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

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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 SiPM modules with different neutron fluxes and tested by laser.
- Eight of them are processed to study their response.
- We analyze SiPM modules before, after irradiation and after annealing at 150 °C

Index	Producer	Dimension [mm×mm]	Pitch [μm]	Distance [cm]	Neutron 1 MeV eg/cm^2 fluence	Charge [mC]	Time [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	$1.0{\cdot}10^{9}$	0.80	1.65
15	Hamamatsu	3 × 3	50	33.46	$1.0{\cdot}10^{9}$	0.95	1.95

Content

Done:

- Irradiated SiPM modules in Padova
- We process data and extract photon spectra using two different methods:
  - Simple method
  - Markov method removing background from waveform.
- Gain as function of bias voltage for extraction breakdown voltage
- Gain as function of overvoltage (difference between bias and breakdown voltages)
- Table with breakdown voltages and slopes
- Comparison time resolutions (for Markov and simple algorithms):
  - First, second, third and others (including second and third) using recognized spectra
- Darkcount rates for SiPMs

To Do:

- Review current results to fix problematic fits
- Irradiation campaign in Legnaro from 22th to 24th April 2024

Extraction breakdown voltage for SiPM #14

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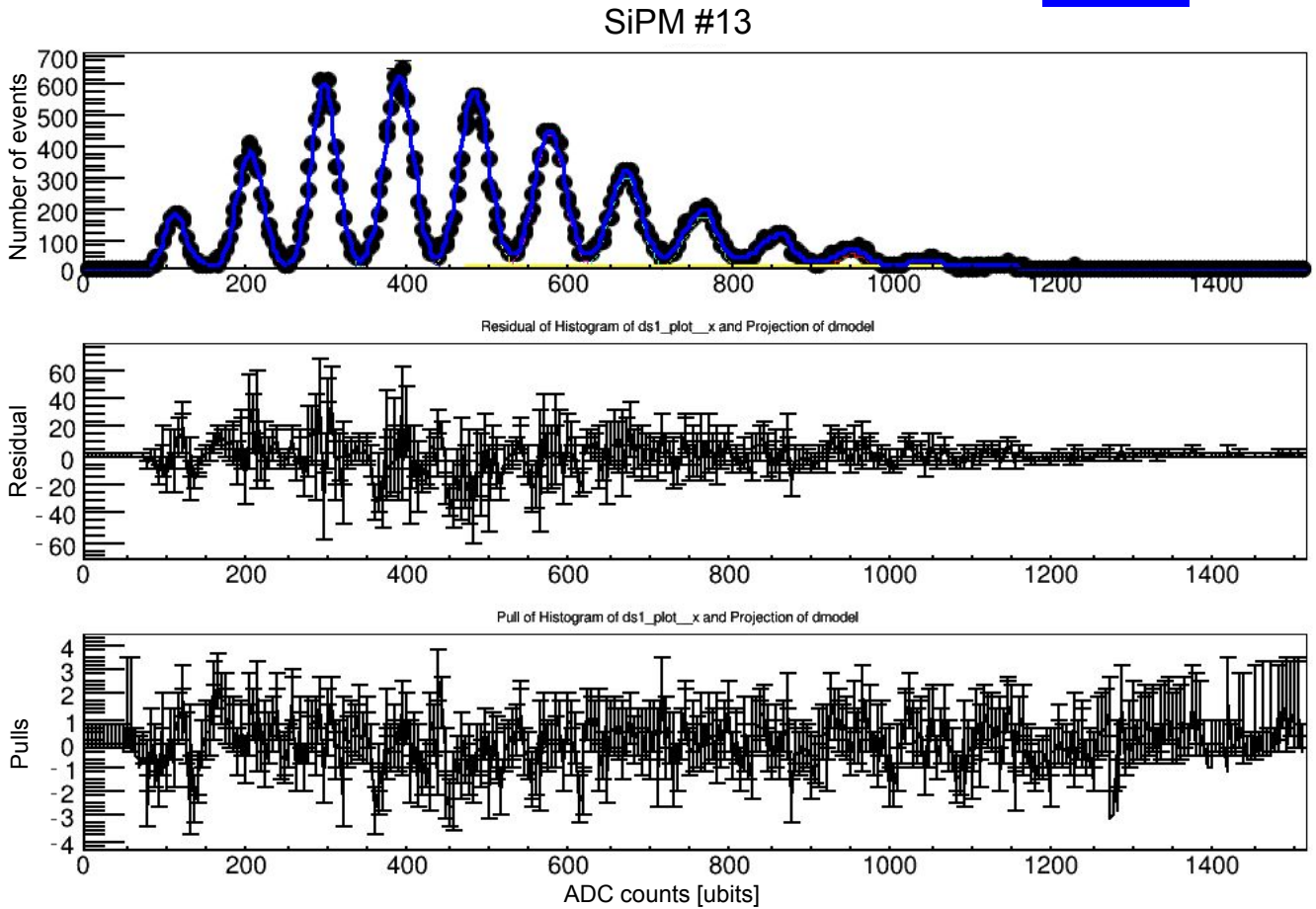
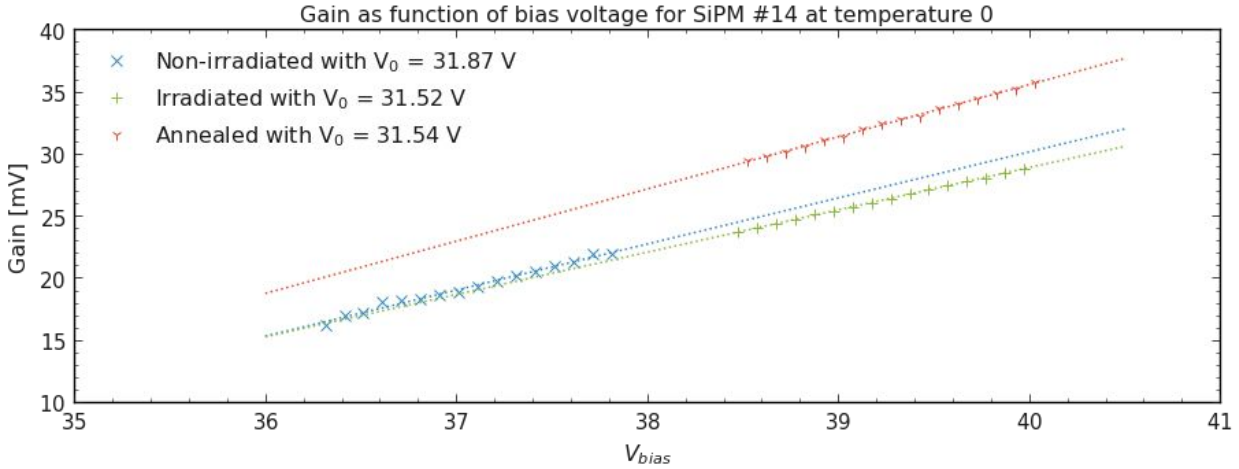
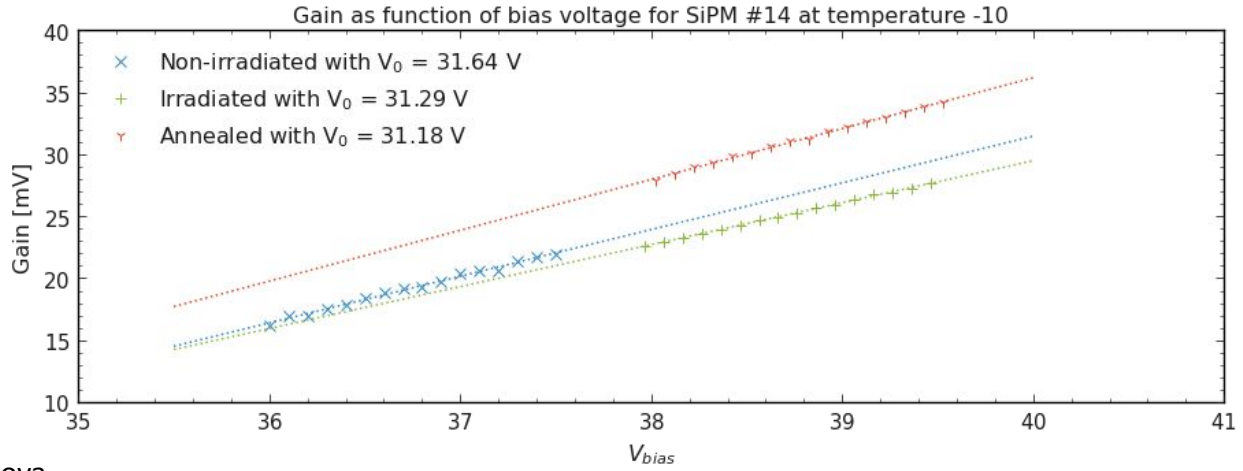
Fit of photon spectra

- 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

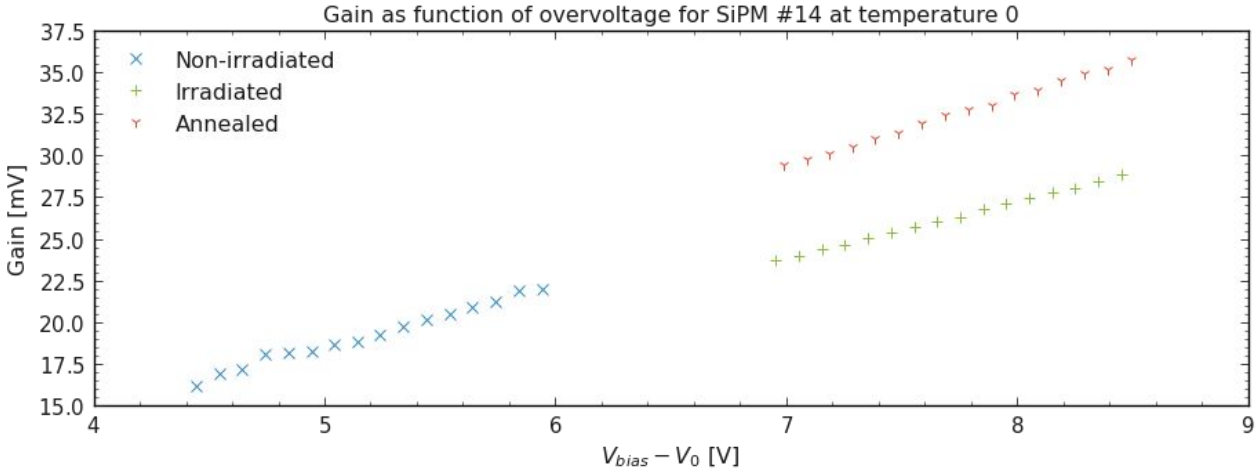


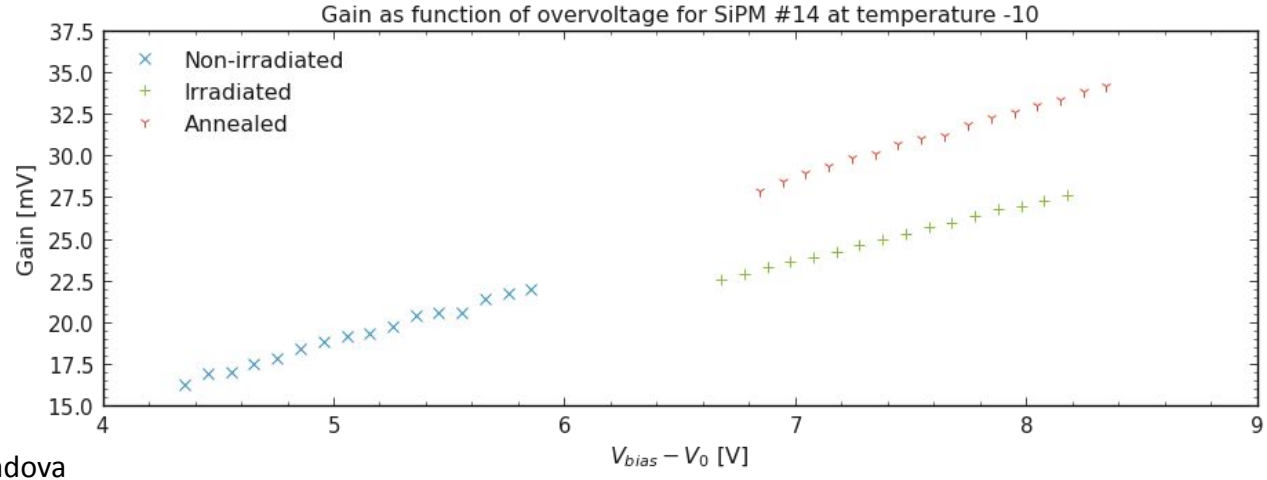
Gain as function of bias voltage





Gain as function of overvoltage





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 [μm]		15	15	15	15	50
Temperature [°C]	Status	Breakdown voltage [V_0]	Breakdown voltage [V_0]	Breakdown voltage [V_0]	Breakdown voltage [V_0]	Breakdown voltage [V_0]
20	No-irradiated	32.36 ± 0.80	32.70 ± 0.84	32.24 ± 1.16	32.43 ± 1.88	38.10 ± 2.24
	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
10	No-irradiated	33.72 ± 1.98	32.39 ± 0.51	31.71 ± 0.82	32.17 ± 1.52	38.31 ± 2.24
	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
0	No-irradiated	31.43 ± 1.41	32.07 ± 1.22	31.33 ± 1.68	31.87 ± 1.40	38.34 ± 8.88
	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
-10	No-irradiated	30.61 ± 2.58	31.65 ± 1.45	31.31 ± 0.82	31.64 ± 1.05	37.25 ± 9.79
	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
-20	No-irradiated	31.79 ± 1.59	31.18 ± 1.52	30.70 ± 0.98	31.13 ± 2.00	37.92 ± 6.71
	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
-30	No-irradiated	31.45 ± 0.62	31.33 ± 0.60	30.87 ± 0.81	30.91 ± 0.99	36.17 ± 1.42
	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
-35	No-irradiated	30.66 ± 3.92	30.96 ± 0.35	30.61 ± 0.28	30.84 ± 0.71	34.55 ± 5.39
	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
	Irradiated	30.19 ± 0.79	30.54 ± 0.61	30.14 ± 0.45	30.35 ± 0.28	36.59 ± 2.63

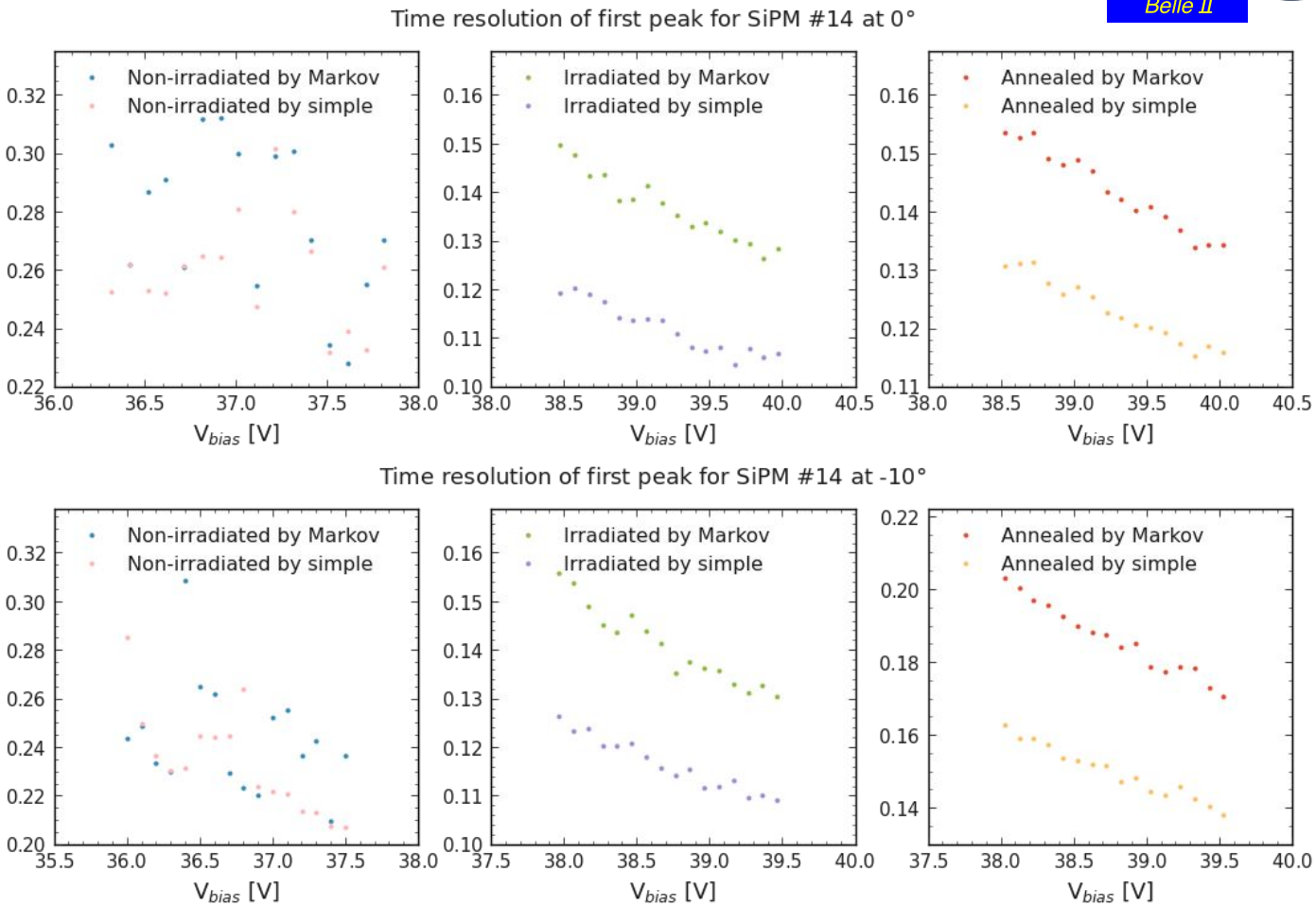
- For Hamamatsu device the breakdown voltages agree with previous measurements
- For some FBK devices, the breakdown voltages do not agree with previous measurements.
- After finishing studies related to breakdown voltage, we will continue with extraction time resolution

Slopes at temperatures for SiPMs

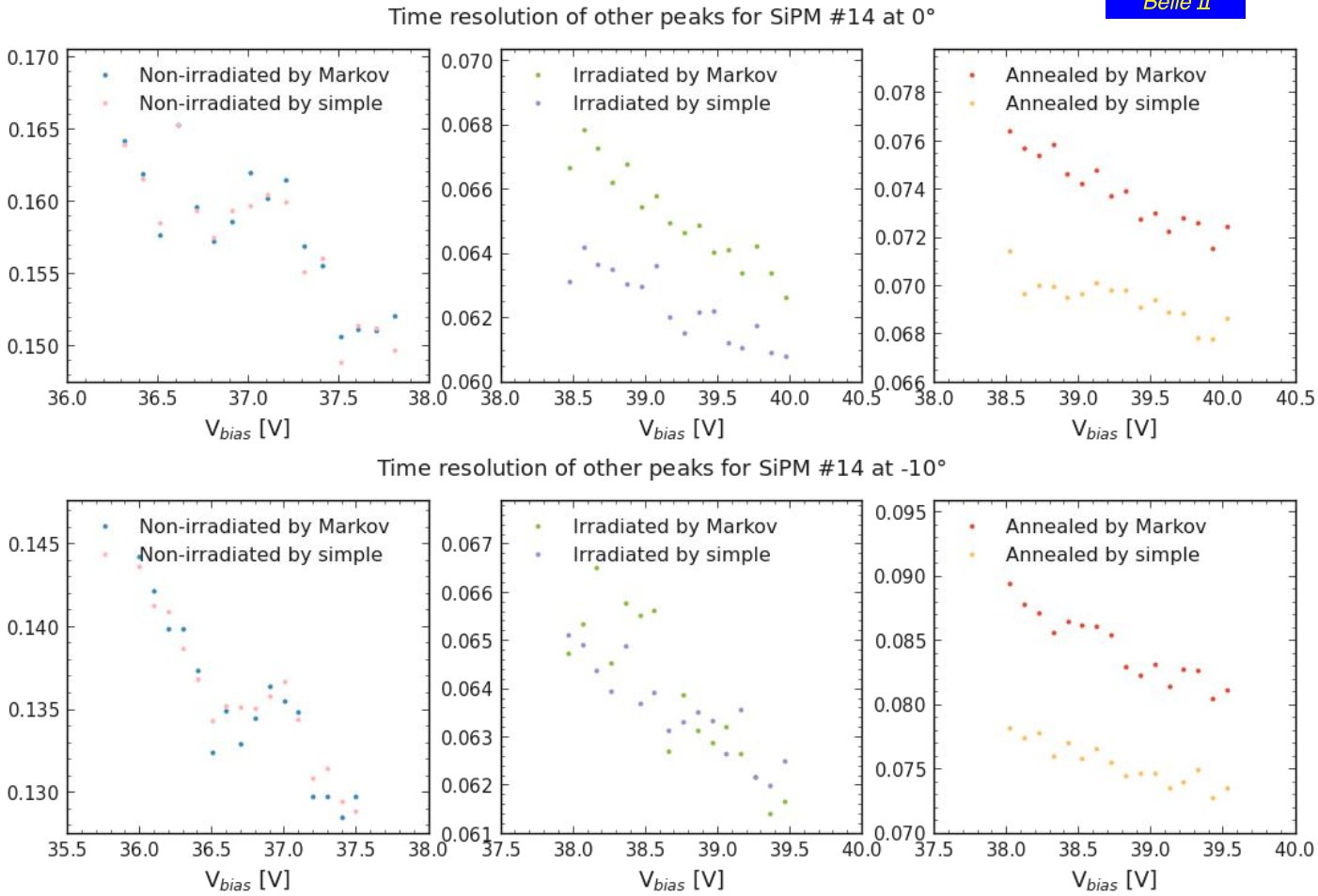
Index of SiPM		11	12	13	14	15
Producer		FBK	FBK	FBK	FBK	Hamamatsu
Dimension [mm×mm]		1 × 1	1 × 1	1 × 1	1 × 1	3 × 3
Pitch [μm]		15	15	15	15	50
Temperature [°C]	Status	Slope	Slope	Slope	Slope	Slope
20	No-irradiated	2.815 ± 0.045	4.215 ± 0.070	3.894 ± 0.091	3.822 ± 0.144	5.050 ± 0.201
	Irradiated	2.098 ± 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
10	No-irradiated	4.546 ± 0.179	4.101 ± 0.042	3.670 ± 0.061	3.787 ± 0.116	6.023 ± 0.240
	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
0	No-irradiated	2.754 ± 0.080	4.003 ± 0.100	3.522 ± 0.122	3.707 ± 0.106	6.928 ± 1.103
	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
-10	No-irradiated	2.188 ± 0.118	3.856 ± 0.116	3.606 ± 0.061	3.764 ± 0.081	4.764 ± 0.850
	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
-20	No-irradiated	2.798 ± 0.092	3.657 ± 0.116	3.365 ± 0.069	3.486 ± 0.145	6.756 ± 0.820
	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
-30	No-irradiated	3.000 ± 0.038	3.992 ± 0.050	3.700 ± 0.063	3.654 ± 0.075	5.191 ± 0.137
	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
-35	No-irradiated	2.315 ± 0.191	3.792 ± 0.028	3.578 ± 0.021	3.658 ± 0.054	4.031 ± 0.412
	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
	Irradiated	1.900 ± 0.031	3.547 ± 0.045	3.201 ± 0.030	3.170 ± 0.018	6.098 ± 0.294

Time resolution for first photon peak for SiPM #14

Time resolution for first photon peak

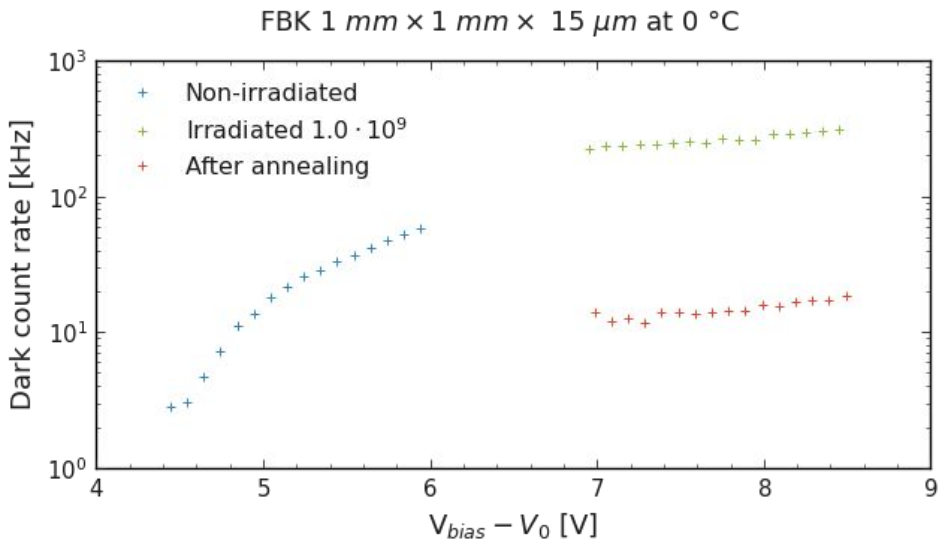


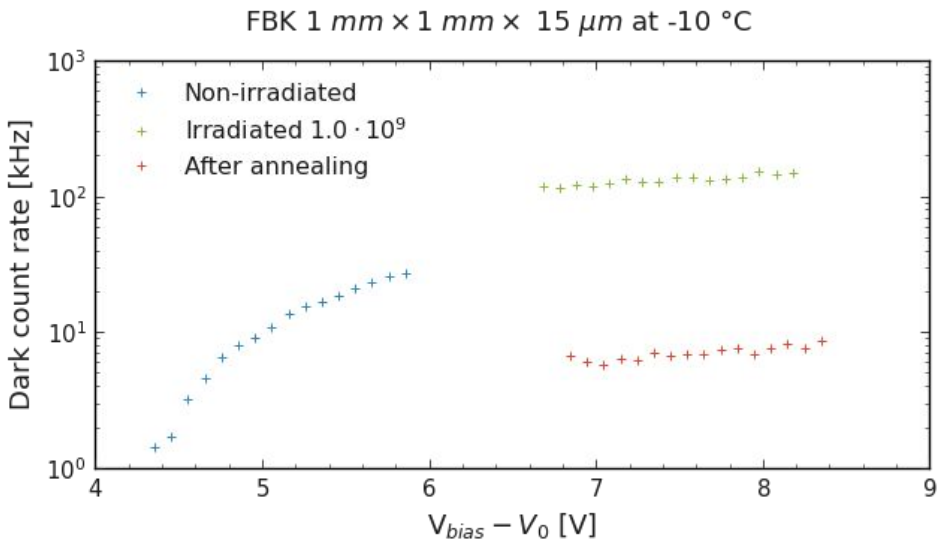
Time resolution for other photon peaks



Dark count rate for SiPM #14

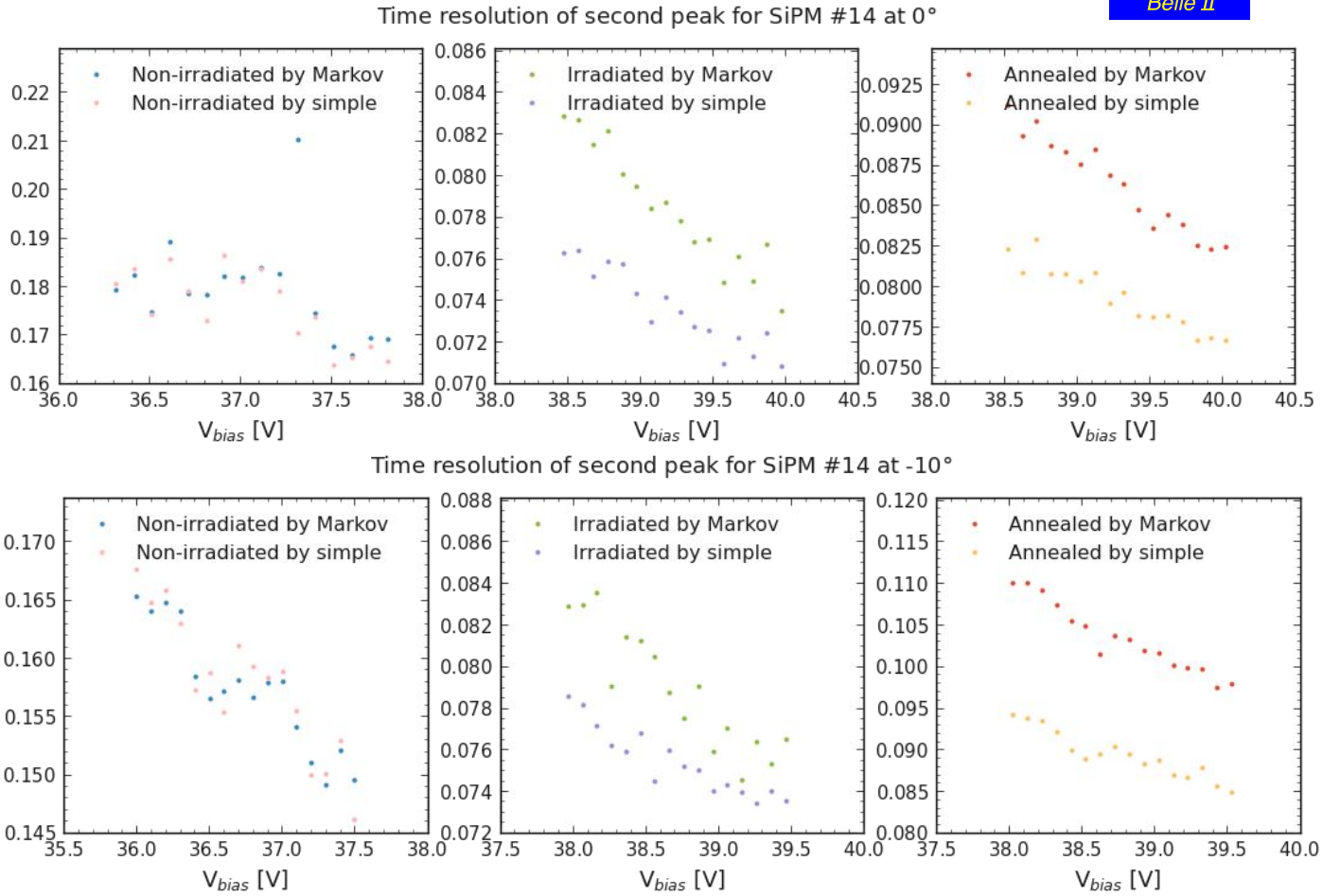
Dark count rate





Backup

Time resolution for second photon peak



Time resolution for third photon peak