Electro-Magnetic Quadrupole Magnets in the LCLS FEL Undulator

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We discuss various aspects of electro-magnetic quadrupole (EMQ) magnets for the LCLS FEL undulator, including their utility in beam-based alignment (BBA), magnet design issues, and impact on tunnel environment, reliability, and cost.

I. BRIEF SUMMARY

The present focusing lattice in the LCLS undulator is based on permanent magnet quadrupoles (PMQs). The motivation for permanent magnets is under question, while various advantages of electromagnetic quadrupoles (EMQs) are becoming more apparent. These advantages are discussed in this note and summarized in the following list.

- EMQs provide a fast verification and refinement of the quadrupole's alignment with respect to the beam position, to a precision of 2-3 μm with a 20% gradient change.
- With the undulator's magnetic center fiducialized to the quadrupole center, this improved alignment should also improve the undulator segment alignment by about 15-20 μm.
- The necessary re-positioning accuracy of PMQs is less than 1 μm in order to reproduce the trajectory after BBA refinement.
- The EMQ design will easily fit into the available $<$ 15 cm of space in each undulator break section.
- The EMQ design can easily accommodate a weak x and y dipole trim coil per quadrupole, removing the need for a an additional vernier-mover on the quadrupole.
- The β-mismatch induced by a 20% gradient change of one quadrupole alters the beam size by just 20%, whereas switching off the quadrupole alters the downstream beam size by a factor of 2.3.
- The gradient tolerance for quadrupoles in the undulator are very loose at 4% rms, removing the need to standardize the EMQ fields with ramp-up/ramp-down procedures.
- The cost of EMQs, including steering trims, power supplies, cooling water, and controls, but without contingency, is estimated at $740,000.
- The power dissipation in the magnets and cables does not present a significant load for the HVAC and LCW systems, nor should this load present a thermal stability or uniformity problem for the undulator hall.
- Measurements of NLC prototype EMQs have demonstrated magnetic center stability against gradient changes, water flow, and thermal effects, well below that needed for the LCLS undulator EMQs.
- EMQs provide some adjustment of the mean β-function, but for this design the lower limit is $\bar{\beta} \approx$ 25 m, with a nominal of $\bar{\beta} \approx 30$ m.

II. INTRODUCTION

The LCLS undulator system contains an array of 33 quadrupole magnets arranged in a FODO lattice. The purpose for these quadrupoles is threefold, (1) focussing, (2) steering, and (3) undulator segment alignment.

(1) The focussing function of the quadrupoles will keep the beta function nearly constant along the undulator at 32 m in the horizontal and 28 m in the vertical plane at 14 GeV, and at proportionally lower values at lower energies. This requires the absolute value of the length-integrated gradient of each quadrupole to be 3.0 T.

(2) The dipole field in an off-axis quadrupole is presently the main steering element for correcting the electron beam trajectory, in general, and for use with the beam-based alignment (BBA) procedure, in particular. The steering angles can be adjusted by remotely changing the horizontal and vertical positions of each quadrupole.

(3) For FEL operation, the electron beam must not randomly deviate vertically from the center of all undulator segments by more than ~70 microns rms ($\Delta K/K_0 \approx 10^{-4}$). With each quadrupole magnet precisely aligned to the center of the adjacent undulator segment (with a CMM before installation), the quadrupole then serves

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effectively as an alignment reference. Since the BBA procedure centers the electron beam in the magnetic center of the quadrupoles to within ∼20 μm, the beam is also adequately centered in the undulator segment.

The present plan for BBA in the LCLS FEL undulator uses large, deliberate energy variations of the electron beam to detect quadrupole magnet and beam position monitor (BPM) transverse offsets. This has been simulated in detail [1], and provides a global, simultaneous calculation of all offsets, where the errors are then highly coupled from magnet to magnet and BPM to BPM. In the simulations this is not a major limitation, but unforseen errors in the method, such as large beam jitter, systematic BPM errors, or significant linac dispersion, suggest that a second complementary method may be of great utility. In addition, final verification and further refinement might be possible by following the main BBA method with a more localized magnet alignment approach.

Permanent magnet quadrupoles are a simple, reliable solution to the focusing requirements in the undulator, however, unless the gradient can be varied (or switched off) by some means, they do not allow a localized determination of the residual magnet alignment error after the initial energy-scan method of BBA has been performed.

Electro-magnetic quadrupoles, or permanent magnet quadrupoles which include some means of gradient variation (such as a large transverse displacement to a field-free region), provide a complementary and more importantly, a *localized* method of determining the magnet misalignment.

In this note we will highlight some of the advantages and disadvantages of EMQ's in an attempt to provide a basis for the decision as to which type of quadrupole should be used in the LCLS FEL undulator. The main parameters are listed in Table II.

TABLE I: LCLS FEL undulator parameters.

parameter	symbol	value	units
electron energy in undulator	E_0	14	GeV
undulator period	λ_u	3	cm
radiation wavelength	λ_r	1.5	Å
und. mean beta-function	β	30	m
focal length of quadrupoles	f	16	m
quadrupole spacing	L	4	m
BPM resolution	σ_b	2	μm
number of quadrupoles	N	33	

III. ALIGNMENT ISSUES

The primary BBA method relies on large electron energy variations to sense quadrupole and BPM alignment errors. As such, the determined errors are highly coupled, leaving some residual alignment error at the 20-μm rms level in each magnet (as seen in Fig. 4). Although the simulations include many sources of error, a real application of BBA may actually produce larger residual alignment errors. Since the undulator segments must be aligned vertically to approximately 70 μm rms, and this is accomplished by initially referencing the quadrupole's vertical magnetic center to the undulator's vertical magnetic center, it is important to achieve vertical quadrupole alignment to much better than this 70 μm level.

A Alignment Resolution

The BBA procedure cannot align to better than the BPM resolution. The final trajectory will be composed of many small, localized 'bumps', with each bump produced by an alignment offset pattern of the three adjacent quadrupole magnets. Treating the focusing lattice as a simple periodic FODO structure, and ignoring the small natural vertical focusing, the magnet offset pattern for a single BPM bump is

$$\mathbf{x_D} \approx \Delta x \begin{pmatrix} 1 \\ 2.25 \\ 1 \end{pmatrix}, \quad \mathbf{x_F} \approx \Delta x \begin{pmatrix} 1 \\ 1.75 \\ 1 \end{pmatrix}, \qquad (1)$$

where $2.25 \approx 2 + L/f$ is for a QF-QD-QF triplet (symbol definitions in Table II) and $1.75 \approx 2 - L/f$ is for a QD-QF-QD triplet. This means that any three adjacent quadrupoles with the first misaligned by Δx, the second by $2.25\Delta x$ (or $1.75\Delta x$), and the third again by Δx, will produce a closed trajectory bump with maximum amplitude of $x = \Delta x L/f \approx \Delta x/4$ (see Fig. 1).

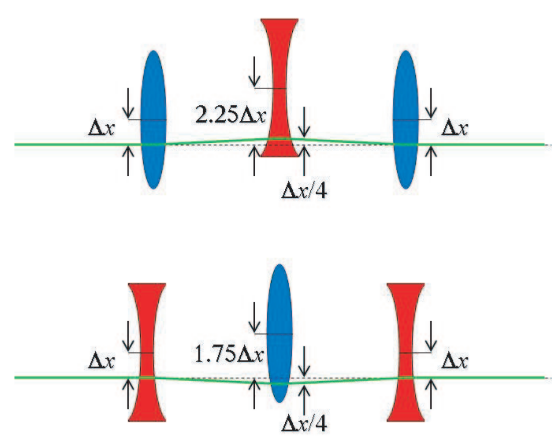

FIG. 1: Trajectory bump of three adjacent quadrupoles.

The total phase delay over the entire undulator induced by N such bumps in two planes is

$$\Delta\phi \approx \frac{4\pi NL}{\lambda_r}\left(\frac{\Delta x}{f}\right)^2. \tag{2}$$

The BPM resolution, σ_b, sets the bump amplitude, $\Delta x/4 \approx \sigma_b$, and from Table I this phase delay is $\Delta\phi \approx$ 160 degrees. This is a tolerable level by itself, but other sources of trajectory error such as undulator pole errors, a 50% increase in BPM resolution, or other unexpected systematic errors, may easily push this to the 360-deg level, or larger, which becomes intolerable. Therefore, a simple way to detect local quadrupole misalignment errors may be very useful.

As seen in Fig. 1 for the middle quadrupole, its magnetic center to beam center position distance is $\Delta x_q \approx 2\Delta x \approx 8\sigma_b$, or about 16 μm. A change in this quadrupole's gradient of $\Delta G/G \equiv \delta$ (e.g., $\delta = 20\%$), will induce an oscillation with maximum amplitude, 90 degrees downstream, of

$$\hat{x} \approx \frac{\delta\Delta x_q\bar{\beta}}{f}, \tag{3}$$

which amounts to 6 μm with $\delta = 20\%$. At 3-times the BPM resolution this is easily resolved (see Fig. 2). Pulse to pulse trajectory variations entering the undulator may occur at the level of 10-20% of rms beam size (4-8 μm rms) but can be 'fitted out' by using upstream BPMs, or averaged out by recording may samples. A simulation of this trajectory fitting is shown in Fig. 3 including 2-μm rms BPM noise. This suggests that with a gradient variation of $\delta = 20\%$, each quadrupole magnet can be repositioned to within 2.3 μm of the beam position; a large improvement over the 16-μm level described above. This 2.3-μm level can be further improved by scanning the quadrupole through several gradient settings and also by averaging the measurements over time.

A possible complementary method to verify and further refine the BBA procedure is to scan each quadrupole gradient by approximately 20% and record the induced kick, converting each kick to quadrupole offset. A D-quadrupole is then moved by 2.25-times this offset, while an F-quadrupole is moved by 1.75-times, and the quadrupole's two adjacent neighbors are moved by 1-times this amount. This is applied to each quadrupole and its two neighbors over the whole undulator. This refinement procedure has been simulated as seen in Fig. 4 (after BBA, but prior to refinement) and Fig. 5 (after refinement). In Fig. 5 the quadrupole magnet alignment has been improved, but the low-frequency component of the trajectory does not improve, since the quadrupoles are moved to the local beam position. The high-frequency component of the trajectory, however, does improve, and this can be seen in the mean phase errors (sum of x and y phase errors), which have been reduced from $(186^\circ + 57^\circ) = 243^\circ$, to $(157^\circ + 20^\circ) = 177^\circ$.

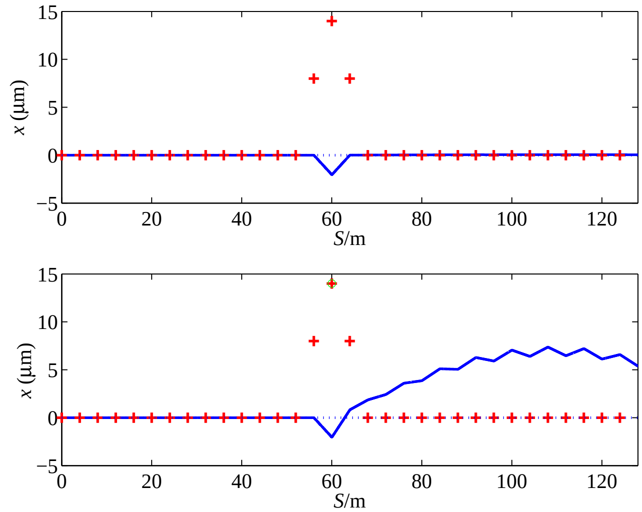

FIG. 2: Trajectory with one bump (top plot), and the same again (bottom plot) but with a relative gradient change on the central quadrupole by $\delta = 0.2$. Red crosses are quadrupole positions and blue line is electron trajectory.

Such a scheme can significantly improve the quadrupole alignment (and therefore the undulator segment alignment), but more importantly, this localized alignment method will uncover poorly converged quadrupole offsets which may have been limited by unexpected systematic errors.

B Quadrupole Magnet Displacement

1 Position Reproducibility

The quadrupole magnets will be on translation stages (movers) and their positions should be reproducible to high precision in order not to randomize the trajectory when the movers are adjusted. Figure 6 shows the x and y trajectories for a perfect undulator system where the quadrupole positions have been moved randomly by 1 μm rms (Gaussian distribution). The figure shows large trajectory changes generated by small re-positioning errors. This trajectory can be improved by adjusting a few key magnets, so the re-positioning tolerance may be somewhat larger than 1 μm. However, a permanent magnet quadrupole which is moved to a field-free region (by many centimeters) and back again, in order to effectively vary the gradient and determine its offset, will not return to its initial x and y position with infinite accuracy. If the 33 quadrupoles are moved out and in sequentially, and their re-positioning accuracy is good to just 1 μm rms, the trajectory will be changed in the downstream quadrupoles by 10-20 μm (see Fig. 6) and the refinement method will not converge. It is possible, however,

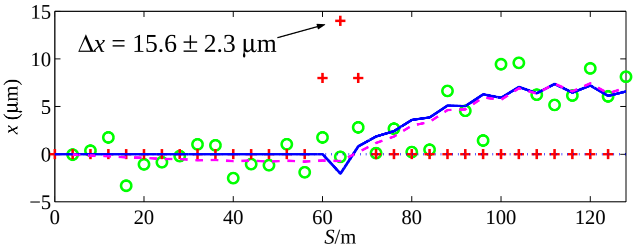

FIG. 3: Simulated measured trajectory with 2-μm BPM noise fitted to incoming position, angle, and a kick at the 17th quadrupole where the kick has been induced by a gradient change of $\delta = 0.2$. Red crosses are quadrupole positions, green circles are BPM read-backs, solid blue line is actual electron trajectory, and magenta dashed line is the fitted trajectory. The fit result predicts the quadrupole to beam position offset of 15.6 ± 2.3 μm (actual is 16 μm).

to adjust a weak dipole trim at or near the quadrupole in order to correct the trajectory after the quadrupole position is restored. This requires additional time and with limited BPM resolution, may not perform as well as will varying the gradient of EMQ's.

2 Vibrations Induced by Cooling Water Flow

Electro-magnetic quadrupoles with water cooling circuits will vibrate depending on system mass, magnet support, and specific water flow. The random vibrations of all 33 quadrupoles will induce trajectory variations which can be scaled from Fig. 6. From this figure it is estimated that a magnet vibration amplitude of ~100 nm rms will generate trajectory jitter of <2 μm rms (below the BPM resolution). Measurements of similar sized NLC quadrupole magnets with 0.1 l/s water flow show 3-4 nm rms vibration at frequencies >20 Hz [2]. With the water flow at about half this level (0.04 l/s) in the LCLS quadrupoles, attaining <100 nm rms vibration amplitude should not be a difficult issue.

3 Stability of Magnetic Center with Gradient Changes

Finally, the quadrupole's magnetic center is not completely independent of its power supply current setting. In the example above with a 16-μm quadrupole offset, the position is well determined to an rms level of 2.3 μm. If the magnetic center of the quadrupole changes by 1-2 μm when the current is changed by 20%, this will bias the positioning result only by about 10% (or 1-2 μm), which is within the measurement resolution and therefore a tolerable level (assuming the magnetic center returns to its original position after the current has been restored). NLC quadrupole magnet measurements have been made

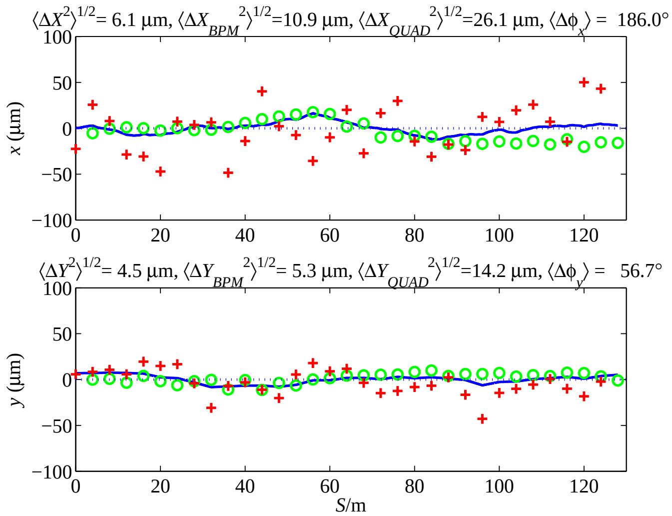

FIG. 4: Trajectories (x at top and y at bottom) after basic BBA procedure. Red crosses are quadrupole positions, blue line is electron trajectory, and green circles are BPM read-backs.

which show magnetic center stability of <1 μm with a 20% gradient change [3]. In addition, these measurements show the magnetic center of the quadrupole is maintained to <1 μm over a temperature variation of 0.8°C.

C Quadrupole Gradient Accuracy

The beta-mismatch amplitude for a relative quadrupole gradient change of $\delta \equiv \Delta G/G$, is given by

$$\zeta = 1 + \frac{1}{2}\left(\frac{\delta\bar{\beta}}{f}\right)^2 . \tag{4}$$

The mismatch amplitude, ζ, effectively scales the emittance in the FEL. A mismatch of $\zeta = 1.1$ has the same effect on the slippage spread as a 10% increase in emittance. Therefore, the mismatch tolerance might be described as $\Delta\zeta \equiv \zeta - 1 \lesssim 0.02$. A fractional gradient error of $\delta = 10\%$ on one quadrupole produces this tolerance, therefore the gradient tolerances are not difficult to achieve (for 33 quadrupoles $|\delta| \lesssim 4\%$ - see Fig. 7).

If a quadrupole is switched off ($\delta = 1$), the mismatch amplitude is $\zeta \approx 2.8$, which implies a beta function up to 5.5-times larger (or smaller) than nominal, producing an rms beam size up to 2.3-times larger than nominal. However, with $\delta = 0.2$, the temporary mismatch is only $\zeta \approx 1.07$ with a relative increase in beta of 1.45, producing a beam size only 1.2-times larger. The larger beam size produced by switching a quadrupole off may be a source for systematic BPM read-back error and may compromise the BBA refinement procedure, while the large

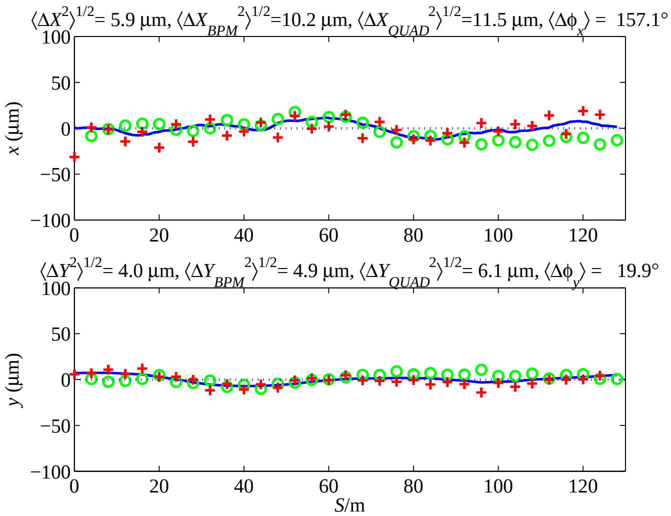

FIG. 5: Trajectory after basic BBA procedure and including local bump alignment refinement (compare to Fig. 4).

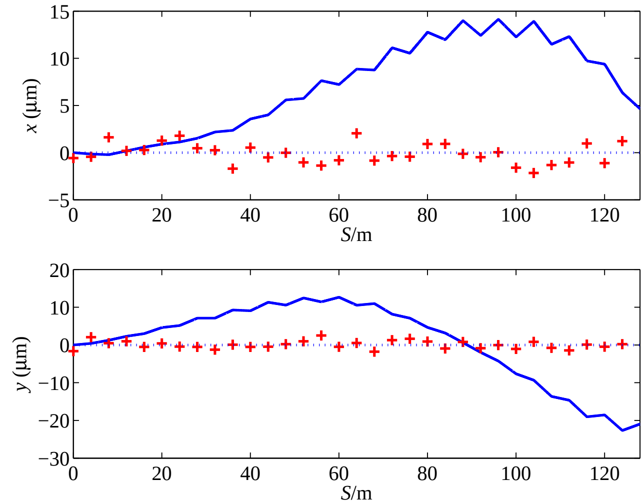

FIG. 6: Trajectories in x and y with all quadrupole magnet positions randomized by 1 μm rms.

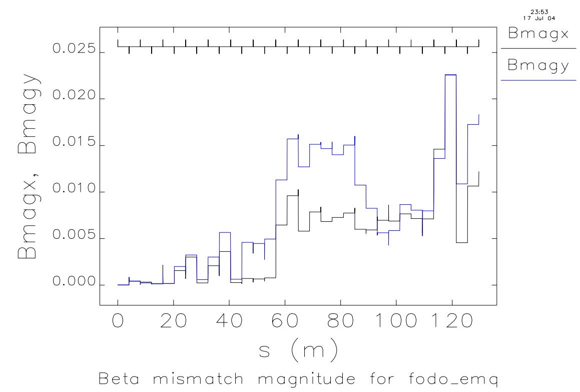

FIG. 7: Mismatch amplitude, $\Delta\zeta$ (or "Bmag"), in x and y along undulator for random quadrupole gradients of 4% rms (Gaussian).

gradient change of 100% is not a necessity in determining the alignment adequately (see Fig. 3).

Finally, EMQ magnets have the possibility to adjust the focusing to compensate for lower beam energies. With permanent magnet quadrupoles, the FODO-cell stability criterion limits the lowest electron energy in the undulator to $E_0 > 1.8$ GeV. EMQ's will allow even lower energies, although this energy level requires deceleration in the 3rd linac section (L3) and will likely be fairly unstable in beam energy. In addition, an EMQ with the possibility of a 20% increase in quadrupole gradient ($\bar{\beta} \approx 25$ m, rather than 30 m) reduces the gain length by 2.5%, or equivalently, generates the same gain length for an emittance which is 3.3% larger. These are not large effects, but are included here for completion.

IV. QUADRUPOLE MAGNET SPECIFICATIONS

An engineering design for an EMQ was developed and its cost was estimated. It is based on a long established SLAC design for weak quadrupole magnets. The SLAC design had recently been improved as a high reliability quadrupole for the NLC injector [3]. The EMQ design described here includes the additional functionality of X-Y dipole trim windings.

The core is made of four solid pieces and is profiled as a single assembly. This choice delivers high accuracy as well as a rigid core which holds the magnetic center to high precision at a low to moderate cost. Water is used to cool the main coil, while the solid wire trim windings are cooled by conduction to the main coil or core.

The EMQ will easily fit into a 15 cm space. Further cost and size reduction may be possible by changing to a solid wire main coil. This would require cooling the core steel and simplifying the coil/current/water connection.

An EMQ is required to have a SLAC approved safety cover that will allow the quads to be powered while access to the Undulator Hall is allowed. Keeping the magnets powered should greatly simplify FEL operational recovery after tunnel access, by stabilizing the undulator heat load and electro-magnetic forces within the magnet. The fusion of this design feature with a thermally insulated 'full core cover' will ensure that excess magnet heat load is not exhausted into the undulator enclosure.

The design seeks to minimize power by adding conductor and results in only 27 W dissipated in the coils per EMQ. More power is dissipated in the cables connecting the EMQ to the power supplies. With a choice of #4 conductor this amounts to 356 W per EMQ assuming an average cable run length of 200 ft. The operating current is a convenient 52 A. The EMQ engineering parameters are summarized in Table II.

The trim windings are rather trivial with only 8 turns required and a totally negligible dissipated power. Parameters for the dipole steering coils are presented in Table III.

TABLE II: LCLS undulator EMQ magnet parameters.

parameter	**symbol**	**value**	**units**
Magnet quantity	N	33	
Magnet core steel length	ℓ_c	7	cm
Effective magnetic length	ℓ	7.4	cm
Magnet bore radius	r	0.4	cm
Max. integrated gradient	$\int \hat{G}_x ds$	±3.6	T
Nom. integrated gradient	$\int G_x ds$	±3.0	T
Maximum pole-tip field	B_p	±0.195	T
Maximum excitation current	I_{max}	±52	A
Turns/coil	n	6	
Power dissipated in magnet	P_m	27	W
Power dissipated in cables	P_c	356	W
Water flow per magnet	dV/dt	0.5	gpm

TABLE III: LCLS undulator steering dipole magnet parameters.

parameter	**symbol**	**value**	**units**
Magnet quantity	N	33	
Effective magnetic length	ℓ	7.4	cm
Maximum dipole field	$\hat{B}$	±50	G
Maximum excitation current	I_{max}	±2	A
Turns/coil	n	8	
Power dissipated in magnet	P_m	0.06	W
Power dissipated in cables	P_c	0.12	W

V. COST ESTIMATE

The cost of EMQs with trim windings, power supplies, controls, cabling (including installation), additional space in the service buildings, and an LCW system was worked out by various SLAC engineers, primarily based on the cost of similar systems at SLAC. The results are tabulated in Table IV. These costs do not include any contingency, nor do they include magnetic measurement and fiducialization costs, but labor costs are included. The costs were chosen to represent what would have to be added to the current budget independent of any subtractions needed for taking out the baseline permanent magnets.

Additional cost savings in magnetic measurements may be possible, against the current budget, if fiducialization and magnetic center are identified for each assembly with complete measurements made only on the first article and selected production samples.

The total costs associated with the addition of EMQs, without contingency or spare parts is $739,000. This appears to be significantly less than the amount budgeted for the baseline permanent magnet quadrupoles which do not have remote rollaway capability.

TABLE IV: LCLS undulator EMQ and steering coil cost summary, without quadrupole magnet movers.

parameter	**value**
Quad and dipole magnet cost/unit	$7000
Quadrupole power supply (/unit)	$6651
Steering coil power supply (/unit)	$3030
Quad power supply racks (/unit)	$606
Rack loading (/unit)	$909
Database and controls (/unit)	$1000
Cables and trays (/unit)	$1080
Engineering and documentation (/unit)	$909
Additional space in service buildings (/unit)	$500
Total cost for 33 units	**$739,053**

VI. CONVENTIONAL FACILITIES ISSUES

The replacement of the baseline PMQs with EMQs entails some changes to the Conventional Facilities and has some cost implications. There are new space requirements, a cooling water system has to be added and additional cable trays are needed. These issues are discussed in this section. In addition we discuss the effect on Undulator Hall air temperature.

A Space Requirements

EMQs will require a small increase in length required for the Undulator System and the associated power supplies will require some more space in the service buildings.

1 Undulator Hall

In order to accommodate the remote roll-away option for the undulator segments it was recently decided to reduce the undulator K value. This change implies a reduction in break section length by about 1 cm for the short breaks and about 2 cm for the long breaks. Since the reduction in long break will not leave sufficient space for diagnostics, it was decided to increase the long break by a distance equivalent to a one-wavelength slippage distance, or 21 cm, which represents an overall increase of the long break by about 19 cm. Considering the 5-cm length reserved for EMQs in the baseline design, this change provides space for up to 15-cm long EMQs, while still increasing the space for diagnostics by at least 9 cm. The overall length of the undulator will increase by about

1.5 m. Since the length of the undulator is about 130 m and the length of the Undulator Hall is 175 m, there is no need to increase the length of the Undulator Hall.

2 Service Buildings

The power supplies and controls for the EMQs will be located in the two service buildings at the ends of the Undulator Hall. Additional space must be provided in these service buildings and additional power and cooling loads must be accommodated. We estimate that 4 racks will be required for the EMQs in each of the two service buildings, with one additional rack in each building for optional trim power supplies, for a total of ten racks. Assuming each rack requires 10 sf of additional service building floor space and using the unit cost of $152/sf that was assumed in the Jacob's value engineering cost model for service buildings, the additional service building capacity need for power supply racks will cost only about $15,000 (included in Table IV), including the trim supply racks. The power supplies will be high efficiency switching type. The heat load of the additional racks in the building should be in proportion to the additional area required, or less.

B LCW System

LCW, not included in the present Undulator Hall design, must be provided for EMQs. Because the cooling load from the EMQs is small, and it is desirable to use cooling water at the same temperature as the Hall temperature, we will use a stand-alone air cooled chiller, located in one of the service buildings, to operate a closed loop system. The cooling load that the LCW must remove is based on 27 W of dissipated power in the coils per quadrupole for a total of about 1 kW. A conservative flow of 0.5 gpm per quadrupole is assumed which implies a temperature rise of the water from the coil heating of about 0.2 degree C. Thus the return water is essentially at the same temperature as the supply water. Trim coils generate very little power and are cooled by contact with the quadrupole coils. The total header flow rate required is around 15 gpm. The header will consist of two 500 ft long ϕ2-inch copper lines with 11 drops, one for each girder, which is sufficient for 60 gpm. This should have plenty of excess capacity for future expansion.

C Cable Trays

To minimize the affect on air temperature the cables carrying the magnet current from the service buildings to the EMQs will be located in trays above the ceiling in the return air plenum. These cables can be installed before the ceiling panels go up. The cables are expected to have very high reliability and the possibility of needing to add extra cables is low. Nevertheless it will be possible to add or repair cables after the ceiling panels are installed, but it will require extra effort and time compared to cables in trays below the ceiling. A single 24-inch wide cable tray above the ceiling running the length of the Undulator Hall is more than sufficient to carry the cables.

D HVAC

The power that is dissipated in the cables that drives the EMQs must be absorbed by the return air in the ceiling plenum. Thus the Undulator Hall proper will not see this dissipated heat. The extra heat will require some additional cooling power from the HVAC system of the Undulator Hall but it will not affect the temperature uniformity in the Undulator Hall. The estimated heating from the cables at operating current is 0.75 W per meter of cable pair for #4 wire. The average cable run length is about 200 ft, so the heat load on the return air for the Undulator Hall is about 1.5 kW. The design heat load on the Undulator Hall HVAC system is about 100 kW; 90% is from fan motors in the air handler units. The additional load from cable heating may therefore be neglected.

E Undulator Hall Air Temperature

The Undulator Hall air temperature can in principle be affected by convective heat transfer from the EMQs as well as convection heat transfer from the LCW system to the Hall air. The amount of heat transfer depends on the temperature difference between the air and the objects, and heat transfer coefficient. By insulating the magnets and LCW lines and keeping the temperature differences small these effects are minimized and made essentially negligible.

1 Cable Drops

At each girder (every third undulator magnet segment) cables will come through the ceiling and run along the girder to power the EMQs. The one way average length of this cable run is estimated at 8 m. The power dissipated in this section of cable will contribute to the temperature non-uniformity in the Undulator Hall. Again using 0.75 W/m we have about 6 W per quadrupole and a total of 200 W for the Hall. This is equivalent to about 1.5 W/m of tunnel length. The HVAC system is designed to accommodate up to 50 W/m of tunnel so the EMQs cable drops dissipate about 3% of the rated limit.

2 Protective Covers

We plan to insulate and put a protective conducting cover on the EMQs so that there is no need to turn the EMQs off when there is access. Transients due to turning quadrupole magnets off and on plagued the operation of the SLC.

3 Insulation of Quadrupoles and LCW Lines

Estimates of heat transfer rates from EMQs and LCW lines can be made based on the typical airflow velocities expected. The range of these estimates spans a factor a 5 because of the range of possible air flow conditions (1 ft/s - 1 m/s, turbulent or transition, flat plate or duct flow, etc). The result is that if a 0.2°C temperature difference develops between the ambient air and the object to be cooled the heat transfer rate will be of order 10 to 50 W per EMQ, including the contribution from the LCW lines. This is a significant amount of power, though still well within the budgeted heat load in the Undulator Hall. These estimates assume no insulation. By insulating EMQ's with 1 cm of polystyrene foam, for example, the heat transfer rate can be reduce to below 1 W per EMQ, even for 1°C temperature difference. Therefore we will insulate the EMQs and the LCW lines.

REFERENCES

[1] *LCLS CDR*, SLAC Report No. SLAC-R-593, 2002.

[2] F. Le Pimpec et al., *Effect of Cooling Water on Stability of NLC Linac Components*, SLAC-PUB-9558, Oct. 2002.

[3] C. E. Rago et al., *High Reliability Prototype Quadrupole for the Next Linear Collider*, SLAC-PUB-8990, Jan. 2002.