ProtoDUNE-HD PDS commissioning, operation & performance

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What is DUNE?

1400 collaborators
200 institutions
35 countries + CERN

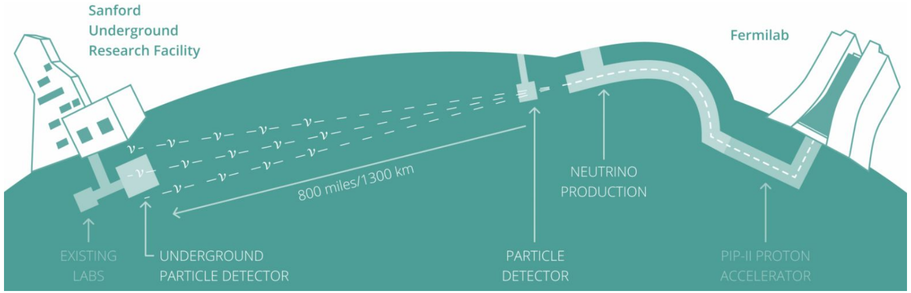
- **Open questions** that DUNE aims to answer

Unification of Forces

WHY DID MATTER WIN OVER ANTIMATTER?

Black Hole Formation

- **Broad-band ν_μ beam:** ~1.2 MW, upgradable to 2.4 MW → **most intense in the world**
- Dual-site experiment for the study of ν oscillations, CP violation, nucleon decay, SN detection...
  - **Near Detector (Fermilab)** to study unoscillated neutrino spectrum and flux constraints
  - **Far Detector (Sanford)**: 4 modules of 17kt liquid argon TPC at 1.5 km underground

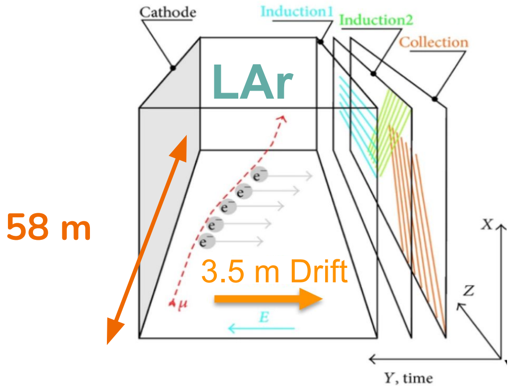


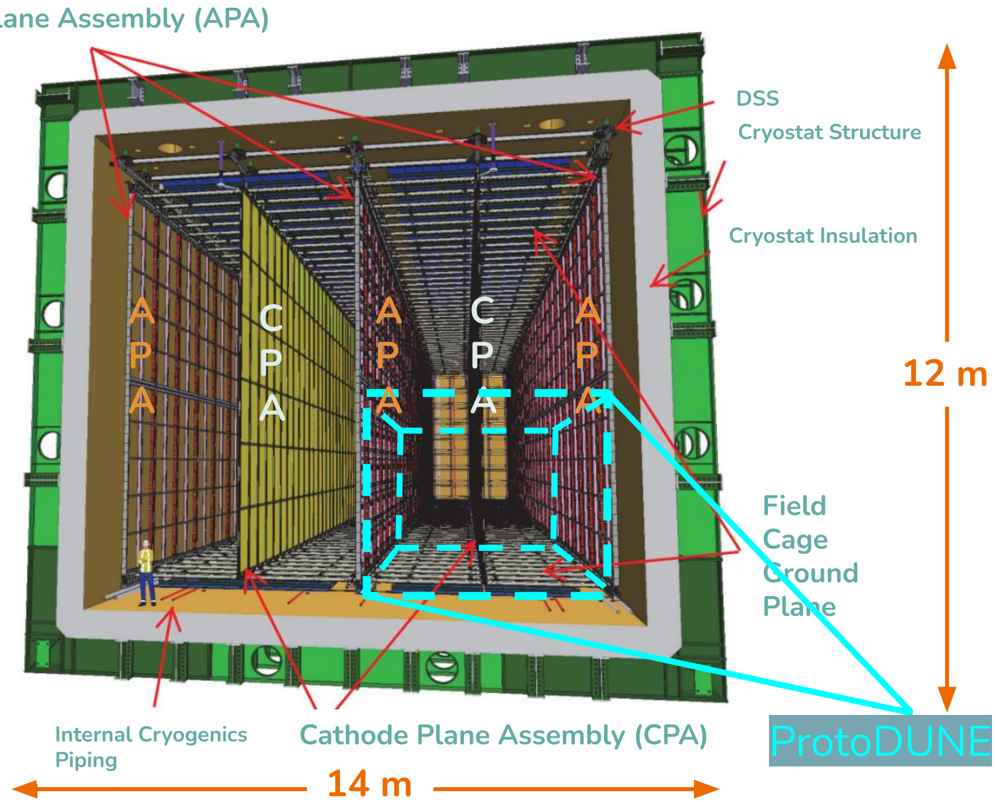
https://www.dunescience.org/

Far Detector (2^{nd} module)

Horizontal Drift

- **Cryogenic** challenge
- 10 kt fiducial cryostat
- 385000 Readout Channel
- 150 APAs, 200 CPAs
- Photon Detection System <u>integrated</u> in the APAs



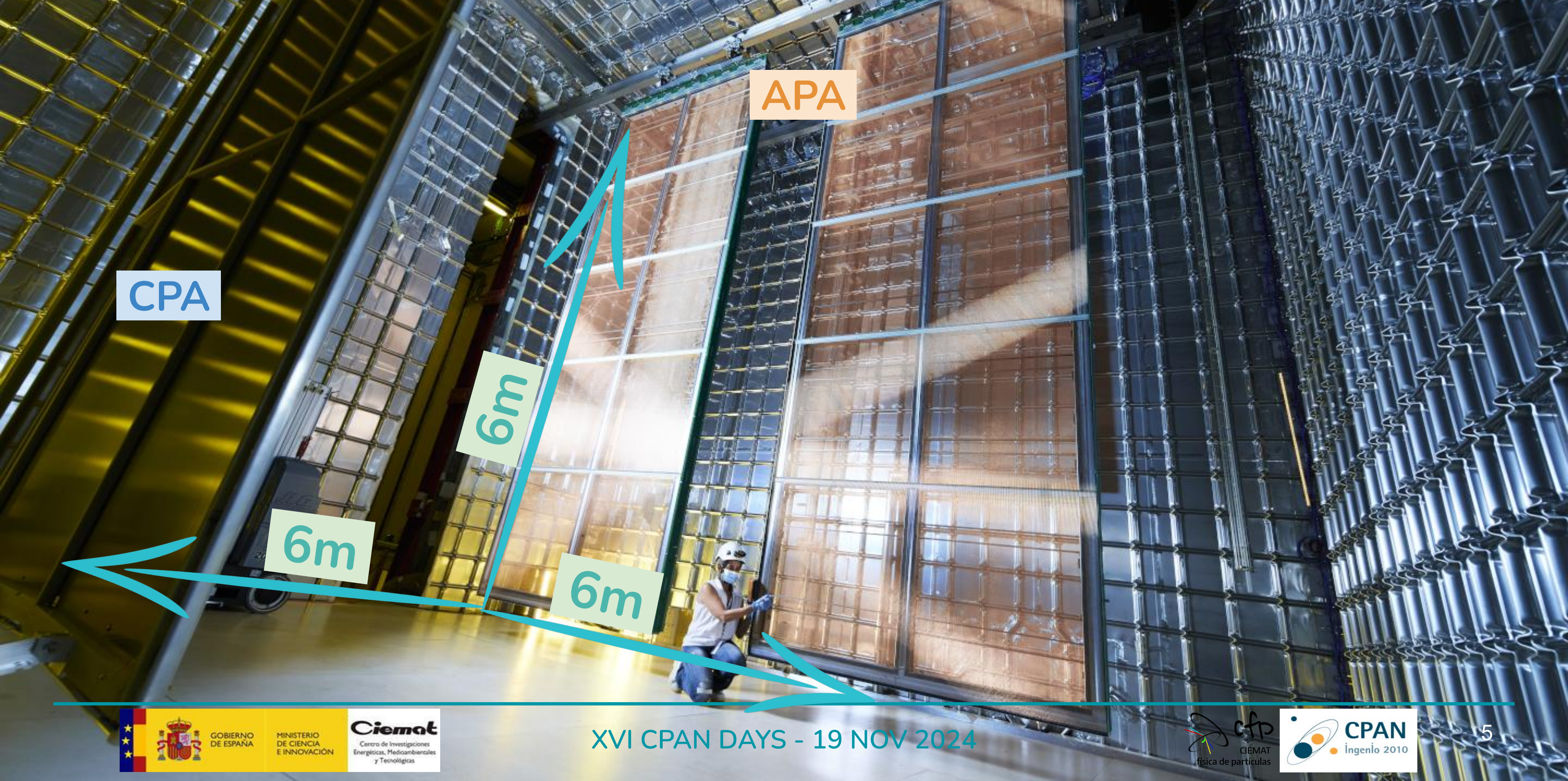


ProtoDUNEs

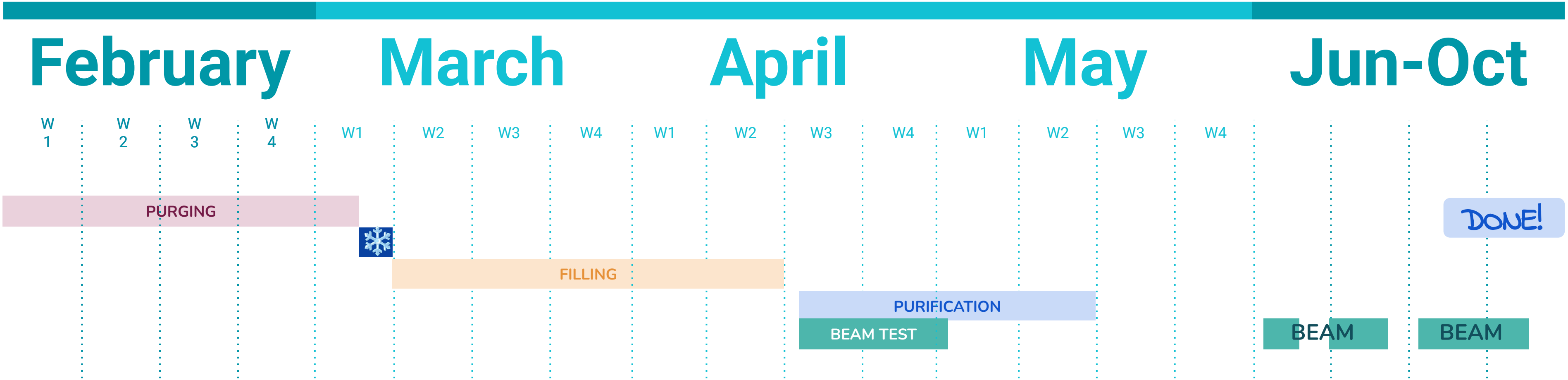
DUNE FD prototypes are built at CERN Neutrino Platform at (1:20) scale and 750 ton total mass of LAr. They have access to a test beam used to validate their performance.

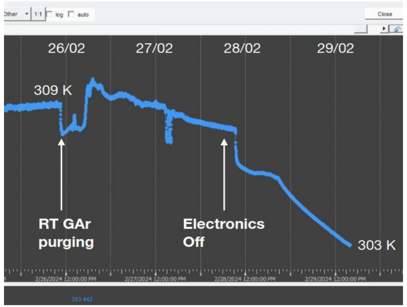
- **ProtoDUNEs Phase I**
  - ProtoDUNE-SP took data **2018-2020** of 0.3-7 GeV charged particle (e, π, μ, K, p) from the beam
- **ProtoDUNEs Phase II**
  - ProtoDUNE-HD started in **2024**
  - Validate final design of 2nd FD model (**2024-2025**)
  - Test baseline design for 1st FD model (**2025**)

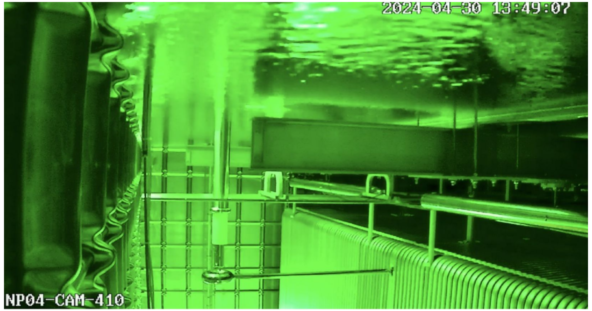
ProtoDUNE-HD installation



ProtoDUNE-HD operation timetable







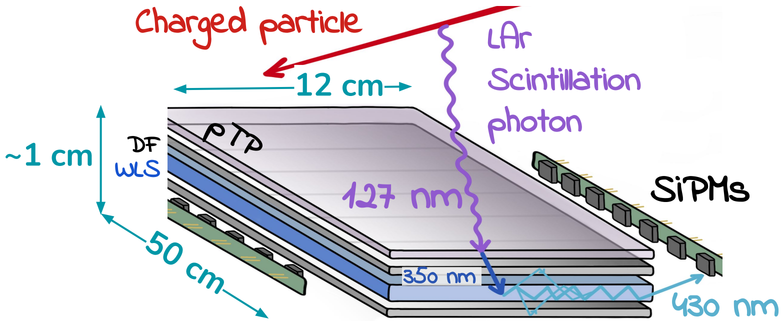
Photon Detection System: X-ARAPUCA

- **Scintillation light** is detected instantaneously on the timescale of the TPC information
- LAr is an **excellent scintillator** (24,000 photons/MeV)
- More light opens additional physics opportunities like **calorimetry** and triggering

Challenges & Advantages

🚫 Emitted VUV photons (**𝝀=127nm**)
🚫 **LARGE detection area** is needed

✅ *Trap* light + shift photons (**𝝀~400nm**)
✅ Compact design



- **Four X-ARAPUCA configurations** installed in ProtoDUNE-HD (combinations 2 SiPM x 2 WLS)
- Tested before their installation in LAr at CIEMAT and Milano Bicocca.
- **Photon Detection Efficiency (PDE) has been measured to be about 2% at 4.5 OV (FBK) & 3.0 OV (HPK)**

  See Eur. Phys. J. C 84, 1004 (2024) 📰

- For the **first time** the X-ARAPUCA performance has been evaluated. This is crucial for DUNE, in particular the determination of the PDE
- New digitizer (DAPHNE) is also being tested.

Detector Overview

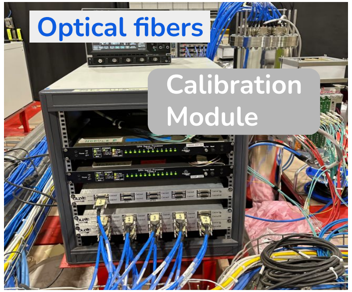
- **160 channels**, with 4 X-ARAPUCA per PDS module
- **7 DAPHNE** boards with **40 channels each**
- APA 1 in full streaming (3 DAPHNE) + APAs 2, 3, 4 in self-trigger (4 DAPHNE)
- Two different SiPM vendors, **HPK** (orange) and **FBK** (light yellow)
- Breakdown voltage needs to be computed for each X-ARAPUCA ($V_{OP} = V_{BD}$ + OV)

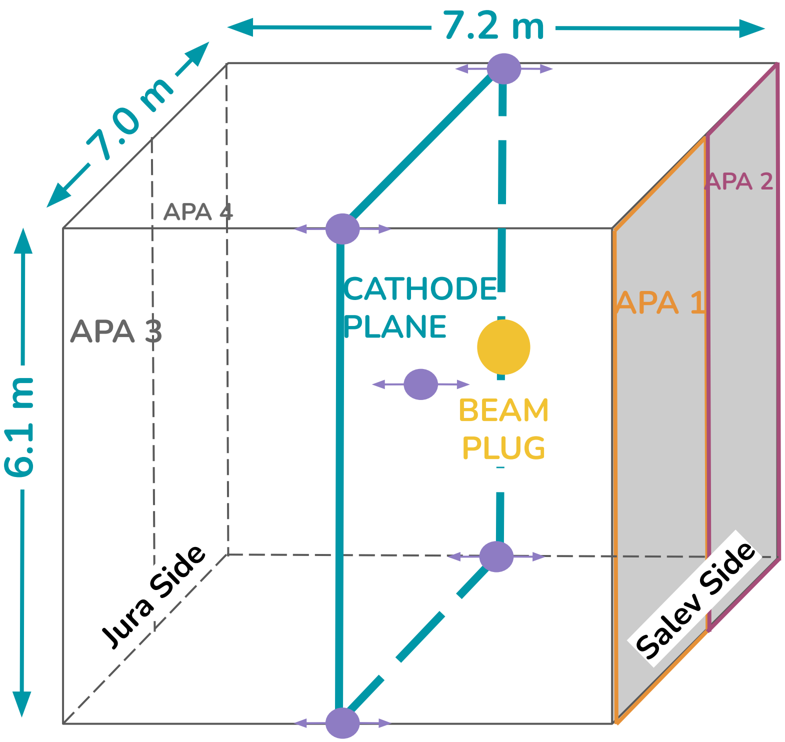
Overvoltages (OV) [V]

	HPK	FBK
40% SiPMs PDE	2.0	3.5
45% SiPMs PDE	2.5	4.5
50% SiPMs PDE	3.0	7.0

Before 9^{th} July
After 9^{th} July

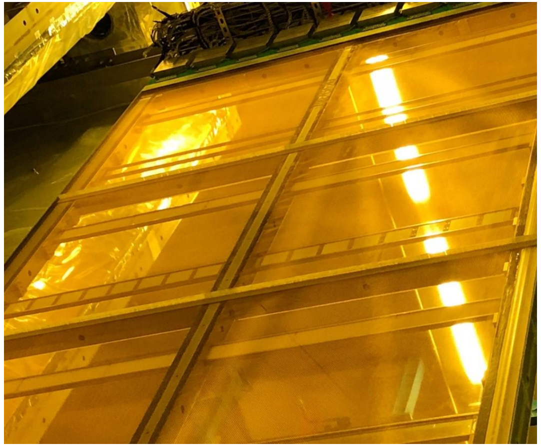
ProtoDUNE-HD: LED calibration system (I)





PDS calibration is **critical** for its characterization, homogeneity and calorimetry studies.

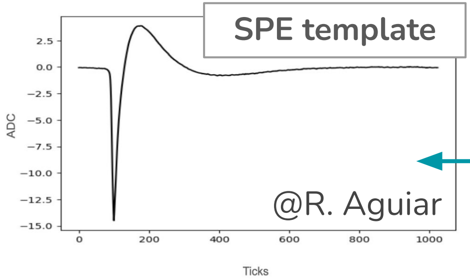
Diffusers located in cathode plane to illuminate PDS channels and carry out their calibration.

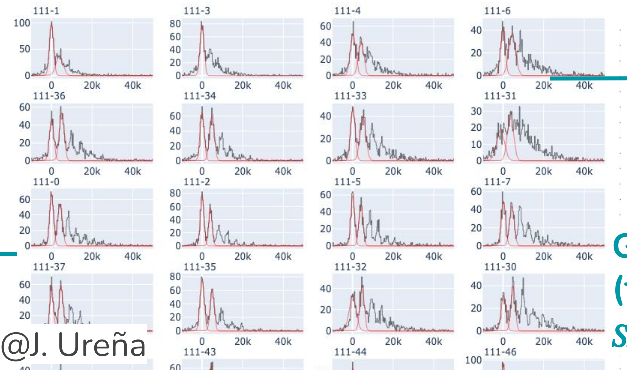


ProtoDUNE-HD: LED calibration results

During the PD-HD commissioning we have:

- **Characterized the DUNE calibration system**
- *Acquired biweekly calibrations during beam-time (2h data taking)*
- **Gain calibration for 160 X-ARAPUCA channels**:
  - **SPE templates for 160 channels** → input for **LArSoft**
  - Channel noise characterization
  - Breakdown voltages
  - LED intensity tuned for different XA groups

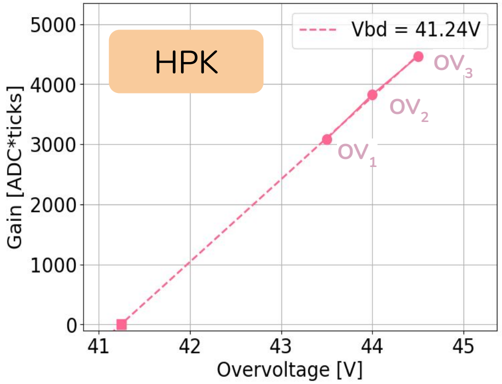


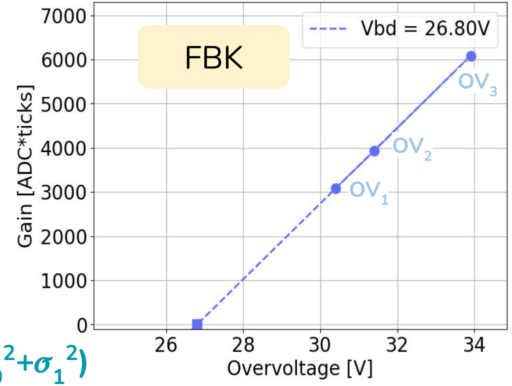


Gain = μ_1 - μ_0 (for 3 OV)

$SNR_1 = \mu_1 - \mu_0 / \sqrt{(\sigma_0^2 + \sigma_1^2)}$

Gain vs V fit to get V_{BD}





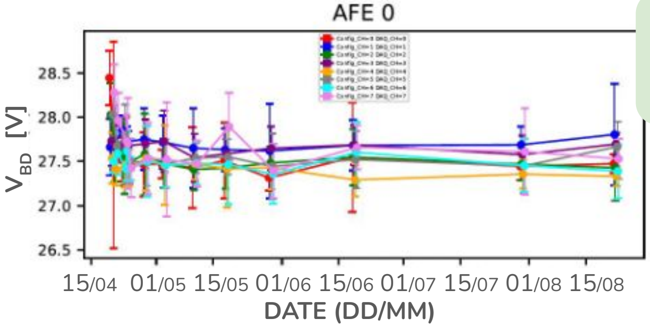
IV Curves

Current vs voltage (IV) curves allow to determine the V_{BD}

Expected V_{BD} mean values from specifications	HPK	FBK
77 K	41.5 V	26.9 V
298 K	51.0 V	32.5 V

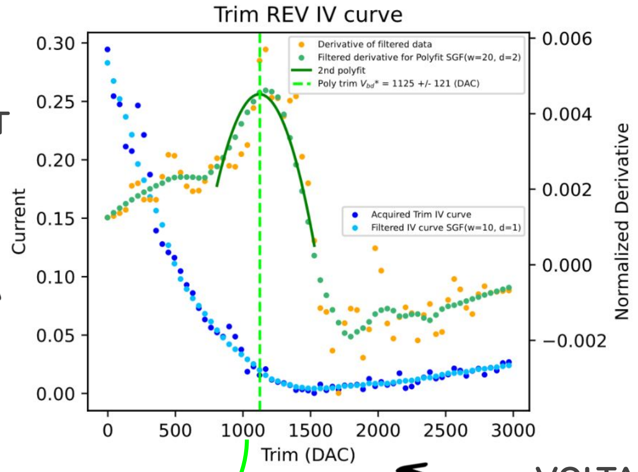
- Acquired **daily** during purging, filling and purification phases
- Once temperature stability was reached → **biweekly** data
- Computed for all DAPHNE channels (3h data taking)

We can check the evolution of V_{bd} with time:



STABLE for all channels along the operation time

CURRENT



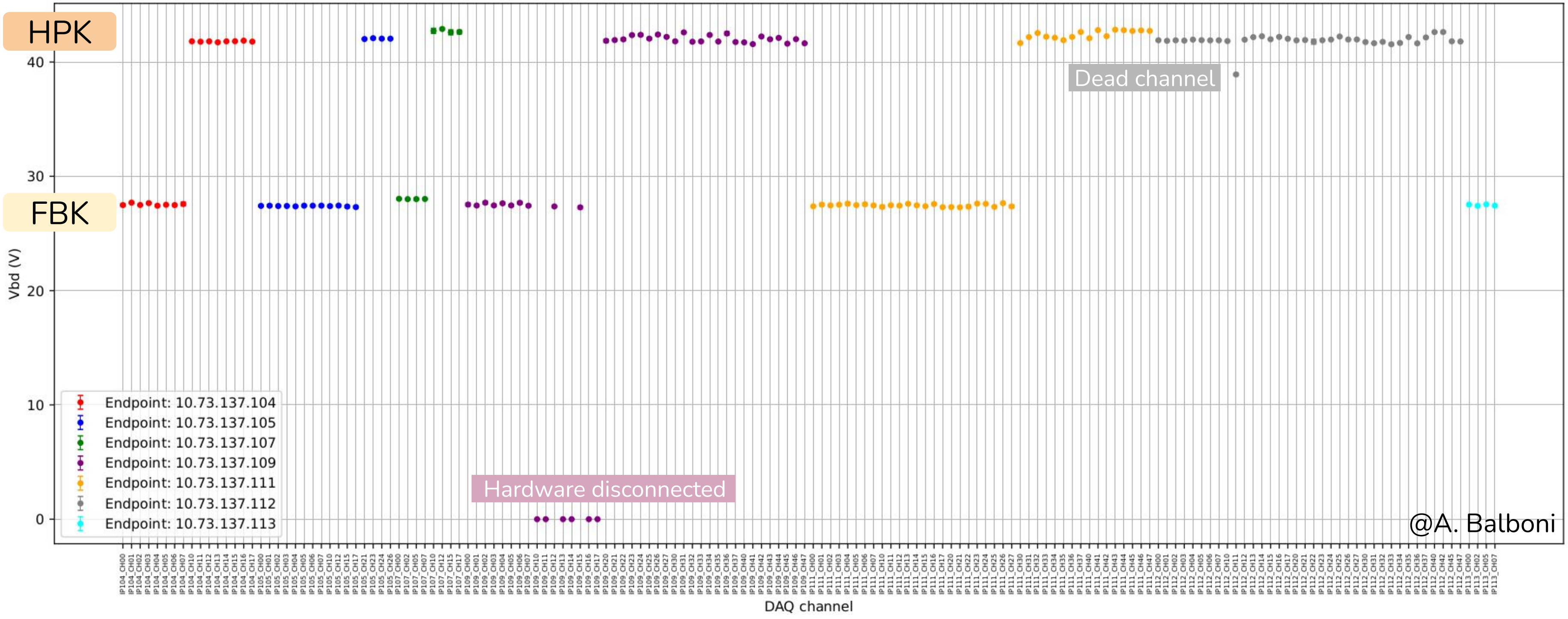
VOLTAGE

V_{BD}: maximum of the 1st derivative

@A. Balboni

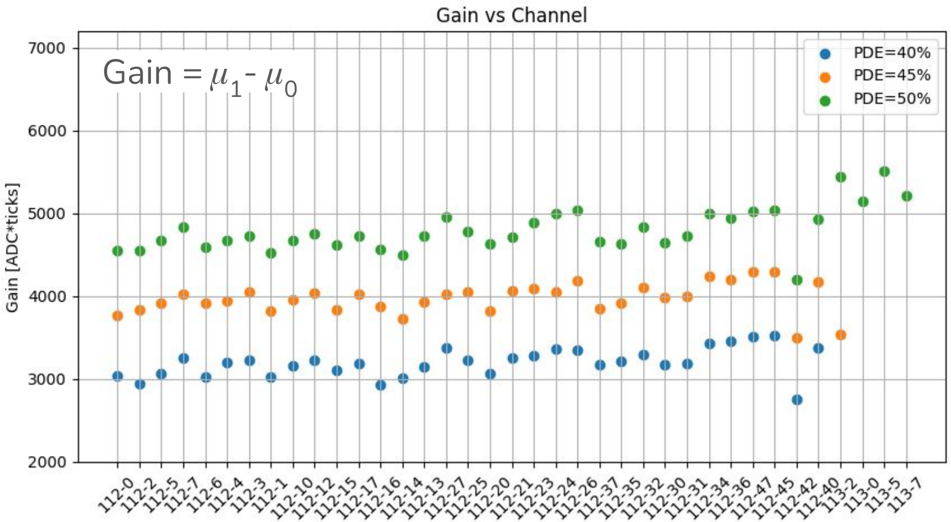
Breakdown voltages

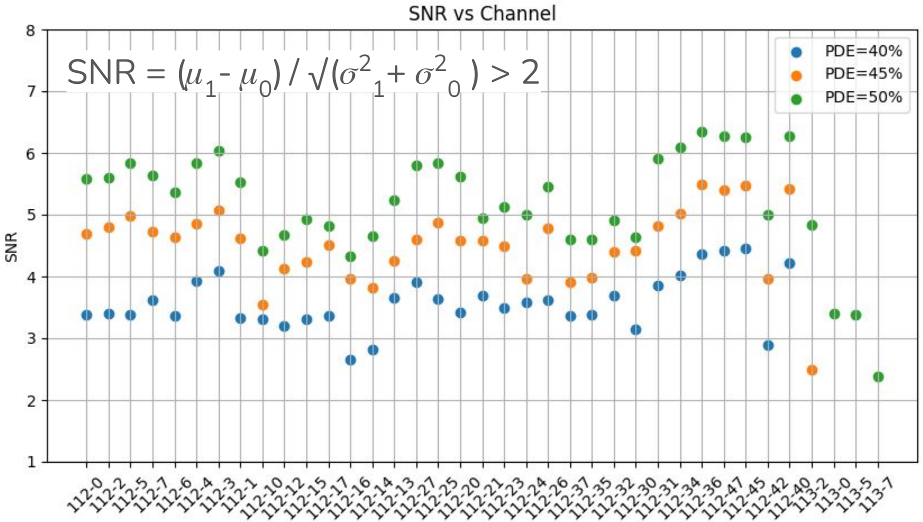
Outputs from **IV curves** + **LED calibration** result on the V_{BD} values being used in the NP04 PDS channels



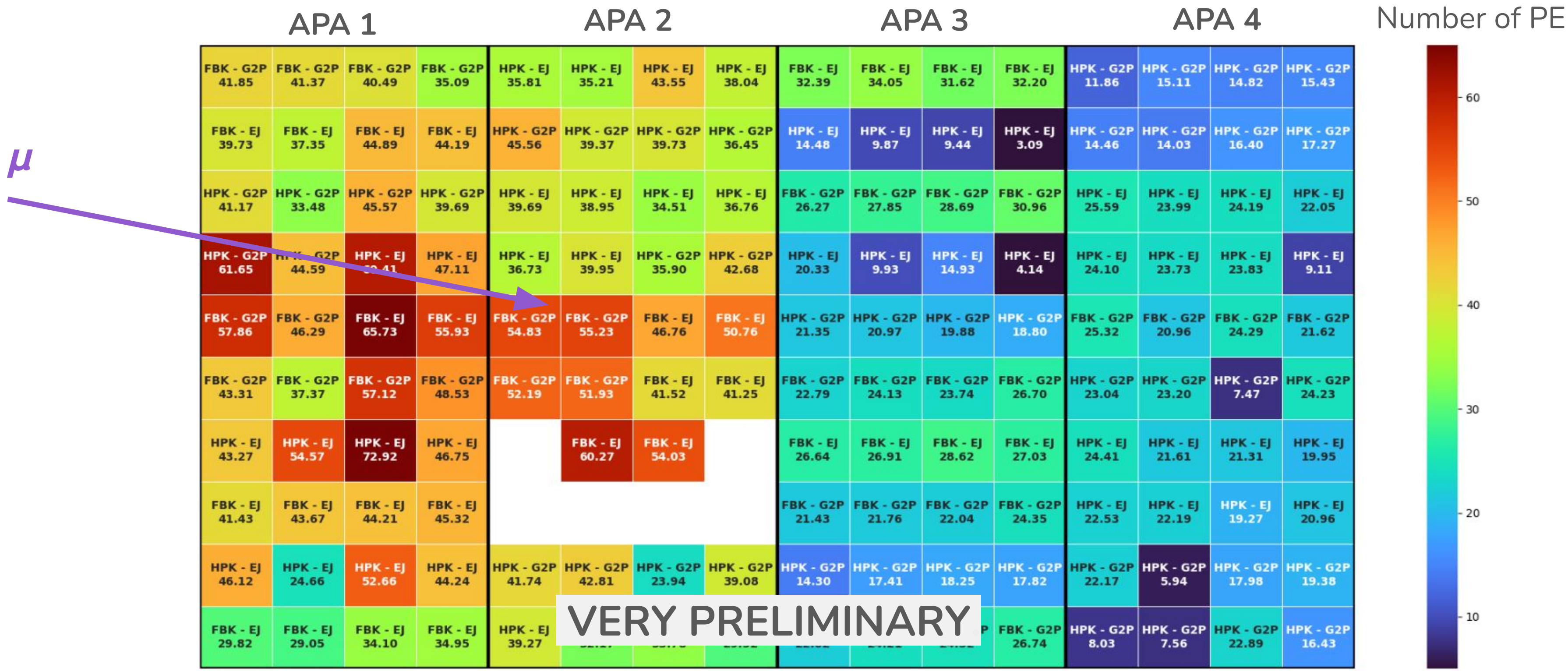
Gain and SNR

- Homogeneous gain response → stable performance
- SNR above requirements





Performance



Conclusions

- PDS channels (XA) had good performance:
  - 96% operative channels
  - Stable and homogeneous response
  - DUNE requirement of S/N > 4 is satisfied
- **Stable operation with beam since July 31th until beam time concluded (September 16th)**
- Minor communication errors identified solved by changing some **fibers**
- Dedicated self-trigger and dynamic range studies have been carried out after the beam run.
- LAr transbase to ProtoDUNE-VD is planned to start in December 2024.
- Calorimetric response and PDE measurements are ongoing

Stay tuned!

THANK YOU!