Plan of the TOP upgrade

Heavy Flavor and Dark Matter Joint Unit Symposium
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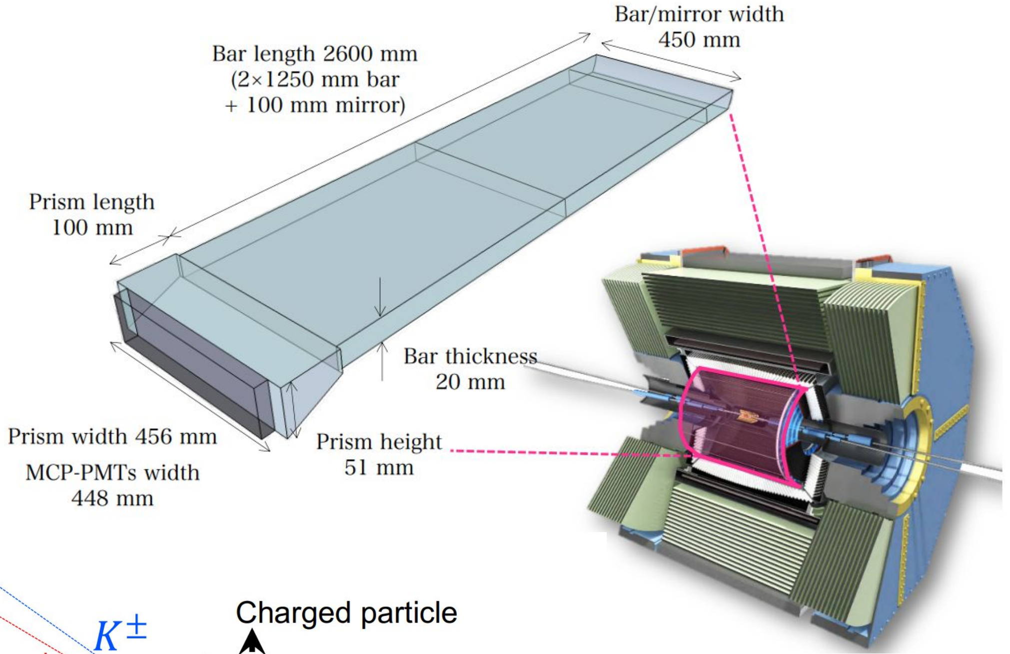
on behalf of TOP Upgrade group

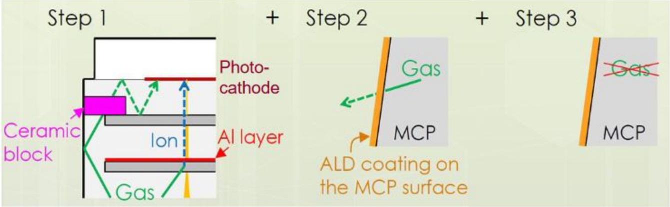
Belle II TOP Upgrade

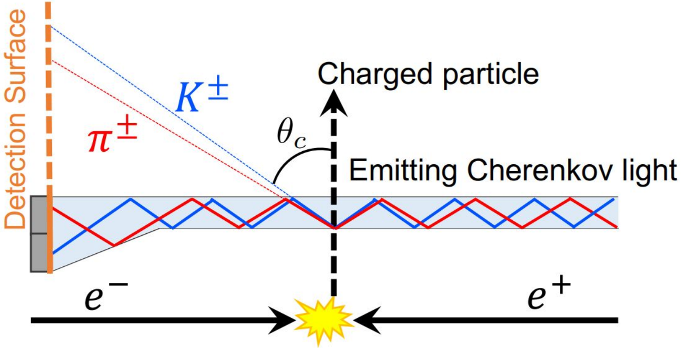
- TOP detector at Belle II
- Our experiences with TOP detector
  - Accumulated charge
  - Quantum efficiency measurement
  - Source of quantum efficiency degradation of MCP-PMTs
- Background level studies
- Replacement of MCP-PMTs in LS1
- Possibilities for MCP-PMTs replacement in LS2
- Comparison between MCP-PMT and SiPM
- GULFstream update
- Thermal gradient
- Background level and expected neutron flux
- First result on irradiated SiPM Hamamatsu
- Further plans with SiPM

TOP detector at Belle II

- 16 TOP modules surround the tracking detector on barrel part for particle identification.
- Each module contains finely fused silica bar, MCP-PMT (Microchannel Plate Photomultiplier Tube) photo-detectors, and high-speed readout electronics.
- Three types of MCT-PMTs has been installed (development steps/generations):
  - Step 1: Conventional
  - Step 2: Atomic layer deposition (ALD)
  - Step 3: Lifetime extended ALD







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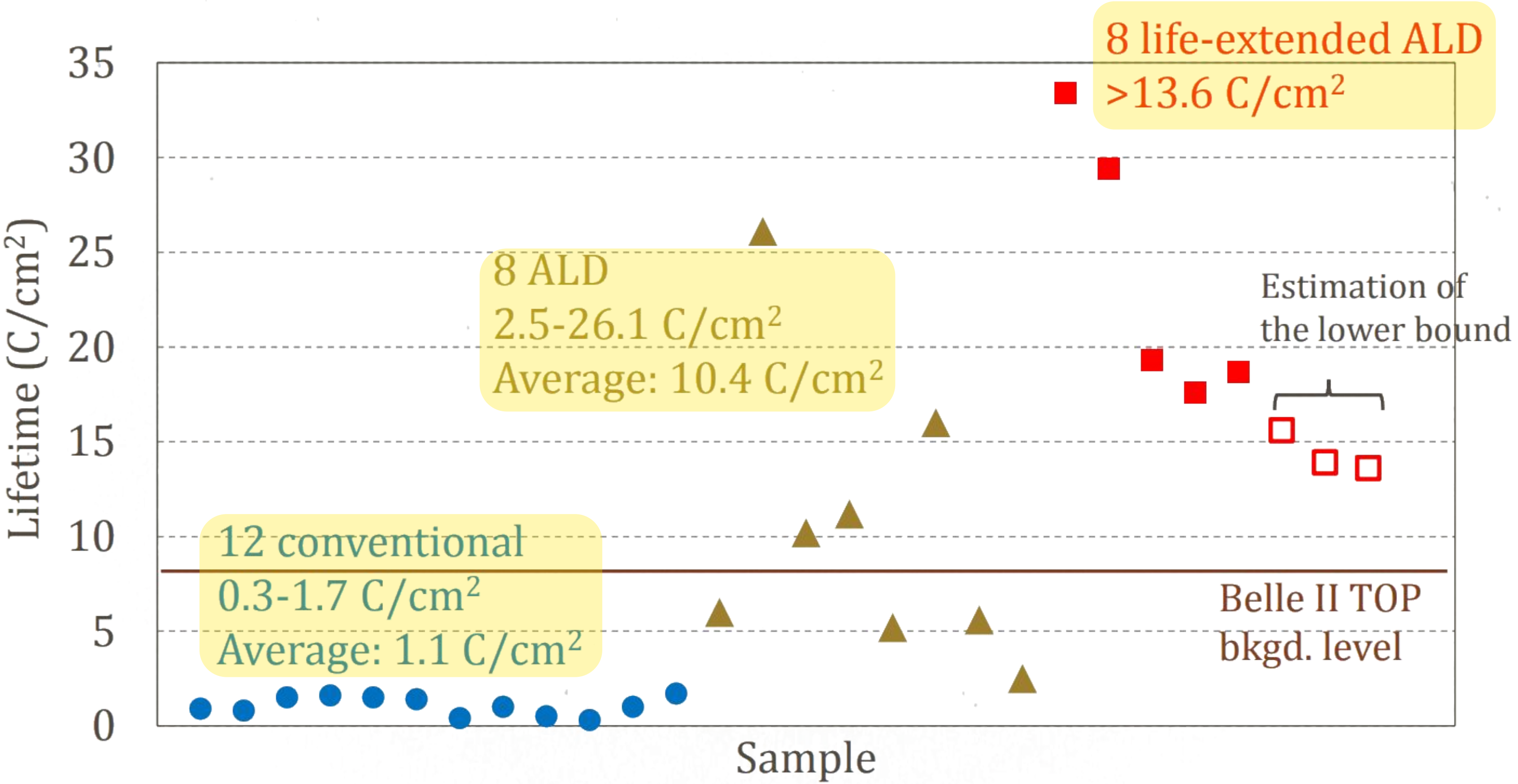
Lifetime measurement of MCT-PMTs in 2017



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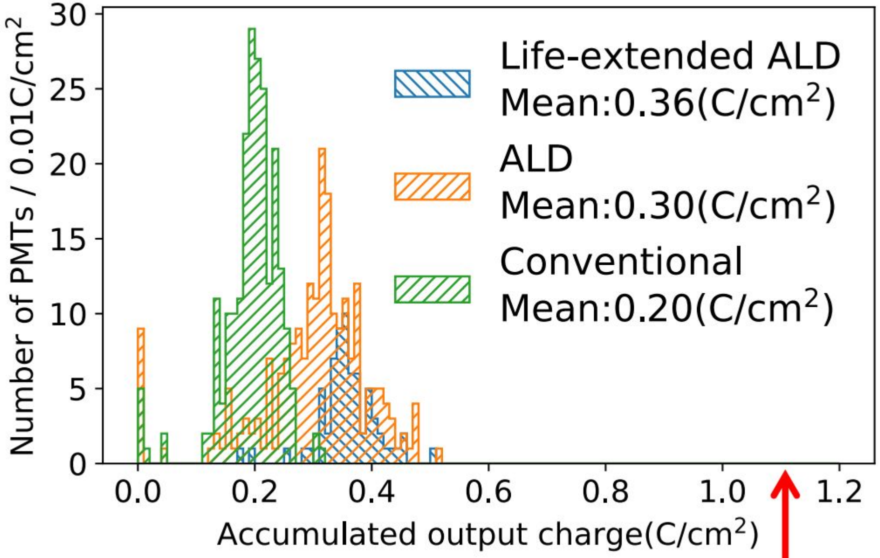
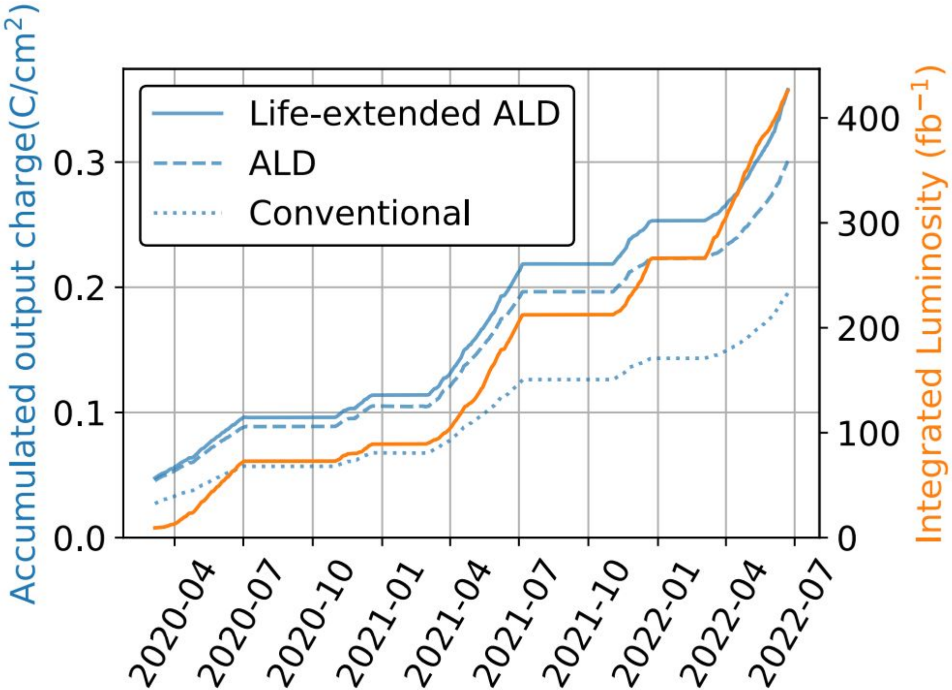
Accumulated charge



Average lifetime of conventional MCP-PMT

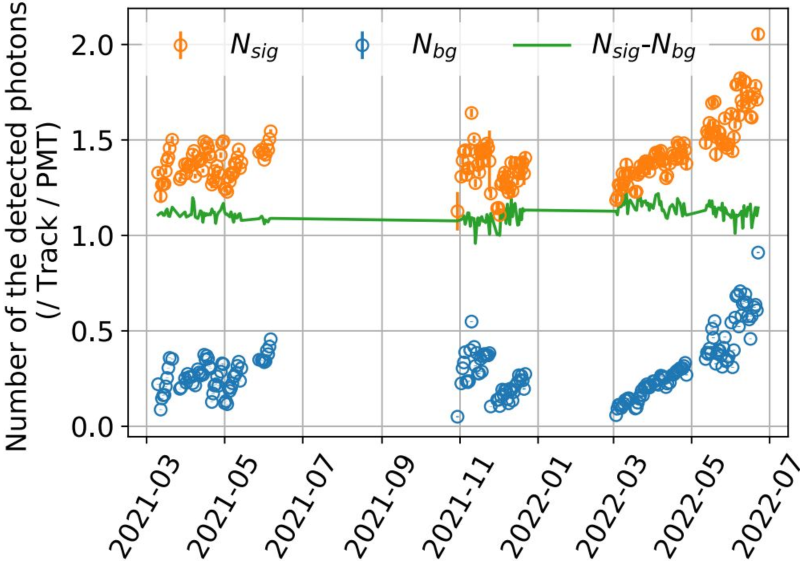


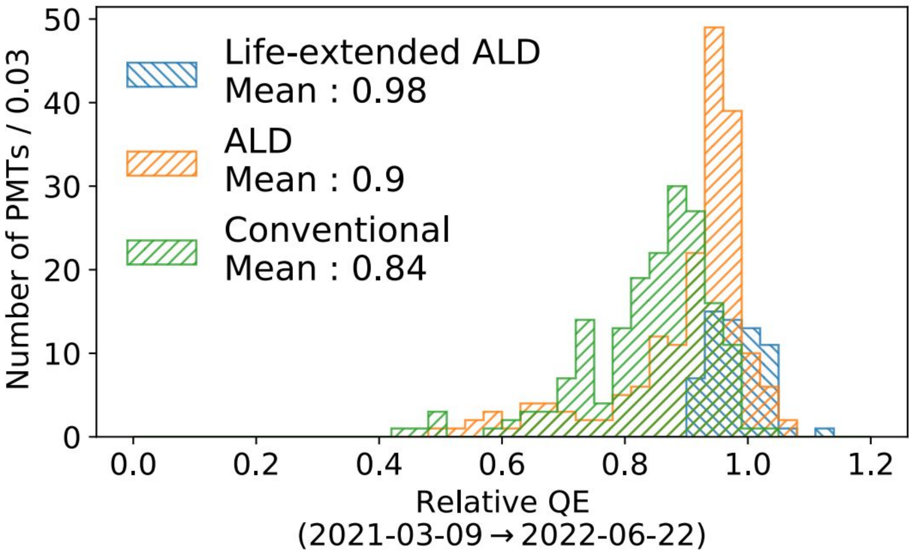
Quantum efficiency (QE) degradation

Quantum efficiency can be measured as difference between number of photons in ee→μμ events (μ generate Cherenkov light signal) and number of photons in no μ events (beam background, physics background dark noise, ...)

Higher than expected quantum efficiency degradation is dependent on type of MCT-PMTs, where conventional MCT-PMTs are highly degraded in comparison to ALD MCT-PMTs

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





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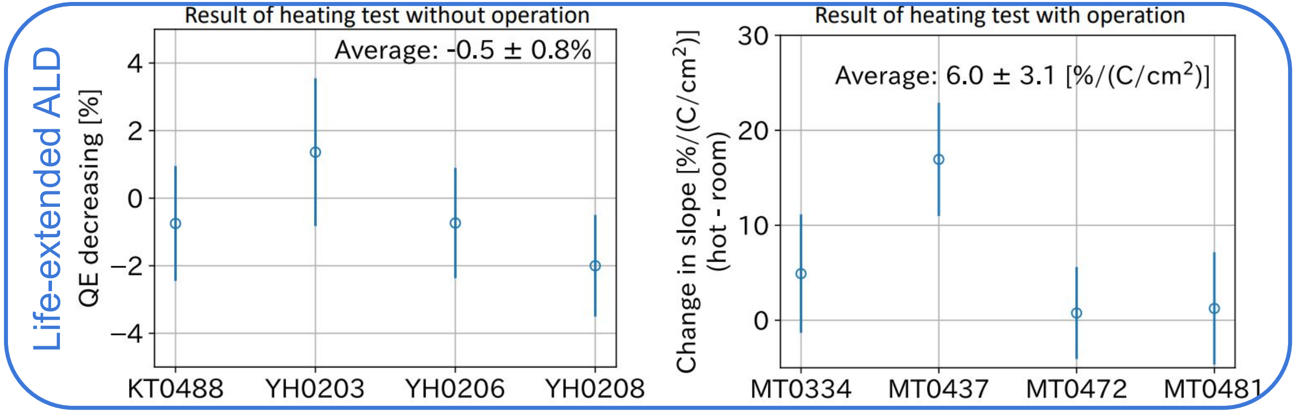
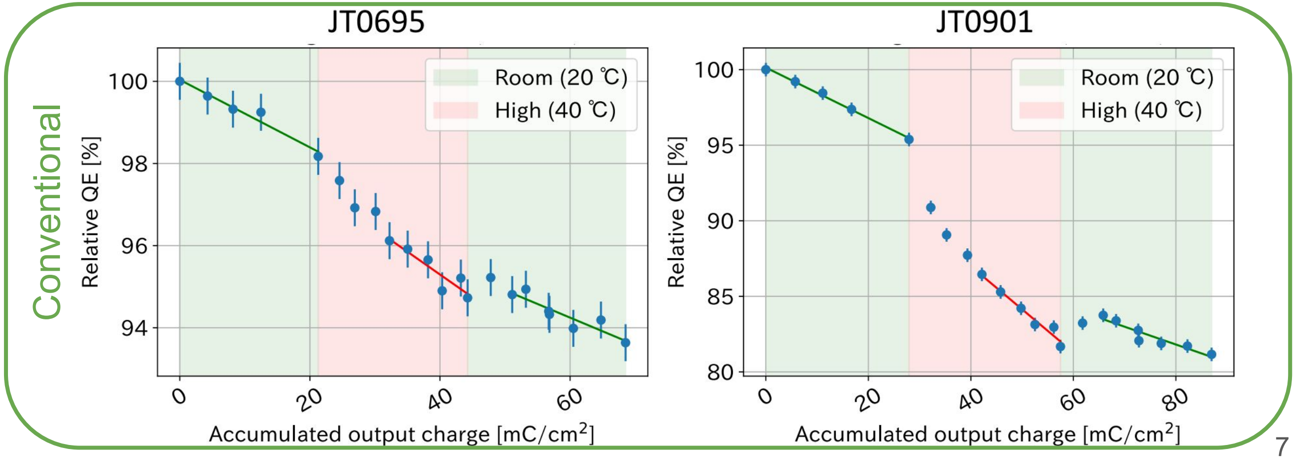
Source of quantum efficiency degradation

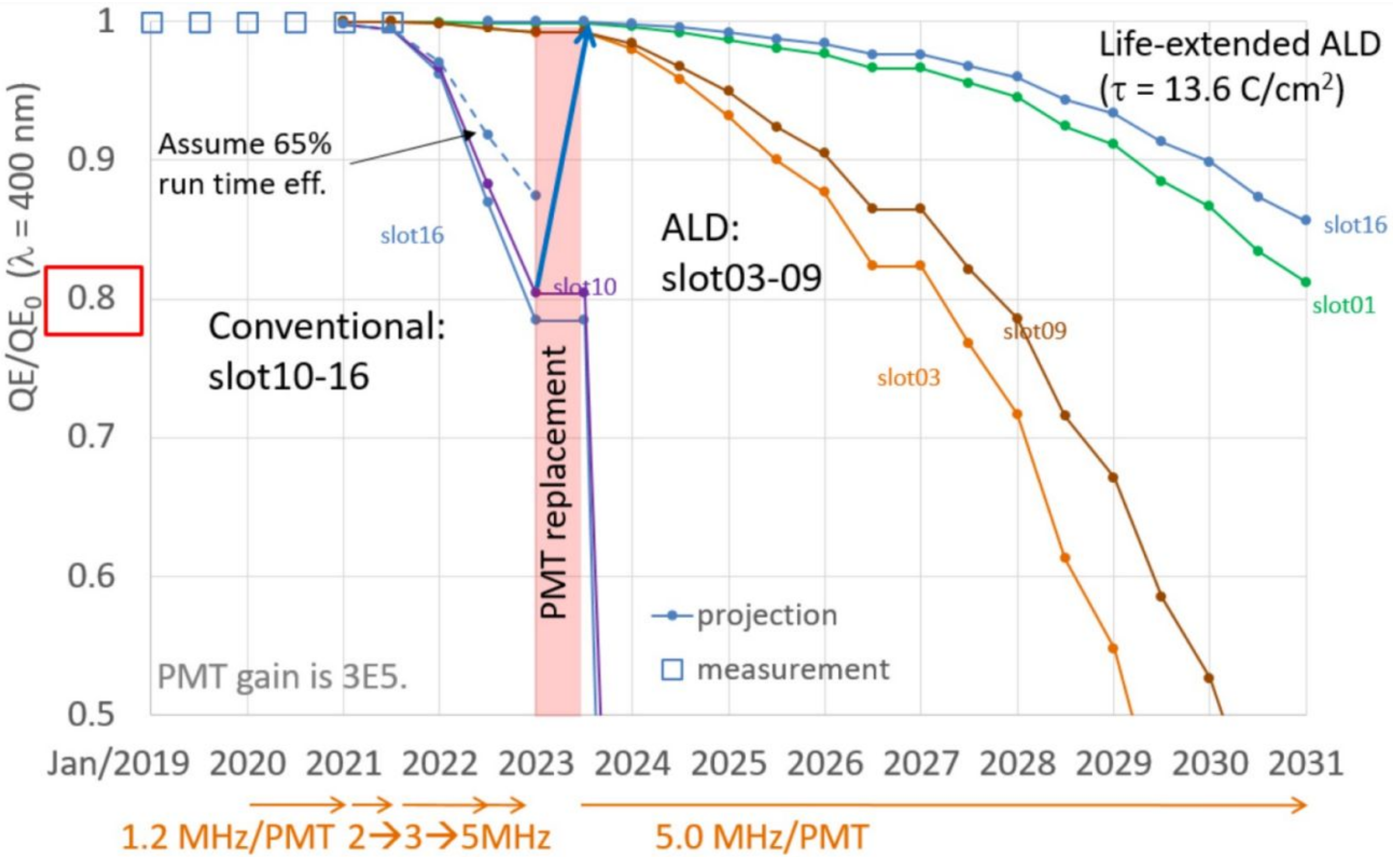
- Temperature difference between lifetime measurement (20 °C) and operation at Belle II (40 °C) due to electronics
- Heating tests have done with several MCT-PMTs
- Life-extended ALD MCT-PMTs reports no degradation
- Conventional MCT-PMTs reports temperature changing characterisation of photocathode, and shorter lifetime with higher temperature





Background level studies

- Expected luminosity is $6.0 \cdot 10^{35}$ cm^{-2} s^{-1} and life-extended ALD MCP-PMT will survive up to LS3 with total rate ~ 9.0 MHz/PMT
  - Single beam ~ 5.0 MHz/PMT
  - Luminosity ~ 3.6 MHz/PMT @ 6.3 $\cdot 10^{35}$ cm^{-2} s^{-1}
- The expected background at LS2 is under study.



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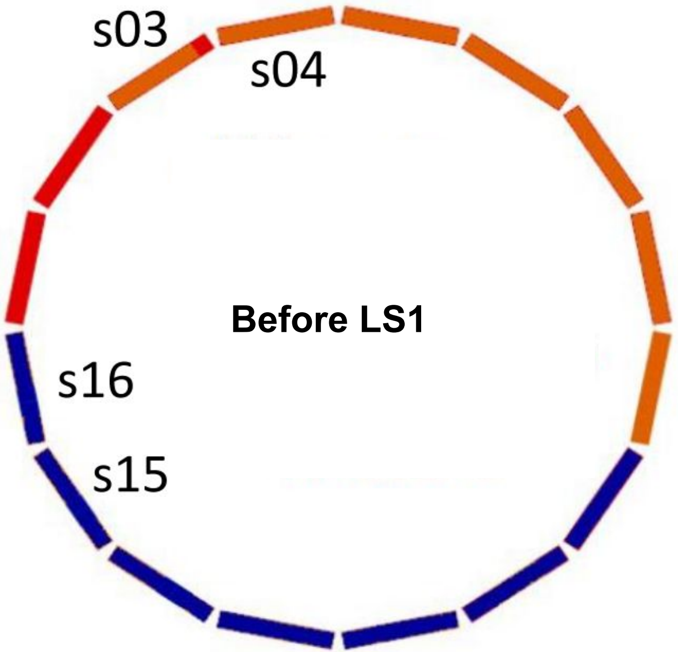
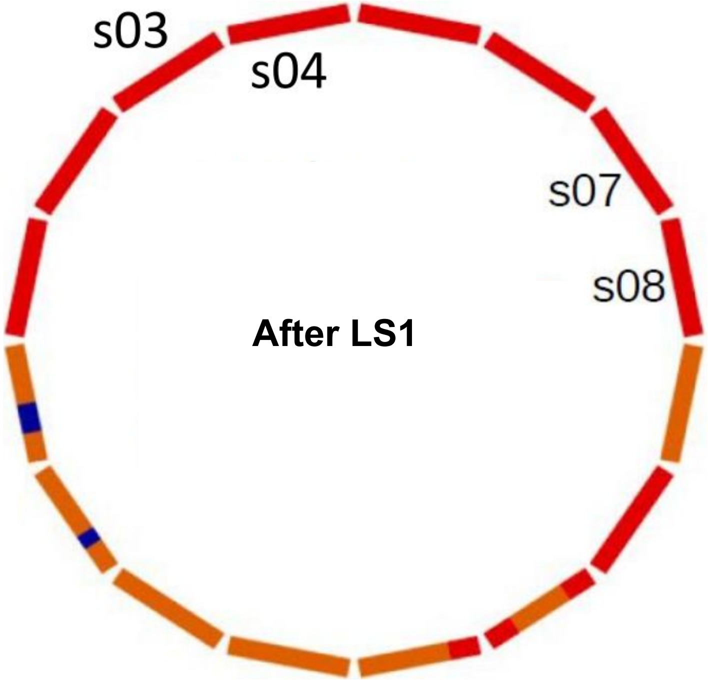
Replacement of MCP-PMTs in this shutdown

- In first long shutdown (LS1 @ 2022), will be replaced most of the MCP-PMTs:



- ➔ In the top part (worse accessible) of the Belle II detector, all ALD will be replaced by life-extended ALD MCP-PMTs.
- ➔ In the bottom part of the Belle II detector, most of the conventional will be replaced by ALD or life-extended ALD MCP-PMTs
- ➔ Due to better accessibility, kept conventional and ALD MCP-PMTs can be replaced in next summer shutdowns, if necessary.



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Possibilities for MCP-PMTs replacement in LS2

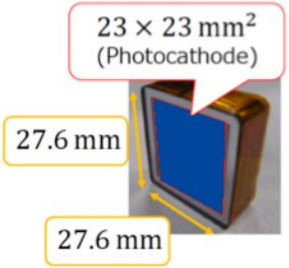
1) Baseline plan for LS2 (>2027) is replacement of ALD by life-extended ALD MCP-PMTs.

- Production plan is ongoing.
- First 90 MCP-PMTs was delivered
- The tests are ongoing
- Funding for the next years under discussion

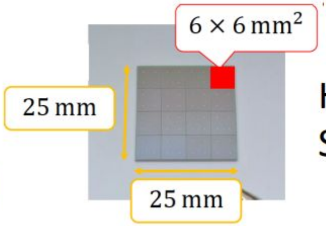
JFY	2021	2022	2023	2024	2025
Production	30	60	60	60	10

2) Another solution is replace MCP-PMTs by MPPC (SiPM)

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

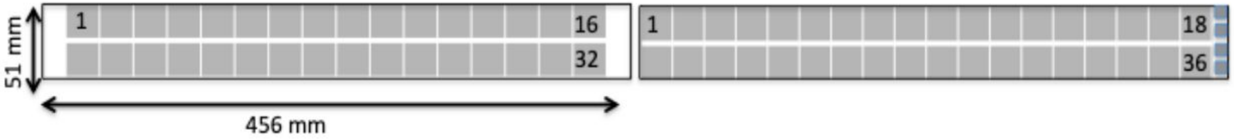


1 MPPC (SiPM)
4x4 channels
6 x 6 mm^2 / channel



Hamamatsu
S13361-6050

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



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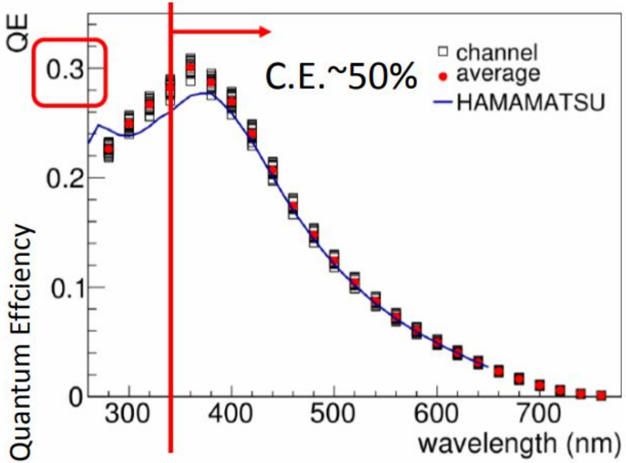
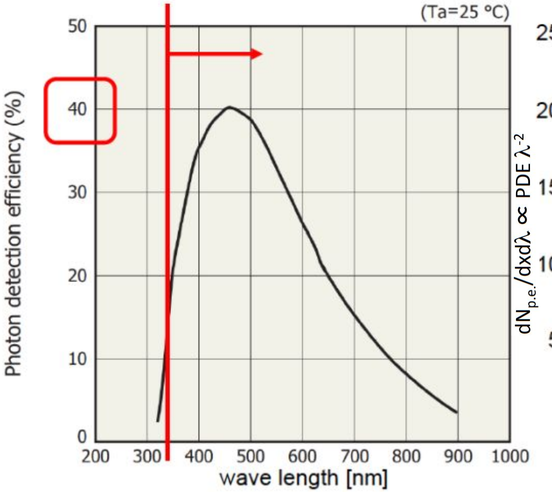
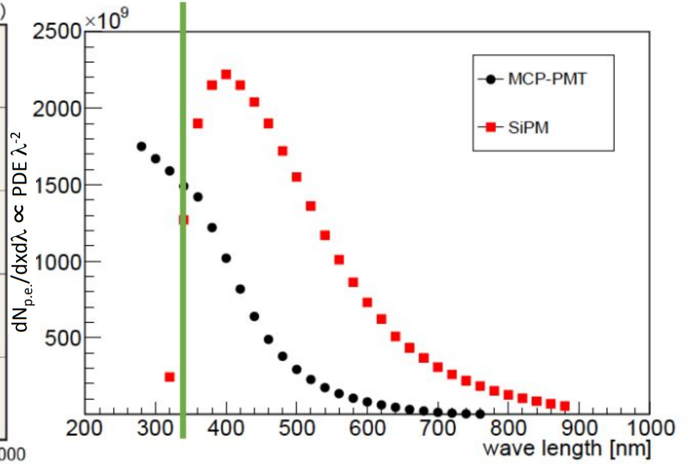
Comparison between MCP-PMT and SiPM

- For MCP-PMTs: Photon detection efficiency = Quantum efficiency ⊗ Collection efficiency
- For SiPMs: Photon detection efficiency = Quantum efficiency ⊗ Avalanche trigger probability ⊗ Fill factor



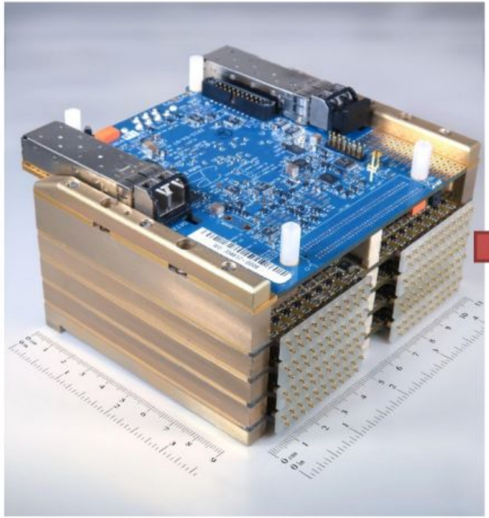


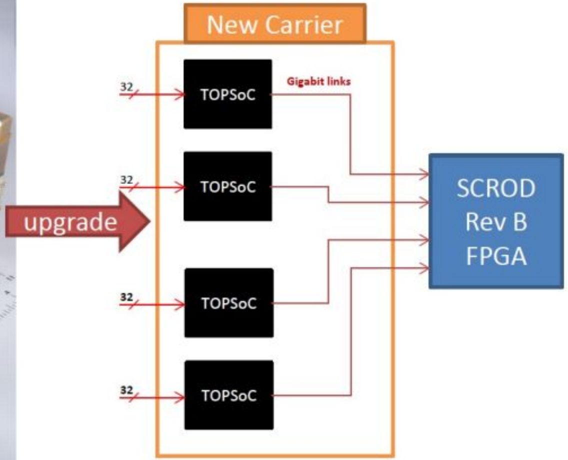


- Photon detection efficiency looks better for SiMPs as for MCP-PMTs
- Count rate exponential increase due to neutron flux can be partially compensated with lower temperature
- SiPMs with lower area have lower count rate, but requires more electronic channels
- If a MCP-PMT is replaces with SiPM with 6x6 mm^2, number of channels will not change (16 channels)
- If a MCP-PMT is replaces with SiPM with 3x3 mm^2, number of channels will be 4 times more (64)

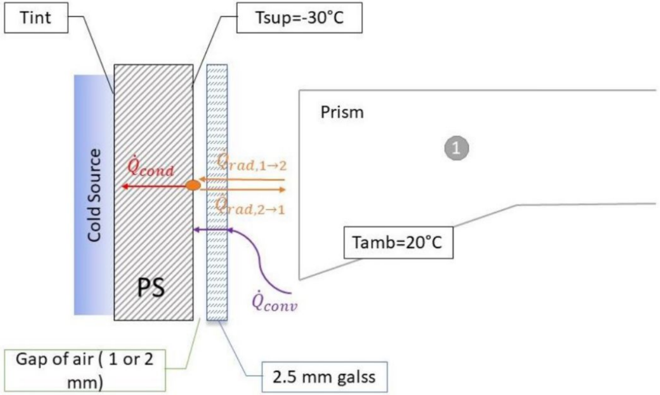
GULFstream update and thermal gradient

- Upgrade of electronics is planned too:
  - Current IRSX ASIC 8-channel 250 nm CMOS will be replaced by TOPSoC ASIC 32-channel 130 nm CMOS
  - It improving power consumption (by decreasing number of carries) and allows to use (4 times) more readout channels
  - Feature extraction inside ASIC rather than using FPGA
  - No pedestal acquisition





- Isolation between SiPM and quartz is needed to reduced thermal gradient (less mechanical stress)



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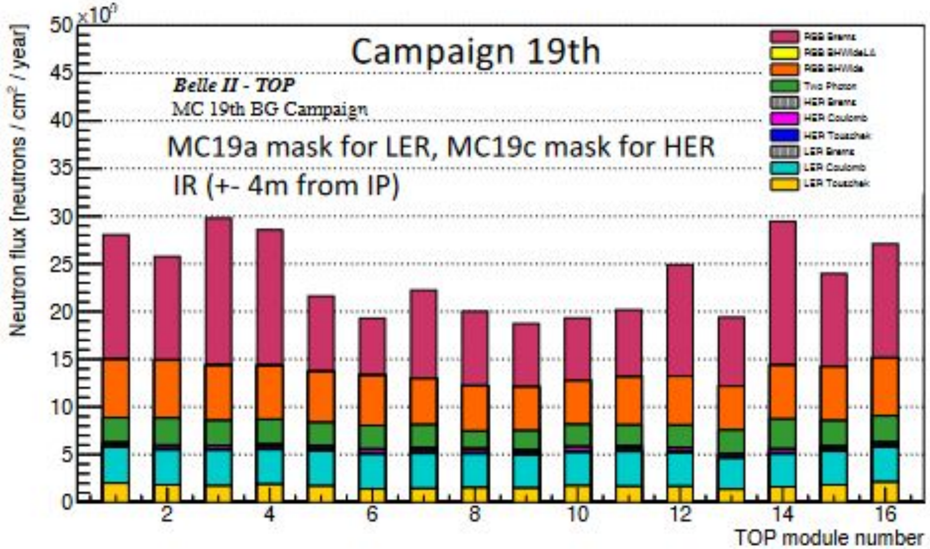
Background level and expected neutron flux

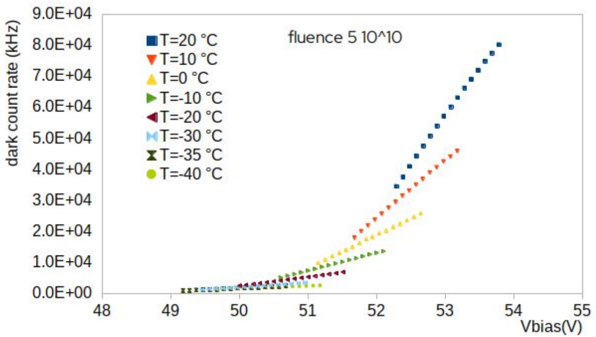
- For MCP-PMT the most crucial background is degradation of quantum efficiency
- Instead for SiPM the most critical is neutron flux, because increase count rate
- Study of neutron flux is part of background studies at LS2, which is ongoing
- Current study (based on 19^{th} Monte Carlo Campaign) report about neutron flux at TOP at level of $2.5 \cdot 10^{10}$ neutrons/cm^2/year (with luminosity $8 \cdot 10^{35}$ cm^{-2} s^{-1})
- Now expected luminosity at LS2 is $6.0 \cdot 10^{35}$ cm^{-2} s^{-1}



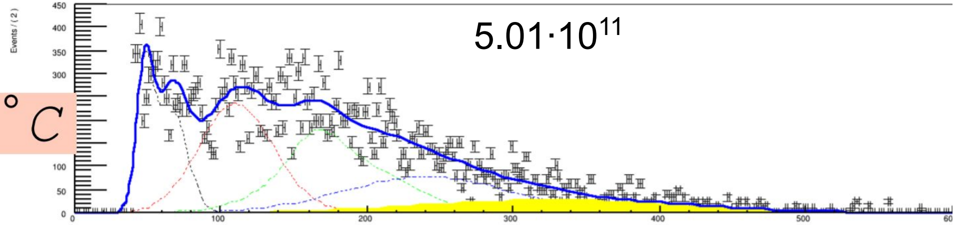
First result on irradiated SiPM Hamamatsu

- In winter 2022, 8 Hamamatsu 1.3x1.3 mm^2 x 50 μm cells (S13360-1350PE) SiMPs were measured in Padova
- SiPMs were irradiated at different distances from target and different integration times
- SiPMs was irradiated with fluences in range from $1\cdot10^9$ to $5\cdot10^{11}$ neutrons cm^2
- Increase of dark counting due to neutron irradiation can be partially compensated by operating SiPMs at low temperature, damages produced by neutron irradiation can be partially recovered with annealing process

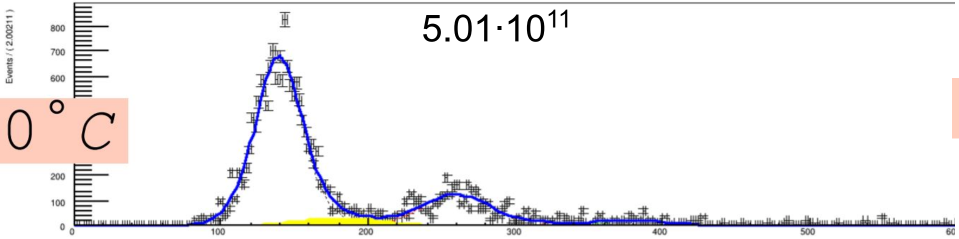
# SiPM	Distance [cm]	Neutron 1 MeV eq/cm^2 fluence	Charge [mC]	Time [h]
0	4.3	$5.01\cdot10^{11}$	7.94	16.34
1	6.8	$2.00\cdot10^{11}$	7.94	16.34
2	9.3	$1.00\cdot10^{11}$	7.94	15.30
3	11.8	$5.01\cdot10^{10}$	5.98	12.31
4	14.3	$2.42\cdot10^{10}$	4.25	8.74
5	16.8	$1.01\cdot10^{10}$	2.44	5.03
6	19.3	$5.00\cdot10^{9}$	1.60	3.29
7	21.8	$1.01\cdot10^{9}$	0.41	0.85



$20^\circ C$



$-20^\circ C$



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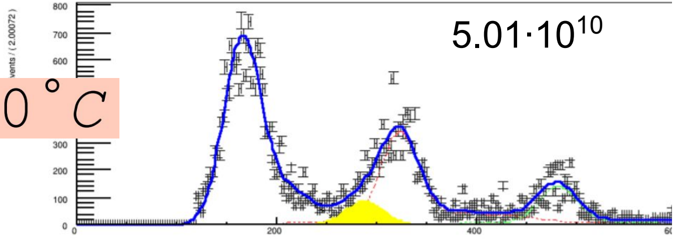

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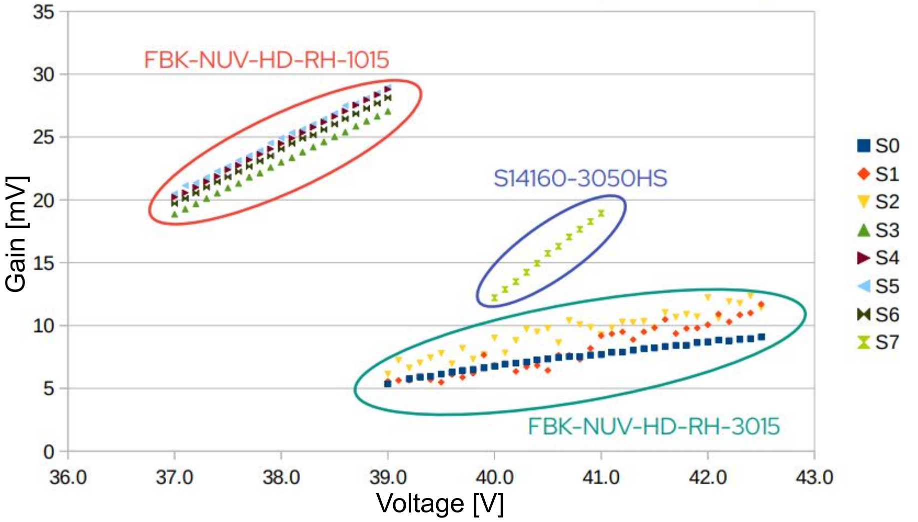
Further plans with SiPM

preliminary results

- In Summer 2023 next irradiated test will be done:
  - 3 FBK 3x3 mm^2 x 15 µm cells (FBK-NUV-HD-RH-3015)
  - 4 FBK 1x1 mm^2 x 15 µm cells (FBK-NUV-HD-RH-1015)
  - 1 Hamamatsu 3x3 mm^2 x 50 µm cells (S14160-3050HS)
- Irradiation measurement based on 16 SiPMs.
- The maximum fluence is planned $1 \cdot 10^{11}$
- The goal is identify the cell size giving better radiation hardness performance (lower cell size is expected to be better).
- Try to recover from irradiation to heat SiPMs around 150 °C for 3 weeks



- After Summer 2023 irradiation tests, a new SiPM prototype will be developed with FBK, the production of masks will take 6 months and cost 50 keurs financed with AIDAinnova (EU project).
- The goal is the further improvements the low field technology (regions with high field increase the count rate)

Conclusions and outlook

- TOP detector is integrated in Belle II and safely operated to first long shutdown (LS1) in 2022
- Higher than expected degradation of quantum efficiency was identified and understood as difference in temperatures in lifetime measurements and operation in Belle II
- During the first long shutdown the most of conventional MCP-PMTs is replacing by ALD MCP-PMTs
- Replacement in LS2 is under discussion with two possible ways:
    a. All ALD MCP-PMTs can be replaced by life-extended ALD MCP-PMTs
    b. All MCP-PMTs can be replaced by MPPCs (SiPM)
        - Better global effective area
        - Better photon detection efficiency
        - Count rate exponential increase due to neutron flux can be partially compensated with lower temperature
        - SiPMs with lower area have lower count rate, but requires more electronic channels
        - Compatible with GULFstream update
        - To reduce thermal gradient, isolation is needed
- First irradiated tests with SiPM is ongoing with aim to identify cell size for better radiation hardness performance, then new prototype will be produced with aim to improve the low field technology
- Background level is under study, but life-extended MCP-PMTs will probably survive to LS3
- In LS2 expected neutron flux at TOP can be $2.5 \cdot 10^{10}$ neutrons/cm^2/year

Backup

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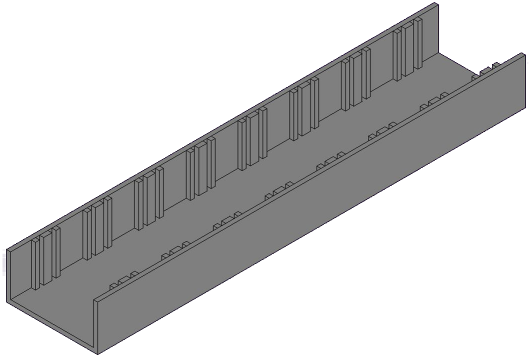

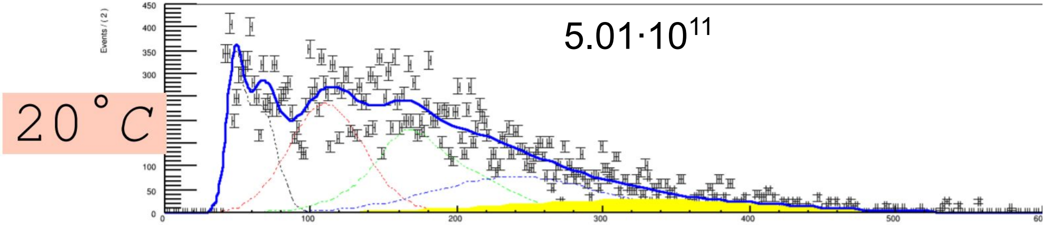

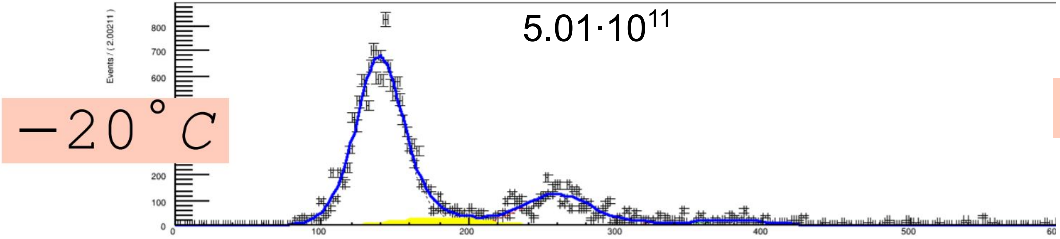

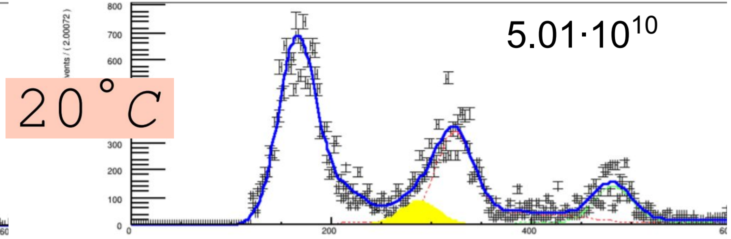

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