EXPERIENCE REPORT WITH THE ALIGNMENT DIAGNOSTIC SYSTEM*

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Abstract

Since 2009 an Alignment Diagnostic System (ADS) has been operating at the undulator of the new Linac Coherent Light Source at SLAC National Accelerator Laboratory. The undulator spans a distance of 132 meters and is structured into 33 segments. Each segment is equipped with four hydrostatic leveling sensors and four wire position monitors. This report describes the set up and reflects the experience gained with the ADS.

UNDULATOR SYSTEM

The purpose of the undulator system is to enable the Self Amplified Spontaneous Emission (SASE) process, which is based on the interaction between an electron bunch and its spontaneous undulator radiation [1].

The undulator system comprises 33 girders each containing one undulator magnet and one quadrupole. The undulator magnet can be moved in and out of the beam with so called x-translation stages and the whole girder can be moved in five degrees of freedom with cam movers. Each girder is equipped with four hydrostatic leveling sensors (HLS) and four wire position monitors (WPM), see Fig. 1.

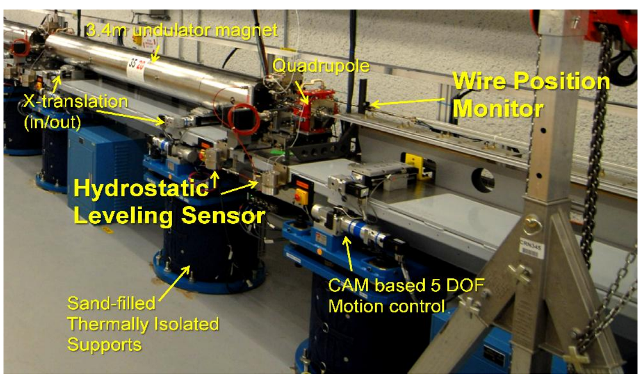

Figure 1: Two of the 33 undulator segments, partly populated.

GOAL OF THE ALIGNMENT DIAGNOSTIC SYSTEM

The X-ray FEL (Free Electron Laser) process puts very tight tolerances on the straightness of the electron beam trajectory (2 µm rms) through the LCLS undulator system [1]. It was unknown how stable the LCLS tunnel and undulator system would be. Therefore, a way to monitor the girder position had to be implemented.

The solution was to track the X, Y and Roll parameters for both ends of each girder and calculate the deviations relative to the least square fit of all girders with a resolution of one micrometer over a time period of several weeks.

Building Blocks of the ADS

The HLS sensors[†] measure the vertical position of the sensors relative to the water surface of a half filled 2 inch diameter pipe running along the center of the girders. Three of the sensors are capacitance based and one is ultrasound based.

The WPM sensors[‡] measure their position relative to a stretched wire. Two wires are stretched along the entire undulator length of 140 meters. The wire - embedded inside a conductive tube - works as an RF transmitter while the sensor consists of four RF receivers. Comparing the RF receiver responses allows calculation of the vertical and horizontal wire position relative to the sensor.

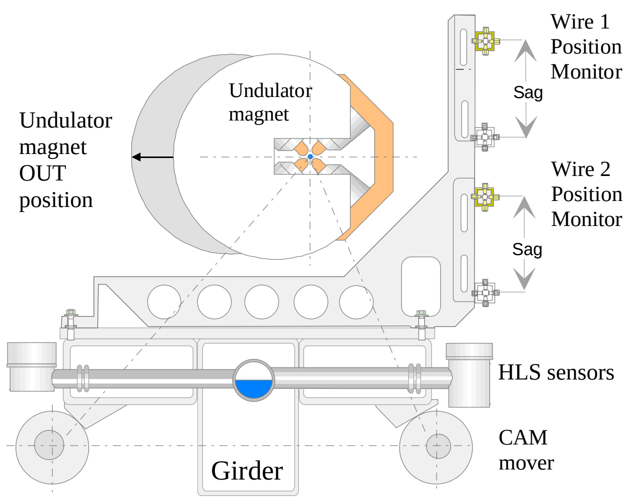

Figure 2: Arrangement and geometry of the HLS and WPM sensors.

Locations of the wire position monitors change along the entire undulator due to the sag of the stretched wires by 160 millimeters as sketched in Fig. 2.

Both sensor types deliver position information every minute. To get the positions of every girder the sensor data are analyzed together based on a least square solution. The result of the adjustment is the (x-, y- and roll) position of both ends of the girder at the nominal beam position.

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[†]Both types were built by Budker Institute of Nuclear Physics, Novosibirsk, Russia.

[‡] The WPM system was originally designed at DESY as contribution to the FFTB experiment at SLAC in 1991.

ADS RESULTS

As mentioned before, the ADS consist of two sensor types. Looking at the timelines individually we expect to see a slow drift of the HLS sensor readings which is caused by microscopic water evaporation of the system and water movements caused by the earth tides. Fig. 3 shows a waterfall view of the HLS reading over a period of 48h. Time progression is bottom to top. The individual lines represent the individual sensors. The progression of the line left to right indicates the change in reading from the sensors, on the bottom is an indicator for the scale of 10 µm. The sinuous lines at both ends are the result of the tide effect. On the right side of the graph is a wedge superimposed on the graph, it shows the constant trend of about 2 µm at all sensors.

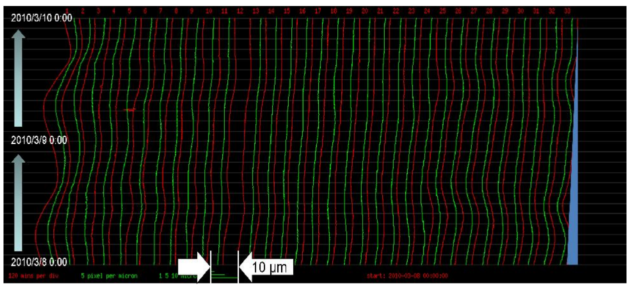

Figure 3: Two days of HLS sensor readings at each end of the 33 girders.

The vertical WPM readings over the same time period as before for the HLS are shown in Fig. 4. Sag changes in the wire get the biggest sensor response in the middle of the system and the smallest response close to the end stations.

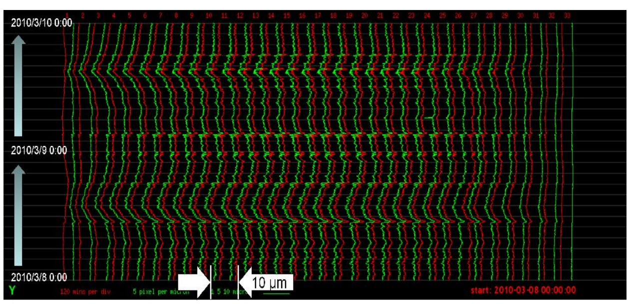

Figure 4: Two days of vertical wire position readings at each end of the 33 girders.

Data analysis depicts the visible readout variations as highly correlated with a change of the sag of the stretched wire. Further test correlates these variations with tiny changes of the ambient temperature in the undulator hall. The temperature sensitivity of the sag of the 140 m stretched wire has been determent as roughly 1 µm / 0.010 K.

The ADS monitors the position of the girders at the beam position. HLS and WPM readings are combined in order to eliminate the influence of the water level, tide effects, wire movements and sag changes. These parameters are estimated as nuisance parameters in the least squares adjustment. The geometry of the individual sensor positions in respect to the girder have to be taken into account.

Fig. 5 shows the ADS results for the vertical position of the beam axis at each end of all 33 girders.

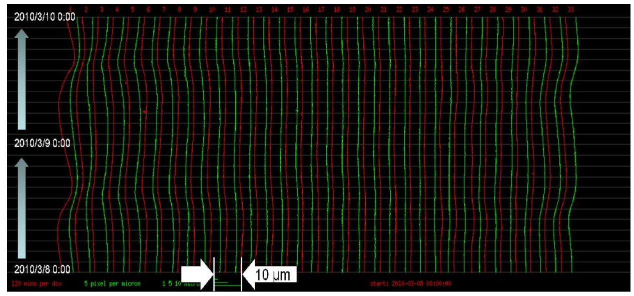

Figure 5: Two days of vertical girder positions of both ends of the 33 girders.

Both ends of the girder are treated as independent allowing for deformation of the girder. The result shows an extremely stable tunnel at the girder positions. The position variation at the first 4 girders can be correlated to the daylight. Even though the complete undulator hall is underground the first girder is only 14 m from the start of the hill as shown in the sketch below (Fig. 6).

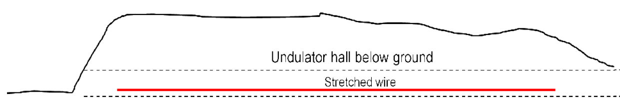

Figure 6: Side view sketch of the undulator hall.

Fig. 7 shows the horizontal WPM readings. The progressively bigger motion of sensors relative to the wire from right to left indicates that the left wire end station is moving. The smaller changes in the readings of the first sensor indicate that this sensor is moving together with the wire end station. In Fig. 8 the final result of the ADS system for this time period of both ends of the 33 girders is shown.

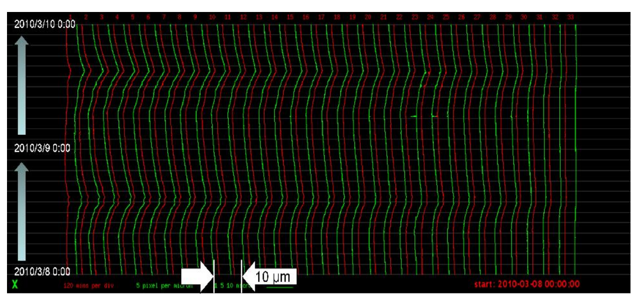

Figure 7: Two days of vertical wire position readings at each end of the 33 girders.

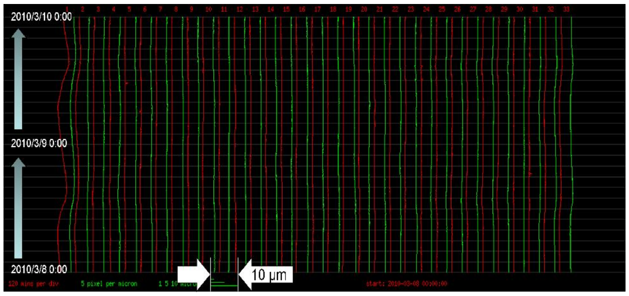

Figure 8: Two days of horizontal girder positions of both ends of the 33 girders.

Motor motion on the girders affects results

Up to now we only discussed the ideal case for the ADS system, without any motor induced movements of the girders. This is not the typical case of how the undulator section is operated now. The lasing of the XFEL beam is very stable, which allows changing beam parameters by moving whole girders using the cam movers and individual undulator segments using the x-translation stages. Fig. 9 shows a waterfall view of the ADS response to a typical day during beam operation when girders are frequently moved.

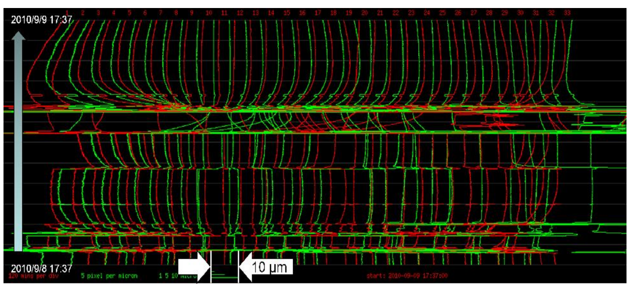

Figure 9: Vertical position results for a typical 24h period of the ADS system.

ADS “QUICK RESPONSE”

To address issues which arise for the ADS if girders are moved, a different algorithm for the data processing had to be implemented to run in parallel with the conventional ADS. This ADS “quick response” (ADS QR) is for short term girder position tracking and is based on the WPM alone. Position results of the ADS QR are shown in Fig. 10 and 11.

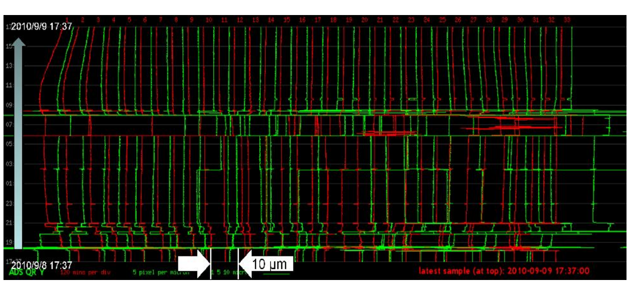

Figure 10: Vertical position results for a typical 24h period of the ADS QR system.

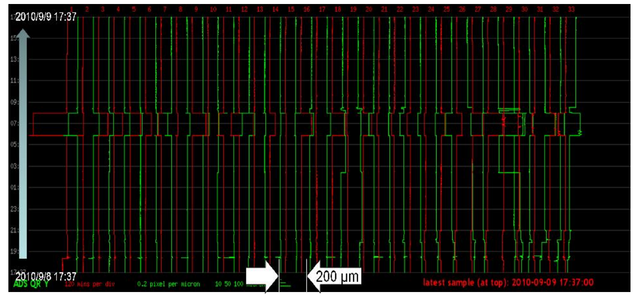

Figure 11: Vertical position results for a typical 24h period of the ADS QR system (Smaller scale factor).

The reasoning behind it can be found in the graph in Fig. 9 where we can see some bowing of the lines. This apparent slow movement of the girders is not real, but is artificially induced through the time it takes for the water in the pipe to reach equilibrium. In Fig. 12 the water distribution in the HLS system is shown after all the girders are moved simultaneously and then kept in one position. Over a period of several hours the water redistributes itself to reach equilibrium again.

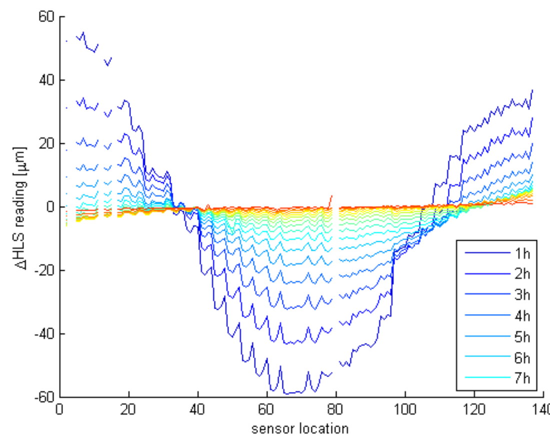

Figure 12: Water re-distribution over a period of 7h after movement off all girders.

Another reason for apparent position changes in the results of the ADS is that there is no external reference for the ADS system. It was decided that the reference should be a least squares fit to all the girders. The areas before and after the girder section are not stable enough at the magnitude we are looking for to provide an external reference, see Fig. 5 and 8.

Fig. 13a shows a reference line fit with all girders at their zero position. In Fig. 13b the change of the reference line is shown after one girder is moved out of position. The relative position of the girders to the reference line indicates apparent movement on every girder even though the other girders stayed in position. Fig 13c shows the result after taking into account the motorized movement of the girder for the calculation of the reference line. This reduces these apparent movements.

For both the conventional ADS and the ADS QR the motorized positions of the girders and segments are acquired from the control system and taken into account.

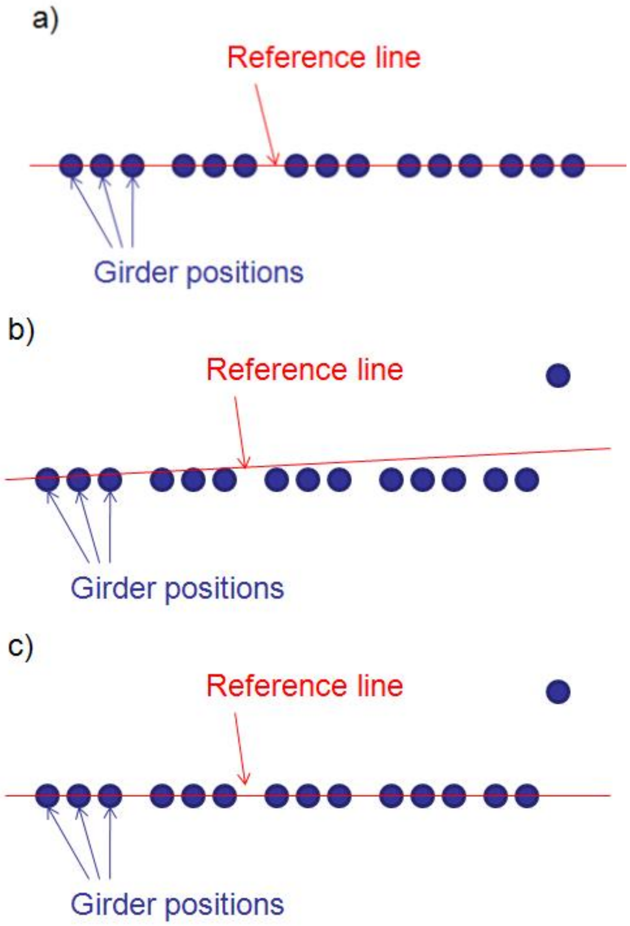

Figure 13: Examples of least square fits of a reference line to girder positions. a) girders at zero position, b) one girder out of position – reference line changes accordingly and c) known movements of individual girders are taken into account for the calculation of the reference line and do not affect its position.

SUMMARY

ADS achieved its original goal of monitoring quadrupole position to the micrometer level.

The system has in continuous operation since March 2009 without any significant failure.

To support the operational mode of motor driven position changes the cam / stage system motion is taken into account for the reference line fit. To address the response delay by the HLS the new ADS QR mode was developed. The ADS QR is designed for short term observation.

Due to lack of HLS data in the ADS QR, a catenary shape deformation of the undulator system would remain undetected.

The full ADS version is required to monitor long term position changes, but it is necessary to wait for the HLS to return to equilibrium after motor motion to obtain valid results.

ACKNOWLEDGEMENT

The author would like to thank Franz Peters for providing the WPM system and for many educational discussions about that system and the ADS in general and Martin S. Peters for his contribution in the data acquisition, set up of the database and for the graphs provided by his system. I would also like to thank all my colleagues for their various inputs to the system design and to this paper.

REFERENCES

[1] H.-D. Nuhn, P.J. Emma, G.L. Gassner, C.M. LeCocq, F. Peters and R.E. Ruland, “Electron Beam Alignment Strategy in the LCLS Undulators,” FEL2006 Proceeding, 2006, Berlin, Germany.