

A Report on the Internal LCLS Undulator Alignment and Motion Review

October 20 – 21, 2005

1. Introduction

The purpose of this internal review of the LCLS Undulator Alignment and Motion Systems was to establish if the proposed procedures and systems could meet the tolerances required for the FEL to operate. The review was convened by Heinz-Dieter Nuhn of SLAC and was conducted on October 20-21, 2005. Appendix A & B contain the meeting agenda with committee members identified and the charge to the committee.

The LCLS undulator is comprised of thirty-three, 3.4 meter long undulator magnet segments placed on an electron beam line that will be an extension of SLAC's existing Linac. Between undulator segments are placed a beam position monitor, a quadrupole magnet and a beam finder wire diagnostic. In order for the SASE FEL to saturate, the electron beam line must be straight to the level of about 5 microns over 10 meters. The BPMs and quadrupole magnets must be aligned relative to the electron beam to an absolute accuracy of 100 microns. The initial alignment of each segment and its associated quad and BPM is established through many steps of assembly onto their support system and their installation and alignment on the beam line. Final alignment will be accomplished through beam-based procedures. This alignment must be maintained during machine operations with minimal impact on x-ray availability.

The review was based on several formal presentations with extensive questions and discussions to elaborate on details. The committee chose to divide the technical systems into six areas: Undulator Tuning and Fiducialization, Quadrupole and Beam Finder Wire Fiducialization, Support Systems and Cam Movers, Assembly, Conventional Alignment, and Monitoring Systems. This report is organized to comment in detail on each of these six areas with discussion, suggestions and recommendations provided. In general, suggestions cover issues that the committee believes should be considered when completing the design details of the undulator system. Recommendations address areas where the committee believes that more effort must be placed to insure the success of the system design and its execution. If this committee were asked to return for a follow-up review, specific documentation that resolves the recommendations would be requested and verbal explanations for how the suggestions were addressed would be expected. The remainder of the report contains a summary of

general comments and answers to the five bullets of the charge to the committee. Detailed observations and suggestions are attached in Appendix C to provide even greater depth.

2. Undulator Tuning and Fiducialization

2.1 Discussion

The physics requirements for the undulator system appear to be thoroughly defined and achievable. The requirements for optical phase error, trajectory wander, and field integrals are consistent with previous work at ANL and DESY. An impressive facility is being built to conduct the necessary measurements for tuning and fiducialization of the undulator segments in a production fashion. The shimming techniques are well thought out covering both the specified trajectory and field integral requirements.

It seems likely that there will be differences in the environmental field seen by each undulator segment during magnetic measurements in the lab and when actually installed in the Undulator Hall. The first effect comes from the differences of the earth's magnetic field in the lab versus the one in the tunnel. The lab has been configured to minimize these potential differences and actual measurements have been made in existing enclosures to attempt to quantify the effect. It was also mentioned that in-situ measurements would be made to address any uncompensated for effects. No detail was given as to how these measurements would be realized. A second and potentially significant source of environmental fields could be the steel in the support girder and pedestals that was presented as the material of choice for these systems. The effect of these structures has yet to be measured but must be demonstrated as negligible or they will have to be incorporated into the measuring bench layout.

2.2 Suggestions

- Consider reversing the sequence of undulator measurement steps 5 and 6 so that straightening the y-trajectory is done before minimizing phase errors.
- Consider using a simple dipole coil wound around the undulator structure to compensate for environmental field effects in the tunnel.
- If mu-metal is to be used as shielding for the in-situ fields its design and installation should be carefully modeled and checked with measurements to insure its effectiveness.

2.3 Recommendations

- Field integral measurements of at least one girder-undulator assembly should be made as soon as possible if magnetic materials are chosen for the support system.

3. Quadrupole and Beam Finder Wire Fiducialization

3.1 Discussion

The addition of harmonic frequencies to the vibrating wire quad centering technique is an elegant method of extracting precision reference data for the fiducialization of the quadrupoles to the 25 μm goal. Care has been taken to quantify and control tolerance stackup so that the quad to undulator alignment accuracies of 60 μm vertical and 125 μm horizontal are achieved. The methodologies are proven and the remaining R&D investigations are well understood. The timing of beam pipe installation into the quadrupole bore remains an issue. If this is done after fiducialization then how does this affect the magnetic centerline?

The beam finder wire (BFW) is a recently added instrument designed to measure the alignment of each undulator section's trailing end with respect to the beam trajectory. The BFW to undulator alignment tolerance is 55 μm vertical and 100 μm horizontal for both initial alignment as well as replacement alignment. A detailed error budget for fiducialization and repeatability has been worked out but testing to find out if tolerances are achievable with the envisioned design has yet to be started. Additionally, while the fiducialization goals seem obtainable, the mounting of the BFW in the vacuum cross that is shared with a pump drop and hard mounted to the undulator vacuum chamber has not been specified in enough detail to evaluate whether the desired alignment tolerances will be reached. This involves the stackup of both measurement errors and manufacturing errors. A corollary to this is that a table of unique offsets for each BFW will need to be kept to standardize measured beam positions to the magnetic centerline of the adjacent undulator segment.

3.2 Suggestions

- Develop a combined fiducialization/manufacturing/assembly alignment budget for the beam finder wire device to pinpoint areas where tolerances may jeopardize the desired goals.

3.3 Recommendations

- None

4. Support Systems and Cam Movers

4.1 Discussion

The basic support structures for the undulator segments and break section components are girders supported from floor mounted pedestals. Overall girder movement can be controlled remotely through a series of cam movers. An additional feature is the desired ability to transversely roll out individual undulator segments without disturbing the alignment of the undulator vacuum chamber or adjacent components. The roll out feature allows for maintenance of each segment as well as rapid replacement of a section with a spare. The support system design and undulator features are to be mechanically interchangeable to enable this rapid replacement.

As presented the sand filled, insulated pedestal is mounted above the tunnel floor on four threaded studs without supporting grout between the mounting plate and the bottom pedestal flange. The reviewers assumed that the air space between the pedestal base and the floor is intended for thermal isolation so that the pedestal takes on the tightly regulated tunnel temperature. Also, the studs are intended to allow for prealignment of the pedestal and cam mover mounts before girders are installed for final alignment. Use of this adjustment mechanism will be rather awkward since the four support points not only over constrain the system but they are also far below the beam line thus increasing the coupling of any motions at the cam positions. A mechanism is supplied to fine adjust the cam mover support plates on top of the pedestal transverse to the beam line. Additionally, general structural details of the design were apparent in the presentations but detailed analysis of the assembly's stiffness and natural frequency were not presented.

The cam mover system that is mounted on the pedestal and moves the girder assembly is being developed at ANL with extensive testing illuminating system weaknesses that are being addressed. The present design showed the coupling effects of yaw and a z-restraint, which in turn caused significant girder distortions. A method of dealing with this was proposed to split the cam bearings into narrowly crowned bearings and use an inverted V shoe contacting both bearing halves simultaneously. Additionally, servomotors with 250:1 gearboxes will be used on the next prototype setup to eliminate the need for motor brakes and provide better resolution. Linear pots are being used to monitor girder motions providing the needed resolution but show wear and repeatability problems.

The final girder design utilizes steel to closely match the coefficient of expansion for the undulator strongback. The design involves 3 box beams welded together in a T-shape and topped with a precisely machined steel plate. This configuration should be quite stiff with the machining steps providing the opportunity to place precision reference points for installation alignment activities. The use of steel is of concern because of the magnetic field considerations mentioned above. With the precise control of tunnel temperatures it is unclear whether matching coefficients of thermal expansion is critical enough to risk the use of steel so close to the beam line.

The roll out feature of the design is realized through the use of two x-slides with sufficient range to move the segment away from the electron beam line. Two precision ground surfaces are provided for a non-kinematic mount of each undulator segment on the slides. It is envisioned that each undulator mounting plate would be custom ground and shimmed to standardize the dimensions from these mating surfaces to the magnetic centerline of that particular segment. The current layout depends on interlocks to protect it from large mechanical forces that would develop if the x-slides at each end of the undulator do not move in coordination with one other.

4.2 Suggestions

- Consider replacing the 4-bolt pedestal support with 3 bolts and moving them as close to the girder as possible.
- Consider structural enhancements that would stiffen the pedestal assembly.
- Review Final Focus Test Beam experience with cam mover systems and reconsider the proposal to use the cam system as a z restraint. See detailed suggestions in Appendix C.
- The repeatability of the linear pots should be checked after they have been fully extended during the roll out phase of undulator movements.
- Consider providing a gross z-adjustment for positioning the girder assembly.
- Reevaluate the choice of servomotors over stepper motors.

4.3 Recommendations

- Keeping in mind the tunnel temperature control plans and the sensitivity of the undulator system to environment magnetic fields, do an engineering analysis of the thermal, magnetic and structural impacts of the use of steel over other materials for the girder assembly.
- Carefully examine the choice of mating surfaces versus a kinematic mount as the interface between undulator segments and the girder assembly. Tolerance stack up, repeatability of placement, interchangeability, and logistics of assembly should all be considered and documented in this process and carefully coordinated with the SLAC Metrology Department

5. Assembly

5.1 Discussion

General intra-girder assembly steps were outlined showing their logical progression from fiducialization, to girder assembly and final alignment in the Magnetic Measurement Facility. The tools to accomplish the alignment at each stage are appropriate and capable of obtaining the desired results. The facility is laid out nicely to accommodate the multiple steps of girder buildup. However, the individual girder component designs have not progressed far enough to do a detailed analysis of manufacturing tolerance stackup to see if there are fitup issues that must be dealt with. Numerous areas exist where this could cause potential problems. The interface point between the beam finder wire assembly and the undulator vacuum chamber as well as the undulator chamber support are examples.

Coordination of the mechanical engineering and design effort with the workforce who will do the assembly is critical to insure a smooth process that will obtain the desired results. No mention was made of what staff would be used to do this assembly, including the installation of each girder in the Undulator Hall. In fact material-handling equipment has been bought by ANL to test for use during installation but it was unclear if ANL staff would be responsible for this phase of installation. This points out the need to establish clear roles and responsibilities, which is also one of the guiding principles of Integrated Safety Management and is critical for the safe buildup and installation of the undulator and its support systems.

5.2 Suggestions

- Differential roll accommodation between girders should be considered for the vacuum system components
- A QA plan for reception of subsystem components must be developed before orders are placed.
- Installation coordination between the collaborating labs should be better defined so that efforts are not duplicated and interface issues can be addressed.

5.3 Recommendations

- Develop a detailed analysis of assembly and manufacturing tolerances for vacuum system components such as beam pipes, flange interfaces, pipe supports, and accommodation for alignment to help guide assembly procedures and QA plans.
- Develop documentation that clearly defines the party or parties who are responsible for evaluating the safety of the undulator system designs and the buildup of hardware from magnets to tunnel.

6. Conventional Alignment

6.1 Discussion

Thorough plans for conventional alignment of undulator components in the tunnel were presented. All facets of the alignment scheme starting with the geodetic aspect of the Undulator Coordinate System, continuing with the high accuracy underground Undulator Hall network, and then the precision component alignment are clear and realistic. These techniques have been demonstrated through previous experiences at SLAC. Some details remain to be worked out such as incorporating the tunnel network infrastructure into the conventional facilities and coordination of the timing and logistics of measurement campaigns in the tunnel. It was noted that the important details of fiducial features are being evaluated with a few remaining issues to be addressed. It was also observed that the logistics for ensuring that cam movers and roll out systems were in a known position when alignment is performed remains to be worked out.

6.2 Suggestions

- None

6.3 Recommendations

- None

7. Monitoring Systems

7.1 Discussion

Beam based alignment is critical for the success of the LCLS. The simulated method realistically models the anticipated alignment errors along with the available adjustment knobs to arrive at an acceptable orbit through the undulator through an iterative approach. The scheme appears well thought out and realistically tested with ongoing updates that reflect the anticipated engineering results. The wire and hydrostatic monitoring systems are showing promise for extending the time intervals between full beam based realignment of the undulator system. These systems utilize proven methods with micron resolutions to provide differential position readback on the undulator girder segments. However, their usefulness in initial installation alignment is limited by the metrology of their absolute offsets from the beam line components. The potential of these systems is just now being realized by the beam line physicists and could prove to be a valuable tool for sorting out the various environmental factors that influence undulator alignment.

7.2 Suggestions

- None

7.3 Recommendations

- None

8. General Comments

8.1 Discussion

The presentations taken as a whole emphasized the importance of controlling tolerance stackup in all phases of construction of the undulator system. This includes detailed steps in magnetic measurement, component fiducialization, manufacturing specifications, conventional alignment methods, fixturing and

monitoring techniques. These considerations along with the complexity of assembly put a premium on close coordination of the SLAC and ANL teams. Good teamwork between these groups is absolutely necessary for success. For this reason, time should be taken to carefully compose interface documents that clearly define the teams' roles and responsibilities for all the components and the various steps of assembly and installation.

A point of concern for the reviewers was in the area of thermal management of the Undulator Hall. While this issue was not directly a part of the review, it is integral to the issues we were asked to consider. The tunnel temperature has been chosen as $20^{\circ}\text{C} \pm 0.1^{\circ}\text{C}$ and will be forced to this point to insure alignment and operating conditions are the same as they were during measurement, assembly, fiducialization, and tuning. The concern with this model is that if the natural tunnel temperature is different than 20°C , actively forcing it to that point may result in temperature gradients (spatial and temporal) that may be very difficult to control. This type of effect was observed during Sector 10 testing of the wire position monitors.

8.2 Suggestions

- Tunnel temperature "control" should continue to be a point of research.

8.3 Recommendations

- Before production, a complete mockup of a support system with the undulator segment and ancillary components should be constructed at ANL and if at all possible moved to SLAC for procedure development and testing.

9. Answers to the Charge Questions

- Is the plan for establishing and maintaining undulator alignment sufficient for the operational needs of the Undulator System?

At this point there appear to be no serious impediments to the success of the plan as presented. Many minor details remain to be investigated and tested to confirm that the very tight tolerances can be met but plans are in place to address all of the presently foreseen problems. In the minds of the reviewers, one major issue remains to be thoroughly analyzed, that is the temperature control of the tunnel and its spatial and temporal effects on undulator alignment.

- Is the plan complete?

For the most part the overall outline of the plan seems to be complete with several areas to be detailed and understood. As mentioned in the recommendations, mockups and trial assemblies will go a long way towards identifying where tolerance stackup is an issue and detailed procedures are called for. Documentation of interfaces, responsibilities and QC plans remain to be fleshed out.

- Are the systems under development capable of meeting the tolerances needed for the alignment plan to be successful. Are there any viable alternatives?

The surveying tools presented are appropriate and state of the art. They will be pushed to their technical limits to deliver the required tolerances but the plans for their utilization address the known weaknesses and probable error sources. The “alignment” systems need continued work as mentioned in the report particularly the cam movers and the cruder but important beam pipe supports. These need to be engineered so that achievable “alignment” tolerances approach the resolution of the surveying methods. Suggestions for improvements are both in the attached notes in Appendix C and in the main body of the report.

- Which technical aspects of the plan represent significant risk to the success of the project?

As mentioned above the thermal control of the Undulator Hall remains as a major concern of the reviewers even though it was not specifically part of this review. The issue of environmental magnetic fields needs further study so that no surprises are encountered during the commission of the system. In particular, this needs attention with respect to material choices for the support systems. Assembly processes, QC plans for receiving parts, and agreements on interface points need further definition to insure success. If this is not done significant risks to schedule and budget could be in the future.

- Is the R&D/test plan appropriate to the needs of the Project?

The current R&D and test plans are impressive in their thoroughness and the results already obtained for the individual components that will make up the alignment, assembly, installation and operational parts of the total project. What remains, as mentioned above, are mockups to practice the developed techniques, test hardware fitups and perfect procedures.

APPENDIX A – Agenda



Internal LCLS Undulator Alignment and Motion Review

Red Slate Conference Room (Bldg 280C, Room 112) , SLAC

Thursday, October 20 - Friday, October 21, 2005

A two-day internal review of the LCLS Undulator Alignment and Motion System will be held at the [Stanford Linear Accelerator Center](#).

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Agenda:

Thursday, October 20, 2005

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| 08:15 - 08:50 | Executive Session | |
| 09:00 - 09:20 | <u>Purpose of the Review and Charge</u> | David C. Schultz , SLAC |
| 09:20 - 10:00 | <u>Physics Requirements</u> | Heinz-Dieter Nuhn , SLAC |
| 10:00 - 10:30 | <u>Undulator Tuning Procedure</u> | Zack Wolf , SLAC |
| 10:30 - 10:45 | Coffee Break | |
| 10:45 - 11:15 | <u>Undulator Fiducialization Procedure</u> | Yurii I Levashov , SLAC |

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| 11:15 - 11:45 | <u>Quadrupole Fiducialization Procedure</u> | <u>Zack Wolf</u> , SLAC |
| 11:45 - 12:15 | <u>BFW Fiducialization Procedure</u> | <u>Zack Wolf</u> , SLAC / <u>Eric Lundahl</u> , SLAC |
| 12:15 - 14:00 | Lunch | |
| 14:00 - 14:30 | <u>Fixed Supports System Description</u> / <u>Support Mover System Description</u> | <u>Emil Trahktenberg</u> , ANL |
| 14:30 - 15:00 | <u>Roll-Away and CAM Motion System Design and Configuration</u> | <u>Jeff Collins</u> , ANL / <u>Emil Trahktenberg</u> , ANL |
| 15:00 - 15:30 | <u>CAM Motion System Controls Programming</u> | <u>Joseph Xu</u> , ANL (via VC) / <u>Jeff Collins</u> , ANL |
| 15:30 - 15:45 | Coffee Break | |
| 15:45 - | Executive Session | |

Friday, October 21, 2005

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| 09:00 - 09:30 | <u>Undulator Alignment Concept & Conventional Alignment</u> | <u>Catherine LeCocq</u> , SLAC |
| 09:30 - 10:00 | <u>Intra Girder Assembly and Alignment Procedure</u> | <u>Robert Ruland</u> , SLAC |
| 10:00 - 10:15 | Coffee Break | |
| 10:15 - 10:45 | <u>WPM Monitoring System</u> | <u>Franz Peters</u> , SLAC |
| 10:45 - 11:15 | <u>HLS Monitoring System</u> | <u>Georg Gassner</u> , SLAC |
| 11:15 - 11:45 | <u>Beam Based Alignment</u> | <u>Paul Emma</u> , SLAC |
| 11:45 - 12:15 | Discussion | |
| 12:15 - 13:30 | Lunch | |
| 13:30 - 15:30 | Executive Session | |
| 15:30 - 15:45 | Coffee Break | |
| 15:45 - 16:30 | Closeout | |
| 16:30 | Adjourn | |

APPENDIX B – Charge to the Committee

Internal LCLS Undulator Alignment and Motion Review

October 20 – 21, 2005

Purpose of the Review:

To establish that the proposed procedures and systems for LCLS Undulator System alignment can meet the tolerances required for the FEL to operate.

Charge to the Committee:

The LCLS undulator is comprised of thirty-three 3.4 meter long undulator magnet segments placed on an electron beam line. Between undulator segments are placed a beam position monitor and a quadrupole magnet. In order for the SASE FEL to saturate, the electron beamline must be straight to the level of about 5 microns over 10 meters. The BPMs and quadrupole magnets must therefore be placed precisely in a straight line. The undulator segments must be aligned relative to electron beam to an absolute accuracy of about 100 microns. The initial alignment is established upon assembly of the segment quad and BPM onto their support, their installation on the beamline, and the final alignment is accomplished through beam-based procedures. This alignment must be well maintained during machine operations with minimum impact on x-ray availability. The LCLS Undulator and Metrology groups have devised equipment and procedures to accomplish the initial and monitor the final alignment. The committee is charged with reviewing these plans. The committee is asked to evaluate the following:

- 1) Is the plan for establishing and maintaining undulator alignment sufficient for the operational needs of the Undulator System?
- 2) Is the plan complete?
- 3) Are the systems under development capable of meeting the tolerances needed for the alignment plan to be successful? Are there any viable alternatives?
- 4) Which technical aspects of the plan represent significant risk to the success of the project?
- 5) Is the R&D/test plan appropriate to the needs of the Project?

The committee is asked to report on its findings in a written report within a reasonable time following the review. All suggestions and comments are welcome.

APPENDIX C – COMMITTEE REVIEW NOTES

APPENDIX C-1

LCLS Undulator Alignment & Motion Review

Physics Requirements

In general, the physics requirements for the undulator system appear to be carefully thought out and achievable. In particular, the requirements for optical phase error, trajectory wander, and field integrals are consistent with what has been achieved elsewhere.

Undulator Tuning

The plans for meeting the requirements for undulator magnetic measurements and tuning appear to be adequate. In particular, the facility under construction for undulator measurements and fiducialization are very impressive. The suggested shim techniques appear to be affective for meeting the specified trajectory and field integral requirements.

Suggestions:

- The sequence of measurement steps presented should be altered so that step 5 (minimize phase errors) follows step 6 (straighten y trajectory), since the y trajectory shims will alter phase errors. The 10° tolerance on optical phase is fairly relaxed; it is likely that phase shimming will not be required.
- Since it is likely that environmental fields will differ from the measurement area to the installation in the tunnel, provision must be made for compensation in-situ. The plan as presented would have undulator field integrals measured in-situ and shimmed to correct field integrals. This is risky since the shims will also alter the trajectory. Consideration should be given to incorporating a simple dipole coil wound around the undulator structure. Correction will require a very small current.
- How will field integrals be measured in the tunnel? In principle, this could be done with beam based measurements, and corrected with the coil suggested above.
- The support system presentation suggests that the undulator support girder will be made of steel. If this remains the plan, the girder will have significant affect on the environmental field in the tunnel. Undulator field integrals should be measured with the steel girder in place. This would ideally be done for all undulators, but, at a minimum, should be done for at least one.

Quadrupole Fiducialization

The vibrating wire system has been thoroughly tested and appears to be very adequate for fiducializing the quadrupoles to the required accuracy. The only apparent issues is the accommodation of the vacuum tube. Does the quadrupole

need to be opened in order to install it around the pipe? If so, how will this affect the magnetic center location? If this is the plan for assembly, the reliability of this procedure will have to be clearly demonstrated.

APPENDIX C-2

Subject: LCLS Undulator Alignment and Motion Review 20 Oct 05

Here are my comments on the presentations we heard on Thursday and Friday of last week. Where everything seemed to be going well, I won't spend much time saying so.

1. Undulator tuning

This work looks well planned and supported by previous work at ANL and DESY. Like many other parts of the undulator system it does have issues of error propagation and tolerance build up. Zack's step 10 shows this explicitly where relating undulator magnetic axis to external alignment tooling balls is the sum of 3 separate types of measurements. There was much discussion of earth magnetic field effects and differences between lab measurements and actual undulator fields once in the tunnel. Both the strong-back and pedestals are steel so their magnetic effects have to be proven negligible or these components have to be incorporated into the measuring bench layout. At the end of the tuning section there was mention of measuring field integrals of individual undulators at their location in the undulator hall. This might be practical on delivery but I doubt it could be done once undulators were mounted.

2. Undulator fiducialization procedure

Using a portable tooling frame carrying a strongly inhomogeneous magnetic field may be the only practical way to relate undulator tooling balls to the undulator's magnetic center. Again there are a number of steps to this metrological sequence. There is an implicit assumption built into the technique that the location of the frame's magnetic null determined on the calibration bench does not shift when the frame is attached to an undulator for determination of the undulator magnetic center with respect to frame's magnetic center using the undulator tuning bench probe. Does the permeable undulator structure distort the field of the needles? The frame's magnetic center should be regularly checked with respect to its tooling balls to correct for any drift of the null location with time.

3. Quadrupole and Beam Finder Wire fiducialization procedure

Adding harmonic frequencies to the standard vibrating wire quad centering technique is a clever method of extracting quad pitch and yaw as well as x & y coordinates of quad center.

The beam finder wire is an instrument recently added to the undulator system whose main purpose is to measure alignment of each undulator section's trailing end with respect to the the beam trajectory. Like many other aspects of undulator alignment, construction and calibration of beam finder wires for each undulator have the danger of a tolerance build up whose systematic and statistical offsets will be difficult to discover during operation. As an historical example of a similar piece of equipment, when SLAC's 2 mile linac was constructed, unknown mechanical offsets in the fiducialization of Laser Fresnel alignment screens with respect to the accelerator section axes led to misalignments of the linac which were much greater than the resolution of the Fresnel lens system itself.

4. Fixed supports and mover system

4.1 Pedestals

The first image of this presentation shows the pedestals standing up off the floor on studs without supporting grout. It took some time to understand the unstated assumption behind this design. The undulator system's temperature is intended to be controlled by air conditioning and to be thermally insulated from the floor. I guess this desire to force undulator temperature to the same value it had during magnetic measurement and shimming comes from the sensitivity of the permanent magnet material to changes in temperature. Whether an air conditioning system can more tightly regulate temperature than the tunnel floor without introducing thermal gradients and distortions as well as its own time structure to the undulator field remains to be seen. As a result of this desire, each pedestal sits raised up above the floor on 4 studs. There are several details of this design which can lower the stiffness and natural frequency of the support structure. There are the studs themselves whose axial and shear stiffness is much lower than the pedestal itself. Then there are the 4 tabs of the pedestal base which act as springs unless gusseted. Finally, the weight of the undulator and support structure is transmitted to the floor through the nut-to-thread interface on the bottom nuts under the pedestal plate. Its a subtle point but carrying dead weight on threads often significantly lowers resonant frequency. This type of support had to be removed from the SLAC FFTB design and replaced by solid columns where bolts were only used to generate hold down force before the support natural frequency was high enough. Using floor studs for manual adjustment of final alignment will be awkward since they are so far below the beamline. Those adjustments would be easier if they were located at the top of the pedestals

4.2 Cam positioners

The choice of servo motors over stepper motors was not clearly justified. In general servo motors with their internal feedback loop are faster, smoother and higher resolution than steppers but none of these performance advantages are particularly important in this application. At 120:1 reduction, a standard 200 pole stepper motor has sub-micron resolution. Speed is not an important issue; average move times of 30 seconds are sufficient. Some people have complained about the buzz heard from steppers but their performance has been adequate in every respect. Furthermore they are cheaper and provide a natural position holding detent which servos do not. In any design, the quiescent state must be zero electrical power otherwise thermal gradients will distort alignment. This is the natural way to run steppers but increasing the gearing on a servo motor from 120:1 to 250:1 in order to turn off its feedback loops will only introduce additional mechanical hysteresis into the system. Its hard to make long gear trains stiff. Brakes that lock in the power off state would seem cheaper and simpler for either stepper or servo even though this costs one more conductor to unlock brake before each move.

The hardening of the undulator shoes which rest on the cams should help performance. It appears that z position of the undulator along the beam line is now fixed by a shoe design that grips the side faces of the cam. A z restraint design like this was tried at SLAC 20 years ago and caused a lot of trouble until it was changed. During operation, the undulator will eventually walk up or down the beamline until it begins to slide against this restraint. Friction here leads to a number of microns of positioning error. The solution was to use a separate link connecting the undulator to the pedestal to fix the z position. The link can be either a strut with rod ends or a flexure rod.

Work at Argonne has pointed out that during undulator yaw motion, cam contact shoes will slide over the cams. This sliding motion will be greatest at the single cam support at the 3-cam end of the undulator. The effective center of rotation for yaw motion is half way between the 2 cams which carry the V shoe at the 3-cam end. When the undulator is asked to yaw around this point, its single cam shoe sweeps across the top of that cam support. The present design has a maximum range of about 1 milliradian yaw. This leads to about .3-.4 mm motion at the single cam support. The first version of 5 cam supports used on the Stanford Linear Collider 20 years ago used self aligning spherical cam bearings to avoid sliding motion. Subsequent versions have ignored this potential problem and used conventional cam follower bearings. This aspect of the positioning system needs further investigation. The cam support system that has been built for magnetic measurement at SLAC has the same potential problem and could be used to investigate it.

One solution proposed at Argonne is to split all cam bearings into two narrow highly crowned bearings and use an inverted V shoe contacting both bearing halves simultaneously. I am guessing that the thinking was for the two side-by-side cam bearings to absorb yaw motion by counter rotation. This will not work and that design may introduce further problems of its own. It is a fact of geometry that a rigid body can be positioned by no more and no less than 6 points of restraint. We have 5 cam contacts plus a z restraint link so each shoe surface can contact its cam at only one point, not two. Making the shoe in the form of an inverted V will not permit it to simultaneously contact both sides of a split cam bearing. As the undulator position is adjusted, the contact position may shift from one half of the split bearing to the other but it can never contact both sides at once if we are dealing with a rigid body. Splitting the bearings only cuts their load capacity in half

4.3 Undulator Transverse Roll-out

Now that undulators are to be supported on intermediate transverse roll-out mechanisms and are no longer kinematically supported on the cam systems, there are new potential problems of over-constraint at the undulator mount interface. The current layout depends on interlocks to protect it from large mechanical forces which would develop if x slides at each end of the undulator did not move in coordination with each other. If one x slide tried to retract the undulator off the beamline but the other did not follow, something would overload or break. Any lack of parallelism between the alignment of these two x translators will lead to bending or twisting of the undulator. Some type of kinematic mount or system of flexures needs to be developed to remove over-constraints¹

5. Installation Alignment

Conventional survey and alignment looks well planned and has been done many times before. SLAC plans to shim mounting surfaces on undulators to standardize the mount dimensions. The goal is for all tuned and fiducialized undulators to be interchangeable. This requires the undulator mount design be coordinated with Argonne. It was not clear whether a similar standardization of dimensions would be done on the support girders for the dimensional relations between their roll-away slides and their cam support shoes. If this is not done, girders must be uniquely aligned at each location in the undulator hall. Alignment of pedestal cam supports will then have to wait for each unique girder to be brought down and installed with its undulator mounted since the quad and undulator fiducials are needed to align the cam positioners on their pedestals.

Because the girders extend considerably beyond the cam positioner pedestals, motion of quadrupoles and diagnostics at the ends of the girder will be magnified. The compliance of beam pipe bellows connecting girder to girder needs to be verified. In particular, twisting needs to be checked since the cam positioner system is capable of roll motion. Beam pipes and the bellows should be designed to survive the maximum range of relative roll between girders.

6. Wire Position Monitors and Hydrostatic Levels

Both these systems are showing promise for extending the time intervals between full beam-based realignment of the undulator system. Both these systems have micron resolution but the WPS and HDL both depend on precision metrology of off-sets so it is uncertain how great a roll they will play in the initial installation alignment. Assuming initial alignment is good enough to transmit beam and start the initial beam-based alignment procedure, WPM and HDL will give valuable tracking of subsequent alignment deformations. While the correlation between signals from these two monitoring systems and actual misalignment may not at first be as direct as expected, the evolution of misalignment will not be a random stochastic process. A branch of control theory called applied optimal estimation will allow the correlations between sensor signals and actual misalignment to be determined.

¹ Thermal expansion of the Ti undulator strong-back is close to that of the steel support girder. Never the less, temperature excursions during storage or installation could lead to forces between these 2 structures. A change of 10°C causes a 25 μm differential expansion between girder and undulator over the 1.9 meters between supports.

Support System

My primary concern is the use of steel supports and girder. These are likely to result in a perturbation to the environmental field that is significant compared to the tolerances on undulator field integrals. The primary reason presented for using steel is that the coefficient of thermal expansion is closely matched to that of the undulator's titanium backing beam. Given the tight temperature control in the tunnel, this should not be an issue. Furthermore, if the mounting of the undulator to the girder is kinematic, moderate temperature excursions should not affect the alignment. The use of steel for girder and supports should be re-evaluated.

Intra-girder Assembly

The assembly procedure appears to be well thought out up to this point. However, many of the component details and component interfaces have not yet been defined. In particular, the vacuum chamber support and integration needs careful attention. Clearance between the chamber and undulator is very tight, especially since this must accommodate lateral motion of the undulator.

Beam Based Alignment

Beam based alignment is critical for the success of the LCLS. The scheme presented appears to be well thought out and well tested.

General Comments

My primary concern is the plan for thermal management. This issue was not directly a part of our review, but is integral to the issues we were asked to consider. My understanding of the thermal management model is the following:

The temp. for undulator measurements. and tuning needs to be fixed and controlled to fine level. The choice is $20^{\circ}\text{C} \pm 0.1^{\circ}\text{C}$ (the fixed temperature choice appears to be somewhat arbitrary, but is fine). The tunnel temperature is forced to the same fixed temperature to insure alignment and operating conditions are the same as they were during measurement, assembly and fiducialization.

The concern with this model is that if the natural tunnel temperature is different than 20°C , actively forcing it may result in temperature gradients (spatial and temporal) may be very difficult to control. An alternative may the following model:

Allow the tunnel to settle at its natural equilibrium temperature. This will likely be somewhat different than 20°C . There must be enough active temperature control to eliminate spatial gradients along the length of the tunnel. The primary affect of operating at a slightly different temperature

will be a uniform, slight change of K. This shouldn't be a problem. The tuning will not be affected. This model assumes that kinematic mounting is scrupulously followed. If not, alignment errors can occur with temperature changes.

Scenario 2 can be tested by tuning an undulator and aligning all components on a girder/supports at 20°C, then retest and recheck alignment at different temperatures.

APPENDIX C-3

LCLS Undulator Alignment & Motion Review

October 20-21, 2005

1. Physics Requirements

The physics requirements for the undulator system are clearly described, well demonstrated, and attainable. Starting from the general requirements and the nominal undulator component parameters, a thorough analysis of the tolerance budget was performed using Genesis Simulations. To meet those tolerance requirements, at component and system level, a realistic and comprehensive alignment procedures sequence was developed.

2. Undulator Tuning and Fiducialization

In order to accommodate for production measurements and fiducialization of undulator system components, an impressive Magnetic Measurements Facility (MMF) lab is under construction. The work planned for undulator tuning is based on previous experience developed at ANL and DESY and is adequate, as well as the instrumentation systems. The proposed poles shimming procedure is well thought and covers both the specified trajectory and the field integral requirements. I suggest performing the shimming to minimize the phase errors after completing both X and Y trajectories straightening shimming.

Because additional field corrections due to Earth magnetic field as well as other possible environmental magnetic fields differences between the tunnel and the MMF lab may be required, under the current plan the undulator field integrals would be measured in-situ and compensated by shimming. There are two issues that remain to be detailed here: how would the field integrals of individual undulators be measured in the Undulator Hall, and how would the correction shimming process take place without influencing the X and Y trajectories straightness. Alternatively, it was proposed installing a mu-metal shield around the undulators, yet to be detailed.

Consideration should be given to incorporating the support steel girder and its pedestals into the measuring bench system and performing field integral measurements on undulator-girder as an assembly at MMF. This would eliminate the influence of the steel girder magnetic effect on the environmental field in the tunnel.

The fiducialization procedure and the error budget associated with each step appear to be realistic.

3. Quadrupole and Beam Finder Wire Fiducialization

The vibrating wire system using resonant frequency is a very elegant and sensitive technique for fiducializing the quadrupoles, with the clear capability to achieve the accuracy requirements. While the system is being constructed, there are still repeatability and bias tests to be completed. During these remaining tests, it was suggested to investigate, even if the measurements on X and Y are performed separately, if there is any correlation propagating through the system.

Other questions still remaining to be detailed would be: when, with respect to the fiducialization process, and how will the beam pipe be installed inside the quadrupole. More specifically, if the beam pipe installation would have any effect on the final quadrupole fiducialization accuracy results.

The Beam Finder Wire Fiducialization was considered in two scenarios: during the initial installation of the BFW, and during the replacement of the BFW. The fiducialization accuracy requirements are only roughly specified, and the detailed error budget is yet to be finalized. With this component, more than others, there is the potential danger of a tolerance build during the fabrication and fiducialization, and also unforeseen mechanical offsets during installation and final positioning. The assembly tolerances for the BFW need to be thoroughly examined so that the wire positions are realistically determined and controlled wrt to undulator axis.

Since no adjustment mechanisms for precision positioning of the cross-wire was provided in the current design, the BFW offsets for each of the 33 Undulator Segments will be needed to be summarize in table. In the current design, the BFW is attached to the vacuum flange and not to the supporting (rigid) steel girder. There is a concern that the BFW fiducialization results (offsets) will change once the Undulator System is brought under vacuum and the flange may move to some extent. Considerable thought to detail is needed to finalize the replacement fiducialization procedure since it starts with implicit assumptions (b and c) built into the procedure and difficult to control. It is also suggested that the assembly defined by the undulator beam pipe, BFW, Ion pump needs to be examined for installation /assembly procedures and rigidity.

4. Support and Movers System

With respect to the design of the girder supports (pedestals), the location of the 4 vertical stand adjustment bolts should be reexamined. I suggest moving the elevation adjustments from the bottom (floor) support plates to the top support plates, as close as possible to the girder. Other suggestions are considering using 3 instead of 4 vertical adjustments points for the girder, and also providing Z adjustment capability for the CAM Support Plates and girder assembly.

The cam-shaft mover system being developed is capable of meeting the specification requirements on both transverse directions, and the testing program appears adequate. During testing a series of problems with the CAM mover system have been recognized and changes have been implemented to improve performance. More in-depth tests are under consideration. Among them, checking the repeatability of linear potentiometer after being fully extended (undulator roll-out - roll-in scenario).

No details were presented on how the undulator beam pipe (vacuum chamber) is aligned and supported, while its tight alignment tolerances must allow the undulator roll-out motion under tight clearance. Currently, it was no apparent provision for X adjustment capability for the vacuum chamber.

5. Conventional Alignment and Intra Girder Assembly

The conventional survey and alignment plans are very well thought and well demonstrated through previous experience. Even if the complete Undulator System alignment exceeds the capabilities of traditional survey techniques, the tolerance requirements for the conventional alignment phase still calls for high-end level of surveying methodology and instrumentation. All the details presented, starting with the geodetic aspect of the Undulator Coordinate System, continuing with the high accuracy underground Undulator Hall network, and then the precision components alignment and monitoring, are clear and very realistic. There are some details left to be worked out, such as incorporating the tunnel network infrastructure into the conventional facilities plans.

The intra-girder assembly and alignment is very well thought at the concept level. In order to finalize the planning, more engineering details (including drawings) about specific components and their interfaces need to be defined.

6. Beam Based Alignment

The Undulator System alignment can be achieved at the required tolerance level only using the beam-based technique. The plan presented for Beam Based Alignment appears to be well thought out and supported by detailed simulations.

7. Monitoring Systems

The monitoring systems proposed consist of a Wire Positioning System (for horizontal monitoring) and a Hydrostatic Leveling System (for vertical monitoring). The systems are well developed and their limitations are being thoroughly investigated. They also show great potential for easing BBA requirements.