

1 Milikelvin-precision temperature sensing for advanced
2 cryogenic detectors

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5 **Abstract**

Precise temperature monitoring —to the level of a few milli-Kelvin— is crucial for the operation of large-scale cryostats requiring a recirculation and purification system. In particular, the performance of Liquid Argon Time Projection Chambers —such as those planned for DUNE— heavily relies on proper argon purification and mixing, which can be characterized by a sufficiently dense grid of high-precision temperature probes. In this article, a novel technique for the cross-calibration of Resistance Temperature Detectors (RTDs) in cryogenic liquids (argon and nitrogen) is presented, obtaining an unprecedented precision of 2.5 mK.

6 *Keywords:* Detectors, Liquid Argon, Cryogenics, Temperature, RTD, Purity,
7 Computational Fluid Dynamics

8 **1. Introduction**

9 Precise temperature sensing is essential in large cryogenic detectors, where the circulation
10 and purification of cryogenic liquids can have a major impact on overall detector perfor-
11 mance. In these systems, uncontrolled temperature differences can modify the cryostat
12 dynamics, ultimately affecting the physics sensitivity of the experiment. In this work, we
13 present the calibration procedure of a novel temperature monitoring system developed
14 for a prototype of the future DUNE experiment.

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15 DUNE, which stands for Deep Underground Neutrino Experiment [2], is expected to
16 begin taking data towards the end of the decade. It aims at performing comprehensive
17 neutrino oscillation analyses,—broadly exploring the Charge-Parity violation parameters
18 phase-space and resolving the neutrino-mass hierarchy problem [6]. Its vast physics pro-
19 gram also includes searches for hypothetical proton decay channels [3], multi-messenger
20 astronomy from supernovae and neutrino bursts [8], and explorations of Beyond the
21 Standard Model (BSM) physics [7]. With the most powerful neutrino beam ever built,
22 produced at Fermilab, the experiment follows the long-baseline neutrino oscillations ap-
23 proach, with two detectors. The Near Detector, also at Fermilab, will characterize the
24 unoscillated neutrino beam. The Far Detector (FD), located in the Sandford Under-
25 ground Research Facility (SURF), 1300 away from the ND and 1.5 km underground, will
26 measure the oscillated flux.

27 DUNE phase I far detector will have two Liquid Argon Time Projection Chambers
28 (LArTPC), and is expected to operate by 2029. DUNE phase II will complement with two
29 more modules by mid 30's, aiming at a total fiducial mass of 40 kilotonnes. The detector
30 technology has been established, with excellent tracking and calorimetric capabilities,
31 in several smaller-scale experiments [10, 13]. The first demonstration of the technology
32 at the kilotonne scale has been carried out at the CERN Neutrino Platform as part of
33 the ProtoDUNE program. In particular, the ProtoDUNE-SP experiment [1] reproduced
34 the detector components of the second DUNE FD module [4] at a scale 1:1 with a total
35 argon mass 20 times smaller (770 tonnes). It was operated from mid-2018 to mid-2020,
36 constituting the largest monolithic LArTPC to be built and operated up to date [5, 9].

37 During ProtoDUNE-SP operation, the level of impurities was kept way below 100 ppt
38 oxygen equivalent using a cryogenic recirculation and purification system [1, 9]. This is
39 fundamental in a LArTPC, as the 3D images produced by charged particles traversing
40 the detector can be exponentially attenuated by medium impurities such as nitrogen,
41 oxygen and water, biasing the energy measurements by absorbing ionization electrons.
42 Three purity monitors, based on the ICARUS design [25], were installed outside the
43 active volume of the TPC to measure the electron lifetime, which is inversely related
44 to the residual concentration of impurities. They ran twice a day to monitor the argon
45 purity and thus to provide the necessary corrections for posterior data analysis.

Achieving the necessary argon purity has been possible thanks to the studies based on computational fluid dynamic (CFD) simulations, and the experience gained with previous LArTPC demonstrators such as LAPD [11] and the 35-tonne prototype [12, 18], which have paved the way to operate large-scale cryostats requiring low concentrations of impurities. These studies have also shown that it exists a strong correlation between temperature and purity in the liquid argon volume. The distribution of impurities is insensitive to small ($\mathcal{O} \sim 1$ K) absolute temperature variations, but strongly depends on the relative vertical temperature gradient. As the bulk volume in the cryostats needs to be continuously mixed with the incoming purified argon to ensure the purification of the whole LAr volume, the temperature distribution acts as a clear indicator of that mixing: a homogeneous temperature distribution indicates that the liquid is being properly mixed, whereas large temperature gradients constitute a clear symptom of deficient mixing. If the LAr bulk volume is not mixed properly, a stratification regime can develop: a significant portion of the liquid remains unpurified, generating ‘dead’ regions inside the detector. Hence, a constant monitoring of this temperature gradient can identify and mitigate potential failures of the purification system. In ProtoDUNE-SP, this gradient was predicted to be about 15 mK by the CFD simulations [1, 4].

The CFD simulations also predict, in spite of homogeneous mixing, that the concentration of impurities may also vary across the cryostat volume, requiring a position-dependent electron lifetime correction. The Purity Monitors themselves are intrusive objects which cannot be deployed inside the active volume, rather in only a few well-defined locations near the cryostat walls; thus, precise inference of the electron lifetime map requires alternative methods, as the one proposed in this article. A net of temperature sensors cross-calibrated to the <5 mK level should allow the measurement of a 15 mK temperature gradient, which can be used to constraint CFD simulations, providing a data-driven prediction of the impurity concentration. The main limitations of this new approach are the precision of the cross-calibration of the temperature sensors and the accuracy of the simulations. In this article, precise temperature monitoring for ProtoDUNE-SP will be described with particular emphasis on sensor calibration.

75 **2. The temperature monitoring system of ProtoDUNE-SP**

76 ProtoDUNE-SP [1] was the single-phase (SP) demonstrator of DUNE far detector second
77 module [4], currently known as Horizontal Drift (HD) module. The elements constitut-
78 ing the TPC, its associated readout electronics and the photon detection system, were
79 housed in a 8x8x8 m³ cryostat that contained the LAr target material. The cryostat,
80 a free-standing steel-framed vessel with an insulated double membrane, is based on the
81 technology used for liquefied natural gas storage and transport. A cryogenic system main-
82 tains the LAr at a stable temperature of about 87 K, and ensures the required purity
83 level by means of a closed-loop process that recovers the evaporated argon, recondenses
84 it, filters it, and returns it to the cryostat, keeping the LAr level at about 7.3 m from the
85 bottom membrane. ProtoDUNE-SP was exposed to a charged particle test-beam from
86 October to November 2018, and later recorded cosmic rays until January 2020 [5, 9]. It
87 was finally emptied and decommissioned in Summer 2020.

88 In order to understand the LAr behaviour inside the cryostat and validate the CFD
89 simulations, 92 high-precision temperature sensors were installed inside ProtoDUNE-
90 SP, near the active volume. These sensors were distributed in two vertical arrays, or
91 Temperature Gradient Monitors (TGM), and two horizontal grids below and above the
92 TPC, respectively. Three elements were common to all systems: sensors, cables and
93 readout electronics. RTD technology [22] was chosen for this application. It consists of a
94 metallic element whose resistance changes with temperature. This resistance is measured
95 by feeding the RTD with a known current and measuring the resulting voltage. Based
96 on previous experience from other prototypes [12], Lake Shore PT102 platinum sensors
97 [21] with 100 ohms resistance at room temperature were chosen. Sensors were mounted
98 on a 52x14 mm² PCB with an IDC-4 connector, such that they could be plugged-in at
99 any time. Several versions of the PCB have been explored, finally converging to the one
100 shown in Fig. 1, which minimizes the contact of the sensor with the PCB while keeping
101 the sensor protected.

102 A careful choice of the readout cable and the connections are essential to obtain the
103 required temperature precision. See for example [22] for a detailed description. A custom
104 cable made by Axon [14] was used. It consists of four American Wire Gauge (AWG) 28
105 teflon-jacketed copper wires, forming two twisted pairs, with a metallic external shield

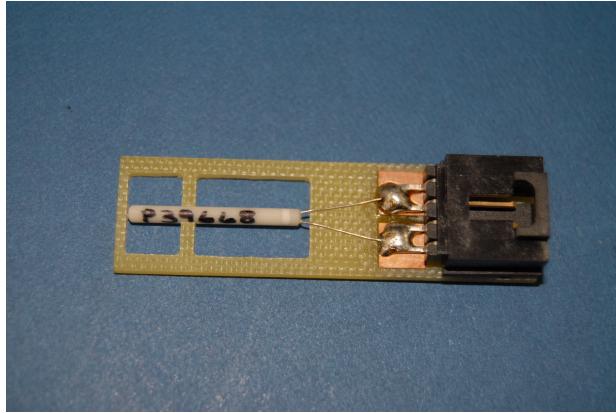


Figure 1: PCB support with temperature sensor and IDC-4 connector. The transition from two wires at the sensor to 4 wires at the readout is clearly seen. The sensor has a length of 2 cm.

and an outer teflon jacket. The outer diameter of the cable is 3.7 mm. Teflon was chosen for its good thermal properties and low out-gassing. The metallic external shield (connected to the readout in one end and left floating at the sensor's end) and the twisted pairs are crucial to reduce the effect of external electromagnetic noise pickup. When RTDs are far from the voltmeter, the resistance of cables and connectors are added to the one of the sensor, biasing the temperature measurement. This bias can be subtracted to some level, but cannot be fully controlled since the resistance of those elements also depends on temperature. To minimise the impact of this effect a four wire readout is introduced [22], such that the voltage is measured in the vicinity of the RTD.

The last common element is the readout system, consisting of a very precise 1 mA current source to excite the sensors and a 24 bits ADC to measure the voltage. The readout system will be described in detail in section 3.

As previously mentioned, ProtoDUNE-SP CFD simulations predict vertical temperature gradients as low as 15 mK [1]. A relative precision better than 5 mK was required to validate and tune those simulations with sufficient confidence. Three main ingredients are necessary to obtain such a precision: i) high quality and stable temperature probes, ii) a very precise readout system, and iii) a precise calibration, both for the readout and the sensors. As mentioned above, two TGMs were deployed in ProtoDUNE-SP: one could be moved vertically and hence calibrated *in situ*, while the other one —static—

125 fully relied on a prior calibration in the laboratory. In this article, the calibration of the
126 static TGM [17] sensors is described in detail. This device consists of a vertical array
127 of 48 sensors, installed 20 cm away from the lateral field cage.

128 The calibration was performed once in spring 2018 (a few months before the operation
129 of ProtoDUNE-SP), and several times after ProtoDUNE-SP decommissioning. In this
130 article the calibration setup, procedure and results will be described in detail. Compar-
131 ison between the different calibration campaigns will be addressed, revealing important
132 information about systematic uncertainties and RTD ageing.

133 **3. Readout system**

134 A precise and stable electronic readout system is needed to achieve the required precision.
135 In previous versions of the calibration system, each sensor was connected to a different
136 and independent electronic circuit and thus, fed by a different current and read by a
137 different ADC channel. It was soon realized that the measured temperature difference
138 between any two pairs of sensors was heavily affected by the electronic offset between
139 channels. This offset was not constant, and showed dependence on ambient temperature
140 and humidity, which affected both the current source and the ADC, generating variations
141 of tens of mK for the measurement of a single calibration constant between sensors. A
142 variant of an existing mass PT100 temperature readout system developed at CERN for
143 one of the LHC experiments [16] was adapted to solve this problem. The system consists
144 of an electronic circuit that includes:

- 145 • A precise and accurate 1 mA current source for the excitation of the temperature
146 sensors based on an application of the Texas Instruments precise voltage reference
147 REF102CU with a possibility to adjust $\pm 10\text{nA}$ with Keithley 2001 multimeter
148 [15, 23].
- 149 • A multiplexing circuit based on the Analog Devices ADG1407BRUZ multiplexer
150 with ultralow internal resistance in an 8-channel differential configuration. The
151 readout circuit contains three multiplexers, providing a readout capacity of 24
152 channels. The multiplexing circuit and the current sourced are realised in a single
153 card (see Fig. 2).

- 154 ● A readout system based on National Instruments Compact RIO-FPGA device [19]
 155 equipped with a NI-9238 analogue input module that provide 24 bits of resolution
 156 over 1 volt range [20]. By programming the Van Dusen equation the readout
 157 calculates the temperature in Kelvin units. The Compact RIO also drives the
 158 control bits of the multiplexers

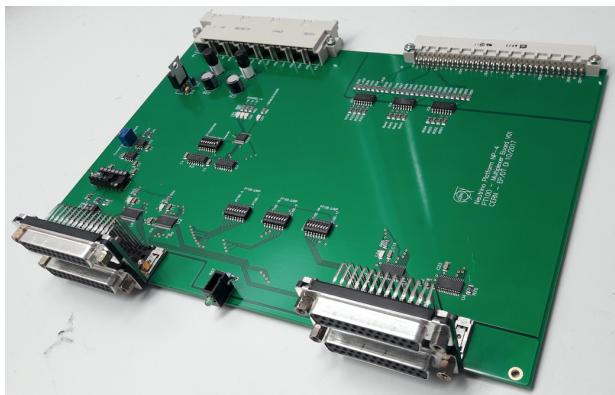


Figure 2: Current source and multiplexing card with 24 channels.

159 One of the features of the readout circuit is the serialization of the current source exci-
 160 tation for all the sensors connected to the same board, such that the same 1 mA current
 161 is delivered to all of them. Multiplexing the signal of the sensors such that they can be
 162 readout by the same ADC channel minimises the residual offset due to the electronics.
 163 This system was used during the calibration campaigns presented in this article and also
 164 for the temperature measurements during ProtoDUNE-SP operation.

165 The readout was not considered a potential source of bias during the calibration
 166 campaign prior to the installation in ProtoDUNE-SP (see Sec. 4) and it was not stud-
 167 ied in detail at that time. However, aiming to improve the calibration results after
 168 ProtoDUNE-SP operation, a more thoughtful study of the readout was performed before
 169 the calibration campaigns presented in Sec. 5. In particular, the twelve channels (7-18)
 170 used for sensor calibration were investigated. It was found that, despite the multiplexing
 171 system, a small residual offset between channels still exists. Fig. 3 shows the offsets of
 172 channels 8-18 with respect to channel 7, computed using twelve 20 ohms low Temperature

173 Coefficient of Resistance (TCR)³ precision resistors, with an equivalent temperature of
 174 76 K. Two of those, High Precision 1 (HP1) and High Precision 2 (HP2), are selected as
 175 the measurement samples and connected to the reference channel (7) and the channel be-
 176 ing calibrated (from 8-18), while leaving all other channels connected to other secondary
 177 resistors to let the current flow through the system. The readout offset between chan-
 178 nel 7 and channel X, $\Delta T_{7-X}^{readout}$, is then computed using the results of two consecutive
 179 measurements:

- 180 1. HP1 in channel 7 and HP2 in the channel X being calibrated. The offset between
 181 the measured temperatures is

$$\Delta T_{7-X}^A = T_X^{HP2} - T_7^{HP1} + \Delta T_{7-X}^{readout}. \quad (1)$$

- 182 2. HP2 channel 7 and HP1 in the channel X being calibrated. The offset between the
 183 measured temperatures is

$$\Delta T_{X-7}^B = T_X^{HP1} - T_7^{HP2} + \Delta T_{7-X}^{readout}. \quad (2)$$

184 Because of the very low TCR of the resistors, it can be assumed that the resistances
 185 are constants in those two measurements ($T_7^{HP1} = T_X^{HP1}$ and $T_7^{HP2} = T_X^{HP2}$). Thus,
 186 the offset between channels 7 and X can be computed as the average between those two
 187 measurements:

$$\Delta T_{7-X}^{readout} = \frac{\Delta T_{7-X}^A + \Delta T_{X-7}^B}{2}. \quad (3)$$

188 The results in Fig. 3, show an offset of up to 2.5 mK when comparing directly with
 189 channel 7, while the offset between any other two channels is below 1 mK, indicating that
 190 there is something special about the first channel being readout. Error bars in that figure
 191 correspond to the standard deviation of four independent measurements (repeatability)
 192 of the same offset (see Fig. 3). As it can be observed the error is below 0.5 mK, what
 193 probes the great repeatability of the readout. These offsets are more likely due to parasitic

³The temperature coefficient of resistance is defined as the change in resistance per unit resistance per degree rise in temperature. Typically $\pm 5\text{ppm}/^\circ\text{C}$.

resistances in the different lines that are multiplexed. This finding allowed a correction to the measurements taken during the subsequent calibration campaigns, improving the obtained precision.

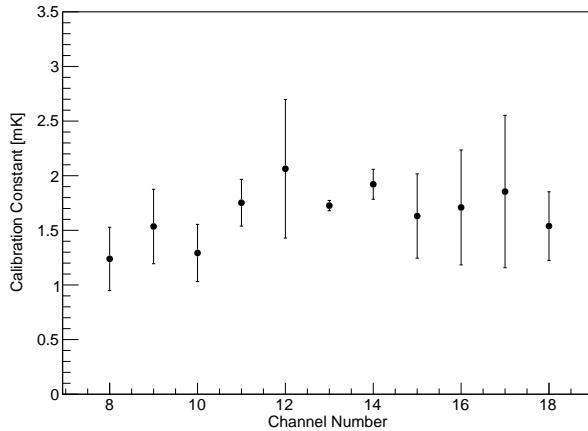


Figure 3: Offset between readout channels 8-18 and channel 7, used as reference. Points correspond to the mean of the 4 independent measurements and the error bars are their RMS.

4. Calibration before the installation in ProtoDUNE-SP

The Lake Shore Cryotronics company provides PT102 RTDs with a temperature reading dispersion of about 0.1 K, which is insufficient for ProtoDUNE-SP's requirements. While the company offers additional calibration to the 10 mK level, the cost is prohibitive. R&D on sensor calibration was identified as a crucial ingredient for the success of the ProtoDUNE-SP temperature monitoring system. For this particular application, sensor calibration consists in finding the temperature offsets between any pair of sensors when exposing them to the same temperature. The experimental setup used for the calibration of RTDs before their installation in ProtoDUNE-SP had two main components: i) the readout system used to monitor the sensor's temperature (described in the previous section) and ii) the cryogenics vessel and the associated mechanical elements used to put sensors together under stable cryogenics conditions. They were developed to achieve a relative calibration with a precision better than 5 mK.

210 *4.1. Experimental setup*

211 The mechanics of the calibration setup evolved considerably since the initial tests until
212 the final Static TGM calibration. Offset stability and repeatability drove this evolution.
213 The final setup (see Fig. 4) consisted of the following elements:

- 214 • A polystyrene vessel formed by an outer box with dimensions $35 \times 35 \times 30 \text{ cm}^3$ and
215 4.5 cm thick walls, and a dedicated polystyrene cover, complemented by extruded
216 polystyrene panels glued into the inner walls and floor of the outer box, to conform
217 an inner empty volume of $10 \times 10 \times 20 \text{ cm}^3$.
- 218 • A $10 \times 10 \times 20 \text{ cm}^3$ 3D printed polylactic acid (PLA) box with two independent con-
219 centric volumes, placed in the inner volume of the polystyrene vessel. Its purpose
220 is twofold: i) to contain LAr, since polystyrene is porous to it, and ii) to create an
221 smaller inner volume with further insulation and less convection.
- 222 • A cylindrical aluminum capsule, to be placed in the inner volume of the PLA box,
223 with 5 cm diameter, 12 cm height and 1 mm thin walls. It had a circular aluminum
224 cover with a small opening to extract the cables and to allow LAr to penetrate
225 inside. The capsule was used to slowly bring sensors to cryogenic temperatures by
226 partial immersion in LAr with no liquid inside, minimizing thermal stress. Alu-
227 minum was chosen for its high thermal conductivity.
- 228 • A 3D printed PLA support for four sensors, to be placed inside the aluminum
229 capsule, keeping sensors always in the same position with respect to each other and
230 to the capsule walls.

231 The system described above provides stable conditions in the inner volume, with
232 three levels of insulation: the outer polystyrene vessel and two PLA box LAr volumes.
233 The aluminium capsule is key to this system and its usage constituted a turning point in
234 the R&D since it minimises thermal shocks, which were identified as the main limiting
235 factor for the repeatability of the sensor's offsets. Indeed, variations of several tenths
236 of mK were observed in initial tests without the capsule. The problem was attributed
237 to thermal shocks when, after many immersions in LN₂, one of the sensors suffered a
238 dramatic change in its offset (see Fig. 5). Examination at the microscope revealed cracks
239 in the outer RTD ceramics (see Fig. 6).



Figure 4: Final calibration setup. Left: polystyrene box with PLA box and aluminum capsule. Middle: aluminum capsule. Right: Sensor's support with four sensors.

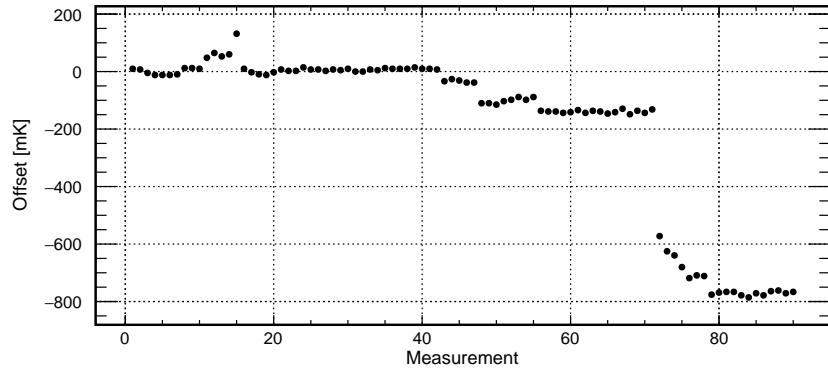


Figure 5: Offset between two sensors for 90 immersions in LN₂. A drop of 800 mK is observed.

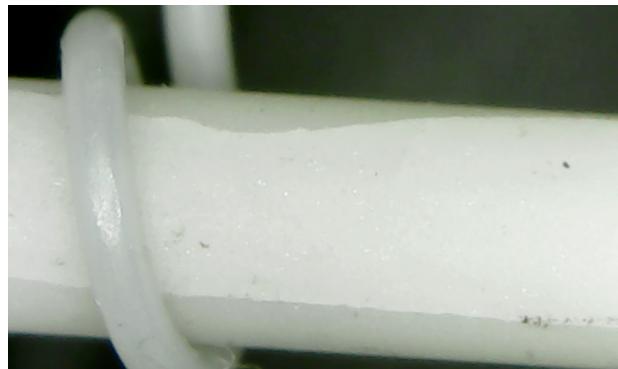


Figure 6: Cracks observed with the microscope in the ceramic of the sensor.

240 4.2. Calibration procedure

241 The calibration procedure relies on the assumption that all sensors in the capsule are at
 242 the same temperature. This limits the number of RTDs in a single run to four, since
 243 i) they should be as close as possible to each other and ii) as far as possible from the
 244 capsule walls (the sensor closer to the wall could be biased). Two different methods,
 245 described schematically in Fig. 7, were used to cross-calibrate all 48 sensors in runs of 4
 246 sensors:

- 247 1. **Reference method:** all sensors are calibrated with respect to a reference one, in
248 sets of three sensors (the fourth one would be the reference sensor, which must be
249 present in all runs). In total there are sixteen calibration sets.

250 2. **Tree method:** Four different sets of sensors can be cross-calibrated by performing
251 a second round of measurements with a single promoted sensor from each of those
252 four sets. Since there are 16 sets in total, a third round of measurement is needed
253 to cross-calibrate the four sets in the second round.

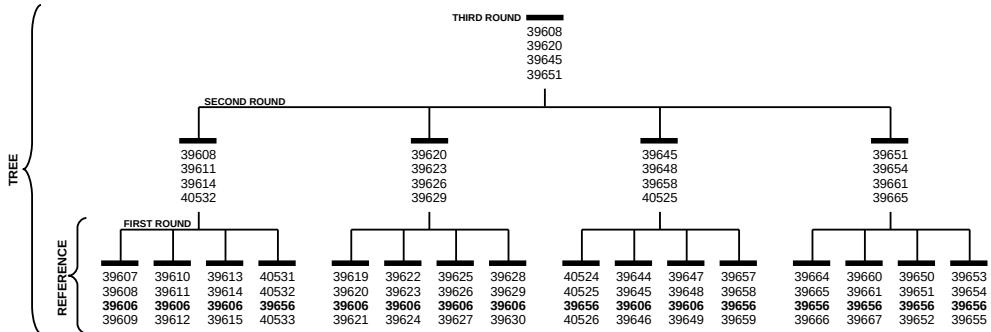


Figure 7: Schematic view of calibration sequence. Each number represents a different RTD, and the numbers in bold represent the reference sensors. The first round consists on a direct calibration respect to a reference sensor. The second and third rounds are needed to relate all sensors independently of the reference sensor.

The reference method was expected to be more precise since any two sensors were related through a single intermediate sensor (the reference one), while for the tree method the relation between any two sensors required more than one intermediate sensor. For example, the offset between sensors i and j in different sets, related through sensors k and l in the second round, would be $\Delta T_{ij} = \Delta T_{ik} + \Delta T_{kl} + \Delta T_{lj}$. For sensors related

259 through the third round an additional term should be added, further increasing the offset
260 uncertainty.

261 Offset repeatability is one of the key parameters to be understood since the laboratory
262 calibration must be applicable to the real detector. This was studied by performing four
263 independent calibration runs for each set of four sensors. However, because thermal
264 fatigue of the reference sensor (64 thermal cycles for 4 repeatability runs) was a strong
265 concern, three secondary reference sensors were used to regularly monitor the response
266 of the primary reference sensor.

267 The following procedure is applied for each set of four sensors. First, they are placed
268 inside the aluminium capsule. The sensor with the highest serial number is placed in the
269 orange connector, and the one with the lowest in the red. The central connector closer to
270 the red one is used for the reference sensor. These positions are easily called by numbers
271 from 1 (orange) to 4 (red), as shown in Fig. 8-left.

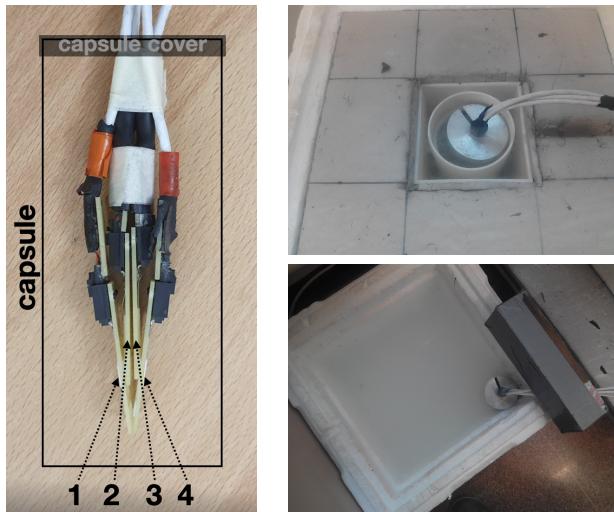


Figure 8: Left: Picture of sensor order inside the flask. Position 1 corresponds to highest serial number and 4 to lowest; position 3 is reserved to reference sensor. Top: Flask partially introduced in LAr. Bottom: Flask partially introduced in room water to warm up sensors before performing a new measurement.

272 After filling the PLA box with LAr, the aluminum capsule is partially immersed (see
273 Fig. 8-right-top) such that the air inside cools-down slowly, avoiding direct exposure
274 of the sensors to LAr, which would result in a thermal shock. When the monitored
275 temperature approaches the one of LAr (< 95 K), which takes about 15 minutes, the

276 capsule is completely immersed, being filled with liquid. The PLA box is then completely
 277 filled with LAr to account for evaporation during the cool-down phase. Finally, the
 278 polystyrene vessel is closed using the polystyrene lid. The actual calibration runs for
 279 forty minutes.

280 When the measurement is finished, the capsule is extracted from the liquid, emptied
 281 of LAr and partially immersed into another polystyrene box filled with water at room
 282 temperature (see Fig. 8-right-bottom). The warm-up process takes about ten minutes.
 283 When sensors have reached a temperature around 250 K a new independent measurement
 284 can start.

285 Fig. 9 shows the typical evolution of the temperature for the four sensors in the capsule
 286 during the warm-up and cool-down processes. A sudden fall to 87 K is observed at about
 287 1950 seconds, which corresponds to total immersion of the sensors in LAr. Notice also
 288 that two of the sensors have lower temperature during the cool-down process; those are
 289 sensors 1 and 4, the ones closer to the capsule walls.

290 For each set of sensors the procedure described above is repeated four times, resulting
 291 in four independent measurements of the same offset. These measurements are used to
 292 compute a mean offset value and its standard deviation (repeatability from now on).

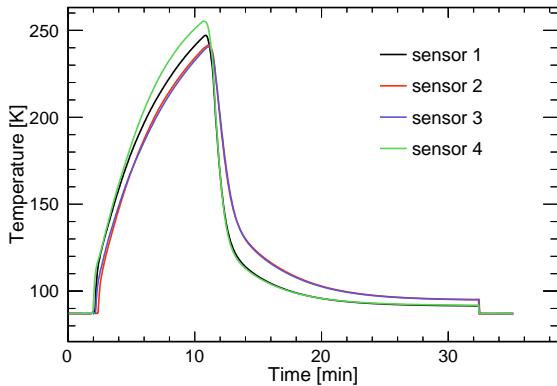


Figure 9: Temperature evolution during the warm-up and cool-down processes between two consecutive runs.

293 *4.3. Calibration results*

294 Here we present the results of the calibration using both calibration methods, a study of
 295 the consistency of these results, and a preliminary estimation of the systematic uncer-

296 tainty of the calibration process.

297 *4.3.1. Results on the first round of measurements*

298 Fig. 10 shows the offset of three different sensors with respect to the reference sensor as
299 a function of time, and for four independent calibration runs. The offset is more stable
300 for the sensor closer to the reference (position 2), while external sensors (positions 1
301 and 4) have larger variations, but present similar patterns between them. This effect
302 is attributed to the geometry of the system, with sensors at different heights and not
303 symmetrically positioned with respect to the capsule walls, and was taken into account
304 when developing the second version of the system, presented in Sec. 5.

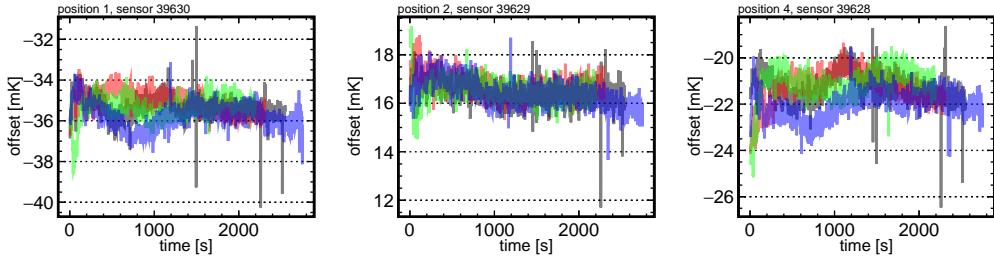


Figure 10: Offset between the reference sensor and each of the three sensors in a set, as a function of time. Each colour represents an independent measurement.

305 The mean offset for each sensor and each calibration run is computed as the average
306 in the time range between 1000 and 2000 seconds, found to be the most stable region
307 for most sensors. The standard deviation of the four measurements is taken as the
308 uncertainty, also referred from now on as repeatability. As shown in Fig. 11, uncertainties
309 are in general below 1 mK, demonstrating the great level of repeatability achieved.

310 *4.3.2. Time walk correction for reference sensors*

311 Time evolution of the response of sensor 39606 was studied by periodically (every \sim 20 im-
312 mersions) computing its offset with respect to three secondary reference sensors, 39603,
313 39604 and 39605. For each of those additional calibrations, two runs were taken in-
314 stead of four in order to minimize thermal fatigue of the reference sensor. As shown
315 in Fig. 12-left, the offset, computed as the mean of those two runs, varies linearly at a
316 rate of 0.07 mK/immersion, which suddenly increases to 0.22 mK/immersion after 60
317 runs. This change in the slope may be related with the frequency of immersions, which

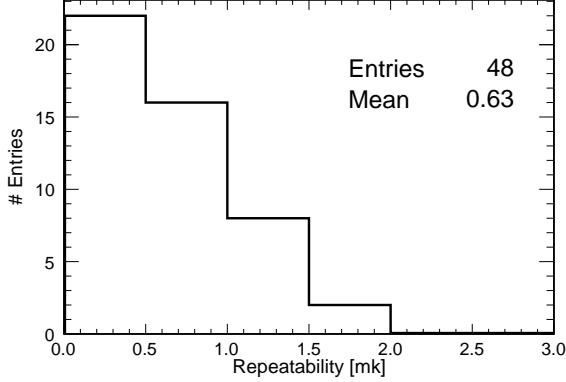


Figure 11: Distribution of the repeatability for calibration runs in the first round.

increased from 3/day to 5/day. Sensor 39606 was initially used for other purposes, and the calibration of the 48 sensors conforming the static TGM started approximately at immersion 40. Given this change in its response, sensor 39606 was substituted by 39656 as primary reference for the last quarter of the TGM calibration in order to avoid further fatigue and potential untraceable behaviour. The evolution of the new reference sensor is shown in Fig. 12-right. It is worth noting that the same slopes are valid for the three secondary reference sensors in both cases, supporting the idea that the change observed in the offsets can be exclusively attributed to thermal fatigue of the reference sensor.

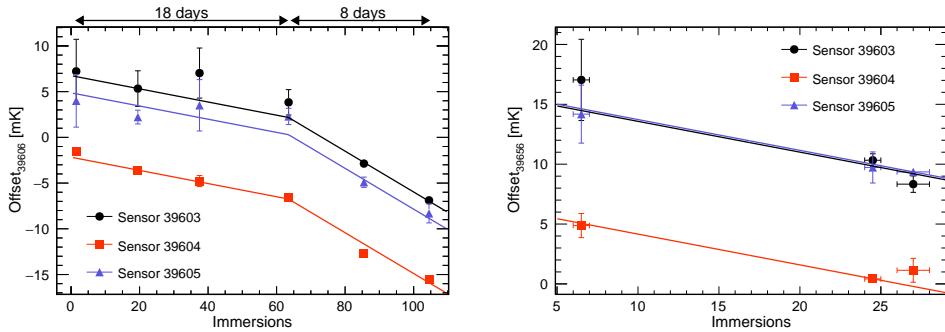


Figure 12: Offset between the reference sensors (39606 on the left panel and 39656 on the right panel) and the three secondary references as a function of the number of immersions. Offsets for sensor 39604 have smaller errors because of its position inside the capsule. Solid lines correspond to the parametrization in Eq. 4.

The zero intercept in both panels of Fig. 12 corresponds to the unbiased offset (or the

327 offset at $N_{inmersion} = 0$) of each of the secondary reference sensors with respect to the
 328 primary reference. In order to compute the unbiased offset for a sensor s , a time walk
 329 correction after N immersions is calculated as

$$\Delta T_{s,06}(N=0) = \begin{cases} \Delta T_{s,06}(N) + (0.072 \pm 0.003) * N & N < 63.5 \\ \Delta T_{s,06}(N) + (0.072 \pm 0.003) * 63.5 + \\ \quad +(0.223 \pm 0.007) * (N - 63.5) & N > 63.5, \end{cases} \quad (4)$$

$$\Delta T_{s,56}(N=0) = \Delta T_{s,56}(N) + (0.168 \pm 0.007) * N. \quad (5)$$

330 All sensors can be related to the same primary reference sensor, 39606, adding the
 331 unbiased offset between sensors 39606 and 39656, $\Delta T_{56,06}(N=0)$, to sensors calibrated
 332 with respect to 39656. By averaging over the three secondary reference sensors, the value
 333 obtained is $\Delta T_{56,06}(N=0) = -9.19 \pm 0.13$ mK.

334 4.3.3. Results on the reference method

335 Fig. 13 shows the offset of all sensors with respect to the 39606 reference. As it can
 336 be noticed, the dispersion of the offsets is compatible with 0.1 K, the value quoted by
 337 the vendor. Fig. 14-left shows the distribution of the repeatability of the computed
 338 calibration constants after applying the different corrections, showing an average value
 339 below 1 mK.

340 4.3.4. Results on the tree method

341 The offsets are computed in this case with respect to an arbitrary reference among
 342 all sensors being calibrated. Selecting as reference a sensor present in the third round
 343 (see Fig. 7) minimises the number of operations to compute the offset, and hence the
 344 uncertainty when computing the offset. Sensor 39645 was chosen as reference. Fig. 14-
 345 right shows the distribution of the repeatability of the computed calibration constants,
 346 the mean of which is slightly below the one obtained for the reference method. Thus,
 347 it is confirmed that despite the higher number of intermediate sensors to relate any two
 348 sensors, the additional uncertainty introduced by the time walk correction makes the
 349 tree method superior to the reference method. Moreover, the reference method suffers a
 350 —not yet known— systematic error associated to the time wall correction model.

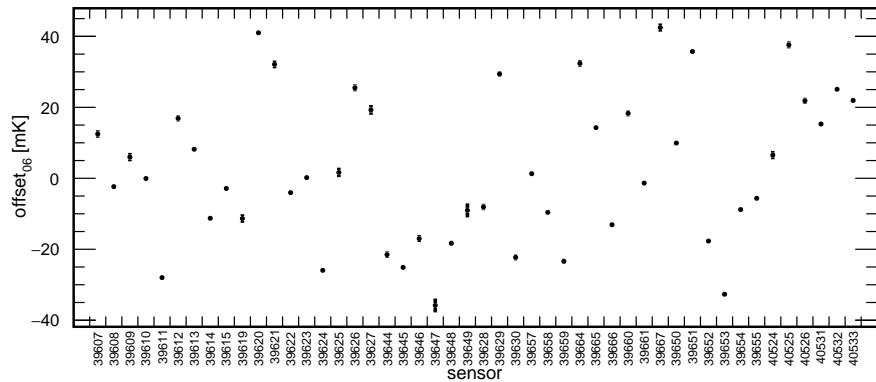


Figure 13: Offset of each sensor with respect to reference sensor 39606 using the reference method.

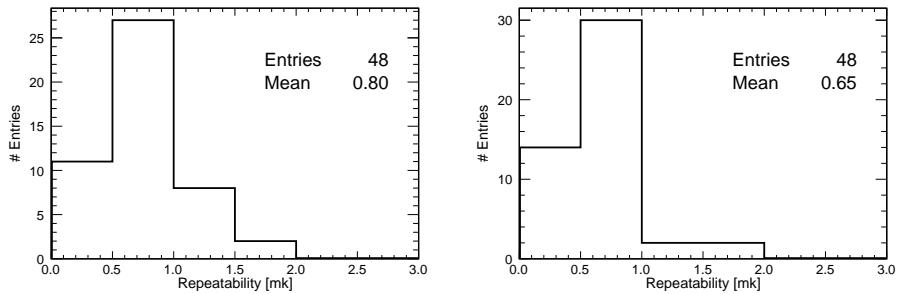


Figure 14: Left: repeatability distribution for the reference method. Right: repeatability distribution for tree method.

351 4.3.5. *Consistency cross-check and error estimation*

352 The uncertainties presented so far are in general below 1 mK, and they correspond to
353 the standard deviation of the four independent measurements of each calibration con-
354 stant plus the error propagation associated to the required corrections (time-walk for
355 the reference method, addition of calibration constants for the tree method, and the
356 uncorrected electronic residual offset for both). These corrections are likely to include
357 unknown systematic effects in the final calibration constants. In order to estimate the
358 overall final precision of the calibration, the following cross-check was performed. The
359 calibration strategy provides two different calibration constants for each sensor, one for
360 the reference method and another for the tree method. In the case of the sixteen sensors
361 used in the second round of the calibration tree, these two values are statistically inde-
362 pendent of each other, since they rely on different runs. Indeed, the reference method
363 uses only the runs in the first round while the tree method for those sensors uses only
364 runs in the second and third round. Thus, those 16 sensors can be used to estimate the
365 precision of the calibration procedure by comparing the results of the two methods.

366 By construction, the result of subtracting the calibration constants obtained in the
367 two methods should be compatible with the offset between sensors 39645 and 39606,
368 $\Delta T_{45,06} = \Delta T_{s,06} - \Delta T_{s,45} = T_{45} - T_{06}$, used as reference for the tree and reference
369 methods respectively. This offset is found to be -25.1 ± 0.7 mK by direct measurement
370 of the two sensors (see 10th column in Fig. 7). Fig. 15 shows this benchmark with (left)
371 and without (right) time walk corrections for the 16 sensors aforementioned, probing
372 the self-consistency of this correction. The standard deviation of this distribution, 2.4
373 mK, is an estimation of the quadratic sum of the total uncertainty of both calibrations.
374 Assuming that the reference sensor method has a larger uncertainty than the tree method
375 due to the time walk correction, an upper limit of 1.7 mK for the total error of the tree
376 method can be assumed. In the same way, this is the inferior limit for the total error of
377 the reference method. In both cases, these errors are less than half of what was originally
378 required for the TMS.

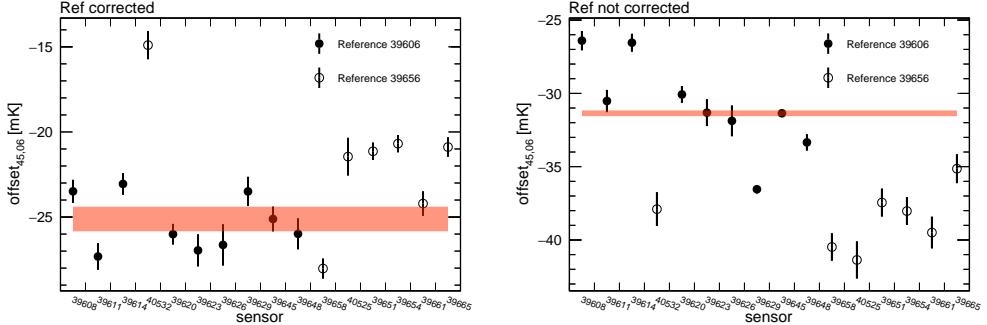


Figure 15: $\Delta T_{45,06}$ computed through all sensors of the second stage of the calibration procedure. Left: applying corrections. Right: not applying corrections. A clear improvement is obtained using the corrections on the reference sensor. The red line represents the expected value of this calibration constant.

379 5. Re-calibration after ProtoDUNE-SP operation

380 After ProtoDUNE-SP decommissioning in 2020, temperature sensors were disconnected
 381 from the TGM and re-calibrated several times (see Table 1), using both LAr and LN2 as
 382 cryogenic liquid. The comparative analysis of those re-calibrations not only offers insights
 383 into the long-term stability of the sensors but also elucidates any potential dependencies
 384 on the choice of the cryogenic liquid. Although DUNE will use LAr, massive RTD
 385 calibration would benefit from using LN2, given its higher accessibility and lower cost in
 386 Spain.

date	cryogenic liquid	# sensors in capsule
March 2018	LAr	4
February 2022	LN2	14
March 2023	LN2	14
July 2023	LAr	14

Table 1: Calibration runs with indication of the date, the cryogenic liquid used and the number of sensors inside the capsule.

387 In this section, a description of the setup used for these new calibrations, the changes
 388 applied to the procedure as well as the results and conclusions of these calibrations are
 389 presented.

390 5.1. Evolution of the calibration setup

391 The Horizontal Drift far detector module will have more than 500 precision sensors [4],
392 making the use of the calibration setup impractical for calibration purposes, since it
393 can only accommodate four sensors simultaneously. Significant modifications have been
394 introduced in order to increase this number to twelve, while maintaining the precision
395 achieved during the 2018 calibration campaign. This was accomplished by positioning
396 sensors at the same height, to avoid any potential vertical gradient, and following a
397 cylindrical configuration, under the assumption that convection inside the capsule has
398 rotational symmetry. This symmetry is also kept outside the capsule in all concentric
399 cryogenic containers, having added a fourth independent volume which should further
400 reduce convection inside the inner capsule. This notable advancement greatly streamlines
401 the calibration process and serves to reduce both statistical and systematic errors asso-
402 ciated with the procedure. Fig. 16 shows the different elements of the new calibration
403 setup, which are described below:

- 404 • A polystyrene box with dimensions $55 \times 35 \times 30 \text{ cm}^3$ and 4.5 cm thick walls with
405 a dedicated cover of the same material.
- 406 • Extruded polystyrene rectangles with a cylindrical hole of 12.5 cm diameter and
407 25 cm height, to conform the inner volume.
- 408 • A PTFE container with 12.5 cm diameter, 25 cm height and 2 mm thick walls to
409 fit in the hole left in the box. The approximate volume is 2 L.
- 410 • A 3D printed PLA cylinder with two independent concentric volumes, placed inside
411 the PTFE container.
- 412 • A cylindrical aluminum capsule to be placed in the inner volume of the PLA cylin-
413 der. It has 7 cm diameter, 14 cm height and 1 mm thick walls.
- 414 • A 3D printed PLA holder for 14 sensors, 12 of them forming a circle (the ‘corona’)
415 and the other 2 at the center, to be used as references. This support can be attached
416 to the aluminum capsule at a fixed height. Cables are naturally extracted from the
417 top of the assembly. A detailed view of this holder can be found in Fig. 16.

- 418 • The readout electronics, described in Sec. 3 has been retained from the previous
 419 setup.
- 420 • A more cost effective cable with similar performance has been used. Produced by
 421 TempSens [24], it has four twisted cables instead of two separated twisted pairs
 422 and an additional Kapton insulation layer between the shielding mesh and the four
 423 conductors. Its diameter is 2.7 mm.

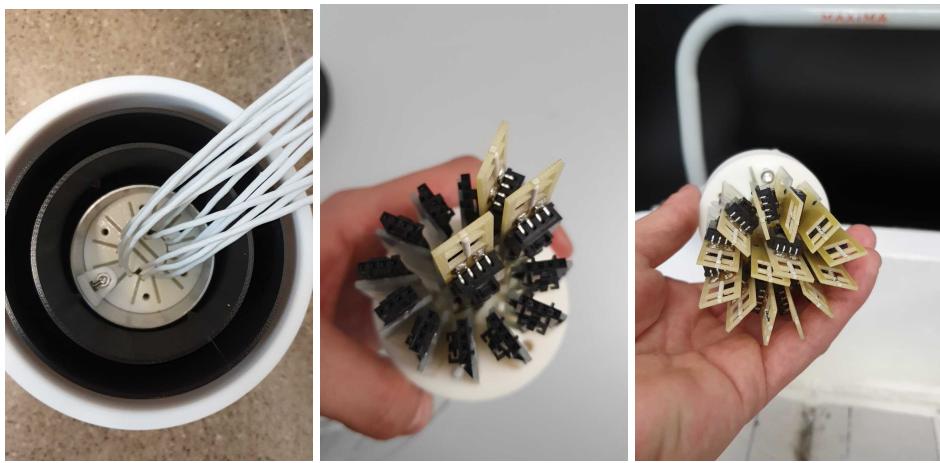


Figure 16: Left: The four concentric volumes. Center: A view of one of the references and two corona sensors. Right: The 12 corona sensors plus the 2 references.

424 *5.2. Calibration procedure*

425 The sensor support was originally designed to accommodate two reference sensors in
 426 the center (see Fig. 16), enabling both the reference and tree calibration methods.
 427 However, it was soon observed that temperature variations between corona and reference
 428 sensors were significantly larger than those between any two corona sensors. This effect
 429 is attributed to the convection pattern inside the capsule, which is expected to have
 430 rotational invariance, and hence favour sensors disposed following a cylindrical symmetry.
 431 This can be observed in Fig. 17-left, where the offset between two corona sensors is
 432 nearly constant in time in four independent measurements, and in Fig. 17-right, where
 433 the offset between a corona and a reference sensor shows a more chaotic behaviour.
 434 Consequently, only the ‘tree’ calibration method was considered during the calibrations
 435 after ProtoDUNE-SP decommissioning.

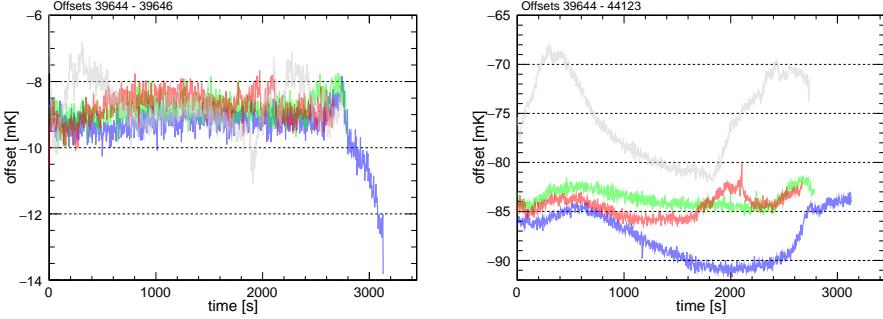


Figure 17: Left: The 4 measured offsets between two arbitrary sensors in the corona. Right: The 4 measured offsets between a sensor in the corona and one of the references, at the center.

436 The new calibration tree, shown in Fig. 18, contemplates four 12-sensors sets in the
 437 first round, and a unique second round with three promoted sensors from each of the
 438 sets in the first round. With this scheme, promoted sensors only suffer 8 baths, avoiding
 439 the necessity of a time-walk correction.

440 The experimental procedure is similar to the one presented in Sec. 4. Two small
 441 variations were introduced. First, the several concentric containers are cooled down
 442 for 40 minutes before introducing the aluminium capsule for the first time in a day,
 443 slightly improving the results of the first calibration run. Second, the warm up process
 444 is accelerated using a heat gun, avoiding the use of water.

445 5.3. Calibration results

446 A sensor in the second round is chosen as reference, since this minimizes the number of
 447 operations for non promoted sensors. On the other hand, since there are three promoted
 448 sensors per set, there are also three ways of computing the offset with respect to the
 449 reference for the nine non promoted sensors in a set. The calibration constant for those
 450 sensors is computed as the weighted average of the three ‘paths’, while its uncertainty is
 451 computed as the standard deviation of the three values. The absolute reference chosen
 452 for the rest of the analysis is sensor 40525.

453 For each of the paths, the error on the offset can be computed by quadratically adding
 454 the individual uncertainties on each of the terms contributing to that specific offset.
 455 Then, the average path offset is computed as the weighted mean of the different paths
 456 by considering the different path offsets errors that are involved. Finally, the uncertainty

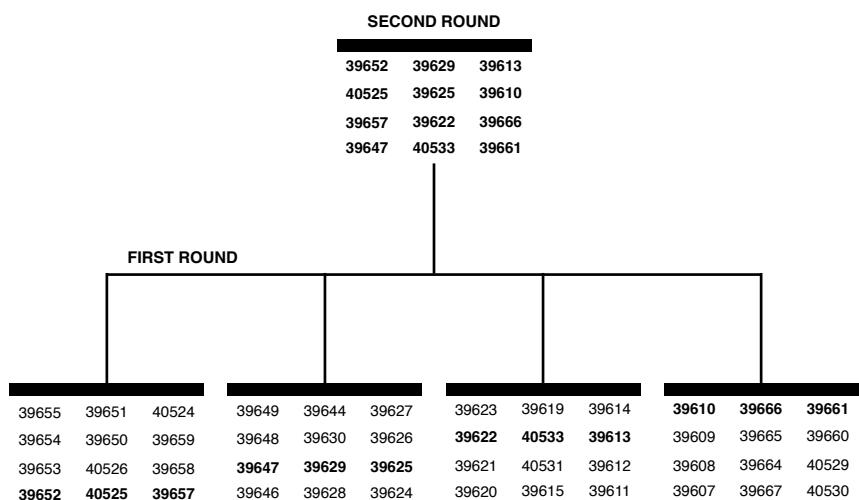


Figure 18: Schematic of the calibration strategy used with the new setup. Each of the sets contains 12 sensors, all of them placed in the corona, plus 2 references at the center. Sensors in bold in the first round are promoted to the second round.

457 on the average path offset is computed as the standard deviation of the involved path
 458 offsets.

459 Fig. 19 shows the distribution of the repeatability (defined in Sec. 4.3.1) for the three
 460 new calibrations mentioned in Table 1. In all three cases the error is slightly above 1 mK.
 461 Mean values are larger than the ones obtained in the 2018 campaign. This is attributed
 462 to the increased capsule size and the larger distance between sensors inside the capsule.
 463 This hypothesis is supported by Fig. 20, showing the repeatability as a function of the
 464 distance to the reference sensor in the corona for a particular measurement. However,
 465 there is no substantial difference between the repeatability obtained for LN2 and LAr
 466 calibrations.

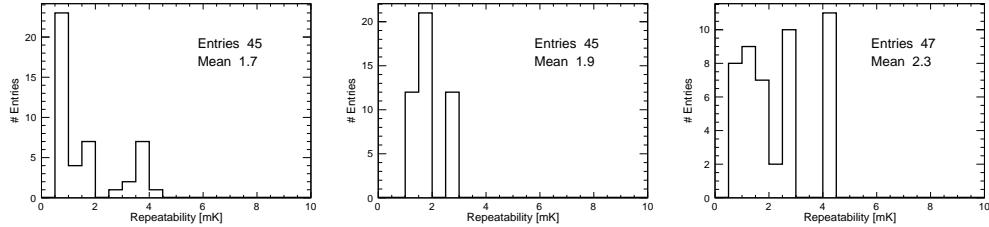


Figure 19: Repeatability distribution for the new calibrations. Left: LN2-2022. Middle: LN2-2023, Right:LAr-2023

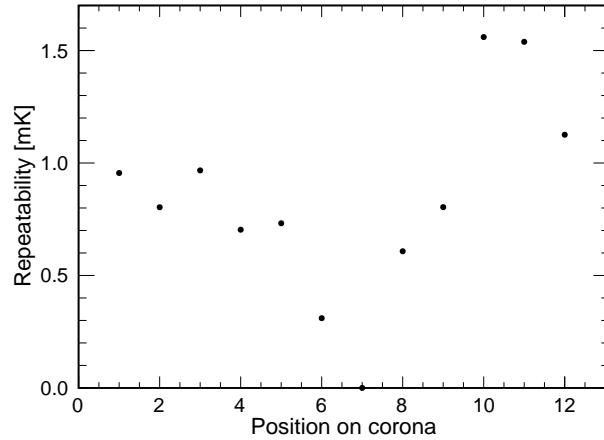


Figure 20: Repeatability as a function of position in the corona for the first set of the LAr-2023 calibration campaign.

467 Comparison between LN2 and LAr calibrations can also be used to understand the
 468 dependence of the calibration constants on the absolute temperature. This is shown
 469 in Fig. 21 along with other comparisons between calibration campaigns. The standard
 470 deviation of the distribution is lower when comparing two calibrations in the same liquid
 471 (LN2 in this case). However no bias is observed when comparing calibrations in two
 472 different liquids, indicating that offsets are insensitive to a 10 K variation in absolute
 473 temperature.

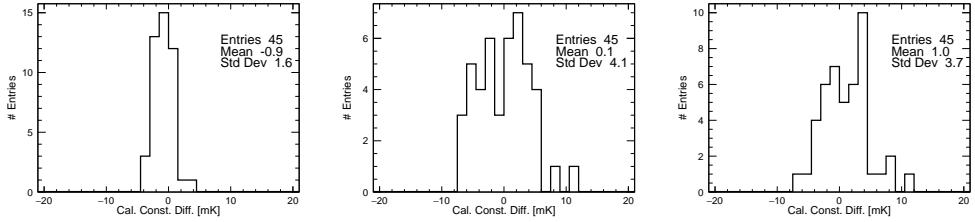


Figure 21: Difference between offsets for two calibrations. Left: LN2-2023 and LN2-2022. Middle: LAr-2023 and LN2-2022. Right: LAr-2023 and LN2-2023.

474 Ageing and long term stability have also been addressed. The left panel of Fig. 21
 475 shows no difference between the offsets calculated in LN2 with a delay of one year. A bet-
 476 ter understanding of this effect is achieved by comparing with the LAr-2018 calibration,
 477 as shown in the next section.

478 5.4. Comparison between new and old calibrations

479 Fig. 22 shows the distribution of the offset difference between the LAr-2018 and LAr-
 480 2023 calibrations. The mean of the distribution is -0.1 ± 0.6 mK, excluding any relevant
 481 systematic drift. The standard deviation of the distribution, 4.0 mK, is only slightly
 482 larger than the ones obtained in the comparison between newer calibrations, which could
 483 be due to the unknown contribution of the uncorrected readout offsets, pointing to small
 484 or non-existing ageing effects. This can also be observed in Table 2, summarizing the
 485 results of all possible comparisons between calibration campaigns, showing the mean and
 486 standard deviation of those comparisons. The lowest standard deviation, 1.6 mK, is
 487 obtained for the LN2-2022 to LN2-2023 combination, which is somehow expected since
 488 i) the cryogenic liquid is the same, ii) ageing should be small since there is only one year
 489 difference and iii) having use the same readout channels, readout offsets cancel out.

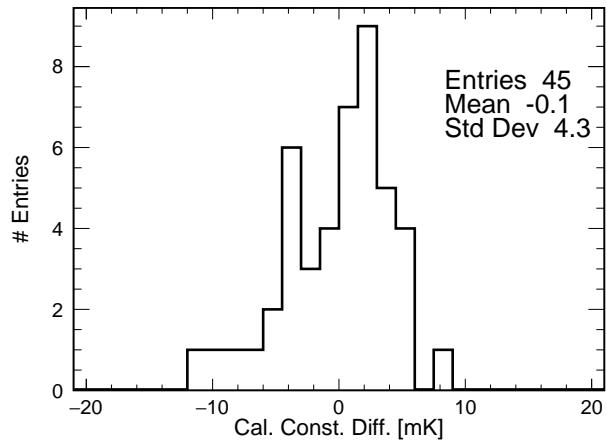


Figure 22: Difference between offsets for LAr-2018 and LAr-2023 calibration campaigns.

	LAr-2018	LN2-2022	LN2-2023	LAr-2023
LAr-2018	-	0.0, 3.5	0.9, 3.9	-0.1, 4.3
LN2-2022	-	-	0.9, 1.6	-0.1, 4.1
LN2-2023	-	-	-	-1.0, 3.7
LAr-2023	-	-	-	-

Table 2: Mean and standard deviation of the difference between the calibration constants obtained in two calibration campaigns.

490 The difference between the constants obtained in two calibration campaigns can be used
491 to estimate the total calibration error. Since ProtoDUNE Horizontal Drift (ProtoDUNE-
492 HD), the next iteration of the ProtoDUNE-SP detector, and DUNE will use LAr, the best
493 estimation of the error would come from a LAr to LAr comparison close in time to the
494 actual detector running. Being this combination not available, three other combinations
495 can be used. The combination (LN2-2022)-(LN2-2023) has a standard deviation of 1.6
496 mK, which should be the quadratic sum of the the errors of individual calibrations.
497 Assuming this error is the same for both campaigns the single calibration error would be
498 1.3 mK. In this comparison the readout channel offsets cancel out, but real fluctuations
499 in those offsets contribute to the estimated single calibration error. Comparison between
500 LAr-2018 and LAr-2023 also brings some insights into the single calibration error. The
501 standard deviation is in this case 4.3 mK, corresponding to a single calibration error of
502 3.0 mK. However, this value includes the uncorrected readout offsets as well as the effect
503 of some potential ageing. Finally, comparison between LAr and LN2 calibrations in the
504 new campaigns, avoids the readout offset and ageing problems, but suffer from potential
505 dependence on the cryogenic liquid. Those comparisons have similar standard deviation
506 of the order of 3.8 mK, corresponding to a single calibration error of 2.7 mK. This figure
507 establishes an upper limit on the LAr calibration error. One can safely conclude that the
508 individual calibration error in LAr is in the range 1.6-3.0 mK. This value is consistent
509 with the one obtained using a different method for the LAr-2018 calibration, 2.4 mK (see
510 Sec. 4.3.5).

511 6. Conclusions

512 The DUNE experiment will require the construction and operation of the largest cryostats
513 ever used in a particle physics experiment. This makes the continuous measurement of
514 temperature gradients in liquid argon crucial for monitoring the stability of the cryogenics
515 system and for detector calibration. R&D on the calibration of RTD probes started in
516 2017, leading to promising results for sensors installed in the DUNE prototype at CERN.

517 The first setup proved the viability of the method, obtaining a calibration error of 2.4
518 mK. A key component was the readout electronics, with an intrinsic resolution better
519 than 0.5 mK in the comparison between two channels. The mechanics was also crucial,

520 with several insulation layers consisting of independent concentric volumes, ensuring
521 minimal convection in the inner volume. Sensors were contained in an aluminium capsule,
522 enabling slow cool-down and warm-up processes, found to be fundamental to guarantee
523 the integrity of the sensors and to minimize the effect of ageing.

524 The calibration system was later enhanced to accommodate the large-scale calibration
525 required for the DUNE detectors. The capacity of the inner capsule was increased from
526 4 to 14 sensors, while improvements were made to the insulation and symmetry of the
527 system to minimize temperature differences between sensors. The new system has slightly
528 worst repeatability for sensors in the same set, but reduces the statistical and systematic
529 errors associated to the calibration tree, needed to relate any two sensors in different
530 calibration sets. Calibration with the new setup has achieved a precision in the range of
531 1.6-3.0 mK, substantially better than the 5 mK DUNE requirement.

532 Another difference between the new and old calibrations is the use of a different
533 cryogenic liquid. While DUNE will use LAr, LN₂ is cheaper and more accessible in
534 Spain, simplifying the process of massive calibration for DUNE detectors. The 10 K
535 difference between those liquids has a minimal effect on the calibration constants.

536 A comparison of the four calibration campaigns has provided valuable insights into
537 aging effects, with no evidence of RTD aging observed over a five-year period. This
538 highlights the stability and reliability of the PT-102-based system.

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