7th July 2018

Four Dimensional Calorimeter with Both-Side Readout of the CsI Calorimeter in the $K_L \to \pi^0 \nu \bar{\nu}$ Search

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On behalf of the KOTO collaboration

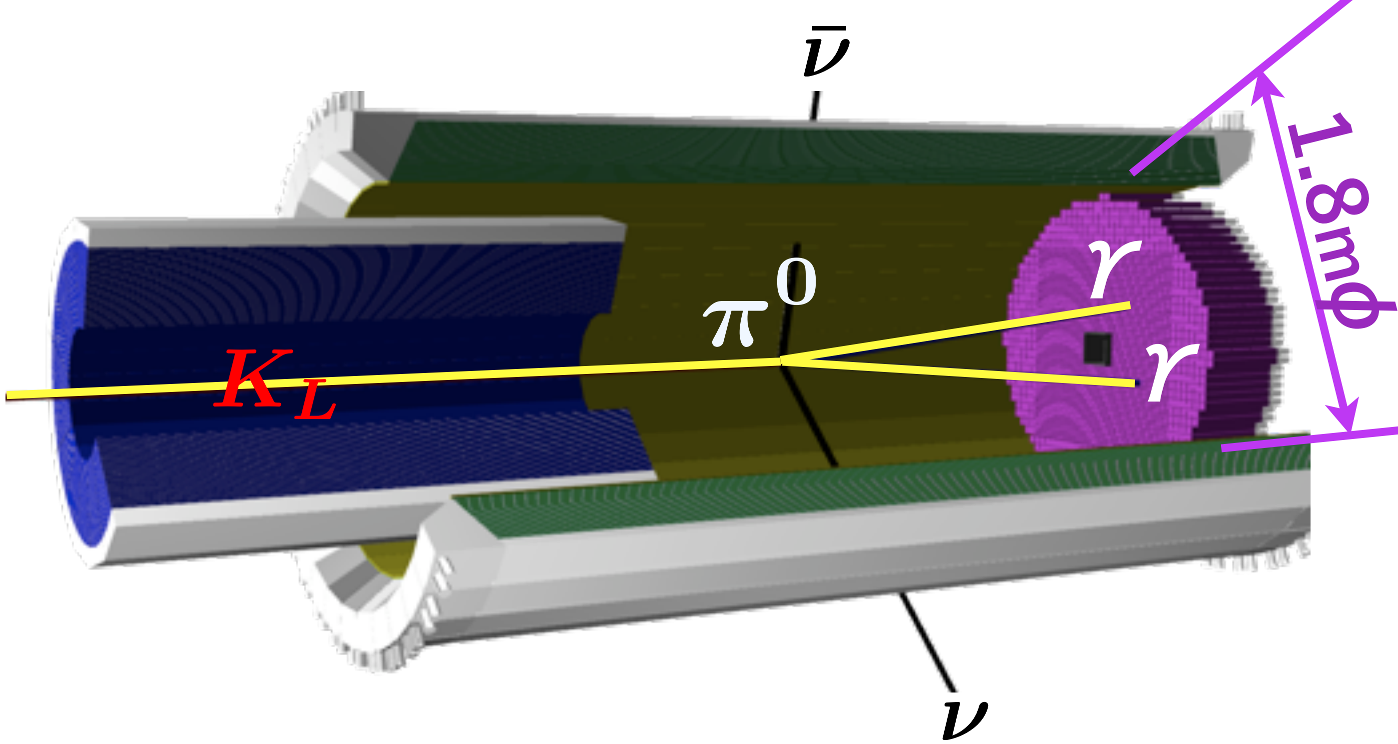
ICHEP 2018 @Seoul

KOTO ➡ Study of $K_L \to \pi^0 \nu \bar{\nu}$

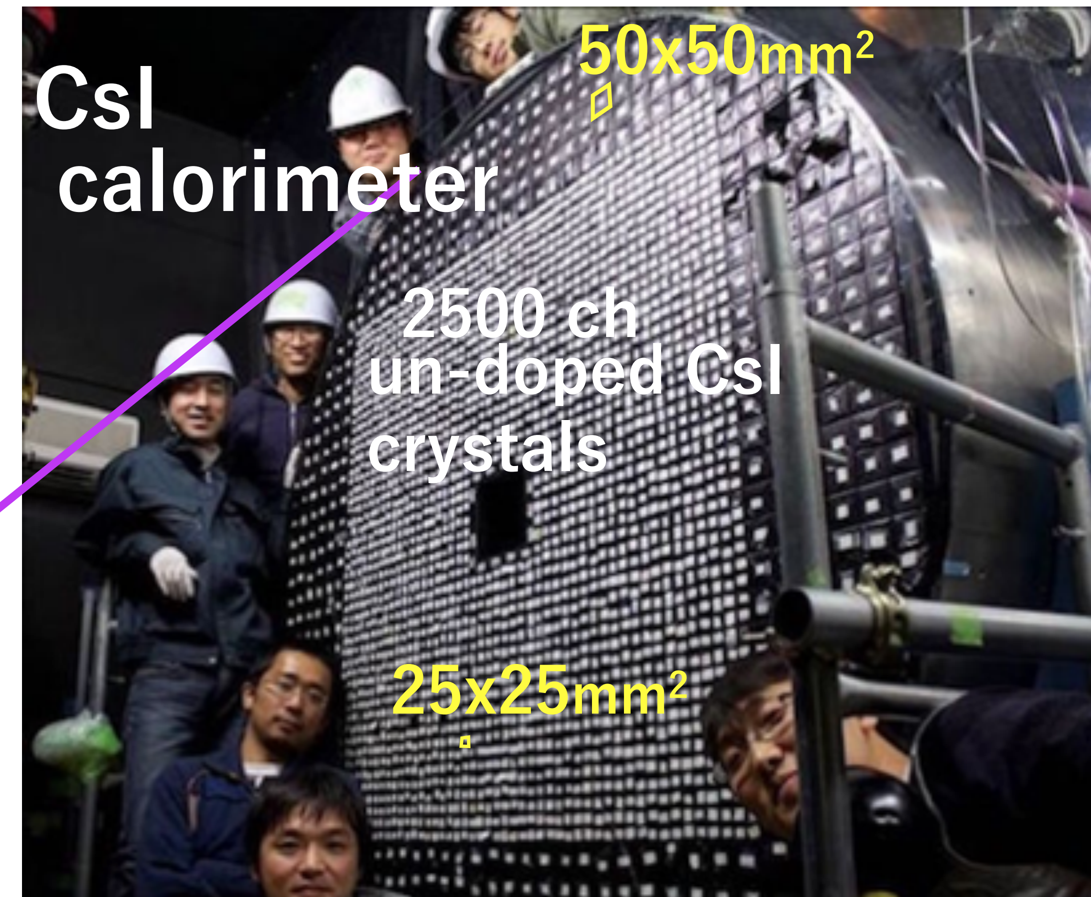
direct $\not{CP}$: the Standard Model - Bf: 3×10^{-11}
sensitive to BSM

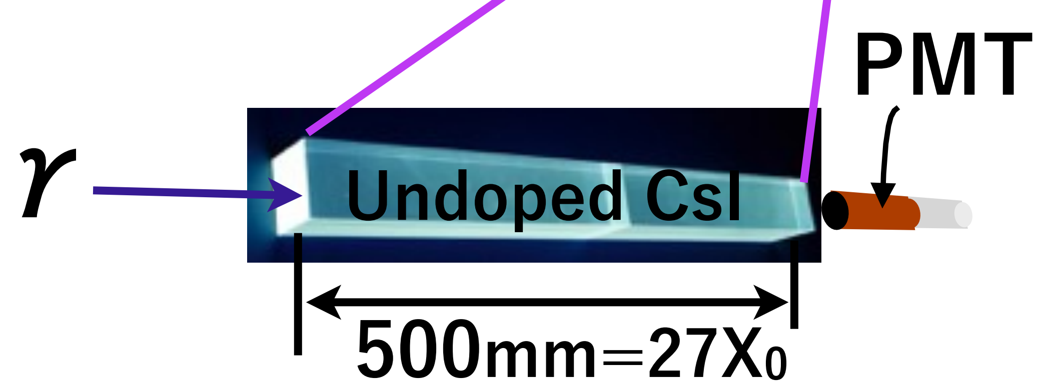
a **golden needle** in a haystack

J-PARC Tokai
in Japan

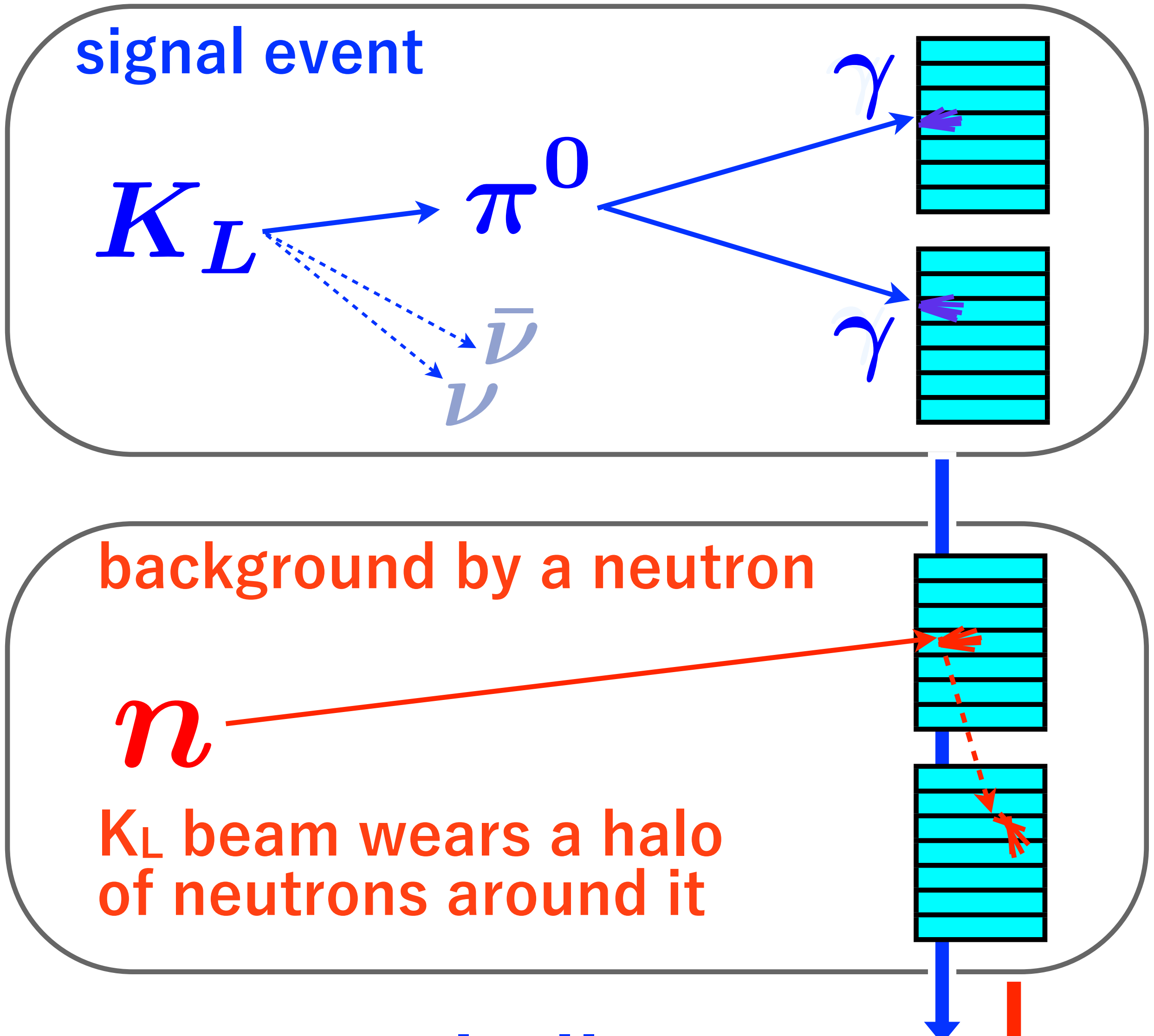


hermetic veto counters





Neutron BG: a neutron fakes two showers in the calorimeter



γs interact in **shallow** region
neutrons reach **deeper**

1.3×10^{-9} Single event sens.

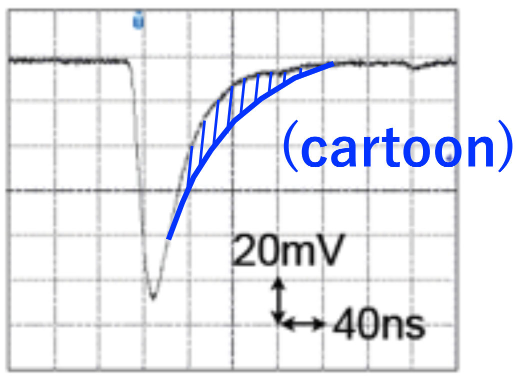
background source	#BG
Halo neutron hitting CSI	0.24±0.17
Halo neutron hitting upstream detectors	0.04±0.03
η background	0.03±0.02
KL->π+π-π0	0.05±0.02
KL->2π0	0.02±0.02
other BG sources	0.02±0.02
Sum	0.40±0.18

New Results (ICHEP2018, KOTO; K.Shiomi) $< 3\times10^{-9}$(90% C.L.)

neutron BG : $K_L\to\pi^0\nu\bar{\nu}$ SM prediction = 10:1

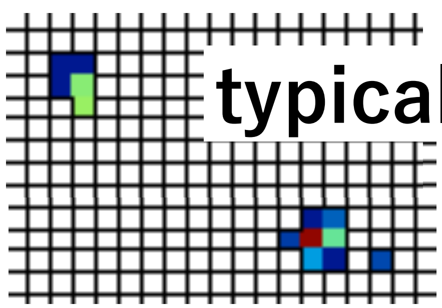
Methods already used in the analysis

Compare pulse shape : use t

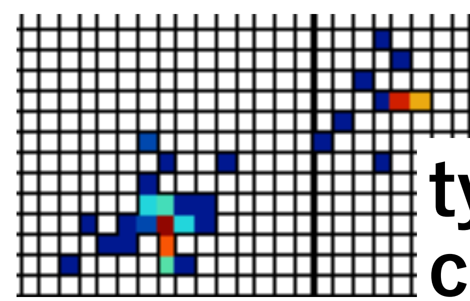


neutron pulses have slow component

Compare cluster shape : use x, y

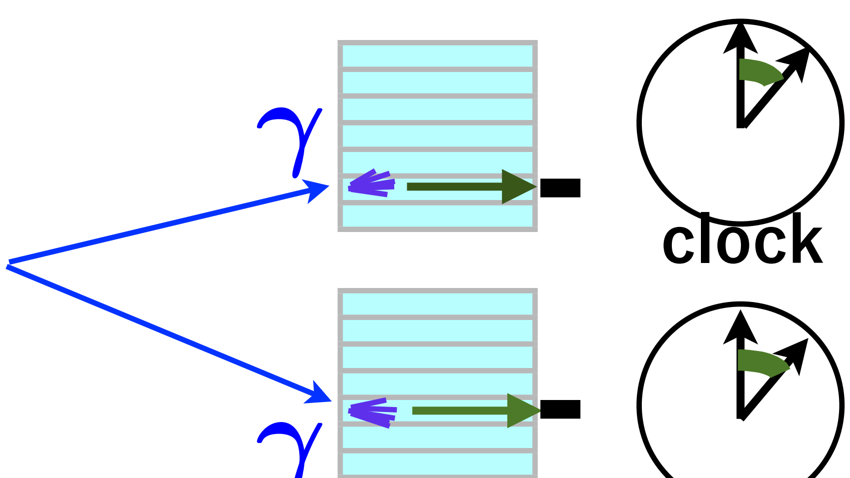


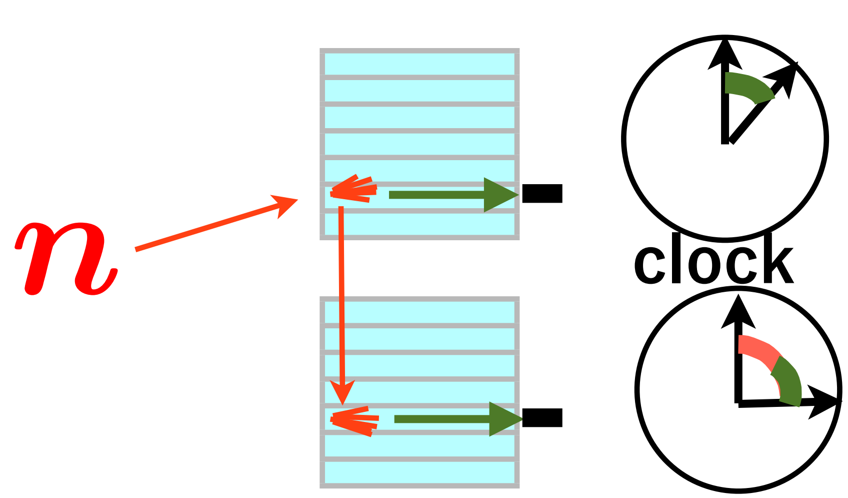
typical γ clusters



typical neutron clusters

Compare timing difference of two clusters : use t

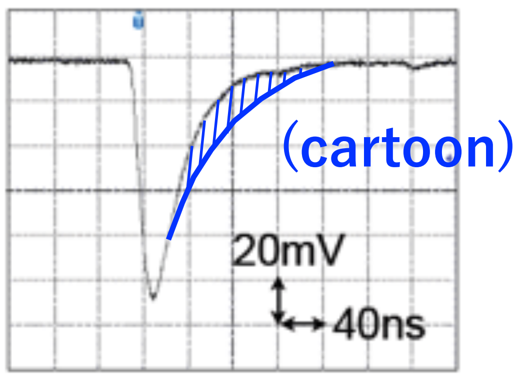




timing difference can work

Methods already used in the analysis

Compare pulse shape : use t



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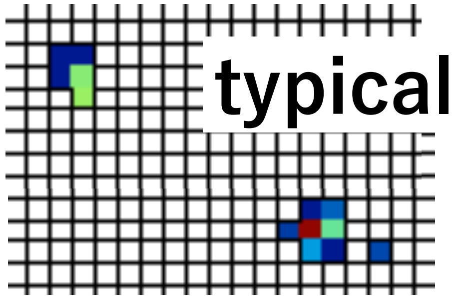
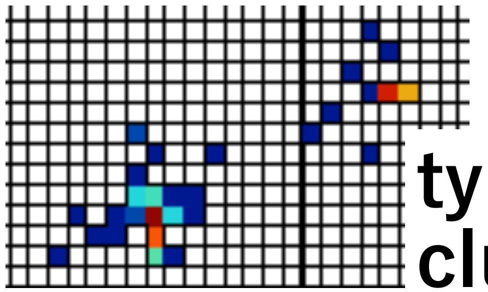
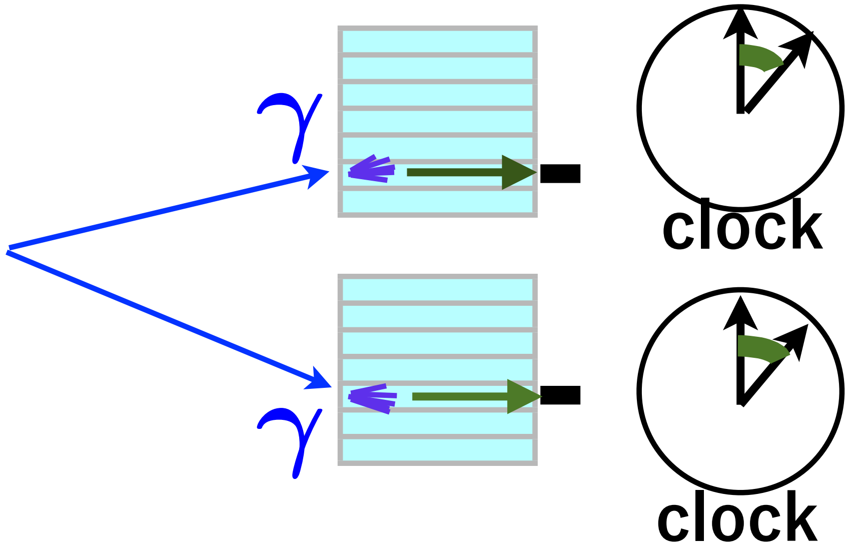


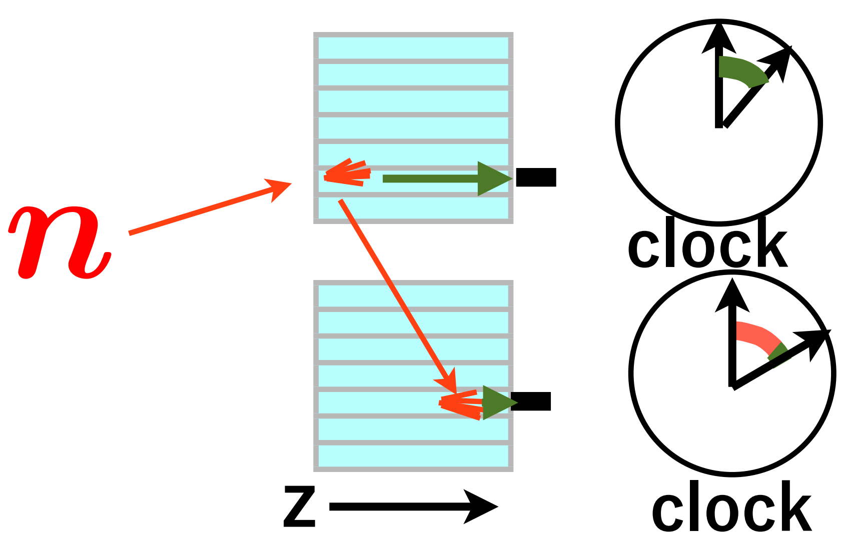
typical γ clusters



typical neutron clusters

Compare timing difference : use t





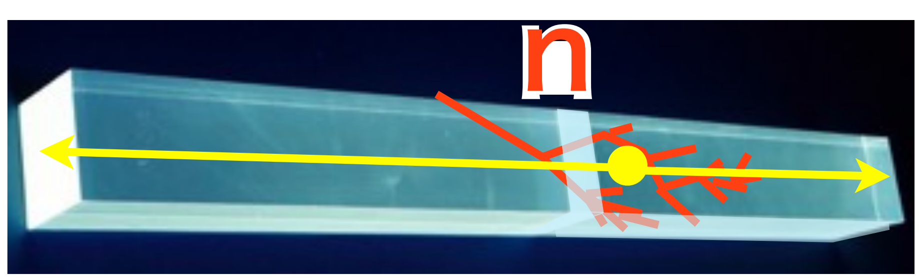
timing difference is not long enough

Upgrade: use position z

with previous method we use t, x, y, and z (4-dim).

Current setup

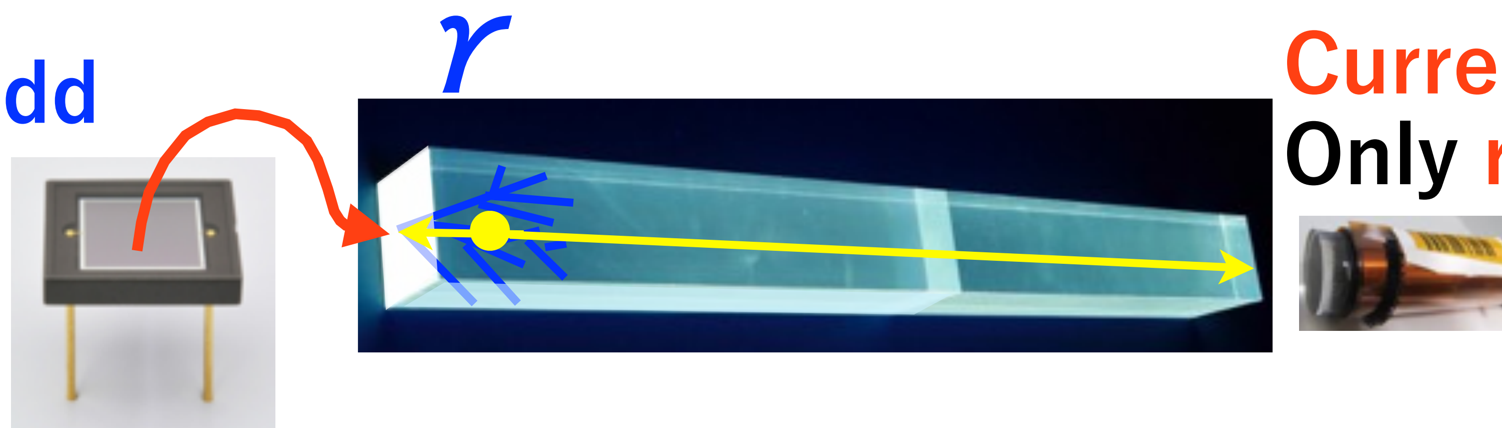
Only rear-end readout with PMT



Upgrade: use position z

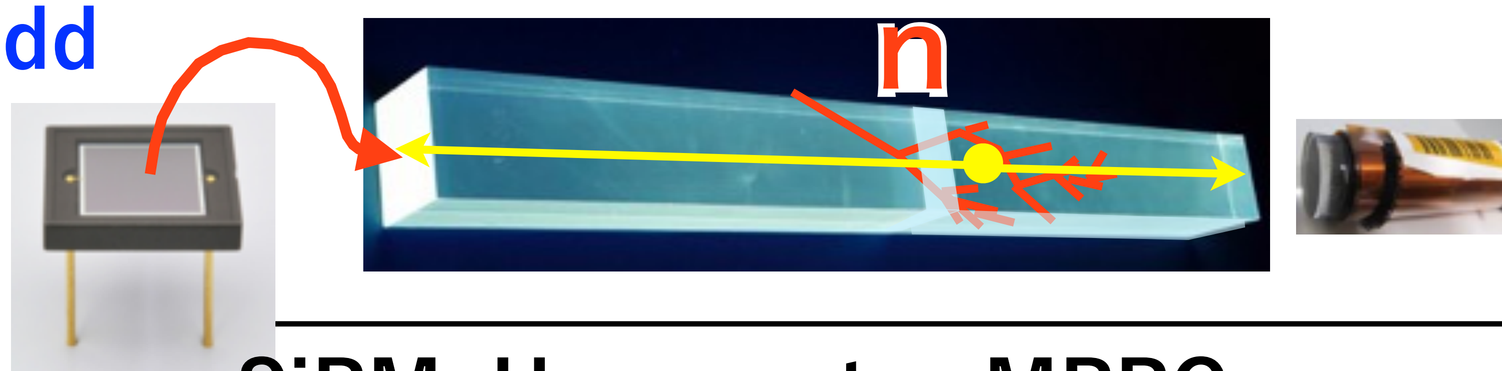
with previous method we use t, x, y, and z (4-dim).

add



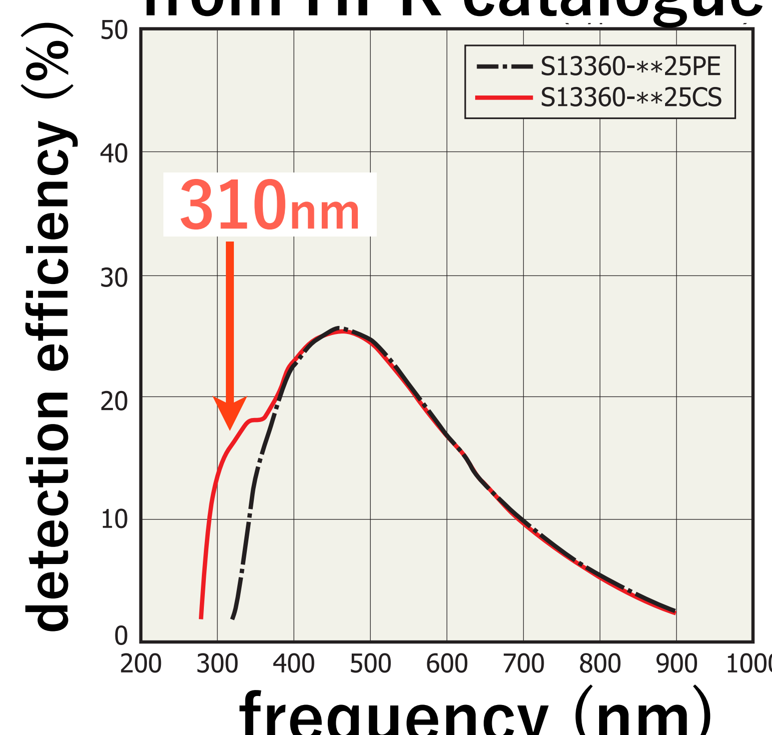
Current setup
Only rear-end readout with PMT

add



SiPM: Hamamatsu MPPC
50 μm pitch in 6×6 mm^2 =14400 pixel
Gain: 1.7×10^{6} @ V_{break} + 3V
UV transparent silicone window
$0.01X_0 \times 1cm^2/6.25cm^2$ crystal surface

from HPK catalogue



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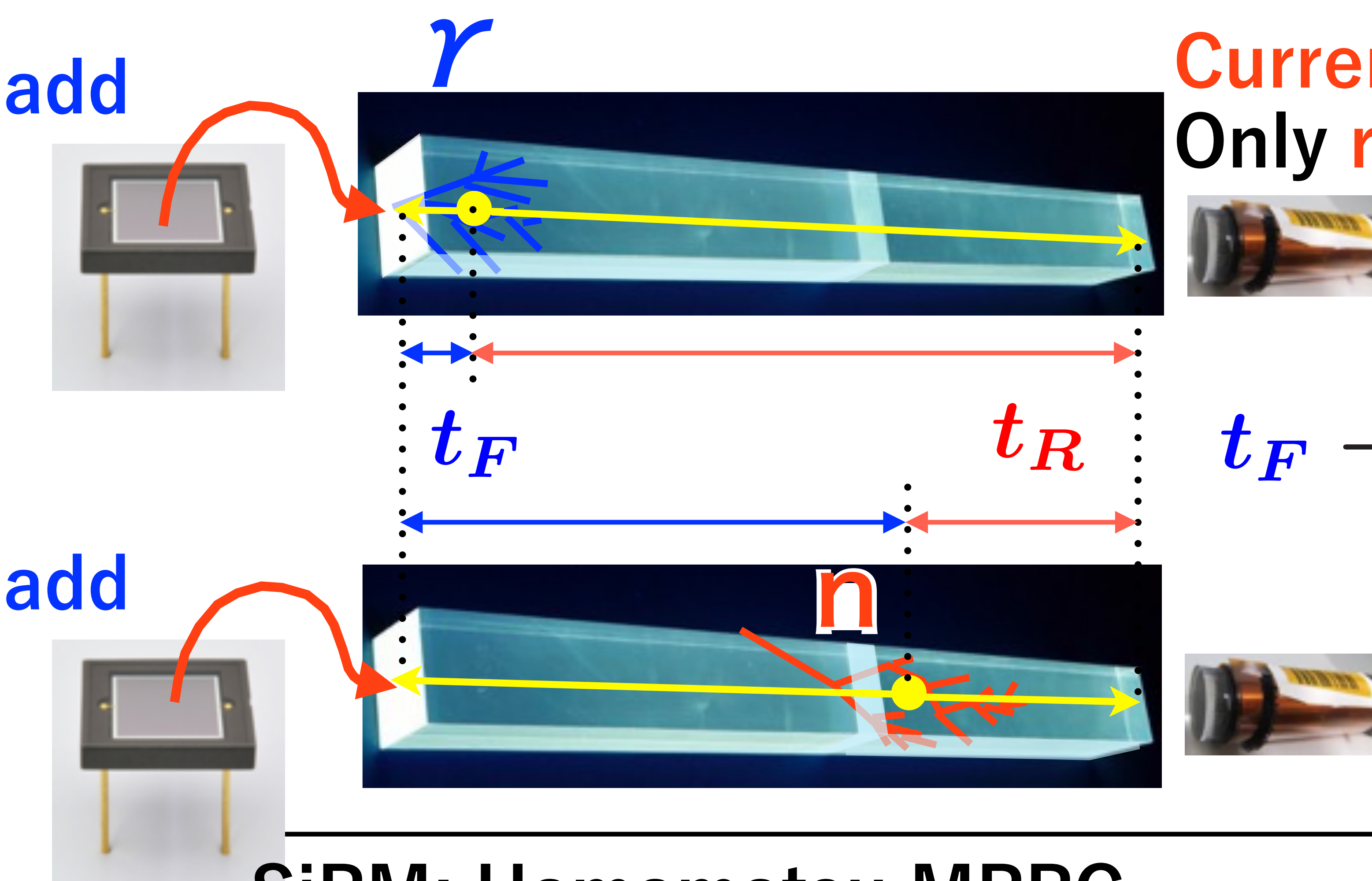
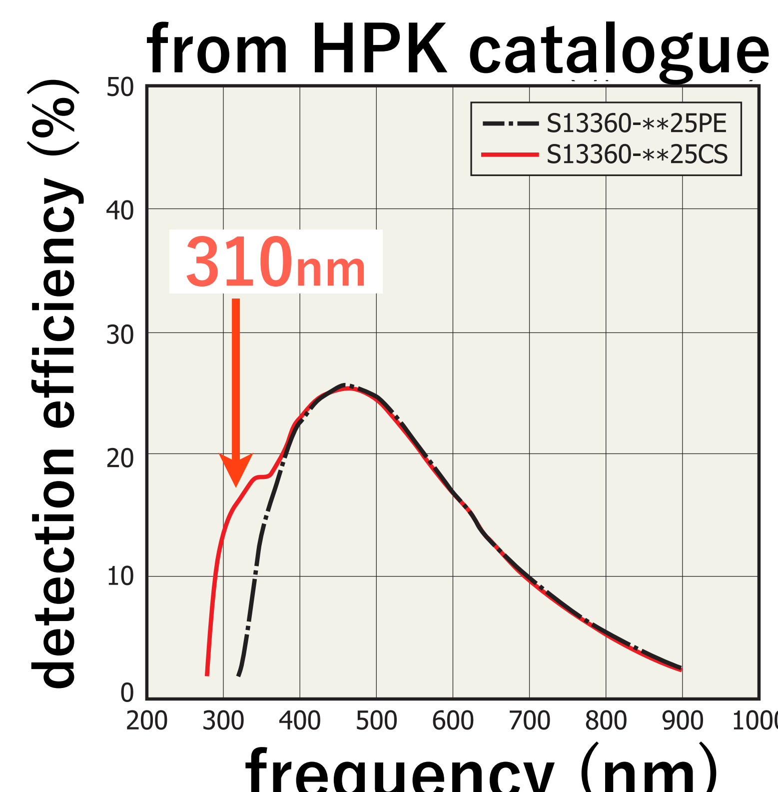


$$t_F - t_R = \Delta t \propto z_{\mathrm{cluster}}$$

SiPM: Hamamatsu MPPC
50 μm pitch in 6 × 6 mm² = 14400 pixel
Gain: 1.7×10^6 @ V_{break} + 3V
UV transparent silicone window

$0.01 X_0 \times 1\,\mathrm{cm}^2 / 6.25\,\mathrm{cm}^2$ crystal surface



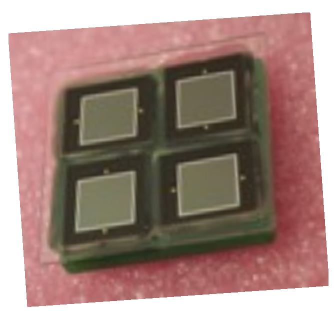
Outline

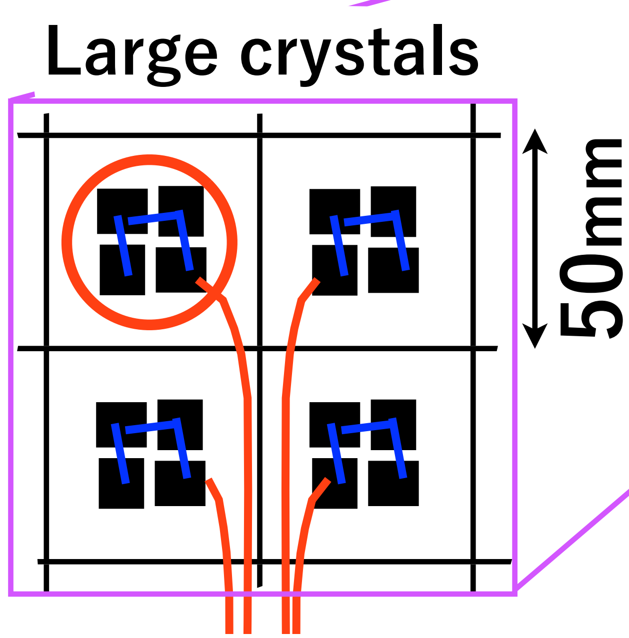
- Readout:
  - □ need to reduce # of channels
- Radiation hardness
  - □ MPPC damaged due to irradiation
- Performance
  - □ conversion of timing information to z
  - □ σ_t at high energy and radiation hardness
  - □ reduction power of n Background

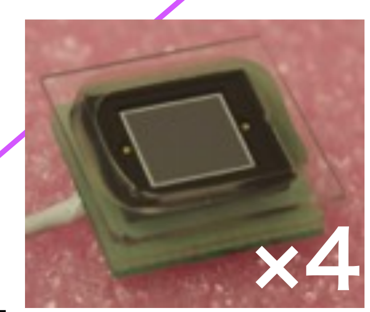
Readout

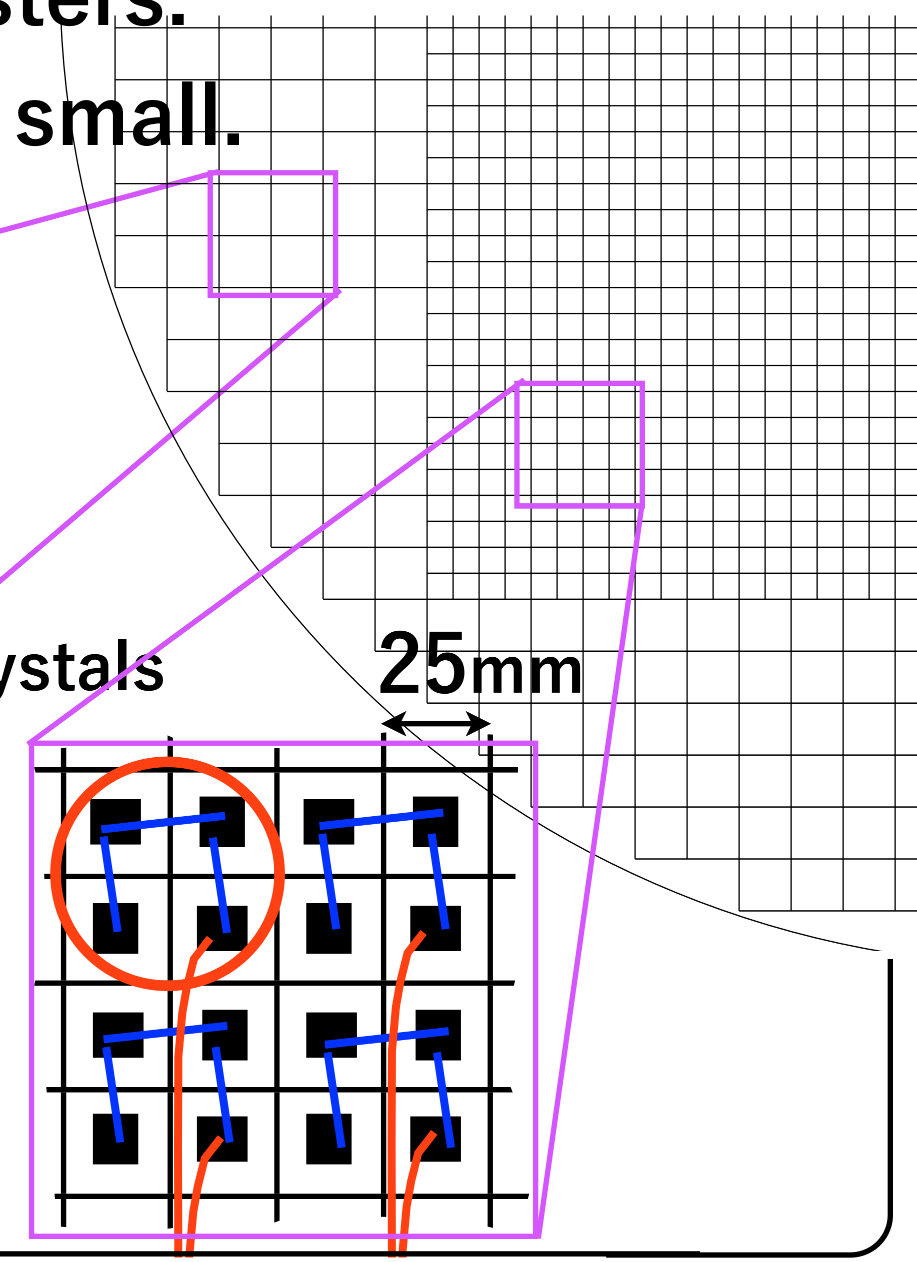
- We need realistic number of DAQ channels,
- to reduce material budgets on the front surface,
- need only for timing measurement of clusters:
  - 100×100mm² segmentation is enough small.

4-MPPC readout









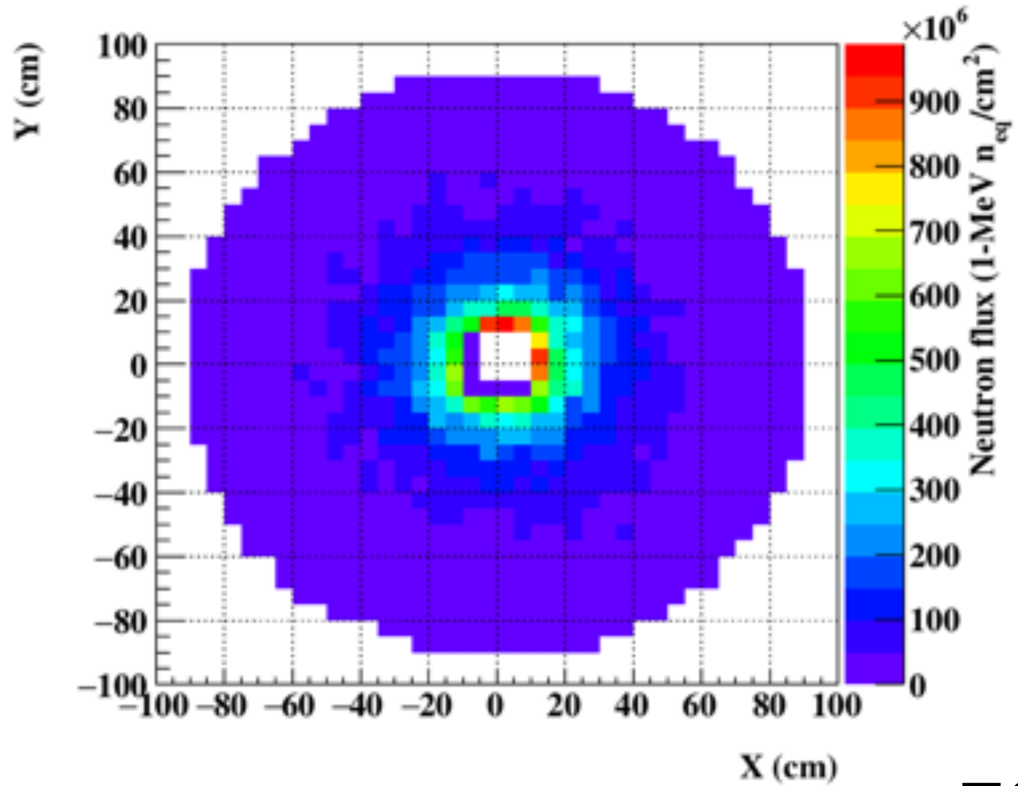
Four MPPCs: read out together in a readout group

[4-MPPC]×4 sum-amp ➡ 100×100mm²/channel;
4096➡ 256 channels

Outline

- Readout:
  - ☑ need to reduce # of channels
- Radiation hardness
  - ☐ MPPC damaged due to irradiation
- Performance
  - ☐ conversion of timing information to z
  - ☐ σ_t at high energy and radiation hardness ☐
  - ☐ reduction power of n Background

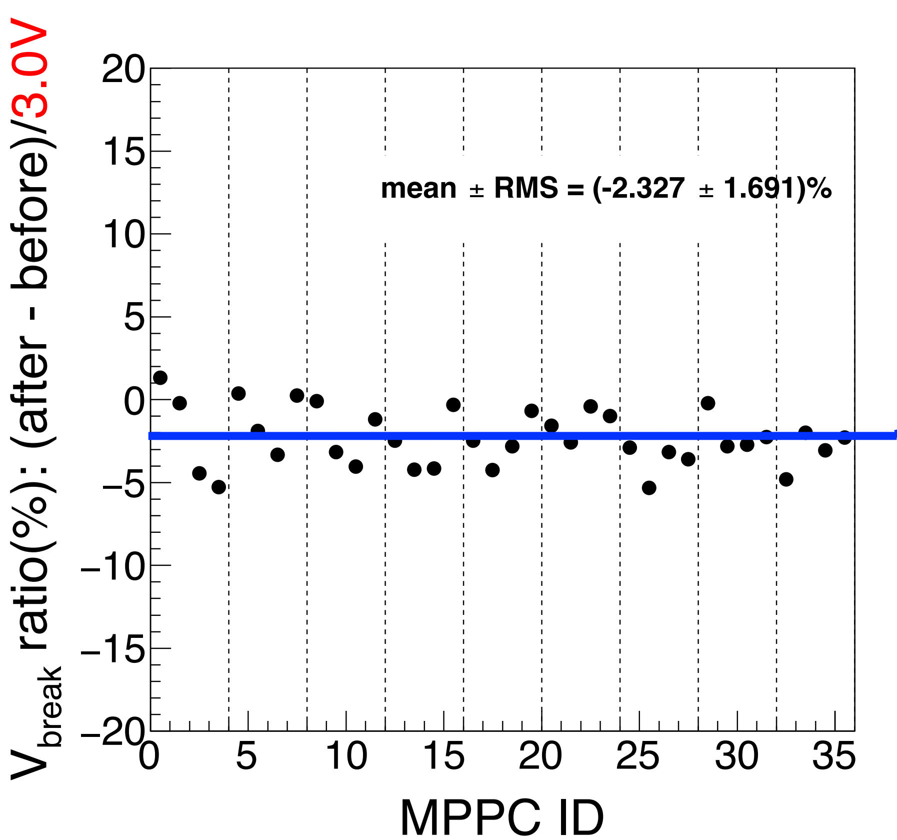
Radiation hardness of MPPC



a simulation predicts:

max 10^9 n_{1MeV}/cm^2

to reach SM (3×10^{-11})



Effects of 1.5× to reach SM

items :	after irradiation
Dark current(V_{over} = 3V) :	×100 (0.5 μA➡50 μA)
ΔV_{break}/3V(use) :	-2%(no problem)
light sens. variation(%) :	(-1.8±1.5)%

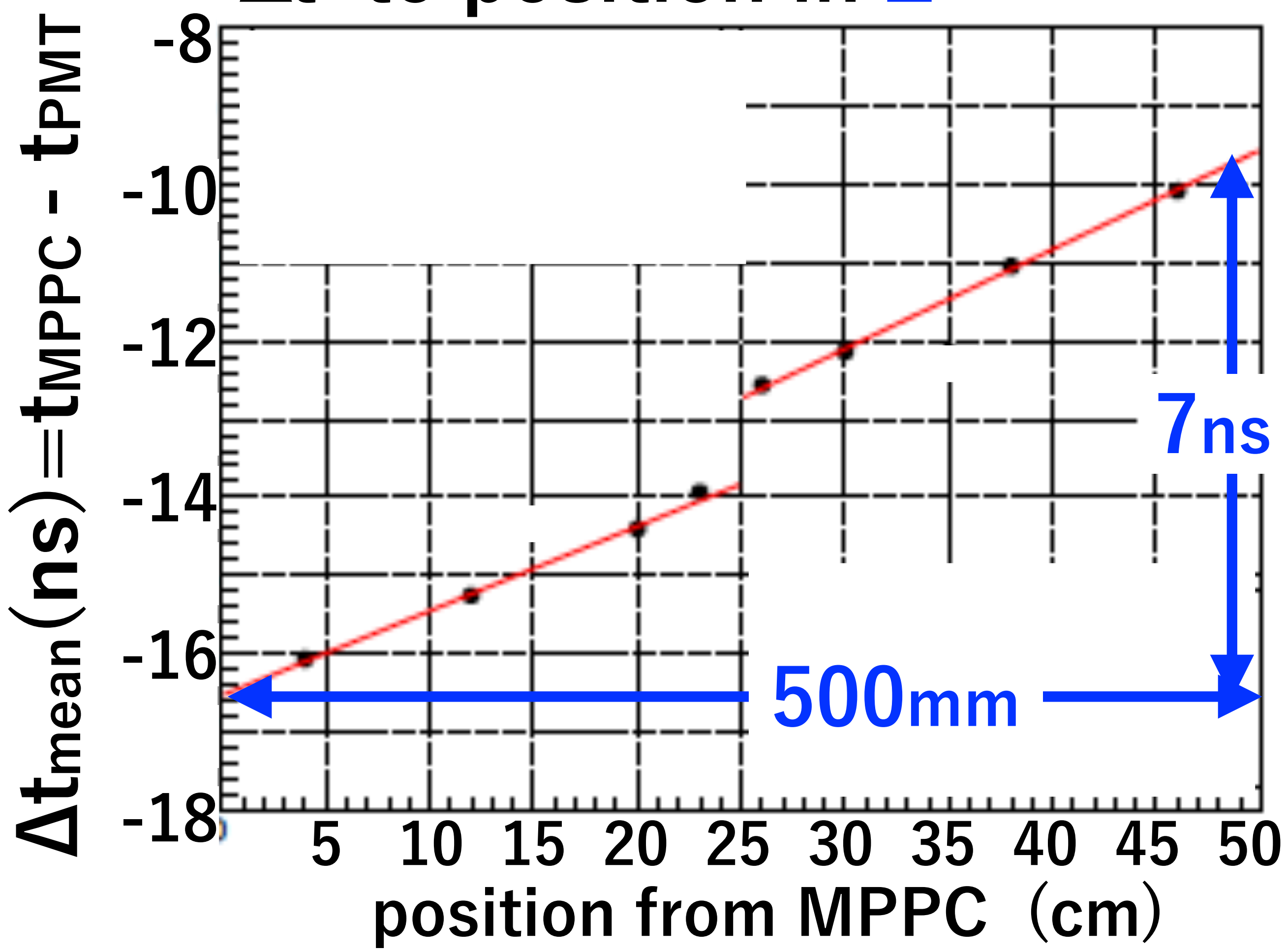
Outline

- Readout:
  - ☑ need to reduce # of channels
- Radiation hardness
  - ☑ MPPC damaged due to irradiation
- Performance
  - ☐ conversion of timing information to z
  - ☐ σ_t at high energy and radiation hardness ☐
  - ☐ reduction power of n Background

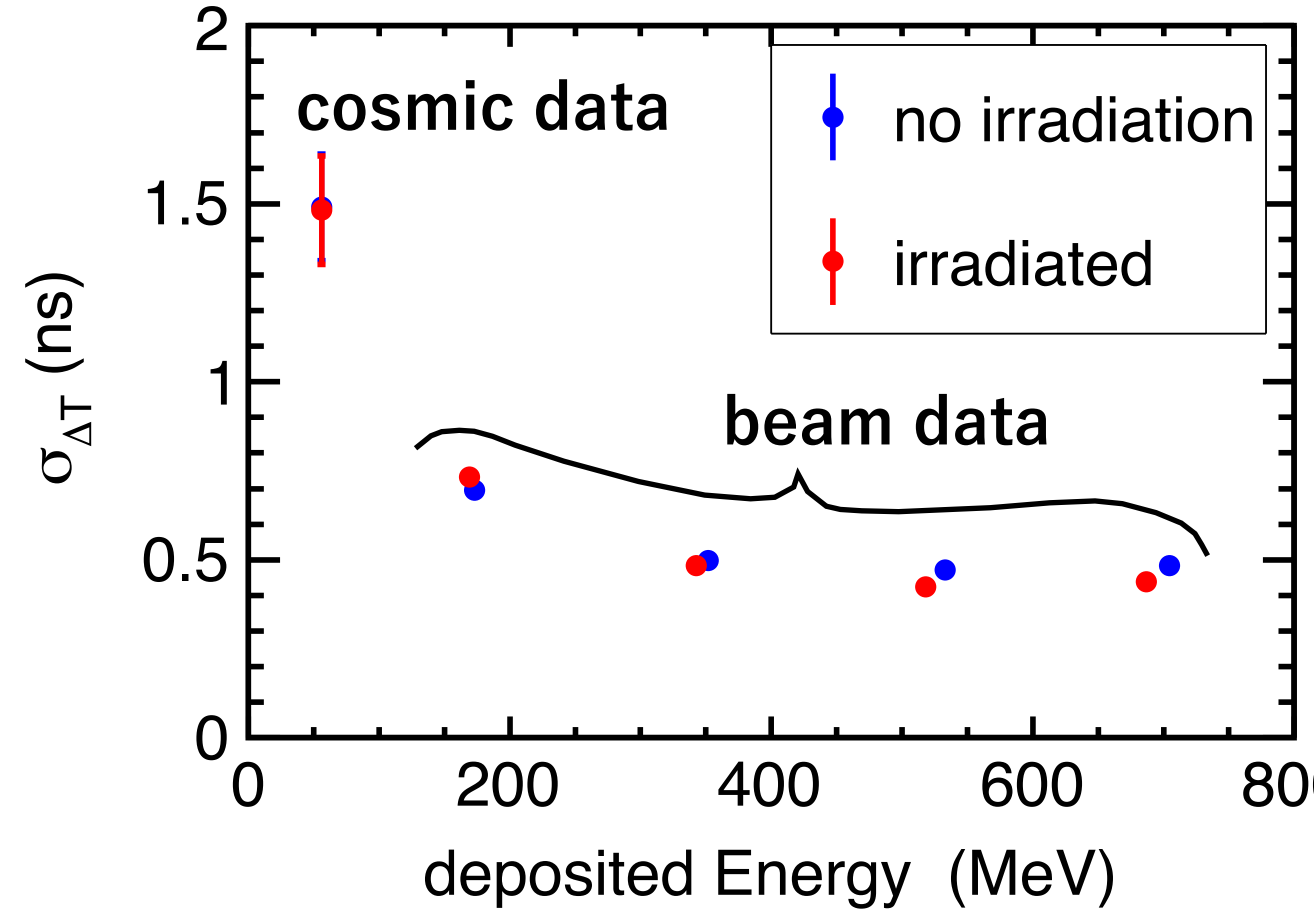
Performance: Δt and σ_t

Cosmic rays

Δt to position in Z



Beam test at ELPH in Tohoku



No effect due to irradiation.

- **Δt can be converted to z.**
  - **Δt gap on center is caused by glue joint.**

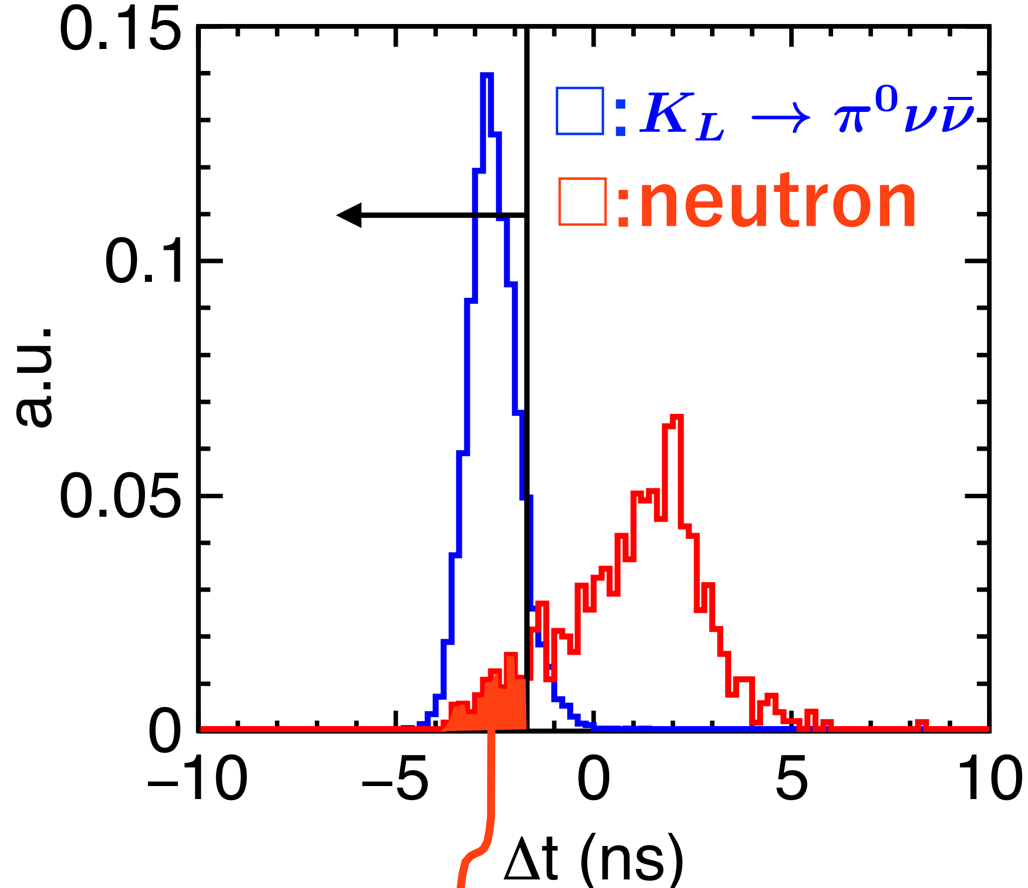
Out line

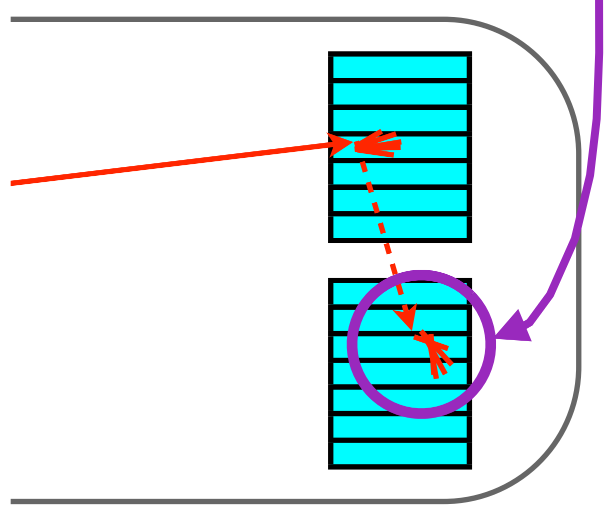
- Readout:
  - ☑ need to reduce # of channels
- Radiation hardness
  - ☑ MPPC damaged due to irradiation
- Performance
  - ☑ conversion of timing information to z
  - ☑ σ_t at high energy and radiation hardness ☑
  - ☐ reduction power of n Background

Performance: in KOTO (simulation)

Each event has two clusters ➡two Δt (min Δt & max Δt)

$K_L \to \pi^0 \nu \bar{\nu}$ / n background separation uses **max Δt**





@90% efficiency for $K_L \to \pi^0 \nu \bar{\nu}$

reduced to (8.8 ± 1.3)% < 1/10

Outline

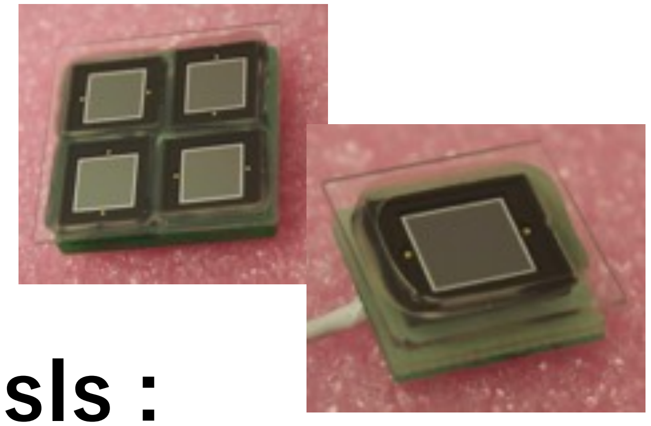
- Readout:
  - ☑ need to reduce # of channels
- Radiation hardness
  - ☑ MPPC damaged due to irradiation
- Performance
  - ☑ timing converting to z,
  - ☑ σ_t at high energy and radiation hardness ☑
  - ☑ reduction power of n Background

with new method, we can reduce neutron background to the SM level.

Summary

- We are going to upgraded the KOTO CsI calorimeter to distinguish neutron from γ with four dimensional shower reconstruction.
- It uses both-side readout technique with 4096 MPPCs,
- We can suppress the neutron background to below SM prediction with this method.

Status and schedule of installation



Status toward the installation

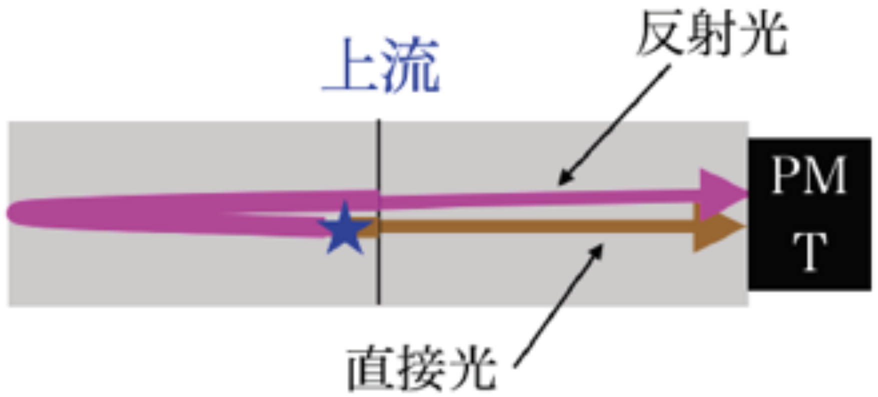
- [x] Establish feasible design gluing MPPCs on CsIs :
  - each MPPC glued on quartz plate ➡ each quartz glued on CsI
- [x] glue 4096 MPPCs on quartz plates,
- [x] IV curve of MPPCs glued on the quartz.(done 2/3)
- [x] out-gas from every introduced materials (almost done)
- [ ] light sensitivity test of every MPPC on quartz

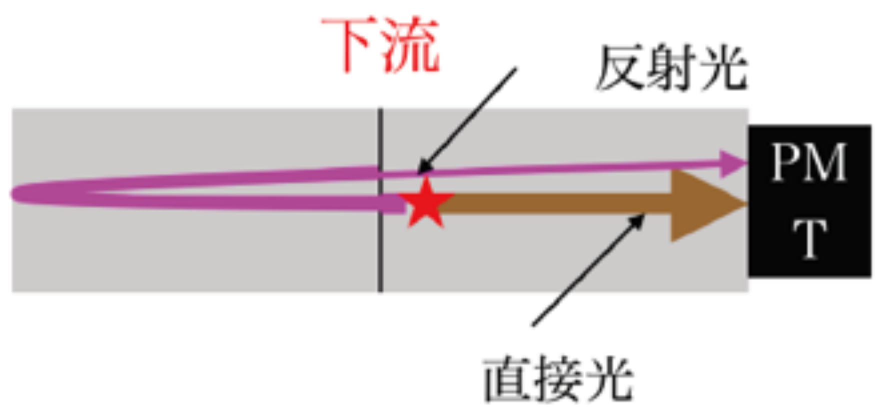
Schedule

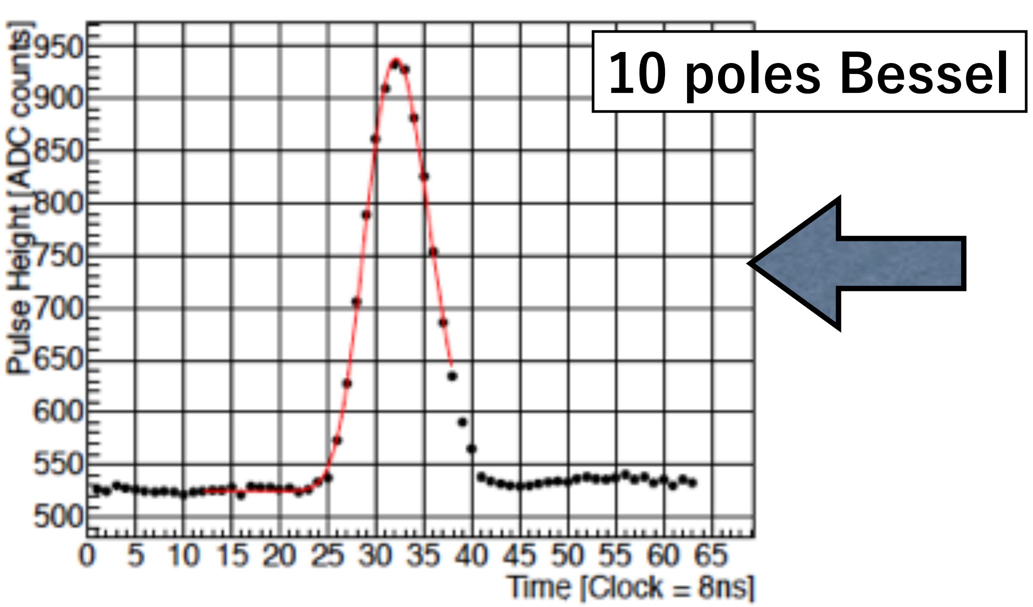
2018-July	- test light sensitivity of every MPPC/Quartz - Detector disassembly
August - middle of October	- glue MPPC/quartz on CsI @ J-PARC
October - December	- setup @ J-PARC
2019-January	- test run @ J-PARC

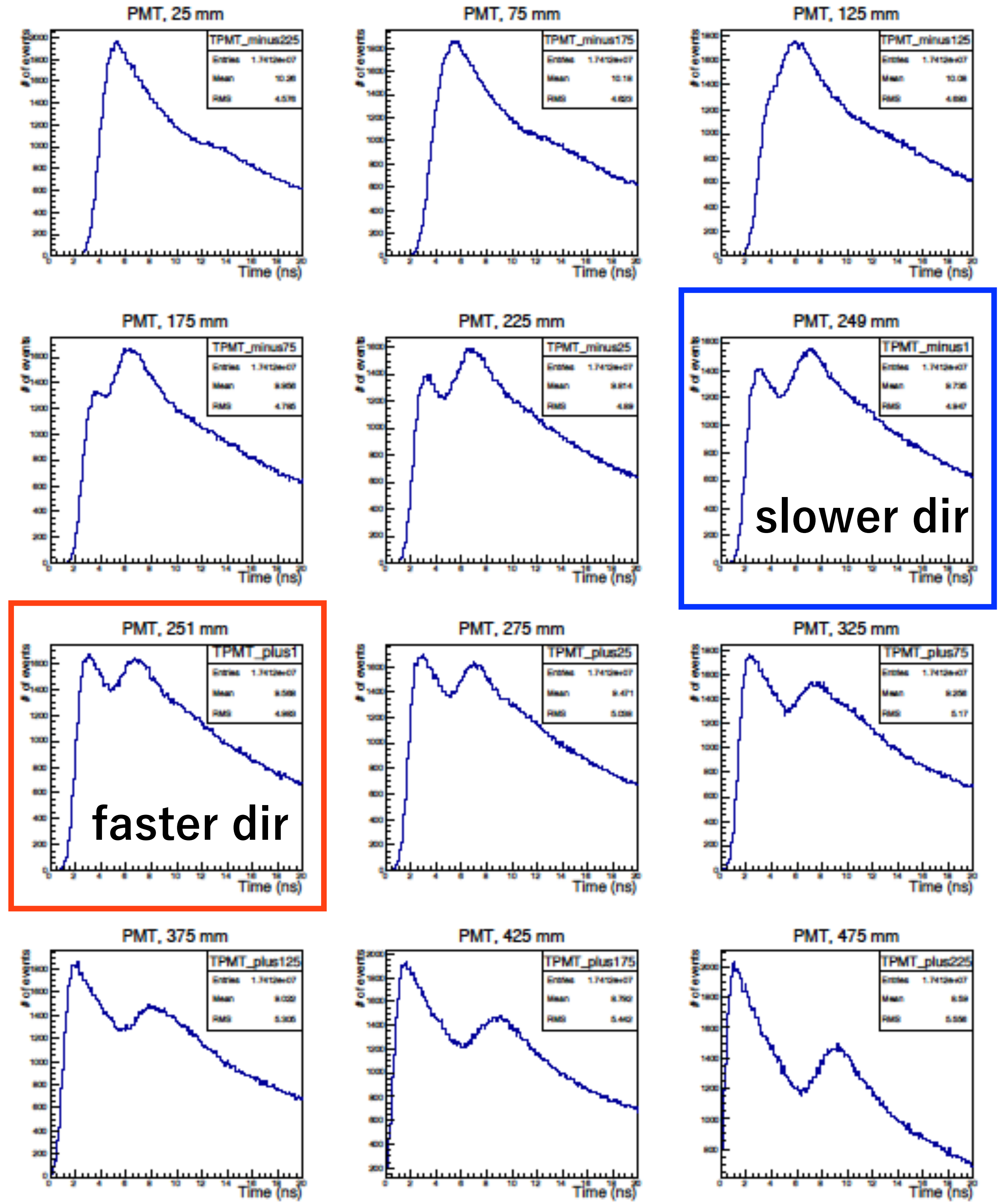
Backup

Distance from MPPC



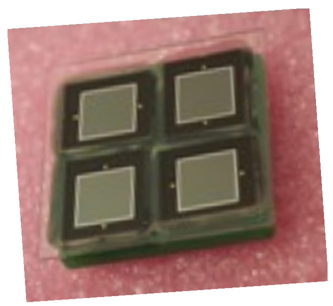


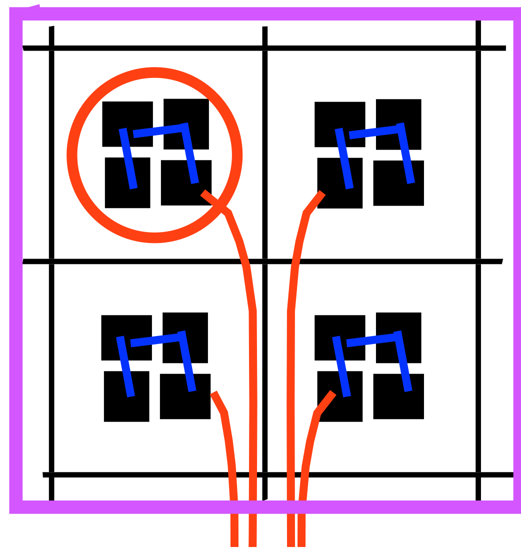


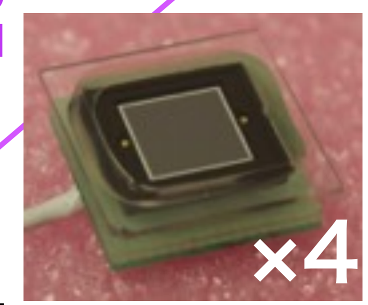


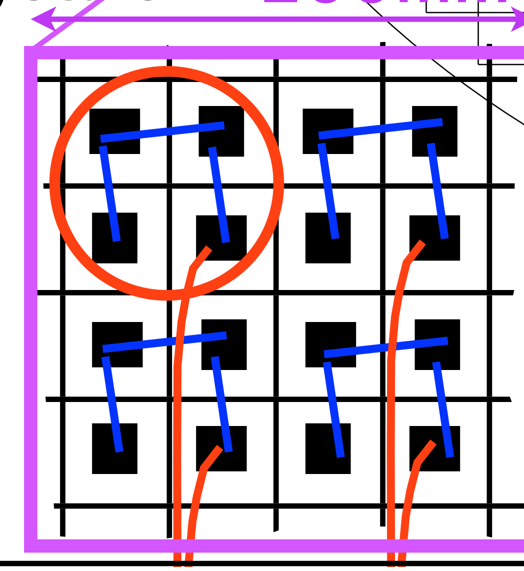
Readout

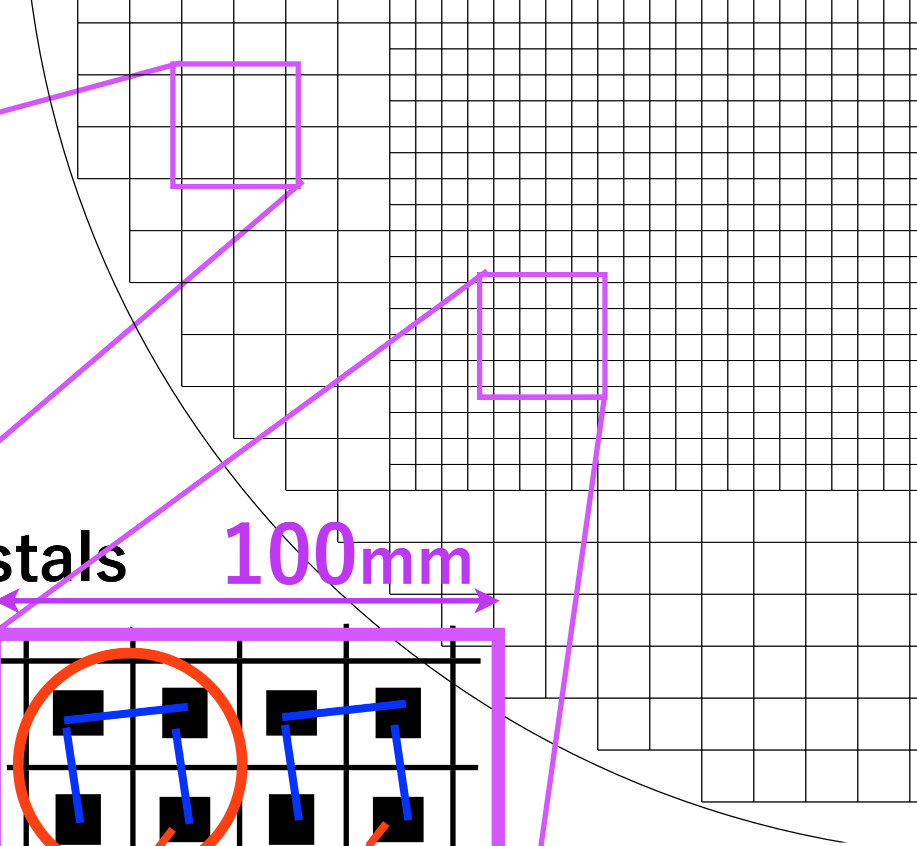
4-MPPC readout







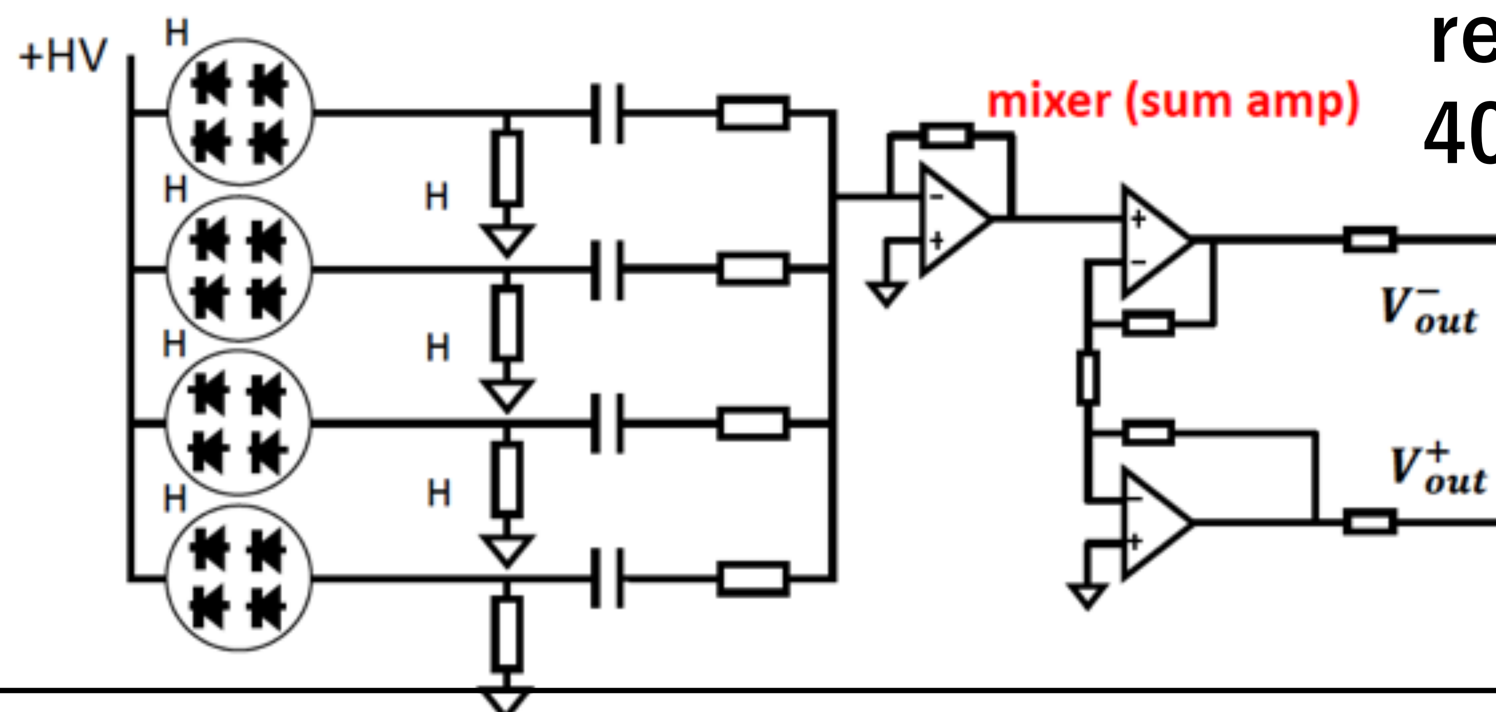


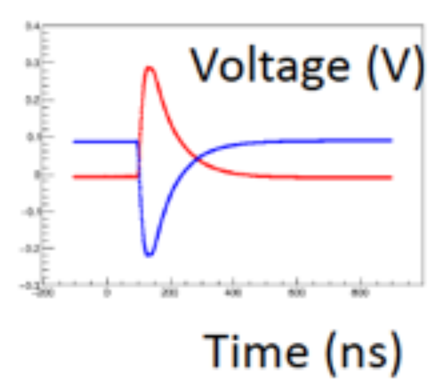


Four MPPCs: read out together in a readout group

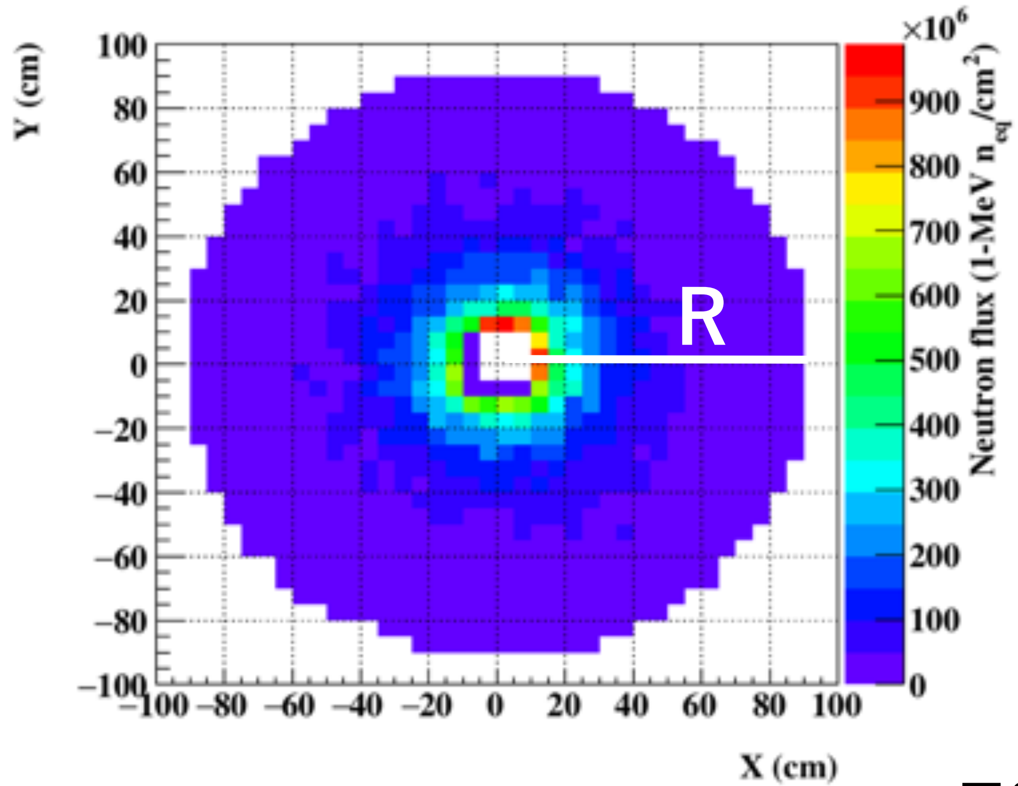
[4-MPPC]×4 sum-amp

100×100mm²/channel
referring to cluster size
4096 MPPCs ➡ 256ch.





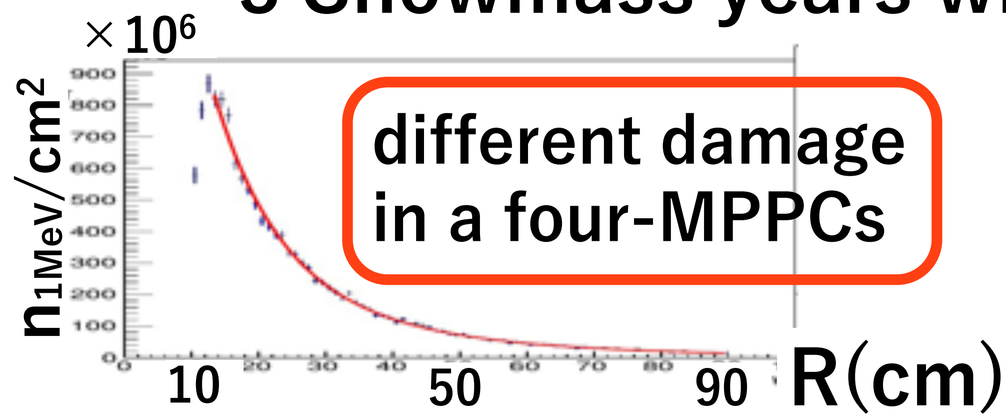
Radiation hardness of MPPC



a simulation predicts

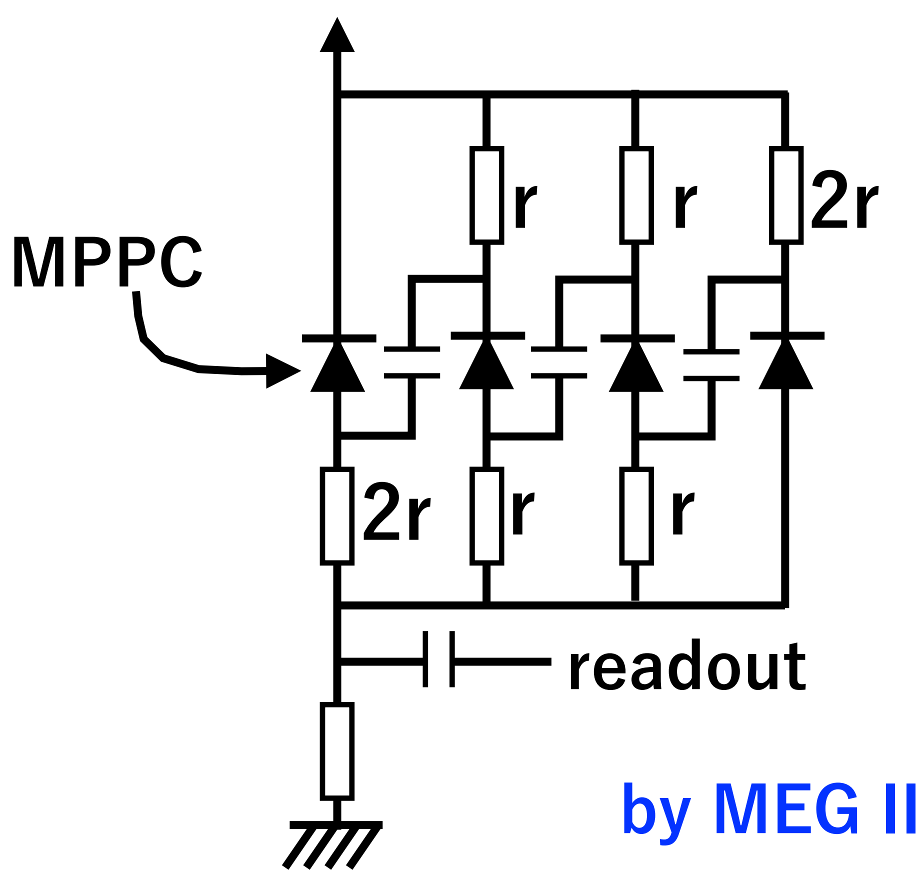
max 10^9 n_{1MeV}/cm^2

3 Snowmass years with 100kW



Effects of 1.5×3 Snawmass Y.

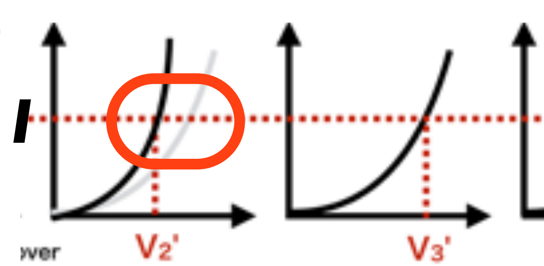
items :	after irradiation
Dark current(V_{over} = 3V) :	×100 (0.5μA➡50μA)



by MEG II

Different damage ➡ different Dark Current

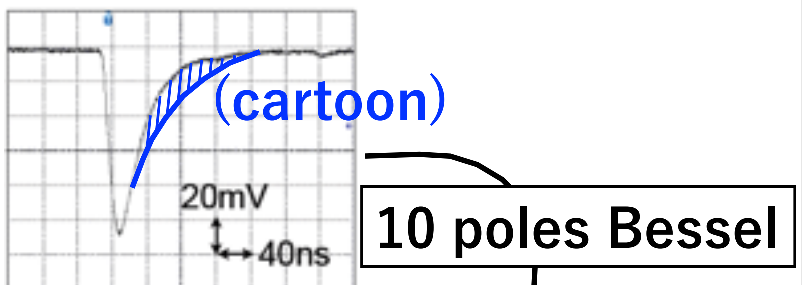
➡ Different Bias V (4-serial)

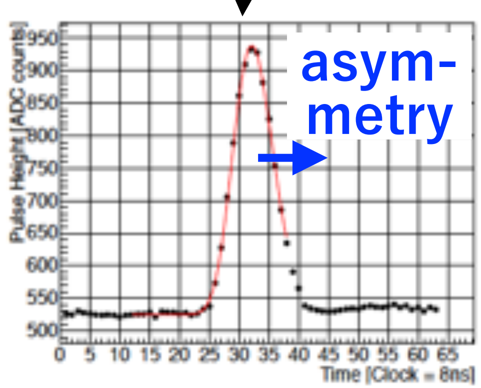


➡ Serial for signal
Parallel for bias ➡ independent on DC

Three reduction tech. already

pulse shape likelihood ratio	Cluster shape χ^2 cut	Cluster shape discrimination
1D information (t)	2D information (x, y)	3D information (x, y, t)
Neutron pulses have slow components.	compares the cluster shape in x and y dim. with MC means.	compares the cluster shape + hit timing; neural net.

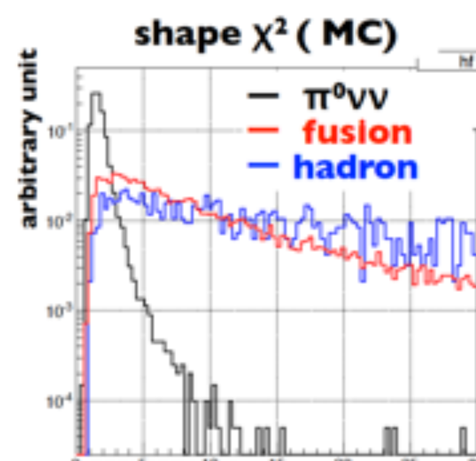


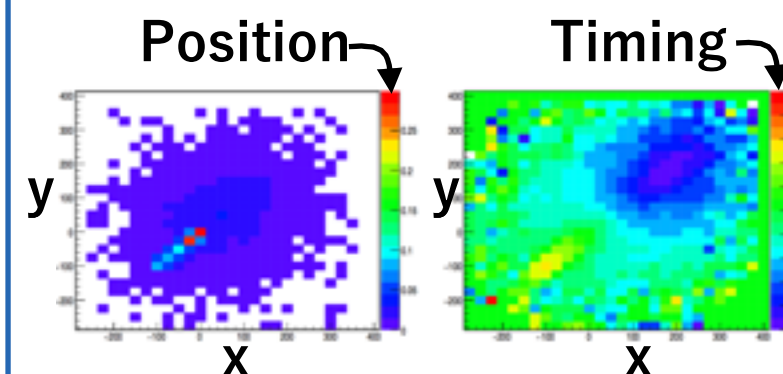


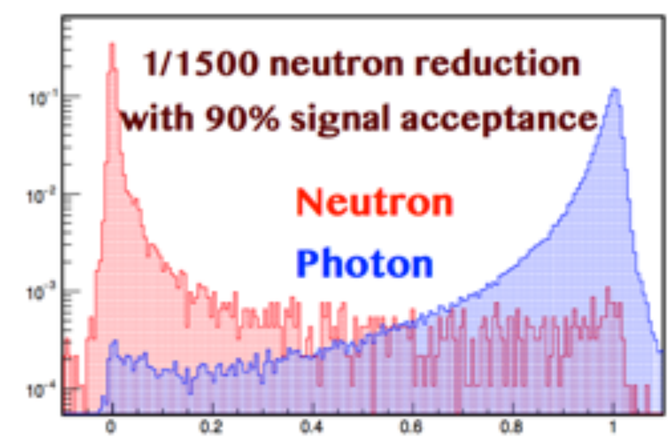
$$F(t) = A \cdot \exp\left[\frac{-(t-t_0)^2}{2\{B(t-t_0)+\sigma_0\}^2}\right] + C$$

increase

$$\chi^2 = \sum_i^N \frac{1}{N} \frac{(e_i/E_{\rm rec} - \langle e_i/E_{\rm true}\rangle_{\rm MC})^2}{\sigma[e_i/E_{\rm true}]_{\rm MC}}$$



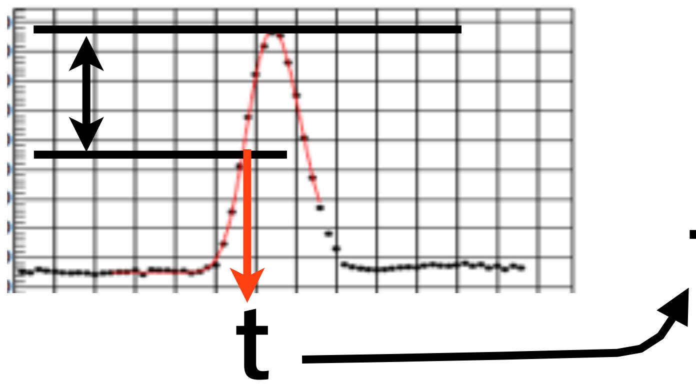




0.24 event in 1.3×10^{-9} single event sensitivity

+ vertex times estimated from cluster hit times.

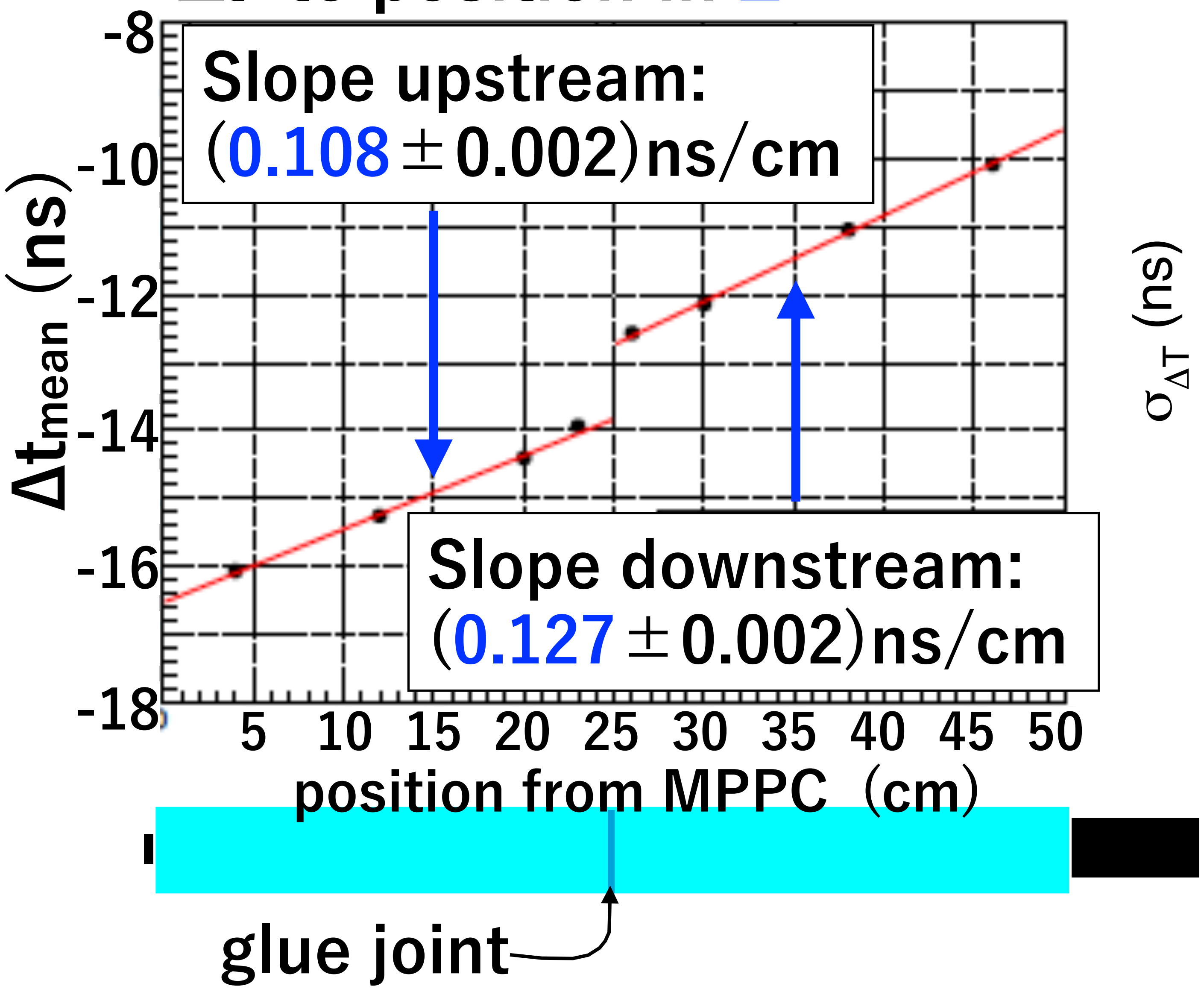
Performance: Δt and σ_t

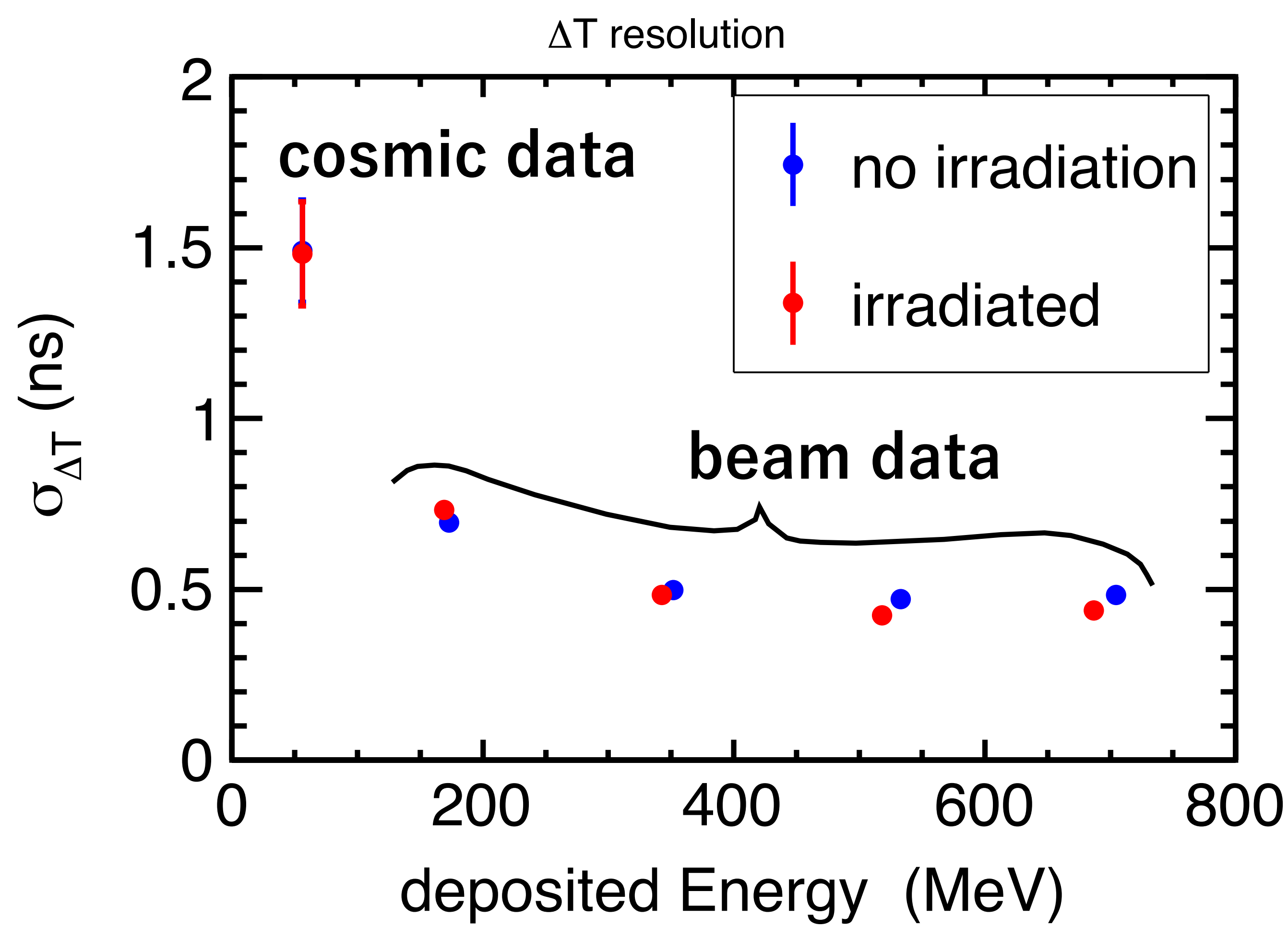


t by the constant fraction method

Cosmic lays

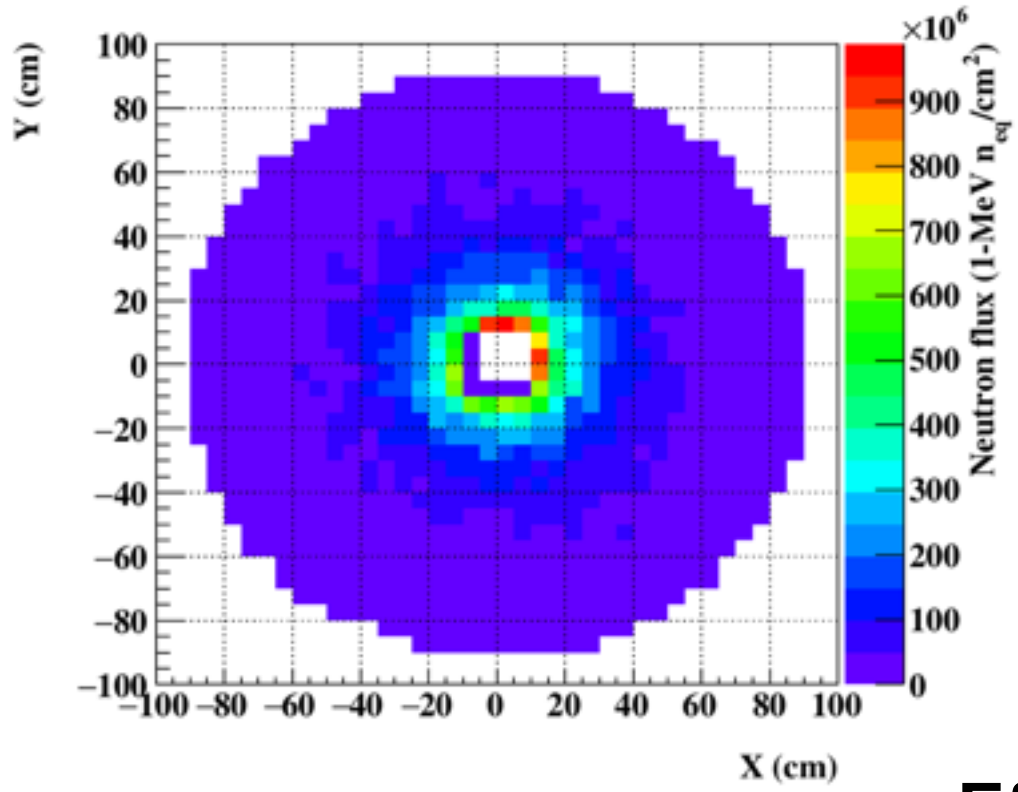
Δt to position in Z





No effect by irradiation.

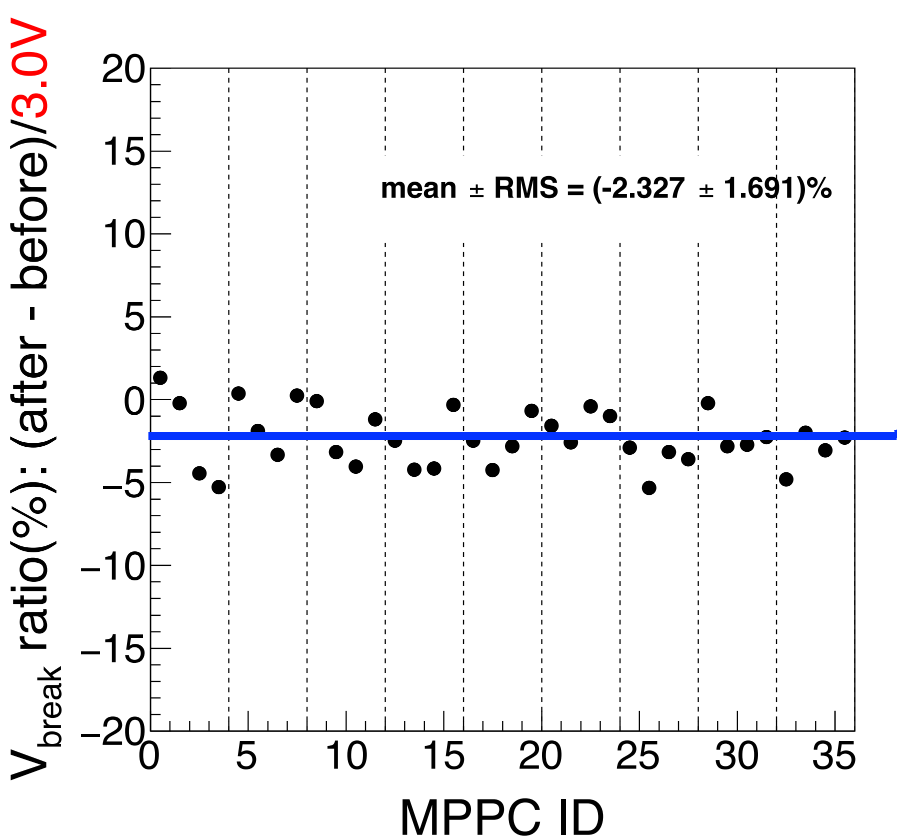
Radiation hardness of MPPC



a simulation predicts:

max 10^9 n_{1MeV}/cm^2

3 Snowmass years with 100kW



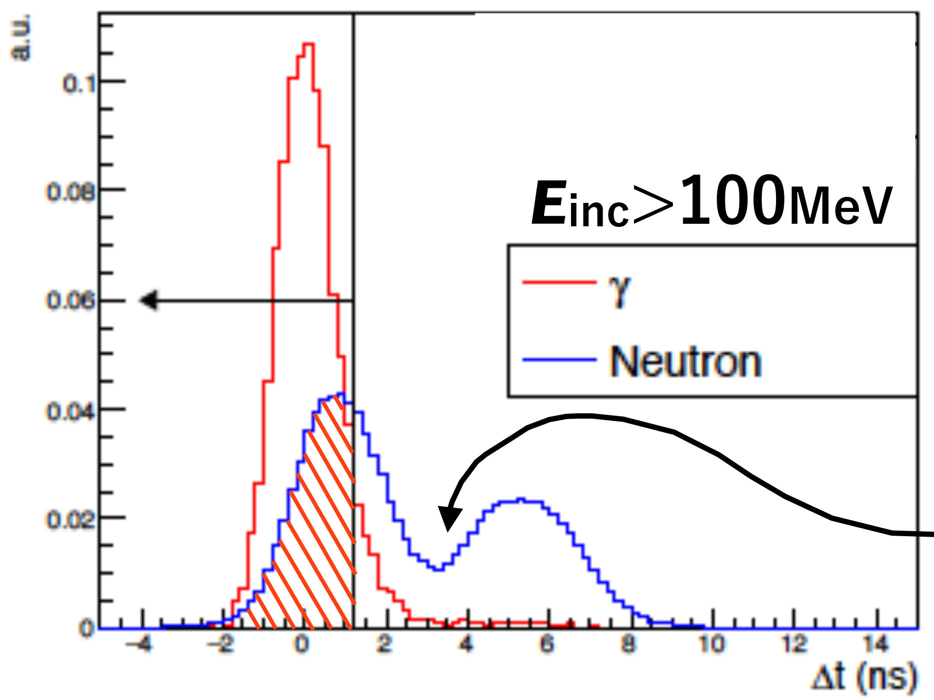
Effects of 1.5×3 Snawmass Y.

items :	after irradiation
Dark current(V_{over} = 3V) :	×100 (0.5μA➡50μA)
ΔV_{break}/3V(use) :	-2%(no problem)
ΔV_{break} among 4MPPCs :	(3.5±1.5)%➡(2.8±1.3)%
light sens. variation(%) :	(-1.8±1.5)%

Performance: Separation γ, n

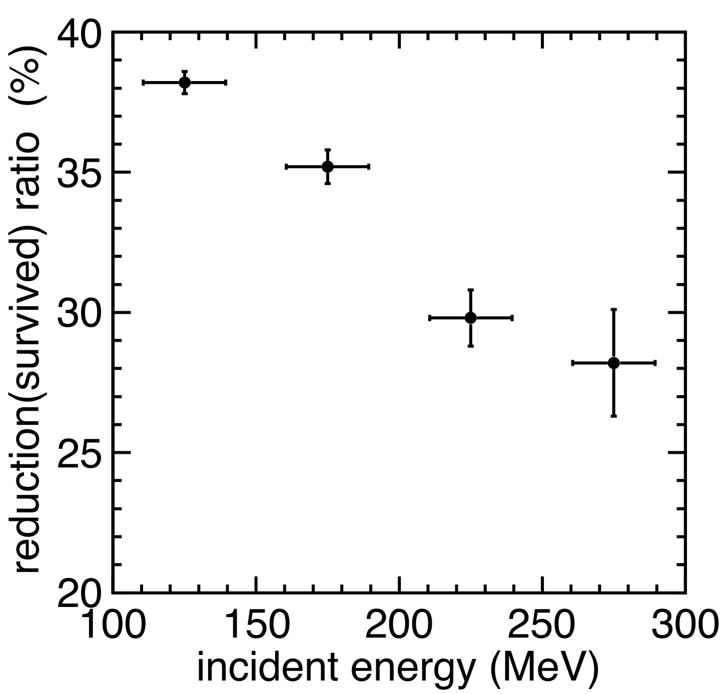
Beam test at RCNP in Osaka

neutron ~400MeV, γ / n tagging by TOF



@90% efficiency for γ in crystals

- neutron has a wide distribution
- neutron reduction ratio: 36%
- a gap caused by a glue joint at the center.

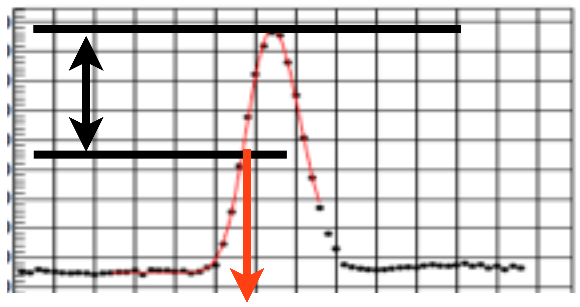


Reduction ratio of single neutrons
@ 90% efficiency for γ

$$\Delta t\text{: cluster} = \frac{\sum_i^{N_{crystal}} \Delta t_i \cdot E_i}{\sum_i^{N_{crystal}} E_i}$$

Performance: Δt and σ_t vs. z

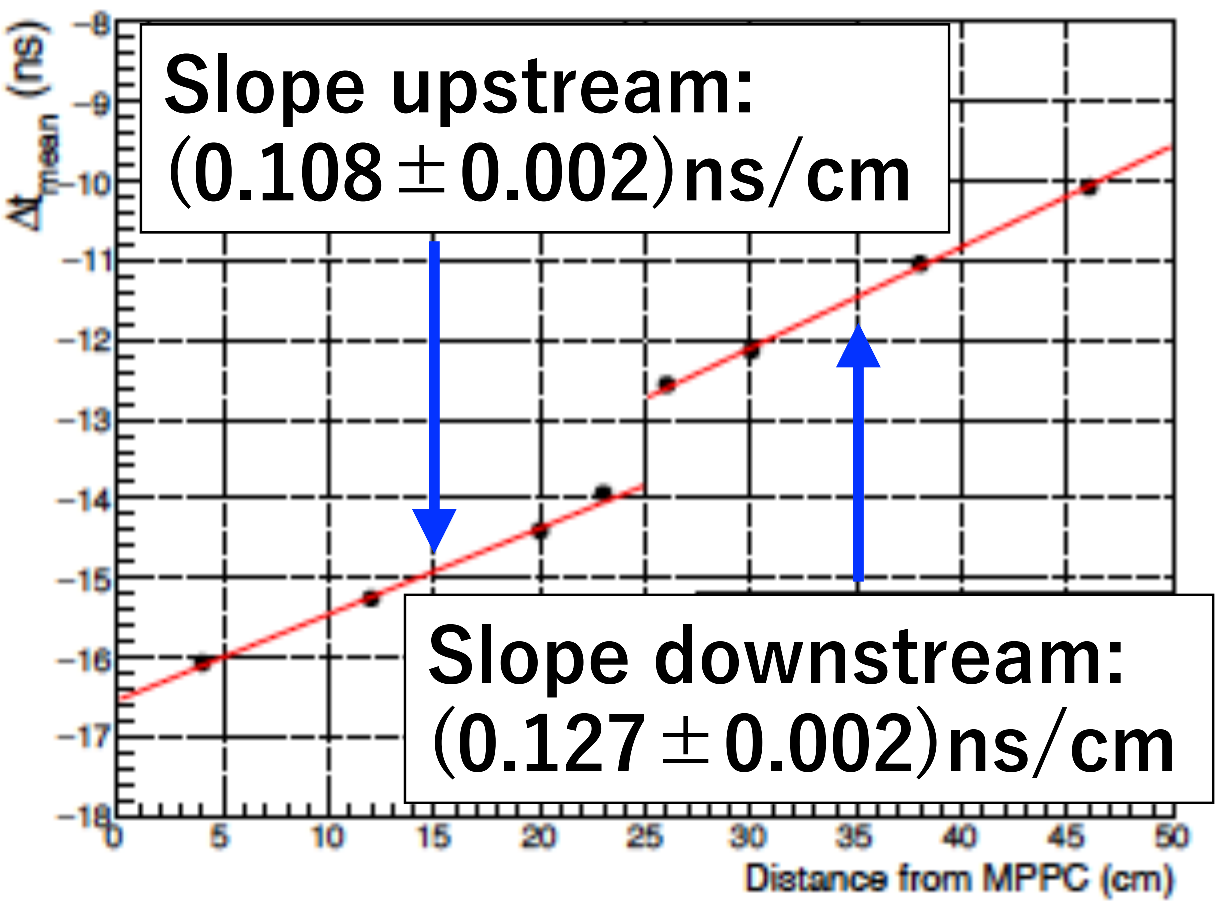
with a cosmic test



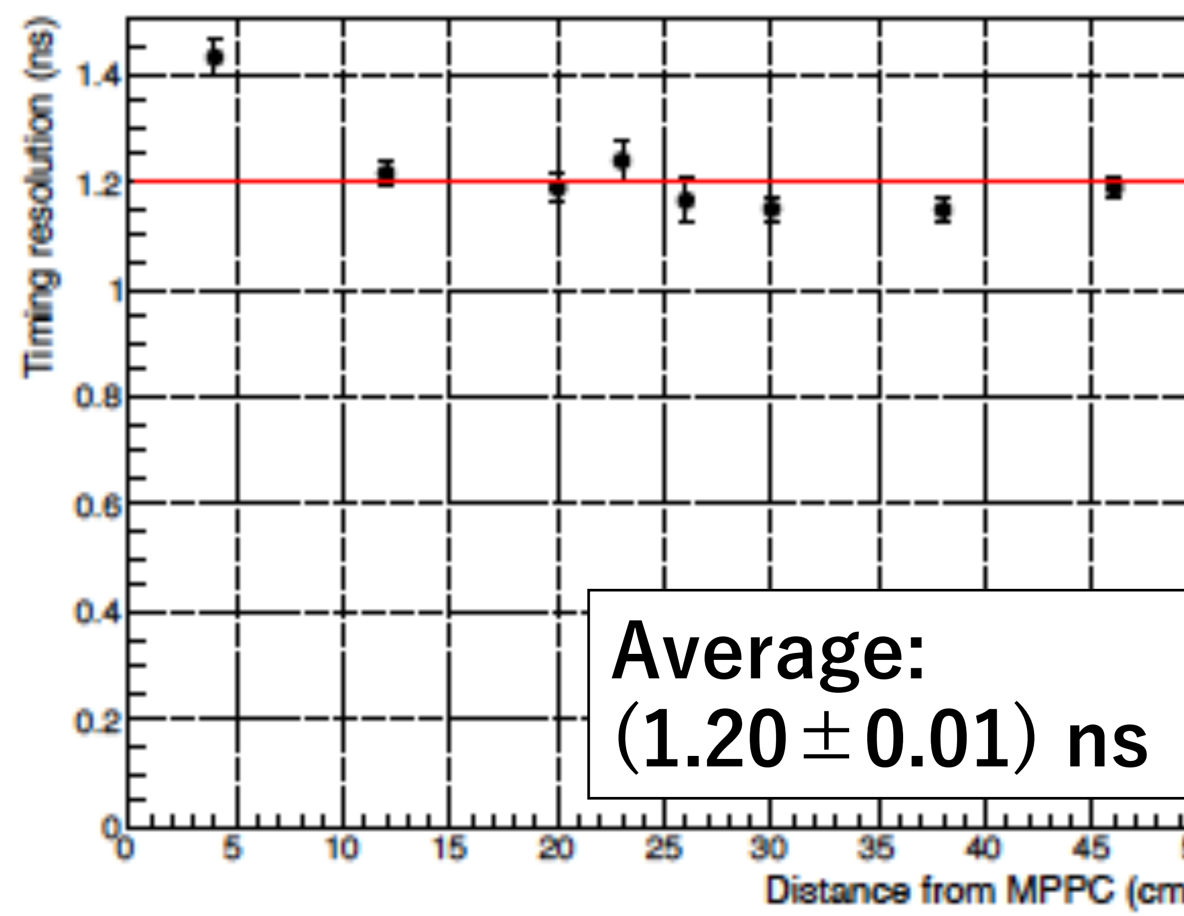
t

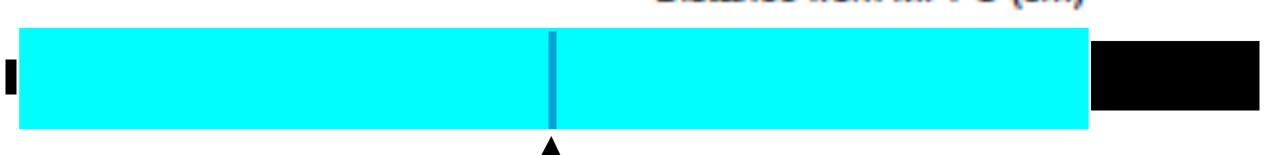
t by the constant fraction method

Δt v.s. position (typical)



σ_t v.s. position (typical)

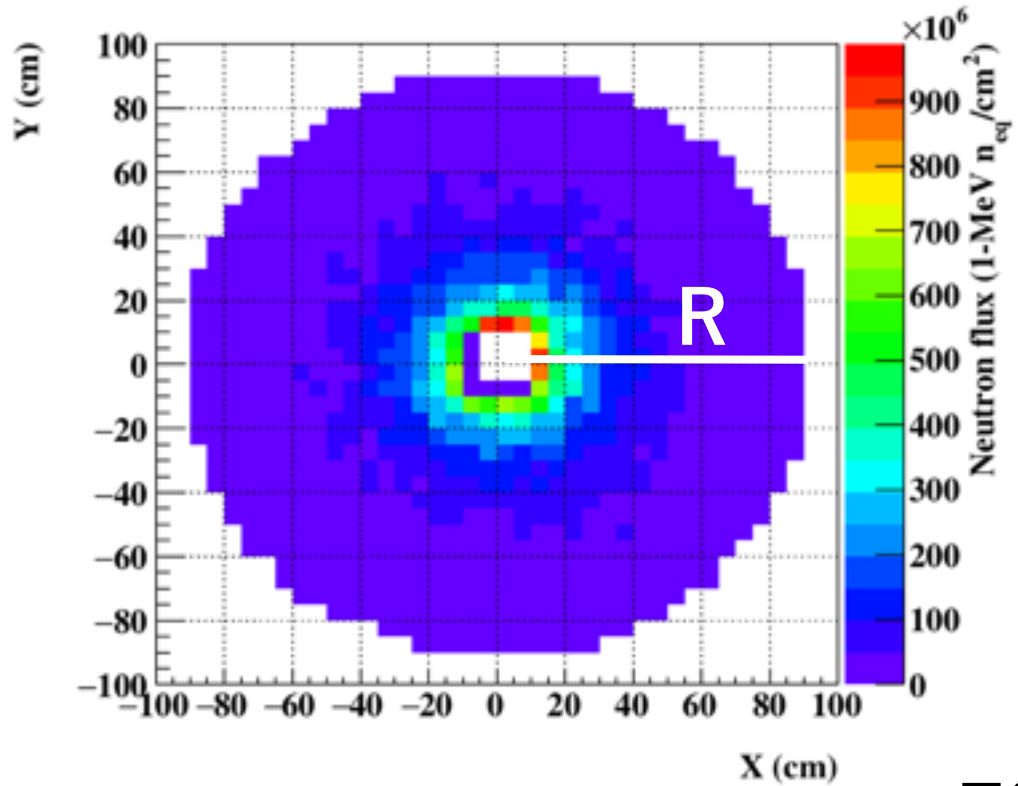




glue joint

σ_t =1.2ns, uniform σ_t on z

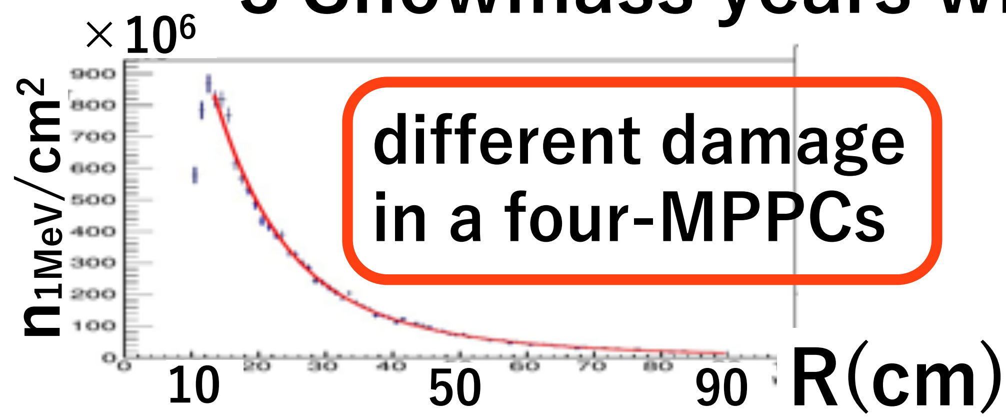
Radiation hardness of MPPC



a simulation taught

max 10^9 n_{1MeV}/cm^2

3 Snowmass years with 100kW



different damage in a four-MPPCs

Effects of 1.5×3 Snawmass Y.

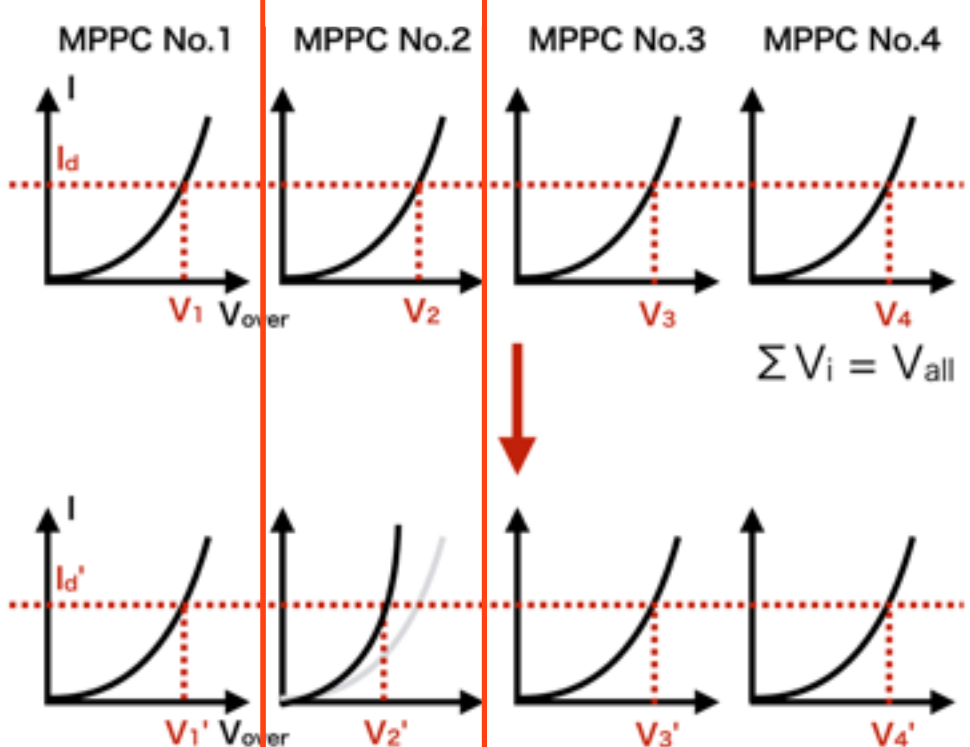
items :	after irradiation
Dark current(V_{over} = 3V) :	×100 (0.5μA➡50μA)

Different damage ➡ different Dark current

➡ Different Bias V (4-serial)

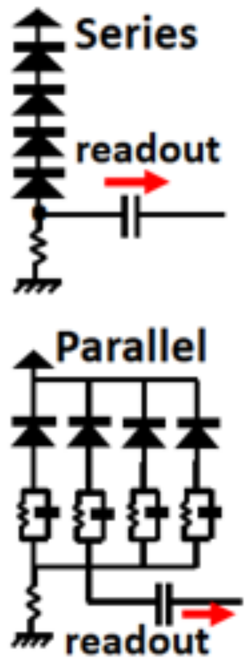
➡ Serial for signal
Parallel for bias

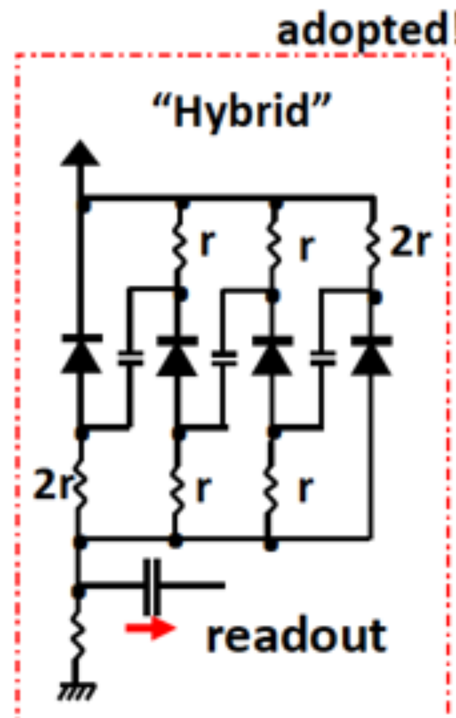
case: only No.2 has a radiation damage



Circuit board for 4-MPPCs

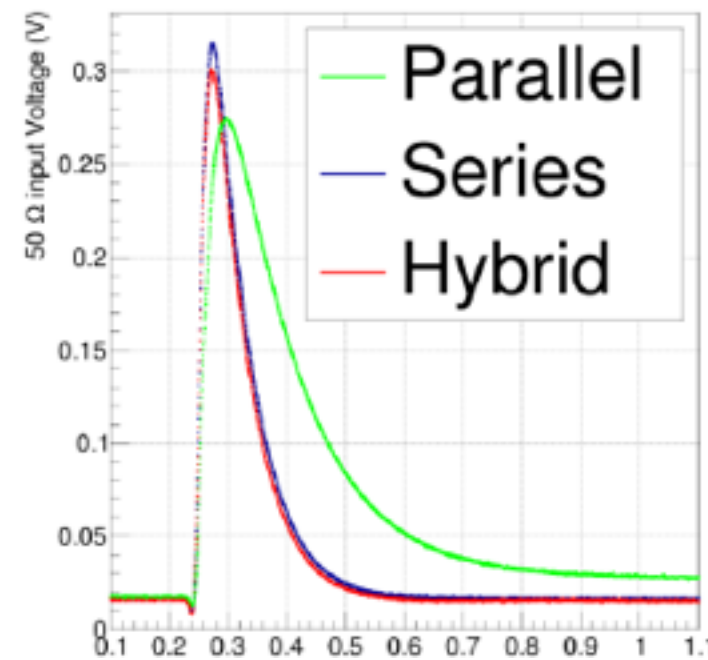
Serial connection
fast pulse,
bias depends on current
Parallel connection
slow pulse
bias not depend on current





signal➡serial
bias ➡parallel

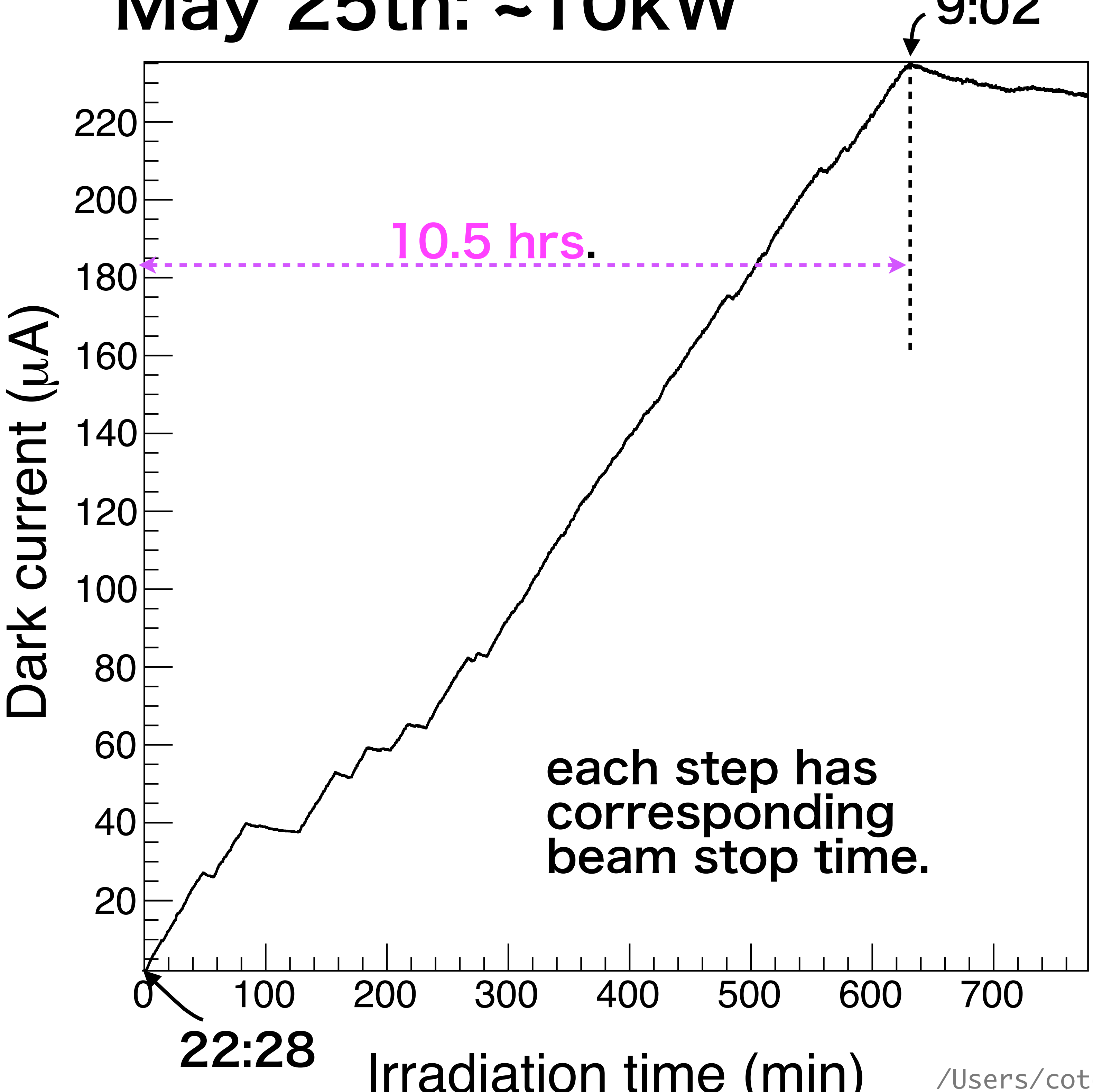
bias not depend on current



still fast pulse of hybrid case

Irradiation was measured by the dark current

May 25th: ~10kW



corresponding to $1.5\times10^{9}n/cm^{2}$

Dark current should increase up to 235μA

Ratio irradiation / dark current was taken from RCNP-80MeV experiment (Jan 2017)

total 10.5 hrs.

Good agreement with simulation.

Full simulation says:

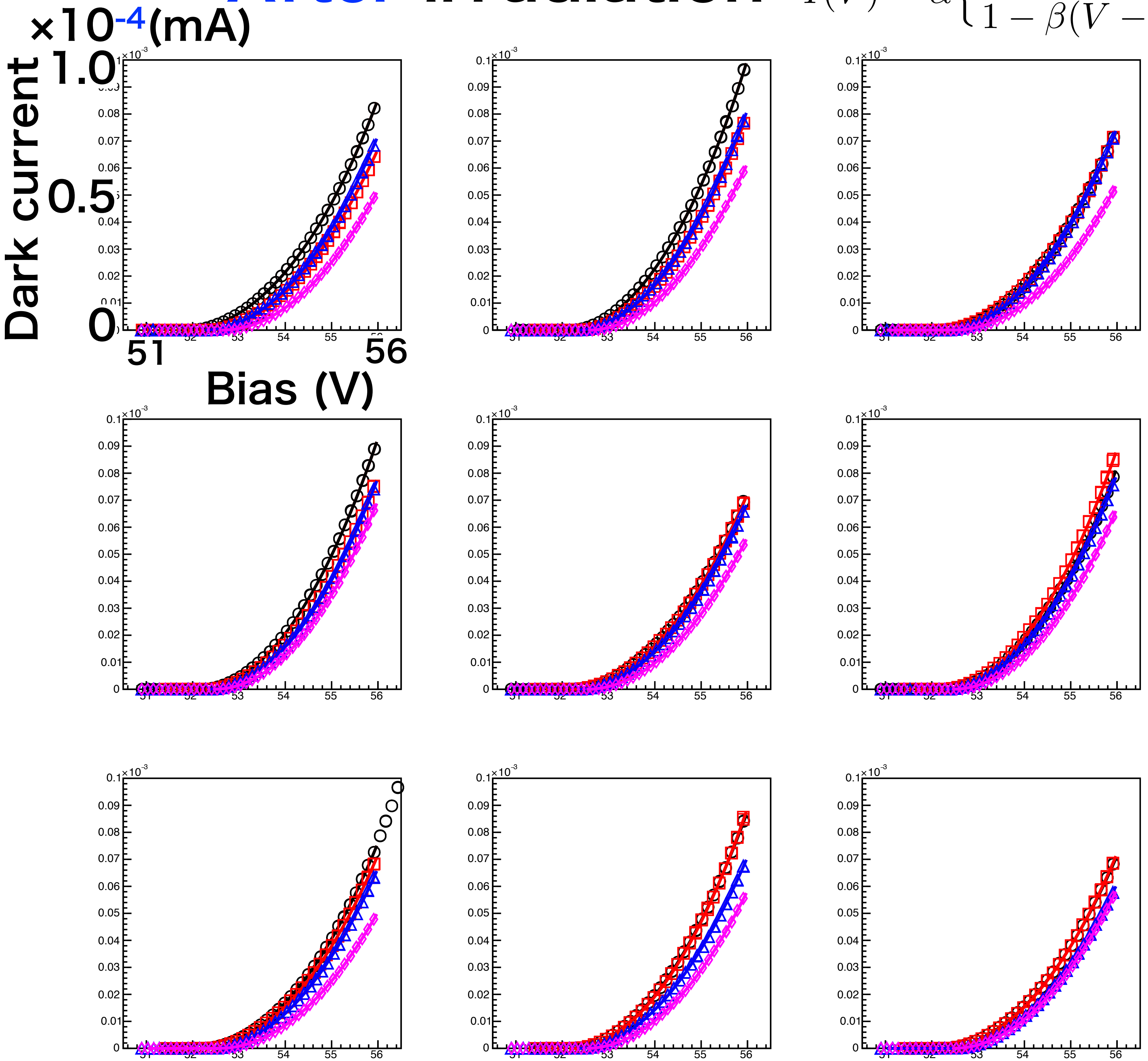
$1.5\times10^{9}n/cm^{2}$ needs 12.5hrs.

IV curve at J-PARC:26th May

After irradiation

$$I(V) = \alpha\left\{\frac{1}{1-\beta(V-V_{\rm bd})^2}\right\}(V-V_{\rm bd})^2 + \gamma : (V \geq V_{\rm bd})$$

$$I(V) = \gamma : (V < V_{\rm bd})$$

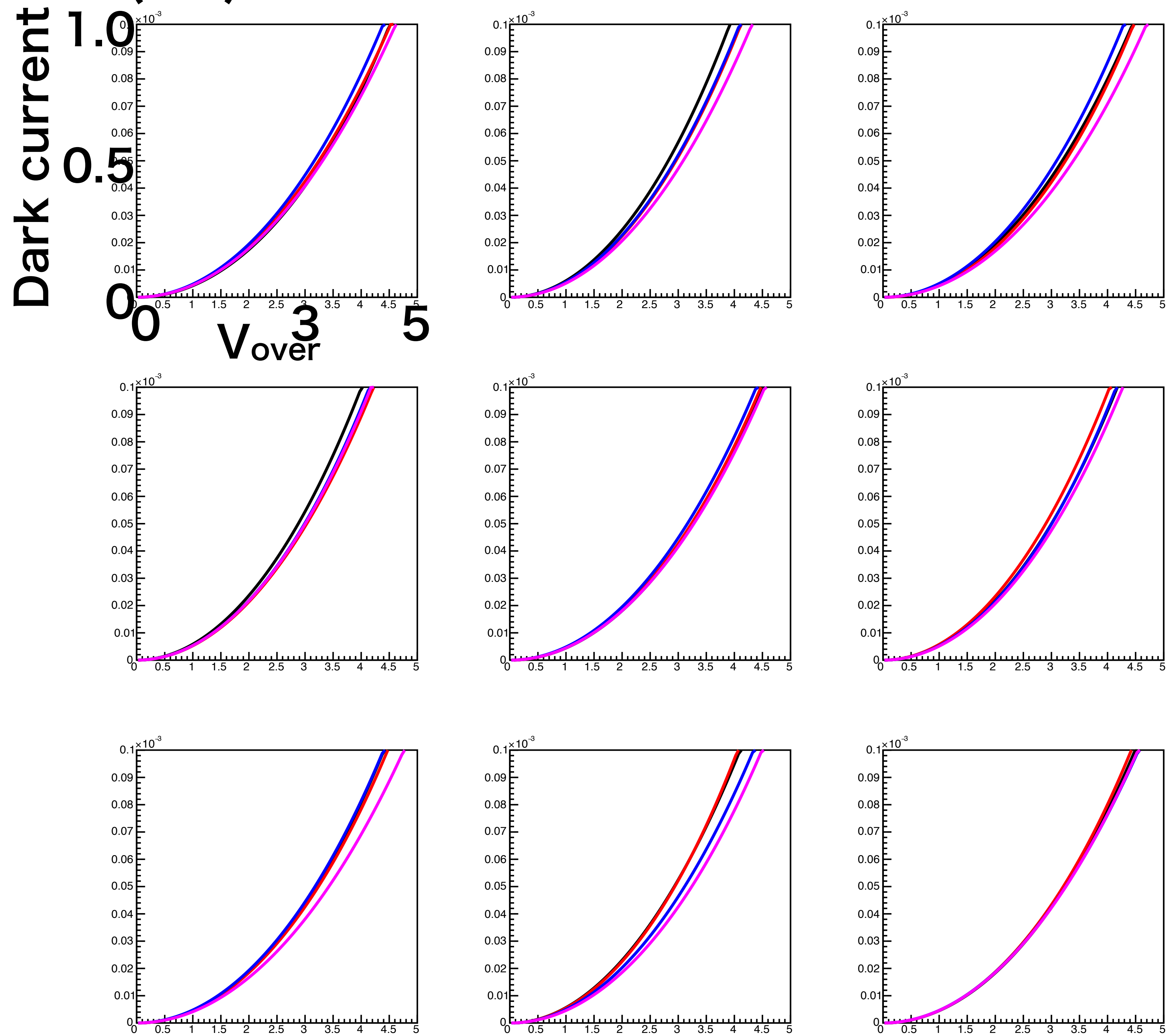


Result curves from V_0

After irradiation

$$I(V) = \alpha\left\{\frac{1}{1-\beta(V-V_{\rm bd})^2}\right\}(V-V_{\rm bd})^2 + \gamma : (V \geq V_{\rm bd})$$

$$I(V) = \gamma : (V < V_{\rm bd})$$



only result functions are drown.

parameters

$$\alpha, \beta, \gamma + V_{\rm bd}$$

horizontal = V_{over}

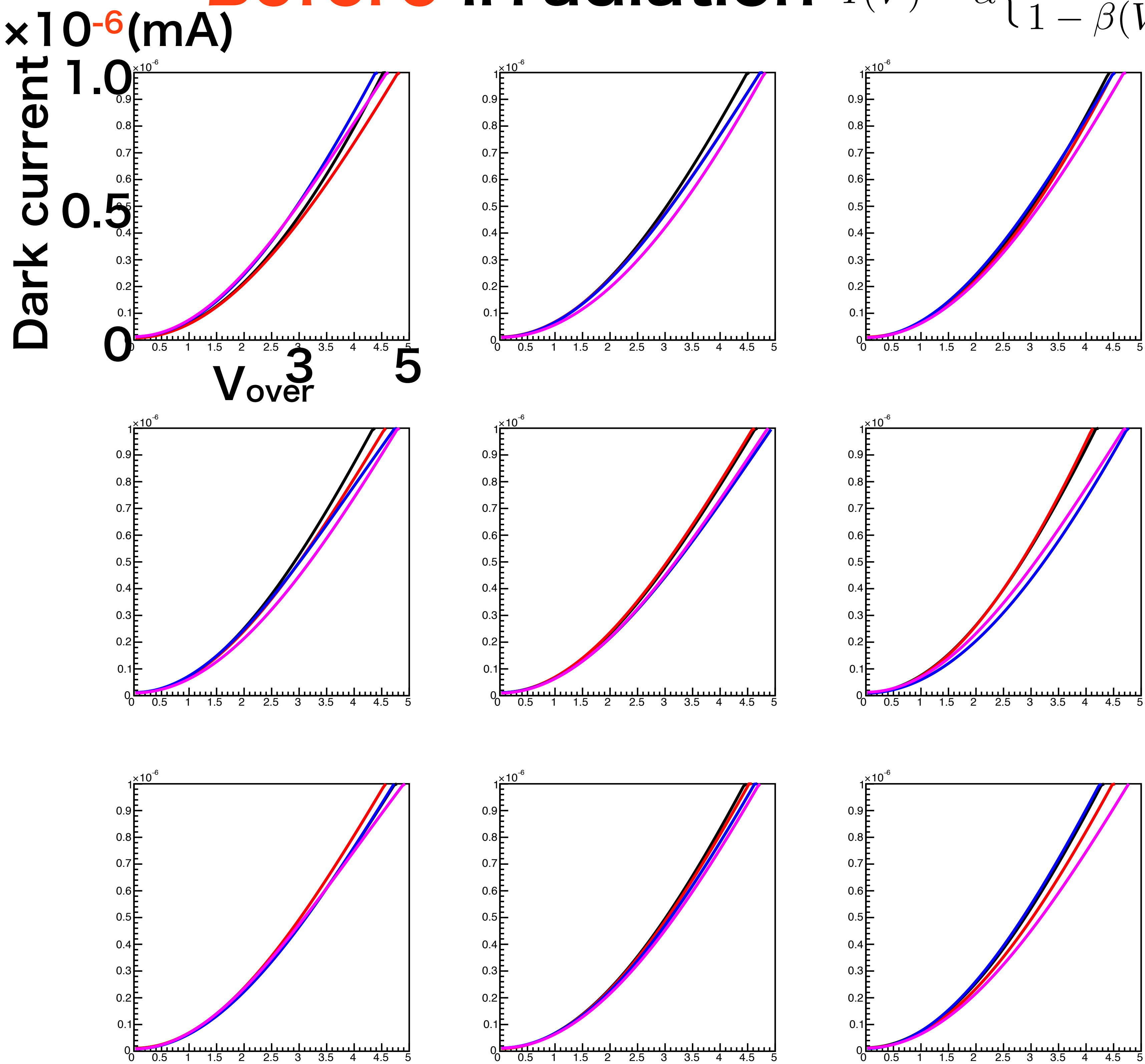
$$V_{\rm bd} \rightarrow 0$$

Result curves from V_0

Before irradiation

$$I(V) = \alpha\left\{\frac{1}{1-\beta(V-V_{\mathrm{bd}})^2}\right\}(V-V_{\mathrm{bd}})^2+\gamma : (V \geq V_{\mathrm{bd}})$$

$$I(V) = \gamma : (V < V_{\mathrm{bd}})$$



only result functions are drown.

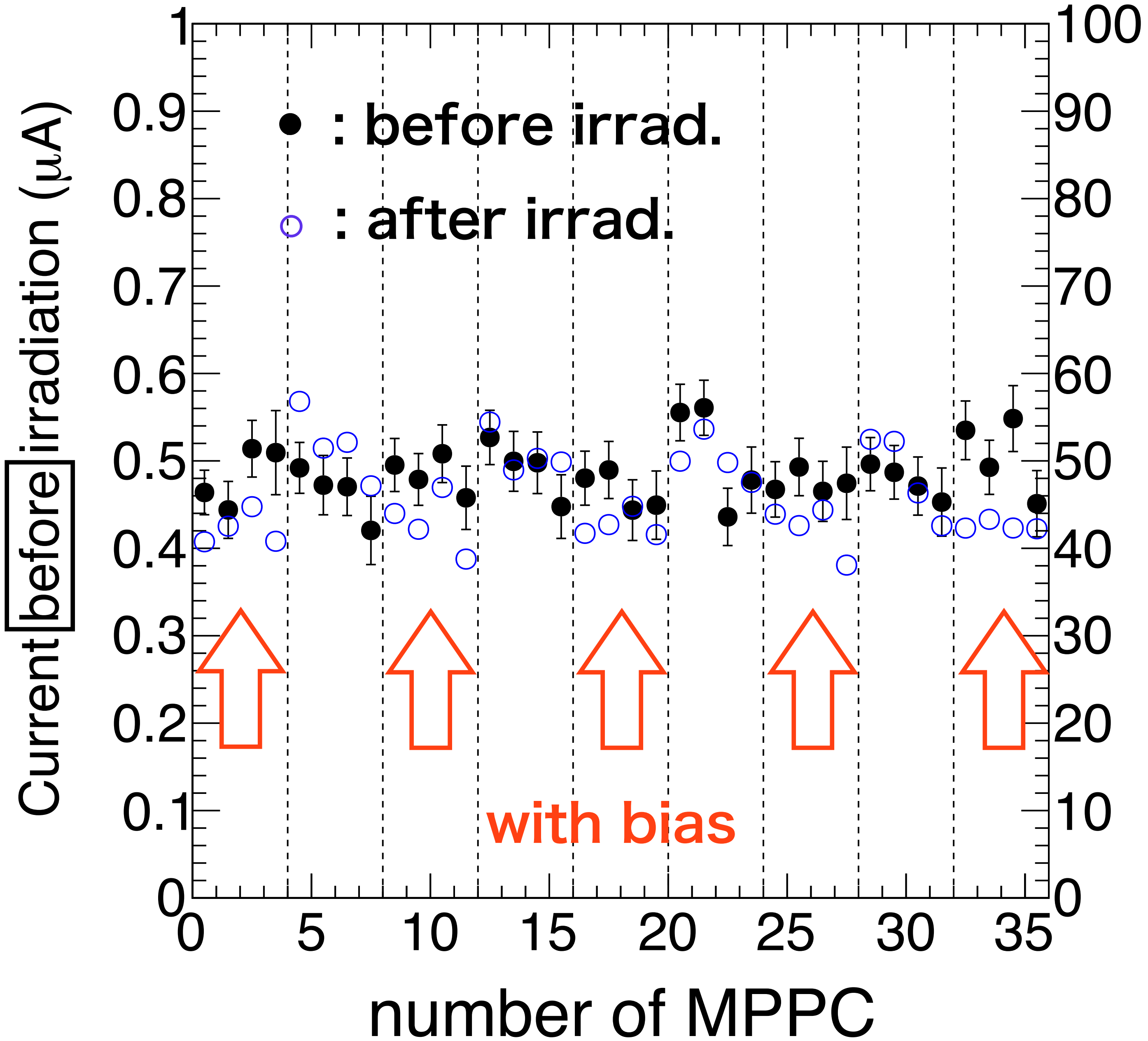
parameters

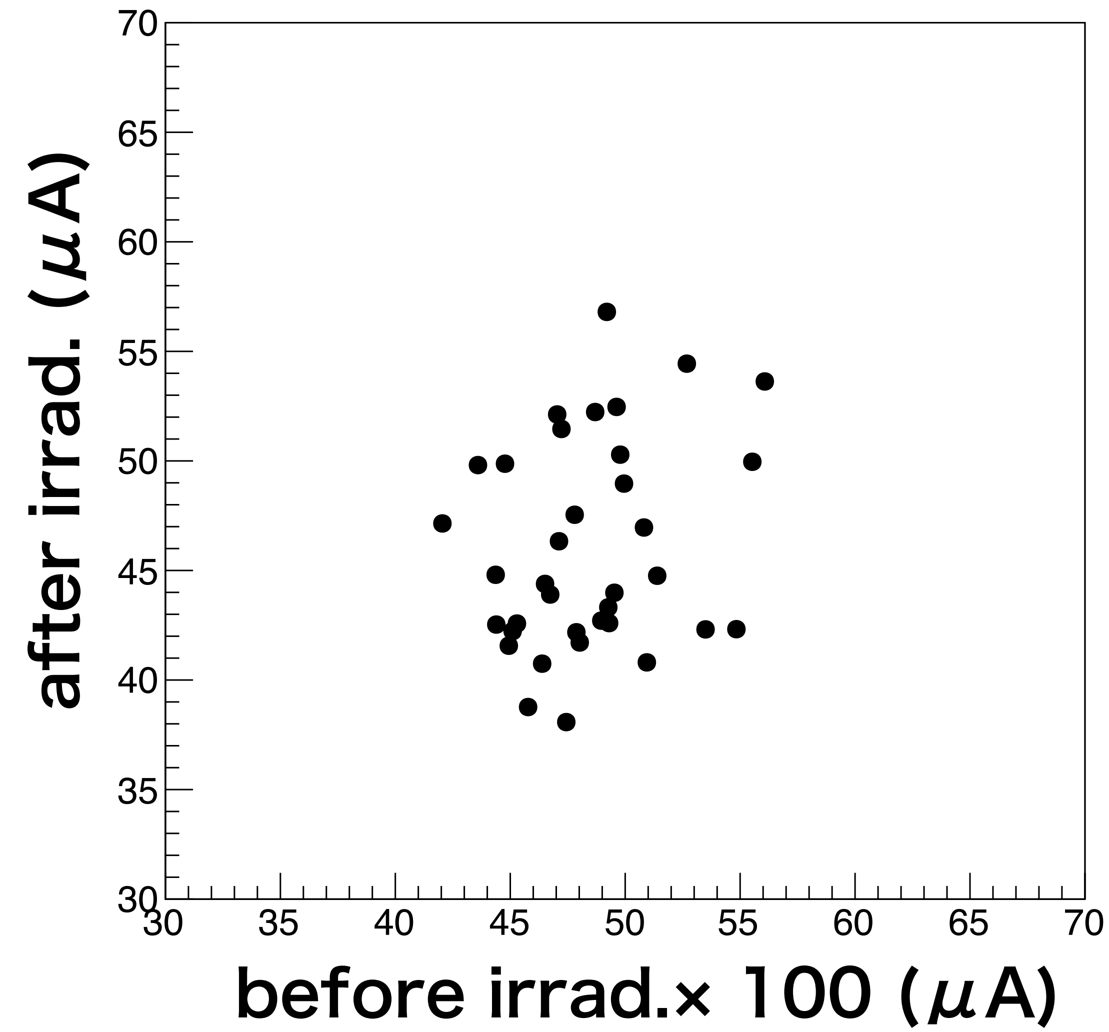
$$\alpha, \beta, \gamma + V_{\mathrm{bd}}$$

horizontal = V_{over}

$$V_{\mathrm{bd}} \to 0$$

Current at V_{over}=3V





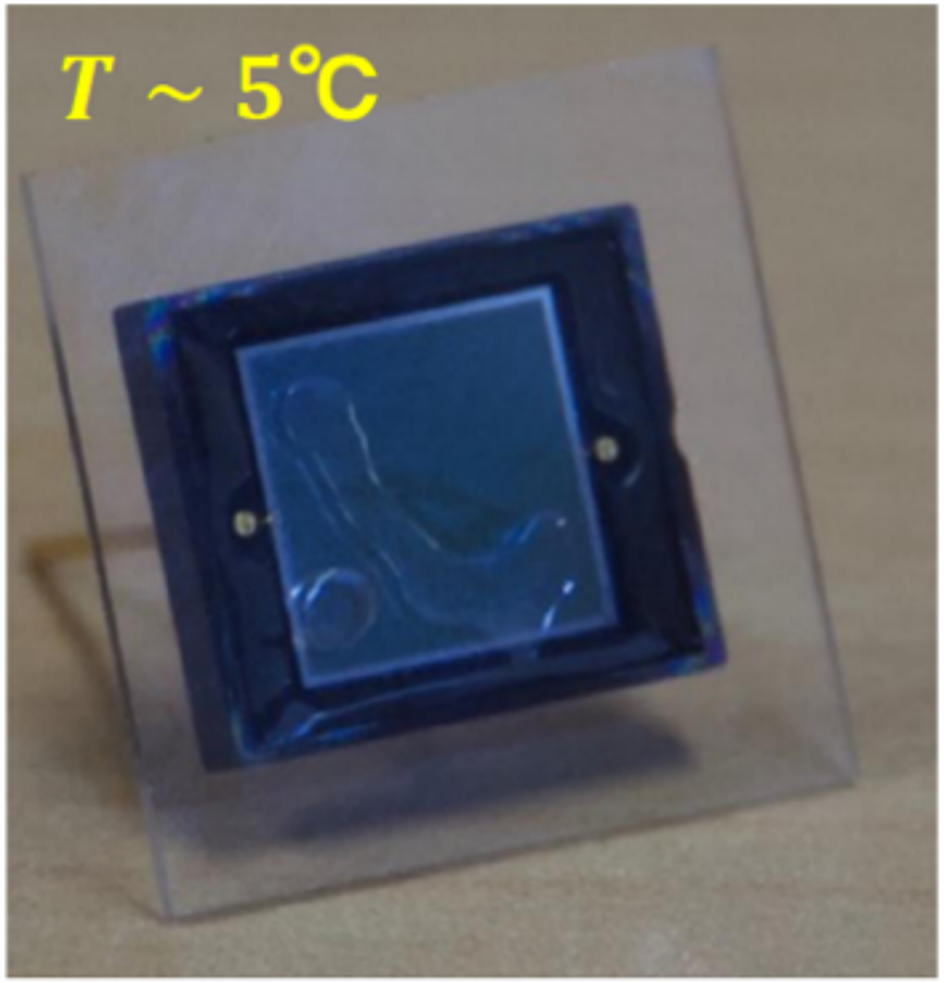
- Dark current increases ~100 times by factor 1.5 of 3 SnowmassY w/ 100kW.
- increasing uniformly.

- Increase of dark current does not depend on exist of bias voltage.

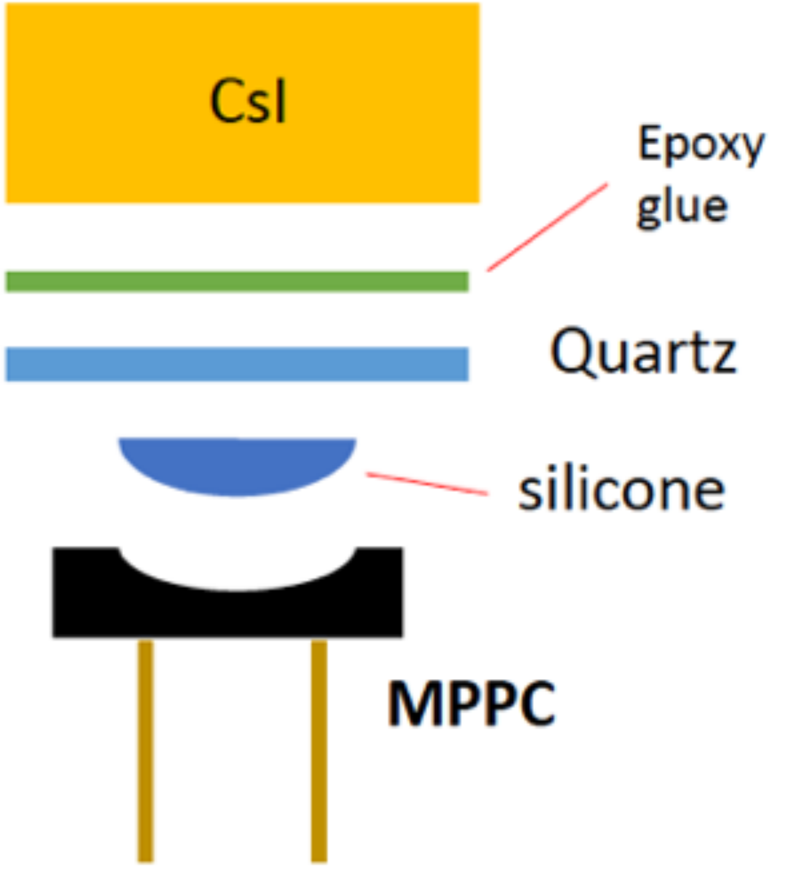
/Users/coterra/Documents/00Projects/00KOTO/IVcurveMay26BfrAft

Gluing of MPPC on the CsI surface

- Difficulties to glue MPPC
  - Concave shape of MPPC
  - Epoxy glue does not cure well on CsI surface
  - bubbles appear at low temperature



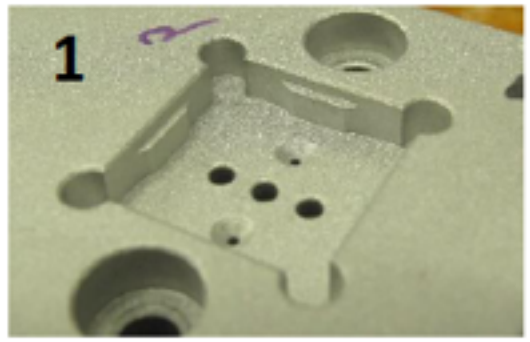
Quartz plate to assure the flatness and transparency in advance



Fabrication of MPPCs

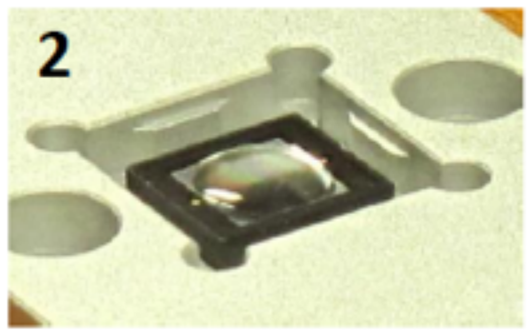
1

Insert MPPC on jig



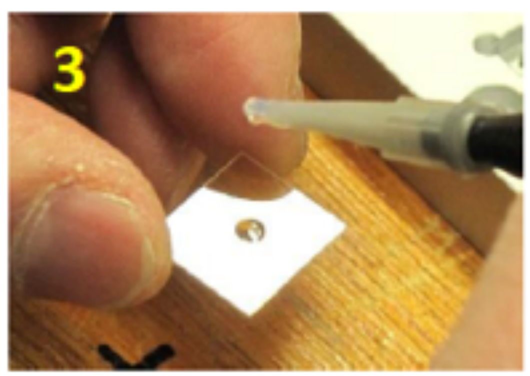
2

Drop glue

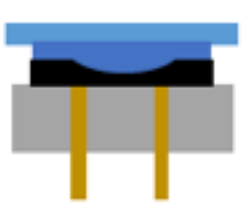


3

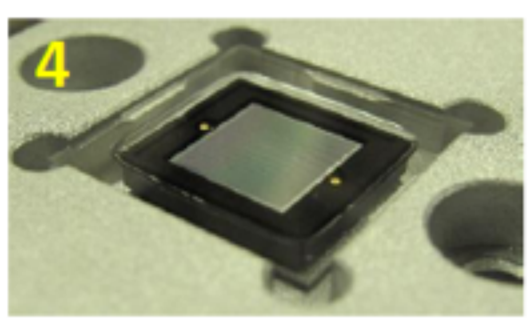
Drop glue on quartz



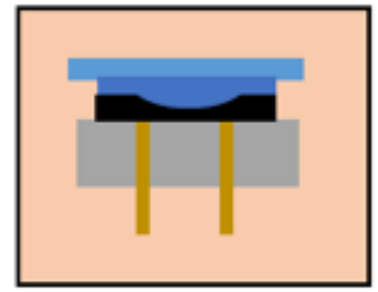
4



wait for cure keeping the quartz floated



5



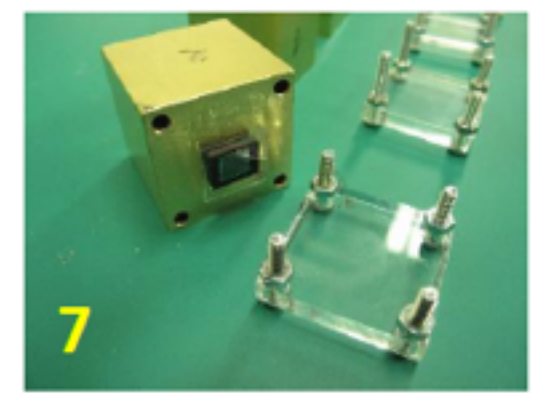
Put MPPCs into oven and wait 24 h (keeping 45 deg)

6

dispense epoxy glue (araldite 2011)

7

apply weight



8

wait 24 h for cure