Fibre-Based Temperature Monitoring System for DUNE FD-II

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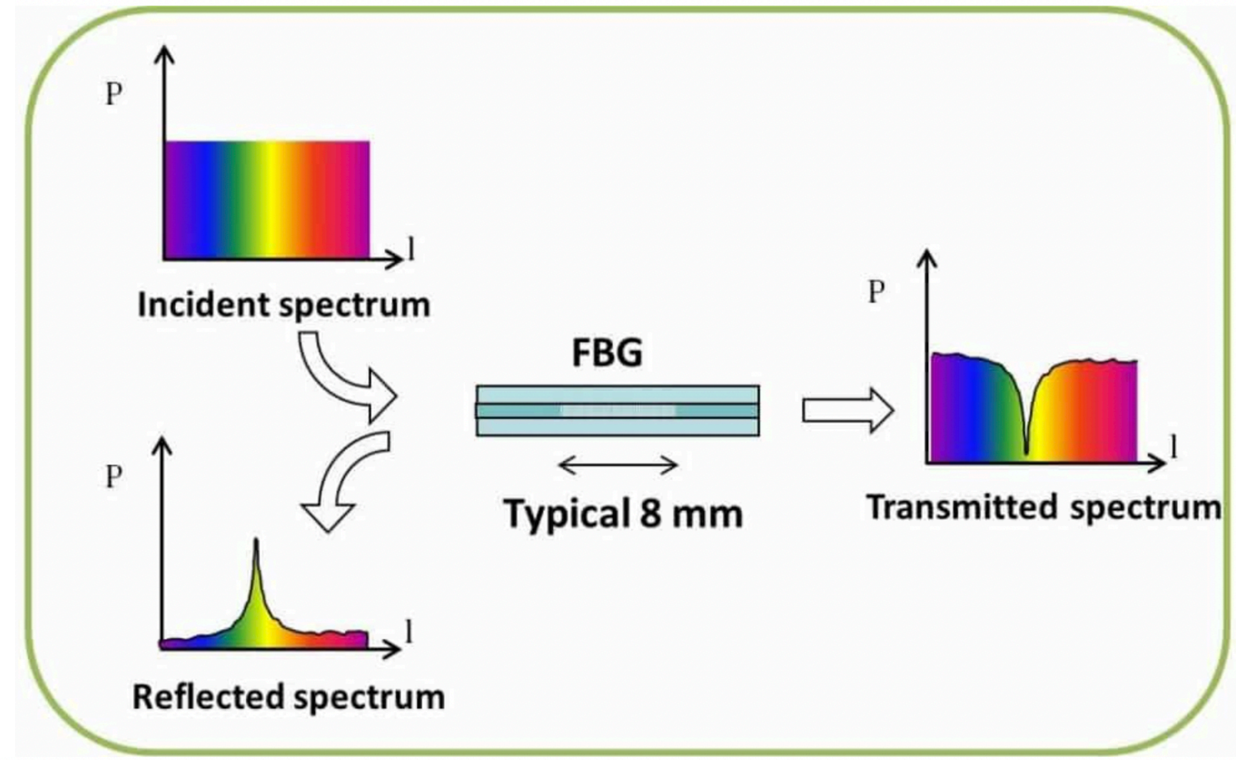
Why is it necessary to change the technology?

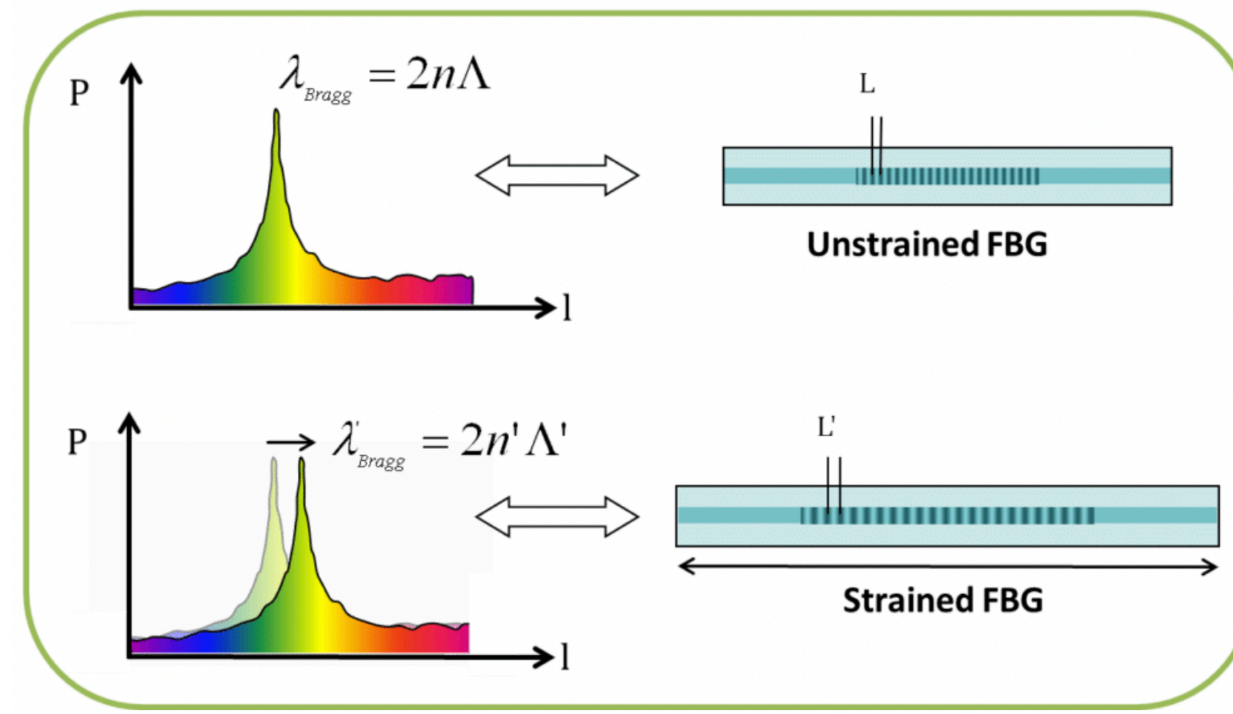
- As it is well-known, for the **HD configuration** the TMS is based on standard **RTD**s for the temperature mapping of the liquid inside the cryostat: sensors on the APA, ullage, inlets, pipes, pump, PrMs, walls…
- Due to the **HV in the VD configuration**, copper wires cannot be used to read out the signal of the sensors -> One solution is to **use optical fibres** instead.
- This is the same motivation as it is for the SoF and PoF that will be tested in ProtoDUNE-VD soon.
- During the last decades, a new technology emerged: **Fibre Bragg Grating** (FBG) technology which has been widely used to measure extensive quantities (Temperature, Strain, Pressure…) over long **long distances** and/or large volumes.
- It has been used mostly in large infrastructures as **oil pipes** or new **buildings** to monitor the status of the structure: the flow in the pipe, the tilt of the building, stratification of natural gas…

https://technicasa.com/application/

Principle of operation of FBG.

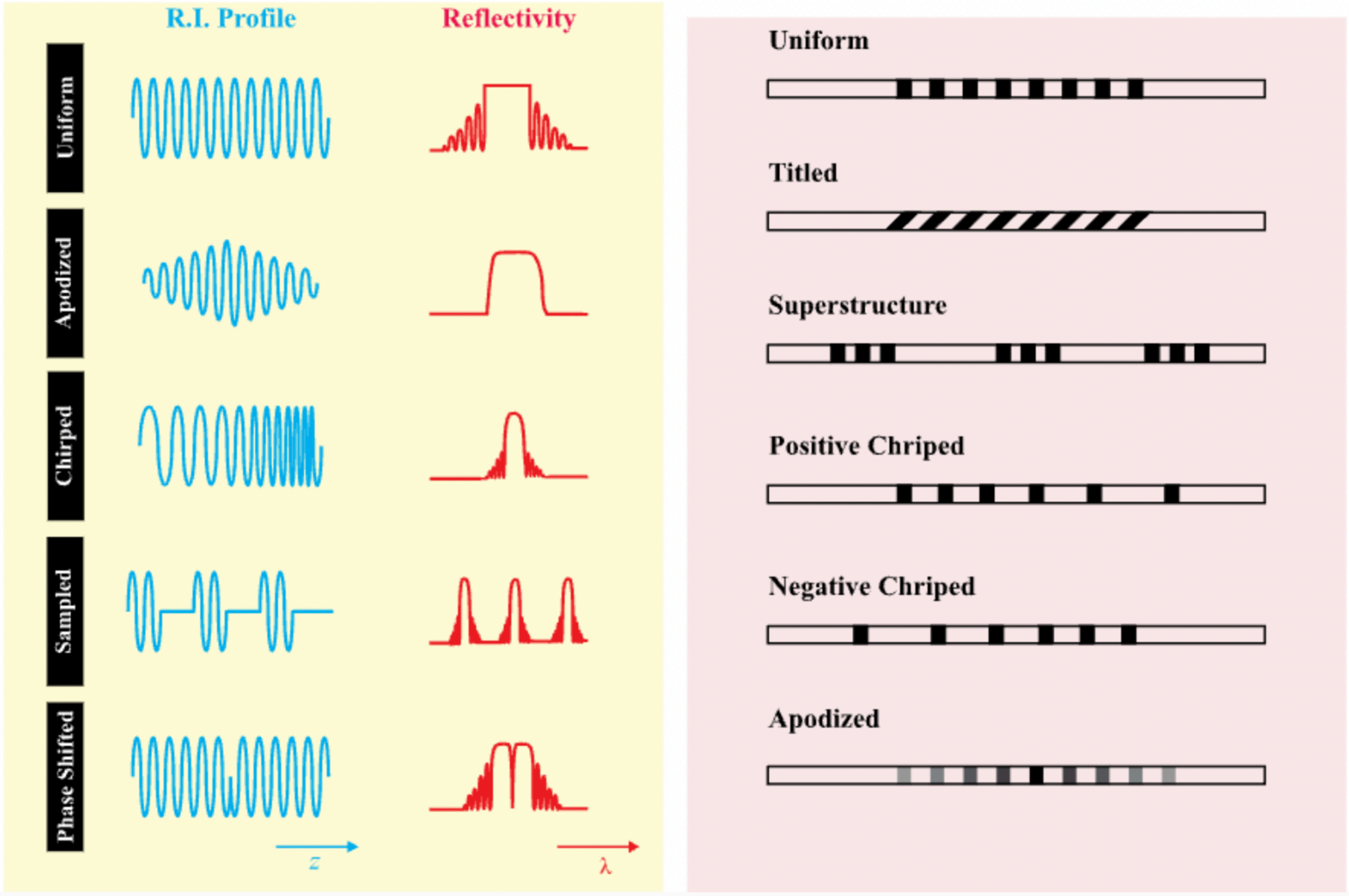
- Fibre Bragg Gratings are made by laterally exposing the core of a single-mode fibre to a periodic pattern of intense laser light. The exposure produces a **permanent increase in the refractive index of the fibre's core**, creating a fixed index modulation. This modulation is called **grating**.
- When the **Bragg condition** is fulfilled, **small amounts of reflected light** signals coherently interfere at each periodic refraction change combining into a **large reflection** at a particular wavelength.
- This condition is fulfilled at the so-called **Bragg wavelength** of the grating.
- The **Bragg wavelength varies** when external changes on the fibres are applied, as temperature or strain. The measurement of these Bragg wavelength changes allows to measure the source of the change, i.e. temperature.





Types of gratings: Primary Gratings

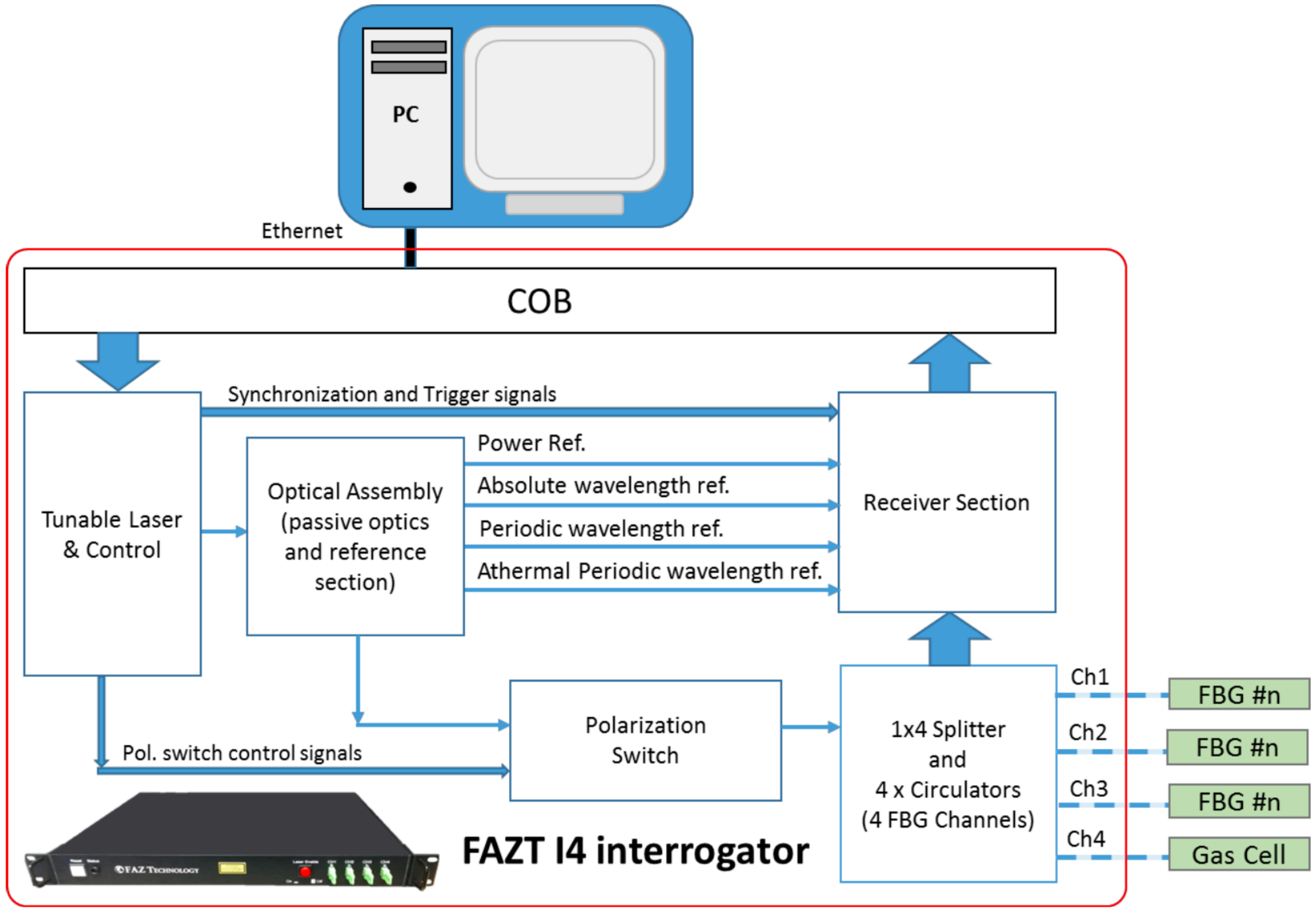
- There is a large variety of grating types to be engraved on the fibres.
- Depending of the **grating profile** the shape of the reflected signal will change according to the needed requirements.
- For example, if one wants to **suppress the side lobs**, one should go for **apodized** gratings.



Proc. of SPIE Vol. 10208 102080P-1

Principle of operation of Optical Interrogators.

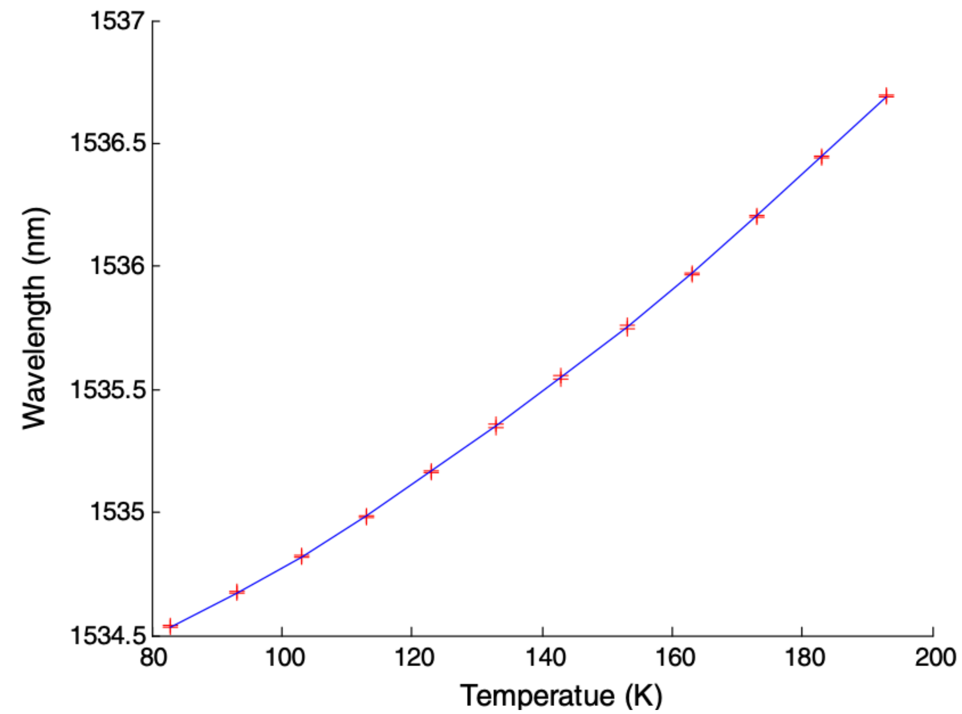
- The interrogator is based on a semiconductor **laser diode** delivering a high level of precision and accuracy.
- The laser scans the **C-band** (~1540 nm) at a sweep rate of 1kHz (running rate of 0.1 pm/ns).
- The **output** of the laser is **polarised** and the power output is split over the different channels.
- The typical minimum detectable power (**noise floor**) at the receiver end **<40dBm**.
- The received reflected signal is sampled with 1pm resolution. Usually they can track **~30 sensors per channel** @1kHz sampling rate -> **480 sensors tracked at 1kHz** for a 16-channel device.

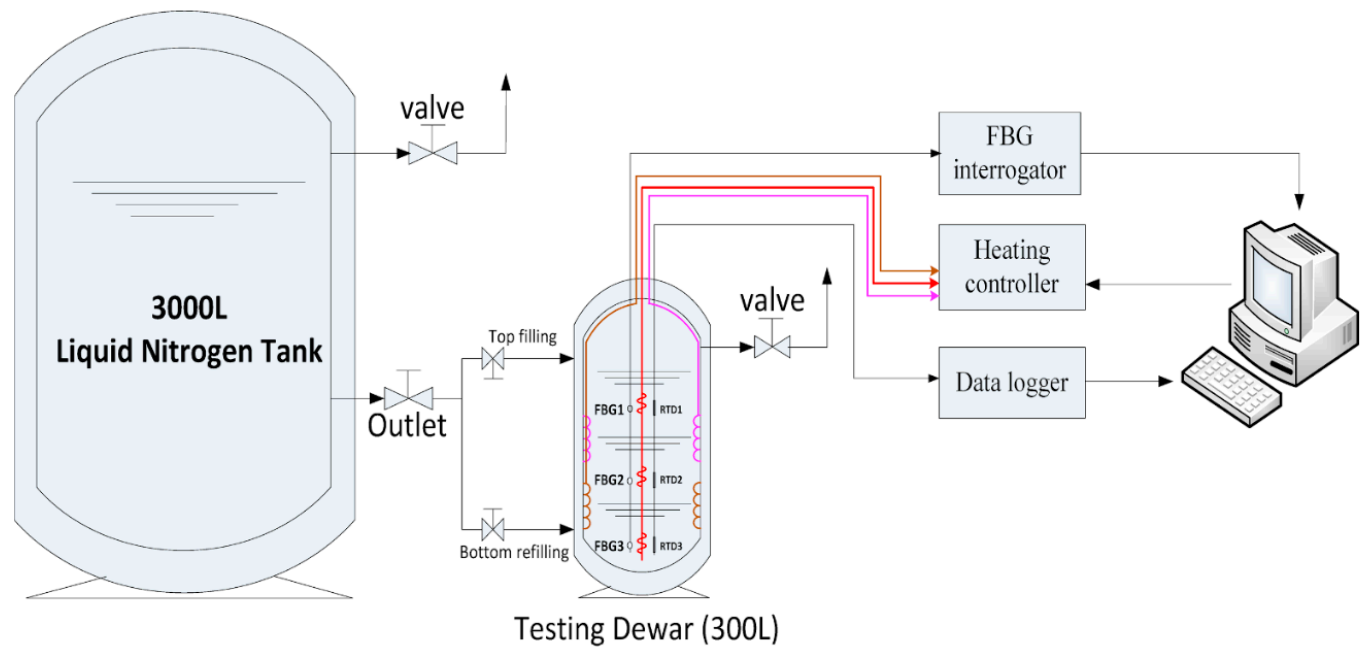


Liquified Natural Gas TMS.

https://doi.org/10.1016/j.cryogenics.2018.11.001

- The aim of the study was to check whether FBGs are **suitable to measure stratification in the LNG** inside the storage tank.
- FBGs can resolve the temperature difference of ~2K artificially created between the top-bottom of the testing dewar.





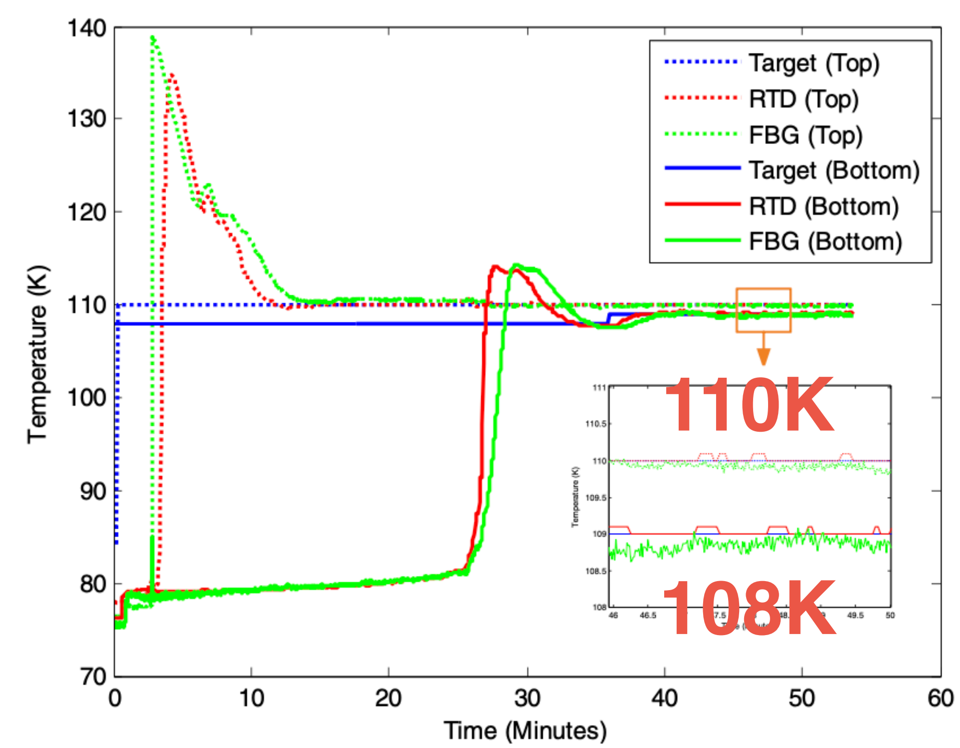
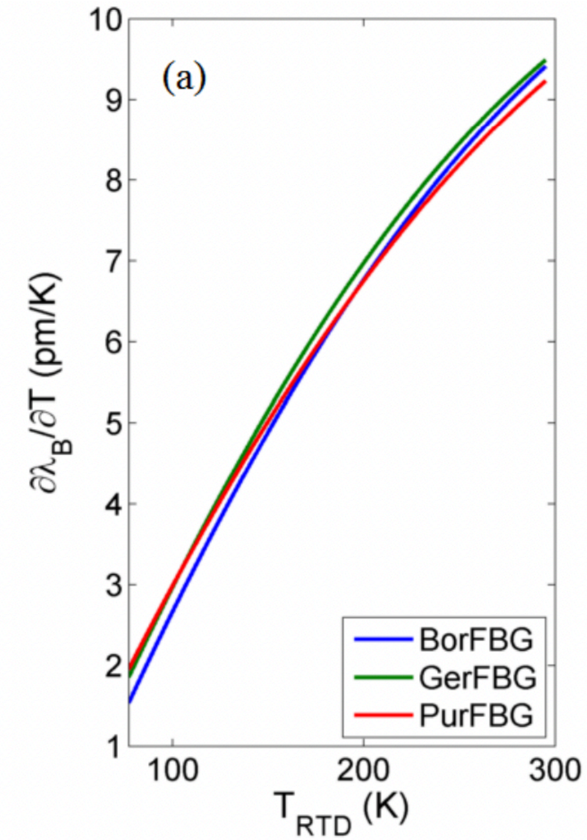


Table 1
Design central wavelength of the reflected spectrum and actual reflected spectrum.

No.	1	2	3	4	5	6
Design spectrum	1530	1535	1540	1545	1550	1555
Actual spectrum	1527.988	1534.896	1539.099	1542.555	1546.306	1550.447

FBG for Temperature measurements

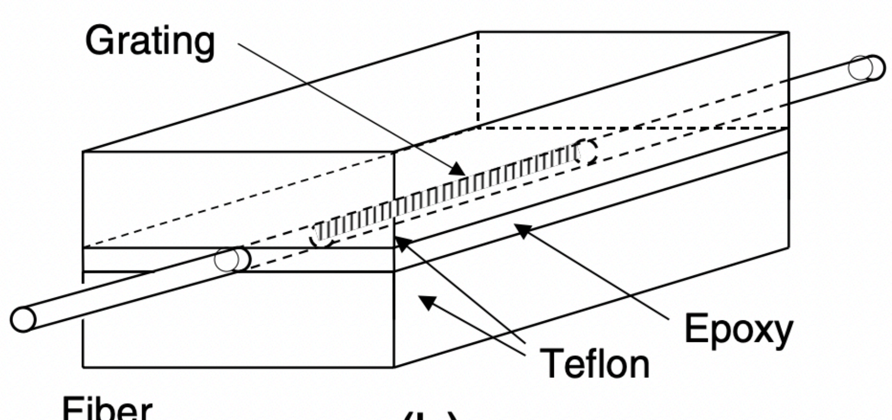
DOI: 10.1364/OE.22.027681



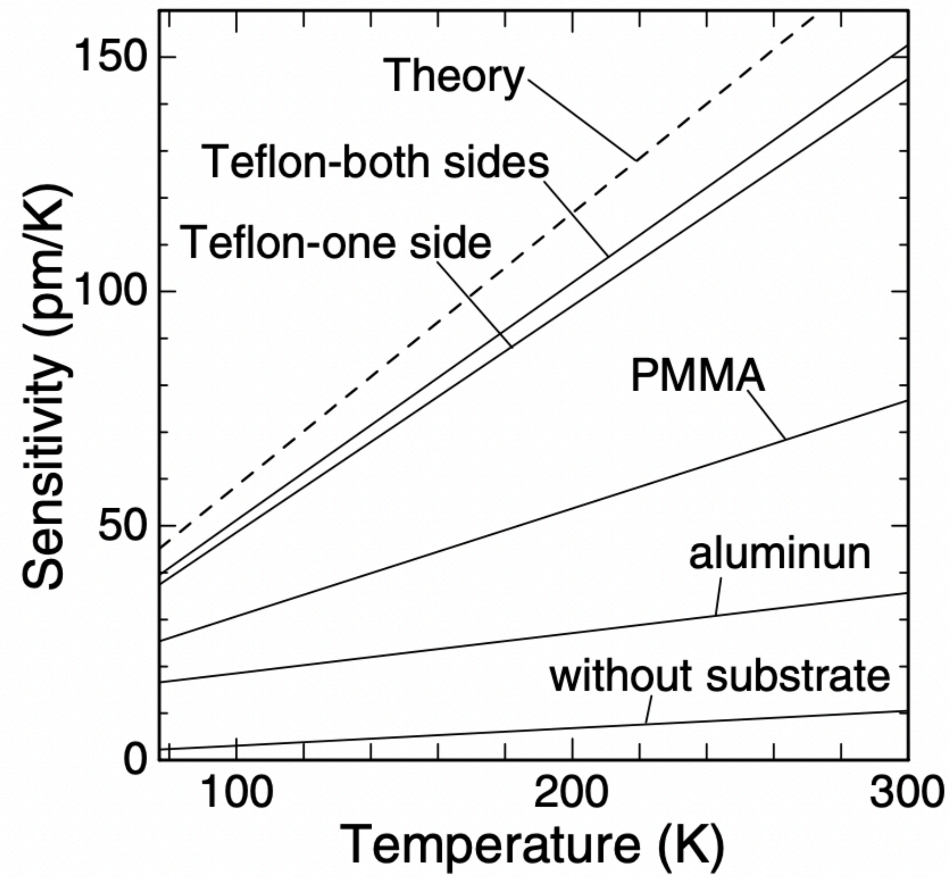
Hill, Kenneth O., and Gerald Meltz. "Fiber Bragg grating technology fundamentals and overview." *Journal of lightwave technology* 15.8 (1997): 1263-1276.

- **Low-temperature** measurements with FBGs poses **additional challenges** compared to room-temperature measurements.
- The $\delta\lambda_B$ is proportional to the sum of the **thermo-optic** $\alpha_{n,T}$ and **thermal expansion** $\alpha_{\Lambda,T}$ coefficients:
  $\xi = \alpha_{n,T} + \alpha_{\Lambda,T} \rightarrow \delta\lambda_B = \lambda_B^0 \cdot \xi \cdot \delta T = \psi_T \delta T$
- The **wavelength temperature sensitivity** ψ_T is usually of the order ~10 pm/K for T>273K.
- By **bonding the FBG in between two teflon substrates**, the temperature sensitivity was increased at 77K up to 39 pm/K.
- If the center **wavelength** can be **determined** with a **0.1 pm accuracy**, then one can expect a resolution of **~2.5 mK** at 77K for this specific configuration.

Meas. Sci. Technol. 12 (2001) 914–917



(b)

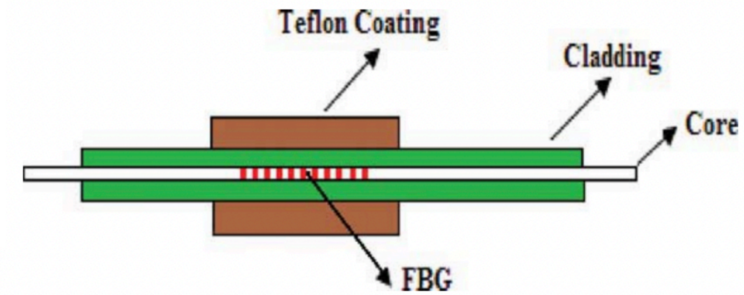


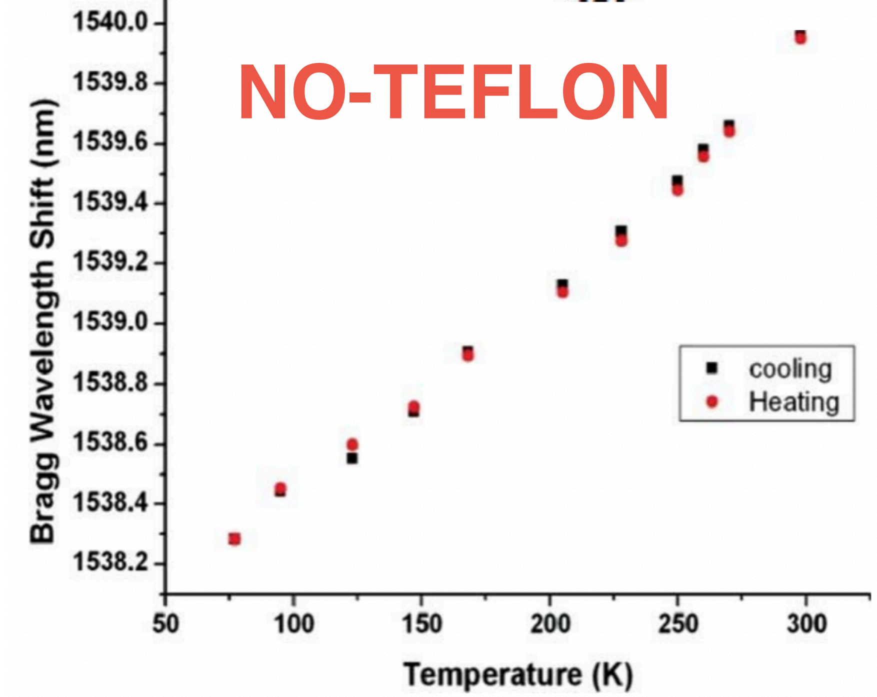
Current Sensitivities achieved

- By adding thin layers of **PMMA or Teflon** on both sides of the sensors, several authors have shown a **remarkable increase in the thermal sensitivity** of the Bragg Wavelength.

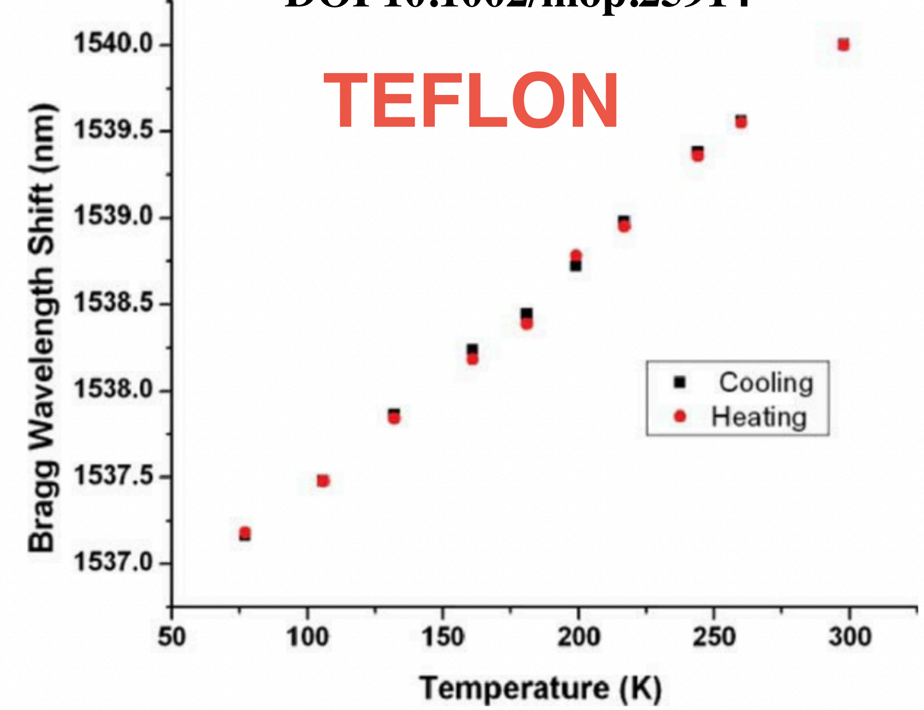
Parne, Saidi, et al. "Polymer-coated fiber Bragg grating sensor for cryogenic temperature measurements." *Microwave and optical technology letters* 53.5 (2011): 1154-1157.

- In this paper, they study the change in ψ_T as a function of the thickness of the Teflon layer. For their specific sensor, **without coating it was 7.59 pm/K** and with 40 μm Teflon coating they **increased up to 12.85 pm/K**, at 77K -> $\delta T \sim 7.5mK$
- Also, the addition of Teflon coatings further increase the **linearity** over a wider temperature range of the sensors.





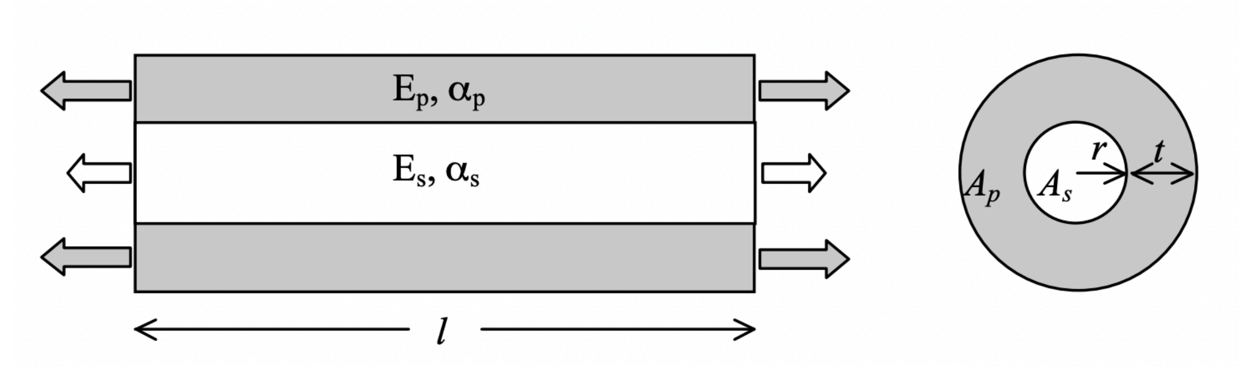
DOI 10.1002/mop.25914

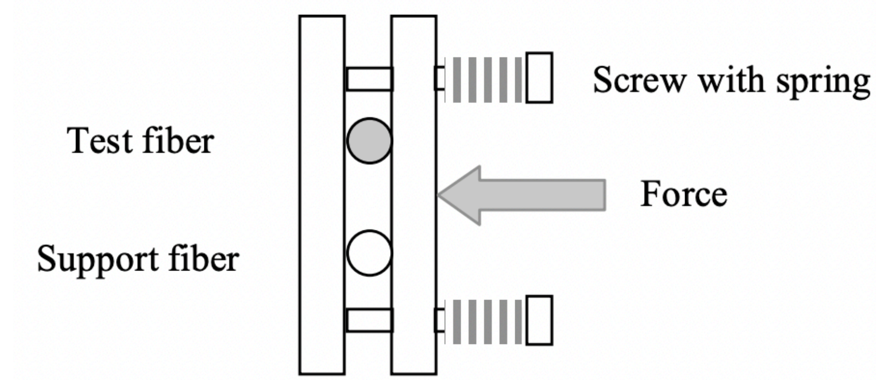


Current Sensitivities achieved

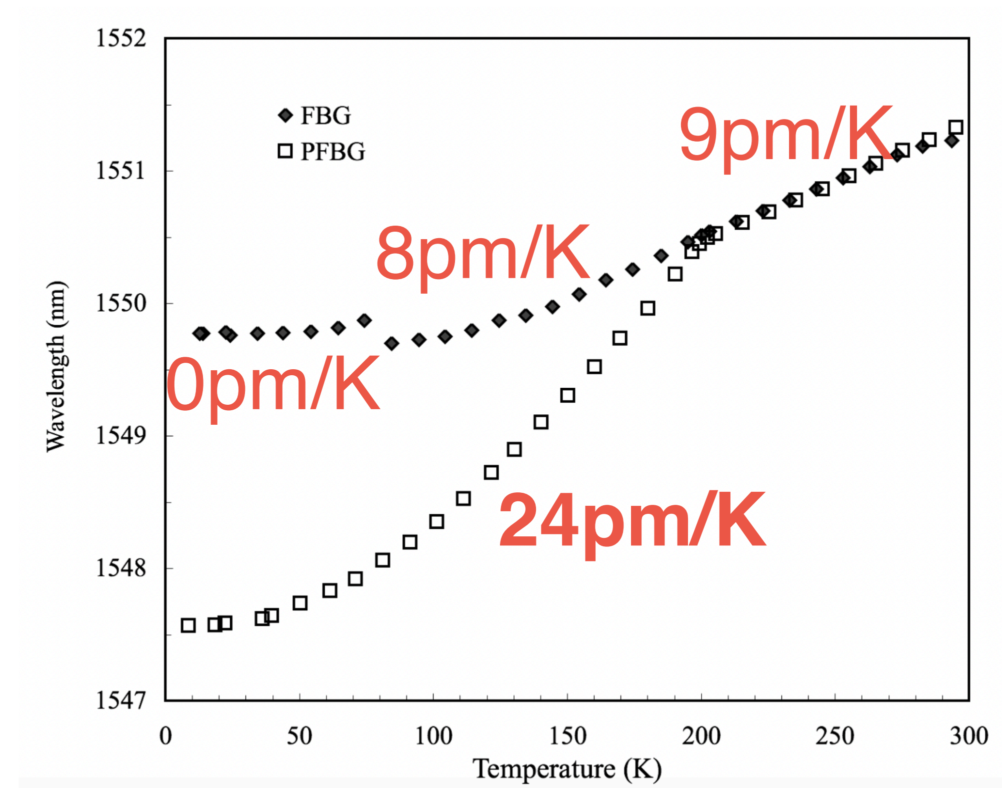
Pater, Ruth H., and Stanton L. DeHaven. *Effects of Coating and Diametric Load on Fiber Bragg Gratings as Cryogenic Temperature Sensors*. No. Paper-6933-3. 2008.

- The addition of PMMA or Teflon coatings implies **sacrificing the flexibility** of the optical fibre because of the need of bounding to a rigid substrate.
- In this paper, the authors studied the effects of polymer coatings ranging from 11 to 62 microns and the use of **pressurised FBGs** (PFBG).
- PFBGs can be obtained by inducing a **small diametric load** to normal FBGs. They turn to be more sensitive at cryogenic temperatures. This phenomenon is attributed to the change in the thermo-optic coefficient.
- They studied both configurations in the range 4.2 (He) to 295K (Room), obtaining very **high sensitivity for the PFBG at cryogenic temperatures** -> $\delta T \sim 4mK$





Coating thickness, t	$\Delta\lambda_B^{FBG}$ (nm)	$\Delta\lambda_B^{PFBG}$ (nm)	$\Delta\lambda_B^{PFBG} - \Delta\lambda_B^{FBG}$
11 µm	1.51	3.78	2.27
22 µm	1.99	4.15	2.16
62 µm[a]	3.38	5.60	2.22



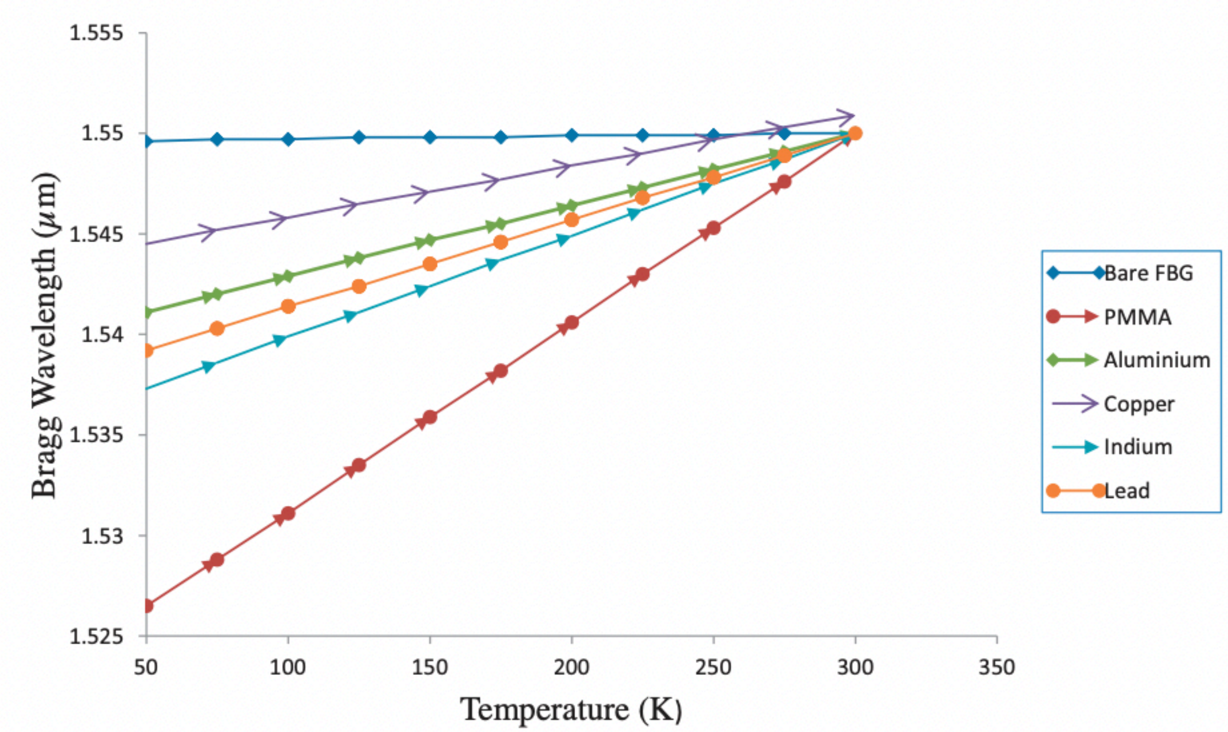
Simulations of different coating materials

https://doi.org/10.1016/j.ijleo.2015.10.014

Coating material on FBG	Sensitivity (pm/K) [a,b]	Sensitivity (pm/K) (Simulation results)	Improvement in sensitivity (%)
Copper	23.60[b]	25.6	8.47
Aluminium	20.93[b]	35.6	70.10
Lead	31.36[b]	43.2	37.70
Indium	33.53[b]	50.8	51.50
PMMA	43.92[a]	94.0	114

- In this paper, the authors show the resolution obtained when coating a bare FBG with different materials of thicknesses 20 μm.
- The **difference in thermal expansion coefficients** of silica and that of the coating material causes **stress** on the sensor provoking an increase in thermal sensitivity.
- The simulation gives a sensitivity as high as **94 pm/K** when **PMMA** coated, but measurements made by other authors found it to be **43.92 pm/K instead**.
    - https://doi.org/10.1364/ACP.2011.831103

Material	Thermal expansion coefficient (m/m °C)
PMMA	61×10^{-6}
Aluminium	23.03×10^{-6}
Lead	28×10^{-6}
Indium	33×10^{-6}
Copper	16.6×10^{-6}



Preliminary Considerations

- We are **NOT interested** in an **absolute** temperature measurement, but in a **relative measurement** between any pair of sensors -> **OFFSET**.
- What it matters is to have the ability to track the Bragg reflection peak of several sensors with enough resolution in order to be able to resolve mK-differences in temperature.
- Assuming the intrinsic error of a temperature measurement on two single sensors A & B: $\delta T_A, \delta T_B$, the error on the difference of temperature between A and B follows: $\delta \Delta T_{A-B} = \sqrt{\delta T_A^2 + \delta T_B^2}$
- Assuming the errors on A & B to be the same δT, the **error on the difference** can be approximated by: $\delta \Delta T_{A-B} = \sqrt{2}\delta T$

Requirements & Objectives

- The principal requirement is to achieve enough precision to **resolve** the expected ~15-20 mK **temperature gradient** inside the DUNE cryostat.
- An additional requirement is to build a **real-time high-precision temperature map** of the LAr.
- The main objective of the R&D team is to achieve the **same resolution as existing for the RTD**s: ~2-3 mK.
- An additional objective is to construct a flow **model** based on CFD simulations to **predict the impurities concentration** based on the temperature map.

Experimental Set-Up at IFIC

- During the last several months we have been discussing with several companies that fabricate both interrogators and FBGS.
- In October we finally found the appropriate company (**OPTICS11, Netherlands**) supplying an interrogator that meet the requirements.
- Also, we agreed to sign with an FBG manufacturing company (**FBGS, Belgium**) an **NDA** to develop during the 2022-2026 period the fibres with the needed sensitivity to meet the requirements.
- The **interrogator** was **shipped to IFIC yesterday** (9th November) and is expected to be delivered soon. The quotation for the **FBGs** was also requested on 4th November and they are expected to be at IFIC by the **end of this year**, after placing the PO.

OPTICS11: I4-16 Interrogator

- The **I4G-16** is a 16 channel interrogator able to provide peak detection for up to **30 FBGs per channel**.
- The instrument features **0.1 pm precision** and reproducibility smaller than 100 fm.
- It comes together with the DAQ with Ethernet connection to the computer and **2 test fibres for the initial tests at IFIC**.
- The wavelength range of the scan lays between **1529** and **1568.2 nm** (C-band).
- It has **2 polarisation switching states** that the user can enable to disentangle the polarisation-dependent effects of the reflections.

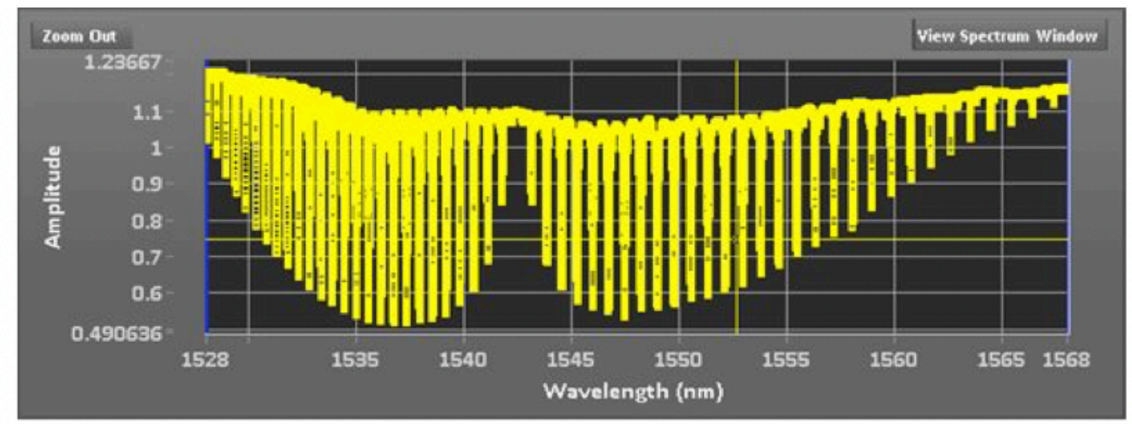
Performance

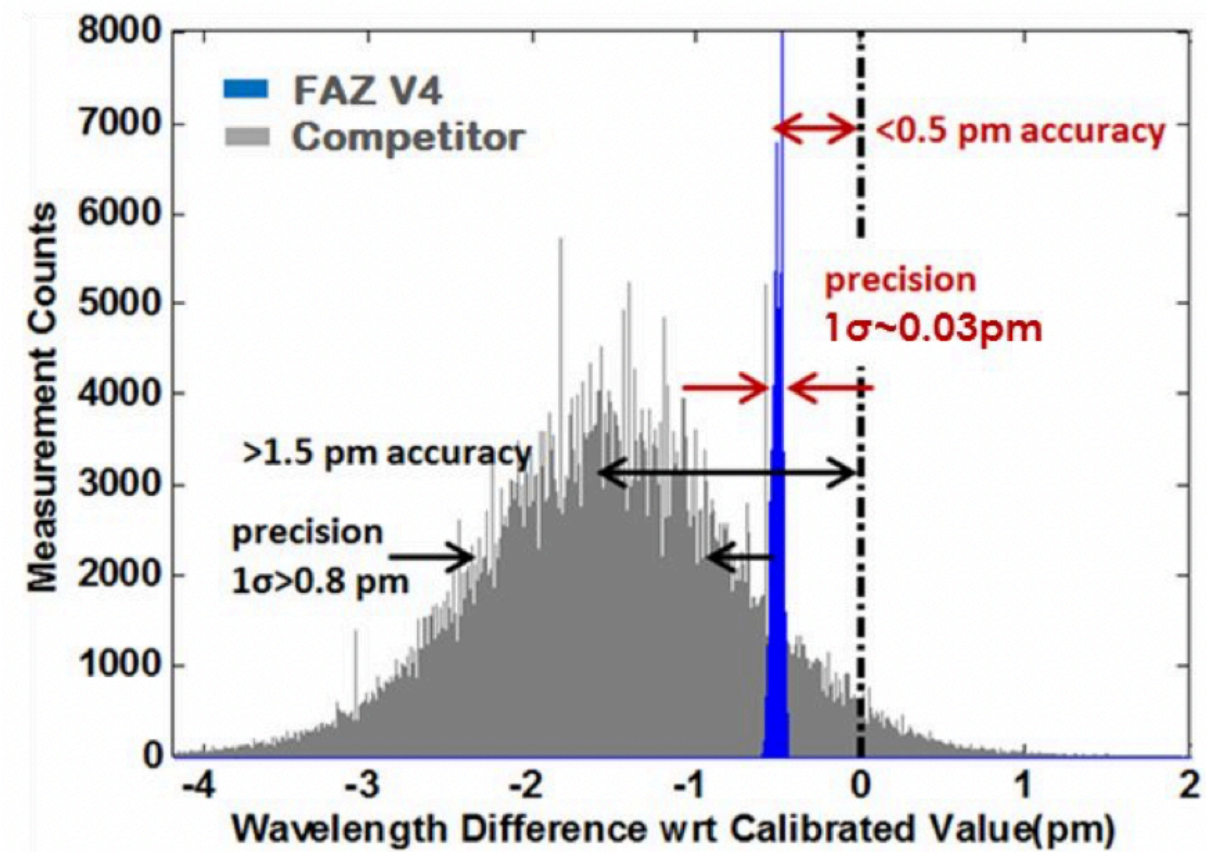
Wavelengths Range	39.2nm	1529nm to 1568.2nm
Number of Channels	16	
Number of Sensors per Channel (see Note 1)	1 to 30	16ch * 30 = 480 sensors (assuming 1.2nm spacing of FBG sensors)
Wavelength Sample Size / Resolution	1 pm	
Wavelength Absolute Accuracy	< 1 pm	Gas Cell and MZI referenced with PM circuit to guarantee long-term performance
Wavelength Precision	< 0.1 pm	Standard deviation of a tracked HCN P10 Gas Cell line measured >8-hours
Wavelength Repeatability (see Note 2)	< 0.1 pm	
Laser Line-Width	20 MHz	Self-heterodyne measured line-width at static wavelength
Laser Output Power per Channel (see Note 3)	+0 to +3dBm	Performance is maintained even with 20dB optical power loss
Scan Frequency / FBG Processing	250Hz	
Scan Frequency (Full Spectrum @ 1pm)	1 Hz	1Hz for 16 channels with 1pm resolution
Polarization Switching States	2 States	Switches polarization state every sweep when user enabled
Sensor Range / Distance	0 to 10 km	Lead-in cable (0 to 7.5km), FBG section (0 to 3.25km)

doi: 10.1117/12.2262103

I4G wavelength-precision measurement

- To check the accuracy on measuring a single wavelength over long-term periods, a P10 gas cell was used.
- The gas cell is emitting **narrow well-known wavelengths** that the I4G is tracking over a 8 hours measurement.
- All measurements lie within a gaussian distribution of **0.03 pm at 1 sigma**, for a specific wavelength.
- **We usually take the conservative number of 0.1 pm resolution** instead, but these tests will be performed also at IFIC to check what is the real resolution at the wavelength-measuring points.

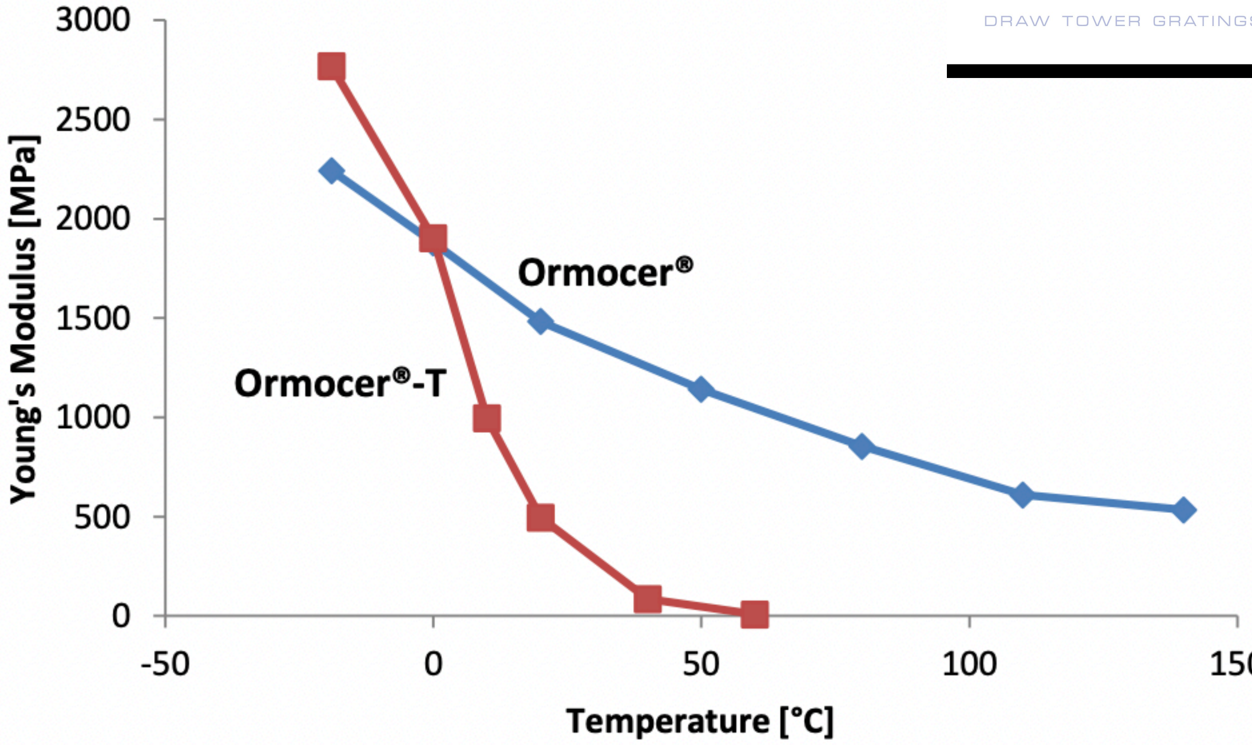


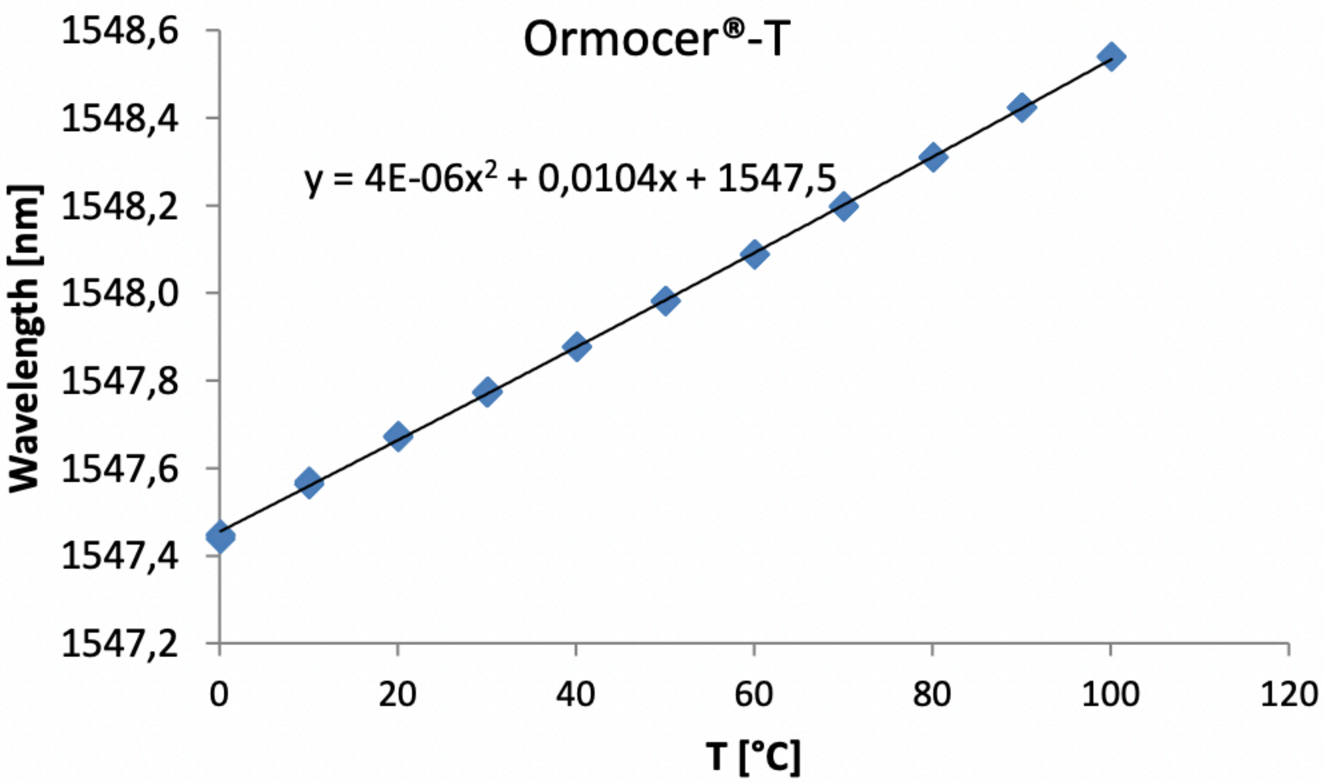


FBGS, S.A. : R&D plan

https://fbgs.com/wp-content/uploads/2019/03/Introducing_and_evaluating_Ormocer-T_for_temperature_sensing_applications.pdf

- FBGS uses **Draw Tower Grating** (DTG) technology to produce the fibres and engrave the gratings after the coating process, which is very **cost-efficient**.
- They have two different patented coatings (Ormocer and Ormocer-T). **Ormocer-T** is more suitable for temperature sensing applications as it has **larger thermo-elastic coefficient** and therefore is more sensitive to temperature changes above 273K.
- We ordered **two identically-manufactured fibres** in stock with 11 sensors each that only **differ in the coating** to study the behaviour of the two coatings at cryogenic temperatures.
- The initial study will consist in **characterising the thermal sensitivity** of the 11 sensors over the range 77-300K. With this information, the next iteration will focus on adding more **coatings** or apply **other techniques** to the sensors in order to further increase their sensitivity.

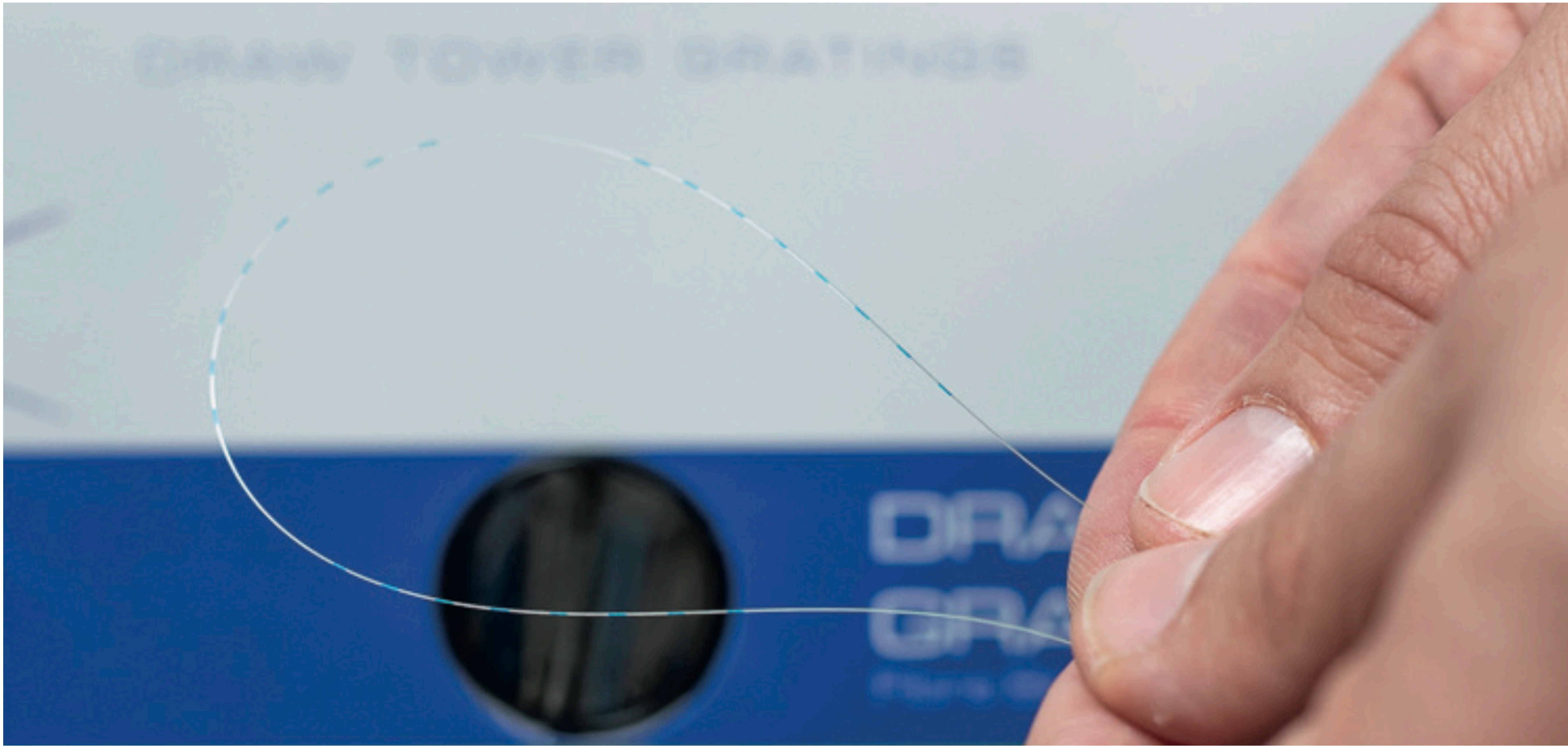




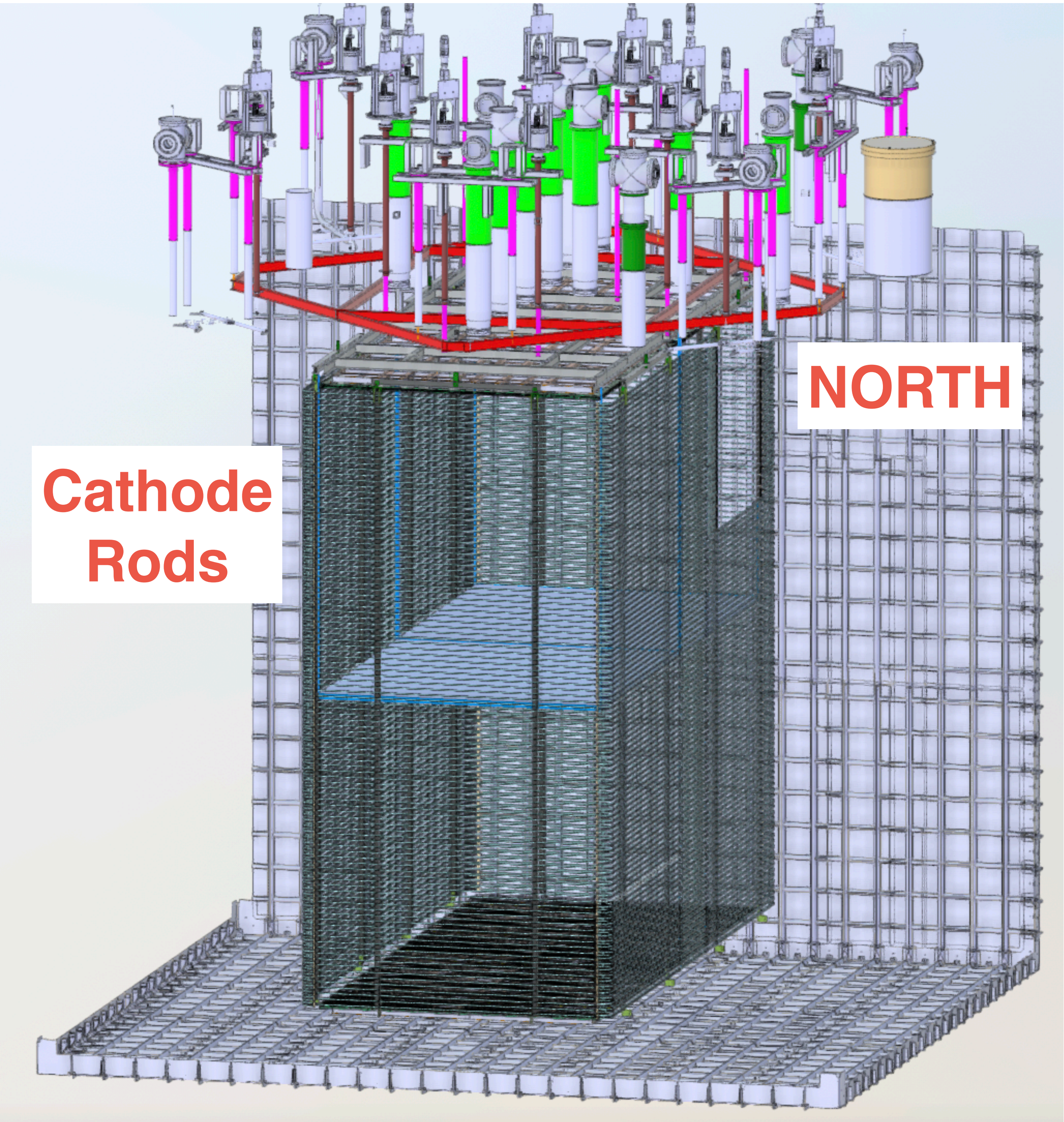
FBGS, S.A.: Sensors Specifications

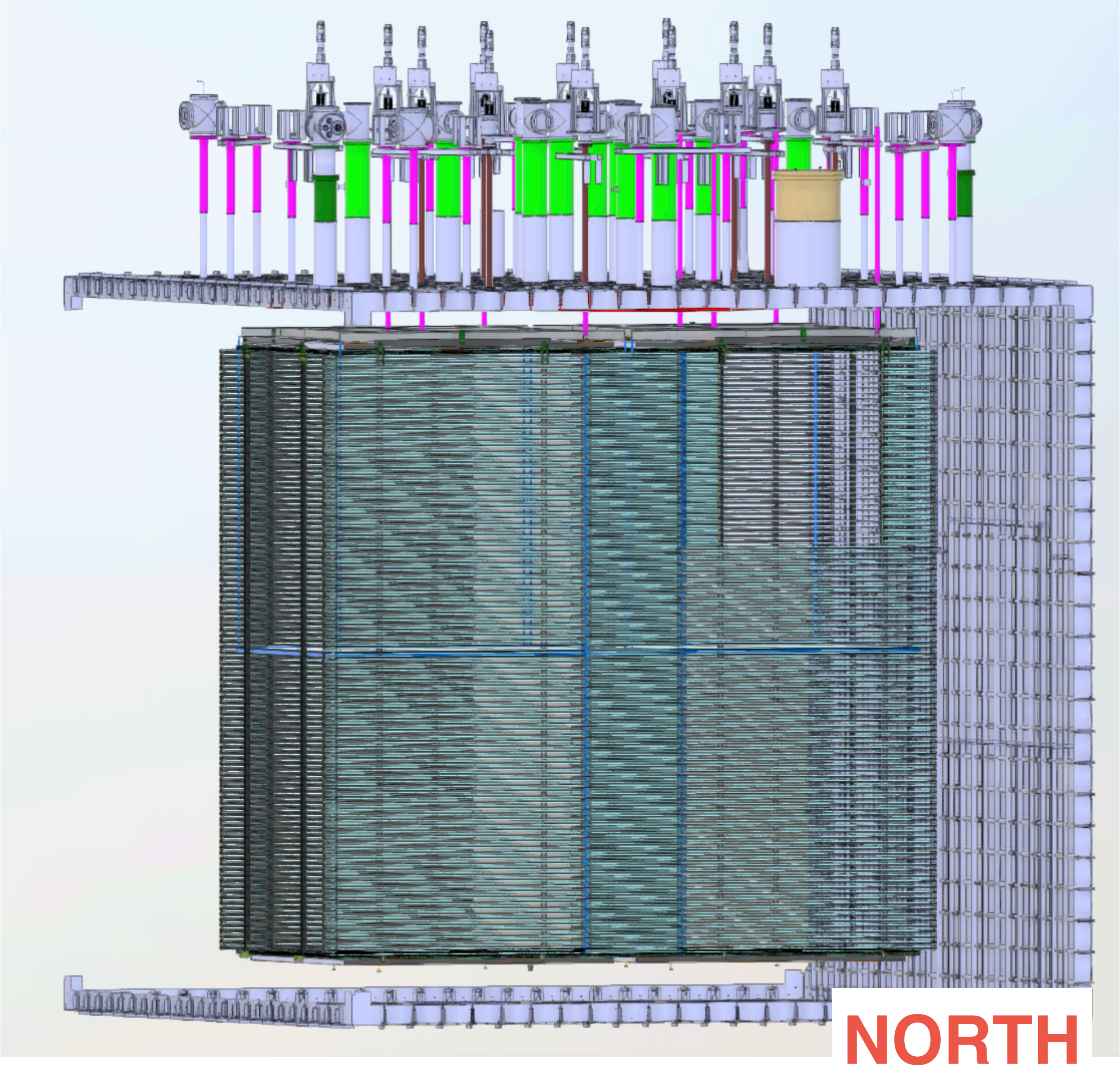
- The sensors we are producing for the PD-VD installation will have **this specifications**.
- With the thermal sensitivity of **6.5 pm/K** and the interrogator resolution we expect to achieve **temperature difference resolutions of the order of: ~15 mK.**
- This resolution could not be sufficient to resolve the temperature gradient, although the **resolution could be improved** in several ways: decrease the sampling rate (**more statistics** per point), attach them to a higher thermal-expansion-coefficient material…

Parameter	DTG-A3	
Reflectivity (for grating length of 8 mm)	>15%	
FWHM (for grating length of 8 mm)	100 pm	
Centre wavelength (extended range upon request)	1510 nm to 1590 nm	1460 to 1620 nm
Absolute Wavelength accuracy[1]	≤ 0.5 nm	≤ 0.8 nm
Relative Wavelength accuracy	≤ 0.3nm	≤ 0.5nm
Side Lobe Suppression (SLS)	≥ 10 dB (typical)	≥ 10 dB (typical)
DTG® length	1 to 10 mm / 8 mm (typical)	
Attenuation	< 8.6 dB/km	
Mode Field Diameter (MFD) @ 1550nm	6 µm (typical)	
Numerical Aperture (NA)	0.26 (typical)	
Cladding diameter	125 µm ± 1 µm	
Coating type[2]	ORMOCER®/ORMOCER®-T / One layer Acrylate	
Coated fibre diameter	195 µm (typical)	
Tensile load at break[3]	> 50 N (corresponds to >5% strain)	
Temperature sensitivity[4] (formula: $\Delta\lambda/(\lambda \times \Delta T)$)	6.5 $K^{-1} \times 10^{-6}$ (typical)	
Strain sensitivity[1] (formula: $\Delta\lambda/(\lambda \times \Delta\varepsilon)$)	7.8 $\mu\varepsilon^{-1} \times 10^{-7}$ (typical)	
Operational temperature range[5]	-200°C to 200°C for ORMOCER®	
	-20°C to 200°C for ORMOCER®-T	
	-20°C to 90°C for One layer Acrylate	



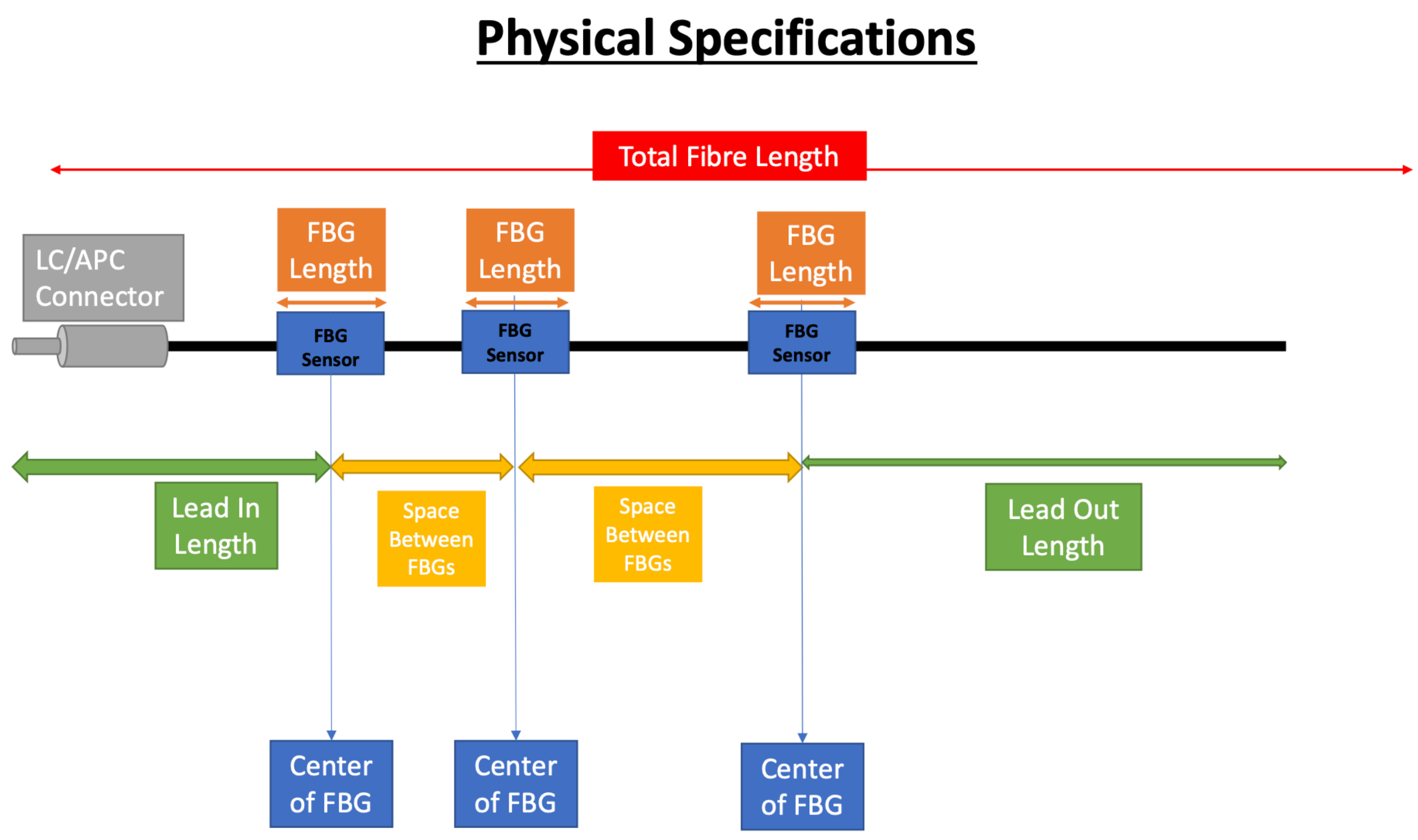
ProtoDUNE-VD Schematic Design





ProtoDUNE-VD sensors.

- For the PDUNE-VD installation we ordered **5 ~20-meter long fibres** with different characteristics.
- **Vertical Gradient**: 4 fibers, 2 of them with 15 sensors in the active volume and another 2 with 30 sensors -> 18.5 m long
- **Horizontal gradient**: 1 fibre wit 15 sensors -> 20.5 m long.
- The fixture of the fibres to the cathode rods or to the field cage profiles is **still under consideration**, most likely they can be **directly glued**.



- We are now looking for the appropriate **flanges to feed-through the fibres**. Usually the flanges use FC/APC connector but fibres come along with LC/APC, so this is something to take into account.
- Sensors have a **typical length of 8 mm**.

Further considerations

- In principle, the **minimum quantity** of fibres per batch that the company is fabricating **is ~200m**.
- We have agreed with them to **shorten this quantity** as for the IFIC tests 200m is too much, and for the **iterative R&D** it would become too expensive to carry out several iterations.
- We are already considering the possibility to **add Teflon coatings to some of the sensors** in order to achieve higher resolution in temperature.
- With the current wavelength resolution of the interrogator, to be conservative, **one should aim for thermal sensitivities on the fibres as large as 100pm/K to achieve ~1mK resolution**. OPTICS11 is developing a new device (**I4P**) which is more capable and we are in touch with them to perform some tests in the future, if needed.

Summary & Conclusions

- FBG technology is **suitable** for monitoring temperature at very-low temperatures with enough resolution to **meet the consortium requirements**.
- The **long-term sub-mK precision** of large volumes has **not been reported** in the literature, as far as I know. It represents a technical challenge that could lead in **new technology** in a rapid-growing engineering field as it is FBG.
- An **R&D plan** has been **agreed** with already two companies to further increase the sensitivity of the interrogator and the fibres in the coming years.
- The **I4G interrogator is already on its way to IFIC** along with some test fibres for the preliminary tests.
- The **FBGs to be installed in PD-VD are almost designed** and ready to be produced for the manufacturer.
- The **calibration set-up** (thermal insulator and fibres holding) for the characterisation of the fibres is **already built**.
- The **PD-VD TMS** installation will consist more on a **mechanical installation** than on a detector performance test. Although, some **relevant physical results** may come out of the PD-VD run.

Thank you for your time!

Questions?

Backup slides

Set-Up at IFIC laboratory: thermal insulating system.

- To characterise the offsets between the sensors in the fibres one needs to have all sensors at the same temperature enough time to perform the relative calibration.
- To do that, the idea is to roll-up the fibres on a teflon cylinder so that all gratings lie very close along the same vertical within few centimetres.
- By the moment, we will use the same calibration set-up as we use for the RTDs to keep temperature constant, we just need to fabricate the teflon support.
- In the future, we expect to acquire a 1l LN2 dewar with optical feedthroughs to control temperature, pressure and relative humidity.

- The radius of the teflon support must be of the appropriate size so that when rolling-up the fibre all sensors lie along the same vertical.