Summary of SiPM tests and comparison

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on behalf of MiB, Bologna, Ferrara, CIEMAT, Prague, IFIC and NIU groups

DUNE Collaboration Meeting

Jan 26, 2021

SiPM Tests overview

In the last year, we performed a large number of tests on several 6x6mm^2 SiPM models carried out from different laboratories.

The aim of the test is to compare performances in order to select **1 HPK** and **1 FBK** model.

Measurements, performed at LN2 temperature, are:

- **I-V curve**
- **Gain**
- **Noise (correlated and dark)**
- **S/N**

Hamamatsu
- HR - 50
- HR - 75
- LR - 50
- LR - 75

FBK
- NUV-HD-Cryo
- Triple Trench

These measurements were performed with SiPM voltage to obtain 40%, 45% and 50% of PDE.

Each split was tested by at least two laboratories. All tests were done with the same cold amplifier except for Bologna and NIU (useful for systematics checks).

Laboratories overview (Hamamatsu)

			LN2 - First cycle							LN2 - Last cycle						
Institute	**Model**	**# SiPM**	**Vbd**	**Rq**	**Gain**	**AP**	**XT**	**DCR - burst**	**DCR + burst**	**Vbd**	**Rq**	**Gain**	**AP**	**XT**	**DCR - burst**	**DCR + burst**
M-Bicocca	HR-50	13	X	X	X	X	X	X		X	X	X	X	X	X	X
	LR-50	4	X	X	X	X	X	X		X	X	X	X	X	X	
	HR-75	3								X	X	X	X	X	X	X
FZU-Prague	LR50	5	X	X		X	X	X	X							
	HR-75	13	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Ciemat-Madrid	HR-50	6	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	LR-50	4	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	LR-75	6	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Valencia	HR-50	6	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	LR-50	4	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	LR-75	6	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Bologna	LR-50	2	X	X		X	X		X	X	X		X	X		X
	LR-75	5	X	X		X	X		X	X	X		X	X		X
Ferrara	LR-50	4	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	LR-75	6	X	X	X	X	X	X	X	X	X	X	X	X	X	X
NIU	HR-75	10	X	X	X	X	X			X	X	X	X	X		

Laboratories overview (FBK)

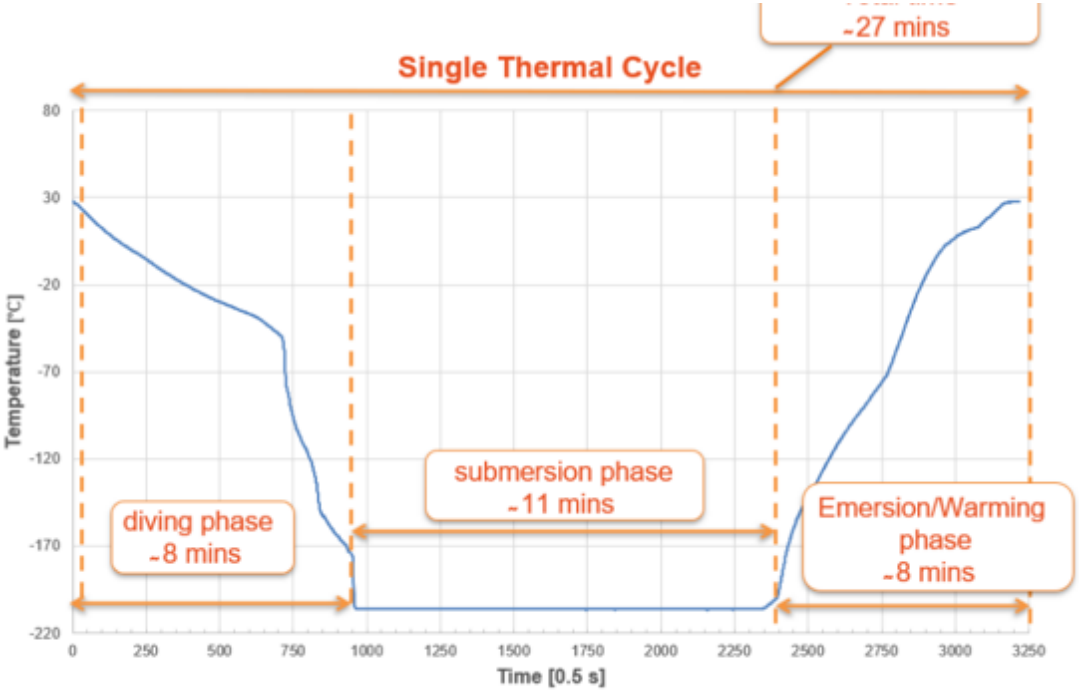
			LN2 - First cycle								LN2 - Last cycle							
Institute	**Model**	**# SiPM**	**Vbd**	**Rq**	**Gain**	**AP**	**XT**	**DCR - burst**	**DCR + burst**	**S/N**	**Vbd**	**Rq**	**Gain**	**AP**	**XT**	**DCR - burst**	**DCR + burst**	**S/N**
M-Bicocca	NUV-HD-Cryo	10	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	Triple Trench	17	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
FZU-Prague	NUV-HD-Cryo	4									X	X	X	X	X	X	X	
Ciemat-Madrid	NUV-HD-Cryo	4									X	X	X	X	X	X	X	X
	Triple Trench	6									X	X	X	X	X	X	X	X
Bologna	NUV-HD-Cryo	4	X	X	X	X	X	X	X		X	X	X	X	X	X	X	
	Triple Trench	5	X	X		X	X		X		X	X		X	X		X	
Ferrara	NUV-HD-Cryo	5	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	Triple Trench	6	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X

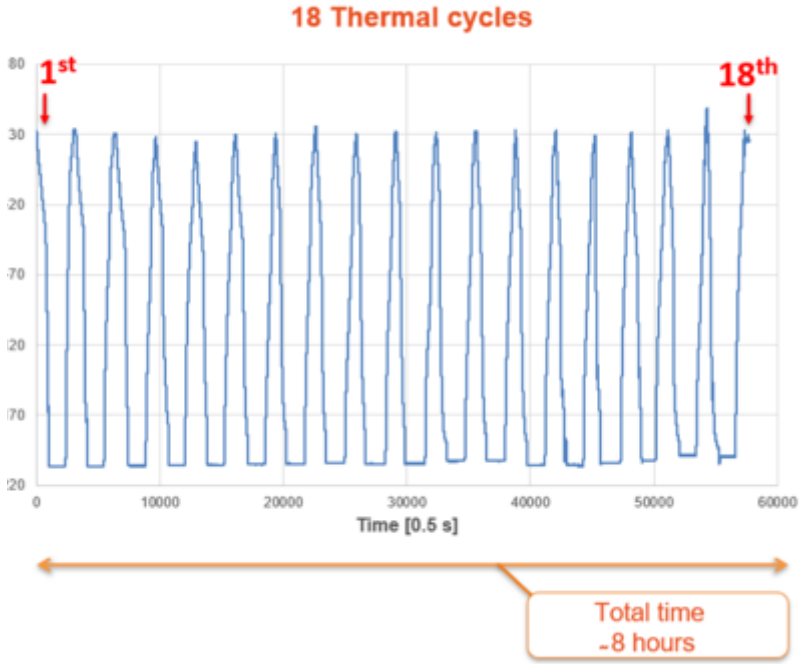
All SiPM were tested before and after a cycle of 16 thermal cycles, to obtain 20 cycles in total (2+16+2).

*Institutes without “first cycle” measurements got SiPM from other institutes where thermal cycles were done before.

Slow thermal cycles @Bologna

All the laboratories followed the same specific procedure for thermal cycles.





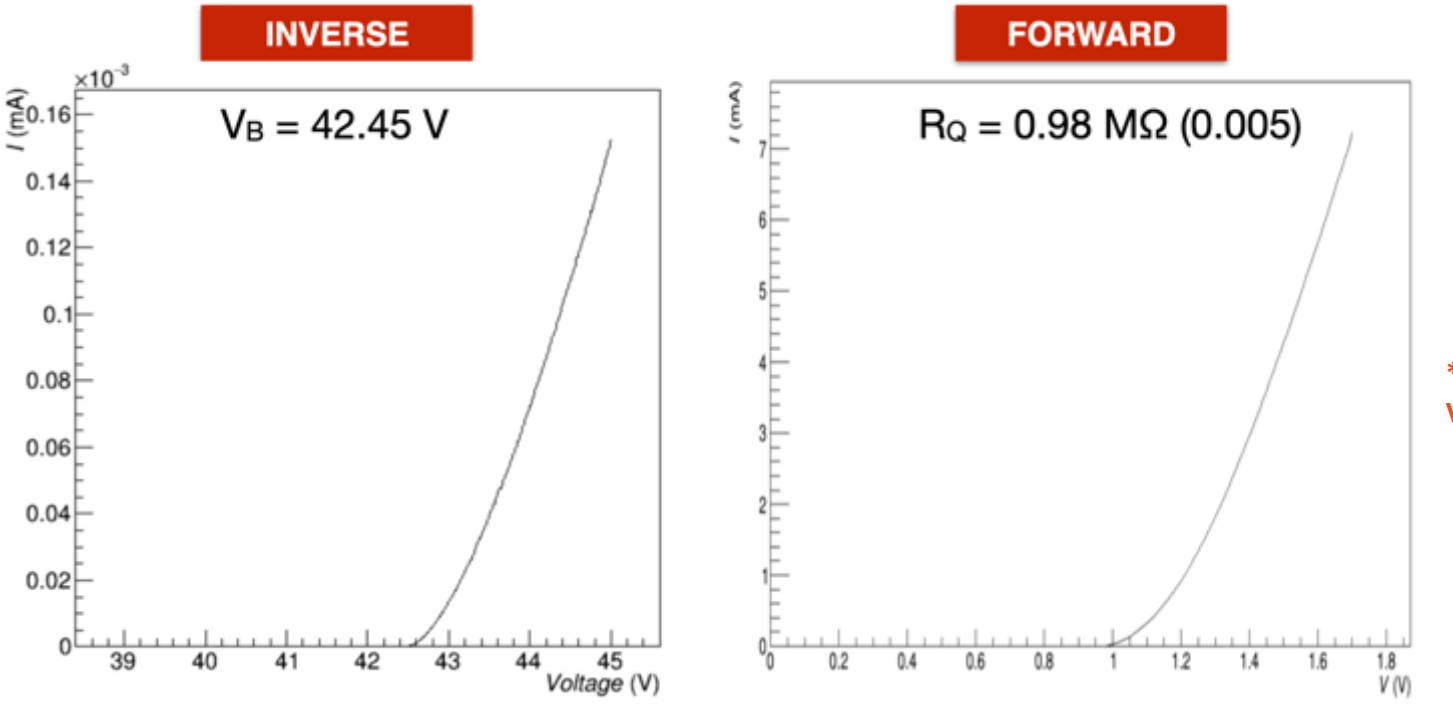
SiPM tests summary

- **I-V curve**
- Gain
- Noise (correlated and dark)
- S/N

I-V curves measurements

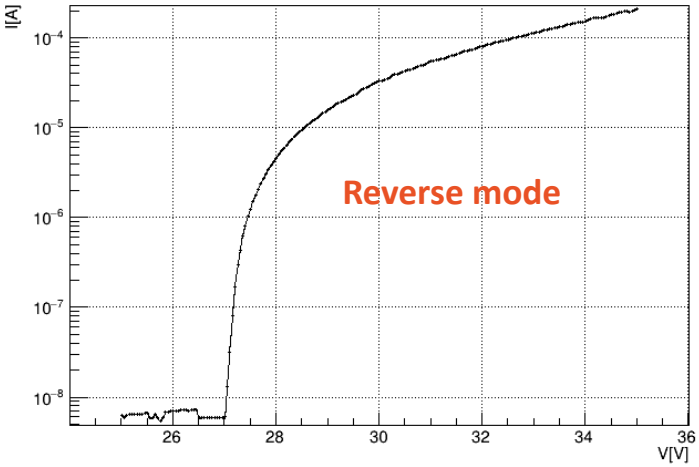
Breakdown voltage is measured with SiPM in reverse mode.

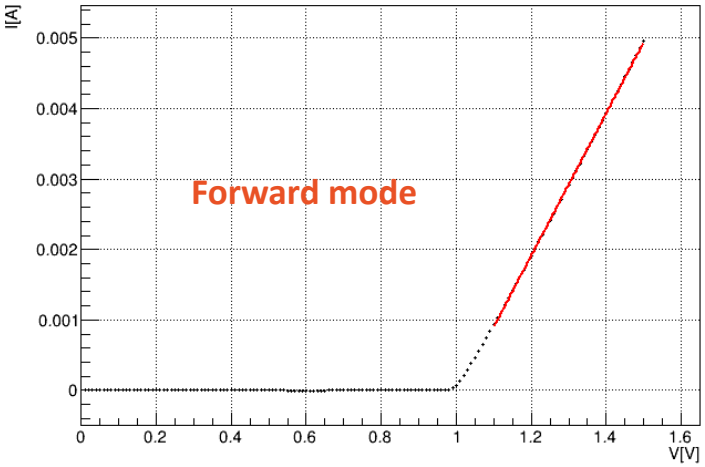
Quenching resistance is measured with SiPM in forward mode (between 1.1 and 1.5 V). The measured resistance must be multiplied for the micro-cells number, in order to obtain the quenching resistance value.



* HPK 6050-LRQ @IFIC-Valencia

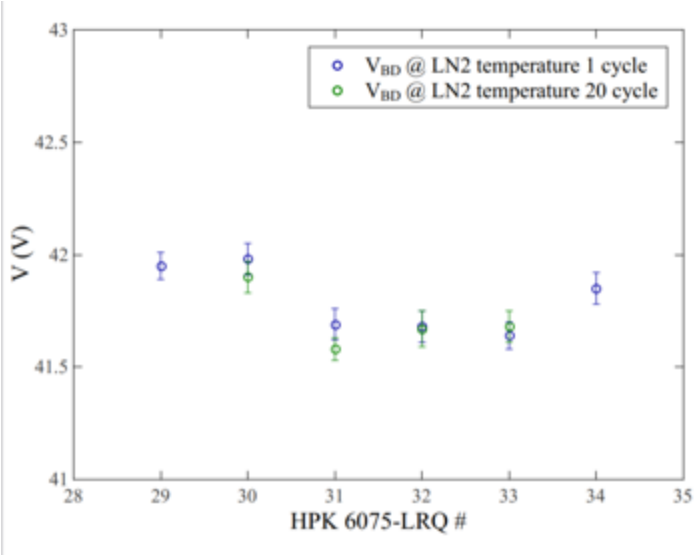
I-V curves measurements

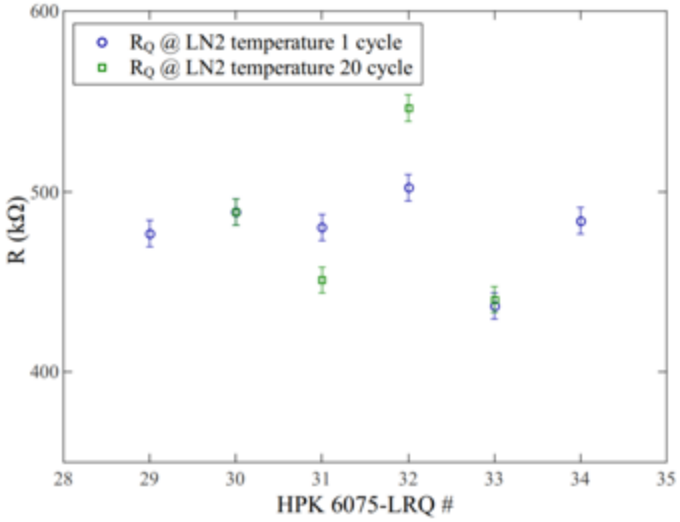




* FBK-Cryo @M-Bicocca

* HPK 6075-LRQ @Ferrara

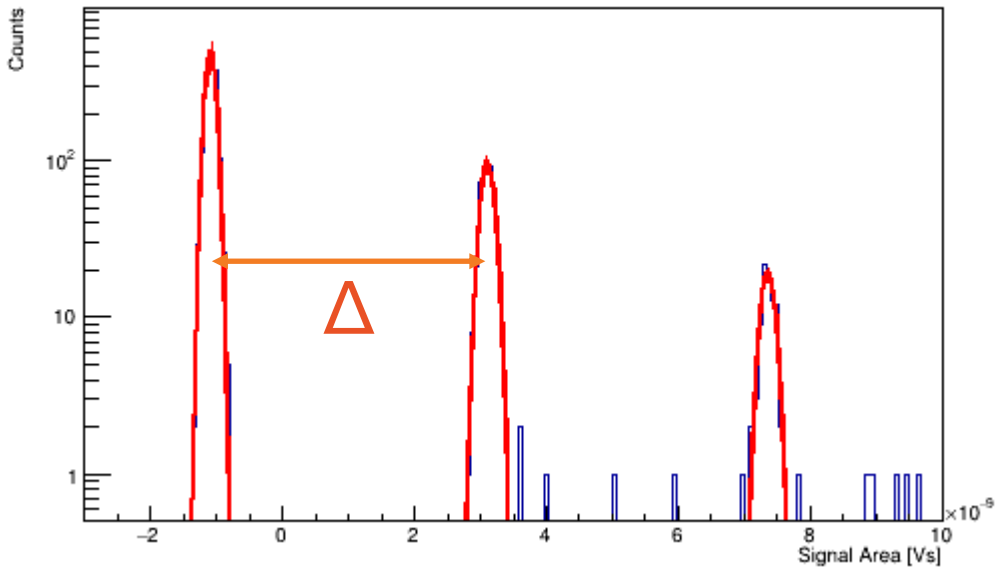




SiPM tests summary

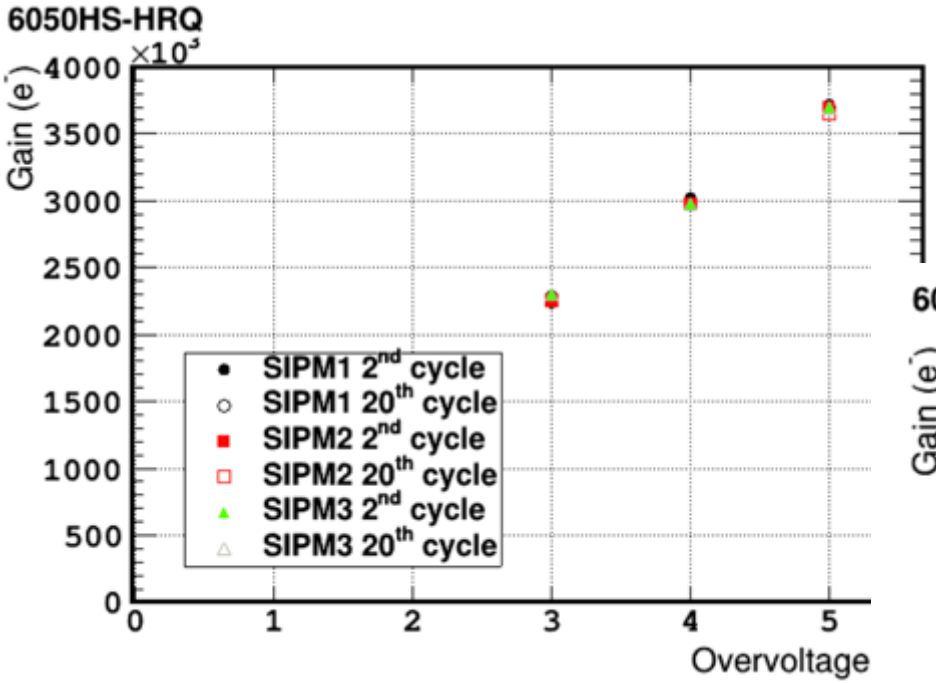
- I-V curve
- Gain
- Noise (correlated and dark)
- S/N

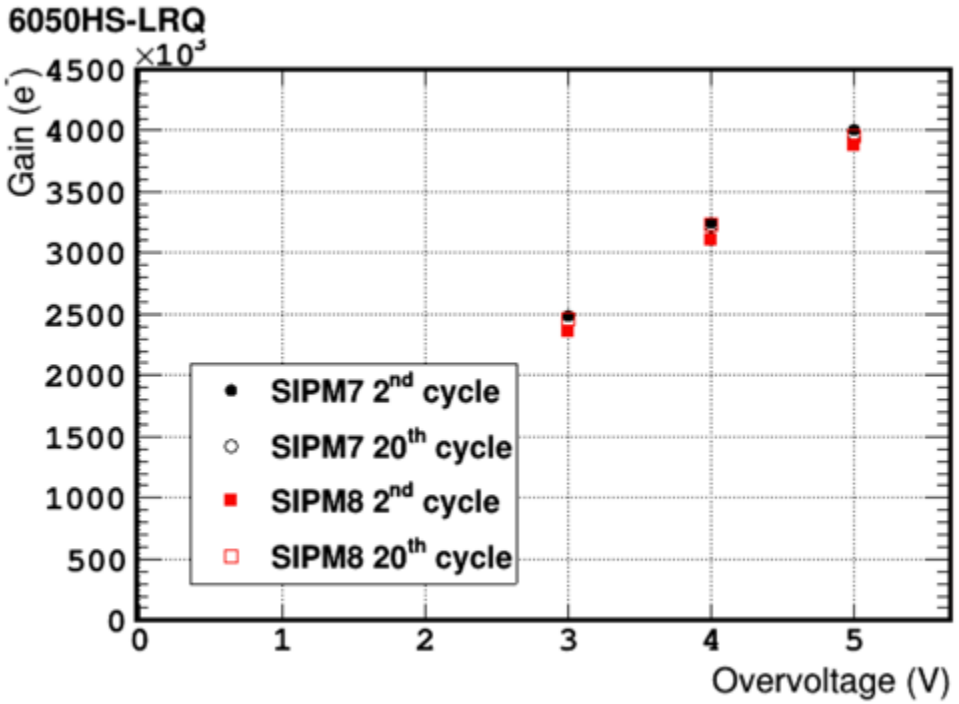
Gain measurements



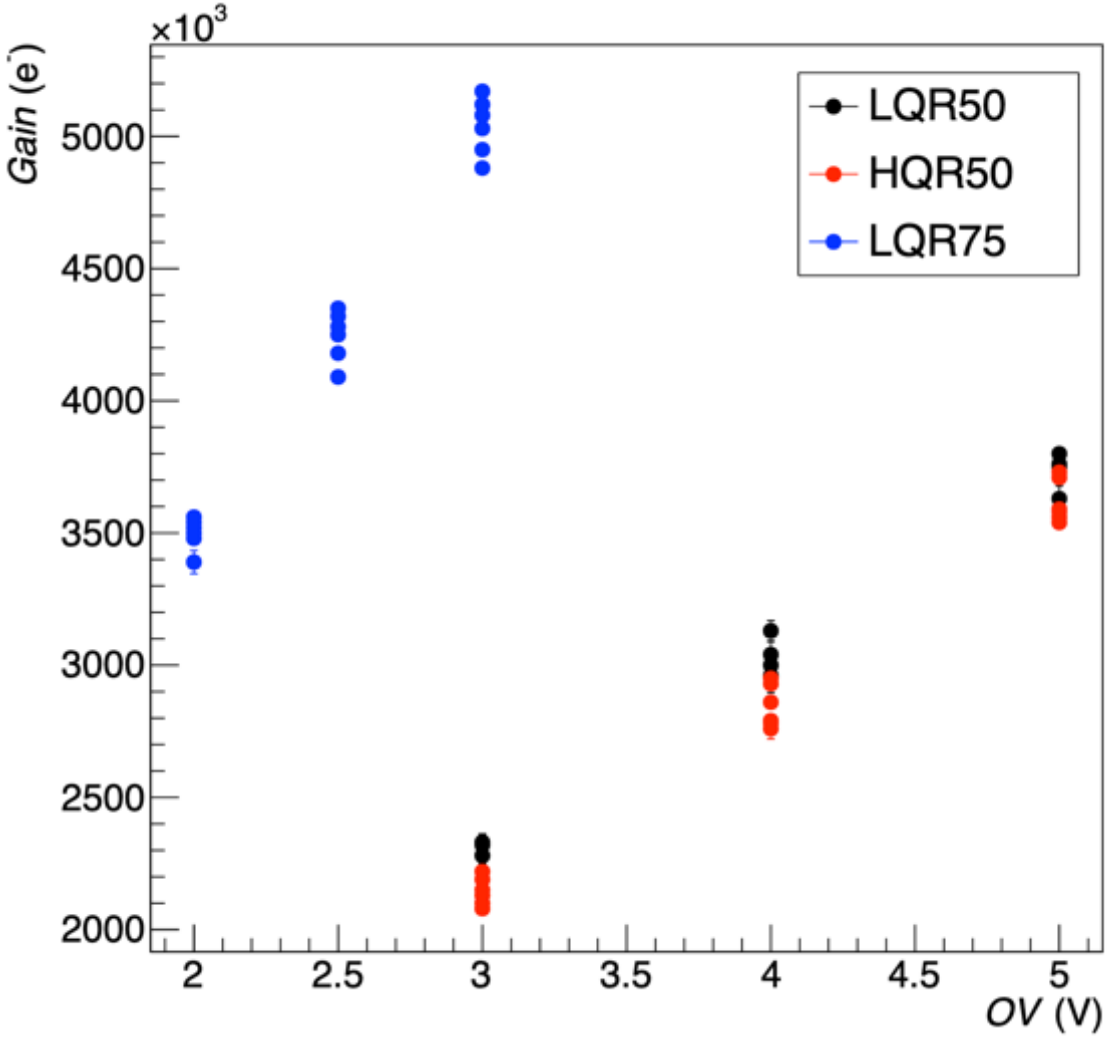
- The gain measurements were performed with the SiPM enlightened by a LED pulser.
- Waveforms per SiPM per OV have been collected with an oscilloscope (2 µs window and 2 ns sampling).
- The waveform integral is then plotted, the distance between 0 pe and 1 pe peak is the gain.

Gain VS ov measurements (6050HS-HRQ/LRQ at CIEMAT-Madrid)





Gain VS ov measurements (HPK @IFIC - Valencia)

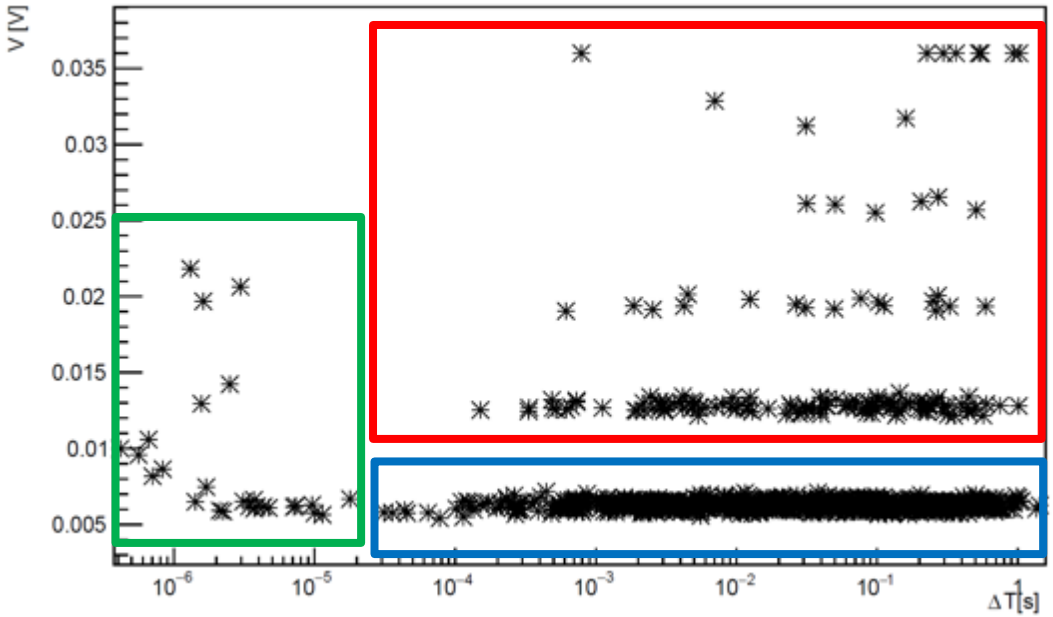


*summary of all HPK gain measurements

SiPM tests summary

- I-V curve
- Gain
- **Noise (correlated and dark)**
- S/N

Dark Noise measurements

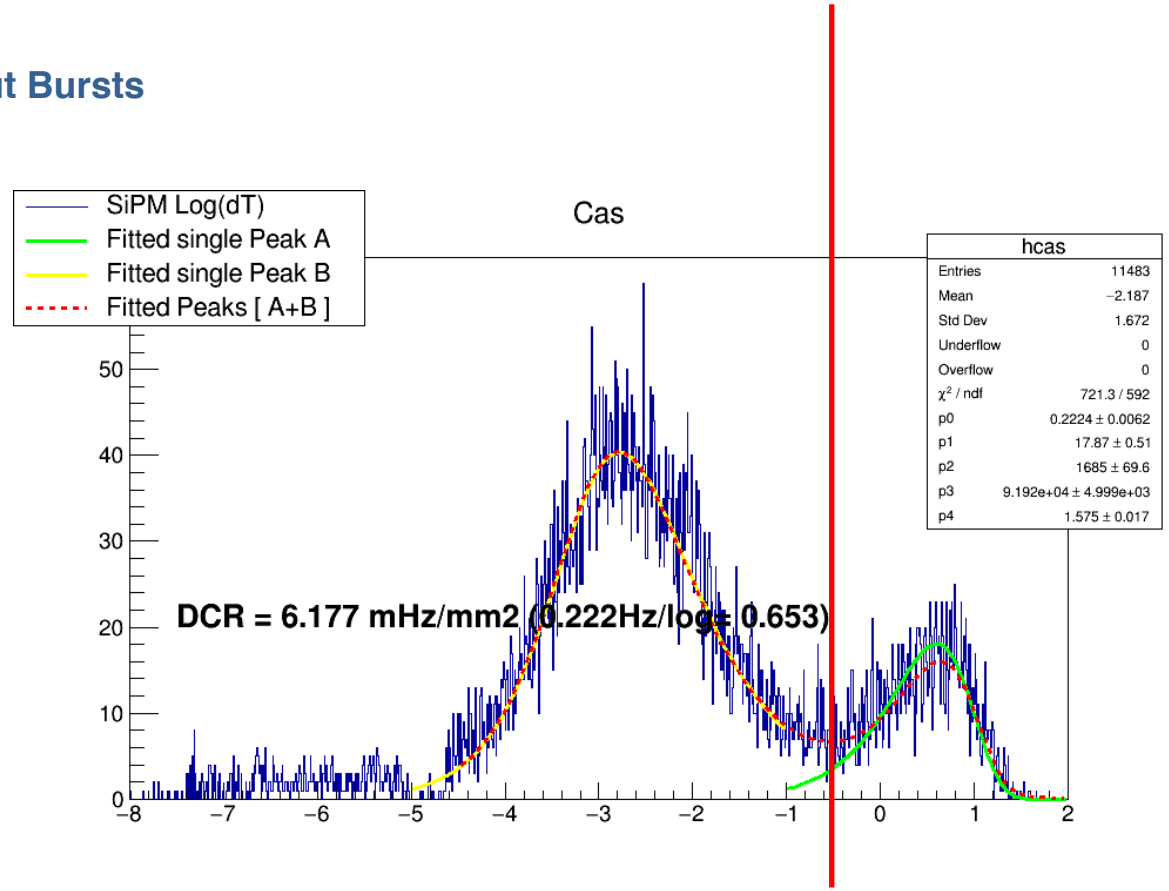


- For dark measurements, waveforms were acquired in dark condition, triggering at 0.5 pe level.
- As **crosstalk** the ration between events with peak > 1.5 pe and the ones with peak > 0.5 pe is considered.
- The **afterpulse** probability is the number of events with one or more peaks after the **main pulse**, divided by the number of main pulses.

DCR – Crosstalk [%] (HRQ-6075HS @Prague)

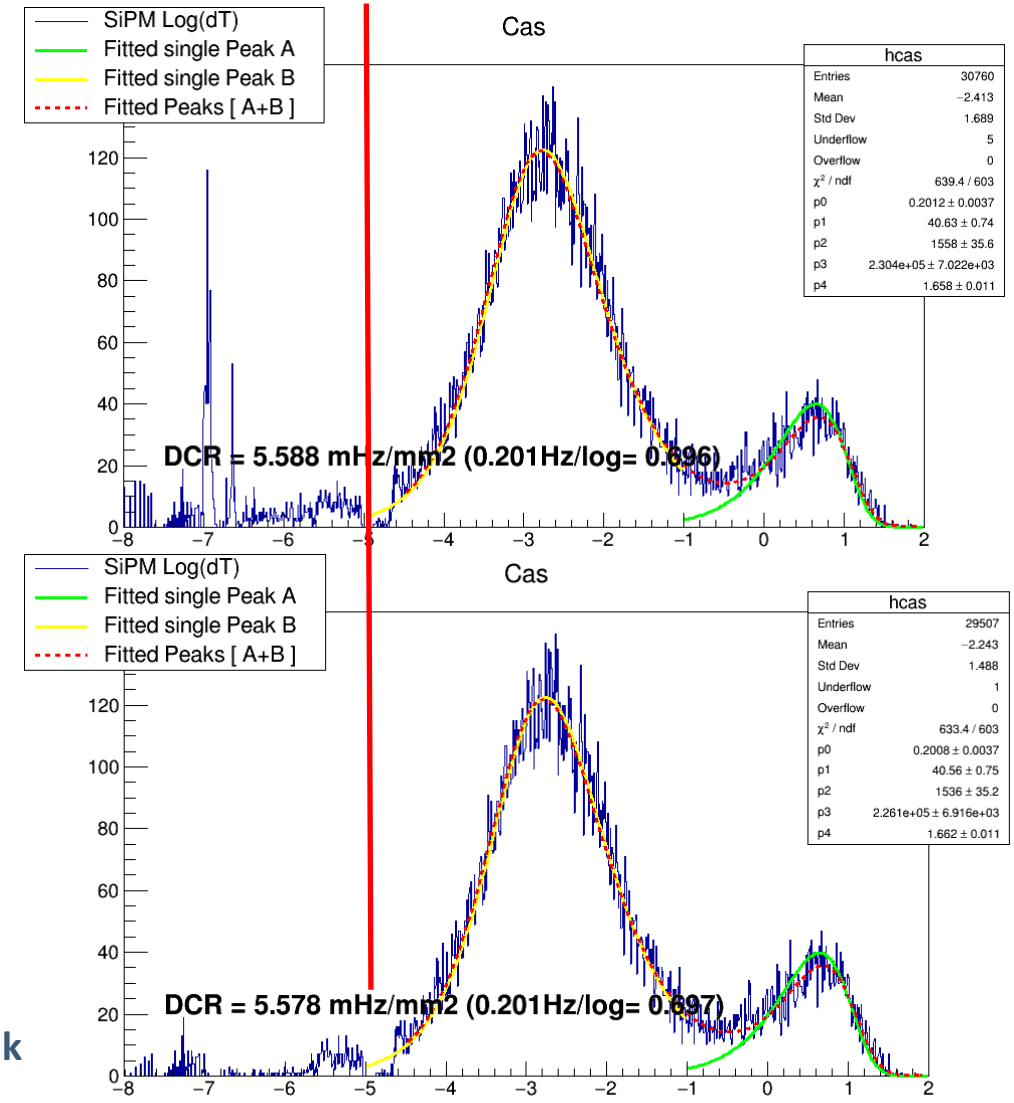
Crosstalk with Bursts		DCR without Bursts
10.50		11.40
9.20		14.50
9.70		15.90
9.00		13.20
9.20		15.80
9.22		16.50
9.29		16.00
9.15		15.90
9.03		15.10
9.13		14.90
9.50		15.20
7.27		14.60
8.67		16.04
9.14		15.00
7.8%		9.3%

3V (PDE 50%)



DCR – After pulses [%] (HRQ-6075HS @Prague)

All noise		Noise filtering Int(sig)> 0.75*Int(1pe)
3.20		1.51
7.82		2.70
7.50		2.60
12.60		2.37
6.63		2.46
9.51	3V (PDE 50%)	2.56
7.35		2.27
4.63		2.60
5.93		2.91
4.50		2.21
7.50		2.67
6.18		2.21
10.78		2.86
7.23		2.47
37.5%		15.2%

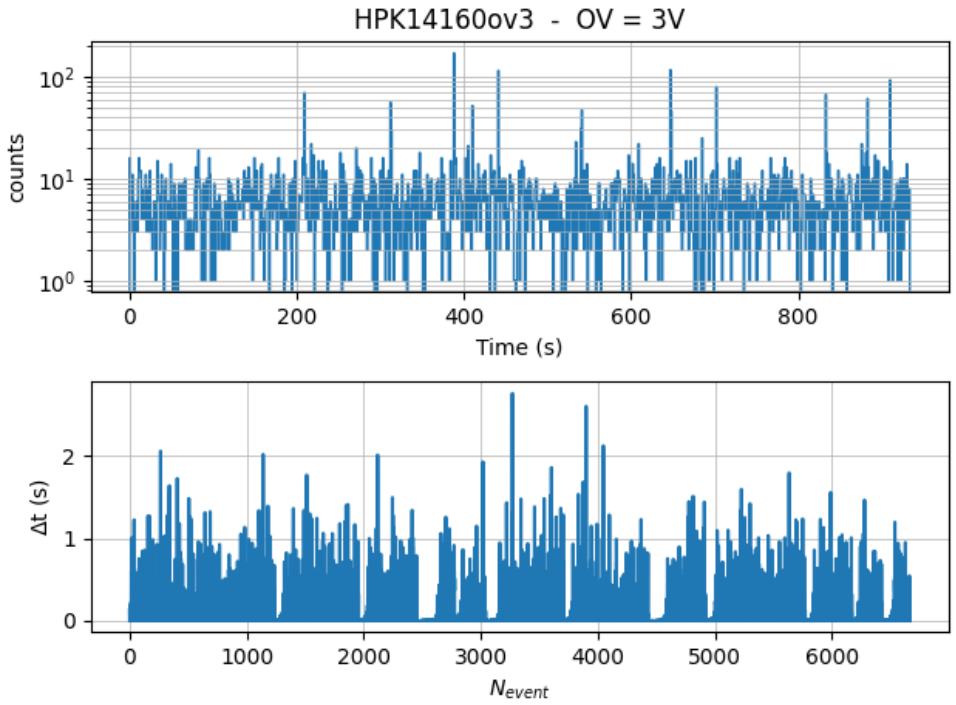


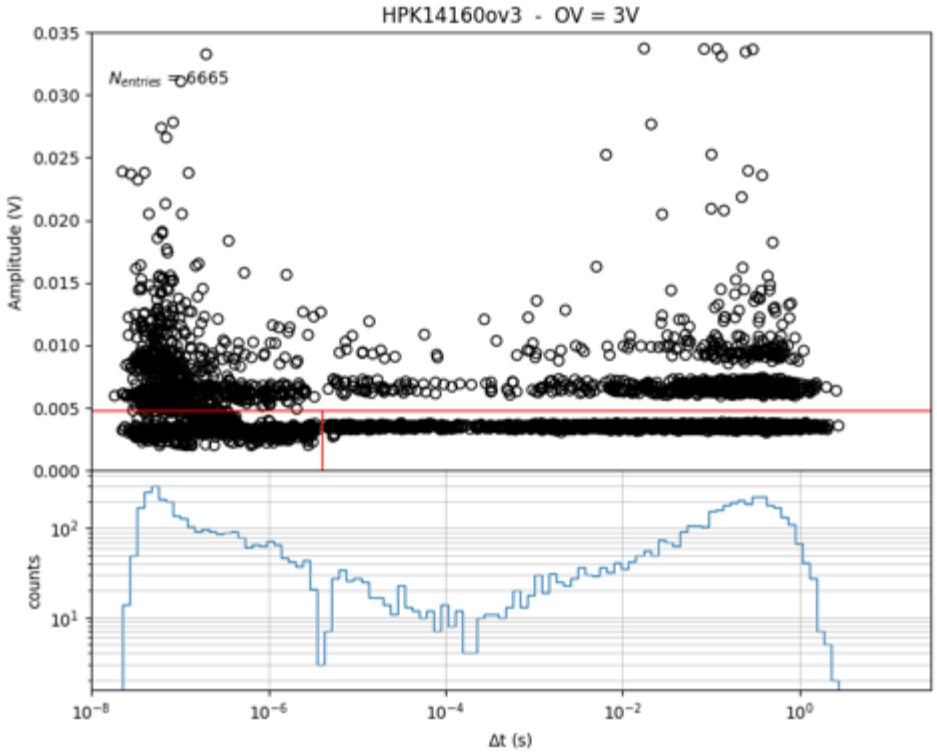
*more results from Prague in the following talk

DCR measurements (HPK14160 @Ferrara)

DCR measurements at 3 OV

- V_{bd} = (31.5 ± 0.1) V
- R_q = (84.1 ± 0.2) Ω
- **DCR** = (117 ± 1) mHz/mm^2





*both saturating events and bursts are present here

*more on bursts: Understanding the Bursts of Events observed in Dark Current Measurements for SiPM Detectors, A. Minotti talk.

Time stability of DCR@M-Bicocca

On 30th Oct. 2020 in MiB we started a long-term test with one S13360-HQR.

We performed this measurement in the **Bicocca Cryogenics Laboratory,** which is a clean environment for e.m. pickup; dark room and cryogenic infrastructures; all instruments after an UPS+ e.m. filter.

To further remove ambient light, we wrapped the SiPM with an aluminum foil and black insulating tape

Unluckily we had 2 black-outs in Mib (9th Dec and 7th Jen), so the SiPM went out.

The thermal condition did not change, since we did not remove the device from LN bath.

Time stability of DCR

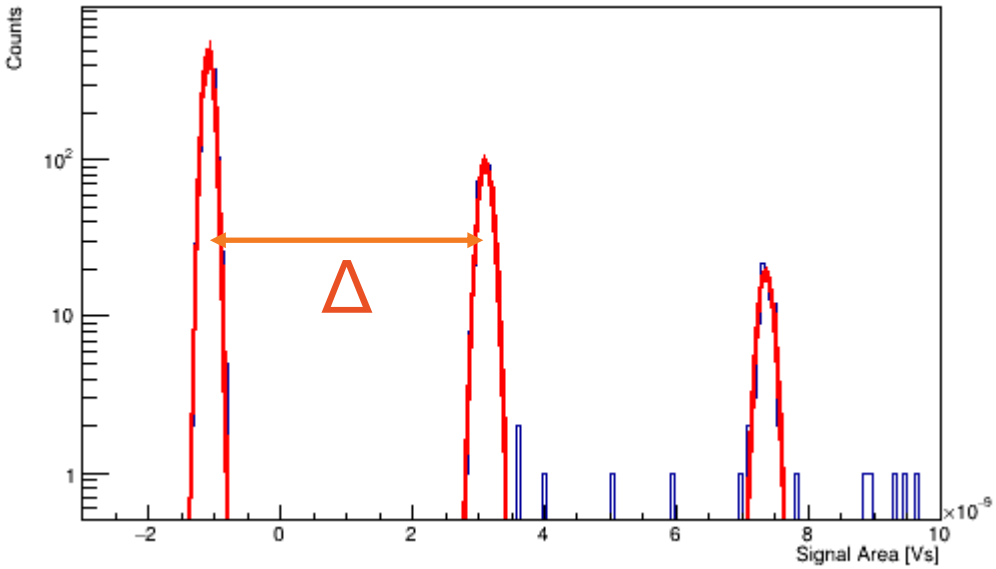
(mHz/mm^2)	with bursts	without bursts
30/10/2020	40.76	5.06
03/11/2020	25.70	3.08
10/11/2020	28.14	3.34
13/11/2020	24.67	2.92
20/11/2020	30.77	3.55
25/11/2020	29.96	2.58
27/11/2020	28.18	2.75
04/12/2020	24.60	3.39
10/12/2020	54.11	4.33
18/12/2020	23.84	3.51
22/12/2020	42.53	3.13
30/12/2020	43.70	4.06
08/01/2021	26.83	4.03
15/01/2021	22.57	5.72
22/01/2021	31.15	3.05

No evidence of DCR increase with time.

SiPM tests summary

- I-V curve
- Gain
- Noise (correlated and dark)
- S/N

S/N ratio



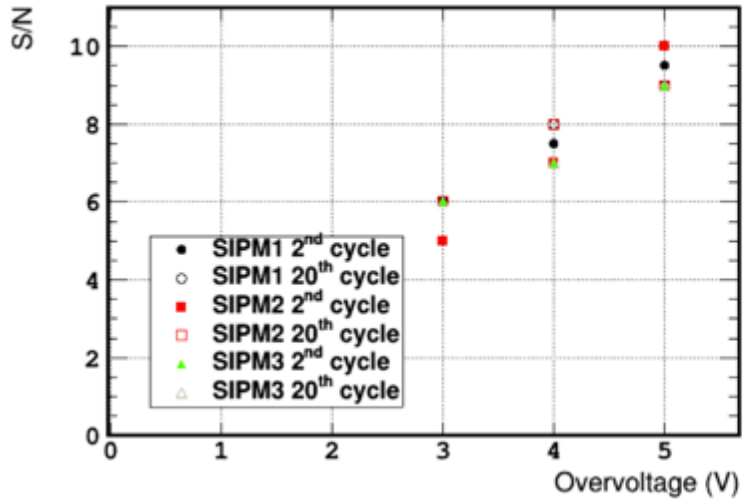
To measure the S/N ratio, the same waveforms collected for the gain were used.

Three S/N definition have been considered:

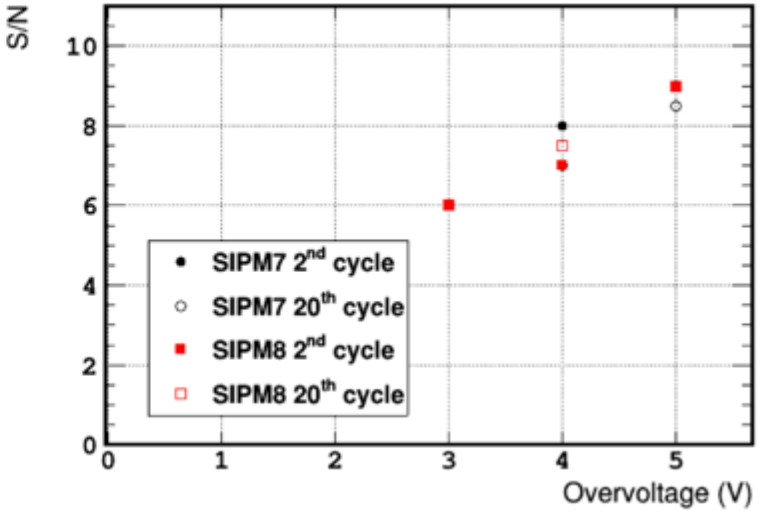
- S/N 1 = Δ/σ_{1pe}
- S/N 2 = Δ/σ_{0pe}
- S/N 3 = $\Delta/\sqrt{[(\sigma_{1pe})^2+(\sigma_{0pe})^2]}$

S/N vs ov (6050HS-HRQ/LRQ & 6075HS-LRQ @CIEMAT-Madrid

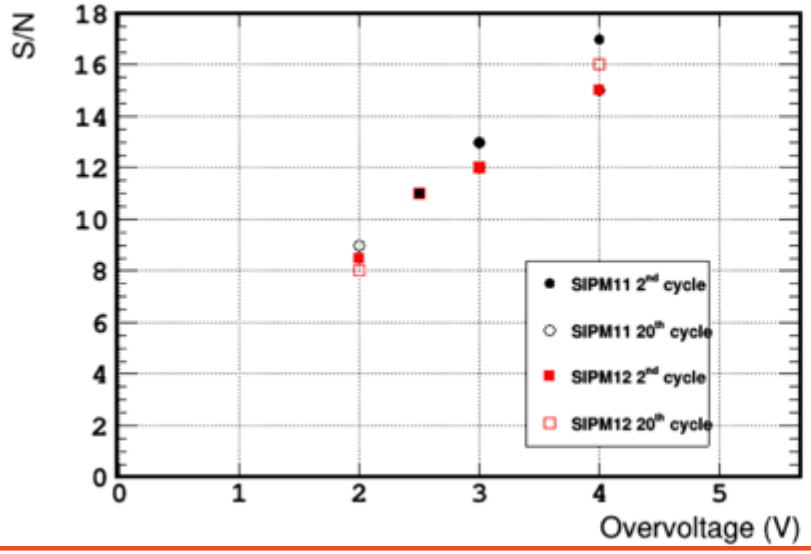
6050HS-HRQ

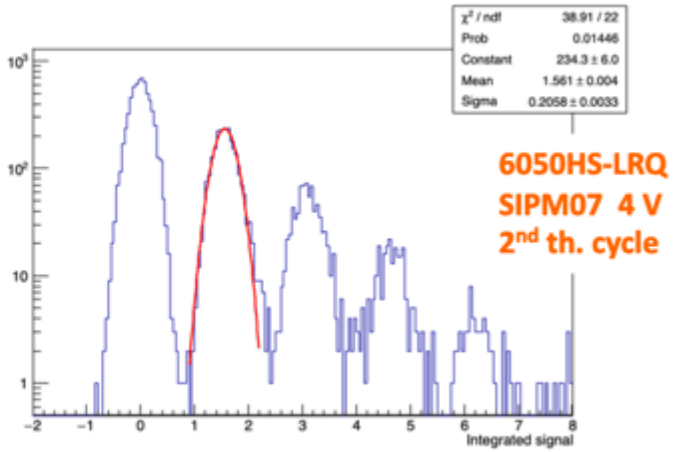


6050HS-LRQ



6075HS-LRQ





Global Results for Hamamatsu

from Antonio Verdugo (CIEMAT)

Global Results – GAIN differences

Institute Gain / HPK Nominal Gain @OV3				
	HR50	LR50	HR75	LR75
M-Biccoca	2,65	2,23	1,23	
Ciemat-Madri	1,33	1,42		1,32
IFIC-Valencia	1,26	1,36		1,26
Ferrara		0,79		0,64
FZU-Prague			1,69	
NIU			1,19	

Gain at each institute dived by Hamamatsu Nominal Gain at OV3

Pixel size (µm)	PDE	Gain
50	40	1,70E+06
75	50	4,00E+06

Hamamatsu Nominal gains (OV=3 and 25ºC)

- Last results from Milano for HR75 shows a gain similar to the other institutes

Global Results – After pulses

			Cycle 2		Cycle 20		Diff (%)
Model	# SiPMs	PDE (%)	Afterpulses(%)		Afterpulses(%)		
			Mean	Std Dev	Mean	Std Dev	
HR-50	25	40	1,27	0,13	2,06	0,16	62,81
		45	1,94	0,14	3,50	0,19	79,92
		50	2,12	0,17	3,95	0,21	86,34
LR-50	20	40	0,09	0,03	2,15	0,15	2170,24
		45	0,10	0,03	2,62	0,17	2529,53
		50	0,27	0,04	5,13	0,21	1820,27
HR-75	3	40	2,30	1,49	1,63	0,44	-29,32
		45	3,12	1,56	2,35	0,66	-24,86
		50	3,92	1,31	2,78	0,23	-29,06
LR-75	12	40	1,03	0,17	1,41	0,15	36,27
		45	2,39	0,29	1,83	0,16	-23,42
		50	2,85	0,26	2,96	0,18	3,88

- Slightly better on 75µm SiPMs.
- No clear difference between HR-75 and LR-75, against expected.

Global Results – Crosstalk

			Cycle 2		Cycle 20		Diff (%)
Model	# SiPMs	PDE (%)	Xtalk (%)		Xtalk (%)		
			Mean	Std Dev	Mean	Std Dev	Mean
HR-50	25	40	7,49	0,35	7,15	0,34	-4,50
		45	8,86	0,33	8,71	0,34	-1,69
		50	11,38	0,37	10,92	0,36	-4,05
LR-50	20	40	10,38	0,35	9,96	0,47	-4,00
		45	9,95	0,39	11,23	0,39	12,87
		50	11,15	0,36	13,38	0,37	20,05
HR-75	3	40	6,07	0,79	6,16	0,05	1,42
		45	7,78	0,55	7,03	0,30	-9,64
		50	8,82	0,66	9,85	0,14	11,63
LR-75	12	40	8,91	0,39	9,47	0,32	6,30
		45	11,62	0,52	10,18	0,35	-12,44
		50	14,34	0,52	11,84	0,34	-17,46

- Best HR-75 and worst LR-50

Global Results – DCR with Bursts

			Cycle 2		Cycle 20		Diff (%)
Model	# SiPMs	PDE (%)	DCR + B (mHz/mm²)		DCR + B (mHz/mm²)		
			Mean	Std Dev	Mean	Std Dev	Mean
HR-50	19	40	70,65	1,65	38,74	0,98	-45,16
		45	82,28	2,39	81,57	1,68	-0,85
		50	64,75	1,74	53,25	0,92	-17,75
LR-50	21	40	57,80	1,03	54,08	0,96	-6,43
		45	58,36	1,26	60,29	1,06	3,30
		50	65,09	1,34	71,92	1,01	10,49
HR-75	3	40	29,79	3,76	26,33	2,20	-11,59
		45	32,43	5,01	27,77	0,80	-14,37
		50	34,18	2,74	31,73	5,36	-7,14
LR-75	12	40	58,87	1,94	42,14	0,65	-28,43
		45	54,10	22,94	50,70	0,75	-6,29
		50	69,12	2,20	50,88	0,68	-26,39

- Best HR-75 and worst LR-50

Global Results – DCR without Bursts

			Cycle 2		Cycle 20		Diff (%)
Model	# SiPMs	PDE (%)	DCR -B (mHz/mm²)		DCR -B (mHz/mm²)		
			Mean	Std Dev	Mean	Std Dev	Mean
HR-50	25	40	22,86	1,32	7,36	0,83	-67,81
		45	23,51	1,85	8,73	0,68	-62,86
		50	22,23	1,20	9,65	0,46	-56,60
LR-50	15	40	12,21	0,51	12,79	0,67	4,77
		45	11,51	0,61	13,70	0,70	19,01
		50	20,27	0,92	16,62	0,85	-17,99
HR-75	3	40	5,11	0,67	4,60	0,24	-9,86
		45	5,75	0,67	5,57	0,17	-3,17
		50	6,27	0,57	6,46	0,73	2,98
LR-75	12	40	8,00	0,76	6,10	0,32	-23,70
		45	8,99	1,42	6,58	0,34	-26,83
		50	11,87	1,06	9,07	0,41	-23,56

- Best HR-75 and worst LR-50

Figures of merit results

- Gain vs correlated noise: G / (XT + AP) x 1000
- Gain vs DC with bursts: G / DC(with B) x 1000
- Gain vs DC without bursts: G / DC(without B) x 1000

➢ To avoid the bias introduced by the gain differences between institutes I have used the HPK nominal gains at room temperature for this calculation.

Pixel size (µm)	OV/PDE(%)	Gain
50	5/50	2,80E+06
75	3/50	4,00E+06

HPK nominal gains
(from datasheet)

Model	PDE (%)	G vs CN	G vs DCR + B	G vs DCR - B
HR-50	50	207,36	43,25	125,96
LR-50	50	245,31	43,02	138,14
HR-75	50	313,98	81,93	446,22
LR-75	50	232,67	40,51	235,96

Results with data from cycle 2

Model	PDE (%)	G vs CN	G vs DCR + B	G vs DCR - B
HR-50	50	188,25	52,58	290,25
LR-50	50	151,24	38,93	168,45
HR-75	50	316,78	86,06	433,32
LR-75	50	270,30	55,03	308,70

Results with data from cycle 20

Global Results for FBK

Global Results – GAIN differences

			LN2 - First cycle		LN2 - Last cycle(20)		
Model	#SiPM	PDE(%)	Gain		Gain		DIFF %
			STD	MEAN	STD	MEAN	
NUV-HD-Cryo	23	40	2.99E+06	2.64E+06	2.15E+06	2.97E+06	-12.71
		45	3.51E+06	3.13E+06	2.52E+06	3.56E+06	-13.45
		50	4.03E+06	3.63E+06	2.91E+06	3.37E+06	7.19
Triple Trench	29	40	3.85E+06	3.20E+06	2.72E+06	3.25E+06	-1.48
		45	4.52E+06	3.78E+06	3.20E+06	3.84E+06	-1.76
		50	5.21E+06	4.45E+06	3.71E+06	4.71E+06	-5.90

Model	PDE (%)	FBK results	Our results
NUV-HD-Cryo	40	1.88E+06	2.97E+06
	45	2.25E+06	3.56E+06
	50	2.68E+06	3.37E+06

Can't compare TT results from FBK yet, we're going to perform further gain measurements in the next few weeks.

Global Results – Correlated noise

			LN2 - First cycle		LN2 - Last cycle(20)		
Model	#SiPM	PDE(%)	After pulses (%)		After pulses (%)		DIFF %
			STD	MEAN	STD	MEAN	
NUV-HD-Cryo	23	40	0.23	1.82	2.16	2.29	-25.93
		45	0.38	2.31	0.95	1.96	15.02
Triple Trench	29	40	0.68	1.77	0.08	1.24	30.08
		45	0.04	1.75	0.45	1.50	14.42

			LN2 - First cycle		LN2 - Last cycle(20)		
Model	#SiPM	PDE(%)	Xtalk (%)		Xtalk (%)		DIFF %
			STD	MEAN	STD	MEAN	
NUV-HD-Cryo	23	40	5.37	20.82	7.49	23.20	-11.42
		45	5.45	25.64	4.50	23.67	7.67
		50			2.69	26.72	
Triple Trench	29	40	0.03	10.65	2.27	10.65	0.03
		45	0.65	14.19	2.31	12.93	8.91

Global Results – DCR with/without bursts

			LN2 - First cycle		LN2 - Last cycle(20)		
Model	#SiPM	PDE(%)	DCR+burst (mHz/mm²)		DCR+burst (mHz/mm²)		DIFF %
			STD	MEAN	STD	MEAN	
NUV-HD-Cryo	23	40	77.80	106.99	45.62	93.91	12.22
		45	83.11	103.23	61.30	113.39	-9.84
		50			78.73	118.90	
Triple Trench	29	40	60.69	91.08	52.16	85.12	6.55
		45	57.14	94.60	52.04	82.62	12.66

			LN2 - First cycle		LN2 - Last cycle(20)		
Model	#SiPM	PDE(%)	DCR-burst (mHz/mm²)		DCR-burst (mHz/mm²)		DIFF %
			STD	MEAN	STD	MEAN	
NUV-HD-Cryo	23	40	0.10	23.13	6.34	23.11	0.09
		45	2.06	23.12	5.53	22.50	2.69
		50			3.34	29.36	
Triple Trench	29	40	4.17	25.58	6.89	22.58	11.75
		45	5.56	24.93	8.01	22.87	8.30

Conclusions

There are not significant differences on measurements results and all the SiPM models fulfill the DUNE specifications.

For **Hamamatsu**, both 75µ SiPMs show better figures of merit than 50µ SiPMs because of the higher gain for the same PDE while keeping similar or lower values of XT, AP and DCR.

Comparing both 75µ SiPMs, the HR-75 have better results than LR-75 in terms of XT and DCR.

Everything considered, best model for HPK is HR-75.

For **FBK**, we're going to perform further gain measurements on Triple Trench in the next few weeks.

Anyway, at the current status of the tests, Triple Trench is preferred since it shows better performance in terms of dark rate and correlated noise (especially crosstalk)