Photosensors, mounting, testing

60% Single Phase Photon Detector Design Review

June 19th 2020

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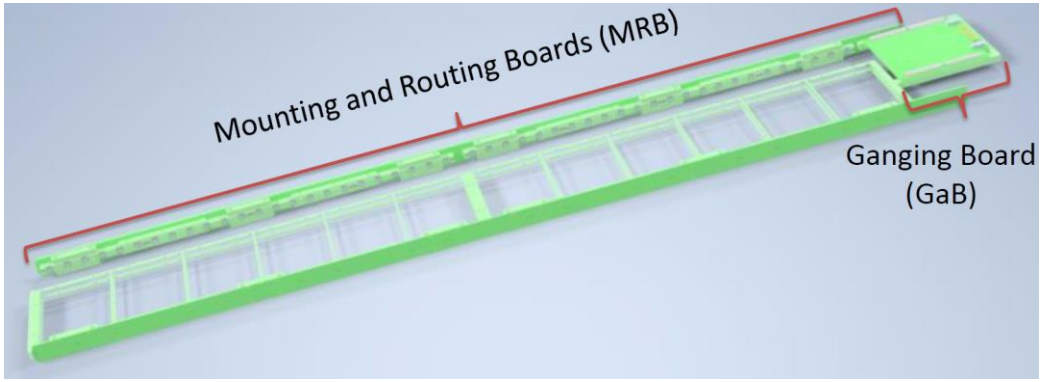
Rationale

Silicon Photomultipliers (SiPM):

- Compactness to be embedded in the X-Arapuca
- High PDE at 430 nm
- Cover uniformly a good fraction of the lateral side of the WLS: flexibility in the choice of the form factor → optimal choice 6x6 mm^2 interspersed along the X-Arapuca
- Can be operated at cryogenic temperature with major advantages in term of dark noise (DCR)
- Can be operated in ganging mode to reduce the electronic channel within the physics requirements of DUNE → optimal choice 48 SiPMs per supercell (1 electronic channel)



Half-module
(2 supercells)

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

Low level specs	Value
Max nominal operating V	[50 V at cold]
Dark count rate (DCR)	<100 mHz/mm^2
Correlated noise	<35% [see Alex's talk]
Time resolution	<1 μs
Thermal cycles	>20
Recovery time	$\tau \approx$ a few μs
PDE at 87 K	>35% at nominal OV
High level specs	**Value**
Dynamic range	1-2000 p.e.
S/N>4	Per supercell (48 SiPMs)
Trigger	1.5 p.e.

General strategy

- **Vendors**: several vendors in the market but **none** provide certification of operation at 87 K and some minor companies cannot afford a production of such size
- Pre-selection: two vendors have agreed to develop custom products for DUNE and test them down to 77 K: **Fondazione Bruno Kessler (FBK)** and **Hamamtsu Photonics (HPK)**
- In July 2019 we defined the protocol for the development of these custom products in the headquarters of FBK - Trento (Italy) - and HPK - Hamamatsu (Japan)
- We want to pursue **a two vendor scheme** because
  - **It mitigate the risk of withdrawal of a vendor** (see the sensL experience in 2018)
  - It is a driver for **cost reduction**
- The two vendor scheme will be tested in **ProtoDUNE-SP Run II:** 2 APA with FBK SiPMs and 2 APA with HPK SiPMs
- If successful, it will be applied in the first DUNE module, as well.

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 (see Claudio's talk)
- Test the X-ARAPUCA with the new photosensors (see below)

Planning and schedule

Careful planning is essential to avoid duplication of efforts, have enough redundancy and match the schedule with safe contingency. It has been a significant but successful effort. **More that 60 people involved.**

Planning for the SiPM tests in the DUNE pre-production phase

See docdb n.18234

Bologna CIEMAT Milano-Bicocca NIU Prague Valencia **25 SiPMs samples**

4 + 4 SiPMs from the “standard DUNE split” of FBK (NUV-Cryo) and HPK (50 μm, LQR)

12 + 13 SiPMs from the other splits: two independent measurements per split

Bologna + Ferrara: setup for the tests of the 250 sample boards (40 boards per split) distributed to the other labs **250 SiPMs samples**

CIEMAT and Milano: test of a supercell

Milano-Statale and Bicocca: electrical tests up to the ganging circuit (+ LNS v. C. Gotti’s talk)

Bologna + Ferrara: multiplexed setup **ProtoDUNE Run II SiPMs**

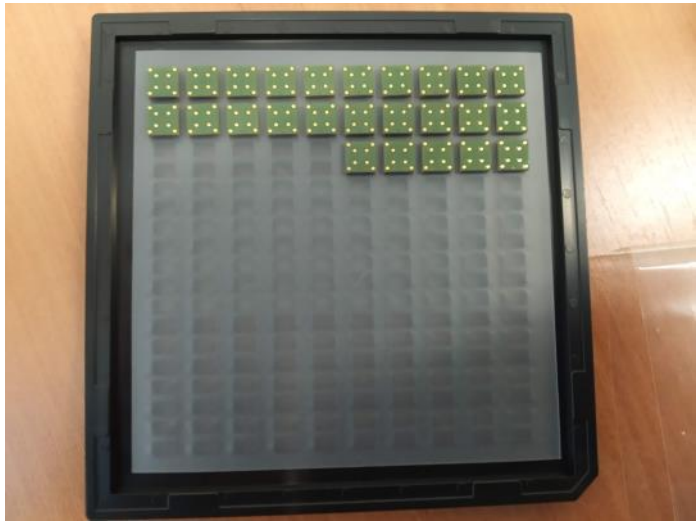
The four HPK spilts:

- 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. 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

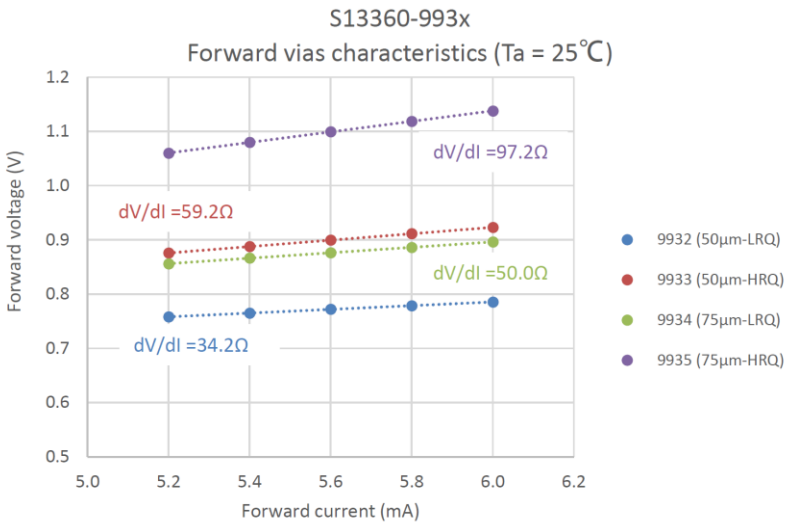
Table 1: The DUNE pre-production splits

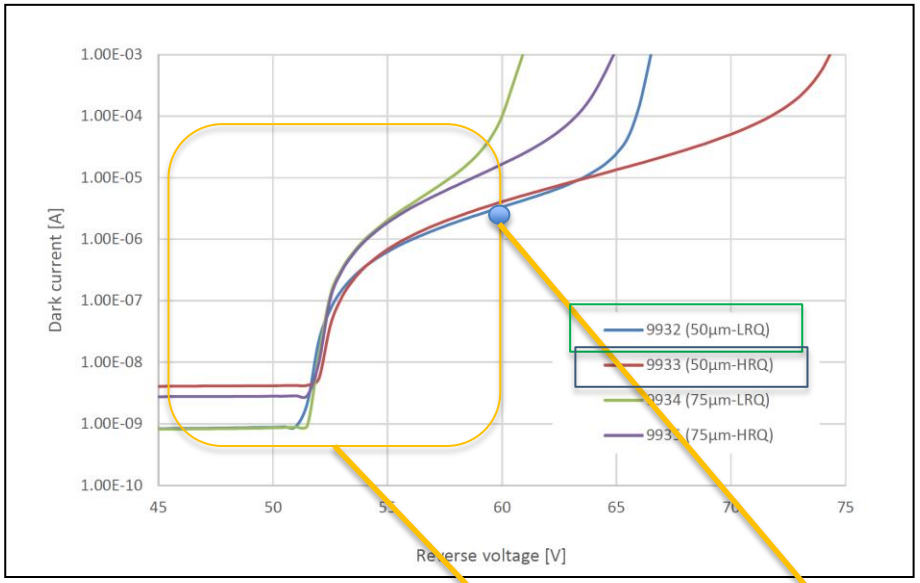
The four HPK spilts



Milano-Bicocca, Bologna, Madrid,
Valencia, Prague, NIU
Already delivered according to the plans

HPK measurements at 300 K

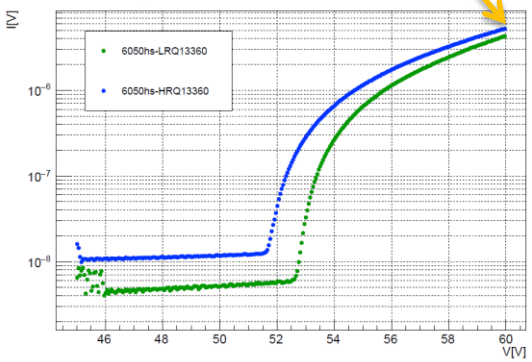




Confidential

Current status: these measurements are under validation. **First results are in good agreement**.

Preliminary



FBK

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Table 1: The DUNE pre-production splits

Two types:

NUV-HD-Cryo in SMD package and wire bond

«Triple trench» to reduce correlated noise

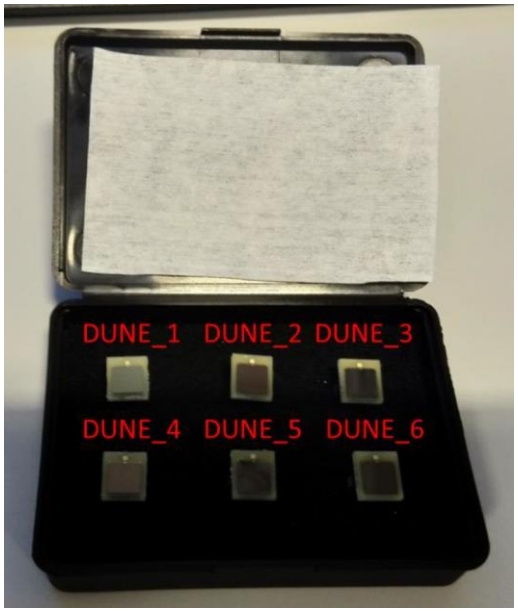
Two wafers are ready and delivered to FBK (produced in Lfoundry: test of technology transfer already done «for free»). Packaging of:

25 sensors of the DUNE standard split (NUV-HD-Cryo)

25 sensors of the “triple trench”

We will give green light to the rest of the run (250 sensors per type + 3000 sensors in NUV-HD-Cryo) after the chacterization of these 50 sensors

FBK measurement at 77 K



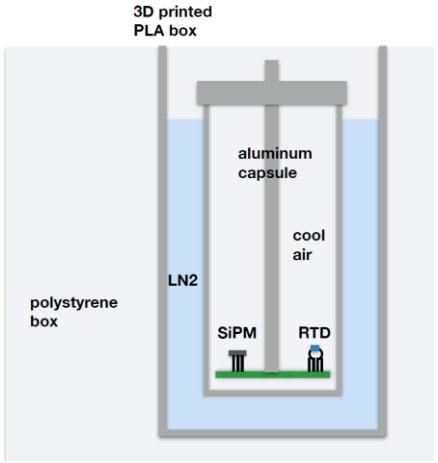
	Vbd [V]
DUNE_1	27.12
DUNE_2	27.16
DUNE_3	27.16
DUNE_4	27.15
DUNE_5	27.25
DUNE_6	27.12

SiPM parameters:

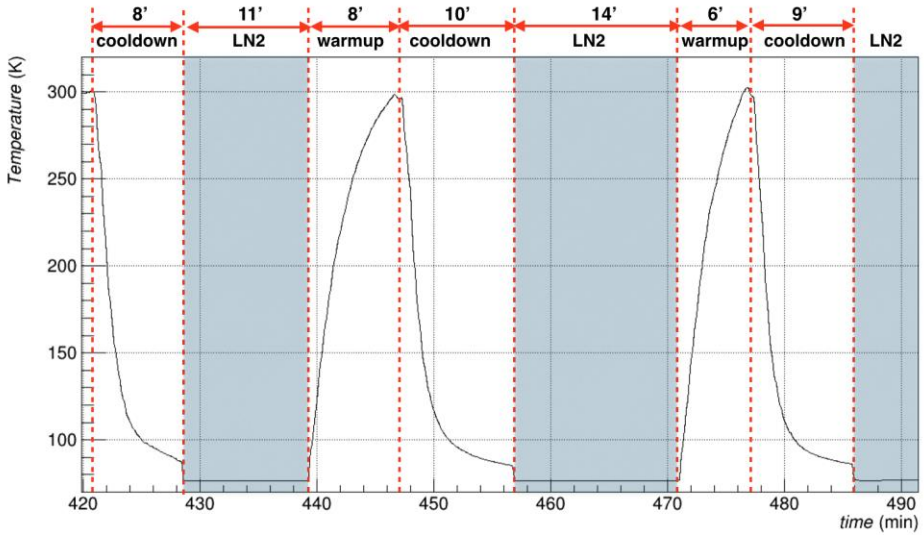
Breakdown Voltage (at RoomT)	~32.8 V		
Active Area (nominal)	6x6 mm^2	*Device Type*	NUV-HD-Cryo
Cell pitch	30 µm	*Junction type*	p-on-n

Tests plans (ongoing)

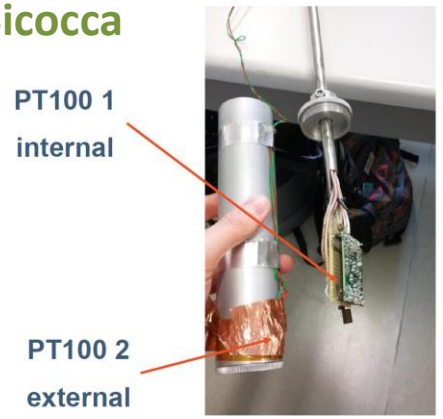
- I-V current at room and 77 K before the 20 thermal cycles for all SiPMs
- Full characterization (see below) at 77 K before 20 thermal cycles
- 20 thermal cycles



Valencia



Milano Bicocca

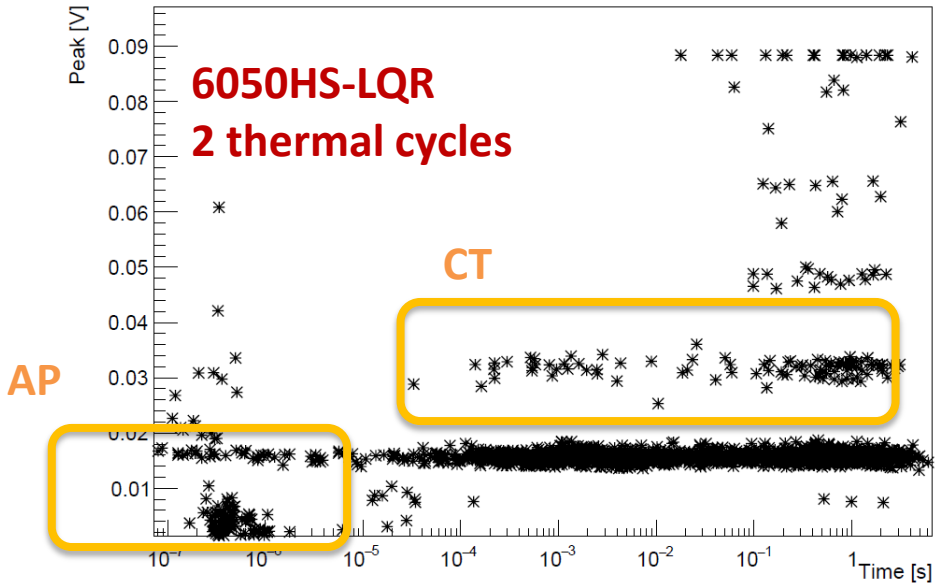


Final characterization

Test to be done after the 20 thermal cycles:

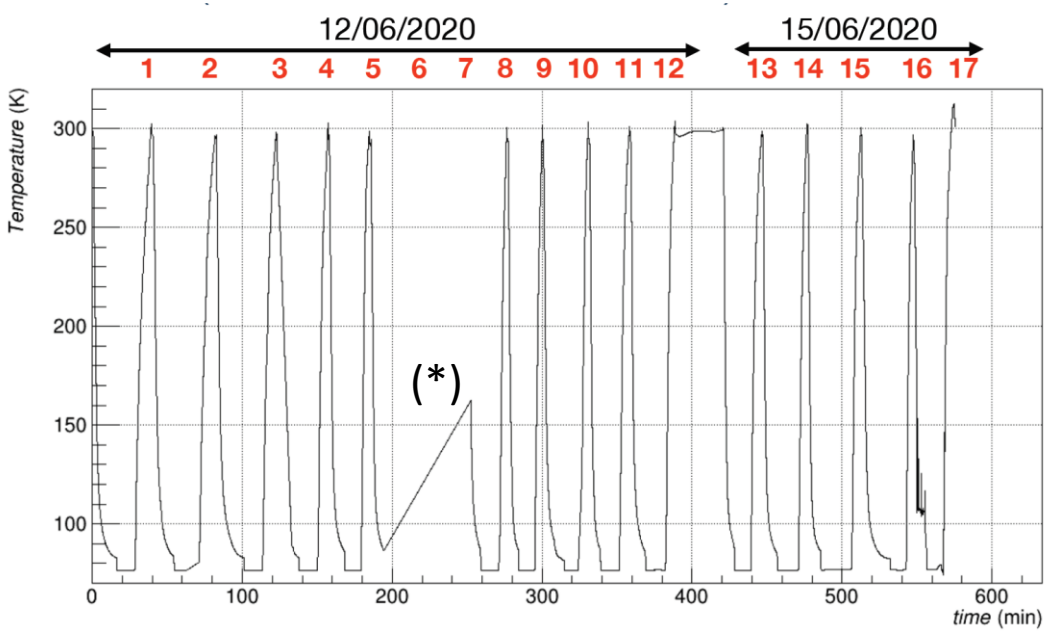
- I-V current at room and 77 K for all SiPMs
- S/N of the photopeaks and gain with the standard amplifier optimized for 1 SiPM for 40%, 45% and 50% PDE (+3, +4 and +5 OV for HPK with 50 μm cell pitch)
- DCR waveform acquisition triggered at 0.5 p.e. with absolute time stamp
- Size and number of the afterpulses

Preliminary



Preliminary results

- I-V curve at room temperature seems consistent with info from vendor
- **Important**: up to now no problems reported after thermal cycles (2-3).
- Tests of 1 sensor with 20 thermal cycle in progress.



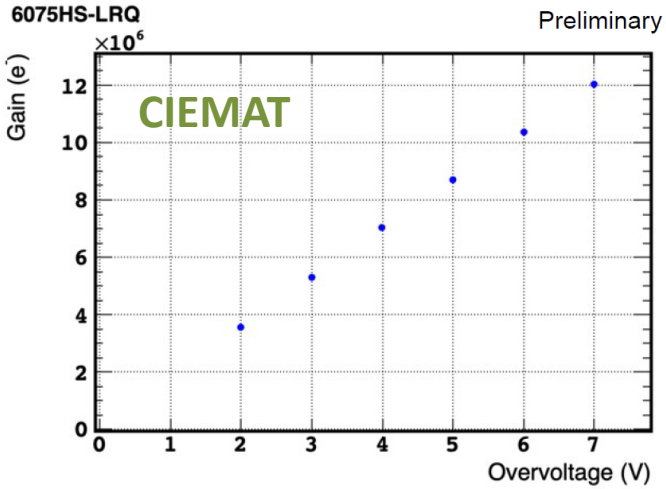
(*) Problem with temperature readout

The sensor remained fully operational and the I-V curves are compatible before and after the cycles (test done on Wed June 17)

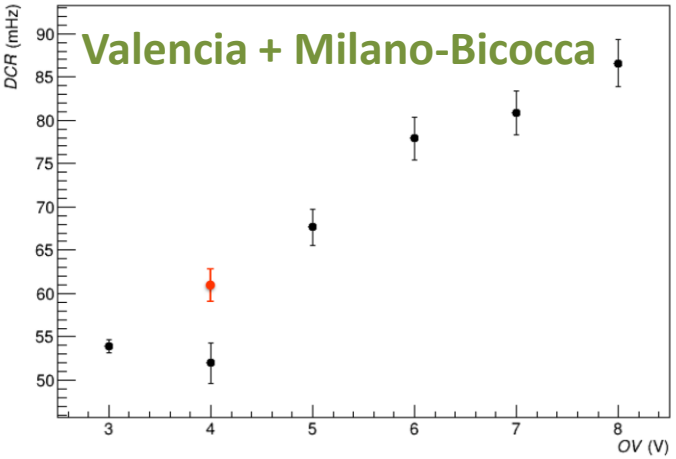
Preliminary results (77 K)

OV (V)	Gain (e-)
3	(3.58±0.01)10^6
4	(5.29±0.01)10^6
5	(7.01±0.01)10^6
6	(8.70±0.01)10^6
7	(10.35±0.02)10^6
8	(12.01±0.04)10^6

GAIN



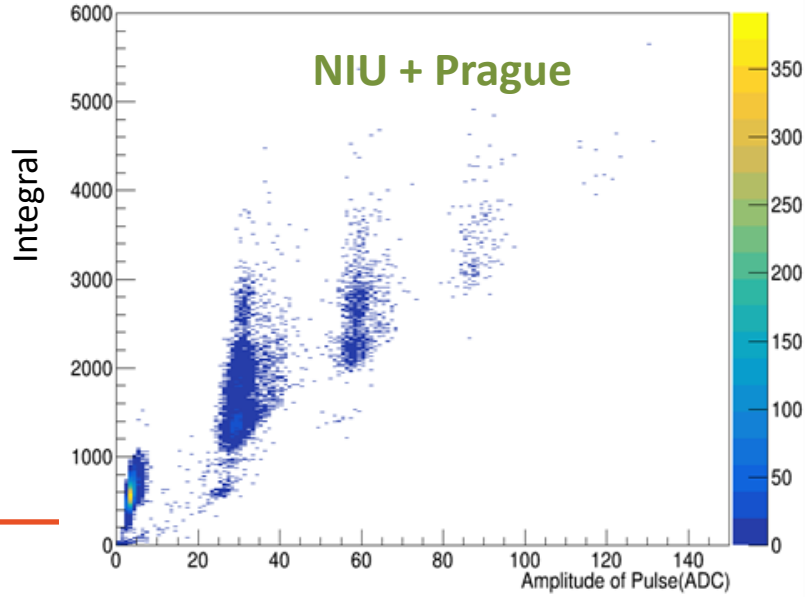
Dark count rate



Correlated noise: Milano-Bicocca

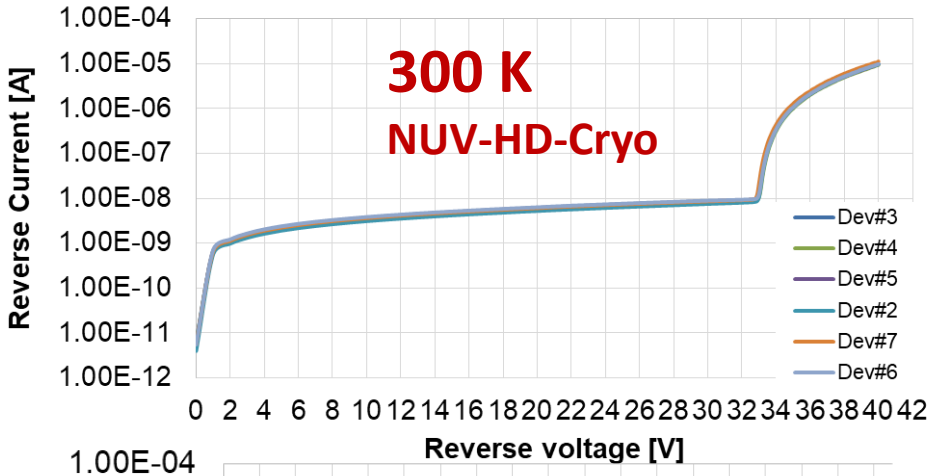
Number	OV	Cross talk (%)	Afterpulse (%)
6050HS-LQR 1	+3	5.1	7.28
1	+4		
1	+5		
6050HS-HQR 17	+3	5.9	5.8
17	+4	5.9	6.1
17	+5	9.7	8.9

Integral vs peak



Preliminary results

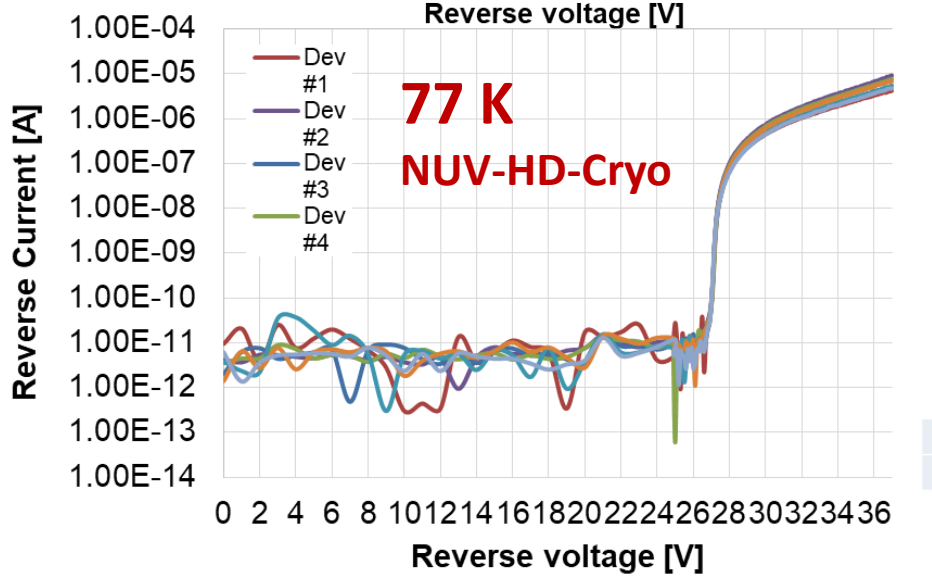
Standard DUNE split (NUV-HD-Cryo) produced and under packaging. We already have results both from FBK and from DUNE (Milano-Bicocca). Triple trench split produced and under packaging (no results yet)



V_bk= 33.2 V
Dev stand: 48 mV
Max-min: 130 mV

Forward curve

24.5	22.1	19.9	25.1	23.8	20.7	Rfw [Ω]
913.8	826.2	740.7	937.8	888.6	773.0	Rq [KΩ]



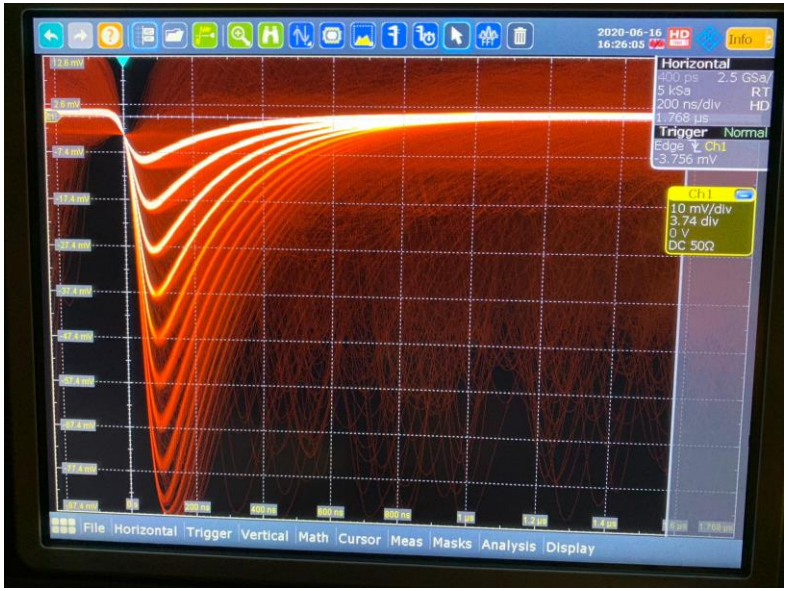
V_bk= 27.12 V
Dev stand: 22 mV
Max-min: 70 mV

Forward curve

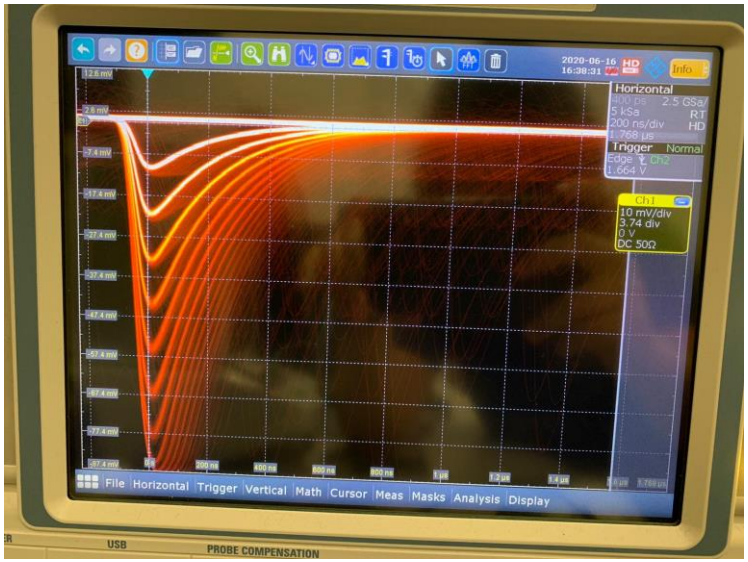
90.16	88.9	86.3	84.6	93.9	89.0	89.8	Rfw (Ω)
3.4	3.3	3.2	3.2	3.5	3.3	3.4	Rq (MΩ)

Functional characterization (DCR, gain etc.)

77 K with LED in autotrigger (0.5 p.e.)



77 K triggered by the LED



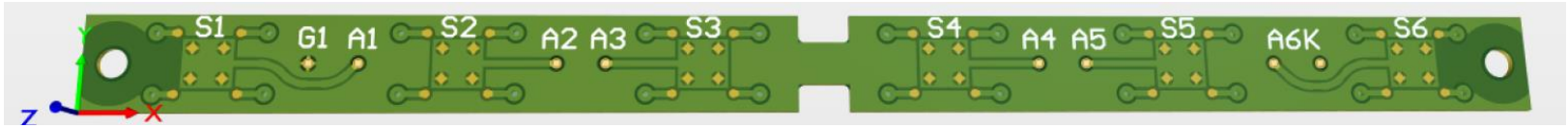
Measurement campaign and data analysis in progress

High level specs

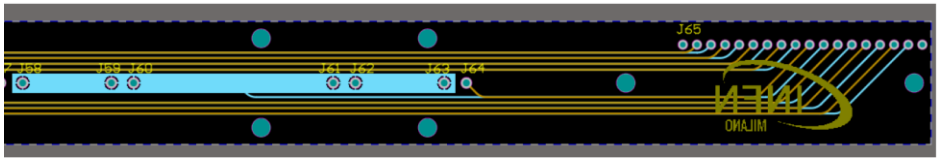
High level specs require the full electronic chain: SiPM, SiPM board, Signal lead board, cold amplifier, DAPHNE, and requires the second batches of splits (250 sensor per split)

Packaging: SiPM in SMD package soldered on a SiPM board already designed by INFN Milano-Statale.
HPK: the 40 boards (about 250 SiPMs) will be produced and soldered by SCEN, Italy
FBK: the 40 boards will be produced and soldered directly by FBK (through the packaging firm)
Footprint and design finalized

SiPM board



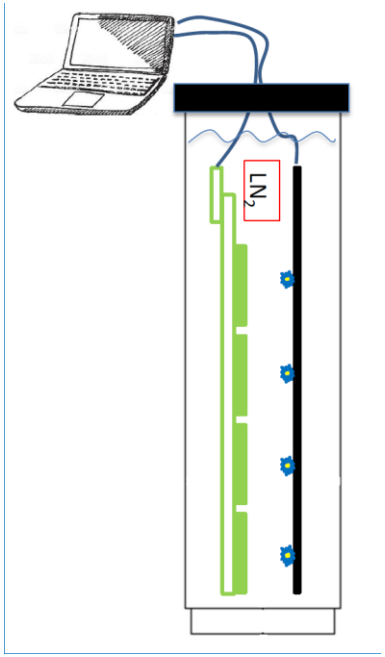
Detail of the signal lead board

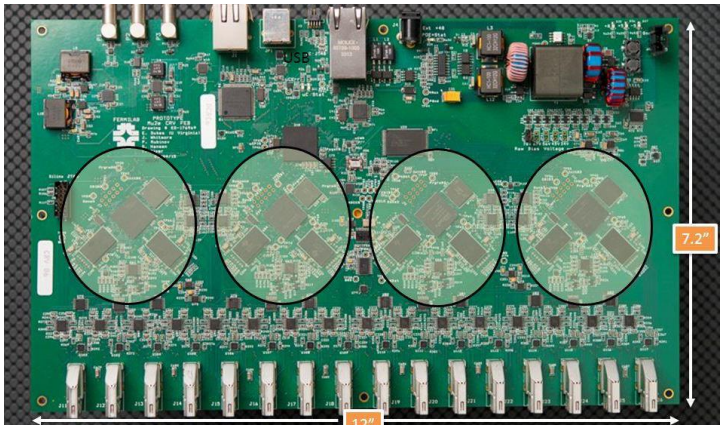


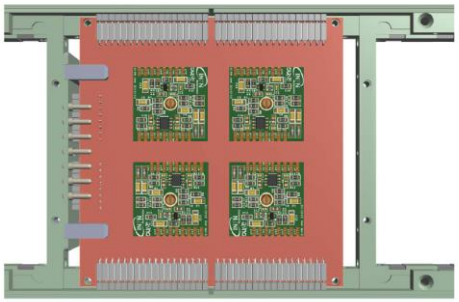
High level specs (II)

Cold amplifier: change of passive component for the ganging configuration (see Claudio's talk): **test in lab with 8 SiPM boards**. DAPHNE: see Javier's talk

TESTS of 1 supercell







Purely passive components + SiPMs (LASA, Milano)

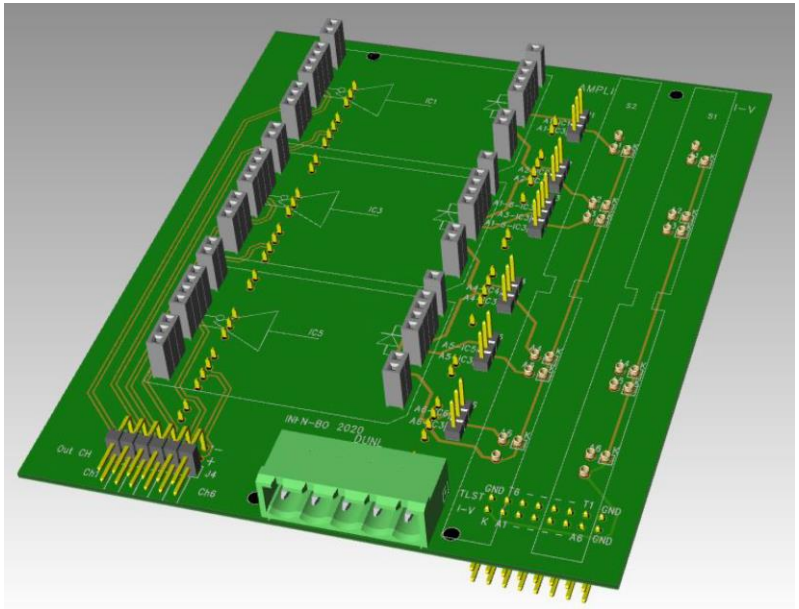
Passive components + SiPMs + ganging board + DAPHNE

250 SiPM samples

Aims:

- Test uniformity with sensors belonging to at least two wafers
- Test of the ganging scheme
- Thermal tests and I-V curve with larger statistics: scalable to the 4000+4000 sensors

Bologna and Ferrara are developing a semiautomatic system for the evaluation of the I-V curve.



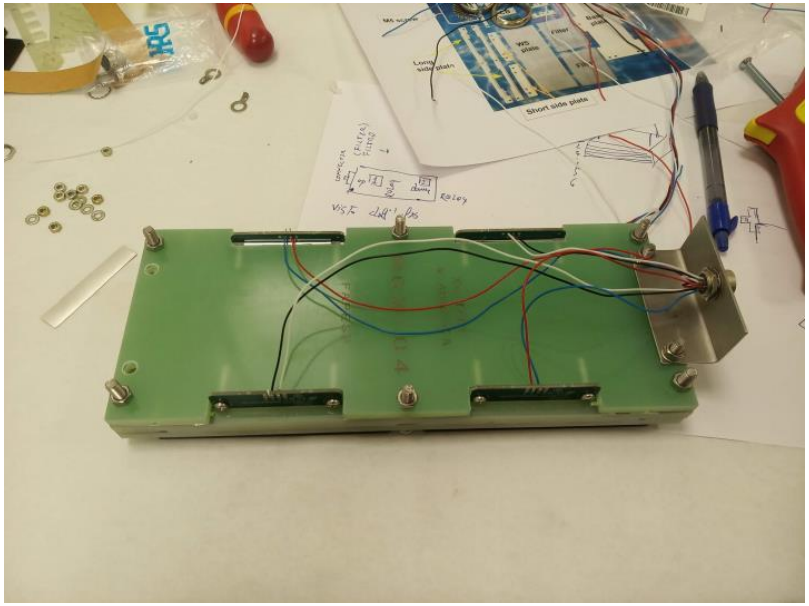
Strategy:

- 250 SiPM tests shared among labs
- 4000+4000 SiPM led by Bologna and Ferrara with the semiautomatic system

Test of X-ARAPUCA

Aims:

- Test an X-Arapuca with the new sensors
- Test an entire supercell in final configuration with cosmics, LED and an alpha source



Conclusions

Item	Status	Expected	Note
Production of the splits	OK		1 split under packaging
Test facility for low level specs	OK		
Tests of low level specs	Ongoing	Final results in <1 month	COVID-driven
250 batches	Dies already available for all splits	September	All order places
High level specs test facilities	In preparation	September	
Tests of high level specs	To be done	October	
Select 1 split for FBK and 1 split for Hamamatsu	On the basis of previous tests	Delivery of the 4000+4000 sensors already in the SiPM boards in Jan 2021	