

Characterization of irradiated SiPM for the TOP detector at the Belle II experiment

Padova meeting 28/3/2024

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Content



Done:

- Irradiated SiPM modules in Padova
- Gain as function of bias voltage
- Gain as function of overvoltage
- Comparison time resolutions (for Markov and simple algorithms):
 - First, second, third and others (including second and third) using recognized spectra
 - All photon peaks using unrecognized spectra
- Darkcount rates for SiPMs Preliminary (Missing and no-processed data)
- Change parameters in Markov algorithm and share them Backup
- Update table with fitted breakdown voltages and slope with uncertainties

To Do:

- Add fitted spectra (one bias voltage ~ 1.0 per temperature per SiPM)
- Check results and provide better fits if needed
- Irradiation campaign in Legnaro from 22th to 24th April 2024

Tests with irradiated modules in Padova



- In Belle II, MCP-PMTs with extended lifetime have been installed and they have limited lifetime depending on accumulated charge.
- We are trying to understand if they eventually can be replaced with SiPMs.
- We irradiated 24 SiPMs modules with different neutron fluxes and tested by laser.
- Eight of them are processed to study their response.
- Collected data are read from modules and analyzed.

_	Inder	Producer	Dimension	Pitch	h Distance Neutron 1 MeV		Charge	Time
	Index		$[mm \times mm]$	$[\mu m]$	[cm]	$\rm eg/cm^2$ fluence	[mC]	[h]
	8	FBK	3×3	15	18.36	$1.0 \cdot 10^{10}$	2.86	5.88
	9	FBK	3×3	15	18.24	$5.0 \cdot 10^{9}$	1.41	2.90
	10	FBK	3×3	15	33.24	$1.0 \cdot 10^{9}$	0.94	1.93
	11	FBK	1×1	15	15.86	$2.0 \cdot 10^{10}$	4.26	8.77
	12	FBK	1×1	15	30.86	$1.0 \cdot 10^{10}$	8.07	16.61
	13	FBK	1×1	15	15.74	$5.0 \cdot 10^9$	1.05	2.16
	14	FBK	1×1	15	30.74	$1.0.10^{9}$	0.80	1.65
	15	Hamamatsu	3×3	50	33.46	$1.0 \cdot 10^{9}$	0.95	1.95 3
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Breakdown voltages at temperatures for SiPMs

Index of SiPM		11	12	13	14	15
Producer		FBK	FBK	FBK	FBK	Hamamatsu
Dimension [mm×mm]		1×1	1×1	1×1	1×1	3×3
Pitch $[\mu m]$		15	15	15	15	50
Temperature		Breakdown	Breakdown	Breakdown	Breakdown	Breakdown
[°C]	Status	voltage [V ₀]				
	No-irradiated	32.36 ± 0.80	32.70 ± 0.84	32.24 ± 1.16	32.43 ± 1.88	38.10 ± 2.24
20	Irradiated	32.55 ± 1.75	32.03 ± 0.27	31.87 ± 0.49	32.13 ± 0.75	37.57 ± 0.98
	Annealed	32.29 ± 0.66	32.14 ± 0.57	31.91 ± 0.65	32.19 ± 0.75	38.00 ± 0.93
	No-irradiated	33.72 ± 1.98	32.39 ± 0.51	31.71 ± 0.82	32.17 ± 1.52	38.31 ± 2.24
10	Irradiated	32.13 ± 1.25	31.87 ± 0.35	31.36 ± 0.57	31.86 ± 0.32	37.22 ± 0.48
	Annealed	32.00 ± 1.03	31.91 ± 0.67	31.52 ± 0.61	32.16 ± 0.53	37.46 ± 1.03
	No-irradiated	31.43 ± 1.41	32.07 ± 1.22	31.33 ± 1.68	31.87 ± 1.40	38.34 ± 8.88
0	Irradiated	28.79 ± 2.70	31.21 ± 0.53	31.30 ± 0.41	31.52 ± 0.34	36.98 ± 0.52
	Annealed	31.63 ± 0.65	31.57 ± 0.37	31.49 ± 0.38	31.54 ± 0.53	37.19 ± 0.53
	No-irradiated	30.61 ± 2.58	31.65 ± 1.45	31.31 ± 0.82	31.64 ± 1.05	37.25 ± 9.79
-10	Irradiated	31.65 ± 0.63	31.24 ± 0.42	30.94 ± 0.36	31.29 ± 0.32	36.63 ± 0.31
	Annealed	31.38 ± 0.42	31.26 ± 0.46	30.95 ± 0.41	31.18 ± 0.67	36.67 ± 1.02
	No-irradiated	31.79 ± 1.59	31.18 ± 1.52	30.70 ± 0.98	31.13 ± 2.00	37.92 ± 6.71
-20	Irradiated	30.95 ± 0.53	30.92 ± 0.30	30.61 ± 0.33	30.94 ± 0.50	36.19 ± 0.82
	Annealed	30.85 ± 0.86	30.94 ± 0.25	30.66 ± 0.38	30.71 ± 0.42	36.25 ± 1.62
	No-irradiated	31.45 ± 0.62	31.33 ± 0.60	30.87 ± 0.81	30.91 ± 0.99	36.17 ± 1.42
-30	Irradiated	30.48 ± 0.37	30.61 ± 0.40	30.43 ± 0.32	30.50 ± 0.83	35.80 ± 0.46
	Annealed	30.19 ± 1.78	30.61 ± 0.27	30.43 ± 0.52	30.37 ± 1.05	36.20 ± 0.98
	No-irradiated	30.66 ± 3.92	30.96 ± 0.35	30.61 ± 0.28	30.84 ± 0.71	34.55 ± 5.39
-35	Irradiated	30.58 ± 0.48	30.47 ± 0.43	30.21 ± 0.37	30.08 ± 1.45	35.57 ± 0.58
	Annealed	30.45 ± 1.61	30.43 ± 0.40	30.32 ± 0.40	30.27 ± 1.33	35.68 ± 1.75
40	No-irradiated	30.71 ± 0.70	30.68 ± 0.46	30.16 ± 0.97	30.65 ± 0.58	35.71 ± 0.84
-40	Irradiated	30.19 ± 0.79	30.54 ± 0.61	30.14 ± 0.45	30.35 ± 0.28	36.59 ± 2.63



- For Hamamatsu device the breakdown voltages agree with previous measurements
- For some FBK devices, the breakdown voltages do not agree with previous measurements.
- After finishing studies related to breakdown voltage, we will continue with extraction time resolution

Slopes at temperatures for SiPMs



Index of SiPM		11	12	13	14	15
Producer		FBK	FBK	FBK	FBK	Hamamatsu
Dimension [mm×mm]		1×1	1×1	1×1	1×1	3×3
Pitch	Pitch [µm]		15	15	15	50
Temperature	Temperature					
[°C]	Status	Slope	Slope	Slope	Slope	Slope
	No-irradiated	2.815 ± 0.045	4.215 ± 0.070	3.894 ± 0.091	3.822 ± 0.144	5.050 ± 0.201
20	Irradiated	2.098 ± 0.072	3.739 ± 0.020	3.526 ± 0.034	3.490 ± 0.051	4.633 ± 0.081
	Annealed	4.342 ± 0.057	4.376 ± 0.049	4.267 ± 0.055	4.348 ± 0.064	6.301 ± 0.103
	No-irradiated	4.546 ± 0.179	4.101 ± 0.042	3.670 ± 0.061	3.787 ± 0.116	6.023 ± 0.240
10	Irradiated	3.043 ± 0.075	3.771 ± 0.026	3.388 ± 0.038	3.458 ± 0.022	4.709 ± 0.040
	Annealed	4.317 ± 0.088	4.366 ± 0.058	4.158 ± 0.050	4.460 ± 0.047	6.131 ± 0.113
	No-irradiated	2.754 ± 0.080	4.003 ± 0.100	3.522 ± 0.122	3.707 ± 0.106	6.928 ± 1.103
0	Irradiated	1.454 ± 0.081	3.563 ± 0.038	3.443 ± 0.028	3.405 ± 0.023	4.917 ± 0.046
	Annealed	4.217 ± 0.054	4.282 ± 0.031	4.249 ± 0.032	4.201 ± 0.044	6.239 ± 0.060
	No-irradiated	2.188 ± 0.118	3.856 ± 0.116	3.606 ± 0.061	3.764 ± 0.081	4.764 ± 0.850
-10	Irradiated	2.757 ± 0.035	3.661 ± 0.031	3.353 ± 0.025	3.383 ± 0.022	4.950 ± 0.028
	Annealed	4.194 ± 0.036	4.236 ± 0.039	4.058 ± 0.034	4.101 ± 0.055	6.076 ± 0.113
	No-irradiated	2.798 ± 0.092	3.657 ± 0.116	3.365 ± 0.069	3.486 ± 0.145	6.756 ± 0.820
-20	Irradiated	2.668 ± 0.029	3.580 ± 0.021	3.287 ± 0.022	3.291 ± 0.033	4.876 ± 0.073
	Annealed	4.023 ± 0.069	4.148 ± 0.021	4.002 ± 0.031	3.950 ± 0.033	5.975 ± 0.176
	No-irradiated	3.000 ± 0.038	3.992 ± 0.050	3.700 ± 0.063	3.654 ± 0.075	5.191 ± 0.137
-30	Irradiated	2.384 ± 0.018	3.509 ± 0.028	3.267 ± 0.021	3.159 ± 0.054	4.853 ± 0.041
	Annealed	3.764 ± 0.137	4.066 ± 0.023	3.970 ± 0.042	3.874 ± 0.083	6.349 ± 0.114
	No-irradiated	2.315 ± 0.191	3.792 ± 0.028	3.578 ± 0.021	3.658 ± 0.054	4.031 ± 0.412
-35	Irradiated	2.435 ± 0.024	3.472 ± 0.031	3.207 ± 0.024	3.025 ± 0.090	4.808 ± 0.052
	Annealed	3.923 ± 0.129	4.013 ± 0.033	3.953 ± 0.032	3.873 ± 0.105	5.914 ± 0.191
40	No-irradiated	3.077 ± 0.044	4.217 ± 0.040	3.808 ± 0.079	4.021 ± 0.049	5.952 ± 0.092
-40	Irradiated	1.900 ± 0.031	3.547 ± 0.045	3.201 ± 0.030	3.170 ± 0.018	6.098 ± 0.294



SiMP #11



Gain as function of bias voltage for SiPM #11









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Vbias







Gain as function of overvoltage for SiPM #11









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Time resolution for first photon peak for SiPM #11



Time resolution of first peak for SiPM #11 at 20°



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Time resolution of first peak for SiPM #11 at 0°



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Time resolution of first peak for SiPM #11 at -20°



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Time resolution of first peak for SiPM #11 at -35°



Time resolution for second photon peak for SiPM #11



Time resolution of second peak for SiPM #11 at 20°



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Time resolution of second peak for SiPM #11 at 0°



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Time resolution of second peak for SiPM #11 at -20°



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Time resolution of second peak for SiPM #11 at -35°



Time resolution for third photon peak for SiPM #11



Time resolution of third peak for SiPM #11 at 20°



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Time resolution of third peak for SiPM #11 at 0°



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Time resolution of third peak for SiPM #11 at -20°



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Time resolution of third peak for SiPM #11 at -35°





Time resolution for other photon peaks for SiPM #11



33

Time resolution of other peaks for SiPM #11 at 20°





Time resolution of other peaks for SiPM #11 at 0°



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Time resolution of other peaks for SiPM #11 at -20°



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Time resolution of other peaks for SiPM #11 at -35°




Dark count rate for SiPM #11

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Dark count rate for SiPM #11 at -20°



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SiMP #12

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Gain as function of bias voltage for SiPM #12

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Vbias















Gain as function of overvoltage for SiPM #12

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Time resolution for first photon peak for SiPM #12



Time resolution of first peak for SiPM #12 at 20°



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Time resolution of first peak for SiPM #12 at 0°



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Time resolution of first peak for SiPM #12 at -20°



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Time resolution of first peak for SiPM #12 at -35°





Time resolution for second photon peak for SiPM #12



Time resolution of second peak for SiPM #12 at 20°



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Time resolution of second peak for SiPM #12 at 0°



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Time resolution of second peak for SiPM #12 at -20°



Jakub Kandra, INFN Padova



Time resolution of second peak for SiPM #12 at -35°





Time resolution for third photon peak for SiPM #12



Time resolution of third peak for SiPM #12 at 20°



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Time resolution of third peak for SiPM #12 at 0°



Jakub Kandra, INFN Padova



Time resolution of third peak for SiPM #12 at -20°



Jakub Kandra, INFN Padova



Time resolution of third peak for SiPM #12 at -35°





Time resolution for other photon peaks for SiPM #12



Time resolution of other peaks for SiPM #12 at 20°



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Time resolution of other peaks for SiPM #12 at 0°



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Time resolution of other peaks for SiPM #12 at -20°



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Time resolution of other peaks for SiPM #12 at -35°




Dark count rate for SiPM #12



74







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Dark count rate for SiPM #12 at -20°



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SiMP #13



Gain as function of bias voltage for SiPM #13













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Gain as function of overvoltage for SiPM #13

Gain as function of overvoltage for SiPM #13 at temperature 20





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Time resolution for first photon peak for SiPM #13



Time resolution of first peak for SiPM #13 at 20°



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Time resolution of first peak for SiPM #13 at 0°





Time resolution of first peak for SiPM #13 at -20°





Time resolution of first peak for SiPM #13 at -35°





Time resolution for second photon peak for SiPM #13



Time resolution of second peak for SiPM #13 at 20°



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Time resolution of second peak for SiPM #13 at 0°



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Time resolution of second peak for SiPM #13 at -20°



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Time resolution of second peak for SiPM #13 at -35°





Time resolution for third photon peak for SiPM #13



100

Time resolution of third peak for SiPM #13 at 20°





101

Time resolution of third peak for SiPM #13 at 0°





102

Time resolution of third peak for SiPM #13 at -20°





Time resolution of third peak for SiPM #13 at -35°





Time resolution for other photon peaks for SiPM #13



105

Time resolution of other peaks for SiPM #13 at 20°





106

Time resolution of other peaks for SiPM #13 at 0°





107

Time resolution of other peaks for SiPM #13 at -20°





Time resolution of other peaks for SiPM #13 at -35°




Dark count rate for SiPM #13



110





111

Dark count rate for SiPM #13 at 0°





112

Dark count rate for SiPM #13 at -20°





Dark count rate for SiPM #13 at -35°





SiMP #14



Gain as function of bias voltage for SiPM #14





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V_{bias}







Gain as function of overvoltage for SiPM #14



















Time resolution for first photon peak for SiPM #14



Time resolution of first peak for SiPM #14 at 20°



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127

Time resolution of first peak for SiPM #14 at 0°





Time resolution of first peak for SiPM #14 at -20°



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Time resolution of first peak for SiPM #14 at -35°





Time resolution for second photon peak for SiPM #14



131

Time resolution of second peak for SiPM #14 at 20°





Time resolution of second peak for SiPM #14 at 0°





133

Time resolution of second peak for SiPM #14 at -20°





Time resolution of second peak for SiPM #14 at -35°





Time resolution for third photon peak for SiPM #14



136

Time resolution of third peak for SiPM #14 at 20°





137

Time resolution of third peak for SiPM #14 at 0°





138

Time resolution of third peak for SiPM #14 at -20°





Time resolution of third peak for SiPM #14 at -35°





Time resolution for other photon peaks for SiPM #14



Time resolution of other peaks for SiPM #14 at 20°





Time resolution of other peaks for SiPM #14 at 0°



142



143







Time resolution of other peaks for SiPM #14 at -35°




Dark count rate for SiPM #14



Dark count rate for SiPM #14 at 20°





147

Dark count rate for SiPM #14 at 0°





Dark count rate for SiPM #14 at -20°



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SiMP #15



Gain as function of bias voltage for SiPM #15





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V_{bias}





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Gain as function of overvoltage for SiPM #15

















Time resolution for first photon peak for SiPM #15



Time resolution of first peak for SiPM #15 at 20°





Time resolution of first peak for SiPM #15 at 0°



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164

Time resolution of first peak for SiPM #15 at -20°





Time resolution of first peak for SiPM #15 at -35°





Time resolution for second photon peak for SiPM #15



167

0.26 0.22 Non-irradiated by Markov Irradiated by Markov Annealed by Markov 0.24 Non-irradiated by simple Irradiated by simple Annealed by simple 0.20 0.24 0.22 · . : 0.20 0.18 0.22 0.18 0.16 0.16 0.20 0.14 0.14 0.18 ∟ 40.0 0.12 L 40.5 40.5 41.0 41.5 42.0 42.5 41.0 41.5 42.0 42.5 43.0 40.5 41.0 41.5 42.0 42.5 43.0 V_{bias} [V] V_{bias} [V] V_{bias} [V] Time resolution of second peak for SiPM #15 at 10° Non-irradiated by Markov Irradiated by Markov Annealed by Markov 0.28 0.24 0.20 Non-irradiated by simple Irradiated by simple Annealed by simple 0.26 0.22 0.18 0.24 0.20 0.16 0.22 . . 0.20 0.18 0.14 0.18 0.16 ∟ 40.0 0.16 L 0.12 L 40.5 40.5 41.0 41.5 42.0 41.0 41.5 42.0 42.5 43.0 41.0 41.5 42.0 42.5 43.0 V_{bias} [V] V_{bias} [V] V_{bias} [V]

Time resolution of second peak for SiPM #15 at 20°



Time resolution of second peak for SiPM #15 at 0°





Time resolution of second peak for SiPM #15 at -20°



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Time resolution of second peak for SiPM #15 at -35°





Time resolution for third photon peak for SiPM #15



172

Time resolution of third peak for SiPM #15 at 20°





173

Time resolution of third peak for SiPM #15 at 0°





Time resolution of third peak for SiPM #15 at -20°





Time resolution of third peak for SiPM #15 at -35°





Time resolution for other photon peaks for SiPM #15



Time resolution of other peaks for SiPM #15 at 20°





Time resolution of other peaks for SiPM #15 at 10°





179

Time resolution of other peaks for SiPM #15 at -20°





Time resolution of other peaks for SiPM #15 at -35°




Dark count rate for SiPM #15



182





183

Dark count rate for SiPM #15 at 0°





184

Dark count rate for SiPM #15 at -20°









SiMP #8



Time resolution for all photon peaks for SiPM #8



188

Time resolution of all peaks for SiPM #8 at 20°





189

Time resolution of all peaks for SiPM #8 at 0°





190

Time resolution of all peaks for SiPM #8 at -20°





Time resolution of all peaks for SiPM #8 at -35°





Dark count rate for SiPM #8



193





194





195





Dark count rate for SiPM #8 at -35°





SiMP #9



Time resolution for all photon peaks for SiPM #9



199

Time resolution of all peaks for SiPM #9 at 20°





200

Time resolution of all peaks for SiPM #9 at 0°





201

Time resolution of all peaks for SiPM #9 at -20°





Time resolution of all peaks for SiPM #9 at -35°





Dark count rate for SiPM #9



204











206



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SiMP #10



Time resolution for all photon peaks for SiPM #10



Time resolution of all peaks for SiPM #10 at 20°





211

Time resolution of all peaks for SiPM #10 at 0°





212

Time resolution of all peaks for SiPM #10 at -20°





Time resolution of all peaks for SiPM #10 at -35°





Dark count rate for SiPM #10



215





Dark count rate for SiPM #10 at 0°


Dark count rate





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Dark count rate







Backup



Markov parameters tuning using SiPM #14

Background iterated 10 times

amps



times

Difference between background and original waveform

amps

times



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Background iterated 20 times



Difference between background and original waveform



Background iterated 30 times



Difference between background and original waveform



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Background iterated 40 times



Difference between background and original waveform



Background iterated 50 times



Difference between background and original waveform



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Background iterated 60 times





Difference between background and original waveform

Background iterated 70 times

amps



Difference between background and original waveform

times



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Background iterated 80 times



Difference between background and original waveform



Signal waveform extracted using Markov algorithm





Markov parameters tuning using SiPM #15

Background iterated 10 times



Difference between background and original waveform



Signal waveform extracted using Markov algorithm



Background iterated 20 times



Difference between background and original waveform



Signal waveform extracted using Markov algorithm



Background iterated 30 times



Difference between background and original waveform



Background iterated 40 times



Difference between background and original waveform



Background iterated 50 times

amps



Difference between background and original waveform

times



Background iterated 60 times



Difference between background and original waveform



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Background iterated 70 times



Difference between background and original waveform



Signal waveform extracted using Markov algorithm



Background iterated 80 times



Difference between background and original waveform



Signal waveform extracted using Markov algorithm



Fit of photon spectra



SiPM #13 700 events 600 500 Number of 300 200 400600 1400 200Residual of Histogram of ds1_plot_x and Projection of dmodel 60 E Residual 20 - 20 - 40 60 200 400 600 800 1000 1200 1400 Pull of Histogram of ds1_plot_x and Projection of dmodel Pulls 0 200 400 600 800 1000 1200 1400 238

ADC counts [ubits]

• Photon spectra are extracted

- Photon spectra are fitted sum of convolution poissonian and gaussian distribution to extract gain and average of photons
- From gain we can extract breakdown voltage

Fit of time resolution

- Split photon spectra into two regions: first photon peak (green) and other photon peaks (red)
- For #13 SiPMs, we fit first photon peak (green) and all photon peaks (green + red)



