during FEL operation.

The success of the laser wire monitor for measuring micron beams at the SLAC Linear Collider Final Focus (7) prompted us to investigate a method of measuring Compton scattering from a 1 μm × 10 μm laser "spot" (2). The spot would be created by focusing an intense pulse of 1.06 μm light from a high-powered laser (e.g., a 100 MW peak pulsed YAG laser). Because of the large background expected from bremsstrahlung and high-energy undulator photons, a measurement of degraded energy electrons at the end of the undulator might offer better performance. A principal problem with the laser spot monitor is that, due to possible changes in laser optical components over time caused by the high pulsed laser power and radiation environment, the absolute stability of the laser spot position is uncertain and there is no clear method for monitoring it. Another drawback is that if the electron beam is off the laser spot, there is no indication of which way to steer.

Uncertainties in performance of the DR and laser spot monitors led us to concentrate on specifying an appropriate non-intercepting rf BPM pickup and processing system for the LCLS undulator. Several high-frequency (rf) position monitor technologies were evaluated, operating either within the undulator gap or in the drift spaces between undulator sections. The devices and their calculated performance are identified and summarized in Table 2.

TABLE 2. rf BPM Design Parameters. BPM locations are either within the LCLS undulator pole gap (U) or in the drift spaces between undulator sections (D). Values for center accuracy are estimated.

Monitor Type	Parameters	Center Ac'cy	Resolution	Oper. Freq.	Issues
Wall Current (U)	z=6 mm R_B=2 Ω	100 μm	0.7 μm/nC	> 1 GHz	Ferrite saturation
Stripline (U)	z=9 mm Z_o=40 Ω	100 μm	0.2 μm/nC	2–5 GHz	Strips on ceramic cyl
Microwave Aperture (U)	3.0×1.5 mm slot to waveguide	100 μm	0.1 μm/nC	> 50 GHz	Op. freq > chamber cutoff; HOM errors
Cavity (U)	ϕ_{ID}=7 mm z=2.8 mm	50 μm	1 μm/nC	~ 32 GHz	f_o ~ cutoff; low Q
Stripline (D)	z=40 mm Z_o=50 Ω	50 μm	0.2 μm/nC	0.5–2 GHz	Technical maturity
Cavity (D)	ϕ_{ID}= 60 mm z=5 mm	5 μm	0.2 μm/nC	~ 6 GHz	Robust; TM_{010} mode

The region within the undulator gap considerably restricts the BPM mechanics that can be built. For example, the ferrite of the Wall Current Monitor cannot be allowed inside the undulator, nor will it fit. Feedthroughs for monitors within the undulator pole gap are difficult to accommodate. Monitors such as the Aperture Monitor, which operate on Bethe hole radiation, must have small apertures, and as such are strongly influenced by higher order modes. The Cavity BPM within the undulator gap, having beam pipe apertures nearly the size of the resonator end plates, would have a low Q. In addition, the relative compactness of any structure within the pole gap increases fabrication difficulty and raises the operating frequency, contributing to signal cable losses and higher component costs.

BPM structures in the drift regions offer superior performance with fewer design restrictions. Of those investigated, the Cavity BPM best meets the design requirements. Because of the natural symmetry of circular machining and the availability of ultra-precision diamond lathes, micron level absolute mechanical and electrical center accuracy can be achieved.

Excited by the passing beam, the cavity rings down in a set of characteristic frequencies, precisely determined by the cavity dimensions (8). Signal power may be extracted through four precisely machined apertures, each coupled to an external waveguide. The waveguide TM_{010} position-sensitive mode will exist, in two polarizations, only when beam traverses the cavity off axis. This position mode competes with the strong lower frequency (TM_{110}) dominant mode, which can be rejected using both frequency and symmetry discrimination. Presence of the dominant mode, not thermal noise, ultimately limits the achievable position accuracy. A cavity operating at 6 GHz was tentatively designed for the LCLS (1); its parameters are summarized in Table 3.

TABLE 3. LCLS Cavity BPM Parameters

Parameter	Value
Cavity radius	28.5 mm
Cavity length	5 mm
Beam pipe ID	5.0 mm
R/Q (TM_{110})	8.4 Ω at 6 GHz
V_{out} in 50 Ω (TM_{110})	15 μV/nm/nC
Peak E field at 1nC	7.7 MV/m
Long. Loss Factor	37.1 V/pC

CONCLUSION

We propose to install stable high resolution, non-intercepting cavity BPMs and intercepting carbon wire scanner units in the 52 drift sectons between LCLS undulator segments. The absolute position of the electrical centers of the cavity BPMs and of the intercepting wires will be known to < 50 μm rms with respect to a straight line over 11.7 m 1.5 Å gain length intervals after initial installation. This alignment accuracy in itself is likely to be sufficient to establish 15 Å FEL operation. It is also sufficiently accurate to launch a beam-based alignment algorithm which will straighten the electron beam and calibrate BPM offsets to < 5 μm rms with respect to a straight line over the 100 m undulator length, more than adequate for 1.5 Å lasing. The insertable wire monitors will provide an alternate means to measure position and to cross-check beam-based alignment results since they will capable of measuring electron and photon beam position overlap to within 5 μm. The wire monitors will also be used to measure beam profile and emittance. All monitors will be precisely movable and mechanical alignment stability will be maintained to 1 μm rms using a stretched wire positioning system along the undulator.

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