Irradiation SiPMs test at Padova

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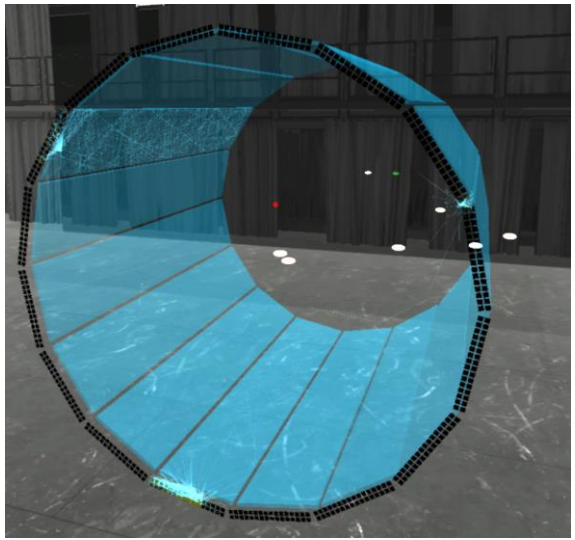
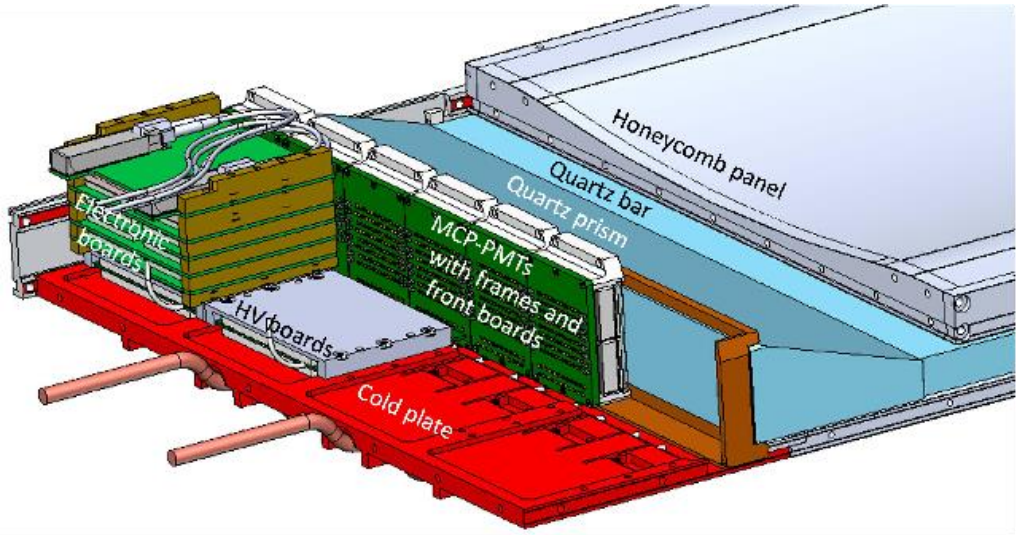
Upgrade of the Belle II TOP detector

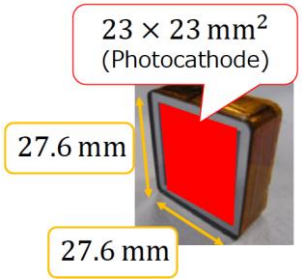




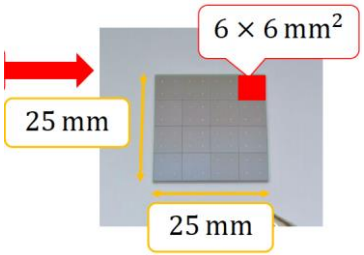
The Belle II TOP is a barrel Cherenkov detector made by 16 quartz modules redout by 512 MCP-PMT photodetectors. Half of the photodetectors have been replaced during LS1 in 2023:
conventional MCP-PMTs (~ 1 C/cm^2) → life-extended ALD MCP-PMTs (> 15 C/cm^2)
Full replacement of MCP-PMTs will be completed during LS2 (~2028).
Also being considered is the possibility of replacing MCP-PMTs with SiPMs

ALD MCP-PMT replacement with SiPMs

1 MCP-PMT 16 channes

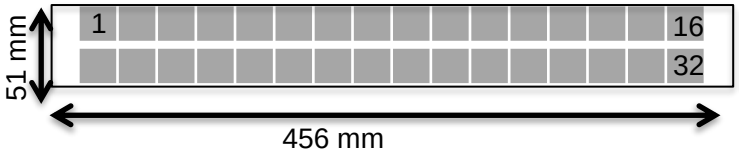


1 MPPC (Multi-Pixel Photon Counter) 16 channels 6x6 mm²



- N_{ch} = 16 x 32 x 16 = 8192
- SiPM 6x6 mm² -> N_{ch}
- SiPM 3x3 mm² -> 4*N_{ch}
- SiPM 1x1 mm² -> 36*N_{ch}

Current detector: 32 MCP-PMT/module



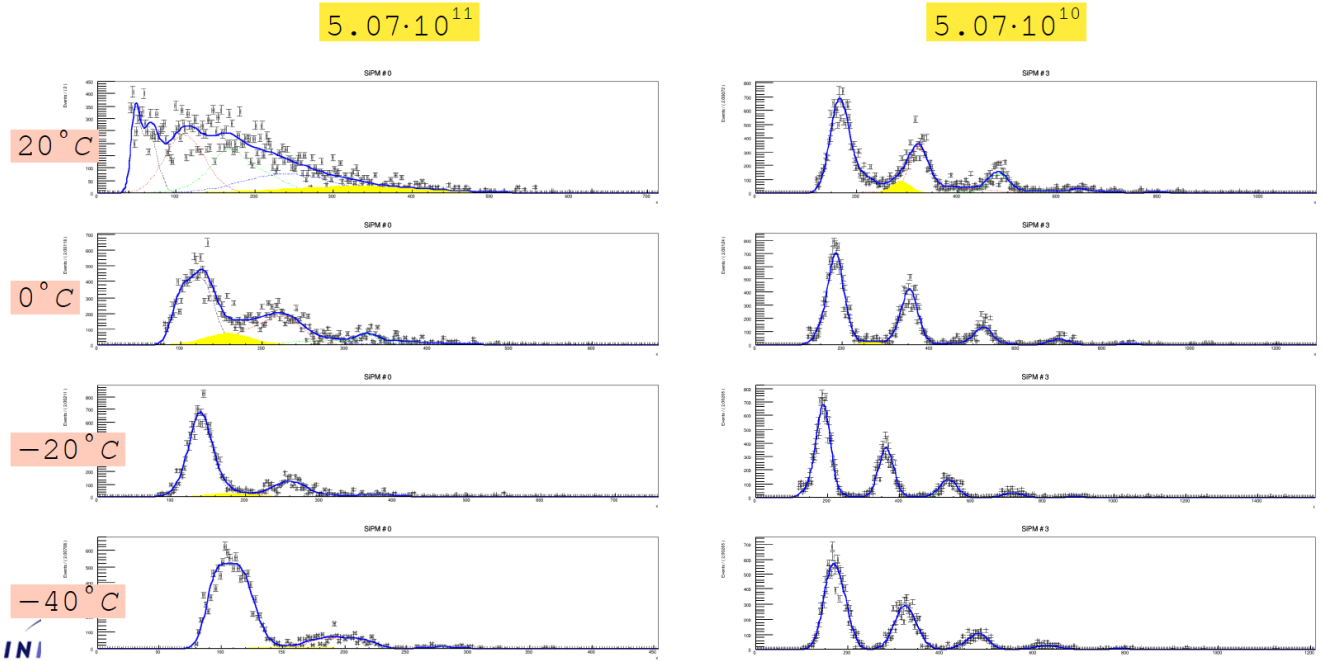
Example: 36 SiPM 16 channels + 4 SiPM 4 channels (S13361-6050AE-04)

	MCP-PMT	SiPM
peak PDE	peak QE (30%) * CE (50%) = 15%	peak PDE = 40%
PMT/SiPM effective area	69% [$(23/27.6)^2$]	92% [$(24/25)^2$]
Global effective area	73%	90%
TTS	~ 50 ps	TTS < 100 ps
Darkcount	negligible	~50 kcps @ 1 mm², 20 ℃

First results of HPK irradiated SiPMs

- We irradiated 8 Hamamatsu SiPMs in 2022 1.3 x 1.3 mm^2 50 μm cell with neutron fluxes from 1 x 10^9 n/cm^2 to 5 x 10^{11} n/cm^2

# SiPM	Distance [cm]	Neutron 1 MeV eq/cm^2 fluence	Charge [mC]	Time [h]
0	4.3	$5.01 \cdot 10^{11}$	7.94	16.34
1	6.8	$2.00 \cdot 10^{11}$	7.94	16.34
2	9.3	$1.00 \cdot 10^{11}$	7.94	15.30
3	11.8	$5.01 \cdot 10^{10}$	5.98	12.31
4	14.3	$2.42 \cdot 10^{10}$	4.25	8.74
5	16.8	$1.01 \cdot 10^{10}$	2.44	5.03
6	19.3	$5.00 \cdot 10^{9}$	1.60	3.29
7	21.8	$1.01 \cdot 10^{9}$	0.41	0.85



Tests with new irradiated modules in Padova

- We irradiated additional 16 SiPMs modules in 2023 with neutron fluxes from 1 x 10^9 n/cm^2 to 1 x 10^{10} n/cm^2 they have been tested inside a dark box with laser source before and after irradiation.
- We annealed all of them at 150 ℃ to check if they can be recovered.
- Eight of them are processed to study their response.
- New irradiation slots have been approved by LNL for 2024 to increase the neutron fluence and to test new SiPMs

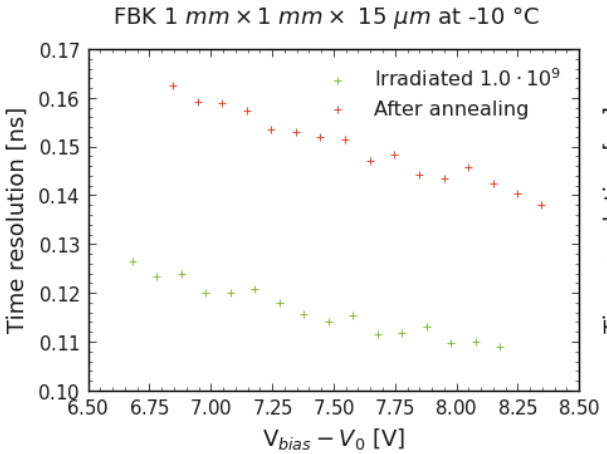
Index	Producer	Dimension [mm×mm]	Pitch [μm]	Distance [cm]	Neutron 1 MeV eg/cm^2 fluence	Charge [mC]	Time [h]
8	FBK	3 × 3	15	18.36	$1.0{\cdot}10^{10}$	2.86	5.88
9	FBK	3 × 3	15	18.24	$5.0{\cdot}10^{9}$	1.41	2.90
10	FBK	3 × 3	15	33.24	$1.0{\cdot}10^{9}$	0.94	1.93
11	FBK	1 × 1	15	15.86	$2.0{\cdot}10^{10}$	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

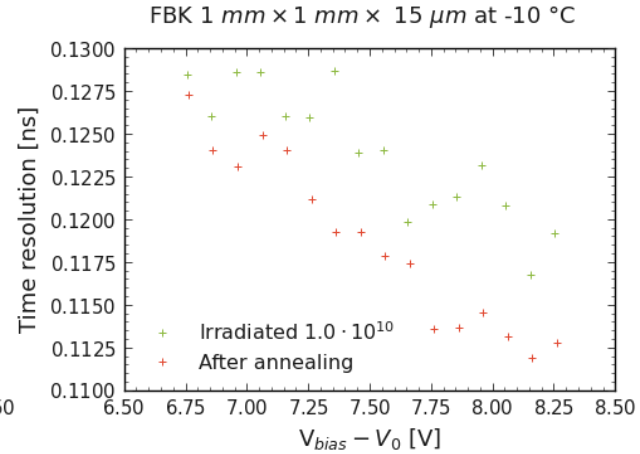
Breakdown voltages at temperatures for SiPMs

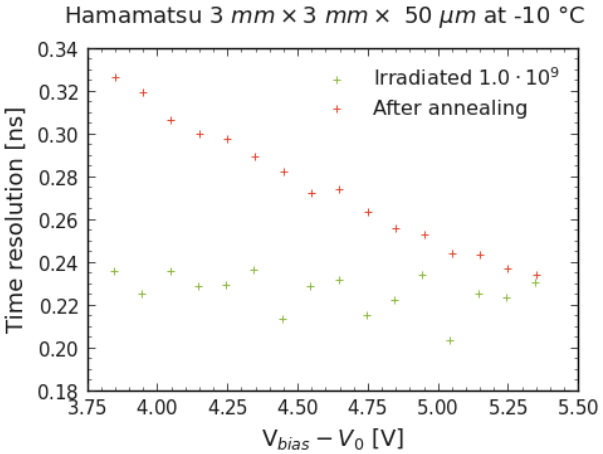
Index of SiPM		11	12	13	14	15
Producer		FBK	FBK	FBK	FBK	Hamamatsu
Dimension [mm×mm]		1 × 1	1 × 1	1 × 1	1 × 1	3 × 3
Pitch [μm]		15	15	15	15	50
Temperature [°C]	Status	Breakdown voltage [V_0]	Breakdown voltage [V_0]	Breakdown voltage [V_0]	Breakdown voltage [V_0]	Breakdown voltage [V_0]
20	No-irradiated	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

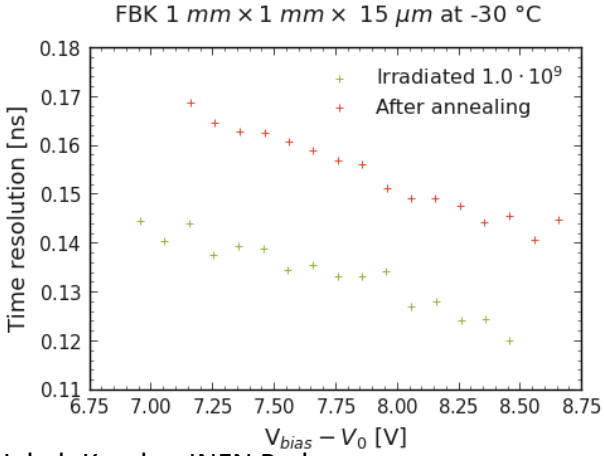
- It is preliminary results for extracting breakdown voltages for some of studied SiPMs
- Extracted values of breakdown voltages are consistent for before irradiation, after irradiation and after annealing.
- Some of the photon spectra are not fitted perfectly and breakdown voltages are affected by large uncertainties, we will try to understand and fix them in next days.

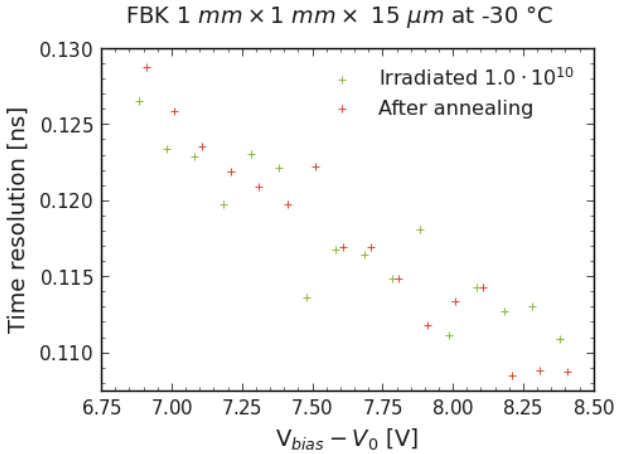
Time resolution using first peak in photon spectra

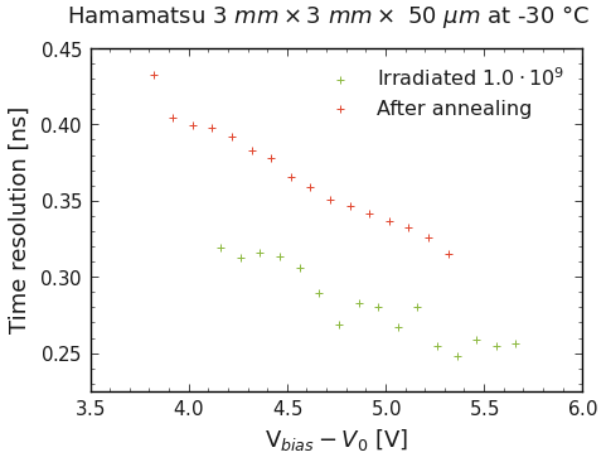




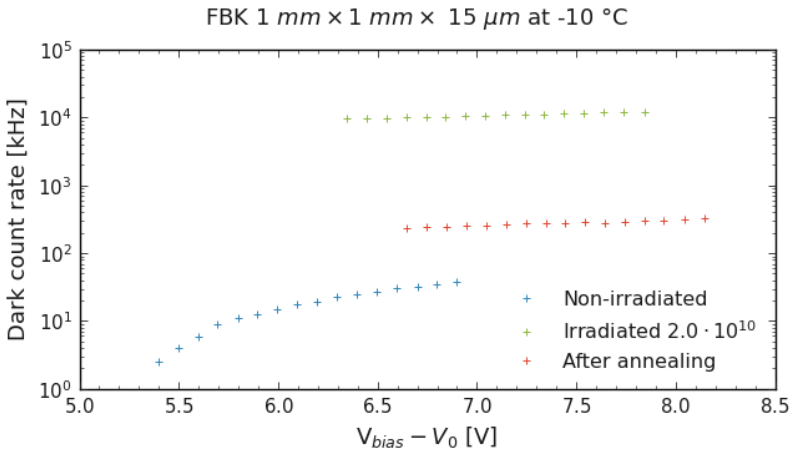


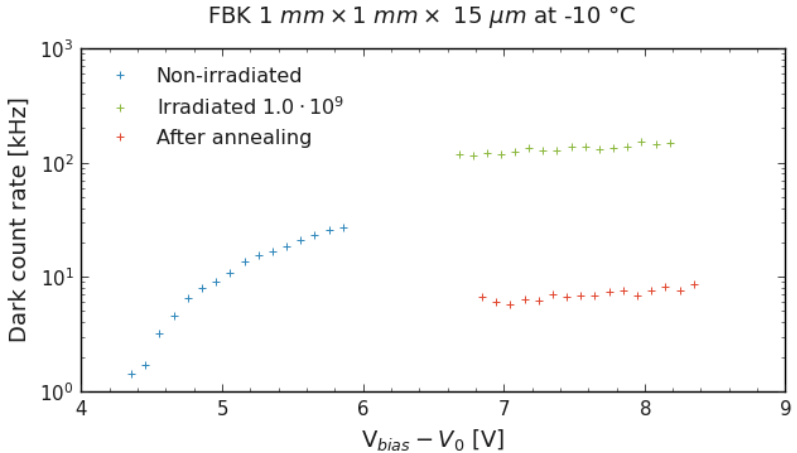


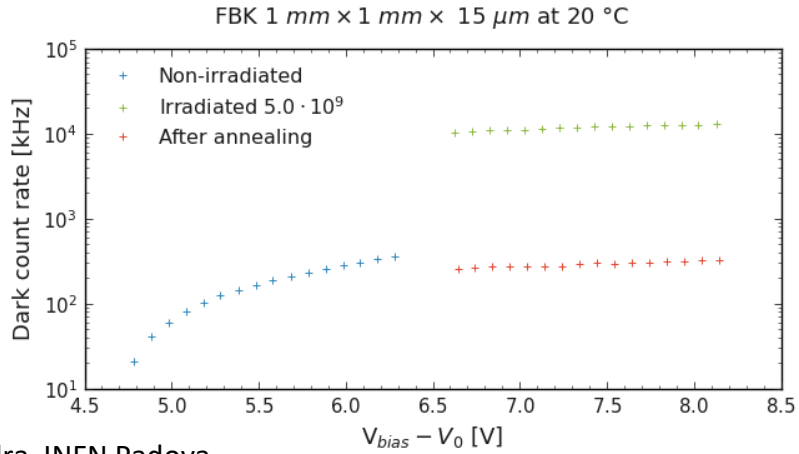


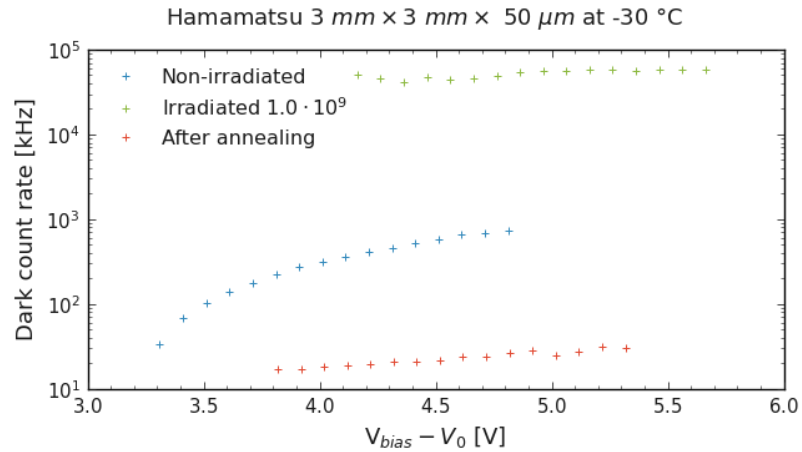


Dark count rate









Conclusions

- We irradiated 8 Hamamatsu SiPMs (S13360-1350PE) in 2022 with neutron fluxes from 1×10^{9} n/cm^2 to 5×10^{11} n/cm^2
- We irradiated 16 SiPMs (4 OnSemi, 4 Kektek, 1 Hamamatsu, 7 FBK) in 2023 with neutron fluxes from 1×10^{9} n/cm^2 to 1×10^{10} n/cm^2
- After readout of irradiated SiPMs they have been annealed at 150 ℃
- Preliminary results for 1 Hamamtsu and 7 FBK SiPMs have been presented.
- New irradiation in April 2024 and June 2024 will be done to increase the neutron fluence and to test new SiPMs