SiPM development for the TOP detector upgrade of the Belle II experiment

DRD4
EFCA Task Force 4
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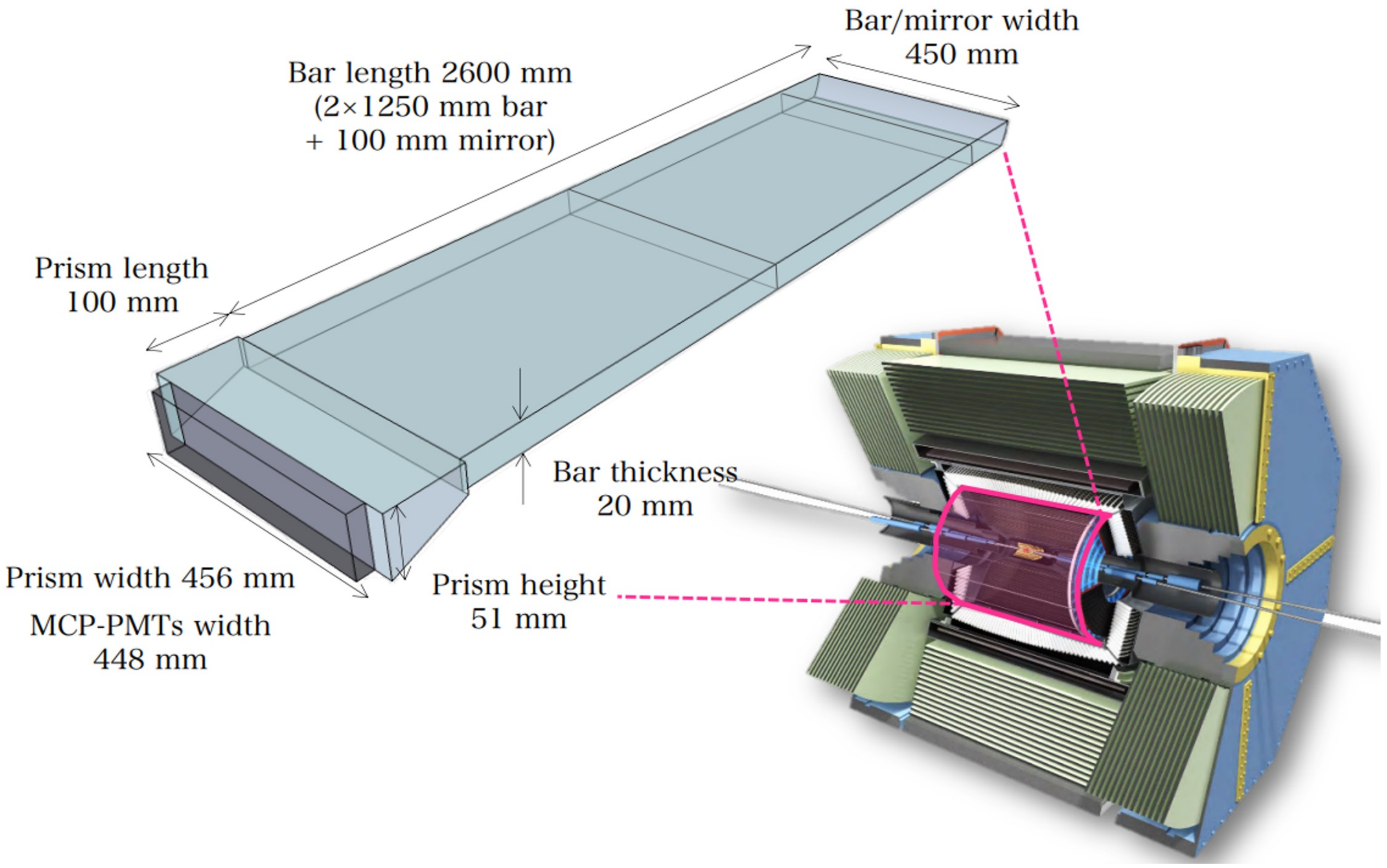
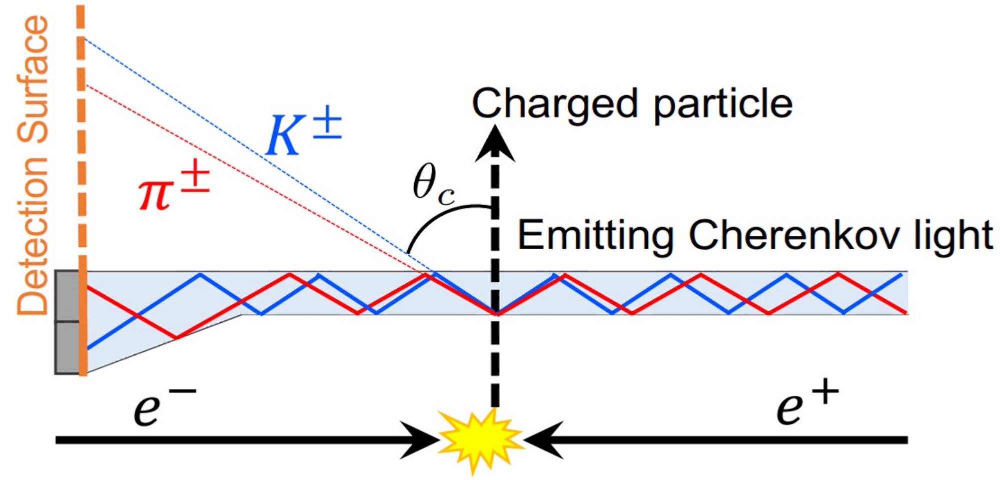
TOP detector
Belle II experiment



- 16 TOP modules surround the tracking detector on barrel part for particle identification.
- Each module contains
  - finely polished surface fused silica bar;
  - fused silica expansion prism;
  - MCP-PMT photo-detectors;
  - high-speed readout electronics.

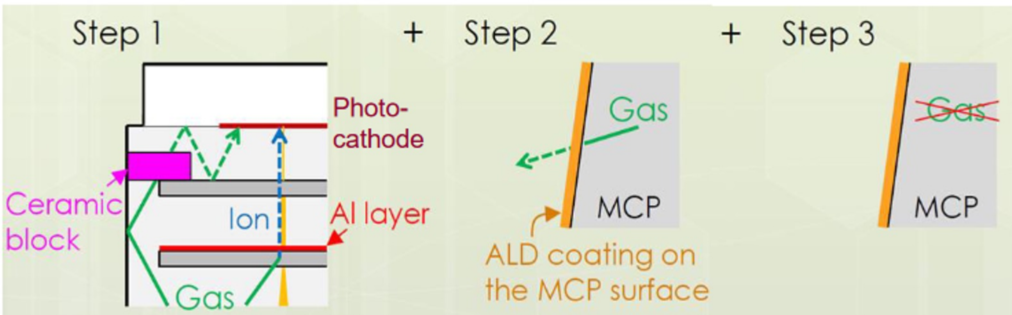


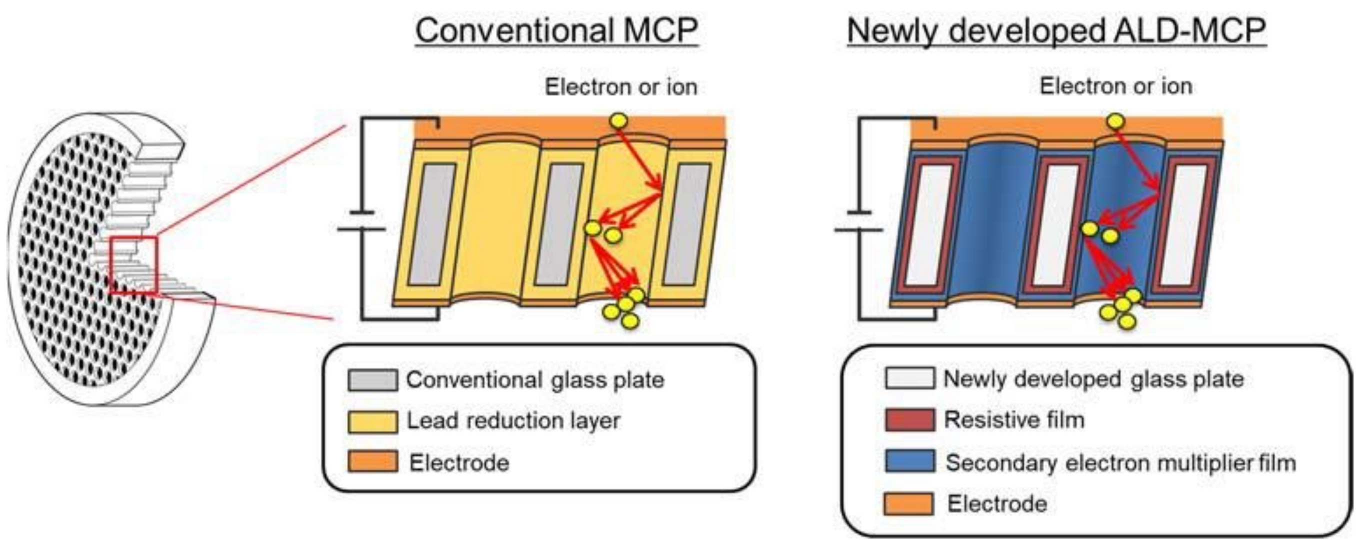
Three types of MCT-PMTs have been installed:

Step 1: Conventional

Step 2: Atomic layer deposition (ALD)

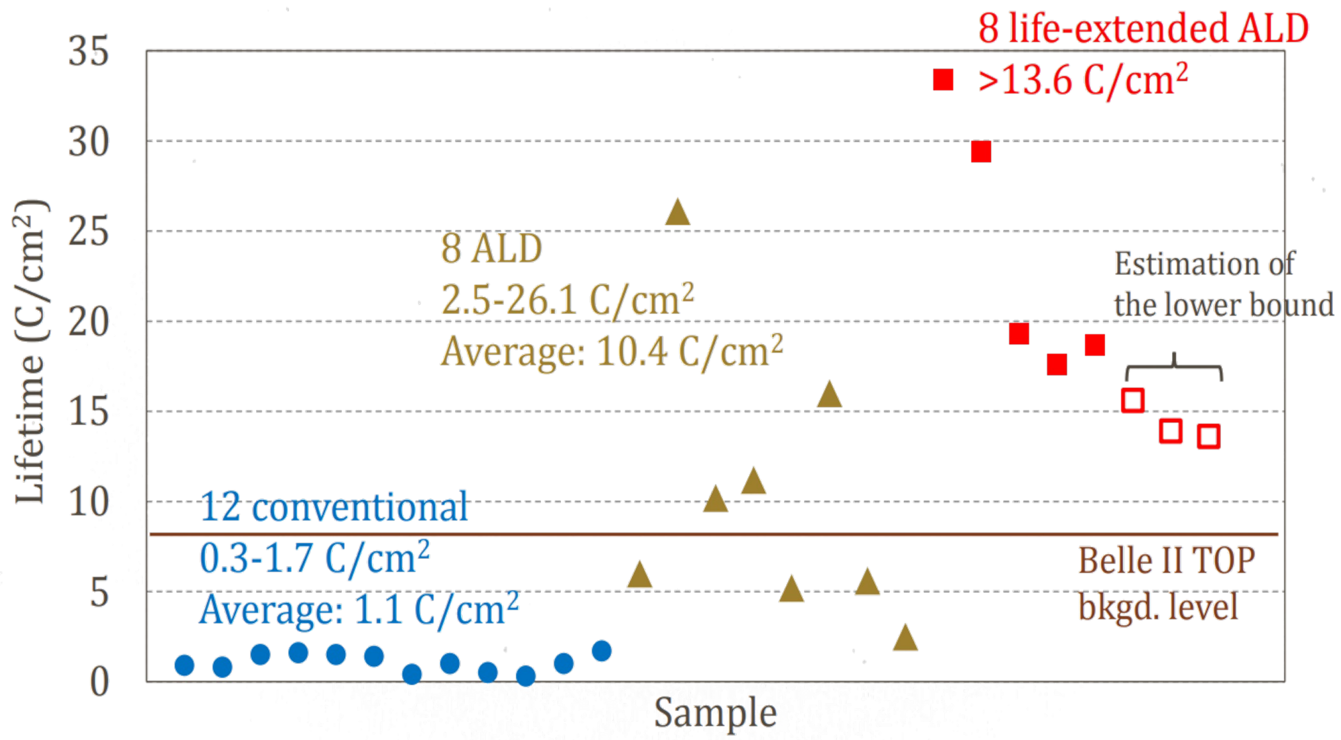
Step 3: Lifetime extended ALD



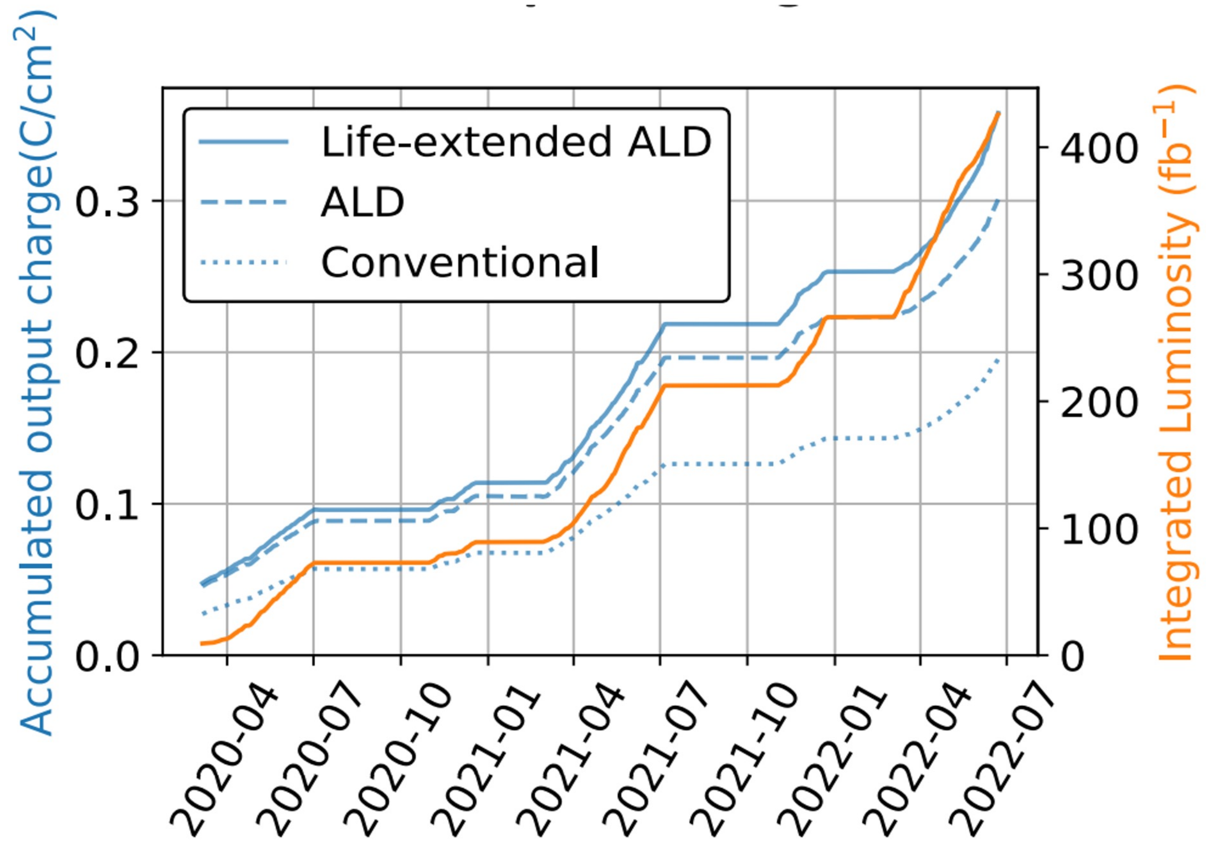


MCP-PMT
QE degradation

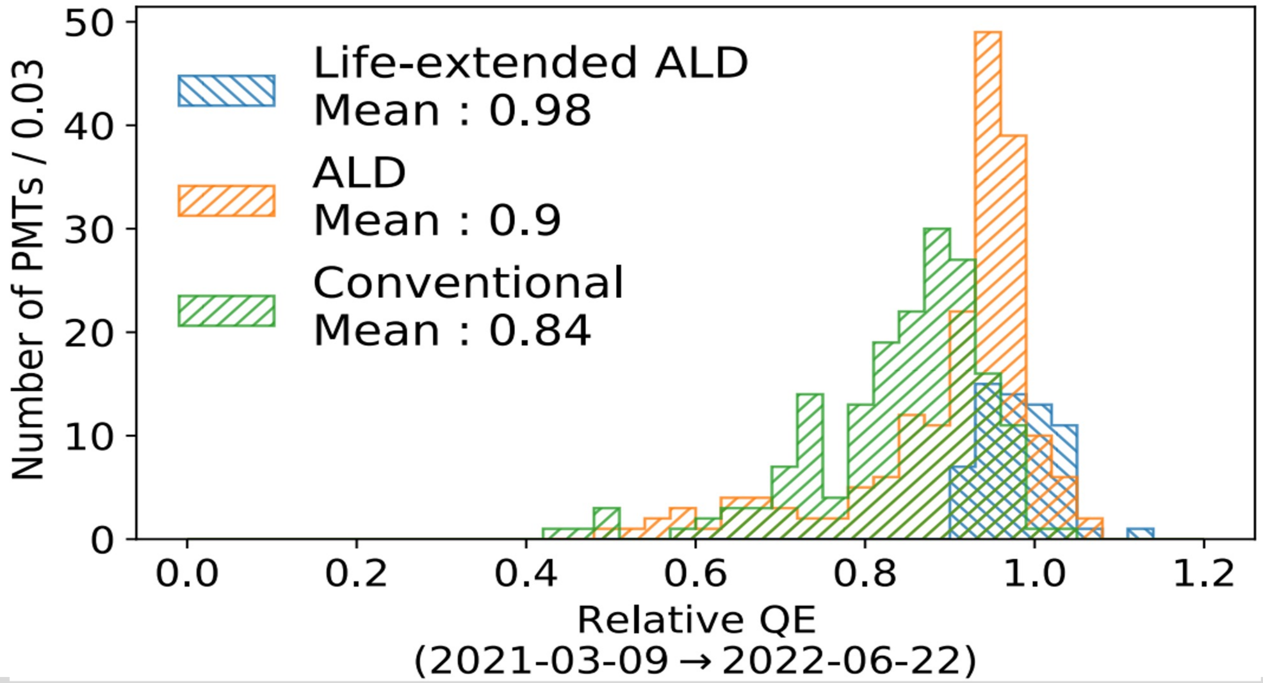
Lifetime: charge (C/cm^2) reducing QE to 80% measured in 2017 with led source



Accumulate charge up to long shutdown



$$\text{Relative QE} = \frac{\text{QE at the end of 2022}}{\text{QE at the beggining of 2021}}$$

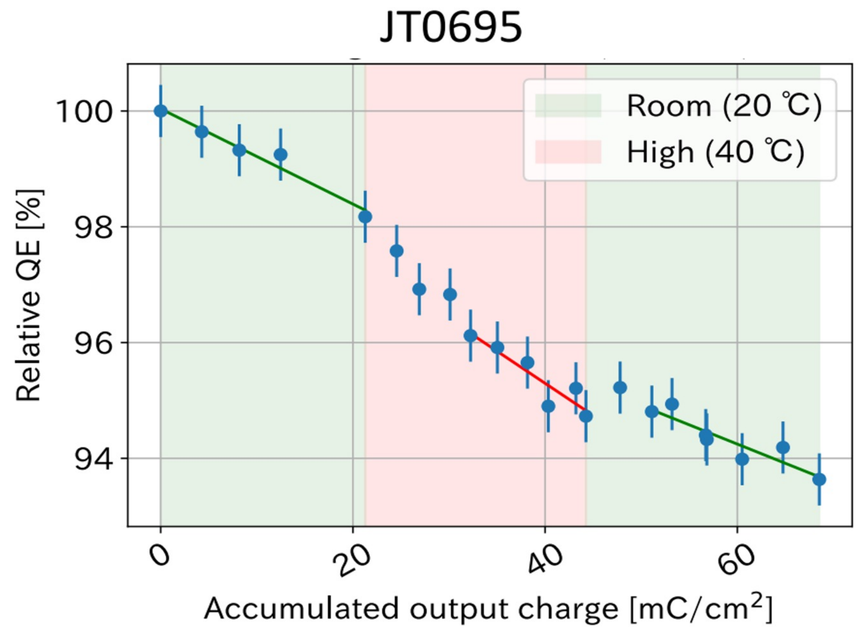


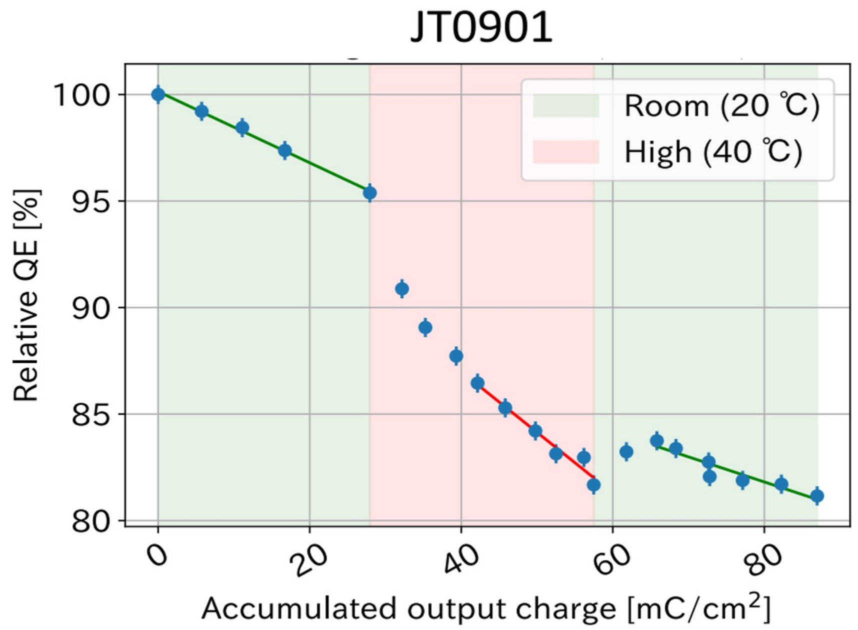
Quantum efficiency can be measured with dimuon events

Higher than expected quantum efficiency degradation has been observed dependent on type of MCT-PMTs

MCP-PMT
QE degradation

Heating due to electronics
can increase the QE degradation



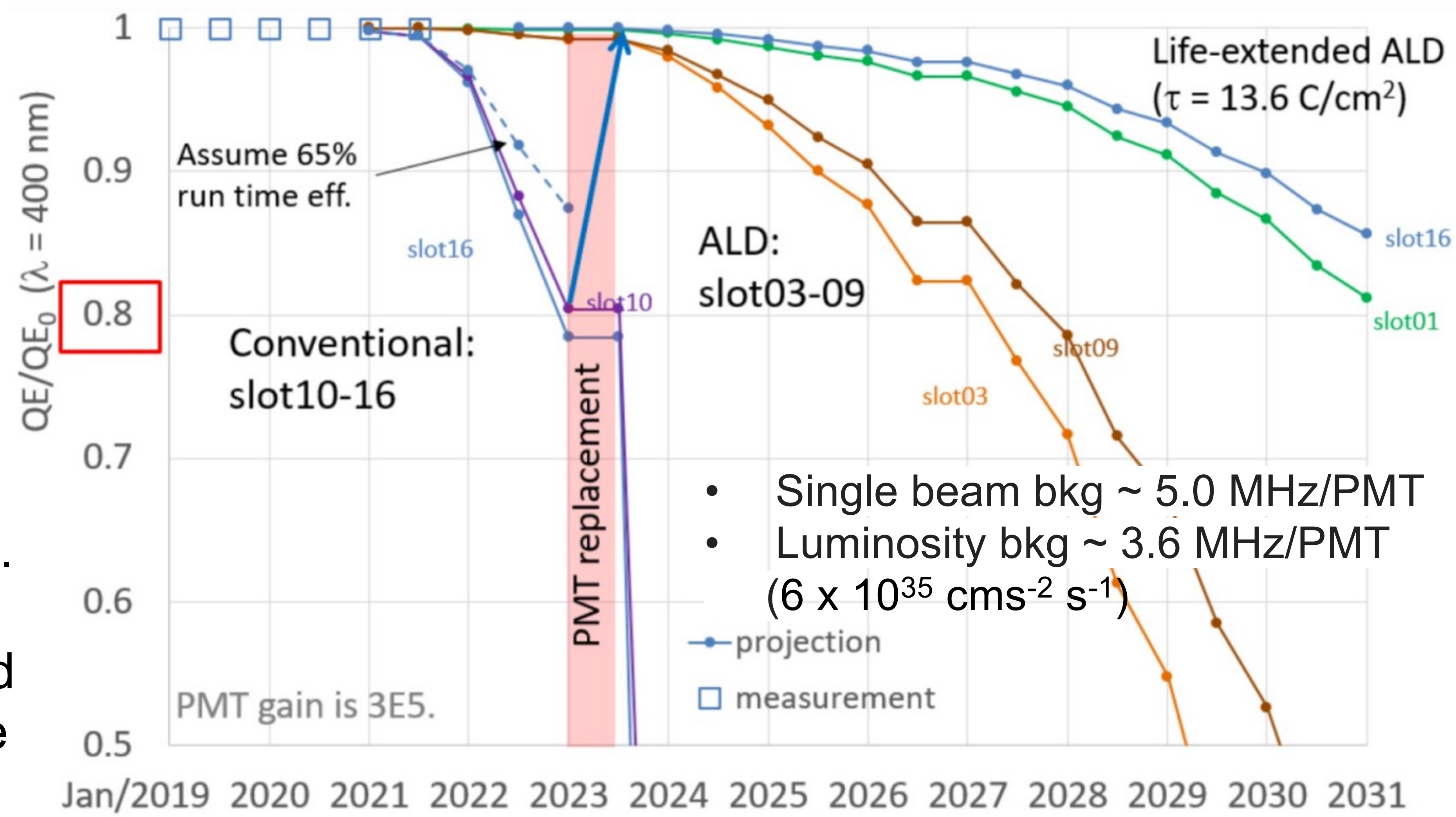


During the current long shutdown
we replaced ~250 conventional
MCP-PMT.

How many years
life-extended ALD can survive
@ $L = 6 \times 10^{35}$ cms^{-2} s^{-1} ?

If the accelerator can reach
even higher luminosities
we do not have a working solution.

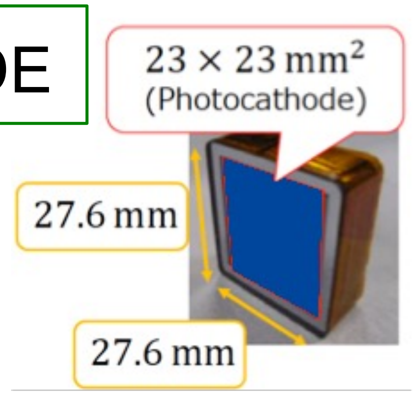
New MCP-PMT developments and
radiation hardness SiPMs must be
investigated.



MCP-PMT replacement with SiPMs

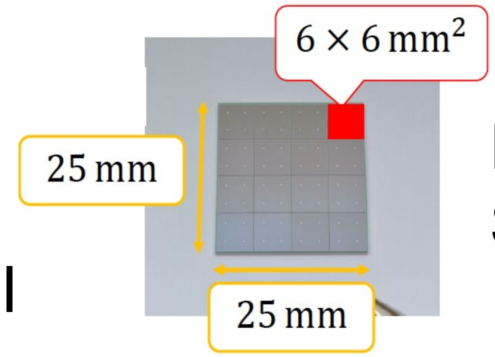
☺ Effective area, PDE

1 **MCP-PMT**
27.6 x 27,6 mm^2



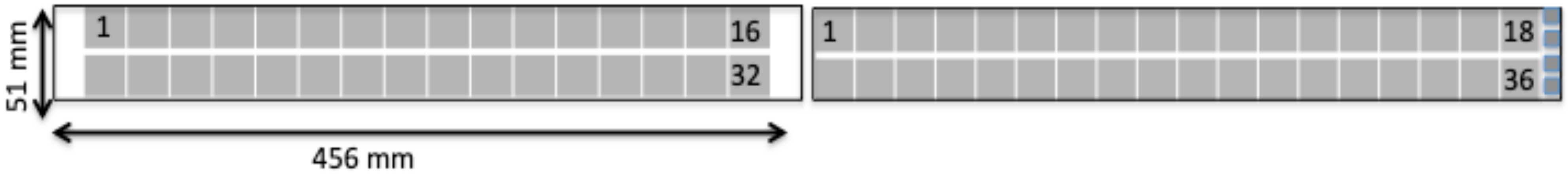
→

1 MPPC (SiPM)
4x4 channels
6 x 6 mm^2 / channel
50 μm cells



Hamamatsu
S13361-6050

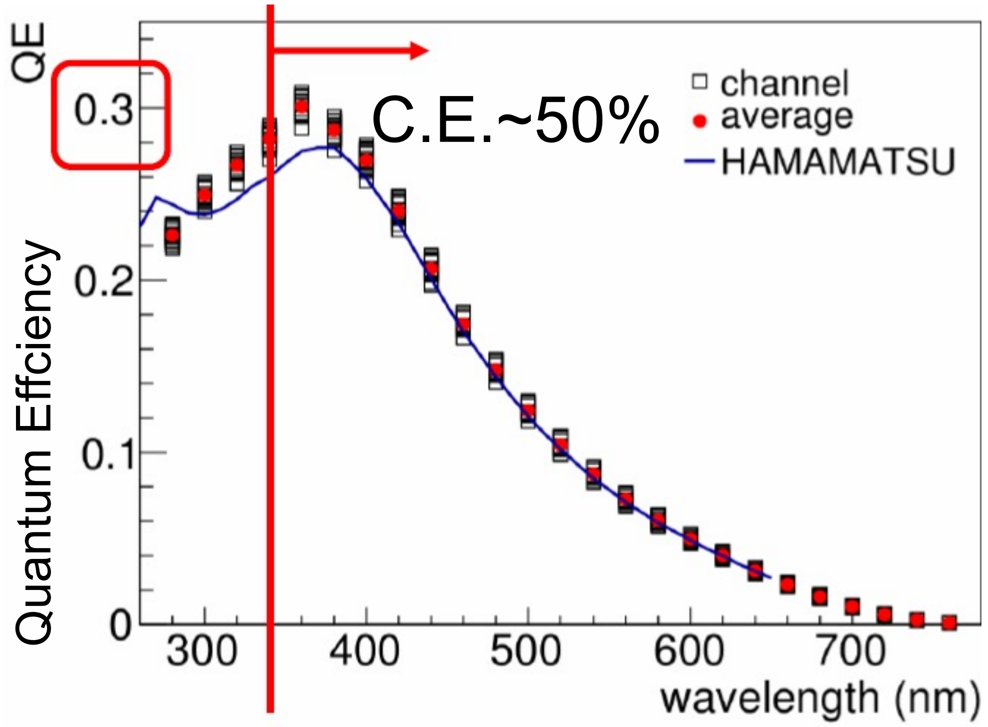
Global effective area **MCP-PMT** 73% **SiPM** 90%

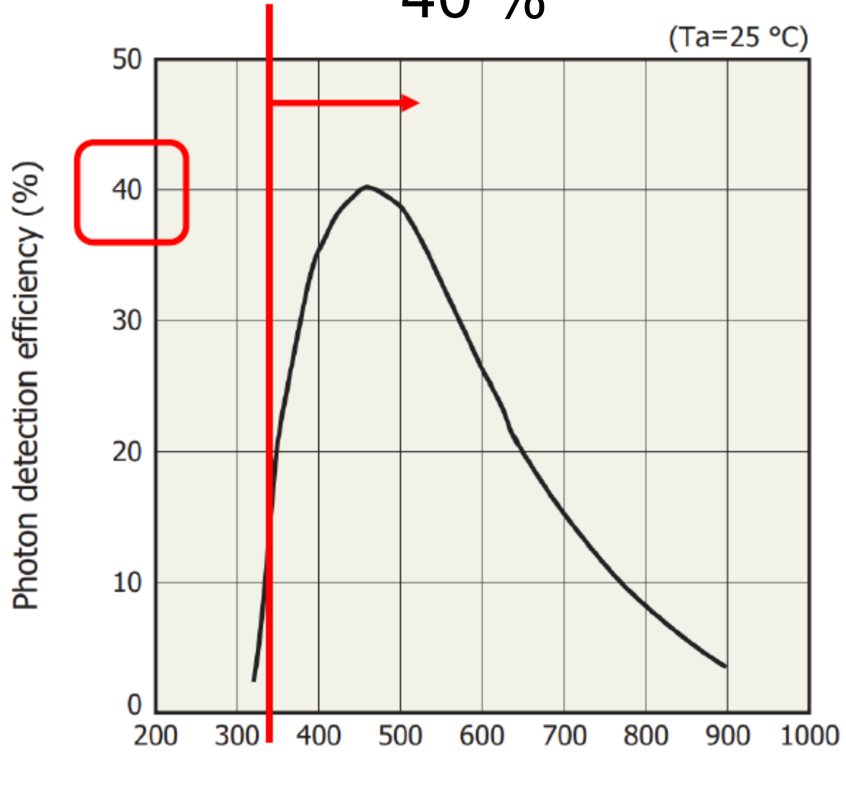


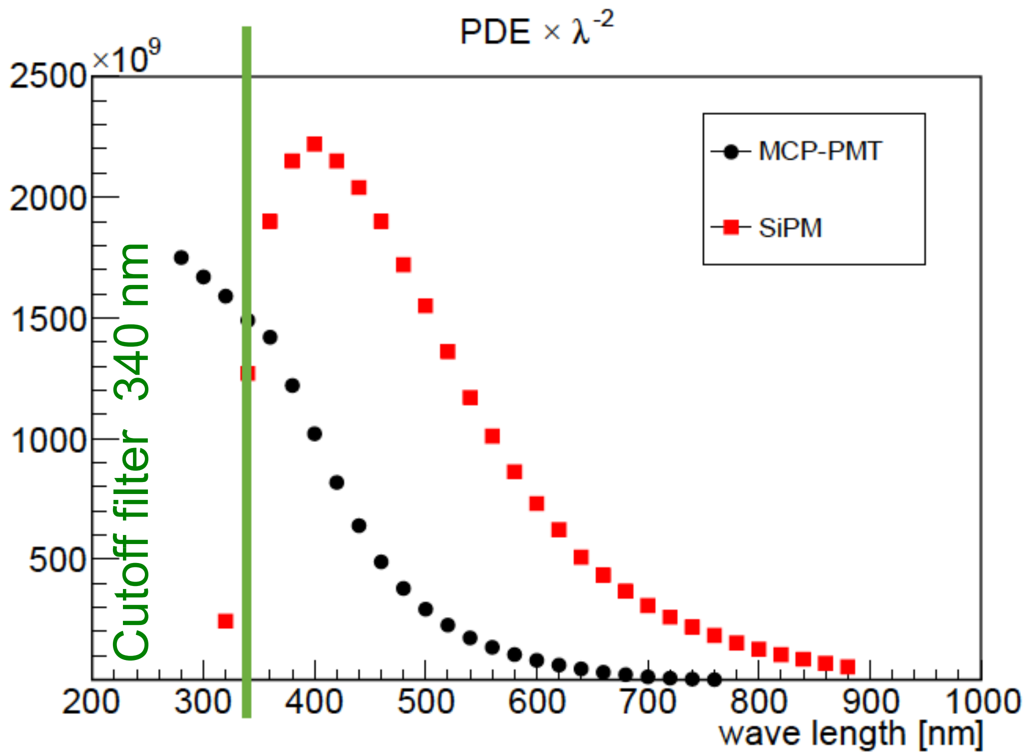
PDE **MCP=PMT**= QE * C.E.
~15 %

PDE **SiPM** = QE * PT * F.F.
~ 40 %

$dN_{p.e.}/dxd\lambda \propto$ PDE λ^{-2}







QE =Quantum efficiency C.E.=Collection efficiency PT=Avalanche Trigger Prob. F.F.= Fill Factor

MCP-PMT replacement with SiPMs

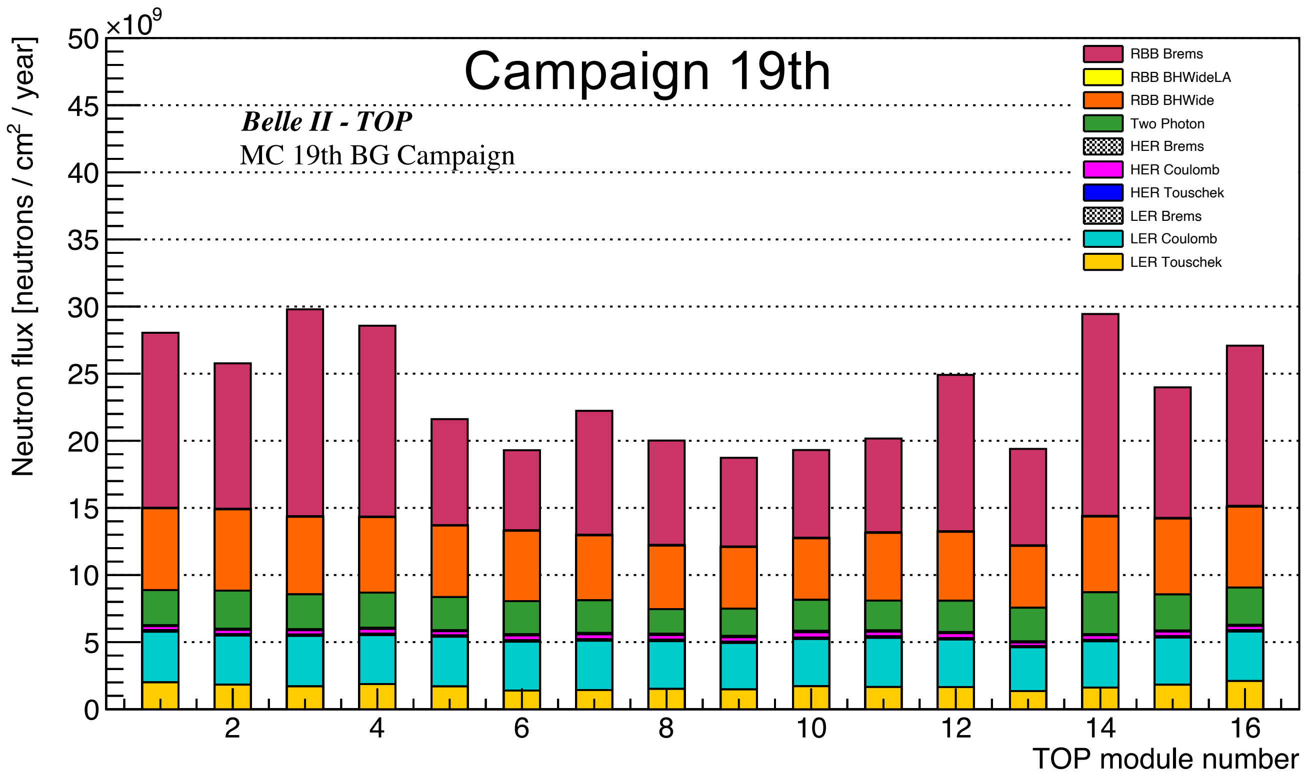
Dark Count, Time resolution

	Sensitive area/channel (mm^2 x mm^2)	Terminal Capacitance (pF)	Dark Count (Threshold 0.5 p.e.)
Hamamatsu S13361-6050	6 x 6	1300	2 MHz (*)
Hamamatsu S13361-3050	3 x 3	320	0.5 MHz

Dark Count @ 25°C MCP-PMT ~ 0.5 Hz / cm^2 SiPM ~ 55 kHz / mm^2

TTS / SPTR MCP-PMT ~ 30-40 ps SiPM ~ 100 ps

Sensible to neutron background



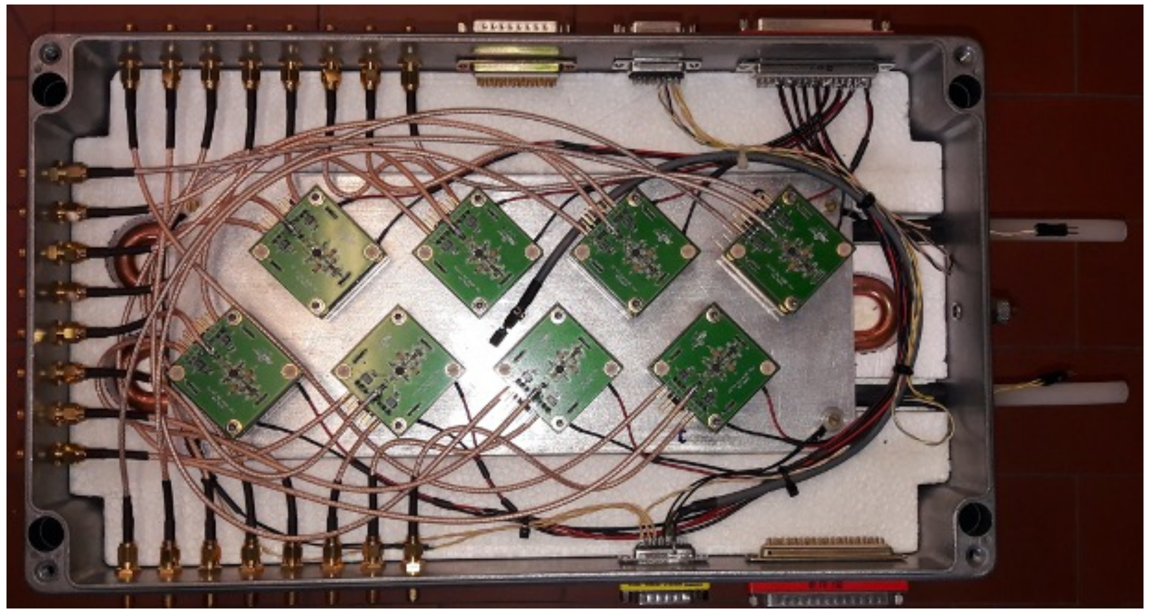
2-2.5 x 10^{10} neutron/cm^2 year @ 8 x 10^{35} cm^{-2} s^{-1}

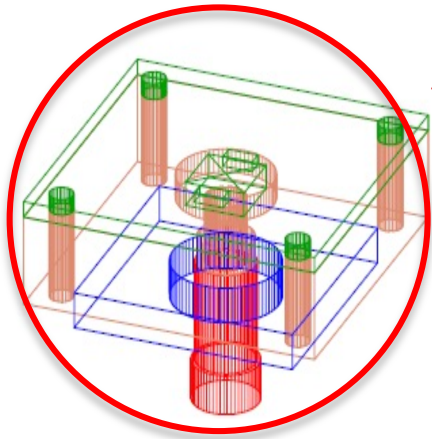
1.5-2 x 10^{10} neutron/cm^2 year @ 6 x 10^{35} cm^{-2} s^{-1}

SiPM test in Padova setup

Tests are ongoing in Padova to measure the characteristics of the SiPMs in the market 1) for different temperatures 2) before and after irradiation.

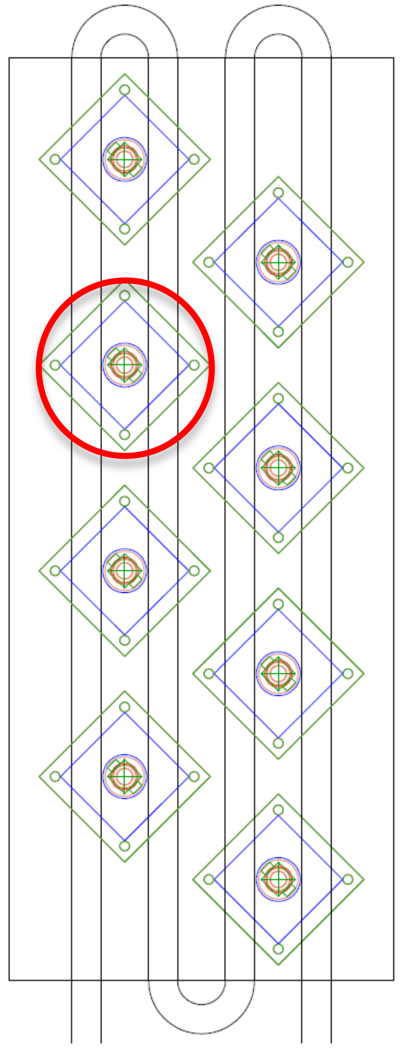
Dark box with SiPM blocks





PCB Amplifier
PCB SiPM with T sensor
PCB peltier

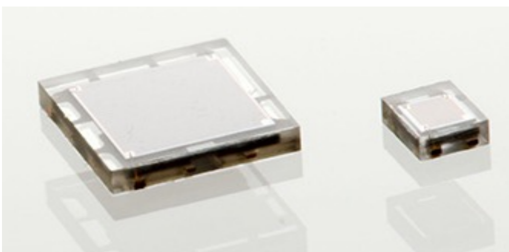
SiPMs illuminated with picosecond laser
T from +20 °C to -50 °C



Cooling plate (glycolate water)

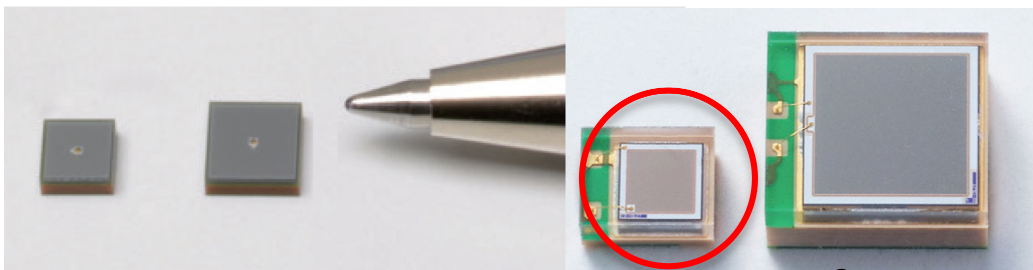
Available SiPMs to be tested

OnSemi (35μm)



1x1 - 3x3 mm^2

Hamamatsu (15-25-50 μm)

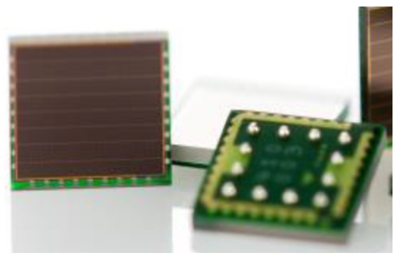


1.3x1.3 - 3x3 mm^2

FBK (15μm)

1x1 - 3x3 mm^2

Ketek (15-35 μm)

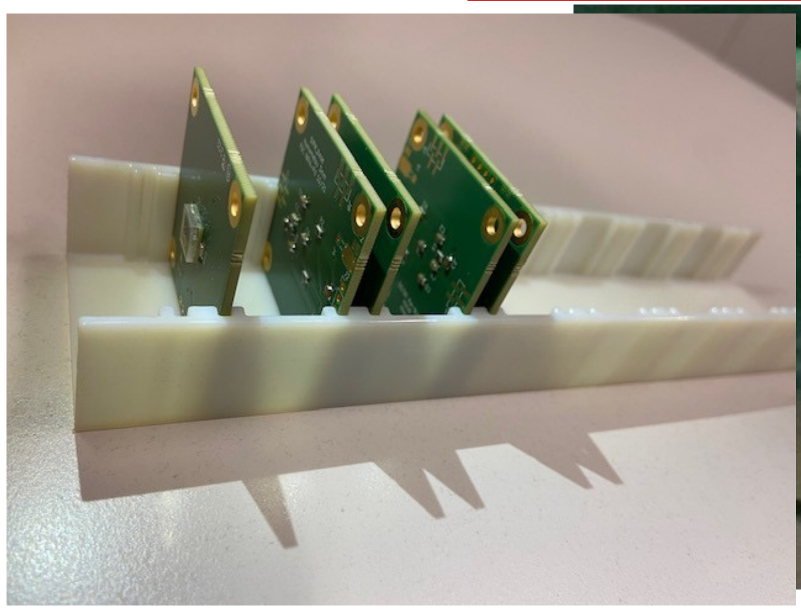


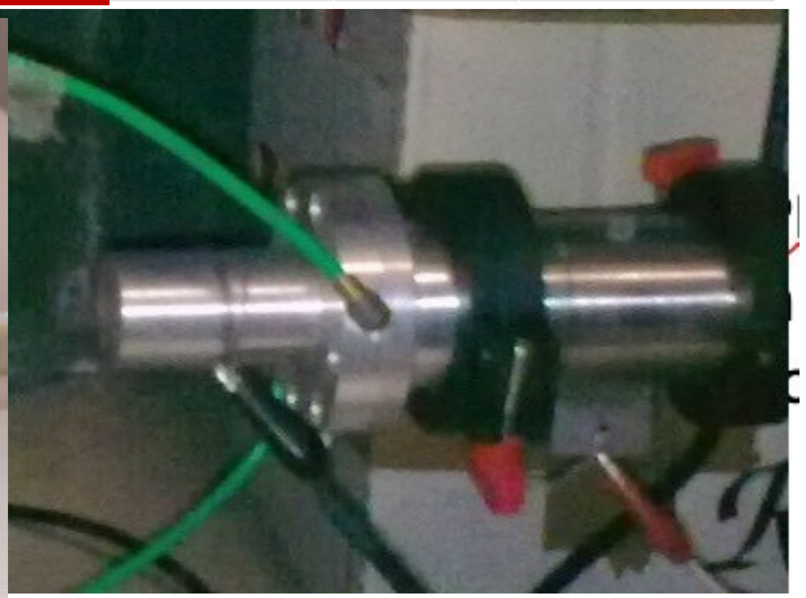
3x3 mm^2

SiPM irradiation test at LNL

8 Hamamatsu S13360-1350PE SiPMs (1.3x1.3 mm^2 , 50 μm cells) have been irradiated in November 2022 at the LNL CN neutron beam facility

SiPM #	distance from target (cm)	neutron 1 MeV eq. /cm^2 fluence	charge (μC)	time (s)	time (hours)
0	4.30	$5.07 \cdot 10^{11}$	$7.94 \cdot 10^3$	58829	16.34
1	6.80	$2.03 \cdot 10^{11}$	$7.94 \cdot 10^3$	58829	16.34
2	9.30	$1.01 \cdot 10^{11}$	$7.43 \cdot 10^3$	55073	15.30
3	11.80	$5.07 \cdot 10^{10}$	$5.98 \cdot 10^3$	44310	12.31
4	14.30	$2.45 \cdot 10^{10}$	$4.25 \cdot 10^3$	31451	8.74
5	16.80	$1.02 \cdot 10^{10}$	$2.44 \cdot 10^3$	18098	5.03
6	19.30	$5.06 \cdot 10^9$	$1.60 \cdot 10^3$	11839	3.29
7	21.80	$1.03 \cdot 10^9$	$4.13 \cdot 10^2$	3059	0.85





4 MeV proton beam on a Berillium target

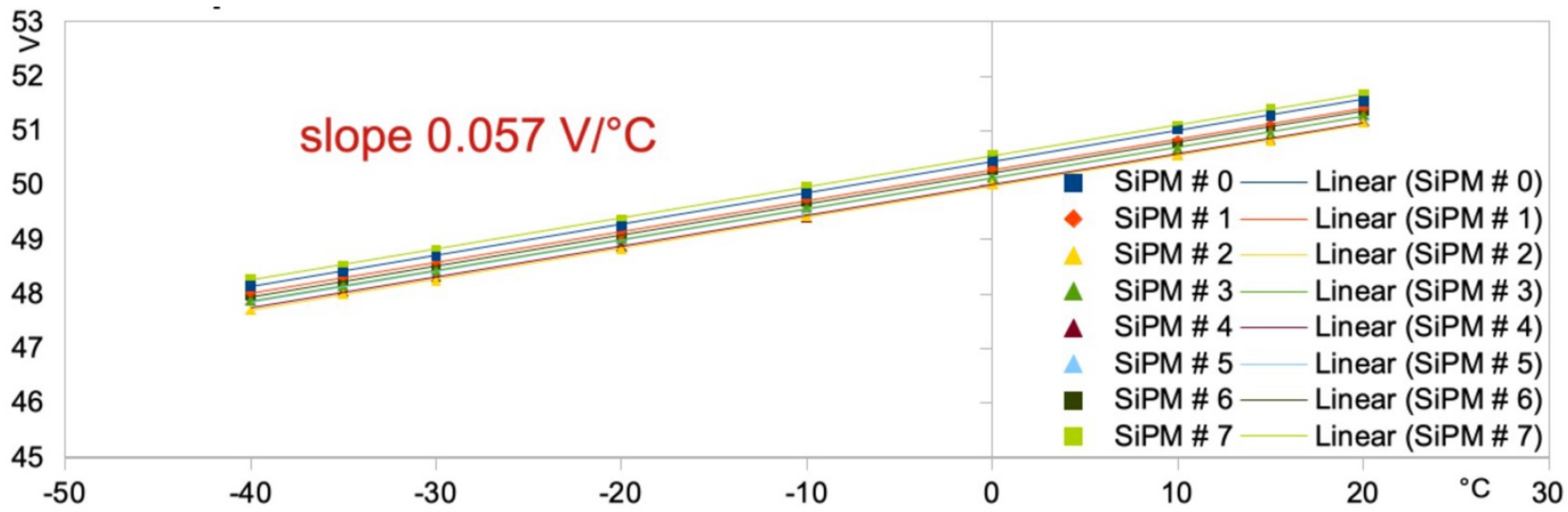
Requested beam current: 135 nA
(max beam current 200 nA)

Available beam time: 3 days

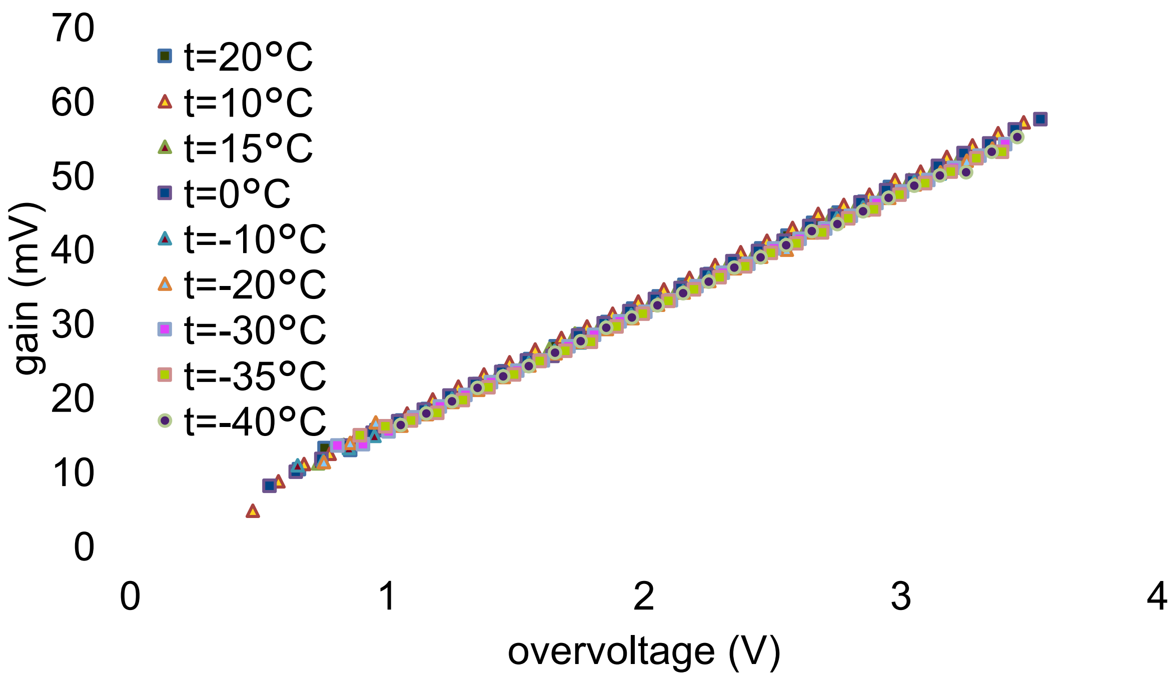
Max. irradiation time: 16.34 hours

neutron fluxes
from 1x10^9 to 5x10^{11} neutrons/cm^2

- breakdown voltage vs. temperature before irradiation



- gain vs over-voltage for SiPM # 0 before irradiation



SiPM irradiation test at LNL

(neutrons / cm^2)

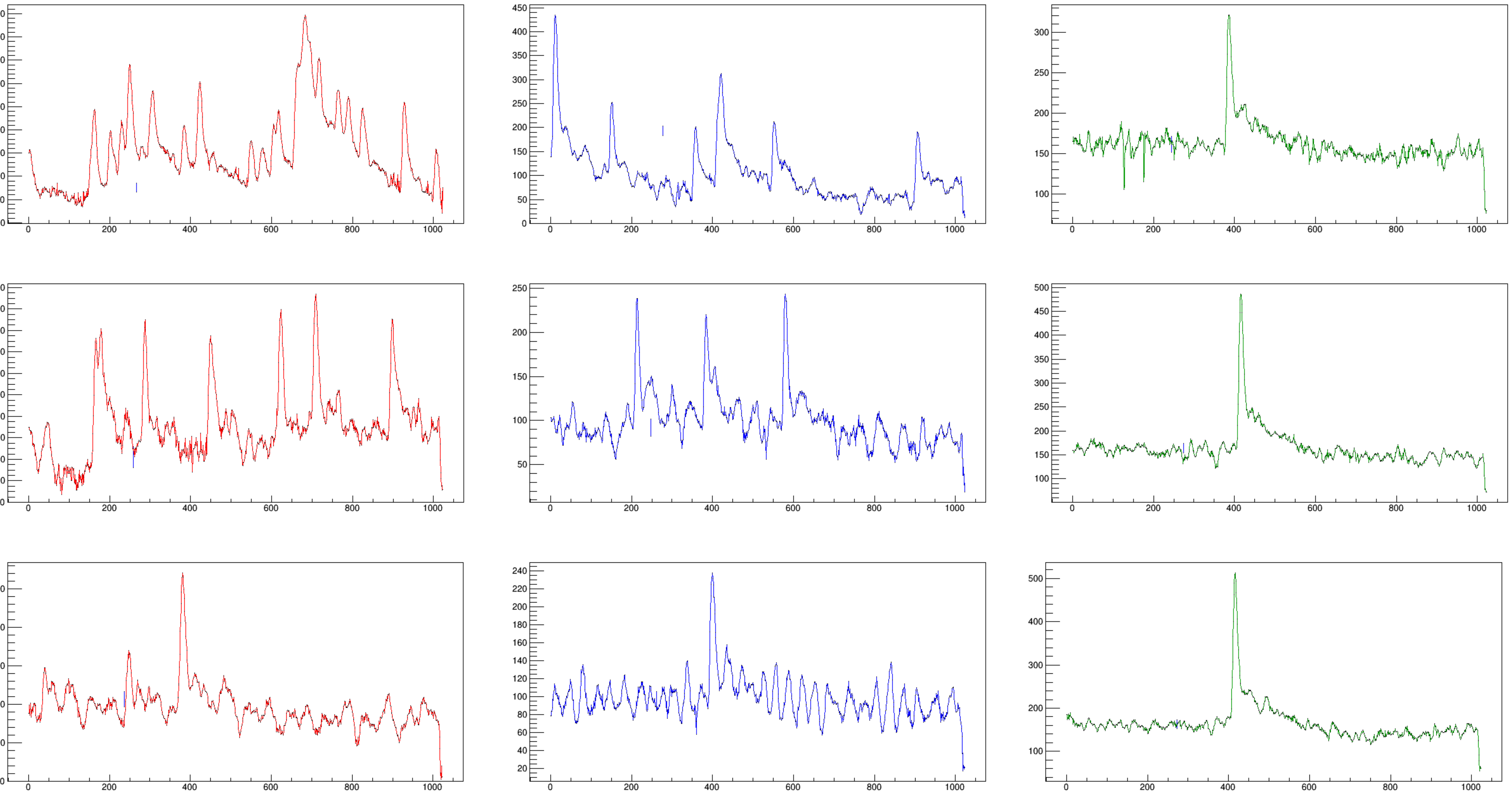
5.07×10^{11} | 5.07×10^{10} | 1.03×10^{9}

ADC

0 °C

- 20 °C

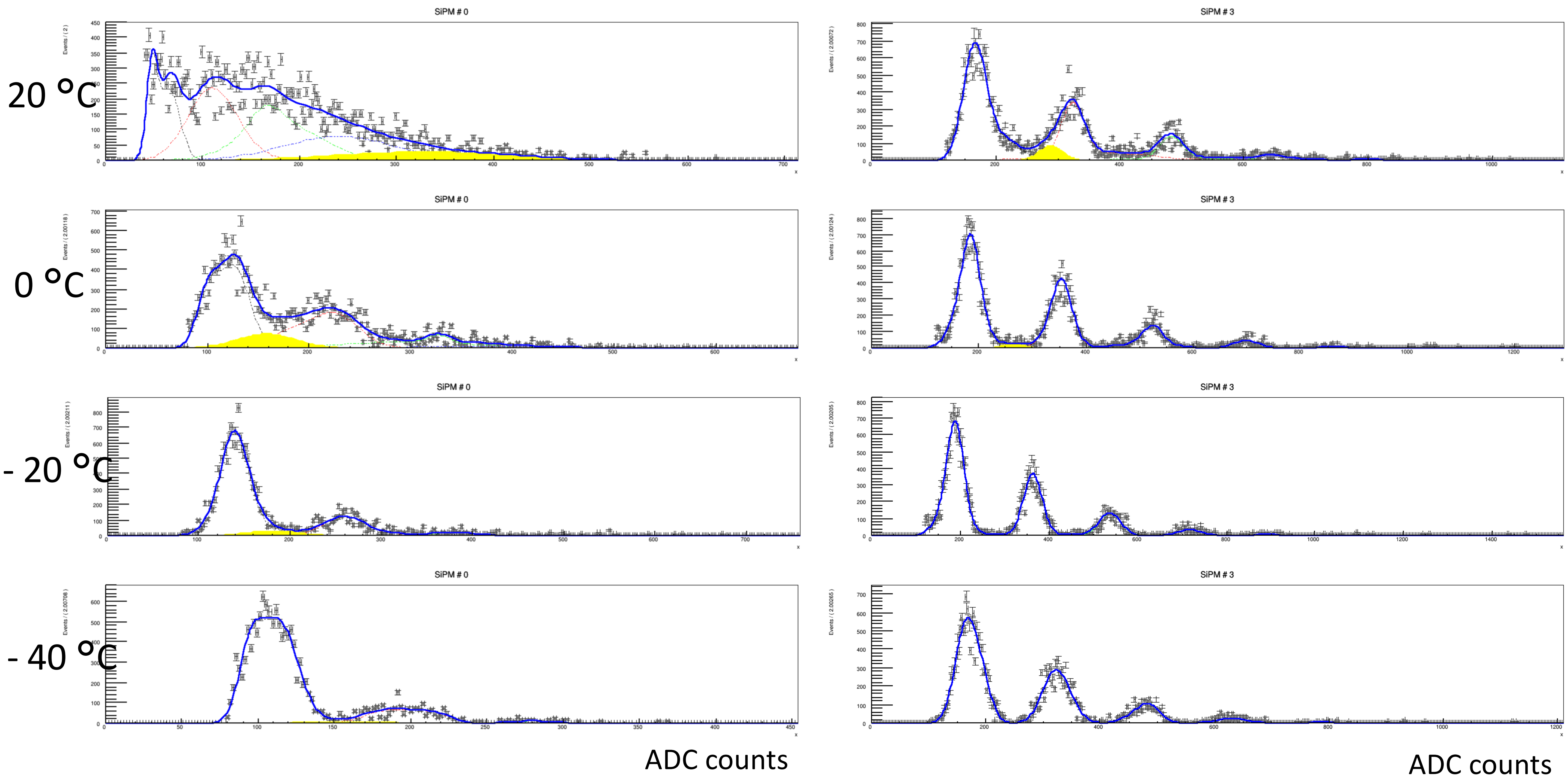
- 40 °C

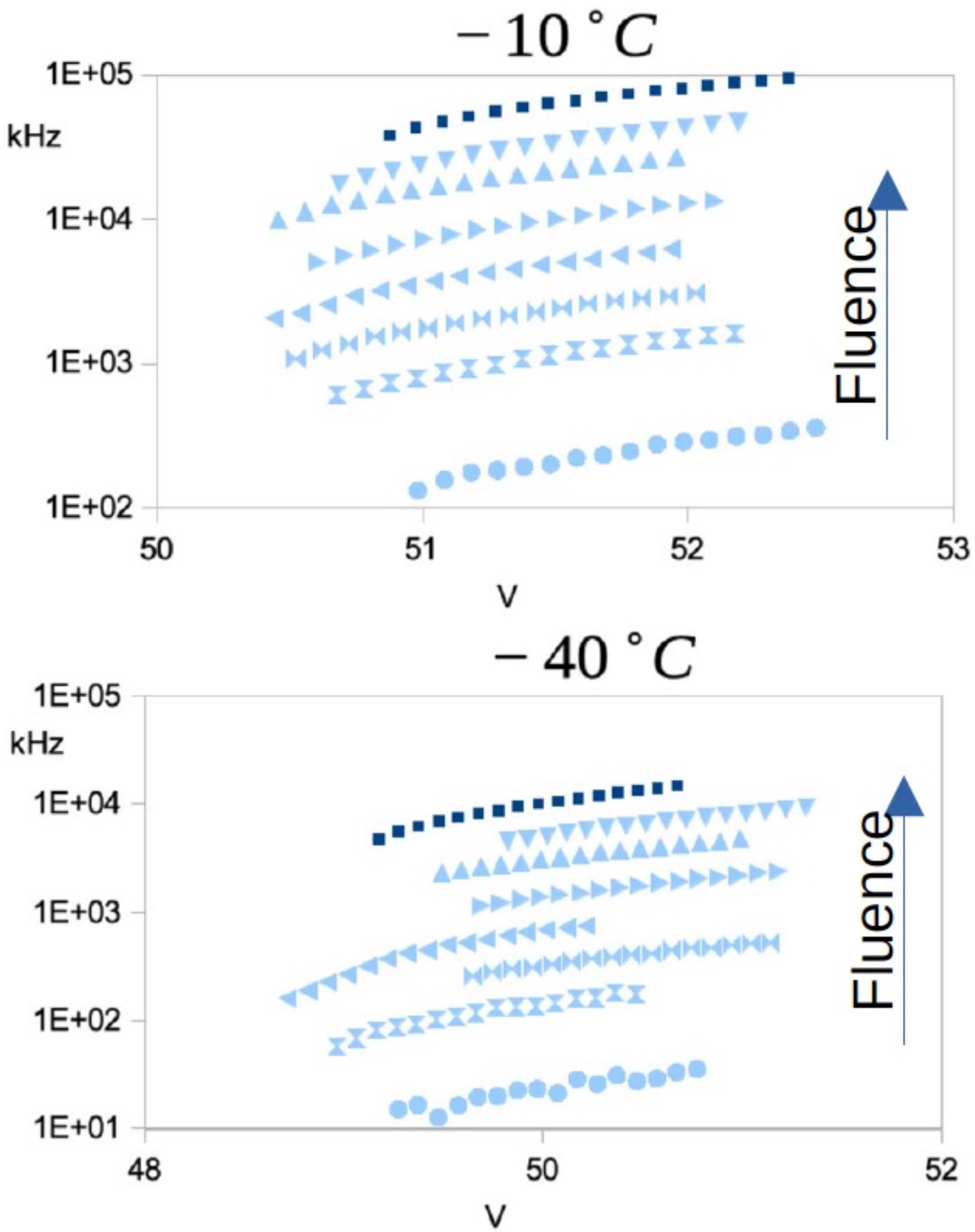


0.2 ns bin

SiPM irradiation test at LNL

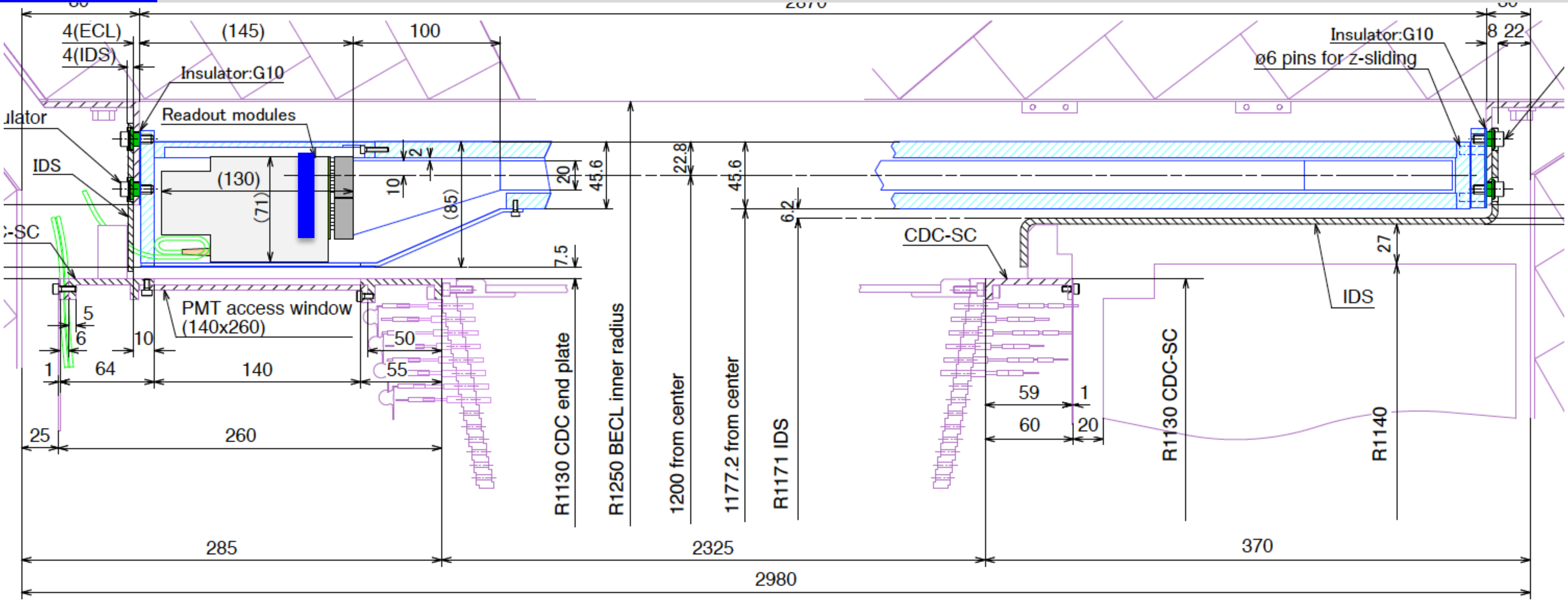
5.07 x 10^{11} neutrons/cm^2 | 5.07 x 10^{10} neutrons/cm^2





Dark counts vs Vbias for
- different temperatures
- different flueces

SiPM cooling options

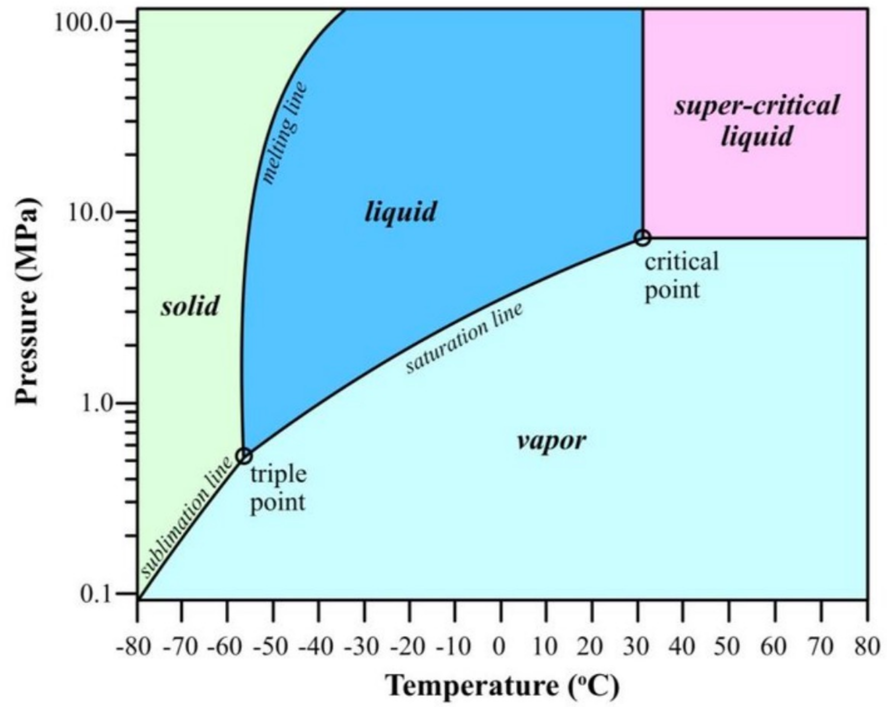


Suppose we want to introduce a cold surface with SiPM @ -30 ^oC

A solution can be a cooling using liquid CO_2 ,

- advantages: green, incombustible, low viscosity
- disadvantages: high pressure
  Saturation line for -30 ^oC at 14.3 Atm
  The pipeline can be small but must hold high pressure

Thermal decoupling with air gap or low thermal conductivity material



Next steps

- new irradiation at the beginning of July
- will irradiate 16 SiPMs
  - 8 are under test

	# Available
4 FBK 1x1 mm^2 15 μm cells	4
3 FBK 3x3 mm^2 15 μm cells	3
1 Hamamatsu 3x3 mm^2 15 μm cells	5

  - other 8 will be tested

2 OnSemi 1x1 mm^2 35 μm cells	6
2 OnSemi 3x3 mm^2 35 μm cells	6
2 Kektek 3x3 mm^2 15 μm cells	5
2 Kektek 3x3 mm^2 35 μm cells	5

- anneal the irradiated batch and make full measurements again
- still improving software to detect peaks in high background environments