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Long term experience with the “industrial” ^3He vapour-pressure thermometer

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Abstract. On the basis of very good experience with a prototype of a ^3He vapour-pressure thermometer installed in the magnet feed box (MFB – prototype of LHC magnet test bench), an upgraded version of this thermometer was developed with emphasis on the improvement of its long term stability, reliability and “series” production. The thermometer is working typically around 1.9 K. This article summarises the key points of the prototype design, its upgrade leading to the “industrial/series” realization, the long term experience and the calibration crosscheck of these thermometers after 15 years of operation.

1. Introduction

During tests of LHC prototype magnets on Magnet Feed Box (MFB) a temperature shift, with respect to the lambda point, of electro-resistive thermometers was observed. In order to obtain a reliable temperature measurement of the magnet, a thermometer of different principle was considered. An ^3He vapor-pressure thermometer with a working range from 0.6 K to 3.3 K and a theoretical precision of better than 1 mK was chosen. On the basis of the good experience with the first ^3He thermometer installed in the MFB it was decided to develop a more “industrial” version of this thermometer and to install it in all the 12 serial Cryogenic Feed Boxes (CFB) which are part of the magnet test facility built to test the LHC dipole and quadrupole superconducting (SC) magnets (tested at their nominal temperature of 1.9 K before their installation in the LHC accelerator).

2. Prototype

The idea to install the ^3He vapour-pressure thermometer into the MFB [1] appeared in 1994. After successful tests of this prototype including a calibration in the CERN cryogenic laboratory, it was installed in 1995 in the MFB. As the ^3He bulb is considered as a temperature standard it was not used as a calibration, but rather as a comparison to the other thermometers to avoid any mistakes in its design. Another crosscheck was done directly on the MFB during the magnet test thanks to an enormous peak of ^4He heat capacity at lambda point. All these measurements confirmed the good precision of this thermometer. The MFB was dismantled and replaced at first by 2 Cryogenic Feeder Units (CFU) [2] and later on by 12 Cryogenic Feed Boxes (CFB) [3] for serial test of LHC magnets. In 2001 the MFB was refurbished in order to build the CAST [4] experiment at CERN. This ^3He test bulb thermometer has been running with some breaks till today.

The principle, design and experience with this ^3He thermometer prototype is described in [5]. The temperature between 0.65 K to 3.2 K is defined by the International Temperature Scale for 1990 (ITS-90) by a ^3He vapour-pressure thermometer. For this reason a more precise thermometer than this international standard cannot be found. On the other hand the international standard thermometer can be used as a common thermometer only if it is also practical.

The three main features of any vapour pressure thermometer are as follows:

- The known relationship between vapour pressure and temperature
- An arrangement of a bulb volume where the pure liquid and vapour phase come to thermal equilibrium



- A pressure transmitter capable to withstand an over pressure of warm bulb (about 5 bara) and measure precisely (and with a long term stability) the absolute pressure

The parameters which are influencing the precision are:

- Impurities in ^3He
- Magnetic field
- Hydrostatic and aerostatic head
- Thermomolecular pressure ratio
- Heat in-leak to the bulb
- Precision of the pressure transmitter

All these parameters, except the precision of the pressure transmitter, can be minimized and/or considered and corrected.

2.1. Prototype results

2.1.1. Principle of the measurement

The principle of the measurement is based on the fact that the ^4LHe of which the temperature is measured has a big and sharp peak of a heat capacity at the lambda point, see Figure 1. The precise temperature of the lambda point depends on pressure see Figure 2 and Table 1 [6]. Considering that the heat capacity of a magnet at about 2 K is negligible the temperature drift of ^4LHe during a warm up can be used for the measurement. During the natural warm up, the temperature of the ^4LHe bath is monitored by the ^3He bulb thermometer immersed in the same ^4LHe bath as the magnet. The temperature curve has a typical shape as it is shown on Figure 3. First the temperature is linearly increasing (part a). Getting closer to the lambda point the temperature increase is very small because of the enormous heat capacity and the curve is nearly flat (part b). When the temperature passes the lambda point the heat capacity of ^4LHe is going down and the temperature increases rapidly (part c). The sharp bend (X) defines the lambda point. In order to be able to compare all analyzed ^3He bulbs on a basis of the mentioned curve, we defined the lambda temperature as the intersection of the horizontal part b and steep part c.

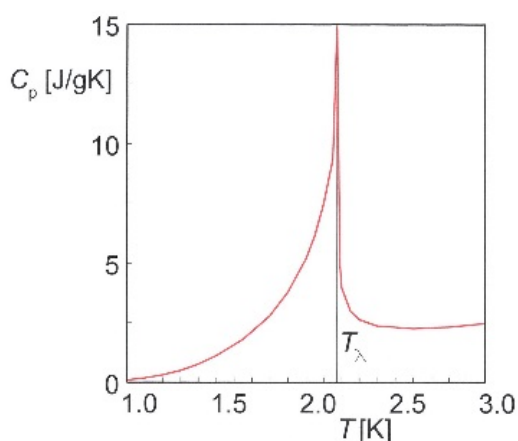


Figure 1: ^4LHe heat capacity versus temperature.

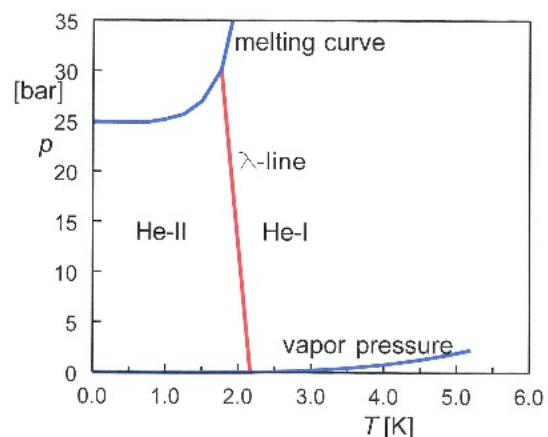


Figure 2: ^4He lambda temperature (red line).

Table 1: ^4He saturated temperature versus pressure.

Temperature [K]	Pressure [bar]
2.164515	1.372581
2.165334	1.287535
2.166153	1.202095
2.166972	1.116252
2.167791	1.029995

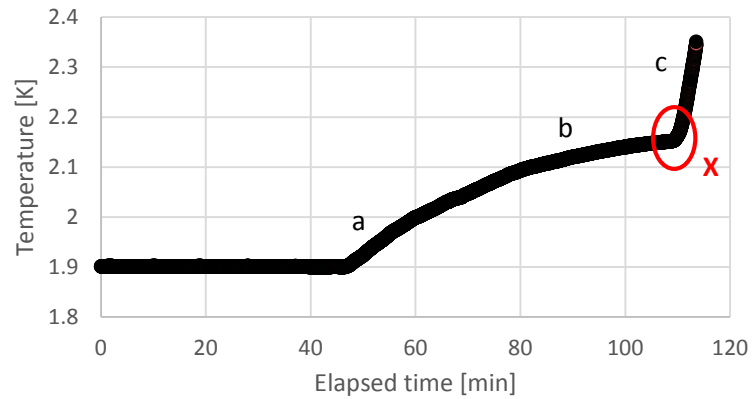


Figure 3: ^4LHe temperature monitoring by ^3He bulb

2.1.2. Results of the measurements in CAST experiment at CERN

The ^3He bulb has been operating in CAST for more than 15 years. Over these years the magnet has been warmed up, cooled down and quenched numerous times. From the vast data available after 2006, we selected to investigate slow warm-ups which were caused by problems in the cryogenic system of CAST. We then compared these data to a measurement performed during a controlled warm-up at the end of 2015. The vapour pressure of the ^3He bulb was calculated from the output voltage using the original calibration table which yields to the following conversion formula:

$$P [\text{mbar}] = 109.994781 \times V [\text{V}] + 0.006261.$$

At this point it should be mentioned that during the 2015 measurement an offset was observed in the value of the vapour pressure of the bulb as recorded by the ABB™ readout with respect to the one indicated in the ^3He bulb digital display. Although the P-V trend stayed the same, the following results are based on the hypothesis that there is an offset in the zero value of the Voltage of the instrument (V_0), which would cause in turn an offset in the recorded value by the software. Thus the above formula becomes:

$$P [\text{mbar}] = 109.994781 \times (V + V_0 [\text{V}]) + 0.006261 \quad \text{for } V_0 = 0.057 \text{ V.}$$

The temperature was then extracted using the following calibration:

$$T [\text{K}] = 1.053447 + \sum_{i=1}^9 \left(a_i \times \frac{\ln(P [\text{mbar}] \times 100) - 7.3}{4.3} \right)^i$$

Where a_i is:

$$a_1 = 0.980106, a_2 = 0.676380, a_3 = 0.372692, a_4 = 0.151656, a_5 = -0.002263,$$

$$a_6 = 0.006596, a_7 = 0.088966, a_8 = -0.004770, a_9 = -0.054943$$

The criterion of selection of the warm-ups was based on the duration of the transition of the temperature of the magnet from 2.09 K to 2.19 K. The curves of the temperature of the magnet with respect to the elapsed time can be seen in Figure 4. The lambda-point of each warm-up can be seen in Figure 5.

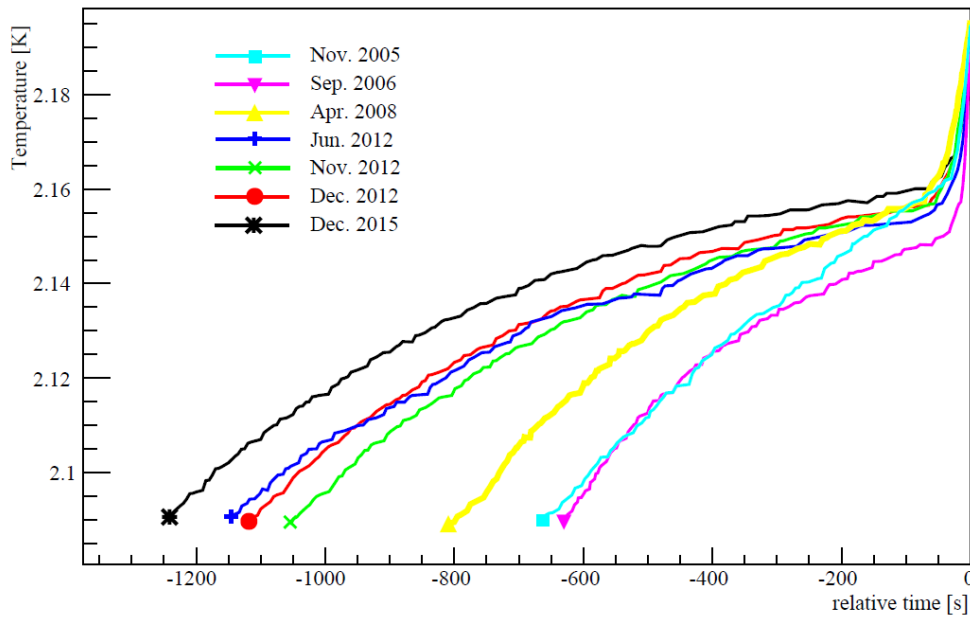


Figure 4: Selected warm-ups of the CAST magnet from 2006 to 2015.

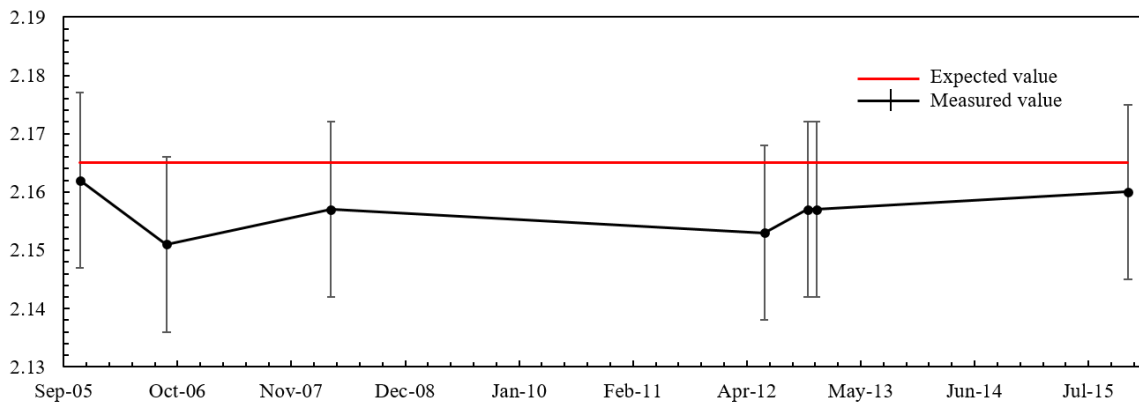


Figure 5: The measured values of the lambda-point in warm-ups of the CAST magnet from 2006-2015 and the expected value taking into account the pressure of ⁴LHe in the cryogenic plant.

2.1.3. Discussion for the CAST measurements

The deviation of the calculated values of the lambda-point from our measurements in the selected data from 2006 to 2015 is within 9 mK. This deviation should be compared to the precision of the instrument which is ± 2.5 mK (± 1 mbar defined by the manufacturer). The ³He bulb has shown remarkable stability in its operation over 9 years in CAST. Although we have corrected the considered offset in the zero-level of the readout system, from Figure 5, it is evident that there is a big uncertainty in the measured value of the lambda-point. This uncertainty is coming mostly from the specific readout system and it is not complementing the precision of the instrument. By designing a more sophisticated readout system this can be greatly reduced.

3. Serial Product

3.1. Improvements

Based on the operational experience with the prototype, the serial product was upgraded as follows:

- Improved pressure transmitter
 - The range of the prototype was 0-1100 mbar with a precision 0.1%. The serial transmitter has a range of 0-300 mbar and manufacturer guaranteed its precision 10 times better than for the prototype.
 - While the pressure transmitter of the prototype was connected to the system via a gasket, the serial transmitter was welded.
- Fully closed volume of ^3He volume with no gasket, see Figure 6
 - All the system was welded or vacuum brazed, thus no valve was used. The prototype had a few gaskets and valves.
 - The filling pipe made of Cu-OFHC was cold welded with a special tool, see Figure 9.
- Capillary
 - Only one capillary of length about 0.7 m and outer diameter 2 mm was used.
 - For simple installation the capillary was not thermally anchored.



Figure 6: Pressure transmitter, ^3He tank with a filling pipe and capillary to ^3He bulb

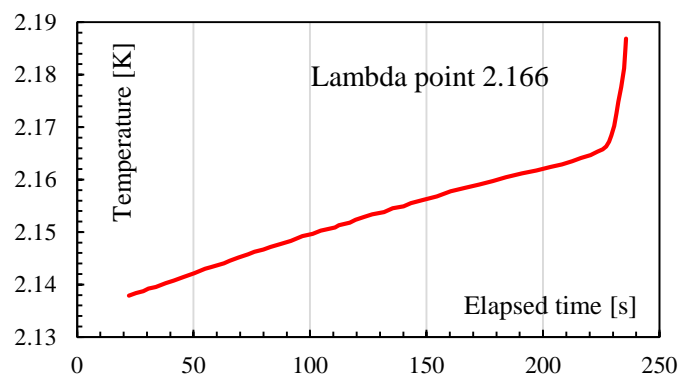


Figure 7: Data from CFB1

- Summary

These modifications ensured a good precision, absolute tightness, compactness and simple integration. This construction allows us to dismantle the thermometer and use it at different facilities. In this case only the length of the capillary can be a limitation.

For the serial product the pressure transmitter Druck LPX 2480-E006, AW300AZ of range 0-300 mbar was used.

3.2. Result of the measurement on serial product

After 10 years of operation on 12 CFBs, the following measurements have been performed at the end of 2015 beginning of 2016. On 5 CFBs available for testing the measurements were performed on a basis of temperature monitoring as explained above. A zoom of the temperature measurement of CFB1 can be seen in Figure 7. The measurements are summarised in Figure 8, considering a pressure of ^4LHe of 1.3 bar, $T_\lambda=2.165$ K and a corresponding ^3He pressure about 264 mbar.

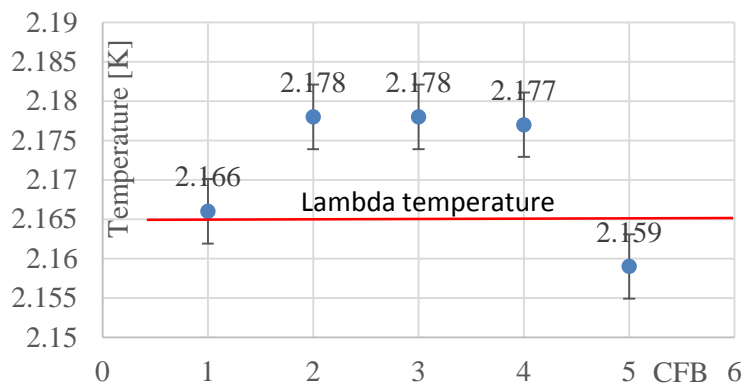


Figure 8: Lambda point for each of the measured CFB.



Figure 9: Cold welded filling tap.

As only raw data were used, the error is slightly higher than expected. One reason is the current analogue input card (Siemens 6ES7331-7KF02-0AB0) of which precision at 25°C is 0.5% corresponds to 1.5 mbar representing a temperature error of ± 3.4 mK. With a more precise card (Siemens 6ES7331-7NF00-0AB0) used its error will be 10 times lower. The overall precision of the pressure transducer is 1 mbar over 10 years, representing an error of ± 2.3 mK. Data of CFB5 were collected by UNICOS control system on which the CFB was migrated recently. UNICOS allows us to obtain precise data and store them for long period. Data of CFB1-4 were collected by original PCVIEW32 control system. These data are stored for limited period, typically one month, and their reading precision is limited. When all CFBs will be migrated to UNICOS more precise measurements will be performed. As 2 from 12 CFBs were dismantled, two ^3He bulbs are available for more precise measurements at CERN Cryolab.

4. Conclusion

More than 10 years of experience confirmed the high reliability, the long term stability and reasonable precision of this thermometer. The precision of the actual configuration is sufficient. Significant improvement to the readout precision can be achieved by replacing the data acquisition and controls card with the newest model. Additionally a detailed measurement of a ^3He bulb in the Cryolab at CERN has been foreseen, which will bring better understanding of its actual precision limits. The bulbs were so reliable and consistent that no other thermometer working at 1.9 K was installed in the CFBs. Furthermore, they showed no signs of degradation or malfunction and they did not require any service.

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