

POSITION STABILITY MONITORING OF THE LCLS UNDULATOR QUADRUPOLES*

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Abstract

X-ray FELs demand that the positions of undulator components be stable to less than 1 μm per day. Simultaneously, the undulator length increases significantly in order to saturate at x-ray wavelengths. To minimize the impact of the outside environment, the Linac Coherent Light Source (LCLS) undulator is placed underground, but reliable data about ground motion inside such a tunnel was not available in the required stability range during the planning phase.

Therefore, a new position monitor system had been developed and installed with the LCLS undulator. This system is capable of measuring x, y, roll, pitch and yaw of each of the 33 undulator quadrupoles with respect to stretched wires. Instrument resolution is about 10 nm and instrument drift is negligible. Position data of individual quadrupoles can be correlated along the entire 132-m long undulator. The system has been under continuous operation since 2009. This report describes long term experiences with the running system and the observed positional stability of the undulator quadrupoles.

INTRODUCTION

The use of stretched wires as reference lines for positional stability control of magnets has been used at SLAC since 1969 [1]. In 1995, a new type of stretched wire system was developed at DESY [2] and installed at SLAC as contribution to the Final Focus Test Beam [FFTb] experiment. For LCLS that system was improved to monitor positional stability of the undulator quadrupoles.

WIRE POSITION SYSTEM

The principles of the wire system are sketched in Fig. 1. A gold plated stainless steel wire is stretched inside a conductive tube over a distance of 140 m. Two RF signals are transmitted from either end of the stretched wire into this coaxial structure. Small antennae (loops) are placed inside the tube. One end of each antenna is connected to the tube. The signal on the opposite end of each antenna is proportional to the current on the stretched wire and inversely proportional to the distance between the antenna and the stretched wire. The wire position can be determined with the signals from two opposing antennae by:

$$X_{position} = C \frac{U_{left} - U_{right}}{U_{left} + U_{right}}$$

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The factor C depends on the monitor geometry and becomes non-linear for larger deviations of the wire from the center.

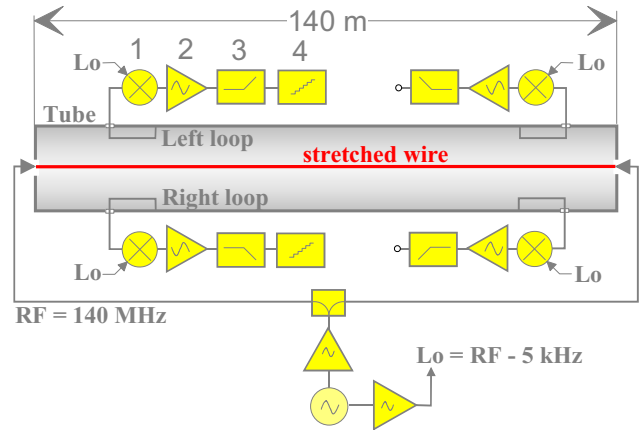


Figure 1: Principle layout. 1=Double Balanced Mixer, 2=Amplifier, 3=Multiplexer, 4=ADC.

Two orthogonal pairs of antennae are called a wire position monitor. Calibration of these monitors together with the associated electronics has to be done in situ by moving the ends of the wire with calibrated translation stages.

Wire Position Monitor

Figure 2 depicts the wire position monitor and the field distribution inside the monitor gap. The four small antennae are equipped with SMA connectors on both ends. Each end can be used as output port. The opposite port needs to be terminated.

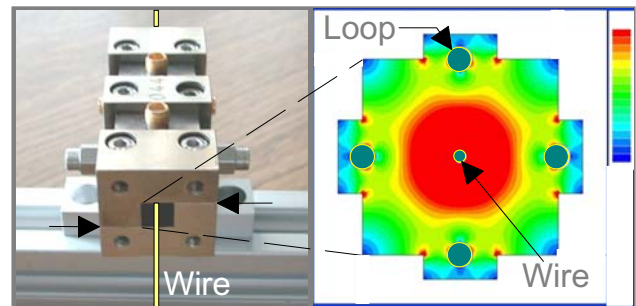


Figure 2: Wire position monitor and field distribution.

Each position monitor is constructed from two symmetric parts, as indicated by arrows (left side). This allows monitor installation and removal without touching the stretched wire. Some wire system properties are given in Table 1.

Table 1: LCLS Wire System Properties

Stretched Wire Length	140	m
Number of Stretched Wires	2	
Stretched Wire Sag	160	mm
Wire Position Monitor Length	74	mm
Wire Position Monitor Gap	8 × 8	mm
Monitor Geometry Factor	2.2	mm
Stretched Wire Diameter	0.5	mm
Stretched Wire Material	Nivaflex®	
Stretched Wire, Au Plating	~ 5	µm
Inner Tube Diameter	9	mm
Sensor Loop Length	27	mm
RF Signal	140	MHz
IF Signal	5	kHz
Position Readout Frequency	1.5	Hz
ADC Resolution	16	BIT
Data Analysis	FFT	

Wire Position Monitor Installation

The position monitors are attached to the component as shown in Fig. 3. Two metallic bellows on both sides mechanically decouple the monitor from the neighbouring setups. This enables the monitor to move with the attached component without relevant resistance.

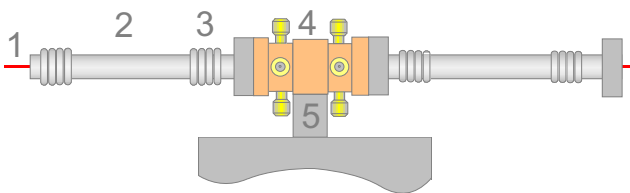


Figure 3: Monitor and tube installation scheme. 1=Stretched wire, 2=Brass tube, 3=Bronze bellows, 4=WPM with eight SMA connectors, 5=Bracket

The entire coaxial system is designed for minimal rf reflections and has to be hermetically sealed for an operational frequency of 140 MHz.

UNDULATOR

The LCLS Undulator [3] spans over a distance of 132 m and is structured into 33 identical segments. The undulator segments have a fixed, but slightly canted-pole geometry, which allows the *K* value to be changed by lateral translations. In addition, each undulator segment can be shifted horizontally to optimize lasing and can also be moved completely out of the beam. One undulator segment is sketched in Fig. 4.

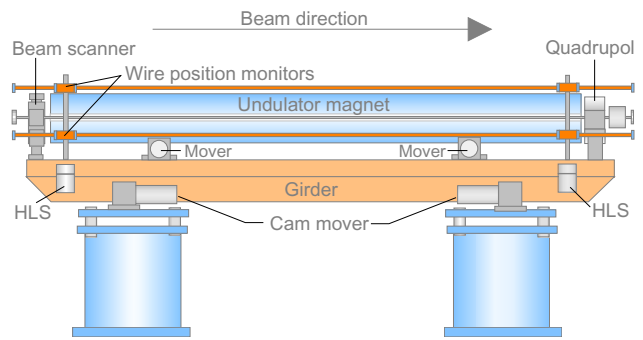


Figure 4: Undulator segment, front view.

All machine components of one undulator segment are placed on top of a common girder. Each girder is freely moveable in x, y, roll, pitch and yaw with a remote control, five-axis cam mover.

Wire Position Monitors at the Undulator

Two independent wires are located and stretched along the entire undulator on one side, one above the other. Two wire position monitors are placed at both ends of each girder. The vertical location of these monitors and the associated tubes varies along the undulator due to the sag of both wires. The highest and lowest monitor locations are shown in Fig. 5

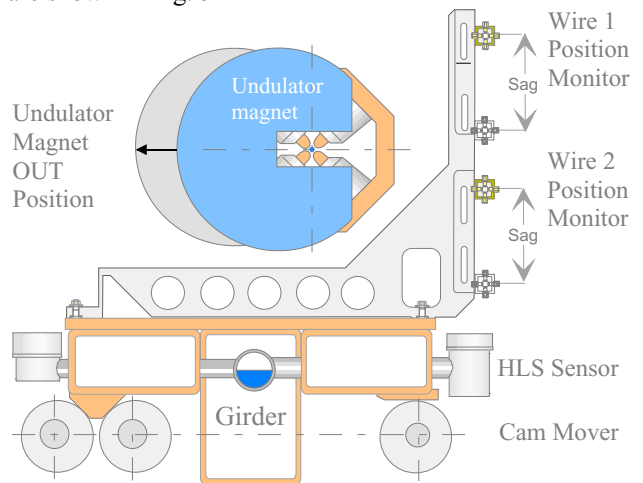


Figure 5: Cross sectional sketch of one undulator segment.

With this geometry x, y, roll, pitch and yaw of all 33 undulator segments can be determined with respect to both stretched wires as common reference lines.

A Hydrostatic Levelling System [HLS] [4] is used to create reference heights on both sides along the entire undulator. The reference lines may move of course, e.g. if the ends of the wires move. But those movements generate highly correlated data along the entire undulator and can therefore be easily corrected to determine the position of each individual segment with respect to the collective of all segments. Consequently, the wire position system cannot detect whether the entire undulator area moves as one solid piece.

MEASUREMENTS

As mentioned above, both ends of each girder are moveable via cam movers. The mover arrangement at one end is shown in Fig. 5. The wire system was used to check girder steering with these cam movers. One of the results is plotted in Fig. 6.

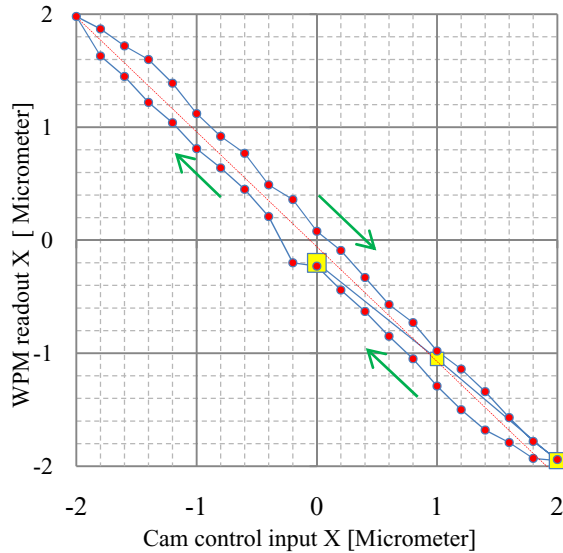


Figure 6: Wire position readouts vs. cam control inputs.

The yellow squares indicate the start track. The red data points were taken sequentially. The sequence for data acquisition is indicated by arrows. Figure 6 depicts the excellent positional performance of the cam mover and wire monitoring systems.

Wire Position Monitor Resolution

To measure position stability in a range of less than one micrometer per day, high resolution and low instrument drift are absolutely essential.

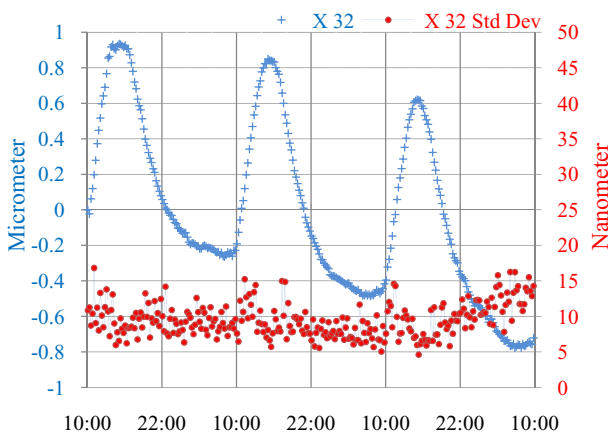


Figure 7: Three days of wire positions at girder 32.

The rf principle and the advantage of the small bandwidth due to the Fourier analysis lead to a signal to noise ratio of > 90 dB. In LCLS, the wire position readout frequency is 1.5 Hz. Averaging of 25 readings results in a standard deviation of about 10 nm as a three

day wire position record at segment 32 in Fig. 7 illustrates.

As data analysis has shown, the daily wire motion of about 1 μm is mainly generated by movements of one wire end station. Wire end station E1 is located upstream and end station E2 is downstream of the undulator, as sketched in Fig. 8.

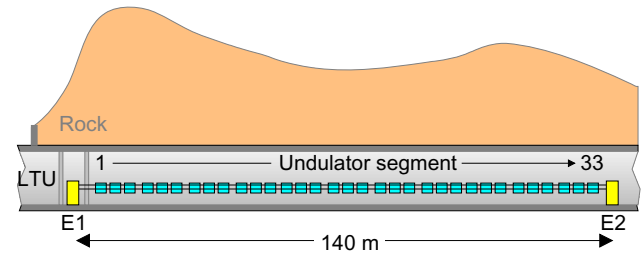


Figure 8: Undulator tunnel, side view sketch.

The entire undulator resides underground. The two wires are stretched between end stations E1 and E2. The Linac-To-Undulator [LTU] tunnel, visible on the left in Fig. 8, is not covered with soil and end station E1 is close to the uncovered region. The air temperature inside the undulator tunnel has been constant within ± 0.05 K. The air temperature inside the LTU tunnel is not regulated. Both air systems are separated by a double door airlock with wire end station E1 inside.

Motion of the Wire End Stations

Figure 9 shows a strip chart record of horizontal wire position readings from one wire at either end of each of the 33 undulator segments.

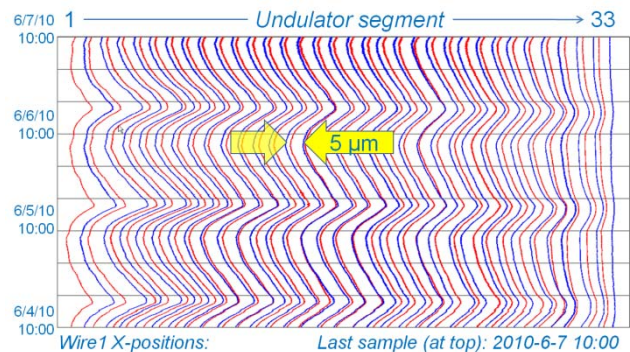


Figure 9: Three days of horizontal wire position readings.

All 66 tracks look highly correlated, with a linear increasing amplitude toward undulator segment 1. The daily movement of the wire at end station E1 is consistent with the proximity of that end station to the uncovered LTU tunnel. Wire end station E2 looks much more stable. In addition to these daily wire motions, Fig. 9 depicts small, slow movements of a few segments with respect to their neighbours of about 0.3 $\mu\text{m}/\text{day}$.

STABILITY OF THE QUADRUPOLES

For each stretched wire, reference lines are obtained by least square fits (horizontally: linear, vertically: catenary) to all position readings from both ends of each segment. The position of each individual quadrupole and beam

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scanner is determined relative to these reference lines using a 3D model of the undulator segment. The horizontal result is shown in Fig. 10 as strip chart record. The blue lines indicate the positions of all 33 quadrupoles and the red lines indicate the positions of the 33 beam scanners.

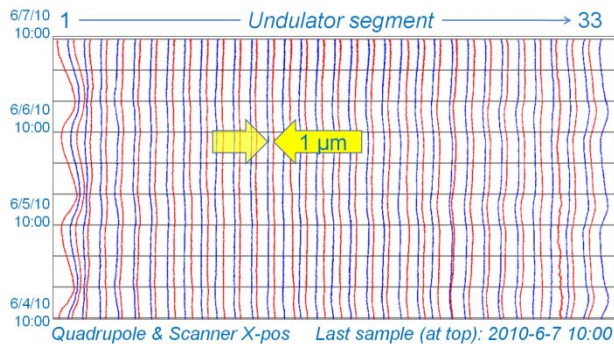


Figure 10: Quadrupoles and Beam Scanners, horizontally.

There is a daily motion of undulator segments one and two, within a few micrometers and simultaneous yaw changes around $0.1 \mu\text{rad}$. As mentioned above, these segments are close to the LTU tunnel. However, they move less than wire end station E1. Over longer time periods, the phase of these motions correlates with sun rise.

Wire Sag Oscillations

Each wire spans a distance of 140 m. One end of the wires is fixed, the other turns around a pulley and is stretched with a free hanging weight of about 50 lbs.

The static friction of these pulleys is low but not zero. Therefore, the sag of the wires is sensitive to the ambient temperature. Three days of vertical wire position readings are shown in Fig. 11.

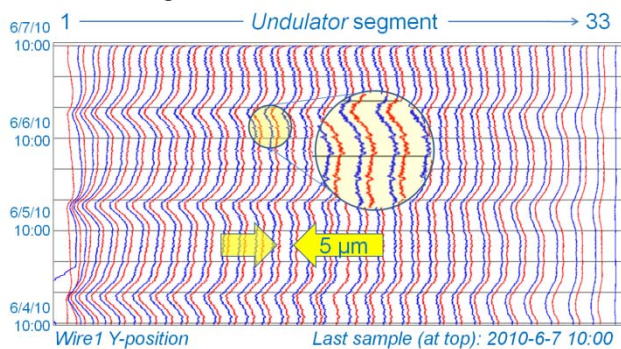


Figure 11: Three days of vertical wire position readings.

The daily vertical motion of the wire at end station E1 seems to be similar to the horizontal, as discussed above, but there are small sag changes with higher frequencies. As further analysis has shown, these changes are generated by tiny variations of the air temperature around the tubes of the wire system. The temperature sensitivity of the sag of both wires turns out to be less than $1 \mu\text{m}/0.01 \text{K}$.

Fortunately, any sag variation affects all readings as catenary change and can therefore easily be corrected. As a result, the vertical positions of quadrupoles and beam scanners are shown in Fig. 12

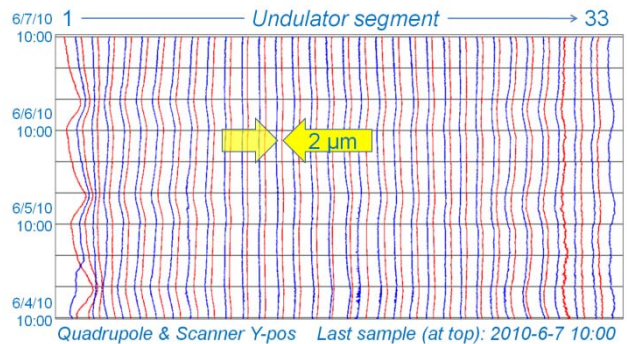


Figure 12: Quadrupoles and Beam Scanners, vertically.

The first few segments move daily within 2 or 3 μm up and down with simultaneous pitch changes $\sim 0.2 \mu\text{rad}$.

CONCLUSION

Stability of quadrupoles in storage rings, FELs, and future accelerator projects has become more and more relevant over the last 30 years. Interpretation of measurements done at different laboratories to get more positional stability data of the accelerator environment has lead to various models. The expected ground motion using these models called for an active feedback to stabilize the LCLS undulator.

It turned out that the constant air temperature ($\pm 0.05 \text{K}$) inside the sandstone undulator tunnel creates a very stable environment. The wire system, which presents a new milestone in the field of position stability measurements in terms of resolution over a long distance, made it possible to characterize this stability. Since short and long term ground motion inside the LCLS undulator tunnel are much smaller than previously expected, active stabilization feedback systems are not necessary.

ACKNOWLEDGMENTS

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