DEEP UNDERGROUND NEUTRINO EXPERIMENT

CALCI meeting
22/04/2020

Temperature monitoring system

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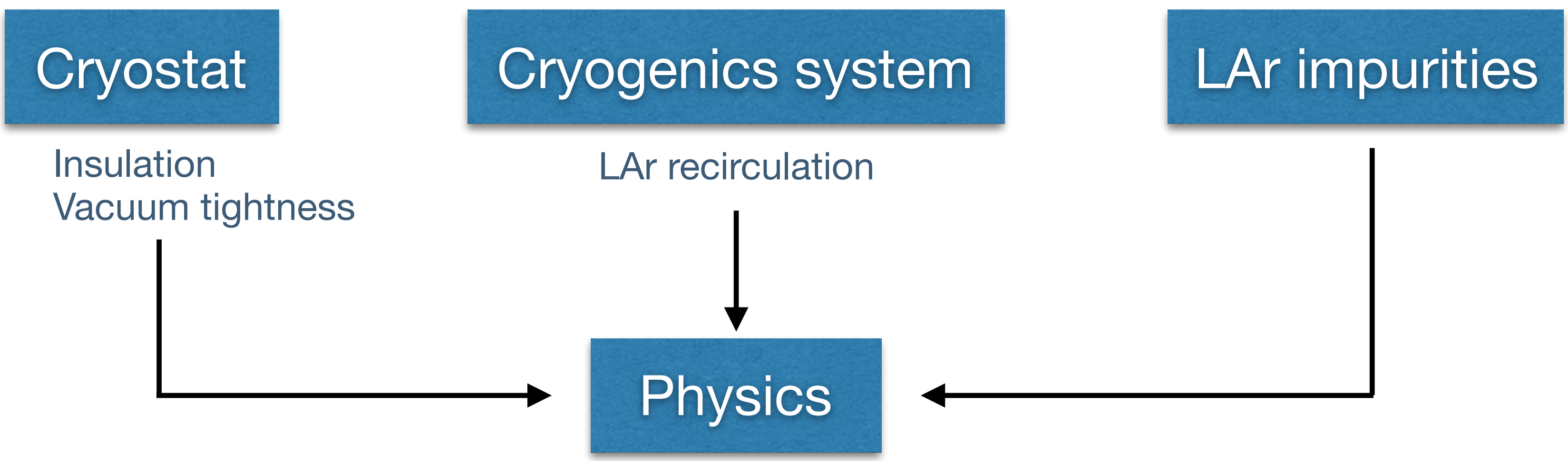
(IFIC-Valencia)

On behalf of the Temperature group: CERN, IFIC, Hawaii, SDSU

Introduction

- The first DUNE far detector module will use the largest cryostat ever built (20xProtoDUNE) for a TPC. Thorough understanding of this huge TPC can only be achieved with extensive detector monitoring
- At least for this module a sufficiently dense 3D grid of temperature sensors should allow us to understand the behaviour of the system during its **operation** and ensure that lack of understanding of LAr velocity, density & purity does not compromise **physics**



Drift velocity, flow (ions), electron lifetime, energy calibration

The system will help in mitigating risks at reasonable cost (< 200 K$/10-kt)

CFD simulations

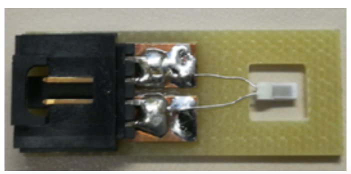
- Used to **design the cryogenic system** in ProtoDUNE and DUNE: number/distribution of LAr inlets/outlets, LAr flow-rate/temperature
- In DUNE (and ProtoDUNE) we will use it to:
  - **Validate the cryogenics system** with temperature and purity data. Get confidence on the full system and detect malfunctioning
  - **Predict LAr properties** everywhere in the TPC after constraining with temperature (purity, level and pressure) data. **These properties are important for offline corrections**
    - Charge attenuation, drift velocity and ion flow
- CALCI working primarily with **SDSU** with some advice from **E. Voirin**

Temperature maps + CFD simulations

is probably the only practical way of **quickly predicting** everywhere in the TPC the **LAr properties that are relevant for Physics**

Precision and standard RTDs

- Precision RTDs have 10 times lower RMS, with same cables and readout
- Excellent reproducibility of 2.5 mK for precision RTDs; significantly (100 mK?) worse for standard RTDs

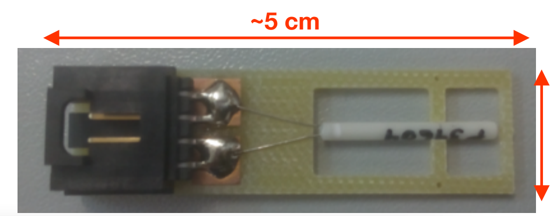


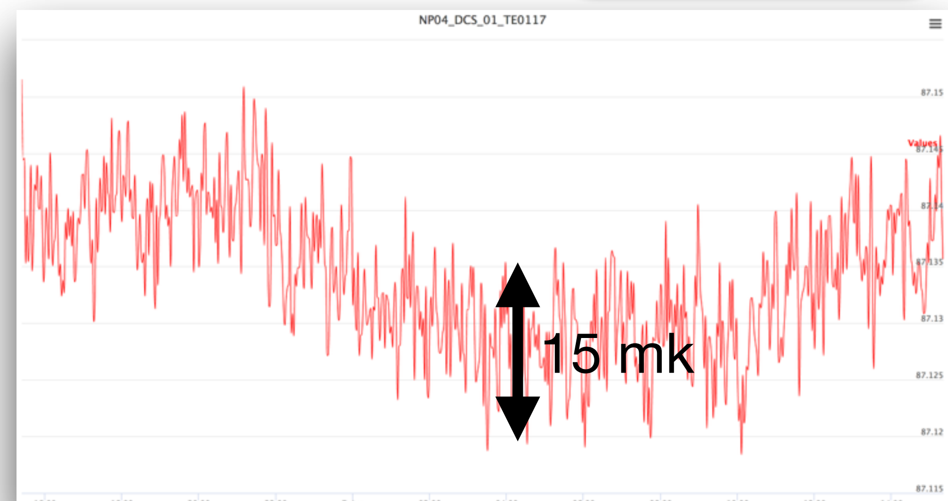
<5 $

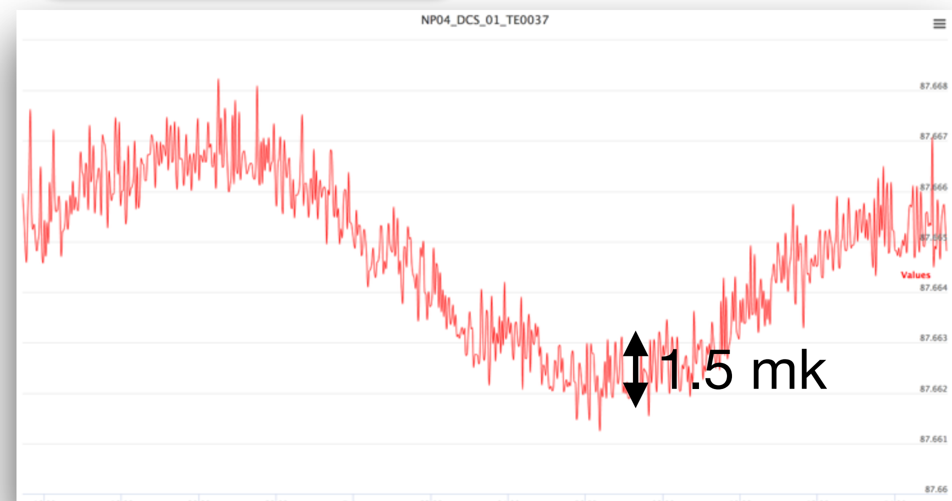
standar sensor

100 $

precision sensor







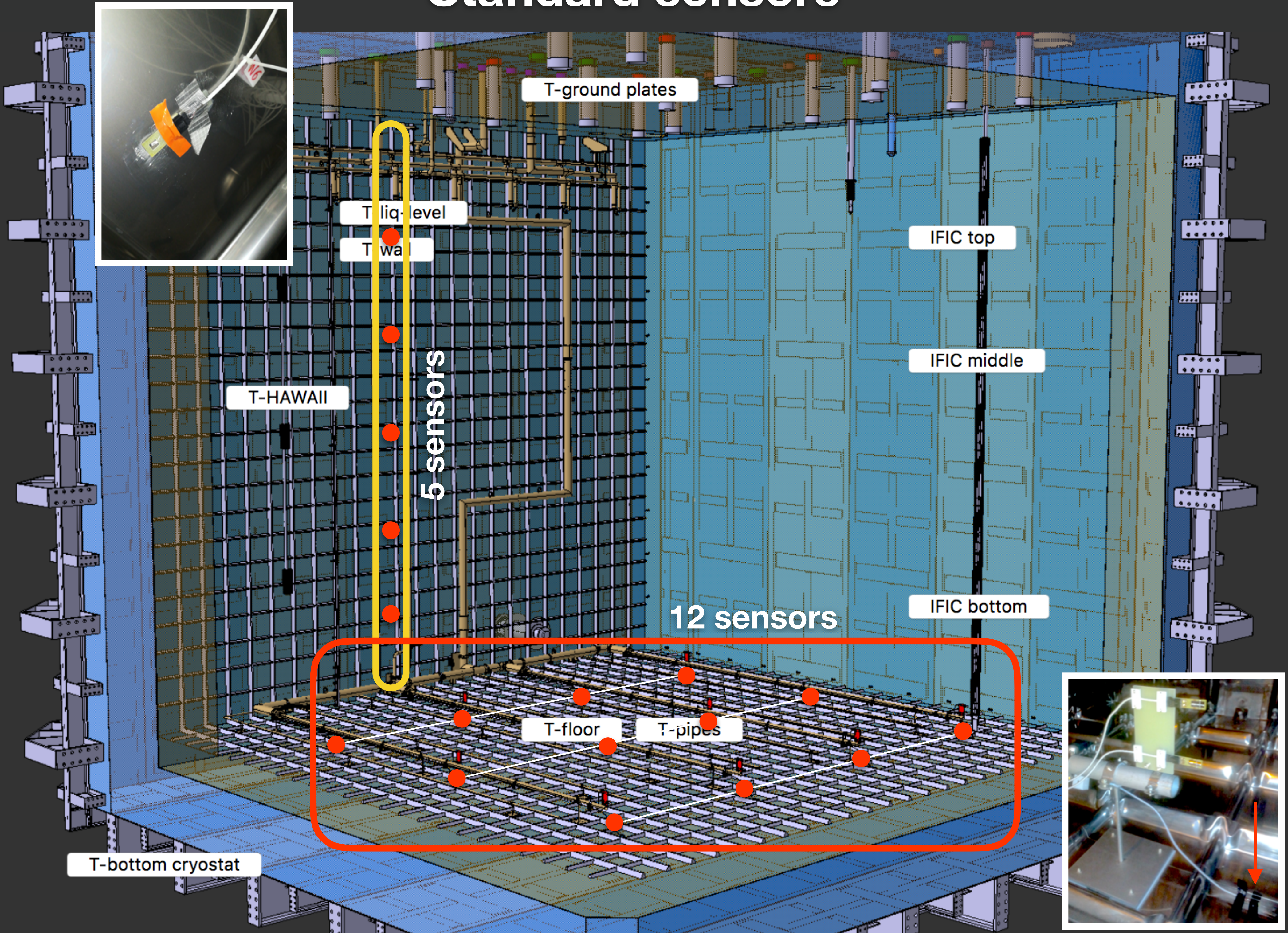
TPC temperature evolution during one day

Motivation of each system

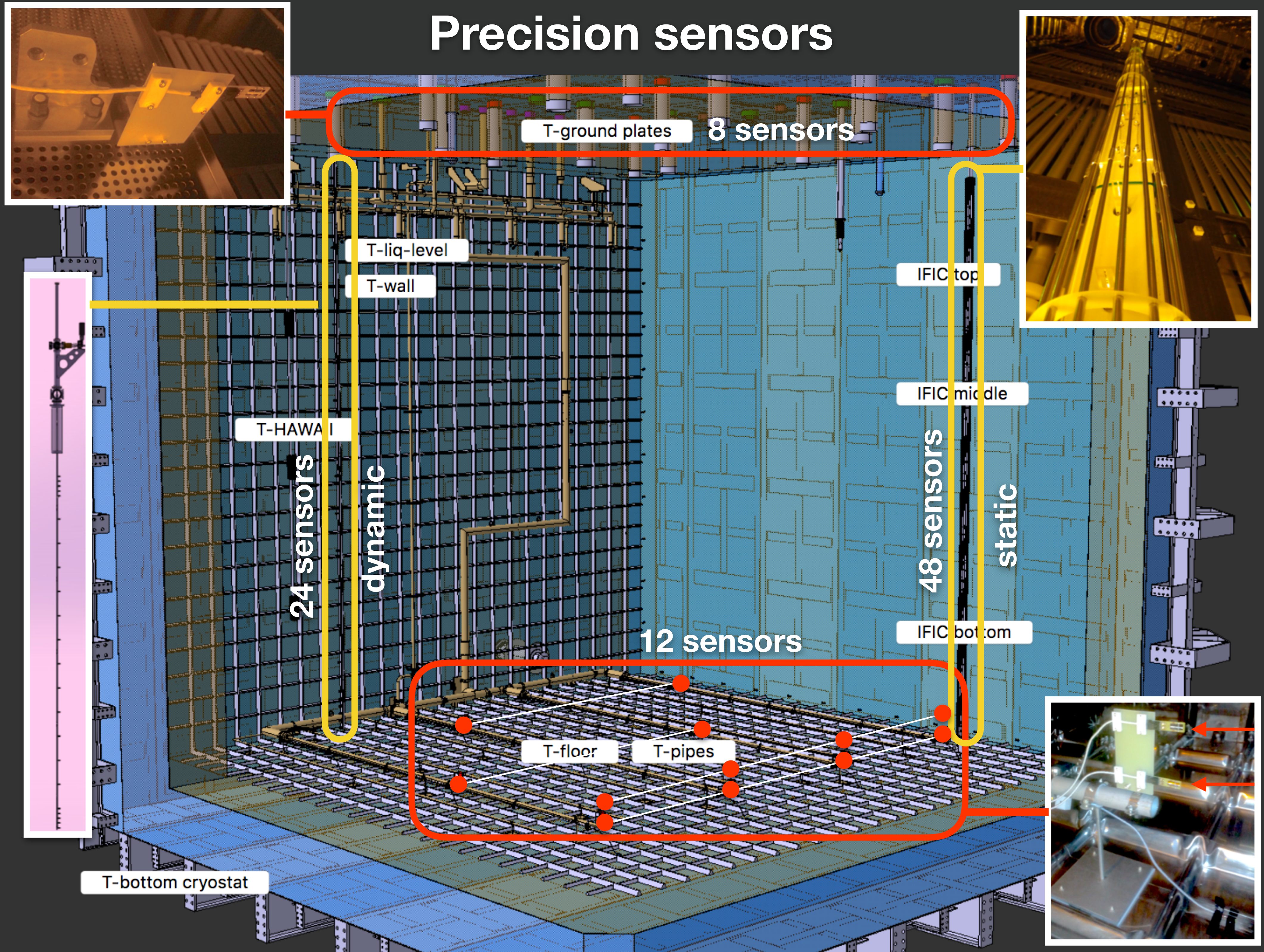
System	Precision	Motivation
Vertical arrays Top/bottom Horizontal 2D grid RTDs at inlets and pumps	~mK	• monitor cryogenics system behaviour during operation • constrain CFD simulations for e-lifetime, drift velocity and ion flow prediction
Floor	20-50 mK	monitor the presence of LAr when filling starts
Walls & roof	20-50 mK	monitor cryostat membrane temperature during cool-down and filling
APA frame	20-50 mK	monitor APA frame temperature during cool-down and filling
Vertical array in gas	20-50 mK	constrain & validate CFD simulations in ullage

Description of ProtoDUNE-SP systems

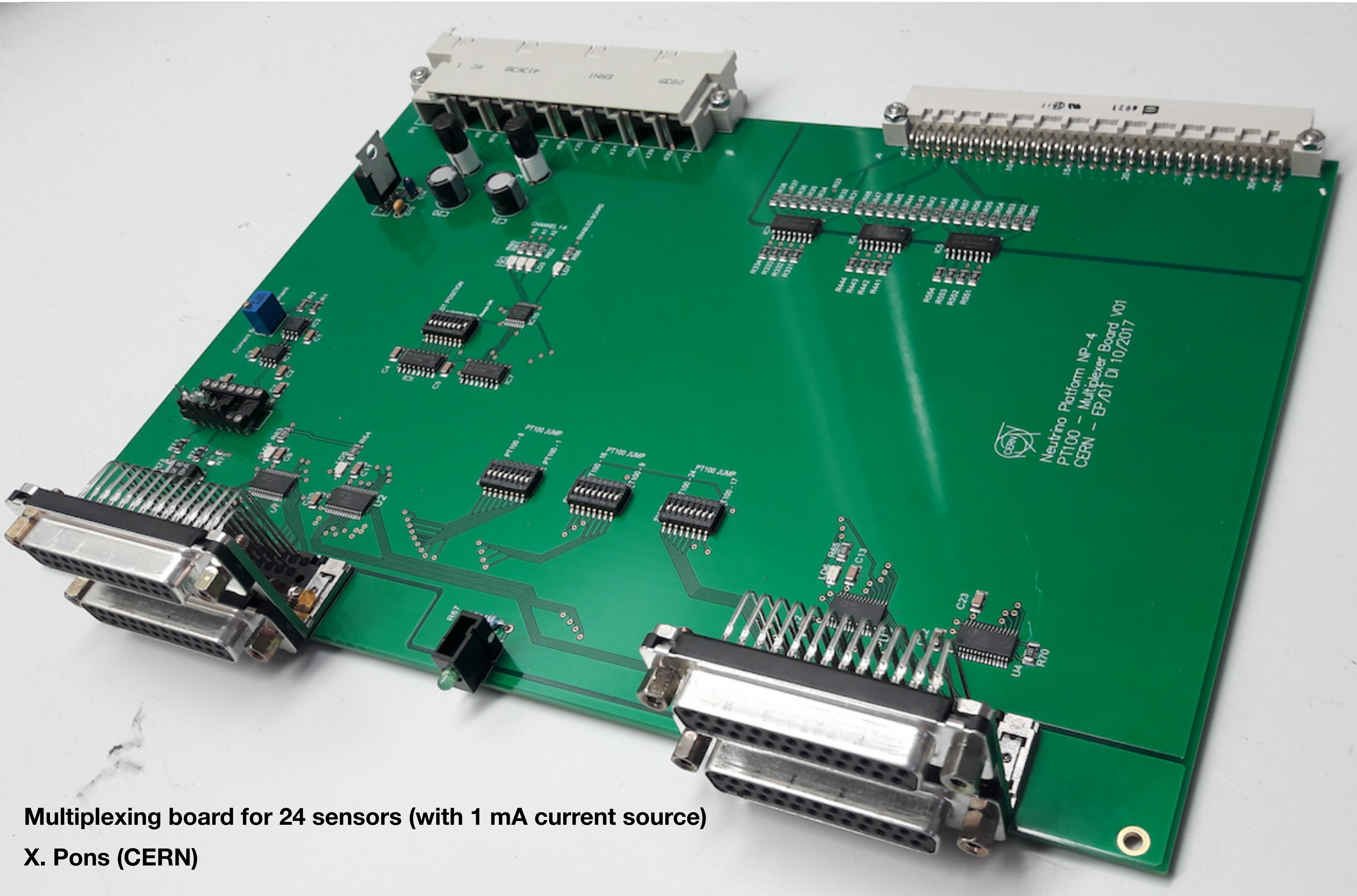
Standard sensors



Precision sensors



Crucial to obtain mK precision



Multiplexing board for 24 sensors (with 1 mA current source)

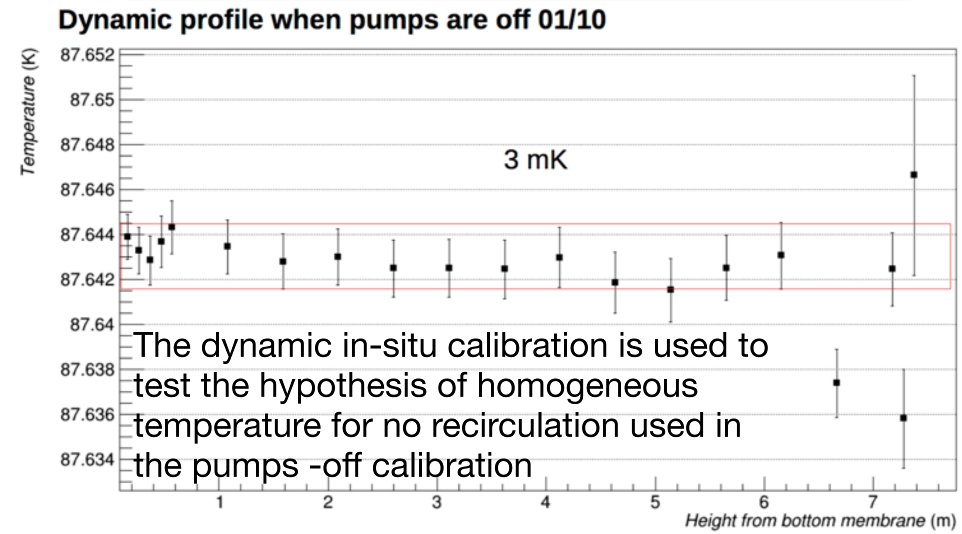
X. Pons (CERN)

Precision RTD Calibration

https://indico.fnal.gov/event/16764/session/17/contribution/157/material/slides/0.pdf

- **Laboratory:** All sensors, but only satisfactory (3 mK) for static T-gradient
- **Dynamic**: Model independent in-situ calibration moving sensors vertically
- **Pump off**: All sensors assuming homogeneous temperature for no recirculation

pumps-off / dynamic comparison



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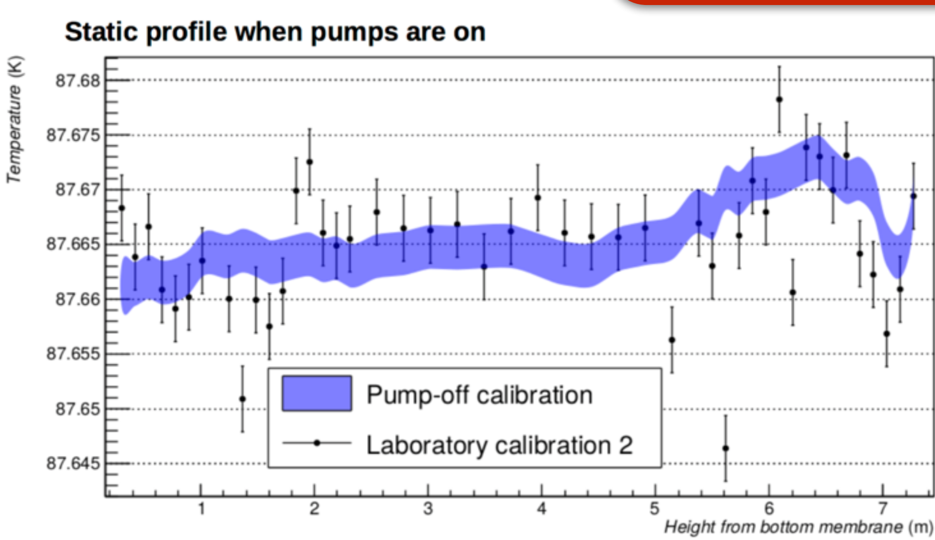
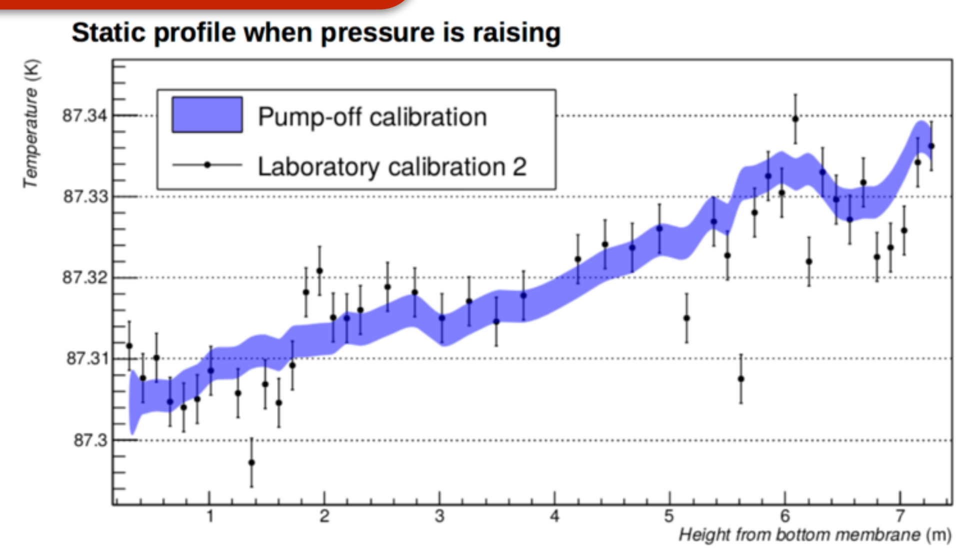
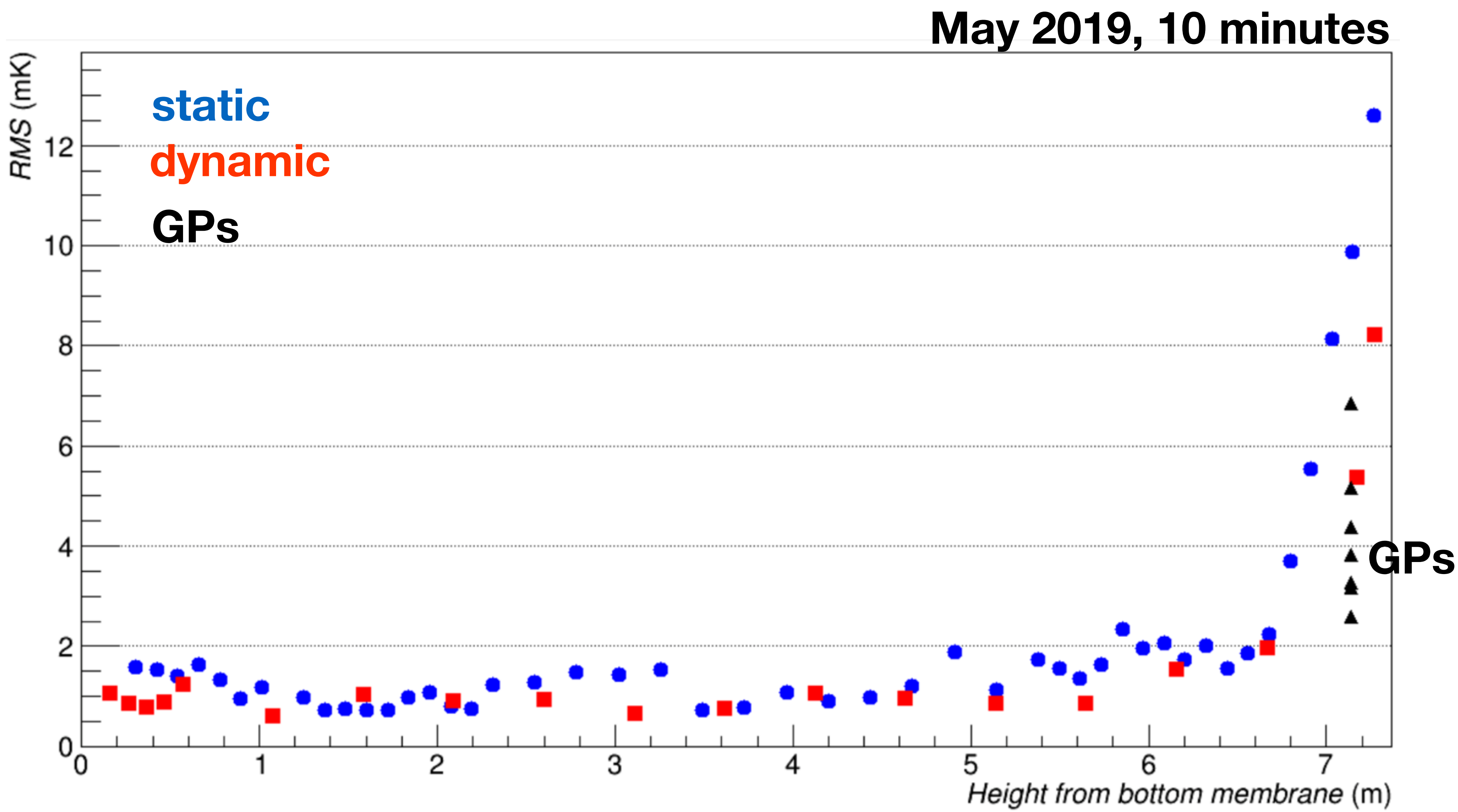




Temperature fluctuations

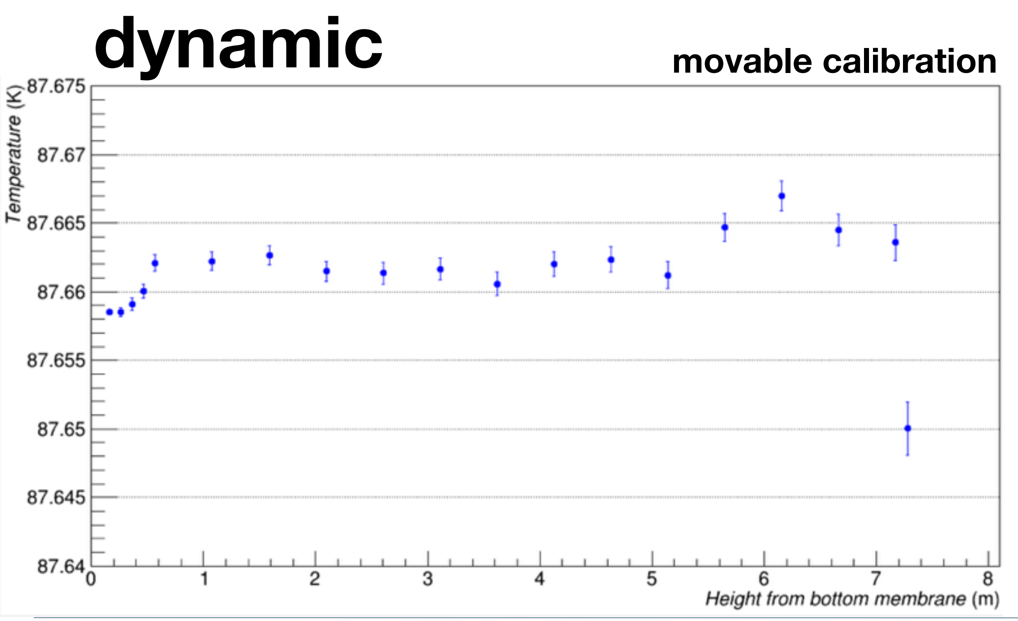
- <2 mK below 6.5 m
- Increase dramatically near LAr surface

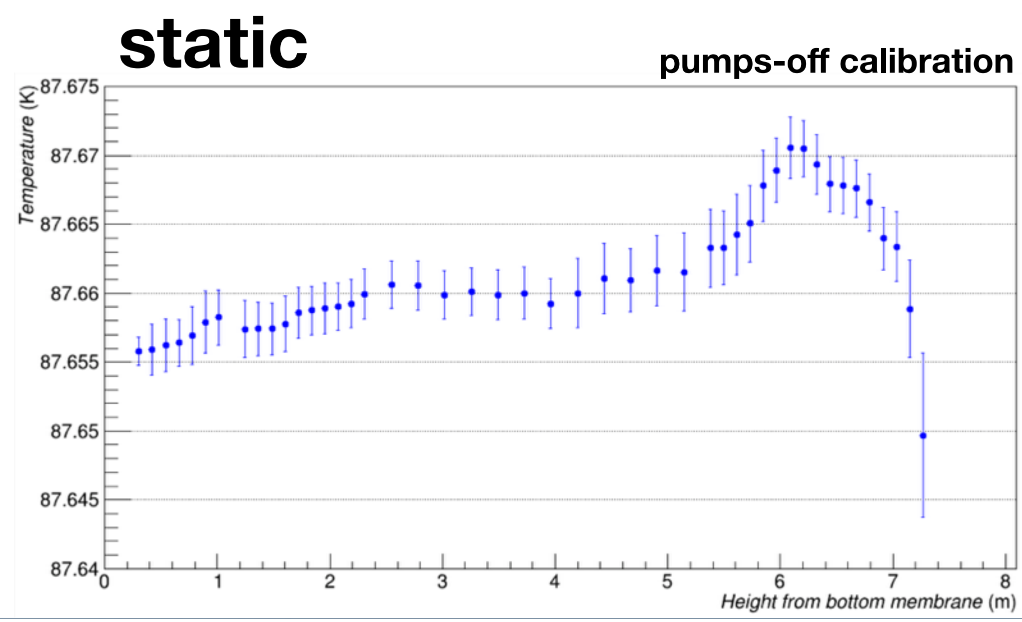


Vertical profiles

- static and dynamic cross-calibrated to each other with pumps-off
- For normal operation:
  - **Gradients below 15 mK**
  - **Larger gradient in static profiler**

Vertical gradient depends on location





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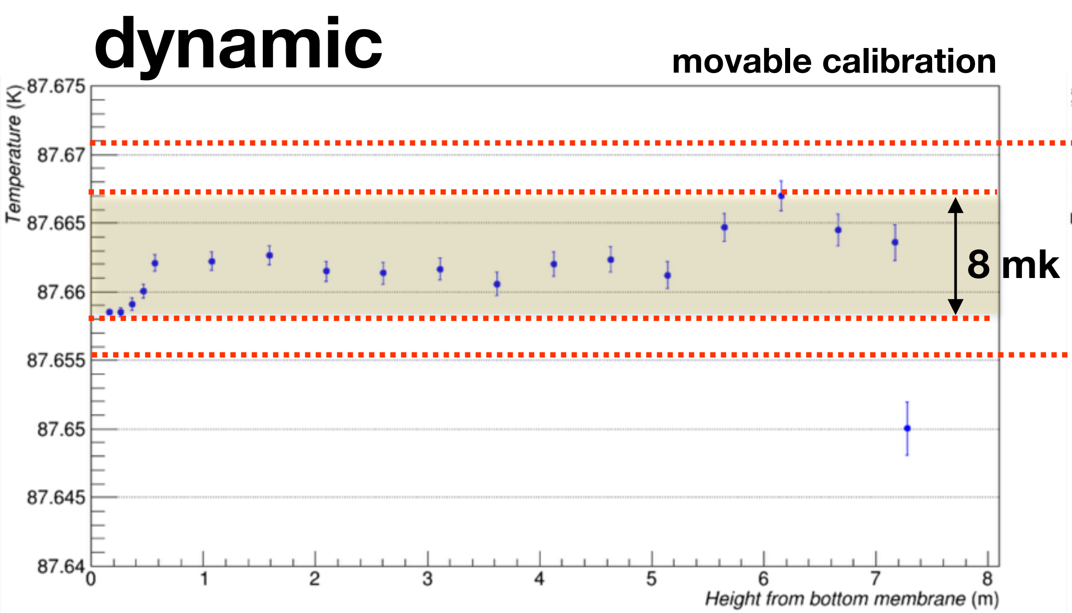

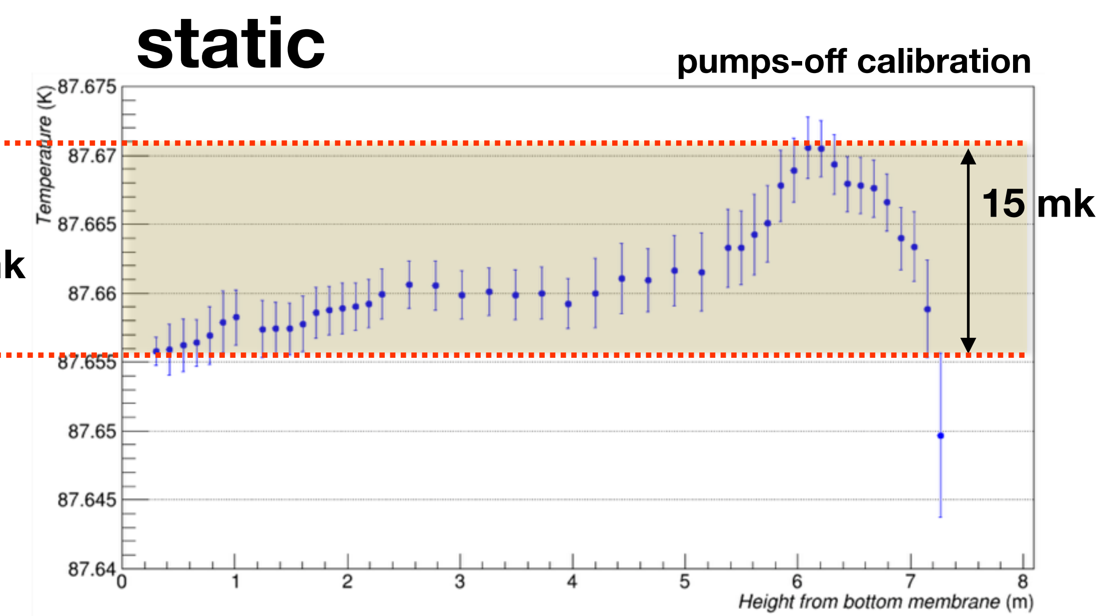

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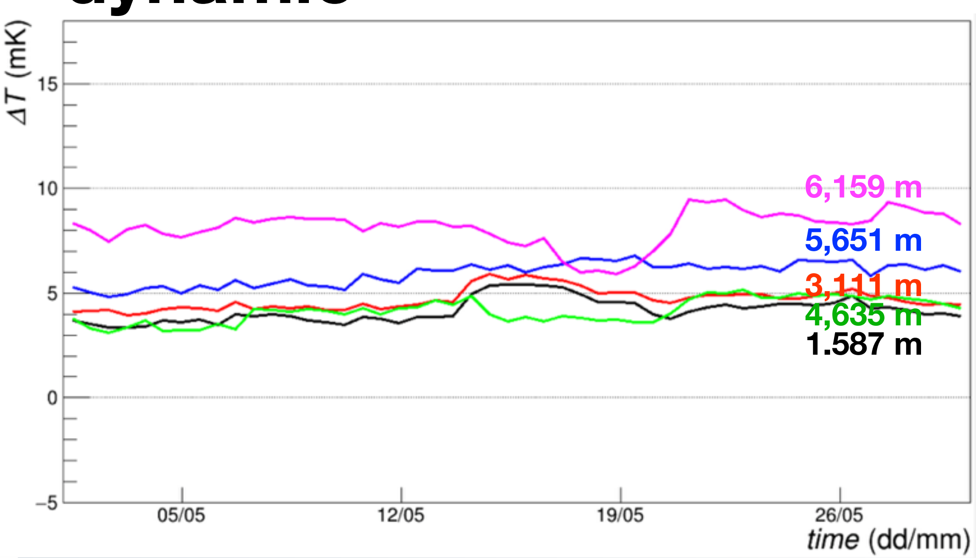
Vertical temperature gradient stability

- ΔT between first sensor and other sensors in the same profiler over one month

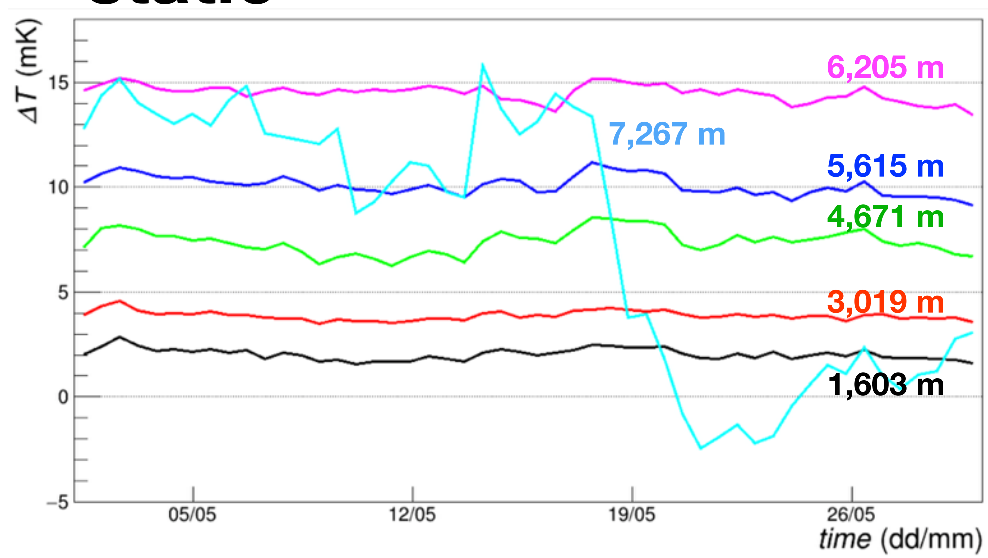
except near the surface

Vertical temperature gradient stable within 2-3 mK

dynamic



static



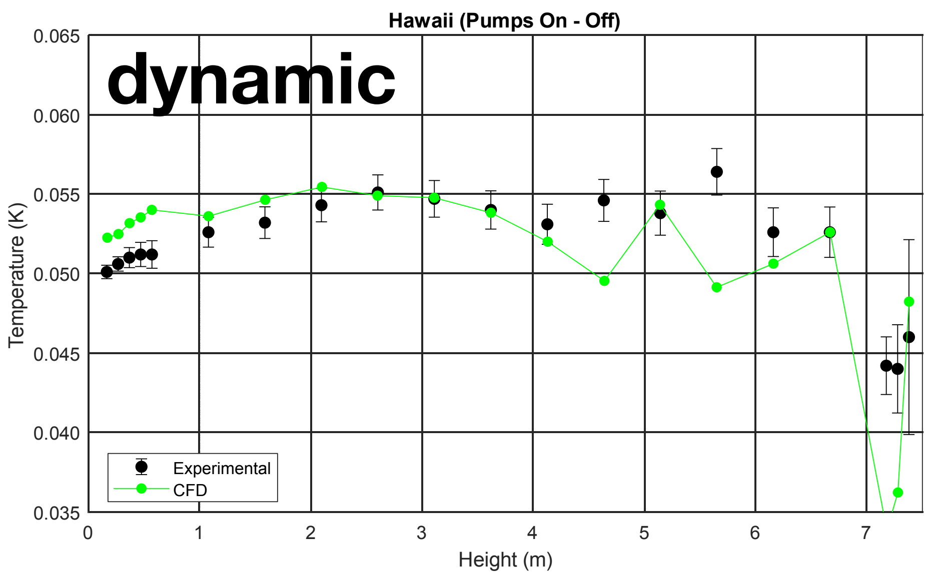
CFD predictions

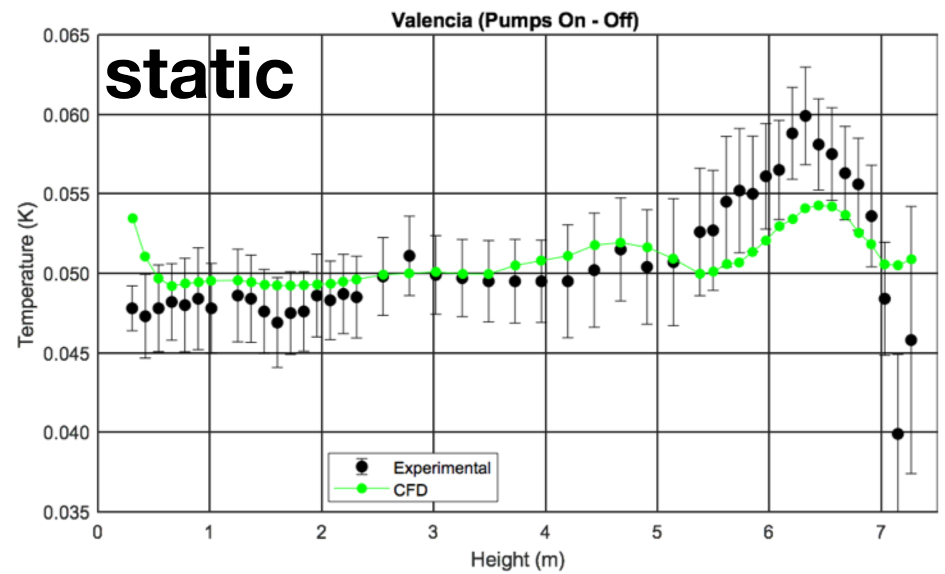
SDSU simulations

- Many different configurations tested. These are the latests simulations:

SDSU ProtoDUNE Modeling 5/7/20		
CFD Input	**Value**	**Implementation Comments**
LAr Surface Height	7.401 m	
Ullage Pressure	1.046 bar	
LAr Surface Temperature	87.5947 K	Saturation temperature at ullage pressure
LAr Flow Rate	1.66801 kg/s	Distributed based on effects of manifold geometry
Inlet Temperature	Surface Temperature + 0.2K = 87.7947K	Applied as weighted average based on mass flow rate
Electronics Heat Source	672 W	Over two regions, along top width of APAs
Distribution Manifold Heat Source	145 W	Preliminary, over four inlet pipes

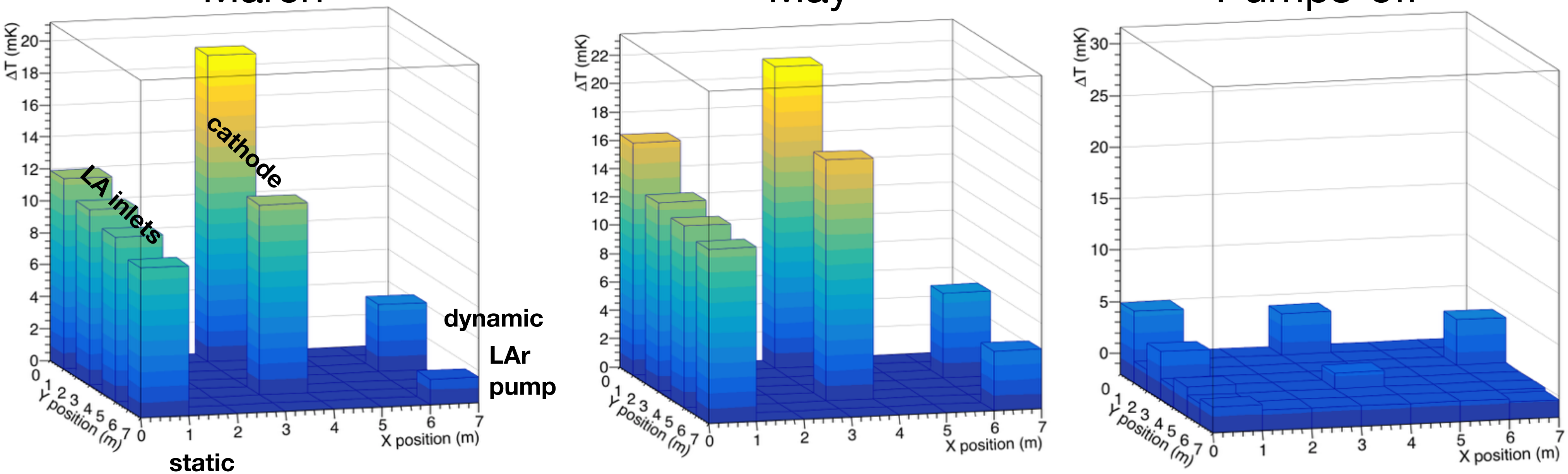
broad features in temperature data are well reproduced in CFD, while there is ongoing effort to refine the simulations to accurately simulate finer details of the temperature gradient profiles



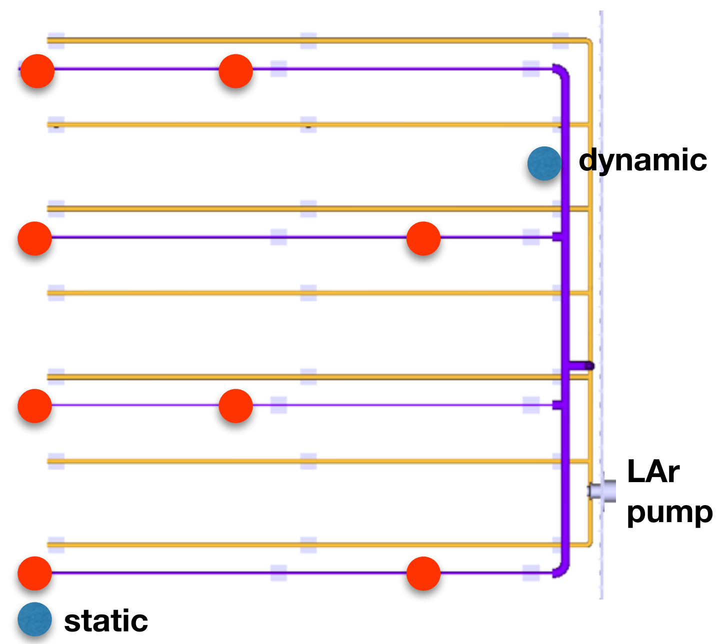


Bottom sensors

March May Pumps-off



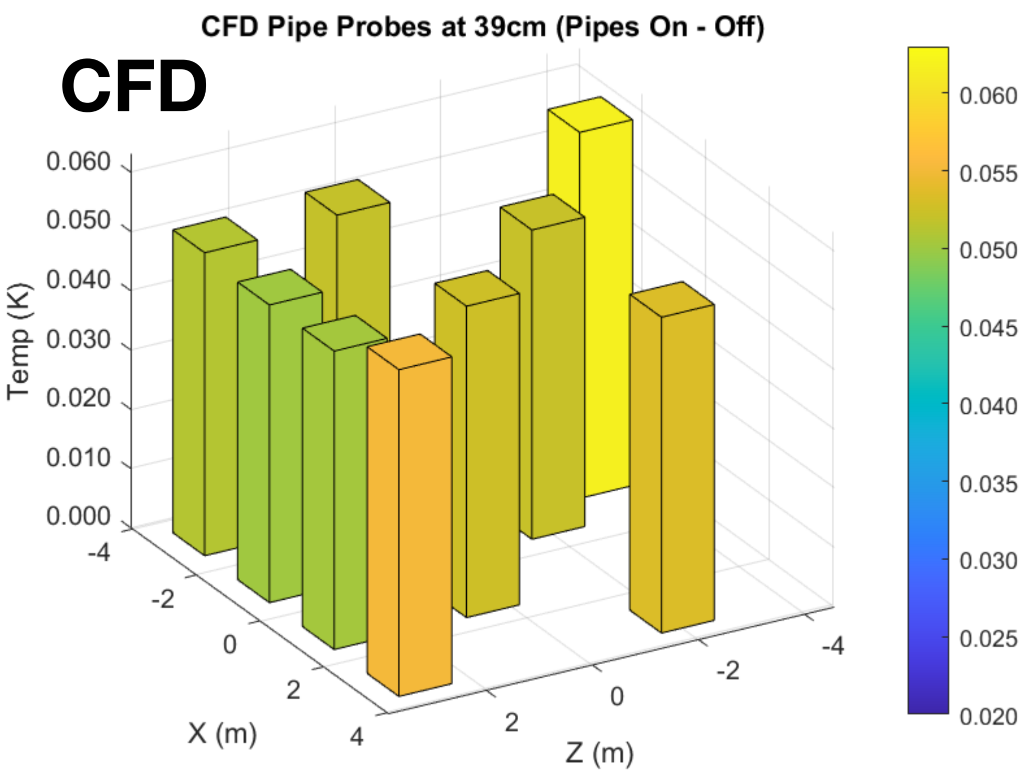
- ΔT between all pipe sensors at 2nd static sensor, all at ~40 cm
- Temperature decreases towards the LAr pump
- Along the pipes (X) temperature is higher in the middle of the TPC

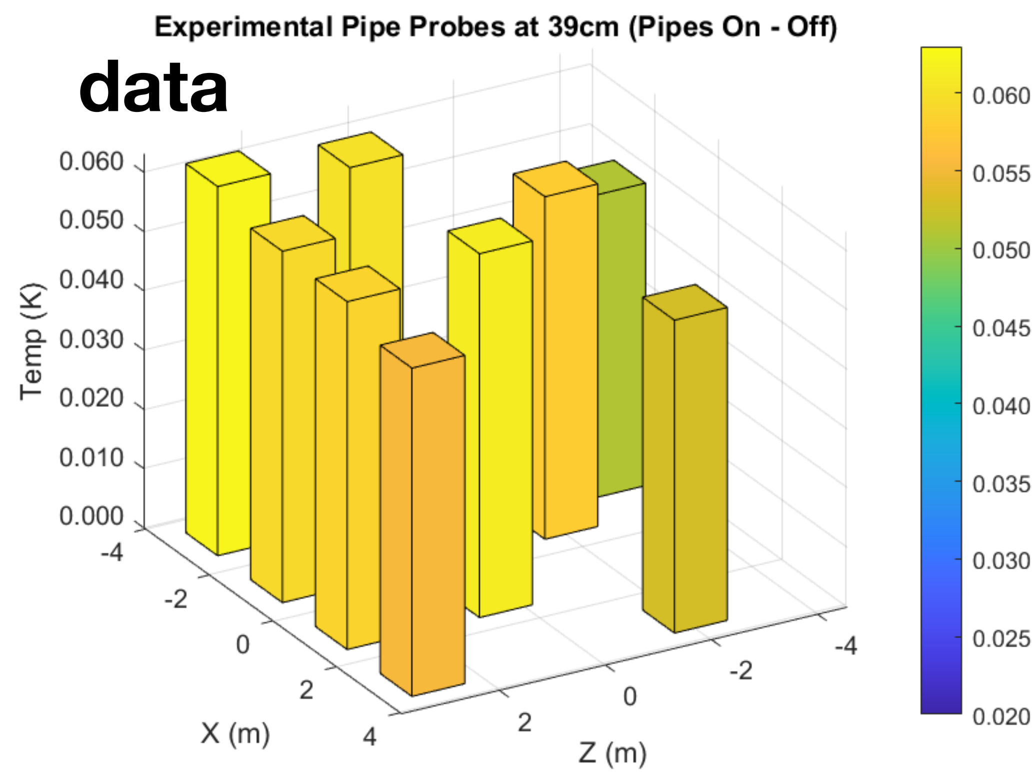


CFD predictions

SDSU simulations

- Not able to reproduce yet the experimental data
- Using different temperature for each inlet is probably the way to go





From ProtoDUNE to DUNE

Lessons learned

- Move vertical arrays closer to active volume: **sensors on APAs**
- Additional sensors to better constrain CFD simulations:
  - Inlets, pumps and vertical arrays in the gas
- The dynamic calibration has an extrapolation error that can be easily removed improving the design
- Remove bottom sensors since there are no ground planes at the bottom

Vertical arrays

Dynamic T-Gradient

A fix array of 48 sensors cross-calibrated with a movable set of 5 sensors. For 3D temperature maps

Sensors on APAs

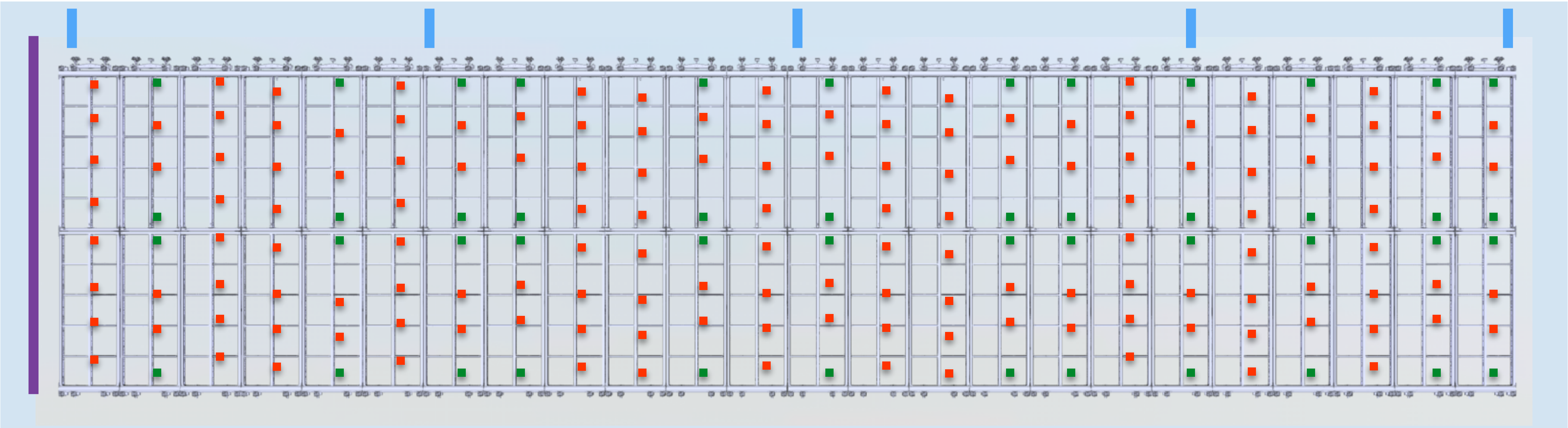
- 8 precision sensors in half of the APA doublets and 4 in the other half (452 in total), cross-calibrated in the laboratory. For 3D temp. maps (**static T-gradient**)
- 4 standard sensors in half of the APA doublets (148 in total), for APA frame temperature **NEW !!!**

Gas arrays

Measure the vertical gradient in the gas at several locations

NEW !!!

side view of an APA row



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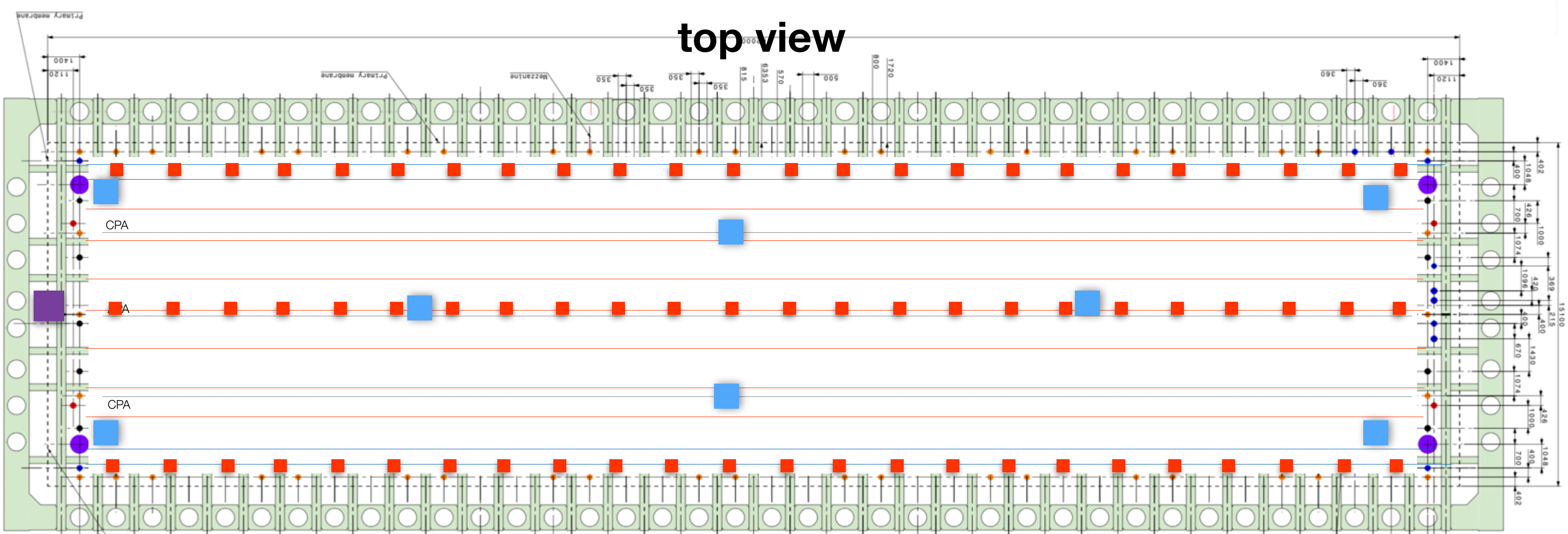
Gas arrays

Measure the vertical gradient in the gas at several locations. Used to constraint CFD simulations

NEW !!!

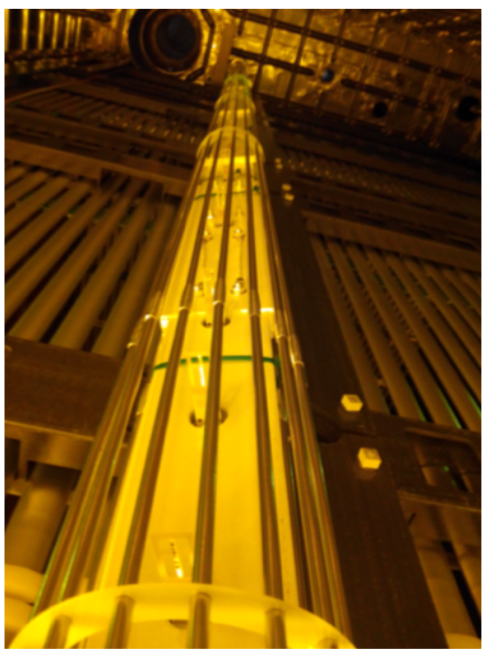


Static T-Gradient: concept

- New design is much simpler and closer to active volume

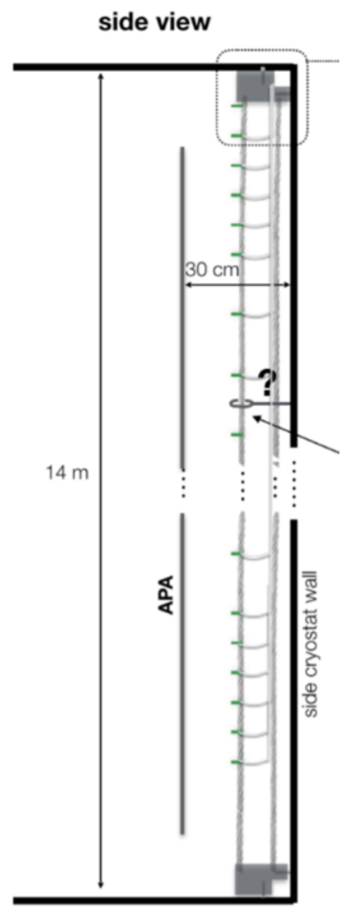
ProtoDUNE-SP

a single array with 48 sensors
20 cm away from the FC



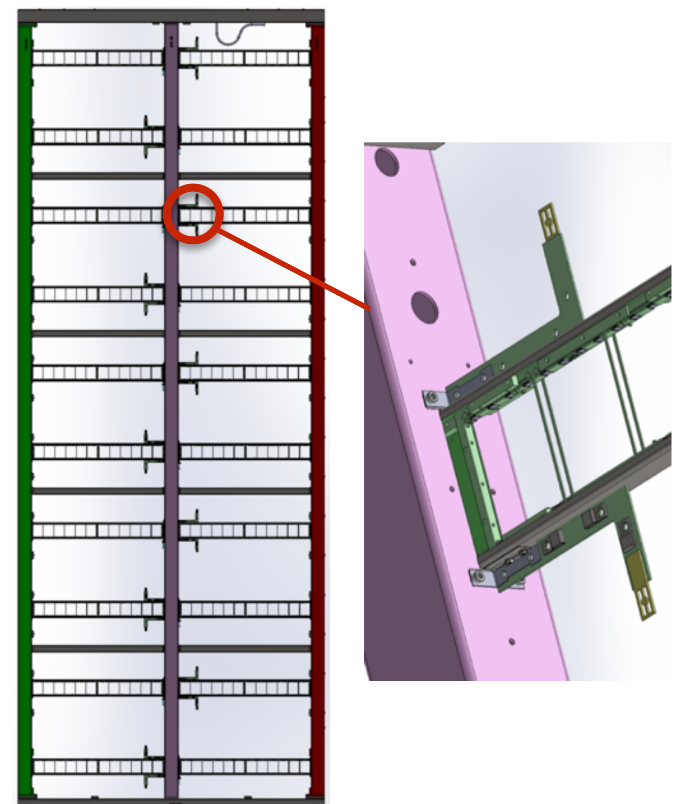
TDR

6 arrays of 48 sensors each
behind the APAs



sensors on APAs

4 sensors in each APA

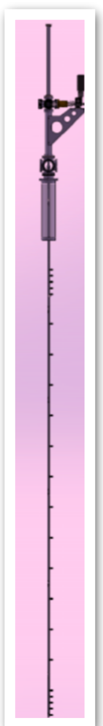


Dynamic T-Gradient: concept

- The updated design addresses the issues raised at the previous review: protection of the viewport and segmented design to account for installation with the limited overhead space

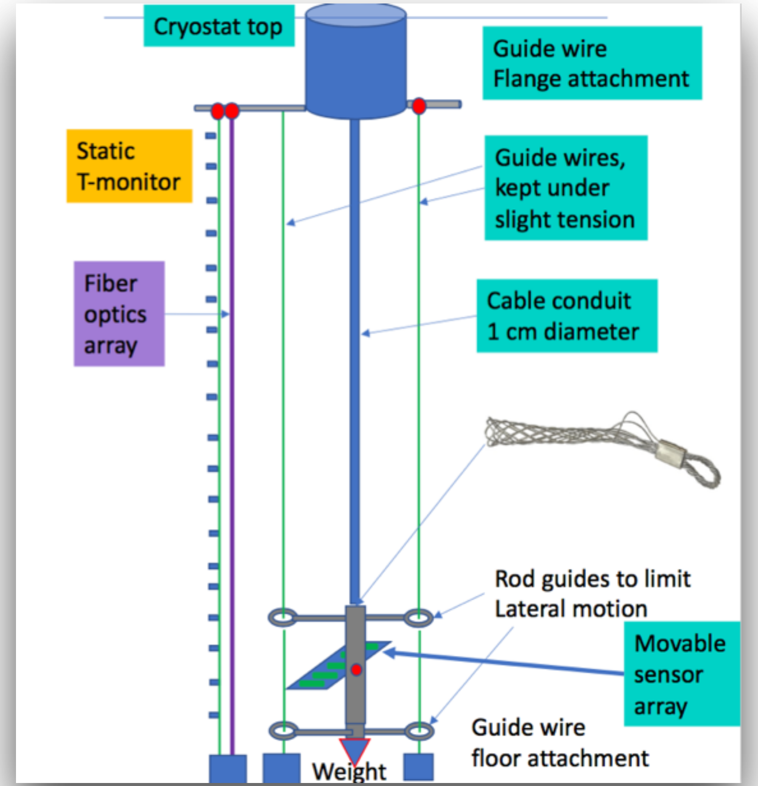
ProtoDUNE-SP

A 24 precision RTD vertical array that can move up and down up to 0.55 m



new dynamic+static concept

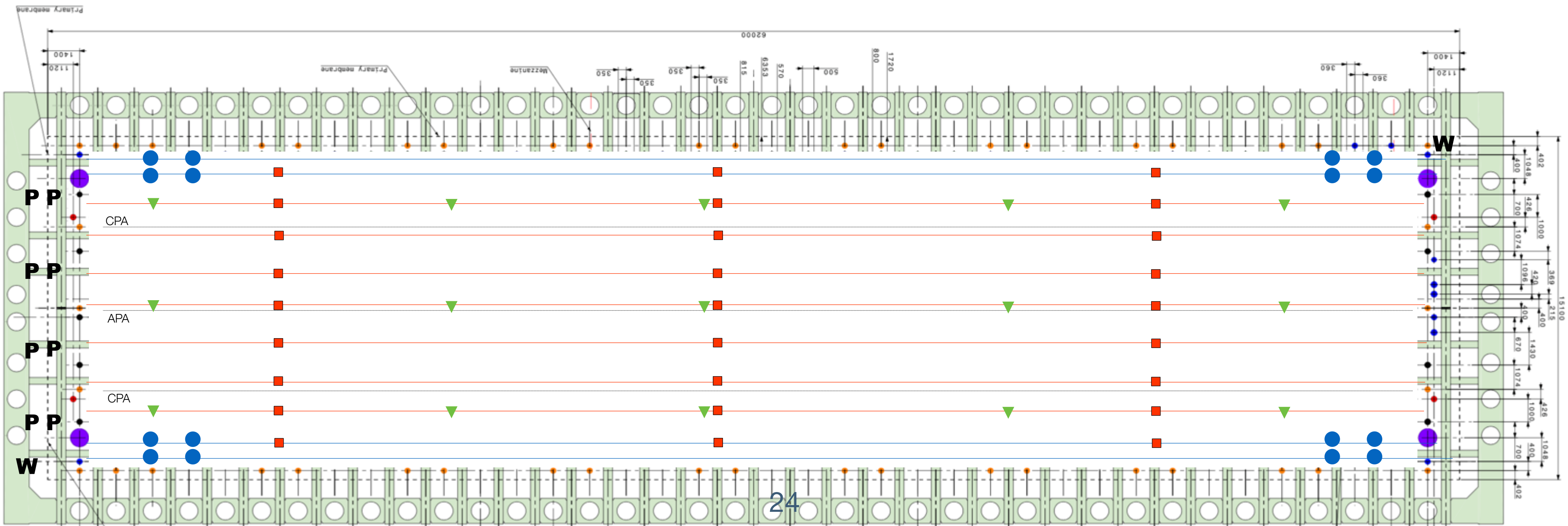
static array with 48 sensors +
a set of 5 sensors moving from top to bottom



Dynamic T-Gradient: calibration

- One of the limitations of the system installed in ProtoDUNE-SP is the extrapolation error because the system can only move 0.55 m
- In the new design the same 5 sensors are used to cross-calibrate all others, so there is no extrapolation error
- The calibration accuracy depends only on:
  - Temperature resolution of the 5 reference sensors:
    - 0.5 mK rms for each sensor
    - Combining the measurements: 0.5/sqrt(5)=0.2 mK
  - Position resolution of the 5 reference sensors: assuming a gradient of about 1 mK/m, a modest position uncertainty of 10 cm would translate into a temperature error of 0.1 mK.
- Thus, we expect a calibration accuracy better than 0.5 mK

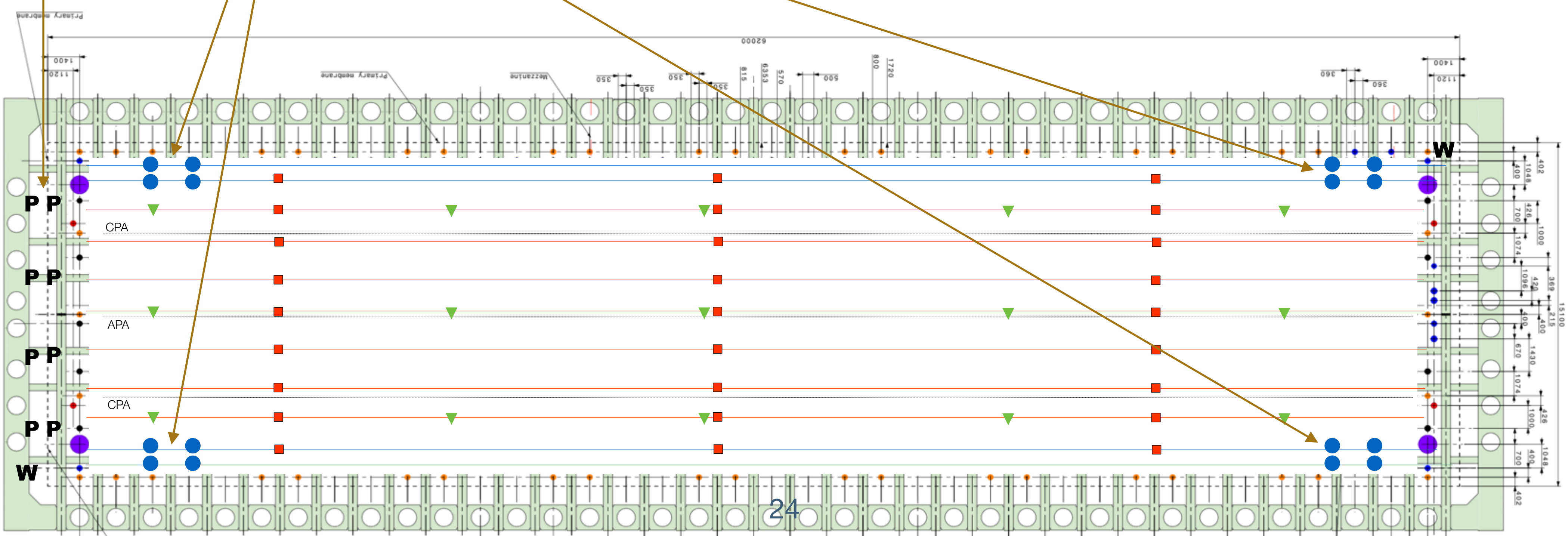
Other temperature sensors



Other temperature sensors

LAr pumps (P) and inlets (●):
Important input for CFD simulations

NEW !!!



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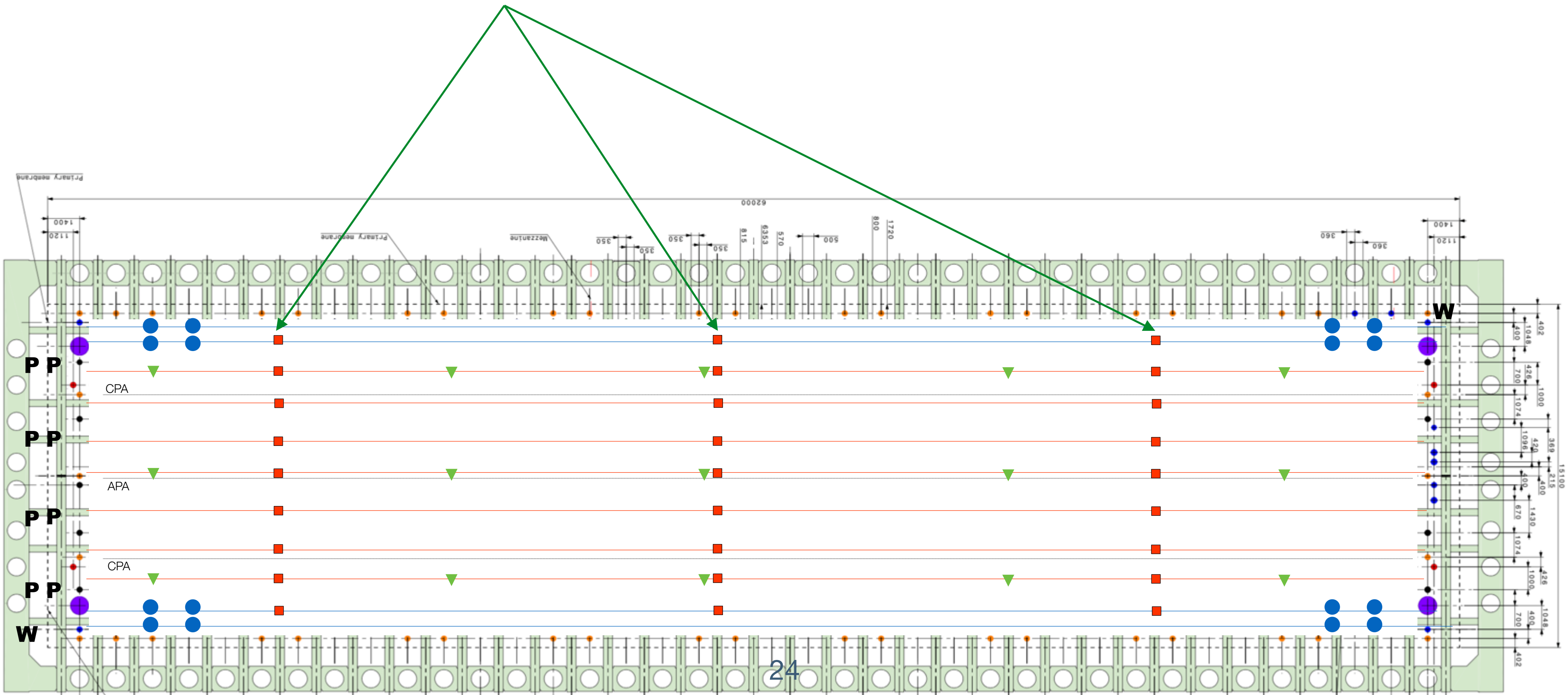
NEW !!!

Top GP sensors (■)
Several transverse sensor arrays to monitor temperature trends between adjacent APA rows



Other temperature sensors

LAr pumps (P) and inlets (●):
Important input for CFD simulations

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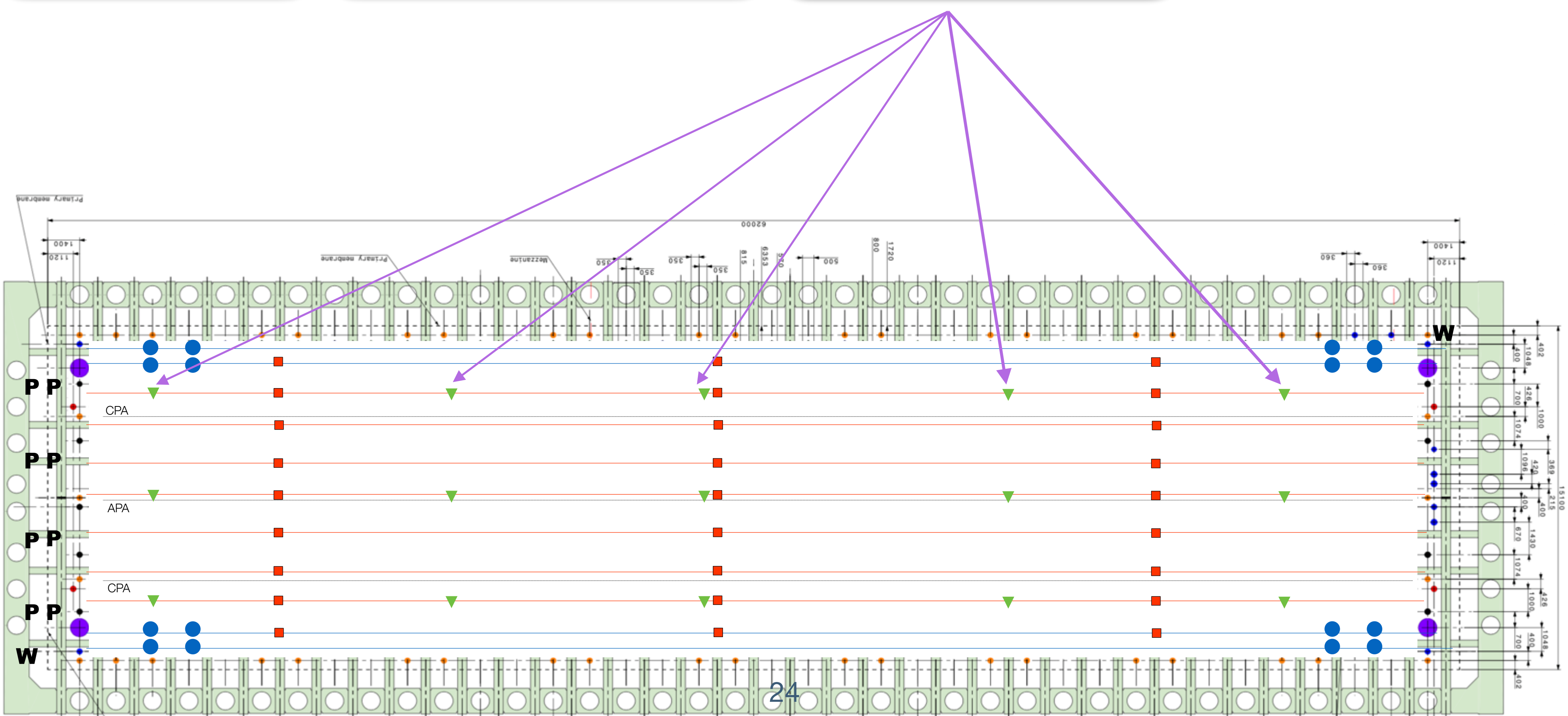
Several transverse sensor arrays to monitor temperature trends between adjacent APA rows

Floor sensors (▼):
Standard sensors epoxied to the floor for detecting the presence of LAr at the start of filling



Other temperature sensors

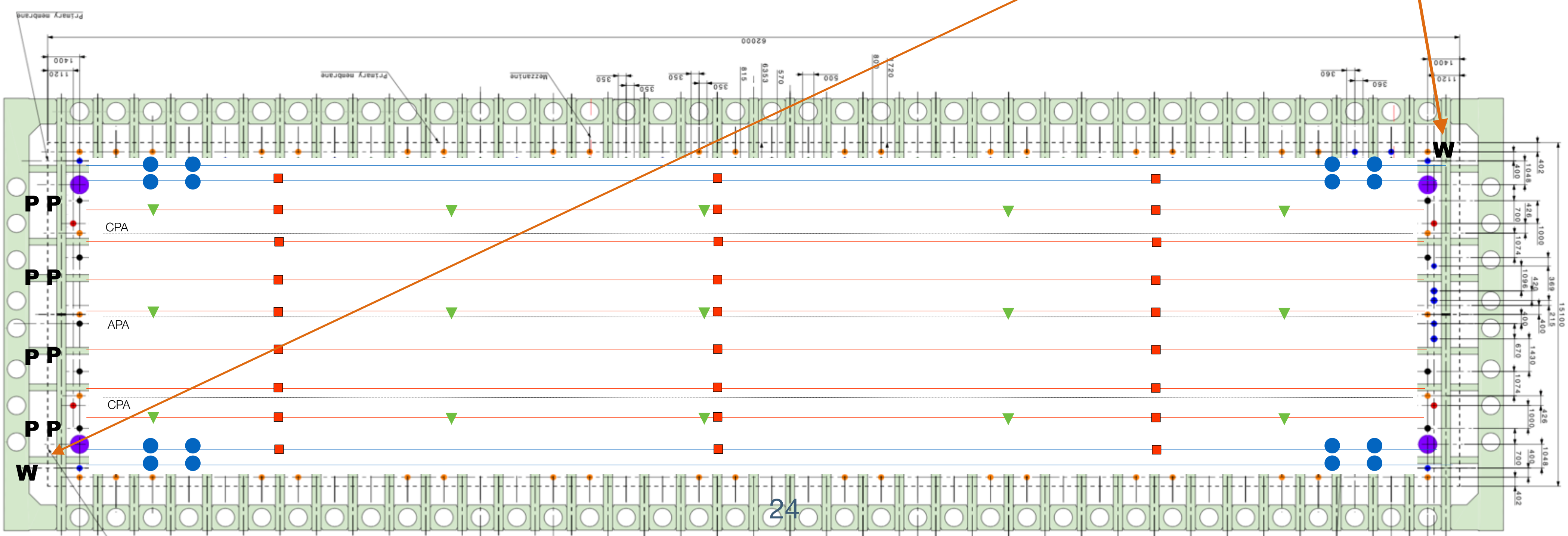
LAr pumps (P) and inlets (●): Important input for CFD simulations

NEW !!!

Top GP sensors (■): Several transverse sensor arrays to monitor temperature trends between adjacent APA rows

Floor sensors (▼): Standard sensors epoxied to the floor for detecting the presence of LAr at the start of filling

Wall sensors (W): Vertical array of standard sensors to measure temperature gradient at the cryostat wall during cool-down



Question I

Does the system have a well-justified role in safeguarding the far detectors and facilitating their operation, and if so, what is the minimum amount of system scope needed to carry out this role?

Motivation of each system

System	Precision	Motivation

Vertical arrays
Top/bottom Horizontal 2D grid
RTDs at inlets and pumps
	~mK	• monitor cryogenics system behaviour during operation
		  • Correct temperature of LAr delivered to the cryostat
		  • LAr mixing properly inside the cryostat

Floor	20-50 mK	monitor the presence of LAr when filling starts
Walls & roof	20-50 mK	monitor cryostat membrane temperature during cool-down and filling
APA frame	20-50 mK	monitor APA frame temperature during cool-down and filling
Vertical array in gas	20-50 mK	

Minimum amount of system scope

- **Sensors on APAs:** complex to establish the minimum: 4 sensors in vertical raw, at 5 different locations along the cryostat sufficient to validate operation of the cryogenic system
- **Dynamic T-Gradient**: essential to validate the calibration of all other systems at any time. One system is the minimum
- **Other sensors:**
  - **LAr inlets**: important to immediately detect an issue with the LAr delivered to the cryostat. **Two (for redundancy) in each side of each of the 4 LAr return pipes. 16 in total**
  - **LAr pump**: not essential for this purpose
  - **Ground planes**: not essential for this purpose
  - **Floor**: **15 sensors** (requested by cryogenics system)
  - **Wall**: **one every three corrugations (13) in two opposite corners** (requested by cryogenics system)

Question II

Does the system have a well-justified role in facilitating the analysis of far detector data, and if so, what is the minimum amount of system scope required to fulfil this role?

Motivation of each system

System	Precision	Motivation
Vertical arrays Top/bottom Horizontal 2D grid RTDs at inlets and pumps	~mK	• constrain CFD simulations for e-lifetime, drift velocity and ion flow prediction (**dynamic array crucial for cross-calibration during the entire lifetime of the experiment**)
Floor	20-50 mK	
Walls & roof	20-50 mK	
APA frame	20-50 mK	
Vertical array in gas	20-50 mK	constrain & validate CFD simulations in ullage

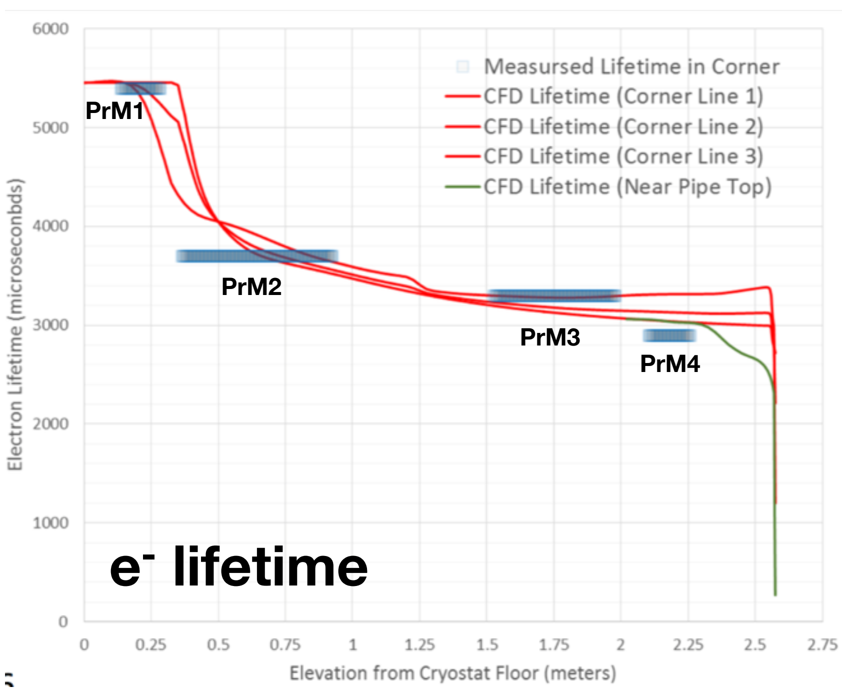
CFD simulations

35t prototype

Purity Stratification study actually triggered by precise temperature measurements

- CFD successfully used to reproduce the observed e- lifetime
- Those simulations also predict the 25-35 mK gradient observed between RTDs in PrM1-3

Erik Voirin
Dune DocDB 1156



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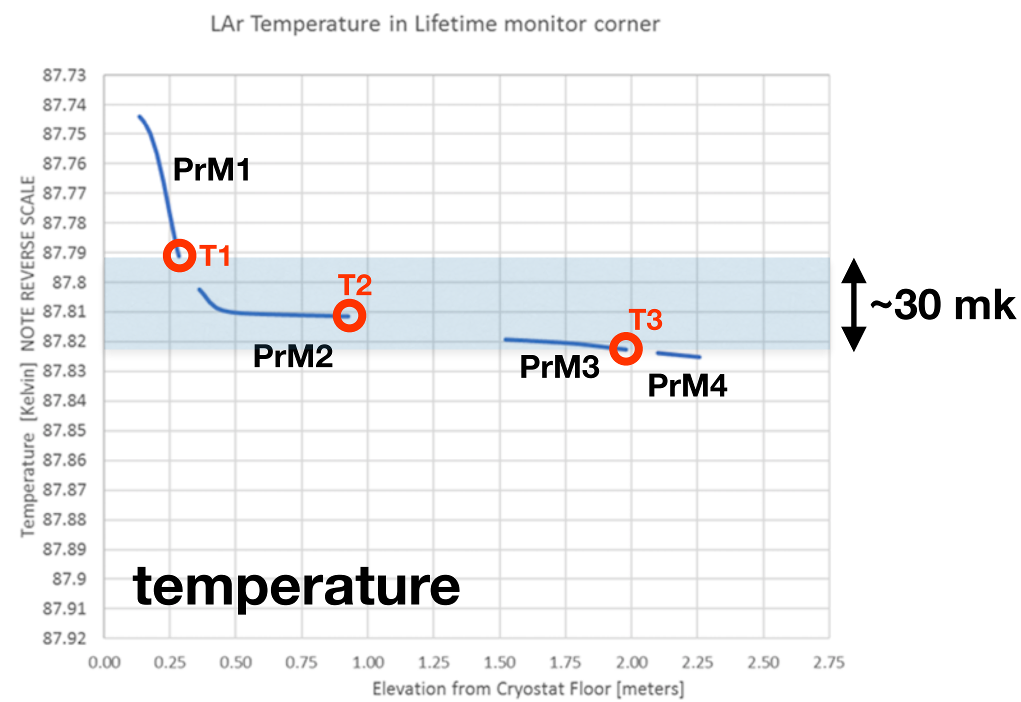

35t prototype showed direct relation between Temperature and e-lifetime

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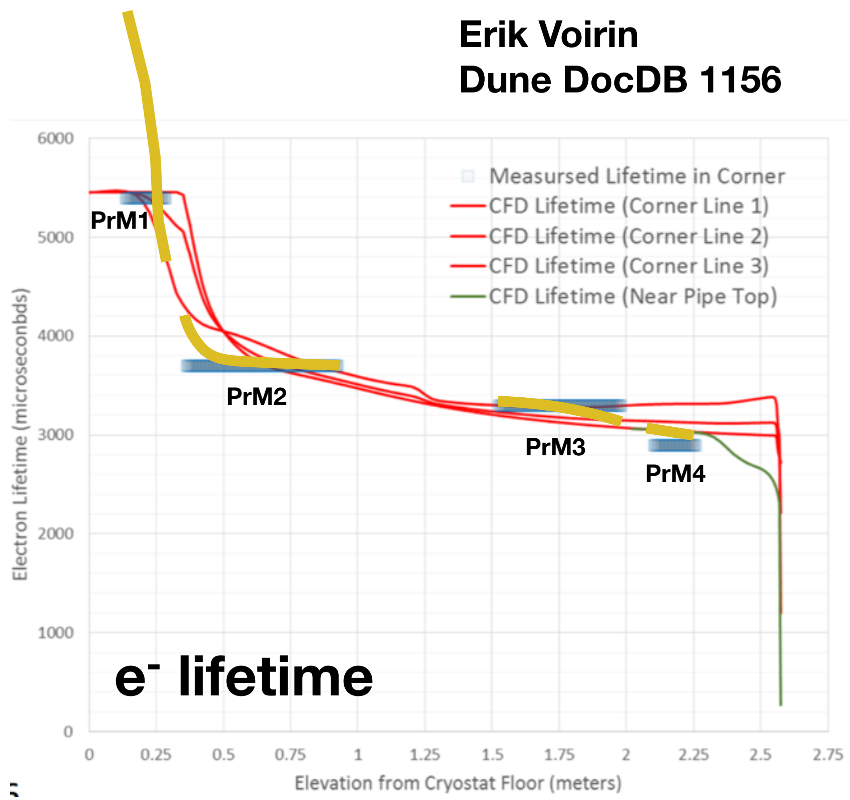
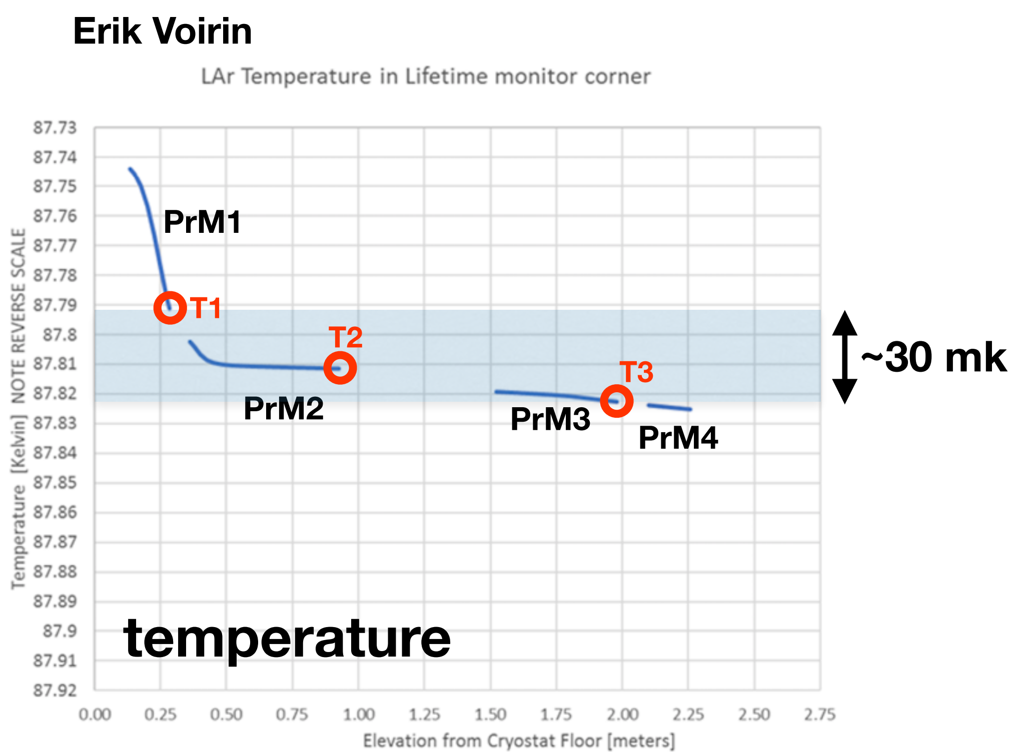


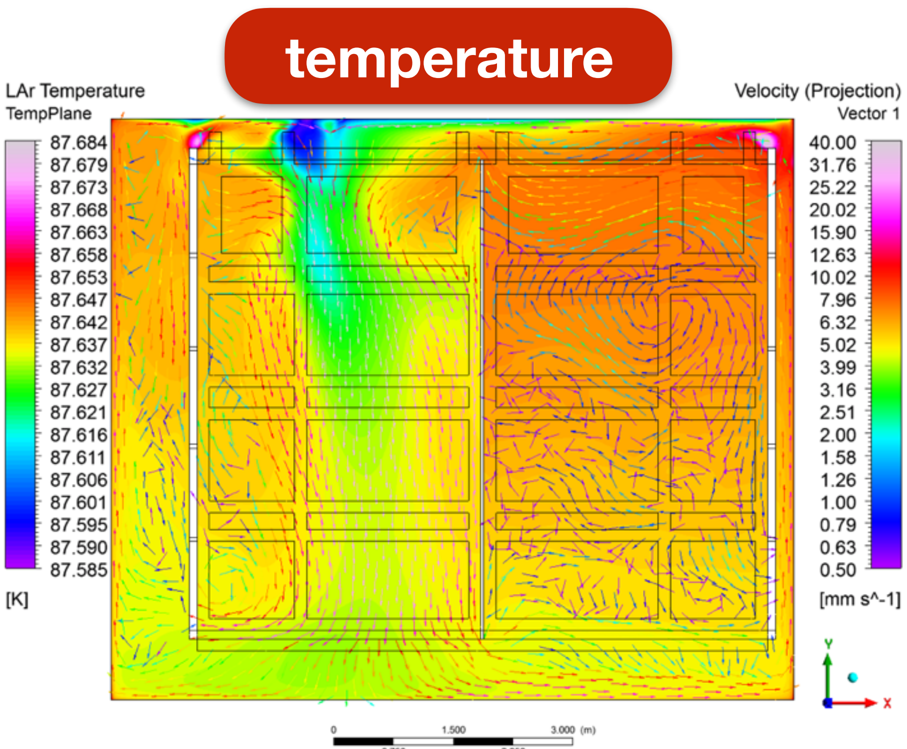


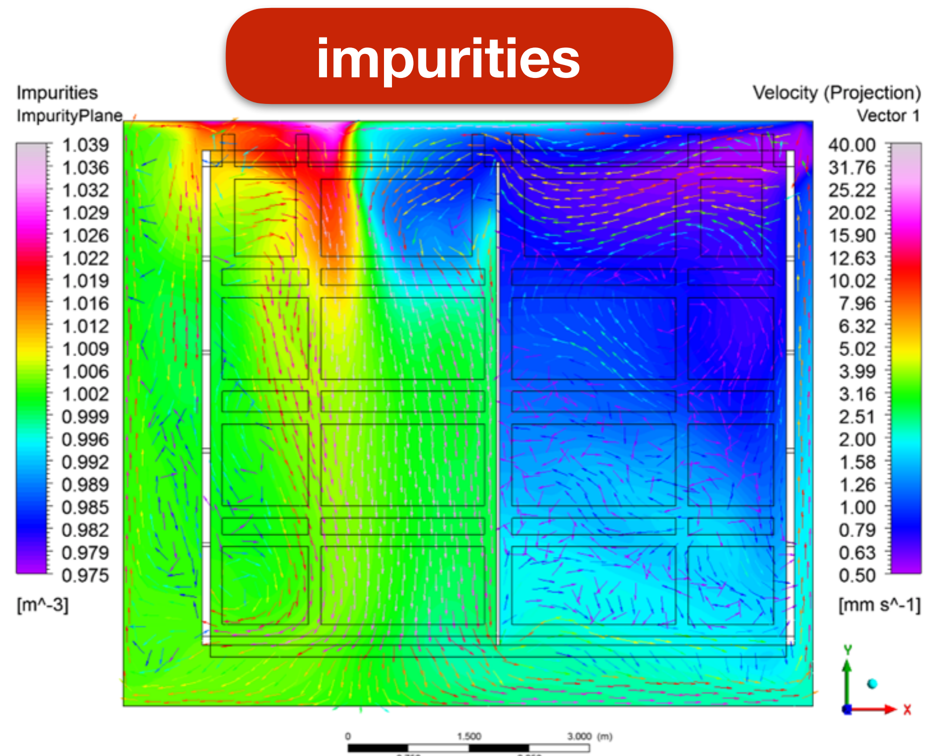
35t prototype showed direct relation between Temperature and e-lifetime

In ProtoDUNE-SP

E. Voirin DUNE-doc-928-v5

- 15 mK gradient observed
- CFD predicts 5% impurity variation, which for 15 ms lifetime translates into 5% charge attenuation
- Assuming a direct relation between temperature and purity we need 1.5 mK precision for 0.5% abs. error on charge attenuation correction



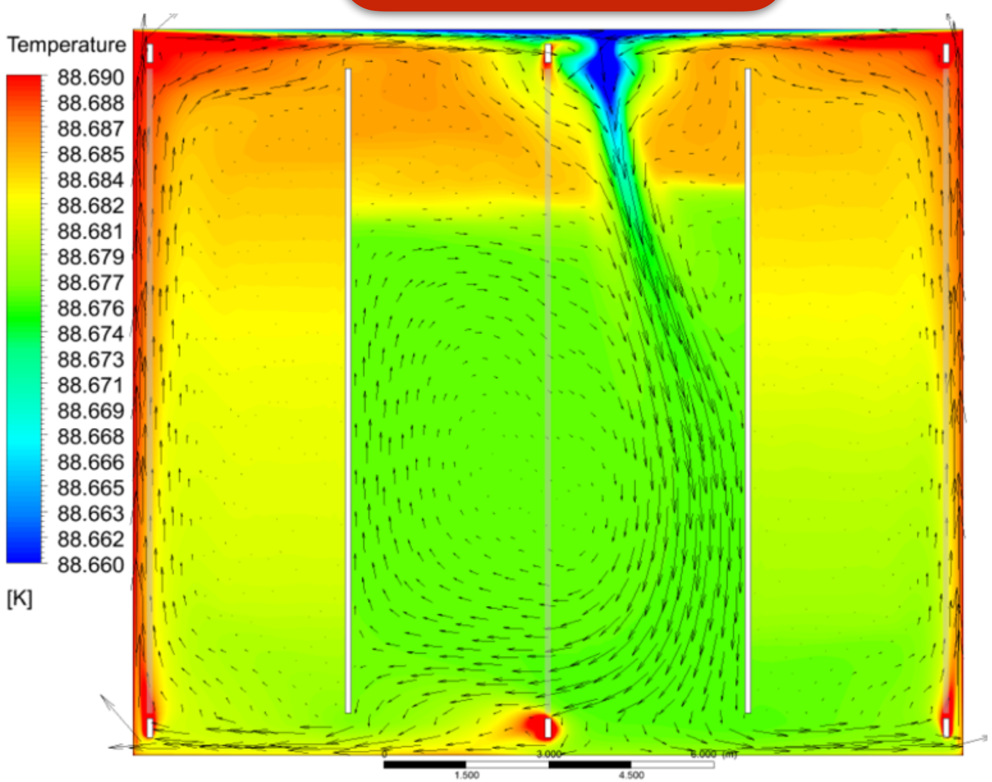


CFD simulations in DUNE

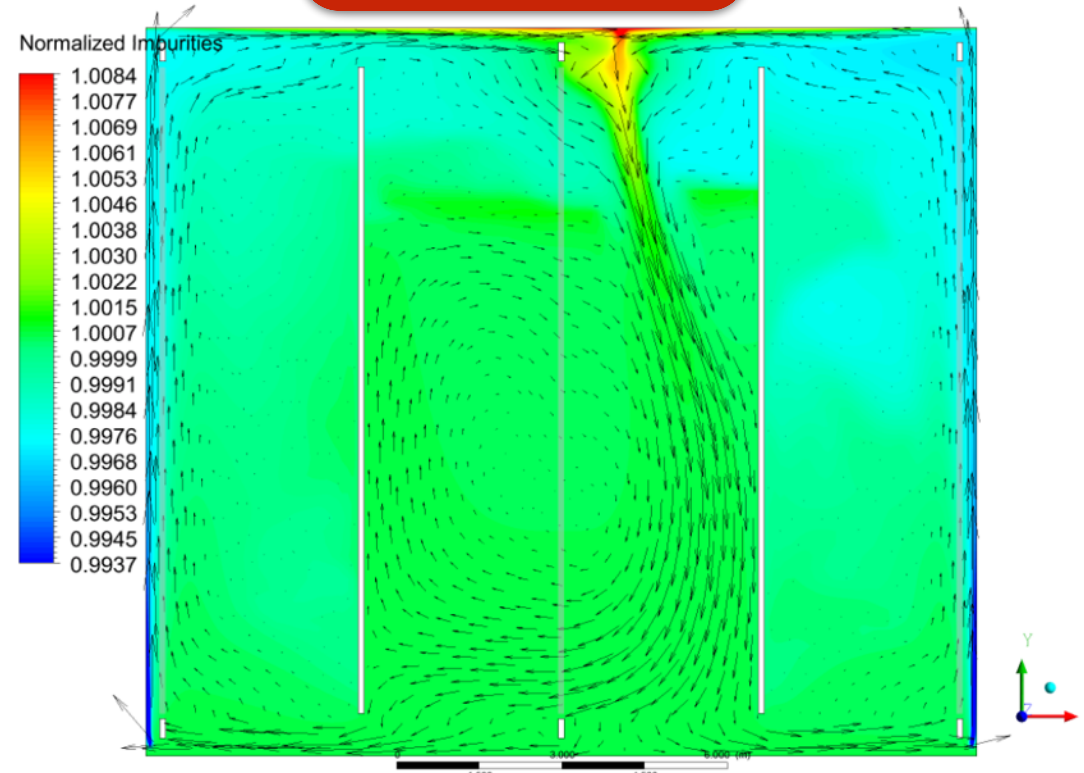
E. Voirin DUNE-doc-1046-v2

- There is a clear correlation between temperature and purity
- Predicted vertical temperature gradient is ~15 mK

temperature



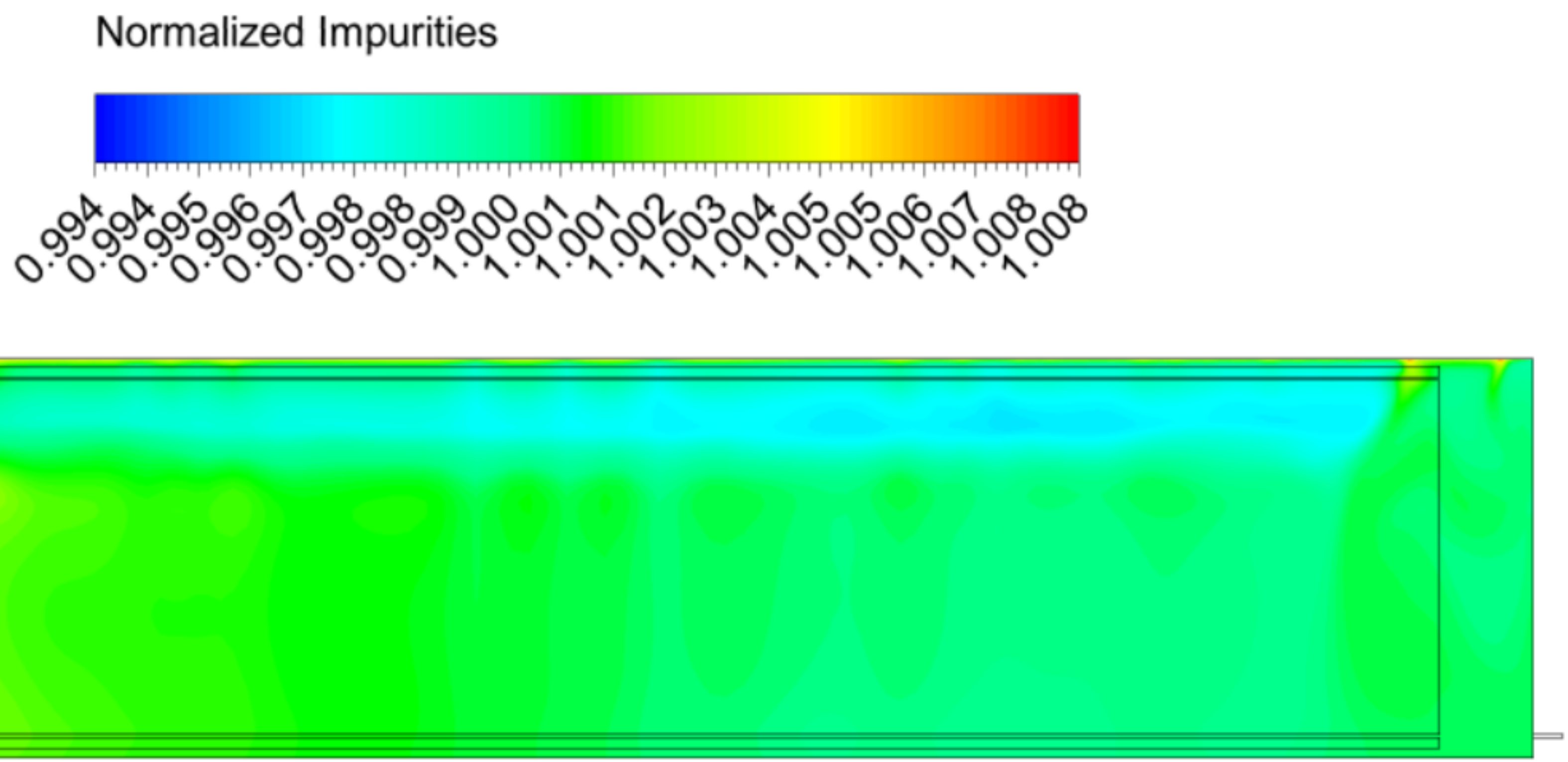
impurities



CFD simulations in DUNE

E. Voirin DUNE-doc-1046-v2

- With the current inlet and pump distribution CFD simulations predict a quite uniform impurity distribution, homogeneous within 1%
- But we should be prepared for surprises: the requirement is that we should be able to map an impurity level variation of 5%, what implies a precision in temperature of 1.5 mK

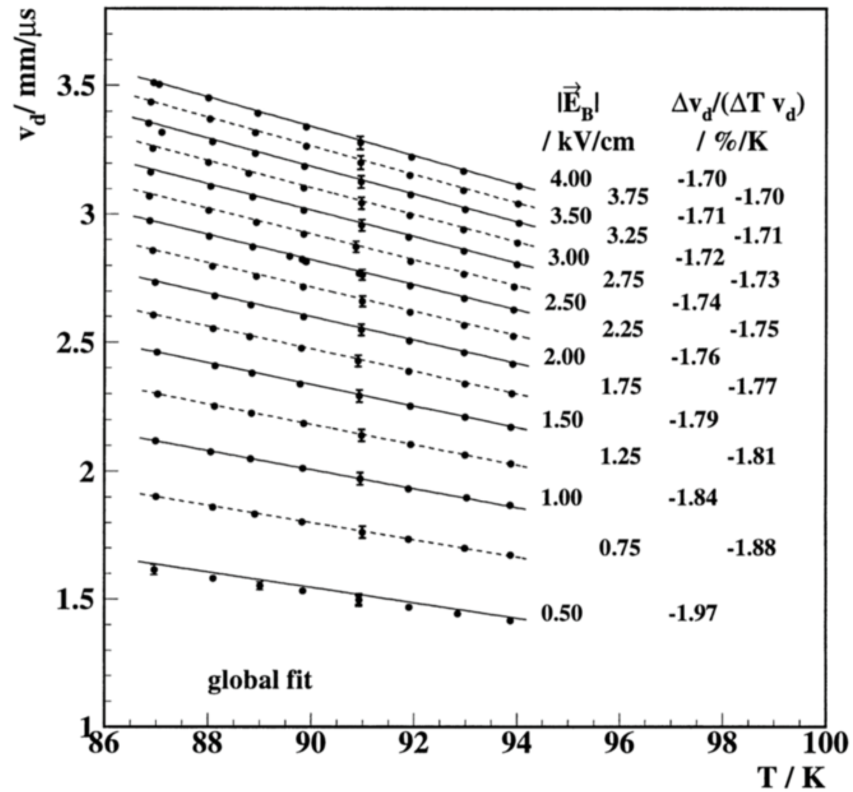


Drift velocity

- The drift velocity depends on absolute temperature

$$\frac{\Delta v_d}{v_d} = -0.0197 \cdot \Delta T(K)$$

NIM A 449 (2000) 288}294



- For the full drift (3.6 m) there is a variation of **0.07 mm/mK**
- For position accuracy of 0.5 cm we need to control the absolute temperature better that 70 mK
- In ProtoDUNE-SP we did not care much about absolute temperature
- Some analysis started

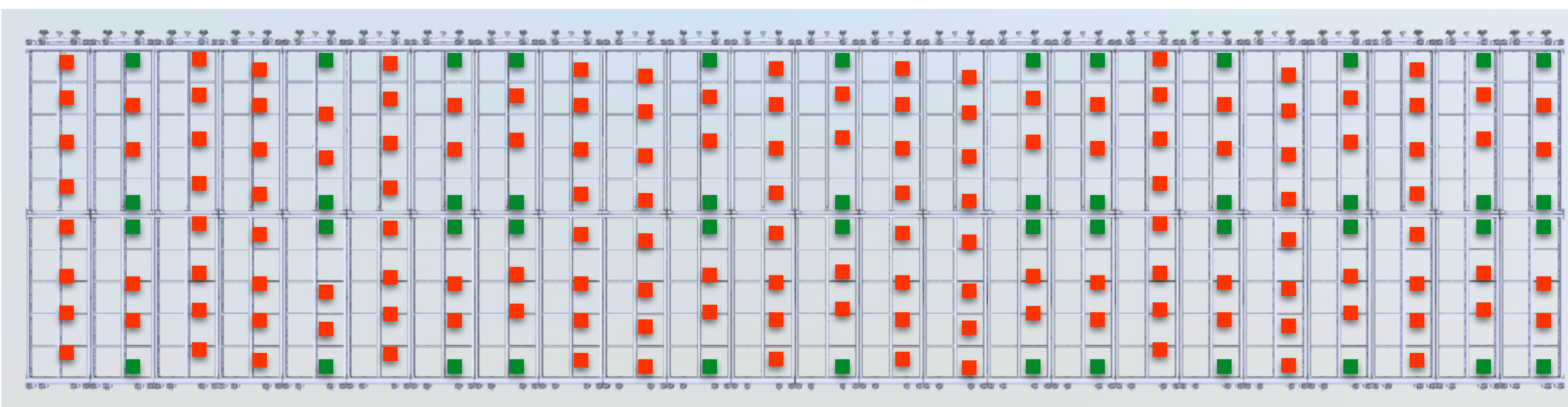
Sensors on APAs I

- The current baseline (agreed with APA and PD consortia) assumes 8 precision sensors in half of the APA doublets and 4 in the other half.
  - Less sensors per APA do not significantly simplify things
  - Less than 8 sensors in vertical row is below optimal number to maximize impact of CFD simulations on physics
  - The parameter to vary is the number of variations in height

■ precision LAr sensor

■ standard frame sensor

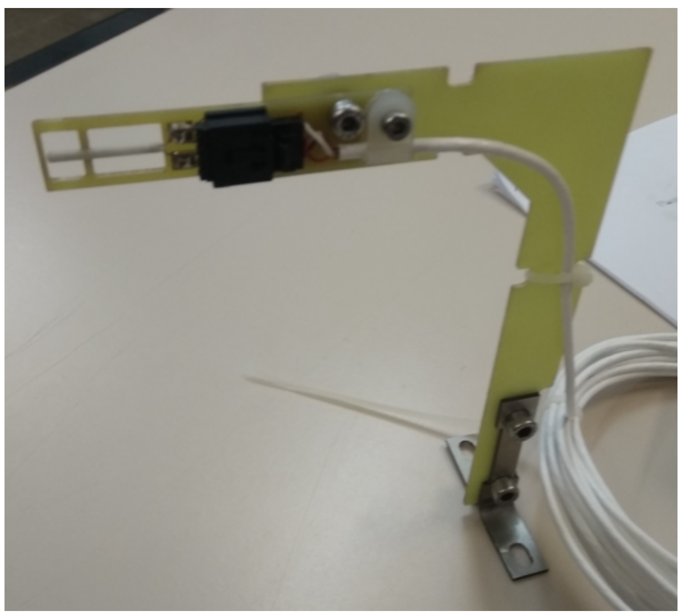
side view of an APA row



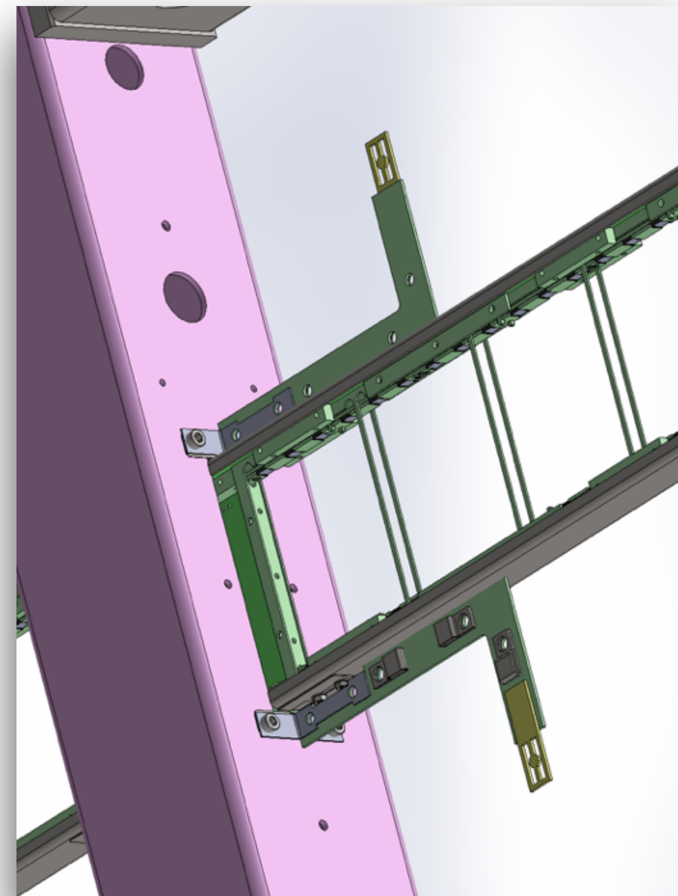
Sensors on APAs II

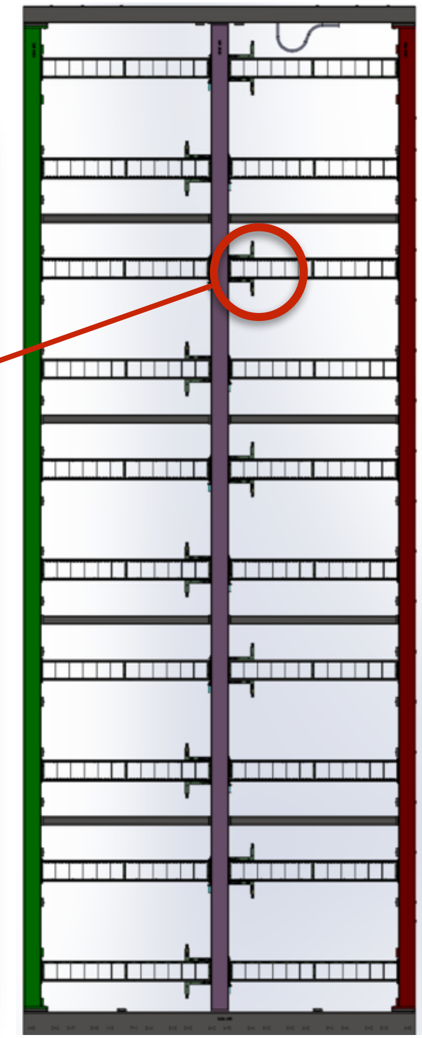
- Each APA will have 4 precision sensors, uniformly spaced
- There are 20 possible anchoring points for the sensors

Final design (J.V Civera), prototyped at IFIC



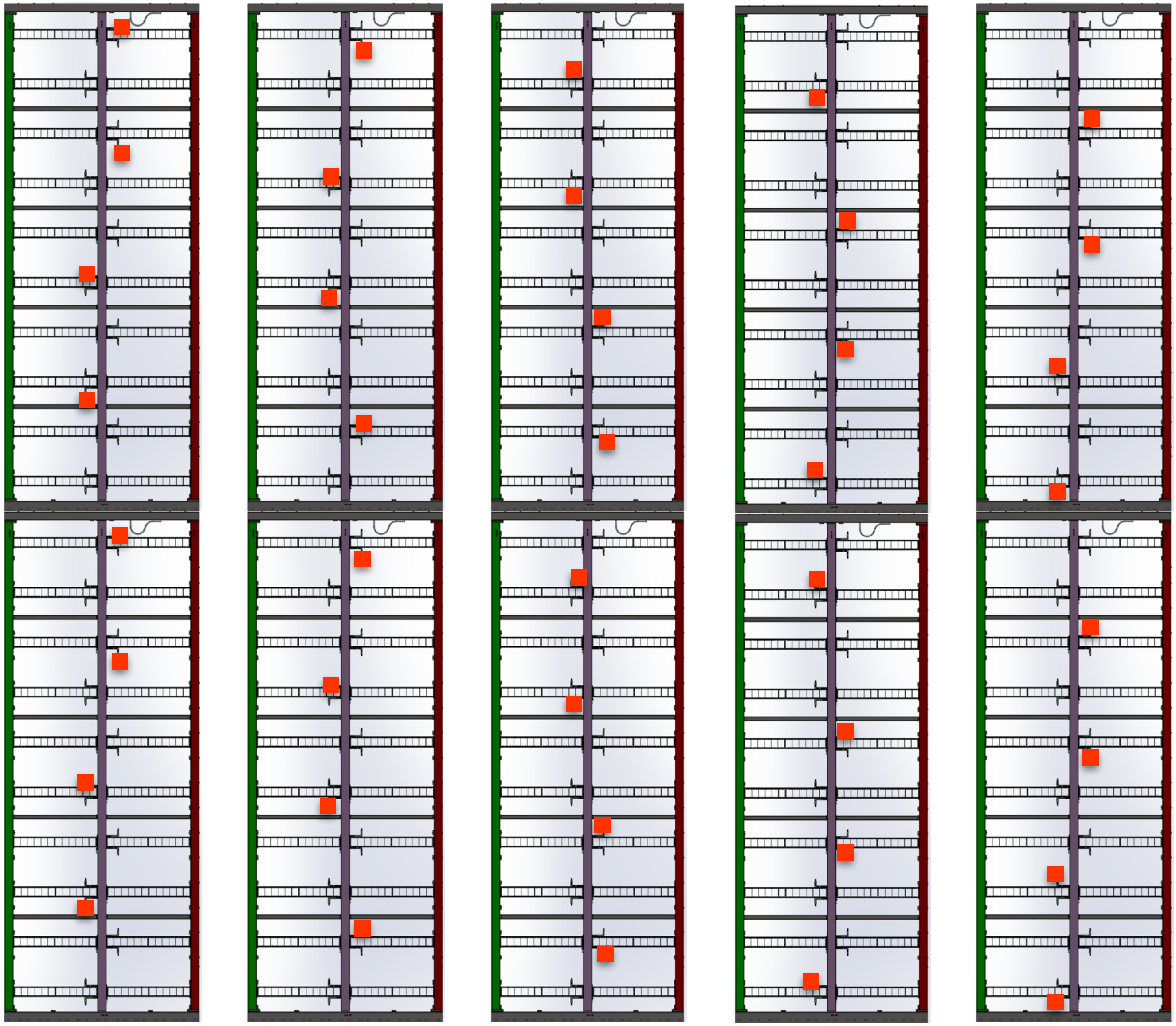
Initial design by D. Warner





Sensors on APAs III

- 5 posible APA configurations (to be agreed with APA consortium)



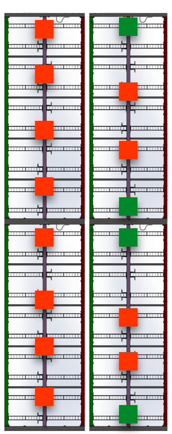
Sensors on APAs IV

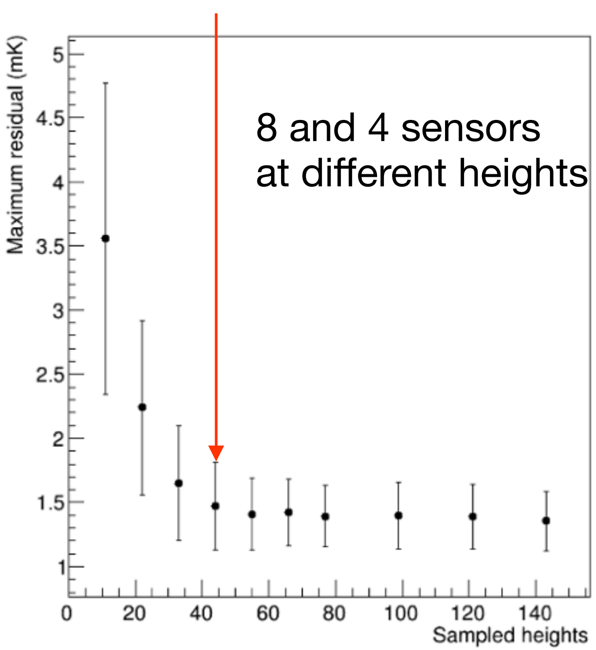
- We have performed several simulations to understand the optimal distribution for a given number of sensors.The FOM is the maximum residual between simulated map and measured map

  - For the 8+4 distribution the FOM saturates at 30-40 different heights (FOM=1.5 mK). For 8 sensors that means **5 different configurations**

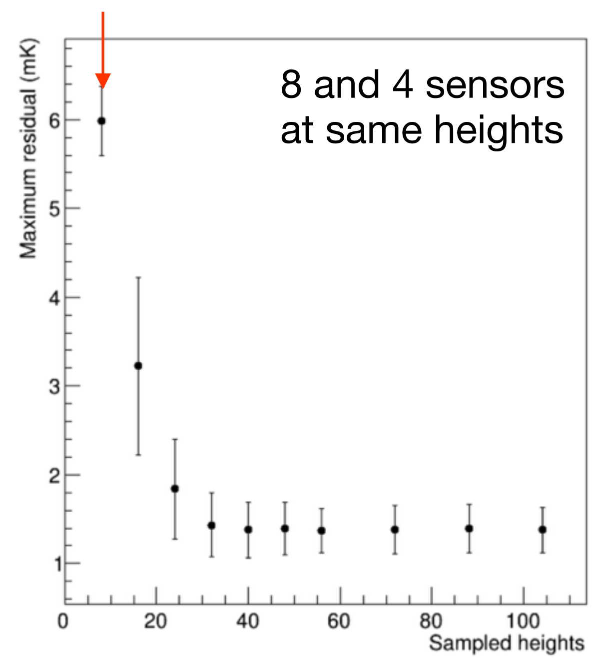
  - A single configuration (8 sampled heights) would have FOM>6 mK

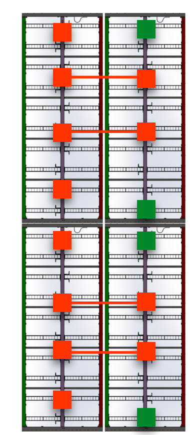
5 configurations





1 configuration

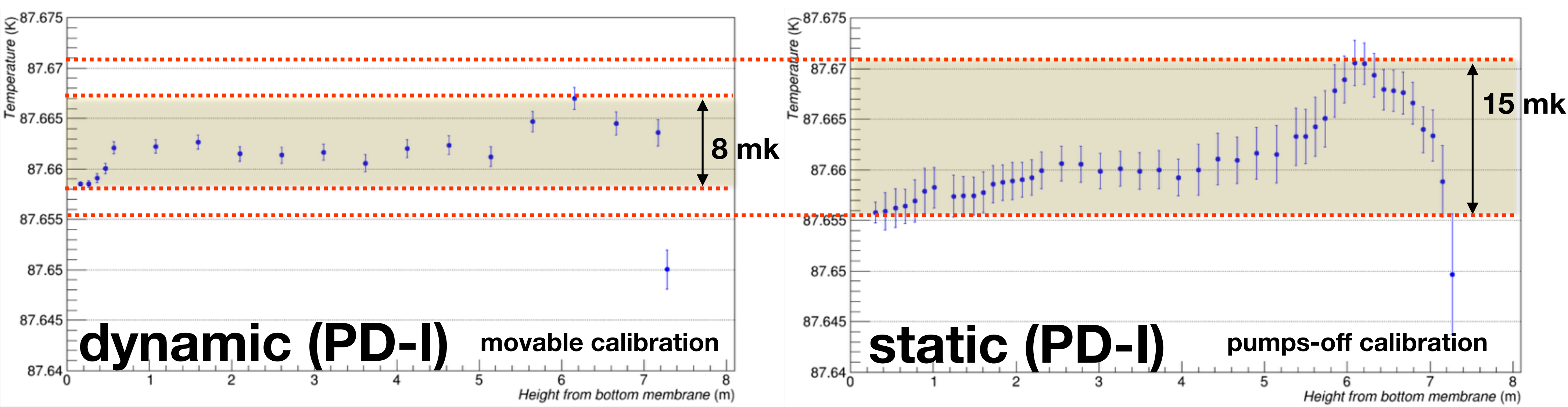




DEEP UNDERGROUND NEUTRINO EXPERIMENT

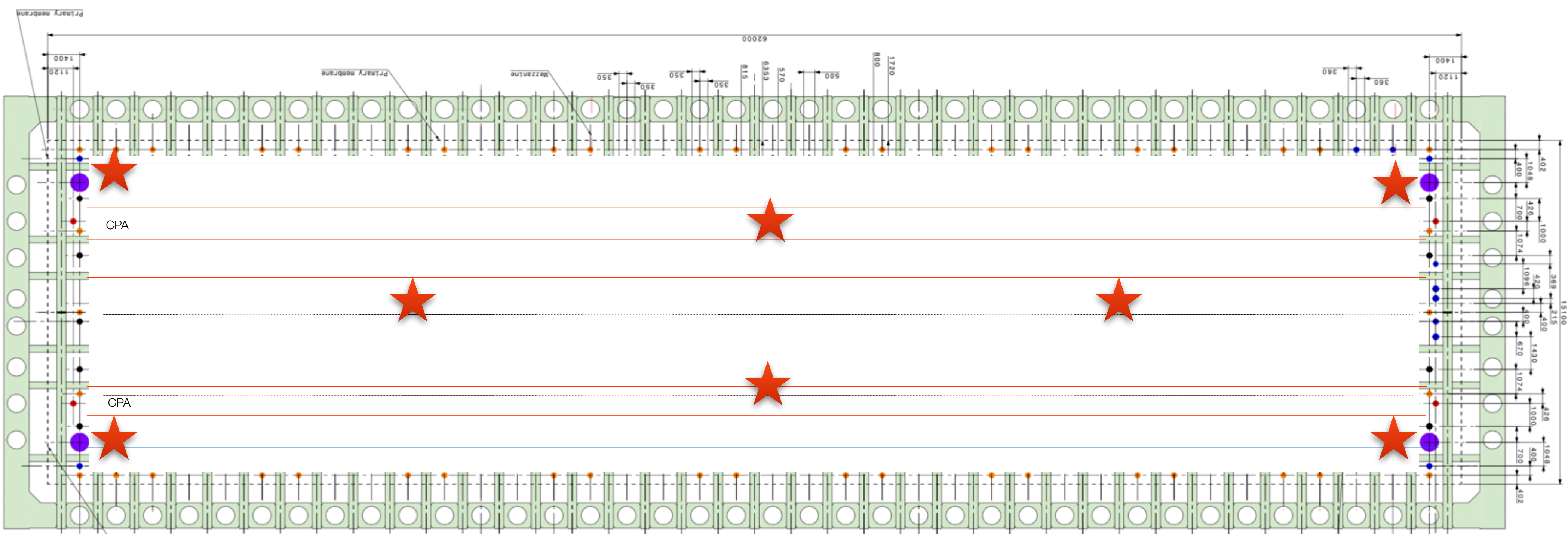
Dynamic T-Gradient

- It has been used in PD-I to establish the overall scale insitu and to test the validity of other calibration methods (pumps-off and laboratory). **This is the only system able to perform a model-independent insitu calibration.**
  - Ideally one system in each side of the cryostat. Given the ports availability only one is foreseen
  - In PD-I, dynamic T-gradient array has 24 sensors, which is at the limit to detect local variations. Since DUNE is double in height, **48 sensors is the minimum**



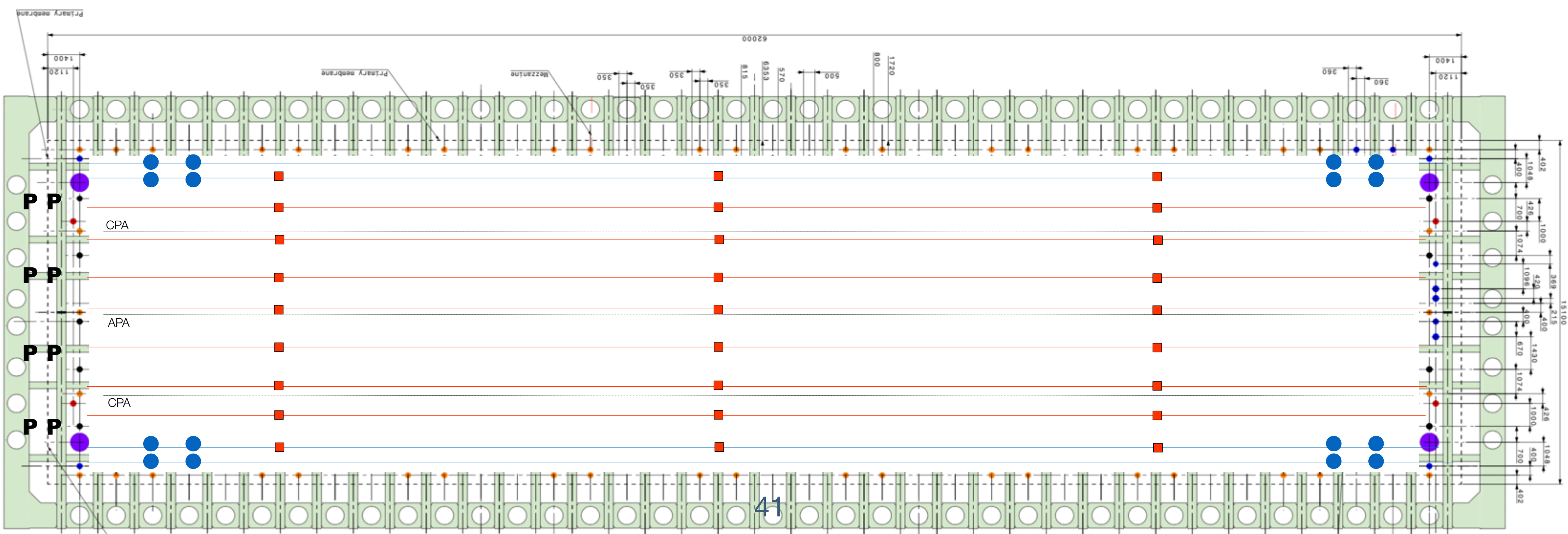
Vertical arrays in the gas

- A conceptual design under development
- Standard RTDs are sufficient – very inexpensive system
- Estimate - a sensor every 10 cm with slightly higher density at the bottom
- GPs or DSS potential anchoring points
- 8-10 vertical arrays considered to be sufficient



Other sensors

- **LAr inlets (●)**: **Two (for redundancy) in each side of each of the four pipes**. In PD-I, sensors at inlets are not in the optimal location limiting usefulness to CFD simulations.
- **LAr pump (P)**: **Two (for redundancy) in each pump**. In PD-I there was no sensor at the pump
- **Ground planes (■)**: At least **two sensors in each active volume at 3 different positions along the cryostat.** Important to have few points between APA rows.



Question III

Have all technical issues related to the feasibility of the system (including those raised in the previous workshops) been resolved?

Sensors on APAs

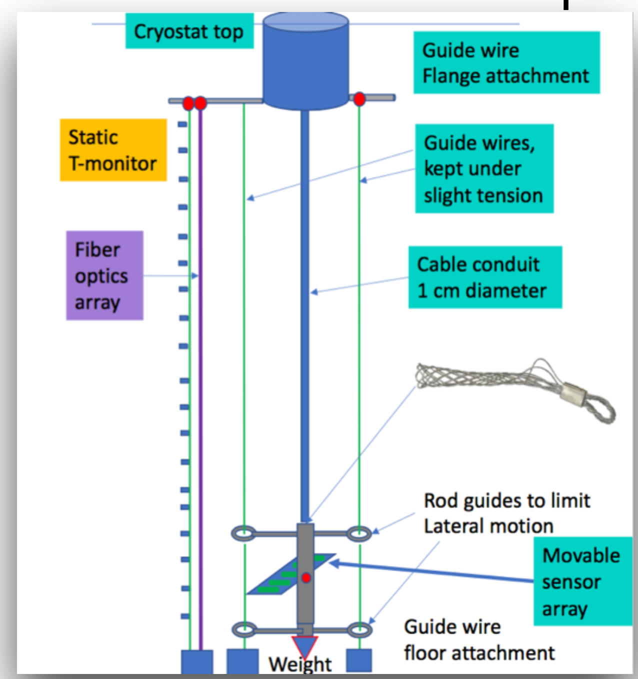
- This is a new system. Mechanical interfaces with APA and PDs consortia have been mostly resolved. Different sensor configurations on APAs add the most complexity. This poses some problems in terms of APA manufacturing and installation. Those issues are being discussed with the APA consortium

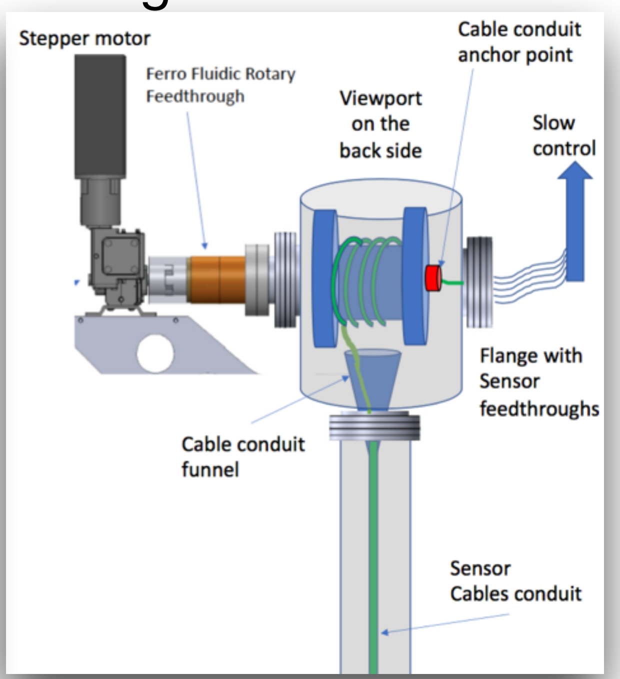
Material sent to PSL for tests in cold box

Dynamic T-Gradient I

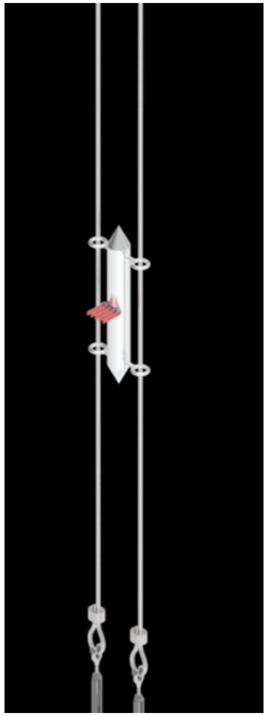
- The updated design addresses the issues raised at the previous review: protection of the viewport and segmented design to account for installation with the limited overhead space.
- The updated design takes advantage of the existing stepper motor and motion mechanism that demonstrated exceptionally smooth motion, without jitter or lateral (swinging) motion in PD-I (as observed by cameras during the motion)

conceptual design





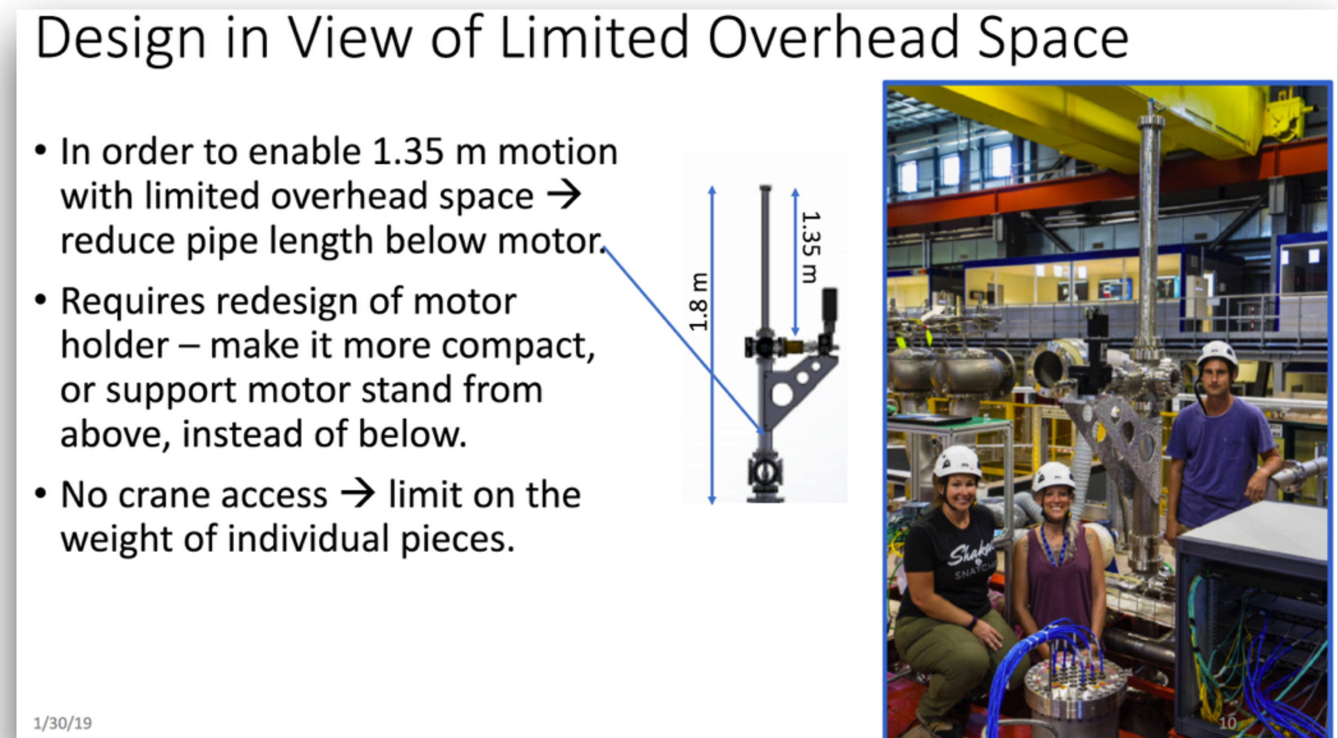
3D model



Dynamic T-Gradient: issues resolved

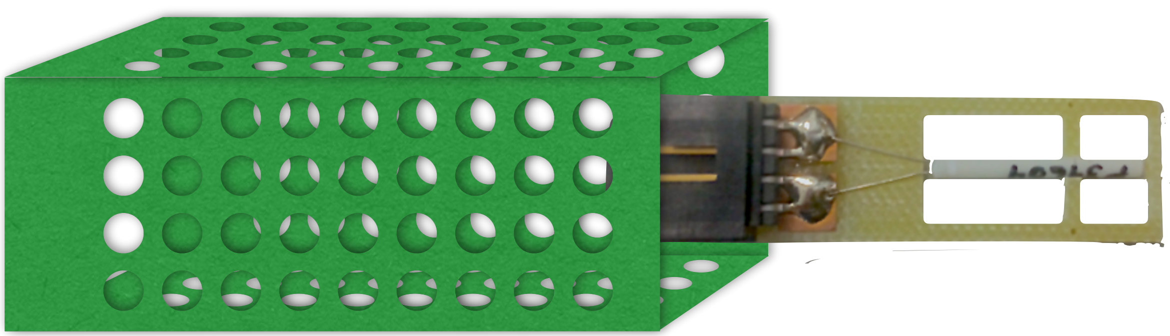
- New segmented design does not require significant overhead space
- The problem with the viewport in ProtoDUNE-SP was due incorrect glass choice (designed for vacuum, but with low pressure rating) and mainly due the lack of hard protection for the viewport (in case it was accidentally hit by an object)

ProtoDUNE-SP design



Other sensors

- **Floor sensors:** main issue is installation, specially interface with temporary floor. Ideally they should be installed before the floor. Most likely pipes will be used to route cables
- **Wall sensors:** no issues identified in ProtoDUNE-SP
- **Vertical arrays in the gas:** no issues identified yet
- **Sensors in pumps and LAr:**
    - We need to identify proper anchoring points, specially for pump sensors
    - They will need a proper encapsulation to avoid any risks in the case of detachment



Question IV

Are there any risks to overall detector performance associated with the implementation of the system, and if so, is there a plan in place for mitigating these risks?

Sensors on APAs

- Potential noise induced in cold electronics is the largest risk
- **The risk is low**: RTDs receive a **DC** current of **1 mA,** cables are shielded and properly grounded
- **Risk assessment**:
  - Tests in ICEBERG, CERN coldbox and later in ProtoDUNE-SP II
- **Risk mitigation**: only if problems arise
  - If the noise is only generated during readout, reduce the live time (take measurements only few times a day)
  - If the problem is permanent, disconnect from readout and ground the sensors that are problematic

Dynamic T-Gradient monitor

- Electronic noise not expected to be an issue – no problems in PD-I
- Motor noise present only during usage which is rare – once every few months or as needed for estimated 1 hour
- Select viewport glass window rated for the expected pressure and test it prior to installation. Include acrylic protection in front of the viewport to protect it from accidental physical impact
- Test the new system in the high bay facility prior to installation in PD-II to verify smooth deployment
- Utilize high bay for a mock up deployment of the system that is twice as high for DUNE.

Other sensors

- **Floor and wall sensors**: no risk identified
- **Pump and inlet sensors**:
  - Potential detachment of the sensor given the proximity to a strong LAr flow
  - **Risk assessment**: the system will be tested in PD-II
  - **Risk mitigation**: properly encapsulate the sensor

Question V

Is there a credible plan in place for demonstrating system performance in ProtoDUNE-II?

Plans for ProtoDUNE - II

- **Sensors on APAs**:
  - Each of the 4 APAs will be instrumented with 4 RTDs (2 are precision RTDs) cross-calibrated (lab. and pumps-off) with all other sensors in the cryostat.
  - Their temperature will be compared with the one of those other sensors, some of them nearby. Also a comparison between pumps off and laboratory calibration will be done.
- **Dynamic T-gradient**:
  - the system will be prototyped for PD-II
  - The dynamic calibration will be compared with pumps-off calibration and laboratory calibration. The temperature will be compared with the of sensors sensors in nearby APA. Notice that its performance depends only on the ref. sensor position accuracy
- **Other sensors**: for LAr inlets and pump
  - For redundancy, two contiguous sensors will be installed at each of those five locations. Comparison between pumps on and pumps off is a crucial tool in this case

ProtoDUNE-SP II milestones

	Milestone	Date
Sensors on APAs	3D model available	2020, February
	system prototyped at IFIC	2020, February
	system tested at PSL coldbox	2020, July (?)
	system tested at ICEBERG	2020, September (?)
	fabricate all elements and send them to APA production factories	2020, October
Dynamic T-gradient	3D model available	2020, September
	System fabricated	2021, June
	tests at a high bay facility	2021, July
Gas arrays	3D model available	2020, September
	system prototyped at IFIC	2020, November
Sensors at pumps and inlets	3D model available	2020, July
	system prototyped at IFIC	2020, September
Calibration of all precision	APA sensors (8 units)	2020, September
	calibration starts for all other sensors (~100)	2021, January
	calibration ends	2021, March

Question VI

Does the functionality of the system justify its overall cost?

Question VI

- Based on the previous arguments and on the system cost, we think the answer is yes

Only M&S

	# sensors	cost/sensor	common	TOTAL
sensors in APAs	452	140	10000	73280
dynamic T-gradient	48	140	20000	26720
sensors in LAr inlets	16	140	5000	7240
sensors in pumps	8	140	2000	3120
sensors in GPs	27	140	2000	5780
wall sensors	26	15	1200	1590
floor sensors	15	30	3000	3450
gas arrays	100	15	5000	6500
readout	592	8	10000	14736
TOTAL				**142.416**

Charge Part II

Review Committee Charge – Part II: Based on their evaluations of the individual systems, the review committees are asked to classify each of the proposed systems in terms of the following categorizations:

1. Essential – Experiment should not be run without this system in place.

2. Highly-desirable – Strong justification for including this system but not viewed as absolutely necessary.

3. Advantageous – Good arguments exist for why this system might be useful but not fully justified in terms of its contribution to overall detector performance.

4. Debatable – System could potentially be useful but not fully supportable based on current arguments.

- **Sensors on APAs**: Some distribution of precision sensors along the height and length of the cryostat is **essential.**
- **Dynamic T-Gradient: essential** for a model independent in-situ calibration giving a reference for all other sensors, at all times
- **Other sensors**:
  - **LAr inlets**: **essential** to immediately detect cryogenics system malfunctioning
  - **LAr pumps**: **highly-desirable** as input/cross-check for CFD simulations
  - **Gas arrays**: **highly-desirable** as input/cross-check for CFD simulations
  - **Ground planes**: **highly-desirable** to reduce extrapolation error to region between two APA rows
  - **Floor**: **essential** to detect the presence of LAr when filling starts (probably the more inexpensive way)
  - **Wall**: **essential** to measure the cryostat membrane temperature during cooling down and filling