MEG II実験陽電子タイミングカウンターの改修及び性能見積り

米本 拓、他MEG IIコラボレーション

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21aT1-1

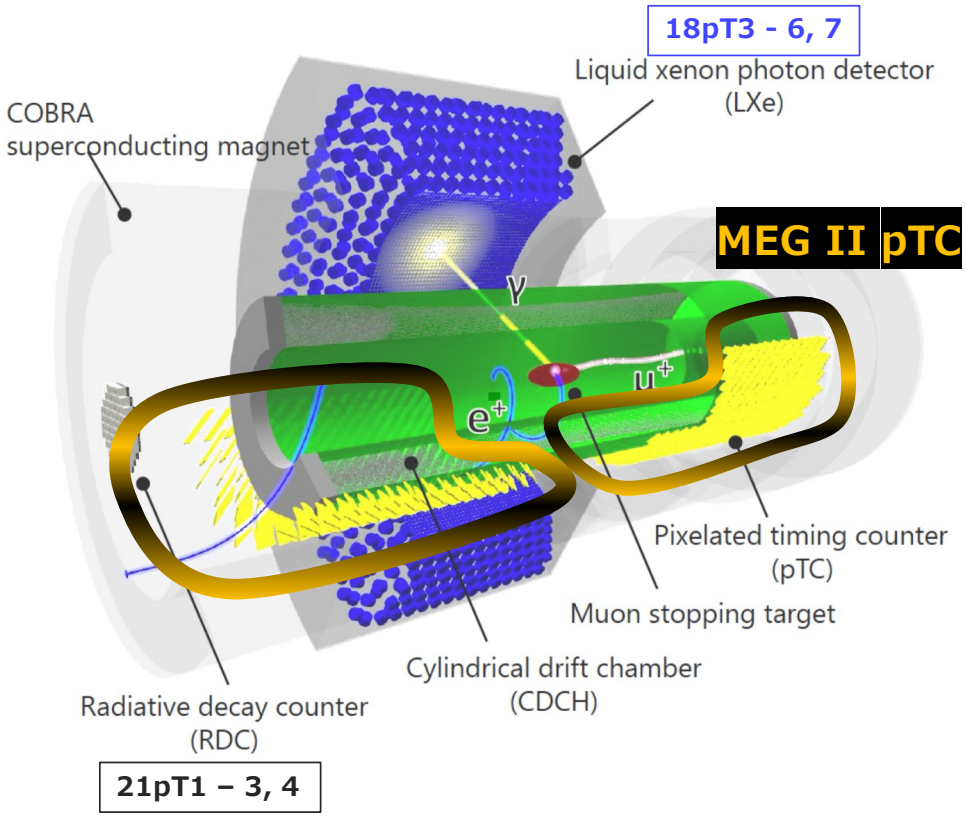
Topics

1. Introduction
   - ❖ MEG II experiment
   - ❖ pixelated / positron Timing Counter (pTC)
     - ○ pixels, performance so far

2. Pixel refurbishment plan
   - ❖ Test and performance of new SiPMs
   - ❖ Performance comparison with the past production
   - ❖ Mass production in 2024
   - ❖ Estimation of pTC performance after replacement

3. Summary

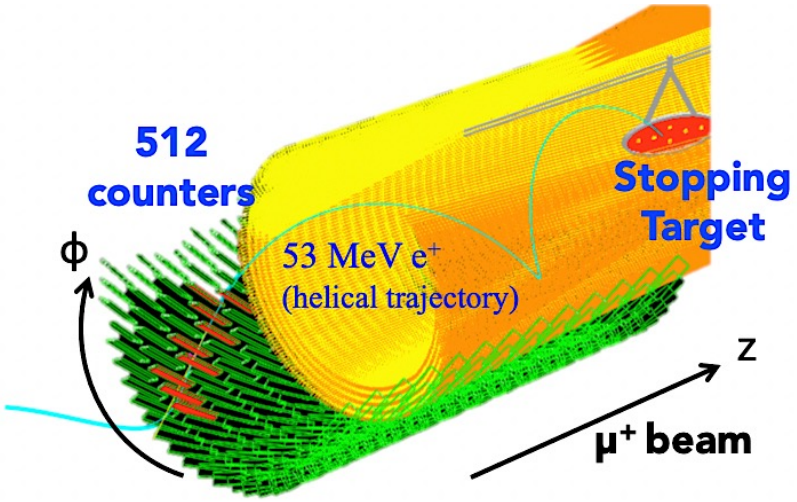
MEG II experiment

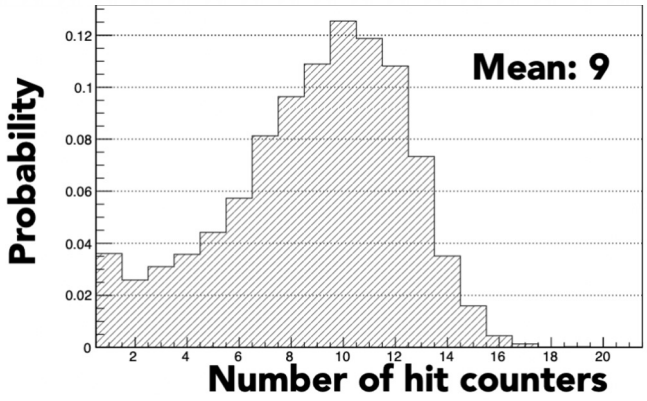


"The design of the MEG II experiment"
Eur. Phys.J.C 78, 380 (2018)

- Search for cLFV process $\mu \to e\,\gamma$ with aimed sensitivity: **6 x 10^{-14}**
  - An order better from the current upper limit: $\mathcal{B}(\mu \to e\,\gamma) < 4.2 \times 10^{-13}$ (MEG result, 2016)
- The physics run started in 2021
  - Analysis on 2021 data: Eur. Phys. J. C 84, 216 (2024)
  - Analysis on 2022 data: 18aT2 - 6, 7

pixelated Timing Counter (pTC)

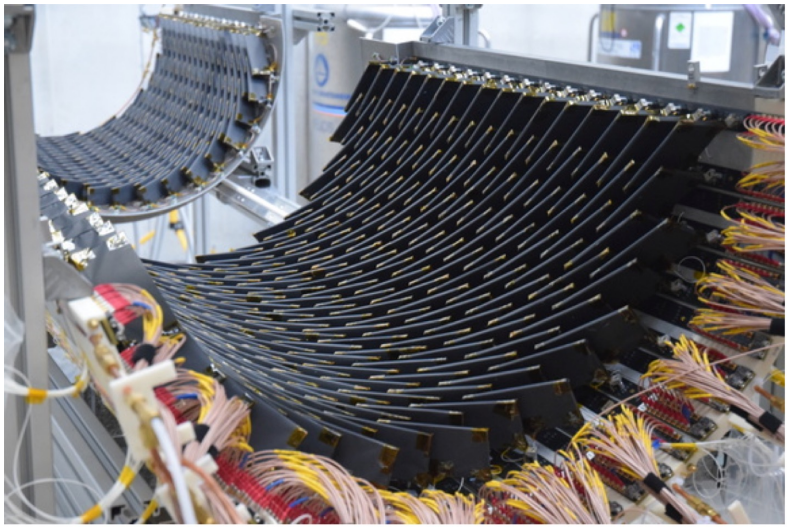


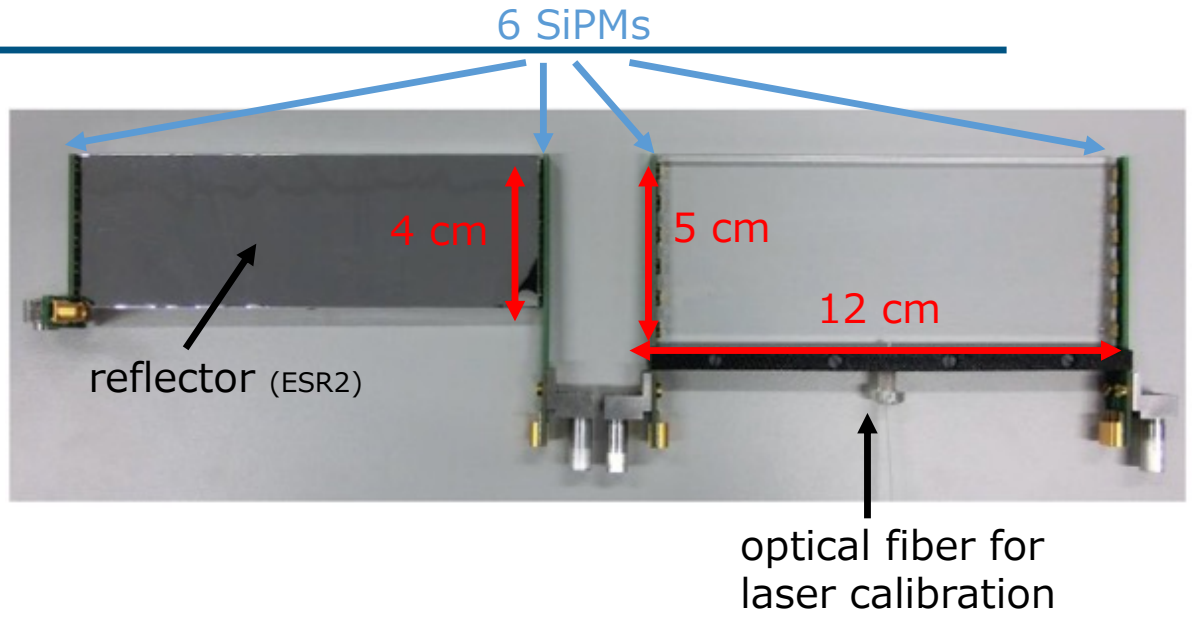


Concept

- **Improve e^+ time resolution by multiple-pixel-hit scheme.**
- Upstream 256 + Downstream 256 = **512 pixels**
- Mean ~ **9 hits** (MC, signal e^+)

pTC: pixels

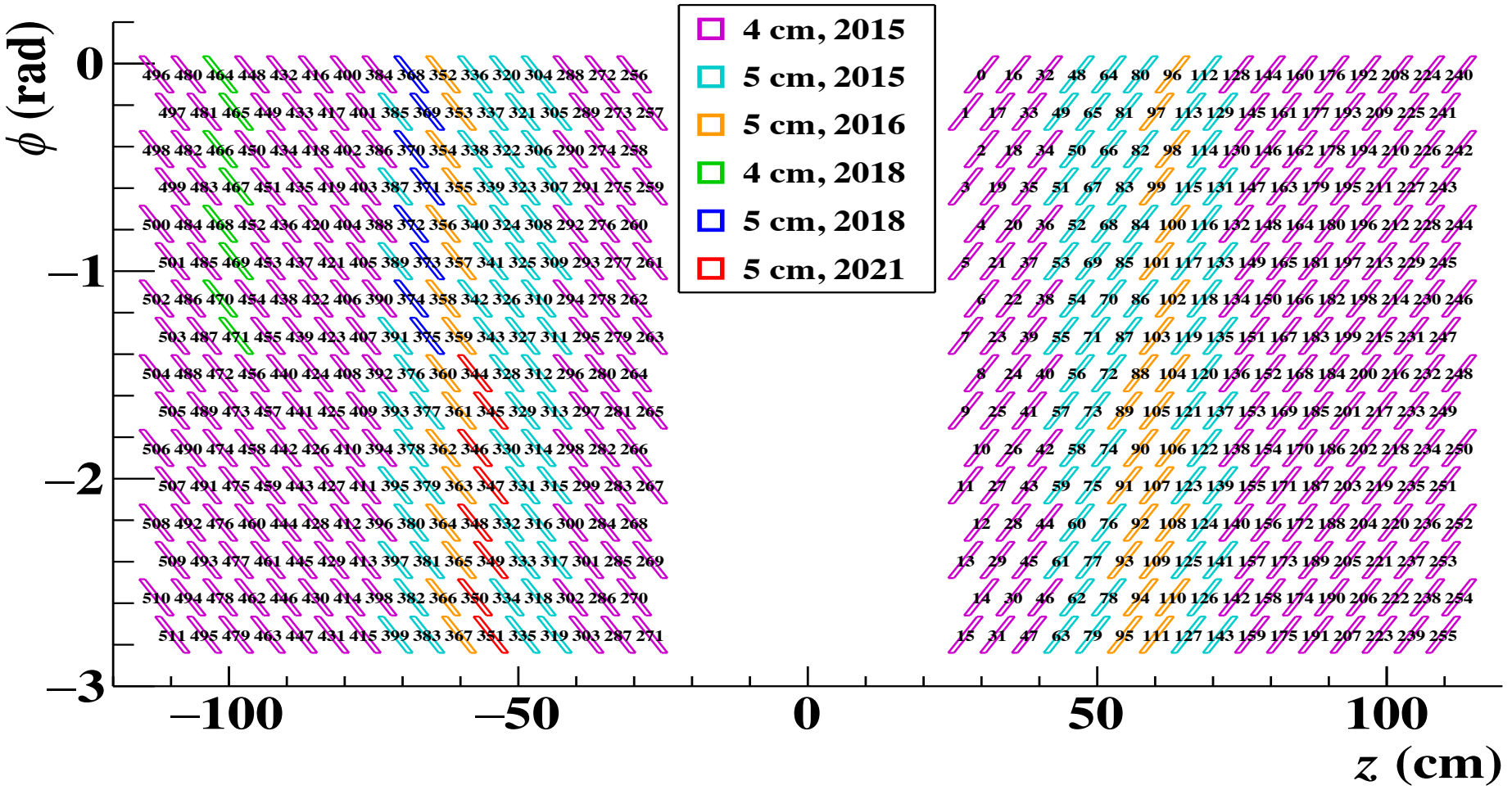




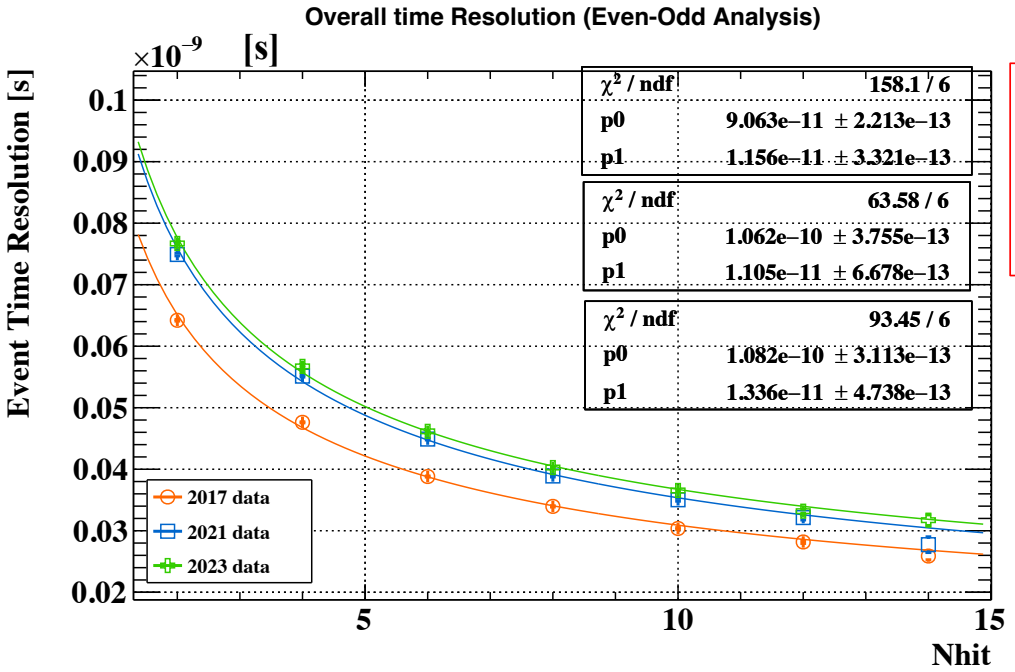
- Upstream 256 + Downstream 256 = 512 pixels
- 12 cm × 5 cm (4 cm) × 5 mm plastic scintillator (BC422).
- Read by series connection of 6 SiPMs on both side.

(AdvanSiD, ASD-NUV3S-P High-Gain, 3 x 3 mm^2, 50 x 50 μm^2, $V_{breakdown}$ ~ 24 V).

pTC: pixels


4 cm, 2015
5 cm, 2015
5 cm, 2016
4 cm, 2018
5 cm, 2018
5 cm, 2021
ϕ (rad)
0
−1
−2
−3
−100
−50
0
50
100
z (cm)

pTC: performance so far



Period	t_{e^+} resolution for 9 hits
pilot run 2017 Nov.	37.1 ps
2021 Oct.	38.4 ps
2023 Jun.	38.5 ps

for Michel e^+ data in 2017, 2021, 2023

$\sigma^2_{\text{inter-pixel}}$: precision of the timing calibration

$$\sigma_{\text{pTC}}(N_{\text{hit}}) = \sqrt{\frac{\sigma^2_{\text{intrinsic}} + \sigma^2_{\text{inter-pixel}}}{N_{\text{hit}}} + \text{const.}}$$

- **Single counter resolution:**

$$p_0 = \sqrt{\sigma^2_{\text{intrinsic}} + \sigma^2_{\text{inter-pixel}}}$$

90.6 ps (2017) → 108 ps (2023)

- **Overall resolution:**

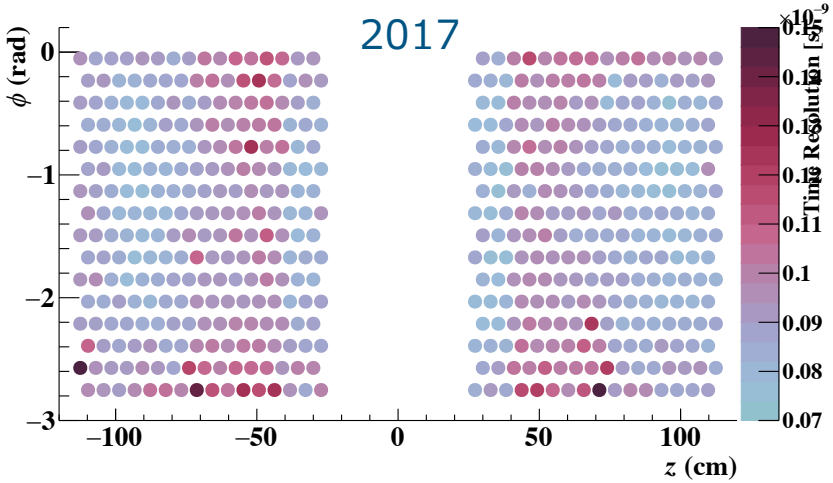
$$\sum_{N_{\text{hit}}} \sigma_{\text{pTC}}(N_{\text{hit}}) \times rate(N_{\text{hit}})$$

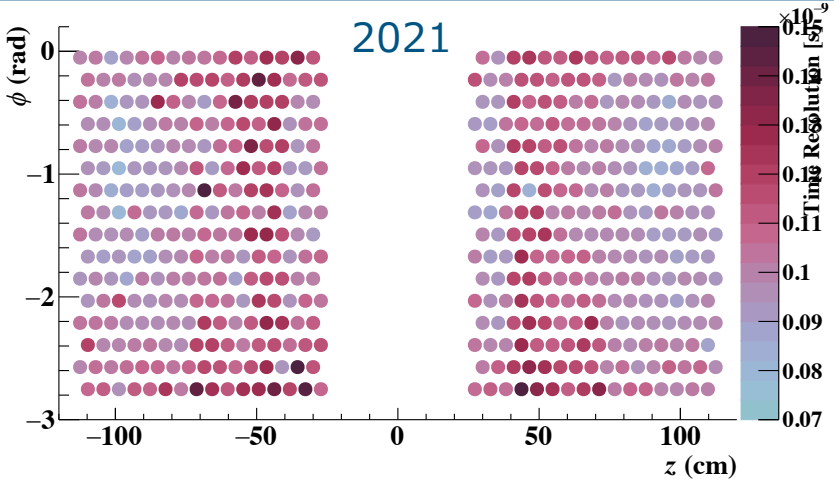
37.4 ps (2017) → 44.4 ps (2023)

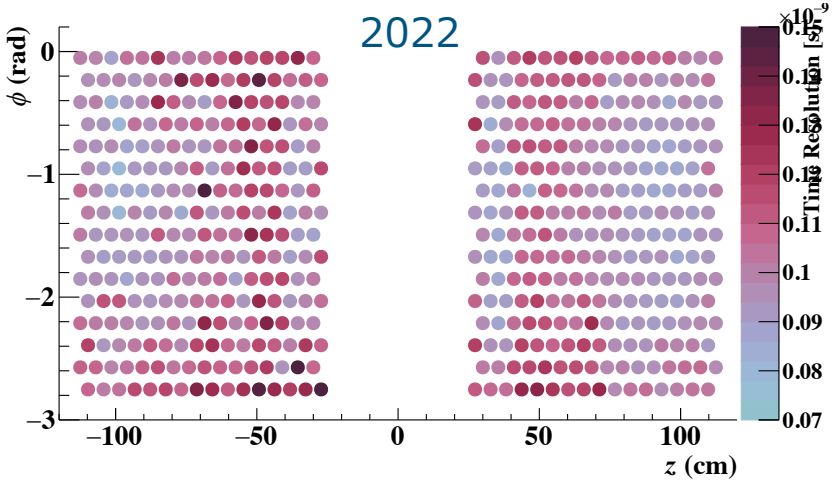
pTC: performance so far

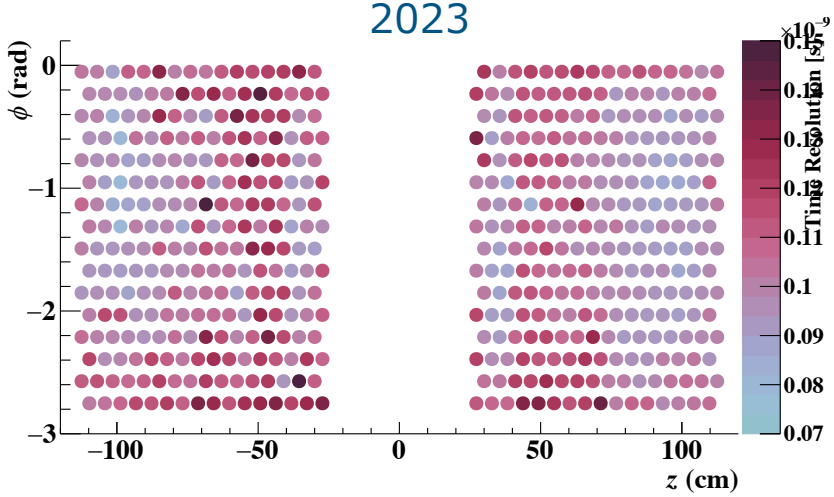
Timing resolution for Michel e+

70 ps – 150 ps

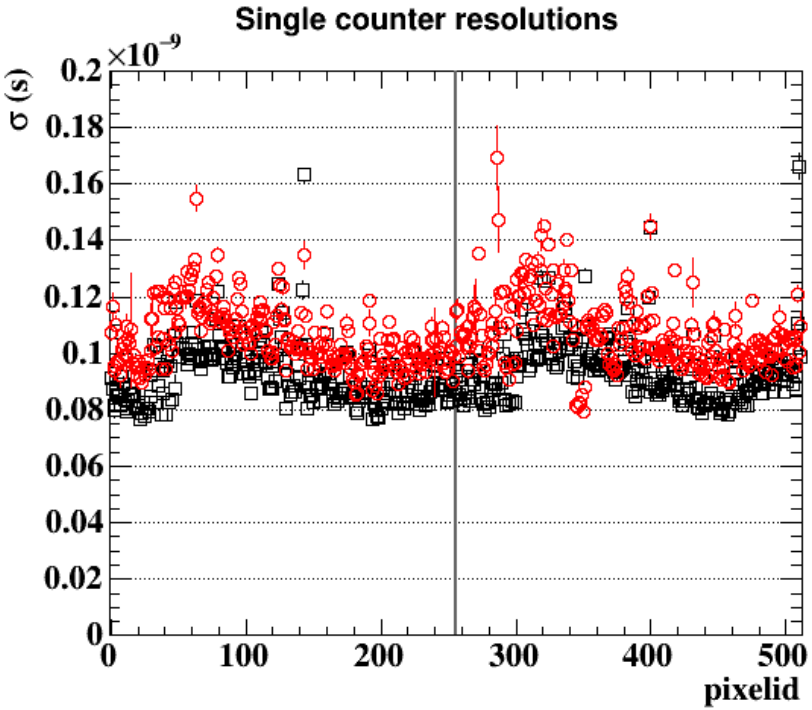








pTC: performance so far



- Single counter resolutions estimated with a reference time from other counters on the same Michel e^+ tracks.

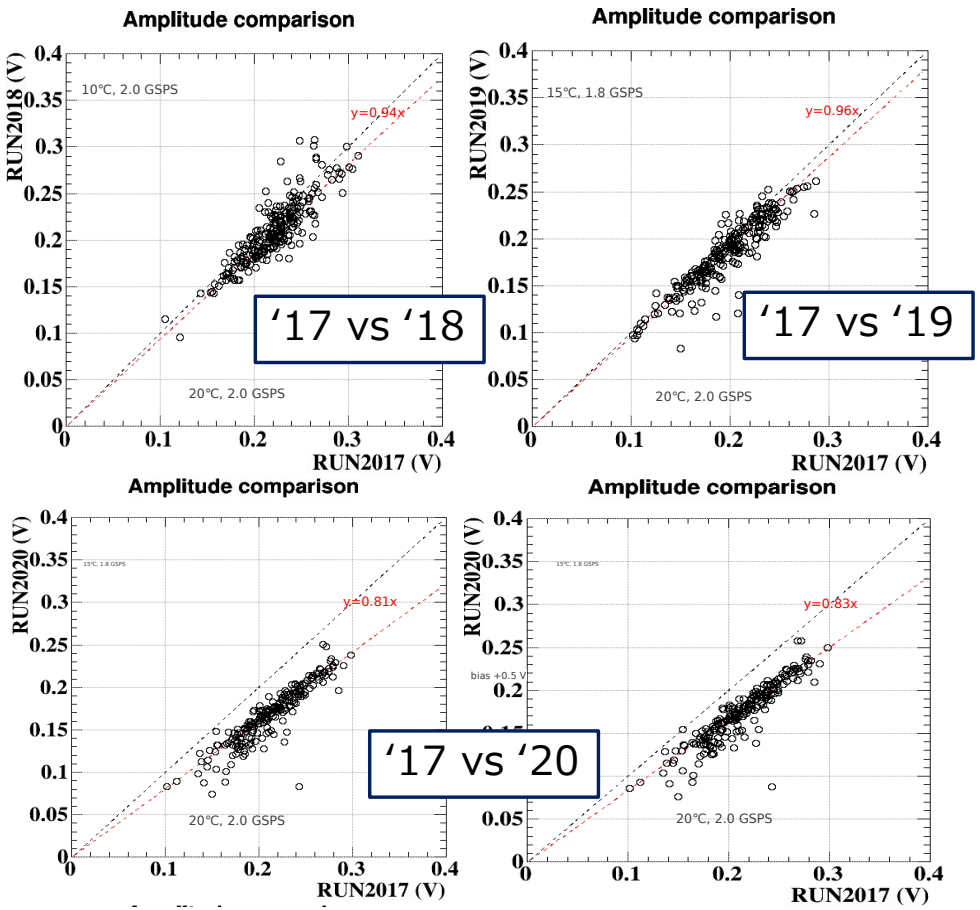
$$\sigma_{\text{single}}^{\text{new}} = \sqrt{\sigma^2(t_{\text{hit}} - t_{\text{ref}}) - \sigma_{\text{ref}}^{\text{old}\,2}}$$

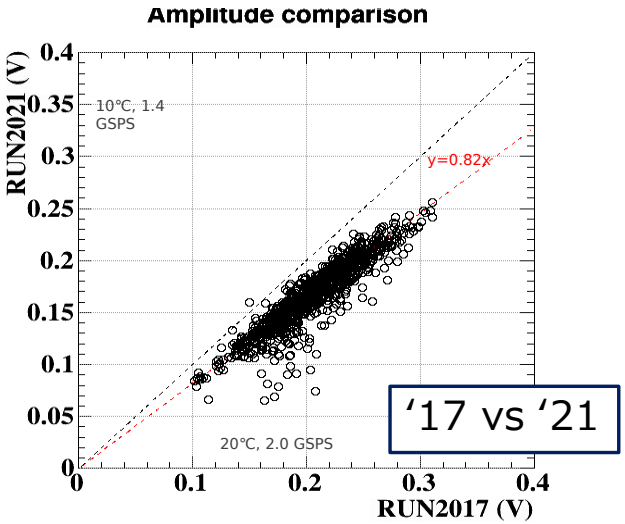
- General degradation from 2017 (black) to 2021 (red) was observed as well.

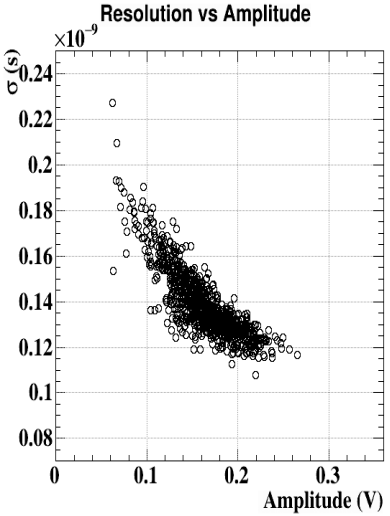
Figure 1: Single counter resolutions in 2017 (black) and in 2021 (red). The bumps in resolution around pixel id equal 50 and 300 are due to presence of 5 cm wide pixels.

"Operational results with the pixelated Time Detector of MEG II experiment during the first year of physics data taking"
Nucl. Instrum. and Methods A 1046, 167751 (2023)

pTC: performance so far (pulse height)







- Pulse height (=light yield) on each SiPM array has decreased.
- It strongly correlates to its time resolution.

"Operational results with the pixelated Time Detector of MEG II experiment during the first year of physics data taking"
Nucl. Instrum. and Methods A 1046, 167751 (2023)

pTC: performance so far

terribly bad resolution counters were investigated

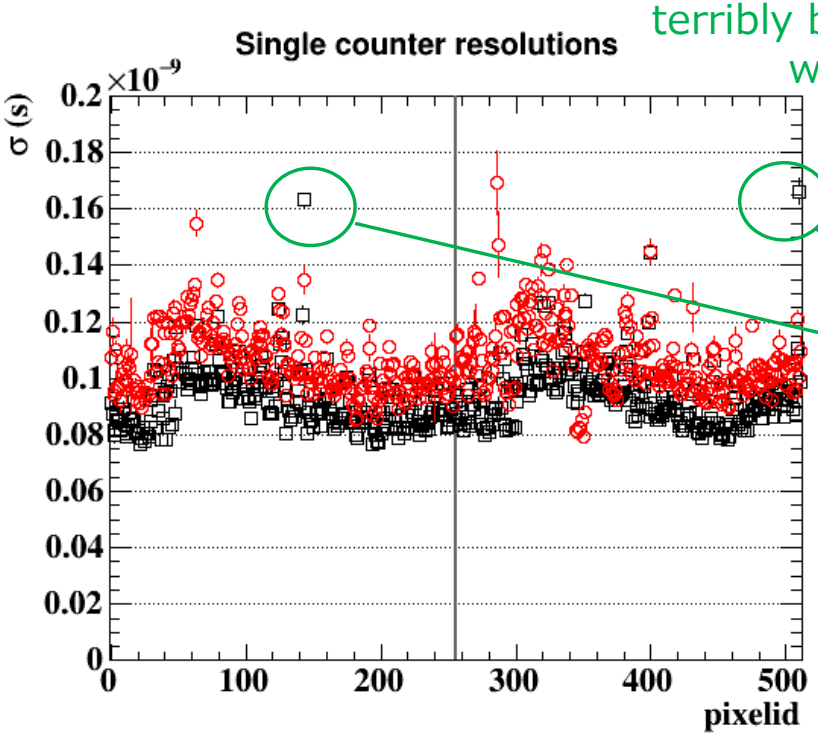


Figure 1: Single counter resolutions in 2017 (black) and in 2021 (red). The bumps in resolution around pixel id equal 50 and 300 are due to presence of 5 cm wide pixels.

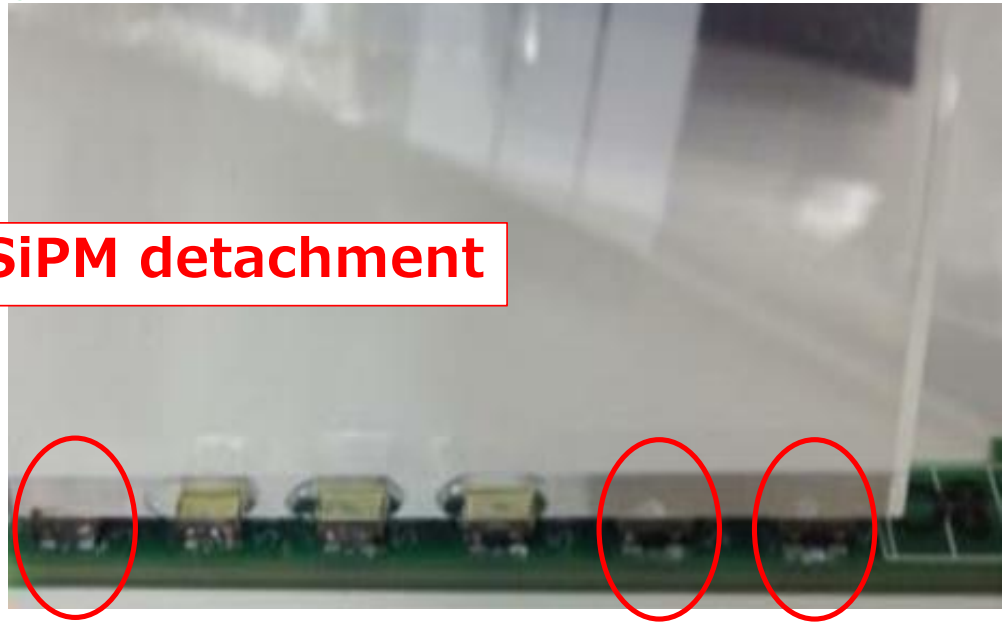
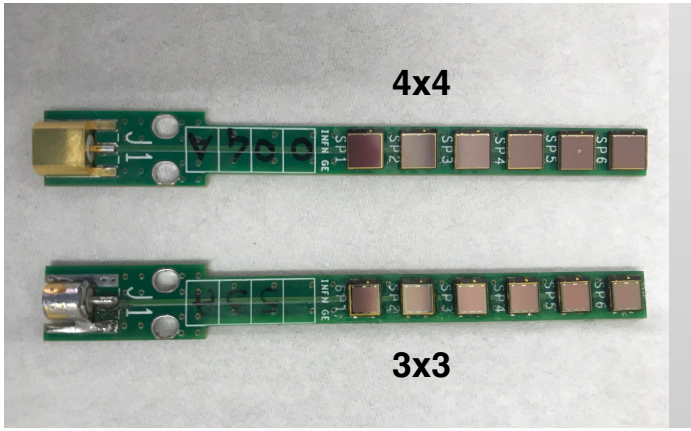


Figure 3: Counter suffering detachment: 3 adjacent SiPMs still glued are visible through the scintillator; 3 SiPMs, 2 on the right and one on the left, are detached, due to air between scintillator and SiPM, and are hardly visible.

"Operational results with the pixelated Time Detector of MEG II experiment during the first year of physics data taking"
Nucl. Instrum. and Methods A 1046, 167751 (2023)

Pixel refurbishment plan

- SiPM: ASD-NUV3S-P (3x3 mm^2 active area)
  -> ASD-NUV4S-P (**4x4 mm^2 active area**)
- 46+40 pixels will be newly producted.
- Performance of pixels

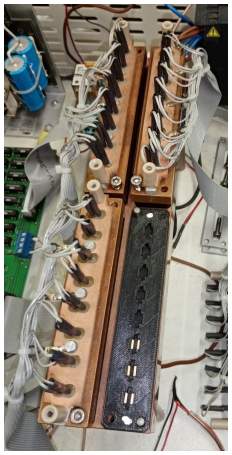


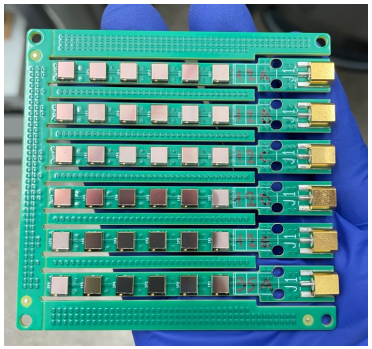
Counter Producion	SiPM model	note	Time resolution in Lab. test	# of counters installed	Time resolution in pTC operation
2016	ASD-NUV3S-P	50x50 um^2 pitch	~ 85 ps	448	~ 95 ps
2018, 2021	ASD-NUV3S-P	40x40 um^2	~ 70 ps	40	~ 80 ps
2023	ASD-NUV4S-P	40x40 um^2	~ 70 ps	16	N.A.
2024	ASD-NUV4S-P	40x40 um^2	~ 70 ps	8	N.A.

Counter Production

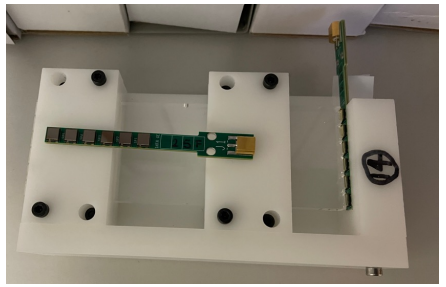
Single SiPM test → Soldering into series connection → SiPM array test → Counter assembly → Counter test

- IV-curve





- IV-curve
- Pulse height

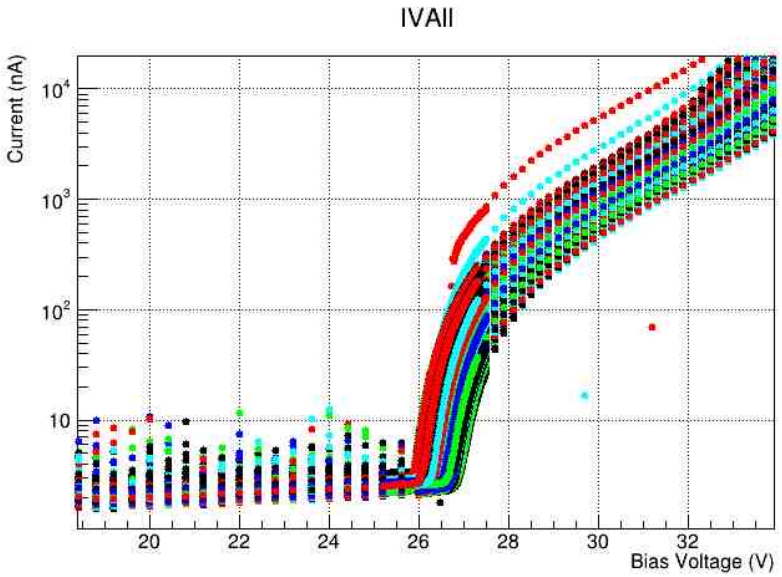


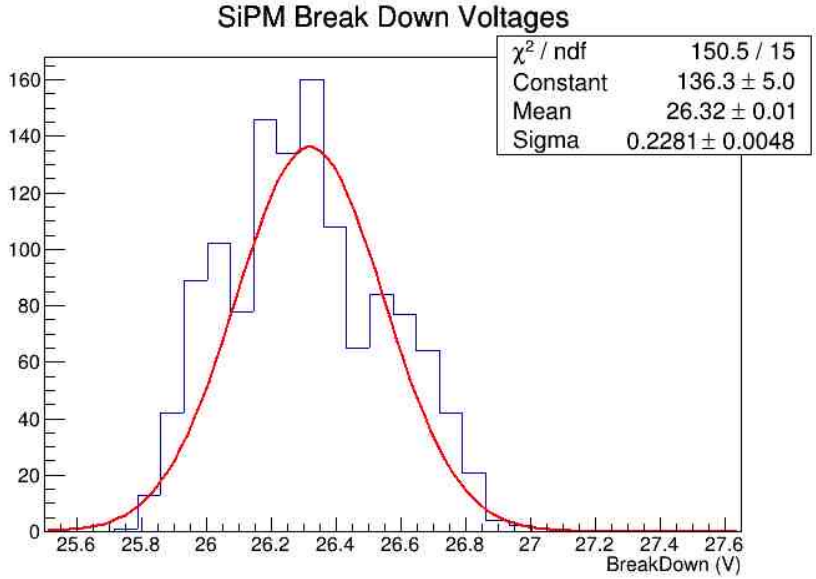
- Time resolution with voltage, position

- 6 SiPMs with similar V_{BD} are grouped and soldered into series connection on PCB.
- The temperature is controlled by a thermal chamber and set to 30degC through the tests.

the procedure is as reported by 西村@JPS2015秋季大会

Single SiPMs - IV curve, grouping





- All the SiPMs operate properly measured for I-Vs and BVs.
  - To be ordered a company to perform soldering the 6 pieces into one array.

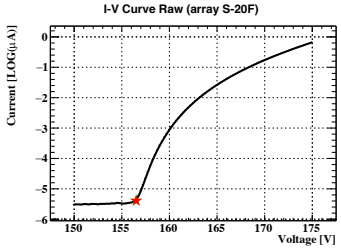
- V_{BD} of single SiPM: 25.8 – 26.9 V

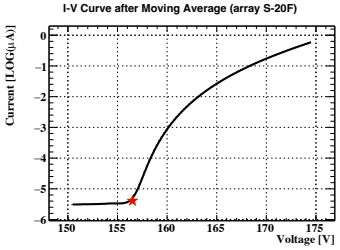
SiPM arrays IV curve

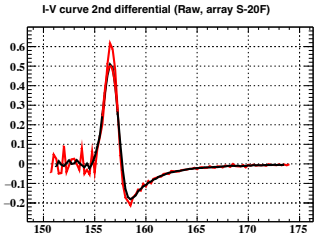
V_{BD} of array ~ 156 -160 V

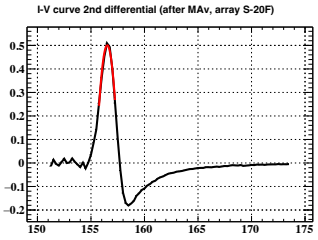
Normal

S-20F



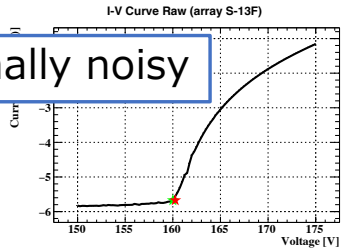


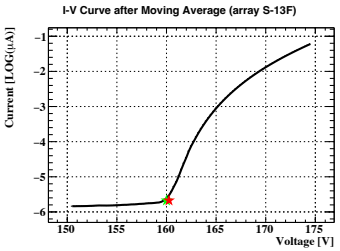


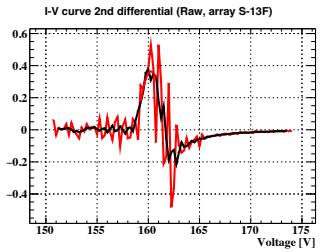


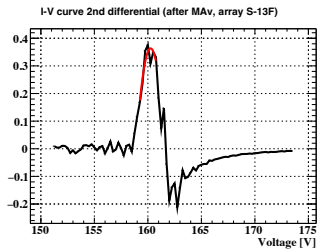
Occasionally noisy

S-13F



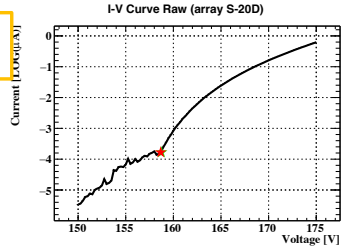


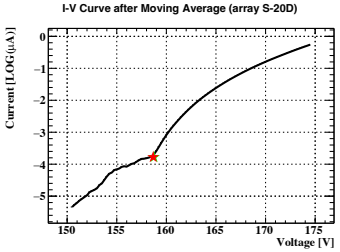


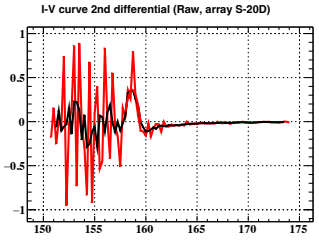


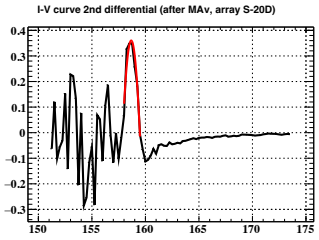
Strange

S-20D



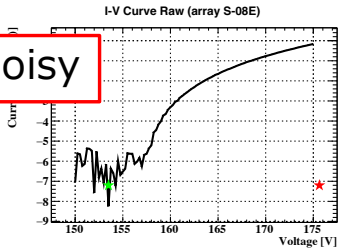


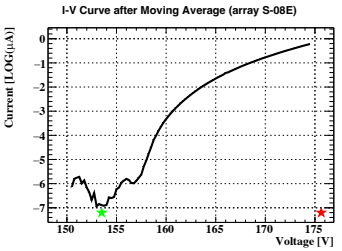


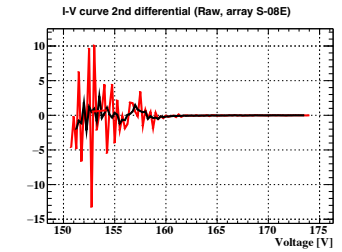


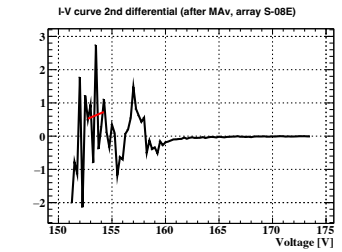
Fatally noisy

S-08E



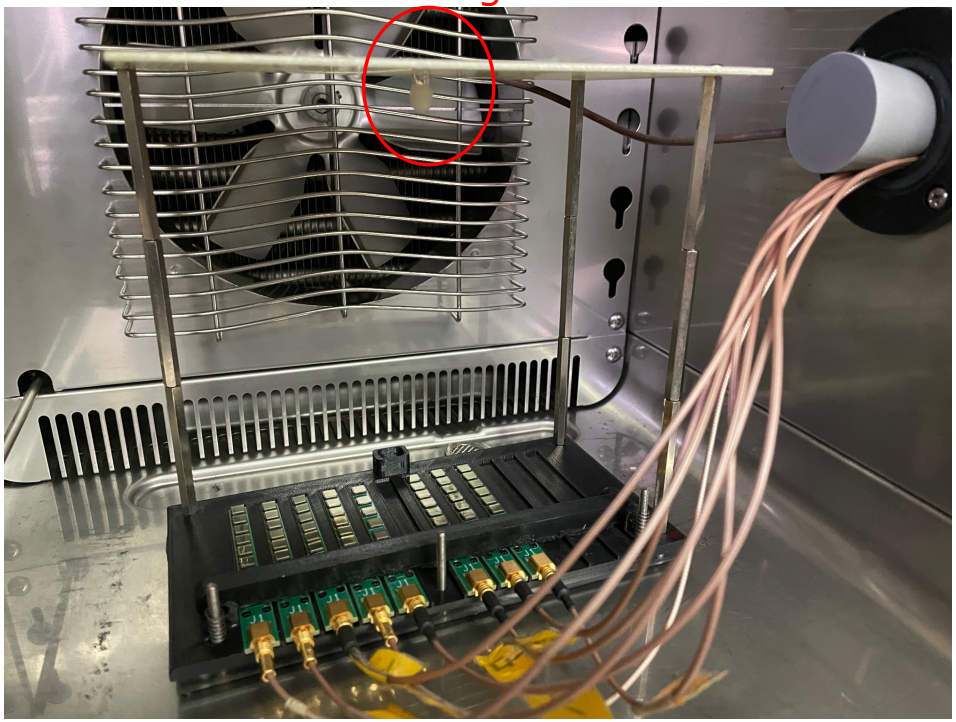




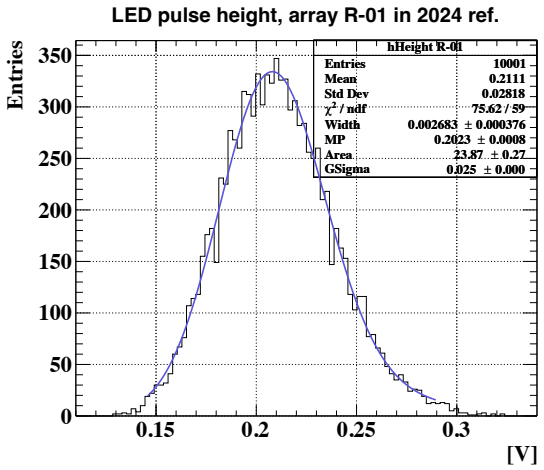


Light yield check

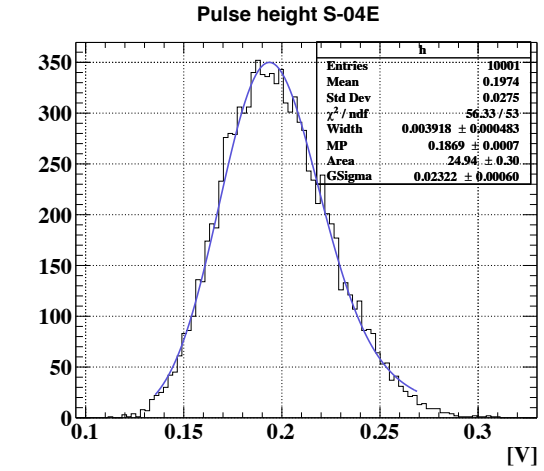
LED light



SiPM arrays



Prototype in 2023 measured in 2024 as ref.



New array in 2024

Rough estimation of improvement

$$t_e = \frac{\sum_i^{N_{\mathrm{hit}}} t_i}{N_{\mathrm{hit}}} \Rightarrow \sigma_{t_e} = \sqrt{\sum_i^{N_{\mathrm{hit}}} \frac{\sigma_i^2}{N_{\mathrm{hit}}^2}} \overset{\sigma_i \simeq \sigma}{\sim} \frac{\sigma}{\sqrt{N_{\mathrm{hit}}}}$$

$$N\sigma^2 \rightarrow N(1-p)\,\sigma^2 + Np(a\sigma)^2 = N(1-(1-a^2)p)\sigma^2$$

$$\Rightarrow \underbrace{\sqrt{(1-(1-a^2)p)}}_{\text{improvement factor}} \frac{\sigma}{\sqrt{N_{\mathrm{hit}}}} \sim 0.95 \frac{\sigma}{\sqrt{N_{\mathrm{hit}}}} \quad p \simeq \frac{1}{5}, a \simeq 0.7$$

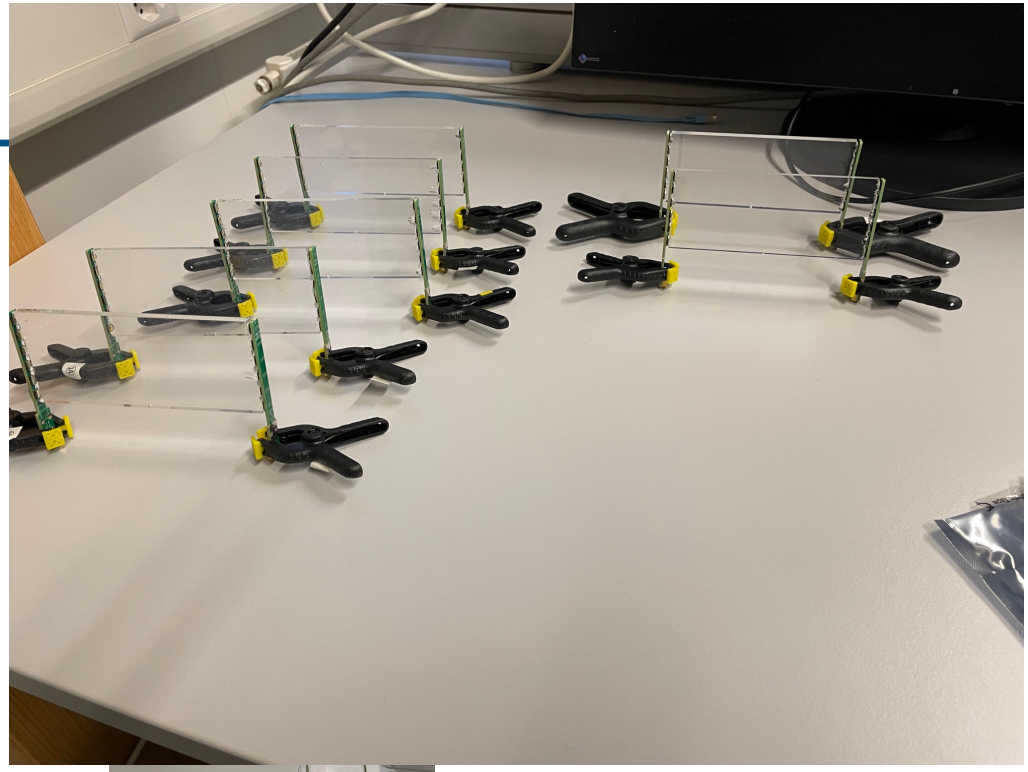
- Detail estimation will be done by Toy MC simulation.
- The results will be compared, and the improvement factor will be considered whether useful.

Summary

- MEG II timing counter has been on long-term operation.
  - Resolution degradation had been expected and reported.

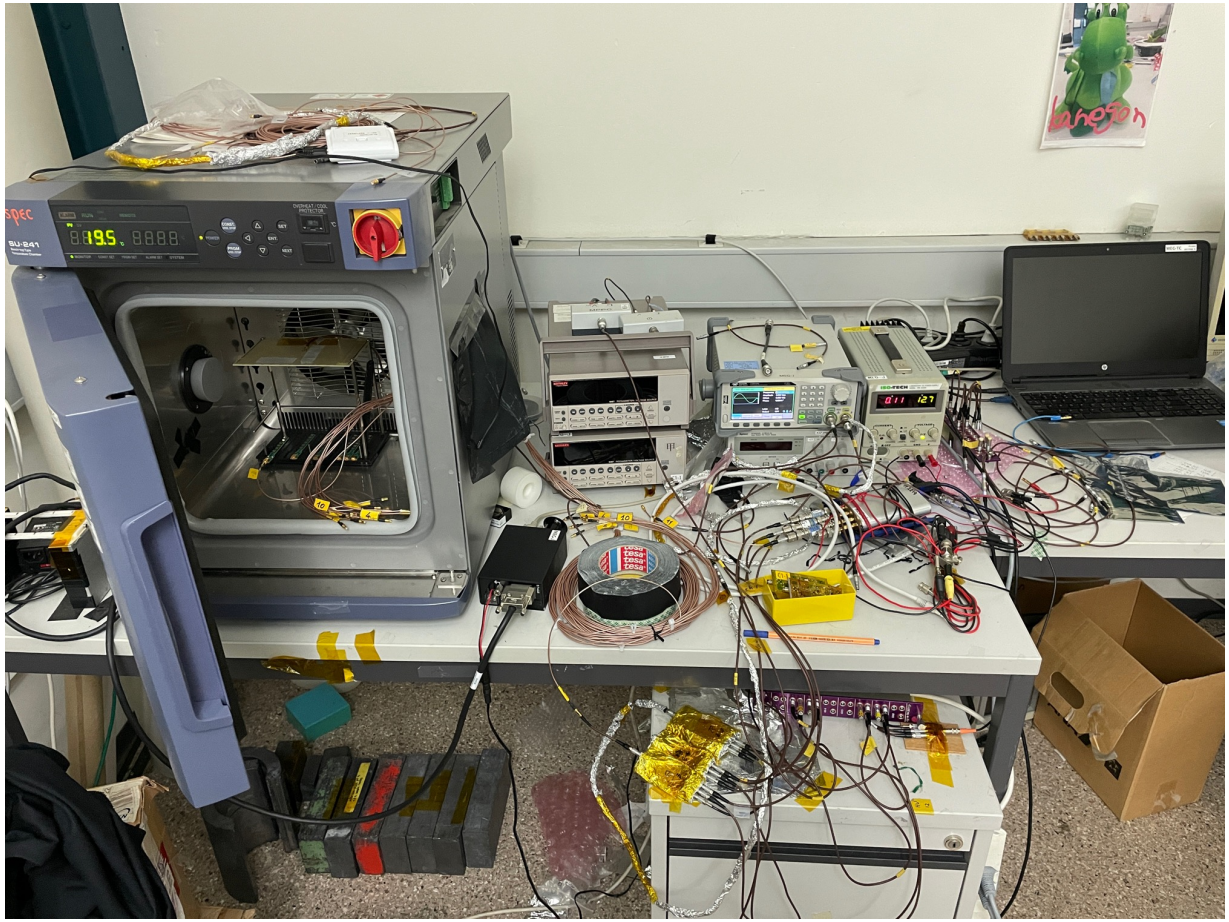
- 96 pixels (out of 512) refurbishment plan is ongoing
  - IV test, pulse height test has been done.
  - Counter test is ongoing.
  - Will resolve them for coming years of MEG II run. ~ 5%

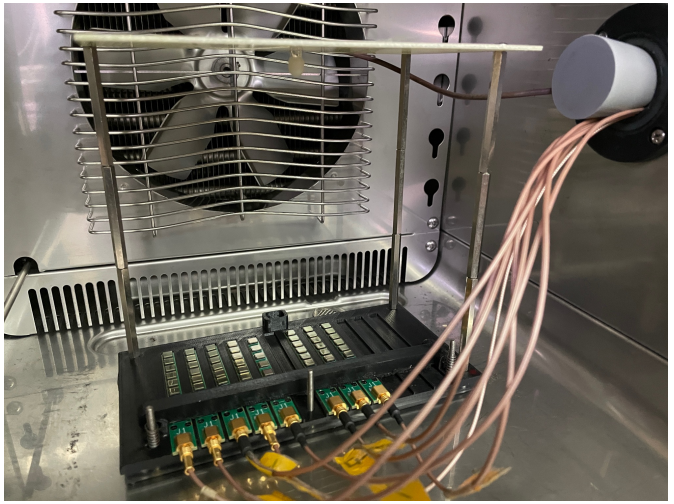
Ongoing!



Back up

LED test





Dark current history in 2021

- 93 Days in 2021 + 1 Day ref. in 2023
  - To follow in the same HV config.
  - After 171 Days under muon beam.
    (108 in 2022 + 63 in 2023)

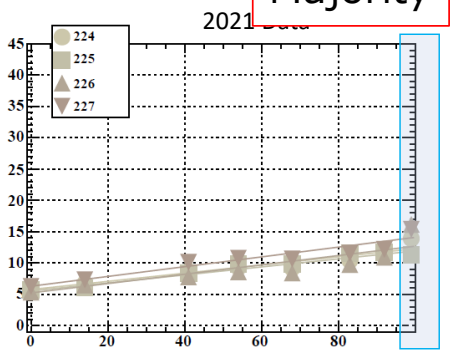
- Almost all the pixels show the similar increment.
  - **By +5 - 10 μA for 264 Days.**

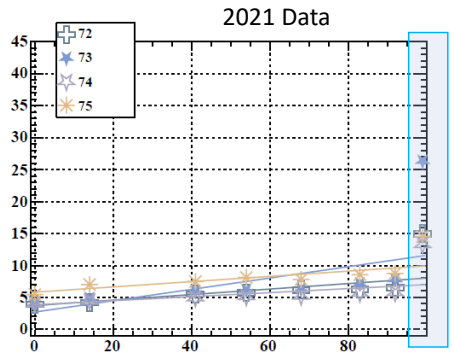
- Prediction (converted from 宇佐見@'17秋季大会)
  - +5 - 7.5 μA
  - 2 x 10^{10} ~50-MeV-positrons /cm^2 ~ 6 Gy
  - eff. NIEL -> 10^9 1-MeV-neutrons /cm^2

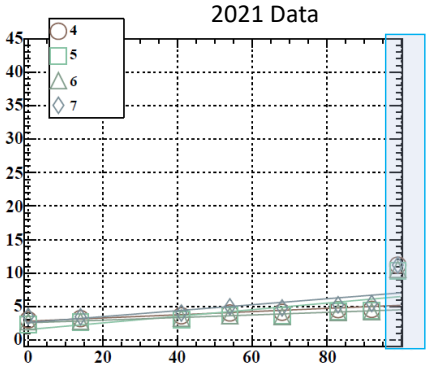
2021 Current + 2023 Current at 2021 HV conf.

from 16 Aug. to 17 Nov. (2021) + on 9 Aug. (2023)

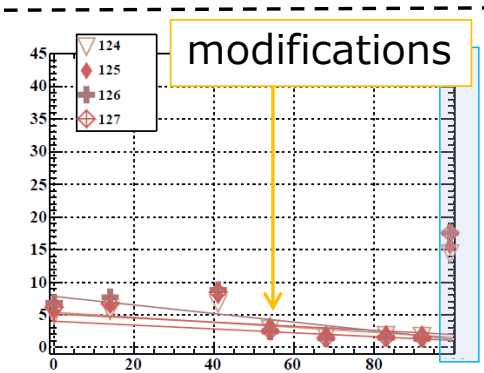
Majority





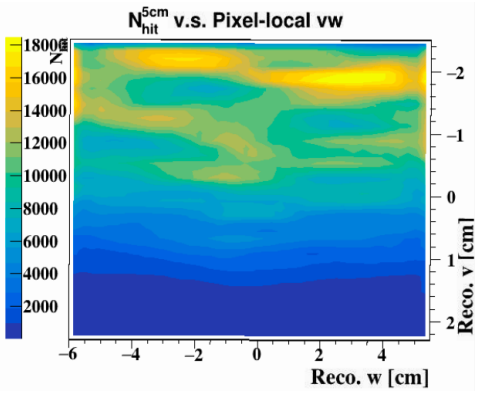


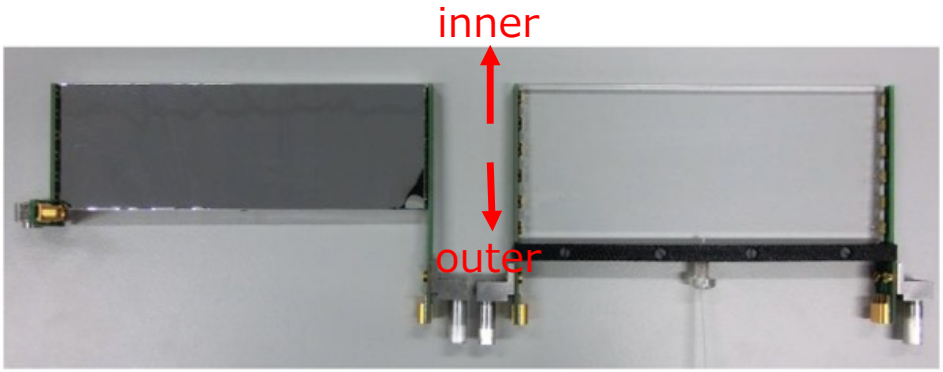
modifications



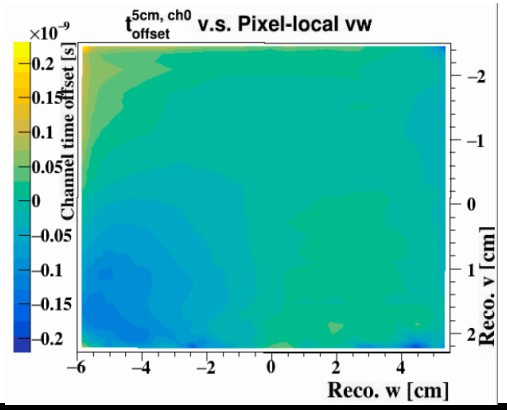
Development in analysis side

- Radiation damage accumulates more on the inner side of SiPMs.





- It causes a difference of the response of pixel, on the hit position of a passing particle.
  - Regard as time offsets depending on the hit position.
  - Offset correction resolves the problem.



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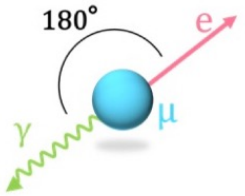
MuEGamma Decay



- One of charged lepton flavor violating (cLFV) decays, which is forbidden in the Standard Model.

- Many of the new physics beyond the Standard Model (BSM) predict that the branching ratio is $\mathcal{O}\,(10^{-13})$ – $\mathcal{O}(10^{-14}\,)$ where an undiscovered particle in $\mathcal{O}(10)$ TeV mediates the process.

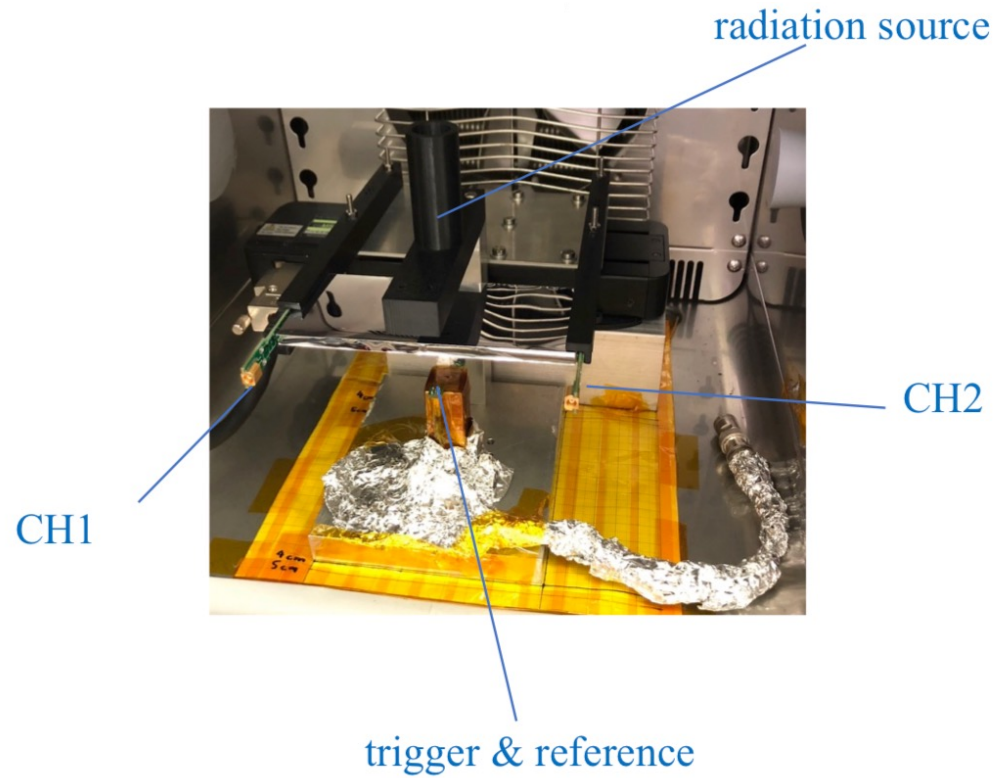
- Upper limit on the branching ratio was obtained by the MEG experiment: $\mathcal{B}(\mu \to e\,\gamma) < 4.2 \times 10^{-13}$ (90% C.L.)

Resolution Lab. test

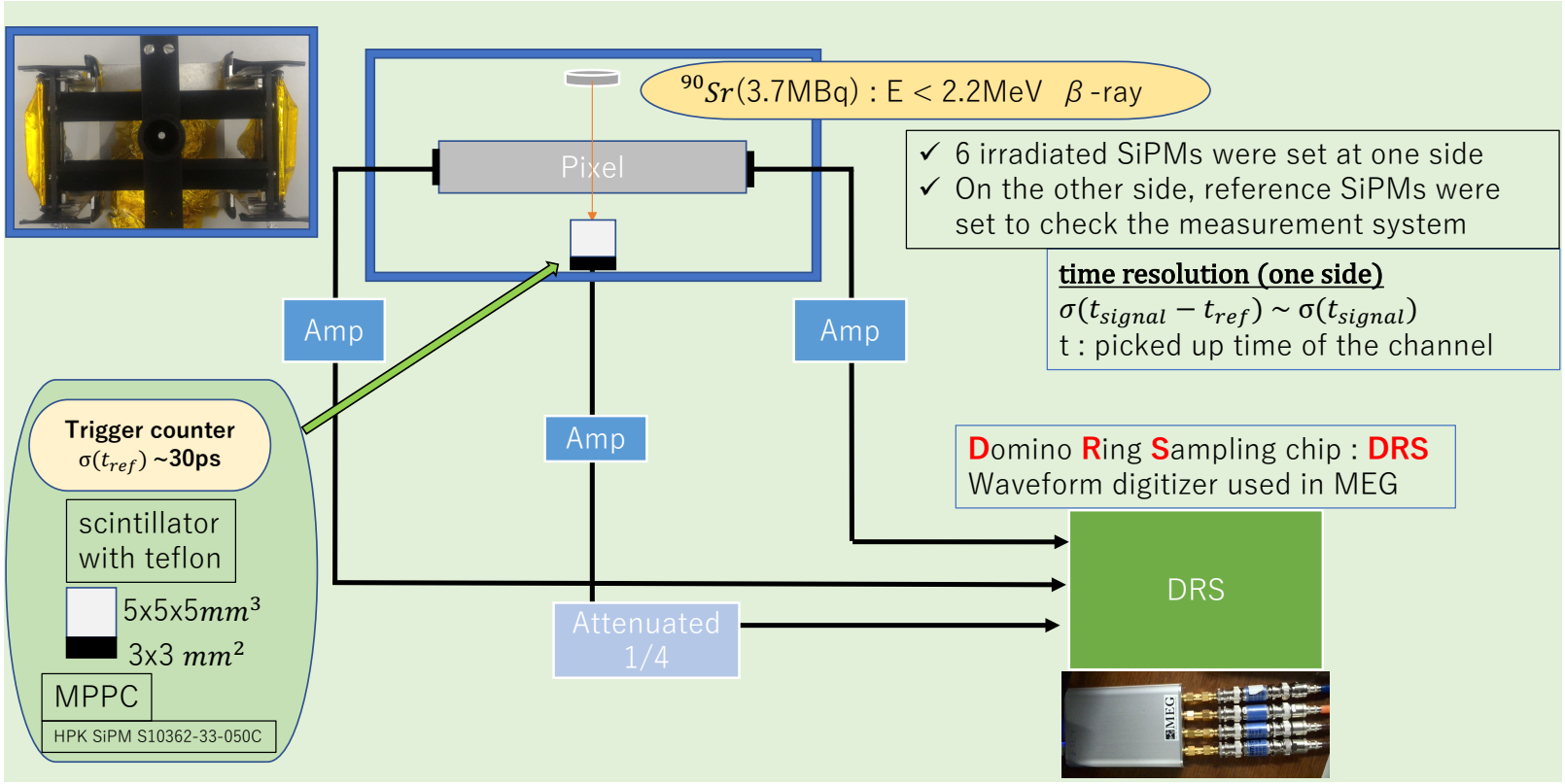
- Set a pixel to the moving stage in a thermal chamber (~30 degC).
- Apply V_{bd} + 24 V to each PCB.
- Triggered with β-ray source (Sr^{90}) and reference counter, to obtain time resolution for

$$t = (t_1 + t_2)/2 - t_{ref}$$

at three positions.



Resolution Lab. test



Time resolution evaluation

- $t_{\mathrm{ave}} := \frac{1}{n_{\mathrm{hit}}} \sum (t_i^{\mathrm{reco}} - t_0^{\mathrm{reco}} - TOF_{i,0})$

(single pixel / channel)

- $t_{\mathrm{even}} := \frac{1}{n_{\mathrm{hit}}/2} \sum (t_{2i}^{\mathrm{reco}} - t_0^{\mathrm{reco}} - TOF_{2i,0})$

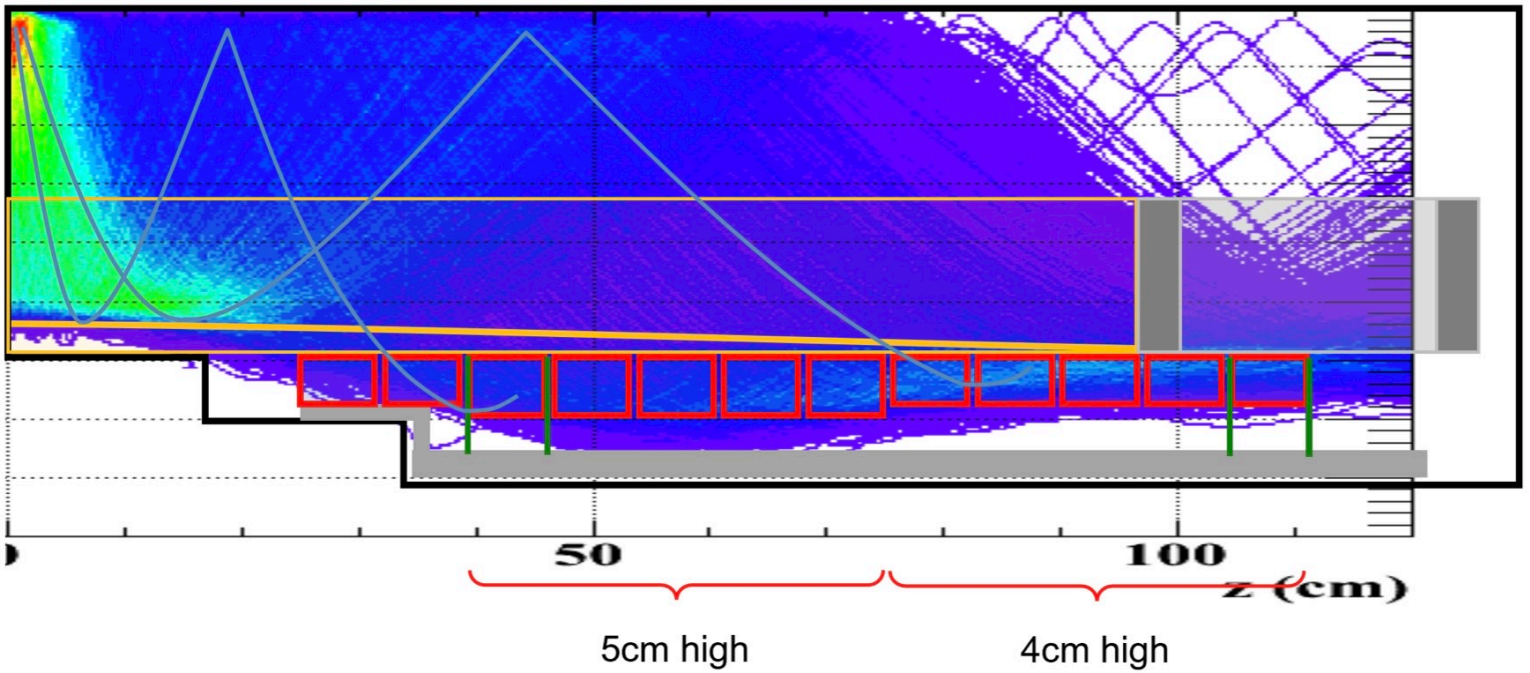
$t_{\mathrm{odd}} := \frac{1}{n_{\mathrm{hit}}/2} \sum (t_{2i+1}^{\mathrm{reco}} - t_0^{\mathrm{reco}} - TOF_{2i+1,0})$

$\sigma(N_{\mathrm{hit}}) = \sigma(t_{\mathrm{even}} - t_{\mathrm{odd}})$ **(even-odd)**

- 2 complemental methods.
  - Single counter resolution evaluation, depends on the tave from nearby counters.
  - Even-odd analysis is not sensitive to 1st order of i-th systematics on the tracking.

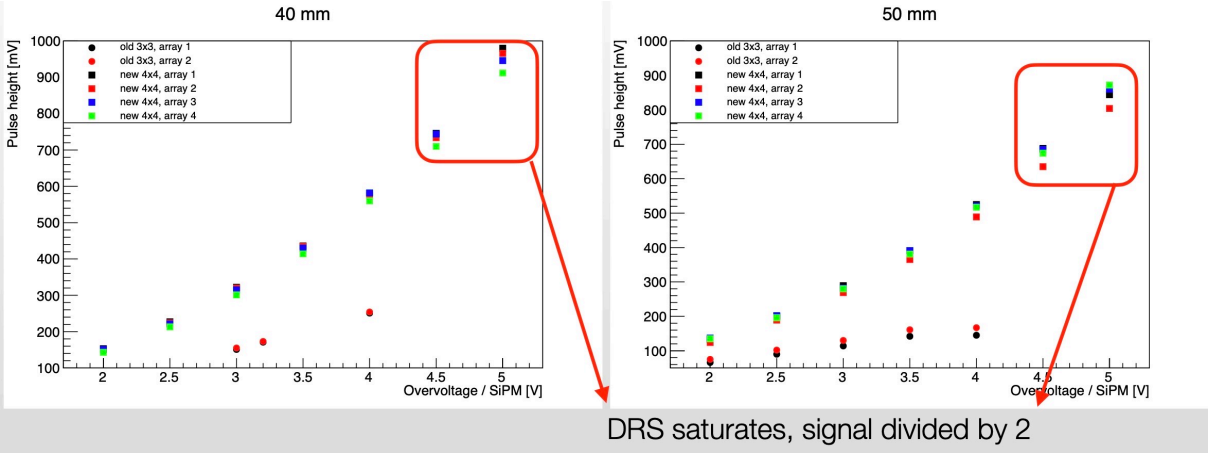
Pixels

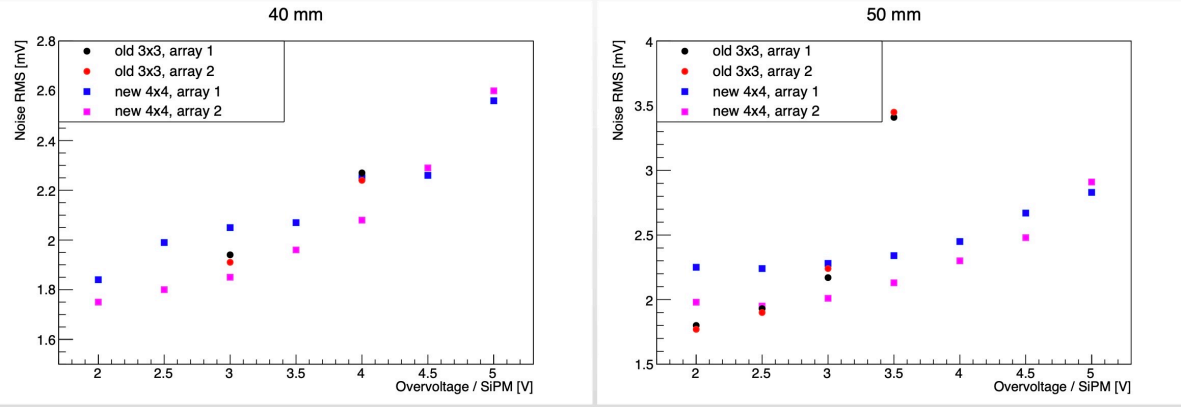
- 4cm, 5cm



New Pixels

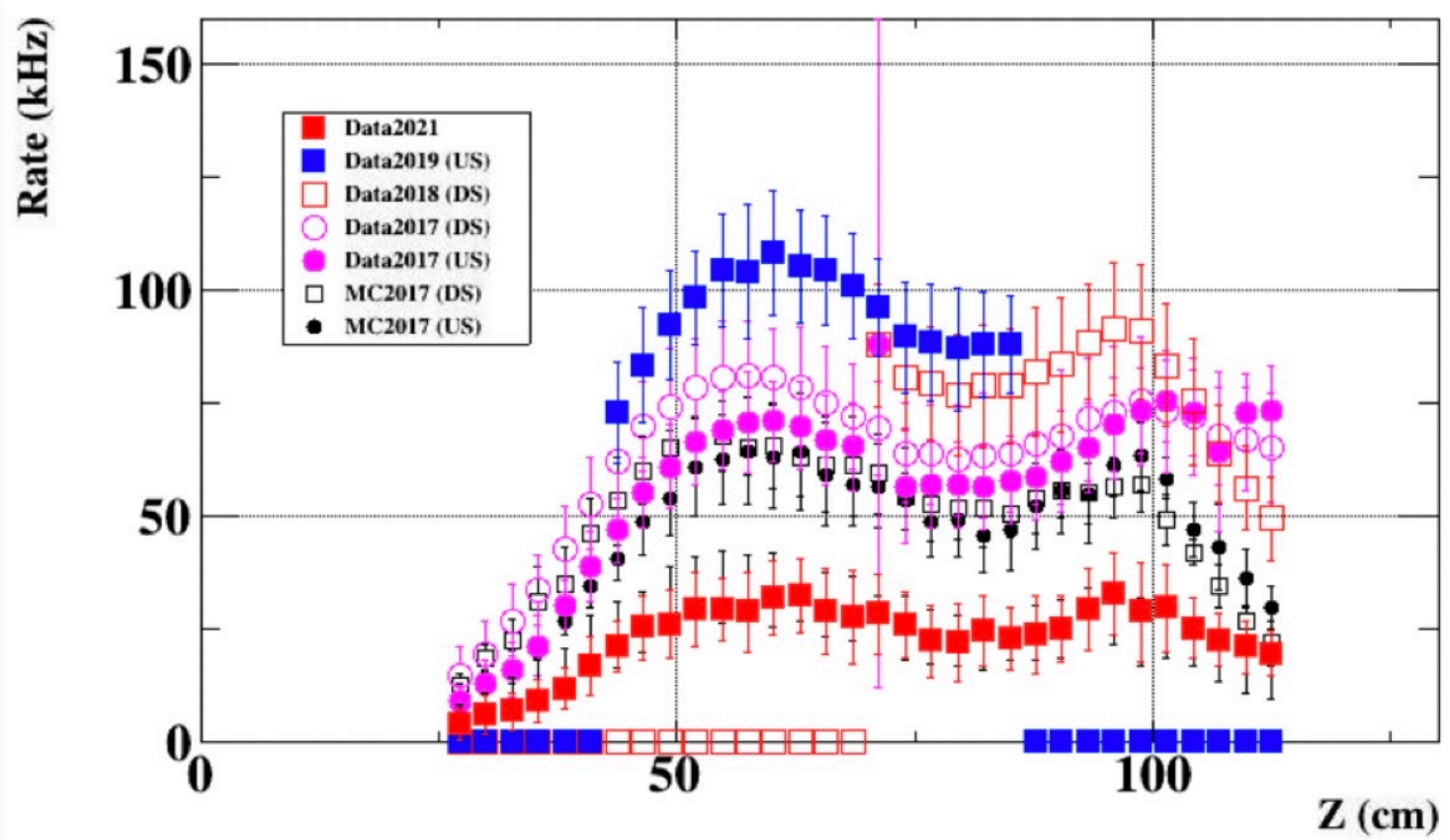
- 4cm, 5cm





Hit rate

- 2017 – 2021 ~ generally halved



Presumed increment

- Muon beam
  - 2021: 93 Days (16 Aug – 17 Nov)
  - 2022: 108 Days (1 Aug – 17 Nov)
  - 2023: 63 Days (7 Jun - 9 Aug)

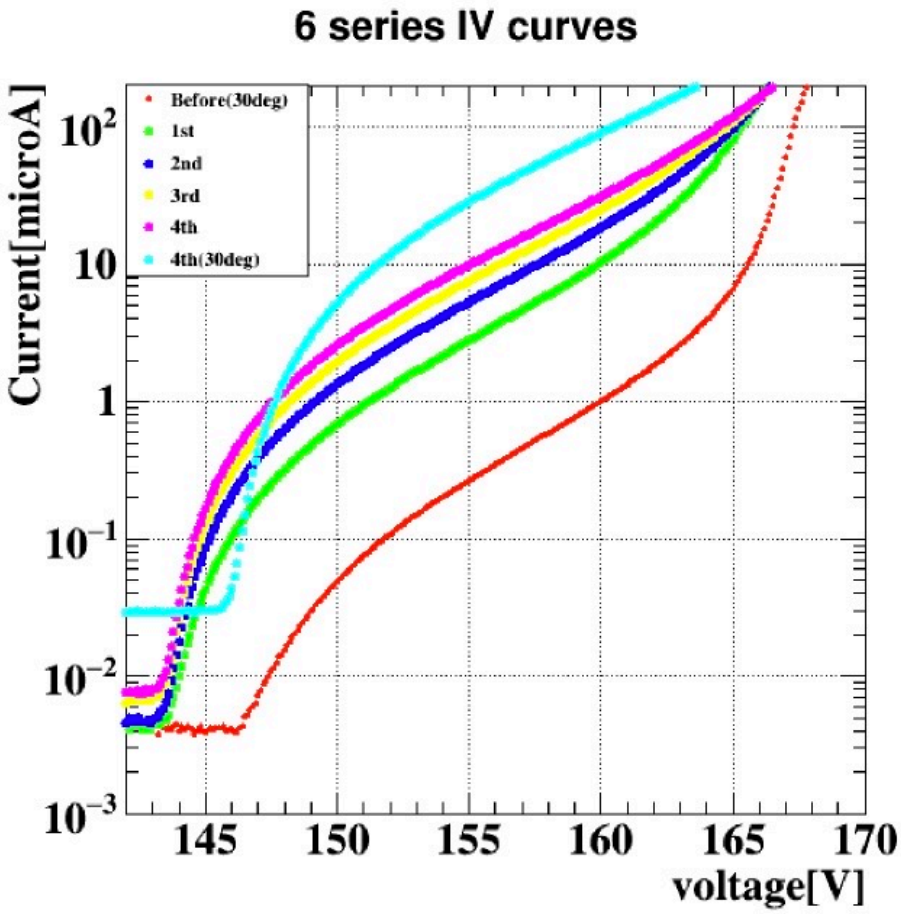
- Presumed increment
  - ~100 uA (from 2017 commissioning)
  - 525 days, 30 degC

$$0.2346\ \mu A \times \frac{24\ \text{hours}}{31\ \text{hours} + 55\ \text{min}} \times 7\ \text{days} \times (25 \times 3)\ \text{weeks} \sim 93 \mu A \qquad (5.1)$$

Irradiation test (‘16-’17)

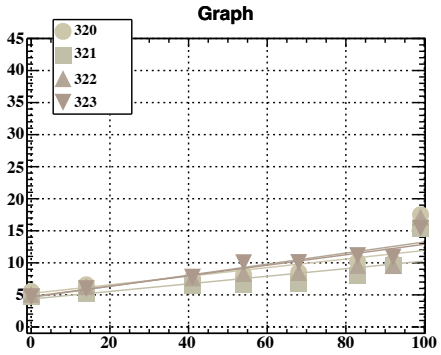
- equivalent to
  +100 uA increment for 160V

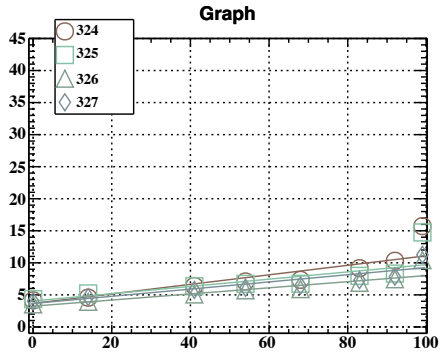
  -> +30 uA @ 10 degC

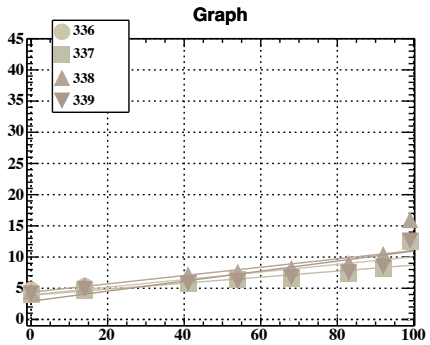


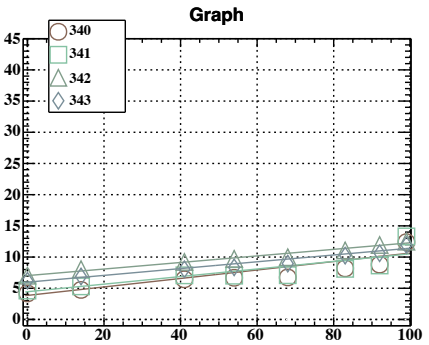
Examples (1, DS-pTC)

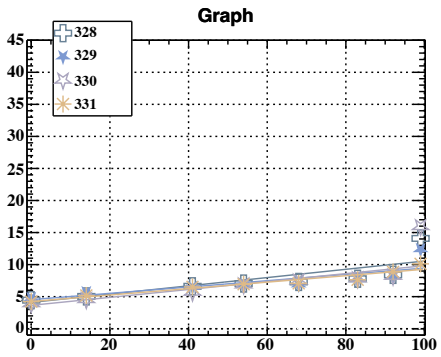
- Number = channel No.
  (e.g. pixel 0 contains ch0-1, pixel 1 contains ch2-3)

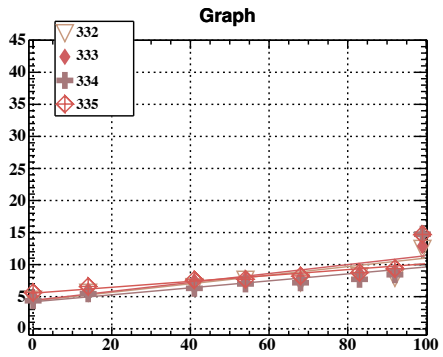


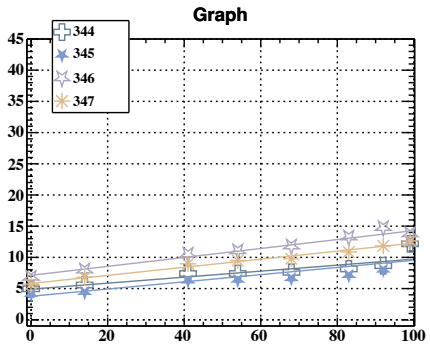


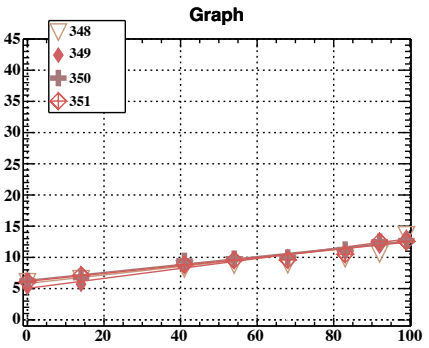






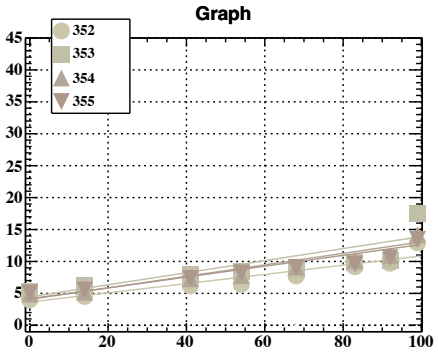


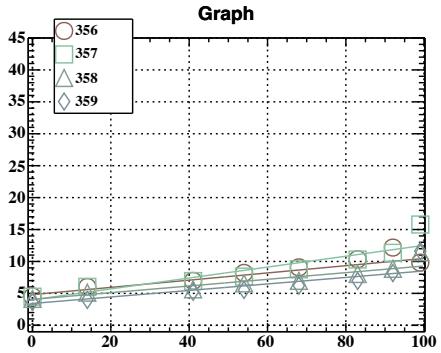


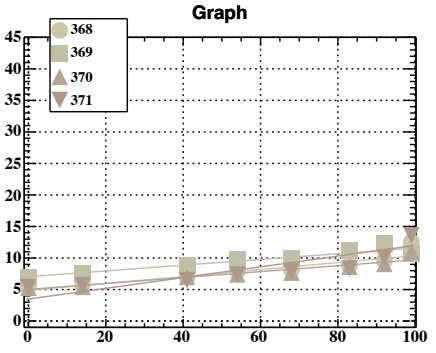


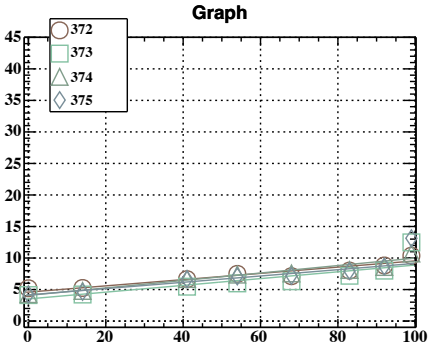
Examples (2, DS-pTC)

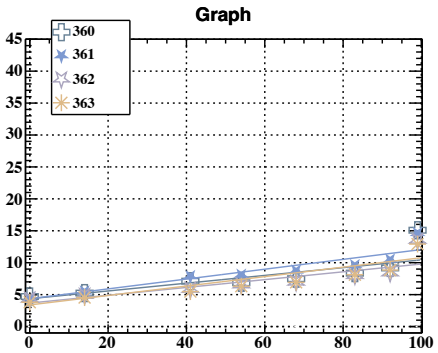
- Number = channel No.
  (e.g. pixel 0 contains ch0-1, pixel 1 contains ch2-3)

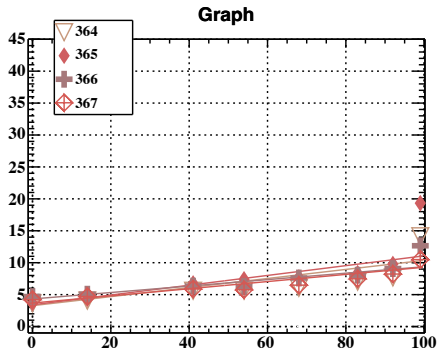


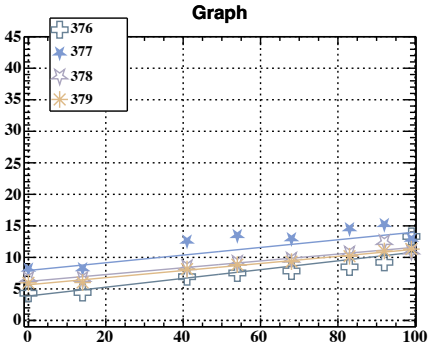


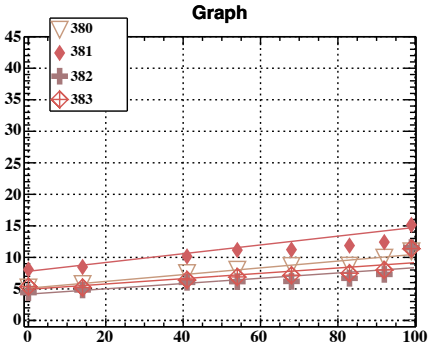






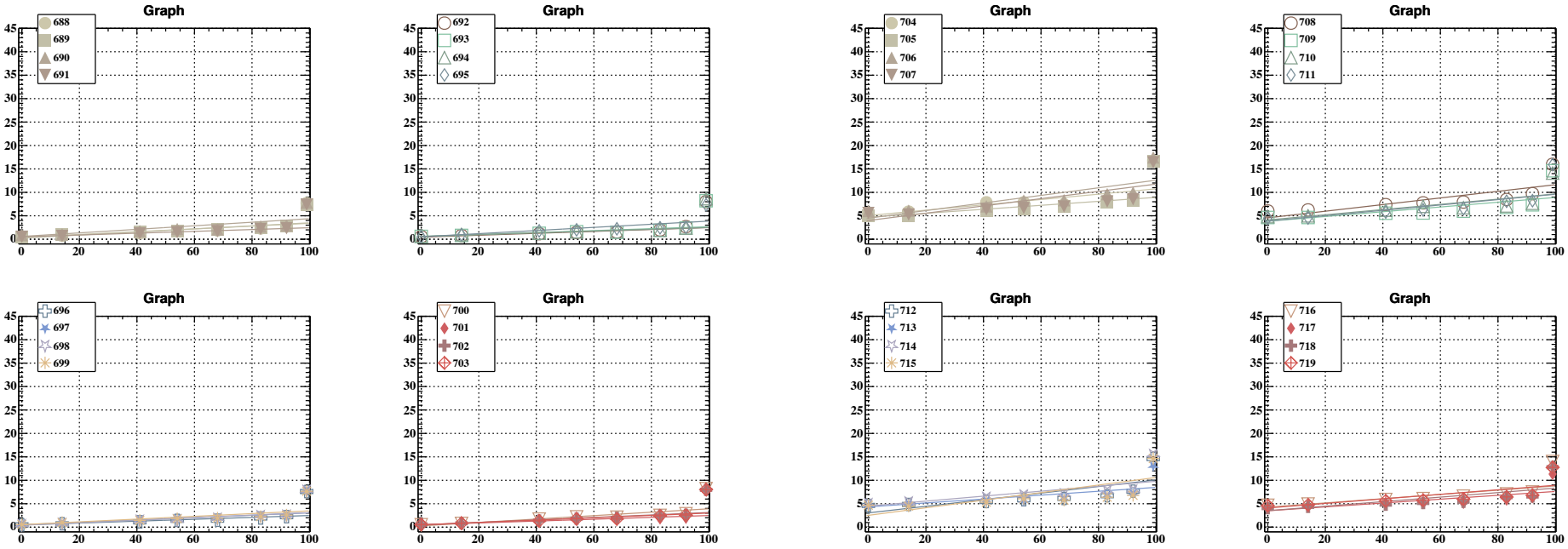






Examples (3, US-pTC)

- Number = channel No.
  (e.g. pixel 0 contains ch0-1, pixel 1 contains ch2-3)



Examples (2)

- Number = channel No.
  (e.g. pixel 0 contains ch0-1, pixel 1 contains ch2-3)