Radiation Induced Effects on Hydrostatic Levelling Sensors

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In preparation for the permanent alignment system of the LHC low beta quadrupoles, several irradiation tests had been carried out since 2000 in order to validate the use of capacitive HLS sensors. The sensors will be located in areas where significant radiation doses are predicted. Tests have shown perturbing offsets in the sensors' signals as a function of the dose rate. Due to these observations, a theoretical study regarding the HLS sensors has been undertaken. This has shown that at high dose rates the ionization of the air inside the sensors causes charge recombination and this perturbs the position measurement. One correction model is proposed, and is compared to the sensors' signals monitored during the irradiation tests in 2005.

1. PRECISE MEASUREMENTS AND RADIATION PROBLEMS

The installation of geodetic measurement equipment in a radiation environment, like that in particle accelerators, needs proof of radiation hardness and full functionality in the given conditions. The influences on the sensors can be of different types, ranging from perturbation of the measurements in a known and compensable way to non-compensable drift phenomena. Tight alignment tolerances of several microns as found in the final focussing magnet regions, require any influence on the sensor due to radiation to be determined.

According to the CERN policy, all electronic components have to be qualified as radiation hard before being installed in the experiments and the accelerator. For the Large Hadron Collider (LHC) project, a test facility in TCC2 was set up in 1999 to study the influence of radiation on instrumentation which is going to be installed in the tunnel. Particle beams similar to those that will be circulating in the LHC are available in this test facility at CERN [2].

The Large Scale Metrology group (TS/SU) took advantage of this setup from 2000 to 2003 in order to test the sensors which will be used for the alignment of the LHC final focus magnets. These magnets, situated within 50 m of the experiment's interaction points, will be strongly affected by radiation dose rates of up to 16,000 Gy/year. In 2004 and 2005, additional tests at the irradiation facility CEA in Saclay (France) were carried out to complete the test series and study some phenomena in more detail.

2. RADIATION TESTS

For equipment validation in radiation environments many different aspects can be taken into account. Finding answers to two basic questions was the main goal of the tests on the low beta magnet monitoring sensors. First, do the sensors withstand the high radiation doses that are expected during 20 years operation of the LHC [6]? Second, can influences on the sensors be observed and if so, can they be modelled?

2.1. Test Facilities

2.1.1. TCC2

This irradiation test facility operated by CERN allows the exposure of equipment to LHC-like radiation types in an area of 10 m^2. In a radiation-safe control room on the upper floor, data acquisition systems can be installed for the read out of the sensors during the tests. Modifications to the data acquisition or real-time analysis is possible. A dose rate exposure of about 3 Gy per hour can be achieved in this facility. Over a period of 15 weeks per test series, a total dose between 700 Gy and 2,000 Gy has been accumulated.

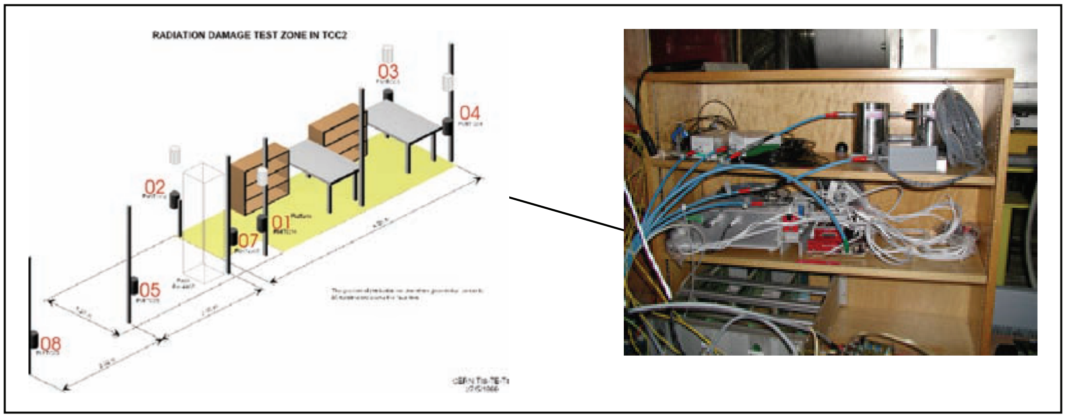

Figure 1: radiation damage test zone in TCC2

These irradiation tests have been designed to provide radiation hardness qualification of commercial off-the-shelf electronics for the LHC tunnel. As a part of these tests, the identification of radiation sensitive components and their replacement with radiation hard items had to be studied. Complete systems had to be validated and the equipment life-time had to be evaluated.

The life-time evaluation for the sensors installed in the highly radiation affected region of the inner triplet was difficult at the low dose rates provided at TCC2.

2.1.2. CEA Saclay

Two irradiators – Pagure and Poseidon – operated by CIS bio international at CEA in Saclay (France) have been used for tests at higher dose rates. The Pagure irradiator can host large volumes of several cubic meters. For small volumes dose rates of up 20 kGy per hour can be achieved. The Poseidon irradiator can provide dose rates of up to 5 kGy per hour. Both can be operated 24 h a day, seven days per week. They use ^{60}Co gamma ray sources, which do not cause any activation of the tested material. Therefore it is possible to return them immediately to the home institute for further tests.

2.2. Test methods

A **Total Ionisation Dose (TID)** test exposes the sensor to a desired quantity of radiation which is achieved by keeping them in a radiation environment at a known dose rate over a certain amount of time. Total Ionisation Dose tests characterize the materials and components used in the sensor. This test is essential for the sensor's qualification, as it provides fundamental information on whether the sensor can stand the radiation dose or not. Measurements on the degradation of the signal during the exposure have been carried out in parallel. For example this can happen due to the drift of components in the sensor. In case changes in the measurement data are observed, they are likely to be non-reversible for this type of test.

Dose rate dependence (DRD) tests are used to determine the influence on a certain radiation dose to the sensor. Offsets at 'beam on' or 'beam off', which might be caused by ionisation inside the sensor, can be quantified in these tests. These effects are generally reversible and can be directly correlated with the dose rate applied, empirical corrections and models which can be derived from such tests.

2.3. Sensors

The tests focussed on HLS sensors of different types, manufactured by FOGALE Nanotech. During this five year test series, modifications were necessary to achieve the best possible design of the sensor and its components, in regards to their radiation hardness. Tests were initially carried out with HLS sensors, which had integrated electronics and a ceramic housing of the electrode (2nd generation as used in LEP). Later developments lead to a stainless steel housing and remote electronics with connecting cable lengths of up to 30 m.

Table I: HLS sensor generations

generation	**HLS sensor**	
	body	**electrode**
2nd	ceramic	on ceramic
3rd	glass	protected behind glass
4th	stainless steel	on circuit print board in body

Figure 2: HLS sensor 4th generation with remote electronic, temperature sensor and cable

During the development of the sensors, major problems occurred with a glass type HLS and therefore this type of HLS sensor was abandoned. The cables to the remote electronics needed some expertise as well, because a radiation hard cable with good shielding qualities was not easy to find. The cable type is important as the transport of the primary, capacitive signal is done via this cable to the electronics.

2.4. Test Series

In the test series between 2000 and 2004, only prototype sensors with remote electronics were used. They were either based on the 2nd and 3rd generation off-the-self sensors or on the prototypes of the 4th generation of HLS sensors. Hardware costs to test several sensors of the same type during one test series are immense; therefore only one sensor per stage of expansion has been tested. In consequence, no statistical results could be drawn from the measurements and the different HLS sensor types. In 2005, sets of three sensors were used in their final LHC design for each test; therefore comparisons of the different measurements are possible.

In contrast to previous tests where the dosimetry was achieved by few dosimeters for the whole setup, the 2005 test's dosimetry determination has been done with radiophoto luminescent (RPL) glass dosimeters and Alanine dosimeters attached to every sensor. This was essential for the statistical evaluation of the dose rate dependence tests.

2.4.1. Tests 2000 – 2004

Tests were carried out on HLS sensors with integrated and remote electronics. The sensors were installed on a fix target to avoid additional effects of a water network. The sensors as well as the electronics were exposed at the same time to radiation during these tests. The measurements in 2000 showed a drift of the sensors right from the beginning, which has been detected as a mechanical instability in the setup.

In 2001, short cable lengths for remote electronics were used, as the electronics were supposed to be hosted under the magnets. The sensors, as well as the electronics and cables were irradiated at the same time. Due to failure of the electronics after approximately 800 Gy during the TID test, Marin (2004) concluded, that the use of remote electronics is only possible in a place with less than 10 Gy per year. This prompted on further investigation into an extension of the cable length to 30 m. Prototype development of sensors with remote electronics, as well as of generation four of the HLS sensors were carried out in consequence.

During tests in 2004 only the sensor was exposed to radiation. The electronic was placed outside because it was likely to fail at lower dose rates. In this configuration, a stable signal of the sensors has been obtained for a total dose of 67,000 Gy. This result was obtained for 2nd generation as well as for 4th generation HLS with remote electronics.

While sensors were exposed to radiation, an offset of the signal was observed and lead to further investigation of a possible dose rate dependence. Investigations lead to the idea that ionisation in the HLS vessel might be the cause of this effect, as previously proposed by Coosemans et al. (1999, 2000) [4, 5].

2.4.2. Tests 2005

The tests in 2005 were carried out in order to complete the information obtained from the tests in previous years, but with at least three sensors per test to allow for statistical comparison. These tests were carried out in cooperation with FOGALE Nanotech. The final HLS design for the LHC had to be validated in the TID test. The dose rate dependence tests at different dose rates were necessary as well to conclude on the phenomenon seen in 2004.

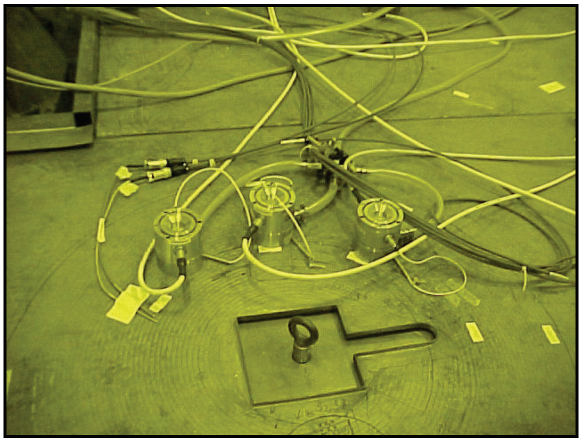

Figure 3: setup of sensors around the radiation source (2005)

Sensor TID test

Two HLS sensors already used in the 2004 test series have been installed in a hydrostatic levelling network to test their performance under real environmental conditions, e.g. to investigate influence of humidity during irradiation. One of the HLS was a second generation sensor; the other was a fourth generation one. Both remote electronics were situated outside the test bunker. The dose rate was supposed to simulate 10 years of LHC operation with an annual dose rate of 16,000 Gy as the worst case scenario; therefore the HLS were exposed to dose rates of 2,200 Gy/h during 72 hours.

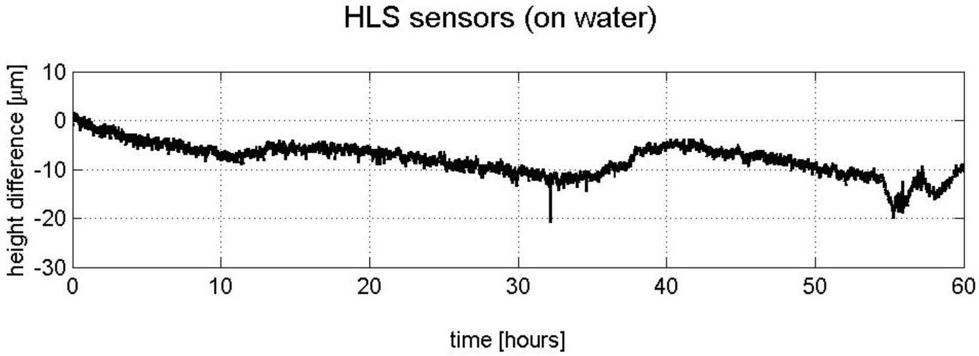

Figure 4: Δh between two HLS measuring on water during TID test

Both prototype sensors succeeded the test and were able to resist a total dose of 225,500 Gy cumulated in 2004. In parallel, two HLS sensors of the fourth generation were tested in the same irradiation conditions, measuring on a target. The sensor exposed to the radiation showed reliable results at a total dose of 158,500 Gy.

One sensor of the 4^{th} generation was exposed in the DRD test to another 21,500 Gy, which makes a total of 180,000 Gy for this sensor without any signs of degradation.

Electronic TID test

As the electronics were the sensitive part in previous tests, a TID test at a high dose rates would be inappropriate. Therefore they have been exposed to different dose rates. From the set of three electronics, two failed at total dose rate of about 700 Gy, the other one at 1200 Gy (figure 5).

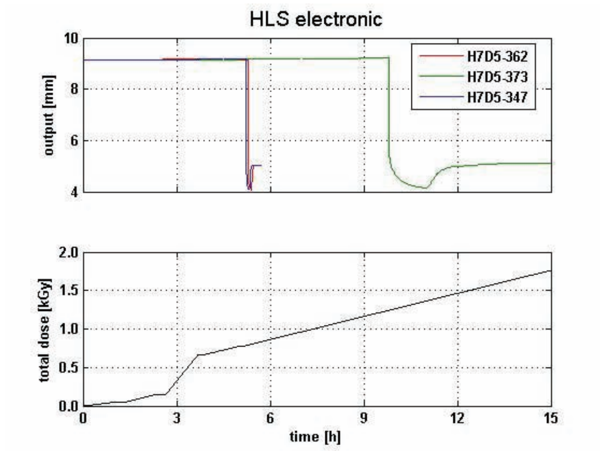

Figure 5: electronics break down

The necessity for remote electronics has been confirmed during this test. The installation of the remote electronics has to be done in places where dose rates of a maximum of 10 Gy per year can be expected (Marin, 2004). For example, this is the case in the survey galleries dedicated to the radial link of the ATLAS and CMS experiment, or behind the shielding in a service tunnel for the LHCb and ALICE experiment [7].

Though the electronics failed during the test, it was not a permanent failure of any of the components inside. The problem was caused by a sort of saturation of the electronics. Heating the electronics for one week at 50 °C made them return to normal operating conditions.

Sensor DRD test

For the dose rate dependence test, a series of measurements of one hour each were planned. The sensors were exposed to a dose rate of 50 Gy, 100 Gy, 500 Gy and 1,000 Gy before having a dose of 1,500 Gy per hour for a period of 12 hours. Finally the one hour measurements at lower dose rate were repeated in inverse order.

Figure 6 shows the steps observed at the different dose rates. The red and green curve are sensors of the 4th generation, the blue curve is from a sensor with a ceramic support of the electrode. All curves show an echelon form when the sensors are exposed to radiation and the quantity of the offset is strongly correlated to the applied dose rate. Peaks in the curves are caused by a vacuum pump which allowed the evacuation of the air inside the HLS vessel. The pumping was an essential part of these tests and was introduced due to the assumptions made after the 2004 test. With an ionisation phenomenon of the air inside the vessel, one was able to show, that the influence could be minimized by evacuating the vessel. This is clearly visible with the ceramic sensor (blue curve). The 4th generation sensors have too much mechanical stress on the electrode caused by the vacuum, that the deformation of the electrode is more important than the reduction of the signal due to evacuation of the vessel.

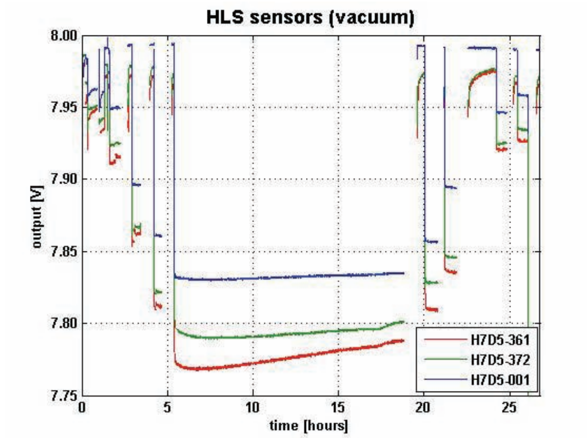

Figure 6: offset radiation

3. THEORY AND MODEL OF DOSE RATE DEPENDANCY

Tests on HLS sensors in 2004 showed an offset when the sensors were exposed to radiation. As the electronics were situated outside the irradiation chamber, the offset must be due to radiation effects acting on the sensor. Similar observations have already been made by Coosemans et al. (1999) during tests at the LEP spectrometer [4].

Dimovasili et al. (2005) made the assumption that the enclosed air volume in the vessel of a HLS system can be assumed to act like an ionization chamber and therefore similar physical processes can be observed inside the vessel. The model derived from the radiation tests in 2005 is based on the Bragg Gray principle [1].

This hypothesis has been evaluated with a series of tests on three HLS sensors. Figure 3 shows the setup around the radiation source. The source itself is not shown in the figure. The sensors were exposed to doses of 50 Gy/h, 100 Gy/h, 500 Gy/h, 1000 Gy/h and 1500 Gy/h.

The derivation of the following model is special to the capacitive sensors used for non-contact measurements. With this technology a change in the capacitance ΔC observed by the sensor is directly linked to a change in the distance between the electrode of the sensor and the target

$$\Delta C = \frac{\varepsilon_o \cdot \varepsilon_r \cdot S}{\Delta h} \tag{1}$$

with ε_0 as the absolute permittivity in vacuum, ε_r the dielectric constant of air, S the surface of the electrode and Δh the variation of the distance between the electrode and the target. This can also be described by an output voltage

$$V_{out} = (V_{offset} + \frac{1}{C_e} \cdot V_e \cdot C_{ref}) \cdot G \tag{2}$$

where as C_e is the measured capacitance, C_{ref} is the reference capacitance, V_e is the voltage applied between the plates of the capacitor and G is the scaling factor (gain) of the electronic.

By the assumption, that a HLS sensor acts like a condenser ionisation chamber a hypothesis was established. It was supposed to be confirmed by the empirically determined values of the measurement. The link between HLS and condenser chamber is the fact that they are built as a capacitor. As the Bragg-Gray conditions are met with this assumption, one can calculate the ionization current by the following equation:

$$I_{ion} = \frac{D \cdot m \cdot S_g}{W \cdot S_w} \tag{3}$$

where I_{ion} is the induced ionization current and D is the dose rate in the air inside the vessel. The mass of the air inside the vessel is describe with m, W is a constant that depends on the gas used and the ratio S_g/S_w is the mass stopping power of the gas.

Relating the dose rate and therefore also the ionisation current (3) to the voltage output of the sensor shows a non-linear, proportional offset and is according to Dimovasili [1], the proof of recombination in the HLS vessel.

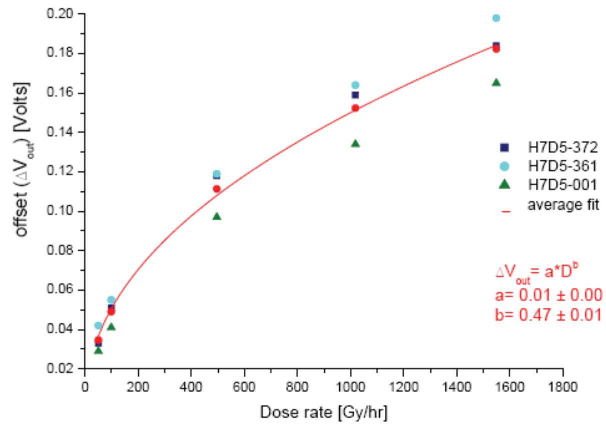

Figure 7: measured voltage offset for all sensors and average curve (red)

The influence of radiation on the HLS sensors leads to the question whether corrections can be applied for the measurements.

As shown in figure 7, the voltage output changes in dependence of the dose rate. The ionisation of the air inside the HLS vessel causes a change to the measurements as the voltage V_e applied to the capacitor to maintain a stable electric field is in consequence reduced by the electronic. This is misinterpreted by the electronic as a change of capacitance C_e. The result is a decrease in the output voltage V_{out}, which could be misinterpreted as a change of height (2).

The corrected height calculation for a HLS is done with the parameters of a polynomial providing the calibration curve $f(V_{out}, c_0, \ldots, c_x)$ with c_0 to c_x as coefficients of the polynomial. Additionally, a function $f(V_{out},D)$ has to be applied where as V_{out} is the output voltage measured and D is the radiation dose applied to the sensor. This defines the transformation of voltage measurement data to height information via the equation:

$$h = f(V_{out}, c_0, \ldots, c_x) + f(V_{out}, D) \tag{4}$$

To validate the results obtained for radiation influence compensation, a comparison between the theoretical parameter calculation from equation 2 and the experimental setup test was carried out. The results in table II show a theoretical variation of Δh. Since the nominal distance between electrode and target is known, a hypothetical offset due to radiation can be determined from the measurements. The results agree within one percent. Therefore the method can be seen as valid for the compensation of radiation induced effects on HLS sensors.

Table II: comparison between theoretical determination and experimental values

Dose rate Gy/h	**Δh (theoretical) µm**	**Δh (experimental) µm**	**Difference %**
50	21.10	21.06	0.21
100	27.34	27.29	0.21
500	59.18	59.06	0.20
1000	81.79	81.64	0.19
1500	98.96	98.79	0.18

4. CONCLUSION

Irradiation test for HLS sensor validation were carried out at different facilities at CERN and at CEA. Modifications on the sensor design have been done in order to get radiation hard equipment for the LHC. Remote electronics, cable lengths of 30 m for the transport of the primary signal and new electrode design were introduced. Ionisation of the air inside the vessel at high dose rates lead to investigations on a compensation model.

Three major conclusions can be drawn from the tests in the last five years. First, the modification of the sensors and the development of remote electronics were necessary with respect to the dose rates of the LHC. The sensors can provide reliable measurements within some microns if the electronics are installed in a radiation safe environment. Second, the second and fourth generation of hydrostatic levelling sensors have passed the total ionization dose test. The simulated test period was ten years of LHC operation. Third, ionization in the air between sensor and water surface occurs and can be compensated with a model that has been determined.

These extensive tests were essential to prepare the survey group for the online monitoring and alignment of the LHC final focusing magnets. Modifications on HLS alignment sensors had been done to customise them to the high radiation doses expected in this and future particle accelerators.

References

[1] E. Dimovasili et al., "Radiation induced effects on the sensors of the Hydrostatic Leveling System for the LHC low beta quadrupoles", CERN Technical Note TS-2005-052, Geneva (Switzerland), August 2005.

[2] R. Rausch et al., "Qualification of electronic components and systems in a LHC tunnel radiation environment", EPAC conference, Paris (France), June 2002

[3] A. Marin, W. Coosemans, "Radiation tolerance of positioning sensors and their conditioners used for the LHC low beta magnets", poster presentation, International Workshop on Accelerator Alignment, Geneva (Switzerland), October 2004

[4] W. Coosemans et al., "Performance of wire position sensors in a radiation environment", International Workshop on Accelerator Alignment, Grenoble (France), October 1999

[5] W. Coosemans et al., "Determination of accuracy of Wire Position Sensors", CERN Note CERN-SL-2000-029, Geneva (Switzerland), July 2000

[6] LHC Design Report, Volumes I-III, CERN

[7] A. Herty et al., “Status of the alignment of the LHC low beta quadupoles”, International Workshop on Accelerator Alignment, CERN (Switzerland), October 2004