FD2-VD SiPM
Production readiness review

Francesco Terranova
Univ. of Milano Bicocca and INFN

Feb 3, 2025

Purview

We are addressing a Stage-1 (long lead component procurement) for FD2-VD because:

- The SiPM have reached PRR maturity since there are mostly based on the FD1-HD SiPMs with minor changes
- SiPM procurement is a key item in the FD2-VD PDS schedule due to the long lead time. At the time of writing, they are not in the DUNE critical path

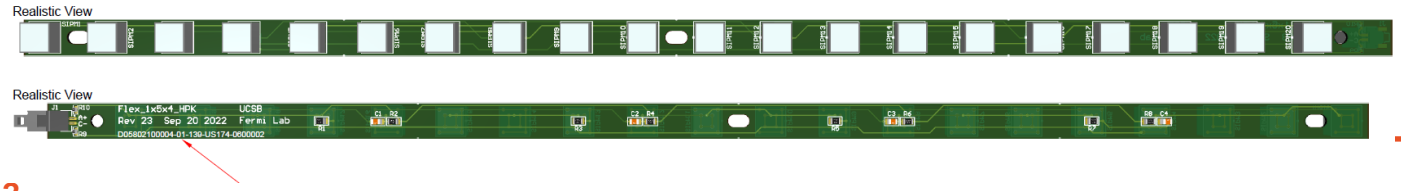
This presentation will:

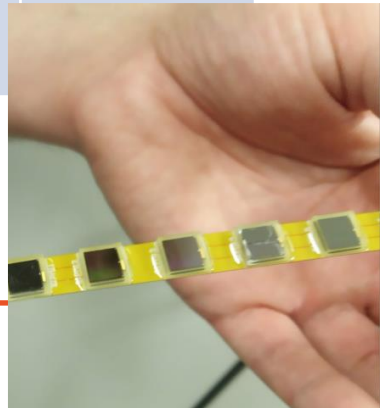
- Address the main items of relevance for the procurement
- Address the items mentioned in the Committee charge
- Present the documentation available in EDMS

Items to be procured

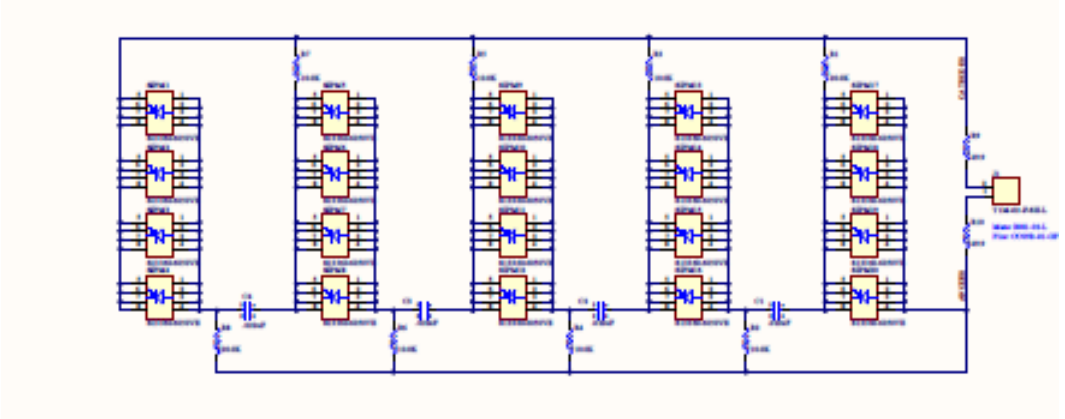
FD2-VD requires 107,000 SiPM to populate the membrane and cathode tiles. Unlike FD1-HD, where the basic unit is a 6-SiPM G10 board (SiPM board), FD2-VD employs **flexi boards**. Each board hosts 20 SiPMs, whose topology correspond to the hybrid ganging mode employed in FD2. We are going to procure **5600 flexi including 5% spares.**

Tiles	Flexi Boards	SiPMs	cold electronics	vendor
320 double-sided (cathode)	2560 + spares (2650 total)	53000	SoF-PoF	HPK
204 single-sided (membrane)	1632 + spares (1700 total)	34000	FBK cold electronics (former “HD-style”)	FBK
148 single-sided (membrane)	1184 + spares (1250 total)	25000	HPK cold electronics (former “VD-style”)	HPK

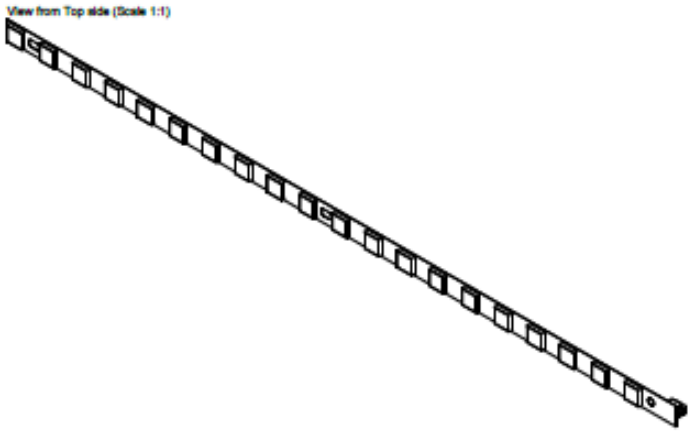


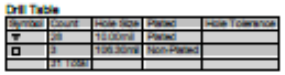


Schematics of the hybrid ganging mode



The FD2-VD flexi board (gerber, BOM and drawing available in the repository)





SiPM specifications are identical to FD1

Specification	Value	Notes
SiPM Dimensions	6x6 mm^2	
Packaging Format	SMT	Compatible with the flexi board
Cell pitch	40-100 µm	Single value for all SiPMs in the batch
Protective encapsulation of the SiPM	Silicone or epoxy resin	Single type for all SiPMs in the batch
Min PDE at nominal voltage (Vop)	>35% at 430 nm	Measured at room temperature
DCR	<200 mHz/mm^2	Measured at 77 K
Cross talk probability	<35% at Vop	Measured at 77 K
Afterpulsing probability	<5% at Vop	Measured at 77 K
Gain	2-8 × 10^6 at Vop	Measured at 77 K
Fall time constant of the signal	600 ns +/- 250 ns	Measured at 77 K
Breakdown voltage spread (Vbk)	<200 mV (max-min)	On groups of >8 flexi selected by the supplier
Breakdown voltage spread (Vbk)	<2 V (max-min)	On the batch

SiPM grouping has beed adapted to the number of SiPM in a FD2-VD tile

Vendors

To avoid any performance risk, DUNE has chosen the same vendors and the same SiPMs as for FD1-HD. These SiPMs were validated in lab, during the construction test of ProtoDUNE-HD and in the ProtoDUNE-HD run. **No issues were encountered at that phase.**

Similarly, during the preparation of FDR, the hybrid ganging scheme was tested in the cold-box and in the lab, reaching the FD2-VD specification. The outcome of the coldbox test suggested the use of FBK and/or HPK SiPM for the membrane and the use of HPK SiPM, which exhibit a lower cross-talk (safety margin against the lack of tunability of the Power-over-Fiber) for the cathode tiles

As a consequence, we have setup a two-vendor-scheme tender, where

- Each vendor produces the SiPM and populate the flexi board
- Each vendor employ as subcontractor the same company that produced the flexi boards during the R&D phase led by UCSB – Cirexx, US
- Each vendor is responsible for the whole basic unit, which must fulfill the specification detailed in the QC document

Changes with respect to FDR

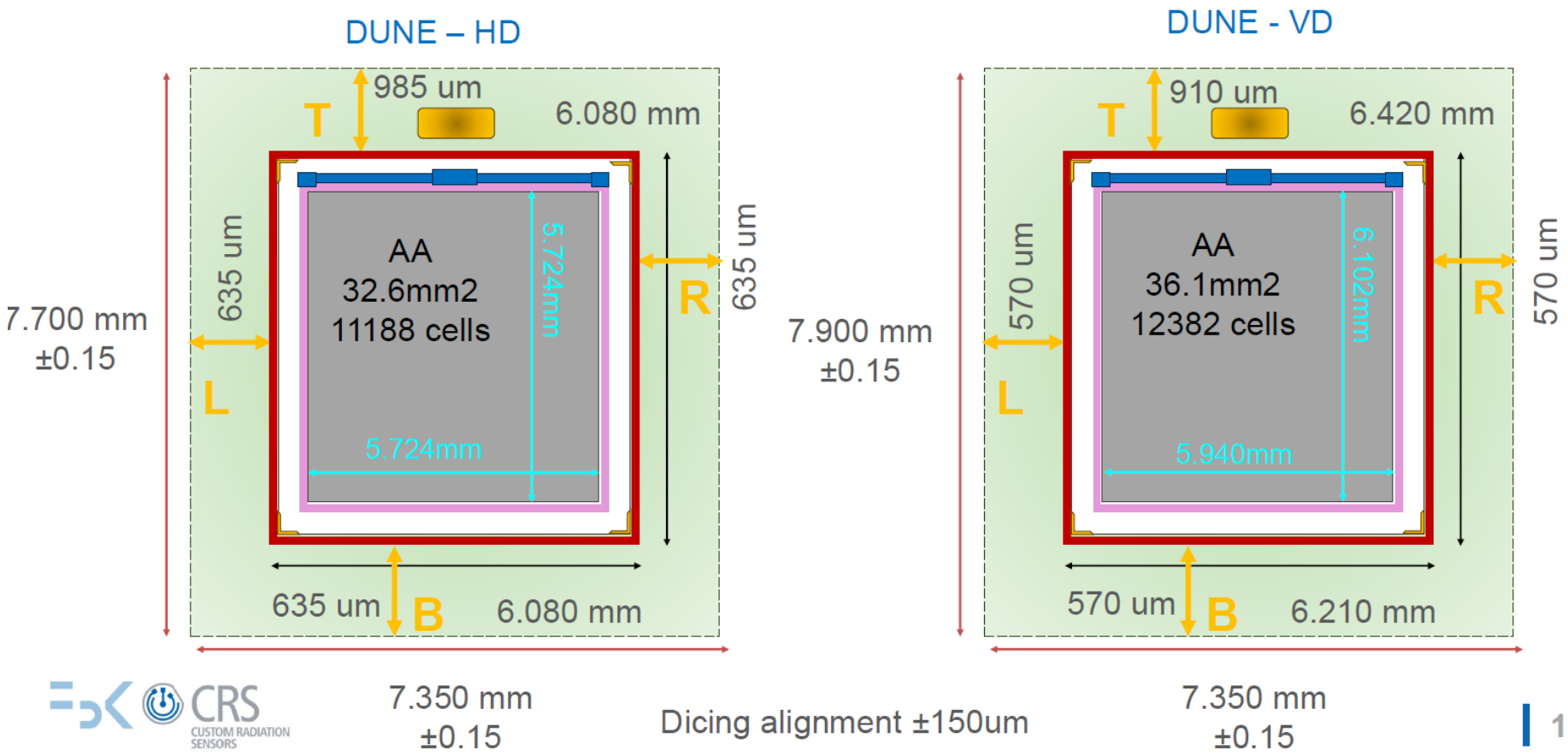
Only two changes occurred in the design with respect to FDR

- Flexi board: in the past, the SiPM production, flexi production and population were carried out by three different companies. Now the process is performed by each vendor separately (but using the same Cirexx flexi boards)
- SiPM: we requested FBK to increase by 10% the SiPM active area because the use of a double-pixel-ring-guard reduced this are by 10% with respect to the original specification

These changes were validated in 2024:

- the FBK membrane tiles tested in the December coldbox are identical to the ones that will be produced during the tender: **no issue encountered**
- The HPK membrane tiles tested in the December coldbox are identical to the ones that will be produced during the tender: **no issue encountered**

FBK: active area layout



Additional tests

During the construction of the coldbox, one of the HPK flexi showed an anomalous current when installed in the membrane frame. This board was promptly replaced for the test. This was, anyway, surprising because the flex passed both the QC test at the vendor site and the QC test in Milano Bicocca.

We formally asked an investigation to Hamamatsu and returned the board to Japan. We received the investigation report in December, where it was demonstrated that one of the SiPM border was accidentally damaged during the installation in the membrane tile and the accident is not due to the flexi quality/production

Concerning, the 10% active area increase of FBK, this was visually validated at the microscope but we don’t have enough sensitivity to check if there is a corresponding increase of the dark count rate by 10% because our measurements have a typical 50-100% precision. Data taken in Milano Bicocca and FBK are consistent with this statement and we did not observe any additional change in correlated noise

Actions at the tender stage

Invitation will be sent to FBK and HPK after the PRR. The vendors need to

- Produce a sample of 10 flexi plus 12 “single” SiPM
- confirm the mechanical specification detailed in the flexi executive drawings
- provide the location of the datamatrix that uniquely identify the flexi board

INFN will then validate the final product by:

- perform the full QC test for the flexi (see below)
- perform the full FD1-HD QC test for the “single” SiPM
- if products are in spec, we will sign the contract and commence mass production

Note: Why are we asking also “single SiPM”? Hybrid ganging prevent us from testing each SiPM individually. We thus need to have single SiPMs from the same production lot to ensure that the SiPM parameters (V_{bk}, DCR, cross-talk) are the same as in FD1.

Procurement plan

After the signature of the contract, we expect each vendor to complete the production in about 8 months with 2 months of contingency. Assuming first delivery in May 2025, we expect:

Date	HPK	FBK
5/25	480	210
6/25	480	210
7/25	480	210
8/25	480	210
9/25	480	210
10/25	480	210
11/25	480	210
12/25	480	210
1/26	60 + cont.	20 + cont
2/26	cont.	Cont

QC strategy

The QC strategy reaps the experience gained in FD1. In particular,

- The average failure rate of a single SiPM in FD1 was 0.3%. Therefore, a defective board or flexi is an exceptional occurrence. Replacing an entire flexi due to a single defective SiPM is feasible, and all vendors are willing to replace whole units even if the issue is caused by just one faulty SiPM.
- All defective SiPMs in the FD1-HD mass production showed a large Dark Count Rate **fully correlated** with a large reverse current at a higher-than nominal overvoltage.

In spite of the fact that hybrid ganging does not allow single SiPM tests, we are confident that QC at flexi level can spot any defective SiPM by:

- Perform the three standard thermal cycles as in FD1-HD (**cryogenic resilience**)
- Illumination of each SiPM separately at room temperature to observe the change of voltage between anode and cathode (**SiPM disconnected**)
- Perform I-V curve in reverse to measure V_bk for the entire flexi
- Perform **"extended" I-V curve** in reverse to spot noisy SiPM

QC at the vendor site

As for FD1-HD, each flexi will come with a “room temperature” datasheet showing:

- the breakdown voltage at 300 K for each SiPM
- the position of the SiPM in the flexi
- the current of each SiPM at nominal overvoltage

Each flexi has a silkscreen QR code with a unique identifier that will be recorded in the DUNE part database.

Each flexi has a 3-year guarantee: a defective flexi will be replaced by the vendor at any time during the warranty period

QC at the DUNE labs: CACTUS-VD

QC at cryogenic temperature (77 K) will be performed by the CACTUS-VD facility. It

- Reads out the QR code of the flexi and store it in the local database
- Perform the thermal cycles with the temperature gradient employed for FD1-HD (DUNE cooling protocol – see the documentation of the FD1-HD SiPM PRR)
- Acquire and analyze the standard and extended I-V curves in reverse.
- Offer permanent storage of selected raw data and populate the DUNE part database with high-level information for each part (SiPM flexi board).

CACTUS-VD (as CACTUS) will be equipped with the software tools to populate the DUNE part database with the flexi ID, Vbk at 77 K, and I-V curve in reverse at 77 K.

What is CACTUS-VD?

it is a test facility very similar to CACTUS (FD1-HD). It is made of

- a Dewar that hosts 30 flexi board per run [ARPEGE75 (ARPEGE75N-L-103, 72 liters)]. A moving system driven by Labview
- A dark cabin that host the entire system equipped with illuminating LEDs
- A cold board hosting the 30 flexi. Design completed. Procurement in progress
- Two warm boards reading the current from 15x2 flexi. Each channel is read by a FE board developed for CACTUS and modified to match the dynamic range of the flexi boards
- DAQ and analysis software inherited from CACTUS

Commissioning is planned in April 2025

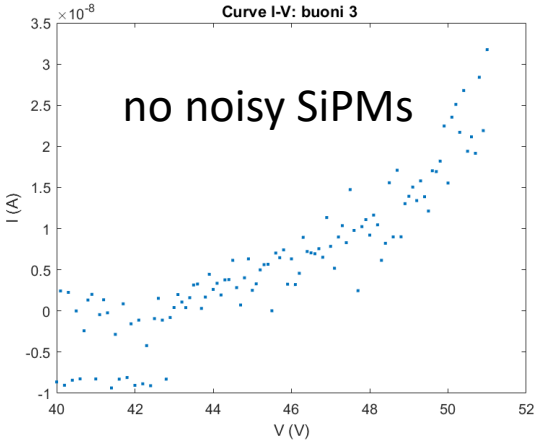
CACTUS-VD operating sequence

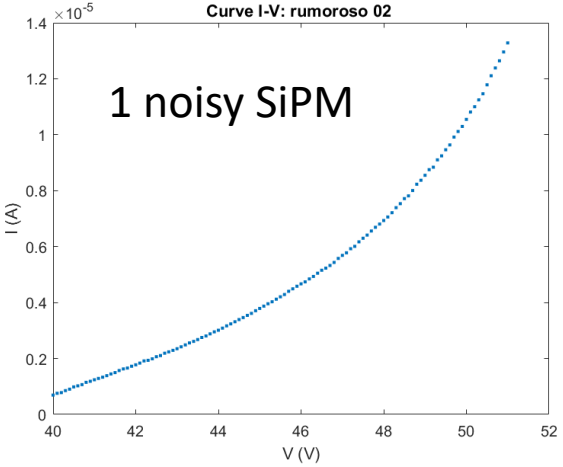
1. **Visual Inspection**
   - Flexi boards are delivered in trays designed to match the capacity of the CACTUS-VD system (30 flexi per tray).
   - Trays are transported inside antistatic ESD bags, which are opened only at the beginning of the QC process.
   - The operator inspects the integrity of the ESD bag and selects the tray for testing following the ESD countermeasures outlined in Section 4.
   - The mechanical integrity of the tray is checked as part of this step.
2. **Disconnection Test at Room Temperature**
   - The operator scans the QR code of each flexi board in the tray using the CACTUS barcode readout system, which populates the local CACTUS database.
   - Disconnection tests are performed for all flexi boards in the tray.
3. **Room temperature and Cryogenic Testing (77 K)**
   - The 30 flexi boards are mounted on the CACTUS-VD cold board. A standard I-V curve in reverse is acquired at room temperature.
   - The cold board and the 30 flexi are cooled down to 77 K using the FD1-HD CACTUS cooling protocol.
   - A standard reverse I-V curve is acquired at 77 K for each flexi and recorded in the local CACTUS database.
4. **Thermal Cycling**
   - Two additional thermal cycles are performed. During the third cycle:
     - Both the standard I-V curve and the extended I-V curve are acquired.
     - Data is recorded in the local CACTUS database.
5. **Post-Test Inspection**
   - After the third cycle, the flexi boards are warmed to room temperature and detached from the cold board.
   - The operator performs a disconnection test and visually inspects each flexi board for any damage sustained during the thermal cycles.
6. **Defective Flexi Handling**
   - Defective flexi boards are labeled and set aside for return to the vendor for replacement.
   - The data for both the standard and extended reverse I-V curves is permanently uploaded from the CACTUS local database to the DUNE part database.

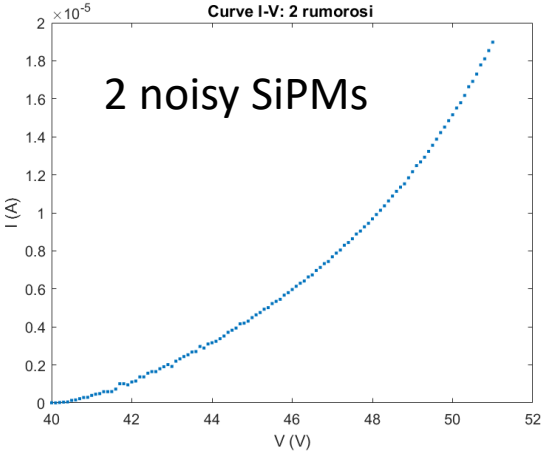
Are we sure that CACTUS-VD can spot defective SiPM?

We tested the CACTUS-VD protocol in 2024 by

- Selecting FD1-HD boards showing 1 defective SiPM
- Building “fake” flexi boards where these SiPMs were arranged in hybrid ganging mode
- Check that the defective SiPM appears as an anomaly in the “extended” I-V curve (reverse)







Throughput

CACTUS-VD tests 30 flexi per “shift”, including the SiPM handling, disconnection test, and data analysis. The shift duration is estimated to be 5 hours. The throughput is 660 flexi per month in 1 shift mode

As a consequence a single facility located in Milano Statale can perform the test without delaying the SiPM delivery and we can run in 2-shift if needed

Date	HPK	FBK	CACTUS-VD
5/25	480	210	660
6/25	480	210	660
7/25	480	210	660
8/25	480	210	660
9/25	480	210	660
10/25	480	210	660
11/25	480	210	660
12/25	480	210	660
1/26	60 + cont.	20 + cont	660
2/26	cont.	Cont	340

Charge and documentation

Charge	Answer
Has the consortium responded appropriately to the relevant recommendations from past design reviews and are they closed?	No recommendation from FDR. One recommendation from the FD1-HD SiPM PRR (ESD) addressed both in CACTUS and CACTUS-VD
Are there any further relevant reviewer comments and recommendations based on design changes implemented since the FDR?	We validated the flexi entirely produced by the vendors and the 10% increase of the FBK active area
Has the current design been validated sufficiently to give confidence that the components to be procured are the correct ones?	Yes based on the fact that the SiPM are identical to FD1-HD and minor changes were validated in the coldbox

Charge and documentation

Charge	Answer
Is there a credible plan in place for how the components will be procured? Are the required quantities including spares well understood?	Tender documentation is in place. The vendor have already been selected and pre-validated. Quantities and spares are well understood and funds were assigned accordingly
Have the appropriate QA/QC requirements been defined to flow down in the procurement documents to the supplier	Yes. For additional details not covered in this presentation see the qc document
Is there a credible plan for how the components will be shipped, handled and stored upon receipt?	Shipping, handling and storage follows the same procedures as FD1-HD (see qc document)
Is an effective QC plan for acceptance testing in place in order to ensure the parts received meet specifications?	It is based on QC at the vendor site for room temperature characterization and CACTUS-VD for cryogenic characterization