SiPMs for FD2-VD

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The SiPMs for FD2-VD

Basic requirements identical to FD1-HD:

- Cryoreliability [protocol defined for FD1-HD – see PRR documentation]
- DCR< 200 mHz/mm^2 [negligible with respect to radiogenic background]
- Cross talk: <25% at nominal overvoltage
- RMS V_{bkd} <200 mV in (at least) a group of 160 SiPM ("grouping")
- S/N>4 in ganging mode (see D.Christian's talk)

This is an asset because extensive R&D, tests, and preproduction were carried out for the FD1-HD SiPM in 2020-2022. Production Readiness Review passed on Dec 2022. The mass production is ongoing (first lot delivered and tested in April 2023)

Quantities:

- 160 SiPMs per tile in 20 SiPM flexi boards
- Total: 5900 flexi boards (including 9% spares), 118,000 SiPMs (i.e. 1/3 of the SiPMs purchased for FD1-HD)

QA/QC:

- Tests at the level of flexi boards
- Sample tests before installation in the boards to monitor production lots

Achievements for FD1-HD

In 2019-2021, DUNE carried out an R&D in collaboration with two vendors (Fondazione Bruno Kessler – FBK – and Hamamatsu Photonics - HPK) to develop **custom cryogenic SiPMs**

- Prototype downselection completed in 2021: NUV-HD-Cryo Triple Trench from FBK and S16517 from HPK are within specs and will be installed in FD1-HD (and FD2-VD!)
- Full test and production chain validated in 2022 for ProtoDUNE-HD. 40 modules (about 50%-50% per vendor)
- Mass test facility (“CACTUS”) commissioned and tested during the construction of ProtoDUNE-HD
- Production Readiness Review passed on Dec 2022

We needed to demonstrate only a few items for FD2-VD

Are both sensors OK for the FD2-VD hybrid ganging? (see previous talks)

Are the CSP appropriate for populating the flexi boards?

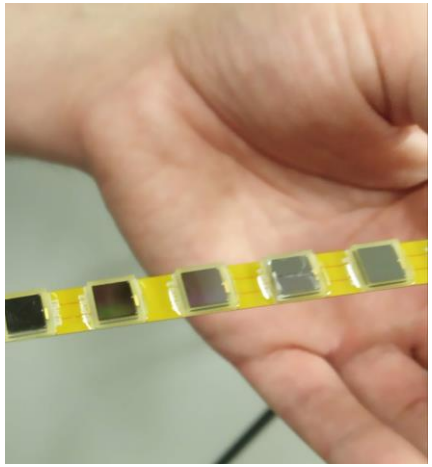
Do they require a special QA/QC procedure?

SiPM reliability in flexi boards

The reliability of the production chain from the silicon wafer to CSP is not an issue because it was validated for FD1-HD. However, the board population procedure had to be re-designed because the HD SiPM boards are rigid and based on a G10 layer, while the Kapton-based VD boards are flexible

Hamamatsu (HPK): SiPMs were mounted (soldering) in the flexi boards in the R&D phase of FD2-VD (2021) and tested in a standalone setup in Milano Bicocca

FBK: SiPM are die-attached to the boards using the same conductive glue as in FD1-HD. Since the flexi boards can be bent during assembly, we needed to find the optimal thickness of the epoxy resin between the SiPMs. This layer guarantees that the SiPMs does not detach when the board is bent. The deposition was optimized in spring 2022 and tested during the ProtoDUNE-VD production



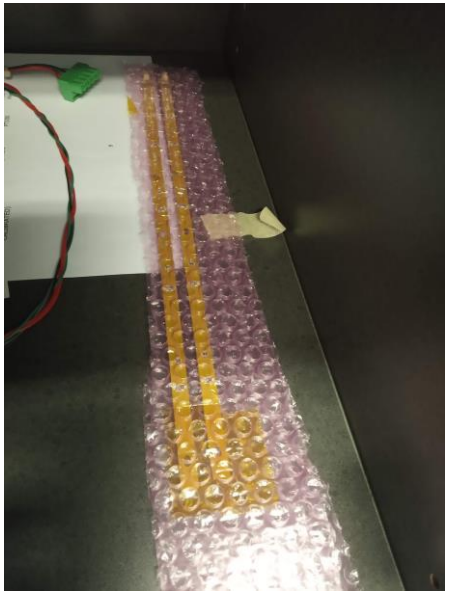
The ProtoDUNE-VD preproduction

All ProtoDUNE-VD tiles are equipped with SiPMs belonging to FD1-HD. We placed both HPK and FBK SiPMs in the cathode and in the membrane. Since the SiPMs have different breakdown voltage (FBK is smaller), we have two flavors of the DC/DC converter.

The flexi boards were produced by Cirexx. SiPM population were carried out by FBK for the FBK boards using the optimized die-attach + epoxy layer procedure and by SCEN (Trieste, Italy) for HPK.

After installation of the SiPMs in the flexi boards, we tested them in CIEMAT (Madrid) and Milano Bicocca (INFN) using the same protocol we will be using for the FD2-VD mass production

We observed only one failure in one FBK flexi board due to a short in a SiPM attach after a thermal cycle. We spotted it by measuring the I-V curve at 77 K. FBK replaced the board within one week.



Tuning QA/QC for FD2-VD

In FD1-HD, the boards are rigid and the number of SiPMs per boards is just 6. In addition, the boards have pins that allow for testing each SiPM separately. We adopted this conservative solutions (which has mechanical drawbacks in mounting) because we didn't have large statistics data on the failure rate. Such a conservative approach is not possible for FD2-VD:

- The boards are flexible and the SiPMs are hybrid-ganged. We cannot test the SiPMs separately
- Due to hybrid ganging, we cannot measure the current in forward mode
- We can measure the I-V curve in reverse mode and, therefore we can estimate the weighted breakdown voltage before connecting the board to the PoF+DCEM (cathode) or DMEM (membrane)

Can we deliver a QA/QC procedure to spot single-SiPM failures and monitor the quality of each production lot during mass production?

Expected failure rate

The measured failure rate in ProtoDUNE-HD is 0.08%. We know it because we had failures in a few boards and we were able to identify the SiPM (only 1 per board!) that was responsible for it. We also know the cause of the failure but – conservatively – we are assuming that no further improvements are possible.

For FD2 PDS, we will only be able to test SiPMs in groups of 20 except for small samples (see below) and, therefore, we will request the vendor to replace the entire flexi board in case of failure of the QC test points of the SiPM flex boards. It implies a “waste” of 0.08%*20= 1.6% of the SiPMs that will be covered by the 1-year guarantee from the vendor (same contract type of FD1-HD)

The vendors have shown that they can fulfill the grouping spec for >192 SiPMs (1 FD1-HD module). We can test this claim indirectly by measuring the weighted V_{bkd} in group of 20 and - directly - by measuring a subsample of SiPMs before the board population

QA/QC protocol (I)

Validation of the production process. At the beginning of the mass production, each vendor is requested to provide a “pre-production” lot to guarantee that the products fulfill the DUNE specifications. Each SiPM of the pre-production lot will be extensively tested for cross-talk, after-pulse, gain, high-precision DCR to ensure compliance with the DUNE specifications. Further, the SiPM will be installed by the vendors on the flexi boards and we will perform QA tests on the boards to ensure compliance with the results obtained at CERN Cold Box and ProtoDUNE-VD. **The measurements of the “pre-production” samples represent the QC test point of the production process.**

Facility: the test of each SiPM of the pre-production lot is done before the installation in the flexi boards and the same SiPMs are tested (in group of 20) after the installation of the board [see below]

To be defined: size of the pre-production lot (FD1-HD: 720 SiPMs)
Company in charge of populating the HPK board (HPK or SCEN?)

QA/QC protocol (II)

Validation of the production lots

Once the mass production is commenced, compliance with specifications that monitor deviation from the pre-production performance will be carried out by testing the flexi boards in Milano Bicocca and Valencia to match the production rate of the vendors (up to 500 SiPM flex boards per month - a “production lot”).

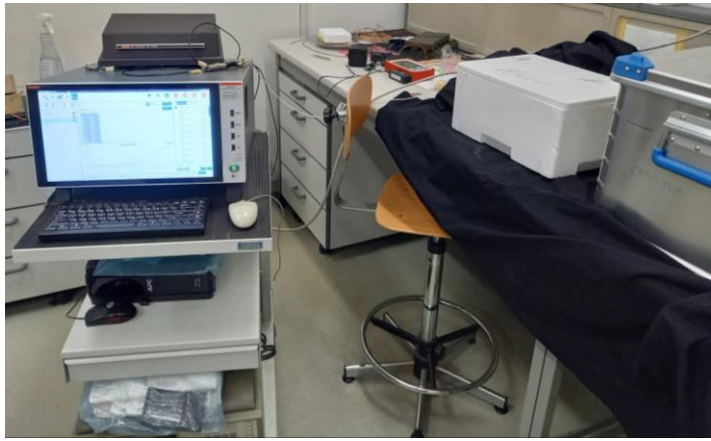
Facility: a modified version of the CACTUS facility (FD1-HD) + the same facility used for the single SiPM tests in the pre-production phase

To be defined in view of PRR: do we want to tests SiPMs prior to board population even during the production phase? At present, we are assuming the same quantity of FD1-HD, i.e. 5% of the SiPMs of each lot will be tested prior to installation to the boards [quite conservative and pretty cumbersome for what concerns logistics]

QA/QC protocol (III)

The test protocol for the boards consist of:

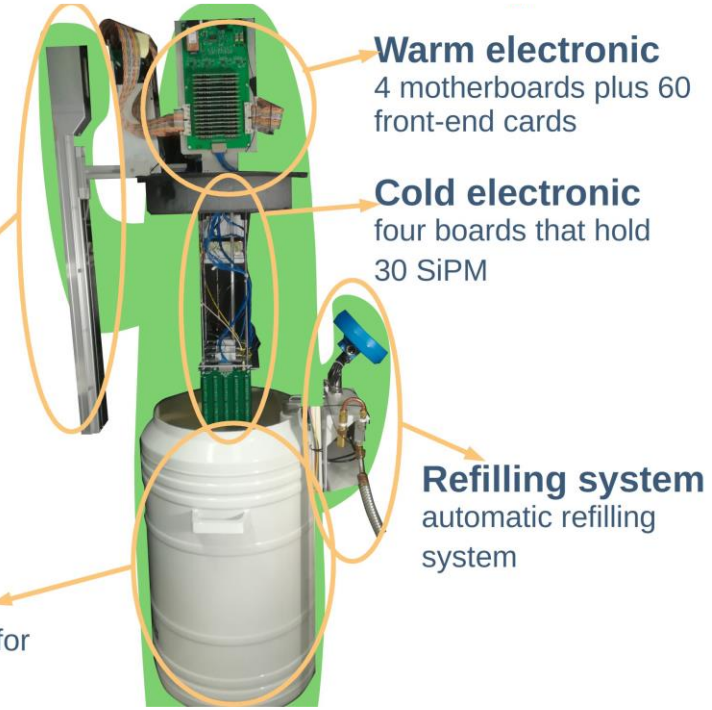
a) Measurement of I-V curve at room temperature
b) Measurement of I-V curve at the first and third thermal cycle at 77 K
    a) Determination of V_{bk}
    b) Identification of anomalous currents at V_{op}
c) Check of disconnected SiPM after the third thermal cycle by illuminating each SiPM with a LED and masking all other SiPMs

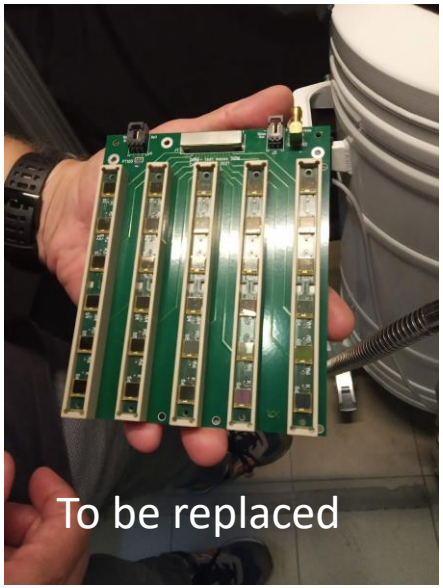


The test protocol for the single SiPMs (sample test prior to installation onto the boards) is the same as for FD1-HD (see PRR documentation)

Facilities (I): CACTUS@VD

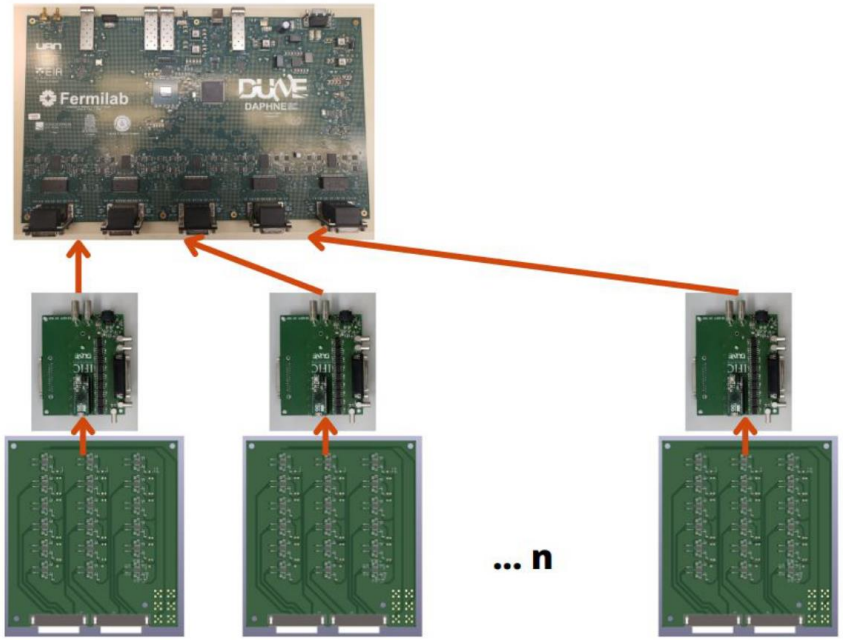
Features:
- Modularity;
- Automatic;
- Easy replication;

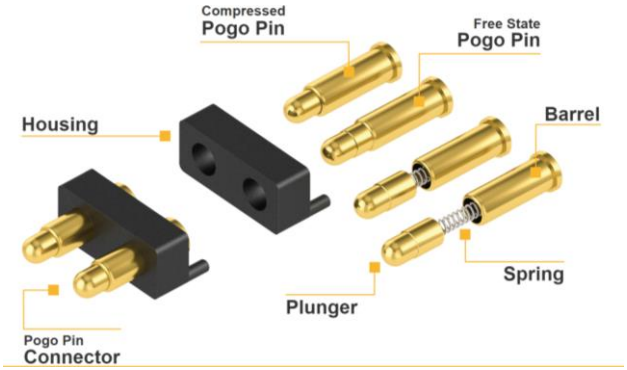




- We need to modify the cold boards of CACTUS to host the flexi boards
- We want to check dead SiPMs (open circuit) by illuminating each SiPM with a LED movable LED and measuring the current at reverse bias. For ProtoDUNE-VD we performed this test at room temperature after three thermal cycles. We may modify CACTUS to do the same at 77 K, if needed.

Facilities (II)





MASSIBO (Valencia): it measures Dark Count Rate, cross-talk, after pulse, V_{bkd} and $R_{quenching}$ for each SiPM with a multiplexer connected to a picoammeter. We need to modify the cold board to host the SiPMs and bias them through pogo-pins (i.e. spring-loaded pins). The reliability of the pogo pin solutions was already checked for FD1-HD in Prague in 2021 (but was needed in FD1-HD due to the decision to install pins in the G4 boards)

Procurement

Procurement is under the responsibility of Italy (INFN), Spain and Czech Republic and funds are already allocated. We will employ the same two-vendor scheme as in FD1-HD (50% FBK, 50% HPK)

Production lots are delivered every months and corresponds to 500 SiPM boards (10,000 SiPMs per month). The mass test facilities (CACTUS@VD) will be in Italy and Spain plus the MASSIBO facility in Valencia

Expected lead time after the contract signature: 4+12 months. Acceptance tests performed in parallel.

The T_0 depends on the date of the PRR and the outcome of the tender. In FD1-HD we needed four months between PRR and the signature of the contract.

Conclusions

- The production and test of the SIPMs for FD2-VD is less critical than FD1-HD because it inherits most of the experience gained in HD and no additional R&D was needed
- We needed some optimization work in 2021-2022 to demonstrate that:
  - The SiPMs used for HD fulfil the VD specifications when operated in hybrid ganging mode
  - The SiPM CSP can be safely installed in the flexi boards
- QA/QC was defined using the same strategy of FD1 but we cannot measure each SiPM separately after the installation in the board. Hence:
  - QC of the production process done before and after the installation in the boards using a pre-production sample
  - QC of the SiPM boards done by CACTUS-VD
  - QC of the lot quality (10,000 SIPMs/lot) done before installation in a sample (SiPM taken from all different wafers used in the lot)
- Expected failure rate (0.08% at the SiPM level) is reassuring