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Stability of the LCLS Undulator Hall

Implications of Wire Alignment System Measurements made at the FFTB in 1994 and 1996

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Stability of mechanical and electrical offsets of the bpm's in the LCLS undulator section is critical to obtaining and maintaining stable FEL lasing. Simulations show that for the LCLS running at 1.5 Angstroms if the electron beam develops a 2 micron rms deviation from a perfectly straight line over a distance of about 10 meters, the FEL saturation length will increase by one gain length.[1] Nominally the feedback system will take changes in the electron beam trajectory, measured by the bpm's, calculate and apply orbit corrections relatively easily. However, the efficacy of this technique relies on the ability of the bpm system to detect real electron beam trajectory changes at the level of 1 micron rms. One source of error in the determination of the electron beam trajectory is through changes in the mechanical or electrical offsets of the bpm's. Such offset errors are erroneously imposed on the real beam trajectory by the feedback system. Bpm mechanical and electrical offsets can be determined by beam based alignment techniques using electron beams of different energies. However this measurement is time consuming and cannot be used during normal operation. Therefore it is of paramount importance to keep mechanical and electrical offsets as stable as possible — on the scale of a few microns over a period of at least a day.

As part of the R&D for the NLC, studies were carried out in 1994 and 1996 in the FFTB tunnel where the LCLS undulator is to be housed, which measured magnet motion using a wire alignment system with an inherent resolution of 100 nm. The reference wires extended in four sections for a total length of about 440 feet starting near magnet QA2 near the muon shielding in the beam switchyard and ending about 85 feet out into the research yard section of the FFTB. The planned location for the LCLS undulator section partially overlaps the area where the measurements were made. Two papers were written describing measurements made with the system: one by Assmann, Salsberg and Montag,[2] and another by K. Flöttmann[3]. I will discuss the results from these papers and what they imply for the LCLS.

As both efforts were mainly interested in the effect of magnet motion on the obtainable electron beam spot size and the stability implications to future linear accelerators, they concentrated on finding the most stable conditions that could be obtained, even if such conditions could only be obtained for a short time and over a limited area. In the LCLS case it will be necessary to have adequate stability for essentially year round operation over the full 120 m length of the undulator and there is no possibility of choosing an alternate site which might be quieter. Approximately 80% of the tunnel where the measurements were made were within the relatively stable underground (beam switchyard) portion of the FFTB. Unfortunately for the LCLS, about 80% of the undulator will be located in the less stable above ground (research yard) region of the FFTB tunnel.

For example, the data used by Assman et. al. was

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taken from a six day period chosen with "extreme care" so as to minimize the temperature variations in the tunnel. The magnets were switched on and the tunnel closed for one week before the measurement started. They chose the rainy season during which to make the measurements to minimize the daily outside air temperature variations. Also they took the measurements during a time without beam. Nevertheless there was an unavoidable Monday morning tunnel access whose effect dominates the data. In the case of Flöttmann, the data was collected over a longer period of time, 14 days. About halfway through the measurements, the FFTB magnets were switched on and the effect can be seen dramatically in the measurements. Flöttmann concentrated on analysis of data from the second half of the run because conditions were most stable then. In both papers anomolies in the data which indicated large motions were dismissed when quoting stability numbers because the causes could be either be identified or presumably would not be of interest for linear collider R&D. In the LCLS case such anomalies might very well be present during operation unless appropriate changes can be made to the existing site.

I will summarize the observations below. The stability numbers refer to the measurement of the distance between a tension controlled wire and bpm-like wire monitors that were attached to magnets which were located atop the Anocast stands that were used to hold up the FFTB magnets. The stands are mounted on concrete columns that are built into the underlying sandstone bedrock. Motion of the endpoints of the wire as a whole was taken out of the data by subtracting an appropriate fit to the observed motions. For example, if all magnets were displaced horizontally along a perfectly straight line, the readings would be interpreted as the motion of the wire terminators and no magnet motion would be counted. The distance between adjacent measurement points varied but was typically about 7 m. Each section of wire was approximately 40 m long so spatial correlations over a distance of 40 m or longer were eliminated from the data by the fitting procedure. Where several magnets were mounted close together on the same support the readings were averaged together.

Assmann et al. Measurements

Assmann et al. made measurements in wire sections 1 and 2 of the four wire sections available over period of 140 hours in March 1996. Section 1 starts near the muon shielding and runs for about 40 m toward the research yard. Section 2 starts immediately after section 1 and is also about 40 m long. Both sections are completely within the beam switchyard housing and about 50 feet below the surface of the earth. The paper contains plots of the data from 6 magnet positions in section 2 taken over a two hour period, and from the horizontal and vertical readings from the middle magnet in section 1 taken over 140 hours. Excerpts of the data are shown in Figures 1 and 2. The data show,

- typical short term drift rate of order 1-2 microns over 2 hours in each of the section 2 magnets
- medium term drift rate of 3.5 microns over 100 hours in the section 1 magnet
- vertical spikes where the magnets appears to move up to 5 microns and then return to the original position occurred every few minutes in the section 2 magnets
- a total range of motion during the measurement period of 15 microns over 180 hours in the section 1 magnet.

"Drift rate" means here that the measurement data has a component that appears to vary linearly with time, at least over the period of time indicated. The short term drift rate of the section 2 magnets indicates that a 2 micron rms would be reached in substantially less than 24 hours as the measured drift velocities would extrapolate to motions of the order of 20 - 50 microns. If there were no spatial correlation among magnets the rms motion assuming constant drift velocity would be 6 - 15 microns over 24 hours. While there is significant spatial correlation on the 10 m scale visible in the data, it does not appear to be sufficient to conclude the uncorrelated rms motion is below the 2 micron level in 24 hours needed for less than once per day beam based measurement of the bpm offsets.

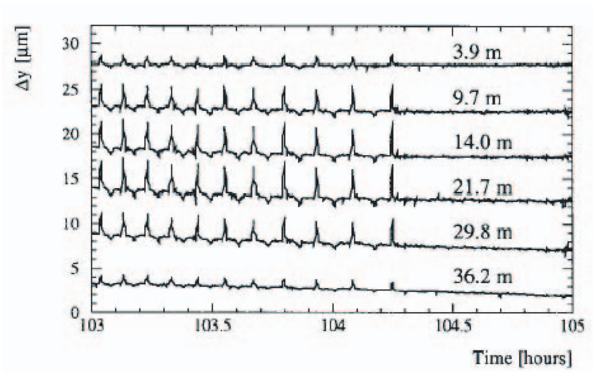

Figure 1: Vertical magnet positions are plotted as a function of time. The distances indicate approximately the distance from the magnet to the muon shielding inside the beam switchyard.

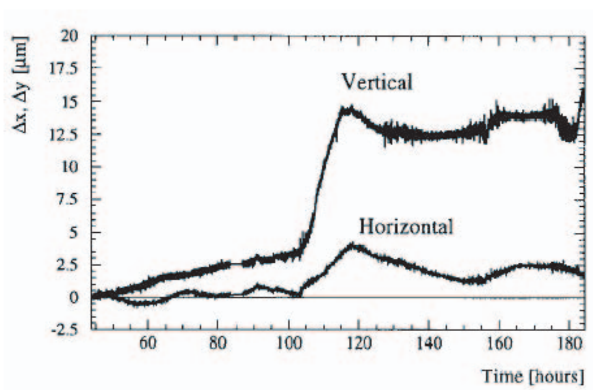

Figure 2: Vertical and horizontal magnet position for a magnet located well inside the beam switchyard portion of the FFTB.

On top of the short term drift, spikes were observed on all magnets positions on the section 2 wire. These were correlated from magnet to magnet in the sense that they all moved in the same direction. However the end magnets had much smaller spike amplitudes compared with the middle four magnets. The source of the spikes was not identified but the authors concluded that it was neither electronic nor thermal.

Out of the dozen or so magnets that were measured the data from only one in the middle of section 1 was plotted in the paper for the full 140 hours. It was not clear whether this represented a typical, particularly stable, or particularly unstable magnet.

It is worth noting that in the Assmann et al. paper the data was fitted to the "ATL law".[4] The ATL law is a phenomenogical observation that the rms relative position change σ of two points attached to the ground a distance L apart, after a time T obeys

$$\sigma^2 = A \cdot T \cdot L$$

where A is a constant dependent only on the site. The rule is equivalent to saying the relative positions of two points obey a random walk process, hence the variance grows as the square root of time, with a step size that is proportional to the distance between the points. When the entire data set was used for the fit, including data from the Monday morning access, they found a value for A that grew linearly with time interval and concluded that the ATL law did not apply. In fact the value for A reached about 9×10^{-6} $\mu\mathrm{m}^2/(\mathrm{m} \cdot \mathrm{s})$ for a measurement interval of only 14 hours. They also calculated the value for A excluding data from the Monday access and got a value about 20 times lower. This lower value, 5×10^{-7} $\mu\mathrm{m}^2/(\mathrm{m} \cdot \mathrm{s})$ was used to estimate that the LCLS would need to measure the bpm offsets about once per month [5] .

The ATL law is a very useful tool used to estimate the effects of magnet motion on beams. However there are several assumptions implicit in the estimation of the time interval between beam based offset measurements for the LCLS which might be difficult to realize in practice.

The data suggests that the ATL law really does not work at this site over the time scales of one week. It was only by excluding the largest real motion data that the low value of A was obtained. The LCLS will have accesses and there may be other 'cultural' effects that occur on a daily or weekly basis which can also produce large motions and are not present in the data sample from 1996. Using an estimate obtained by excluding the data from the access day one implicitly assumes there will be no such events in the future without even really understanding what happened in the past. In fact there may be a better predictor of magnet motion than the ATL law in this case. If all magnet stands were simply moving at more or less constant velocities, which differed from stand to stand,[1] the ATL law would not work as the variance would grow in proportional to time. This was in fact the statistical behavior observed in the full data set. On long time scales, this constant drift hypothesis would seem as reasonable as the random walk hypothesis assumed by the ATL law, but lead to very different predictions for the beam based measurement interval.

Another assumption is that the observed stability measured in sections 1 and 2 is the same as it would be for the rest of the undulator. This is especially doubtful since the majority of the undulator will reside in the research yard section of the FFTB tunnel. The above ground section of the FFTB is subject to large daily heat fluctuations from the outside air and sunlight, as well as stresses from the research yard pavement which expands during the day and contracts at night. It is further assumed that the measurements can be applied to year round operation of the LCLS. On the contrary it is likely, as the authors themselves suggest, that greater motions occur during other seasons. Finally, the data was only collected over 6 days so it does not support extrapolation to periods of one month.

[1]G. Fisher, in the detailed paper *SLAC Site Geology, Ground Motion and Some Effects of the October 17, 1989 Earthquake* (1989) SLAC-358, page 6, mentioned that if one looks at alignment data from the linac on a year by year basis, on the average the motion is nearly always in the direction it took in earlier years.

Flöttmann Measurements

The data from Flöttmann is similar in character to the Assmann data but is more detailed and covers a longer period of time. In addition Flöttmann measured magnet stand temperatures and attempted to understand the thermal component of the observed motions. The data was taken during a two week period in the spring of 1994. Both raw data and data corrected for wire motion, delibrate magnet motion of less than 3 microns total range, and known thermal expansion effects are given. Flöttmann used all four wire sections available including the last section which is partly in the research yard portion of the FFTB housing. The data were presented in a chart recorder format with a scale of 10 microns/division. An example is shown in Figure 3. On day six of the run the FFTB magnets were turned on and the magnet stand temperature went up about 3 degrees C within the next 24 hours.

From the data presented in the paper one can see,

- About 100 micron range of motion occurred over 14 days for one magnet in the research yard section of the FFTB.
- Overall about 1/2 of the observed range of motion can be explained by measured stand temperature changes and the known thermal expansion coefficients. The remaining motion is unexplained but largely correlates with turning the magnets on.
- A 15 micron motion over 7 days was observed at a favorable location in the buried section of the FFTB.
- A 3 micron day-night periodic motion was observed at a favorable location in the buried section of the FFTB.
- The research yard section as a whole seems to move through a range of 35 microns vertically and 30 horizontally periodically on a daily basis relative to the beam switchyard portion of the FFTB, independent of magnet stand temperature. The daily motion can be seen in Figure 4.

- The research yard section shows an additional drift rate of around 5 micron per day.

- Temperature correlated drifts anywhere from about 1/2 of theoretical to 5 times theoretical were present.

- Just as it turned out for the Assmann et al. data, it proved impossible to obtain 'stable conditions' for more than a week at a time. Besides the major changes brought about by turning the magnets on, there are numerous spikes and steps, of 5 to 10 micron size, that occur roughly once per day.

A glance at the Flöttmann measurement in Figure 3 shows that the measured mechanical stability of the both the underground and especially the above ground section of the existing FFTB is far worse than a few microns per day required for LCLS by at least an order of magnitude. The most egregious motions occured during access or when magnets were turned on and the temperture rose 3 degrees C. It is expected that the LCLS undulator hall will have good inside air temperature control which will mitigate some of the motions, but it is largely unknown how much this can help. Flöttmann found that overall about half of the measured motion was accounted for by the change in the magnet stand temperature, so we might expect if nothing else is changed, the motion for a temperature controlled LCLS undulator hall to be about half as much as was observed historically. However, the LCLS has to be stable essentially year-round, except for short transients, and almost certainly the historical measurements underestimate the size of the motions that can occur during the worst time of the year.

Unfortunately is not possible to extract much information about the spatial correlation of the motions over 10 m separation distance from the Flöttmann paper especially at the level of precision of 1 micron per day, due to the large size of the observed motions and the limited data presented. Magnets that were located in different wire sections, roughly 40 m apart, did not seem to have correlated motion. From figure 18 in Flöttmann's paper one can roughly estimate that the range of the uncorrelated component of motion from magnet to adjacent magnet (an average of 7 m apart) is at the level of 4 or 5 microns over 24 hours.

Implications

For stable operation of the LCLS FEL at 1.5 Angstroms the electron beam trajectory must be straight within 2 micron rms over 10 m — at least an order of magnitude smaller than the observed magnet motions in the FFTB measured relative to a best fit straight wire approximately 40 m long. The Flöttmann and Assmann et al. data suggest that if the mechanical stability of the support system for the LCLS undulator bpm's is not greatly improved relative to the FFTB magnet stands, the process of measuring of the bpm offsets, which involves at least three different beam energies, will need to be done more than once per day.

The causes of the motions are not well understood but both cultural and natural causes are known to be present. A factor of 2 stability improvement might be expected by maintaining tight internal air temperature control, but there still remains a substantial shortfall in performance. In the data the presence of correlations over magnet separation distances of longer than 10 m leads to overestimates of the relative motion that can be expected over the 10 m (or less) length relevant to the LCLS. On the other hand the measurements were made in favorable locations and during the most stable time of the year, consequently we should expect significantly more motion would be present during the rest of the year and in the less favorable locations of the LCLS undulator bpm's. The net effect of shorter correlation length and less favorable conditions could be either positive or negative.

New Support Options

Given the possibility that relatively poor stability might result with an FFTB style support system for the bpm's, one is led to consider other means to reduce the risk. Three basic approaches present them-

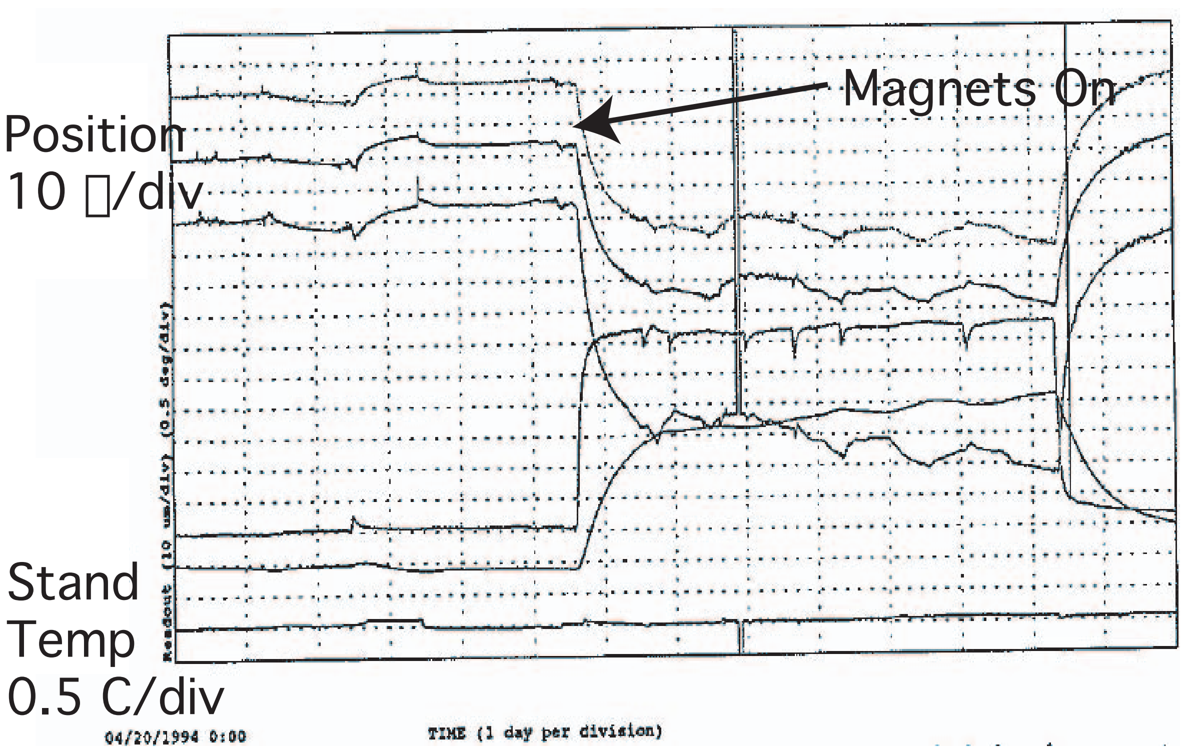

Figure 3: Magnet position and magnet stand temperature traces are shown for the QT3 magnet over a period of 14 days.

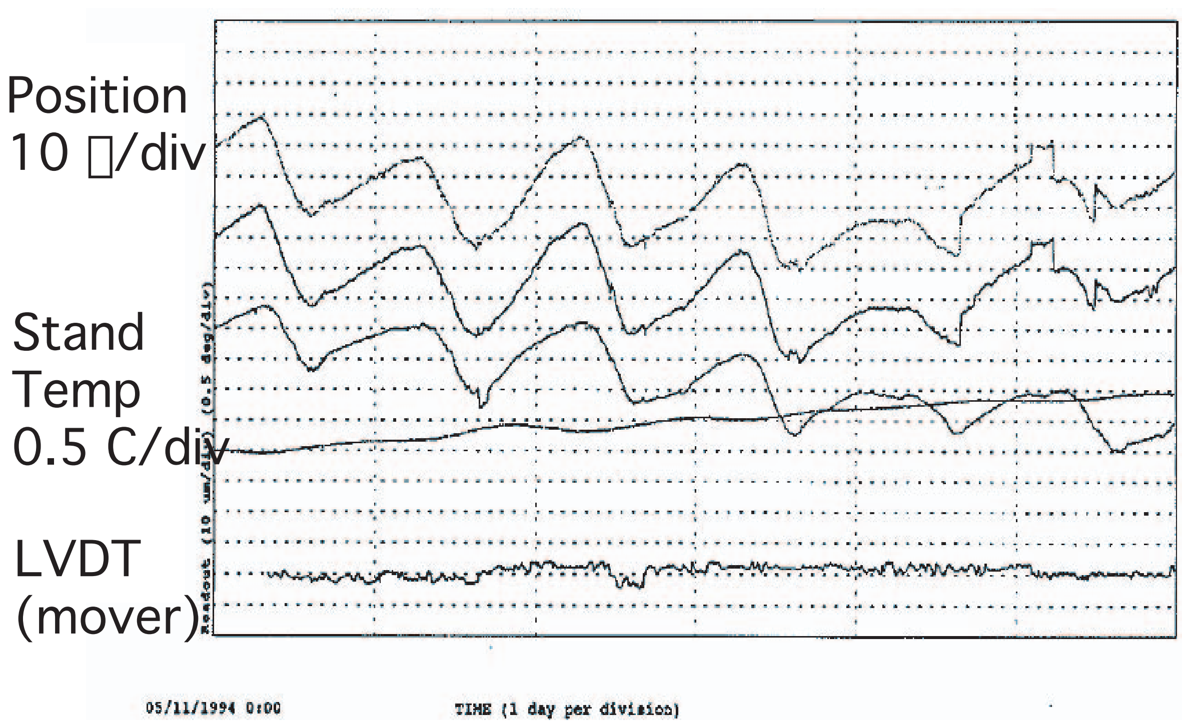

Figure 4: Magnet position and magnet stand temperature traces are shown for the QC4, located in the research yard, over a period of 7 days. Large daily motions are present.

selves which are explained in the following sections.

- Geotechnical Improvements
- Undulator Monitoring System
- Ground Motion Isolated Strongback

Each approach could be taken more or less independently of the others, or all could be pursued simultaneously. Geotechnical improvements could be done at whatever level was cost effective and would reduce the demands on the monitoring system and the strongback stability. A ground motion isolated strongback would likewise reduce the demands on the monitoring system. By employing multiple approaches we reduce the demands on any one system and improve the overall performance. Ideally the overall system can be made stable enough that the need for remeasurement of mechanical offsets will not have a significant impact on running time.

Geotechnical Improvements

Geotechnical improvements could be made to the undulator hall and surrounding earth to reduce the temperature fluctuations of the foundation, walls, ceiling and even bedrock — all of which can contribute to motion of the bpm's through thermal expansion and contraction. The undulator hall structure and foundation could to some extent be mechanically decoupled from the surrounding research yard pavement and even bedrock. In addition there may be motion of the ground associated with changes in the water table which in principle could be addressed through drainage modifications. Once the basic layout and location of the undulator hall is fixed this approach could be pursued with geotechnical engineers. One such speculation is shown schematically in Figure 5.

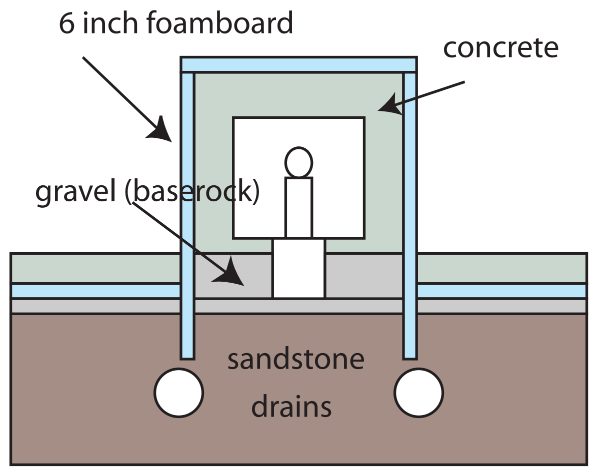

Figure 5: Schematic showing some geotechnical modifications to the exiting FFTB housing that might improve the bpm support stability. Foamboard 6 inches thick will essentially block heat flow at the level needed and reduce the transmission of stresses from the research yard payment to the FFTB housing. Drains deep in the sandstone insure the water table stays well below the base of the support.

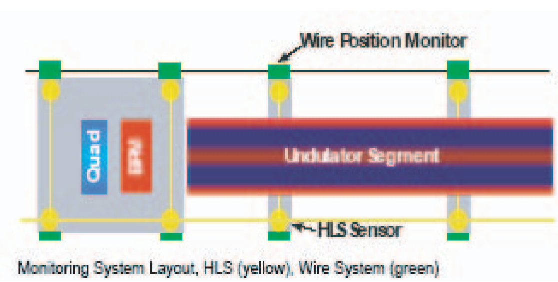

Figure 6: Schematic showing the layout of a wire positioning system for the LCLS undulator section. The HLS is a hydrostatic level detection system for vertical measurements.

Undulator Monitoring System

An undulator monitoring system which can measure motion of bpm's with respect to reference wires and a hydrostatically determined level and then compute the changes in the bpm mechanical offsets, is described in chapter 12 of the LCLS CDR. Figure 6

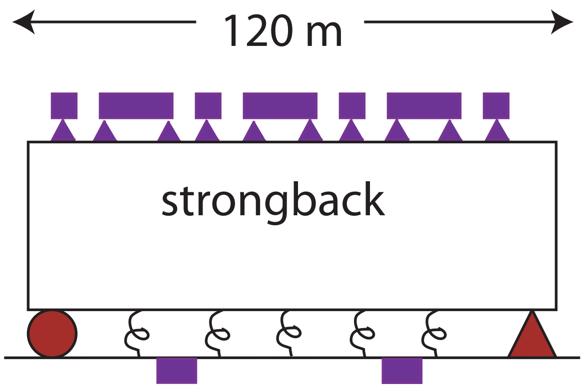

Figure 7: A schematic showing a single long stiff support stronback on which components of the undulator are mounted. The strongback is mechanically isolated from ground motions and thermally well insulated so that it does not develop significant thermal strains. Several utility troughs are jumped over with this method. There a quite a number of such troughs in the FFTB and in the research yard which would present difficulties if they had to be removed and rerouted.

shows a brief schematic of the system. This system would monitor the bpm, quad, and undulator positions simultaneously. If this system were truly stable there would be little concern for the actual stability of the supports as offset changes could be fed into the electron beam feedback system quickly and undulators and quadrupoles could be moved using the cam movers, as long as the actual motions were not outside the bandwidth of the monitoring and correction devices. Generally speaking vibration is not an issue for the LCLS bpm's because the amplitude of vibrations is not large enough to be significant — typically only 10 - 100 nm. So to the extent this system is stable we would not need to perform another round of beam-based measurement of the offsets.

Ground Isolated Support Strongback

As mentioned above, the root causes of the observed magnet motions are not well understood. It seems likely that the bedrock itself does not have adequate stability. In this case the support of the bpm's will have to be isolated from motion of the bedrock and a new concept of a support system is needed. One such idea is to mount all the components, bpm's, quads, and undulators, on (or in) a single 120 m long strongback structure that is isolated from the ground motion by compliant supports. The stability of the strongback would then determine the position of the bpm's so their stability would not be at the mercy of the the local ground motion. Such a structure can be made stiff to resist transverse deformations over a length of less than or equal to 10 m so that incidental forces don't produce excessive motions. Deformations over lengths of more that 10 m will not decrease the FEL output, though in principle they could affect the output beam steering. Because of the enormous length, the strongback will have to be assembled in place and compliant supports will be needed to support the gravitational load. Only the end points need to be tied to the ground, one with a pivot and one free to expand. A version of this idea is shown in Figure 7, with the undulator and bpm/quad segments placed above the strongback There is also the possibility that the undulator components could be located within the strongback structure thereby allowing for more cross-sectional size and stiffness and providing a natural mini-environment for the undulator. In this case access through the wall of the strongback would need to be provided.

References

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