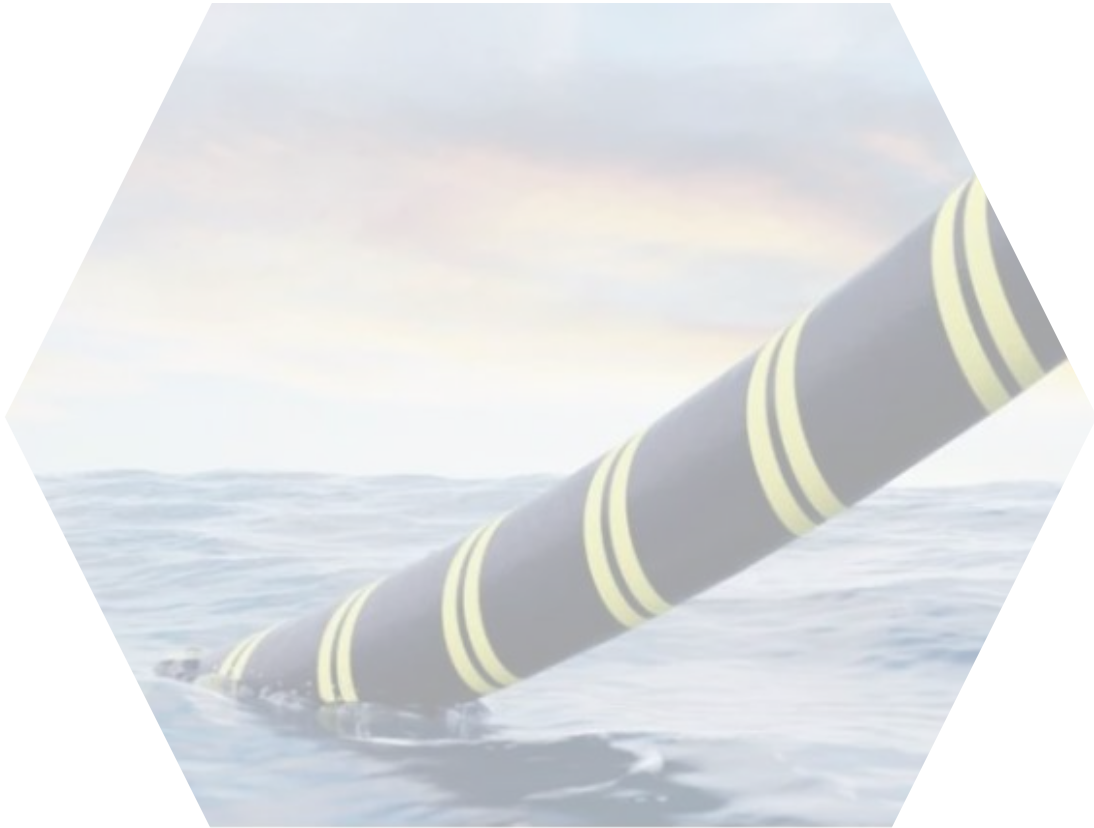




D6.6



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ABBREVIATIONS AND ACRONYMS

Abbreviations / Acronyms	Description
EOM	Electro-Optic Modulator
PD	Partial Discharge
HFCT	High-Frequency Current Transformer
HVDC	High-voltage direct current
DWDM	Dense Wavelength Division Multiplexer
WDM	Wavelength Division Multiplexer
OB	Optical Box

1 INTRODUCTION

1.1 Objectives of WP6 and its Relation to PD Detection

WP6 focuses on the development of advanced sensing technologies for real-time condition monitoring of HVDC cable systems. Among its goals is the deployment of innovative point sensor based on optical fibre for partial discharge (PD) monitoring. PD detection is a critical component for assessing insulation integrity and preventing catastrophic cable failures. Within this context, WP6 aims to integrate PD sensing solutions that are both scalable and compatible with long-distance HVDC cables contributing directly to the predictive maintenance strategies defined in WP5.

1.2 Purpose of Deliverable D6.6

The purpose of this deliverable is to report on the progress achieved in Task 6.4 regarding the development and validation of a new fibre-based PD measurement system, designed to meet the performance requirements for HVDC cable monitoring. This report provides a technical overview of the fully passive PD sensing subsystem under development, including its main components: the two types of passive PD sensors (one with a large bandwidth for high-sensitivity environments and another with a small bandwidth for cost-effective deployment), the compatible fibre optic multiplexers, and the corresponding interrogator.

This document describes the system architecture and its applications in both DC and AC environments, with a particular focus on its installation configuration in cable joints and terminations. It includes the product breakdown structure (PBS), technical characteristics, and the methodology followed during development, from mathematical modelling to hardware prototyping.

Moreover, this report includes test results obtained from preliminary validation campaigns carried out in laboratory conditions using a partial discharge (PD) generator. These tests were designed to assess the performance of the newly developed sensing system in a controlled environment, allowing the evaluation of its frequency response, sensitivity, and detection capabilities. The correlation between the injected PD signals and the detected events by the fibre-based system serves as the basis for validating its technical viability and accuracy for future integration into HVDC cable systems.

The report concludes with an evaluation of the system's potential for integration into ageing prediction models developed in WP5 and outlines next steps towards future iterations and integration into demonstrators as planned in subsequent deliverables.



2 Product Breakdown Structure (PBS)

This section presents the structural breakdown of the system components developed for partial discharge (PD) detection, including both the fibre optic-based sensor elements and the interrogator units. The breakdown distinguishes between large and small bandwidth designs and reflects the modular nature of the overall system architecture.

2.1 UHF/VHF Passive PD Sensors (Large and Small Bandwidth)

2.1.1 Large Bandwidth (BW)

- Electro-Optic Modulation Unit to encode PD event into optical signal.
- Optical Coupling Interface.
- Polarization control module.
- High-Frequency Current Transformer (HFCT) to capture fast PD transient currents.
- Signal Conditioning elements.
- Module to control the optimal operational point of the sensor.

2.1.2 Small BW

- New-Developed Electro-Optic Modulation Unit to encode PD event into optical signal.
- Optical Coupling Interface.
- High-Frequency Current Transformer (HFCT) to capture fast PD transient currents.
- Signal Conditioning elements.

2.2 Optical Fibre Multiplexers

- Dense Wavelength Division Multiplexer (DWDM): Supports channel isolation for simultaneous interrogation of dual PD sensors.

2.3 PD Sensor Interrogators

2.3.1 Large Bandwidth

- Laser Emission Module.
- Optical Receiver module for DP signal demodulation and operational point control.
- Signal Acquisition and Analysis: High-speed oscilloscope enables real-time observation and validation of PD occurrence and its waveforms.

- Wavelength-Based Interrogation Scheme.

2.3.2 Small Bandwidth

Common with large bandwidth Interrogator with some minor modifications in the emission part as explained in 3.3.2.



3 Development Progress

This section describes the progress made in the development of the fibre optic system for partial discharge (PD) detection, covering theoretical modelling to sensor prototyping and testing.

3.1 Preliminary Work – Mathematical Modelling

3.1.1 Large Bandwidth

The optical sensing system designed for partial discharge (PD) detection is based on the manipulation and analysis of light polarization states within an interferometric fiber-optic architecture. Induced electric field perturbations generated by the PD events are transduced into optical phase shifts, which can be detected and demodulated using appropriate interferometric techniques. The foundation of the system lies in the interaction between the PD pulses and the optical field propagating through the sensing fiber. This interaction occurs via an electro-optic modulation mechanism, through an electro-optic modulator (EOM). The EOM is driven by an external electrical signal (PD) that modulates the phase of the optical carrier in a polarization-dependent manner. The PD signal, when coupled to the modulator introduces a time-varying phase change in the optical signal.

The EOM operates by splitting the optical signal into two internal arms, that are dynamically modulated by a RF voltage signal, $V(t)$, which change the phase of the optical wave, before the optical signals recombination from the two internal arms. The phase difference between the two branch arms of the EOM is defined as $\Delta\varphi = \frac{\pi V(t)}{V_\pi}$. The EOM encodes the phase shift due to the PD in the optical carrier for light polarized along x-axis.

The system was modelled using Jones calculus, which provides a vector-matrix framework for representing the evolution of the optical field through various birefringent and modulating elements.

At the end, the output field strength, I_{out} , can be calculated by performing $I_{out} = E_{out}E_{out}^*$, where E_{out} is the electric field defining the modulated optical carrier by the PD at the end of the EOM, which results in:

$$I_{out} = A * (|E_x|^2 + |E_y|^2).$$

Here, A is a factor representing the optical gain, coupling efficiencies, and the influence of the time-varying phase change perturbation induced by the PD event. Therefore, via demodulation techniques one can extract time-information about the PD waveform. The math development demonstrated the conceptual integrity of the architecture and confirms its capability to detect and quantify fast, low-amplitude electrical transients in real time.

3.2 PD Sensor Development

3.2.1 PD sensor for large bandwidth

The PD sensor defined for the large bandwidth detection system is illustrated in Figure 1. As the overall sensing architecture requires sensor interrogation in pairs for fault location purposes, the sensor design had to accommodate optical multiplexing and high-frequency signal compatibility. To arrive at the final PD sensor configuration, an iterative development process was undertaken, combining theoretical modelling and experimental validation. The sensor is designed to convert high-frequency electrical signals into optical domain variations through an electro-optic modulation (EOM) mechanism. The architecture ensures passive operation on the sensing side and supports distributed deployment along HVDC cable structures. Focus was given to ensuring broadband response, and compatibility with the interrogation system based on wavelength division multiplexing.

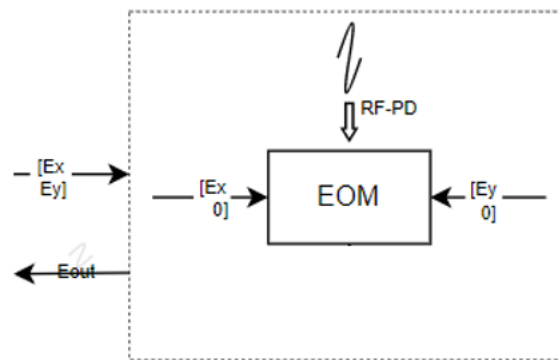


Figure 1: Large bandwidth sensor.

To validate this architecture experimentally, a series of practical tests were conducted. 1) Test of bidirectionality of EOM device. 2) Study on EOM performance. 3) Real low-bandwidth PD injection on optical carrier; the system responded accordingly.

3.2.2 PD sensor for small bandwidth

The University of Valladolid, through its GFOR research group, is leading the development of a low-bandwidth, cost-effective partial discharge (PD) sensor. Lumiker is supporting this development through collaboration and integration activities. The objective of this effort is to create a simplified and more affordable sensing unit that remains compatible with the fibre-optic PD interrogator system.

This sensor is based on a custom electro-optic modulator (EOM) capable of converting the electrical signal from a PD event into a high-frequency optical modulation. The sensor is designed to operate using single-mode fiber at both the input and output, and includes an input polarizer, which imposes specific optical injection constraints. Its target is to ensure basic PD detection functionality with reduced component complexity and manufacturing cost.

To address potential issues arising from the polarization dependency of the sensor, polarization management has been handled at the light source level within the interrogator. This solution allows the system to maintain operational stability without requiring complex polarization-maintaining fiber routing or active polarization control at the sensor side.

Although full frequency characterization is ongoing, the current prototype is expected to exhibit inline losses around 10 dB. The sensitivity performance of the sensor is still under evaluation and will depend on final component optimization and power budget allocation in each application scenario.

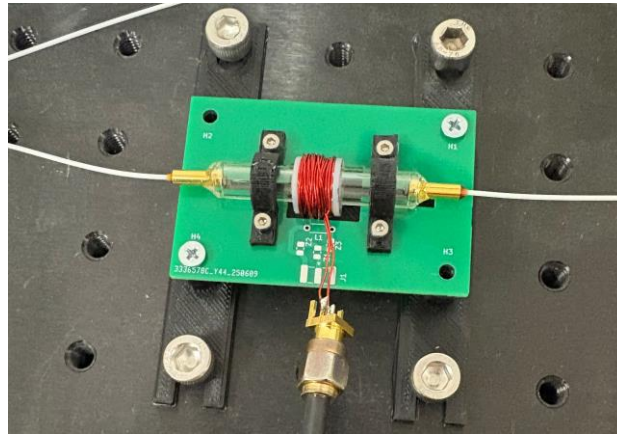


Figure 2. Small bandwidth sensor.

Figure 2 shows the assembled prototype of the sensor, prepared for laboratory testing. Figure 3 displays an experimental trace, confirming that the modulator successfully converts an electrical signal into optical modulation, which is then transmitted and recovered as an electrical signal through the interrogator system.

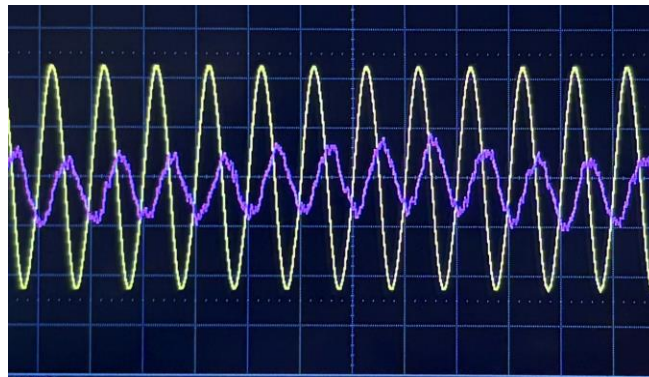


Figure 3. Small bandwidth sensor.

This development opens the door to new sensor integration strategies focused on cost-efficiency, although the solution remains in the experimental validation phase. Deeper sensor specification will be provided in further deliverables as it is currently being tested and specified.

3.2.3 Optical Power Management at EOM

One of the key elements in the design of the interrogator for wide-bandwidth PD sensors is the EOM, which acts as the conversion interface between the PD signal (captured by the HFCT sensor) and the modulated optical signal. For this modulation process to be efficient and linear, it is essential to ensure a stable optical power level at the modulator's input, and more importantly, that this power is aligned with the modulator's required polarization axis.

The transmission system is based on standard single-mode fibre (SMF), which does not maintain polarization over distance. As a result, the polarization of the optical beam arriving at the sensor can vary over time and may not be aligned with the required axis of the modulator. Since EOM is polarization-dependent, any deviation from this alignment would result in a reduction of effective optical power reaching the modulator, compromising modulation efficiency and linearity.

To overcome this limitation, an optical architecture based on a polarization control module has been implemented. This solution guarantees that the EOM receives a constant and reliable input power, without the need for active polarization control systems, thereby simplifying field deployment of the sensor.

3.3 PD Interrogator Development

3.3.1 PD interrogator for large bandwidth

The PD interrogator defined for the large bandwidth PD sensor is depicted in Figure 4. Since for the PD location, the sensors must be interrogated in pairs, an investigation work was done to get to the last PD interrogator. The interrogator system is designed to enable the optical interrogation of distributed PD sensors based on wavelength multiplexing. The core theoretical principle relies on assigning distinct and closely spaced wavelengths to each optical sensor channel, such that their responses can be independently identified. This is achieved through DWDM technology, by assigning a distinct ITU channel to each sensor, ensuring each one responds to its specific wavelength and can be independently interrogated.

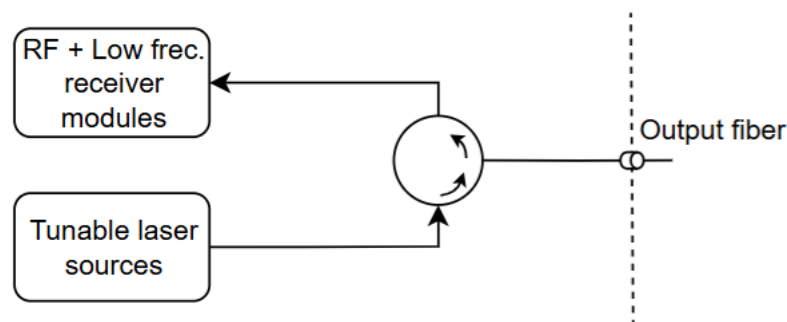


Figure 4. Interrogator for large bandwidth sensor.

To validate this architecture experimentally, a series of practical tests were conducted. 1) The laser channel was modulated using electrical signals from signal generators mimicking PD pulses, and the resulting optical signals were analysed through different receptors and oscilloscope measurements. 2) Characterization of light emission source with WDM and DWDM. 3) Real low-bandwidth PD injection on optical carrier; the system responded accordingly.

The experiments confirmed that the interrogator could isolate and detect low-medium-frequency PD signals, validating its practical functionality and establishing a foundation for fault location and long-distance sensing applications. Essays with multiple sensors will be carried out afterwards to validate the locating feature of the system.

3.3.2 PD interrogator compatibility with small bandwidth sensors

The development of a low-bandwidth PD sensor introduces specific requirements that differ significantly from the wide-bandwidth sensors, particularly in terms of optical interface and polarization handling. While the high-bandwidth sensor uses polarization-maintaining fibers (PM), the low-bandwidth sensor is based on standard single-mode fibers.

Just like the EOM in the high-bandwidth sensor, the low-bandwidth sensor also includes a polarizer at its input. However, due to the use of single-mode fibers, uncontrolled polarization rotation may occur because of environmental effects and fiber birefringence. This poses a challenge, as the optical power incident on the polarization-selective input of the sensor may vary unpredictably, resulting in loss of signal or reduced sensitivity.

To overcome this limitation, instead of relying on controlling the polarization state along the sensor fiber, a polarization control solution is developed inside the interrogator. This ensures that regardless of the state of polarization at the sensor input, there will always be sufficient optical power aligned with the sensor's polarizer axis.

This architecture meets two fundamental requirements:

1. **Polarization diversity** at the sensor input.
2. **Spectral compatibility** with DWDM interrogation, ensured by ITU-grid tuning of both light emitters, allowing continuous readout of specific sensor channels without the need for pulsed interrogation.

This dual-light sources architecture introduces changes at the interrogator level, enabling compatibility with low-bandwidth PD sensors using standard fibers, without compromising the overall system integration strategy.

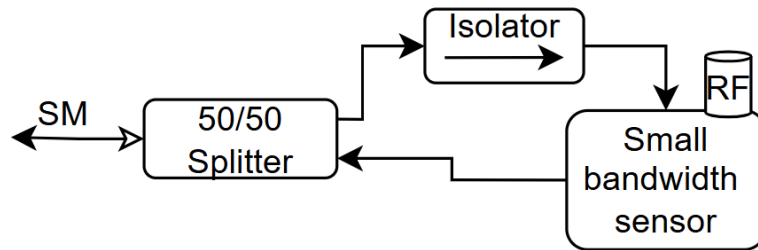


Figure 5. Polarity management for small bandwidth sensors.

3.3.3 PD interrogator PCB and electronic control development

The core control electronics of the partial discharge (PD) interrogator have been implemented on a dedicated multi-layer PCB. The board is organized into clearly defined functional blocks, each responsible for managing a specific subsystem within the interrogator.

1. **Power Management Stage**
This area is responsible for regulating and distributing power to the entire system.
2. **Main Control Unit**
This region houses the core digital control logic of the interrogator.
3. **Light Emission Control Interface**
This section provides the interface and control logic required to manage the operation of the laser modules, including wavelength tuning, enable signals, and status monitoring.
4. **Optional Power Extension Modules**
Expansion slots designed to accommodate additional power modules in case higher laser power output or extended operation is required.
5. **Receiver Modules**
These blocks receive the optical signals from the system and convert them into electrical signals for monitoring and regulation.
6. **Digital I/O Section**
General-purpose digital input/output lines for sensor control, trigger synchronization, and other auxiliary logic functions.
7. **Ethernet Communication Module**
This section handles high-level communication with external systems via Ethernet.
8. **RS-485 / Modbus Communication Interface**
Provides connectivity for industrial fieldbus protocols over copper or fiber, enabling remote configuration and integration.

3.3.4 System logic and control sequence

The partial discharge (PD) interrogator operates as part of a larger system (Figure 4) composed of three main elements:

1. An **industrial computer**, which manages high-level control, configuration, and data processing. Handles the control and coordination of the PD monitoring system.
2. A **rack-mounted oscilloscope**, responsible for capturing high-frequency PD signals offered from the opto-electronic interrogator.
3. The **opto-electronic interrogator**, which manages the optical interface with the sensors and ensures correct system operation. Transfers the PD RF signal from the different measurement points on the field to its coaxial outputs.

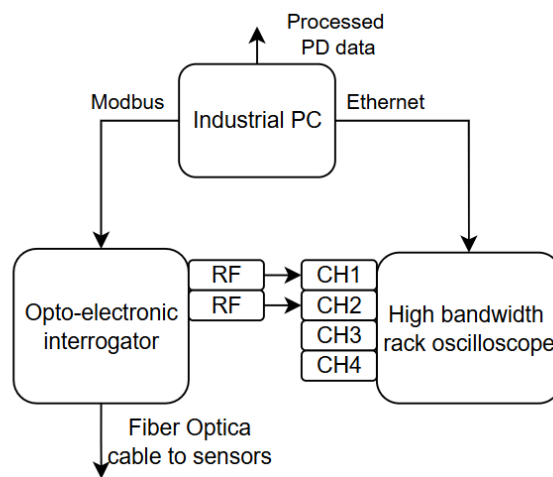


Figure 6. PD system structure.

The interrogator's role is to manage the optical layer and ensure valid RF signal generation. Its operational logic follows a clearly defined sequence.

By default, the interrogator remains in standby mode, awaiting a command from the upper-level industrial PC to monitor a specific section of cable. Upon receiving this instruction, the interrogator configures its lasers to the appropriate DWDM channels corresponding to the sensors installed on that segment.

Once the optical carriers are tuned to the correct wavelengths, only the signals from the selected sensors are present on that specific fiber. However, before any RF output can be considered valid, the interrogator must ensure that each sensor is operating at its optimal point

Once the optimal point is determined the interrogator issues a ready signal to the industrial PC, indicating that the RF output is valid and that PD signal acquisition can begin. From this point, the industrial computer takes control, triggering the oscilloscope to sample the coaxial RF outputs from the interrogator and perform PD signal processing.

This state is maintained until either the measurement session is explicitly terminated, or the interrogator detects a fault condition, such as loss of optical signal integrity or failure to sustain the sensor operating point. In such cases, the interrogator reverts to standby mode, awaiting the next measurement command.

Communication between the industrial PC and the interrogator is handled via Modbus protocol (over RS-485 or fibre), which provides sufficient bandwidth for configuration and control without requiring high-speed data transfer.

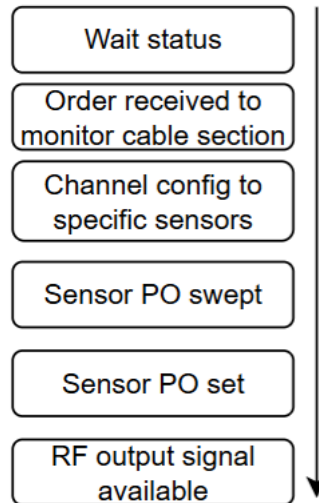


Figure 7. Simplified PD opto-electronic interrogator sequence.

3.4 Testing Results – Correlation of Detected PD Events with Test Data

The correlation analysis aimed to validate the optical interrogator capable of detecting high-frequency PD events using an EOM approach, by comparing its response to both controlled input signals and actual PD events. This analysis was carried out for the large bandwidth.

3.4.1 Signal Generator as PD source

To evaluate the performance of the optical PD system, a controlled laboratory test bench was assembled (Figure 8 below). The system was initially tested using a signal generator producing calibrated voltage waveforms emulating PD pulses, which were injected into the RF port of the EOM. The modulated optical output was monitored through a high-speed receptors and oscilloscope.

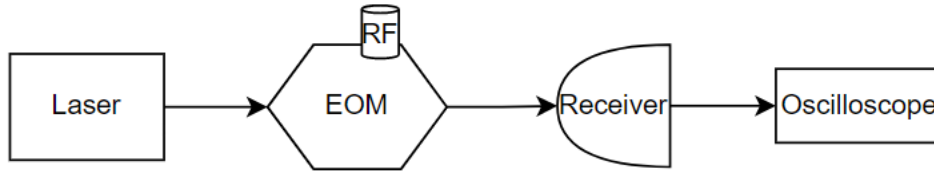


Figure 8. Experimental setup for RF signal injection by signal generator into the RF port of EOM.

3.4.2 PD generator integrated with the optical system

Afterwards, to accomplish real PD testing, first a PD generator was characterized by routing it to itself, passing through a HFCT (Figure 9). From this step it was got that the PD, in pC , is can be equally written in mV_{pp} ($10pC \leftrightarrow 10mV_{pp}$).

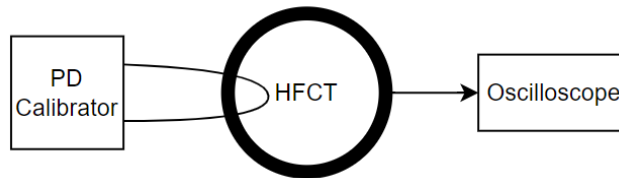


Figure 9. PD calibrator characterization.

Finally, the PD and HFCT replaced the signal generator and were integrated into the optical signal considering the optical interrogator/sensor system (Figure 10). The HFCT signal was routed to the same electro-optic sensor to ensure comparability with previous experiments carried out.

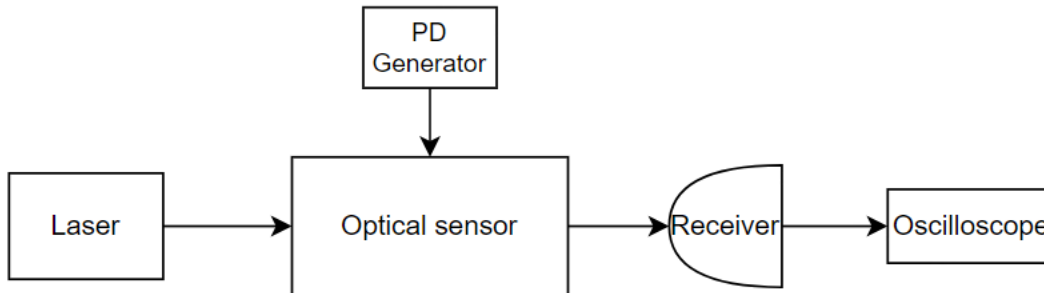


Figure 10. Complete sensor's configuration, considering polarization control and proper power circulation with PD generator.

In both cases, the multiple input RF voltage levels were used at different input optical power, but always under the same conditions to ensure fair comparison. However, it was observed that the optical output signals corresponding to PD generator inputs were of lower amplitude compared to those produced by the signal generator. This discrepancy can be attributed to the intrinsic nature of the waveforms: the continuous oscillatory functions outputted by the signal generator,

whereas PD pulses are brief transients with fast rise times and short-lived oscillatory components that swiftly decay.

Although the RF voltage peaks were matched, the energy content and temporal structure of the signals differ, influencing how effectively EOM responds to each type. Nonetheless, the detected optical waveforms consistently followed the temporal trend of their respective inputs, indicating the system is sensitive to real PD, being capable of reliably encode high-frequency discharge signals.



4 Technical and Operational Characteristics

4.1 Frequency Range

The frequency performance of the PD sensing system is primarily limited by the characteristics of the HFCT. To maximize detection performance, especially for weak PD events in the range of 10 pC or lower, it is essential that the HFCT provides a high signal amplitude at its output. However, passive HFCTs with high sensitivity typically exhibit a reduced bandwidth, requiring a decision on what parameter wants to be maximized, sensibility or bandwidth. After evaluating multiple options, the current system configuration adopts HFCTs with a maximum bandwidth of 150 MHz , which balances sensitivity with frequency response. This constitutes the main bandwidth limitation of the overall system.

It is important to note that the optical transmission chain, including the EOM modulator, optical carriers and electronic receivers, has been designed and validated for operation up to 1 GHz . Therefore, the current bandwidth limitation on the system is component-specific. By implementing HFCTs with extended bandwidth (e.g., 1 GHz), the system is ready to operate at that bandwidth but will have a high reduction in sensibility.

4.2 Sensitivity

Regarding sensitivity, a simulation model was developed to predict the electrical signal expected at the interrogator output as a function of the injected PD magnitude and distance. This model has been validated through a series of laboratory experiments, showing good agreement between simulated and measured results. The validated model was then used to estimate signal levels for different use-case conditions within the project.

For example, in Lumiker's PoC test bench, where sensors are deployed at short distances, the system is expected to detect PD events as small as 10 pC with sufficient signal-to-noise ratio. In scenarios involving longer fiber distances or higher sensor multiplexing, signal attenuation will reduce the output level, potentially limiting the system's ability to detect low-magnitude discharges (see Figure 11).

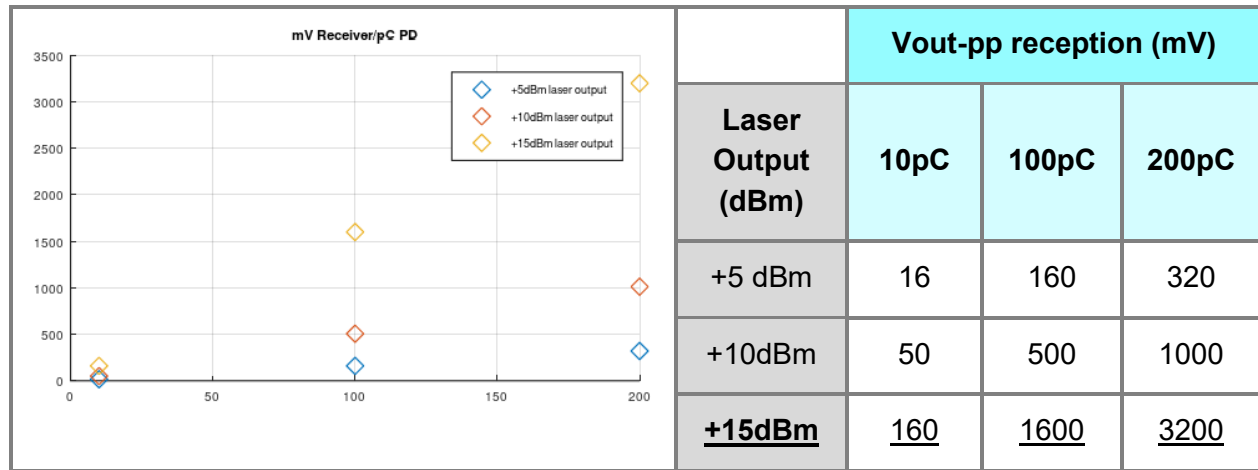


Figure 11. Expected signal amplitude for different PD charges at Lumiker's use case.

In the Lumiker use case, where sensors are deployed at reduced distances and the interrogator operates with an optical power of approximately +15 dBm, the system is expected to achieve a received signal amplitude of ~160 mV for a 10 pC discharge. These values are indicative and depend on total link losses and cable response but provide a useful reference for expected performance.

The system includes a programmable RF gain stage, which allows tuning of the output signal level delivered to the measurement equipment (e.g., oscilloscope). This enables dynamic adjustment of the signal amplitude, either amplification or attenuation, to optimize signal conditioning for analysis.

In addition to the Lumiker use case, the PD monitoring system will be evaluated in three additional deployment scenarios: NEXANS, ENERGINET, and STATNETT. Each of these cases introduces specific architectural differences that affect the expected optical losses and, consequently, the system's sensitivity and expected readings.

The NEXANS case is expected to closely replicate the conditions of the Lumiker testbench. The number of sensors, optical path length, and overall system architecture are comparable. Therefore, the expected signal amplitude at the interrogator output for equivalent partial discharge events should be nearly identical to those estimated for the Lumiker setup. No significant degradation in sensitivity is anticipated for this scenario.

In the ENERGINET configuration, the number of sensors remains similar; however, the system includes a 15 km optical fiber distance between the sensor pairs. This introduces additional optical losses due to fiber attenuation. While these losses reduce the signal amplitude at the interrogator, the effect is modest and still within the operational power margin of the system. The same detection threshold of around 10 pC remains feasible, although with slightly reduced signal-to-noise ratio, depending on the actual cable attenuation profile.

The STATNETT use case presents the most demanding conditions. In this scenario, it has been considered placing 6 distributed measurement locations, each monitoring three PD sensors (one per phase) and with inter-sensor distances of up to 15 km. This topology results in significantly higher cumulative optical losses, due both to extended fiber lengths and the higher number of optical components and splitters in the system. Consequently, the expected signal level at the interrogator output for a given PD magnitude is notably lower than in the other use cases. Detecting very low charge events, such as 10 pC, becomes more challenging in this setup.

	Vout-pp reception (mV)		
Laser Output (dBm)	10pC	100pC	200pC
Nexans	160	1600	3200
Energinet	20	200	400
Statnett	1	8	16

Figure 12. Expected output signal levels at the interrogator for each use case, based on simulation data incorporating optical losses, sensor layout, and system configuration for a +15 dBm system output power.

It is important to note that the signal levels and sensitivity thresholds presented for each use case are based on the current generation of the PD interrogator and its associated optical and electronic components. While the existing configuration provides sufficient performance for the initial deployment scenarios, future iterations of the system are expected to deliver enhanced signal-to-noise ratios to support a greater number of sensors per interrogator unit.

Several strategies are being considered to achieve these improvements. These include increasing the optical output power from the interrogator, enhancing the sensitivity of the HFCT sensors, and integrating more responsive electro-optic modulators. However, one of the most promising areas for optimization lies in the RF reception stage. Current development efforts are focused on identifying and integrating RF receptors and amplifiers with lower noise figures and higher dynamic range, which would significantly improve detection capabilities, particularly under low-power conditions.

Additionally, future system upgrades may incorporate optical amplification, such as EDFA modules, to boost the optical power delivered to the sensors, thereby improving signal integrity across long distances or in systems with extensive multiplexing.

4.3 Long Distance Monitoring Capability

The proposed fiber-optic interrogator architecture is inherently compatible with long-distance installations, as required in HVDC cable systems. The use of continuous optical interrogation over a unique single-mode fiber per sensor ensures that the system can monitor sensors installed at considerable distances without functional degradation.

The primary effects of extended fiber length are:

- **Optical losses:** due to fiber attenuation, which typically amounts to approximately 0.3 dB/km per direction, resulting in a round-trip loss of about 0.6 dB/km .
- **Signal delay:** caused by the propagation time of light in the fiber (approximately $5 \mu\text{s/km}$), which introduces a known time offset between the event occurrence and its detection at the interrogator.

These effects do not compromise the system's capability to detect or locate partial discharges. Optical attenuation is mitigated through effective power management, ensuring sufficient launch power from the interrogator and maintaining adequate dynamic range at the detector. The time delay only affects the absolute timestamp of the received signal, not its waveform integrity.

For PD localization, the system relies on measuring the time difference of arrival between two sensors placed along the cable. To ensure accurate event localization, the fixed time offset caused by the fiber length of each sensing path is characterized during system setup. This allows the processing unit to apply a compensation factor, ensuring that measured delays represent PD positioning on the cable and not propagation-induced delay.



5 System Visual Evidence

5.1 Photographs of the Prototype Hardware (Sensor and Interrogator)

5.2 System and Integration Diagrams

The development of the optical interrogator and sensor system, due to its complexity, was carried out in a modular manner. From the beginning, it was clear that an iterative development process would be necessary for both components, based on the proposed system architecture. On the interrogator side, the architecture included transmission, reception, and WDM blocks. For the sensor, multiple optical components were individually tested and later combined to ensure that all requirements were met both independently and as an integrated unit.

On the interrogator side, integration testing was also performed with the light emission source. This narrow-linewidth laser enables precise emission and supports DWDM usage (see Figure 13). The light module was controlled and used allowing simultaneous emission of the different lasers. Using WDM components, multiplexing and demultiplexing were tested to ensure the correct routing of signals to the optical signal receptors.

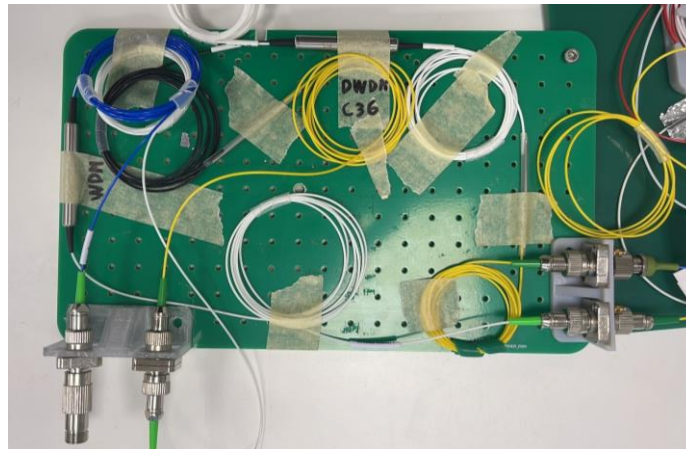


Figure 13. WDM and DWDM configuration for proper sensing of PD events.

DWDM channels were also tested with the light emitter to verify the spectral compatibility with the ITO sensor channels, ensuring that the emitted power remained within the acceptable spectral window for each sensor. These tests allowed for cross-validation of sensor and interrogator compatibility.

Once the systems had been validated individually, full system integration was initiated. The PO control module was connected to the EOM, targeting it to its operation point. The optical emission, along with WDM, was included in the integrated setup, which was designed compactly

for easy maintenance, future servicing, and suitability for industrial installation during testing, as in Figure 14.

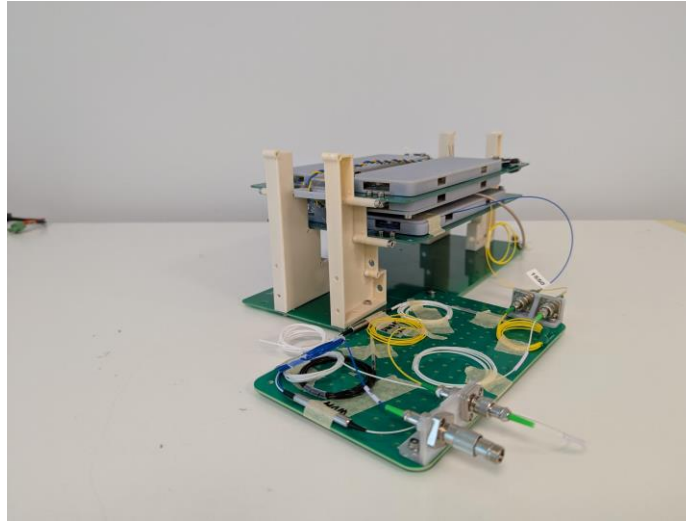


Figure 14. Partial integration of main modules from interrogator and sensor sides.

Inside the Optical Box (OB), the fiber-optic components were mounted onto custom-designed optical PCBs, ensuring mechanical stability, ease of alignment, and maintenance accessibility. This layout facilitates the integration of WDM/DWDM components, polarization controllers, fiber spools, couplers, the EOM, among others (see Figure 15).

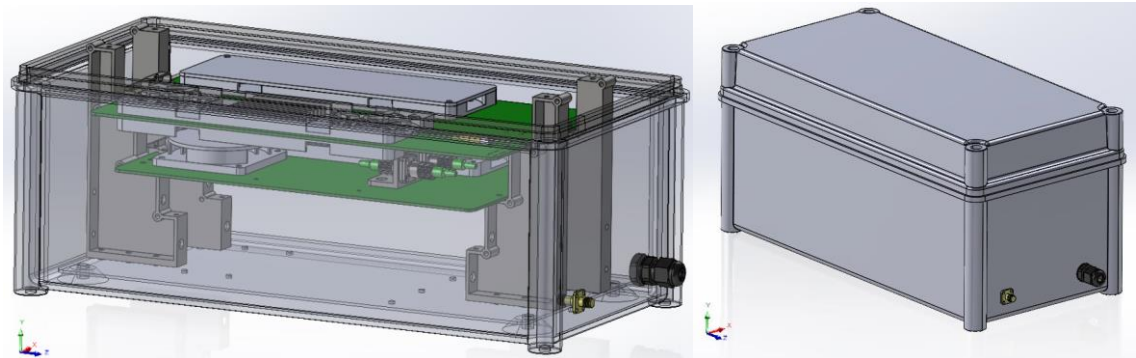


Figure 15. OB of PD.

The electronic control and signal conditioning circuits were organized into a rack-style enclosure, hosting multiple printed circuit boards (PCBs) responsible for signal generation, modulation drive, and photodetection (Figure 16).



Figure 16. Electronic PCB.

System overview showing the integration between electronic and optical subsystems is depicted in Figure 17.



Figure 17. Integrated PD interrogator and PD sensor.

With the complete integrated system, including the OB, interrogator and the electronics PCB, experimental trials were carried out in conjunction with the PD generator and the HFCT. This setup enabled the generation, injection, and detection of partial discharge events under controlled conditions. The integrated architecture allowed for seamless signal acquisition and optical modulation response, enabling the evaluation of system performance under realistic test scenarios. The results obtained from these experiments are presented in Figure 18, illustrating the system's ability to capture and process PD signals with temporal and spectral fidelity using low sensitivity HFCT and optical power input -15dBm to see the lower limit of detection capability. With the new acquired HFCT the sensitivity increased x4.

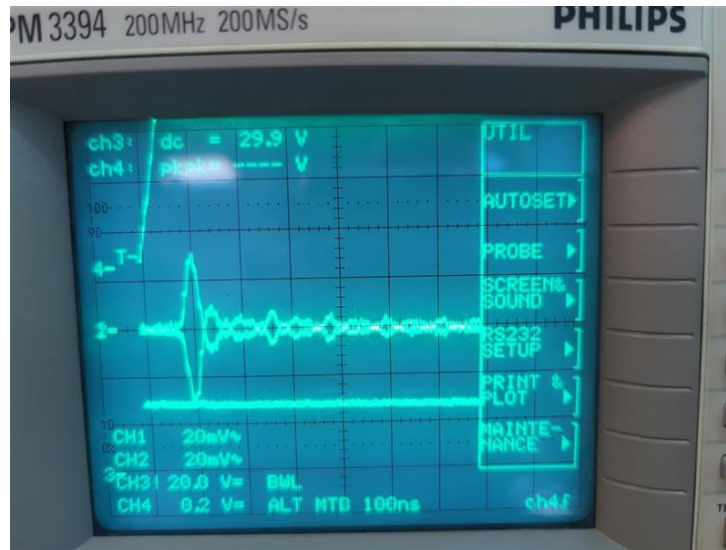


Figure 18. Experimental configuration and resulting PD signal captured by the integrated optical system for a PD of 1000pC.

5.3 Test Results Screenshots and Raw Data Visual

5.3.1 HVDC Cable PD Experiment: Visual Results and Discussion

In this measurement setup, the objective was to investigate the behavior of PD signals in a HVDC cable section. A standard PD generator was employed for signal injection, and a HFCT was used for detection. The cable under test was prepared with both the core conductor and the external conductive shield exposed at the ends, allowing direct electrical connections. The PD generator was connected between the core and the shield to establish a closed-loop circuit. The core was tied to ground, the PD generator was inserted between the core and shield, and the shield was grounded through the HFCT.

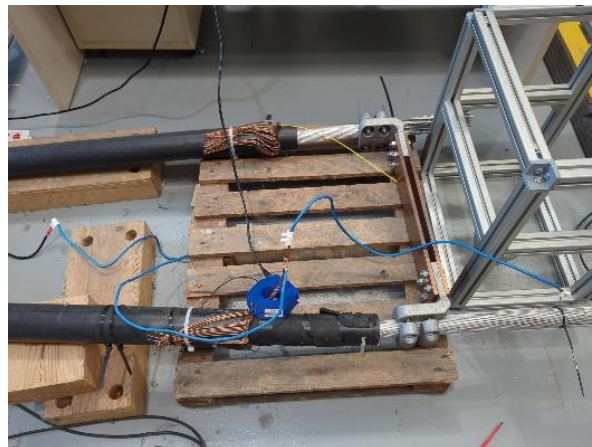


Figure 19. Experimental HVDC cable setup.

The HFCT placement enabled the detection of current pulses traveling through the return path, i.e., from the shield to ground. The intent of this configuration was to analyse the propagation of PD pulses within a realistic HVDC cable structure and to compare the results with previous measurements performed using a short, thin laboratory-grade cable. The latter had distinct propagation characteristics resulting from differences in geometric configuration, characteristic impedance, and insulation properties.

The experimental results indicated that PD pulses in the HVDC cable exhibited a more prolonged decay than those observed in the shorter laboratory cable. This extended decay is consistent with the HVDC cable's greater physical length and lower attenuation, which together support the sustained propagation of high-frequency components and allow for multiple signal reflections along the cable.

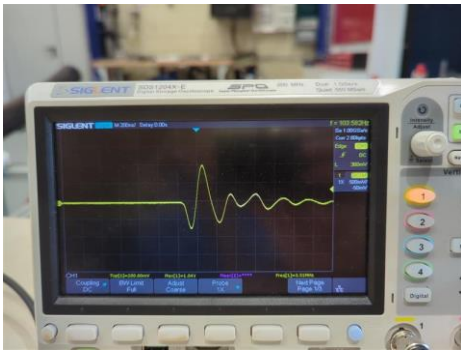


Figure 20. HVDC cable; 1000pC.

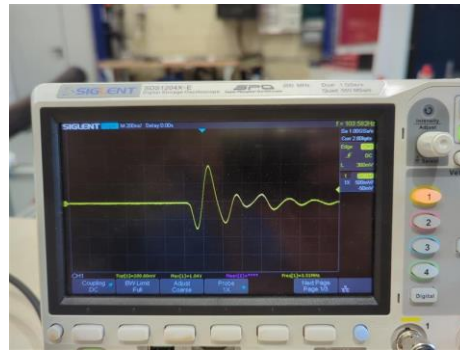


Figure 21. HVDC cable; 2000pC.

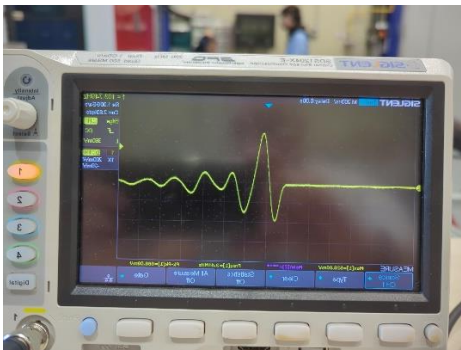


Figure 22. HVDC cable; 500pC.

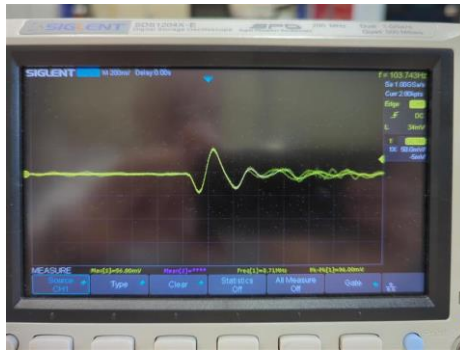


Figure 23. HVDC cable; 50pC.

These findings confirm the relevance of testing in realistic cable environments and suggest the need for connector or impedance adaptation in future system iterations to improve injection efficiency and measurement accuracy.

6 Viability Assessment

6.1 Capability to Detect PD in New Cable Designs

The developed PD detection system has demonstrated a high capability for detecting partial discharges (PD) in next-generation cables for both HVAC and HVDC applications, showing technical specifications that align closely with the requirements established in WP5 of the Grant Agreement.

Its most relevant technical and operational characteristics include:

- Continuous and real-time monitoring capability for HVDC and HVAC cables.
- Use of high-frequency current transformers (HFCTs) with a maximum bandwidth of up to 150 MHz, balancing sensitivity and frequency response.
- Capacity to detect PD events as low as 10 pC.

The system has demonstrated the capability to detect partial discharges as low as 10 pC under optimal power and distance, which is crucial for identifying the earliest manifestations of cable degradation. These early discharges, while low in energy, often produce very short-duration pulses with broadband frequency components exceeding 150 MHz. Reliable detection, therefore, requires both high sensitivity and sufficient bandwidth.

The current 150 MHz bandwidth offers a strong balance, wide enough to capture most early-stage PD signals, while preserving excellent sensitivity to low-charge events. Importantly, although the highest frequency components of incipient PDs may exceed 150 MHz, these discharges also emit energy in lower frequency bands. Therefore, even in early degradation stages, the system can detect and characterize PDs based on their significant low- and mid-frequency content, which falls well within the system's bandwidth. In practice, systems with much higher bandwidth often lose sensitivity, especially without external voltage alimentation of the HFCTs.

In intermediate degradation stages, discharges tend to be more energetic and slightly longer in duration, shifting their spectral content primarily to frequencies below 150 MHz. This makes the current bandwidth particularly well-suited for monitoring this critical phase of cable aging, as it aligns with the dominant frequency content of the signals.

Additionally, the system is ready to operate at higher frequencies when the market offers HFCTs with extended bandwidth and high sensitivity without the need for external powering. This provides a clear path for performance enhancement as technology evolves.

6.2 Planned Integration with Ageing and Prediction Algorithms

Although complete validation has not yet been carried out, it is considered that the information generated by the PD detection system has the potential to provide essential inputs for the aging



and lifetime prediction algorithms defined in WP5. Based on the data the system is currently capable of acquiring, it is expected to contribute to aspects such as:

- Preliminary characterization of insulation aging under real operating conditions by identifying PD patterns associated with degradation processes.
- Generation of datasets that can be used to train and fine-tune WP5's predictive algorithms.
- Early identification of trends or subtle changes in PD events, which could facilitate more effective preventive maintenance strategies.

The system is particularly suitable for this purpose as it is capable of measuring not only the amplitude of the PD pulses but also their repetition rate and evolution over time. Furthermore, based on the relative arrival time of each discharge at different active sensors, the system can estimate the location of the PD event along the cable. This spatiotemporal information adds significant value to the data that will be used by WP5's algorithms.

These capabilities will be further validated later in the project in coordination with the developments carried out in WP5.

6.3 Conclusion and Next Steps

The initial results from the system under development are promising and suggest that it will meet the expectations set out in the project, offering remarkable precision, sensitivity, and reliability in PD detection. However, several key areas for future improvement have been identified in order to achieve most demanding goals:

- Increasing the optical output power of the interrogator to significantly improve system sensitivity.
- Further optimization of optical reception techniques and RF reception stage to increase signal-to-noise ratio, particularly in high electromagnetic interference environments.
- Incorporation of optical amplification through EDFA modules to extend operational capability over long distances and/or highly multiplexed systems.
- Continuous firmware and software improvements, enhancing advanced algorithms for automatic discrimination and classification of PD events.

These upgrades will increase the system's capacity to manage a larger number of sensors per interrogator unit and sensitivity, significantly expanding its applicability.

In conclusion, the system under development is highly viable and suitable for effective integration with the predictive and ageing tools in WP5, making a decisive contribution to improving the reliability and efficiency of HVAC and HVDC transmission network management.

