INTERCOMPARISON TESTS WITH HLS AND WPS

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Abstract

Since the 1990s, hydrostatic levelling sensors (HLS) and wire position sensors (WPS) are used for monitoring applications in the accelerator alignment domain. The sensors are at different levels of development, ranging from prototype to off-the-shelf sensors, and use different technologies to achieve µm resolution.

Both, the Compact Linear Collider (CLIC) project as well as the International Linear Collider (ILC) project, are based on alignment concepts that can use such systems.

The idea of an intercomparison between different types of HLS and different types of WPS was the basis for the CLIC pre-alignment (CLIC-PRAL) workshop which was held at CERN in 2009. An overview on HLS and WPS based alignment systems used in different institutes was given and in conclusion the participating institutes agreed on a sensor intercomparison program.

The objectives of these tests are outlined in this paper, the sensors and the comparison test installations described and results of the first intercomparison measurements are shown.

INTRODUCTION

Proposals for the alignment concepts for the CLIC [2] and ILC [3] projects are based on HLS and WPS systems. Sensors used to monitor these systems are used since over 20 years in the field of accelerator alignment and are widely spread in institutes around the world.

In the last years, more and more monitoring systems have been installed in accelerator complexes and new sensors have been developed in consequence.

The idea of an intercomparison between available monitoring sensors is a logical step to provide an overview about existing technologies. This idea has been proposed in 2009 at the CLIC pre-alignment workshop. The invited institutes presented the current use of their sensors and provided information about the sensor and system specifications.

In the conclusions of this workshop, the will for a collaboration to compare the sensors was expressed. The aim and objectives of this collaboration have been proposed and agreed on by the participants of the CLIC-PRAL workshop [1].

AIM AND OBJECTIVES

The aim of this project is to compare existing HLS and WPS to each other. This takes place by creating the same test criteria, conditions and infrastructure at the institute that hosts the test, as well as using the same analysis methods in the interpretation of the results.

One objective of the tests is defined by the investigation into the sensor performance. Therefore tests are proposed that allow the determination of long-term stability, linearity, repeatability and resolution of the sensor's measurements.

In difference to the individual validation tests that are already carried out for the sensors in each institute, this collaboration allows for the first time the evaluation of the sensors with respect to each other under the same given conditions.

SENSORS

The sensors presented in this section are based on the systems that are already in use at the different laboratories. Similar systems are proposed for CLIC [2] and ILC [3].

HLS

HLS systems are frequently used in particle accelerators for vertical and inclination monitoring applications. A large variety of sensor techniques and measurement approaches exist [4]. However, during the CLIC-PRAL workshop three different types of measurement principles have been identified that are used in particle accelerators.

The most common technique is based on capacitive measurements. This concept is used by sensors of FOGALE nanotech, Edi Meier + partner AG and the Budker Institute of Nuclear Physics (BINP) in systems that are designed for µm resolution measurements. Fermi National Accelerator Laboratory (FNAL) has developped a capacitive low-cost solution with Balluff proximity sensors for a measurement accuracy of some ten µm. As these sensors are used in the Tevatron accelerator, they are named Tevatron-HLS (THLS).

Ultrasound sensors are used in two available systems. The Deutsches Elektronen-Synchrotron (DESY) has developed an auto-calibrating system which is used in the PETRA-III installation [5, 6]. BINP has a system that uses the same ultrasound

Table 1: contributed HLS

Institute	Manufacturer	Name	Type
CERN	FOGALE	cHLS[1]	capacitive
FNAL	FNAL	THLS	capacitive
FNAL	BINP	SAS[2]	capacitive
FNAL	BINP	SAS-E[3]	capacitive
DESY	DESY	uHLS	ultrasound
FNAL	BINP	ULS[4]	ultrasound
USTC	USTC	USTC	CCD

[1] sensor also used at DESY, ESRF and KEK
[2] analog-digital converter readout
[3] Power-Over-Ethernet (POE) readout
[4] sensor also used at SLAC

transducer. Both institutes have developped their own electronic for the systems.

A third technique is a charged-coupled device (CCD) camera that detects the position of a steel pin. The pin is attached to a floating device on the water surface. This solution is used by the sensors of the University of Science and Technology of China (USTC) and is implemented in the National Synchrotron Radiation Laboratory [7, 8].

Since the CLIC-PRAL workshop, the institutes shown in table 1 provided sensors to the intercomparison.

WPS

The use of WPS systems in particle accelerators is less common compared to HLS systems. Therefore only two permanent monitoring systems have been identified to be currently used. Capacitive FOGALE nanotech sensors (cWPS) are installed at CERN for the monitoring of the low-beta magnets at the four interaction points of the Large Hadron Collider (LHC) and for the monitoring of the FLASH undulator section at DESY. The second system, a radio-frequency (RF) signal based system, the wire position monitor (WPM), is installed at SLAC National Accelerator Laboratory (SLAC) in the Linear Coherent Light Source (LCLS) [9].

A prototype system of an optical WPS (oWPS) is developed by Open Source Instruments (OSI) in cooperation with CERN. The sensor uses the type of cameras that is installed in the Brandeis CCD angle monitor (BCAM). The two cameras, installed in a 62 degrees angle, are taking each one image of the wire; the software calculates the wire position as the intersection point of the wire from the images. The cameras and components have been tested for radiation tolerance as they are installed in experiments of the LHC and sensor tests have been carried out at CERN for sensor validation [10, 11].

Sensor design

The objectives with which the sensors were designed have often been related to the project they are used in. Hence the sensors are very different concerning their range and resolution as well as the data acquisition frequency or the radiation tolerance.

This project does not investigate any possible changes of systems or sensors in order to improve the performance of the system. The sensors are used in this intercomparison as they are designed and therefore the reflection on the measurement results must also take into account these design parameters. Three of them will be specified in detail in this paragraph.

Monitoring Function. The later application of the sensor has a major impact on the design and calibration of the sensor. By comparing the different uses of HLS and WPS mentioned above, two uses of a monitoring system can be identified.

Either the system measures the displacement of the object to be monitored and the system needs to provide the ability to measure the displacement accurately in a wide measurement range

or

the observation of the system is used to identify a movement with respect to the initial position and the observed displacement is corrected back to the initial position. In this case only a precise system is needed.

Also the use of the system as a short term system with measurement periods of some days or as a long term system with months and years of continuous sets of measurements can have an impact on the sensor's design.

Absolute Measurements. The calibration of the sensor's measurement with respect to external, geodetic references is a challenge for future monitoring applications [12] and is only limited by the design of the sensor and the mechanical determination of these interfaces with respect to the sensor's measurements. The determination of these parameters has no influence on the sensor's measurement. Therefore they are not evaluated during the first steps of this intercomparison.

Electronics. The chosen readout system for the acquired sensor data can be one limiting factor for the sensor's resolution. A sufficient number of bits and decimal places has to be chosen, when looking into the resolution and precision of the sensor in order not to be the electronics the limiting part of the sensor.

COMPARISON PROGRAMME

The comparison program that has been put in place consists of several phases.

In a first phase, the participating institutes agreed during the CLIC-PRAL workshop on supplying sensors for the test installations and CERN, ESRF, FNAL and SLAC expressed their will to host the intercomparison installations.

In preparation of the test installations, CERN discussed and coordinated the proposals for the configuration and installation of HLS and WPS systems. In parallel, sensors were provided by the institutes shortly after the workshop in order to start tests on the sensors and to allow the host institute to put in place the software and data communication.

In July 2010, the WPS intercomparison installation took place at SLAC. The test bench for HLS was established at CERN and the test infrastructure at FNAL was visited. The sensors are gathering stability data since and are therefore validating the installed sensors and systems.

The next major step will be the start of individual sensor tests for HLS at the test stand at CERN and the moving wire tests for the WPS systems at SLAC.

TEST INSTALLATIONS

The test installations shall allow the comparison of the sensors as defined by the test proposals. For HLS, FNAL provides tests on long term stability where as CERN tests the linearity and other parameters of the sensors. All tests on WPS systems are carried out at SLAC, while CERN continues the investigation into the oWPS qualification.

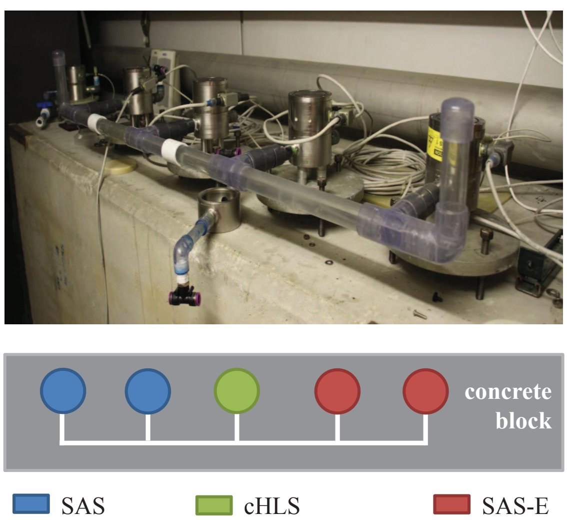

Figure 1: HLS test bench

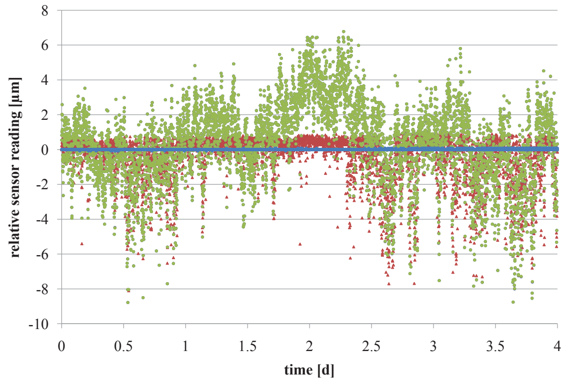

Figure 2: HLS short term stability

The following section is the original version as presented at IWAA 2010. An erratum is established after discussion on the results during IWAA 2010 and a second data analysis after the workshop.

HLS tests at FNAL

The sensor tests are carried out in a tunnel at FNAL. A concrete block, as shown in Fig. 1, or the concrete floor are used for the installation of HLS systems. Until now, the different types of sensors were mainly tested on independent networks. Stability tests were carried out on THLS, capacitive BINP sensors (SAS) with analog/digital converter, capacitive BINP sensors with Power-Over-Ethernet readout (SAS-E) as well as BINP ultrasound HLS. Results of these tests are shown by Volk (2010) [13].

One stability test bench has been installed with one FOGALE nanotech, one BINP SAS, three BINP ultrasound and two BINP SAS-E sensors. The results are calculated of a four day stability test. The results of a four day stability test are shown in Fig. 2. The temperature stability over the period was better than 1 Kelvin.

The capacitive BINP SAS sensor and the FOGALE nanotech sensors show stable measurements to better than 1 µm, with some outliers for the BINP SAS. All ultrasound sensors are perfectly superposed with their measurements, so that signal correlation is very likely to be the cause of the perturbation of ± 6 µm. The BINP SAS-E have a stable signal, but an electronic's noise of ± 15 µm and are not shown in the graph.

Erratum to section HLS tests at FNAL.

HLS tests at FNAL

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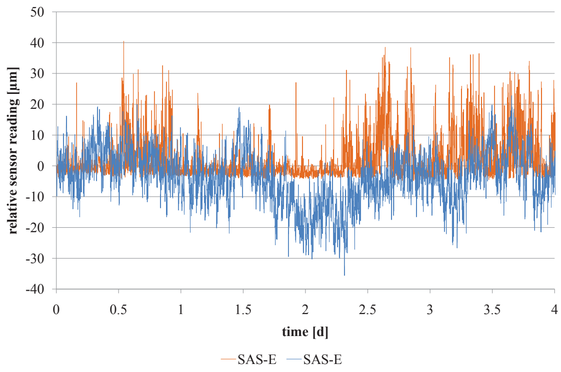

Figure 3: HLS short term stability

mainly tested on independent networks. Stability tests were carried out on THLS, capacitive BINP sensors of SAS or SAS-E type as well as ULS. Results of these tests are shown by Volk [13].

One stability test bench has been installed with one FOGALE nanotech, one SAS, three ULS and two SAS-E sensors. The results of a four day stability test are shown in Fig. 3. The temperature stability over the period was better than 1 Kelvin.

During this setup, the problems occured in the data acquisition for cHLS, SAS and ULS sensors. This can be linked to the power supply of these sensors or a communication problem of the sensors. Some variations of 0.1 µm can be seen in the signal which creates the impression of very stable sensors. In fact, only the SAS-E sensors can be exploited. Fig. 3 shows variations of ± 30 µm, that have no correlation to each other, though the sensors are installed on the same network. The noise of the sensors is approximately 10 µm, which is a lot compared to measurements carried out at CERN with the same type of sensor. This problem can be linked to the previous use of these sensors in radiation environment.

This test has to be repeated with new sensors or by using sensors that have previously only been used in laboratory environment.

HLS tests at CERN

At CERN, the sensors are checked for linearity, resolution as well as for their precision and accuracy. Before starting these tests, the sensors are installed on a common test bench for stability observations. In a second step, they are compared on the same bench for linearity with respect to other sensors throughout their range by varying the level of the water surface. For the relative comparison measurements, the cHLS is considered as reference, as their calibration can be checked on the available infrastructure [14]. Furthermore detailed investigations have been carried out on this type of sensor during the installation of the LHC low-beta magnet monitoring system [15].

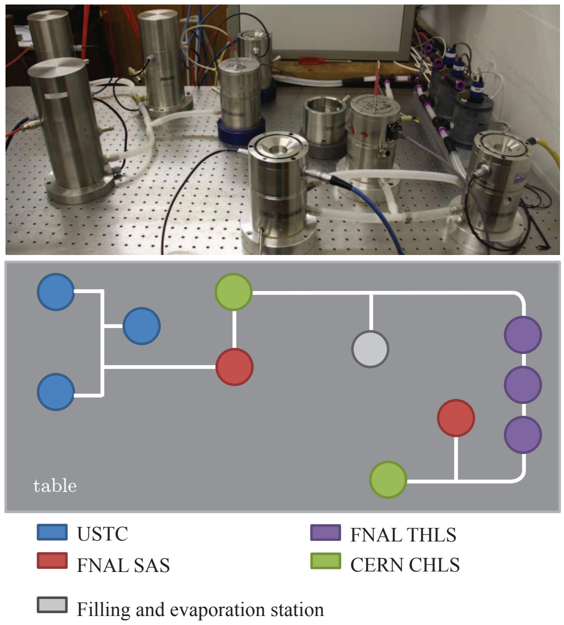

Figure 4: HLS stability bench

The HLS are installed on a table in the calibration laboratory and adjusted to have the best possible overlap of the measurement ranges.

Fig. 4 shows design and configuration of the sensors that are installed on the table. Two cHLS, two SAS-E, three THLS and three USTC sensors are installed. The ultrasound sensors of DESY as well as an automated station to allow the variation of the water height will be integrated soon.

The sensors are linked by flexible water tubes with an inner diameter of 10 mm. The air connection is not installed as all sensors are exposed to the same air pressure. Until the automated station will be installed, a measurement pot is used for the controlled variation of the water level.

A first linearity test was carried out on this installation, as the variation of each sensor with

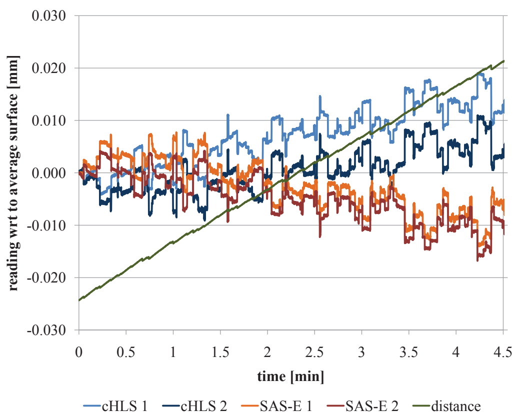

Figure 5: HLS linearity over 1 mm range

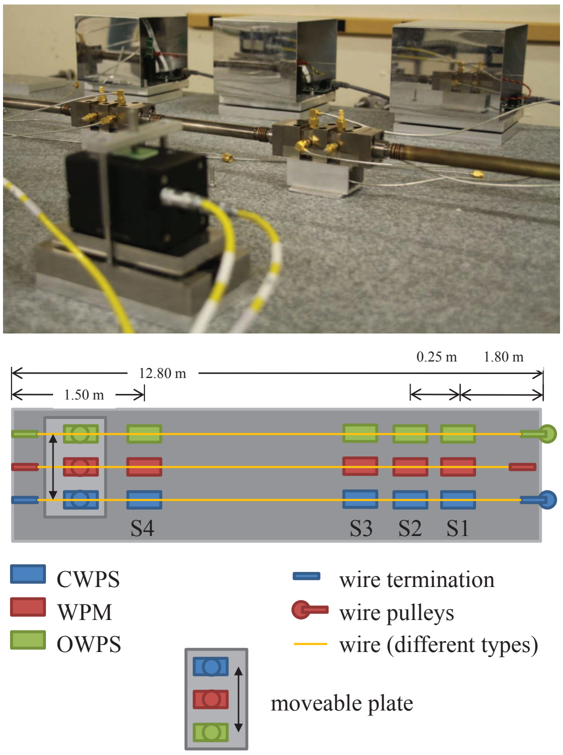

Figure 6: WPS test bench

Table 2: WPS sensor characteristics

criteria		WPM	oWPS	cWPS
range	[mm]	3 x 3	10 x 10	10 x 10
hor. noise	[μm]	0.02	0.99	0.24
ver. noise	[μm]	0.02	0.53	0.23
stability*	[μm]	< 0.20	< 3.00	< 0.75

* stability measurement over a period of 3 weeks

respect to the reference sensors is observed when varying the water level. This test is important for the ultrasound, CCD based and the proximity sensors, as they cannot be integrated to the existing sensor calibration bench at CERN.

The SAS-E and cHLS sensors, both based on capacitive measurements, can be installed on the calibration bench in order to validate their calibration [15]. In addition they will be calibrated at ESRF independently.

Fig. 5 shows cHLS sensors and SAS-E sensor measurements. Deliberately caused evaporation in the system provided a height change in the system of 1.1 mm over the shown period of four days. All sensors follow this variation and the different sensor types do not vary by more than 15 μm over the given distance and with the given calibration function. Extrapolated to the range of the sensors of 5 mm, this is a difference in the calibration function of maximum 75 μm. A linearity test on the calibration bench will be carried out in order to validate this hypothesis.

WPS tests at SLAC

The installation of WPS at SLAC has been carried out in July 2010. The sensors were installed on a 12.8 m long granite table in the geodetic laboratory at SLAC. Fig. 6 shows the layout of the test setup with three different wire sensor types each with its own and independently installed wire. The measurements cannot be carried out on the same wire as the sensors use different measurement technologies. The capacitive FOGALE nanotech sensor uses a conductive carbon-peek wire, the WPM system a gold plated stainless steel wire and the oWPS a wire made of Vectran fibres.

The RF sensors require a protective tube to close the RF loop where as the other systems have no wire protection installed.

To test the resolution of the wire sensors, the readings of sensors S1 to S3 are investigated. The positions of the sensors are shown in Fig. 6. For a time period of 48 h, data was taken with a sampling rate of 30 s. While the oWPS sensors were taking one data sample during this period, the data for the FOGALE system and the RF system was averaged over 30 s time periods.

Since the readings of all sensors change in sync one can assume that the majority of the reading changes are caused by wire changes. To isolate potential sensor drift from actual wire motion, sensors S1 and S3 were used to calculate the wire position at sensor position S2 which is then subtracted from sensor S2 to find the relative readings between them. The results are shown in Fig. 7.

The sensor readings with the wire motion subtracted are then used to determine the stability of the sensor type. To get a better understanding of the stability of the sensors the data was evaluated over a time period of three weeks. The obtained values for noise and stability are shown in table 2.

After the stability tests, a movable plate will be installed, allowing the simultaneous displacement of all wires by the same distance in horizontal and vertical position.

FUTURE STEPS

The next steps for the test installations are the validation of installation of the systems and, for the HLS, the integration of further sensors. This shall be finished by the end of 2010.

In the HLS comparison the sensors themselves are compared to each other, one has also to look into the way the calibration has been carried out for each sensor type in order to understand possible differences.

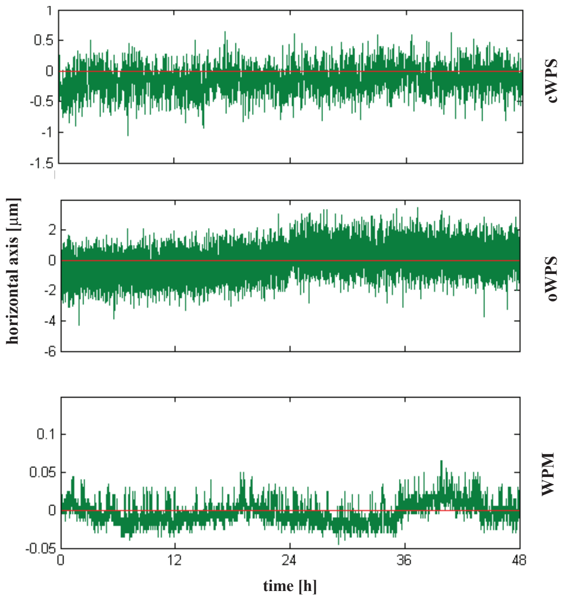

Figure 7: horizontal readings [µm] over a 48 h period

A theoretical examination of the provided calibration data, the data acquisition concept and the sensor concept itself has to be carried out in order to determine a priori and a posteriori values for accuracy and precision of the sensors taking into account external influences, like for example temperature.

HLS that are based on capacitive measurements, will be checked on the automated calibration bench at CERN and also for an independent comparison of the calibrations at the calibration facility at the ESRF.

For the WPS test, the installation of the test bench shall be completed by the end of 2010. The calibration throughout the range of the sensors shall be tested by displacing the wires.

CONCLUSIONS

Monitoring applications that are measuring with respect to a stretched wire or to a water surface and that are providing µm resolution at the same time are used in most particle accelerators. The existing systems and technologies have been identified in 2009 during the CLIC-PRAL workshop. Today's installations are mainly based on capacitive and ultrasound measurements for HLS and on optical, capacitive or radio frequency measurements for WPS.

The participants at this workshop expressed the strong wish to establish a collaboration in order to compare HLS and WPS. In the conclusions of the workshop, institutes immediately proposed to host different test facilities and sensors for the comparison program have been provided shortly after the workshop.

In the months after the workshop, the concept of the comparison program has been validated and test benches have been installed in summer 2010 at FNAL, SLAC and CERN.

The measurements for the validation of the test bench installation are on their way and first results of these tests will be available in 2011. Based on the standard evaluation methods and the results obtained, a second test phase can be considered.

This collaboration will be providing an overview on the monitoring sensors and give criterion for decisions in concepts for future accelerators.

ACKNOWLEDGEMENTS

The authors would like to thank A. Chupyra for the interesting discussions during the workshop that revealed the problems in the data analysis of FNAL measurements and gave indication why SAS-E type sensors showed such an unsatisfying performance during the tests.

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