

# **TWOCRIST: Preparing Proof-of-Principle Experiment for Future Charm Physics**

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## **Abstract**

As part of the 2024 CERN Summer Student Program, work was undertaken to prepare the TWOCRIST experiment to be installed in the Insertion Region 3 (IR3) of the LHC in 2025. Tasks evolved over the course of the summer, but they were primarily in the service of one of three outcomes: verifying that the manufactured vacuum feedthrough boards were made to designed standards; making sure that Peltier cells would be viable to use as a source of cooling for the Pixel detector; or ensuring that the PLC unit is able to monitor the temperature of different positions in the Roman pot. It has been determined that there are no severe faults on the boards, water cooling should be used on the Peltier cell to keep the detector at an appropriate temperature, and all temperature probes in the Roman pots are functional and able to be read by the PLC.

## **Keywords**

CERN Summer Student Project; TWOCRIST; Printed circuit board; Cooling; Peltier effect; Roman pot.

## Contents

|     |                                                             |    |
|-----|-------------------------------------------------------------|----|
| 1   | TWOCRIST . . . . .                                          | 3  |
| 2   | Vacuum Feedthrough Board Inspection . . . . .               | 4  |
| 2.1 | Methodology . . . . .                                       | 5  |
| 2.2 | Results and recommendations . . . . .                       | 5  |
| 3   | Cooling System Tests with Peltier cell . . . . .            | 7  |
| 3.1 | Thermoelectric effects . . . . .                            | 7  |
| 3.2 | Experimental design . . . . .                               | 8  |
| 4   | Test of Temperature Sensors Inside the Roman Pots . . . . . | 15 |
| 5   | Findings and Future Work . . . . .                          | 17 |
| A   | Vacuum feedthrough board diagram . . . . .                  | 19 |
| B   | Additional cooling figures . . . . .                        | 20 |



## 1 TWOCRIST

TWOCRIST is a proof-of-principle experiment to confirm the viability of the future ALADDIN experiment proposed to measure the electric dipole moments and magnetic dipole moments (EDM/MDM) of charmed baryons [1]. While there are differences in the set-up of both experiments, TWOCRIST offers an avenue to physically test the capabilities of a system that has previously been only probed via simulation [2]. A diagram depicting the layout of TWOCRIST is shown in Figure 1.

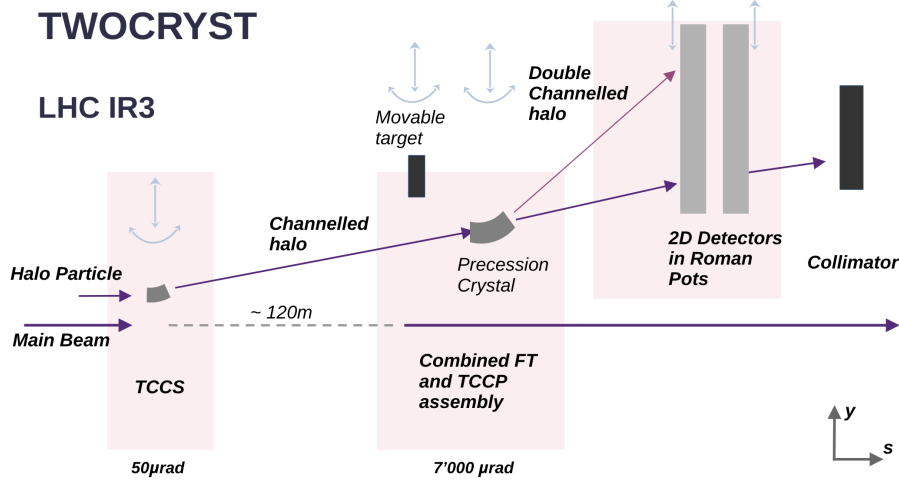
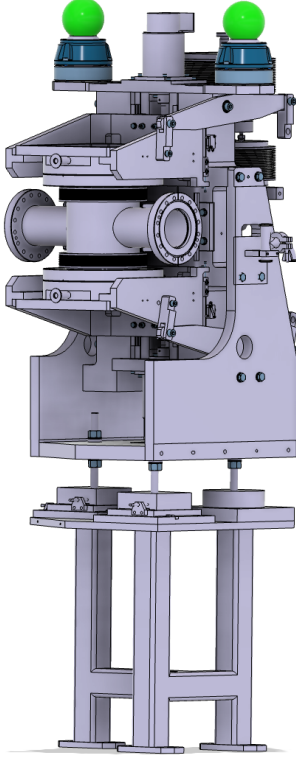


Figure 1: Illustration depicting the layout of the TWOCRIST experiment.

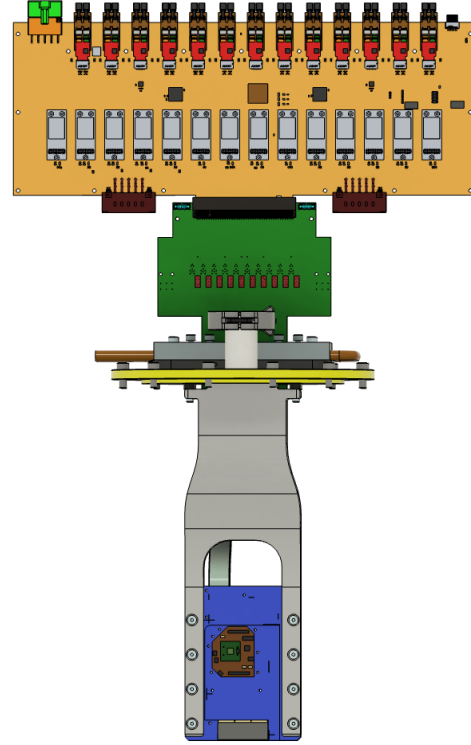
The main components of the TWOCRIST experiment are the two bent crystals, giving the experiment its name. The first crystal in the experiment is the TCCS (Target Collimator Crystal for Splitting), which channels halo particles from the main LHC beam to the second crystal, the TCCP (Target Collimator Crystal for Precession) [1]. Since the experiment uses the halo particles - essentially "waste" particles that are not contributing to the luminosity at the LHC experiments - it is referred to as "parasitic."

The TCCP works via the interaction between the particle's MDM and the strong electric field between atomic planes in the crystal [3]. This causes spin precession governed by known equations, allowing for the MDM and EDM to be derived.

This work deals with the first detector shown in Figure 1, which uses a silicon pixel detector heavily based on the VELO (Vertex Locator) on the LHCb [4]. More specifically, work was performed with the components shown in Figure 2, being the vacuum feedthrough board and Peltier cell, in Figure 2b, and to a lesser extent the ALFA Roman pot, in Figure 2a. The remainder of the report is dedicated to documenting the work performed on each component.



(a) Schematic of the ALFA Roman pot. The main system consists of two vacuum chambers that enter the beam line, which runs through the cylindrical portion of the Roman pot.



(b) Schematic of the TWOCRIST Pixel detector. The green board is the vacuum feedthrough board, and the Peltier cell sits between the black square flange and gray "cold hand".

Figure 2: Mechanical drawings illustrating the portions of the TWOCRIST experiment relevant to this project.

## 2 Vacuum Feedthrough Board Inspection

The TWOCRIST collaboration received five printed circuit boards at the start of June 2024. These boards connect the Pixel detector in vacuum to the in-air components of the experiment by bringing voltage into the detector via low and high voltage (LV/HV) signal lines and sending data signals to the computer managing the experiment. Since they act as a bridge into the vacuum, they are called vacuum feedthrough boards.

Prior to these boards being used in the TWOCRIST experiment, it is essential that they undergo thorough inspection to ensure the vacuum feedthrough boards meet the specifications required for the experiment and that all terminals are connected as designed.

Diagrams of the front (Figure A.1) and back (Figure A.2) of the vacuum feedthrough board can be found in Appendix A. The board can be divided into an "in air" and an "in vacuum" section, with 20 low voltage (LV) terminals and 8 high voltage connections (HVC) on each section and the vacuum section housing both temperature probe connectors (PT100-VR and PT100-VL) and all four flex cable connectors (HSC-F1, HSC-F2, HSC-B1, and HSC-B2). The PT100-VR and PT100-VL are lead outside of the vacuum through the PT100-AR and PT100-AL connectors. Both temperature probe connectors are on the front side of the board, while half of the LV terminals and flex cable connectors are on either side. The HVC connections are unevenly divided between front and back, with 6 being on the front (4 in air and 2 in vacuum) and 2 on the back.

## 2.1 Methodology

Board inspection involved two distinct processes, a visual inspection using a Leica MZ 125 microscope and continuity testing using a Polar Toneohm 550.

Visual inspection allowed for the identification of any faults on the vacuum feedthrough boards from manufacturing. This primarily looked at the soldering and connections between the connectors and board, wherein solder inspection was a purely visual task and verifying connections also involved gently touching pins with probe needles on the Toneohm. From this inspection, it was established which connections required additional scrutiny during continuity testing.

Despite there being no active elements on the board, the utmost caution was taken while performing continuity tests. This meant the usage of both a grounded mat and bracelet to prevent static shocks from connecting with the board, as well as nitrile gloves to reduce board deterioration due to prolonged skin contact. To verify all traces on the board form complete circuits and do not have shorts with neighboring lines, the process of continuity testing started with checking ground connections on all components against other grounds and neighboring data lines. This was followed by checking data lines on all connectors and terminals.

Since the Toneohm provides the resistance of closed circuits, it was possible to get a sense of the characteristic resistance of all traces on the board and note any deviations.

To distinguish between boards, a numbered label from 1 to 5 was applied on the "in air" front side of the board. These numbers were used to denote the inspection details for each board and are used in this report.

## 2.2 Results and recommendations

While verifying the continuity across data lines, it was found that each line type had similar resistances on all boards:

- LV data lines are in the range of  $2 - 5 \text{ m}\Omega$ ,
- HVC lines are in the range of  $0.6 - 0.8 \text{ }\Omega$ ,
- PT100-VR lines are often  $1.4 - 1.7 \text{ }\Omega$ ,
- PT100-VL lines are often  $1.8 - 2 \text{ }\Omega$ ,
- all DTA lines but one are  $2.1 - 2.6 \text{ }\Omega$ , while lines connected to HSC-B2 tended towards a narrower range of  $2.1 - 2.2 \text{ }\Omega$ ,
- the pair of DTA VP023 lines occupy a slightly higher range of  $2.6 - 2.8 \text{ }\Omega$ .

For the CTRL, VMON, NTC, and RESET lines, there is a variation in resistance range associated with whether the line is connected to HSC-F2 or HSC-B2. Lines on HSC-F2 usually vary in resistance on ranges of  $2.2 - 2.5 \text{ }\Omega$ ,  $1.8 - 1.9 \text{ }\Omega$ ,  $1.8 - 1.9 \text{ }\Omega$ , and  $1.9 - 2 \text{ }\Omega$ , respectively. On HSC-B2, these ranges are  $2.1 - 2.2 \text{ }\Omega$ ,  $1.2 - 1.3 \text{ }\Omega$ ,  $1.2 - 1.3 \text{ }\Omega$ , and  $1.2 - 1.3 \text{ }\Omega$ , respectively.

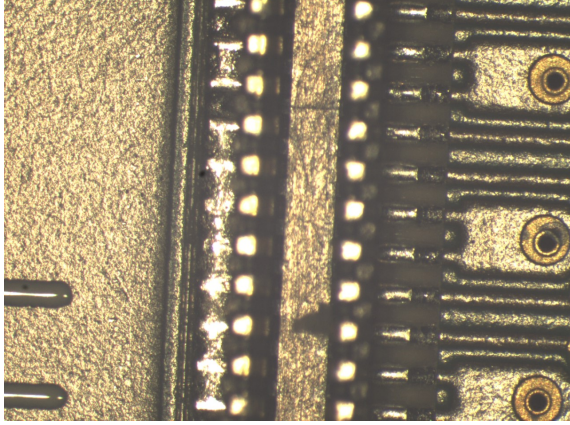
In general, ground connections exhibited a resistance on the order of  $10 \text{ m}\Omega$  to  $100 \text{ m}\Omega$ .

Any deviations from these trends are negligible and will have no impact on the function of the board.

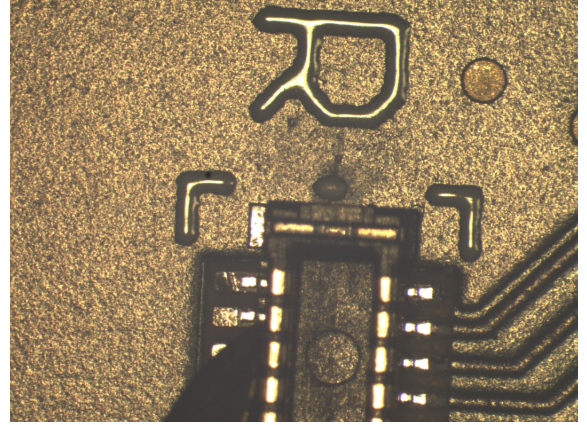
While performing visual inspection, two common faults were identified - pin shorting due to excess solder and disconnected pins, examples of both are given in Figure 3. In all cases of shorting, the pins affected were ground connections on the HSC terminals, therefore any impact on board functionality is unlikely. The components affected by pin disconnects varied between boards, but nearly all boards had a pin disconnected on the PT100-VR - however, since each disconnected pin was paired with another pin on the other side of the connector, it is possible to connect the cables to the side of the terminal with functioning pins. To verify results of visual inspection, continuity tests were performed on the affected

PT100 pins, confirming that they do not form connections with the traces. While the disconnection of ground pins was determined to be relatively benign, the presence of eleven such disconnects on the same connector of board 2 required that the pins be soldered back in place. The remaining disconnected ground pin on board 2 is located on a different connector.

Overall, no shorts between lines were identified, and all traces exhibited continuity. A summary regarding the number of each fault type can be found in Table 1.



(a) On left side of connector, ground pins shorted with solder on HSC-B2 connector. Compared against the pins on the right, soldering shorts are clearly indicated by silver regions between adjacent pins.



(b) Pin not properly connected to board on PT100-VR connector.

Figure 3: Faults found on Board 2 under microscope.

| Board Number | Number of Shorts <sup>a</sup> | PT100 Disconnects | Ground Disconnects |
|--------------|-------------------------------|-------------------|--------------------|
| 1            | 19                            | 2                 | 1                  |
| 2            | 30                            | 2                 | 1                  |
| 3            | 30                            | 0                 | 0                  |
| 4            | 5                             | 1                 | 0                  |
| 5            | 31                            | 0                 | 1                  |

<sup>a</sup> All shorts on ground pins

Table 1: Summary of faults found on vacuum feedthrough boards through visual inspection and continuity testing

Based on the inspection performed, the top three boards recommended to be used in the TWO-CRYST experiment are:

1. Board 3,
2. Board 4,
3. Board 5.

Further electrical tests of the vacuum feedthrough boards are ongoing, specifically checking to see if real data from a VELO module is able to pass through the board without signal deterioration. This is a critical test as it provides an avenue to verify the characteristic impedance of the fast data lines, which would otherwise require a time-domain reflectometer (TDR) to measure.

### 3 Cooling System Tests with Peltier cell

The detector needs to be kept at a temperature of  $< 30\text{ }^{\circ}\text{C}$ , but the estimated power lost as heat ranges from 15 W to 40 W during operation. Thus it is imperative that the detector be cooled with a system that is able to compensate for the addition of heat. Despite Peltier cells having low cooling efficiencies, it was decided to use one as the primary cooling mechanism of the Pixel detector due to their compact size, reliability due to not being composed of moving parts, and lack of materials like refrigerants that may pose issues in the vacuum of the Roman pot. However, it is essential that external cooling be applied to the hot side of the Peltier cell through the vacuum flange to allow the cold side to continue decreasing in temperature. Directly using water cooling on the detector is not possible as a water chiller placed near the Roman pot suffers radiation damage, while installing a chiller in the LHC service tunnels along with the necessary infrastructure is extremely expensive. Additionally, there is the safety concern of any water pipes fed into the Roman pot experiencing high pressure.

Investigations were conducted to determine which combinations of voltage applied over the Peltier and external cooling would produce the desired temperature range on the active detector.

#### 3.1 Thermoelectric effects

The Peltier effect can best be explained by first addressing the Seebeck effect.

Discovered in 1821 by T.J. Seebeck, the Seebeck effect explains that applying a temperature gradient over the junction of two materials induces an electromotive force, thus causing a current to flow in the material [5]. This, along with thermoelectric effects as a whole, indicates that charge carriers are also able to act as heat carriers.

The Peltier effect is the inverse of the Seebeck effect. By applying a current over the junction of two materials, it is possible to induce a temperature gradient [5]. Due to Joule heating, the magnitude of this temperature gradient - especially when it comes to cooling effects - is dependent on the properties of the materials forming the junction. Often, this effect is best achieved by using p- and n-type semiconductors, as illustrated in Figure 4. From this diagram, it is clear to see that the current causes both electrons and holes to flow away from the junction, causing it to cool down while the ends of each material heats up. By configuring the way the p- and n-type materials are connected, it is thus possible to construct Peltier cells that produce a hot and cold side.

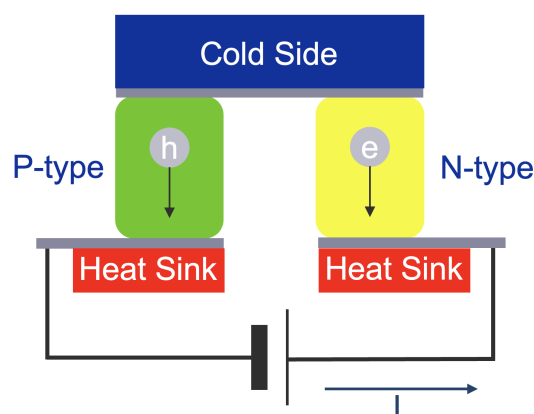


Figure 4: Diagram depicting the Peltier effect. A current running through a metallurgical junction between p- and n-type materials causes charge-carrying holes and electrons, respectively, to flow from one side of the Peltier cell to the other. The motion of the charge-carriers in turn carries heat between the two sides, cooling down one side and heating the other.

### 3.2 Experimental design

To thoroughly investigate the Peltier cell as a cooling mechanism, the experimental set-up shown in Figure 5 is used. Figure 5a is a picture of the components used to simulate the Pixel detector in Figure 2b. A heater with a power output that varies from 15 W to 20 W simulates the heat produced by the detector when in use. Five PT100 probes - platinum resistors with a known relationship between resistance and temperature - are placed in key locations across the device to measure the temperature evolution over time; for instance, one probe is on opposite side of the heater to monitor the temperature of the "detector" and two probes are used to measure the temperature of the hot and cold sides of the Peltier cell. Initially, two Peltier cells are placed side-by-side between the aluminum block and flange. The power supplies, vacuum chamber, and PLC used to read-out the PT100 probes via a WinCC program are shown in Figure 5b. PLC stands for Programmable Logic Controller and enables processes like measuring the resistance across a PT100 and converting it into a temperature to be automated and directly logged in a central database. A majority of the set-up is identical across all investigations performed, however the images in Figure 5 are representative of the set-up used while characterizing the Peltier and investigating fan cooling.

The resistance of the PT100 probes is measured using a 2-wire configuration, meaning that the resistance of the connecting wires introduces uncertainty into the measured value. By extension, this introduces an uncertainty in the temperature reported by the WinCC program. The resistance of the PT100 is governed by Equation 1.

$$R(T) = R_0 + kT, \quad (1)$$

where  $R_0 = 100 \, \Omega$ ,  $k = 0.385 \, \frac{\Omega}{^\circ\text{C}}$ , and temperature is expressed in  $^\circ\text{C}$ .

The resistance across the wires was found to be  $0.2 \, \Omega$ , which can be taken to be the uncertainty of the measured PT100 resistance. To find the uncertainty in calculated temperature, the equation must be rearranged in the following manner:

$$T = \frac{R(T) - R_0}{k},$$

$$\sigma_T = \frac{\partial T}{\partial R} \cdot \sigma_R,$$

$$\sigma_T = \frac{\sigma_{R(T)}}{k}.$$

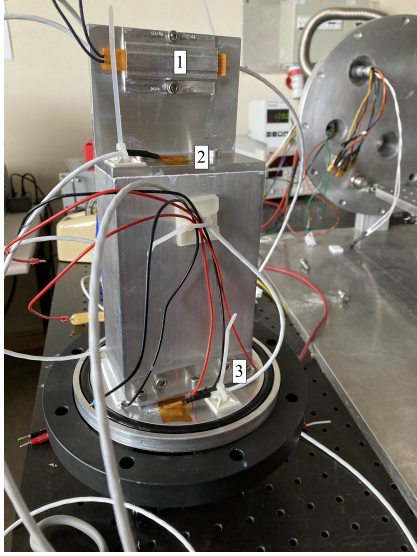
Plugging the values into the last line, it is found that

$$\sigma_T = \frac{0.2 \, \Omega}{0.385 \, \frac{\Omega}{^\circ\text{C}}},$$

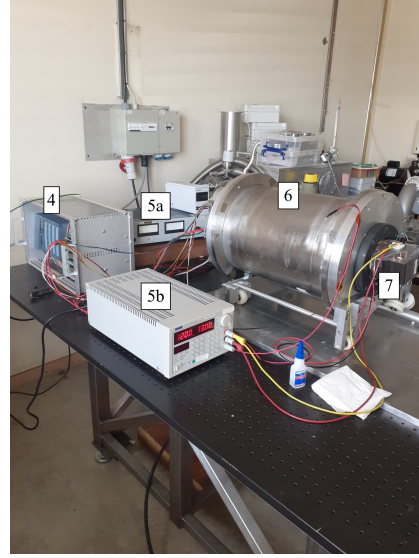
$$\sigma_T = 0.5 \, ^\circ\text{C}.$$

As only the first significant digit is meaningful, the uncertainty associated with the temperature calculated by the PLC is  $0.5 \, ^\circ\text{C}$ , and this value is used in all subsequent analysis.





(a) Series of aluminum blocks connected to vacuum flange and heater to simulate the detector. PT100 probes are attached across the entire piece to measure temperature evolution, and two Peltier cells are between the aluminum block and flange.



(b) An overview of the experimental set-up on VELO lab table, excluding the simulated detector.

Figure 5: List of components - 1) heater (15 W < P < 20 W); 2) PT100 Probe [one of five indicated]; 3) two Peltier cells; 4) PLC; 5a & 5b) power supplies; 6) vacuum chamber; 7) 12 V fan.

Data is collected by running a WinCC program that displays the PT100 readings plotted against current time while the Peltier is given a fixed voltage ranging from 5 V to 25 V in step sizes of 5 V. The system was allowed to evolve until all readings reached an approximately constant value or until the hot side of the Peltier started to approach 80 °C, which would damage the cell. When investigating external cooling methods, the heater and external cooling were turned on at the same time as the Peltier. Afterwards, the data was exported to a CSV file for further processing.

Despite the simulated detector containing two Peltier cells, only one was powered during data collection for Peltier characterization and fan cooling. Since the exterior of the Peltier cell is designed to be thermally conductive, it eventually became apparent that the presence of the second, unpowered Peltier allowed for thermal flowback. For reasons that will be discussed with the results of fan cooling, only Peltier characterization was revisited over a reduced voltage range, 10 V to 20 V, upon modifying the simulated detector to use only one Peltier cell.

### 3.2.1 Peltier characterization

Prior to applying active heating and cooling to the system, the behavior of the Peltier on its own was characterized. Primarily, this was done to verify the linear relationship between the difference in temperature on the hot and cold sides of the Peltier ( $\Delta T$ ) and the applied voltage ( $V_{app}$ ).

The relationship between  $\Delta T$  and  $V_{app}$  is plotted in Figure 6 for both the two Peltier, labelled Trial 1, and single Peltier, labelled Trial 2, configurations. As these relationships are anticipated to be linear, each dataset has a linear function fitted to it.

For Trial 1, the fitting routine produced the following function with an associated reduced chi-squared of 7.97:

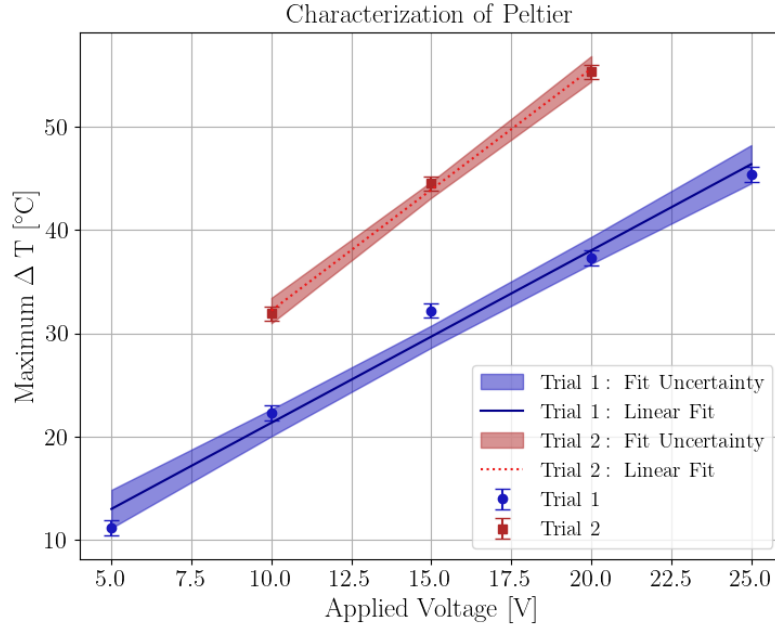


Figure 6: The maximum temperature between both sides of the Peltier cell plotted against the applied voltage. The dataset labelled Trial 1 was collected for the two Peltier configuration, in which only one was powered; the one labelled Trial 2 was collected for the single Peltier configuration.

$$\Delta T = (1.7 \pm 0.1 \text{ } ^\circ\text{C/V}) V_{\text{app}} + (5 \pm 2^\circ\text{C})$$

For Trial 2, the fitting routine produced the following function with an associated reduced chi-squared of 1.08:

$$\Delta T = (2.3 \pm 0.1 \text{ } ^\circ\text{C/V}) V_{\text{app}} + (9 \pm 2^\circ\text{C})$$

While it can be accomplished just as easily through visual inspection, the reduced chi-squared values indicate Trial 1 is not well-described by a linear function, suggesting a difference in Peltier behavior likely due to the presences thermal backflow or more generally that  $\Delta T$  behavior is not strictly linear with voltage.

Additionally, Figure 7 reinforces that the single Peltier configuration produces the best cooling effects as the minimum temperatures achieved by the cold side of the Peltier and the sensor in Trial 2 are roughly 10 °C lower than the temperatures in Trial 1. While it is sensible to conclude that the presence of a heat conductor in the temperature gradient produced by the Peltier would negatively impact the cooling achieved, these results indicate that additional voltage and external cooling would need to be supplied for this unfavorable situation to produce similar cooling results.



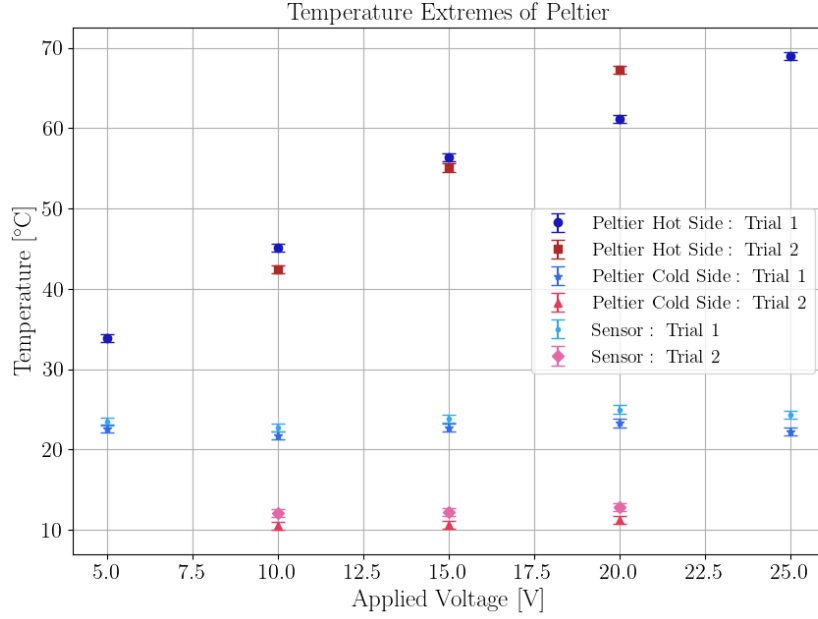


Figure 7: Comparison of the temperature extremes achieved by the Peltier cell at three positions in the experimental set-up plotted against the applied voltage. The dataset labelled Trial 1 was collected for the two Peltier configuration, in which only one was powered; the one labelled Trial 2 was collected for the single Peltier configuration.

### 3.2.2 Fan cooling

The fan used for these tests was a 12 V computer fan that blew air through dissipation layers. It is shown in Figure 8.

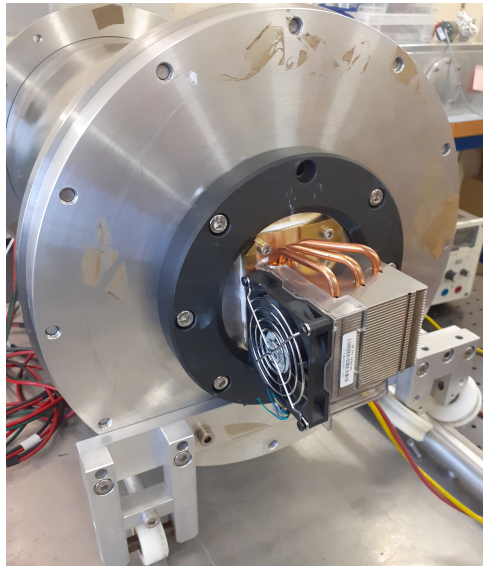


Figure 8: Image showing the fan screwed onto the flange of the vacuum chamber.

The temperature extremes achieved by a fan cooled Peltier are plotted in Figure 9. While the two

Peltier configuration renders the data for the sensor and cold side of the Peltier unusable, the maximum temperatures achieved by the hot side of the Peltier indicate that the 12 V fan is unable to adequately cool off the Peltier. Since the Peltier operates by creating a temperature gradient over itself and the surrounding material, it is essential for the hot side to remain cool to further decrease the temperature of the detector.

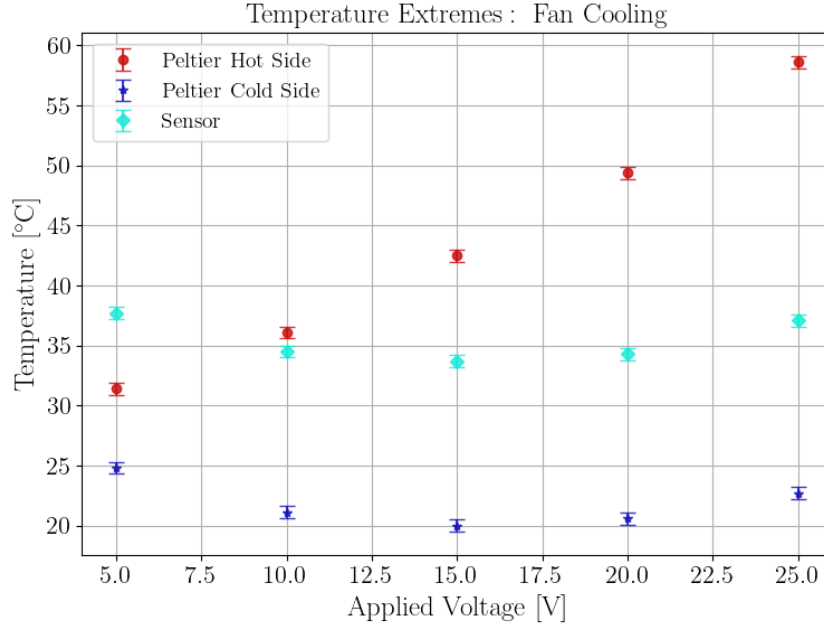


Figure 9: Temperature extremes achieved by the fan cooled Peltier cell with applied heating at three positions in the experimental set-up plotted against the applied voltage.

### 3.2.3 Water cooling

Water cooling was used on the Peltier by using a liquid cold plate connected to a water chiller. The set-up initially used is shown in Figure 10. Since TWOCRIST and ultimately ALADDIN are planned to be installed in the LHC's IR3, the water chiller was set to 27 °C to better simulate the water that would be available at that location [1].

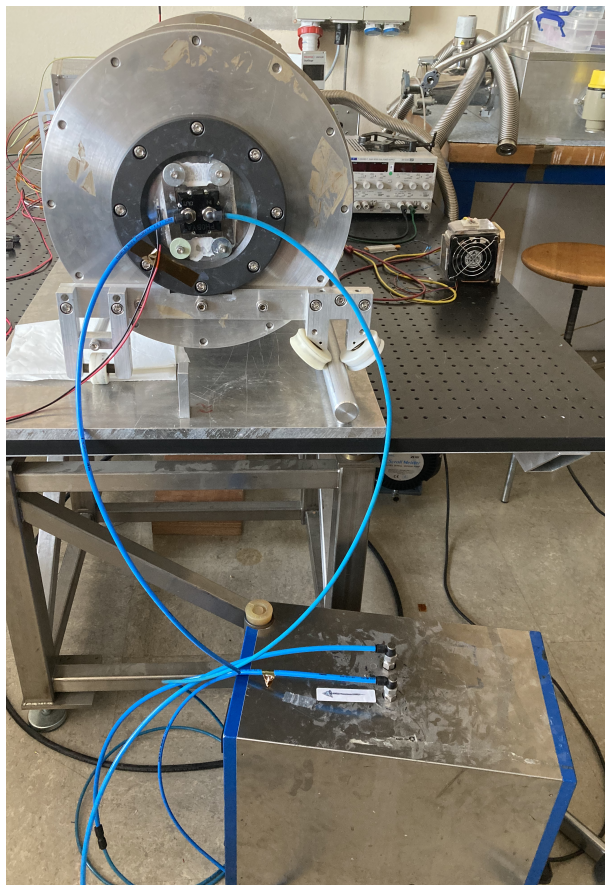


Figure 10: Image of the initial set-up used to investigate the effects of external water cooling, with the small cold plate held onto the flange and the water chiller on the floor.

Looking at the preliminary data, it became clear that the system was unable to achieve the desired temperature range on the sensor and even performed worse than fan cooling. This was likely caused by the mismatch in surface areas between the liquid cold plate ( $5 \times 5 \text{ cm}^2$ ) and Peltier cell ( $5.5 \times 5.5 \text{ cm}^2$ ) as this would prevent the efficient transfer of heat.

To remedy this issue, a larger liquid cold plate would need to be used. However the plate that was purchased for the TWOCRIST experiment was larger than the outermost flange, meaning that the set-up needed to be changed significantly to use it. The materials to construct a new, larger flange were not readily available, as such the possibility of running the experiments in air were considered. In order to validate the results of the in-air results, the temperature evolution of the small plate set-up system with both cooling and heating were compared for when vacuum was drawn in the vacuum chamber and when the chamber was filled with ambient air. The results of this comparison are shown in Figure 11. As the plots qualitatively look very similar, it was deemed that moving the simulated detector into air would be a fair approximation for the results achieved in vacuum.

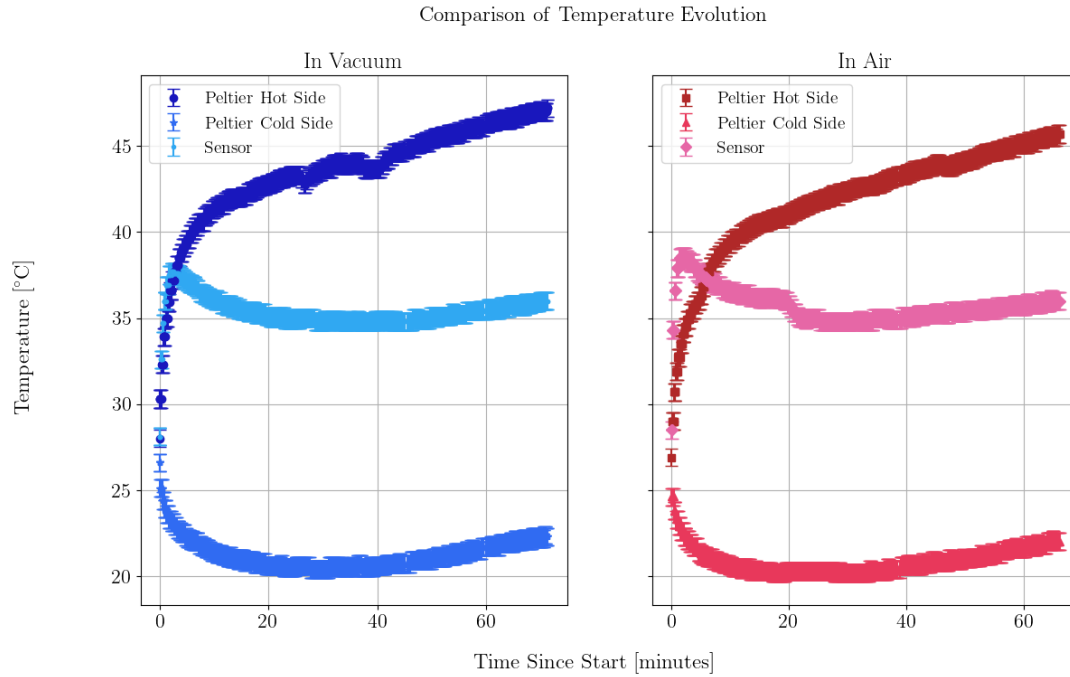


Figure 11: Side-by-side comparison of the temperature evolution of the water cooled (using the small water exchanger) Peltier with applied heating in vacuum, on the left, and in air, on the right. Qualitatively, the evolution is nearly identical for all points of interest.

The new set up and cold plate are shown in Figure 12. To ensure the simulated detector was as thermally isolated as possible, it was placed onto a piece of cardboard elevated from the lab's optical bench with a set of four screws. Clamps were used for stability and ensuring good thermal contact between the flange and cold plate, and small cardboard pieces were placed on the contact points with the flange.

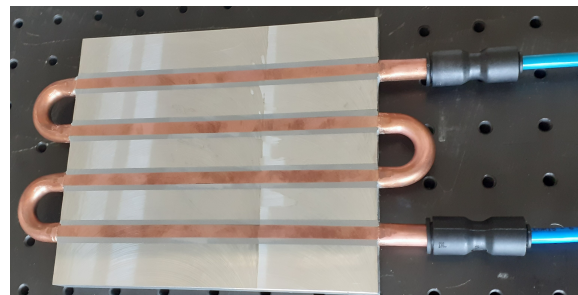
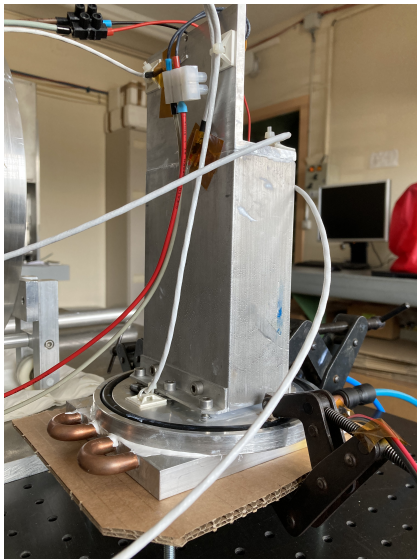


Figure 12: On the left, a simulated detector set up for in-air experiments. On the right, the liquid cold plate that was used in place of the smaller one to improve cooling results.

Overall, the Peltier cooling performed significantly better with water cooling than fan cooling, as shown in the temperature extremes in Figure 13. Once the Peltier is operated with a voltage  $\geq 15$  V, the sensor achieved the desired temperature  $< 30$  °C. However, it must be considered that the 15 W to 20 W range produced by the heater is on the lower range of the heat anticipated to be produced by the detector during operation.

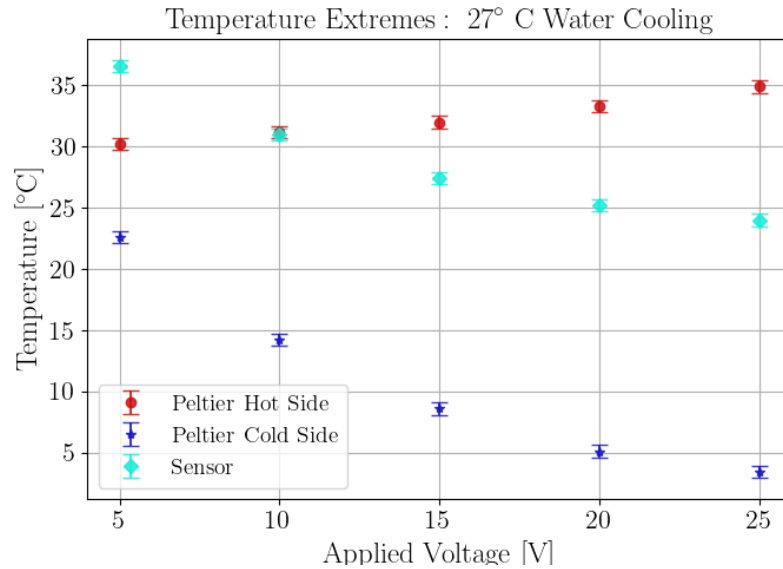
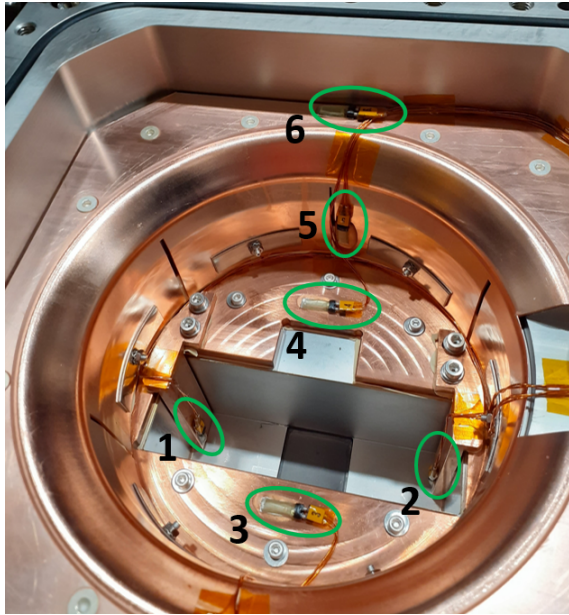


Figure 13: Temperature extremes achieved by the water cooled Peltier cell with applied heating at three positions in the experimental set-up plotted against the applied voltage.

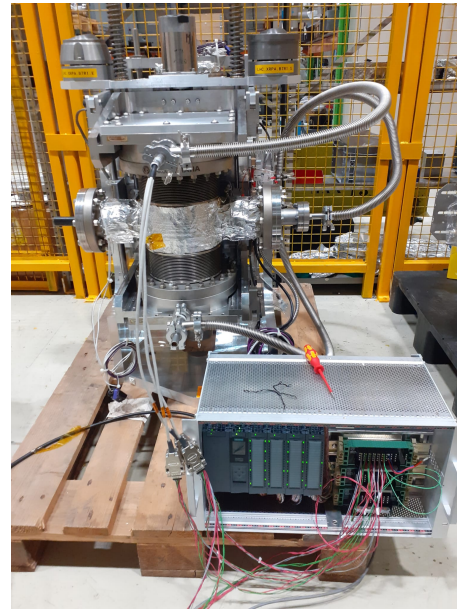
#### 4 Test of Temperature Sensors Inside the Roman Pots

The ALFA Roman pots already have six PT100 probes installed in each, as shown in Figure 14a. The primary concern was whether they could be properly read out with the PLC unit and vacuum feedthrough cable due to the non-trivial wiring configuration of the PT100 probes, as shown in Figure 15. Since the configuration necessitates a 4-wire resistance measurement for each PT100, it was unclear whether or not the PLC would be capable of such measurements, especially since the previous owners of the Roman pot did not use such a unit to read out the temperatures. Fortunately, it was found that this task is easily handled with a routine programmed in the PLC and should increase the accuracy of the measured temperatures. An image of the PLC connected to the Roman pot can be seen in Figure 14b.





(a) An image showing the location and labelling of all 6 PT100 probes in a Roman pot.



(b) Image showing the PLC connected to the ALFA Roman pot via a vacuum feed-through connector.

Figure 14: Images showing the set-up of the ALFA Roman pot, with the interior displayed in a) and the connection between PLC and Roman pot shown in b).

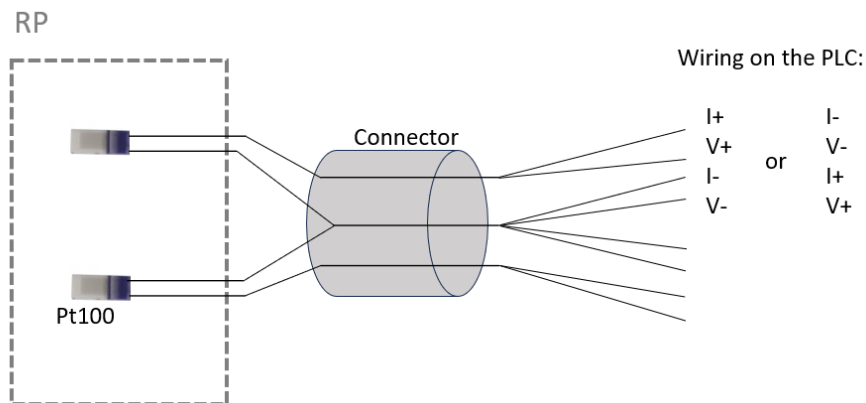


Figure 15: In this wiring configuration, two PT100 probes share a wire connecting to the exterior of the Roman pot (RP) while also having a wire of its own, meaning three wires are connected to two PT100 probes. To allow a temperature reading to be made, each solo wire is split into two wires and the shared wire is split into four (making eight wires total), which allows for the resistance of each PT100 to be measured using a 4-wire configuration.

It is anticipated that all PT100 probes in the ALFA Roman pot should all measure the same, or approximately the same, temperature. To confirm this, a panel was constructed in WinCC - Figure 16 - to provide in-real-time measurements of the temperature according to each of the PT100 probes in the Roman pot and one in-air to set a baseline temperature. As shown in Figure 16, all six PT100 probes measure approximately the same temperature of 28 °C, which is slightly colder than the ambient room

temperature; this is to be expected as the interior of the Roman pot is under vacuum. Working with the ALFA Roman pot indicated that the wires needed to be plugged into the PLC in a specific order, as shown in Figure 15. While the four shared wires can be distributed between their two corresponding PT100 probes in any manner, they must be plugged into both negative ports while the pair of wires leading to each individual PT100 must be plugged into the positive ports - or vice versa.

In the future, the possibility of changing the font color of the temperature read-out panels should be investigated to improve readability or alternatively a more contrasting background color should be used.



Figure 16: Screenshot of WinCC panel during connection to a Roman pot. The top half shows a plot of the change in temperature reading for all PT100 probes connected to the PLC (six probes in the Roman pot and one in the air), while the bottom half shows instantaneous temperature readings.

## 5 Findings and Future Work

Cables have been soldered to LV lines on board 2 to prepare for testing using a VELO sensor, thus allowing for the more meaningful verification that impedance of paired lines is within an operable range. As it was not possible to borrow a time-domain reflectometer, these impedance checks were impossible to make during board inspection. However, the inspections performed did indicate a uniformity in resistances and determined the quality of each board, still making them valuable to future work.

Exploration of the cooling capabilities of Peltier cells has indicated the viability of using external water cooling to support the Peltier's ability to lower the temperature of an active sensor to a range of  $< 30^{\circ}\text{C}$ . To prevent the heating of the Peltier's hot side from outpacing the water cooling, it would be best to operate the Peltier with a voltage between 15 V and 20 V. Additionally, the dangers of running two Peltier cells in parallel were unintentionally shown, as the failure of one Peltier would function analogously to introducing a thermal flowback channel into the system, frustrating the cooling efficiency

of the Peltier.

While work with the ALFA Roman pot was fairly limited over the course of this project, only happening for half of a week, it was verified that all PT100 probes already installed in the Roman pots were operable and checked the functionality of vacuum feedthrough cables to be used on the final TWO-CRYST experiment. Four of the five cables formed perfect connections for all eight lines, but the fifth was found to have a faulty pin that formed unstable connections to the PLC. As there are only four Roman pots, having just four cables is fine, and despite its issues, the faulty one will be kept as a spare.

To prepare the TWOCRYST experiment for its installation in LHC's IR3, significantly more work still must be done by the entirety of the collaboration. However, this work has helped verify the viability of the proposed Peltier cooling system that will ensure that the Pixel detector is able to function as designed.

## Acknowledgements

I would like to express my heartfelt thanks to Nicola Neri and Massimiliano Ferro-Luzzi for supervising me over the course of this program, as well as Federico Zangari and Sara Cesare for helping me with day-to-day activities. Additionally, I would like to thank Raphael Dumps and the VELO Collaboration - especially Morag Williams, Edgar Cid, and Federico De Benedetti - for supporting the progress of this experimental work. This opportunity would not have been possible without CERN and the University of Michigan, as well as funding by NSF Award #PHY-2243608.

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## Appendix

### A Vacuum feedthrough board diagram

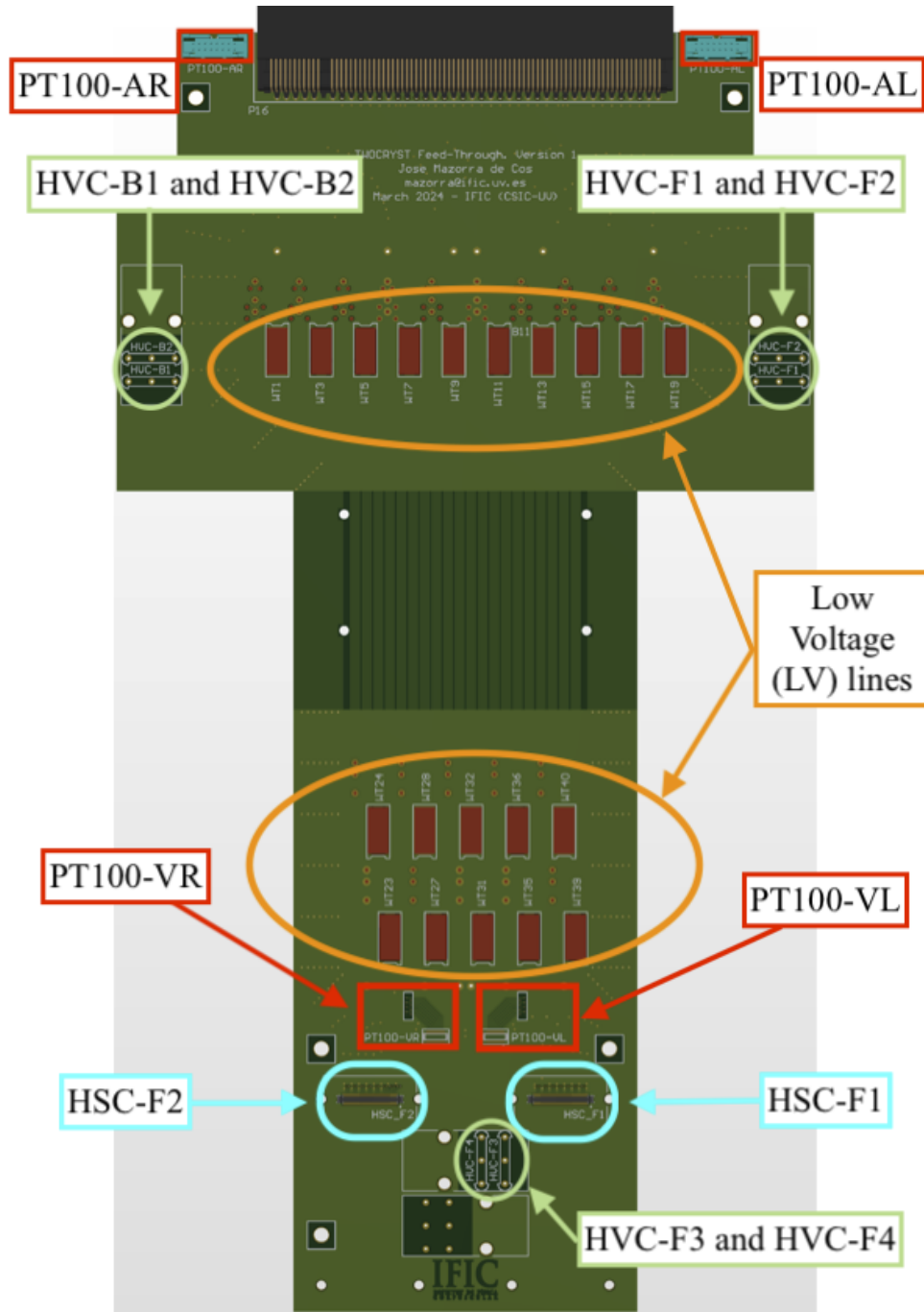


Figure A.1: Diagram of front of vacuum feedthrough board. The main connectors and terminals are highlighted.

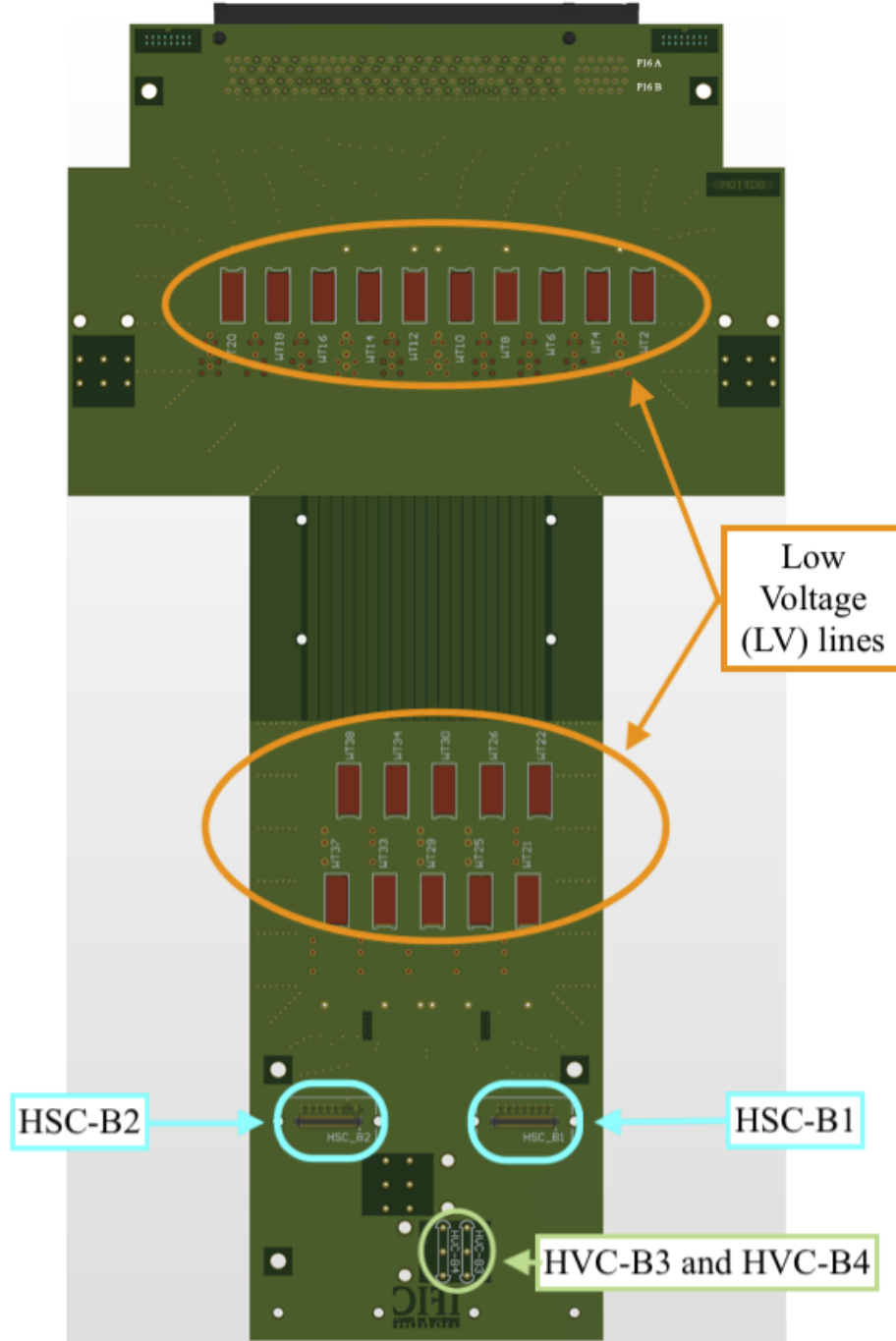


Figure A.2: Diagram of back of vacuum feedthrough board. The main connectors and terminals are highlighted.

## B Additional cooling figures

Though interesting to see, the plots in Figures B.1 and B.2 were not included in the sections about their respective cooling methods as they do not carry as much significance as the characterization plot for the Peltier on its own, shown in Figure 6. This is because the values of  $\Delta T$  are dependent on two other factors in addition to the voltage applied to the Peltier, being the heater and external cooling. While one might anticipate the contributions due these other factors to be a constant effect, it appears that they contribute to a more logarithmic shape to the plots, which is more prominent in Figure B.2. This suggests

a threshold of applied voltage beyond which the cooling efficiency starts to show diminishing returns. Such a conclusion can be seen in the temperature extreme plots, thus this particular plots were deemed redundant to include in the main paper.

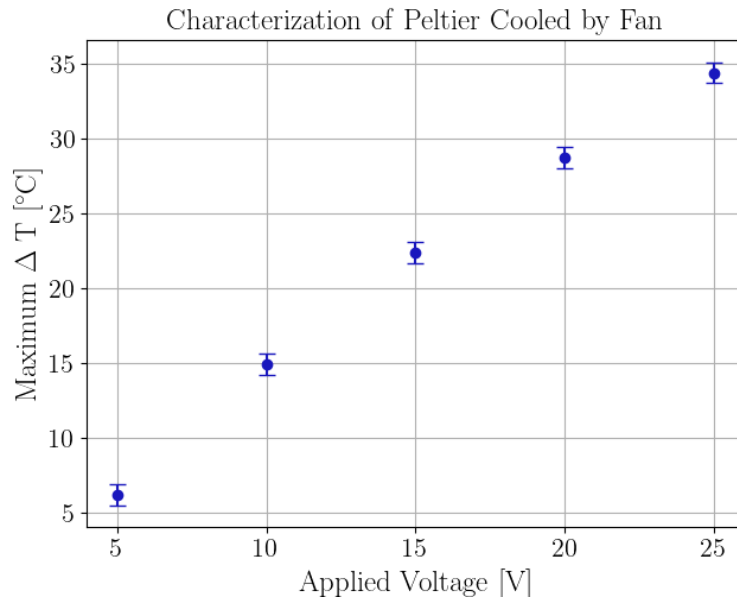


Figure B.1: Diagram of back of vacuum feedthrough board. The main connectors and terminals are highlighted.

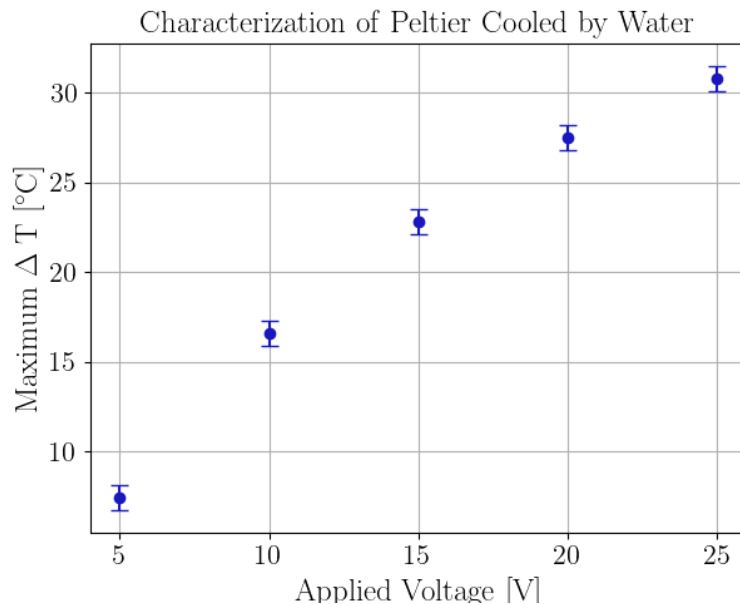


Figure B.2: Diagram of back of vacuum feedthrough board. The main connectors and terminals are highlighted.