Production Readiness Review of the FD1-HD SiPMs

PRR meeting

Nov 29, 2022

Francesco Terranova on behalf of the PDS Consortium
Univ. of Milano-Bicocca and INFN

Goals of this review

- The DUNE APAs and the SiPMs for the FD1-HD Photon detection system are **the most advanced items** in the construction of DUNE
- In both cases, such an advancement occurred in response to funding opportunities and the corresponding spending constraints

Goal of 2021-2022: reach maturity at Production Readiness level to commence mass production. A challenge we believe we have successfully addressed:

- ✓ [Identification of requirements and a dedicated R&D with vendors]
- ✓ Outcome of the R&D and down-selection
- ✓ Test of the down-selected samples in moderate-size batches
- ✓ Test of the samples in realistic conditions ("integration")
- ✓ Production of "module-0" SiPMs (ProtoDUNE-SP Run II aka "ProtoDUNE-HD")
- ✓ Final drawings, specification and contracts
- ✓ QA in the mass production phase

Overview of the documents

Item	Document	PRR charge
Outcome of R&D and downselection	Downselection.pdf	Item 4
Test of the downselected samples in moderate size batches	Downselection.pdf	Item 4
Test of these samples in realistic conditions	Integration.pdf	Item 5
Production of module-0 SiPMs	QA-QC-SiPM.pdf Sec.2	Item 5 and 7
Executive drawings, specs and contract	5 documents + procurement-pdf	Item 2 and 3
QA during mass production	QA-QC-SiPM.pdf	Item 7

Outcome of the previous review

6.2 Comments

- There is still some work to be done for finalizing and validating the packaging.
- The basic specifications are quite loose on some aspects and it might be that some binning is necessary to group devices with similar gain and break-down voltage (as there is a single biasing for up to 48 SiPMs). Using devices from the same wafer might be enough but this is not yet known and the binning process is to be fully defined (who will do it, following which procedure, etc.).
- In view of the remaining work for selecting the SiPM variants, finalizing the packaging and checking the ganging before going to production, the schedule for being ready for protoDUNE-2 is very tight.

6.3 Recommendations

R10. The criteria for selecting one SiPM variant from each supplier are to be defined.
R11. The validation procedure of the packaging must be defined.
R12. The binning need is to be assessed as soon as possible and the binning procedure defined.

I devote the **rest of my talk** to

- Summarize the main results of such an effort
- Address Item 1 of the charge document(*) and, in particular, answer previous recommendations

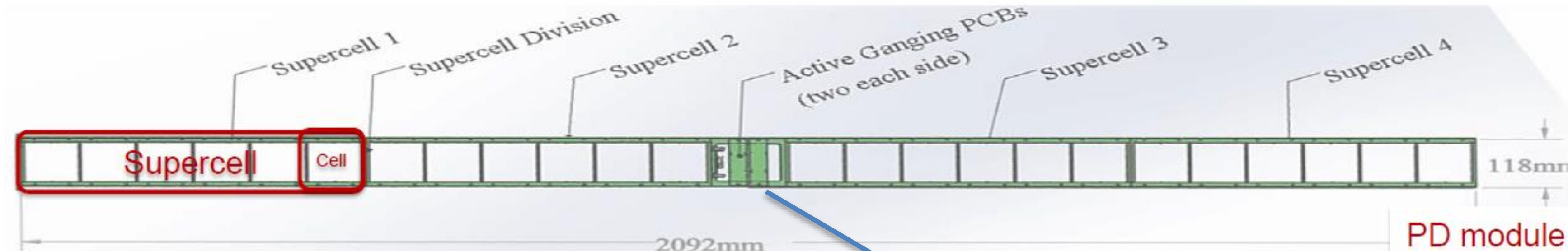
(*) The SiPM specifications, how design choices satisfy the requirements, and whether recommendations from previous reviews have been appropriately addressed

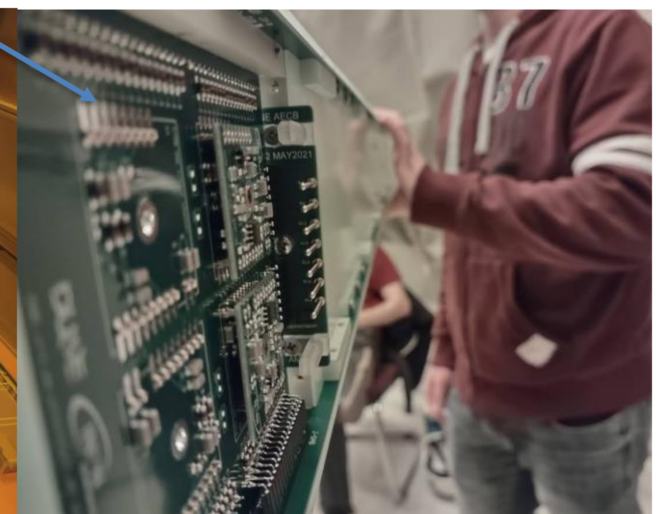
- ○ Definition of the validation procedure of the packaging
- ○ The binning need assessment and the binning procedure definition (if required)

Layout: PDS module

The PDS module is the basic unit for light detection in FD1-HD. It is located inside the APA and comprises four standalone electronic channels (“supercell”)

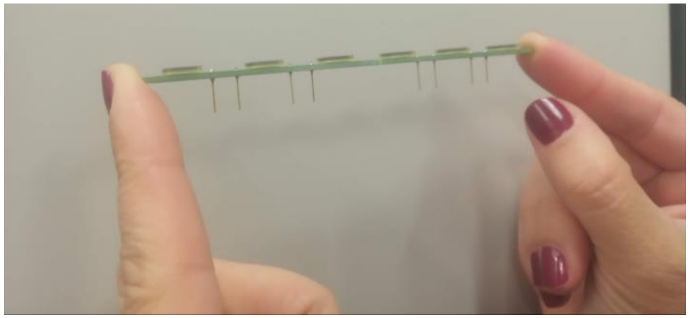
Each supercell is a standalone X-ARAPUCA with dichroic filters, 8 SiPM boards (48 SiPMs) a WLS bar and a cryogenic amplifier

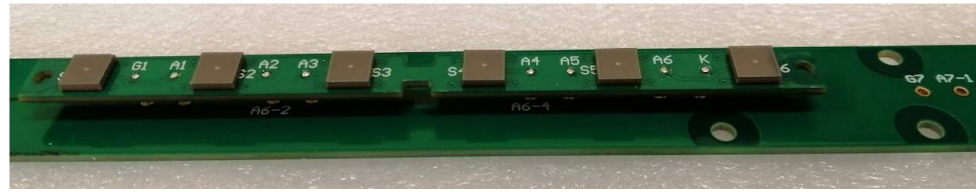


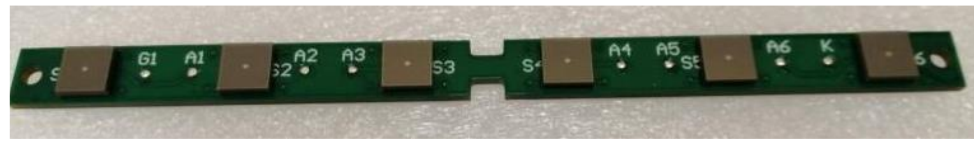


Layout: SiPM board

Each supercell is a standalone X-ARAPUCA with dichroic filters, 8 **SiPM boards** (48 SiPMs) a WLS bar and a cryogenic amplifier







For Quality Assurance, the basic unit (unique ID part) is the SiPM board. It has

- Pins to test and connect each SiPM
- A unique identifier printed as a DataMatrix
- In the DUNE Hardware database is associated with a set of measurements
  - I-V curve in forward and reverse at 300 K
  - I-V curve in forward and reverse at 1st and 3rd thermal cycle at 77 K
  - DCR
  - (for 5% of the sample) full characterization of each SiPM (gain, xtalk afterpulse)

See Executive drawings in EDMS + QA document and database document

DUNE

Challenges and specs

- Size of the production (1 DUNE Module): **288,000 SiPMs**, 192 SiPMs per module, 6000 supercells (i.e. channels) in 150 APAs. **10.4 m^2 of total surface**.
- Cryo-reliability for an unprecedented duration of data taking

High level specs	Value
Dynamic range	1-2000 p.e.
S/N>4	Per supercell (48 SiPMs)
Trigger	1.5 p.e.

The aim of the R&D was to define a set of **low-level specs** that fulfill the high level requirements and are sustainable from the vendors in view of the mass production. In particular:

- What is the maximum cell size that can be ported to a foundry in a reasonable timescale (1 y to match the DUNE schedule)?
- What is the safest packaging that can be ported to 300,000 SiPMs?
- What are the optimal electric parameter that match the PDS cold electronics?

(see A. Verdugo's talk)

Custom products

- Hamamatsu: **world leader** in room temperature SiPMs (MPPC) and major experience in HEP experiment (including neutrinos: T2K-ND280)

  Main weak points for DUNE: DCR relatively high at 87 K and large amplitude of afterpulses due to a too small recovery time

- FBK: legally a research center for applied technology. Signed an agreement that allows FBK to act as a **pure vendor**: the standard production process (design and prototyping in FBK, technology transfer in Lfoundry, and packaging) will be handled internally and the only legal provider of DUNE is FBK. Major experience in cryogenic SiPM (DarkSide) and HEP application (MEG-II, CTA)

  Main weak points for DUNE: polysilicon resistor resulting in shorter peak amplitude (but same integral). Packaging less tested than HPK and larger cross-talk

Implementation of custom SiPMs

Aim: ProtoDUNE-SP Run II (= «pre-production»)

- Test 6 types of SiPMs 6x6 mm^2 developed **specifically for DUNE.** We call them «splits»: 4 from Hamamatsu (HPK) and 2 from FBK
- **25 SiPMs per type** fully characterized at single SiPM level
- **250 SiPMs per type** per in the DUNE SiPM board and tested at single SiPM level (sample) and in ganging
- **4000 SiPMs** FBK and **4000 SiPMs** Hamamatsu for the Run II of ProtoDUNE

In parallel:

- Design the **cold amplifier**, the **SiPM board** and the signal lead board
- Test the X-ARAPUCA with the new photosensors

The four HPK spilts:

- All splits will be based on the **S13360 chip** (Vbk = 50 V at 300 K), terminal capacitance 1.28 nF per sensor, 61.4 nF per 48 sensors.
- All splits will be based on the **HWB technology** because is safer at cryogenic temperature and, if it fails, produces open circuits and not shorts (unlike TSV) [dedicated study by HPK]
- Packaging: we asked HPK to perform a thermo-mecanical study on epoxy versus silicon resin [dedicated study by HPK]. Results indicate that silicon resin is slightly better. We chose **silicon resin**.
- Cell pitch: **50 and 75 μm.** (14331 and 6364 cells per SiPM)
- Quenching resistance:
  HQR (77K) ≈ 4 LQR (300 K).

Vendor	Split	Cell pitch	τ at 87 K
FBK	Standard	30 μm	400 ns
FBK	Triple Trench	50 μm	400 ns
HPK	6050HS-LRQ	50 μm	30 ns
HPK	6075HS-LRQ	75 μm	63.5 ns
HPK	6050HS-HRQ	50 μm	117 ns
HPK	6075HS-LRQ	75 μm	254 ns

Table 1: The DUNE pre-production splits

The two FBK splits

Vendor	Split	Cell pitch	τ at 87 K
FBK	Standard	30 μm	400 ns
FBK	Triple Trench	50 μm	400 ns
HPK	6050HS-LRQ	50 μm	30 ns
HPK	6075HS-LRQ	75 μm	63.5 ns
HPK	6050HS-HRQ	50 μm	117 ns
HPK	6075HS-LRQ	75 μm	254 ns

Table 1: The DUNE pre-production splits

NUV-HD-Cryo in SMD package and wire bond: well established technology thanks to DarkSide

«Triple trench» to reduce correlated noise. Validated during the R&D

Packaging: epoxy was the only safe option – and passed all our tests. Doubts on soldering vs die attach. Die attach was cleary superior because soldering may be performed with a lengthy procedure only to avoid damage of CSP. This solution was fully validated in 2021-22.

R10: downselection criteria

See talk by A. Verdugo

1) fulfillment of all low-level specs. The output is binary (true/false) and prototypes not fulfilling these specs are rejected
2) best performance in cross-talk, after pulse and DCR at 77 K. The output is a figure of merit (FoM) given by the product of correlated noise (cross-talk+after pulse) times the DCR divided by the gain. The down-selected sensor is the sensor with minimum FoM among the prototypes retained after 1)

We include the signal-to-noise as a binary criteria: are the SiPMs (48 SiPM in ganging) giving S/N>4 yes/no. We did not include S/N in the FoM because it depends on the fine-tuning of the cold electronics

It was a wide choice: all split had S/N>4. The downselected SiPM from HPK had a slighter worse S/N that anothe split (at 50 µm) but the final results with the final electronics improved the results well beyond the requirements.

JINST
Published by IOP Publishing for Sissa Medialab
Received: July 27, 2022
Revised: September 27, 2022
Accepted: October 26, 2022
Published: November 14, 2022

Cryogenic front-end amplifier design for large SiPM arrays in the DUNE FD1-HD photon detection system

R11: packaging

Packaging has never been a major issue but we needed a large scale validation!

2021: packaging was studied on vendor's premises to address the items mentioned above:

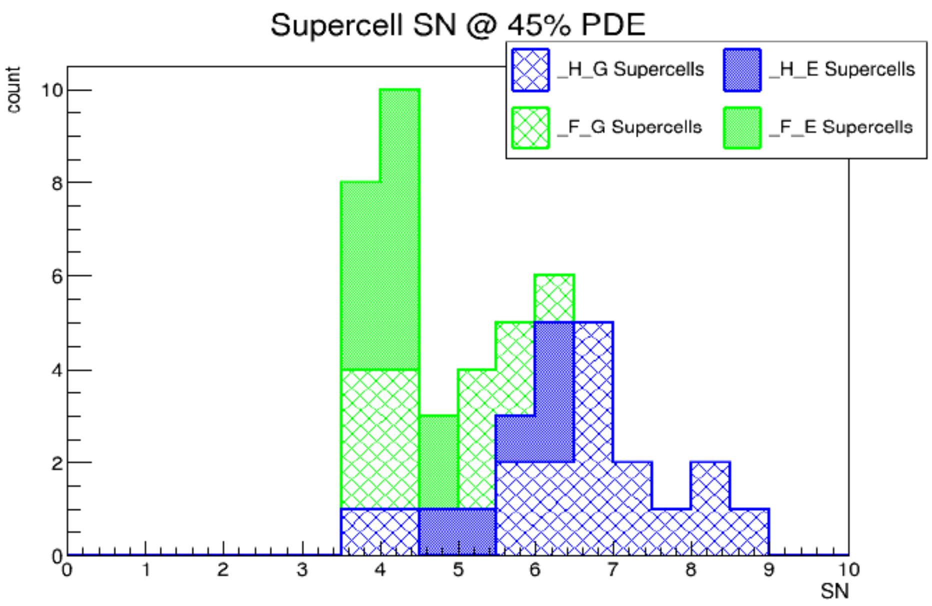
- HPK: thermomecanical studies of epoxy versus silicon indicate silicon as the favorite option, also accounting for the huge experience of HPK in commercializing silicone sensors for crygenic applications
- FBK: epoxy was the only safe option because silicone is a technology not exploited by FBK at large-scale/commercial level. In 2021, FBK performed a dedicated R&D with the packaging subcontractor to validate the attaching method of the CSP in boards. Die attach was find to be the best choice

2021-2022: DUNE test the packaging option suggested by the vendor with 4000 SiPMs per vendor. Thermal cycles and change of electrical properties after 20 "standard" thermal cycles + 2 months of data taking. No failure reported. Detachment/weakening of SiPMs were observed **already at the first thermal cycle for <0.2% of the SiPM. A failure rate that is considered acceptable by vendors, who promptly replaced the defective boards**

R12: grouping

HPK is able to produce SiPM with a V_{bk} maximum variation of 2 V. FBK shows a variation of 1 V. Hence we requested to group SiPM to reduce the min-max spread to 200 mV. Is it enough?

The answer is “yes. We could even leave without grouping but grouping guarantee a safe engineering margin”. This was evident during the ProtoDUNE-HD production were the last supercells were assembled without grouping due to schedule constraints



Worse case scenario: supercell tests made with ungrouped FBK SiPMs

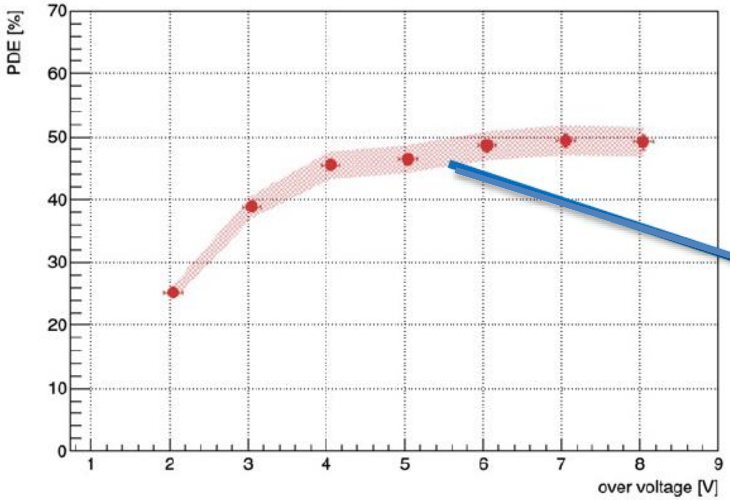
Same results corroborated on simpler configuration (SiPM board test-bench)

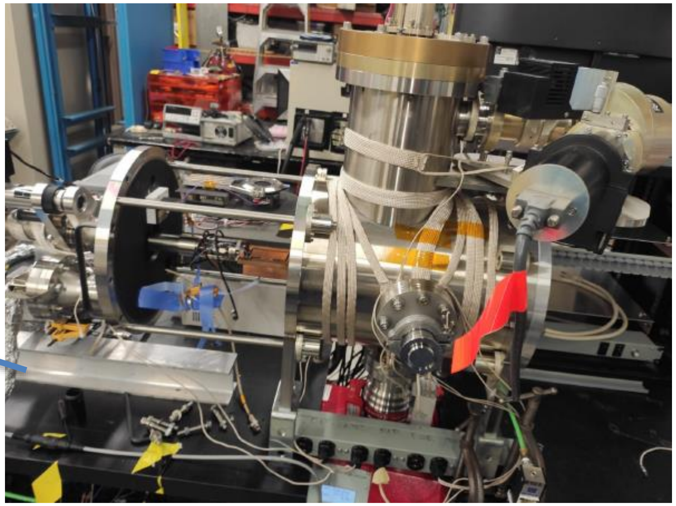
Integration tests and absolute PDE

The SiPM performance (see talk from A. Verdugo and integration.pdf) were validated in more realistic conditions in three campaign:

- 8 boards (48 SiPM) in ganging with cold electronics and 30 m (cold) cable
- SiPM boards in supercells during the production of ProtoDUNE-HD modules
- 5 supercells in liquid argon

Absolute PDE at cryogenic temperature is claimed to be "compatible with PDE at room temperature". We demonstrated it with a dedicated campaign at TRIUMF with FBK sensors. Paper in preparation





Contracts

The procurement of 300,000 SiPMs in their boards will be done through 4 contracts: MCIN-HPK, MCIN-FBK, INFN-FBK, INFN-HPK. Each contract covers about ¼ of the full production.

- Contract specs: they are identical to the low-level specs of ProtoDUNE-HD
- Check of specs before the start of the production: full tests (I-V, thermal cycles, DCR, cross talk, and afterpulse) for 110 boards per vendor
- QA in the production phase (see Procurement.pdf)
  - I-V curves in cold and warm before and after three thermal cycles
  - DCR at cold after three thermal cycles
- Condition for acceptance:
  - For every boards, no damage after 3 thermal cycles, no anomalous currents in I-V curves, no discrepancy in I-V curve at room temperature with respect to vendor data. **Vendor must replace any faulty board within 1 year from delivery**
  - For every "group" (>32 boards) min-max V_{bk} spread <200 mV at 77 K
  - For every lot (500-1000 boards), full test of 5% of the boards performed in Valencia (I-V, DCR, cross talk, after pulse). **Contractor returns the entire lot without additional costs**

Delivery schedule

Delivery is done in lots for a minimum amount of **500 boards per month** (detailed schedule already agreed according to the test rate of the DUNE mass test facilities – see below). HPK starts deliveries on Jan 2023, FBK on Sep 2023.

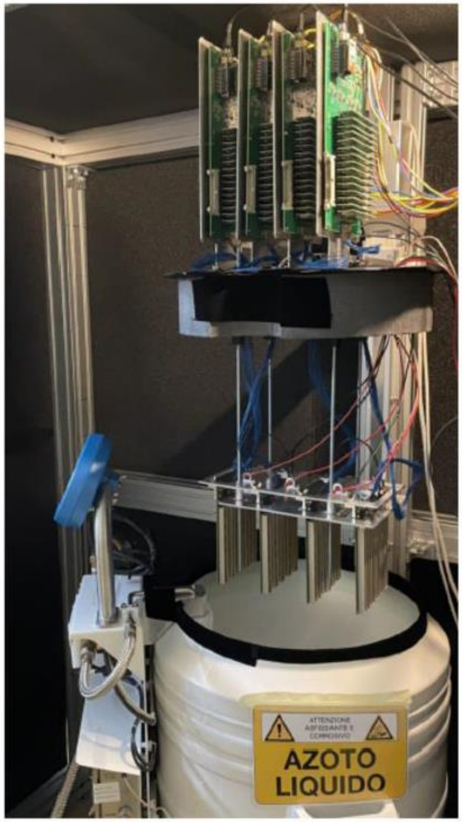
Time (tentative)	Boards per month	Cumulative
15/1/2023	1000	0
15/9/2023	2000	8000
15/1/2024	2500	16000
10/10/2024	Contingency	37500
31/12/2024	Contingency	37500

Completion of procurement: Oct 2024 + 2 month contingency.

Mass test and installation in modules run in parallel. Accepted boards are sent to CSU to be installed in the DUNE PDS modules.

Details in Procurement.pdf

QA/QC



Input data from:

- Five mass test facilities ("CACTUS") with a maximum capacitance of 2000-2500 SiPM boards per month that can be upgraded upt to 4000 boards per month. They perform the SiPM board acceptance tests in Bologna, Ferrara, Granada, Milano Bicocca, and Prague. See M. Pozzato's talk.
- A high precision mass test facility located in Valencia. It performs the full characterization of 5% of the boards for the acceptance of the lot

Output data:

- Accept/reject the board
- Accept reject the lot (Valencia)
- Populate part database of DUNE (HWDB) with
  - Board identifiers
  - I-V curves (main parameter + pdf of curve)
  - DCR measurement
  - High precision measurement (gain, cross talk, afterpulse, DCR) from Valencia

see SiPM Hardware Database and API Description.pdf and QA-QC-Sipm.pdf

Expected failure rate and risk register

Derived from failure rats at ProtoDUNE-HD: 0.4% of boards due to a single SiPM failure (0.07% of SiPMs). It is up to vendors to either replace the board or repair the board replacing the SiPM.

Risk	Likelihood	Mitigation	Effect
Delay in the delivery of the HPK "pre-production" lot[(1)]	Retired for HPK on Nov 2022		
Delay in the delivery of the FBK "pre-production" lot[(1)]	Low	Lot delivered to INFN on Oct 28, 2022. Tests in progress	Delay in the FBK mass production. Estimates in Sec.4 account for a 3-month contingency and further delays of up to 6 months do not affect the schedule
Failure of a fraction of SiPM boards in the QC tests	Medium	Boards are replaced by vendors at no additional cost	Minor delays in the production schedule
Major failure in a production lot	Low	The vendor is requested to adhere to the original production protocol	Delays in the production schedule
Bankrupt or withdrawal from the market of a vendor	Low	Move to a 1-vendor scheme	6-month delay in the production schedule
Test rate of CACTUS lower than expected	Medium	Increase the number of mass test facilities	Increase of cost

References

(item 1) included in the opening talk (F. Terranova) and in procurement.pdf
(item 2 and 3) FBK SiPM boards electrical design **EDMS link**
HPK SiPM boards electrical design **EDMS link**
for reference) grounding reference document **EDMS link**
Commercial datasheet of HPK downselected SiPM datasheet_HPK_S16517.pdf
Commercial datasheet of FBK downselected SiPM Datasheet_SiPM_NUV-HD-Cryo TT.pdf
(item 4) Downselection results document (Downselection.pdf)
(item 5) integration.pdf + Sec.6 of downselection.pdf + Brizzolari_2022_J._Inst._17_P11017
(item 6 and 8) Procurement, contracting, production schedule, costs (procurement.pdf)
Capitolato tecnico (in Italian) (Capitolato_Tecnico_SiPM_DUNE_in_italian.pdf)
(item 7) QA/QC document (QA-QC_SiPM.pdf) + the SiPM Hardware Database and API Description (SiPM Hardware Database and API Description.pdf)