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Ground Motion Improvements in SPEAR3*

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SPEAR3 is a third-generation synchrotron light source storage ring, about 234 meters in circumference. To meet the beam stability requirement, our goal is to ultimately achieve an orbit variation (relative to the photon beam lines) of less than 10% of the beam size, which is about 1 micron in the vertical plane. Hydrostatic leveling system (HLS) measurements show that the height of the SPEAR3 tunnel floor can vary by tens of microns daily without thermal insulation improvements. We present analysis of the HLS data that show that adding thermal insulation to the concrete walls of the storage ring tunnel dramatically decreased diurnal tunnel floor motion.

Keywords: accelerator, synchrotron, radiation, optics, heat, ground motion

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I. INTRODUCTION

The Stanford Synchrotron Radiation Lightsource (SSRL) provides high-energy photon beams to a large variety of users working along a 234-meter circumference electron storage ring (SPEAR3). To minimize errors in the users experiments, it is essential that the electron and the photon beam remain stable over a long period of time. However, maintaining long-term vertical stability of the beam is a real challenge, mainly due to ground motion. A Hydrostatic Leveling system (HLS) observed that the storage ring tunnel floor can shift vertically on the order of tens of microns, diurnally. This led to some difficulties for SSRL users who need the photon beams source to remain stable to about 1 micron. As schematically shown in Fig.1, the floor of SPEAR3 is composed of six sections, with four continuous concrete slabs, forming the north and the south arcs, and two concrete blocks anchoring the East and the West pits. The accelerator is surrounded by a concrete tunnel. Most of the outside of the tunnel is not enclosed by a building, but is exposed to the outside temperature fluctuations.

Several experiments were carried out to try to determine the mechanism that was driving diurnal tunnel floor motion [1]. They were: (a) the roof and the walls of the storage ring were painted white in 2008; (b) highly reflective aluminum Mylar was installed on the asphalt that covers the ground in the middle of the ring in June, 2009; (c) Mylar was also installed on the roof and walls of a portion of the ring, and fans were place inside the ring to promote ambient temperature stability in July, 2009; and (d) in 2011, selected test walls were insulated in the area

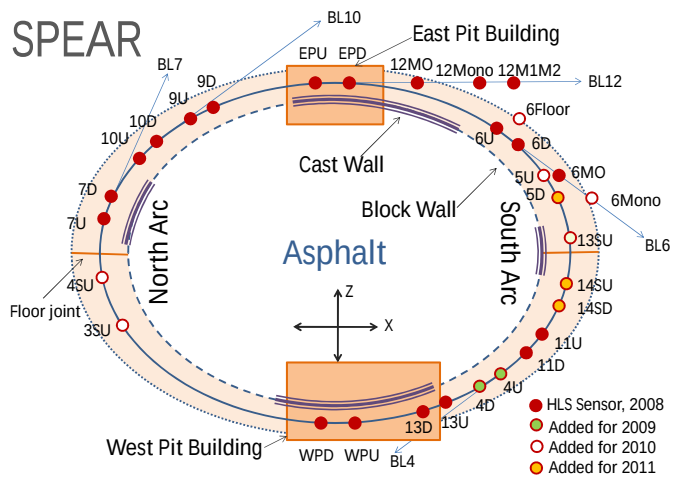

FIG. 1. Schematic top view of the SPEAR which is composed of 6 sections with four continuous slabs forming the north and the south arcs, and two concrete blocks anchoring the East pit and the West Pit. Locations of HLS sensors are shown.

with larger vertical floor fluctuations shown by the HLS data analysis. The purpose of the above experiments was to find ways that could effectively shield the ring and its surrounding structure from cyclic temperature changes to improve the beam stability over a long period to fit users' need. The white paint, and later the Mylar, was intended to protect the concrete tunnel walls of the ring from radiative heating. The Mylar on the asphalt was intended to prevent heating and outward expansion that might translate into vertical or rotational movement of the ring floor. The selected thermal insulation was to minimize diurnal temperature variations in the tunnel walls. These tests gave us confidence to proceed with a project to insulate the whole SPEAR3 ring.

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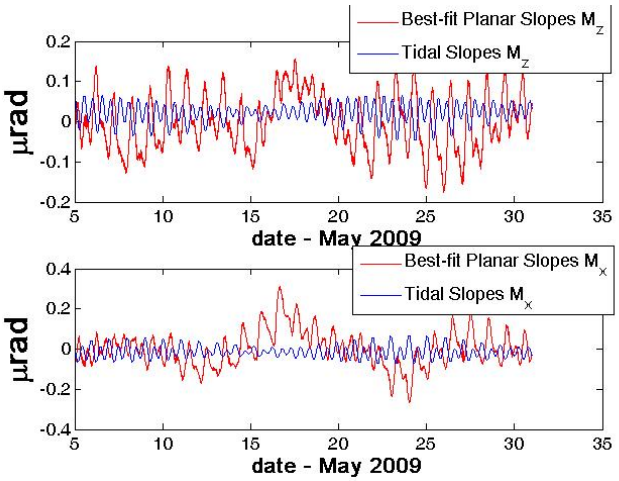

FIG. 2. Comparison of best-planar-fit slopes and simple solid-earth-tidal-model slopes shows that they are in the same order of magnitude. The best-fit slopes approximate the 12-hour amplitude of tidal model within 14% while the 24-hour and 14-day content does not seem to be correlated.

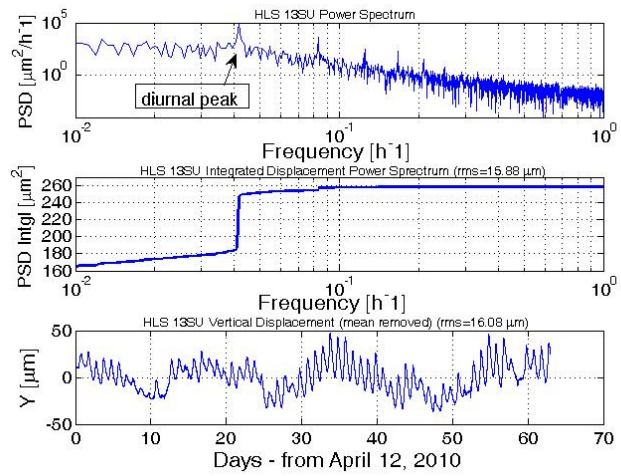

FIG. 3. Measured motion on a single HLS sensor. The top plot shows the power spectral density (PSD) of the vertical motion shown on the bottom plot. The middle plot shows the integrated PSD over a period of 24 hours, and the bottom plot shows that the 24-hour period generates the greatest derivative.

II. DATA ACQUISITION WITH THE HYDROSTATIC LEVEL SYSTEM (HLS)

To measure the vertical floor motion, an HLS was installed, which consists of a series of PVC pipes half-filled with water and placed on the concrete floor around the storage ring [2]. As shown in Fig.1, sensors are placed at well selected points around the ring to measure the water level in reference to a central sensor. The data coming from one sensor shows the amount of vertical movement occurring at that point in relation to a sensor upstream of the East Pit. Initially 20 sensors were installed. More sensors were added with time. Currently SPEAR3 contains 32 sensors, with pairs of sensors placed upstream and downstream of points where photon beam lines move tangentially off from the electron beam. There are also thermocouples (TCs) placed at various locations inside and outside the ring that can provide data on temperature fluctuations taking place over any given time period. We plan to install more HLS sensors, in particular, to characterize floor motion along the photon beamlines outside the accelerator tunnel.

III. CO-PLANES AND DATA NORMALIZATION

Each data set, once collected, was checked for validity and was filtered by a simple outlier data filter. After that, we performed planar extraction to remove co-planar motion before a spectral analysis to understand the relative vertical motions of each sensor point.

When the entire SSRL facility, including the accelerator and photon beamlines, moves as a rigid plane, the photon beams do not move relative to the users experiments. It is only the deviation from co-planar motion that leads to the motion of the photon beam relative to the experimental sample. For this reason, we are only interested in deviations from co-planar motion. With use of the sensors' coordinates, at each discrete time, we calculate the plane that best fits the HLS readings at that time. The deviations from this plane were then obtained by subtraction of the original HLS readings from the fit plane.

It is unclear whether the planar behavior of the ring can be extended onto the photon beamline floor. The beamlines extend tangentially from the ring and are placed on foundations that are distinct from the SPEAR3 tunnel. We are further expanding the HLS system on the beamline floor to better understand relative motion between the accelerator tunnel and photon beamlines.

The dominant frequencies seen in the planar slopes are 12-hour, 24-hour, and 14-day periods, as expected from tidal forces. Through theoretical calculation of SPEAR3 tidal motion using the program Solid_UTC [3], which assumes a solid, uniform earth, we found the 12-hour mode is pretty much correlated with tidal motion while the 24-hour and 14-day measured motion is significantly larger than predicted, as shown in more detail in Fig. 2. Coastal loading from the ocean tides are expected to result in significant changes in earth-tide motion compared to a simple solid earth model, so the results in Fig. 2 are not unreasonable [4]. Nonetheless, we are adding more sensors on the beamline floor to verify that we do not still have diurnal temperature-driven differential motion between the beamlines and storage ring.

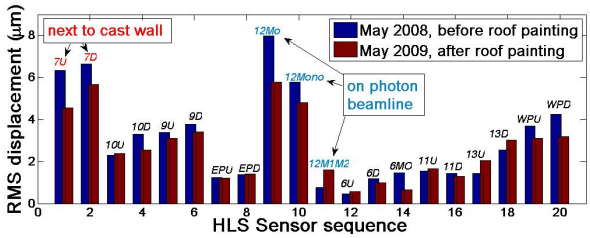

FIG. 4. Comparison of diurnal motion between two months with nearly identical outdoor temperature May, 2008 (before roof painting), and May, 2009 (after roof painting). The HLS sensor sequence is arranged clockwise from top view onto the SPEAR3 as shown in Fig. 1.

IV. SPECTRAL ANALYSIS

After removing coplanar motion, spectral analyses were performed to understand the relative (with respect to the co-plane) slow vertical motions of the sensor locations. The power spectral density (PSD) of vertical motion was calculated for each of the HLS sensors. Fig. 3 shows an example.

The biggest concern for synchrotron radiation experiments is movement of the photon beam on the time scale typical of data collection, which is in the order of 1 hour. So it is the derivative of the vertical motion over 1 hour that matters. Slow motion over the courses of days, even if it accumulates to large amplitude, is not as much of a concern as motion over the course of an hour. Since the 24-hour period motion generates the greatest derivatives, as shown in the bottom plot of Fig. 3, we used the PSD integral over the 24-hour peak as the relevant amplitude of motion for each sensor. We looked at how the height of this diurnal peak changed with each experiment.

Below we describe the related experiments that have been carried out so far.

V. WHITEWASH PROJECT 2008 - AREA WITH WALL EXTENDED BELOW GROUND HAS LARGER GROUND MOTION

During the summer of 2008, all the walls and the roof of SPEAR3 were painted with a white, titanium oxide based paint that also contained a Borosilicate glass additive. This reduced floor motion, according to analysis of data from May, 2008 (before paint) and May, 2009 (after paint). The two months had nearly identical outdoor temperature. However, the daily temperature fluctuation of the concrete roof was reduced by a factor of two with the white paint, and the internal ambient temperature fluctuation of the ring was reduced by 15%. The changes in diurnal motion in 20 sensors are shown in Fig. 4, with the sensors arranged in order as they would be seen in SPEAR3.

Four HLS sensors show relatively large motion in Fig. 4. The two in the middle are not on the accelerator tunnel floor concrete, but on a separate slab under BL12 photon beamline. The two sensors on the left of Fig. 4 are upstream and downstream of BL7 insertion device. In addition to seeing relatively large motion, these two sensors showed the most improvement with the white paint. We looked more carefully on the tunnel wall next to BL7, and we found that it is unique. This section of the inner wall was cast in place with a foundation extending 3 feet below ground, whereas the other sections of the surrounding arc are composed of concrete blocks that rest on the asphalt that covers the middle of the ring (Fig.1). This led to the conjecture that temperature gradients across the wall caused buckling, which transferred forces to the tunnel floor.

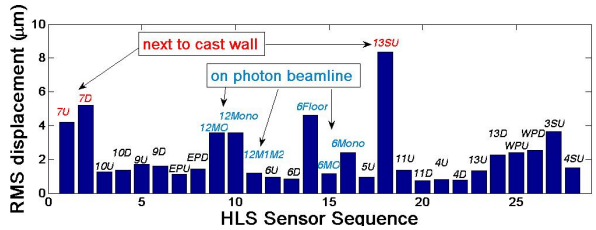

FIG. 5. RMS 24-hour period of motion in 2010.

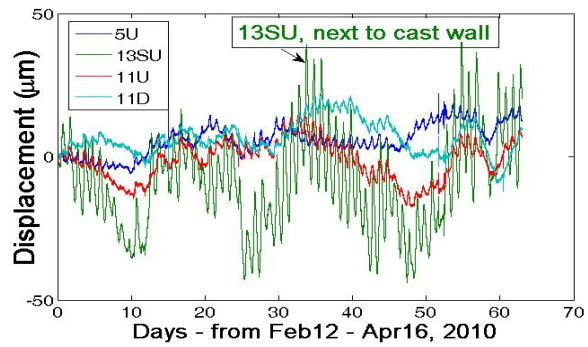

FIG. 6. HLS sensor 13SU shows large motion.

There is a similar section of cast-in-place wall in the south arc. There are also cast walls around the east and west pits (top and bottom of Fig. 1). These east and west pit walls, however, are mostly inside buildings, so they do not see large temperature gradients across the walls.

We added 8 HLS sensors before 2010 run, one of which we placed next to the cast-in-place south arc wall (sensor labeled 13SU in Fig.1). Figure 5 shows diurnal motion including the new sensors. The new 13SU sensor next to the cast wall in the south arc has the largest motion fluctuation.

Figure 6 shows the motion of the 13SU sensor next to the cast-in-place wall compared to the sensors just upstream and downstream. The difference in the amplitude is dramatic and supports our belief that differential heating across the cast walls with foundations creates torque that moves the tunnel floor.

Figure 5 also shows that some of the sensors on sepa-

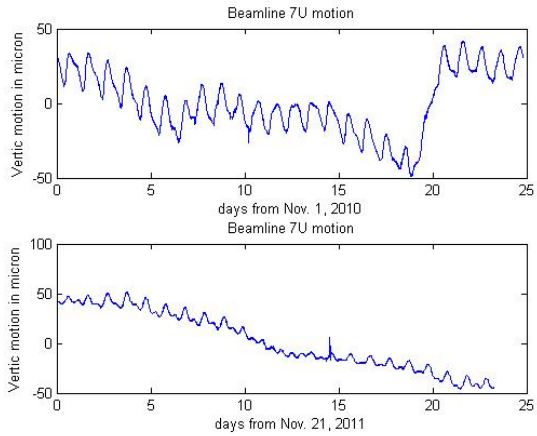

FIG. 7. Comparison of BL 7U vertical motion between Nov. 2010 (before prototype insulation) and Nov. 2011 (after insulation).

rate concrete slabs along the beamlines show larger differential motion relative to the accelerator tunnel sensors. This problem will be investigated further with an expansion of the sensors on the beamline floor.

VI. MYLAR ON ASPHALT PROJECT

Putting Mylar on the asphalt in the center of SPEAR3 reduced the diurnal temperature fluctuations of the asphalt by nearly a factor of 6. Nevertheless, the HLS diurnal variation did not improve. Thermal expansion of the asphalt does not exert sufficient force to move the concrete tunnel floor.

Even the diurnal RF frequency variation in the SPEAR3 orbit feedback did not decrease with the installation of the Mylar, which suggests that the predicted asphalt expansion and storage ring circumference are entirely decoupled.

VII. MYLAR ON RING ROOF AND WALLS PROJECT

The results of the first two experiments prompted the installation of Mylar on the roof and walls of a section of SPEAR3. It was hoped that the Mylar would reduce the temperature fluctuation of the roof by additional factors beyond the reduction caused by the white paint alone. Unfortunately, the Mylar only reduced the outside wall temperature fluctuations by an additional 15% beyond the white paint, which was not enough to give a measurable change in the HLS.

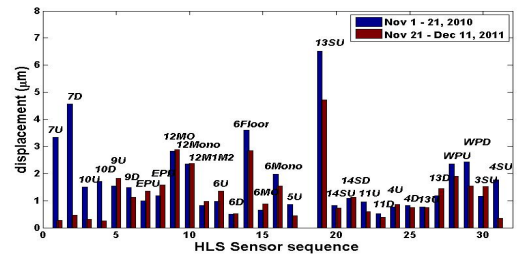

FIG. 8. Comparison of diurnal motion between two nearly-identical-outdoor-temperature months November 2010 (before prototype insulation), and November 2011 (after insulation). The HLS sensor sequence is arranged clockwise from top view of SPEAR3 as shown in Fig. 1. The insulation area around 7U, 7D, 10U, 10D shows significant improvement.

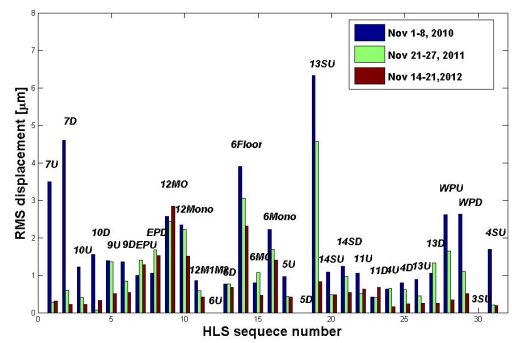

FIG. 9. Comparison of diurnal motion among nearly-identical-outdoor-temperature week November 1 8, 2010 (before 56 ft long prototype insulation in the area around 7U, 7D, 10U, 10D), November 21 27, 2011 (after prototype insulation), and November 14 21, 2012 (after insulation of most of the ring).

VIII. 56-FT LONG PROTOTYPE SECTION OF ROOF AND WALL INSULATION

To further test the conclusion that cast-in-place walls with subterranean foundations drive tunnel floor motion, an enhanced prototype insulation of the tunnel roof and wall of a selected section, 56-foot long, over BL7, was installed in October, 2011. Figure 7 shows a plot of the HLS data comparing the vertical motion of Beamline 7U HLS sensor between two periods, before and after installation of the 56-ft long prototype insulation. The comparison clearly shows that the vertical motion is reduced after the insulation. The spectral analysis in Fig. 8 shows dramatic reduction in diurnal vertical motion at the prototype insulation area (around 7U, 7D, 10U, 10D).

IX. ADDITIONAL INSULATION

Since the 56-ft long prototype roof and wall insulation worked very well in reducing local diurnal ground

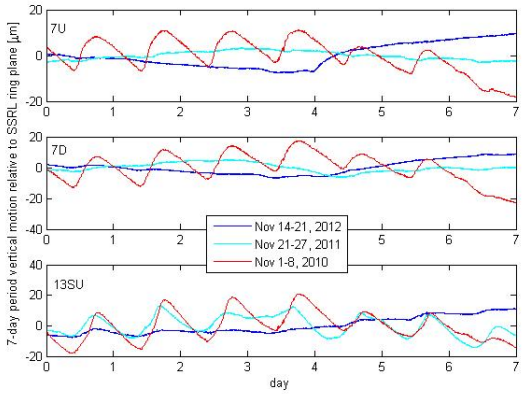

FIG. 10. Comparison of diurnal motion for 7U, 7D, and 13SU among nearly-identical-outdoor-temperature weeks November 1 8, 2010 (before 56 ft long prototype insulation in the area around 7U, 7D, 10U, 10D), November 21 27, 2011 (after prototype insulation), and November 14 21, 2012 (after insulation of most of the ring).

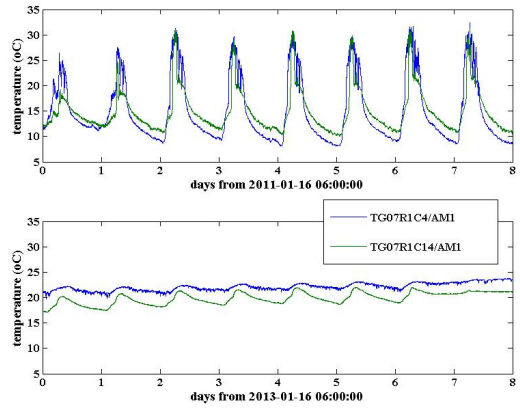

FIG. 11. Comparison of temperature variation just outside the tunnel at two locations with temperature sensors, TG07R1C4/AM1 and TG07R1C14/AM1 for 8 day time period on January 16, 2011 before insulation (top plot) and on January 16, 2013 (bottom plot) after insulation.

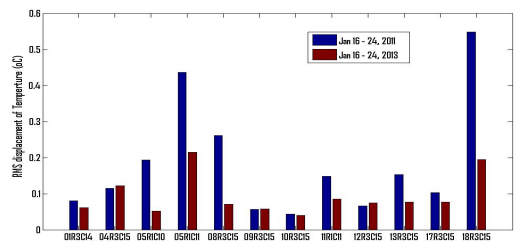

FIG. 12. Comparison of diurnal RMS temperature displacement inside the tunnel at twelve locations with ambient temperature sensors for an 8-day time period on January 16, 2011 before insulation (blue bar) and on January 16, 2013 (red bar) after insulation.

motion, we decided to insulate most of the tunnel, including the other areas where the wall extended into the ground. Installation of this insulation was completed in 2012 and the beamline ground motion was indeed further improved. We took one-week HLS data from November 14 to November 21, 2012 and compared diurnal spectral analysis of these data with those of the previous years. Figure 9 shows the comparison of RMS displacement of ground motion from 28 HLS censors. Ground motion in all areas is generally improved. In particular, the South Arc, the West Pit, where the wall extended into ground, show the most significant insulation improvement over the previous year, as shown by 13SU (located in South Arc) and 13D, WPU, WPD (located in West Pit building) in Fig. 9.

The significant reduction of diurnal motion from insulation is also clear in Fig. 10, where comparison of 7-day vertical motion relative to the SPEAR3 ring co-plane is shown. It clearly shows that the large diurnal motion before insulation (Nov 1-8, 2010 for 7U, 7D, 13SU, and Nov 21-27, 2011 for 13SU) is much reduced after insulation (Nov 21-27, 2011 for 7U, 7D, and Nov 14-21, 2012 for 7U, 7D, 13SU).

X. TEMPERATURE VARIATIONS

While it is clear that insulation led to smaller diurnal temperature variations and thus smaller diurnal ground motion, it gives more understanding to examine the reduction of temperature variation from insulation. Figure 11 shows history plots for two temperature sensors just outside the tunnel, but inside the insulation materials when insulation materials were added. The diurnal temperature variation is about 20 ^oC during January, 2011 before insulation and is reduced to about 3 ^oC during January, 2013 with insulation.

Temperature variations inside the tunnel were also reduced. Figure 12 shows 8-day readings of 12 ambient temperature sensors inside the tunnel. The diurnal temperature variations are clearly reduced for those locations with larger initial temperature variations.

XI. FURTHER LOCAL INSULATION IN BEAMLINE 12 AREA

As shown in Fig. 9, all the large vertical motion areas were much improved after our major insulation effort in November, 2012. The beamline 12 area, however, although with an acceptable vertical motion during November, showed relatively larger vertical motion in the spring and summer months. We suspect this is due to the angle of the sun in the sky for different months heating different parts of the tunnel. Figure 13 shows that its 24-hour vertical motion amplitude increased from its low amplitude of 2 microns during cold days in November,

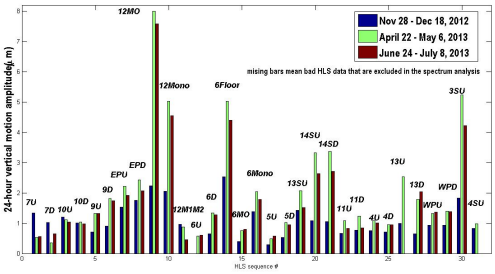

FIG. 13. Comparison of diurnal motion for different months. In this case, we see that the uninsulated area around beamline 12 has a large variation in amplitude of the diurnal vertical motion, depending on the month of the year.

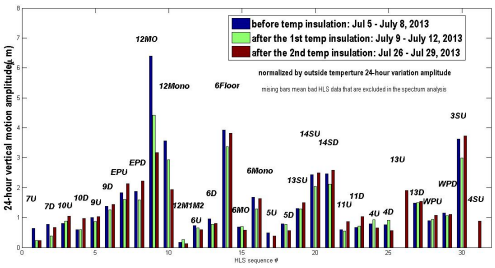

FIG. 14. Comparison of normalized (with outside temperature) diurnal motion before and after insulations during July, 2013 when the outside temperature is high.

2012 to 8 microns during hot days in May and June, 2013. We added some local insulation on July 8, 2013, but were disappointed to find that there was no improvement shown from comparison analysis of 3 days before and after the insulation (note that we realized later that there was indeed some improvement because the outside temperature variation was significantly higher after the insulation which compensated the insulation effect).

We expanded the beamline 12 local insulation on July 25, 2013. Figure 14 shows the 24-hour vertical motion amplitude among 3 periods of time: before the 1st temporary insulation, after the first temporary insulation, and after the 2nd temporary insulation. For fair comparison in figure 14, the amplitudes plotted are normalized to the amplitude of the diurnal temperature variation for the three time periods. The normalized vertical motion is reduced after local insulation was completed. Figure 15 shows the temperature comparison among the 3 time periods used for Fig. 15, while Fig. 16 shows their 24-hour temperature variation amplitudes that were used for normalization.

XII. SUMMARY

Variations in the height of the SPEAR3 tunnel floor have been reduced dramatically since they were measured

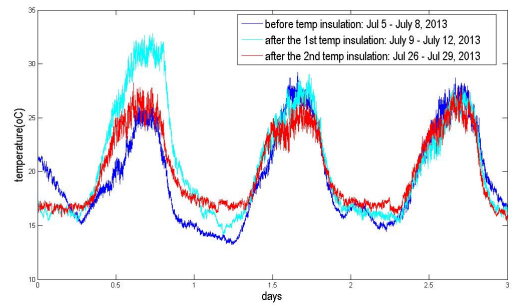

FIG. 15. Outside temperatures before and after insulations during July, 2013.

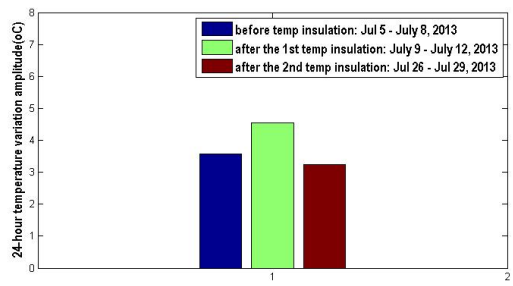

FIG. 16. Comparison of diurnal temperature variation amplitudes before and after insulations during July, 2013.

in 2006 with a hydrostatic leveling system. The reduced floor motion has resulted in improved electron and photon beam stability. Careful data analysis was required to isolate the relevant differential floor motion. The analysis included subtraction of co-planar motion and subsequent spectral analysis of the diurnal component of motion.

Various experiments with paint, Mylar and insulation led us to conclude that areas of the tunnel in which the wall foundation extended below ground have larger diurnal ground motion. The tunnel floor motion was driven by arcing of the concrete tunnel walls, due to differential heating across the walls.

We are presently expanding the HLS to include more sensors along the photon beamlines, so we can verify that the co-planar motion extends to the experimental floor.

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