# Study on Afterglow of LYSO scintillator crystal for MEG II Radiative Decay Counter

MEG II 実験輻射崩壊同定用カウンターにおける
LYSOシンチレーターのアフターグローによる影響の評価

**Ryoto Iwai (東大理)**
**on behalf of MEG II collaboration**

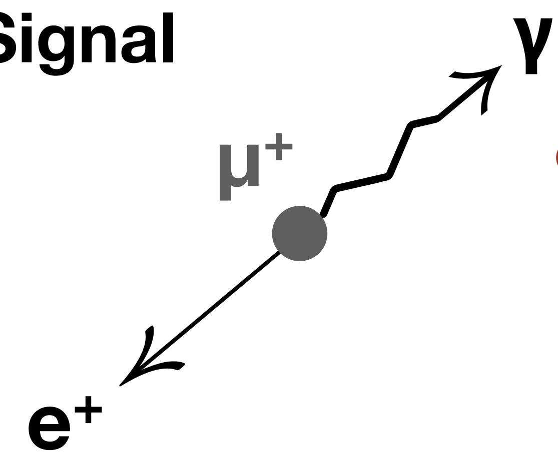
# Contents

# 1. Introduction

- The MEG experiment has been searching for charged lepton flavor violating decay $\mu \rightarrow e\gamma$

**This is predicted to occur at a sizable rate by many models beyond the Standard Model**

**Signal**

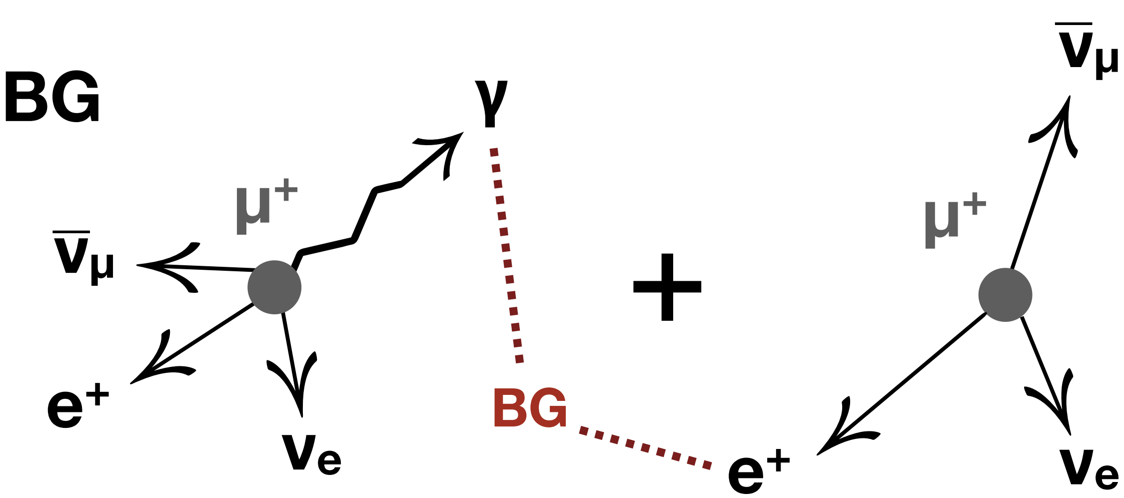



**$e^+$ and γ are emitted ..**

1. **back to back**
2. **at the same time**
3. **with same energy (52.8MeV)**

- The most dominant background (BG) in the experiment

**Accidental BG**



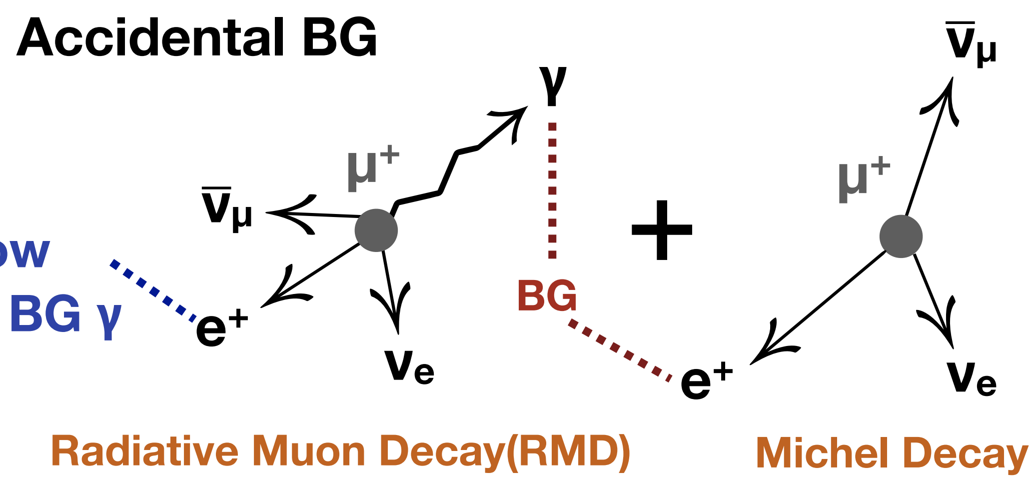

**Radiative Muon Decay(RMD)** **Michel Decay**

- It will be upgraded as MEG II experiment with higher μ beam intensity ($7\times10^7 \mu$/s) with higher BG rate

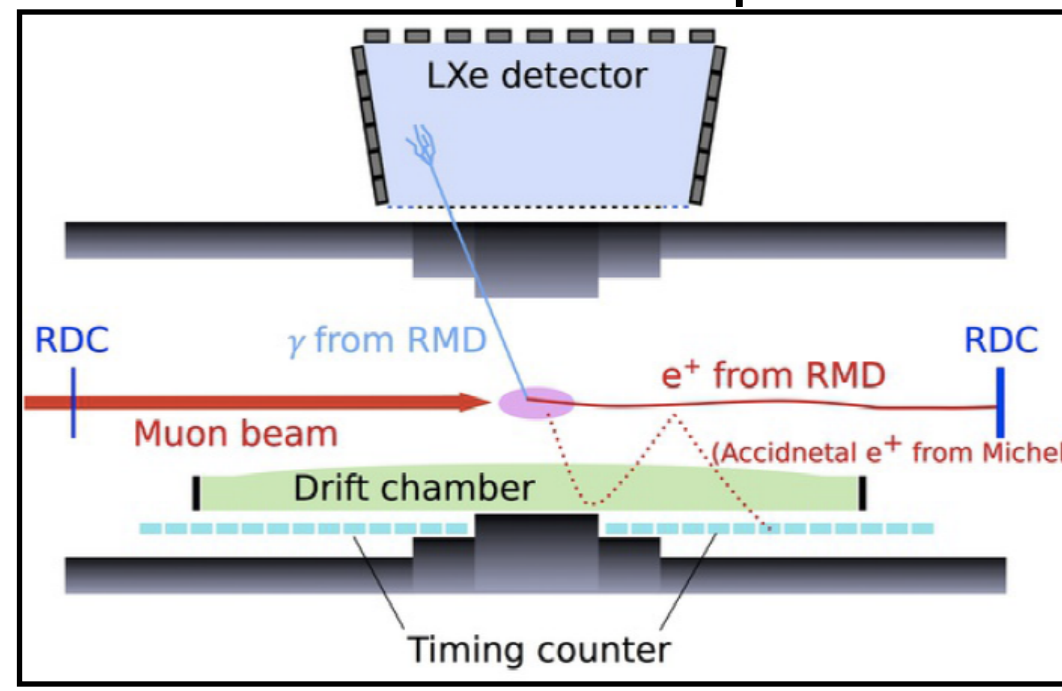
# 1. Introduction

- Radiative Decay Counter(RDC) will be newly installed to identify the accidental BG

RDC measure time coincidence this low momentum $e^+$ and BG $\gamma$

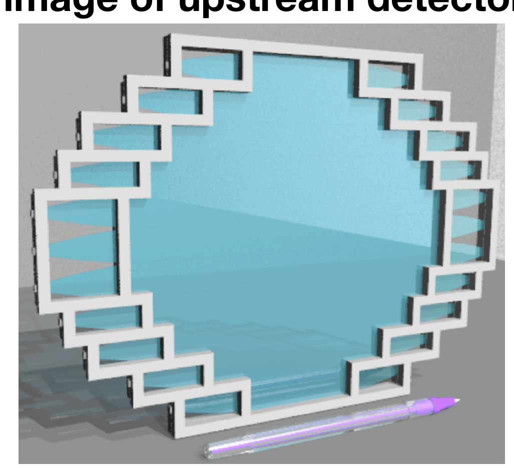



detector will be installed on μ beam axis




- High $e^+$ hit rate for each counter (200~600kHz)
- Downstream detector was constructed and tested in 2015 (detail in next talk)
  → Operation test with μ beam in June, 2016
- Upstream detector will be constructed after R&D
  → Scintillation fibre detector
  → Study of the influence on μ beam is ongoing

image of upstream detector

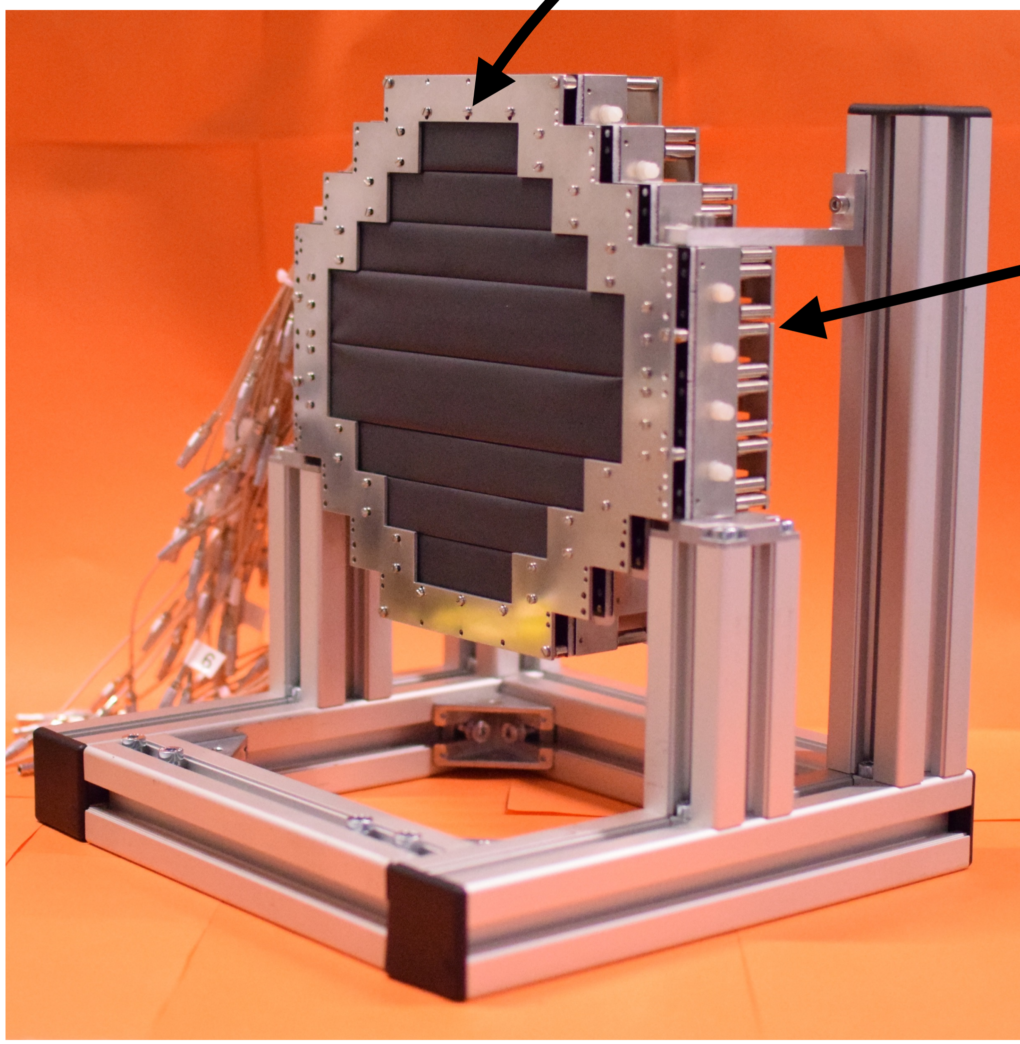


| | MEG II sensitivity |
|---|---|
| w/o RDC | $5.0\times10^{-14}$ |
| w/ downstream | $4.3\times10^{-14}$ |
| w/ downstream + upstream* | $3.9\times10^{-14}$ |

*assuming detection efficiency ~90%

# 1. Introduction

- Downstream detector consists of timing counter & calorimeter



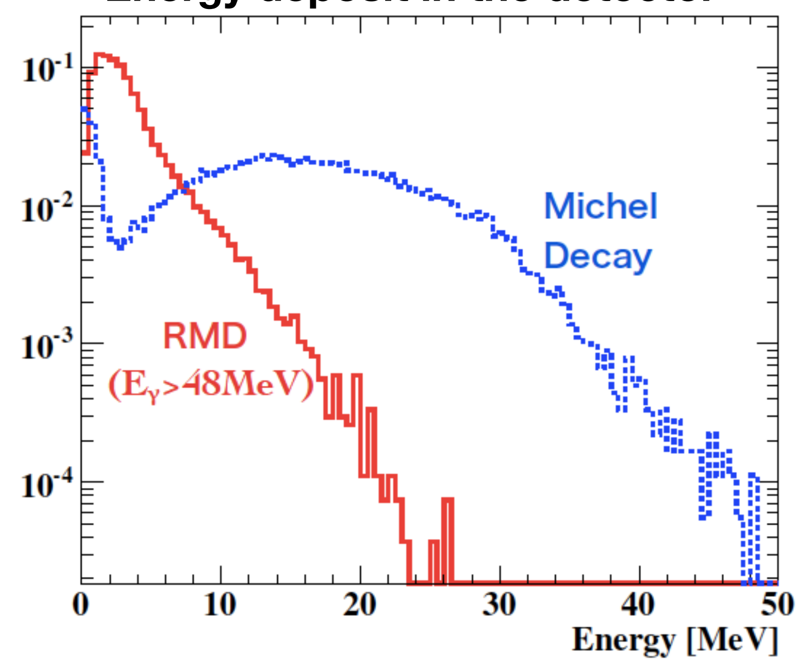
**Timing counter part**

- Measuring timing of low momentum $e^+$
- 12 plastic scintillator bars readout with MPPCs
- ~90psec resolution was obtained

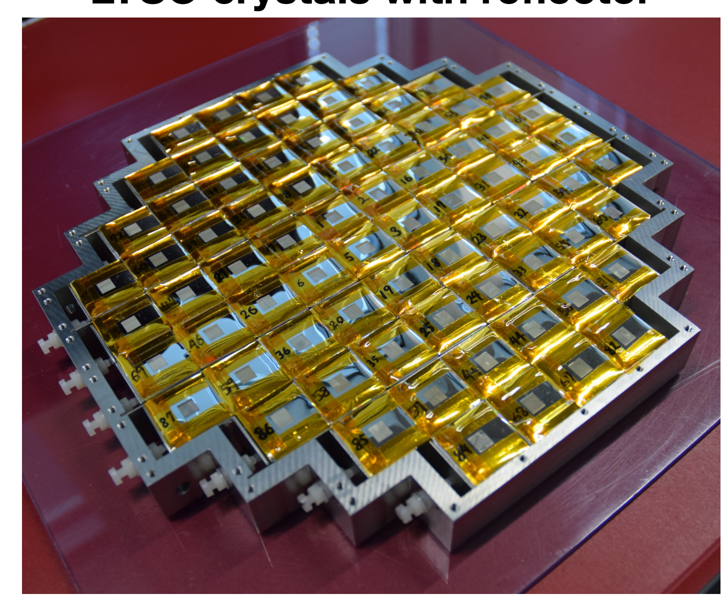
**Calorimeter part**

- Measuring energy to distinguish RMD from Michel Decay
- 76 LYSO crystals readout with MPPCs
- ~6% resolution was obtained (for 1MeV)

**Energy deposit in the detector**




**LYSO crystals with reflector**



- We observed afterglow of LYSO crystal during the mass test

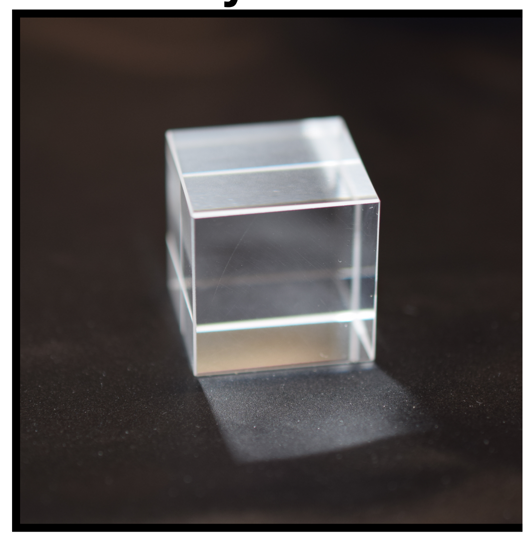
# 2. Feature of LYSO crystal

- LYSO(Lutetium-Yttrium Oxyorthosilicate) is a inorganic scintillator
- It has advantages of a high light yield and fast signal

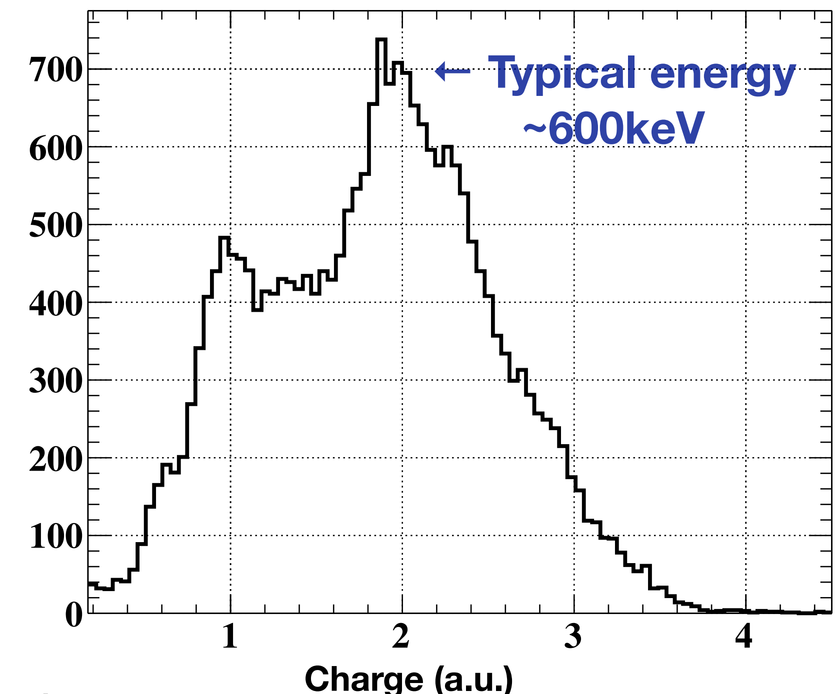
**data from Shanghai Institute of Ceramics**

| | |
|---|---|
| Size | 2×2×2cm³ |
| Density | 7.4g/cm³ |
| Decay constant | 42ns |
| Emission peak | 420nm |
| Light yield | 3×10⁵ ph/MeV |

**LYSO crystal in RDC**



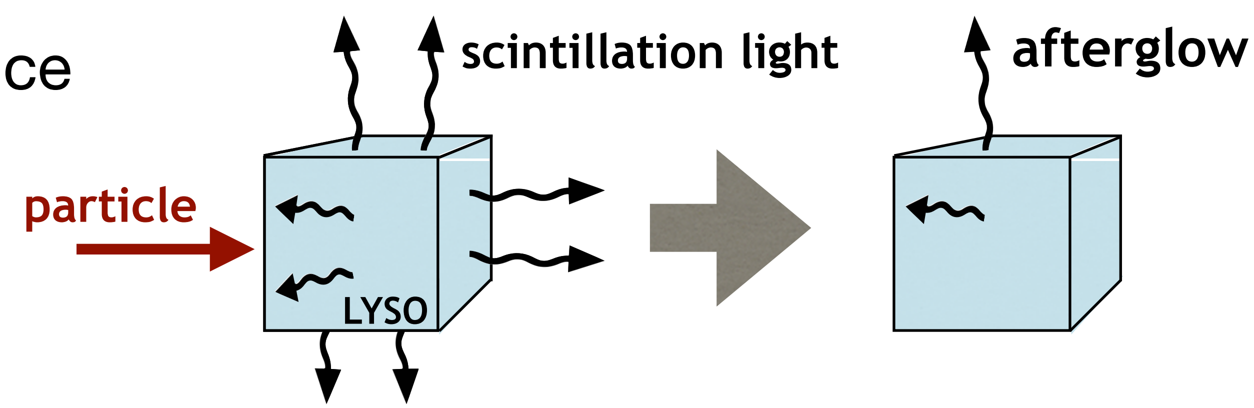
**Lu has inner radiation**




- LYSO is also known to have afterglow (phosphorescence)

→ Some excited electrons are trapped in lattice defect and emit late scintillation light

→ Induce readout noise after irradiation (γ-ray, neutron irradiation in previous study)




- <u>We studied β-ray induced afterglow by monitoring anode current</u>
- <u>We measured several crystals and checked correlation with room light afterglow</u>

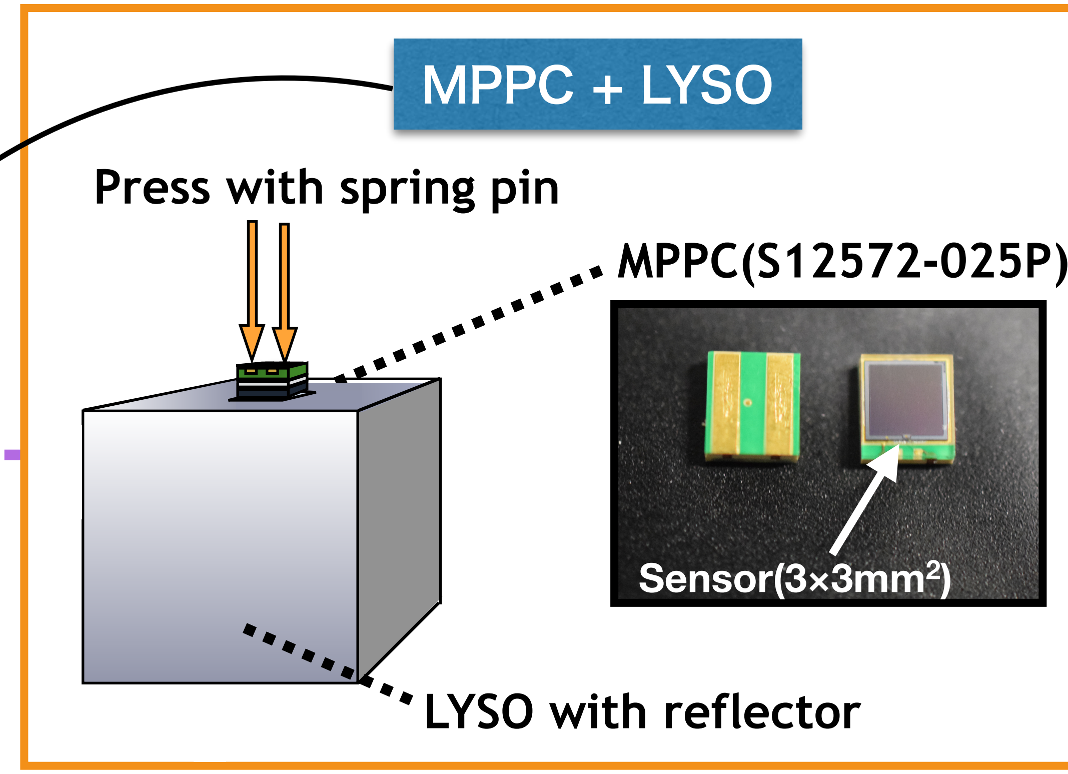
# 3. Afterglow study with room light

- We built a single channel setup to monitor current of MPPC
  → voltage & temperature was also monitored

HV supply (SCS2000)

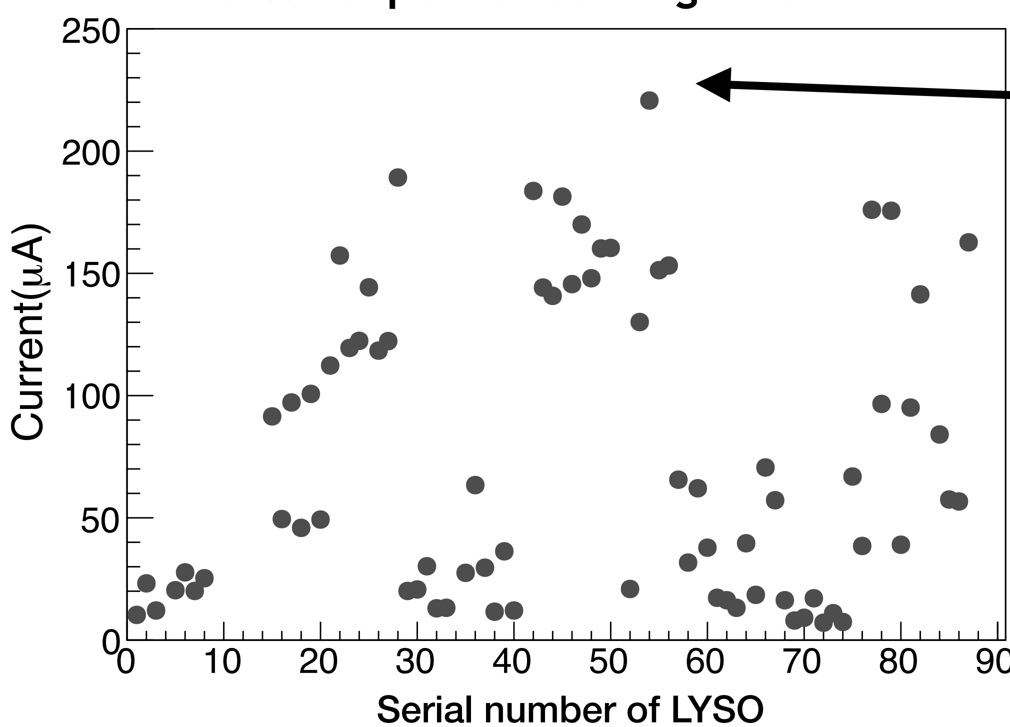
Over voltage of MPPC = 4.02V

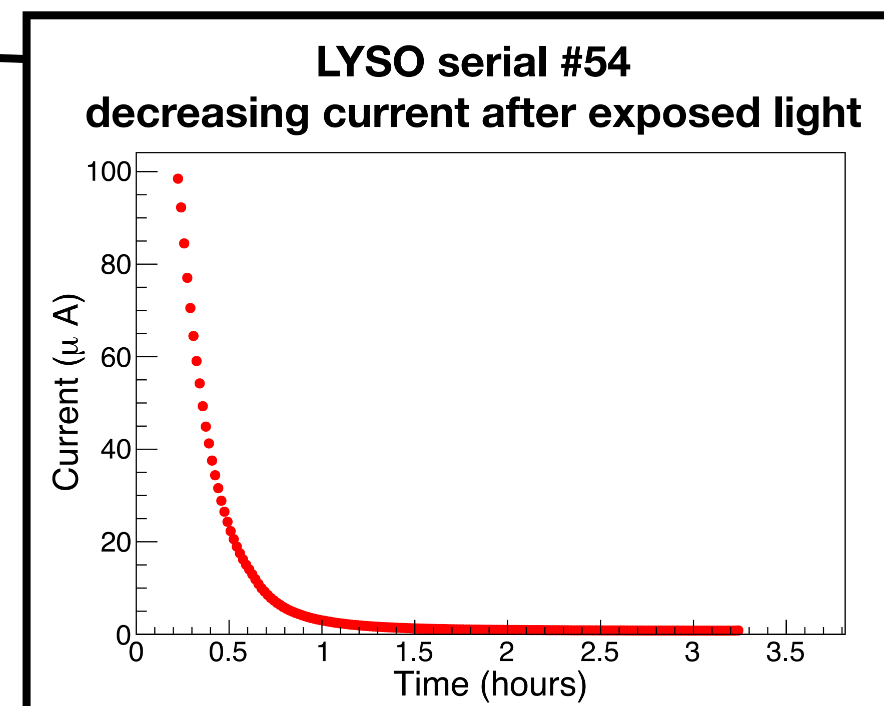
Temperature is constant(30°C)




- We observed afterglow with room light
  (presented at last JPS meeting)

Current readout value with picoammeter
after exposed room light for 24h



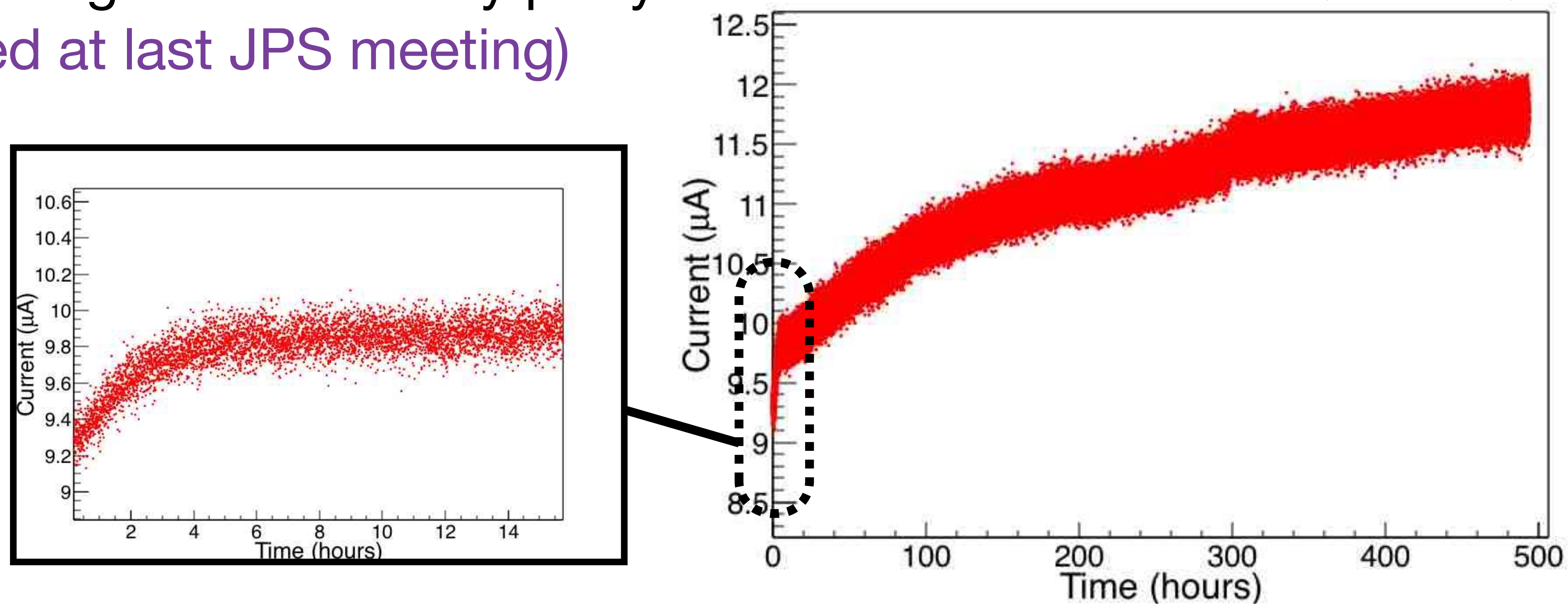



# 4. Study with Sr90 source

- We also observed afterglow induced by β-ray irradiation (presented at last JPS meeting)

- **We observed current increasing exponentially for first few hours**
- **The effect on energy resolution was found to be negligible**

**Current with Sr90 irradiation (LYSO #45)**

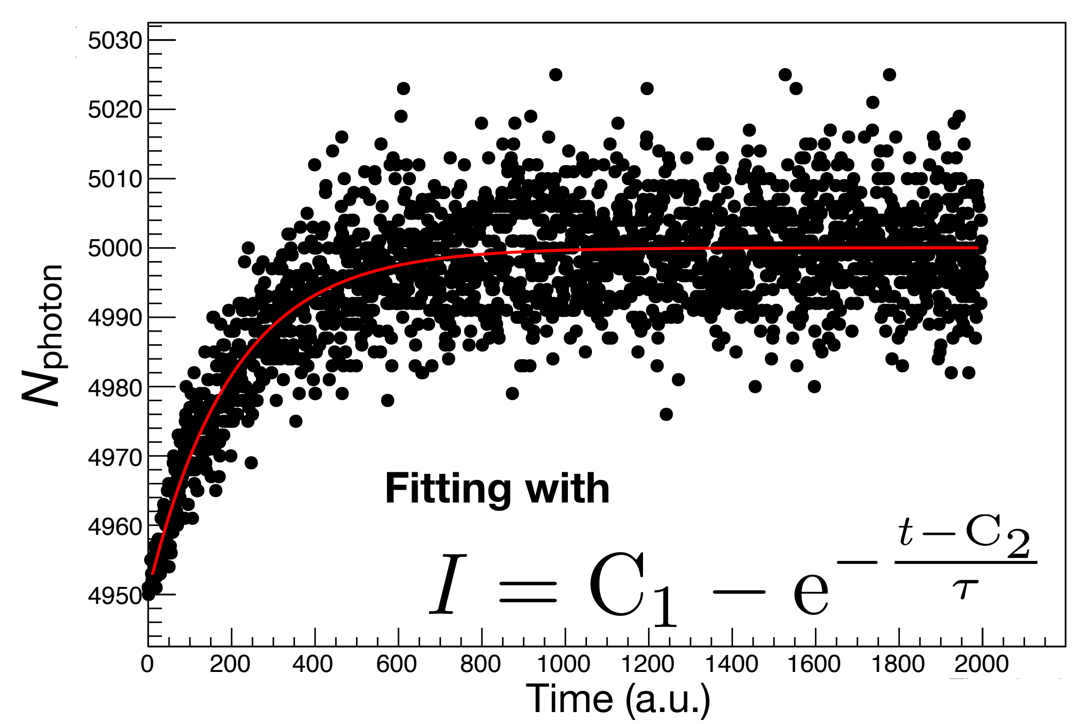



- Why does the current rise exponentially due to afterglow ?

**emitted $N_{photon}$ was calculated with random number following exponential dist.**

→ Trapped electrons will be released with certain probability in $\Delta t$

→ Emitting time will follows geometric dist. (exponential dist. for $\Delta t \to 0$)



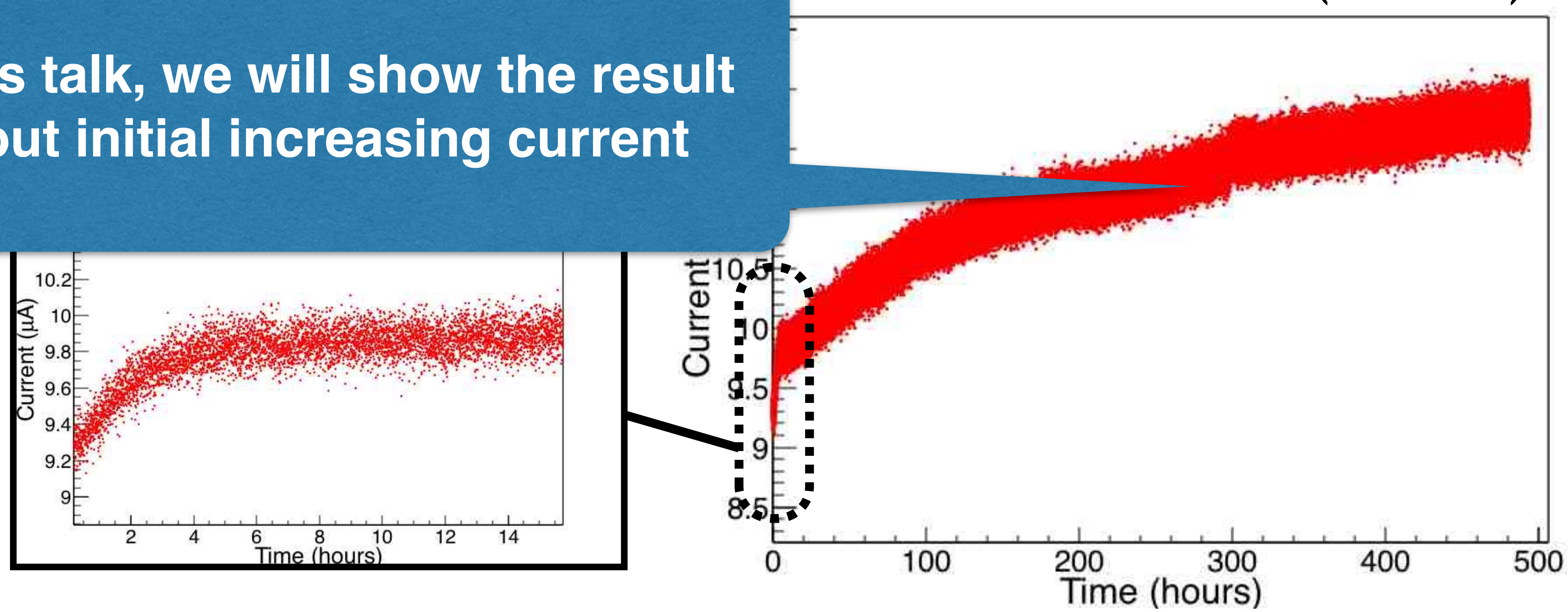
# source

- We also obs
  irradiation (p

- **We observed cu**
  **increasing exponentially**
  **for first few hours**
- **The effect on energy resolution was found to be negligible**

**It is still not clear whether this part is due to afterglow or not**

**In this talk, we will show the result about initial increasing current**




- Why does the current rise exponentially due to afterglow ?

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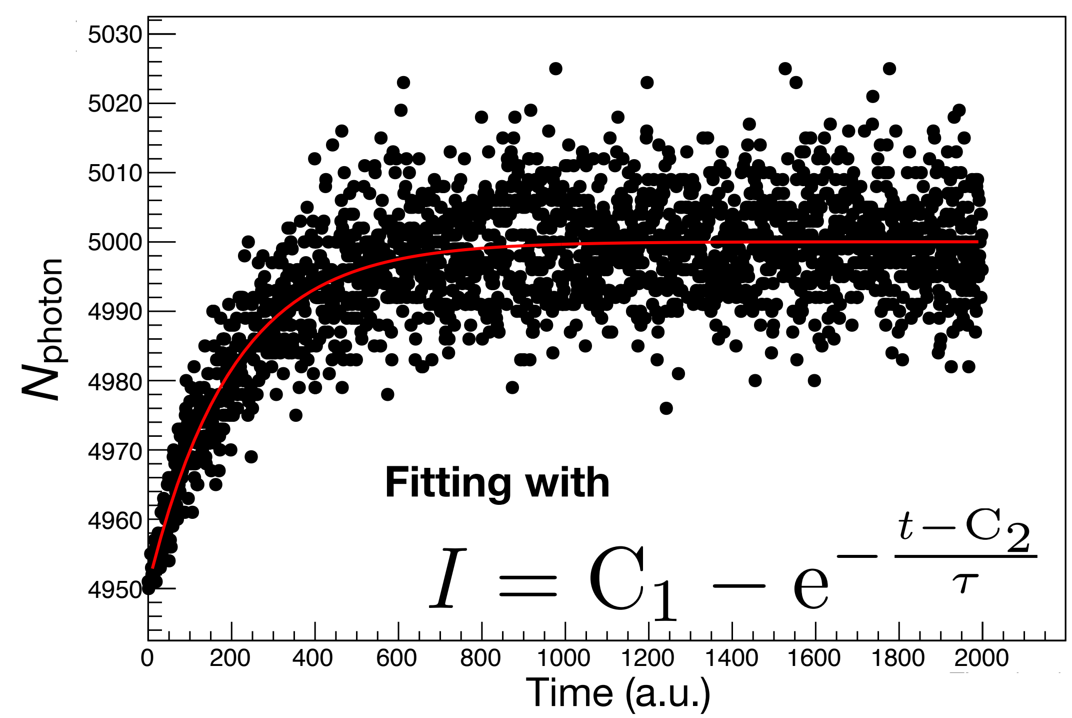
→ Trapped electrons will be released with certain probability in $\Delta t$

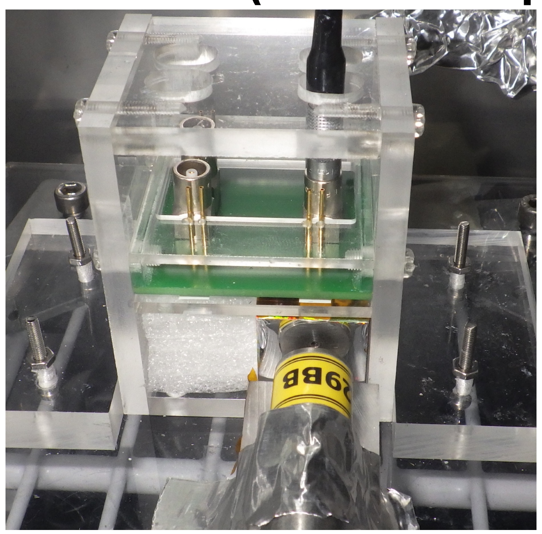
→ Emitting time will follows geometric dist. (exponential dist. for $\Delta t$ → 0)



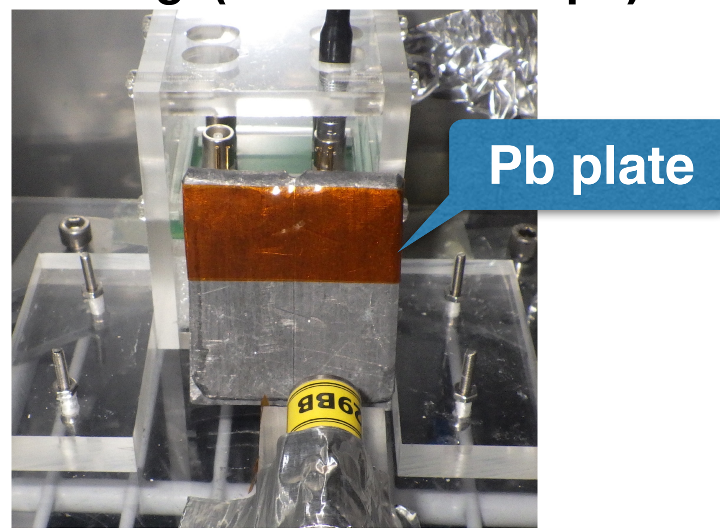
# 4. Study with Sr90 source

- For further study, we checked reproducibility of afterglow with Sr90 (3.7MBq)

**① irradiation (current 7~9μA)**



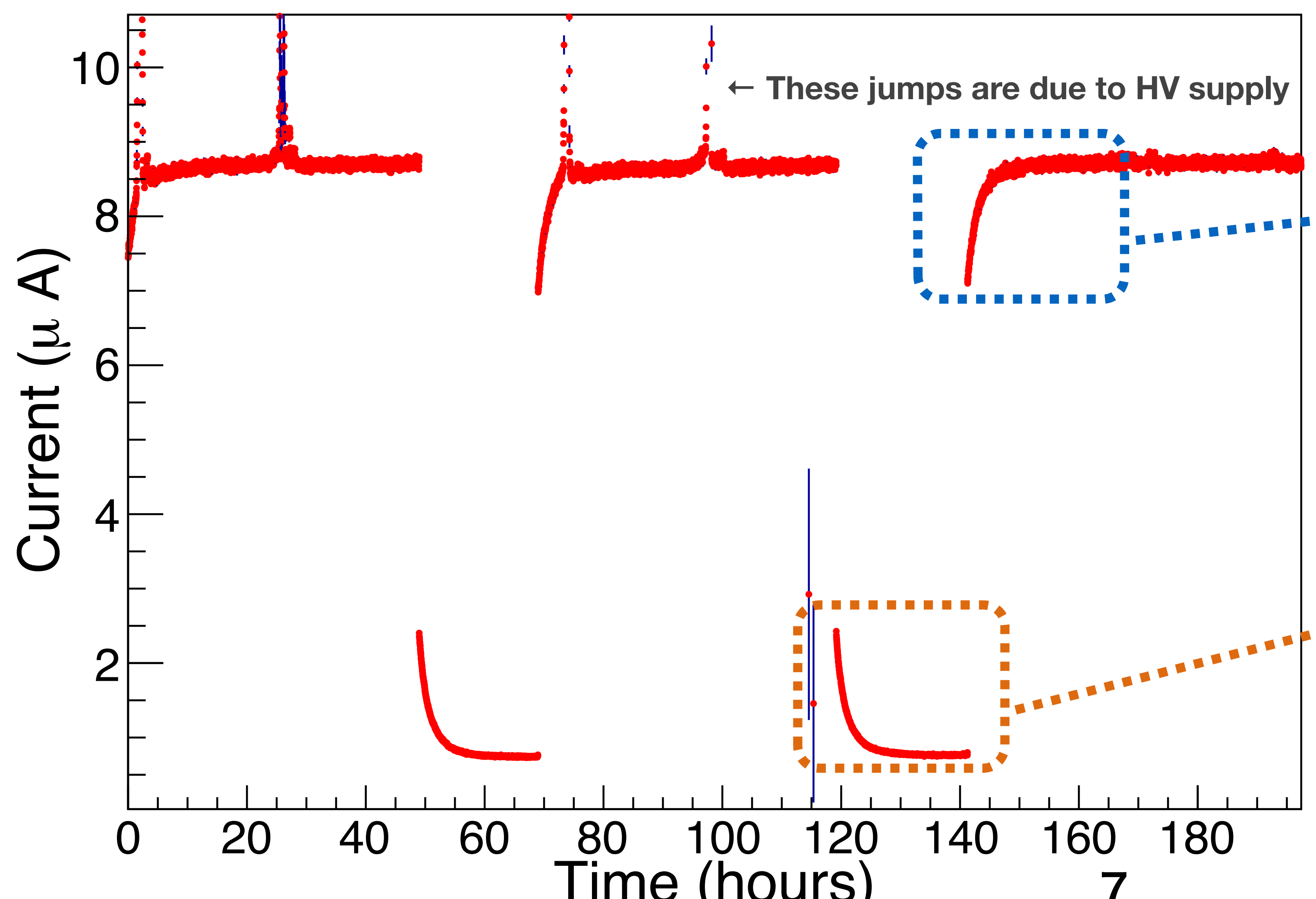
**② shielding (current 0.5~2.5μA)**

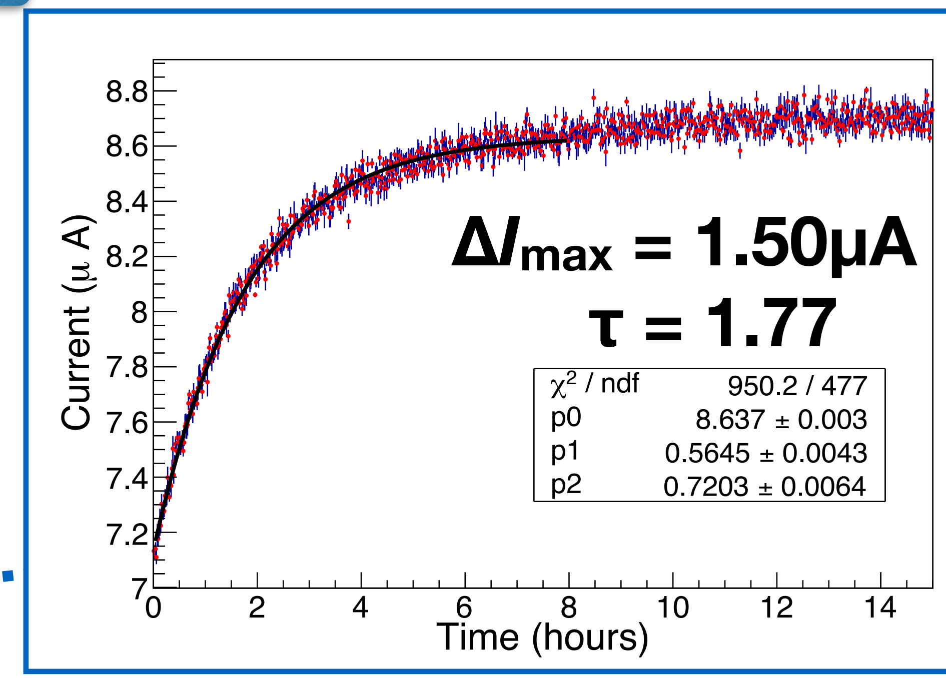


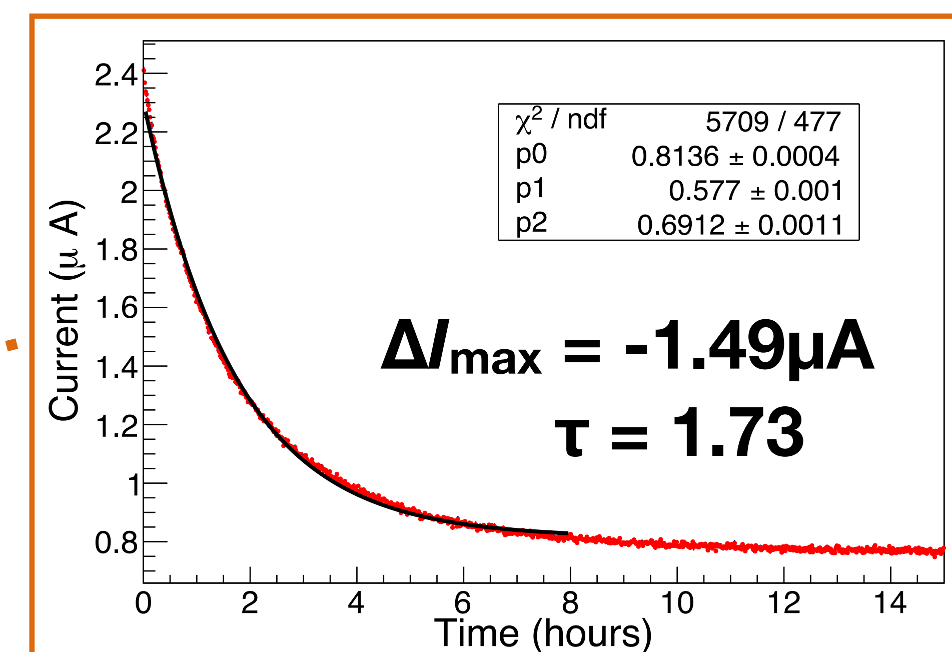

**fitting function**

$$I = \mathrm{C}_1 \pm \mathrm{e}^{-\frac{t-\mathrm{C}_2}{\tau}}$$

**where** $\Delta I_{\max} = \mathrm{e}^{\frac{\mathrm{C}_2}{\tau}}$



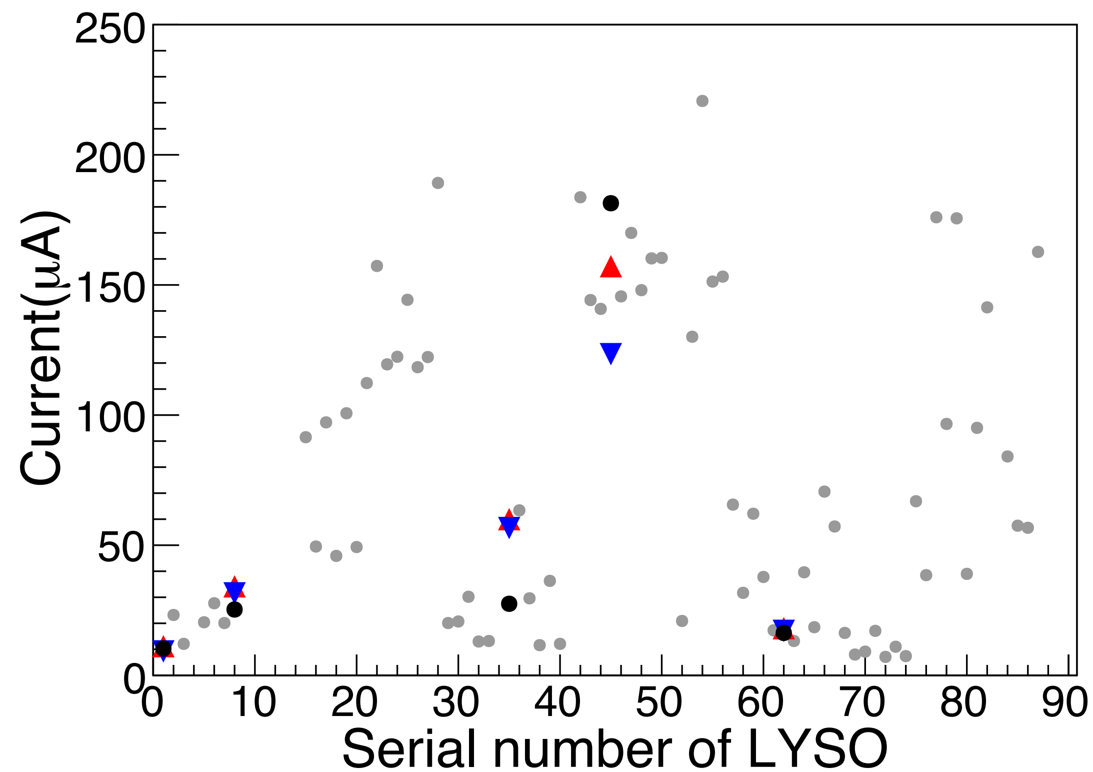



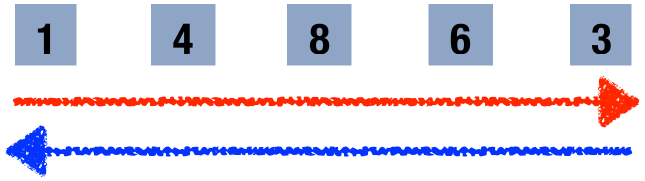
# 4. Study with Sr90 source

- From past study,  room light afterglow are known to have individual difference
- We additionally measured 5 crystals with room light
  → After exposed room light 24h~,  current was measured with picoammeter

**Difference between crystals was confirmed by measuring with reverse order**

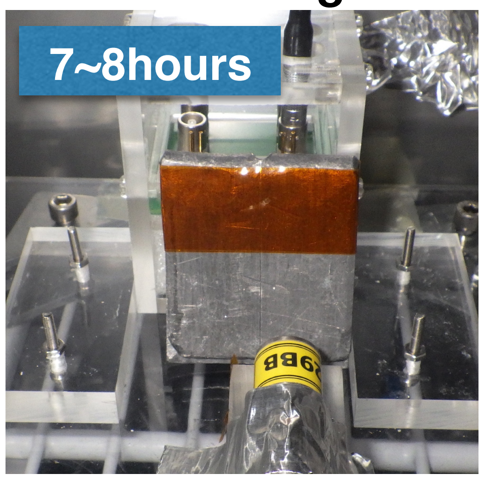




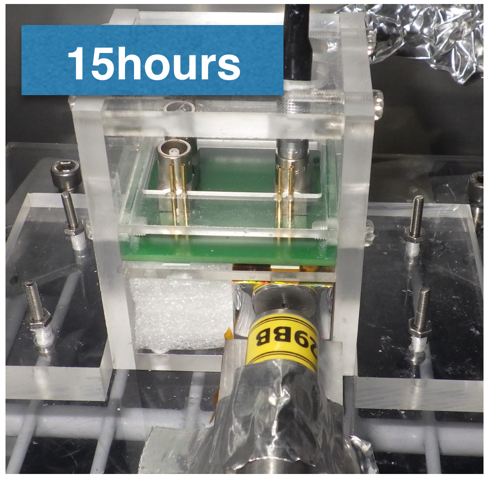



- These 5 crystals were measured with Sr90 (37MBq) and checked correlation
  → Hit rate was also measured after current monitor (~400kHz)

shielding



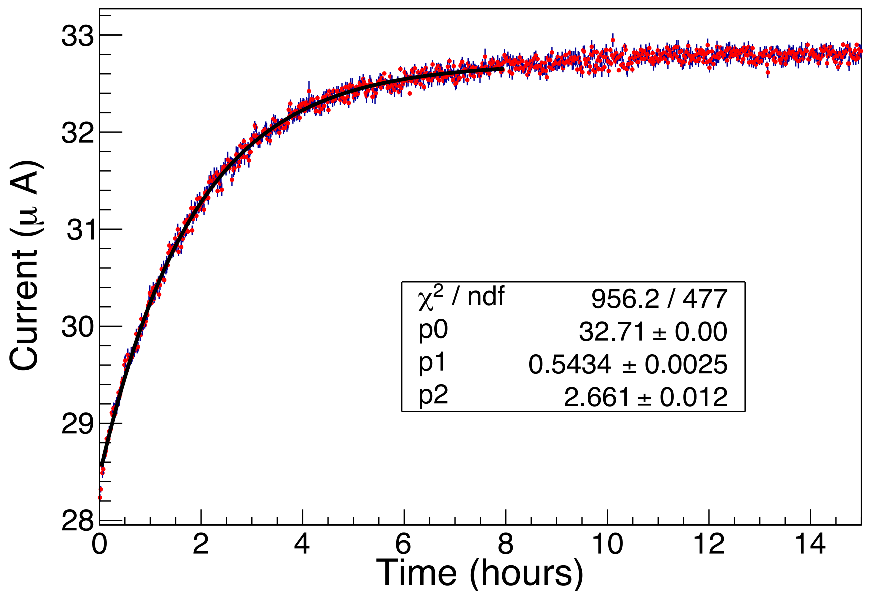

irradiation



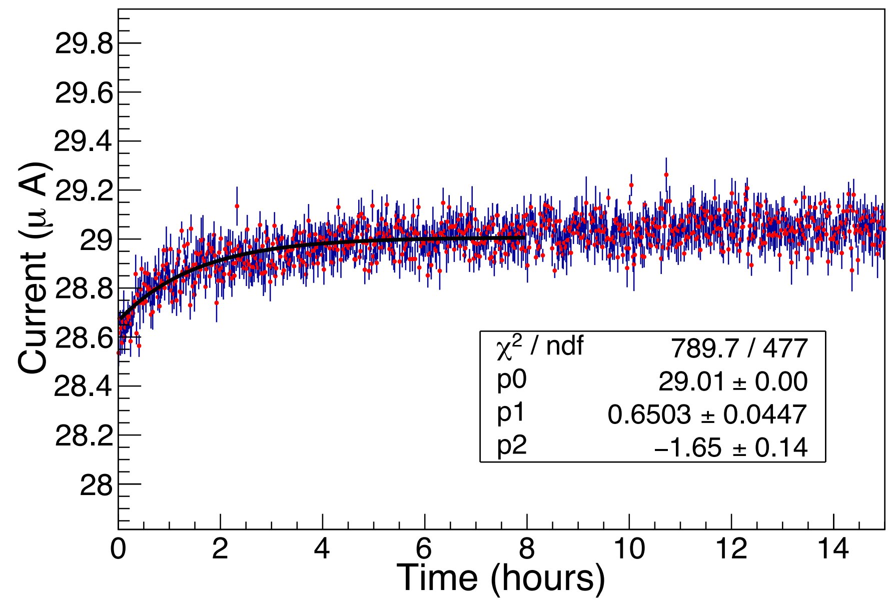
# 4. Study with Sr90 source

- Result of the current (+1 crystal was measured additionally)

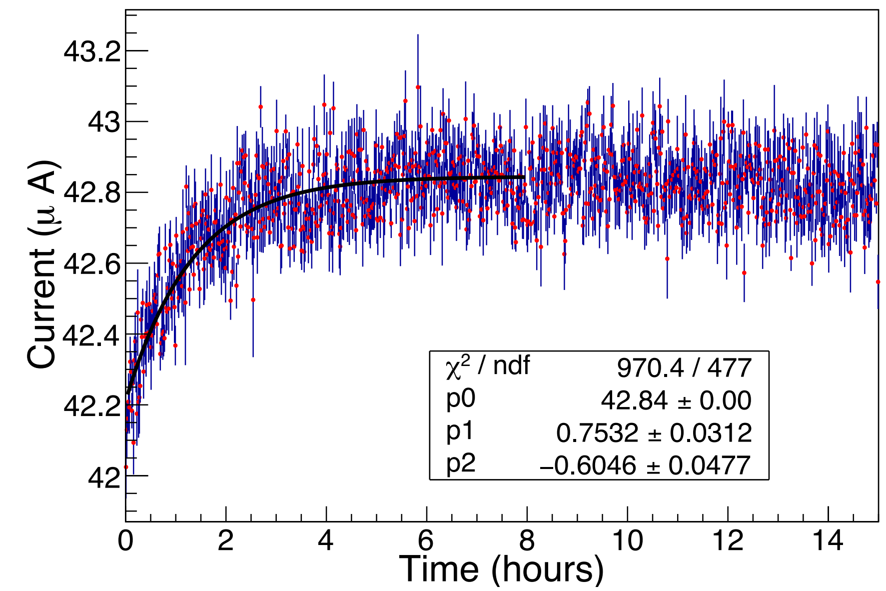
**#45 Δ$I_{max}$ = 4.25μA**



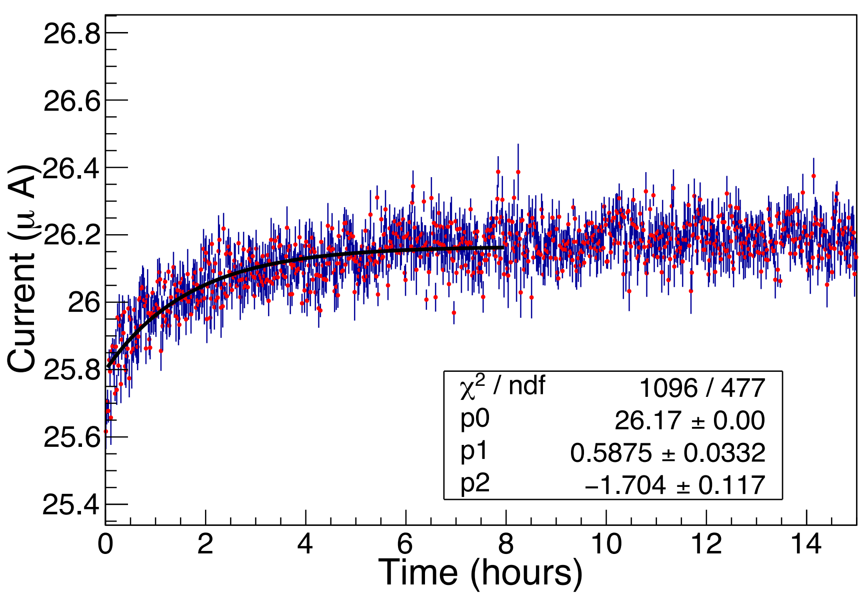

**#1 Δ$I_{max}$ = 0.34μA**



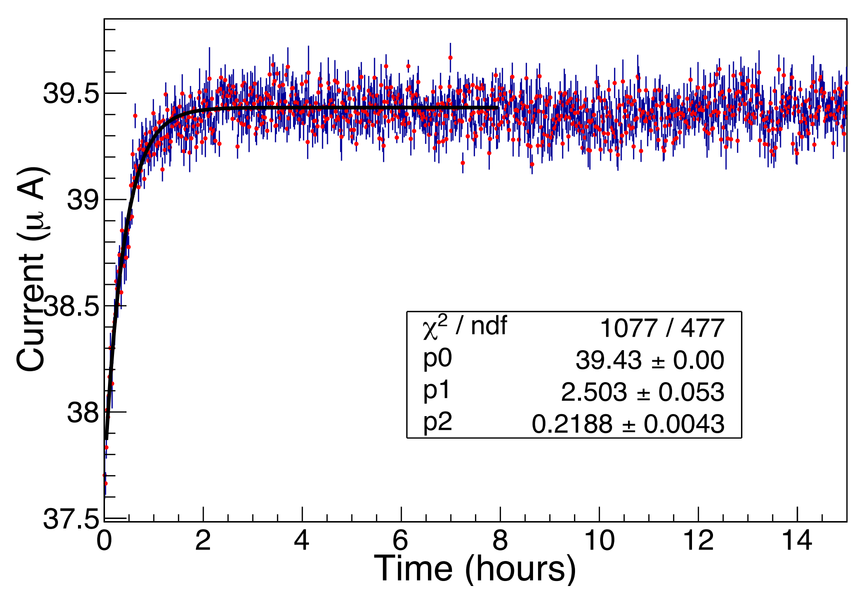

**#35 Δ$I_{max}$ = 0.63μA**



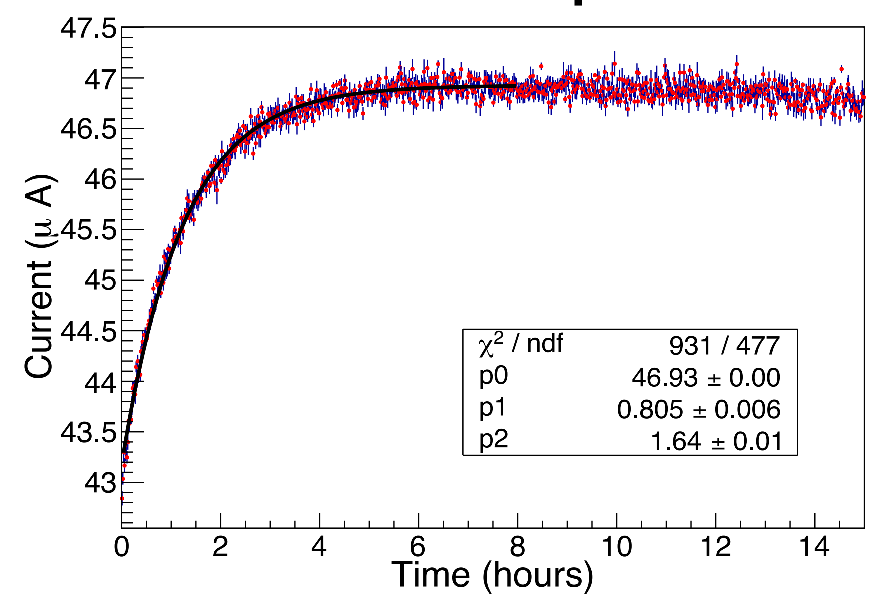

**#62 Δ$I_{max}$ = 0.37μA**




**#8 Δ$I_{max}$ = 1.73μA**

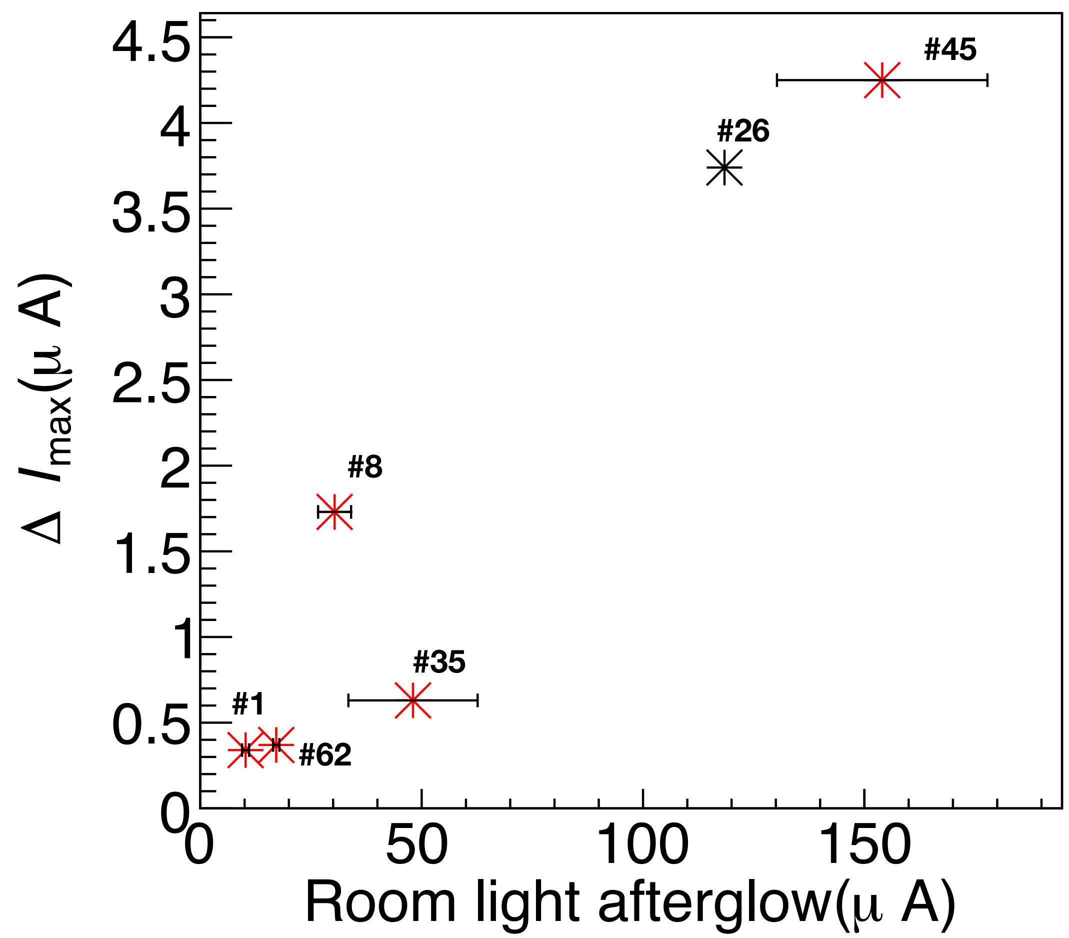


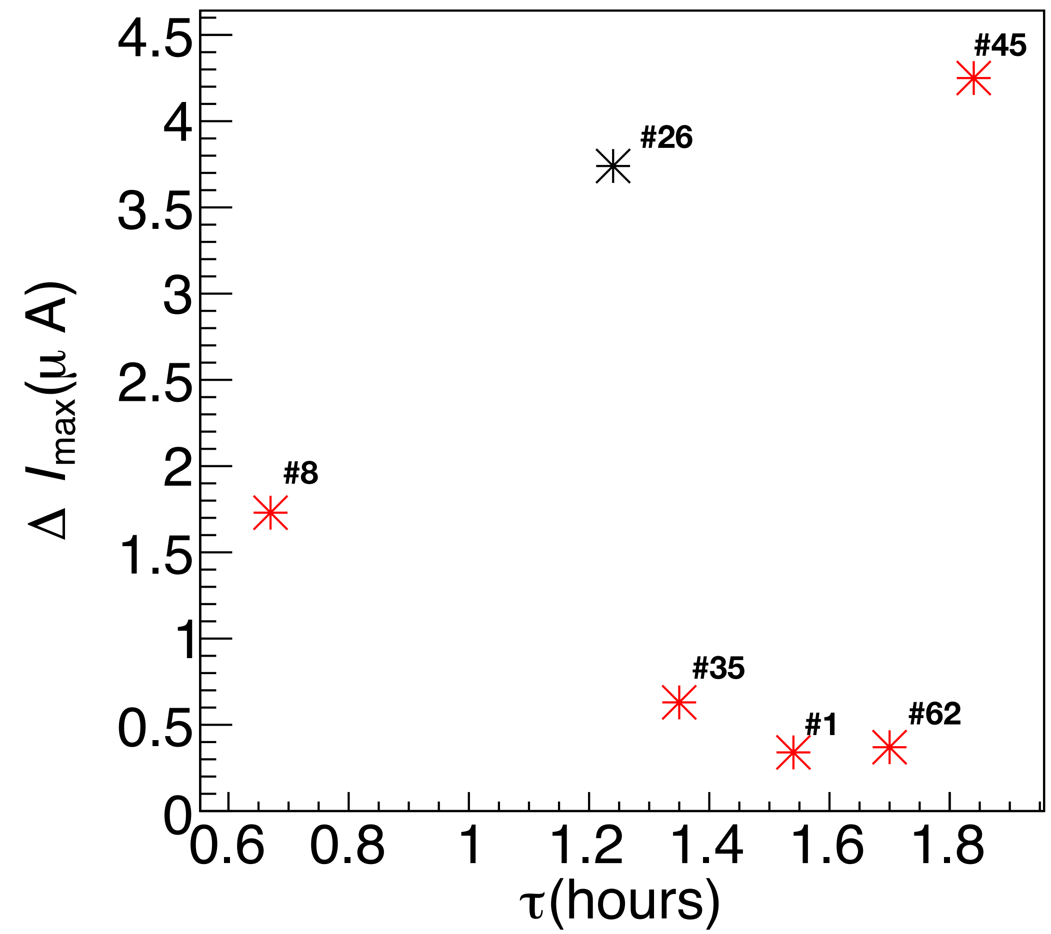

**#26 Δ$I_{max}$ = 3.74μA**



# 4. Study with Sr90 source

- Correlation was checked (**grey** plot shows additional measurement)



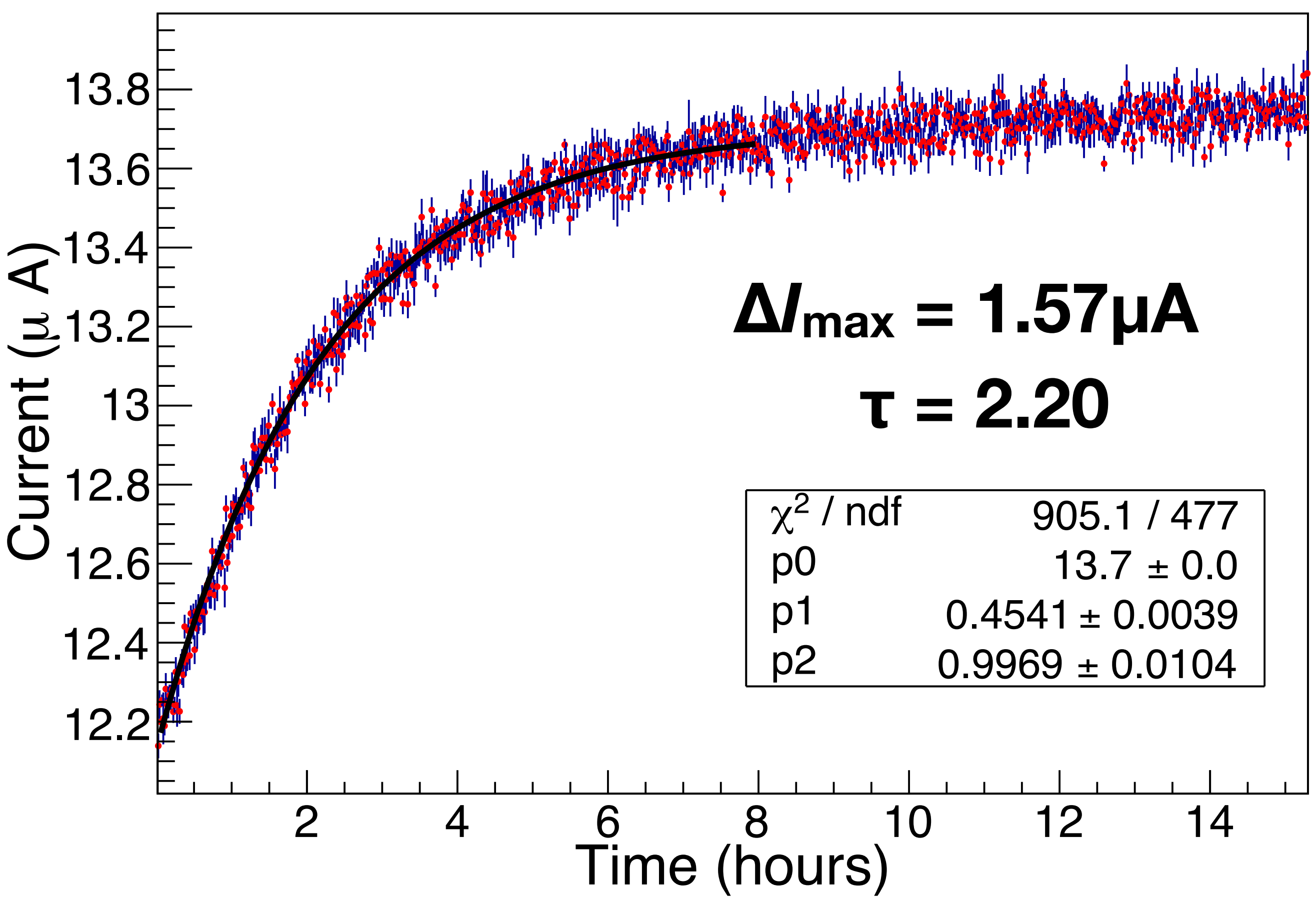

- <u>$\Delta I_{max}$ has a correlation with the amount of increased current with room light afterglow</u>

- This result can be useful to optimize the placement of crystals in the detector

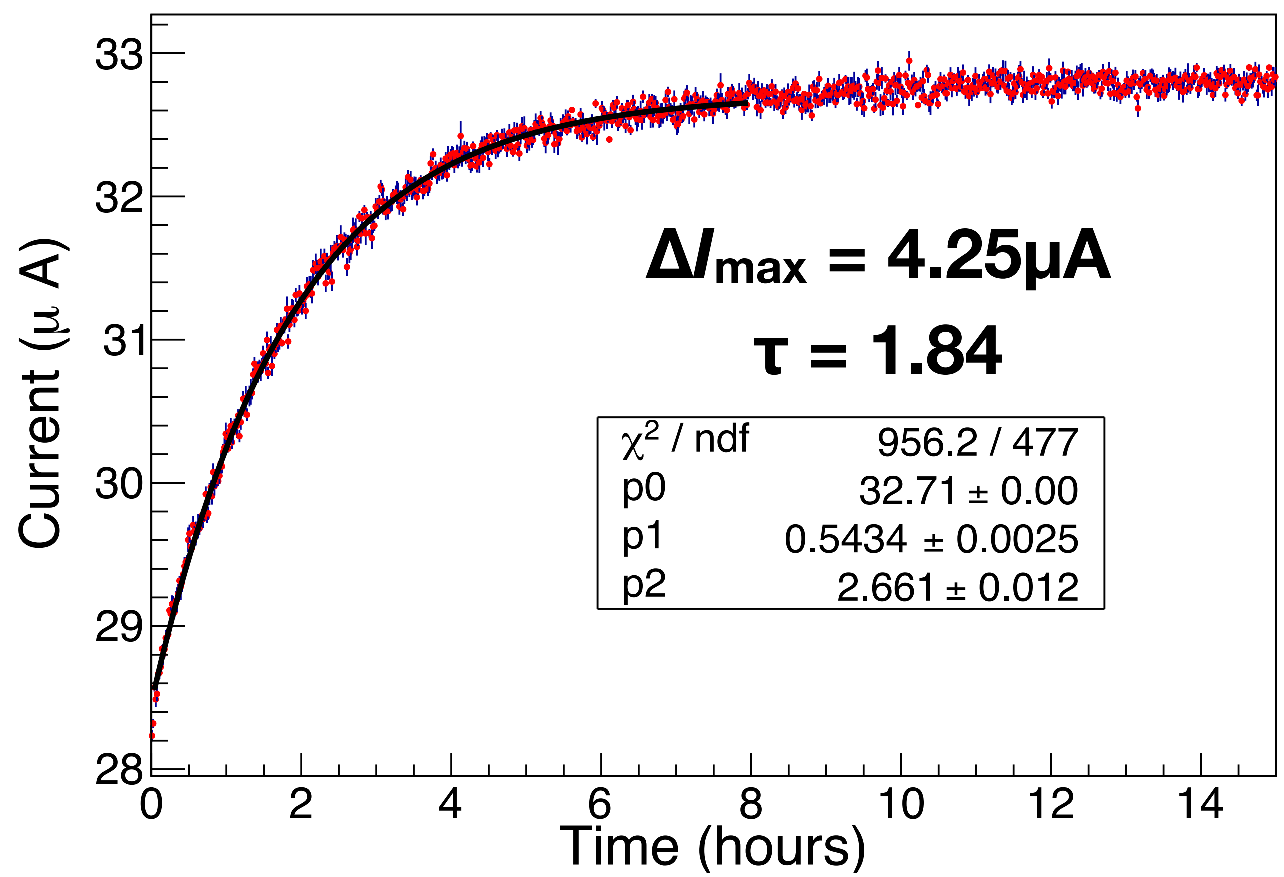
# 4. Study with Sr90 source

- Different strength Sr90 was applied to same crystal (#45)
- $\Delta I_{max}$ & τ are expected to be proportional to hit rate
- Hit rate was measured with discriminator & scaler

**161kHz**




**372kHz**




- <u>$\Delta I_{max}$ was largely changed with different hit rate</u>

# 5. Summary of afterglow study

**We had already observed at the last JPS meeting…**

- Large anode current after exposed to room light in several crystals
- Slowly increasing current during β-ray irradiation
  (the influence on detector operation was estimated small)

**We newly observed…**

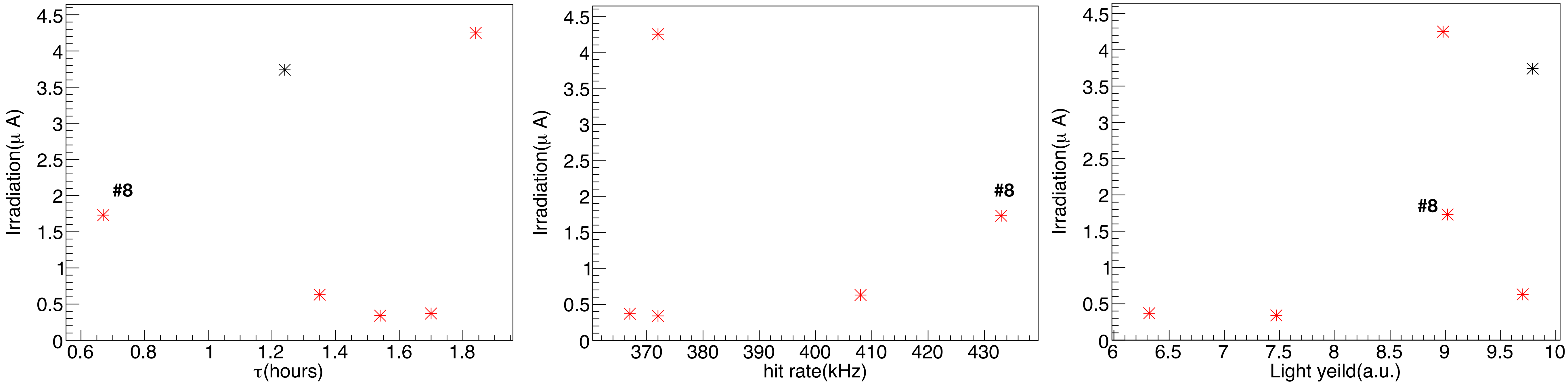
- Current increasing (decreasing) exponentially during (after) β-ray irradiation
- Each crystals have unique $\Delta I_{max}$ & τ for both increasing & decreasing
- $\Delta I_{max}$ has a correlation with afterglow induced by room light
- $\Delta I_{max}$ was largely changed with different hit rate

**We will do next…**

- We will investigate about slowly increasing current
  (also measure scintillation properties)

# Back up

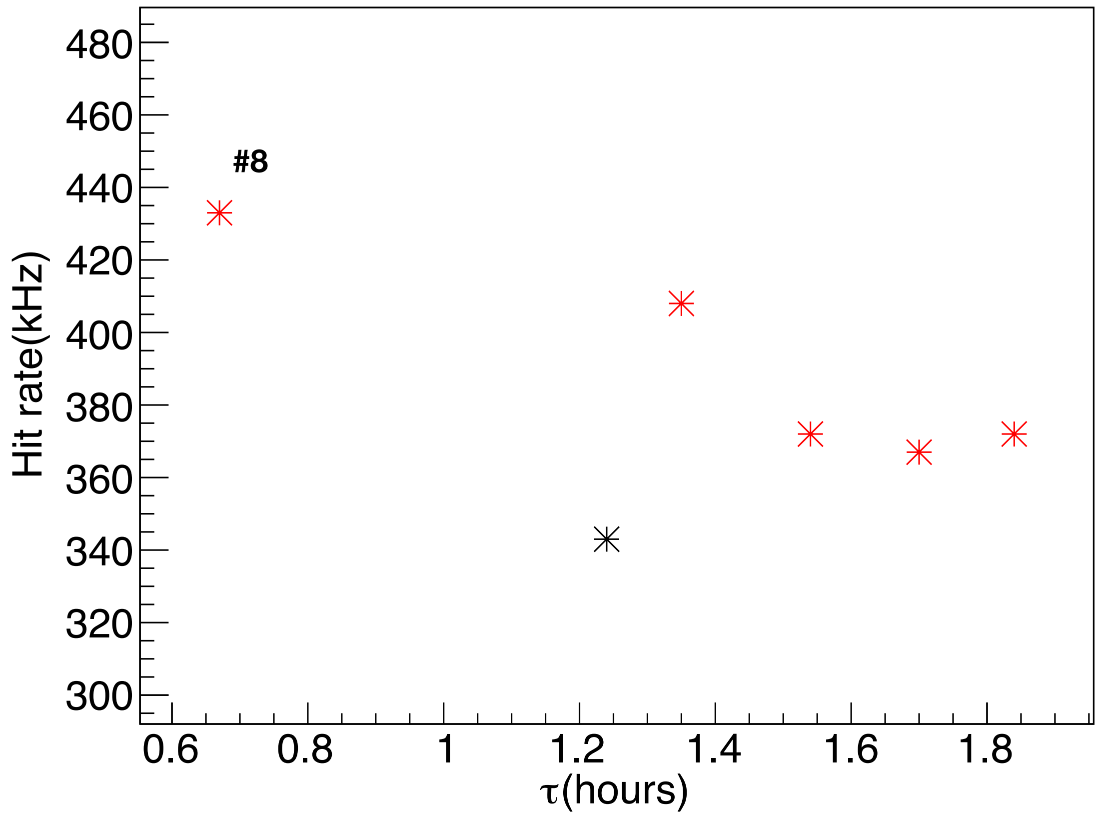
# 4. Study with Sr90 source

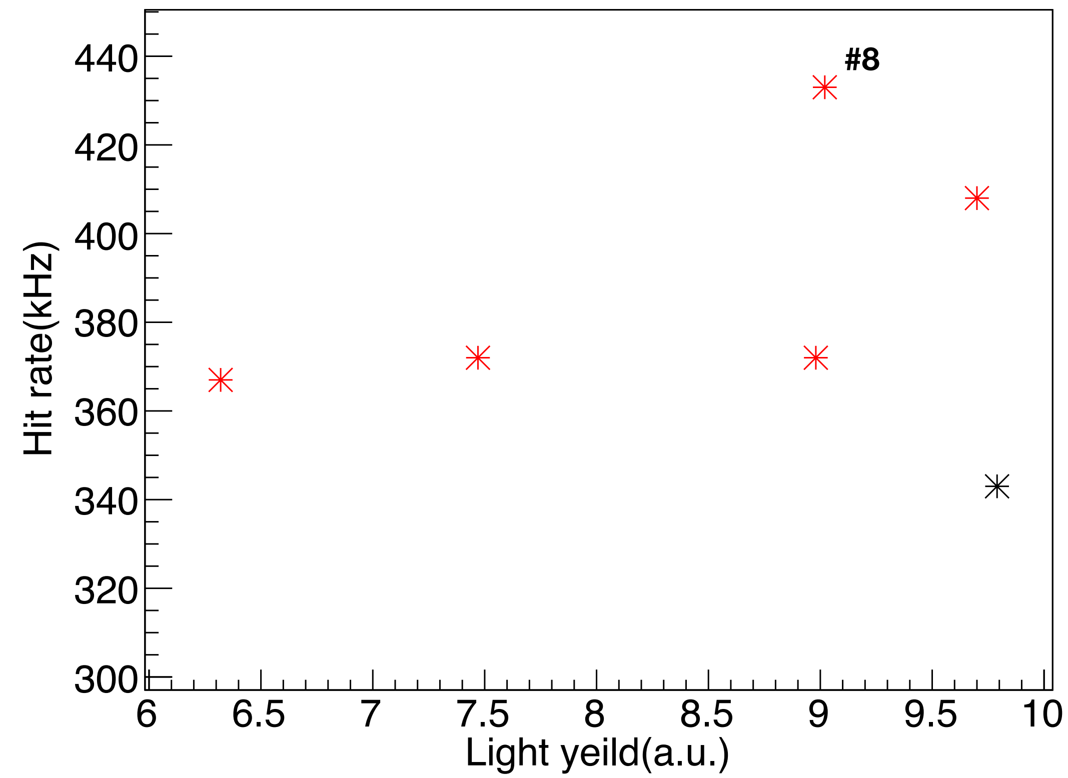



| LYSO serial | meas. order | $\Delta I_{max}$ (μA) | τ (hours) | hit rate (kHz) | light yield (a.u.)* |
|---|---|---|---|---|---|
| #45 | 1 | 4.25 | 1.84 | 372 | 8.98 |
| #1 | 2 | 0.34 | 1.54 | 390 | 7.47 |
| #35 | 3 | 0.63 | 1.33 | 408 | 9.70 |
| #62 | 4 | 0.37 | 1.70 | 367 | 6.32 |
| #8 | 5 | 1.73 | 0.67 | 433 | 9.02 |
| #26 | 6 | 3.74 | 1.24 | 343 | 9.79 |

* light yield was measured by using 1.17MeV peak of Co60

# 4. Study with Sr90 source

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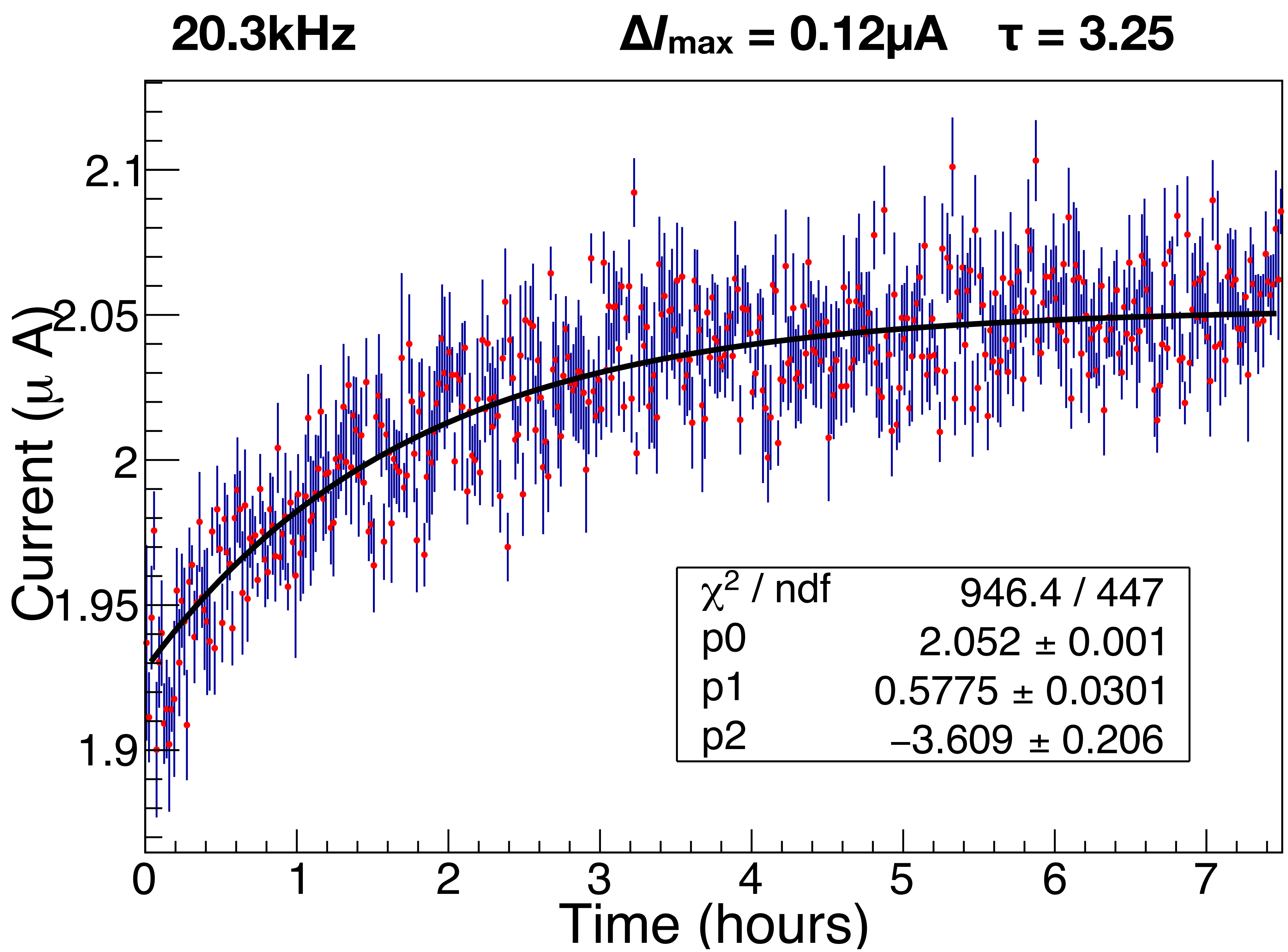
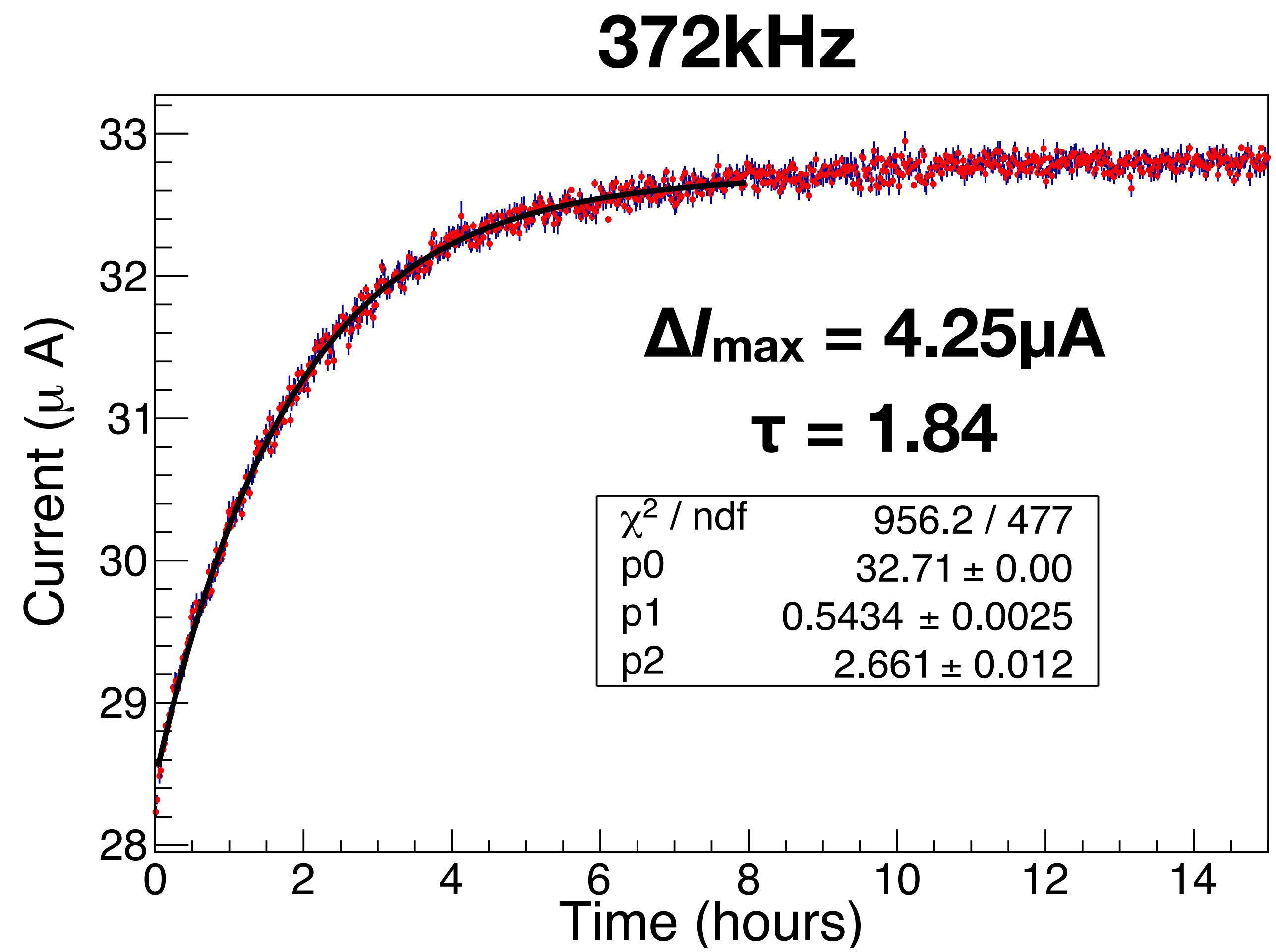
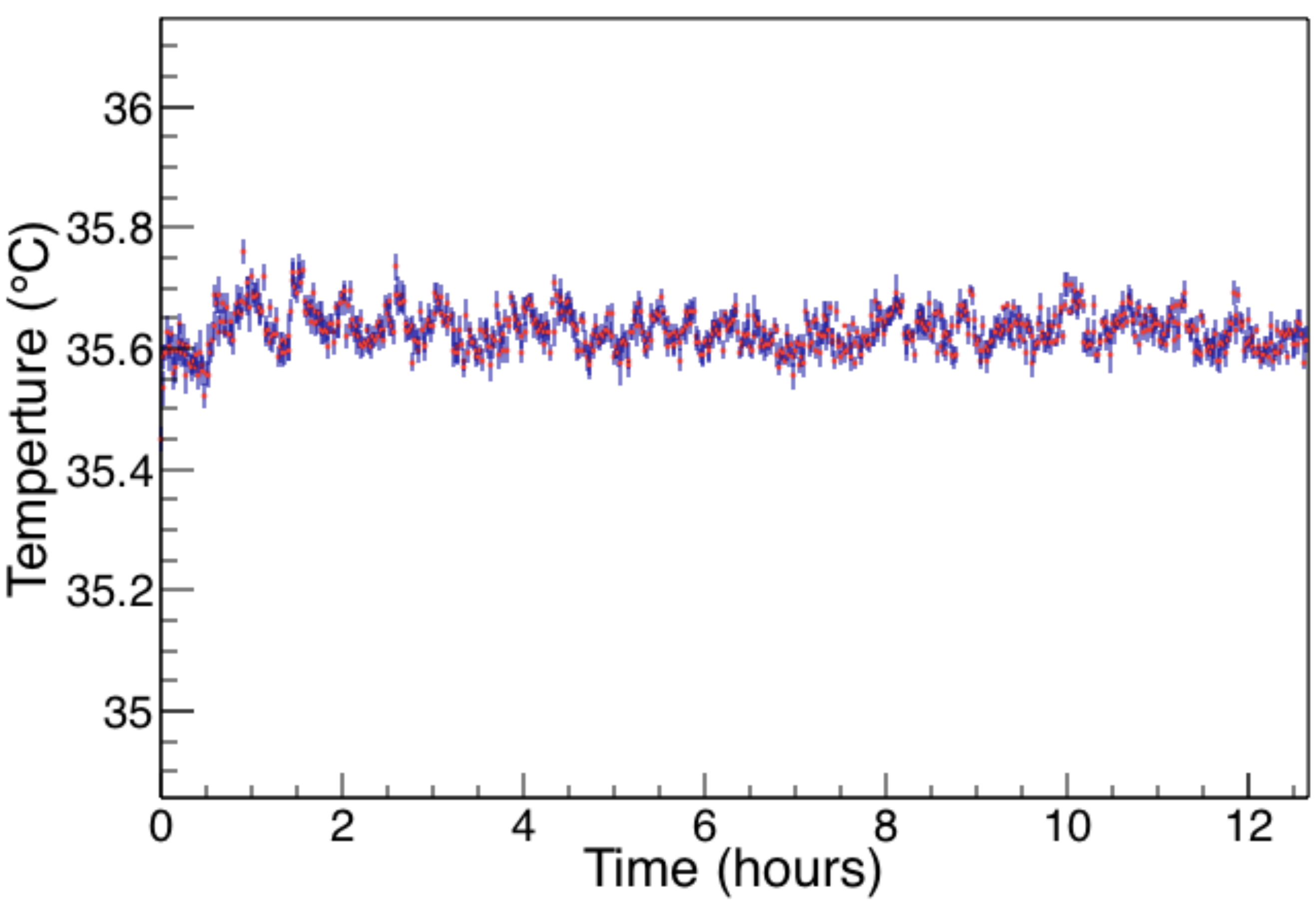
* light yield was measured by using 1.17MeV peak of Co60

# Study with Y88 source

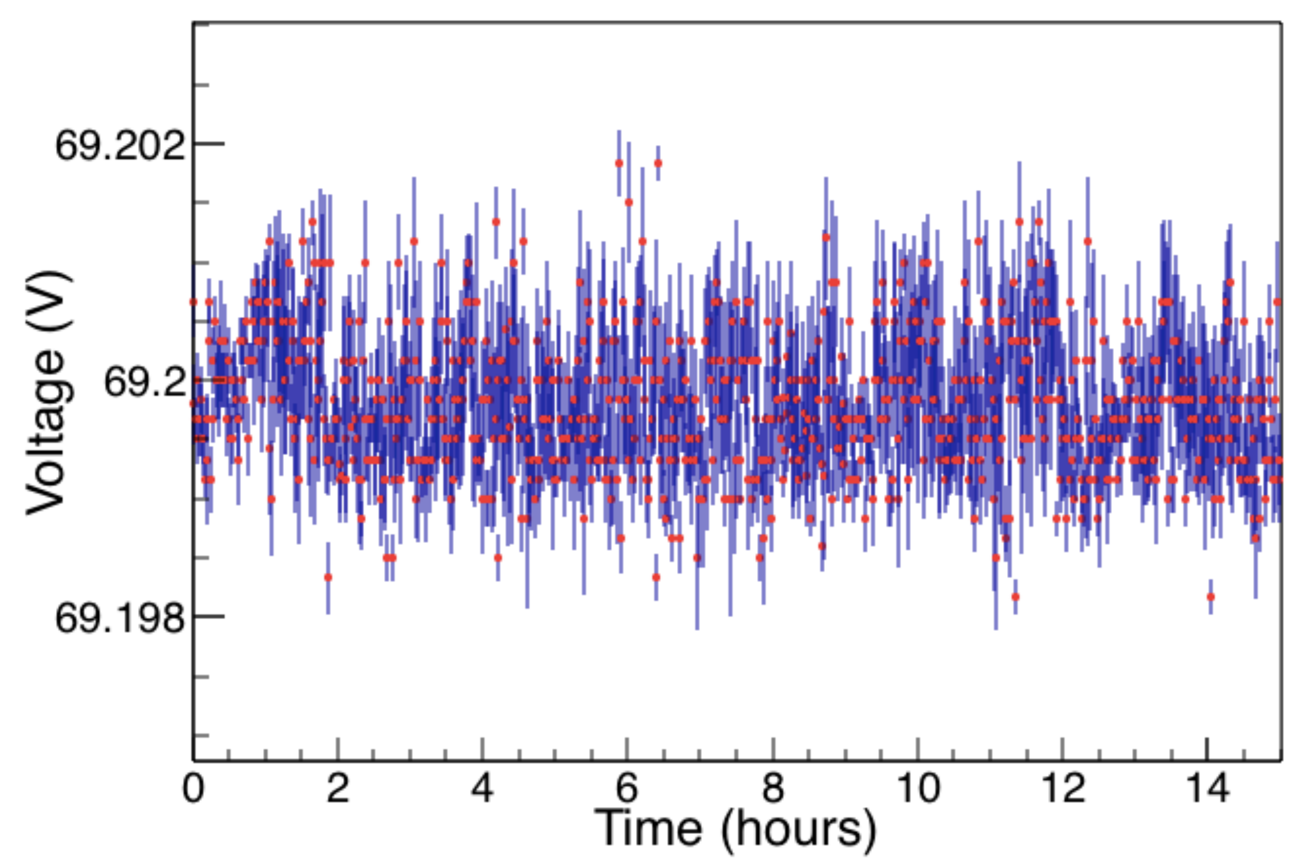




372kHz
$\Delta I_{max}$ = 4.25μA
τ = 1.84
χ² / ndf 956.2 / 477
p0 32.71 ± 0.00
p1 0.5434 ± 0.0025
p2 2.661 ± 0.012
Current (μ A)
Time (hours)

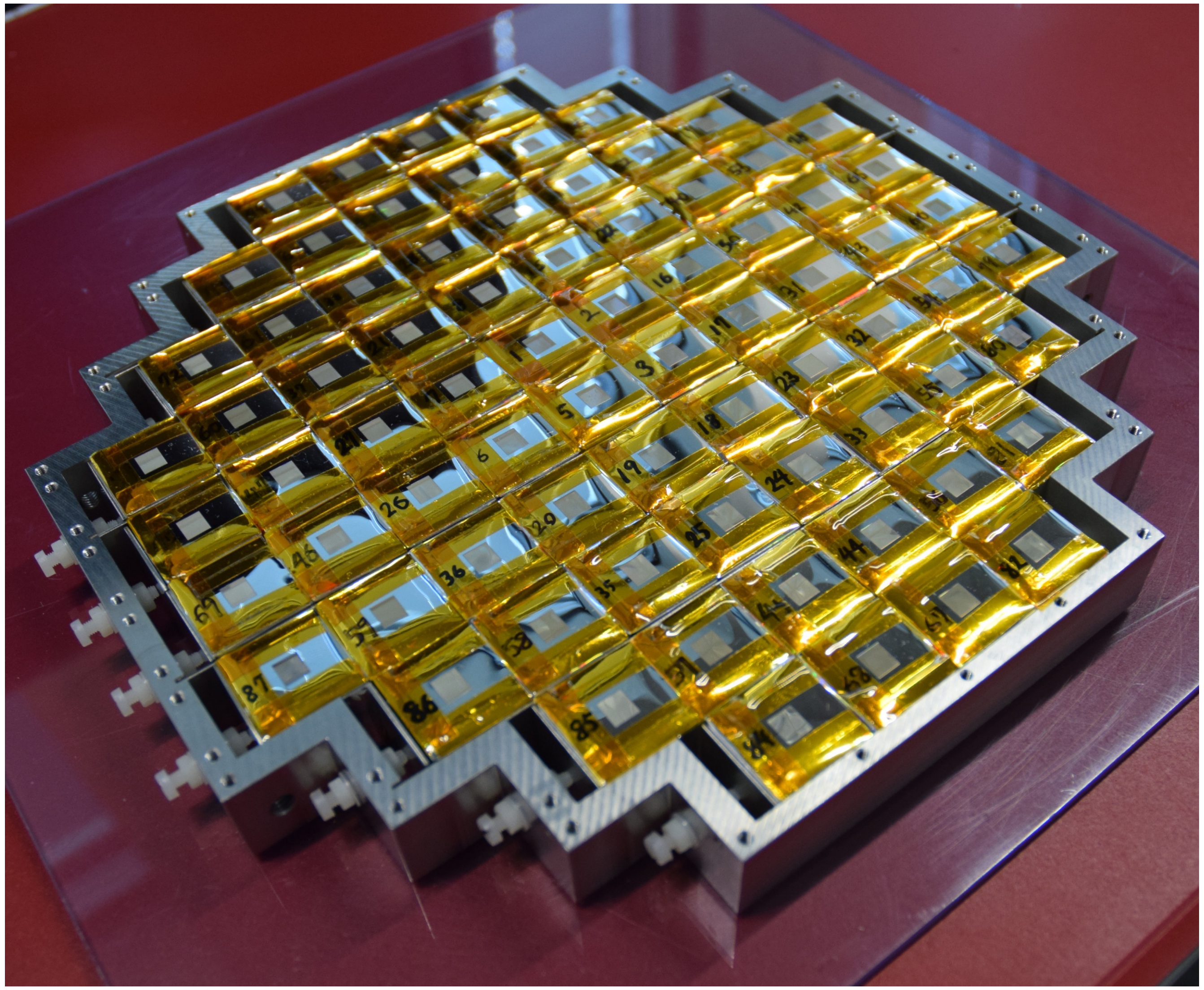
Temperture (°C)
Time (hours)

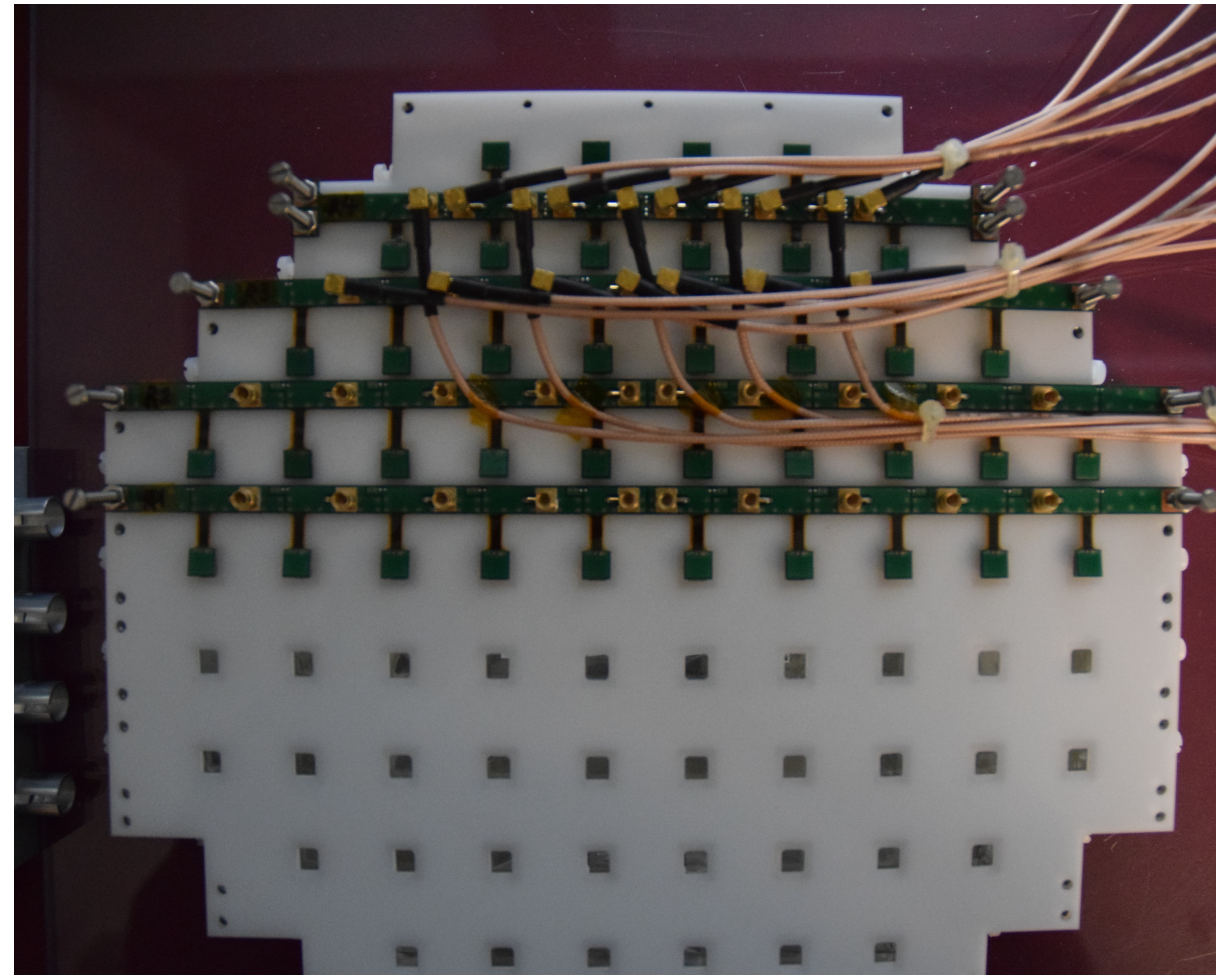
Voltage (V)
Time (hours)

# Pics of Calorimeter part

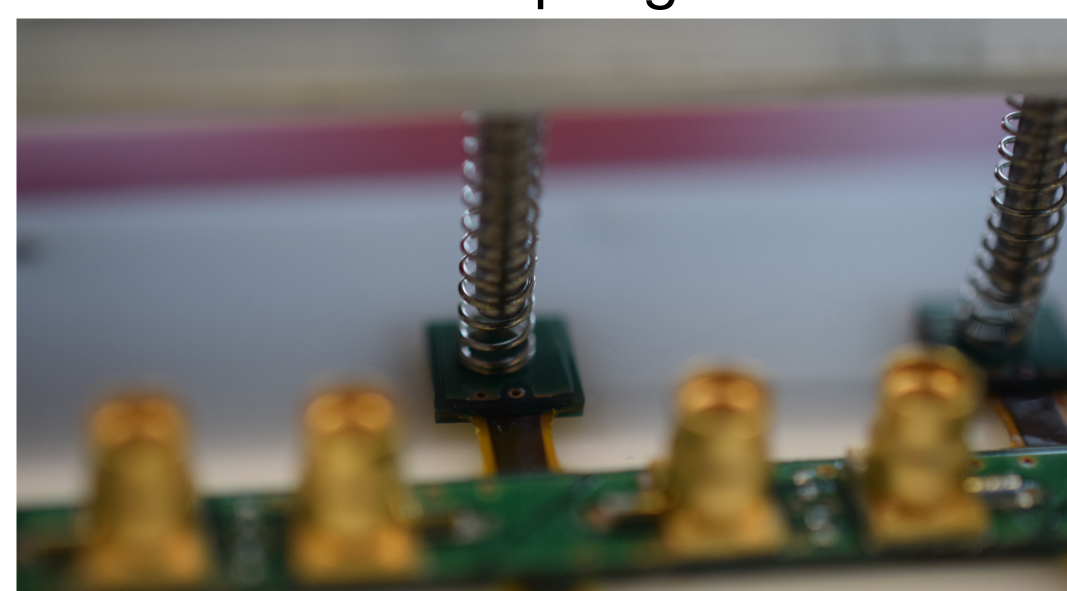
LYSO crystals + main frame



back plane + PCB

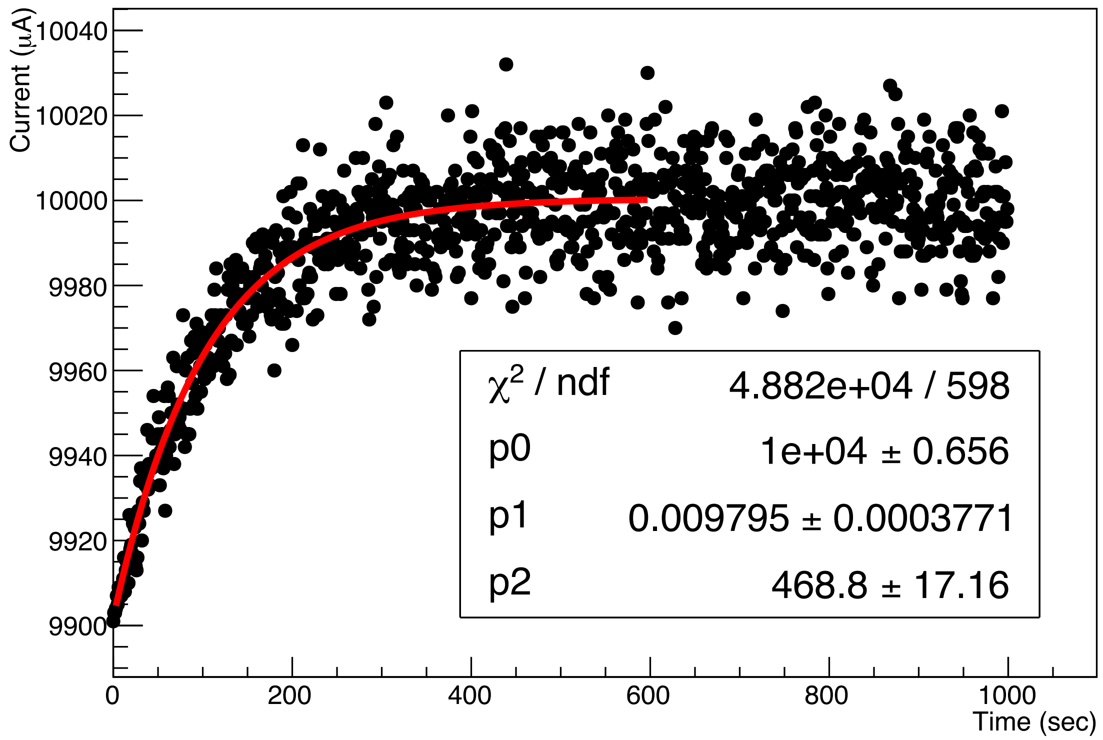


MPPC is fixed with spring



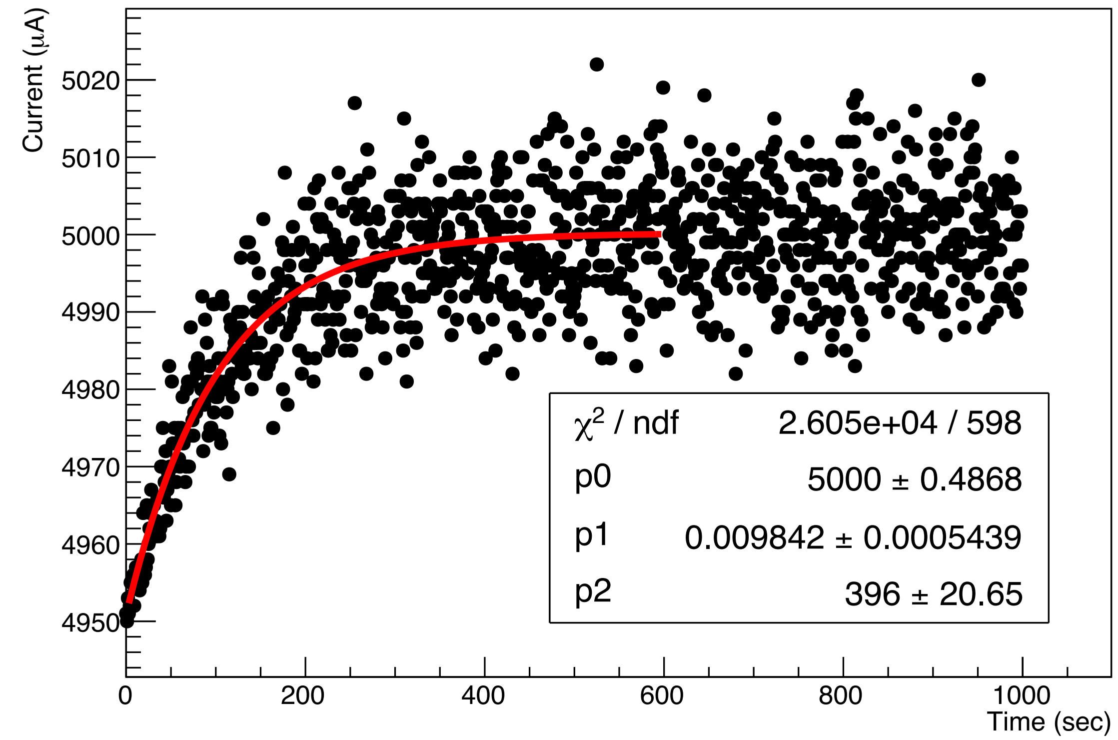
# 4. Study with Sr90 source

incident photons = 5000 per sec



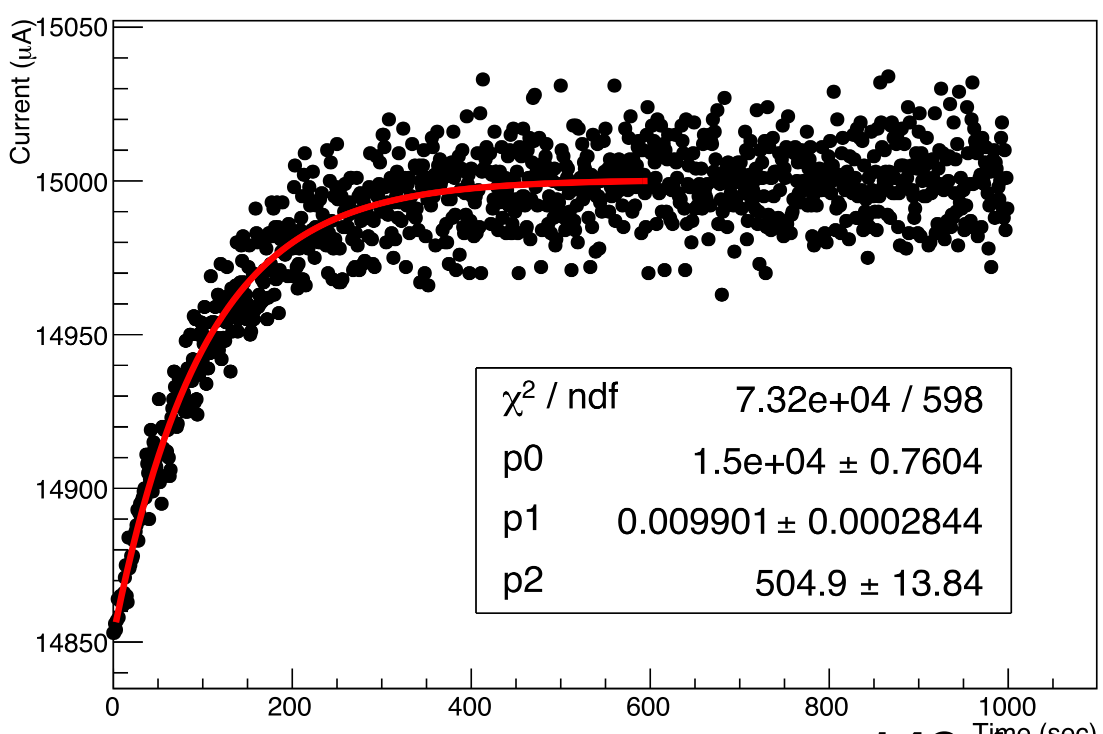

$\Delta I_{max}$ = 10000 τ = 98.9

incident photons = 10000 per sec




$\Delta I_{max}$ = 5000 τ = 49.3

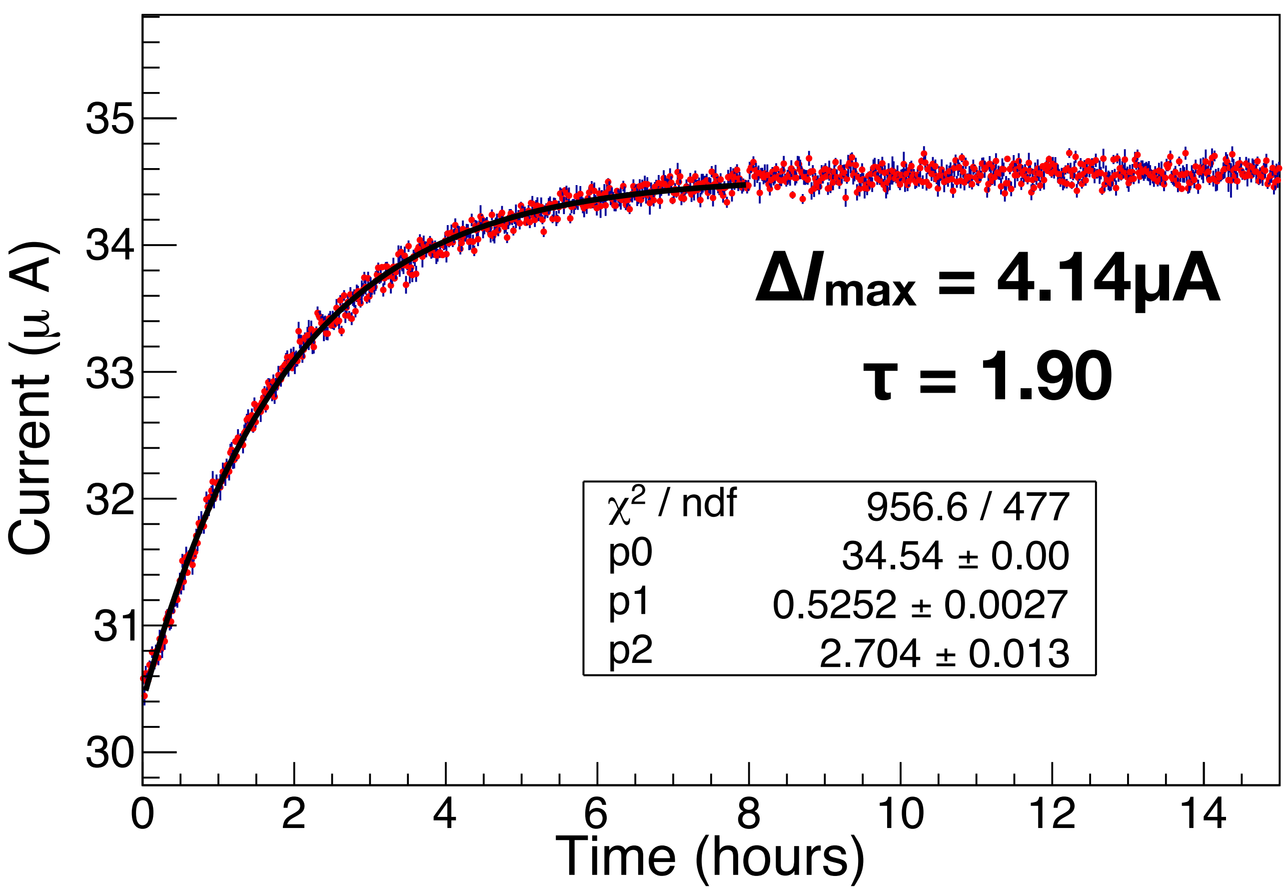
incident photons = 15000 per sec



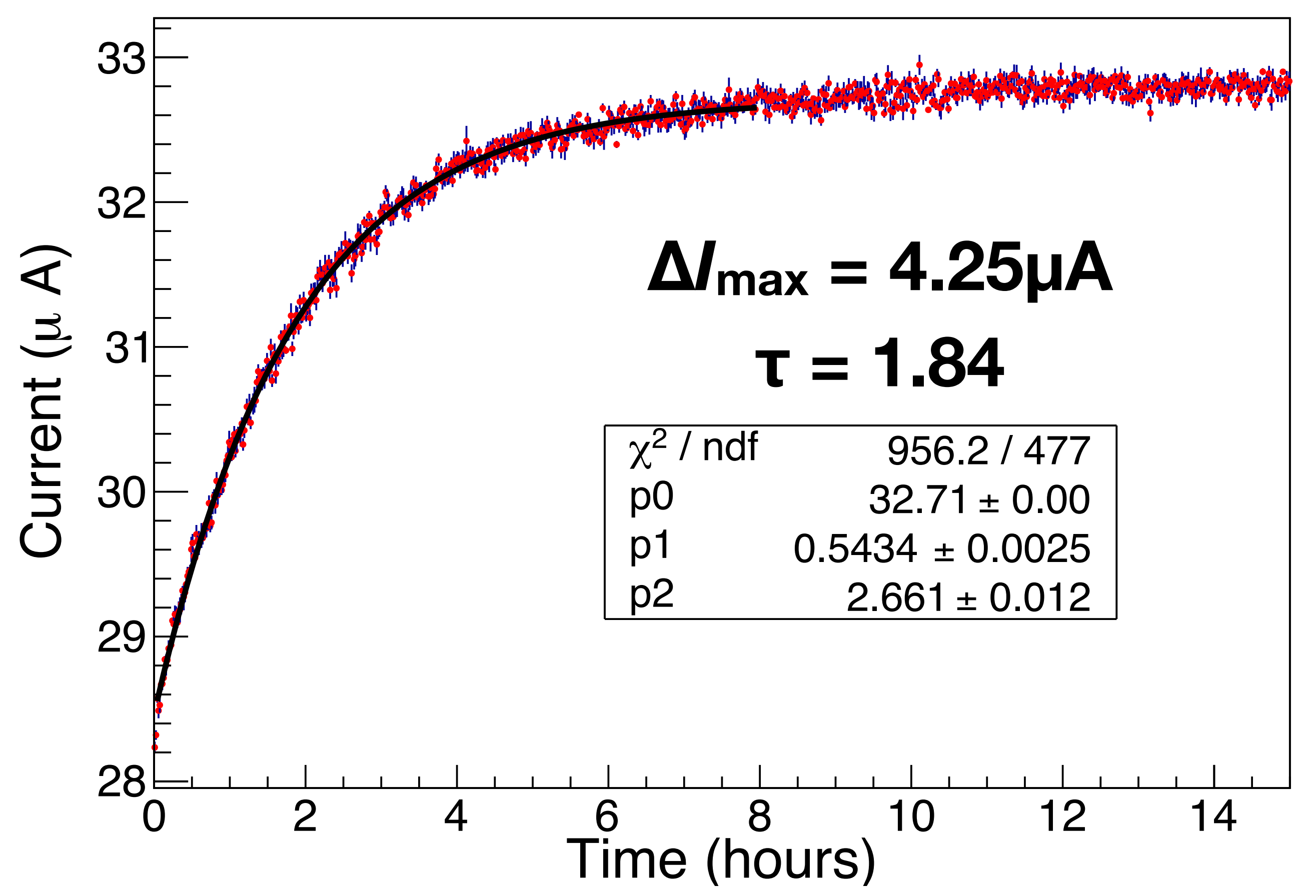

$\Delta I_{max}$ =15000 τ = 148.4

# Reproducibility of $\Delta I_{max}$ & τ in #45

**1st measurement**




**2nd measurement**



## Specifications

Cerium-doped lutetium yttrium oxyorthosilicate crystal ((Lu,Y)2SiO5:Ce, namely LYSO:Ce), is colorless and transparent, character

Cerium-doped lutetium yttrium oxyorthosilicate crystal ((Lu,Y)2SiO5:Ce, namely LYSO:Ce), is colorless and transparent, characterized by monoclinic structure. LYSO not only has excellent scintillation properties such as high light output, short decay time, high density and radiation hardness; but also has its emission peak wavelength 420 nm located in the sensitive region of PMT, and hence the emission can be effectively detected; besides, it has stable physical and chemical properties and hence is convenient for application. Therefore, LYSO is an excellent scintillation crystal.

LYSO can be widely applied in the fields of nuclear medicine, high-energy physics and so on. It benefits detectors for obtaining high time resolution, spatial resolution and miniaturization.

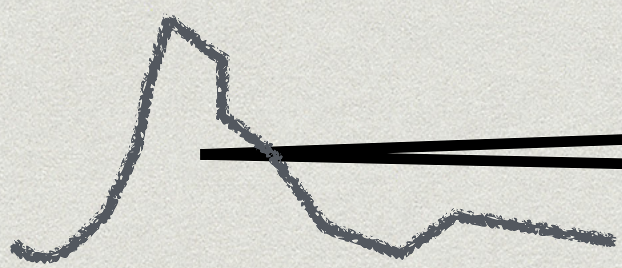
| | |
|---|---|
| Density ($g.cm^{-3}$) | 7.4 |
| Radiation length (cm) | 1.14 |
| Decay constant (ns) | 42 |
| Emission peak (nm) | 420 |
| Light yield ( P.h./MeV ) | 30000 |
| Melting point (°C) | 2150 |
| Hardness (Mho) | 5.8 |
| refractive Index (@405 nm) | 1.83 |
| Hygroscopicity | none |
| Cleavage | none |

# Energy resolution calculation

- How much resolution gets worse if p.e. from AG are increased

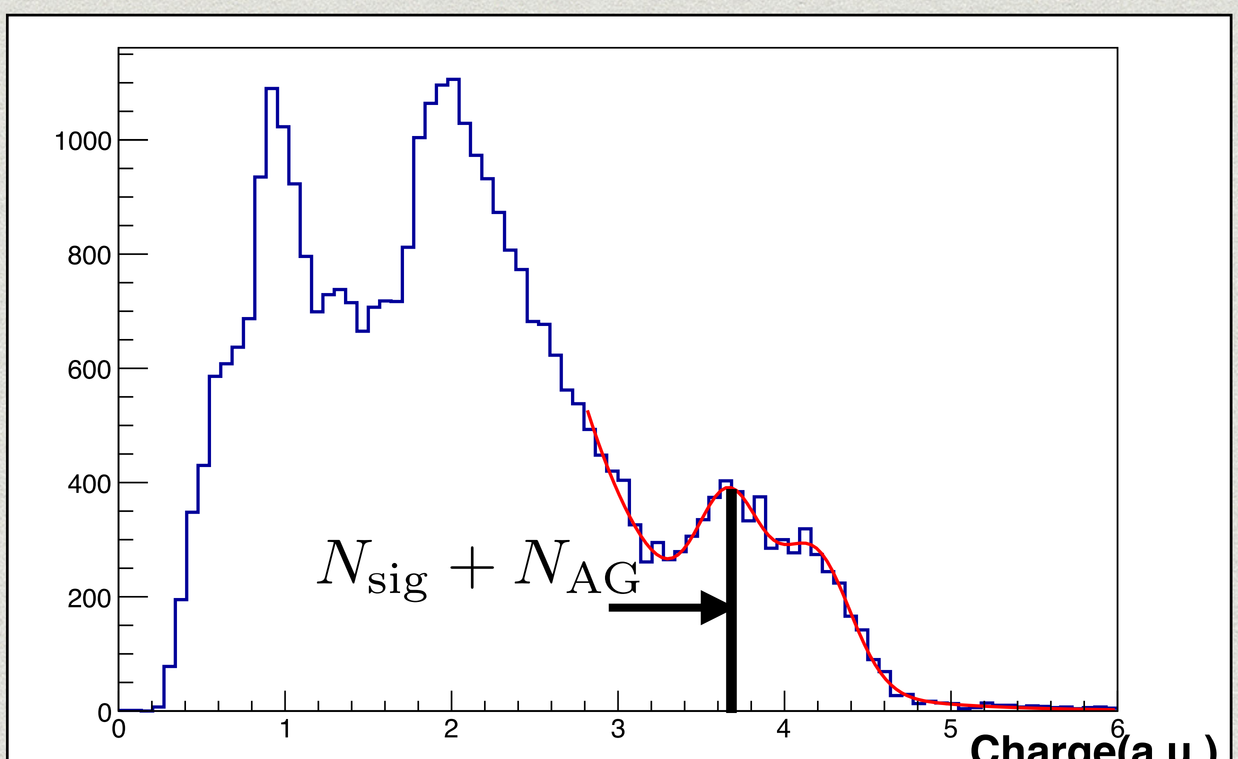
- 2 assumptions

  **1. Single waveform contains $N_{\mathrm{all}}$ photoelectons**



$$N_{\mathrm{all}} = N_{\mathrm{sig}} + N_{\mathrm{AG}}$$

  **2. $N_{\mathrm{AG}}$ shifts mean value in charge distribution**




$$\mathrm{Resolution} = \frac{\sigma_{\mathrm{all}}}{N_{\mathrm{all}} - N_{\mathrm{AG}}} = \frac{\sigma_{\mathrm{all}}}{N_{\mathrm{sig}}}$$

# Energy resolution calculation

$$N_{\mathrm{all}} = N_{\mathrm{sig}} + N_{\mathrm{AG}}$$

$${\sigma_{\mathrm{all}}}^2 = {\sigma_{\mathrm{sig}}}^2 + {\sigma_{\mathrm{AG}}}^2$$

**If it follows a Poisson distribution…**

$$\sigma_{\mathrm{sig}} = \sqrt{N_{\mathrm{sig}}} \quad \sigma_{\mathrm{AG}} = \sqrt{N_{\mathrm{AG}}}$$

$$\Rightarrow \sigma_{\mathrm{all}} = \sqrt{N_{\mathrm{sig}} + N_{\mathrm{AG}}}$$

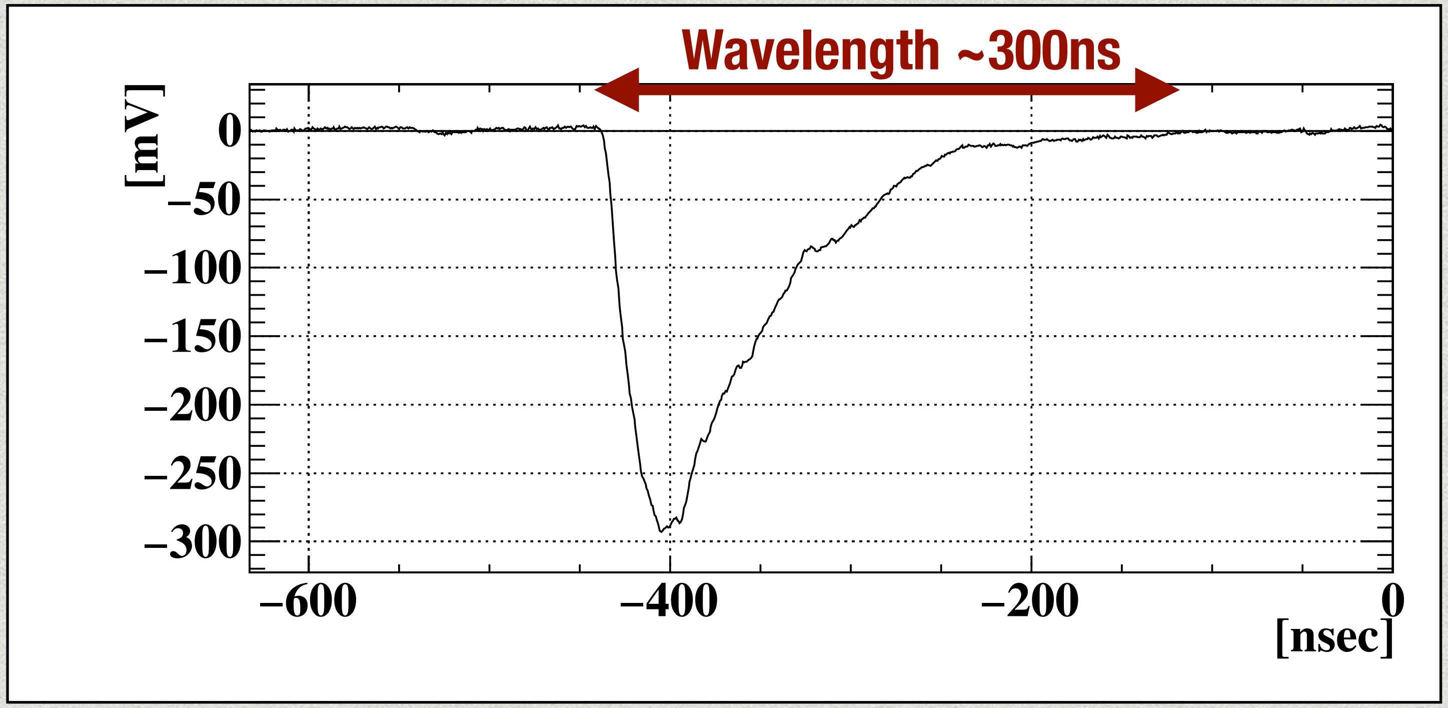
$$\begin{aligned}
\mathrm{Resolution} &= \frac{\sigma_{\mathrm{all}}}{N_{\mathrm{sig}}} \\
&= \frac{\sqrt{N_{\mathrm{sig}} + N_{\mathrm{AG}}}}{N_{\mathrm{sig}}} \\
&= \frac{1}{\sqrt{N_{\mathrm{sig}}}}\sqrt{1 + \frac{N_{\mathrm{AG}}}{N_{\mathrm{sig}}}} \\
&= \frac{1}{\sqrt{N_{\mathrm{sig}}}} + \underline{\mathrm{terms\ \ with\ \ N_{AG}}}
\end{aligned}$$

**We can estimate additional terms from $N_{\mathrm{sig}}$ & $N_{\mathrm{AG}}$**

# Energy resolution calculation

- Consider waveform of 1.17MeV Co60 peak

$$N_{\mathrm{AG}} = \frac{\mathrm{Current[c/s]} \times \mathrm{Wavelength[s]}}{\mathrm{Gain\ of\ MPPC} \times \mathrm{e[c]}}$$




$$\begin{aligned} N_{\mathrm{sig}} &= N_{\mathrm{all}} - N_{\mathrm{AG}} \\ &= \frac{\mathrm{Charge\ at\ 1MeV}}{\mathrm{Charge\ at\ 1p.e.}} - N_{\mathrm{AG}} \end{aligned}$$

- If current is increased 50μA…

$$N_{\mathrm{AG}} \simeq 401$$

$$\begin{aligned} N_{\mathrm{sig}} &\simeq 3491 - 401 \\ &= 3090 \end{aligned}$$

**Resolution gets worse ~0.2%**

# Status of RDC

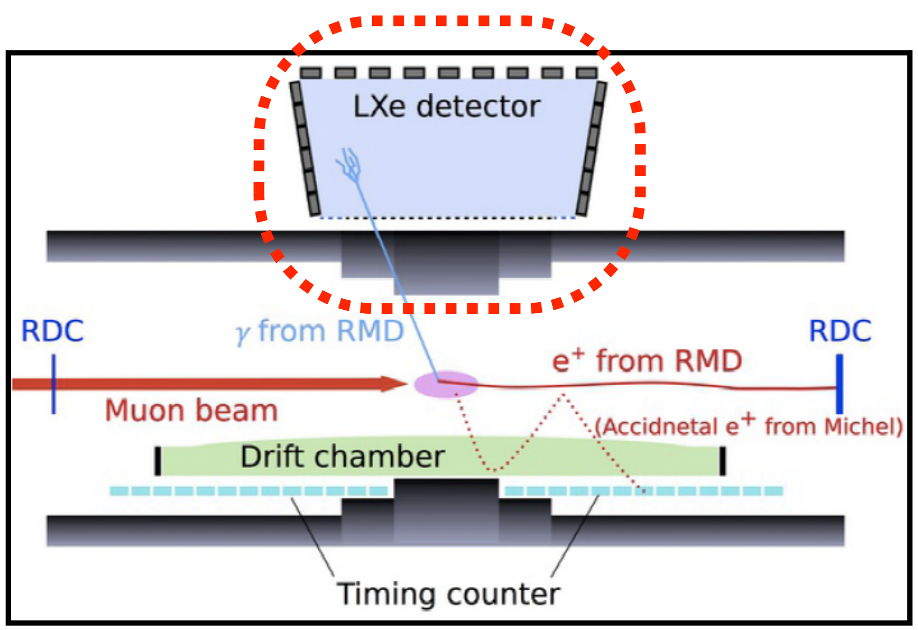
## Downstream detector

- R&D, prototype beam test (~2015)
- Construction and lab test (December, 2015)

  **→ Next talk (S. Nakaura, 19aAH-11)**

- Operation test with μ beam (June, 2016)

  → We will take coincidence with γ by using BGO detector in stead of LXe detector



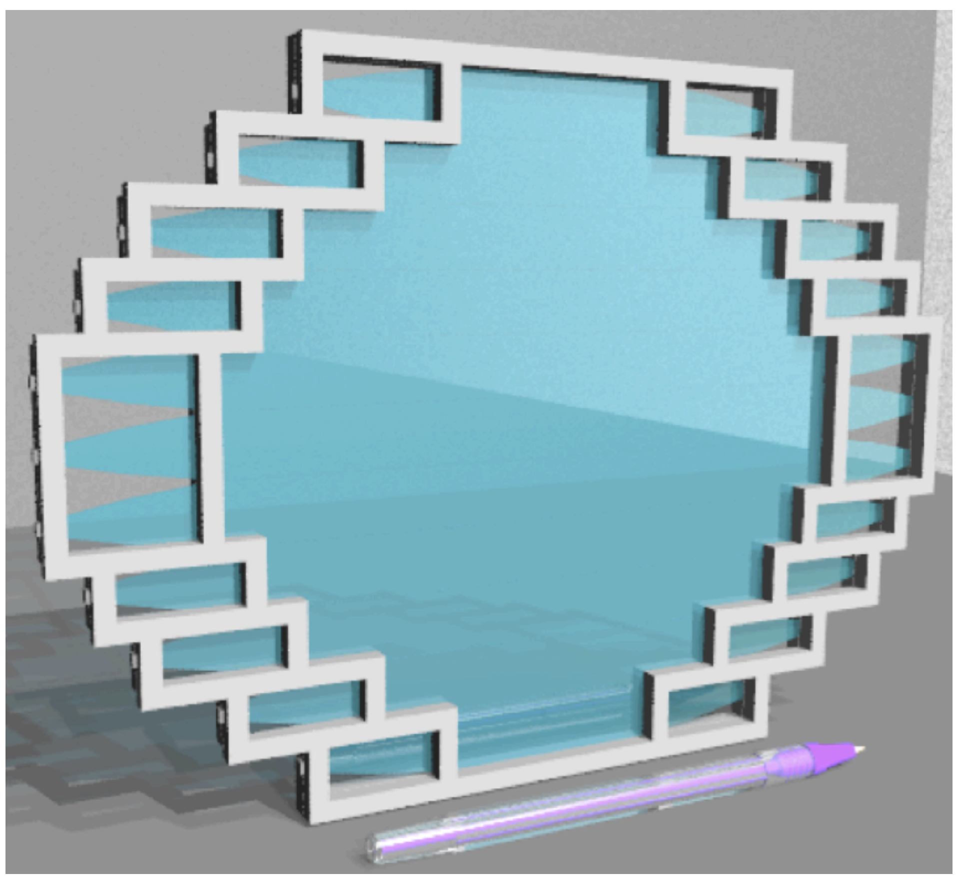

- MEG II Engineering run (in 2016)

## Upstream detector

- R&D, prototype beam test (~2015)
- Monte Carlo study (~March, 2016)
- Construction and operation test (in 2016)

# RDC upstream detector

- R&D is still ongoing
- The influence on μ beam spot on the target was studied with a mock-up
  → $\sigma_x \cdot \sigma_y$ was changed factor of 1.16



**Scintillation fibre**

- Measuring timing of low momentum $e^+$
- 784 scintillation fibers (265-270μm thickness) are used
- MPPC will be used for reading out

**The influence on μ beam was studied with Monte Carlo**

**Efficiency changes with bigger beam spot compared to normal beam size**

| target size | μ stopping efficiency | long track efficiency | TC hitting efficiency | total efficiency |
|---|---|---|---|---|
| standard | -3.13% | -0.61% | -0.21% | -3.90% |
| bigger | -3.00% | -0.74% | -0.25% | -3.81% |

# paper of afterglow

# Gamma Ray Induced Radiation Damage in PWO and LSO/LYSO Crystals

Rihua Mao, *Member, IEEE,* Liyuan Zhang, *Member, IEEE,* and Ren-Yuan Zhu, *Senior Member, IEEE*

sample were wrapped with the Tyvek paper. A collimated $^{137}$Cs source was used to excite the PWO sample. To reduce the effect of the intrinsic natural radioactivity, a collimated $^{22}$Na source was used to excite the LSO/LYSO samples with a coincidence trigger provided by a $BaF_2$ crystal [2]. The $\gamma$-

size of the LSO/LYSO samples. Also shown in this figure is the electronic noise (E-Noice), which is measured without crystals. While the $\gamma$-ray induced phosphorescence (afterglow) is found approaching the E-Noice, so is negligible (at $10^{-5}$ level) in the PWO and BGO samples, it is between $10^{-3}$ and $10^{-4}$ in the LSO and LYSO samples. The LYSO sample from

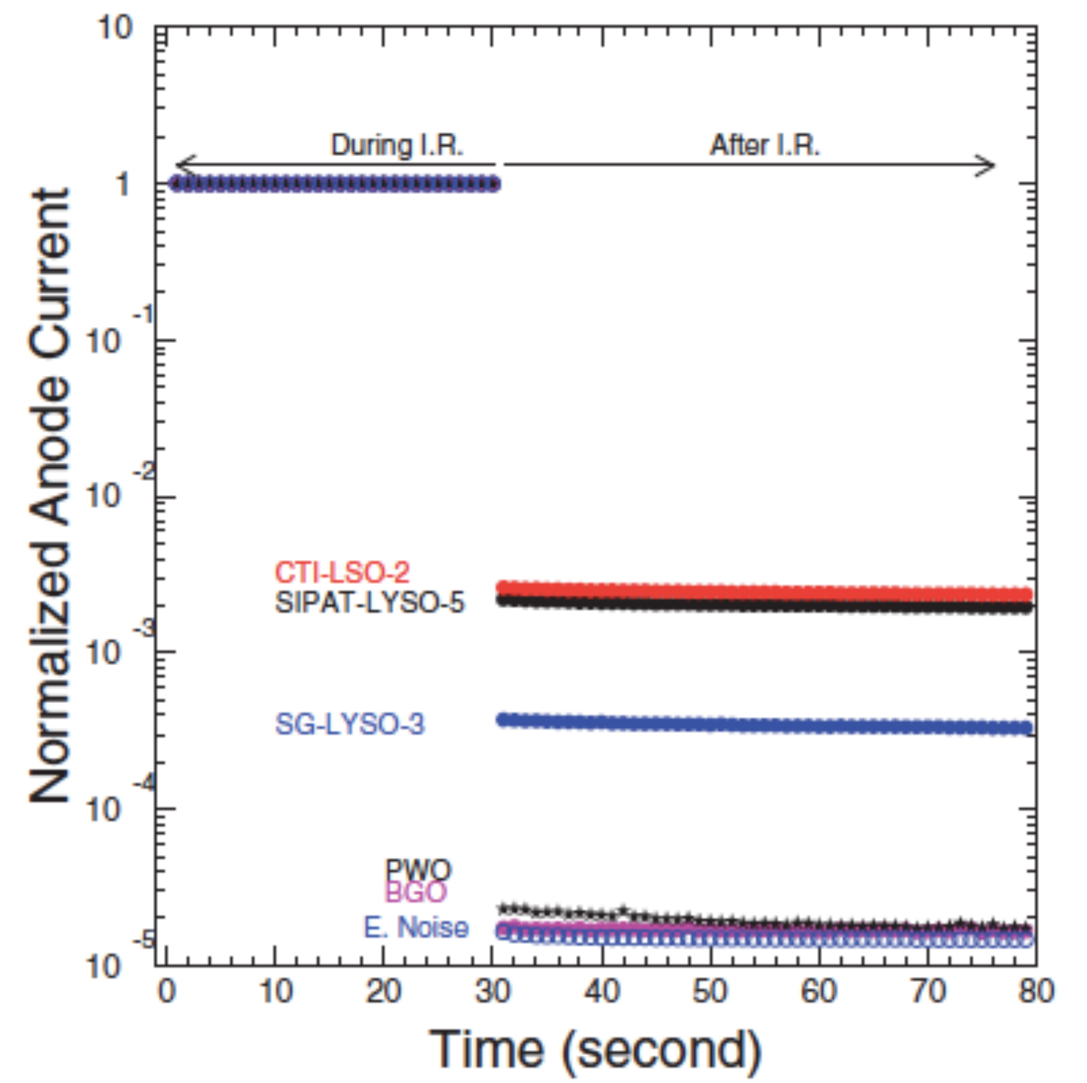



Fig. 10. Normalized anode current is shown as a function of time during and after $\gamma$-ray irradiations for the PWO, LSO/LYSO and BGO samples.

# Effects of Neutron Irradiations in Various Crystal Samples of Large Size for Future Crystal Calorimeter

Liyuan Zhang, *Member, IEEE,* Rihua Mao, *Member, IEEE,* and Ren-Yuan Zhu, *Senior Member, IEEE*

size. 4 MeV neutrons from one $^{241}$Am-Be source and 2.5 MeV neutrons from two $^{252}$Cf sources are used for irradiation source. Neutron induced radiation damage effects in these

sources (red dots), fox six samples. Since the LYSO samples have a strong phosphorescence if exposed to light they have to be kept in dark for more than 24 h before starting the test as shown in the middle top plot for the SIPAT-L2 sample. The reading of the neutron induced photo-currents during irradiations was set to be around hundred nA by adjusting the PMT bias to avoid possible PMT gain saturation. The photo-current was found to be stable during the one week irradiations by the $^{241}$Am-Be source, indicating no cumulative effect from neutrons. Also shown in the figure is the time constant for the cool-down of the neutron induced phosphorescence. It is about 2, 10 and 35 hours for BGO, LYSO and PWO respectively. The

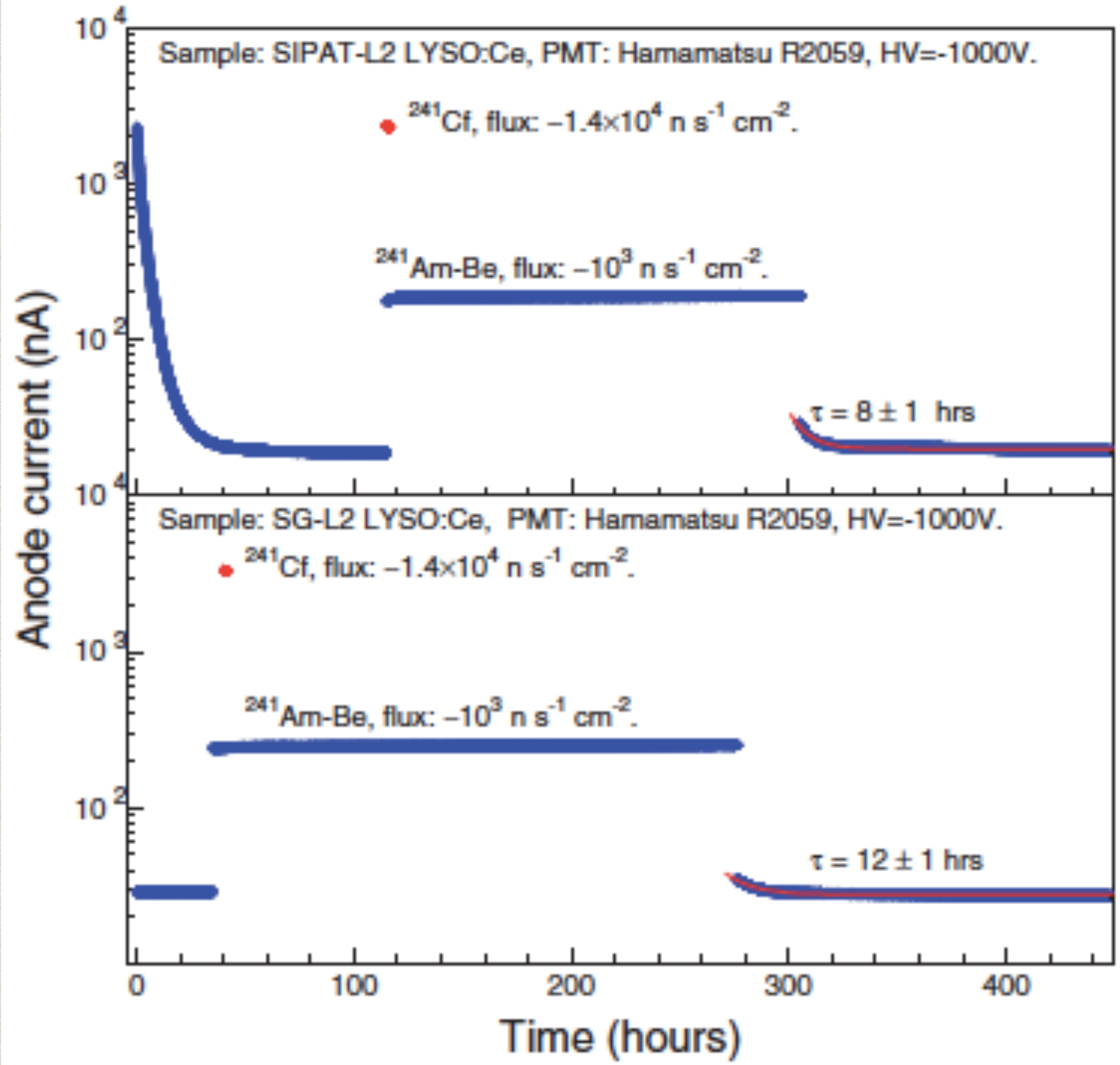



Fig. 5. The anode photo-current measured during irradiations by the $^{241}$Am-Be (blue dots) and $^{252}$Cf sources (red dots) is shown as a function of time for BGO and $CeF_3$ (Left), two LYSO (Middle) and two PWO (Right) samples. Also shown is the exponential fit of the cool-down time of the neutron-induced phosphorescence.

# Large Size LYSO Crystals for Future High Energy Physics Experiments

Jianming Chen, *Member, IEEE*, Liyuan Zhang, *Member, IEEE*, and Ren-Yuan Zhu, *Senior Member, IEEE*

The radiation induced phosphorescence spectra of the CPI and Saint-Gobain long LYSO samples were continuously measured for more than 48 h after 22 h irradiations at 9 000 rad/h. No variation of the phosphorescence spectra were observed for both samples. The amplitude of phosphorescence, normalized to 1 h after the end of the irradiation, were fit to an exponential function

$$A = A_0 + A_1 e^{-t/\tau}. \quad (5)$$

Fig. 18 shows the fit result. The decay time constants of the radiation induced phosphorescence were determined to be 2.5 h and 3.6 h respectively for the CPI and the Saint-Gobain samples. The Saint-Gobain sample is also noticed to have a slightly larger residual phosphorescence. To evaluate the radiation in-

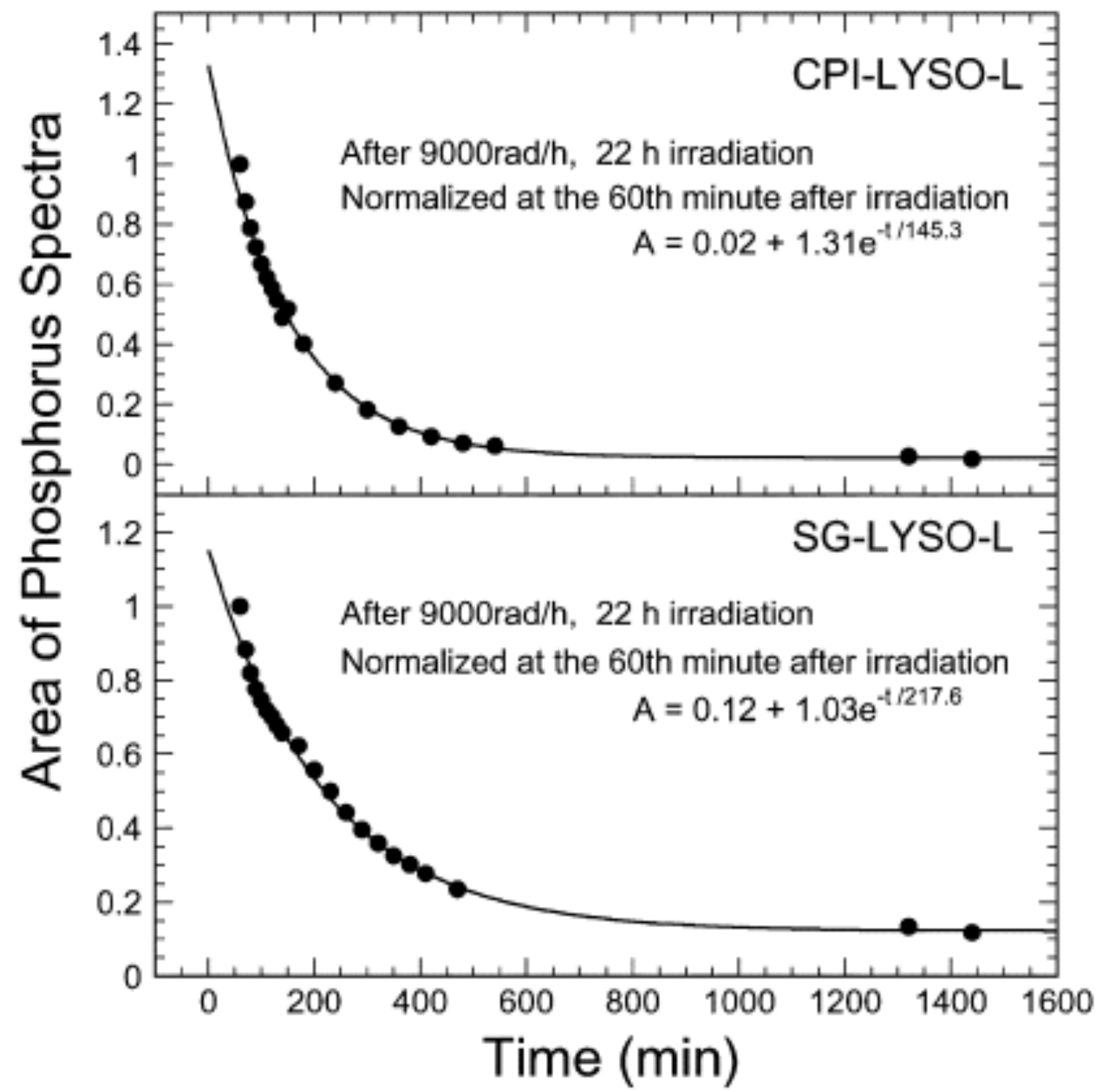



Fig. 18. Amplitude of phosphorescence is shown as a function of time after 22 h irradiation at 9 000 rad/h for the (top) CPI and (bottom) Saint-Gobain long LYSO samples.