On monitoring the temperature and humidity of the BELLE-II detector in the thermal mock-up

Pak Hin (Brian) CHAN, University of Melbourne

Supervisor: Dr. Hua YE

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Abstract

The Belle-II upgrade will allow physicists to have a greater data set to probe for New Physics phenomena. However, despite the many advantages, such as better vertex measurements, there comes many challenges. In particular cooling is a vital problem in the Pixel Vertex Detector of Belle-II. This report will discuss the major issues involved with cooling the Pixel Vertex Detector component, in particular the problem of condensation. It will also describe a methodology of monitoring the thermal environment, both in the thermal mock-up and the Belle-II detector. Experiments conducted via this method will also be outlined.

Contents

1 Introduction

The two ways to probe for physics beyond the Standard Model (SM) or New Physics (NP) is either at the intensity front, or the precision front. The former involves a direct search using high energies at places such as LHC. The latter is an indirect search utilising rare decays. The high event rates at experiments such as Belle-II at SuperKEKB will ensure a high probability of detection, which can give insights into NP phenomena.

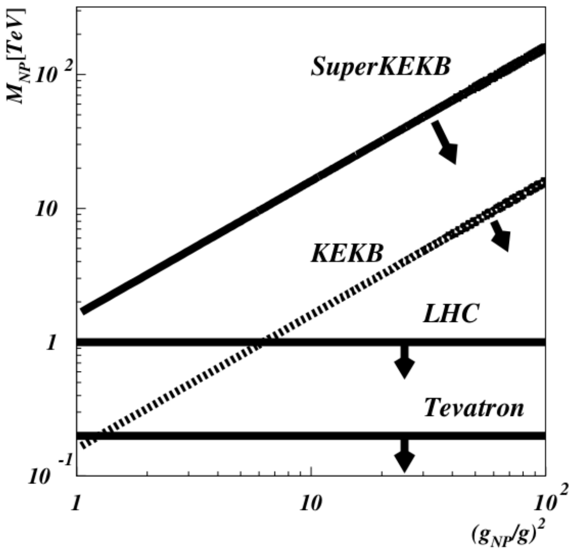

Figure 1: Belle-II experiment at SuperKEKB is highly sensitive to coupling to NP. [1]

The SuperKEKB accelerator in Tsukuba, Japan, operates at asymmetric energies of 7GeV, and 4GeV, for the electron and positron respectively [2]. At these energies $\Upsilon(4S)$ is created optimising the production of B-Mesons, which are used to probe for NP. The asymmetry of energies provides a Lorentz boost to dilate the lifetime of these products.

The Belle experiment, a predecessor of Belle-II, ran from 1999 until 2010 and successfully achieved many of its experimental goals including [1]:

- Establishing CP violation outside of Kaons
- Providing precise measurements on the CKM matrix elements V_{ub} and V_{cb}
- Measurement of rare B-meson decays sensitive to NP such as $B \to K^* l^+ l^-$

The Belle-II experiment will ensure the production of a greater data set (therefore more rare decay events) via a luminosity upgrade (See Table 1).

This upgrade is not only limited to luminosity. In particular, this report will focus on the introduction of Pixel Vertex Detectors (PXD) in order to improve the resolution of

Table 1: Comparison of Belle and Belle-II luminosities. [1]

Experiment	Instantaneous Luminosity ($cm^{-2}s^{-1}$)	Integrated Luminosity (ab^{-1})
Belle	2.1×10^{34} (Actual)	1
Belle-II	8×10^{35} (Designed)	50 (Until 2025)

track and vertex reconstructions.

A further reason for Belle-II's improved vertex measurements is the lowered Lorentz boost. The introduction of nano-beam technology will increase the cross section, but at the same time, also the background. To mitigate this effect, the energy asymmetry is lowered. Therefore the decay length of B-Mesons is shorter, require a higher precision measurement.

2 Detector Components

The minimisation of the material budget is an ever-present problem in high energy physics. The material budget is related to the energy lost as a particle passes through a material. Optimally, the material budget of the vertex detector (VXD) should be low in order to maximise measurements.

2.1 Detector and Dry Volumes

The detector volume is a cylinder which encloses the Vertex Detector (VXD) of Belle-II. The VXD itself comprises of six layers of silicon detectors: Two inner layers of PXD, and four outer layers of Silicon Vertex Detectors (SVD). The two final focusing magnets flank the detector volume. (See Figure 2)

The dry volume is the area in between either the detector volume or the final focusing magnets, and the central drift chamber (CDC). All cables (data, cooling etc.) linked to VXD must pass through this volume. (See Figure 2)

2.2 PXD

Each layer of PXD is comprised of multiple ladders (8 for the inner and 12 for the outer). A ladder includes two PXD modules (See Figure 3) glued end-to-end on their sensor layer. The module can further be separated into a sensitive area (sensor layer and switcher), and readout area (DCD and DHP). The sensitive area is closest to the interaction point and is considered to be in the physics acceptance area. The switchers, DCD, and DHP are application-specific integrated circuits (ASICs), so they produce a

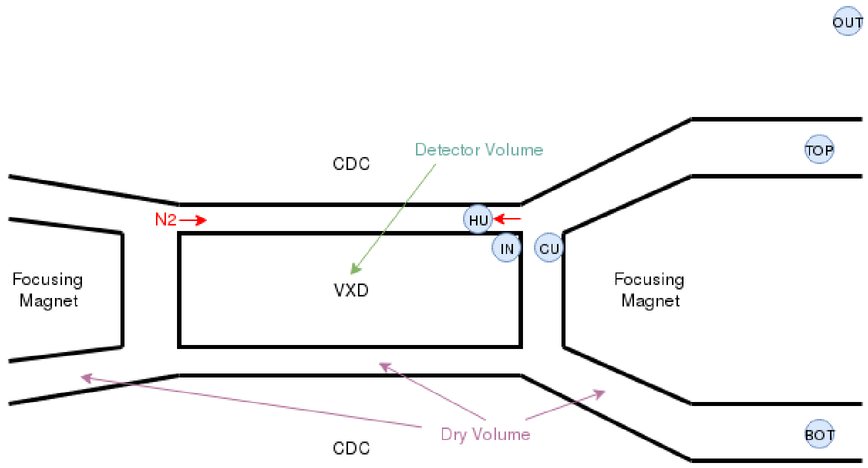

Figure 2: A diagram of Belle-II experiment with dry and volume detectors labelled. The placement of the six sensors for §5 are also shown.

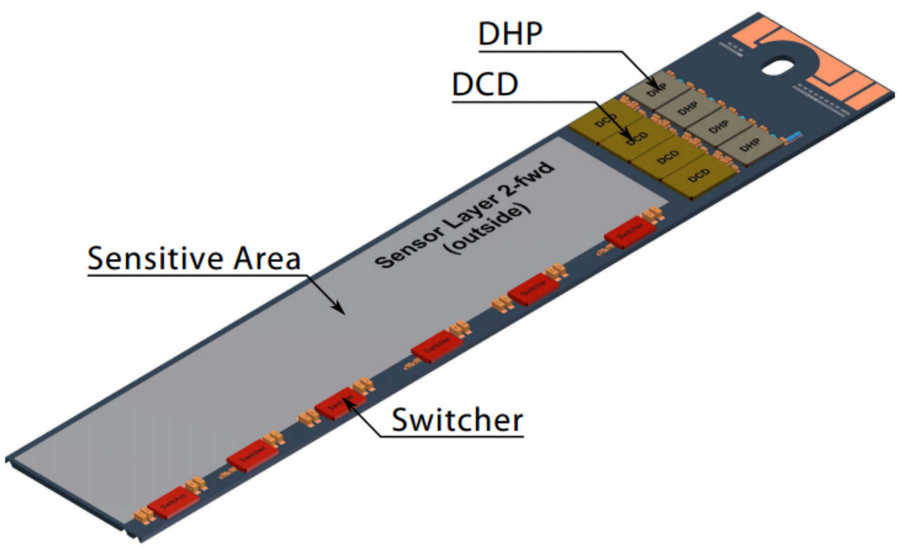

Figure 3: A single PXD module. The left side is glued butt-faced to another module.

heat load of 0.5 W, 4 W, and 4 W respectively.

The PXD was chosen mainly due to low power consumption, low material budget (75 µm thick in the sensor layer), and low intrinsic noise. The sensor layer on each module comprises of 250×768 pixels. The switchers read out each row at a time, and then grounds the entire sensor layer to reset it for the next measurement. The data is then sent to the Drain Current Digitizer (DCD) which digitises the information, and sends it to the Data Handling Processor (DHP) which analyses it. [3]

2.3 Thermal Mockup

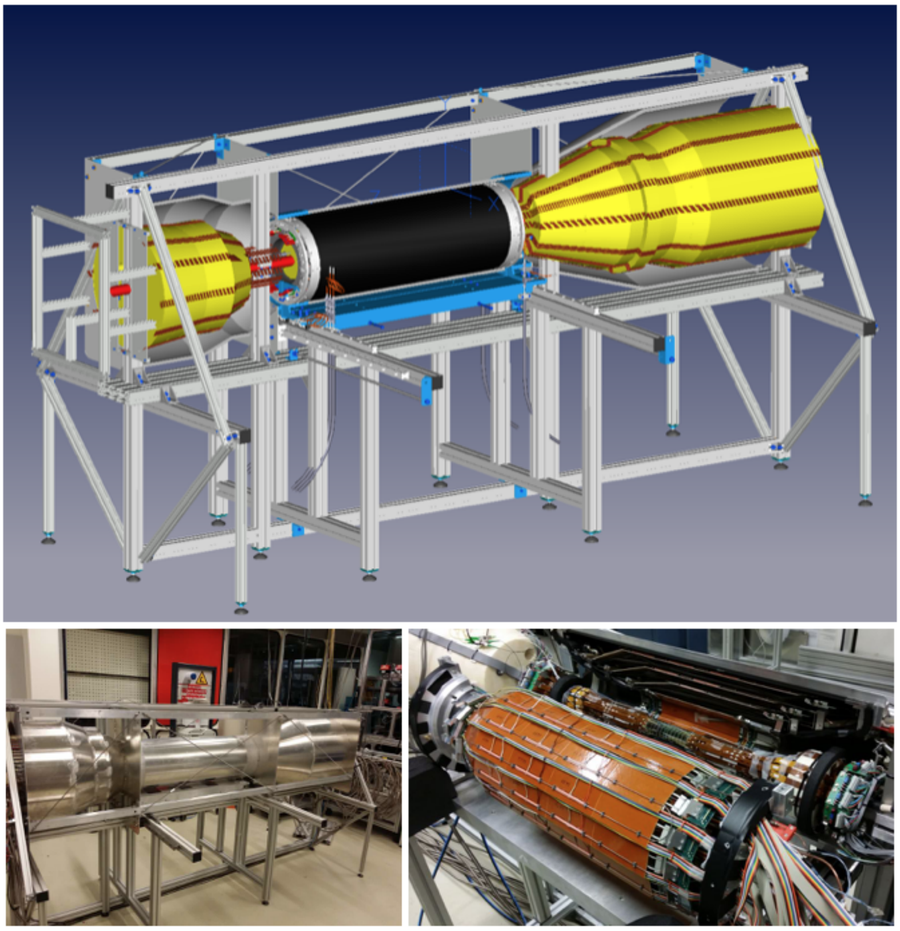

Figure 4: Thermal Mockup at DESY.

In order to verify the cooling requirements and investigate the thermal stress on the VXD, a mock-up was built at DESY. This is a replica of the detector and dry volumes of Belle-II with all its ASICs replaced with resistors to simulate heat load.

3 Thermal Environment

3.1 Necessity of Cooling

As mentioned in §2.2, the ASICs for each PXD module produces approximately 8.5 W of heat load. Elthogether with the SVD and some cables in the dry volume 2 to 3 kW of heat is produced.

It is important to deal with this heat problem for three reasons. Firstly, The ASICs have a limited operational temperature range. Maintaining this temperature is vital for reducing noise due to leakage currents [5]:

- PXD ASICs: below 50 °C
- PXD sensor layers: below 25 °C
- SVD ASICs: approximately 0 °C

Secondly, the beam pipe and CDC must be thermally isolated from the VXD and operate at temperatures of approximately 15 °C and 23 °C respectively. This CDC temperature is required for stable calibration and optimal dE/dx performance. [5]

It should be noted that most of the heat is produced in the readout area with minimal heat load in the sensitive area. Therefore the readouts are placed on the support and cooling blocks (SCB). These readouts are then cooled using 2-phase CO_2 in closed pipes through the SCB. The sensitive areas are cooled using forced N_2. The N_2 can also be used to control the relative humidity. [3]

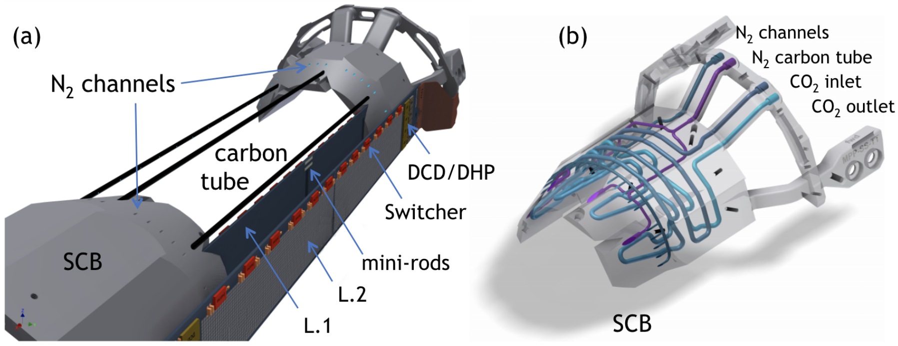

Figure 5: The support and cooling blocks which both the PXD and SVD are attached to.

3.2 Two-phase CO_2 Cooling

The optimum coolant for Belle-II is CO_2 due to operational and physical reasons. [6] The CO_2 operates in the transitional 2-phase between liquid and gas.

Operational advantages:

- Inexpensive

- Non-flammable
- Non-toxic
- Generally stable over time

Physical advantages:
CO_2 in 2-phase has two important properties that can be exploited. Firstly, the temperature depends only on pressure, so if one is known, the other can be calculated. Secondly, it has a large latent heat leading to a low temperature gradient (Figure 6 Top), which means the temperature of CO_2 in and CO_2 out will be approximately the same. Therefore if the pressure is measured before the 2-phase enters and after it exits the experiment, the temperature within the experiment can be known without placing probes inside. This non-intrusive way of monitoring the cooling is ideal for the Belle-II experiment.

Furthermore, since CO_2 in 2-phase has such a high latent heat, for the same amount of energy, much less coolant is required. Therefore, the cooling pipes can be made relatively small (Figure 6 Bottom). This is important since there is limited space in the dry volume. Also the SVD has cooling pipes inside the physics acceptance, so the material budget is also reduced.

3.3 The problem of cooling

An unfortunate side-effect to cooling is condensation. Below a certain dew point temperature, the process of condensation begins. This point is determined by both the actual temperature and relative humidity via the Magnus formula. For −45 to 60 °C at constant pressure, where H_R is the relative humidity (in %) and T is the ambient temperature (in °C) [7]:

$$T_{DP} = \frac{243.12\left(\ln\left(\frac{H_R}{100}\right) + \frac{17.62T}{243.12+T}\right)}{17.62 - \left(\ln\left(\frac{H_R}{100}\right) + \frac{17.62T}{243.12+T}\right)} \tag{1}$$

Furthermore, if the temperature is known, then the partial pressure of the water vapour can be calculated for 1 to 100 °C in units of mmHg, where this time T is in K [8]:

$$p_{vapour} = \frac{H_R}{100} p_{\text{saturation}} = \frac{H_R}{100} 10^{\left(8.07131 - \frac{1730.63}{233.426+T}\right)} \tag{2}$$

In general, a drop in the temperature will cause a rise in the relative humidity. This will then cause a rise in the dew point temperature - a value we wish to minimise. Therefore it is important to control both the temperature and relative humidity.

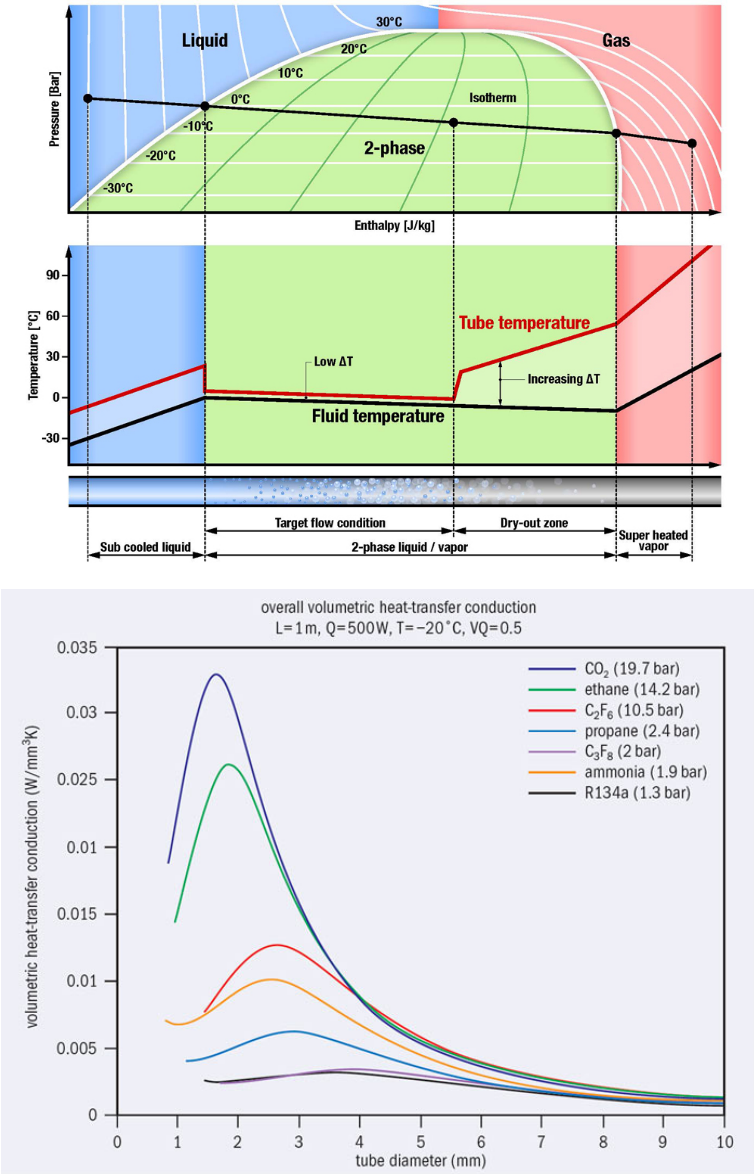

Figure 6: (Top) CO_2 cooling has the advantage of low temperature gradient. (Bottom) CO_2 cooling pipe size is the smallest.

4 Methodology of Measurement

Measurements of the thermal environment are taken using SHT21 sensors connected to raspberry pi's. The control of these SHT sensors is done via python codes. They can be accessed on Github:
`https://github.com/BrianC2/Belle2ThermalMonitor.git`

1. Main: `multi_sensor_readout.py`

2. Auxiliary: `readout.py`

The main code is to read the thermal information for each sensor, and the auxiliary code is to access previously recorded data saved in `.txt` files. Since the raspberry pi has limited i2c (data) channels, GPIO (on/off) channels were used as switches. Each sensor was switched on via GPIO, read through its i2c, and then switched off.

It is vital that everytime the pi is switched on, the GPIO gates are setup for initialisation. This can be done via a simple bash script at `Initialisation/gpioconfig.sh`. To check if the configuration is successful, the `gpiocheck.py` in the same folder can be used.

The main features of the program are:

- Read current time, temperature, humidity data
- Calculate the dew point temperature using Equation 1
- Output data to `.txt` file
- Live plotting using Matplotlib's `animation`
  - Temperatures and humidity drawn on the same x-axis (time)
  - Self-adjusting axis range to fit in plot
  - Adjustable limit on x-axis to limit the time range shown (set as 1 day)
- Basic HTTP server to live access current temperature using url: `http://131.169.103.151:8080` (150 or 151 can be used depending on which pi)

An auxiliary program was used to readout saved data in text files:

- Plot data of a particular time interval in a previous recording session (input as `.txt` file line number)
- Read out MARCO data and draw on the same plot (optional)
- Calculate and plots the actual partial pressure of the water vapour

5 Measurement in Thermal Mock-up Environment

5.1 Sensor Positioning

In order to investigate the effects of cooling, six SHT21 sensors have been carefully placed at various locations of the thermal mock-up (See Figure 2):

- IN. Inside detector volume. To understand CO_2 cooling close to the physics interaction point.

- OUT. Outside thermal mockup. Act as a control.
- HU. Next to N_2 cooling pipe. Monitor the effect of humidity control.
- CU. Next to the copper cooling pipes. Monitor the effects of cooling
- TOP. Top of dry volume.
- BOT. Bottom of dry volume.

5.2 Procedure

The Multipurpose Apparatus for Research on CO_2 (MARCO) was attached to the mock-up to simulate actual cooling at the Belle-II experiment. Although MARCO is less powerful than the final IBBelle cooler to be used at KEK, it is sufficient for the purposes of these tests.

The thermal mock-up was closed after the sensors were placed and MARCO set to run. The effect of cooling on the dew point temperature and humidity was observed. The exact procedure is shown in Table 5.2.

Line no.	Time	Elapsed Time (s)	Procedure
N/A	13:45	0	Origin of the time axis of graph
1	14:00	900	Start N_2: 8L/min to SCB
2	14:04	1140	Start MARCO
3	14:38	3180	Increase N_2: 10L/min to SCB
4	15:32	6420	Increase N_2: 20L/min to SCB
5	15:57	7920	Stop MARCO
6	16:12	8820	Stop N_2

Table 2: Procedure for the MARCO run in the dry volume of the thermal mock-up. The line number corresponds to the lines shown in Figure 7 from left to right.

It should be noted that the GUI of MARCO was restarted every 30 minutes. Therefore there was a periodic interruption to the recorded CO_2 temperature. It was concluded thus that the CO_2 temperature data was not very helpful and precluded from the plots.

There were many indications that the sensors were working properly. For instance when the N_2 was injected, the humidity dropped as expect. These will be seldom discussed. The focus of this discussion will be on the anomalies present in the data. Since the thermal mock-up is a complex system, there could be many reasons for these. Only suggestions will be give as to the cause.

The BOT sensor had an extremely delayed drop in the humidity - it was only after the first N_2 boost that a decline was observed. Geometrically, the N_2 pipes were placed on the upper half of the mock-up. If the volume is not closed properly the gas could have leaked outside, and it may have taken a long time before the N_2 reached the bottom.

Further evidence of a leak can be seen in the humidity levels after the first boost. The humidity slowly increased everywhere except inside the VXD. Even the secondary boost to the N_2 levels did not alleviate this effect.

An important observation is the peak in the dew point temperature shown in the plots. Recall that condensation is a major issue and the temperature must be kept above the dew point. Therefore it is important to understand any causes of increase in that variable.

An initial guess is that perhaps the peak is due solely to temperature drop. As mentioned in §3.3, a drop in temperature can cause a drop in dew point. However to be consistent with theory, there should be no peak in the partial pressure of water vapour. However as shown in Figure 7, there is a peak in the partial pressure, indicating other factors such as a possible leak can come into play.

6 Measurement in Belle-II Volume

A second investigation was conducted, but this time on the Belle-II VXD. In this case, only the PXD were present (not the SVD). One sensor was placed on the SCB in the forward direction (FWD), and the other in the backward (BWD), along with a reference one outside.
MARCO was started with a set temperature of 10 °C. This was reduced in step until −25 °C. At this point, it can be see from Figure 8 that most of the time, the T_{DP} is kept below −30 °C. There fore it is safe to run the cooling for temperatures up to −30 °C in this environment.

7 Further Development

The focus of this project was to develop a methodology to monitor the temperature and humidity of the Belle-II detector. It was shown through experiments on both the thermal mock-up and the Belle-II VXD that the sensors work within reason. This will allow for further experimentation and clarification on some anomalies present in the results.

However when considering the Belle-II experiment, the SHT21 sensors are by no means tested for radiation hardness, and other methods must be used to conduct the monitoring. For instance, the air in the dry volume can be sucked out to be measured outside the detector. Or special fibre optic cables can be used for temperature and humidity detection.

There are, however, improvements that can also be made to the methodology of measurement:

- Introduce automatic browser refresh for the HTTP output
- Introduce live graph to be appended to HTTP server
- Generalise the `readout.py` code to be used not only for the output of `multi_sensor_sht21.py`

8 Acknowledgements

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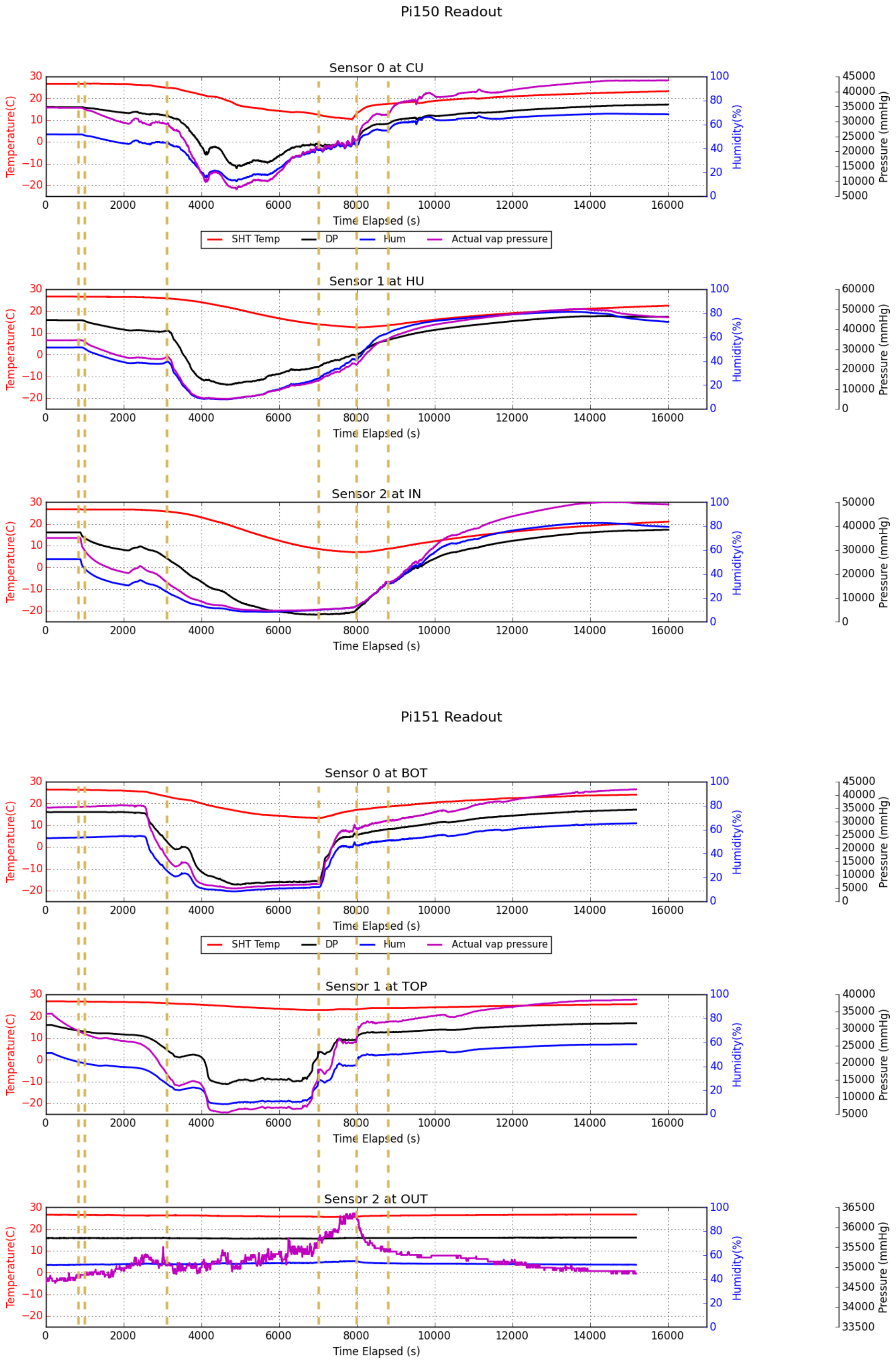

Figure 7: The results of the measurements in the thermal mock-up. The dotted line represents the line numbers in Table 5.2 from left to right. The colours represented are: sensor temperature, sensor humidity, partial pressure of water vapour, dew point temperature.

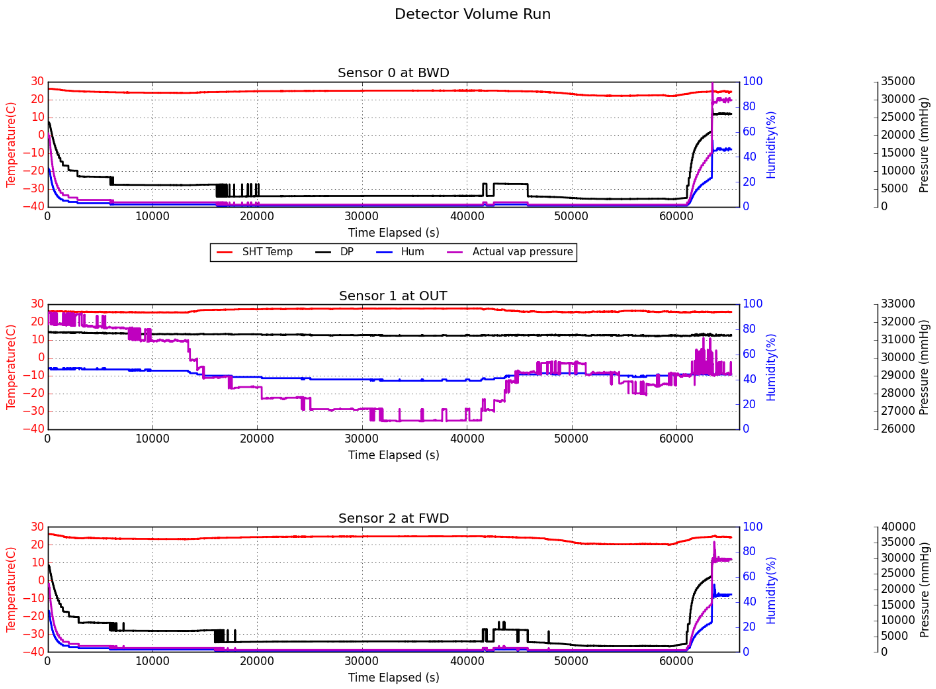

Figure 8: The results of the measurement in the Belle-II volume. The colours represented are: sensor temperature, sensor humidity, partial pressure of water vapour, dew point temperature.

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