SUMMER SCHOOL AT THE IFIC DUNE LABORATORY

Sensitivity Study of the Fiber-Optic Temperature Monitoring System for the Deep Underground Neutrino Experiment

1. INTRODUCTION

The DUNE FD-VD will be the largest Time Projection Chamber (TPC) ever constructed, designed to operate continuously for two decades without access to its internal cryogenic or detector components. Given this constraint, comprehensive and reliable monitoring is essential to minimize operational risks. In addition to supporting detector operations and diagnostics, a high-precision Temperature Monitoring System (TMS) provides a valuable complementary tool for electron lifetime calibration, particularly under conditions where small vertical temperature gradients, as predicted by Computational Fluid Dynamics (CFD) simulations, are present.

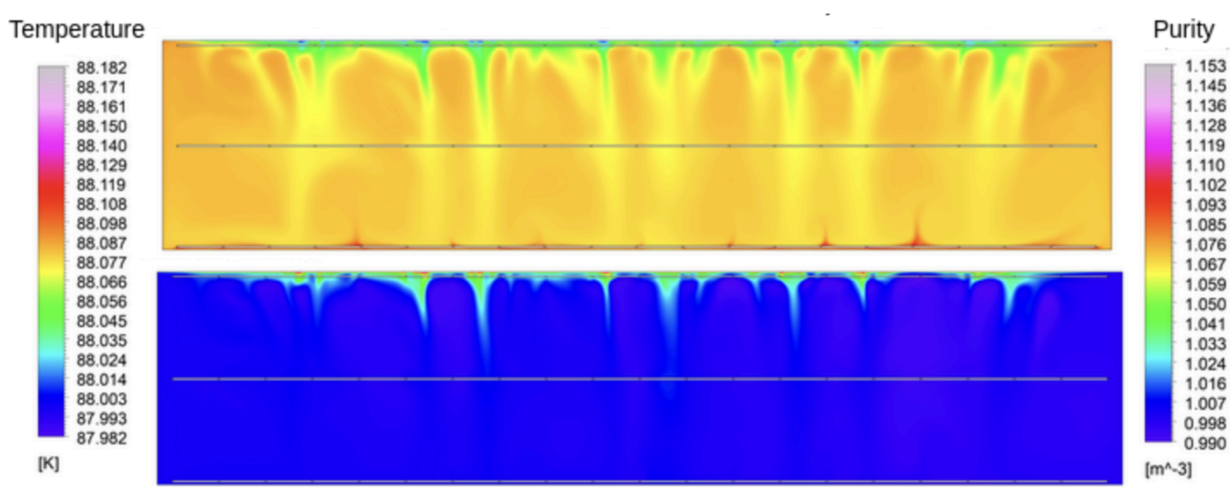


Figure 1. Temperature gradient (top) distributions as predicted by CFD for FD-VD. They can be compared with the normalized impurity (bottom) distribution.

Among all contributors, the injection of warmer liquid argon (LAr) into the cryostat has the largest impact on the LAr recirculation pattern. The injected LAr is expected to be approximately 800 mK warmer than the bulk liquid [1], as measured by the inlet (pipes through which the LAr is introduced) sensors, which are also part of the TMS. This temperature difference makes the inlet flow the primary driver of convective circulation.

2. TEMPERATURE MONITORING SYSTEM

In the vertical drift module, where the electric field is oriented along the vertical axis, the implementation of instrumentation capable of measuring these vertical temperature gradients is particularly challenging.

Optical fibers are highly robust and perform well under harsh conditions such as high or cryogenic temperatures. They are immune to electromagnetic fields and X-rays, and are also minimally invasive, making them highly advantageous sensing devices. **Fiber Bragg Grating (FBG)** [2] constitutes an emerging technology, which has been well studied and used to monitor strain and temperature by tracking changes in its Bragg wavelength peak. Figure 2 shows a schematic representation of how the vertical temperature gradient would be monitored in the VD module with this technology.

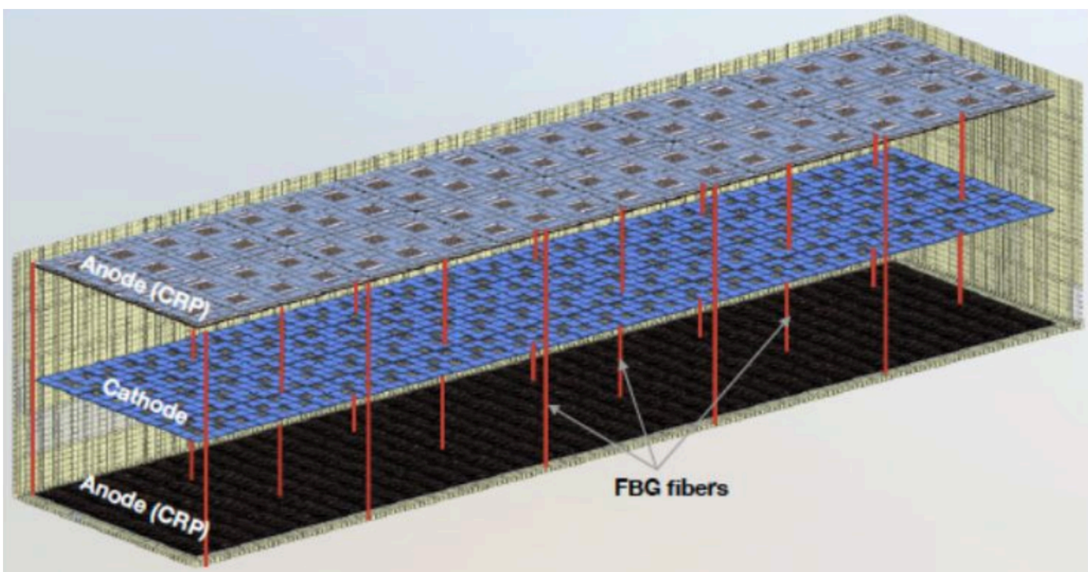


Figure 2. FD-VD Temperature Monitoring System layout schematic. Optical fiber bundles, each approximately 13 m long, will be installed throughout the detector.

<u>A detailed understanding of each sensor's behavior is essential to predict how it will respond during system operation.</u>

2.1. FBG PHYSICS BACKGROUND

Fiber Bragg Gratings are optical sensors created by introducing periodic variations in the refractive index of an optical fiber. These gratings reflect a specific wavelength of light, called the **Bragg wavelength**, while transmitting the remaining wavelengths.

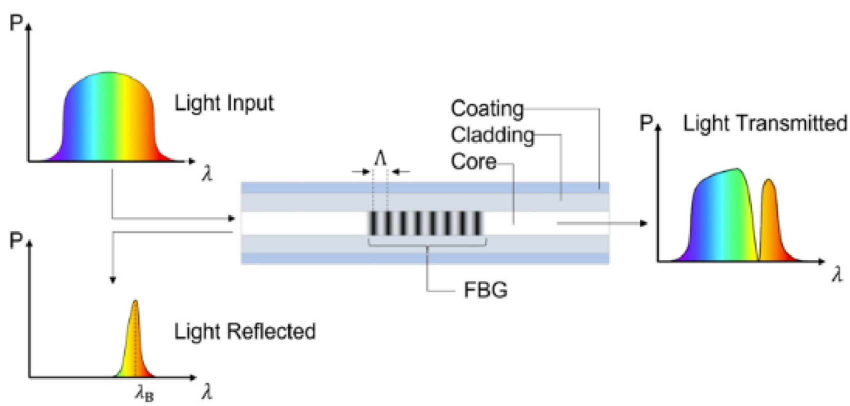


Figure 3. The working principle of an FBG as a sensor.

The Bragg wavelength, λB, is a specific wavelength of light that is reflected by the FBG and is defined by the following formula:

$$\lambda B=2\cdot neff\cdot\Lambda \quad (1)$$

where $neff$ is the effective refractive index of the fiber core, and Λ is the grating period or spacing between the refractive index variations.

Changes in strain or temperature alter $neff$ and/or Λ, leading to a shift in the Bragg wavelength ($\Delta\lambda B$). This shift can be measured to determine the magnitude of the applied stimulus:

$$\Delta\lambda B=2\cdot(\partial neff \cdot \partial T\cdot \Delta T+ neff \cdot \partial\Lambda \cdot \partial\varepsilon \cdot \Delta\varepsilon) \quad (2)$$

where ΔT is the temperature change, and $\Delta\varepsilon$ is the strain change.

By measuring this wavelength shift, FBGs can accurately monitor mechanical deformation and temperature. The sensitivity of an FBG can be improved by using different materials as coatings.

3. LABORATORY TESTS

3.1 EQUIPMENT

The DUNE experiment employs liquid argon as the active detection medium in its far detectors. Neutrino interactions with argon nuclei constitute the basis for the experiment's precision measurements of neutrino properties. Liquid argon is chosen for its excellent detection capabilities and its ability to provide high-resolution imaging of neutrino interactions. To maintain argon in the liquid phase, the detector operates at a temperature of approximately **87 K (-186 °C)**. This cryogenic environment is essential for the operation of the **Liquid Argon Time Projection Chamber (LArTPC)** technology, which enables the precise three-dimensional reconstruction of particle trajectories and accurate calorimetric measurements of the energy deposited in the detector.

For the proper operation of the TMS, studying temperature gradients by analyzing the wavelength shifts of each FBG under cryogenic laboratory conditions is essential. This will be carried out using a setup in which the pressure will be varied to produce controlled temperature changes, allowing us to study the behavior of our sensors.

To obtain a reference temperature measurement, we will use **Resistance Temperature Detectors (RTDs)**, which are well-established sensors and are also integrated into the TMS [1].

Figure 4. RTD Sensor Image.

Inside the laboratory, you will find the different components that make up our setup:

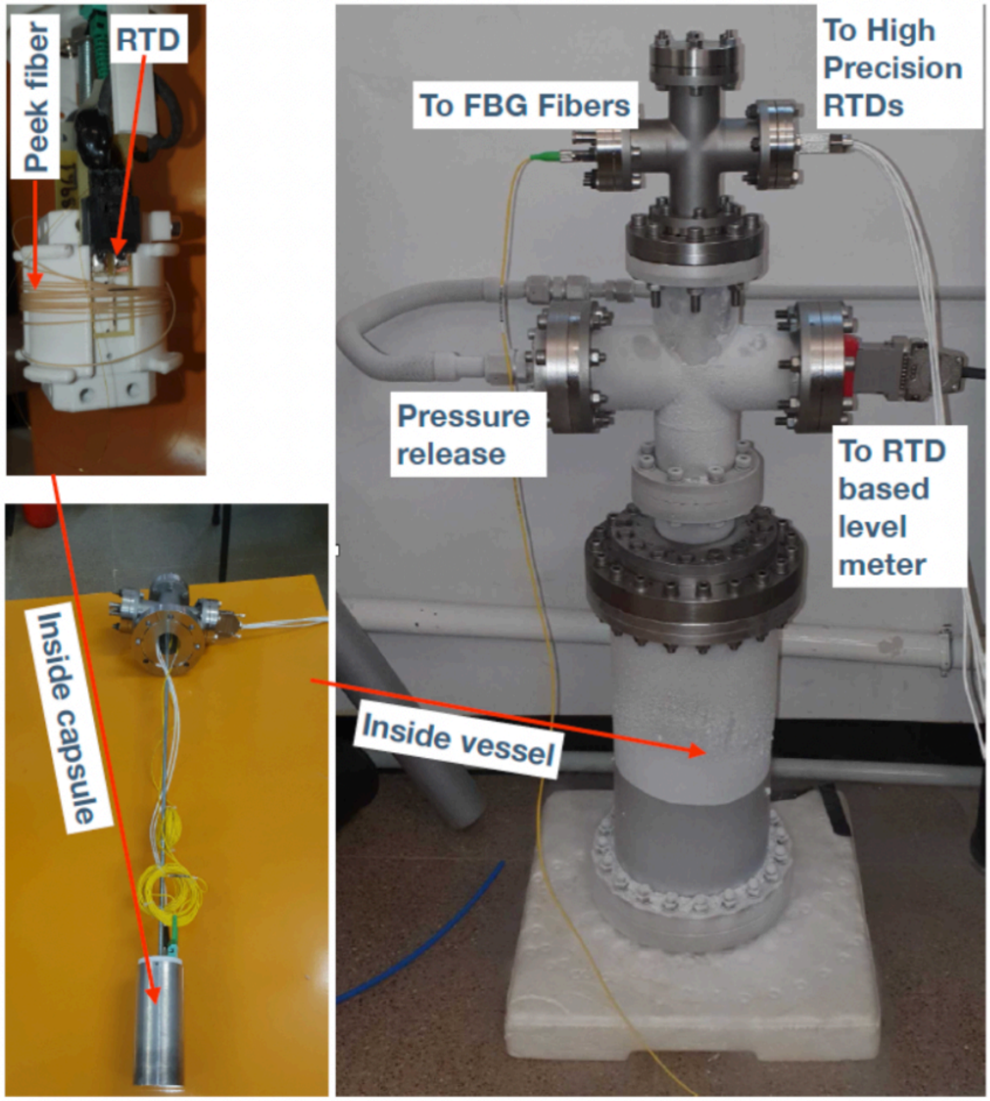


Figure 5. Cryogenic laboratory setup: fiber Bragg grating (FBG) (top left), rod for fiber support and connections (bottom left), and cryogenic vessel (right).

And the interrogator with 16 channels to connect up to 16 different fibers:

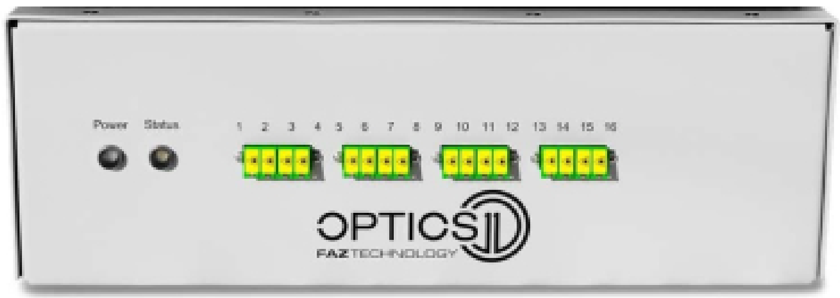


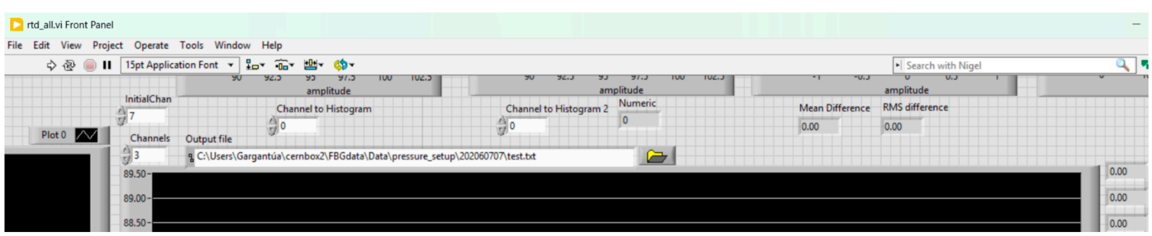
Figure 6. FBG interrogator.

3.1. SETUP PREPARATION

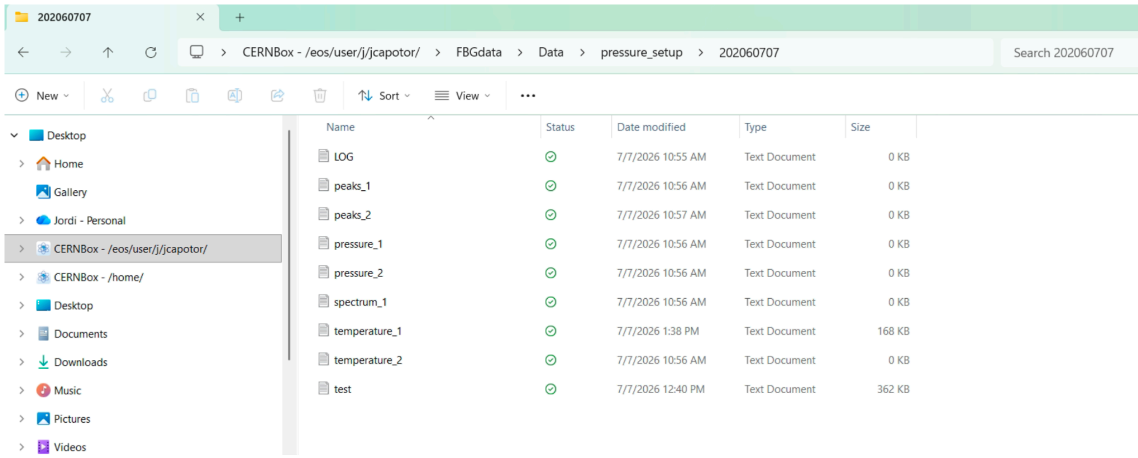
Before starting the tests, the setup must be prepared by following these steps (Note that some of these steps will be carried out by the laboratory supervisors or may already have been completed) :

1) Configure the computer's IP address through the **FortiClient** application to ensure proper synchronization between the interrogator and the computer during data acquisition.

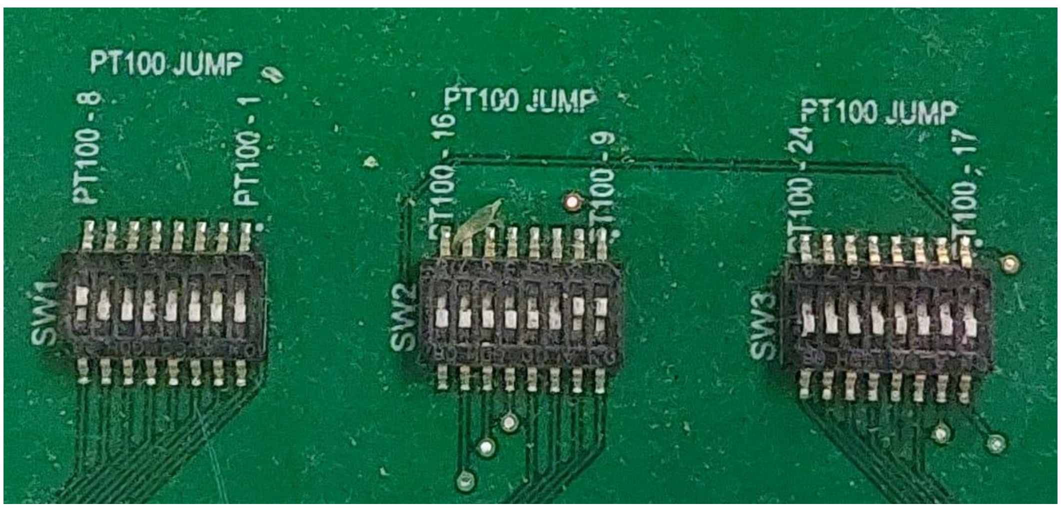
2) Prepare the **LabVIEW** application for the **N_2 filling process of the vessel**. You can use a 'test.txt' file.

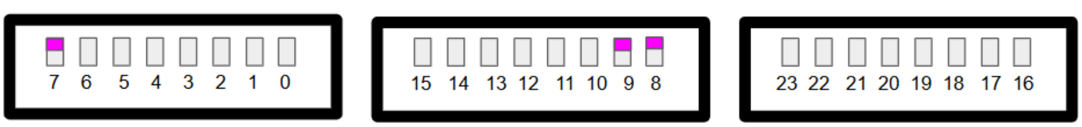


3) Prepare the folder containing the necessary **.txt files** for the test (test, log, Temperature_1, Peaks_1, Pressure_1, Spectrum_1) with the test date. If the files are too large, additional files can be created with the suffixes **_2**, **_3**, etc. These files can then be merged during the data analysis process.



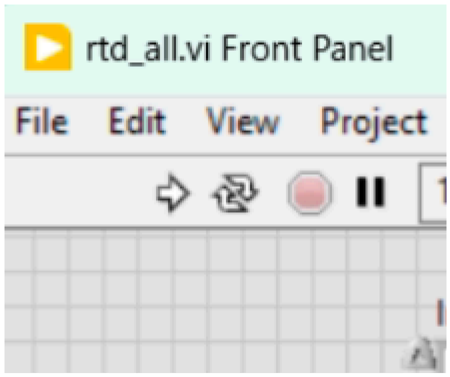
4) Ensure that the pins corresponding to the measurement channels are enabled. During the vessel N2 filling process, pins **7, 8, and 9** must be activated.

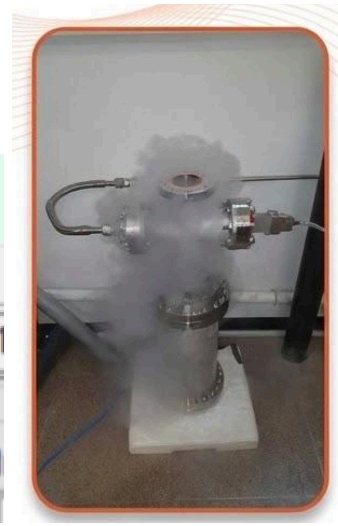




5) Filling the vessel with N_2. This step will be carried out by the laboratory supervisor. Before filling the vessel, you must click "Start" (the white arrow) to begin saving data. During this process, it will be necessary to monitor the measurements provided by the RTDs inside the vessel. As it fills with liquid nitrogen, you will see in real-time how the three RTDs inside the vessel drop from room temperature to approximately 76 K. Remember that, when **handling liquid**

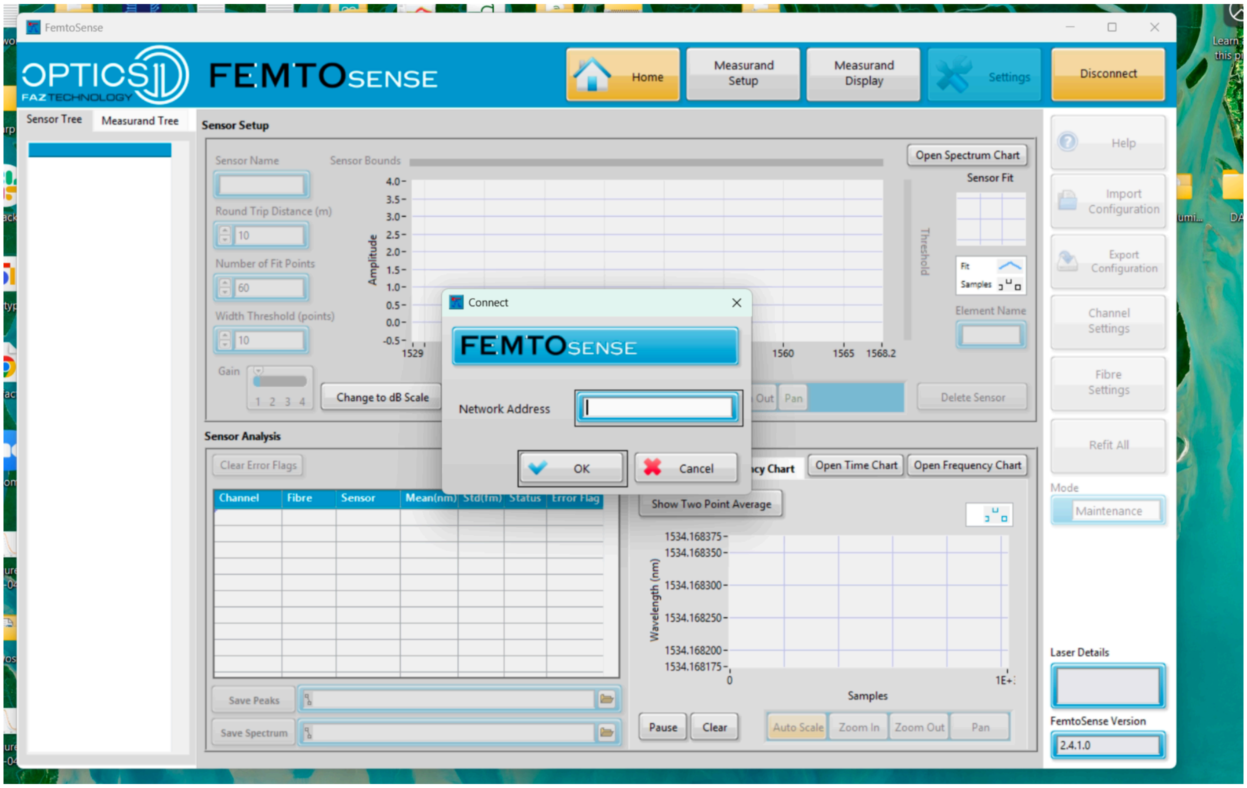
nitrogen, the protective equipment provided by the laboratory supervisors must be worn to ensure safety.





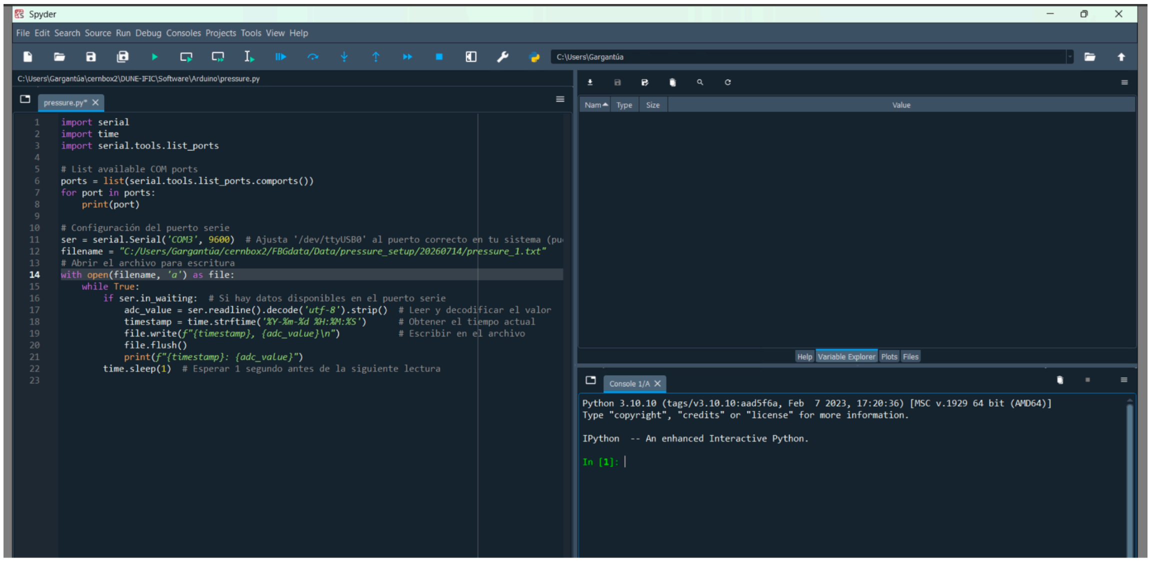
6) Wait **30–40 minutes** for the system to reach thermal equilibrium. At this stage, the fiber is usually installed on the rod; however, this step will have already been completed.

7) **Launching Femto Sense Software.** Simultaneously with the temperature readings, you must open the 'Femto Sense' program on the laboratory PC. The first thing the software will request is the interrogator's IP address, which is written in white on a label (it consists of a series of numbers separated by dots). Once this is done, you will see a tab similar to the image below:

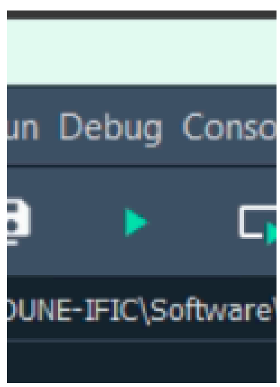


8) **Configuring Data Saving in Femto Sense.** Once the software interface is open, you must configure the output files. Locate the 'save peaks' section, click the folder icon on the right, and select the file `peaks_1.txt`. Then, in the 'save spectrum' section, click the corresponding folder icon and select `spectrum_1.txt`. **Important:** In this practical session, we will not actually save the spectra because the files take up too much storage space. Leave this software configuration prepared. Later, when the entire physical setup is closed and ready for measurement, press the 'save peaks' button and click 'OK' on the pop-up message to overwrite the file and begin saving the data.

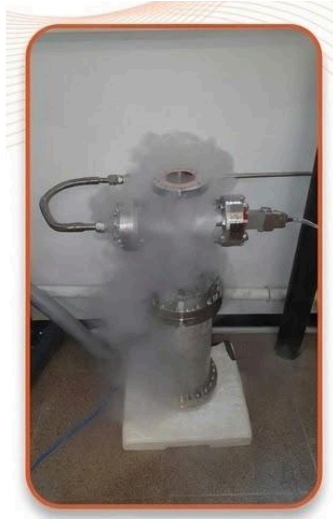
9) **Pressure Data Logging in Spyder.** Next, open the **Spyder** software to access the Python script that records the pressure data from the Arduino. Before running the code, you must change the date in the filename to ensure the new data is saved correctly. If the script gives a port connection error when executed, check the computer's system settings to verify which USB port the pressure-reading Arduino is plugged into, and update the port number within the code to match (ser = serial.Serial('**COM3**', 9600)).



10) **Running the Pressure Script.** Click 'run' in Spyder and observe the pressure readings. Because the valve is still open, the output will display the current time and numbers such as -0.07. This reading is expected and is due to a small systematic offset in the equipment. It is crucial that you do not close the valve until you have confirmed that the entire vessel is properly sealed, a procedure that will be explained in the following steps.

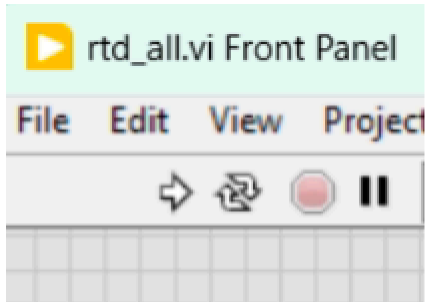


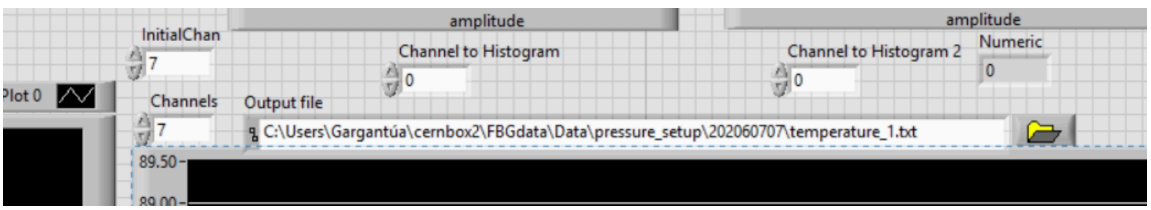
11) **Refilling the Liquid Nitrogen.** The vessel loses nitrogen easily, so it will be necessary to refill it slightly to ensure that the measurements are performed correctly. This refill is generally needed after 30 to 40 minutes have passed, once you observe that the sensors are no longer at 76 K and the internal temperature has risen to approximately 80 or 90 K.



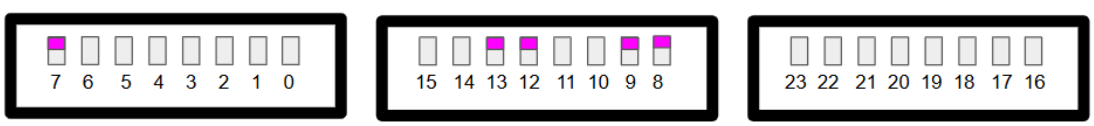
12) **Physical Setup and Connections.** Before connecting the cables, it is highly recommended for convenience to first place all the white spacers on top of the vessel. Next, insert the rod containing the optical fiber and secure it so it rests on top of the spacers. This position allows the fiber to cool down gradually as it remains far from the liquid nitrogen, and makes the connection process much easier. Once secured, connect the small white cable to the vessel for the temperature readings. Additionally, connect the yellow cable, which transmits the optical fiber signal, to port 2 of the vessel and route it all the way to the interrogator.

13) LabVIEW Reconfiguration. Stop the data reading by clicking on the red circle shown in the image below. Once stopped, change the destination file path and select `temperatures_1.txt`. Then, increase the number of active channels from 3 to 7 in the LabVIEW control box, which will allow the system to read the two RTDs inside the aluminum capsule along with the optical fiber and its FBG sensors.





14) After configuring the 7 channels, click on "Start" (the white arrow) in LabVIEW once again to resume data collection ('temperatures_1.txt'). Before starting the new measurements, the following channels (13 and 12) on the connectors must be activated.



15) Starting Data Saving and Gradually Cooling the Fiber. Before beginning this process, it is critical to click the **'save peaks'** button in the Femto Sense software to start recording the measurements. Once active, you may proceed to lower the fiber slowly. Remove the white spacers one by one, waiting approximately 3 to 5 minutes between each one. This allows the rod to go down gradually, ensuring that the optical fiber is submerged into the liquid nitrogen at a controlled pace.

Final Setup with Ice
Formation & Connections.

16) Sealing the Vessel. You will notice that there are holes with screws already in place; insert all the remaining screws to close the vessel, placing a washer and a nut underneath each one. Begin by hand-tightening all of them. **Caution:** Use protective gloves, as the vessel will be very cold. Next, you will need a torque wrench and an Allen key. To apply even pressure and avoid damaging the vessel's seal, the screws must be tightened in a **criss-cross pattern** (tightening opposite sides sequentially). You must apply the torque in three progressive passes: first 8 N·m on all screws, then 12 N·m, and finally 14 N·m. Once this is done, the vessel is completely closed. This step must be reviewed and verified by **Jesús or Vicky** before moving forward.

17) Pressure Regulation and System Stabilization. Now, close the green pressure valve completely by turning it all the way in the opposite direction, and you will see the pressure readings begin to rise. Monitor the display closely; once the pressure reaches 3.5 bar, open the valve minimally just until you hear a very small amount of gas escaping. After this, the system must be left to stabilize for at least one hour. You can confirm that stabilization has been reached by checking the temperature curves in LabVIEW, where only the last two active channels (the ones adjacent to the optical fiber) will be visible. After approximately one hour, you will observe that these readings flatten out to form a temperature plateau at around 90 K.

18) Creating Pressure Plateaus. The next objective is to step down the pressure sequentially to create stable plateaus at 3.0, 2.5, 2.0, 1.5, 1.0, 0.5, and 0 bar. Each plateau must be maintained for approximately 15 minutes. To reach the next level, slowly open the valve to lower the pressure. Once the target is reached, you must actively monitor the display throughout the 15-minute interval, making continuous micro-adjustments—opening or closing the valve minimally—to keep the pressure reading stable and avoid any large deviations.

19) Managing Long Runs and Splitting Data Files. If the experimental run is becoming too long, it is recommended to stop the data acquisition temporarily to switch files. To do this, pause the measurement and change the output filenames from `temperatures_1.txt` and `peaks_1.txt` to `temperatures_2.txt` and `peaks_2.txt` in LabVIEW and Femto Sense, respectively. Once the new files are selected, restart the acquisition.

20) Maintaining the Laboratory Log. Throughout the experiment, you must use the `LOG.txt` file—accessible from the designated folder on the laboratory PC—as your digital lab notebook. It is crucial to document everything you do during the session. Make sure to record the specific times of your actions, any problems or anomalies encountered, and any key observations or things learned during the process.

21) Finalizing the Experiment at 0 bar. Once you have reached the 0 bar plateau and completed its duration, verify that the pressure valve is completely open. After confirming this, you must stop all data acquisition to safely conclude the experiment. Stop the temperature readings in LabVIEW by clicking the red circle, end the pressure logging in Spyder by clicking the square stop button, and finally, halt the optical data collection in Femto Sense by clicking the 'stop peaks' button.

22) Data Upload and Preparation for Analysis. Once today's entire data folder containing all the `.txt` files has been uploaded to CERNBox, it is time to create a ROOT file using the converter (Vicky can do it), which allows for a much faster and more efficient data analysis. However, the analysis and plots can also be performed directly by extracting data from the raw `.txt` files. Students must develop a Python script or a Jupyter Notebook to analyze and understand the content of the text files, and generate three specific plots: temperature vs. time, pressure vs. time, and peaks vs. time.

23) **Identifying Plateaus and Calculating Thermal Sensitivity.** Following the initial plotting, you must select the constant regions (plateaus) from the data to calculate the mean temperature and the mean wavelength for those stable zones. Afterward, you will perform a linear fit using these average values. The resulting slope of this fit corresponds directly to the thermal sensitivity of the FBG sensor (see Data Analysis).

4. Data Analysis

Use run Nº 3 with PEEK-4 fiber (2 FBGs):

You can find the raw data here:

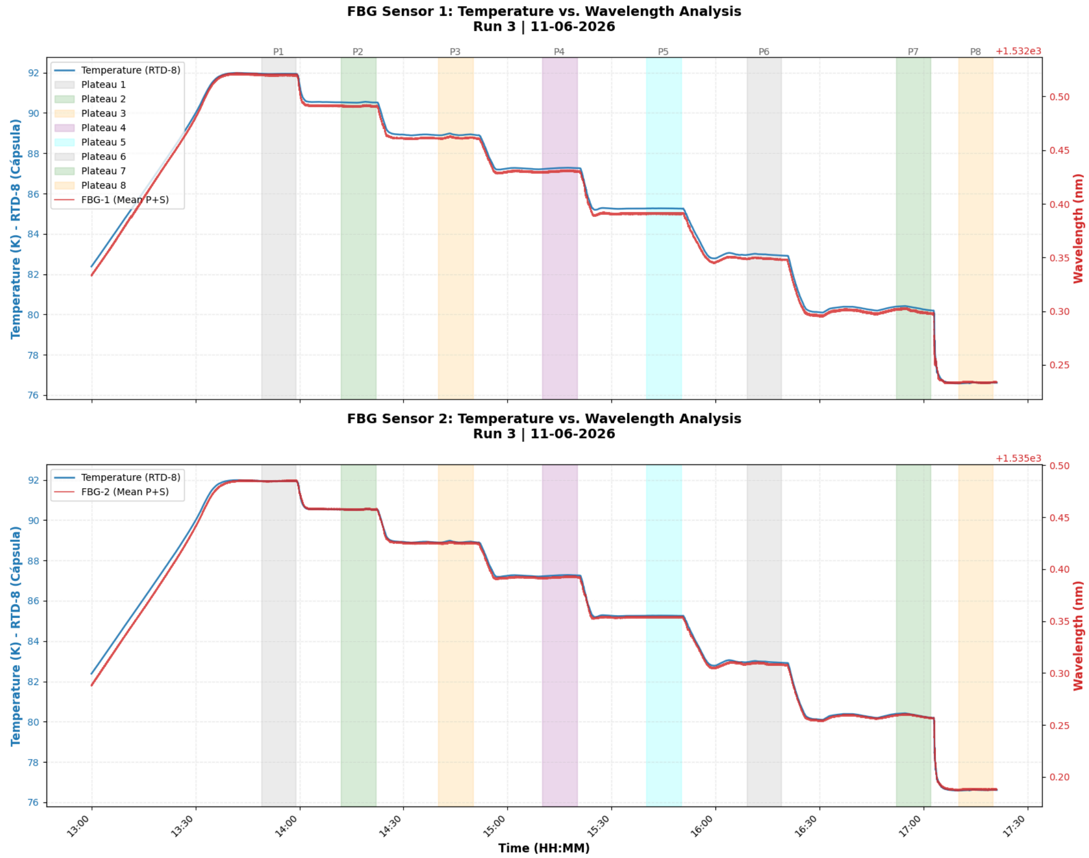
/eos/user/j/jcapotor/FBGdata/Data/pressure_setup/20260611

Root file:

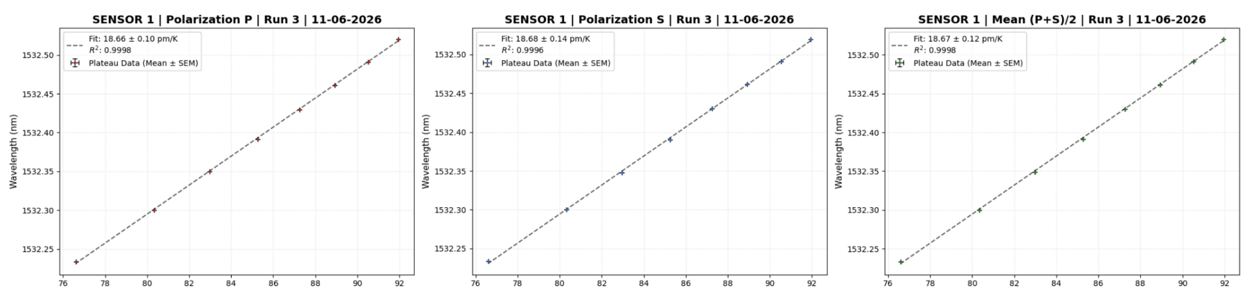
/eos/user/j/jcapotor/FBGdata/ROOTFiles/pressure_setup/20260611.root

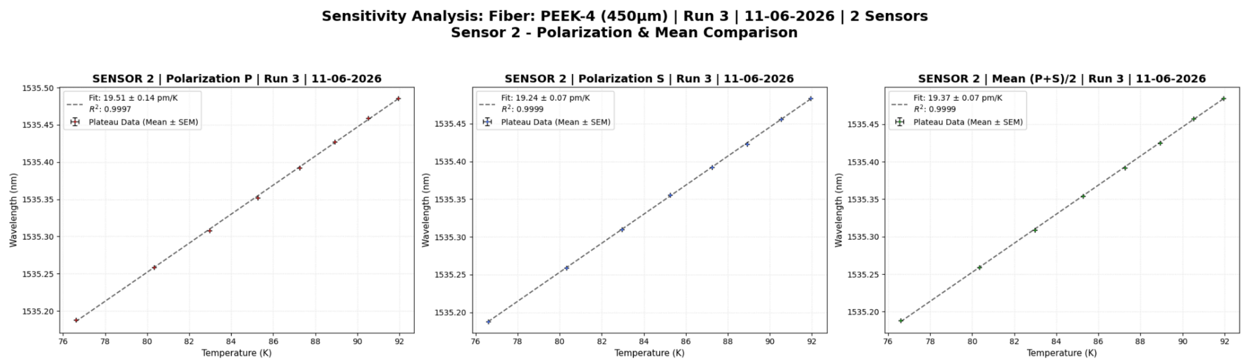
Example (control plots):

PEEK-4 (450µm): Run 3 | 11-06-2026
FBG Wavelength and RTD Temperature Profiles
(Shaded areas represent defined plateaus)



Sensitivity Analysis: Fiber: PEEK-4 (450µm) | Run 3 | 11-06-2026 | 2 Sensors
Sensor 1 - Polarization & Mean Comparison




Sensitivity Analysis: Fiber: PEEK-4 (450µm) | Run 3 | 11-06-2026 | 2 Sensors
Sensor 2 - Polarization & Mean Comparison
SENSOR 2 | Polarization P | Run 3 | 11-06-2026
Fit: 19.51 ± 0.14 pm/K
R^2: 0.9997
Plateau Data (Mean ± SEM)
SENSOR 2 | Polarization S | Run 3 | 11-06-2026
Fit: 19.24 ± 0.07 pm/K
R^2: 0.9999
Plateau Data (Mean ± SEM)
SENSOR 2 | Mean (P+S)/2 | Run 3 | 11-06-2026
Fit: 19.37 ± 0.07 pm/K
R^2: 0.9999
Plateau Data (Mean ± SEM)
Wavelength (nm)
Temperature (K)

REFERENCES

[1] M. Antonova, J. Capó, A. Cervera, P. Fernández, M.Á. García-Peris, X. Pons, Millikelvin-precision temperature sensing for advanced cryogenic detectors, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, Volume 1082, Part 2, 2026, 171062, ISSN 0168-9002, https://doi.org/10.1016/j.nima.2025.171062.

[2] J. Stephen, P. Pal and J. Mathew, "Advances in Cryogenic Temperature Sensing Using Fiber Bragg Grating: A Review," in IEEE Sensors Journal, vol. 25, no. 13, pp. 23514-23525, 1 July1, 2025, doi: 10.1109/JSEN.2025.3566984.