Monitoring Temperature Along High Pressure 2-Phase Coaxial CO2 Detector Transfer Lines

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1 Introduction

The high-luminosity LHC era is fast approaching and the required improvements to both the accelerator and the detectors are monumental in scope. Despite the intricate complexities of each sub-system, a robust and expansive cooling system pervades the entire apparatus. Looking specifically at CMS, due to upgrades to and replacements of a large number of its components, the new cooling system for the HL upgrade must perform orders of magnitude better than the current one. For example, components such as the tracker, the MIP timing detector, and the high granularity calorimeter, will need to be maintained at temperatures as low as -40 °C [1] and require a cooling system capable of 550 kW heat extraction [2]. Comparing this to the current system that goes down to -20 °C with 10 kW heat extraction, the difference is stark and a clear motivator for significant change [2].

This change came in the form of 2 phase accumulator controlled loop (2PACL) CO_2 systems that use accumulators to precisely control the boiling point of CO_2. These systems also allow for the excision of artificial refrigerants from the cooling system, a commonly used gas was CF_4 which has a global warming potential 6630 times greater than that of CO_2 [3]. As a result, 2PACL systems are not only beneficial for the HL upgrades, but they are significantly cleaner and a large step towards sustainability. A crucial element of these systems are coaxial transfer lines that distribute the CO_2 coolant from the cooling plants and distribution manifolds, and serve as internal heat exchangers between the incoming liquid and the outgoing mix of vapor and liquid [4]. Studying the surface temperature of these so called detector transfer lines (DTLs) was the main purpose of this project and report in order to assert that the insulation technology of the lines ensures the surface temperatures are kept below the cavern dew point, avoiding the formation of moisture and/or ice.

2 Experimental Setup

2.1 DTL Prototypes

Located in building 186, the TIF clean room and the Lyon cold room served as hosts to two different kinds of DTL prototypes. The two lines differ in their insulation and rigidity as well as in the number of input lines they contain, this allows for comparison between them and for conclusions to be drawn on which type of insulation should be chosen moving forward.

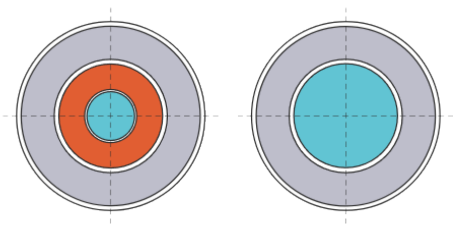


Figure 1: Cross sections of the cold room DTL (not to scale).

Cold Room Line This DTL can be described in two sections: one rigid coaxial section mounted on the outside of the Lyon cold room, between the back of the cold room and the external wall of building 186, and a flexible section inside the Lyon cold room with only the outgoing liquid CO_2 from the plant. Both sections are similar in that they are vacuum insulated, corresponding to the gray areas in Fig.1, with the orange sections corresponding to the mixed-state

CO_2 returning to the plant, and the blue sections the outgoing, liquid, CO_2. An important distinction between the two sections of this line is the temperature environment in which they exist, the rigid section being outside the cold room and exposed in part to direct sunlight while the flexible is in a very insulated and temperature controlled space, had significant effects that will be discussed in this report.

Clean Room Line This prototype is different to the previous one in that it is fully insulated with aerogel instead of vacuum. It is also fully rigid and all along its length is coaxial with four input lines as can be seen in Fig.2 which has the same color code as Fig.1. The DTL was mounted on the wall of the clean room such that it is suspended from supports and does not rest on the ground at any point. As can be seen in Fig.3, the line contains vertical and horizontal sections which are expected to exhibit different behaviors as described in a paper from Pakulski et al. [5]. As can be seen in Fig.3, there are four bellows along the line, one in each straight section, two of which have three temperature sensors each. There are also the three right angle bends in the line, two of which have sensors on them, which together with the bellows present sections that may present irregularities with the insulation due to their difference in structure.

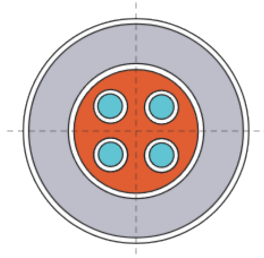


Figure 2: Cross section of the clean room DTL (not to scale).

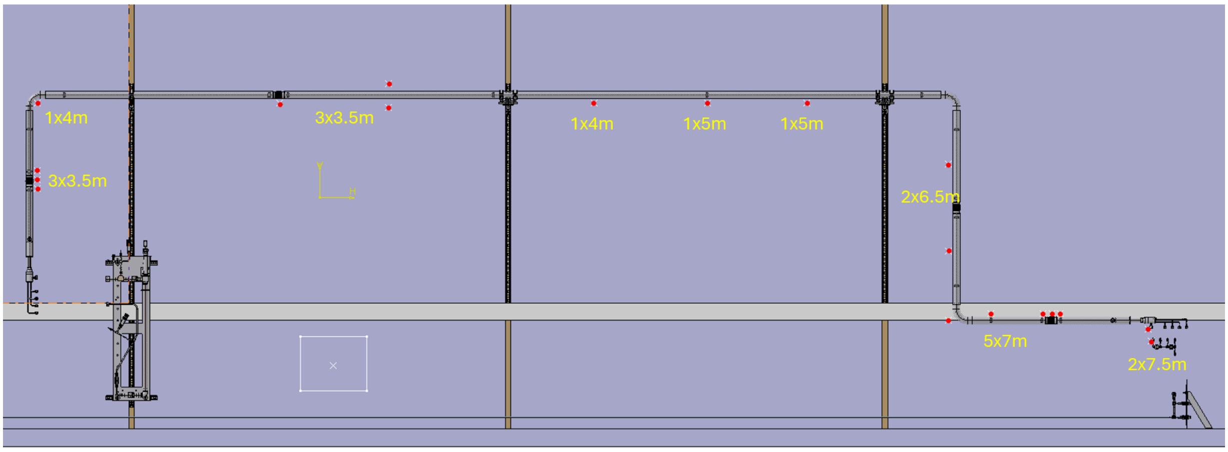


Figure 3: Schematic describing the DTL inside the cold room and the placement locations of the temperature sensors.

2.2 Temperature Sensors and Database Interface

To monitor the surface temperature along the DTLs small PT sensors were used by taping kapton down to the surface of the line and then taping the sensors to the kapton with more kapton, ensuring that the sensors did not short out and ensuring that they were not in direct contact with the metal of the line. A total of 15 sensors were used for the cold room DTL with two ambient temperature sensors, one inside and one outside the cold room, as well as seven sensors on the rigid section and six on the flexible. All the sensors were wired to a Multi Temperature Readout System (MTRS) that is able to support 24 connections, which then in turn uploads the data values to a database.

A data visualization interface was created in Grafana to be able to watch in real time the temperature readings of all the sensors along both sections of the line and compare them to each other. This was done by connecting the database as a data source and creating plots using

SQL queries. The dashboard consists of line plots of each of the fifteen channels as well as a plot containing all of the external line sensors, a plot containing all the internal line sensors, and a plot with all 15. On each sensor, alerts were programmed to start firing when the temperature reading dipped below 12 °C, sending emails when the alerts were tripped was looked into but is unfortunately impossible with Grafana Cloud according to their support team. The dashboard can be shared to a new machine by first downloading Grafana, then importing the json file of the dashboard in Grafana, and finally configuring the data source and reloading each plot. A more detailed step by step procedure for transferring the dashboard is given in the appendix of this paper.

3 Experimental Results

3.1 Initial Passive Results

After connecting the sensors and setting up the visualization dashboard, the temperature data from the 15 sensors was being read and displayed continuously. These passive measurements clearly support a claim made earlier in this report regarding the different temperature environments of the two sections. In Fig.4, channels 1 and 2 correspond to the ambient room temperatures inside and outside the cold room respectively, while channels 11-17 are on the rigid segment outside the room and channels 19-24 are on the flexible in the cold room. It is clear to see that there are two different types of channels in Fig.4 based on the amplitudes of their oscillations in 24 hour periods By looking at which channels are grouped together, the separation indeed corresponds to the interior and exterior channels, with the channels in the cold room having smaller oscillations since the environment is isolated. Another display of the cold room's isolating properties reflected in the data is the approximately 80 hour period where the interior channels sharply dip in temperature and then maintain a relatively constant value. This corresponds to the time when the cold room door was closed in anticipation of CO_2 circulation and the temperature control system of the cold room paired with the thermal insulation of the room meant the day / night temperature cycles became insignificant in the room.

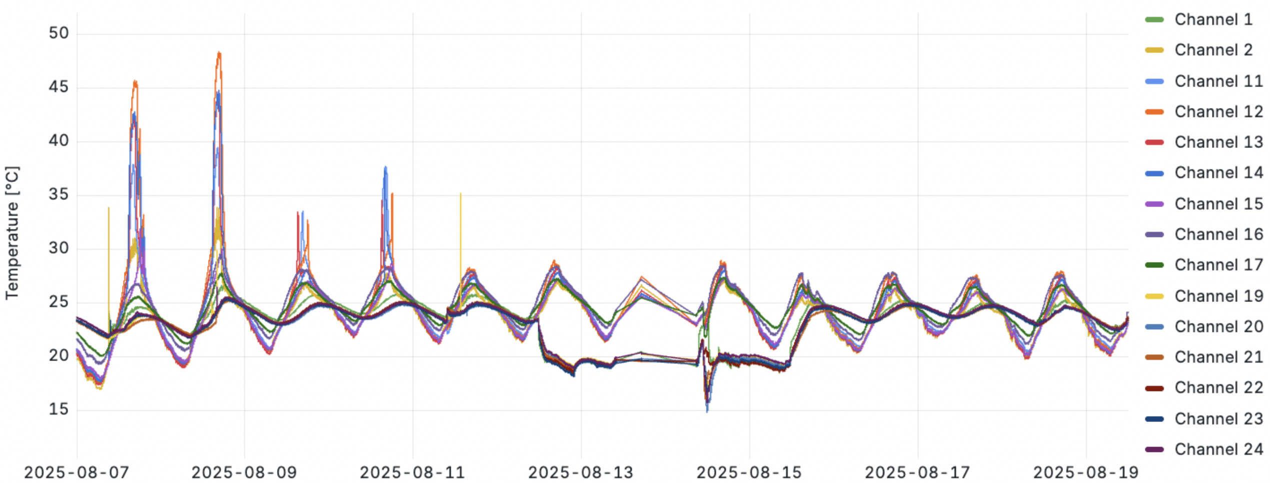
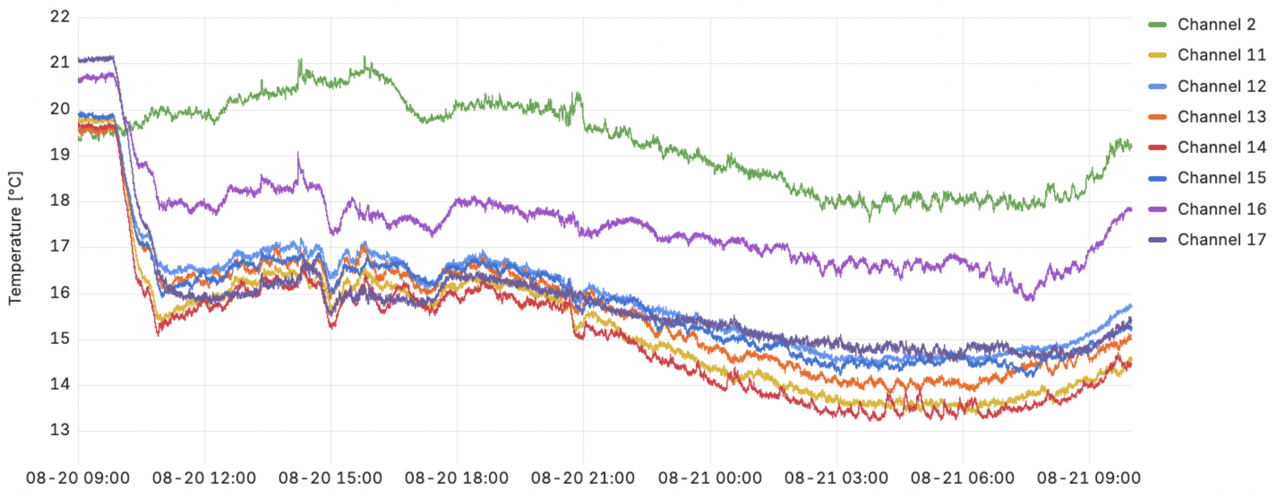


Figure 4: Grafana generated time plot of the temperature in Celsius of each of the 15 sensors over a twelve day period in august 2025.

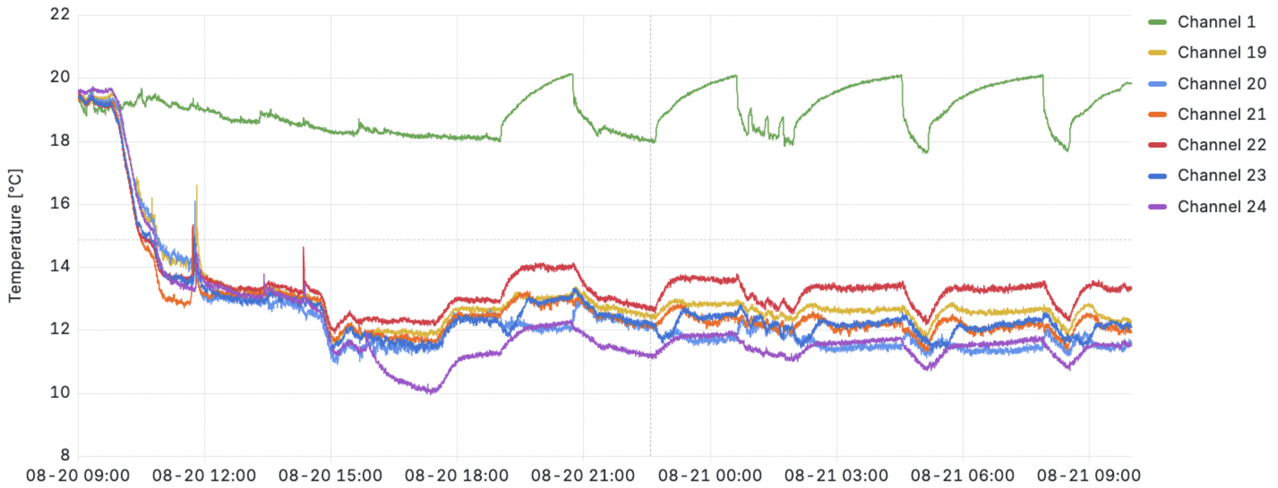
Another interesting observation from Fig.4 is the disappearance of the large temperature spikes displayed in the first four days. After the first two days, it was determined that the direct exposure of the external portion of the line to sunlight was causing the exterior of the line to significantly heat up. As a solution, cardboard was meticulously taped over the windows in question to block all sunlight from hitting the DTL. That being said, the third and fourth day in Fig.4 still display smaller spikes, this is because some sections of cardboard had fallen down over the weekend. They were promptly reinstalled Monday morning and the spikes have since stopped.

3.2 Liquid CO_2 Circulation

Setbacks Following over three weeks of delays in circulation, the CO_2 was finally turned on and circulated on the 13th of August. After about 15 minutes, alert messages indicated a problem with the pump's membrane pressure. One of the two membranes in the pump had ruptured and as a result the pump had to be stopped and the circulation put on pause. This delay lasted another week and as a result the DTL only experienced consistent circulation starting on the 20th of August at around nine in the morning. The circulation lasted about 24 hours and is displayed in Fig.5.



(a) External channels.

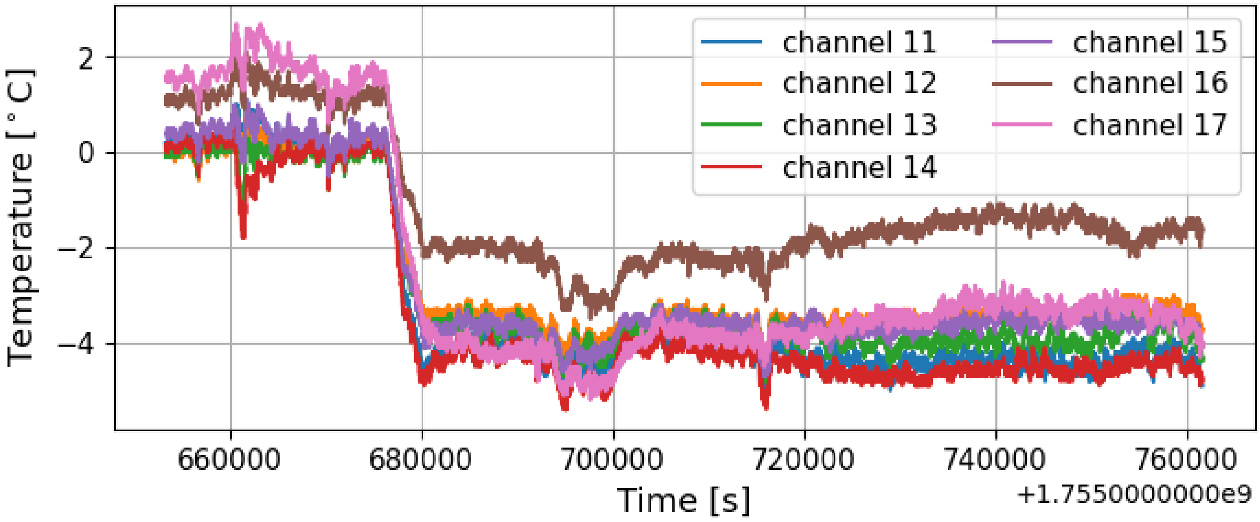


(b) Internal channels.

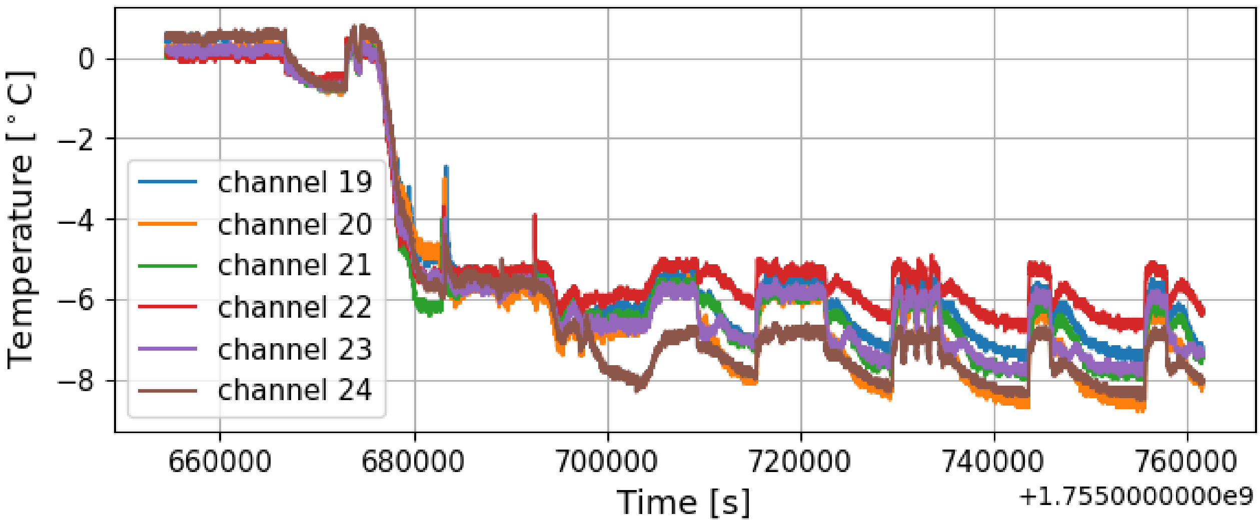
Figure 5: Grafana generated plots of the temperatures, inside and outside the cold room, during the circulation of liquid CO_2.

During this period, liquid CO_2 at -15 °C was circulated starting at the sharp drop off on the left side of the plots in Fig.5, then, an attempt was made to circulate at -35 °C at 15:00 on the 20th as can be seen by the dips in both Fig.5.a and Fig.5.b. Unfortunately, the pump's temperature data indicated that the CO_2 never actually reached -35 but instead stabilized at around -25 °C for three hours before the system was once again set to circulating at -15 °C. The dip corresponding to the lower temperature can be seen in both plots in Fig.5 as well as the bump back up after the return to -15 °C.

Observations and Background Removal The most significant conclusion to be drawn from this is that the rigid section has a smaller response to the CO_2 than the flexible section. In fact, looking at channels 11-15 that are sitting right below 20 °C prior to the circulation and channels 19-24 that hover around 19.5 °C, the latter channels, on the flexible, fall to temperatures of around 13 °C while those on the rigid section fall to about 16 °C. This three degree difference in final temperatures indicate a difference in insulatory capabilities between the two sections of the line.



(a) External channels.



(b) Internal channels.

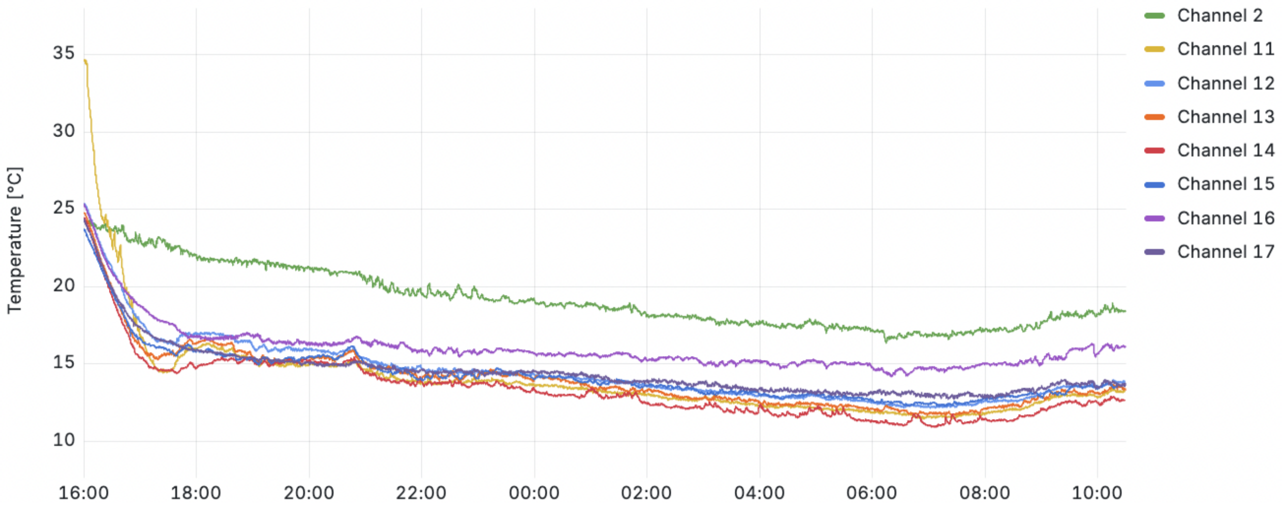
Figure 6: Temperature difference between the channel signals and the background ambient temperature for the respective environments.

To confirm that the difference in temperature drop between the two sections is not a consequence of the different environments but truly a feature of the line segments, a python script was written to subtract out the ambient temperature from the signal. The code works by reading out the data from the csv files corresponding to each channel and then iterating over these data sets. This background removal was complex since the data points between channels are not taken simultaneously and thus have different time, or x, arrays. This problem was solved by assuming that, since the points have a frequency of 10 seconds, the variation between points is small enough that shifting the time values of the channel to align with the background is not a significant change. This shifting was carried out and then removing the background from each channel was a simple difference of arrays. The results are plotted above in Fig.6.

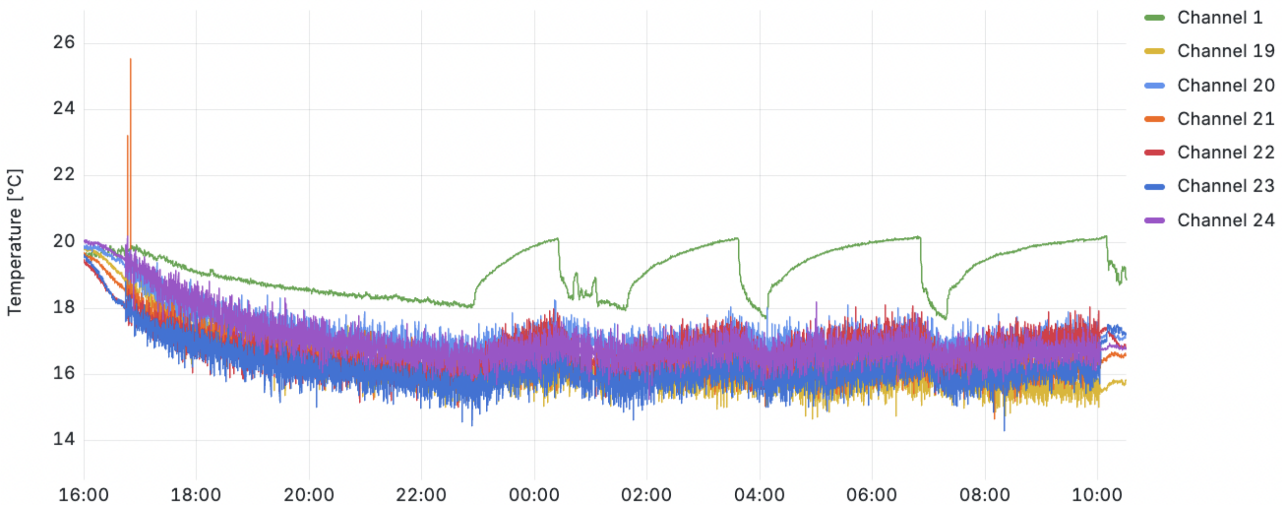
As can be seen from Fig.6, the surface temperature of the flexible line is about seven degrees colder than the ambient room temperature while it is only four degrees colder for the rigid line. In other words, the flexible line dips three degrees lower than the rigid line during circulation, this matches well with the qualitative analysis done from the raw data sets in Fig.5. Also visible in these plots, is the dip in surface temperature when the pump attempted to reach -35 °C, the plateaus in both plots have a sharp drop off, remain steady for some time, and then return to the same level as previously. Channel 24 is an exception, the temperature, after the secondary reduction, keeps lowering in this spot on the line and only recovers when the pump returns to -15 °C. Even in its recovery though, it does not return to the level it had previous to the attempt at lower temperature, it becomes once again stable but about two degrees lower than the other channels on the same line. This behavior seems to indicate that at the ends of the DTL, where sensor 24 is located, there might be an issue with the insulation. More care should be taken to examine this phenomenon in further detail.

Finally, potentially the most striking part of the temperature profiles are the regular sharp bumps on all the interior channels. The fact that they appear also in the ambient room temperature measurement immediately eliminates the possibility that these fluctuations are related to the CO_2 and instead implies that they are environmental in nature. The most logical idea is that they are caused by the cold room's air condition system that ensures a relatively constant temperature in the environment by cooling the room to a lower threshold once it attains a certain upper threshold. This effect is not completely removed by subtracting out the background, but it is reduced. The difference in response to the AC cycles of the air and the DTL likely arises in the different heat conductivity of the materials, air and stainless steel. This means that simply subtracting out the background is perhaps not adequate for the internal channels and that some more involved method of background removal would be better suited for this particular case.

New Vacuum and Second Run Following the underperformance of the flexible portion of the line, its vacuum was redone with the hope that a poor vacuum was responsible for the difference in insulation with respect to the rigid section. The resulting vacuum was a factor 100 better than its predecessor, going from 5×10^{-1} to 10^{-3} mBar. Following this, another circulation run was conducted in the night between the 28th and 29th of August, this time immediately and successfully reaching -35 °C, and the results from the temperature sensors both inside and outside are presented in Fig.7. Immediately the difference from Fig.5.b is clear, the channels on the flexible section remain above 15 °C, an improvement of about 2 degrees over the first run. Note that this improvement is in spite of the fact that the circulating CO_2 is twenty degrees colder than the previous measurement. This measurement confirms that indeed, the vacuum was severely lacking in the flexible section of the DTL as redoing it significantly improved the insulation of the line and made it so that its surface temperature was no longer dipping below the dew point. This last is incredibly important for when the DTLs are installed in the service and experimental caverns of CMS. The internal channels still display the AC patterns previously discussed and the external channels dip lower than in Fig.5.a but this is most likely explained by the colder circulation temperature. An interesting experiment would be to also redo the vacuum in the rigid section and see the change in performance. The large starting temperature of channel 11 is due entirely to its location on the line, it is right next to where the vacuum pump was attached and was heated significantly during the process of reestablishing the vacuum. Following this process the pump was removed and the sensor quickly returned to the anticipated temperature range.



(a) External channels.

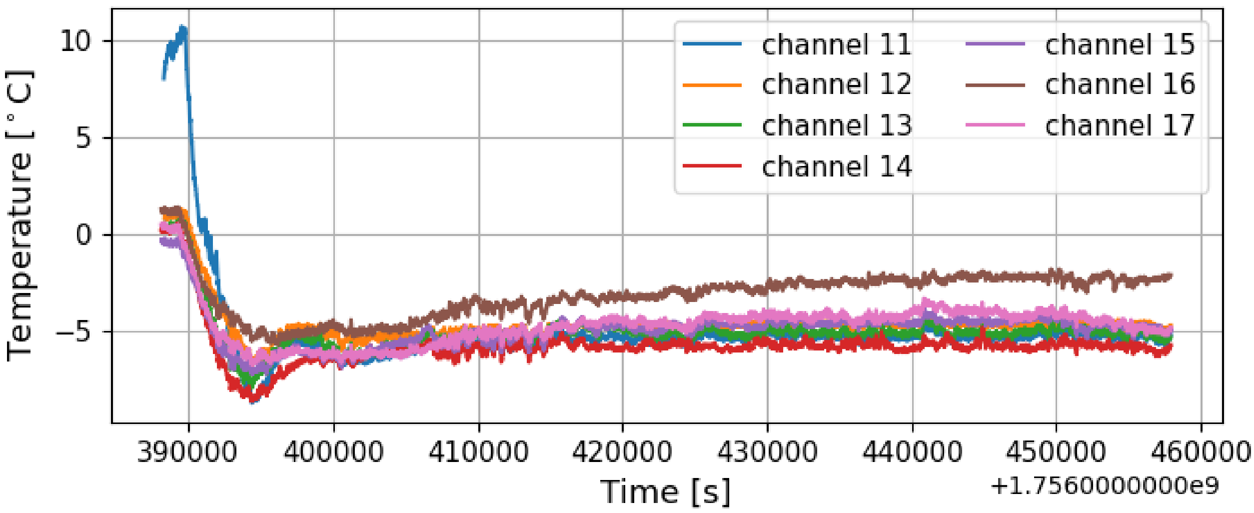


(b) Internal channels.

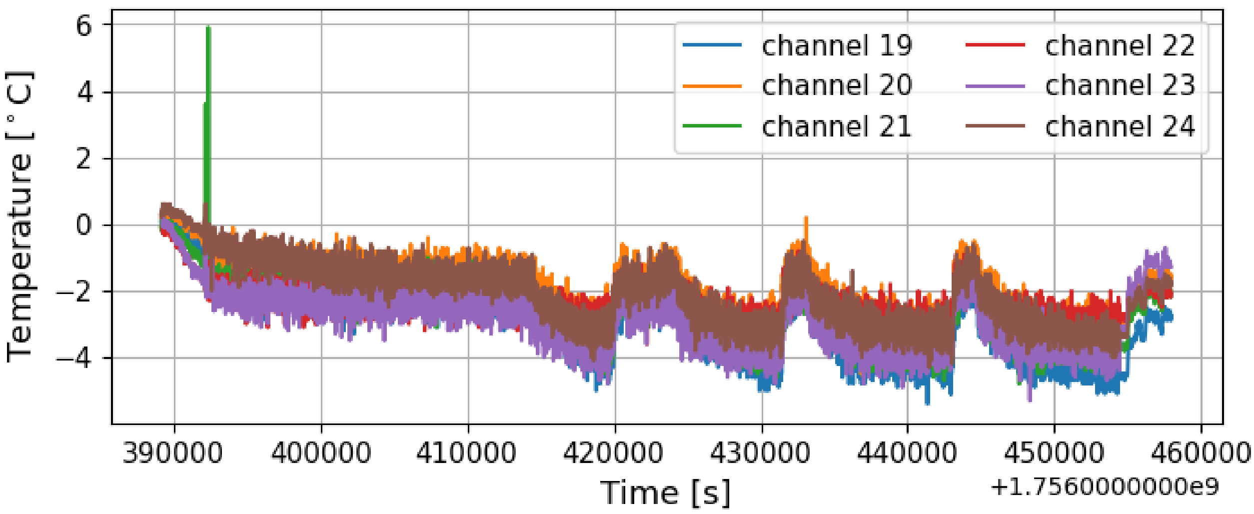
Figure 7: Grafana generated plots of the temperatures, inside and outside the cold room, during the second circulation of liquid CO_2.

A strange phenomenon that emerged in this run is the appearance of significantly noisier signals on the internal channels. All six channels became an order of magnitude more noisy at the same time while the ambient temperature measurement remained the same. The cause cannot be associated with the circulation since they did not begin at the same time, the noise stopped while the CO_2 was still flowing, and the same effect was not seen in the exterior lines. It cannot be room temperature fluctuations since the noise is not seen in the ambient measurement nor can it be associated to the readout system since all channels are connected through the same flat cable. Further thought should be put into explaining this bizarre observation.

The same python script was used to subtract out the background from the second run data as was used in the first run. The results are presented in a similar fashion in Fig.8. From these two plots its is very clear to see that while the exterior section of the line are one degree colder in the previous run, due to the colder CO_2, the interior line performed significantly better. In the second run the interior sensors only dipped about three or four degrees below the room temperature while in the first they went between six and seven degrees below. This significant improvement is confirmation that reestablishing the vacuum in the flexible section was an effective solution to the insulation problem and serves as motivation for redoing the vacuum in the rigid section as well.



(a) External channels.



(b) Internal channels.

Figure 8: Temperature difference between the channel signals and the background ambient temperature for the respective environments for run 2.

4 Next Steps

At the moment, progress is being made that was impossible to include in this report because of its unfinished and ongoing nature. This includes a search for a leak in the clean room line, a non-negligible amount of CO_2 is being lost per unit time from a source somewhere along the line, before circulating low temperature CO_2 it is important to find and resolve this leak. Also, following the success of reestablishing the vacuum in the flexible section, an initiative will be made to reestablish the vacuum in the rigid section of the DTL as well. Additionally, improvements to the python scripts are being implemented to generalize them beyond the scope of the two completed runs and a second Grafana dashboard is being constructed for the eventual clean room runs that must account for the increased number of connections and parameters.

All of the analyses presented in this report deal exclusively with the cold room's vacuum insulated, DTL. While the initial purpose of this project was based in comparing the vacuum insulation with the aerogel insulation, the delays meant that it was impossible to collect data from the clean room setup. As a result, the next big step for this project will be to move the temperature readout system from the vacuum insulated line to the aerogel insulated line in the clean room. All of the necessary cable extensions for this transfer have been acquired. When CO_2 circulates in the clean room setup, the data will permit for comparison between the horizontal rigid sections with different insulators as well as between horizontal and vertical sections of aerogel insulated rigid DTLs.

5 Conclusion

Despite delays that significantly changed the timeline of this project, a robust setup for multi-channel temperature readout along detector transfer lines was implemented and tested. This successful setup has measured two different, independent, runs of CO_2 circulation that have already provided valuable insight to the shortcomings of the lines and areas of improvement. From the first run it was clear that an issue was present in the flexible section, a hypothesis was made that the issue stemmed from a poor vacuum in the line and this was tested directly via a second run after reestablishing the vacuum in the line. This second run showed significant improvement in the line's insulatory capabilities, going from a almost eight degree drop during circulation in the first run to a four degree drop in the second run at even lower temperature. Preparations are being made to also reestablish the vacuum in the rigid section of the same line as well as for transferring the temperature monitoring setup into the clean room for the upcoming aerogel line tests.

References

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Date of consultation: 30.06.25

6 Appendix

6.1 Sharing the Dashboard

The following is a detailed procedure for sharing the data visualization dashboard on Grafana between machines:

1. Install grafana on the target computer the dashboard should be on at the link https://grafana.com/docs/grafana/latest/setup-grafana/installation/.

2. In a browser, go to 'localhost:3000' and log in with the default username and password which are both 'admin'.

3. It will ask to change the password for obvious security reasons, this is not important as it only pertains to the specific computer's login but Stathis and I have used 'DTLtesting25'.

4. To import the dashboard, go to the 'Dashboards' tab, hit 'new dashboard', and then 'import a dashboard'. Drop the json file in and that's all that is needed. Make sure the json corresponds to the latest version of the dashboard on whatever other machine is the most recent user.

5. Finally, to configure the data source for the dashboard go to the 'Connections' tab and then the 'data sources' tab, add a new data source and search for mysql. To configure the new mysql data source fill out the fields as follows: 'irrad2022' in the name field, 'dbod-cms-trk-irrad.cern.ch:5503' in the Host URL field, 'irrad2022' in the database name field, 'dtltif' in the username field, 'DTLtest' as the password, all four of the switches should be toggled to the left, and leave the additional settings in the default positions.

6. Final step is simply to go in to the dashboard and, for each panel, hover over the top right corner and hit edit, then hit the blue 'run query' button. This makes it so that the plots are pulling data from the newly configured data source where the temperature values are stored. The panels may take some time to display data.

7. To share the dashboard it is clearly necessary to have the json file, this can be found easily by clicking on the 'export' button in the top right of the dashboard.