Photon Detection System Readout for the DUNE Far Detector-Vertical Drift

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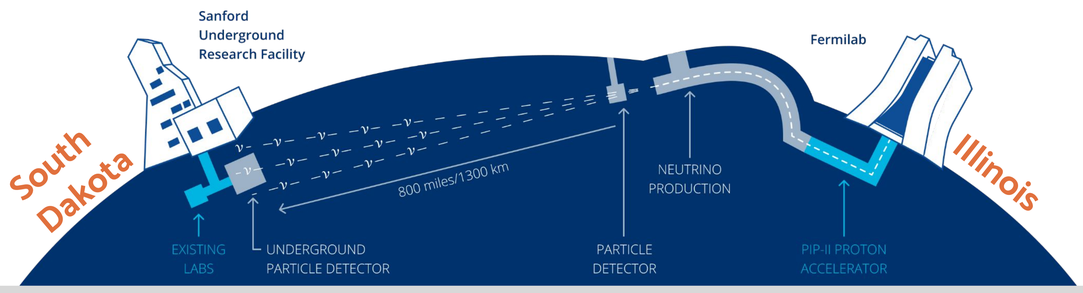
Deep Underground Neutrino Experiment

DUNE is a next-generation international facility designed to study the 3-flavor paradigm and search for new physics in neutrino oscillations. A **νμ / ν̄μ beam** generated at Fermilab is directed towards the SURF installation. It will consist of two detectors, separated by a baseline of 1300 km :

- **Near detector (ND)**: Located 60 m underground at Fermilab. Measures the neutrino beam before oscillation.
- **Far detector (FD)**: Located 1.5 km underground at SURF. Four LArTPC modules based in Vertical Drift and Horizontal Drift technologies.

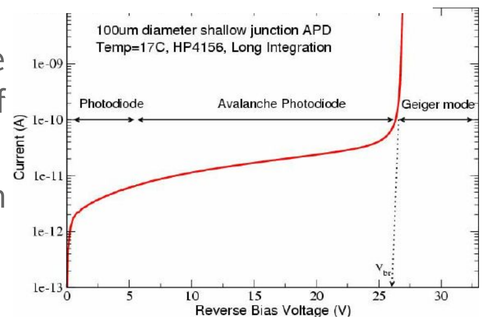


Photon Detection System Readout

Each XA module is equipped with 160 ganged SiPMs, arranged in groups of 20 on **flexible printed circuit board (PCB) strips**.

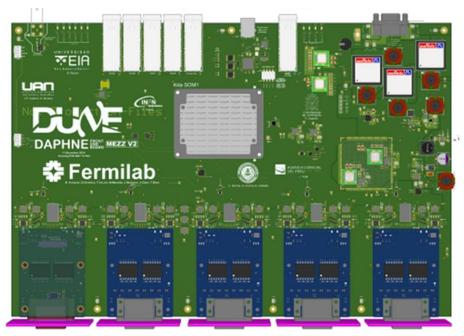
Operating in **Geiger mode**, the SiPMs generate current pulses proportional to the number of detected photons.

The readout electronics is divided in two main stages:



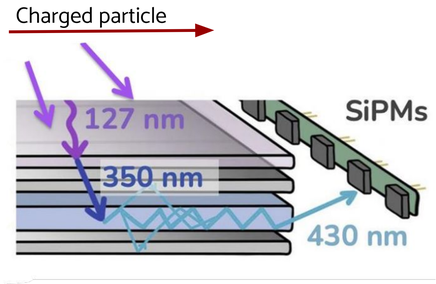
- **Cold electronics:** Located close to the XA and operating at cryogenic temperature, amplifies the SiPM signals. Cathode XA are powered through Power over Fiber, ensuring electrical isolation from the high-voltage system.
- **Warm electronics:** Based on the **DAPHNE** platform, performs signal digitization, timing, trigger generation, data transmission and monitoring of the cold electronics.

CIEMAT contributes through the fabrication and validation of the **DAPHNE membrane mezzanine boards**, which adapt the detector front-end electronics to the DAPHNE readout system.



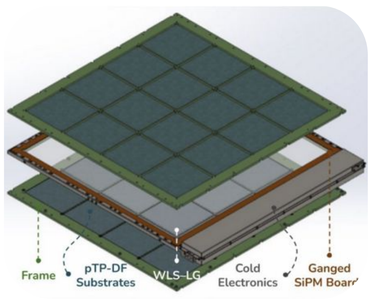
FD-Vertical Drift Photon Detection System

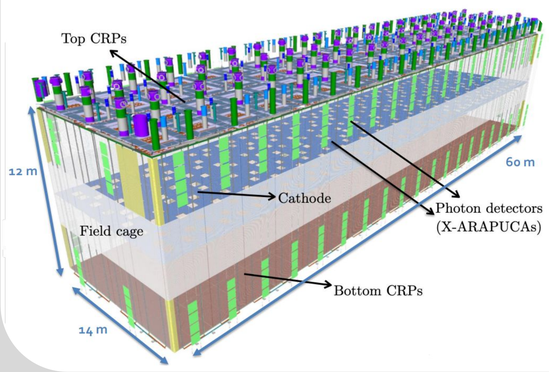
The **Photon Detection System** (PDS) provides precise event timing and complements charge-based reconstruction in the DUNE FD.



When charged particles transverse liquid argon (LAr), they produce scintillation light in the vacuum ultraviolet (VUV) range at 127 nm.

The PDS consists of **X-ARAPUCA** (XA) sensor modules, which shift the VUV light to visible wavelengths and guide the photons to **silicon photomultipliers** (SiPMs) for detection.



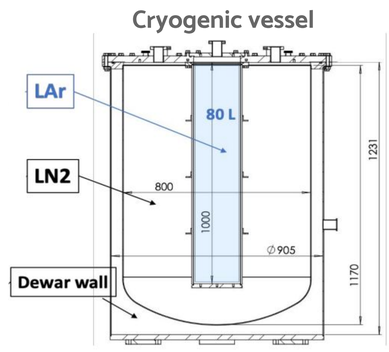


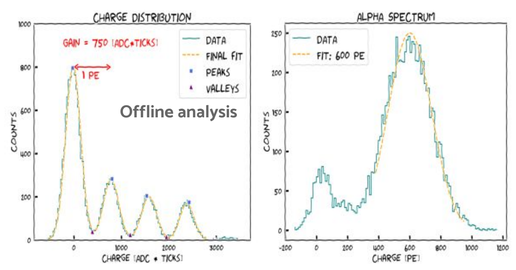
Vertical drift (VD) elements:

- Two drift volumes separated by a central cathode.
- PCB-based anode charge readout.
- 320 double-sided XA on the cathode.
- 352 single-sided XA on the cryostat wall.

X-ARAPUCA R&D at CIEMAT

The **CIEMAT cryogenic facility** reproduces DUNE operating conditions, allowing XA modules to be tested in LAr. The cryostat consists of a multilayer vessel, including a dewar wall, a liquid nitrogen (LN_2) thermal shield and an inner LAr volume where the detectors are installed. With this setup, measurements of the **photon detection efficiency** (PDE) of the XA modules were performed in different configurations.





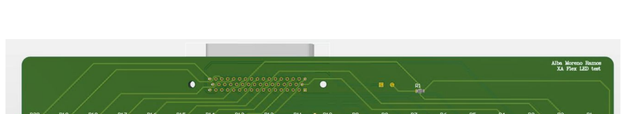
XA waveforms are currently processed offline. As part of an ongoing update, the **CAEN DT2730** digitizer is being evaluated to perform pulse integration in real time and to estimate the dark count rate.

X-ARAPUCA Production at CIEMAT

CIEMAT is responsible for the assembly and characterization of **352 membrane XA modules**, including warm and cold testing before installation.

Pre-assembly test

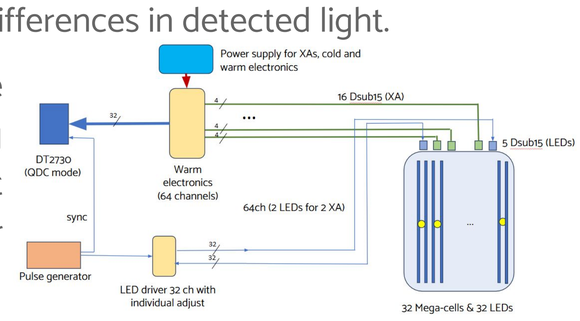
Warm test that consists of a flex support and a PCB with 20 LEDs (one per SiPM). Each LED is activated individually while monitoring the flex output cables to verify the expected current response.



Post-assembly test

The pre-assembly test is repeated using a 160-LED setup. A second validation checks uniform illumination of both channels to ensure all flex boards are operational, with failures identified through differences in detected light.

For large-scale validation, 32 XA modules are installed in a **2500 L cryogenic vessel**, using two LEDs per every two XA units to detect possible malfunctions and extract detector characteristics, like the XA gain.



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