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European Laboratory for Particle Physics*Large Hadron Collider Project***LHC Project Report 980****QUALIFICATION OF SUB-ATMOSPHERIC PRESSURE SENSORS  
FOR THE CRYOMAGNET BAYONET HEAT EXCHANGERS  
OF THE LARGE HADRON COLLIDER**

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**Résumé**

The superconducting magnets of the Large Hadron Collider (LHC) will be cooled at 1.9 K by distributed cooling loops working with saturated two-phase superfluid helium flowing in 107 m long bayonet heat exchangers [1] located in each magnet cold-mass cell. The temperature of the magnets could be difficult to control because of the large dynamic heat load variations. Therefore, it is foreseen to measure the heat exchangers pressure to feed the regulation loops with the corresponding saturation temperature. The required uncertainty of the sub-atmospheric saturation pressure measurement shall be of the same order of the one associated to the magnet thermometers, in pressure it translates as  $\pm 5$  Pa at 1.6 kPa. The transducers shall be radiation hard as they will endure, in the worst case, doses up to 10 kGy and  $10^{15}$  neutrons·cm<sup>-2</sup> over 10 years.

The sensors under evaluation were installed underground in the dump section of the SPS accelerator with a radiation environment close to the one expected for the LHC. The monitoring equipment was installed in a remote radiation protected area.

This paper presents the results of the radiation qualification campaign with emphasis on the reliability and accuracy of the pressure sensors under the test conditions.

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# **QUALIFICATION OF SUB-ATMOSPHERIC PRESSURE SENSORS FOR THE CRYOMAGNET BAYONET HEAT EXCHANGERS OF THE LARGE HADRON COLLIDER**

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## **ABSTRACT**

The superconducting magnets of the Large Hadron Collider (LHC) will be cooled at 1.9 K by distributed cooling loops working with saturated two-phase superfluid helium flowing in 107 m long bayonet heat exchangers [1] located in each magnet cold-mass cell. The temperature of the magnets could be difficult to control because of the large dynamic heat load variations. Therefore, it is foreseen to measure the heat exchangers pressure to feed the regulation loops with the corresponding saturation temperature. The required uncertainty of the sub-atmospheric saturation pressure measurement shall be of the same order of the one associated to the magnet thermometers, in pressure it translates as  $\pm 5$  Pa at 1.6 kPa. The transducers shall be radiation hard as they will endure, in the worst case, doses up to 10 kGy and  $10^{15}$  neutrons $\cdot$ cm $^{-2}$  over 10 years.

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This paper presents the results of the radiation qualification campaign with emphasis on the reliability and accuracy of the pressure sensors under the test conditions.

**KEYWORDS :** Radiation hard, sub-atmospheric pressure, large scale industrial deployment, radiation qualification, strain gauge, LVDT, piezoelectric.

**PACS :** 39.90

## **INTRODUCTION**

### **Description of the Irradiation Test Facility**

The sensors under evaluation were installed underground in the dump section of the SPS (Super Proton Synchrotron) accelerator with a radiation environment close to the one

expected for the LHC. The monitoring equipment was installed in a remote radiation protected area.

A pneumatic diagram of the test facility is represented on FIGURE 1. Three different areas are visible, namely : the control room from which the calibration process can be monitored by an operator, the gallery along which the 160 m long electrical cables and pneumatic tubes are installed and the test zone in which the sensors under test are irradiated. This zone lays 15 m underground. One reference pressure sensor is used for the calibration and is located in the control room.

In the control room, pneumatic and electrical equipment is used to control the calibration process. The pneumatic equipment consists of a vacuum pump, a 20 MPa gaseous helium cylinder connected to a pressure reducing valve, a reference pressure sensor and a calibration pressure regulator. The calibration pressure was formerly controlled with a  $\frac{1}{4}$  turn hand valve which had to be replaced by a micrometric hand valve in order to give a more accurate adjustment over the calibration pressure. The electrical instrumentation consists of a reference pressure sensor controller, constant current supplies and digital voltmeters for excitation and sensing of the sensors under test measurement bridges, remote conditioners, power supplies and relay boxes to control the underground valves, and a computer for control and the data acquisition purpose.

The electrical cables and pneumatic lines are driven along the gallery to the irradiation area in which the sensors under test are connected to a multi-port manifold. On one side, the manifold is fed by the pressurized gas coming from the control room and on the other side it is connected to a vacuum pump. Both sides can be isolated by means of valves.

### Description of Climatic Chamber Tests

In order to separate thermal effects and radiation induced effects, tests were also carried out in a climatic chamber. The instrumentation was basically identical to that used in the irradiation facility, except that the sensors were calibrated at three stabilized temperatures, 283 K, 298 K and 313 K, they did not work under radiation and the pneumatic tubes were only 2 m long compared to 160 m long in the irradiation area.

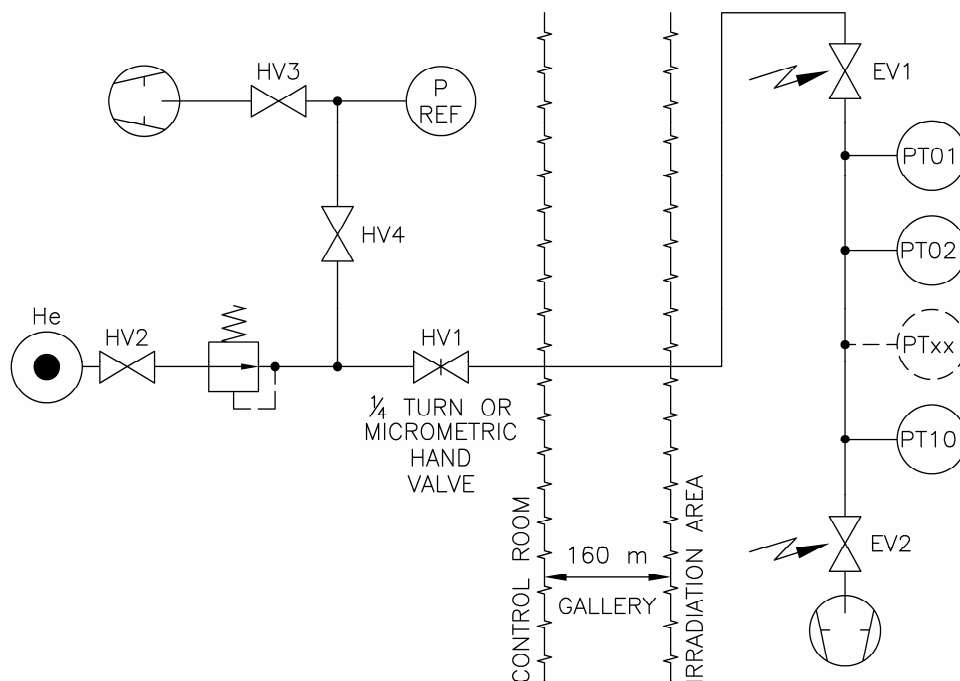


FIGURE 1. Pneumatic diagram of the test facility.

## **Sensor Technologies Tested**

Three different types of pressure sensors have been tested based respectively on strain gauges, LVDT (Linear Variable Differential Transformer) and piezoelectric technologies.

## **OPERATION**

### **Operation in Irradiation Test Facility**

Vacuum is generated at both sides of the pneumatic system, i.e. in the control room and in the irradiation zone. This is necessary because of the lack of conductance along the tubes. Once a vacuum of less than 100 Pa is reached on both sides, the pumps are isolated from the pneumatic piping and the gas can be injected. The injection has been performed by three different means : ¼ turn hand valve, micrometric hand valve and system air inleak. The ¼ turn hand valve has been formerly used for tests and validation for installation in the LHC of 0.4 MPa and 2 MPa high pressure sensors. This valve was however very difficult to use with 1.6 kPa low pressure sensors. It was replaced by a micrometric hand valve which offered a much better control over the pressure to be set and allowed to inject the gas with much smaller overpressure. However, the stabilization was again long to obtain thus this solution has been put aside. The last solution consisted in letting the air inleak of the system to act like a pressure source. When the pressure inside the pipe is between 100 Pa and 5 kPa, the leak rate has a constant value of  $30 \cdot 10^{-6} \text{ Pa} \cdot \text{m}^3/\text{s}$ , which translates to a pressure increase of 0.6 kPa per day. The 1.6 kPa working full scale pressure of the sensors is reached within 2½ days. Hysteresis cycling is impossible for all three calibration methods.

Two LVDT sensors are tested together with their conditioning electronics in the irradiation area, two others with their conditioning electronics placed remotely in the control room. Three sensors with measurement bridges only (i.e. without conditioner) are supplied with constant current and their output is connected to a digital multimeter both placed in the control room. Each sensor is fed by its own DC current supply, but only one multimeter with an integrated scanner is used to read all sensors output signals. This instrument is also used to measure the resistance of two Pt100 temperature sensors, one placed in the control room and the other in the irradiation room.

### **Operation in Climatic Chamber**

Only sensors using strain gauge technology were tested in climatic chamber. The principle of operation is identical to the one used in the irradiation facility [2].

## **EXPERIMENTAL PROCEDURE AND RESULTS**

### **First Irradiation Campaign**

A first irradiation campaign was carried out on all three different types of pressure transducers. The calibration was made with gaseous helium (GHe). The admission of GHe was made by means of a ¼ turn hand valve. TABLE 1 shows a summary of all pressure sensors used with their respective technologies and some information about the conditioning electronics. LVDT sensors have been used with the manufacturer's electronics whether integrated inside the sensors or installed remotely in the control room.

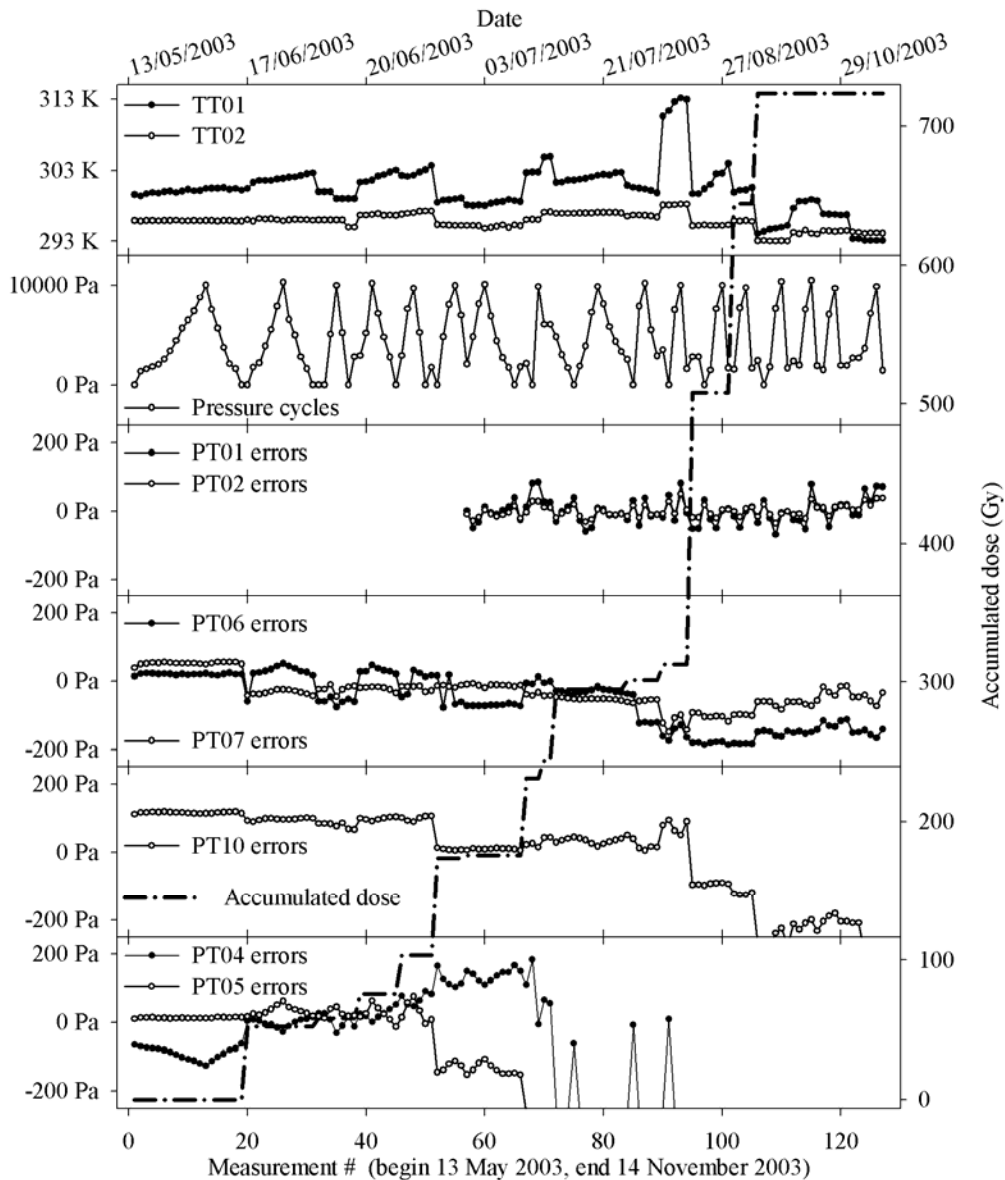
**TABLE 1.** Pressure sensors summary.

Sensor ID	Technology	Electronics	Make & Type
PT01, PT02	Strain Gauge	Remote benchtop electronics	Schaevitz, P1504
PT04, PT05	LVDT	Integrated manufacturer's electronics	Ashdown, APX 100 mbar
PT06, PT07	LVDT	Remote manufacturer's electronics	Ashdown, APX 100 mbar
PT10	Piezoelectric	Remote benchtop electronics	Siemens, Prototype

Strain gauge and piezoelectric sensors have been excited and read with remote benchtop electronics. The full scale of all sensors is 10 kPa.

The results of this first campaign are shown on FIGURE 2. The campaign started on 13 May 2003 and finished on 14 November 2003. PT01 and PT02 were installed on 3 July 2003. The accumulated dose is plotted over the sensor's graphs. The sensors accumulated a total dose of 724 Gy except PT01 and PT02 which accumulated 548 Gy.

The first of the six stacked graphs shows the control room temperature variations (TT01) and the irradiation area temperature variations (TT02). These two sensors are Pt100 and their signals were conditioned with remote benchtop electronics.



**FIGURE 2.** Results of the first irradiation campaign.

The second graph shows the pressure cycles used for the calibrations as they were measured by the reference pressure sensor in the control room.

The four following graphs show the different pressure sensors errors with respect to the reference. They are grouped by sensing technologies and signal conditioning scheme.

One can see that LVDT sensors with built-in electronics (PT04 and PT05) start to degrade after accumulation of 174 Gy. On 3 July for PT05 and 10 July for PT04, they totally broke after accumulation of respectively 176 Gy and 244 Gy.

The only piezoelectric sensor tested (PT10) also started to degrade after accumulation of 174 Gy. After this, its behavior gradually decayed with the accumulated dose. Moreover it showed a clear correlation with temperature variation.

LVDT sensors with remote electronics (PT06 and PT07) showed good behavior under radiation although PT07 had a clear response to the first 52 Gy it received. Nevertheless, they showed specific behavior under the test condition and are left as second choice for integration in the LHC.

Strain gauges sensors (PT01 and PT02) showed very good behavior under the test conditions. In total, they accumulated 548 Gy of doses without noticeable effect.

## Second Irradiation Campaign

After the first irradiation campaign, decision was to focus on strain gauges sensors [2]. The calibration was made with air, using natural leaks to regulate the pressure. Hydrostatic pressure and temperature compensation have been used to correct the results.

Each measurement is averaged over 30 points. The irradiation campaign began on 16 September 2004 and finished on 4 February 2005. During this run, the sensors have accumulated 1800 Gy. Unfortunately, only the total accumulated dose is known for this campaign. The results shown below start on 29 September 2004 and end on 26 November 2004 which represents an accumulated dose of 750 Gy.

The first of the three stacked graphs on FIGURE 3 shows the variations of the temperature in the control room (TT01) and of the temperature in the irradiation area (TT02).

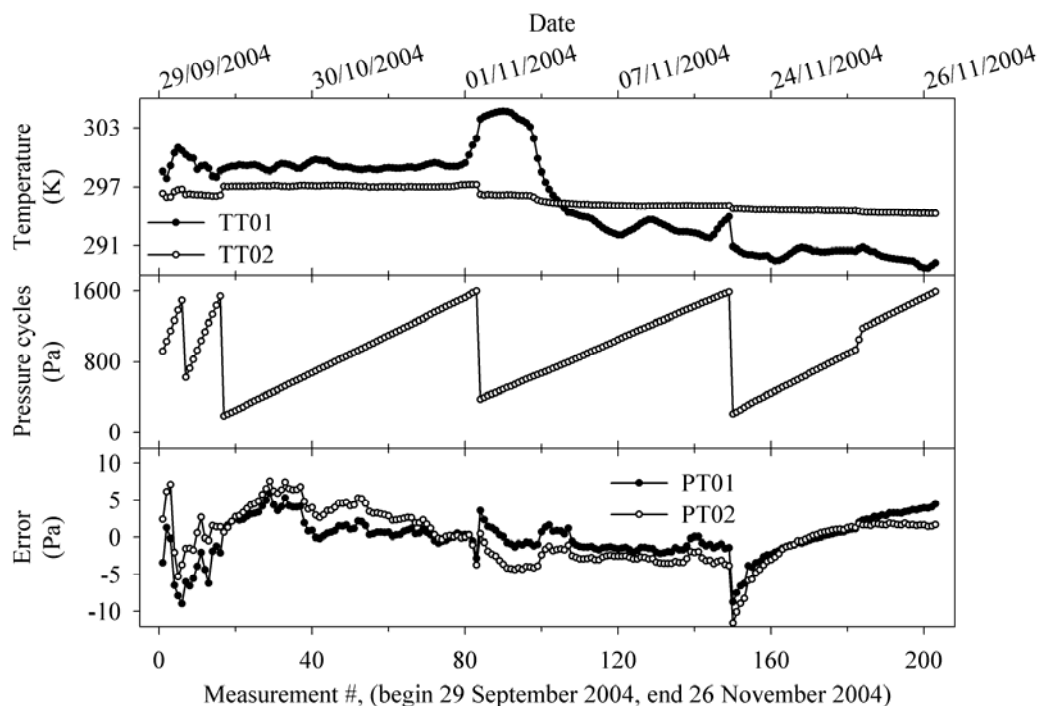


FIGURE 3. Results of the second irradiation campaign.

The second graph shows the pressure cycles. One cycle consists of a pumping time to obtain a residual pressure of less than 100 Pa and then a so called “leak-in” time where the pressure rises.

The third graph shows the errors on both sensors under test. One can see that these errors stay within the specification requirement of  $\pm 5$  Pa. Nevertheless, the poor conductance of the 160 m of pipes between the control room and the irradiation area induces large and non-repetitive pressure offsets between the sensors under test and the reference sensors. This effect was easily noticeable during pumping time because limit vacuum was never the same between pressure cycles. The results presented here are obtained by means of a manual offset compensation. This implies that the offset stability under radiation will be investigated at later time. Nevertheless, the gain stability shows very good behavior under the test conditions.

### Temperature Correction Evaluation

In order to discriminate thermal effects from irradiation effects, tests were carried out in climatic chamber between the two irradiation campaigns [2]. PT01 and PT02 were calibrated at 283 K, 298 K and 313 K. A thermal compensation coefficient has been calculated with the following method :

The temperature response of the sensors is assumed to be linear :

$$U = U_{ref} [1 + \alpha(T - T_{ref})], \quad (1)$$

where  $U_{ref}$  is the output voltage at the reference temperature  $T_{ref}$  (298 K),  $U$  is the output voltage at the current temperature  $T$ .  $U$  and  $U_{ref}$  were measured at different pressures for dependencies checking with this variable too. The thermal coefficient  $\alpha$  is deduced from (1) :

$$\alpha = (U / U_{ref} - 1) / (T - T_{ref}) . \quad (2)$$

FIGURE 4 (left) shows the evolution of  $\alpha$  with the output voltage. One can see that  $\alpha$  is strongly dependant to it (and thus to the pressure) and can be fitted as follow :

$$\alpha = a e^{-bU} + c \quad (3)$$

After numerical curve fitting, PT01 and PT02  $\alpha$  fitting coefficients  $a$ ,  $b$  and  $c$  have been found very close and were thus considered as equal, respectively :

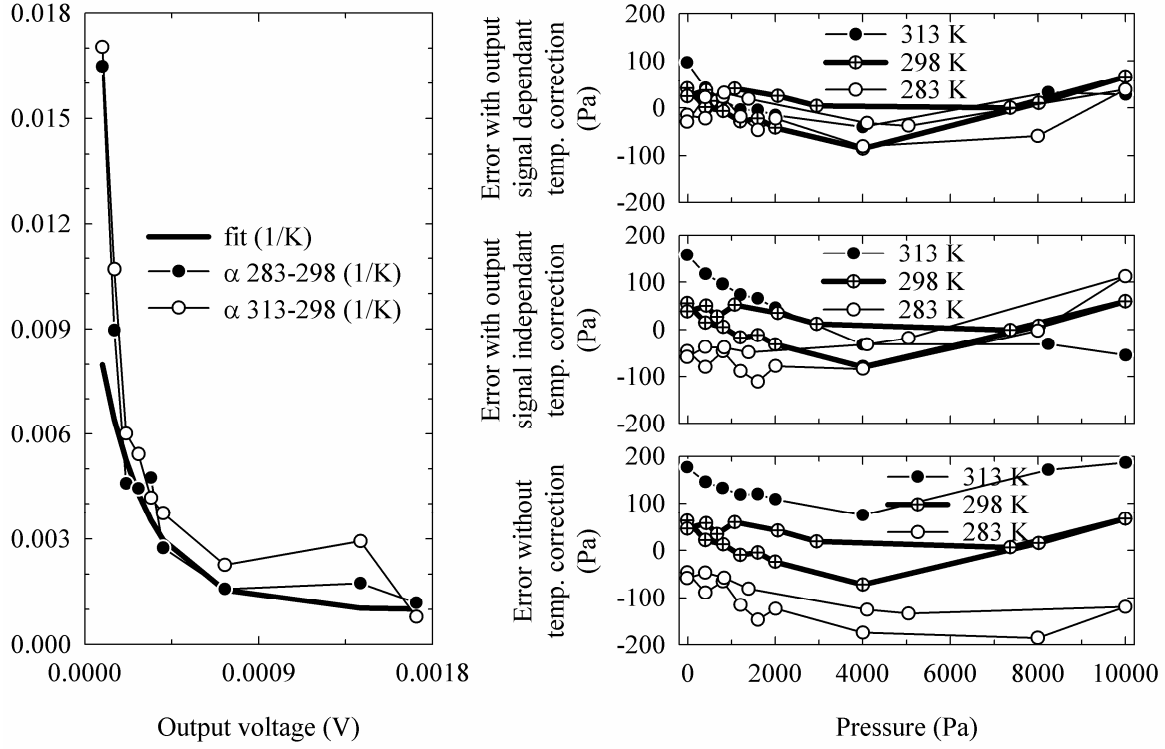
TABLE 2.  $\alpha$  fitting coefficients.

a (1/K)	b (1/V)	c (1/K)
0.01	4000	0.001

A constant  $\alpha$ , i.e. without pressure dependency, has been also computed for comparison.

TABLE 3. Constant  $\alpha$  value.

$\alpha$ (1/K)
0.002



**FIGURE 4.** Evolution of  $\alpha$  with the output voltage (left) and errors on PT01 (right).

FIGURE 4 (right) shows the errors on PT01 for all three schemes : without temperature correction, with output signal dependant and independent temperature correction.

### Hydrostatic Pressure Correction Evaluation

Because the sensors under test lie 15 m below the reference pressure sensor, hydrostatic pressure compensation must be evaluated. Equation (4) gives the dependency of the pressure  $p$  with respect to the elevation difference  $y$  between the two sensors for an isothermal atmosphere :

$$p = p_{ref} + \rho g y \quad (4)$$

Where  $p_{ref}$  is the pressure of the reference sensor,  $\rho$  the density of the gas and  $g$  the earth gravitational acceleration.

The density depends of the gas pressure and temperature  $T$  as :

$$\rho = \rho_{NC} \frac{p}{p_{NC}} \frac{T_{NC}}{T} \quad (5)$$

Where  $p_{NC}$ ,  $T_{NC}$  and  $\rho_{NC}$  are respectively the pressure, temperature and density at normal conditions. Replacing (5) in (4) we find :

$$p = p_{ref} \left( 1 - \frac{\rho_{NC}}{p_{NC}} \frac{T_{NC}}{T} g y \right)^{-1} \quad (6)$$



**TABLE 4.** Hydrostatic pressure correction data for air and helium.

gaz	$\rho_{\text{NC}}$ (kg/m <sup>3</sup> )	$p_{\text{NC}}$ (MPa)	$T_{\text{NC}}$ (K)	T (K)	g (m/s <sup>2</sup> )	y (m)	p
air	1.293	0.1013	273.15	295.77	9.81	15	1.0017 p <sub>ref</sub>
He	0.1785	0.1013	273.15	295.78	9.81	15	1.0002 p <sub>ref</sub>

Because the first irradiation campaign was performed with helium and the second one with air, TABLE 4 gives the hydrostatic correction data for these two gases.

The hydrostatic pressure correction was applied only on the second irradiation campaign measurements performed with air. It was neglected on the first irradiation campaign measurements performed with gaseous helium.

## CONCLUSIONS

Two irradiation campaigns have been conducted in order to test three different pressure sensor technologies. During the first run, the accuracy of the measurements was limited because of the use of a ¼ turn hand valve as pressure regulator. The desired full scale of 1600 Pa could hardly be reached. In the second run, the pressure adjustment was performed by “leak-in”, which permitted to reach the desired 1600 Pa within 2½ day.

Sensors using strain gauge technology showed very good gain stability after accumulating a total dose of about 1300 Gy. After measurement corrections, their errors stayed within the uncertainty specification of ±5 Pa. The temperature correction is of particular importance and shall be carefully designed for the integration in the LHC. Offset dependency could not be studied because of conductance restriction in the pipe. This aspect shall be taken into account for their integration design in the LHC in places where it is foreseen to install them remotely to avoid large irradiation exposure.

Sensors using LVDT technology showed good results only if their electronics is not working under radiation. They are left as second choice for the installation in the LHC.

Piezoelectric sensors are not suitable for the LHC. The tested unit responded very quickly to accumulated doses and showed temperature sensitivity.

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