The Silicon Photomultipliers for FD2-VD

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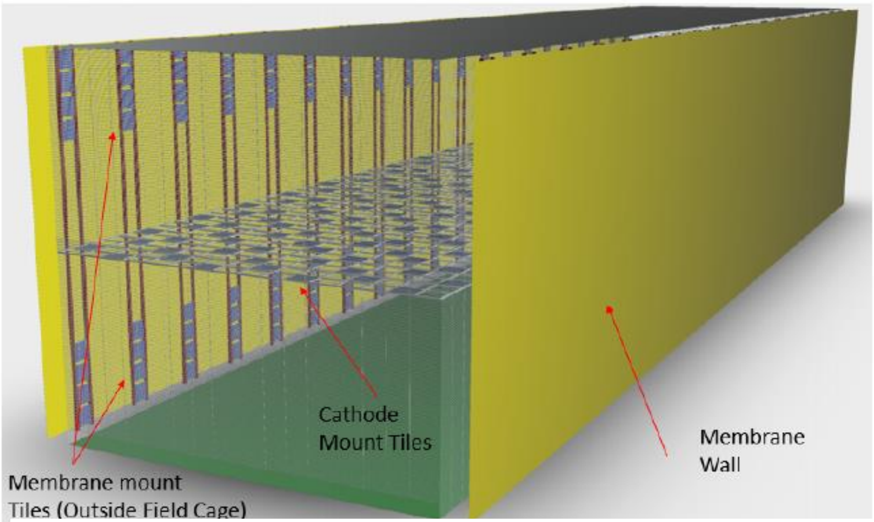
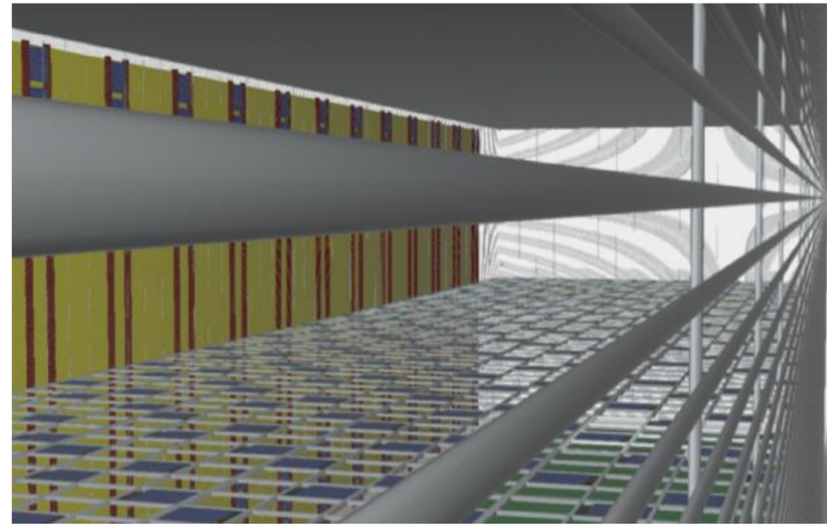
on behalf of the PDS Consortium
May 3, 2022

The PDS of the Vertical Drift





Item	Quantity	Detector Surface
X-ARAPUCA modules	320 double-side	Cathode plane
	320 single-side	Membrane long walls
Dichroic Filters	34,560	
WLS plates	640	
PhotoSensors (SiPMs)	51,200	Cathode plane
	51,200	Membrane long walls
Signal Channels	640	Cathode plane
	640	Membrane long walls
SiPMs per channel	80	
Optical Area	$115\ m^2 \times 2$	Cathode plane
	$115\ m^2$	Membrane long walls
Active coverage	14.8%	Cathode plane
	7.4%	Membrane long walls

1/3 of the SiPMs needed for FD1-HD

Ganging twice the SiPMs of FD1-HD (80 versus 48)

General strategy

- Benefit from the two-year long R&D carried out for FD1-HD to deliver **customized SiPM**s from Hamamatsu (HPK) and Fondazione Bruno Kessler (FBK)
  - Two vendor scheme (reduced risks and costs): we expect 50% of the SiPMs to be produced by HPK and 50% from FBK
  - Cryo-reliability tested in standalone mode using the mass test facility of the Consortium
  - Performance (PDE, dark count rate, cross talk, afterpulse) tested in standalone mode using the facilities of the Consortium
  - Quality assessment during mass production: same principle as FD1-HD (see below)
- Test the VD specific features in Cold Box tests (in progress) and in module-0 (2023)
  - Can we achieve S/N>4 at 1 p.e. with 80 SiPMs in hybrid ganging scheme both for FBK and HPK? (spoiler: yes)
  - Are these sensors appropriate for the use with the Power-Over-Fiber? (spoiler: yes)

The downselected SiPMs: Hamamatsu

In 2019-2021, HPK produced for us four custom sensors and we chose a device that is now called **S13360-9935**

3.1. Structure

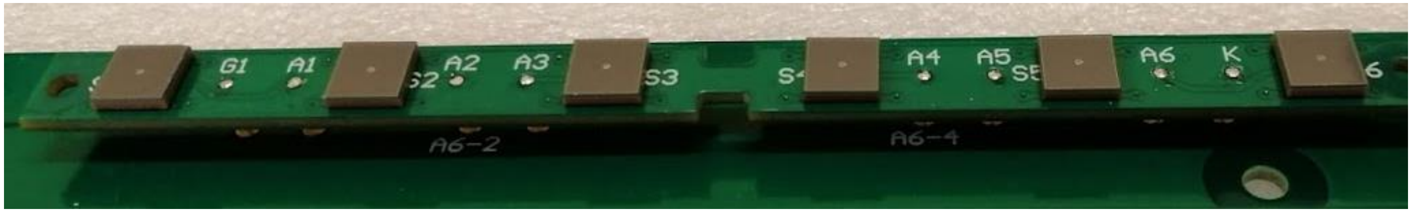
Parameter	Rating	Unit
Effective photosensitive area	6.0(X) ×6.0(Y)	mm
Pixel pitch	75(X) × 75(Y)	μm
Number of pixels	6364	pixels
Window	silicone resin	--
Window refractive index	1.57	--
Package	Surface mount type	--

3.2. Absolute Maximum Ratings *1

Parameter	Symbol	Value	Unit	Remark
Operating Temperature	Topr	-196 to +60	°C	No dew condensation. *2
Storage Temperature	Tstg	-196 to +80	°C	No dew condensation. *2
Maximum temperature cycle (below -40°C to room temperature)	--	10 times	--	Please avoid rapid temperature change.
Soldering condition	Tsol	240°C peak, 3 times	--	MSL : 5a *3

Main features:

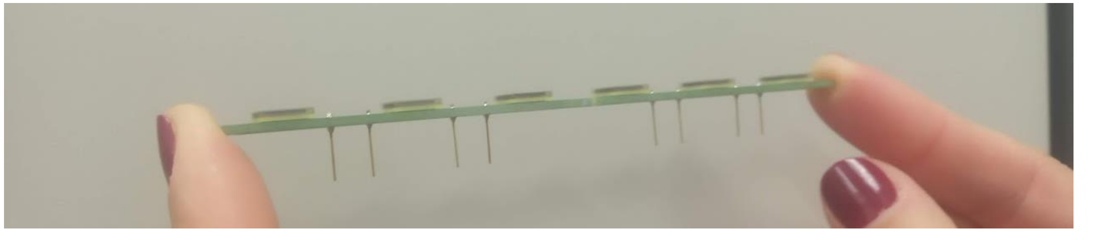
- Reliable down to 77 K
- Large cell-pitch
- Low capacitance (1300 pF)
- Operating voltage at 77 K is 45 V (Vbkd+3V)



The downselected SiPMs: FBK

In 2019-2021, FBK produced for us two custom sensors and we chose a product that is now called **NUV-HD-CRYO-TT (Triple Trench)**

Parameter	Rating	Unit
Effective photosensor area	6.0 (X) x 6.0 (Y)	mm
Pixel pitch	50	µm
Window	Epoxy resin	
Package	Surface mount type	



Main features:

- Reliable down to 77 K
- Moderate cell-pitch
- Low capacitance (2500 pF) [but **higher than HPK**]
- **Very low** operating voltage: at 77 K is 31.5 V (Vbkd+4V)

DUNE specs

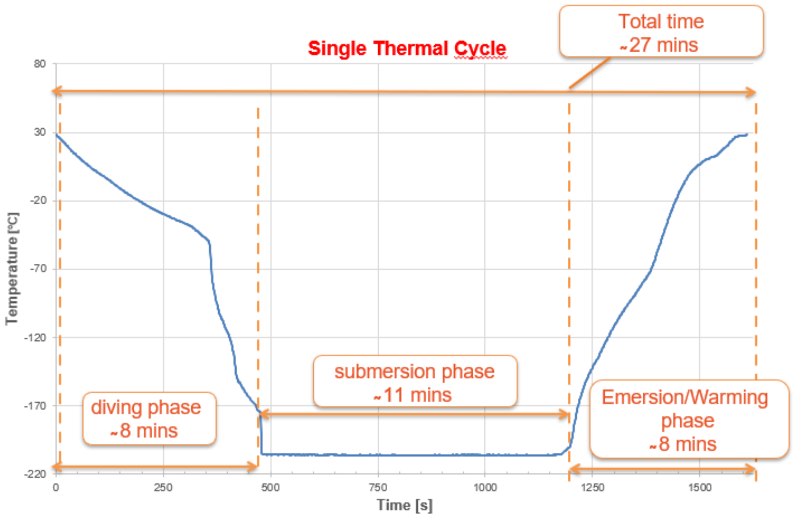
Spec	Rating	Note
Min PDE at nominal voltage (Vop)	>35% a 450nm	Room temperature (*)
DCR	<200 mHz/mm^2	77 K (**)
Cross talk	<35% at Vop	77 K
Afterpulse	<5% at Vop	77 K
Gain	>2 10^6 at Vop	77 K
Breakdown voltage spread (Vbk)	<200 mV (max-min)	On 160 SiPM group selected by the supplier (***)
Breakdown voltage spread (Vbk)	<2 V (max-min)	whole production

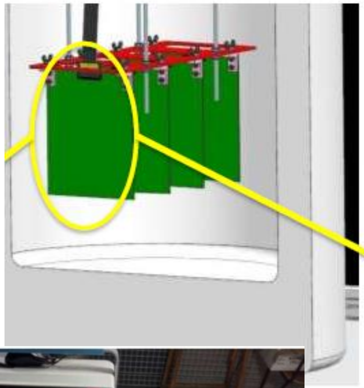
(*) Measured at 77 K In Dec 2021 at TRIUMP: no evidence of change with respect to room temperature [paper in preparation]

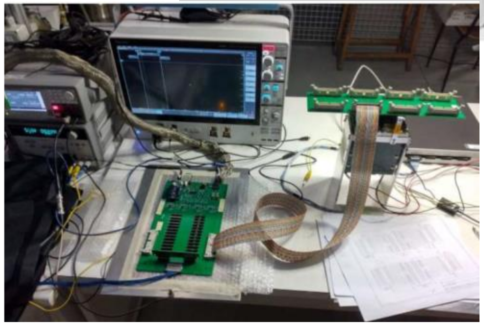
(**) Assuming a 1.5 p.e. trigger as for FD1-HD. Actual performance of downselected SiPMs: 60 mHz/mm^2

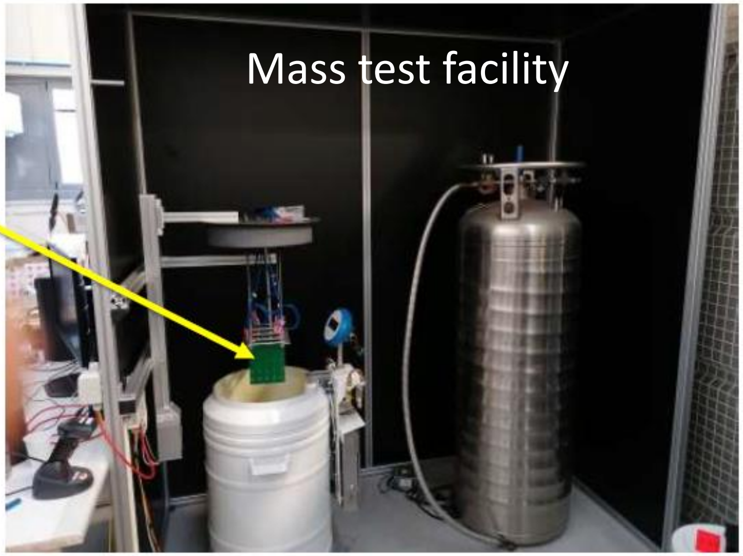
(***) already achieved for FD1-HD

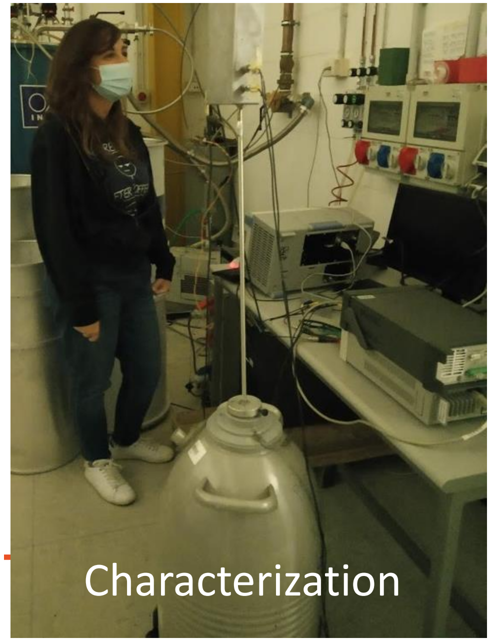
Cryoreliability and characterization







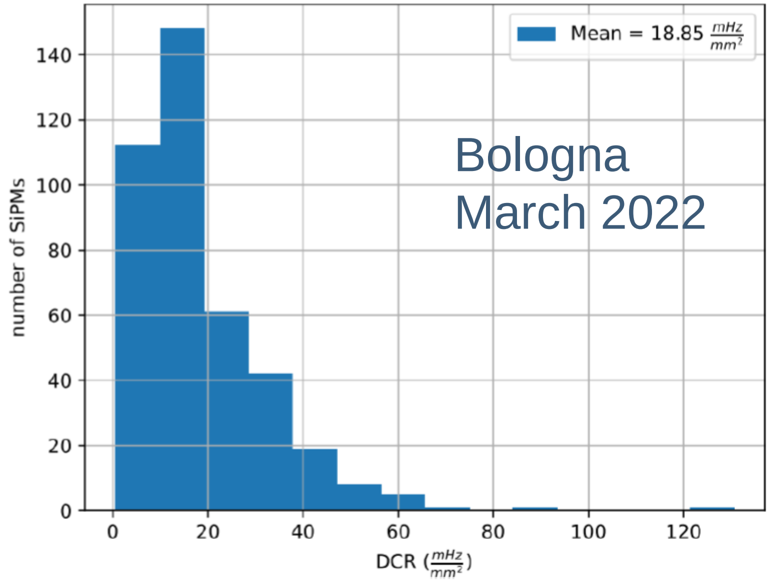


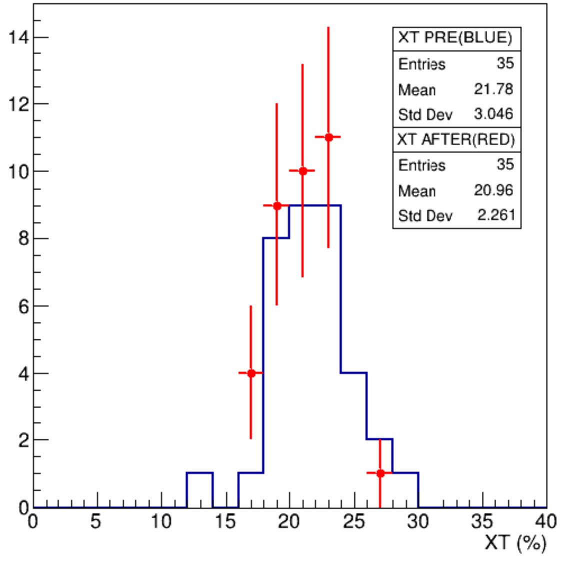


FBK sensors

We tested about **2000 SiPMs**:

- Cryoreliability: 99.9% of the sensors OK (2 failures)
- All within specs
- Variation among batches (wafer) does not exceed 1 V: grouping is necessary but can be achieved without special efforts



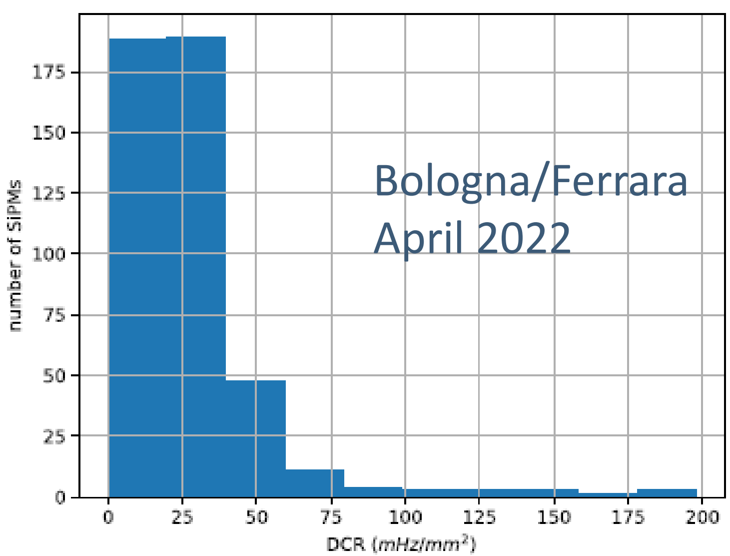


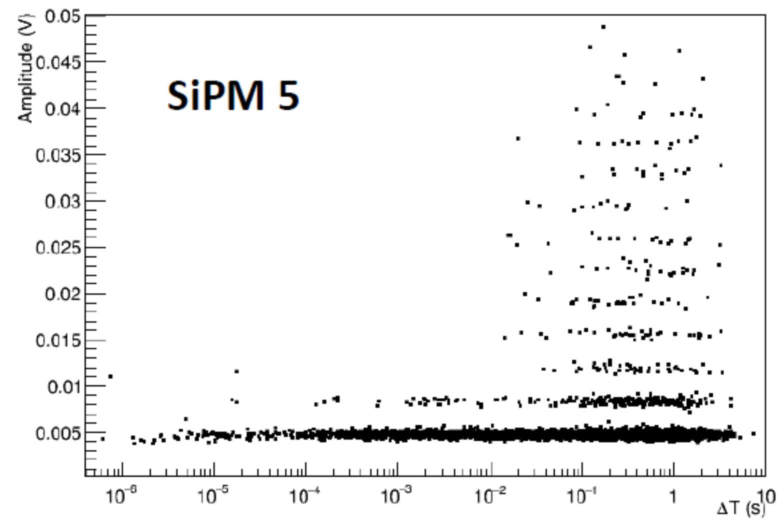
Valencia
Dec 2021

HPK sensors

We tested about **4000 SiPMs**:

- Cryoreliability: 99.95% of the sensors OK (2 failures)
- All within specs
- Variation among batches (wafer) does not exceed 1.5 V: grouping is necessary but can be achieved without special efforts





CIEMAT (Madrid) Apr 2021 +
Valencia, Oct 2021

SiPM boards for FD2-VD

FD1-HD: “Rigid” (G10) boards gathering 6 SiPM per boards

FD2-VD: “Flexible” (Kapton) boards gathering 20 SiPM/board

Mounting scheme: tested at FNAL and Milano Bicocca with a standard supplier (SCEN, Trieste, Italy). No issues from the electrical standpoint.
Tested with HPK sensors OK. Planning to install FBK sensors in the next few months.
Open issue: should we outsource it to FBK and HPK as done for FD1-HD or we rely on a third party (SCEN) even in the mass production test?

Ganging

In 2022 we addressed a prominent issue:

Can we achieve the DUNE specs both with FBK and HPK when ganging in hybrid or conventional mode? This is important because:

- FBK sensors have a terminal capacitance that is nearly twice the capacitance of HPK
- On the other hand, the FBK SiPMs have a smaller breakdown voltage which eases the operation of the PoF (and reduce costs).

Ideal scenario:

FBK sensors for the cathode tiles

HPK sensors for the membrane tiles where the use of PoF is less critical

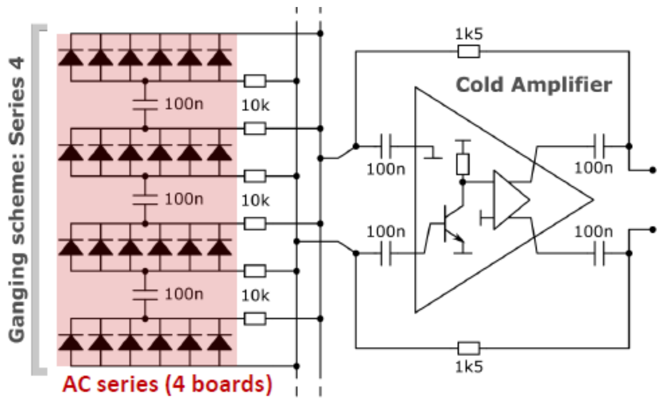
Strategy:

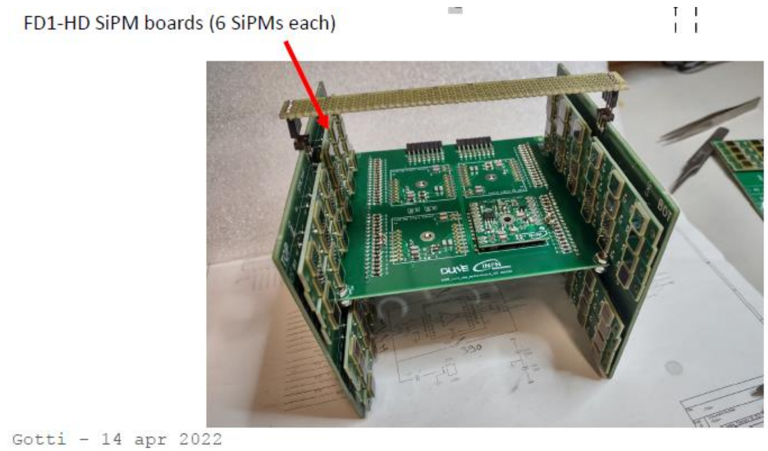
- Perform standalone tests of FBK and HPK SiPMs in ganging mode
- Test the final performance in Module-0 both in cathode and membrane tiles (we will have cathode tiles with both FBK and HPK SiPMs for greater safety)

Results

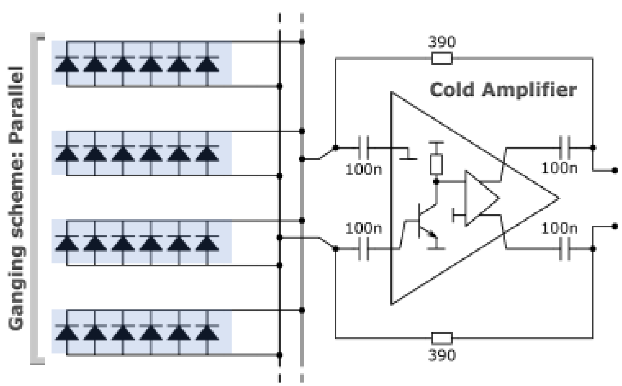
Case 1: HPK (i.e. low capacitance) SiPMs in hybrid ganging scheme. OK – see previous talk

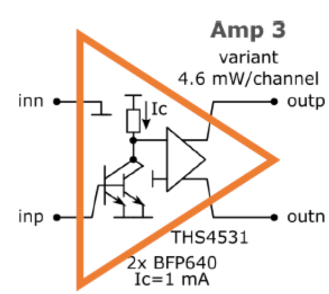
Case 2: FBK (i.e. “high” capacitance) SiPMs in hybrid ganging scheme



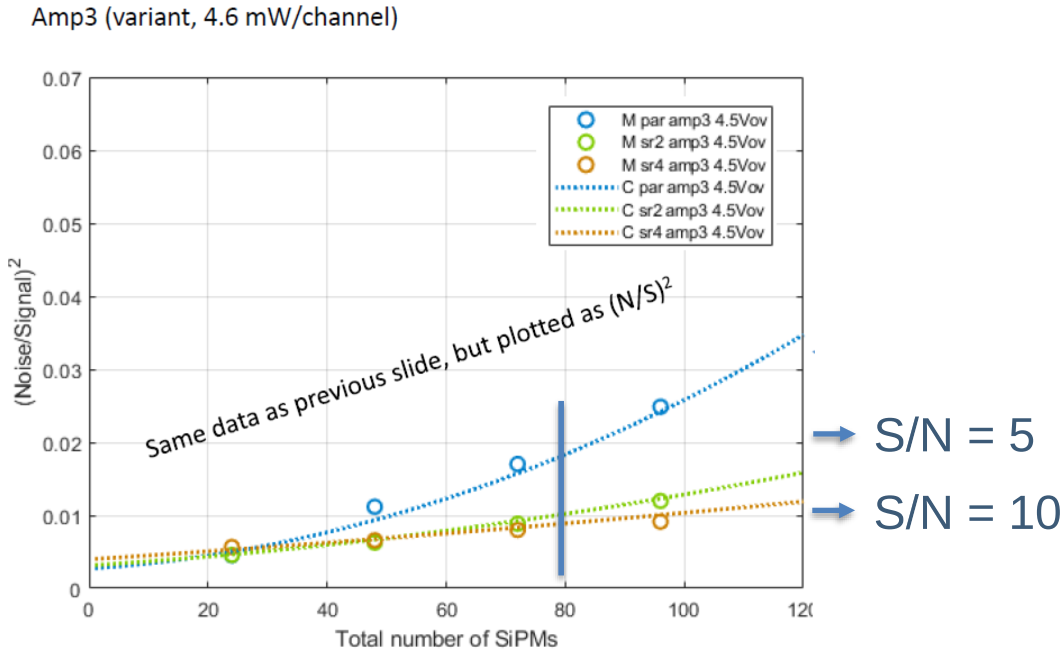


Case 3: FBK (i.e. “high” capacitance) SiPMs in parallel ganging scheme

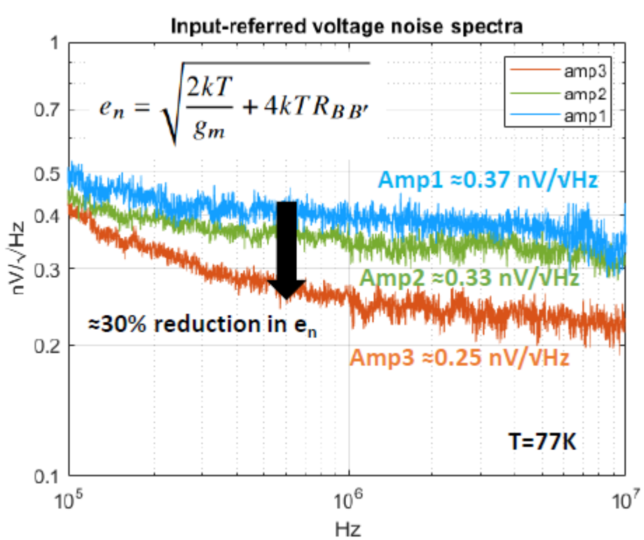


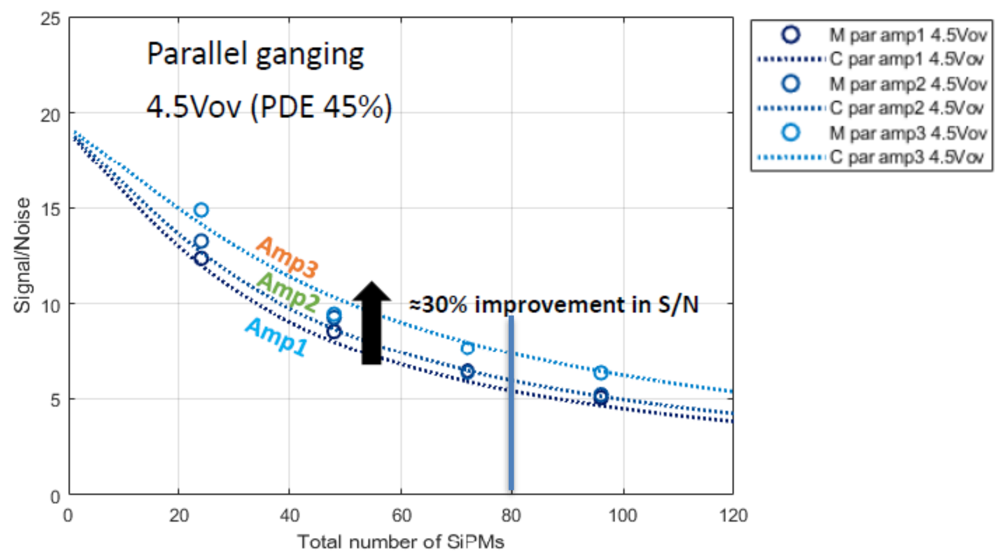


Case 2: FBK+hybrid ganging



Case 3: FBK+parallel ganging





Mass production

- 51200 SiPMs from FBK, 51200 from HPK (+5% spares)
- Production rate (established for FD1-HD): max 4500+4500 per month limited by the number of mass test facilities.
- **1 year production**:
  - SiPMs produced and soldered in Kapton boards
  - Tested in 4 mass production centers (most likely: Bologna/Ferrara, Milano-Bicocca, Granada + 1 US). Tests as in FD1-HD:
    - Thermal tests (3 cycles)
    - I-V curve at room and 77 K for all SiPMs
    - Dark Count Rate (DCR), cross talk and afterpulse for 5-10% of the SiPMs

    [Need to modify the mass test facilities to handle 20-SiPM flexi boards]
- Delivery to production centers (1 US and 1 EU) in parallel with the SiPM production as soon as the boards are tested

Conclusions

- The FD2-VD SiPM R&D benefited from the 2-year R&D carried out for FD1-HD
- The two-vendor scheme and vendor products are appropriate for the needs of FD2-VD:
  - **Hamamatsu S13360-9935 and FBK NUV-HD-CRYO TT fully in specs**
- HPK has a lower capacitance but higher V_{bk} than FBK. Hence, the optimal choice should be "HPK for membrane" and "FBK for cathode" tiles but all options are within specs
- Latest ganging studies show that the cold amplifiers of UCSB and Milano-Bicocca work well both with FBK and HPK. Even better (S/N>10) with the hybrid ganging
- Mass production is less challenging than FD1-HD but requires an overhauling of the mass test facilities to cope with the flexi boards