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Design of a 0-50 mbar pressure measurement channel compatible with the LHC tunnel radiation environment

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Abstract. The monitoring of cryogenic facilities often require the measurement of pressure in the sub 5'000 Pa range that are used for flow metering applications, for saturated superfluid helium, etc. The pressure measurement is based on the minute displacement of a sensing diaphragm often through contactless techniques by using capacitive or inductive methods. The LHC radiation environment forbid the use of standard commercial sensors because of the embedded electronics that are affected both by radiation induced drift and transient Single Event Effects (SEE). Passive pressure sensors from two manufacturers were investigated and a CERN designed radiation-tolerant electronics has been developed for measuring variable-reluctance sensors. During the last maintenance stop of the LHC accelerator, four absolute pressure sensors were installed in some of the low pressure bayonet heat exchangers and four differential pressure sensors on the venturi flowmeters that monitor the cooling flow of the 20.5 kA current leads of the ATLAS end-cap superconducting toroids. The pressure sensors operating range is about 1000 to 5000 Pa and the targeted uncertainty is +/- 50 Pa which would permit to measure the equivalent saturation temperature at 1.8 K within better than 0.01 K. This paper describes the radiation hard measuring head that is based on an inductive bridge, its associated radiation-tolerant electronics that is installed under the LHC superconducting magnets or the ATLAS detector cavern; and the first operational experience.

1. Introduction

Most commercial sensors are available with embedded electronics that provides the pressure reading through either an analog electrical signal or as a digital value when using a communication fieldbus. The pressure is deduced from the deformation of a diaphragm that can be sensed by a variety of methods. An example for the selection criteria for electric power plants is shown in [1].

The LHC initial design (figure 1) foresaw about 225 pressure sensors installed in every single LHC cell that, for the regular arc, has a length of 107 m. A qualification campaign was undertaken to test different types of sensors. One major constrain was to keep the cable length short implying that either the passive measuring cell was compatible with the radiation tolerant electronics cards [2] or the manufacturer provided an active sensor with an analog output capable of withstanding the LHC radiation environment. After the radiation tests, one of the sensors based in a strain gauge satisfied the requirements [3], unfortunately it was impossible to procure even the additional small quantities required to end the qualification campaign. Sensors based in a variable reluctance technology with remote electronics were also tested, however the cable effects were not mastered by the commercial signal conditioning as its length and shape had a non-negligible impact on the readout.
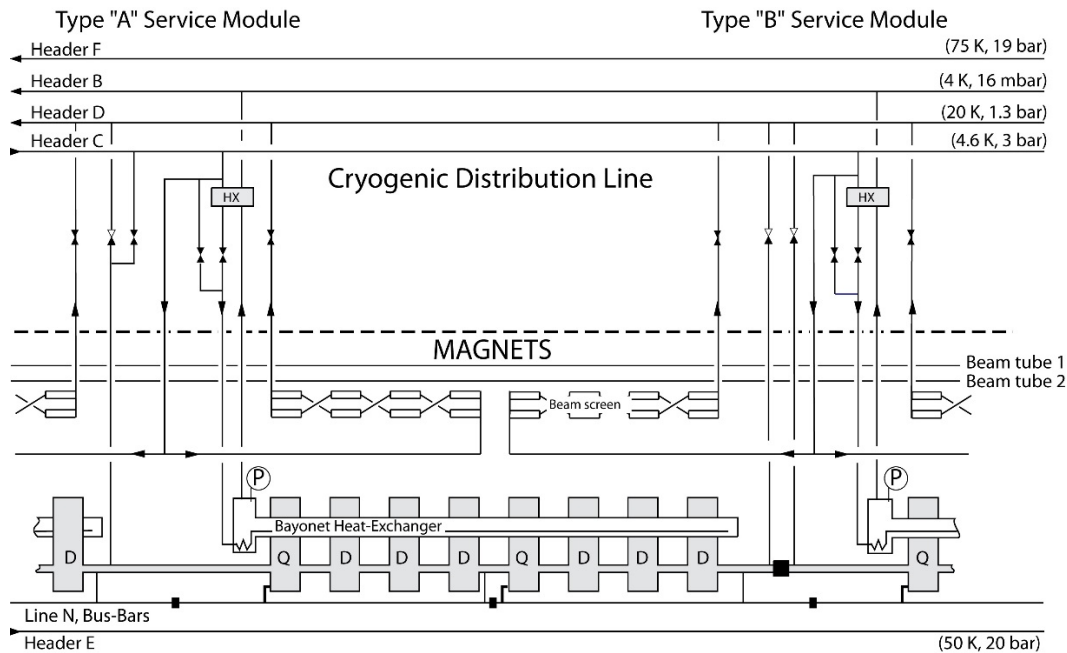
Figure 1. LHC 107 m long standard cell made of six dipoles (D) and two quadrupoles (Q), each magnet is immersed in a static pressurized He bath and is equipped with a thermometer that permit to infer the saturation pressure of the evaporating liquid helium flowing along the bayonet heat exchanger. The 5000 Pa sensor (P) is located in the decanting pot at the end of the bayonet.

The second application is the measurement of the helium mass flow of the 20.5 kA ATLAS End Cap Toroid current leads. Presently the flow is measured in a side ATLAS cavern after 150 m long gaseous helium return lines. It results in a significant integration time lag of the measurements and could induce a fast dump of the magnet in case of perturbation in the cryogenic system. To shorten the response time, new Venturi flowmeters are installed in the main cavern as close as possible to the magnet. This configuration requires however that the sensors and the local electronics withstand the radiation level in the cavern of the ATLAS detector with 100 % reliability as any failure of the flow measurements will provoke a quench of the ATLAS toroid and a stop of the detector physics for about a week.

The pressure sensors that have been tested were of the variable reluctance type and a custom made radiation tolerant electronics has been designed. The selected pressure sensors are fully welded devices without embedded active electronics manufactured either by Niche Sensor (France) or Valydine (USA). As these are purely mechanical devices, they are assumed to be radiation hard by design as radiation effects are not expected to change the mechanical, electrical or magnetic properties.

The main requirement for a sensor head installed in the LHC tunnel is to comply with the radiation environment that can reach a Total Integrated Dose (TID) of up to 1 kGy. Such a radiation level complicates the use of electronic devices as they are affected by drift on most analog parameters and digital devices are prone to Single Event Effects (SEE) that can corrupt any digital state resulting in wrong calculations or sudden loss of functionality. Furthermore, the LHC tunnel access is extremely restricted requiring the use of robust devices that do not require in-situ calibration for durations between 2 to 5 years separating the long stops that permit to perform complex routine maintenance or corrective procedures. The targeted accuracy of ± 50 Pa in the range 0 to 5 kPa can be met by commercial pressure sensors that typically have embedded intelligence in order to correct temperature effects and that store an individual calibration; such devices cannot be qualified for a radiation environment as it would impose on the manufacturer the complex and costly quality assurance procedures required when designing radiation tolerant electronics.

2. Calibration procedure

The sensors were tested by using a LabView® based automated calibration test bench; its main components is a custom made pressure regulator that sets any pressure within ± 10 Pa in the range 0 to 13 kPa, a climatic chamber (Votsch Industrietechnik model VT 3050) with a -30 to 100 °C temperature range and the pressure reference is provided by a MKS 690A Baratron with a 0 to 13.3 kPa absolute pressure range. The differential pressure sensors are calibrated by applying vacuum on the low pressure port and the MKS as reference in the variable pressure port. Additionally, the differential sensors are checked also at nominal line ambient pressure with a commercial portable gauge pressure calibrator and a hand pressure pump. Care is however required in order not to exceed the maximum permitted differential pressure that for the most delicate sensor is twice the span or 10 kPa.

A calibration run can last up to half a week and several temperature cycles are performed, each cycle has a duration of about 23 hours. Figure 2 shows the consecutive calibration steps that each may have a different duration. The pressure calibration cycle is started after an idle time used for having an adequate temperature homogeneity of the pressure sensor mechanical assembly.

The sensors readout are obtained either by standard digital laboratory multi-meters or in digital format through the WorldFIP® network [2]. The complete data set is analyzed off-line in order to provide the best mathematical fit.

3. Pressure sensor electronics signal conditioning

Radiation induced drift is similar to temperature effects and both have to be compensated for accurate measurements of analog electrical signals. On the electronics side, radiation effects induce drift in most parameters of analog amplifiers and when fast hadrons are present, as is the case for the LHC, it easily produces transitory Single Event Effects (SEE) that corrupts digital circuits or may even destroy power electronic circuits. The LHC electronics is based on a set of proven technologies [2] and any new design takes advantage of this library of components although radiation qualification campaigns are usually required because of obsolescence of integrated circuits or of new functionalities that cannot be met with the existing circuits.

To cope with radiation or temperature induced drift, the radiation-tolerant electronics is based on a comparison bridge topology. For resistance-type temperature sensors, the comparison is done with a fixed resistor that has a very low temperature coefficient (typically 100 ppm/K or better) and for the pressure sensors a second reference coil is used (figure 3). The devices produced by Niche sensors are described here [4] and they include the drop resistors and a sensing coil that is almost completely decoupled from the diaphragm measuring the force induced by the pressure; this second coil is used for providing the reference signal. The Validyne model DP10 is used as differential sensor only, it is made by two coils that are equally affected by the applied pressure. The bridge comparison configuration is obtained by measuring only one of the coils and by using a second unconnected sensor of identical characteristics. The resistors in series with the coils and the temperature sensor shown in figure 3 are added in the electrical connector.
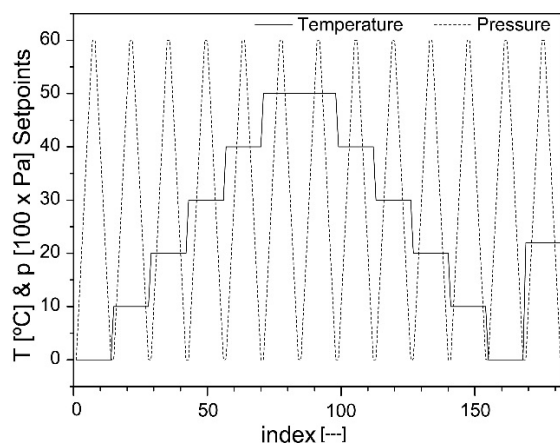

Figure 2. Typical calibration cycle. The duration is approximately 23 hour and a full calibration has several such cycles.
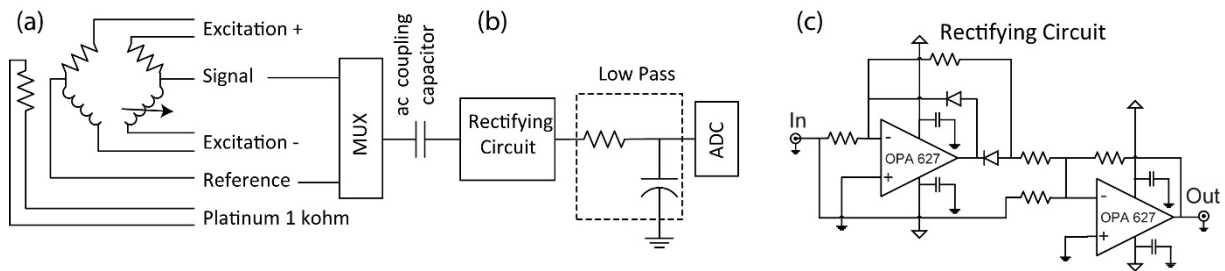
Figure 3. Pressure sensor electrical schematics of the signal conditioning. (a) Pressure sensor with platinum 1 kΩ temperature sensor and "fixed" reference and sensing signal coils. (b) Signal acquisition with common amplifying and conditioning stages and ADC. (c) Rectifying circuit.

The conditioning electronics provide a square voltage excitation signal with a frequency that can be adjusted between approximately 5 and 100 kHz. The optimum frequency depend on the loading of the sensor, it means on the cable type and length. The frequency is selected in order that the signal is dominated by the increase of the voltage across the coil inductances resulting in a quasi-triangular waveform [4].

All analog measurements share the same ADC and are multiplexed sequentially through analog switches that have been recently qualified up to very high radiation levels [5]. The ac signals share the same conditioning electronics and any drift affects in the same proportion the signal and reference waveforms, permitting to make a ratio-metric measurement that is relatively insensitive to radiation and temperature effects on the condition that all integrated circuits are properly qualified. Offset voltages are removed on the input waveforms by the ac coupling capacitor (figure 3) and on the amplifiers by subtracting a "zero" signal that is acquired during each measurement cycle. The rectifying circuit is the most delicate and low input offset amplifiers shall be used, in particular the first stage offset cannot be fully compensated because of its clipping diodes that amplify a single polarity of the signal and do not permit to determine the offset polarity. The OPA 627 input offset drifts with the radiation dose [6] and if required it can be removed by an external trimming circuit. For these particular pressure conditioning electronic channels, the maximum TID shall not exceed 100 Gy and the offset drift shall not have an impact in the overall uncertainty of the measurements.

4. Pressure sensors

The sensors selected are fully welded devices ensuring a high robustness against leaks of gaseous helium that is a critical issue for sensors operating in sub-atmospheric pressure conditions. The sensors supplied by Niche are made specifically for CERN and include a temperature sensor. The coil used as reference
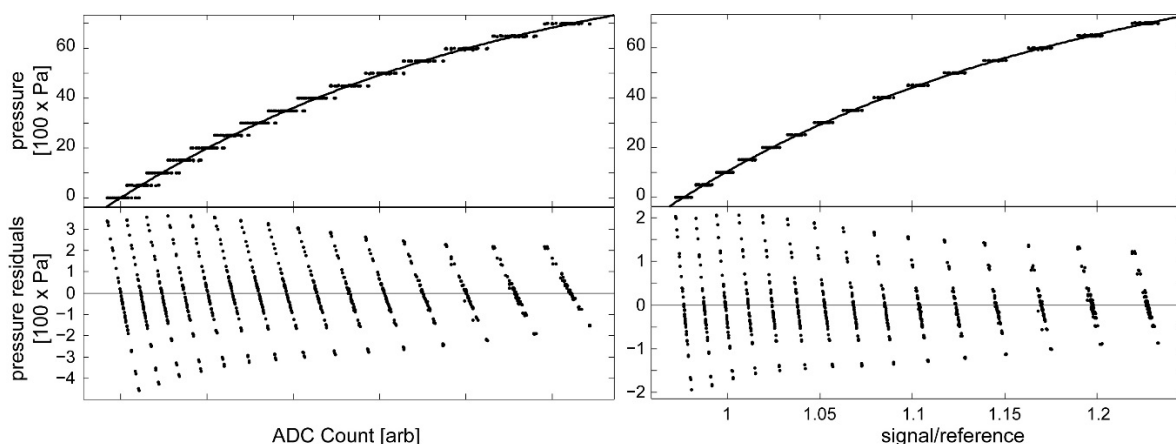

Figure 4. Pressure readout and associated pressure residuals for a 0-6'000 Pa absolute pressure sensor when using the signal readout (left, ADC count) and the ratio-metric calculation of signal over reference values (right).

is slightly affected by the sensed pressure as can be inferred from [4] but the ratio-metric measurement improves significantly the spread with temperature (figure 4).

The LHC requires an uncertainty of about 50 Pa, the data shown in figure 4 exceeds by a wide factor the targeted value even if considering a narrower temperature variation range than the 0 to 50 °C used during the calibration cycle. The pressure estimation therefore require additional mathematical treatment and figure 5 shows the pressure residuals by using a third degree polynomial with 2 parameters that are the temperature and the ratio-metric value of the signal over reference.

Figure 5 shows that the Niche sensors are well within the specifications even for extreme operational temperatures ranging from 0 to 50 °C; both the absolute and differential devices have similar performance. The Validyne DP10 sensors on the other hand exhibit hysteresis on the pressure data and this effect cannot be compensated by a mathematical approximation; the residuals are about four to five times larger than for the Niche sensors. This higher dispersion cannot be deduced from the Validyne DP10 data-sheet that lists hysteresis effect only for pressure cycles (0.5% of the pressure excursion or 30 Pa in this case) along a thermal sensitivity shift of 1% of the reading per 14 K that may refer to a temperature cycle effect.

As mentioned previously, a sensor based on variable reluctance technology and its connecting electrical cable shall be considered as a single unit when using remote conditioning electronics, the loading of the pressure cell is strongly affected by cable parameters like its linear capacitance or inductance. Figure 6 shows the measured residuals for a sensor optimized and calibrated for a 15 m long cable and for which different cables are used. Excluding the cable used for the calibration, none of the other cables with a length ranging from 9 up to 50 m provided satisfactory results concerning the measurement accuracy.

The cable type has also a strong impact on the usability of variable reluctance pressure cells. For instance bending or moving of conventional shielded cables have a non-negligible impact on the signals and such cables shall be avoided as they would require an in-situ calibration; in such a case it is usually impossible to study temperature effects. The data presented in this paper concern double shielded cables for which each twisted pair has an independent shield and the group of twisted pairs have an external shield; the external shield is connected to ground on both sides of the cable, and the internal shields are connected only on the electronics side. The external shield connection is critical and its impedance shall be kept as low as possible meaning that drain wire pigtail connections shall be forbidden. Accuracies as shown in figure 5 are obtained with a cable length from about 9 till 50 m long cables; tests have also been performed with cables as long as 100 m for which there is a slight degradation in the overall performance.
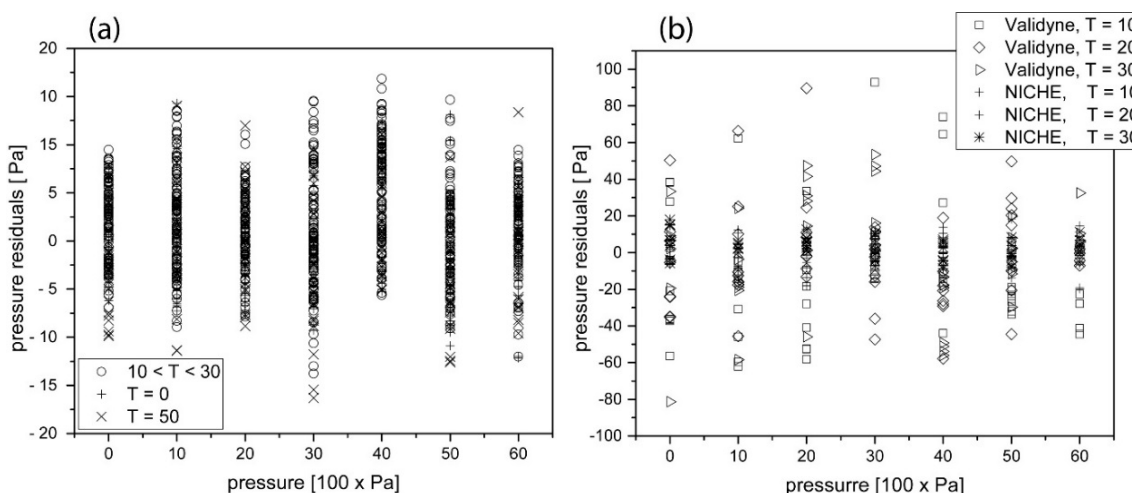

Figure 5. Pressure residuals versus measured pressured and varying temperature. (a) Absolute Niche pressure sensors, 8 units. (b) Differential pressures sensors, 2 units of each brand.
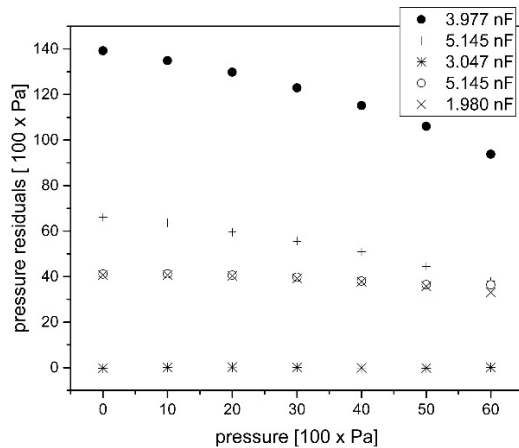
Figure 6. Pressure residuals for different cables. Cables capacitance was either 0.1 nF/m or 0.2 nF/m and the corresponding length 20 and 50 m or 9, 15 or 20 m. The electronics was optimized for the 15 m long cable.

5. Field Results

LHC experimental data is available at present only for the absolute Niche pressure sensors installed inside the LHC tunnel. These sensors are connected via a capillary to the decanting pot of the bayonet heat exchanger and measure the saturation pressure of the liquid helium as it evaporates when flowing along the bayonet pipe that is about 100 m long. The "Line B" (figure 1) is connected to the cold compressor unit that is approximately 2.7 km away.

The Niche pressure sensors can be compared with the commercial sensors that equip each cold compressor unit, these sensors are high grade industrial units with a measuring range of 0 to 25 kPa and the measuring accuracy shall be of the order of ± 50 Pa. Figure 7 shows the difference between two of the four Niche and commercial cold compressor sensor pairs, the decanting point pressure is higher because of the pressure drop across the liquid-gas heat exchanger ("HX" in figure 1) and along the 2.7 km long pumping line B. This pressure drop depends on the mass flow that is adjusted by the control valves and this explains why the pressure difference is not constant.

The liquid helium that evaporates while flowing along the bayonet heat exchanger cools the superconducting magnets, its saturation pressure sets the minimum temperature that can be reached. This minimum temperature shall take into account the temperature difference across the bayonet walls due to the Kapitza resistances and the thermal conduction across the bayonet that is made of copper. Figure 8 shows the evolution of the magnets temperature while the cooling flow is increased resulting in overflowing the bayonet heat exchanger until liquid helium reaches the decanting pot. When liquid is present in the decanting pot the pressure suddenly increases and both the level and pressure oscillate indicating that helium drops reach the sensing capillary.
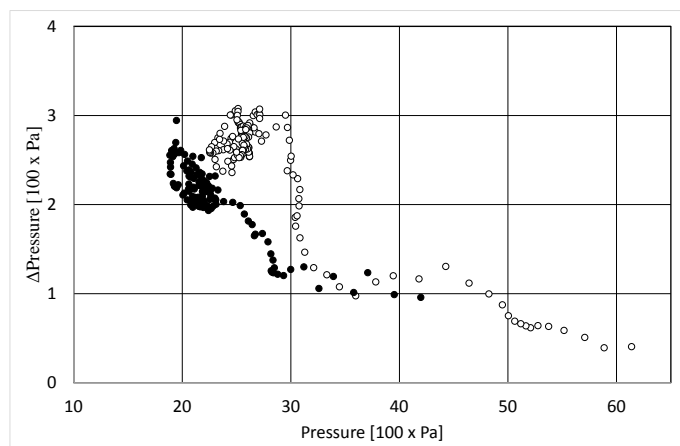

Figure 7. Pressure difference between two inductive sensors measuring the bayonet heat exchanger and the commercial sensor installed at the inlet of the nearest LHC cold compressor.
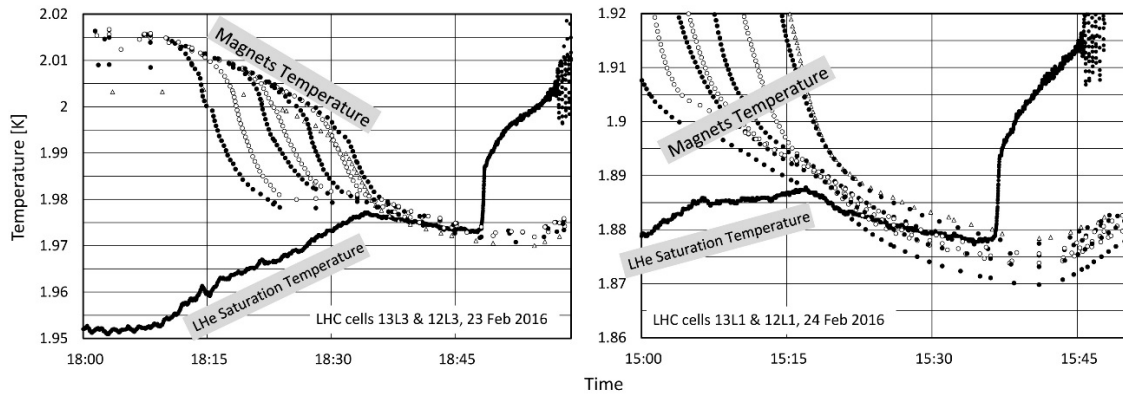
Figure 8. Comparison for two different LHC cells between the saturation temperature of the liquid helium flowing along the bayonet and magnets temperature. Magnets are sequentially cooled when the fluid advance along the bayonet.

When the liquid helium is present along the full bayonet length the magnets temperature and cooling helium saturation temperature can be compared. Such an experiment was carried for each LHC cell equipped with the Niche absolute sensors and the difference between the saturation pressure and magnets temperature is below 0.006 K, this confirms that the real life accuracy is about 50 Pa. The difference between the temperatures deduced from the thermometers and from vapor pressure thermometry is due to long term drift of the Cernox™ temperature sensors that are present since the first LHC cool-down done in 2007, to the reproducibility of the Cernox™ characteristics after its calibration, to the measuring accuracy of the radiation tolerant electronics deployed in the LHC tunnel and to the uncertainty of the measurement of the saturation pressure. The data shown in table 1 indicates a reproducibility better than 0.01 K that was the long term design target when selecting the LHC temperature sensors.

Table 1. Saturation temperature (Sat T) deduced from absolute pressure sensor and magnets temperature. Increasing/decreasing magnet number the closer to the LHe outlet/decanting pot. Incorrect temperature sensor data is crossed-out.

	Sector 7-8		Sector 8-1		Sector 1-2		Sector 2-3	
	T [K]	ΔT [K]	T [K]	ΔT [K]	T [K]	ΔT [K]	T [K]	ΔT [K]
Sat T	1.897		1.878		1.938		1.974	
Magnet 1	1.900	0.003	1.880	0.002	1.937	-0.002	1.973	-0.001
Magnet 2	1.894	-0.003	1.879	0.001	1.936	-0.003	1.976	0.002
Magnet 3	1.895	-0.002	1.875	-0.004	~~1.961~~	~~0.023~~	1.974	0.000
Magnet 4	1.896	-0.001	1.876	-0.002	1.937	-0.002	1.974	0.000
Magnet 5	1.893	-0.004	1.875	-0.003	1.938	0.000	1.975	0.001
Magnet 6	1.903	0.006	1.875	-0.004	1.937	-0.001	1.976	0.002
Magnet 7	1.899	0.001	1.877	-0.002	1.937	-0.002	1.976	0.002
Magnet 8	~~1.803~~	~~-0.095~~	1.871	-0.007	1.938	0.000	1.974	0.000

6. Conclusions

Variable reluctance sensors are shown to be compatible with the LHC requirements and it is assumed that they are intrinsically radiation-hard as it is a fully welded metallic structure and both mechanical and magnetic parameters are insensitive to the expected radiation doses that shall not exceed 1'000 Gy. The electronics unit are separated from the sensor heads by a double shielded cable with a length between 15 or 30 m.

Experimental field data is presently only available for the absolute pressure sensors manufactured by Niche, the measured pressure is coherent with the industrial pressure sensors installed about 2.7 km away at the level of the LHC cold-compressors that cool down the LHC magnets below 4.2 K. Furthermore the absolute pressure sensors have permitted for the first time to cross-check that there is no measurable drift of the Cernox™ temperature sensors, about 5'400 such sensors are installed in the LHC accelerator.

At present, Niche is having problems in manufacturing passive sensors and this is a major issue for new projects and also for dealing with spare devices. This is the reason why sensors from Validyne were also tested, unfortunately there is a factor of about four in the degradation of the measurement accuracy. Presently, the radiation tolerant electronics used by CERN's cryogenic control system is compatible with bridges based in strain, piezoelectric or variable reluctance; and the investigation of passive pressure sensors is continuing in order to be able to cope with replacement or new projects.

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