Temperature measurements in the ProtoDUNE-SP cryostat

Motivation

The ProtoDUNE-SP cryostat will be the largest ever build, with internal dimensions 855x790x790 cm^3. The active volume is 6 m high, 7 m wide and 7.2 m deep (along the drift direction). It is crucial to understand the temperature of liquid argon throughout the cryostat since this will not only affect physics but also the correct functioning of the full cryogenics system, including the liquid argon homogeneity and purity. The temperature of liquid argon affects the electron drift velocity with a gradient of about -1.9%/K, and hence needs to be measured throughout the LAr volume to ≤ 0.1 K precision. At the same time, it has been demonstrated in a smaller prototype at Fermilab (the 35t prototype) that vertical temperature gradients as low as 0.02 K resulted in the stratification of liquid argon. The cryogenics system injected and removed argon at the bottom of the cryostat. The clean injected argon was colder than the bulk and failed to mix with the LAr above, and efficiently remove impurities through LAr recirculation, reducing the electron mean lifetime and severely affecting the detector performance (see Fig. 1). The design of the ProtoDUNE-SP cryogenics system addresses this problem in the following way: purified LAr is injected at the bottom of the cryostat with a 0.4 K higher temperature than the bulk LAr, improving the mixing and recirculation of the entire LAr volume. The experience of the 35t has emphasized the importance of the design of the argon circulation system and the resulting vertical temperature distribution. Computational fluid dynamics calculations are being used to predict the temperature distributions for the DUNE detector but the validity of the entire concept is yet to be verified in a real detector with large enough dimensions such as ProtoDUNE-SP. With this purpose in mind, a set of high precision temperature sensors will be installed at different heights in the detector along with three purity monitors to measure the electron lifetime. The need for a detailed vertical temperature profile has been identified as one of the crucial milestones towards the first 10 kton DUNE detector.

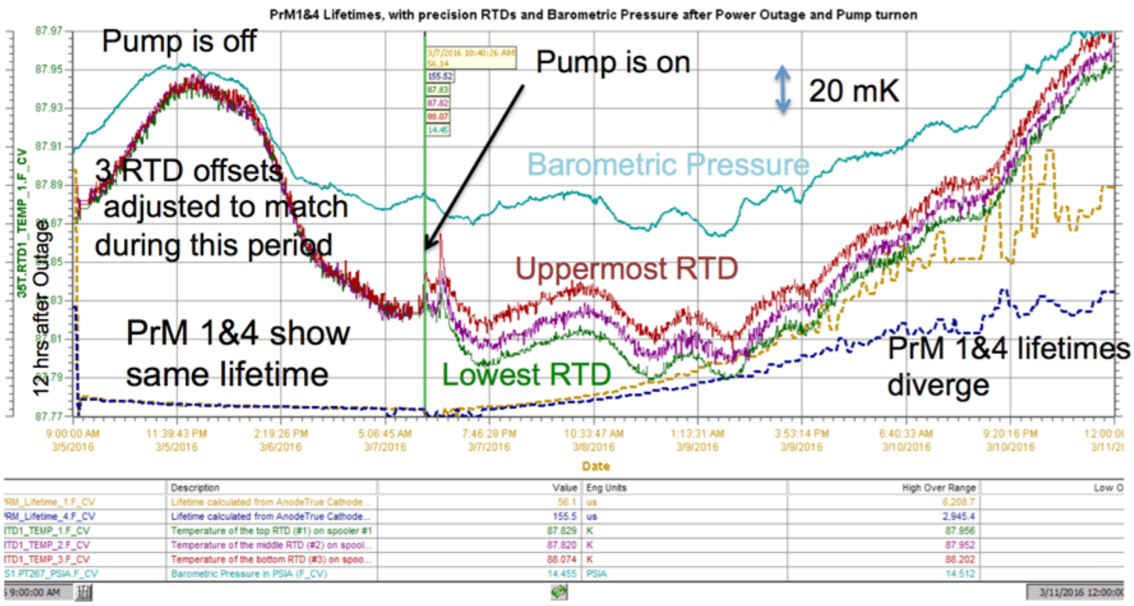


Figure 1. Correlated instrumentation measurements at the 35 t prototype. Temperatures at three different heights in green, purple and red. Pressure in aquamarine. Electron lifetime measured by purity monitors in golden and dark blue.

Requirements

The requirements for the system are based on fluid dynamics simulations and on prior experience with the 35 t prototype. As shown in Fig. 1, when the recirculation pump was switched on and LAr was recirculating, a difference in temperature of 20 mK was correlated with a factor of 3 difference in the electron lifetime, indicating a clear stratification of LAr. On the other hand, the expected temperature gradient (based on the cryogenic fluid dynamics simulation) in the active region of the ProtoDUNE-SP cryostat is below 10 mK, as shown in Fig. 2. Based on those facts the following set of requirements has been identified:

- The temperature of the LAr should be measured with an absolute precision of 50 mK to guarantee a successful drift velocity measurement
- The relative precision of the temperature measurement should be better than 10 mK to measure the vertical temperature gradient with sufficient precision. Such measurement precision is required to effectively benchmark the simulations and to gain detail understanding of the cryogenic system efficiency.
- The temperature profile should be obtained for the full height of the cryostat, even beyond the active region, since the temperature variations in those areas will affect the temperature profile and fluid dynamics in the active region too
- Of particular interest are temperature measurements in the regions close to the LAr inlets

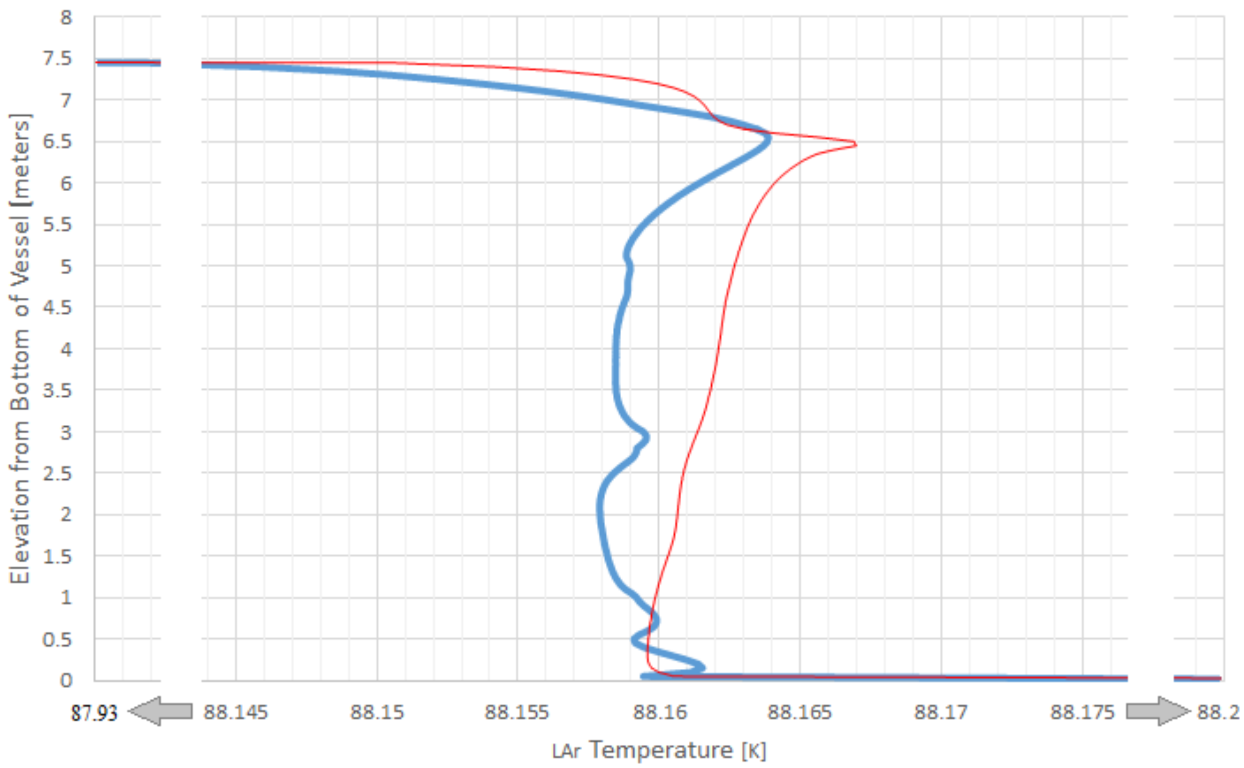


Figure 2. Liquid argon temperature as a function of height for two different locations in the cryostat

System overview

A set of high precision temperature sensors will be installed inside the cryostat. The distribution of sensors has been studied carefully and their final locations (see Fig. 3) have been decided based not only on the requirements, but also on the available cryostat ports (see Fig. 4), the available space between the TPC and the cryostat walls, the existence of mechanical elements where sensors can be attached and the electric potential from the field cage. Two devices will measure the vertical temperature profile at two different locations. They are referred to as T-gradient monitors. One of the T-gradient monitors will be installed in port 9.6 (the Hawaii T-gradient monitor); this monitor can move vertically which allows for precise cross-calibration between the sensors in-situ and for measurements with high spatial resolution. The other one (the Valencia T-gradient monitor) will be installed in port 14.4. This monitor provides measurements in a second x-y location far from the first set. It is static and also covers the entire height of the cryostat. Apart from the two T-gradient monitors there will be a number of temperature sensors distributed at the top and at the bottom of the cryostat, to provide a detailed 3D temperature map. They will be complemented by a set of standard RTDs which are attached to the inner cryostat surfaces and will be used to monitor temperature during the cryostat cool-down and filling.

It should be remarked that when ProtoDUNE-SP started discussing the need for temperature sensors, only a limited set of ports were available (as indicated in Fig. 4). The Hawaii T-Gradient monitor will be installed at the port 9.6 (visible in Fig. 4), which is behind the APA. The APA is at ground potential, which simplifies the design process as metal parts can be safely used for construction in this location. Sensors will be mounted on a set of rods that are connected with mating pins. Sensors are soldered to the PCB boards and boards are then screwed to the rods for temperature insulation. The plan is to install sensors every 50 cm, with an increased granularity of 10 cm at the very top and bottom 50 cm of the detector for cross-checks and measurements of more rapid temperature changes expected in these areas. A total of 22 sensors will be installed. The entire assembly hangs from the top flange, enclosed in the welded bellows that allows the structure to move up and down in order to cross-reference the sensor temperature readings, in order to maximize precision of the relative vertical temperature gradient measurement. While the flange with 4 SUBD 25-pin connectors is the baseline feedthrough design, special feedthroughs that would allow uninterrupted connection between sensors and the readout system are also under consideration. Additional details of the system are provided in Appendix 2.

The Valencia T-Gradient monitor is described in detail in Appendix 1. It will be installed at port 14.4 (see Figs. 3 and 4). This port has been chosen because it is far apart from the other T-Gradient monitor and in a region where the electric potential is tolerable (~60 kV). The system consists of a main mechanical structure made of three aluminum plates of 1.5 cm thickness, 8 cm width and 254 cm length. Sensors will be installed at the edge of cylindrical supports made of insulating material and oriented perpendicularly to the aluminum structure. There will be 36 sensors in total, 18 sensors will be installed on the bottom aluminum plate with a 12 cm spacing, and 18 in the other two plates, with a 30 cm spacing between sensors. A cylindrical grid (11 cm in diameter), formed by narrow metallic rods, will provide electric field shielding for sensors and cables. The system will hang from the top of the cryostat chimney, which will be closed hermetically with a flange with six SUBD 25-pin connectors.

As described in Appendix 3, additional high precision sensors will be installed on the top ground planes and on the bottom cryogenic pipes. The map is the same in both cases (indicated with a red T in Fig. 3). The LAr inlets have been identified as critical regions for temperature monitoring and have driven the configuration of the sensors' map. Several other locations had initially been considered (APA frames, bottom ground planes) but they were eventually discarded for various reasons.

A custom readout system have been developed by CERN EP-DT department. It consists of a very precise current source to excite the sensor, providing a continues DC current of 1 mA and a very precise 24 bit voltage meter with four channels. To avoid the need for more than 70 readout channels, utilizing low measurement frequency that can be as low as 0.01 Hz, a set of multiplexing cards will be used. With this configuration, each of the T-gradient monitors can be read by a single channel; another channel will be used by the top-bottom sensors and the fourth one by the cryostat wall sensors.

For the Hawaii T-gradient monitor an alternative readout system is also considered, the Lakeshore 218. The test in the LAPD (Liquid Argon Purity Demonstrator) detector will be carried out in May 2017 to benchmark the performance of the two systems. While Lakeshore 218 is a commercial system that was successfully used in the 35 ton prototype LAr TPC, the CERN EP-DT system is simpler to customize for a large number of channels. However, the precision of the measurement with the two readout modules will be used as a selection criterion.

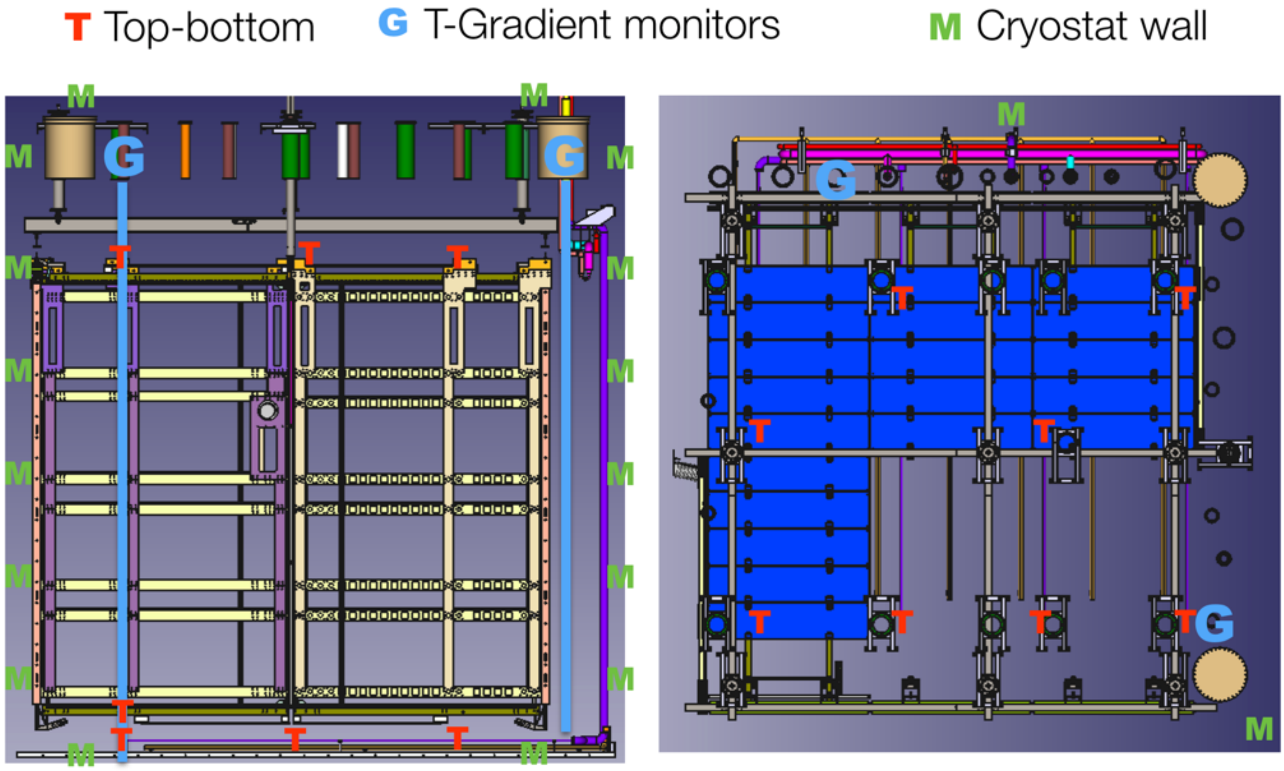


Figure 3. Sensors' map. Left: side view. Right: top view.

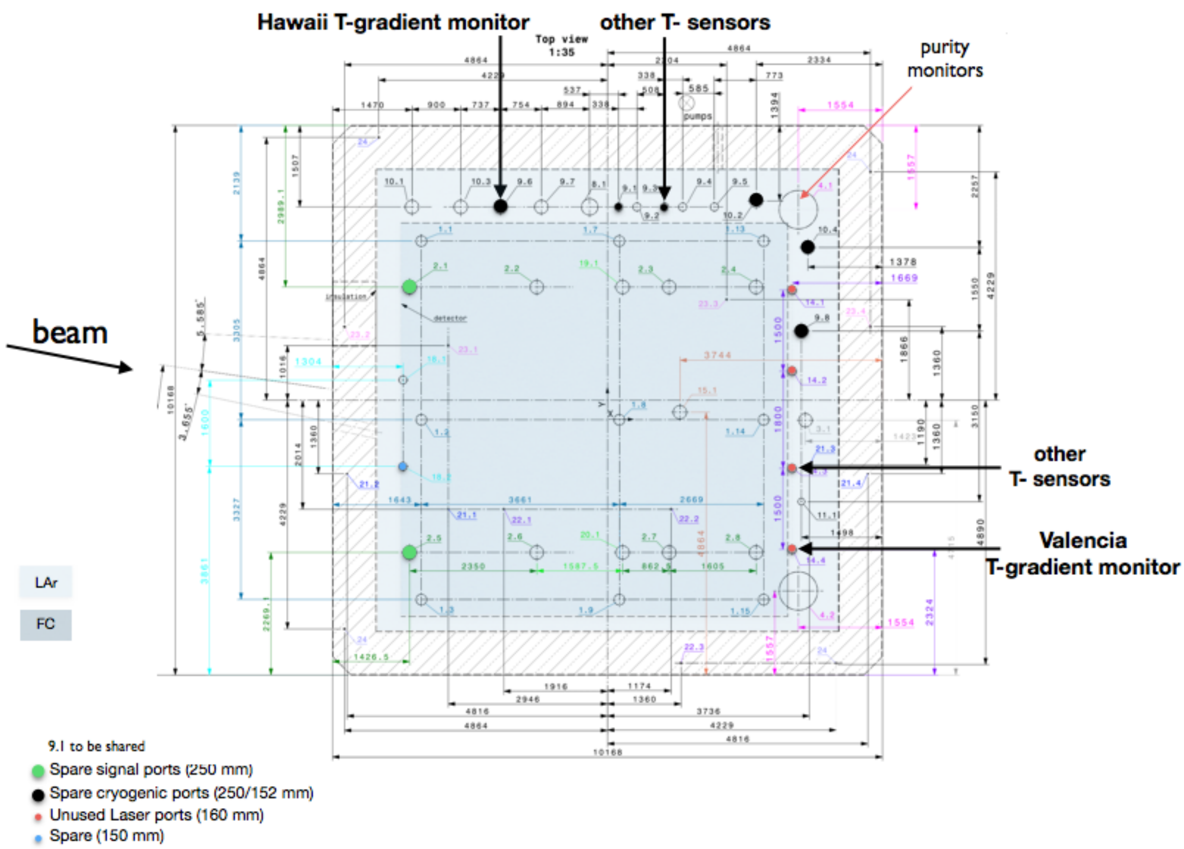


Figure 4. The top view of the cryostat with the list of all ports, indicating availability, as well as the ports used by the T-Gradient monitors and other T-sensors.

Sensor choice

Platinum sensors with 100 Ω resistance (PT100 series), produced by Lakeshore will be used except for the membrane sensors that may come from Minco. The sensor choice is adequate for the temperature range of interest: 83-92 K. In this temperature range these sensors have high reproducibility of just 5 mK and absolute temperature accuracy of 100 mK. In addition, the use of 4-wire readout greatly reduces, and potentially resolves the issues related to the lead resistance, any parasitic resistances, connections through the flange and general electromagnetic noise pick-up.

The Lakeshore PT102 sensors have being previously used in the 35t prototype, giving excellent results as can be seen in Fig. 1. Lakeshore provides two other PT sensors, the PT103 and PT111, which have the same performance, but are slightly smaller in size. However, PT103 and PT111 have a higher price. Since there are no strict space constraints for the T-gradient monitors, PT102 is the preferred choice. As shown in Fig. 5, the PT102 sensor has a length of 21 mm, which can easily be accommodated in the ProtoDUNE-SP T-gradient monitors.

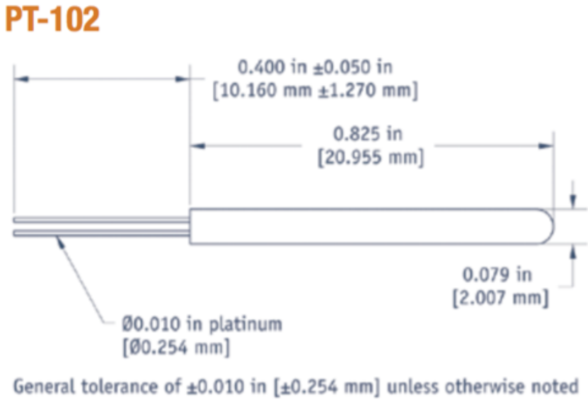


Figure 5. Schematics of the Lakeshore PT102 sensor.

Readout system

The proposed readout system for the temperature gradient monitors is based on a variant of an existing mass PT100 temperature readout system developed at CERN for one of the LHC experiments.

The goal of this system is to achieve the same precision as a reference system (Lakeshore 218) that the collaboration had evaluated as being appropriate, but with reduced cost and space utilization.

The system consists of three parts:

1. An accurate current source for PT100 excitation, implemented by a compact electronic circuit using high a precision voltage reference from Texas Instruments.
2. A multiplexing circuit based on an ADG707 Analog Device multiplexer electronic device;
3. A high resolution and accuracy voltage signal readout module based on National Instruments NI9238, which has 24 bits resolution over 1 Volt range. This module is inserted in a National Instruments Ethernet DAQ backplane, which will distribute the temperature values to the main Slow Control Software through the standard protocol, OPC UA. The Ethernet DAQ will include also the multiplexing logic.

The first setup, consisting of the current circuit and the National Instruments NI9238 module with a capacity of 4 temperature sensor readout, has been produced at CERN and sent to the University of Hawaii, in order to compare the performance of the system in reference to a Lakeshore 218 device. The multiplexing circuit is not included in this system.

A second identical setup is being built at CERN with the purpose of calibrating the PT100s at IFIC (Valencia). In parallel, CERN has been developing the multiplexer stage, which will be installed in the NP04 cold box test stand and connected to the slow control system.

The evaluation of the system is still on-going: in the unlikely event that the results are not satisfactory in terms of precision, stability and reproducibility, an alternative readout based on Lakeshore 218 devices will be utilized. Otherwise, CERN will produce the readout system for both temperature gradient monitors of NP04.

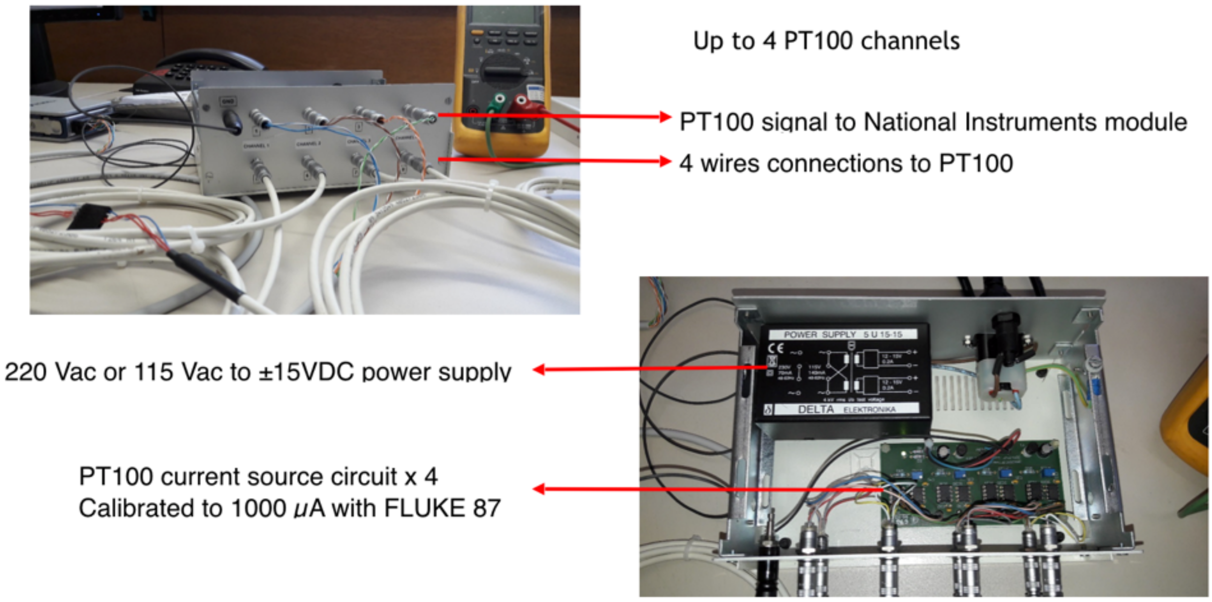


Figure 6: The first four channels readout module being tested at the University of Hawaii.

Sensor calibration

While the absolute accuracy of the Lakeshore PT102 is 100 mK, Lakeshore company offers in-house high accuracy and precision calibration of the sensors. However, the price of the calibrated sensors (Lakeshore PT102) is five times higher, when calibration to ~10 mK accuracy. This calibration covers a very wide range of temperatures (from 30 to 325 K), which is not necessary for our application, but at the same time could be probably improved in the range of interest for ProtoDUNE-SP. This is why we plan to calibrate the sensors at IFIC. For this purpose, a small dewar, already available at the institute, will be used (see Fig. 7). This dewar can sustain pressure of up to 15 bars. The conceptual design of the calibration system is shown in Fig. 8. A PCB with 12 sensors, three of them calibrated by Lakeshore, will be used to cross-calibrate the other 9 sensors. The dewar will be filled with LAr at 88 K. A small amount of liquid nitrogen will be used to lower the LAr temperature and measure the response of the sensors at several points, using the calibrated sensors as reference. To rise the temperature above 88 K an electric heater will be used. In this way a curve of voltage versus temperature will be obtained for each sensor in the range from 85 to 91 K, which is sufficient for our needs, since ProtoDUNE-SP plans to operate in the range of 88±1 K.

All sensors will also be calibrated at room temperature. As described below, this calibration is necessary for comparison with the sensor readings once the final cables and connectors have been soldered and mounted in the mechanical structure during the test assembly of the T-gradient monitor in Valencia.

Once all sensors are calibrated both at cryogenics and room temperatures, they will be soldered to their final cables. Final calibration will be done with the corresponding cables to check for possible biases introduced by the cables or connectors. Again this will be done at both cryogenics and room temperatures. It is also under consideration moving the calibration system to CERN and calibrating all sensors using the final readout system already installed on its corresponding electronics rack.

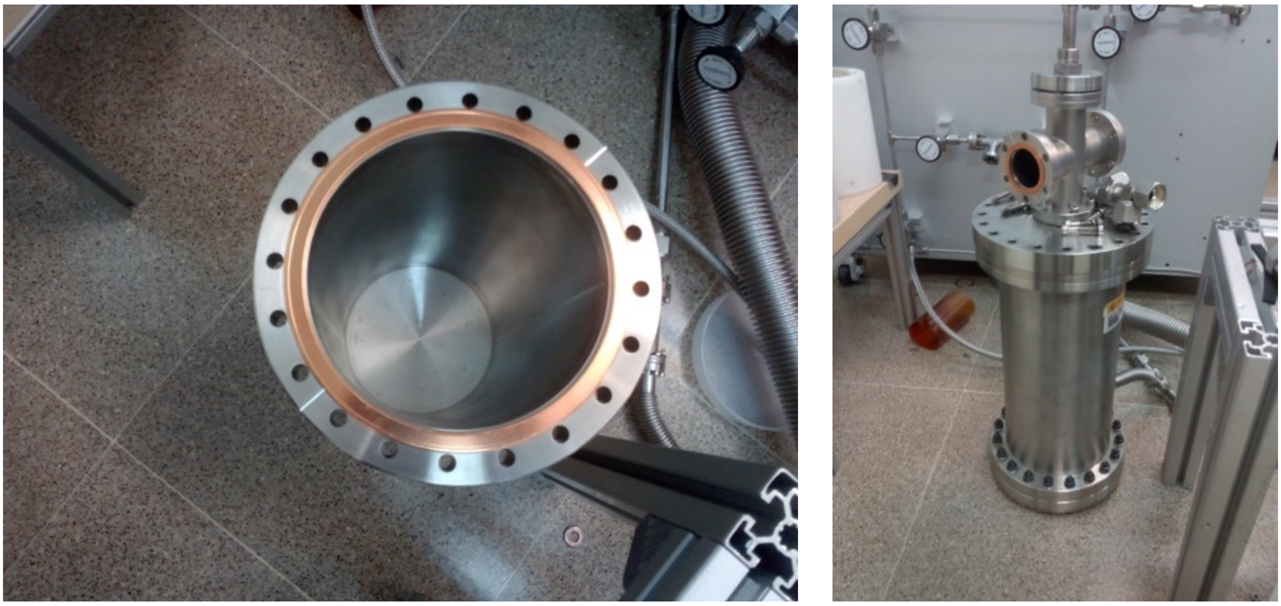


Figure 7. Dewar at IFIC-Valencia.

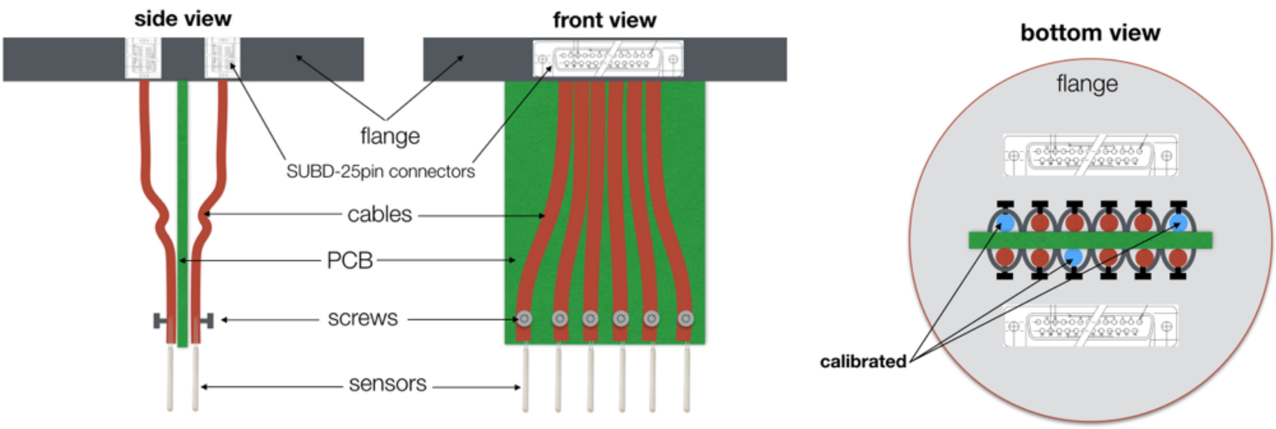


Figure 8. Conceptual design of the calibration system

Answers to review charge questions

Does the Cryogenic Instrumentation design meet the requirements? Are the requirements/ justifications sufficiently complete and clear?

The requirements of the system have been described above. The proposed T-gradient monitors meet the requirements based on the experience from the 35 ton where 20 mK variations introduced LAr stratification were observed, and based on the cryogenic liquid flow which predicts variations below 10 mK. T-gradient monitors will measure the vertical T-profile with a relative precision of 5 mK thanks to their ability to cross-reference sensors (with a moving system in one case and with a precise calibration system in the other) and to the choice of high reproducibility sensors Lakeshore PT102. The T-gradient monitors will be complemented by additional high precision sensors located in critical places as are the LAr inlets and the region above the TPC.

ProtoDUNE-SP, being the first kton scale prototype, is the ideal place to test new ideas. Redundancy, as well as testing different approaches is also important, and this is why two T-gradient monitors will be installed.

Does the design represent a good development path towards DUNE?

The different subsystems can be in principle extrapolated to DUNE. For example, the Valencia T-Gradient monitor has been designed in a modular way with sections no longer than 2.5 m, which could be easily installed in DUNE. The shielding grid has been kept independent of the aluminum structure, such that it can be removed for DUNE, which does not need it because all T-Gradient monitors will be behind the APAs (at ground). As expleined in Appendix 1 the weight of the system for DUNE will not be much higher since the additional aluminium structure is compensated by the removal of the stainless still shielding greed. Sensor calibration is also important since this will considerably reduce the price for DUNE, where the number of sensors will be much higher.

Regarding the Hawaii T-gradient monitor, we believe that its dynamic choice meets the requirements allowing easy installation with its modular design. The entire assembly is put together by connecting 36 inches (91.44 cm) stainless steel segments on which the PCB boards with sensors are mounted. The system is rather light and doubling the height needed for DUNE does not present additional engineering challenges.

And we should emphasize, even if it turns out that DUNE requires different designs, these systems are making important measurements which will be the only experimental test we have on the fluid dynamics models used for DUNE.

We also believe that the R&D investment on developing systems to cross calibrate temperature sensors to the few mK level will have long-term benefits for any system used in DUNE.

Does the design lead to a reasonable production schedule, including QA/QC, transport, installation and commissioning?

As explained in detail later in this document (Appendices 1 and 2), the schedule for the T-gradient monitors has ample time for design, production and testing.

The schedule is tighter for the sensors which attach to the cryogenic pipes and the cryostat walls since their installation will happen in a few months. The most critical aspect of the schedule are: the cable choice and the sensor calibration.

Is the installation plan sufficiently far advanced to assure that the detector can be installed as designed?

Sections devoted to the installation plan for each of the subsystems are located in the appendices. At this point there is a reasonable understanding of the interface with the cryostat, available space and installation constraints.

The installation of the T-Gradient monitors will be tested in Valencia and Hawaii respectively well in advance so that any problems that may arise may be resolved on a timely manner.

Are all internal interfaces between components (cryostat, cryogenics, TPC) documented, clearly identified and complete?

T-gradient monitors are basically independent of everything else in the detector. They will be installed at the end once all other elements are in place. The main interface points between the T-gradient monitors and the cryostat are the 9.6 and 14.4 flanges. The entire installation is planned through these access ports. A precise installation plan and schedule is being discussed with the corresponding experts and detailed documentation is under development.

Additional T-sensors do have interfaces with other detector components. The support of the sensors and the cable routing is discussed in detail in Appendix 3.

Are the interfaces with the slow control system well defined and understood?

All temperature sensors in the detector will use the same readout system. The team in charge of designing the readout system is the same as the one responsible for the slow controls.

Is the grounding and shielding of the Cryogenics Instrumentation understood and adequate?

Grounding and shielding has been discussed with the relevant experts in ProtoDUNE-SP (L. Bagby and T. Show). The entire Valencia system (aluminum plates and vertical grid will be connected to the detector ground). Cables will be EMC shielded with the shield connected to the flange. Discussions on the Hawaii system and in particular issues to do with the motor are just starting.

Are operation conditions (when will/can instrumentation be turned on) listed, understood and comprehensive?

The T-gradient monitors and all other high precision sensors will be taking data continuously. The current of 1 mA for the excitation of the sensors will, in principle, ramp up only once, when the system is switched on. The measurement frequency will have to be defined. The current baseline is a measurement per minute of all sensors. Since the motor that moves the Hawaii system may well produce noise that interferes with the operation of the TPC, such moves will require a permit from the slow controls system.

Are the analyses of the Cryogenics Instrumentation components sufficiently comprehensive for safe handling, installation and operation at the CERN Neutrino Platform?

No specific analysis has yet been carried out given the state of the design. The analysis will be developed in the next few months as the design is finalized. The systems do not involve massive components and the design will incorporate fixturing to enable convenient installation.

Is the Cryogenics Instrumentation quality assurance, quality control and test plan adequate?

Several simulations are being developed for the Valencia T-gradient monitor. The mechanical rigidity of the system will be first studied with Ansys and then tested at IFIC with several prototypes. Ansys is also being used to understand the thermal interference between the metallic structure and the sensors. A contingency plan is considered in the case the expected biases are too large and cannot be disentangled: the aluminum plates will be substituted by a FR4 structure and vertical shielding grid will cover the 360º. Finally, a 3D electrostatic simulation with Comsol is being developed. No surprises are expected, but in the case the field is close the the 30 kV/cm limit the radius of curvature of some of the elements would have to be enlarged. There is also the option of testing some conflictive pieces in a HV setup at CERN. During the tests carried out at IFIC, the entire system will be assembled and the readout system will be tested.

QA, QC and test plans will be carried out by the University of Hawaii, in Hawaii and at Fermilab using the existing LAPD cryostat.

Have applicable lessons-learned from previous LArTPC devices been implemented into the device testing and into the system design?

The T-gradient monitors requirements are based on experience from the operation of other LAr devices, and in particular the 35t prototype, where stratification was observed.

In addition, the dynamic system proposed for the Hawaii T-gradient monitor benefit from the RTD spooler used in the 35 ton detector. While the deployment scheme is different, the need for the dynamic system was directly motivated by the experience from the 35 ton detector prototype.

Appendix 1: The Valencia T-Gradient monitor

Figure A1.1. Left: the ProtoDUNE-SP cryostat on January 2017 with the temporary construction opening. Right: Detail of the cryostat roof with the manhole and the chimney where the Valencia T-Gradient monitor will be installed (with white cover).

Mechanical design

Several constraints have been driving the design of the T-Gradient monitor. The system will operate very close to the TPC field cage, at 15 cm from a region where the electric potential is 50 kilovolts. The LAr breakdown point is known to be above 50 kV/cm. To be on the safe side, any point inside the ProtoDUNE-SP cryostat is required to have an electric field below 30 kV/cm. Given the sensor dimensions (2 mm diameter) and the sensor wire diameter (0.254 mm) the field around the wire would be larger than 100 kV/cm, leading to a high risk of discharges, which could severely damage the TPC. To avoid that, the system has to be shielded. Several options were considered, including a C-shaped aluminum tube. As a final solution, a stainless steel grid that envelopes the sensors along vertical axis, has been chosen because it guaranties much better LAr flow around the sensors. The result of the simulation with Comsol is shown in Fig. A1.2.

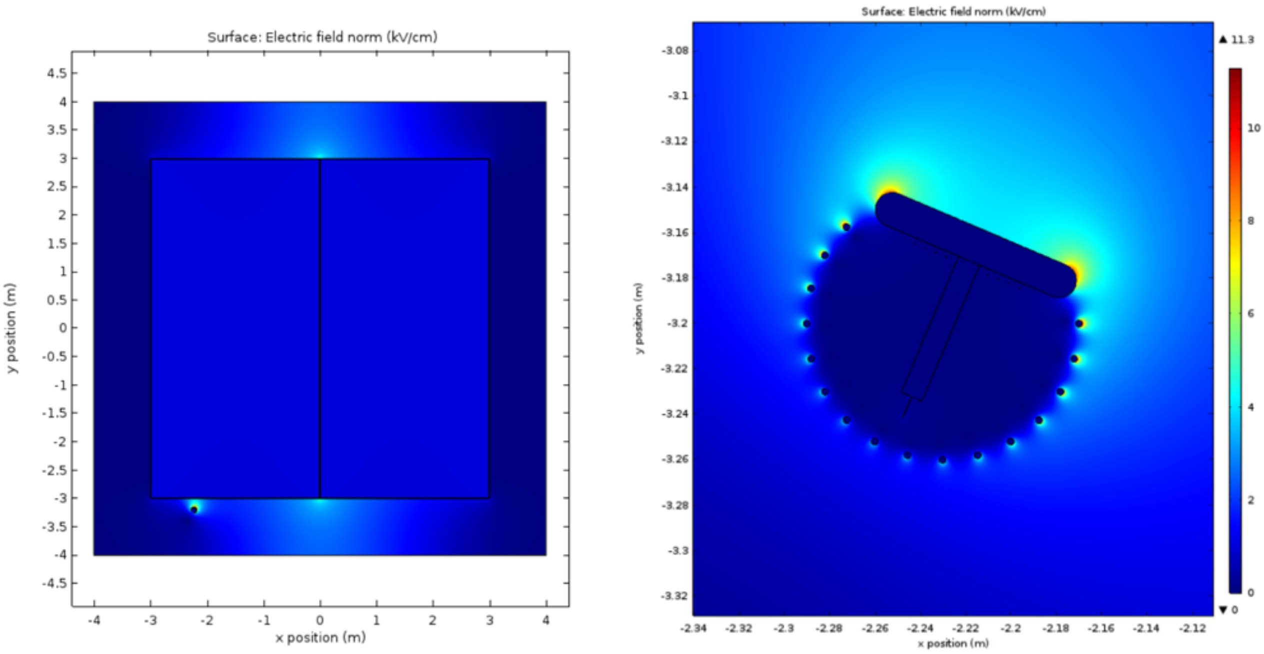


Figure A1.2. 2D Comsol electrostatics simulation of the T-Gradient monitor. Left: entire cryostat. Right: zoom of T-gradient monitor region.

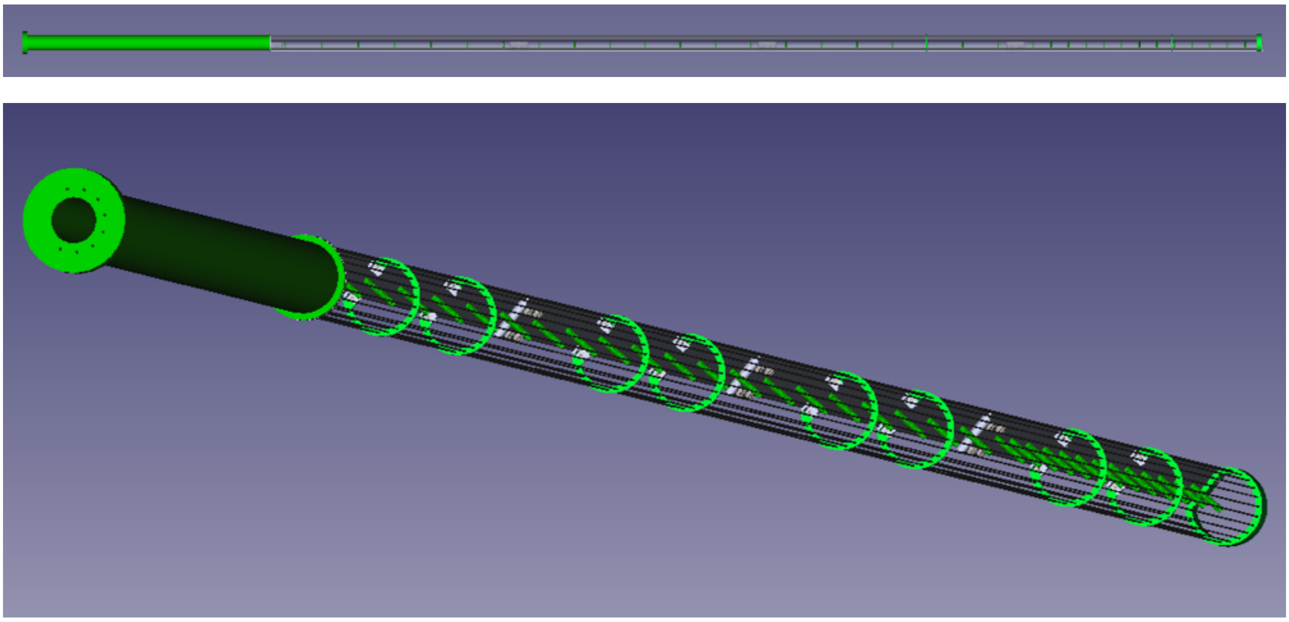


Figure A1.3. 3D model of the Valencia T-Gradient monitor. Top: side view. Bottom: perspective view.

Figure A1.3 shows a rather advance design of the system. To give rigidity to the stainless steel grid and to provide better shielding in the region closer to the field cage, a set of edge-rounded aluminum plates will be integrated with the grid. Aluminum has been chosen because it is lighter than steel and easier to machine. The width of the plate is such that cables can be easily embedded on the side facing the sensors, providing a sufficient shielding at the same time. The plate width will be 1.5 cm, which ensures the necessary mechanical strength and rigidity. There will be three plates, each 254 cm long, assembled together by fastening ~20 cm long aluminum plates in the inner part (such that no special screws are needed) leaving 1 cm clearance between two plates to account for shrinkage when cooled to LAr temperature (see Fig. A1.4 for details). In order to thermally insulate the plates, a non-conductive material will be placed between the long plates and the connecting plate. A cable will connect two adjacent plates to provide grounding.

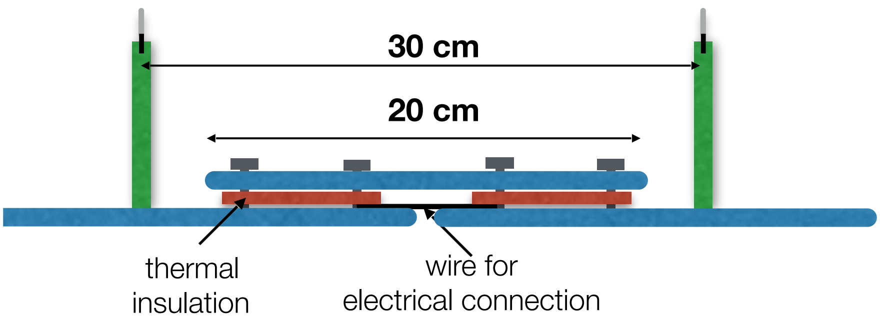


Figure A1.4. Conceptual design of the interface between the two aluminum plates.

Each sensor will be installed at one end of a FR4 cylinder with a longitudinal cut, to host the cable (see Fig. A1.5). The other end will be fastened onto the aluminum plates. To keep the sensor at a fixed position and angle a soft screw near the edge will be used.

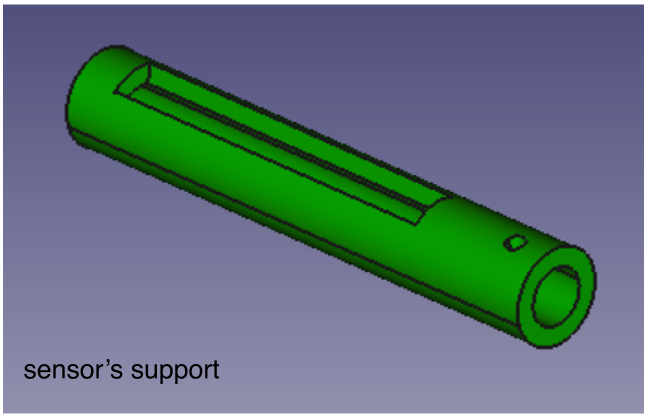


Figure A1.5. 3D model of the sensor's support with a longitudinal cut to introduce the cable and a small hole close to the edge to host the screw.

Cables will be routed close to the structural plates at both sides of the sensor supports (see Fig. A1.6). In order to distribute the weight of the cables throughout the aluminum structure, the cable bundles will be attached at two positions on each plate (every ~127 cm). The cables will have sufficient slack to avoid breaking in the unlikely case that they shrink more than the aluminum plates.

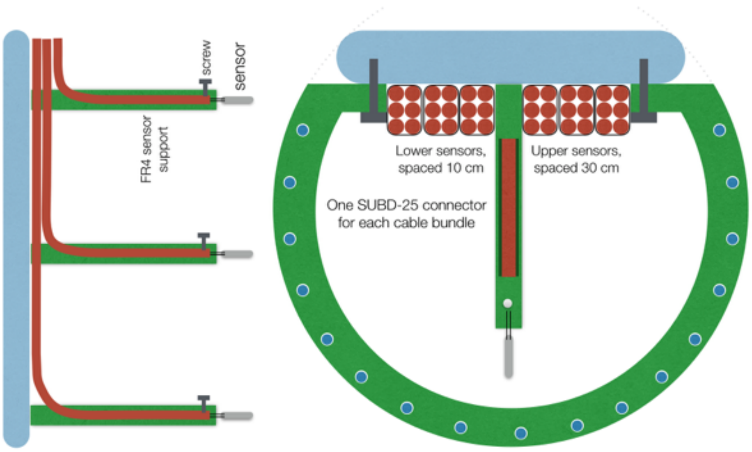


Figure A1.6. Conceptual design of the cable routing

In order to thermally insulate the aluminum structure from the flange, which is at room temperature, a FR4 cylinder of 175 cm will be used to connect the aluminum plates and the flange (see Fig. A1.7). This cylinder will only contain the cable bundles.

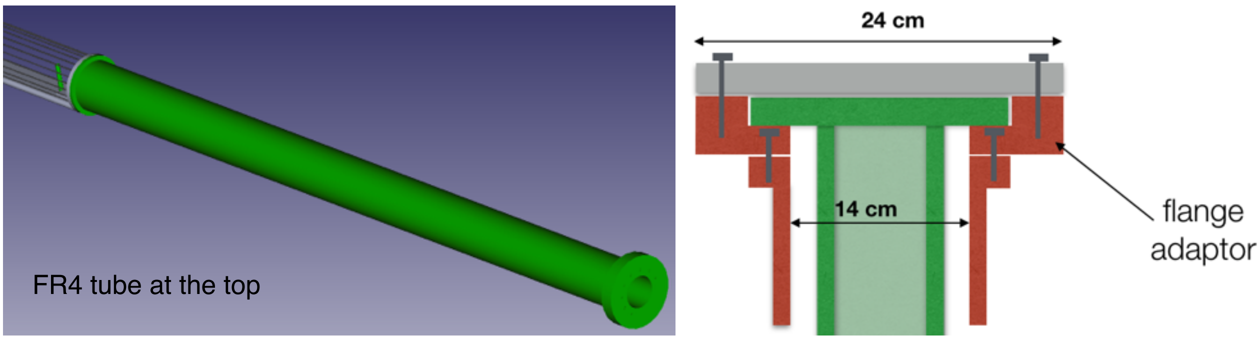


Figure A1.7. Left: 3D model of the FR4 tube at the top of the T-gradient monitor. Right: conceptual design of the FR4 tube resting on the flange adaptor.

The electric field shielding is realized with a metallic grid consisting of a set of 16 vertical stainless still rods with 3 mm in diameter. To keep them vertical and at the same distance from each other (1.5 cm, corresponding to 15º), a set of FR4 disks with 3.5 mm diameter holes will be used (see Fig. A1.8 for details). The disks will be screwed into the aluminum structure with the help of two L-shaped aluminum pieces, as shown in Fig. A1.8-right. The stainless steel rods will not be attached in any way to the FR4 disks, so that they can freely move. Notice that the aluminum structure and the stainless steel grid have different coefficients of thermal expansion and will behave differently when in cold. For this reason the SS rods will be fixed (screwed) to a special aluminum disk connected to the top FR4 tube (see Fig. A1.9).

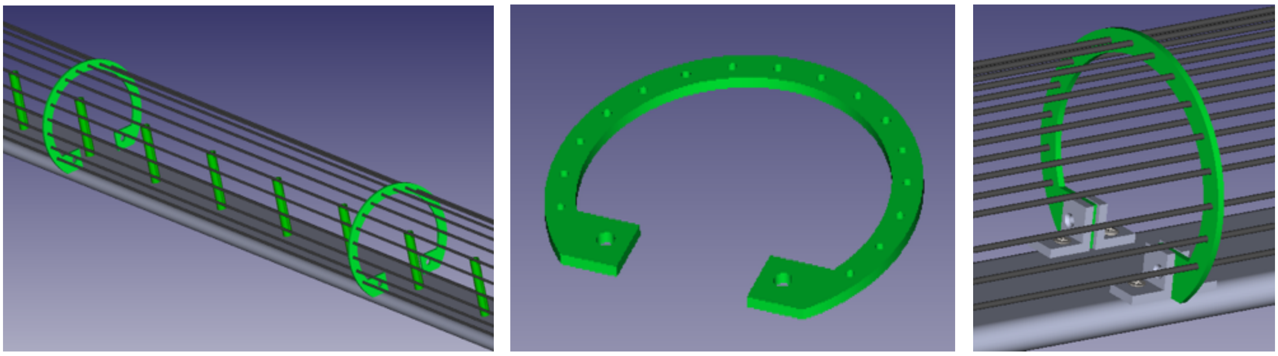


Figure A1.8. Left: 3D model of the region with the FR4 disks, the sensors' supports and the E-field shielding grid. Middle: detail of the FR4 disk. Right: the detail of the connection between the FR4 disk and the aluminum plate.

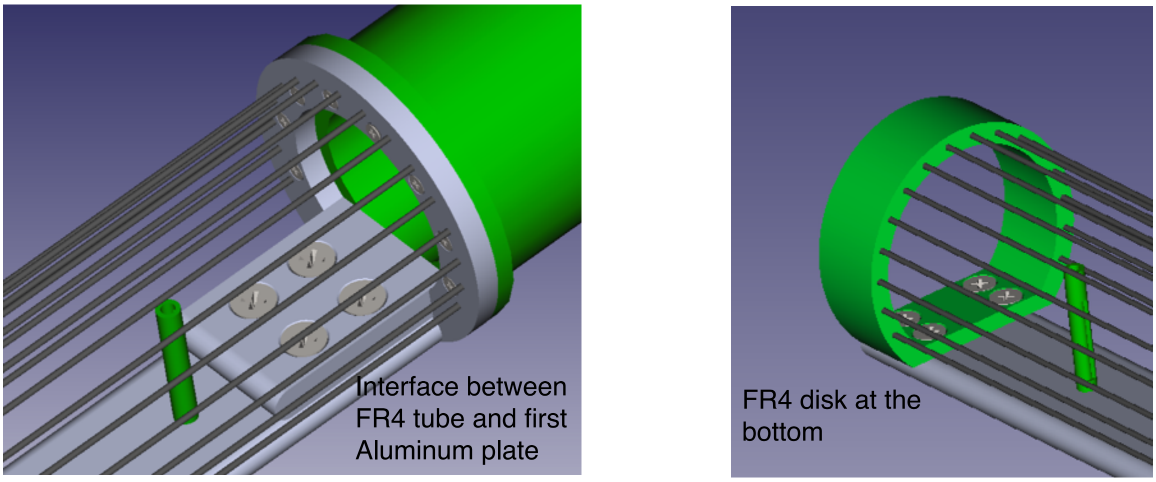


Figure A1.9. Left: 3D model of the connection between the top FR4 tube and the first aluminum plate. Right: 3D model of the FR4 disk at the bottom of the T-gradient monitor.

Since the entire T-gradient monitor is hanging from the flange, even a very small angular motion can result in large enough horizontal amplitude at its bottom tip, to touch the field cage. Thus, any significant lateral movement of the entire vertical array represents a risk to the field cage and electronics. This risk is mediated by a cylindrical cup installed at the bottom of the cryostat, enveloping the lower end, and by which the lateral motion of the lower tip of the array will be confined. The cup will be made of stainless steel such that its weight guaranties that it does not move, since it will not be fixed to the cryostat floor. The cup will be welded into a square stainless steel plate with dimensions that provide a tolerance of about 1 cm with the corrugation of the cryostat membrane. The height of the cup should be such that it takes into account the shrinkage of the aluminum structure, which will move upwards by about 8 cm for the entire system.

Cables

In order to maximize the precision of the temperature measurements and at the same time to guarantee good behaviour in cold and low outgassing the following requirements have been identified:

- 4 wires per sensor
- Teflon jacketed (FEP, PTFE) cables
- Twisted pairs
- EMC shielding every two pairs

Initially, flat ribbon cables were considered since they could be easier to handle. They have been finally discarded for several reasons:

- There are no commercially available cables that satisfy all the requirements. Companies as Axon-cable could made custom cables of these characteristics but they are very expensive.
- If a single cable per sensor is used the system is more versatile and the same cables can be used for additional sensors, which are not disposed in arrays.
- As shown in Fig A1.6 simple cable bundles can be easily configured.

Several models have been identified (see Fig. A1.10). We are also in contact with Axon-cable and waiting for a quote (see Fig. A1.11). Since in al cases the jacket will contain fluorine a derogation from CERN safety is required. A decision for the cables will be taken in two weeks.

BELDEN

SHIELDED CABLE MULTIPAIR, 2PAIR, 1000FT, 22AWG, 300V, RED

Technical Data Sheet (94.39KB) EN
RoHS compliant

Jacket Colour	Red
No. of Pairs	2 Pair
Wire Gauge	22AWG
Conductor Area CSA	-
Reel Length (Imperial)	1000ft
Reel Length (Metric)	304.8m
No. of Max Strands x Strand Size	7 x 30AWG
Voltage Rating	300V
Jacket Material	FEP
Conductor Material	Tinned Copper
External Diameter	3.759mm
Product Range	-

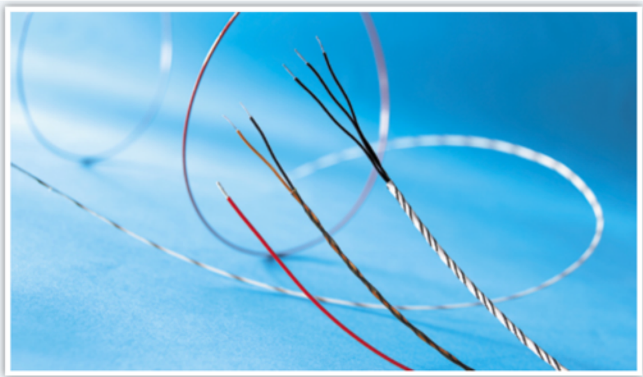
ALPHA WIRE

Multipair Screened Cable, Communication, Slate, 2 Pair, 24 AWG, 1000 ft, 304.8 m

Technical Data Sheet (130.99KB) EN
RoHS compliant

Jacket Colour	Slate
No. of Pairs	2 Pair
Wire Gauge	24AWG
Conductor Area CSA	-
Reel Length (Imperial)	1000ft
Reel Length (Metric)	304.8m
No. of Max Strands x Strand Size	7 x 0.2mm
Voltage Rating	150V
Jacket Material	FEP
Conductor Material	Tinned Copper
External Diameter	4.318mm
Product Range	-

Figure A1.10: Two cable options found at farnell.com



Axon' Cable supply a large range of wires and cables in compliance with **ESCC standards** for the space industry. Lightweight and highly resistant, they have been designed to meet the challenging requirements of the **launchers** and **satellites** including internal cabling of electronic boxes, LEO applications and cryogenic applications. From single core hook-up wires to coaxial cables and data bus cables, Axon' offers a large range of ESA wires and cables.

Advantages | Construction | Applications | Pricing

- Excellent penetration resistance under pressure.
- Excellent radiation resistance.
- Non-flammable.
- Resistance to most chemicals.
- Suited for thermal, mechanical or laser stripping.
- Good flexibility and low spring back effect: ESCC 3901 013.
- Resistance to atomic oxygen environment (ATOX): ESCC 3901 018.
- Controlled impedance for optimal data transmission (ESCC 3902 002 and ESCC 3902 003).
- Operating temperatures:
  - - 100°C to+ 200°C
  - - 200°C to + 200°C
  - - 200°C to + 180°C

Advantages | **Construction** | Applications | Pricing

Single wires, pairs, multi-stranded or shielded wires in compliance with ESCC standards:

- ESCC 3901.001: polyimide insulated wires and cables
- ESCC 3901.002: lightweight polyimide insulated wires and cables
- ESCC 3901.012: extruded cross-linked ETFE insulated wires and cables
- ESCC3901.013: polyimide insulated wires and cables
- ESCC3901.018: Celloflon®/polyimide/PTFE insulated wires and cables
- ESCC3901.019: Celloflon®/polyimide insulated wires and cables
- ESCC3901.021: Polyimide insulated wires and cables
- ESCC3901.024 : Wires and cables made with an abrasion resistant PTFE tape
- ESCC3902.002: Coaxial, triaxial and databus cables made with a Celloflon® dielectric and a PFA insulation.
- ESCC3902.003: Spacewire quadribus cable made with a Celloflon® dielectric and a PFA jacket

Figure 18: Axon-cable option.

Installation procedure

The T-gradient monitor will be assembled outside the cryostat, in horizontal position, on the platform above the cryostat. After the assembly is finished, it will be erected in the vertical position and introduced in the cryostat though port 14.4. The installation procedure will be tested at IFIC. Below, the different steps of the installation procedure are described:

1. **aluminum plates assembly:** The first step consists of the assembly of the aluminum plates, which constitute the main structure of the system. The three plates will be placed on the floor aligned with each other. Fig. 9 shows a conceptual design of the different elements involved in the connection between the two plates. First, the wire, that connects electrically each pair of plates, will be installed, followed by the insulating layer. Finally, there is the connecting plate with 4 screws on each side.
2. **Installation of top FR4 tube:** Prior to the cable installation, the FR4 tube will be connected to the aluminum plates with the help of the interface aluminum disk.

3. **Installation of sensor's support:** Once all plates are put together, the sensor's supports can be easily installed by screwing them into the aluminum plates.
4. **Installation of cables and sensors:** Cables will be distributed in bundles at IFIC, during the first phase of the test installation. In that way, we will make sure that all cables have the necessary length from the flange to its corresponding FR4 support in the aluminum structure. All cables with sensors will be passed through the FR4 tube at the top. Once all bundles are in place, with each sensor near its corresponding support, each cable can be introduced through the hole at the sensor's support and fixed with the screw.
5. **Installation of the shielding grid:** To build the shielding grid, the FR4 disks will be installed first, as shown in Fig. . The next step consists of introducing the 7.25 meters long stainless steel rods through their corresponding holes in the FR4 disks, starting from the bottom disk (the farthest from the FR4 tube). Finally, each rod is screwed into the top aluminum disk.
6. **Rotate into vertical position:** Once the entire system is mounted on the floor it can be rotated.
7. **Introduce into the cryostat:** The T-gradient monitor will be introduced into the cryostat with the help of a crane. Once the T-gradient monitor is introduced in the cryostat it will be positioned on the top of the flange adapter on which it will rest.
8. **Positioning into the cup at the bottom of the cryostat:** The T-gradient monitor will be introduced into the cup at the bottom of the cryostat with the help of an operator that will guide the cryostat through the manhole.
9. **Connect SUBD connectors to the flange:** After rotating the system in such a way that it will form an angle of 23º with respect to the field cage, the six male SUBD connectors will be connected to the flange. Notice that cables are a bit longer than necessary, so that they can be easily connected.
10. **Put flange in final position and screw:** The final step consists in closing the cryostat port with the flange

Test installation and quality control/assurance in Valencia

The full installation procedure will be tested in Valencia, except the final part: introducing the system into the cryostat. Any complications that may arise during those tests will be studied carefully and solutions will be implemented.

With the system fully assembled, it will be connected to the readout and a set of readings with all sensors and their final cables will be taken at room temperature. Those measurements will be compared with the ones taken during the calibration process in order to check whether cables/connectors have introduced any visible offsets or fluctuations. Comparison between adjacent sensors can be done in order to detect those effects, with the assumption that the temperature will be the same.

Transportation

Since sensors will be soldered into their corresponding cables only once, a small protection box will be use to avoid sensor damage during transportation. Cables will be distributed in bundles at IFIC. Each bundle will have its own box.

There will be three aluminum plates, 2.54 m long, with a total weight of 26 kg, such that they can be easily transported in a standard car. To avoid scratches that can compromise the high voltage performance, each plate will be properly packed into individual boxes.

Stainless still rods will be 3 m long. There will be 48 rods, with a total weight of 33 kg. They can be easily transported in a car. The rods will be soldered at CERN.

The rests of the elements (FR4 disks, connection plates, interface disks and sensors' supports) are small and will be transported with ease.

On site quality control/assurance

Once mounted, the system will be tested onsite. Tests will be equivalent to the ones described in the previous section except for the fact that they will use the final readout system, already mounted in the definitive electronics rack.

Schedule

	2017									2018				
	Apr	May	Jun	Jul	Aug	Set	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
Conceptual design	x													
Engineering design	x	x	x											
Prototyping		x	x	x	x	x								
Design calibration system	x													
calibration commissioning		x												
Sensor calibration			calibration of “other sensors” to be installed in August-Sep.			x	x							
Fabricate mechanical structure						x	x	x						
cable preparation and sensor-cable calibration								x						
sensor-cable assembly into mechanical structure									x					
tests in Valencia										x	x			
test at CERN												x	x	
installation														x

Table A1.1: Schedule for the Valencia T-gradient monitor

Development towards DUNE

The 10 kton DUNE detectors are twice as high as ProtoDUNE-SP. Thus the T-gradient monitor should be twice as long in order to cover the entire height of the cryostat. There is another important difference between DUNE and ProtoDUNE-SP and is that in DUNE no electric field shielding is necessary since all T-gradient monitors would be behind the APAs. Those two differences can be easily taken into account without major changes in the design. The system can be doubled in length by having six aluminum plates instead of three. Regarding the shielding grid, it can be easily removed (also the FR4 disks) without affecting the rest of the system. As shown in Table A1.2, the total weight will be similar because the longest aluminium structure is compensated by the removal of the shielding grid.

The installation process will be different but it can be easily extrapolated to DUNE given the modularity of the system (the longest piece is 2.54 m long). In DUNE it would have to be assembled once in the cryostat, starting from the flange at the top. A single section of the aluminum structure only weights 8 kg and can be easily held by a person. The installation procedure is very similar to the one in ProtoDUNE-SP, except that it will be done in a vertical position.

	SS shielding grid	Aluminum plates	Total
ProtoDUNE	28,9529856	24,6888	53,6417856
DUNE	0	49,3776	49,3776

Table A1.2. Masses for some of the elements of the T-gradient monitor in ProtoDUNE-SP and DUNE.

Appendix 2: The Hawaii T-Gradient monitor

Mechanical design

The Hawaii T-Gradient monitor will be installed at the port 9.6 (visible in Fig. 4), which is behind the APA. The APA is grounded, which simplifies the design process as the metal parts can be safely used for construction in this location.

Based on the simulation of the expected temperature profile in ProtDUNE-SP shown in Fig. 2, the expected temperature variations will be small and slowly changing over the detector height. Thus, the system will have to measure the vertical temperature profile with high precision and at points that are relatively far apart. The solution to these requirements is a movable system that will allow cross-referencing sensors in different locations, and thus achieving the relative measurement precision of as few as 5 mK, which is the reproducibility uncertainty of the selected Lakeshore PT102 sensors. This is also more than an order of magnitude better than the absolute measurement precision of the selected sensors which is 100 mK. The plan is to install sensors every 50 cm, with increased frequency of 10 cm at the very top and bottom 50 cm of the detector, for cross-referencing and precise measurements of more rapid temperature changes expected in these edge areas. The total of 22 sensors will be installed. Details of the conceptual design have been carried out by the engineer C. Kendziora from Fermilab.

Measurement procedure: the first temperature readout is taken with the lowest sensor all the way at the bottom of the cryostat. If we are not interested in the details of the temperature at the very top and bottom, the entire system is moved up 50 cm and the second measurement is taken. In this way, the lowest sensor is cross-referenced with all upper sensors in 50 cm steps. If the system is moved up another 50 cm, the second set of cross-referenced measurements is made. The space above the flange will allow for additional 50 cm movement up for a total 1.5 m range of motions. This redundancy will be very important in case any of the two adjacent sensors malfunction. For a refined measurements at the very top and bottom of the cryostat, smaller 10 cm steps up will be made, finely sampling areas where rapid change of temperature may be expected.

Sensors will be mounted on a set of rods that are connected with mating pins. Fig. A2.1. shows one of the 36 inches (91.44 cm) long rods with two sensor carrier boards mounted and mating pin holes at the top and bottom. Each of the rods weights just 8 lb (3.632 kg) which allows easy manual handling. In addition to the mating holes, there are larger holes that will be used during the installation process.

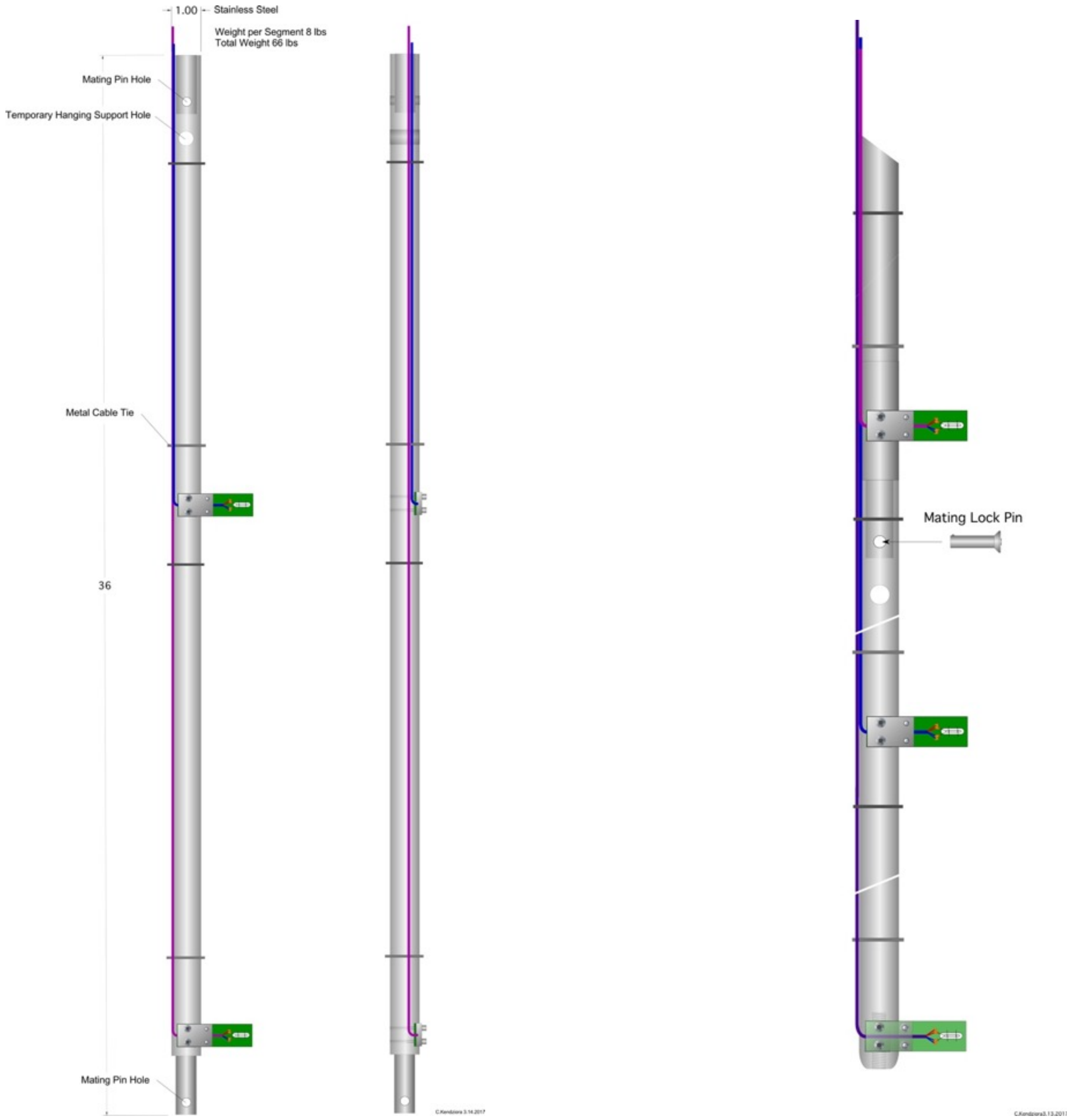


Fig. A2.1. Figure on the left shows one of the rods with two PCB sensor carriers shown. At the top and bottom are visible mating holes used to connect rods. Cables are routed along the rods and fastened in places for even load distribution. Sensors are soldered to the green PCB boards. Large hole at the top will be used during installation to hang the assembly from the flange while new segments are being added. Figure on the right shows the detail of the connection between the two rods with a mating lock pin which cannot be unscrewed accidentally or by vibrations.

Sensors are soldered to the PCB boards and boards are then screwed to the rods to ensure temperature insulation. Fig. A2.2. shows details of sensor mounting on the PCB, and PCB mounting on the carrier rods. A wide hole is cut in the PCB around the sensor to allow free flow of LAr. As a protection of the fragile sensors and their pins, sensor is kept in place with soldered suspension wires, looped around sensors for stability. Cable is soldered to the sensor pins on the PCB and a extruded channel on the PCB is used to guide the cable toward the rod. The cable is sandwiched between the PCB and stainless steel mount preventing any tension on the pin soldering joints. This can be seen in the Fig. A2.3.

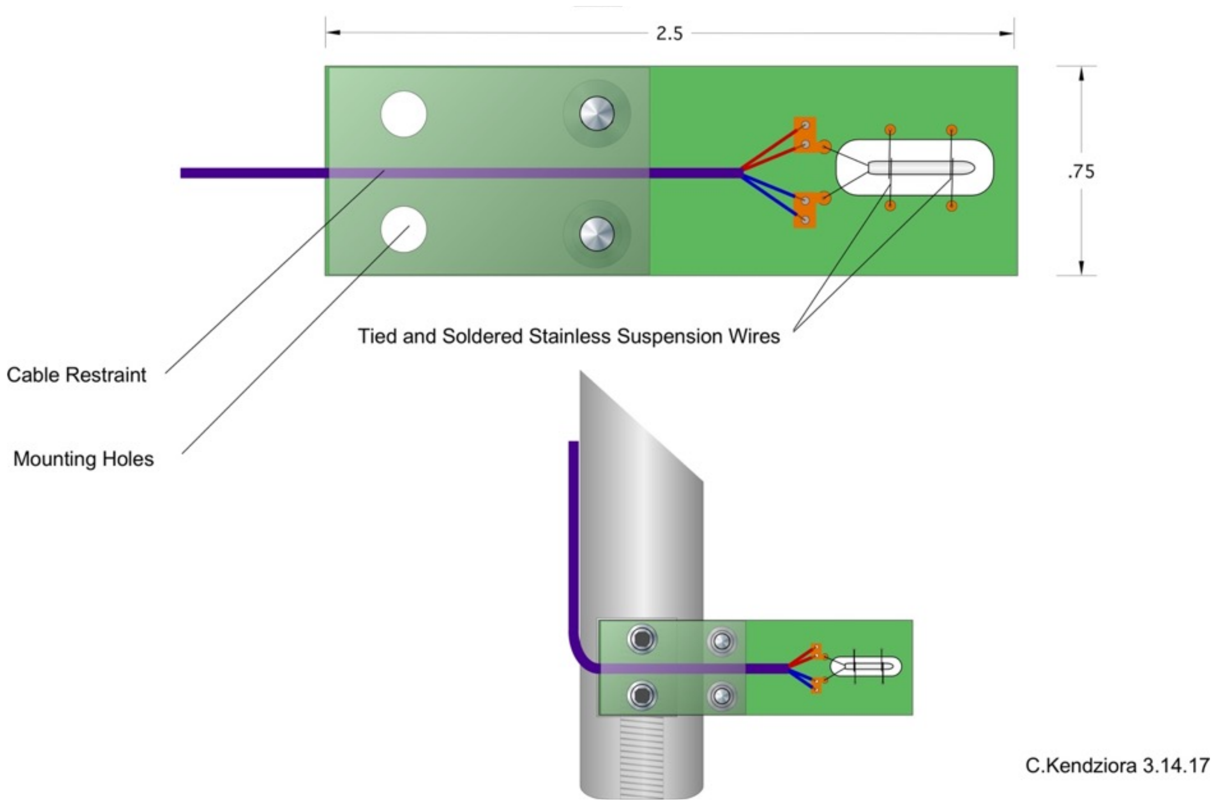


Fig. A2.2. Details of the sensor mount and PCB mount on the rod are shown along with the dimensions of the PCB.

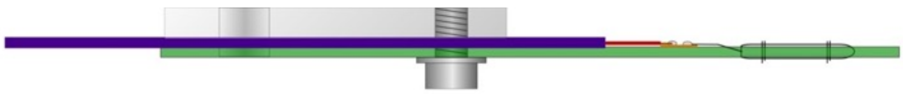


Fig. A2.3. Details of the cable restraining system at the sensor are shown. By sandwiching the cable between the PCB and stainless steel rod mount, the sensor soldering joints are tension free during construction and installation.

The top of the drive assembly is hanging from the flange. A long bellows is welded on the top of the flange. The bellows allows the entire system to move upward in the vertical direction beyond the flange level, while staying contained within the bellows, preserving the integrity of argon cryostat. In this way, the cross-calibration of the adjacent sensors can be achieved in as few as two steps (take the temperature measurement, move up 50 cm and take the second temperature measurement) and just minutes apart: time interval too short for changes in the argon's vertical temperature profile. Fig. A2.4. illustrates the concept of the vertical motion of the system. The vertical movement of the bellows is controlled using a rack and pinion gear connected to a stepper motor which can position the entire array with submilimeter precision. The stepper motor is controlled via a laptop computer. Fig. A2.5 shows the drive assembly on the top of the flange.

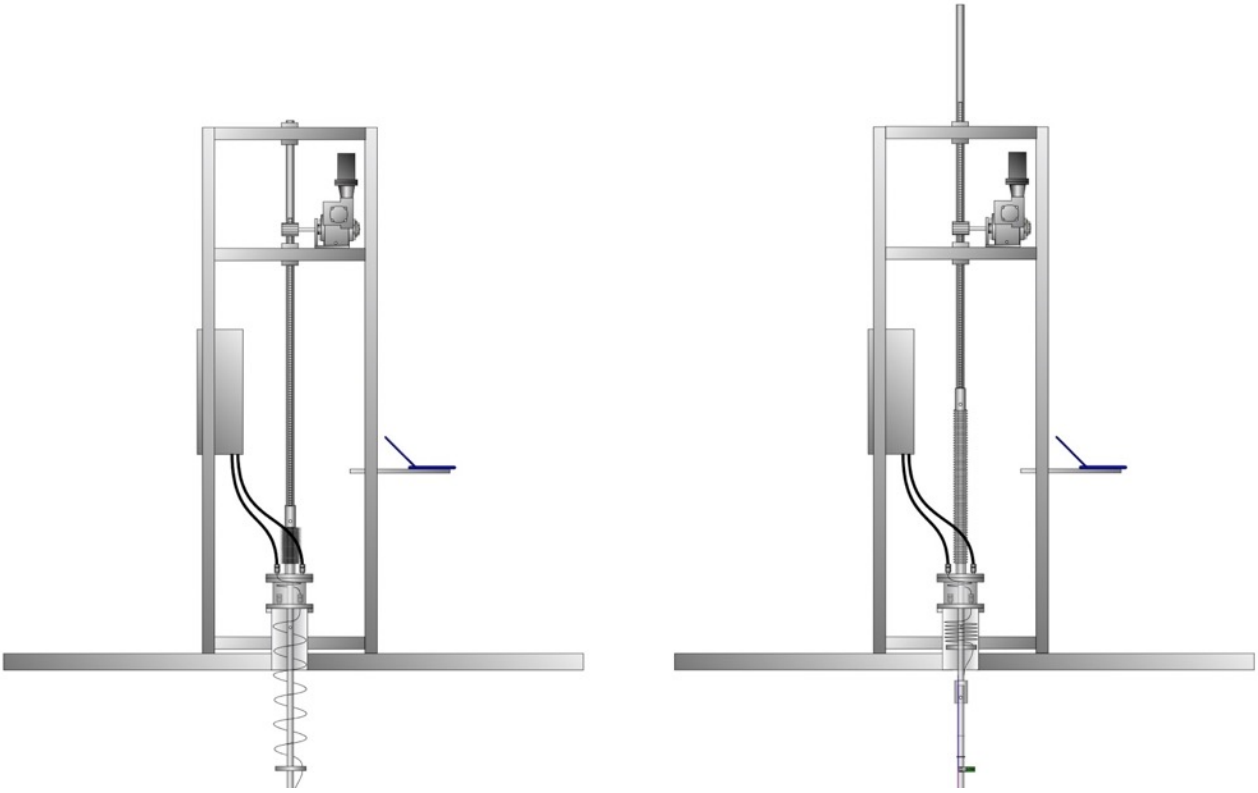


Fig. A2.4. The T-gradient monitor in the expanded and contracted position. The system remains contained within bellows at all times, eliminating risk of gas leaks due to motion.

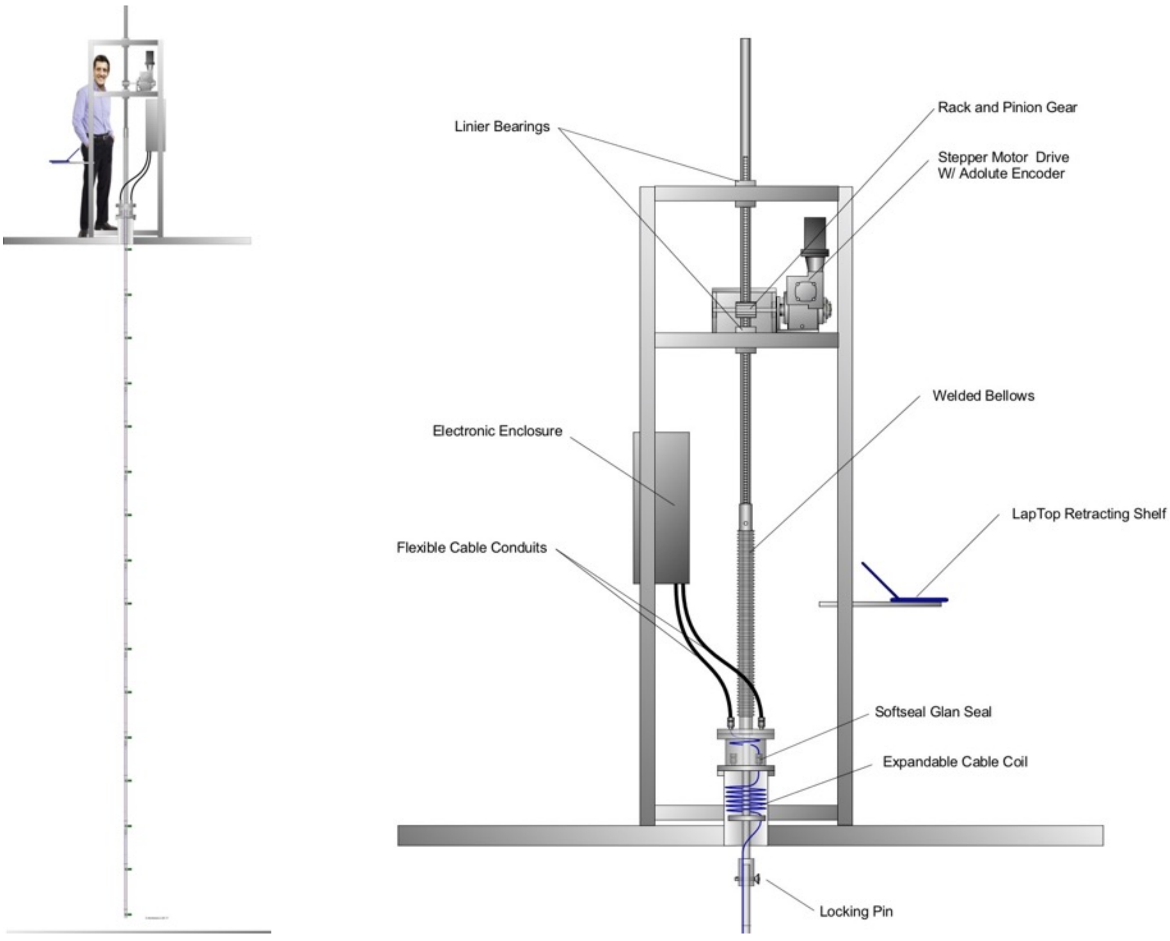


Fig. A2.5. On the left is the Hawaii T-gradient monitor overview with a person next to the drive assembly for perspective. On the right are the details of the assembly drive showing details of the seal, welded bellows, stepper motor, rack and pinion gear and electronic enclosure.

The rod assembly is connected to the rack and pinion gear with a mating pin. A special recessed push-button quick-release pin will used that ensures the safety of the connection. Fig. A2.6. shows details of connecting the rod assembly to the drive mechanism.

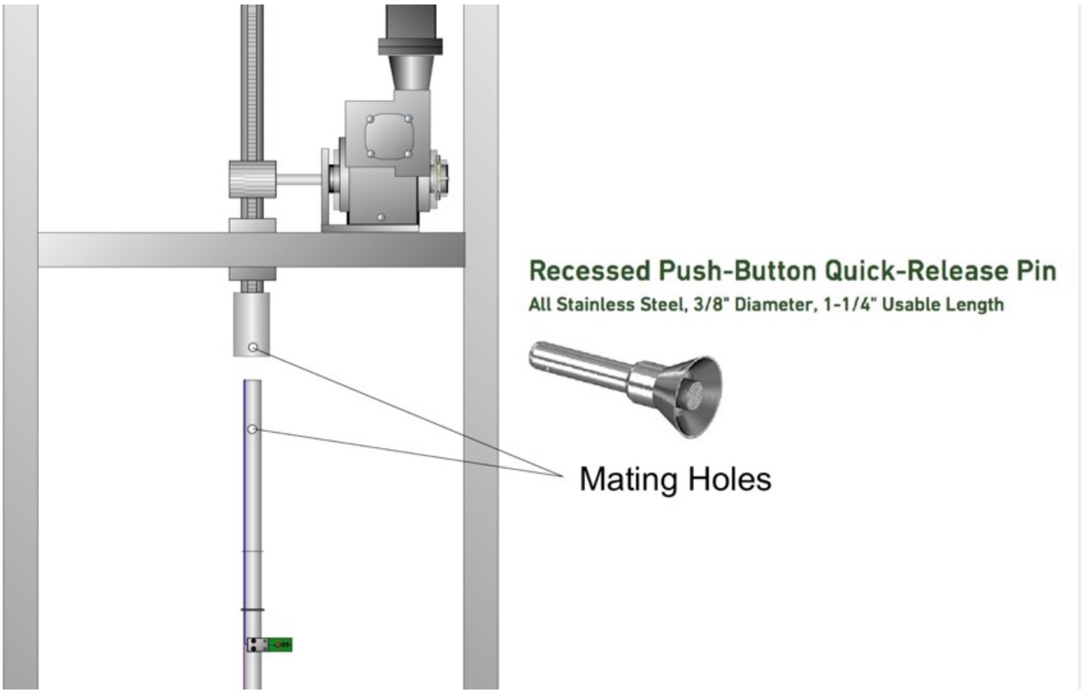


Fig. A2.6. Details of connecting the rod assembly to the rack and pinion gear with a special recessed push-button quick-release pin is shown.

Restraining cup at the bottom of the cryostat

The restraining cup will be placed at the bottom of the detector to disable any dangerous lateral motion of the assembly that may act like a gigantic pendulum. The cup will be fastened to the floor and have 1.8 m high metal grid to allow easy flow of LAr while limiting any possible swing.

Cables and feedthroughs

Experience from the 35 ton detector prototype showed that, despite the four point connections of the sensors, the readout was influenced by connectors and feedthroughs. The solution to this problem is to minimize bad connections and that will be achieved in a following way:

- Use continuous cables with connections only at the sensor and readout. For this purpose we would like to utilize special type of feedthroughs using novel compression Conex technology shown in Fig. A2.7.
- Utilize only soldered connections in argon
- All cables have the same length
- Cable restraints at each sensor
- Sensors securely mounted on printed circuit boards.

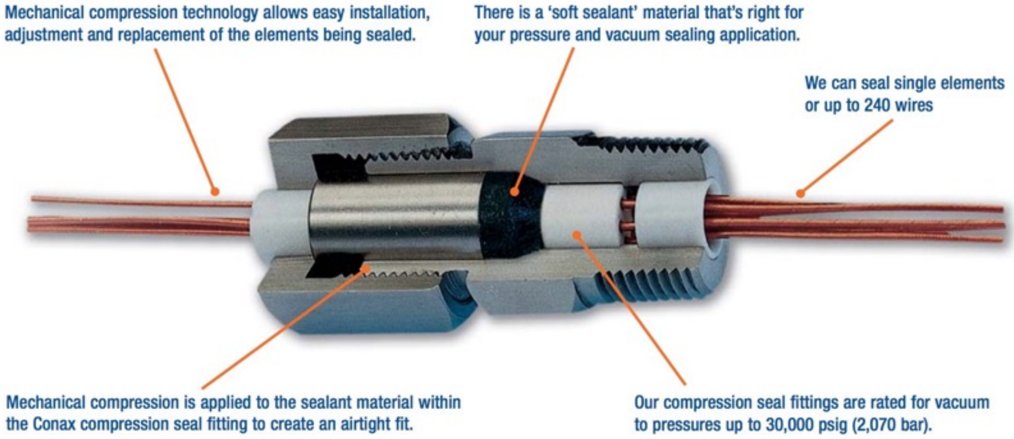


Fig. A2.7. shows the Conex feedthrough that provides compression seal without the need to cut the cable.

Installation procedure

Installation procedure assumes feeding segments through the top flange and assembling the stainless steel rods along the way.

Fig. A2.8. shows details of the T-gradient monitor installation process.

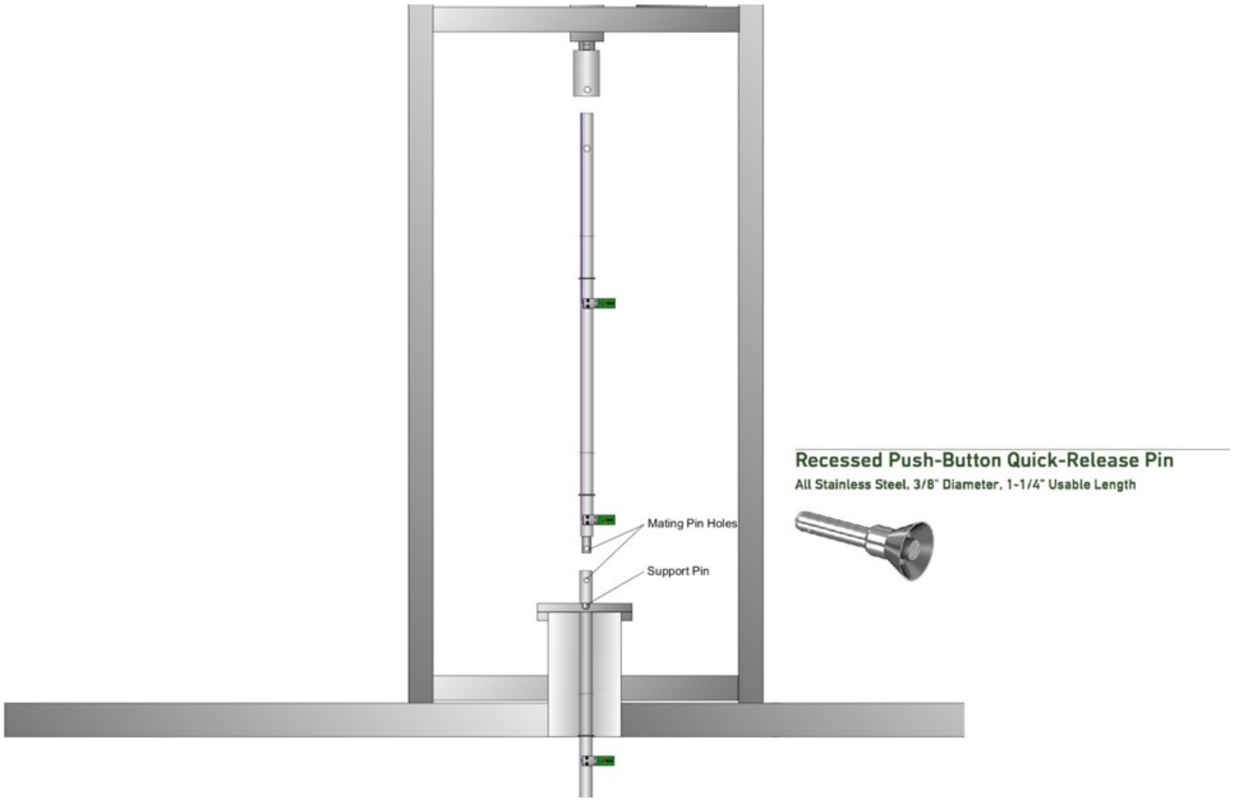


Fig. A2.8. shows details of assembling the T-gradient monitor through the flange on the cryostat.

Quality control/assurance

The system will be assembled and tested in Hawaii. A mock up flange will be used for this purpose. Test installation will serve to solve any identified installation problems.

All sensors will be tested prior and after installation with a readout system and potential sources of noise will be identified.

Schedule

Design will be finalized by early Fall. Fabrication will take about one month in the Fall. Test installation and quality control tests will be conducted in winter 2018 with expected installation at CERN in the Spring 2018.

Development towards DUNE

In case of favorable performance in ProtoDUNE-SP, this system can directly be replicated in DUNE.

Appendix 3: Other temperature sensors in the ProtoDUNE-SP cryostat

The T-gradient monitors will only cover two fixed XY positions in the cryostat. Additional sensors calibrated to the same precision will be used to complement those measurements, with the aim of providing a 3D temperature map, as precise as possible. Furthermore, the cryogenics group is interested in measuring the temperature of the inner cryostat membrane during the cool-down and filling processes. With this purpose a set of standard RTDs will be mounted on the cryostat walls.

Mechanical design

Extensive research was done to identify mechanical elements where additional RTDs could be installed. Shown below is the list that was considered, with pros and cons of the different elements and the final choices:

- *TPC end walls*: This is the area surrounding the FC aluminum profiles at high electric potential. Sensors and cables in this area would need electric field shielding, which would dramatically complicate the design. Therefore those elements were rejected as potential RTD mount locations.
- *APA frames*: They were initially considered because there is no electric potential behind them. However, there is very little space available, since most of the space is taken by wires.
- ***Top ground planes***: This is a favorable place to locate RTDs since there is no electric field above them and the available space is sufficient. They are also sufficiently close to the active area.
- *Bottom Ground planes*: The same as for the top ground planes, there is no field beyond these ground planes (below in this case). However, the installation of the sensors in this area is complicated because this would have to be done very early in the installation process.
- ***Bottom cryogenics pipes***: They constitute an alternative to the ground planes at the bottom of the cryostat. They have the advantage that the sensors and cables can be easily installed at the time when there is nothing in the cryostat except the pipes.
- ***Cryostat walls***: It has been recommended not to weld anything to the cryostat walls. It has been suggested to use the corners (joints between two — not three — walls), which are reinforced. This is a good place for the standard RTDs since they have to touch the walls. However, those areas are not very useful for the high precision 3D map since the proximity of the walls will affect the temperature changes in a different way, compared to the Ar temperature in the active detector volume.
- *Detector support structure*: The detector support structure has been rejected, because it is above the liquid argon surface.

Fig. A3.1. shows the map for top (left) and bottom (right) sensors. The pattern is the same for both, except for the set of additional sensors at the pipe's edges which are disposed at two different heights. This additional set of sensors is planned since it located in a particularly interesting region where LAr flows into the cryostat. Fig. A3.2. shows a conceptual design for the sensor's support, for both sets of sensors, the ones on the pipes and on the ground planes. Notice that the ones on the pipes may have to be rotated if the false floor is sufficiently close in height to the pipes. This would not be a major problem since cables and sensors could be installed before the false floor, with the sensors' supports in the horizontal position, which would then be rotated 90º right after the false floor is removed.

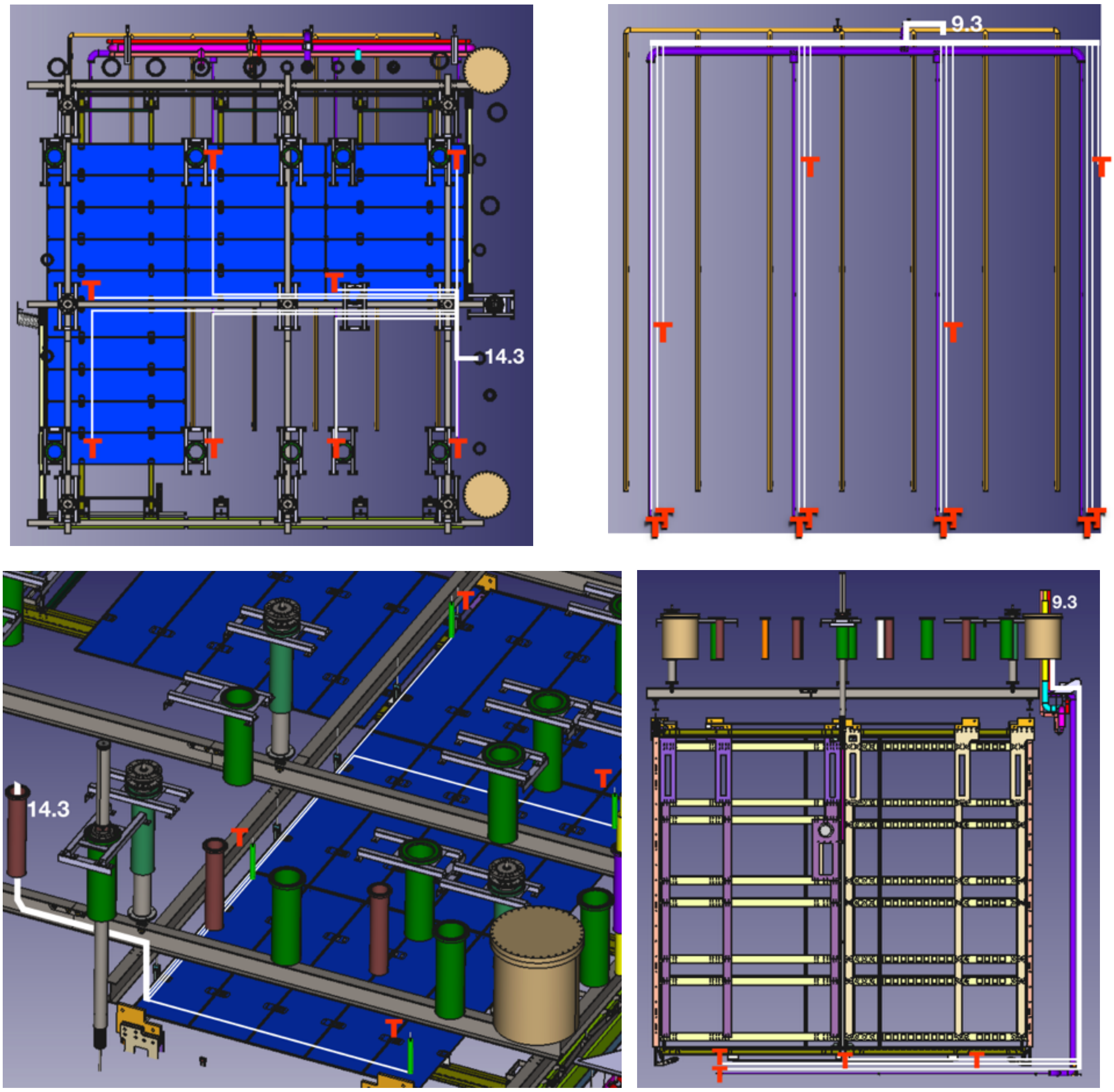
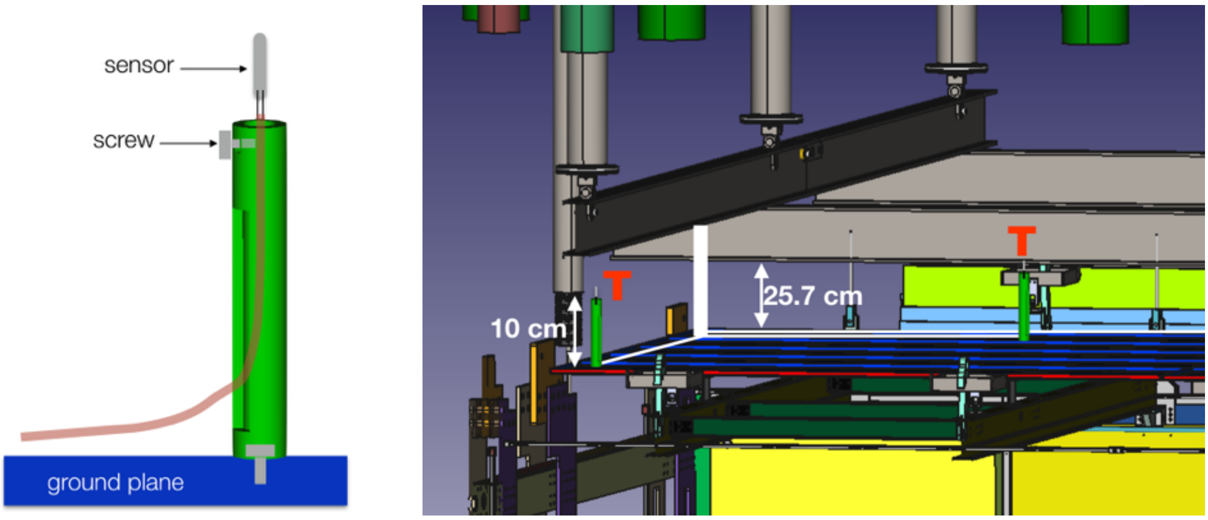
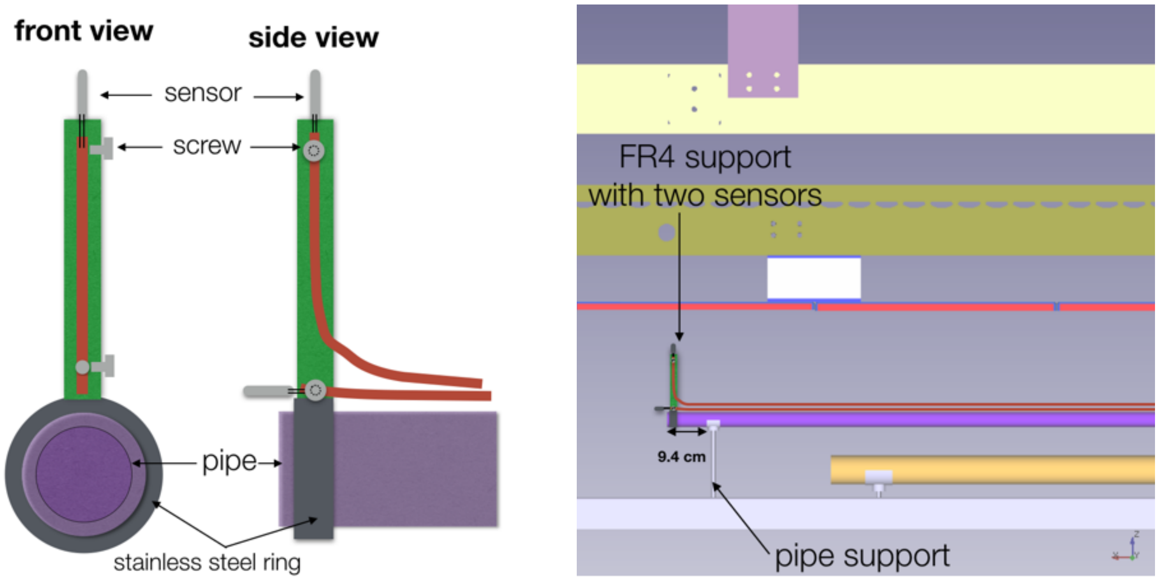


Figure A3.1. : Map of sensors and cable routing at the top (left) and at the bottom (right).



FigureA3.2. Conceptual design of the support for the ground plane sensors.



FigureA3.3. Conceptual design of the support for the pipes' sensors

Cables

As for the T-gradient monitors several cable configurations have been considered. In the end, it was decided to use the same type of cable as for the Valencia T´gradient monitor.

Installation procedure

The installation sequence for the additional RTDs is shown in Fig. A3.3.

	pipes	End of June, beginning of July: Pipes are mounted on the cryostat
end July-Sep 27	**bottom sensors**	Install sensors (12 sensors) on the **bottom pipes** and route cables from sensors to the bottom of the vertical section of the LAr pipe
end July-Sep 27	**bottom sensors**	Install sensors on the **cryostat floor** (2 sensors)
end July-Sep 27	**false floor**	Install false floor
end July-Sep 27	**false floor**	Once false floor is installed the scaffolding can be used to route cables from the bottom of the vertical section of the LAr pipe to port 9.3
end July-Sep 27	**wall/roof sensors**	Sensors/cables can be also installed on the lateral walls and roof of the cryostat. North cables will go to port 14.3 and south ones to port 9.3
Nov 7-Jan 5	**top GP sensors**	For each top GP module in the clean room, sensors and cables are installed (8 sensors in total)
Nov 7-Jan 5	**top GP sensors**	CPA/FC/GP modules are move sequentially into the cryostat. As they arrive there we route the cable to modules beside
Jan 5-20		south GPs are rotated and cables between GP modules are tighten and routed towards port 14.3
Jan 5-20		north GPs are rotated and cables between GP modules are tighten and routed towards port 14.3

FigureA3.3. : Tentative installation sequence and schedule.

Quality control/assurance

All sensors will be calibrated with their final cables at IFIC. During the calibration process all kind of tests will be carried out to check the accuracy and the reproducibility of the measurements.

Schedule

	2017									2018				
	Apr	May	Jun	Jul	Aug	Set	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
Conceptual design	x													
Engineering design		x												
Prototyping		x	x											
Design calibration system	x													
Calibration system commissioning		x												
Sensor calibration			x											
Cable preparation and sensor-cable calibration				x										
Installation of bottom sensors					x	x								
Installation of membrane sensors					x	x								
Installation of top sensors								x	x					
Deployment of GPs										x	x			

Table A3.1: Schedule for the additional RTDs

Development towards DUNE

This system can be used in DUNE without any major additional complications. Few items will have to be considered:

- *Sensor and cable choice*: Similar sensors and cables could be used in DUNE. However, having in mind the DUNE timeline, additional research will be conducted to identify superior sensors and/or cables that may be available at the time.
- *Sensor supports:* In principle, the same supports could be used.
- Sensor c*alibration:* The calibration system will evolve towards a more sophisticated system able to test more sensors at the same time, since the number of sensors requiring calibration will be much higher and the cables will be much longer.

- *Sensors' map: The sensors' map will be* different for DUNE, however similar reasoning used to identify adequate locations in ProtoDUNE-SP, can be applied again.
- *Cable routing:* The cable routing will have to be studied in conjunction with the sensors' map. An important advantage in case of DUNE is that the sensors' map will be defined prior to the ports' map, reducing the number of design limitations encountered in ProtoDUNE-SP.