oWPS VERSUS cWPS

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Abstract

The strategy of the CLIC pre-alignment relies on Wire Positioning Sensors (WPS) measuring the radial and vertical offsets with respect to a stretched wire. A precision below 2 µm and an accuracy of 5 µm over a whole range of measurement of 10 mm per axis are required for these sensors. Two types of sensors, based on two different technologies are under development and study at CERN: the capacitive sensor (cWPS) is already in use for the monitoring of the position of the low beta triplets in the LHC and the optical sensor (oWPS) is currently under development with Open Source Instruments. The cWPS had to be upgraded in order to reach the specifications required by the CLIC alignment. The oWPS is a new development especially designed to the CLIC demands. The paper presents the two types of sensors, the developments, as well as the latest results obtained in validation tests. These two types of sensors are part of a common test setup: results of intercomparison tests achieved on this setup are detailed.

INTRODUCTION

The strategy of pre-alignment for the Compact LInear Collider (CLIC) is under study at CERN and is based on stretched wires and Wire Positioning Sensors (WPS). More than 60 000 sensors would be installed, measuring radial and vertical offsets with respect to more than 40 km of stretched wires, with a precision below 2 µm and an accuracy of 5 µm, over a range of 10 mm. To fulfill such requirements, sensors based on two different technologies are under development and validation at CERN: optical WPS (oWPS) and capacitive WPS (cWPS). This paper introduces the two different types of sensors, their principle of measurement and their main characteristics. The sensors were first validated on individual test benches prior to their installation on a test setup for their inter-comparison. The test benches and test setup are presented, as well as the associated results.

oWPS

This sensor is developed and manufactured by Open Source Instruments Inc. under GNU General Public Licence [1]. The design was proposed in 2006, one first version of oWPS (oWPS1) was manufactured and tested successfully in 2009 [2], prior to the second and latest version, presented below.

Measurement principle

The sensor consists of two CCD cameras mounted rigidly on a support equipped with a kinematic mount. These cameras take pictures of the stretched wire from two different angles, under red light provided by an array of LEDs flashing synchronously. The position of the wire is deduced from each CCD by image analysis. As the position and orientation of each camera have been determined previously in a calibration process, the position of the stretched wire can be deduced in the coordinate system of the sensor. As a matter of fact, each camera provides an image plane with a wire line, and their intersection provides the wire mean axis with respect to the kinematic mount of the sensor (see figure 1).



Figure 1: oWPS from concept to reality (OSI Inc.)

Version 2 of oWPS is composed by:

- TC255 image sensors from Texas Instruments, 336x243 pixels, with 10 μm square pixels
- An array of nine LEDs, each LED emitting 20 mW of 620 nm red light
- A PT1000 temperature probe glued on the sensor side between the two CCD
- An A3022 WPS head, developed by OSI inc., allowing simultaneous exposure of both images, during the flash by LED array.

In this latest version, the image sensor is more sensitive to red light (infra-red light for version 1) and is combined with a larger aperture (500 μ m instead of 250 μ m for version 1). Consequently, excellent images are obtained with a 10 ms exposure (instead of 300 ms for version 1) with respect to a silver coated Vectran wire. The acquisition time is limited by the readout system, and is about 1.8 Hz per sensor.

Kinematic mount

The base plate of each sensor is manufactured in hardened aluminium and is equipped with kinematic mounting surfaces (cone, conical chamfer and plane) allowing the fastening of the sensor on 3 balls with a diameter of 0.250 inches with one central mounting screw. A torque of 0.1 Nm is applied during that stage in order to keep the installation precision of the oWPS below 1 μ m without damaging the kinematic mount surfaces.

During the calibration process, a sensor coordinate system is defined with respect to the 3 mounting balls; the wire position is also determined in that system. In consequence, once associated with its calibration parameters, each sensor provides directly the wire position in its coordinate system [3].

Stretched wire as reference

First tests on the version 1 of oWPS were performed with carbon PEEK (Polyether ether ketone) wire used for cWPS measurements. But the results were not entirely satisfactory: the wire, which is a carbon fiber wrapped by two thin plastic threads in PEEK, appeared to be nonuniform longitudinally, and some bright spots were visible on the images, due to light reflection from the plastic braid.

Vectran fiber, a multifilament yarn spun from liquid crystal polymer (LCP) was then tested as it appeared to have a smaller linear mass, a higher tensile strength, minimum moisture absorption, an excellent creep resistance and a low thermal expansion. But, the first tests demonstrated that this white wire is transparent to infrared and hardly visible on the images. A second drawback was discovered: it is not anti-static. A black Vectran wire was then manufactured, but tensile strength tests concluded that its tension strength was inferior to the white Vectran wire.

The latest development was the metallization of Vectran wire by silver plasma coating. The wire is now anti-static and can be easily detected and analyzed by the image algorithms. Irradiation tests were performed with success at a total dose of 330 kGy and no impact on the ultimate stress of the fibers [4].

The 3 types of wire: carbon PEEK, white Vectran and silver Vectran are shown in figure 2, with on top an image of the wire recorded by a CCD camera and on bottom a picture of each wire.



Figure 2: different types of wires (on top: image of the wire, on bottom: picture of the wire)

Validation tests

As soon as delivered, the sensors have been submitted to individual qualification tests: linearity tests and interchangeability tests. The linearity tests have been performed on a dedicated bench which is the assembly of two high precision linear stages mounted at 90° with a range of 100 mm, a bidirectional repeatability of $\pm 0.2 \ \mu m$ and a resolution of the linear encoder of 0.1 μm . The displacements carried out by the tables have been controlled by a Coordinate Measuring Machine (CMM) with a Maximum Permissible Error (MPE) of 0.3 μm + 1 ppm. A default of perpendicularity was identified, but is now very accurately determined and can be compensated.

This is the first time that precise linearity tests could be performed. The linearity tests made in 2010 were affected by the limited precision of the used stages, the fact that the reference wire was moved and not the sensor and that the white Vectran wire was hardly detectable using an oWPS1 Sensor [2].

Considering the displacements performed by the stages as reference, the linearity offsets obtained at the center of the sensor are in the order of 5 μ m and reach 10 μ m at the limits of the sensor (see Figure 3).



Figure 3: linearity offsets on an oWPS2 sensor

The linearity is better in vertical than in the radial direction. We do not yet understand the change in wire position with temperature as seen by the oWPS.

A compensation of the temperature effects could be performed provided that the temperature during calibration and measurements are precisely monitored.

Interchangeability tests have been performed on a dedicated metallic plate, equipped with 3 kinematic interfaces. Two sensors were installed on the external interfaces in order to control the stability of the stretched wire, while 5 different sensors were installed on the middle interface. A standard deviation of $\pm 1.8 \ \mu m$ in radial and $\pm 5.8 \ \mu m$ in vertical was obtained between the readings [5].

cWPS

From relative to absolute measurements

The cWPS is not as recent as the oWPS. A first version of cWPS was delivered in the early 1990s. In this version, only two measurement electrodes (one per axis of measurement) allowed the determination of radial and vertical offsets with respect to a stretched wire. A few improvements later:

- 4 measurement electrodes (two per axis of measurement),
- 2 ceramic reference surfaces installed on the sides of sensor in order to provide electrical insulation of the sensor and better repositioning.

More than 60 sensors are now installed on the LHC inner triplets [6]. The cWPS carry out a monitoring of the position of quadrupoles in a severe environment (high radiation fluences and magnetic fields) with a micrometric resolution [7]. But cWPS installed in the LHC perform only relative measurements. Taking into account a global budget of error including the adjustment of the electrical zero of each sensor with respect to its reference surfaces, the installation of the sensor on its mechanical support, and the centering of the mechanical support with respect to the fiducial, it can be estimated that the zero of each sensor is determined within \pm 50 µm with respect to the fiducial on which it is installed. Such a value of accuracy does not fulfill the CLIC requirements, and a new kinematic mounting plate, based on the oWPS concept, was proposed by CERN in 2009 [8].

Kinematic mount

There is an additional requirement in the case of cWPS: the sensor must be electrically insulated from its support. Ceramic balls with an 8 mm diameter and a sphericity tolerance of 1 μ m are the adequate solution. They can easily be measured by a CMM and are stable over time.

An independent plate, with a cone, conical chamfer and plane interfaces is permanently associated with each sensor.

Two ways of fastening the sensor on the 3 balls have been developed: a solution "gate" and a solution "spring" (see figure 4). In the first case, the sensor is maintained on its 3 balls by a central force applied by a screw installed on a "gate". The electrical insulation of the sensor is kept thanks to a fiberglass shim installed between the sensor and the screw. In the second case, the sensor is kept on the 3 balls from below, thanks to a spring in fiberglass. This second solution can also be applied when the sensor is installed "head down" in a facility. The first solution has been tested on 17 sensors and 36 centering per sensor. A transversal repeatability ranging from 0.6 μ m to 1.8 μ m and a vertical repeatability ranging from 0.5 μ m to 1.0 μ m was obtained [9].



Figure 4: Fastening of cWPS sensor

Each sensor is delivered by the manufacturer with its associated functions, linking voltage measurements to offset measurements in millimeter with respect to the ceramic reference planes. The new mechanical interface added below each sensor creates a new coordinate system canceling the calibration functions given by the manufacturer. A new linearity bench has been designed in order to calibrate these upgraded cWPS. The bench is a combination of two displacements tables, with a resolution of displacement of 10 nm over a stroke of 75 mm. A middle range switch provides the zero reference for all the sensors and makes them interchangeable.

Associated stretched wire

The stretched wire in use in the LHC is made of carbon PEEK. It has a diameter of 0.4 mm, a linear mass of 235 g/km and 230 N of breaking tension [10]. The carbon PEEK wire has a conductibility above 0.025 m/ Ω .mm², which is the minimum admissible value required by the manufacturer. Another wire is associated to cWPS: a carbon PES (poly ether sulfone) wire, where the plastic threads in PEEK have been replaced by PES, which is slightly less radiation resistant, but has otherwise the same characteristics.

As carbon PEEK and carbon PES wires are fragile, a third wire is used for special applications: carbon Kevlar (the carbon fiber is braided by yarns of Kevlar). Apart from a larger diameter and a higher linear mass, this wire has a major drawback: its high sensitivity to hygrometry variations. The choice of the type of wire for series of measurements is very important, knowing that in addition each cWPS must be calibrated with respect to the type of wire to be used. As a matter of fact, calibration functions determined for a carbon PEEK wire cannot be used for measurements with respect to a carbon PES or a carbon Kevlar wire. A scale factor can be applied on the readings of a sensor measuring with respect to two different types of wires. The scale factor between carbon PEEK and carbon PES is of the order of 10 µm per millimeter of range, while the scale factor between PEEK and carbon Kevlar is of the order of 50 µm per millimeter of range [9]. Several drums of carbon PEEK wire have been purchased during the last years and there is also a scale factor between wires coming from different manufacturing lots of the same type of wire, which is not negligible with a value of 100 µm per millimeter of range. On the other hand, tests have shown that there is no scale factor between wires coming from the same manufacturing lot [11].

Absolute test bench

Thanks to this micrometric interchangeability, cWPS provide pseudo absolute measurements: they have the same zero in their coordinate system, but the position of zero is not known at the micron level with respect to the 3 balls. A dedicated test bench has been developed to solve the problem [8] and the determination of zero for all the sensors is under progress.

INTER-COMPARISON TESTS

Introduction

First inter-comparison tests have been performed at SLAC in July 2010 [12]. Several sensors from 3 different

types: oWPS version 1, cWPS and RF sensors, were installed along 3 parallel wires (Vectran fiber, carbon PEEK and gold plated stainless steel) on a granite table along 12.8 m (see figure 5). The fixed stretching device (or wire termination" of each wire was installed on a movable plate.



Figure 5: Inter-comparison between sensors at SLAC [11]

Direct inter-comparison between sensors types was not possible: the displacement provided not repeatable results. But an analysis per wire was possible, knowing the longitudinal position of the sensors along their wire, a "line fit" was performed. Sub micrometers residuals were obtained for RF sensors. A scale factor of 2% was obtained on cWPS, which could be explained by a difference between the different types of wires used for the calibration and on the facility; the issue with the scale factor between wires was not known at that time. Residuals of the order of 3 μ m were calculated for oWPS. Unfortunately, this test setup had to be dismounted allowing no further tests to be performed. The new version of oWPS has been tested on another facility at CERN.

Description of the facility at CERN

oWPS and cWPS have been installed on a test setup where the validation of the CLIC pre-alignment strategy on short range is under progress [13]. The test facility consists of two sets of two girders, each girder being equipped with one cradle per extremity (see figure 6). Each cradle hosts the 3 balls mechanical interfaces of 1 oWPS and 1 cWPS. The position of all balls was determined within a few microns in the coordinate system of the girder on a CMM [13]. Two concrete blocks with reference sensors have been installed independently on each side of the girders.



Figure 6: Configuration of oWPS and cWPS sensors

In this facility, the oWPS and cWPS have undergone several tests: noise, repeatability/reproducibility of dismounting and reinstallation, displacement of stretched wire and short term measurements. The results of the tests are presented in the following paragraphs.

Noise of sensors

The noise peak to peak is comprised between 5 to 8 μ m concerning cWPS sensors (one raw measurement per 1.5s) (see Figure 7). At the beginning of the facility, when there were no other technical systems and no other cables, the noise was inferior to 1 μ m. This is a critical value: in case of an active alignment, the sensor readings will have to be integrated over several seconds to obtain a mean value with a standard deviation that is acceptable (below 2 μ m) [14].

The noise peak to peak is below $2\mu m$ for oWPS (see Figure 7), except when actuators supporting the girders are switched on: the noise increases by a factor 2! Investigation into the problem shows that the noise is getting into the sensor and enters the system through the flexible and not shielded cables between the camera and the circuit board, not through the Ethernet cables [15]. This could disappear with a better insulation of the bottom plate of the sensor. Two solutions can be envisaged: an anodic oxidation of the bottom plate itself or the use of ceramic balls instead of steal balls.



Figure 7: noise of radial measurement for oWPS (left) and cWPS (right)

Repeatability, reproducibility and interchangeability of oWPS and cWPS sensors

The repeatability tests were performed by the same operator. The sensor was removed from its kinematic ball interface and re-installed following a given procedure. After each installation, the new radial and vertical readings of the sensor were registered. The operation of dismounting / remounting was performed 10 times per sensor. Concerning cWPS, offsets of maximum 2 μ m have been observed, for the 2 axes. The system of fastening was a "fiberglass spring" type, and no differences were detected between sensors hold "head up" or "head down". The repeatability is even better concerning oWPS, with a maximum offset smaller than 1.5 μ m [5].

The reproducibility tests were carried out by different operators, following different procedures. Offsets of maximum 3 μ m were detected concerning cWPS.

During the interchangeability test, different sensors are installed on the same mechanical interface. Additional sensors check that the wire has not been displaced during these installations. In consequence, the same radial and vertical offsets with respect to the wire should be given by the sensors. Concerning cWPS, maximum offsets of 10 μ m were observed, with a mean around 3-4 μ m. Concerning oWPS, the interchangeability is a bit higher

with a maximum offset of 14 μm and a mean around 6 - 8 $\mu m.$

Test of displacement of the wire

Once the sensors have been validated individually on the facility, with the repeatability, reproducibility and interchangeability tests, they are ready for a joint validation. The most efficient test consists of displacing the wire along its vertical and radial axes by a few millimeters and checking that proportional displacements are seen by the sensors, taking into account their longitudinal position along the wire. The real displacement at the level of each sensor (radial and vertical offsets monitored by the sensor) is compared to the theoretical displacement that should be seen.

Position	Displacement (mm)		Offset (µm)	
	Rad.	Vert.	Rad.	Vert.
PAB	1.183	0.832		
B4			-1	0
B2			1	0
B3			1	1
B1			0	-3
B5			-2	-4
PBB	-1.102	-0.105		
Δ	2.285	0.937		

Table 1 : offsets after displacement test of cWPS sensors

Position	Displacement (mm)		Offset (µm)	
	Rad.	Vert.	Rad.	Vert.
PAM	-2.581	1.184		
MCD			0	-1
MCA			3	2
MCC			-3	4
MCD			-1	2
PBM	-0.197	0.096		
1	2 384	1.088		

Table 2: offsets after displacement test of oWPS sensors

Table 1 and table 2 present these offsets, as well as the displacement performed at each extremity of the wire. Offsets after displacement are smaller for cWPS.

Short term stability tests

Short term measurements have been performed during 13 consecutive days, with an acquisition rate of one value per minute, each value being the average of 40 readings. The graphs below presents a zoom over 2 days on the readings of oWPS and cWPS sensors belonging to the same cradle (for a clearer illustration, only readings from the most representative sensors are shown) as well as temperature variations.

In vertical (Figure 8), both sensors see the same displacement of cradle, due to temperature variations. In radial (Figure 9), the readings cannot be compared: additional tests will be needed in order to have a better understanding of the temperature effect.



Figure 8: impact of temperature (green) on oWPS (red) and cWPS (blue) on vertical readings



Figure 9: impact of temperature (green) on oWPS (red) and cWPS (blue) on vertical readings

Strategy and scripts of compensation are under discussion, knowing that several parameters must be integrated:

- The offset between the temperature of calibration and the temperature of use of the sensor
- The expansion of the sensor itself, that has an effect on the distances between the cameras, and consequently on the calibration.

Summary

In summary, the performances of the two types of sensors obtained during the validation tests on the facility are presented in table 3.

Table 3: summary of sensors performance

	oWPS	cWPS
	(µm)	(µm)
Noise	2	8
Repeatability	< 1.5	< 2
Reproducibility	< 2	< 3
Interchangeability	6 - 8	3 - 4
Resolution (integration of 60 measurements)	< 0.5	< 0.5

CONCLUSION

oWPS is a sensor that has been developed recently, for the needs of the CLIC pre-alignment. The first validation tests performed with this sensor show that its performances are comparable to the upgraded version of cWPS: it is less noisy (and this could be even improved if the electrical insulation of the sensor is implemented). allow reproducible and stable measurements, even if the temperature effects will have to be compensated. The wire associated with oWPS is promising too: with a smaller linear mass and a stronger breaking tension, sag is less important than for carbon PEEK wire. A conductive version of the Vectran wire is currently under development and could be associated with cWPS. Some tests remain to be carried out for absolute measurements. But first results obtained on the facility at CERN confirm that oWPS sensors perform absolute measurements within a few microns [5]. The next step is now to develop a more compact version of oWPS, which would be radiation hard.

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