26th September 2017

An SiPM application for the KOTO CsI calorimeter

K. Kotera Osaka University
on behalf of KOTO collaboration.

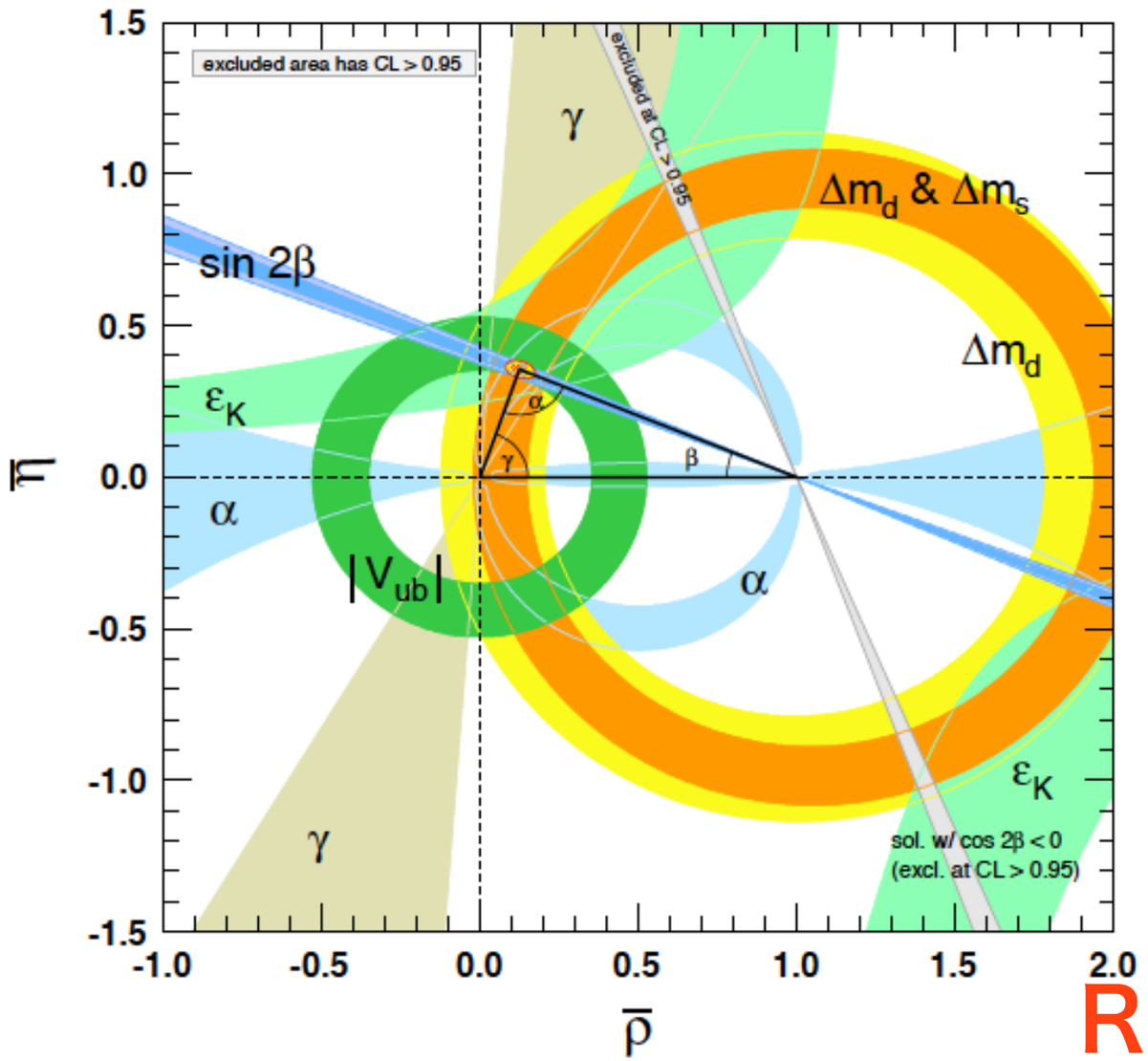
KOTO experiment

Search for $K_L \to \pi^0 \nu\bar{\nu}$

Purpose of KOTO

Fix of η: height of CKM unitary triangle via $K_L \to \pi^0 \nu\bar{\nu}$

Im



Re

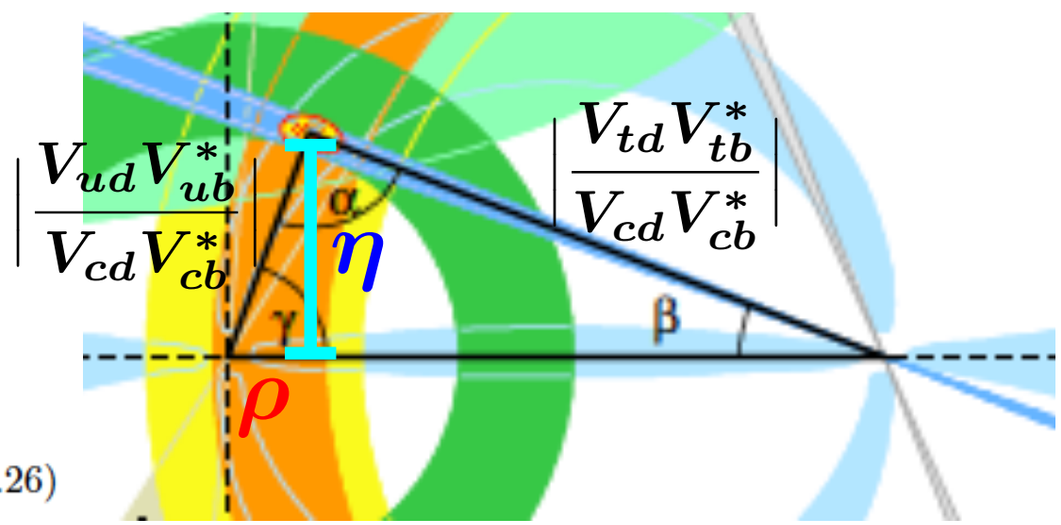
Figure 12.2: Constraints on the $\bar{\rho}, \bar{\eta}$ plane. The shaded areas have 95% CL.

$$\bar{\rho} = 0.124^{+0.019}_{-0.018}\,, \qquad \bar{\eta} = 0.356 \pm 0.011\,. \qquad (12.26)$$

$$V_{\rm CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}.$$

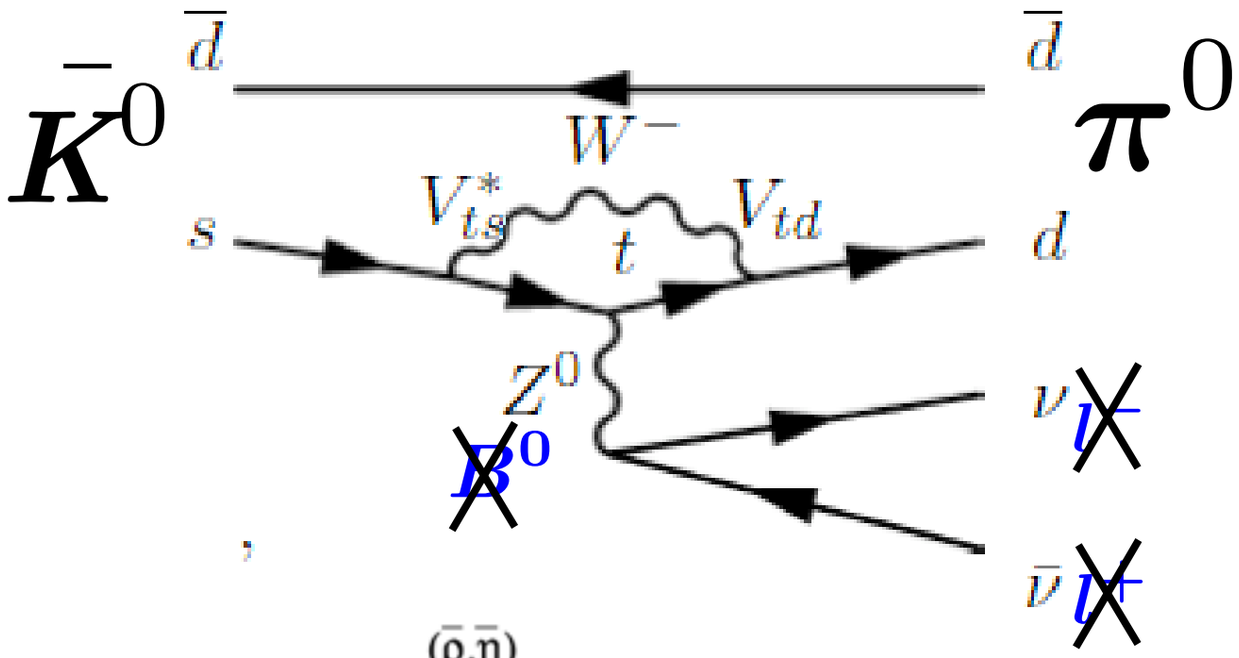
CP violation parameters

$$= \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}$$



Purpose of KOTO

Fix of η: height of CKM unitary triangle



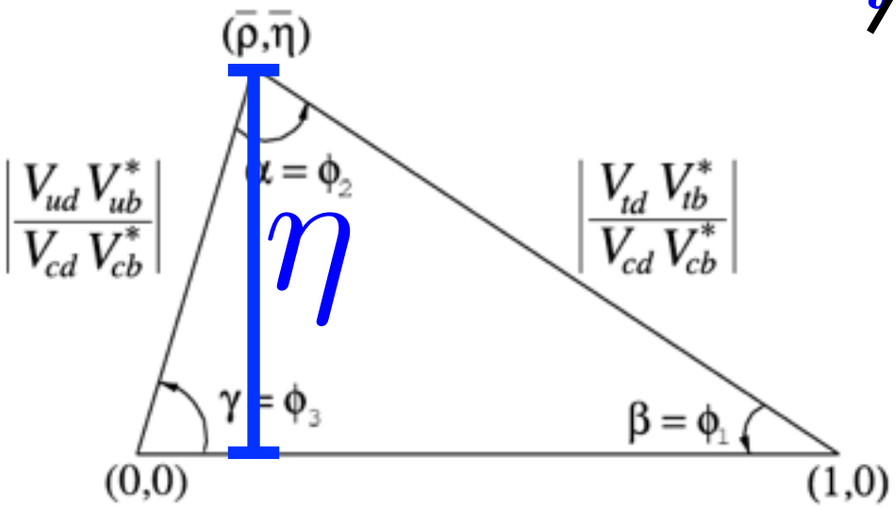


Figure 12.1: Sketch of the unitarity triangle.

$$V_{\rm CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)\,.$$

Pure Weak interaction
only Z^0 (cannot B^0)

$$K_L \sim \frac{1}{\sqrt{2}}(|K^0\rangle - |\bar{K}^0\rangle)$$

note: mixing

$$A(K_L \to \pi^0\nu\bar{\nu})$$
$$\propto A(K^0 \to \pi^0\nu\bar{\nu})$$
$$-A(\bar{K}^0 \to \pi^0\nu\bar{\nu})$$
$$K^0 \to V_{td}^* V_{ts}$$
$$\bar{K}^0 \to (V_{td}^* V_{ts})^*$$

only imaginal part lives

$$i\eta$$

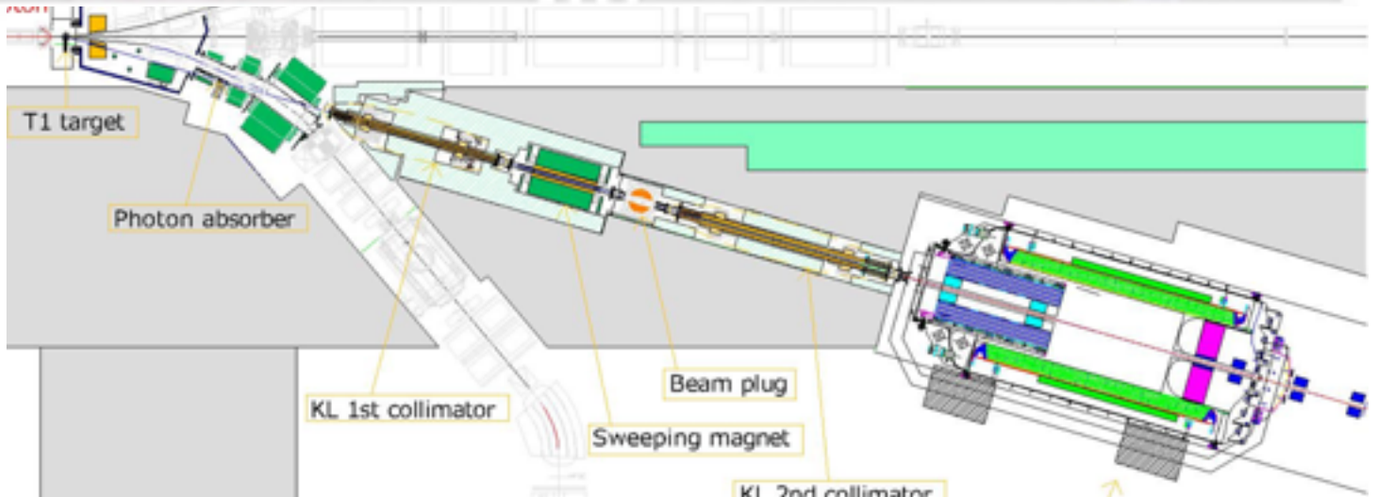
JPARC, Hadron hall

Proton Accelerator Research Complex

Ichinoseki

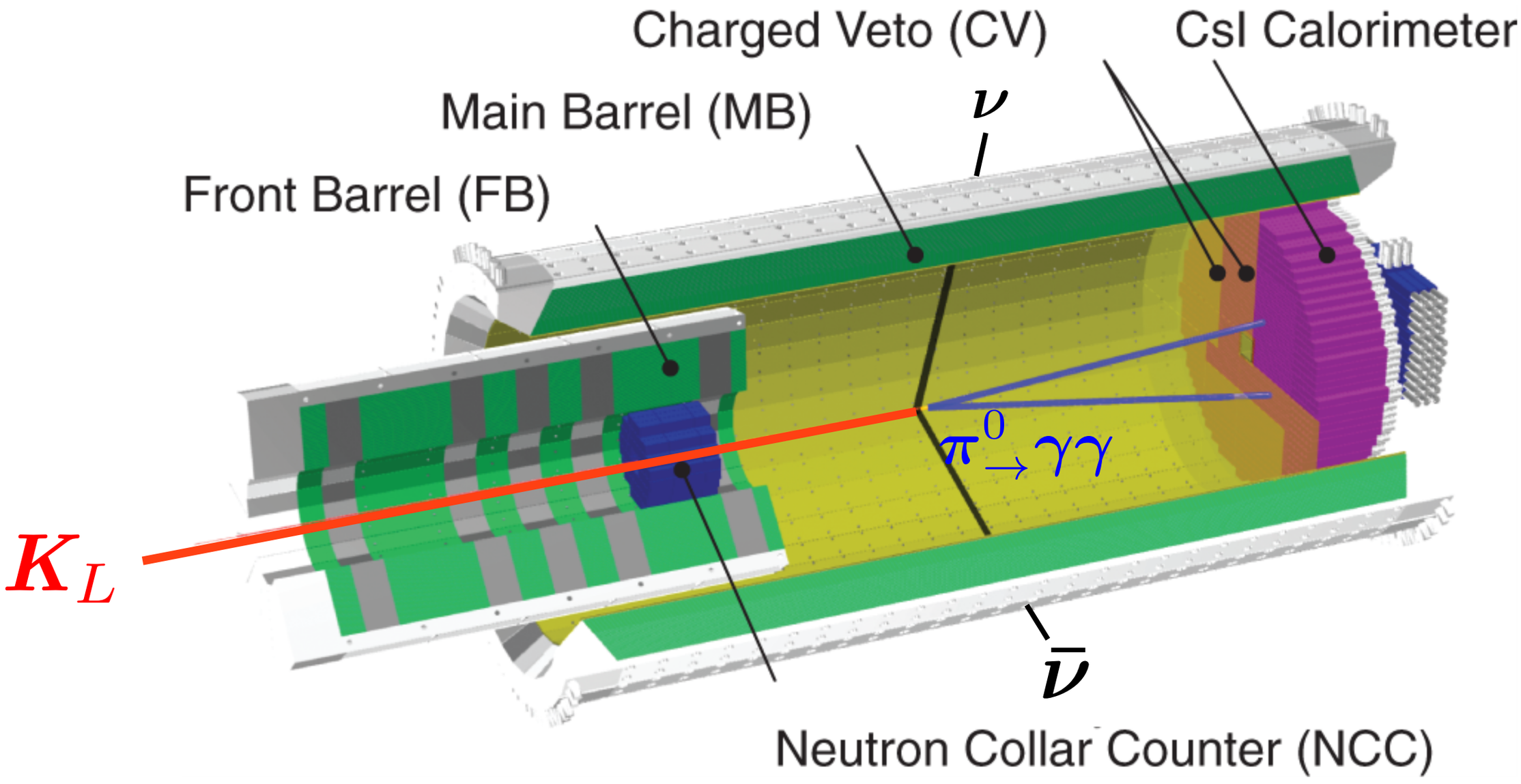
Sendai

Pacific ocean



KOTO detector

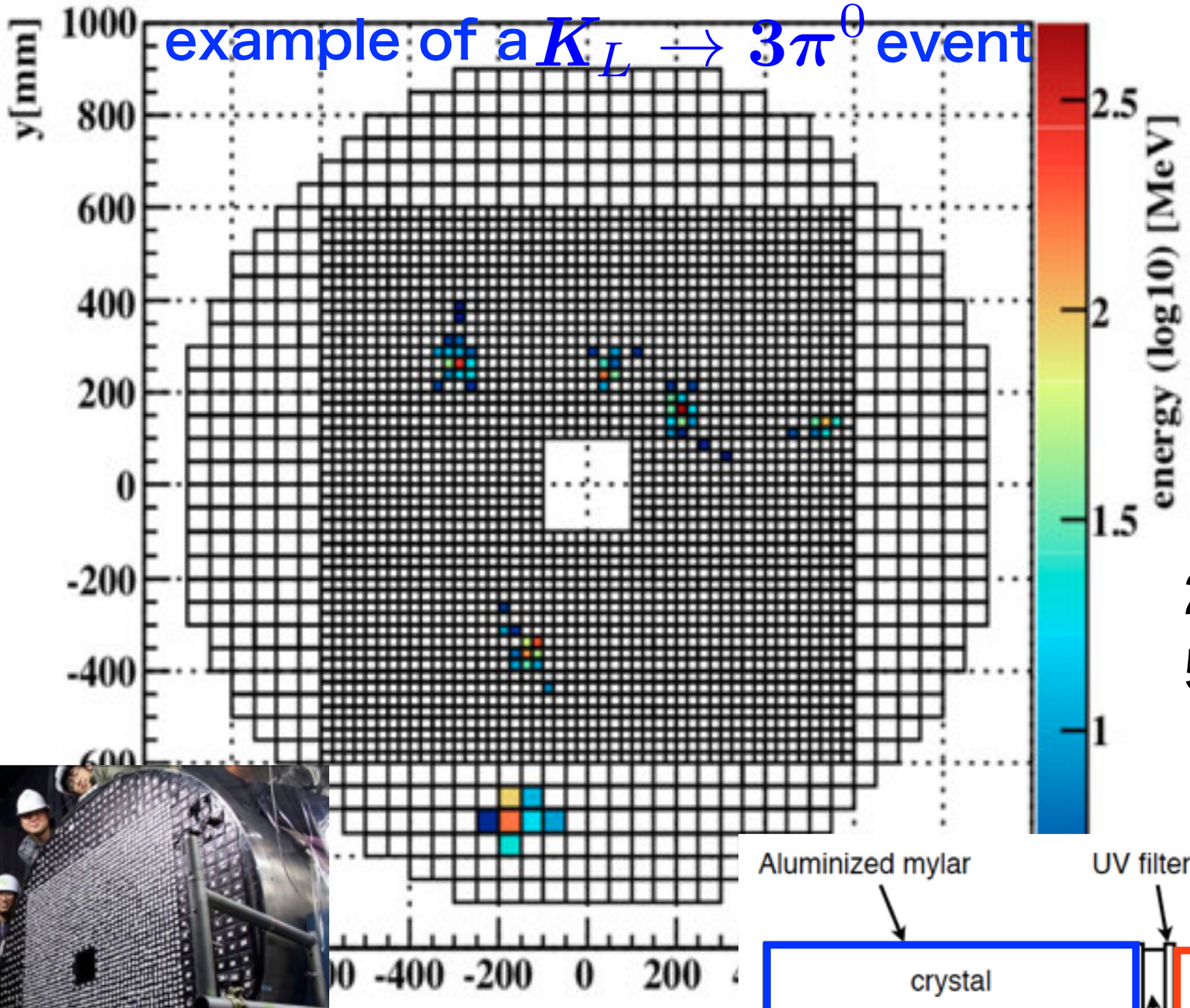
$K_L \to \pi^0 \nu\bar{\nu}$: Br=(3.0±0.3)×10^{-11} S.M.



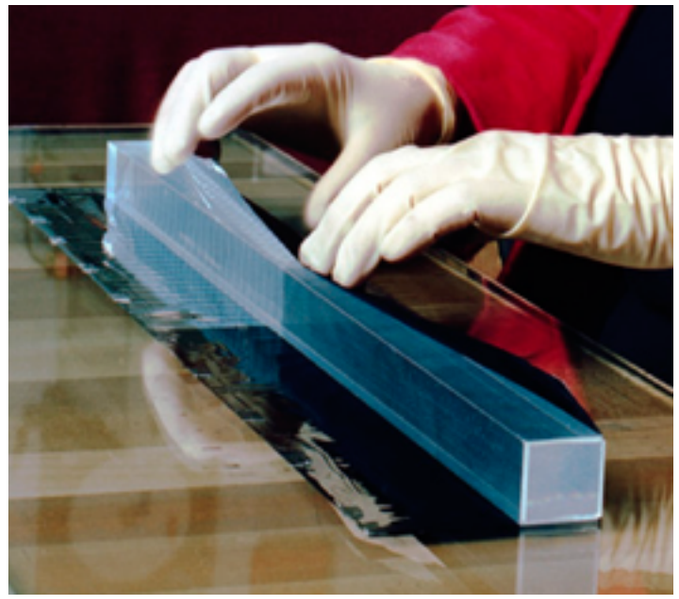
Only signal $\pi^0 \to \gamma\gamma$ **➡ found on CsI Cal**

Key: prevent background

CsI calorimeter

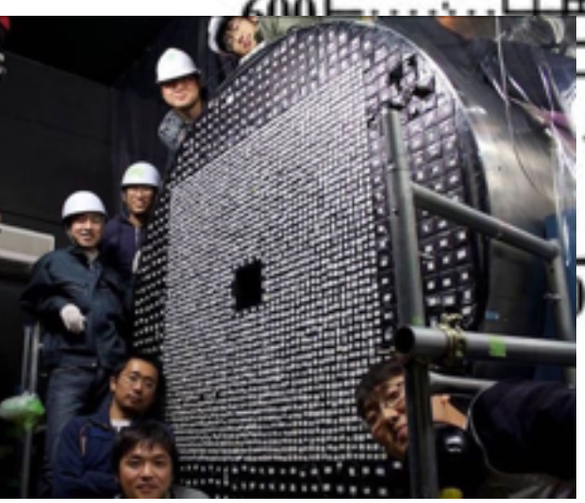


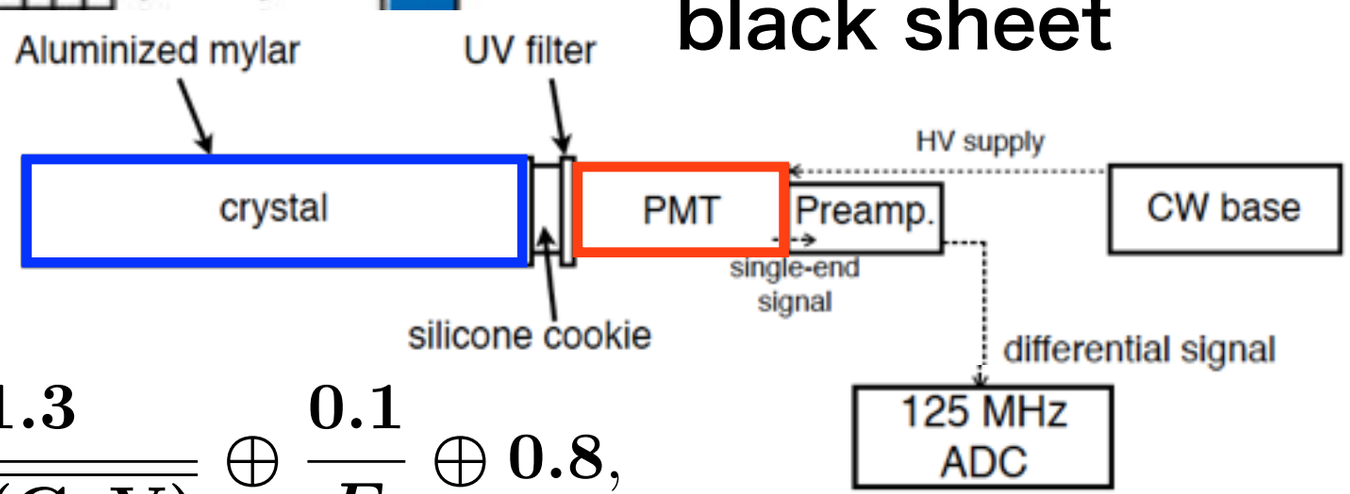
Pure CsI 27X0



2.5x2.5x50cm³x2240
5.0x5.0x50cm³x476

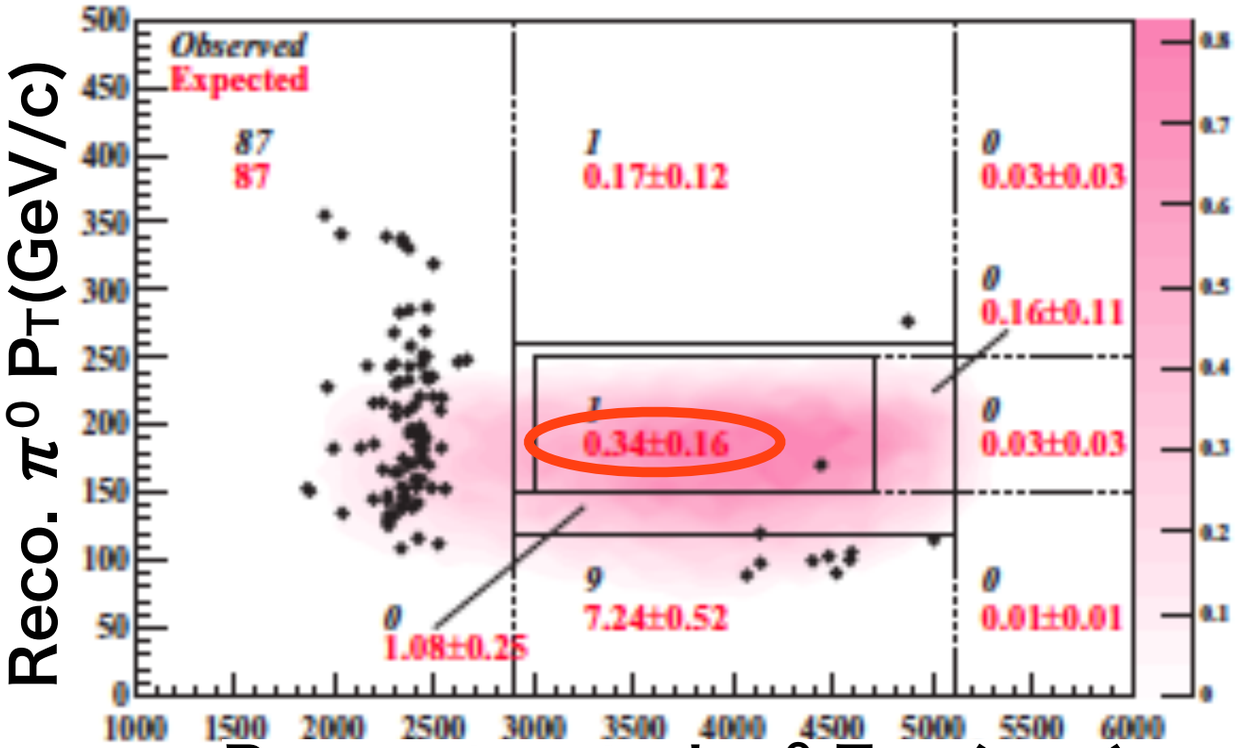
aluminized mylar
black sheet





$$\frac{\sigma_E}{E}(\%) = \frac{1.3}{\sqrt{E(\mathrm{GeV})}} \oplus \frac{0.1}{E} \oplus 0.8,$$

Published latest result



1 event exists.

MC expects: 0.34±0.16 event

0.18±0.15: beam halo neutron

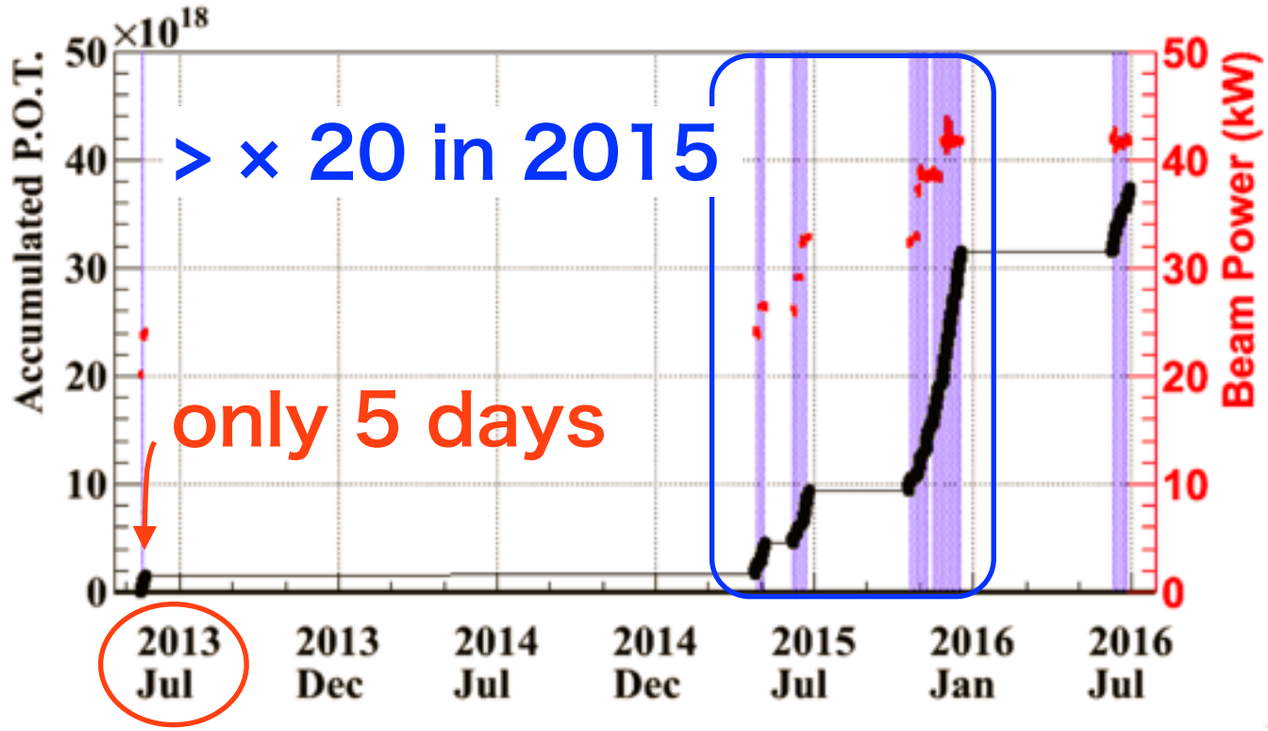
➡ Br=3.0×10^{-11}

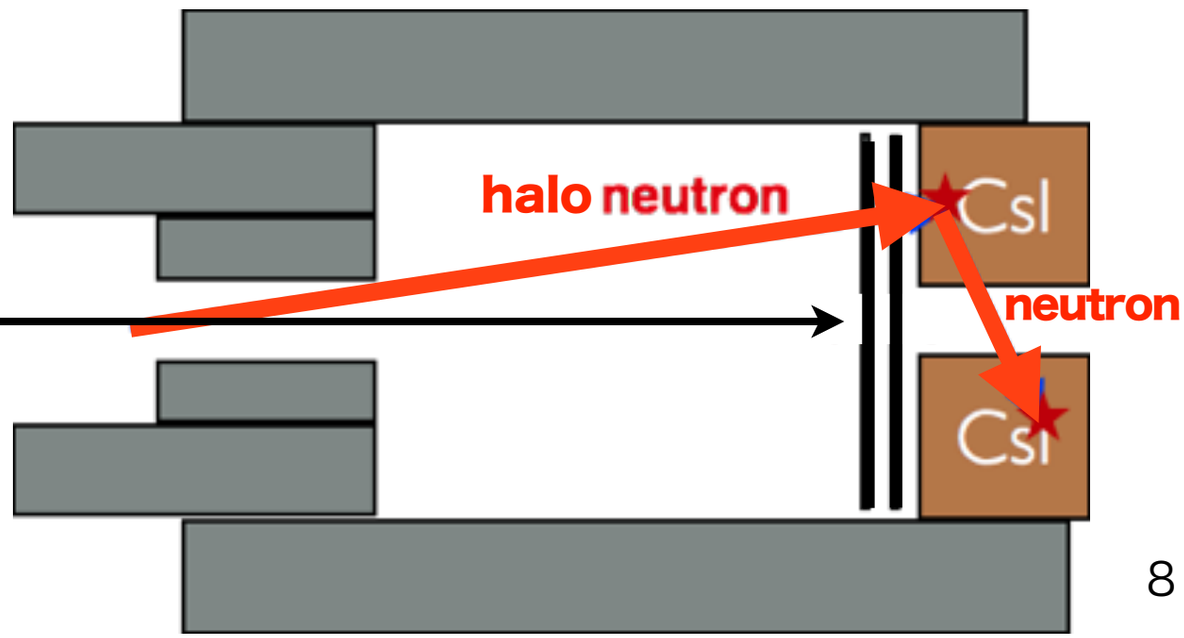
: need to reduce 3 order

2013 data

$< 5.1\times10^{-8}$ (90%C.L.)

PTEP: Volume 2017, Issue 2, 1 February 2017, 021C01





To resolve

Discrimination of n / γ

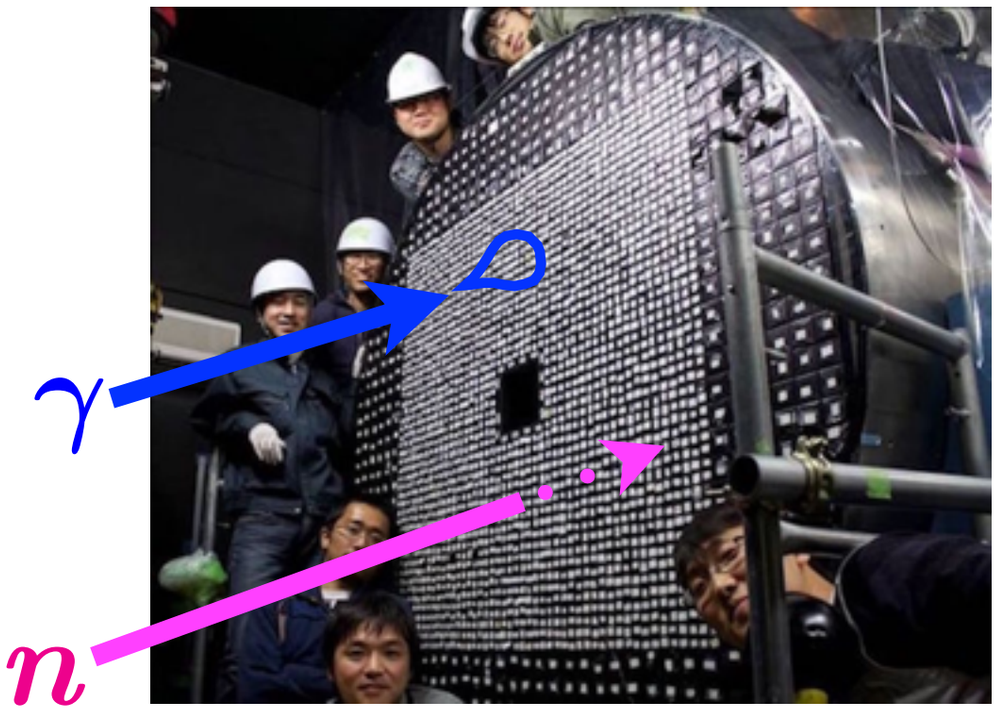
- Cluster shape (χ^2)
- Cluster shape (Neural net)
- Pulse shape

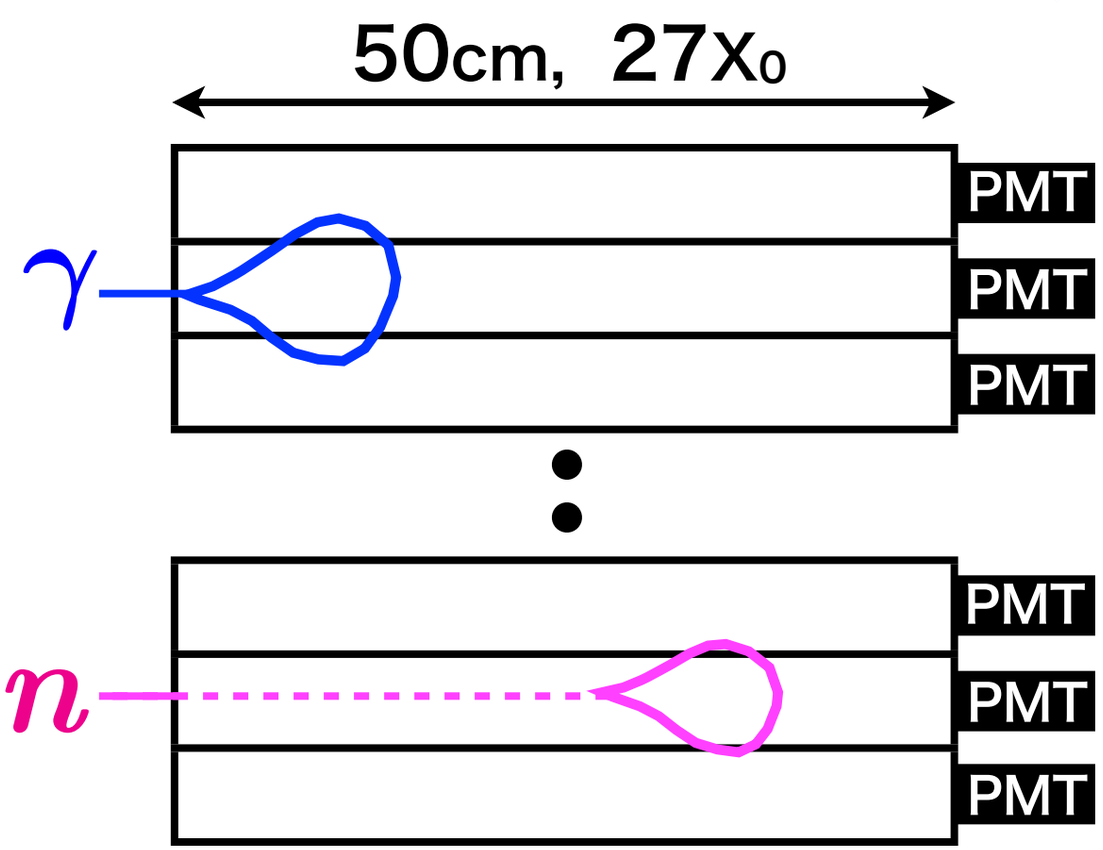
} 1/35 already achieved

➡need one more order

+ CsI Calorimeter both end readout

rejection power : $\times\mathcal{O}(10)$





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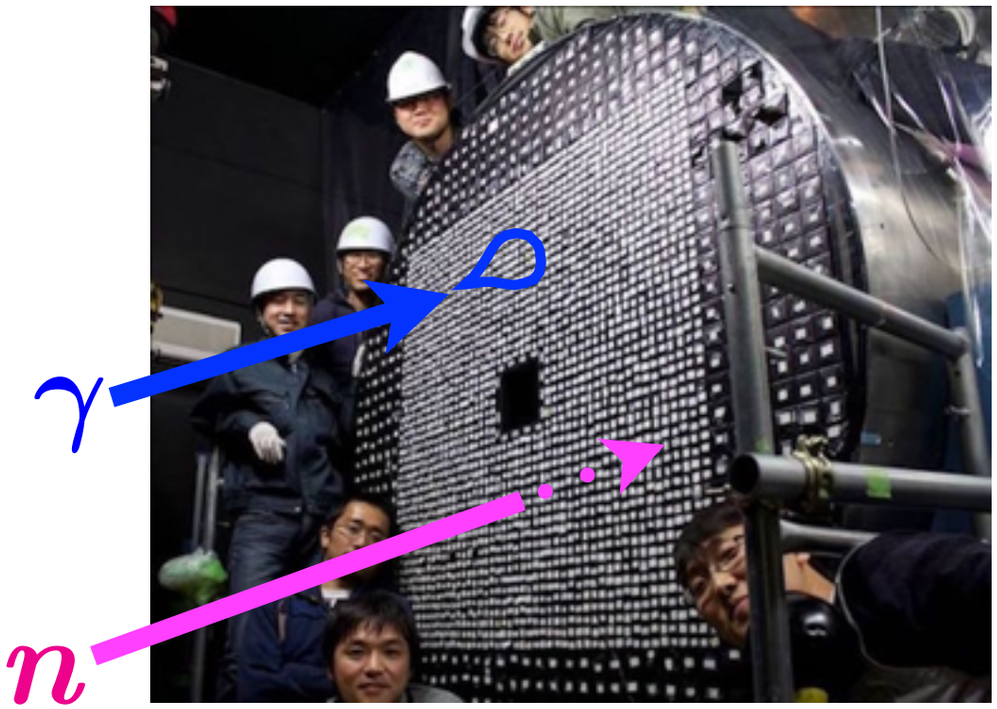
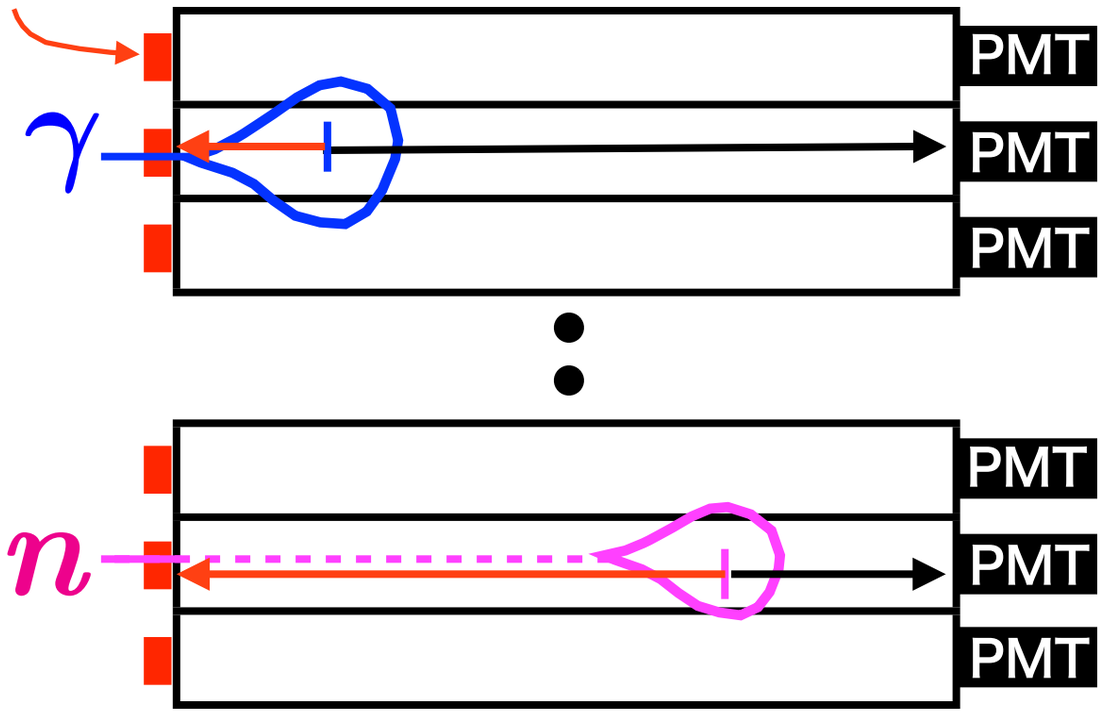
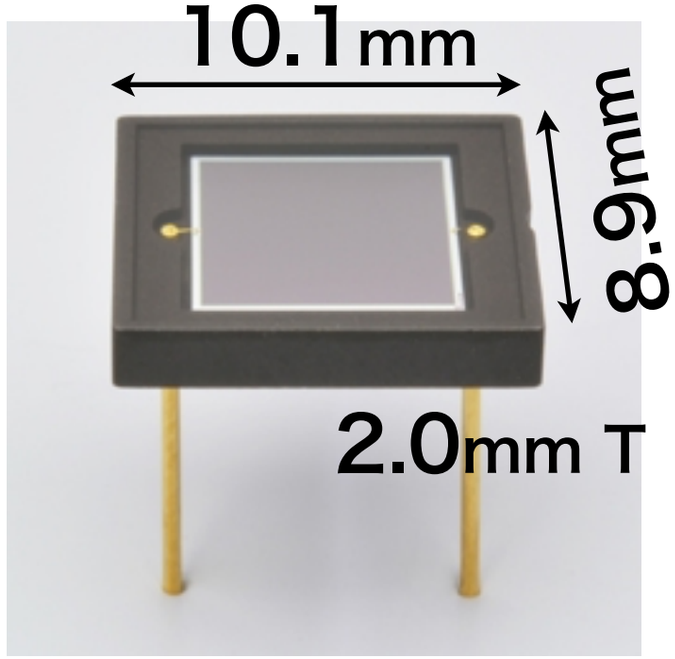


SiPM : time difference with PMT



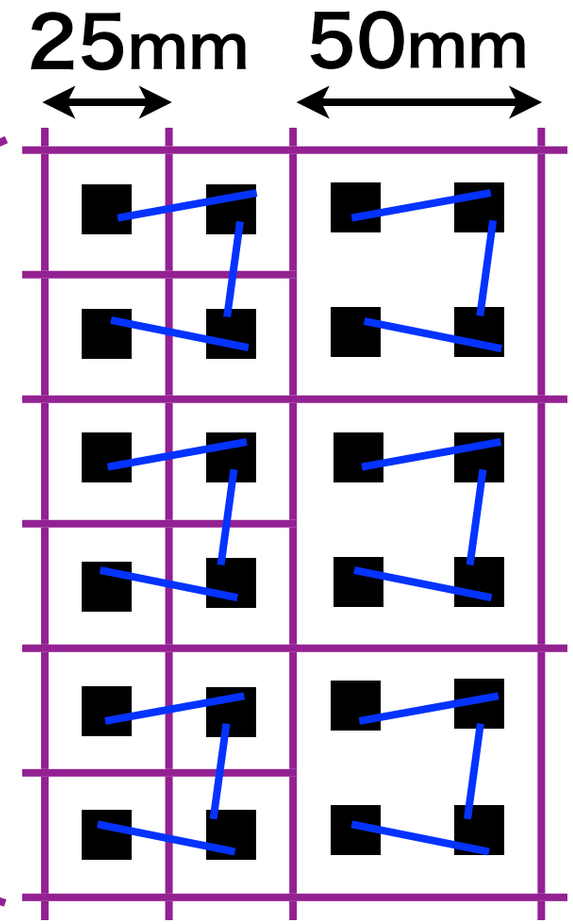
MPPC(Multi-Pixel Photon Counter)



Sensor area: 6 × 6 mm^2
Pixel pitch: 50μm
Package: Ceramics
Dark count rate: 2×10^6 cps
Gain: 1.7×10^6 @ V_{break} + 3V
Response range: 270-900nm (max 450nm)

Silicone cover allows UV transparency

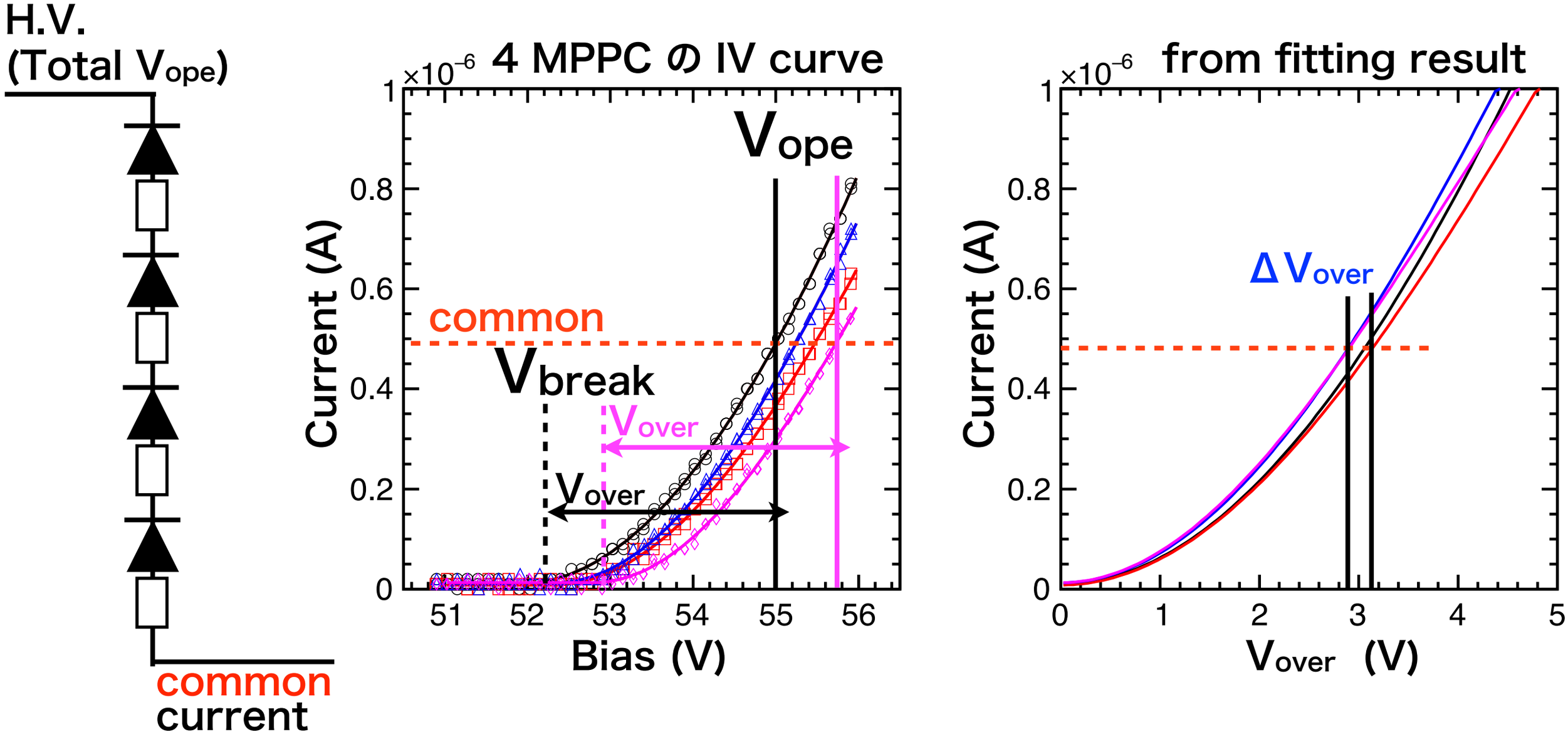
Configuration on CsI



4-MPPC serial

Serial connection

- 4-MPPC has a common current
- variation of V_{break}➡ shifts the IV curve



Response

- Before vs after irradiation

Requirement

Lower energy boundary : 3 MeV/MPPC

CsI photon yield/MPPC : 6 p.e./MeV

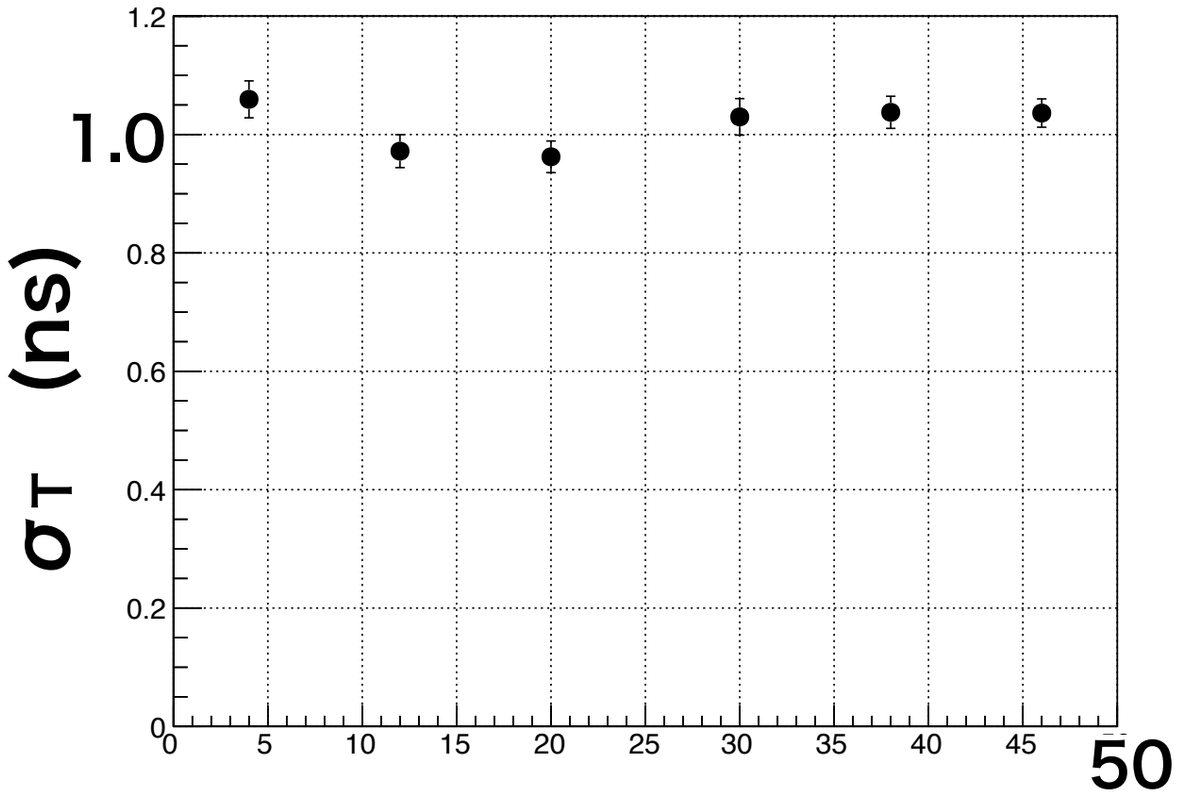
} 18 p.e./MPPC

not difficult requirement for before irradiation

still OK after irradiation?

Timing information

Cosmic ray



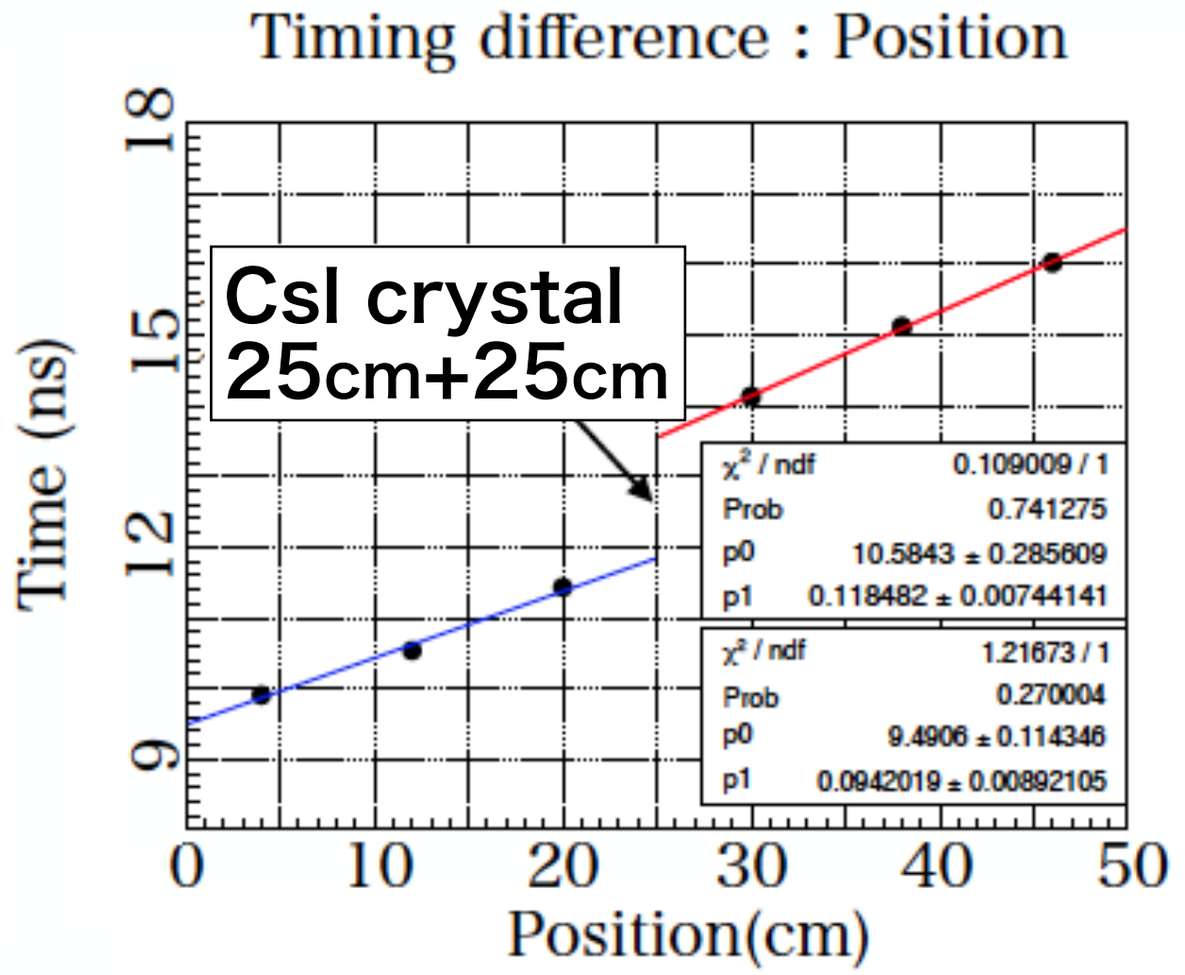
$$\sigma_t(\mathrm{ns}) = \frac{0.12}{\sqrt{E(\mathrm{GeV})}} \oplus 0.10,$$

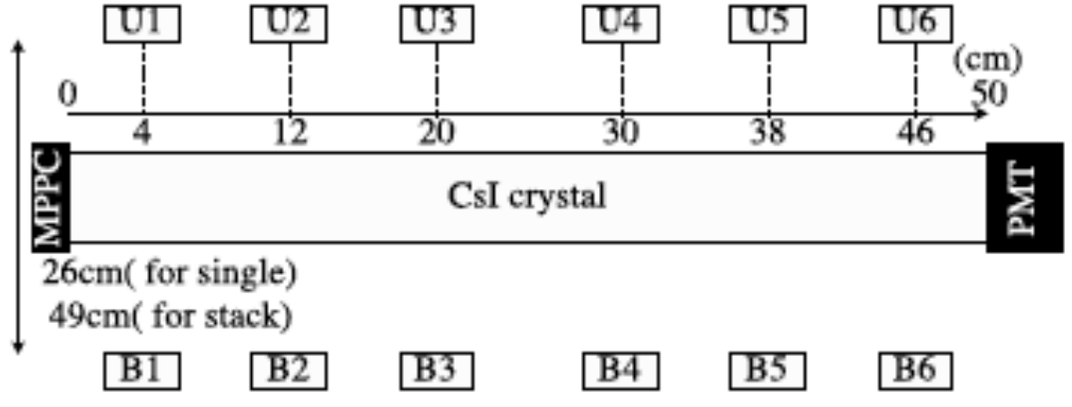
σT = ~1ns

timing resolution

MPPC-PMT

constant fraction

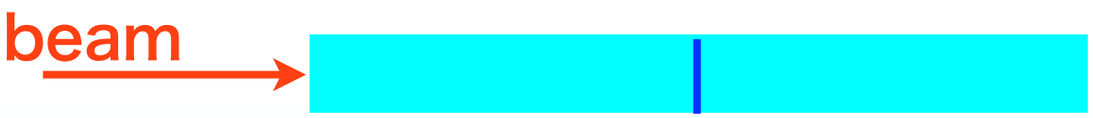


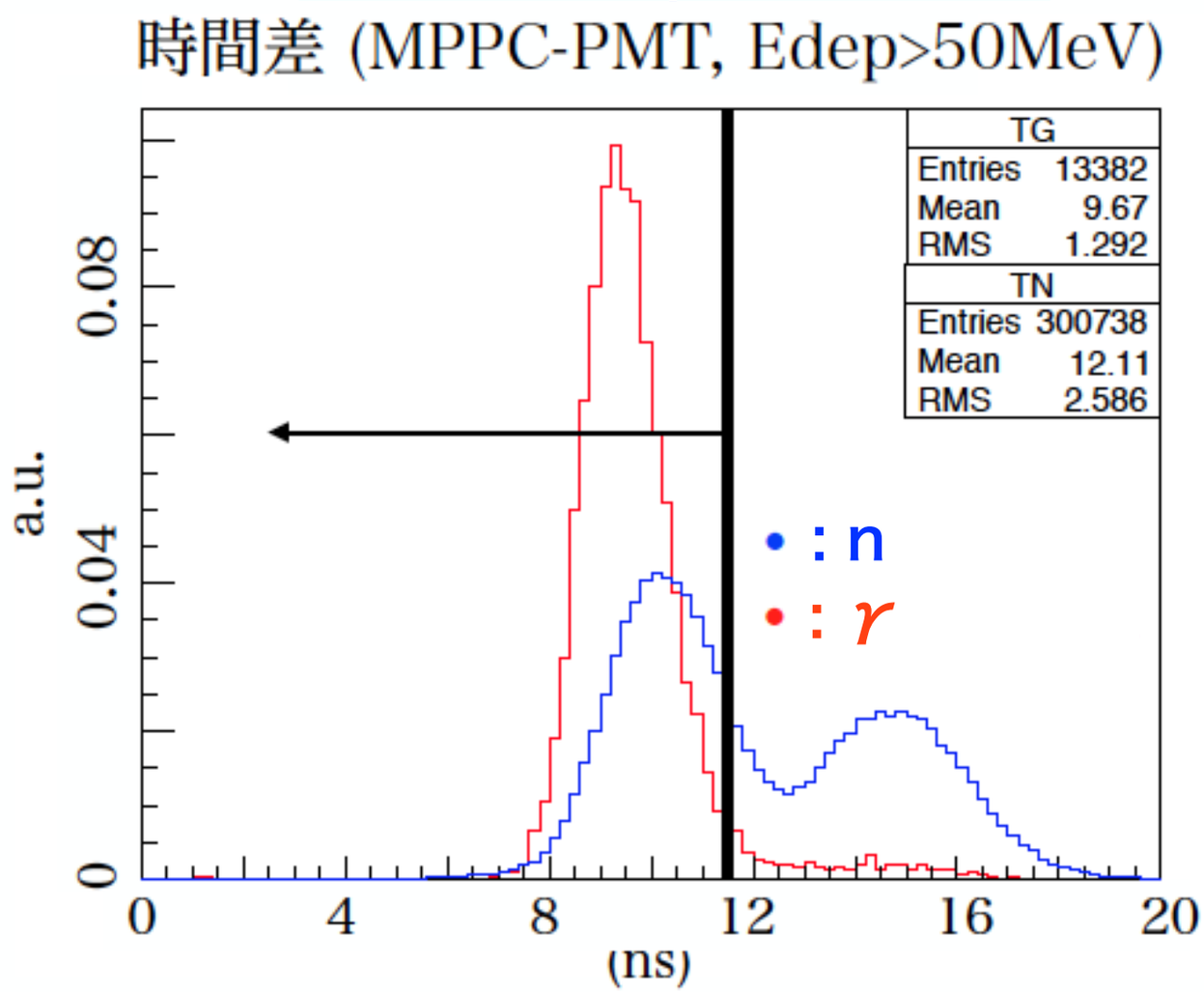


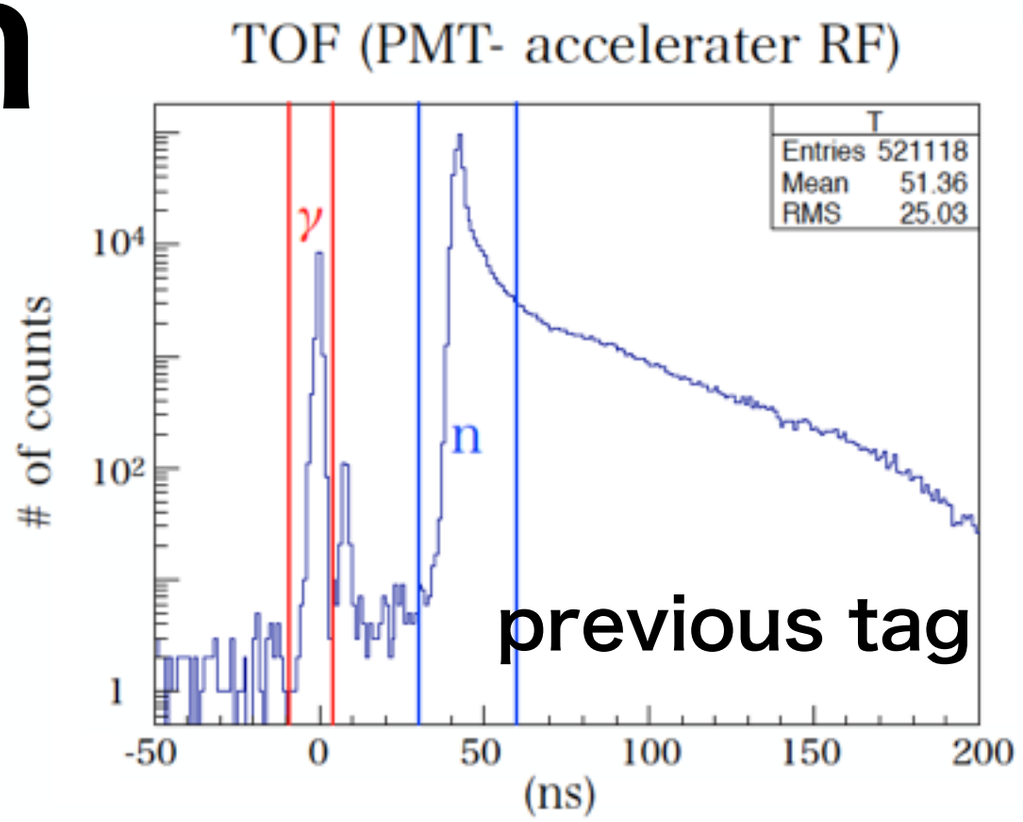
γ-n separation

Test beam at the Research Center for Nuclear Physics (Osaka U Feb.2017)

400 MeV neutrons

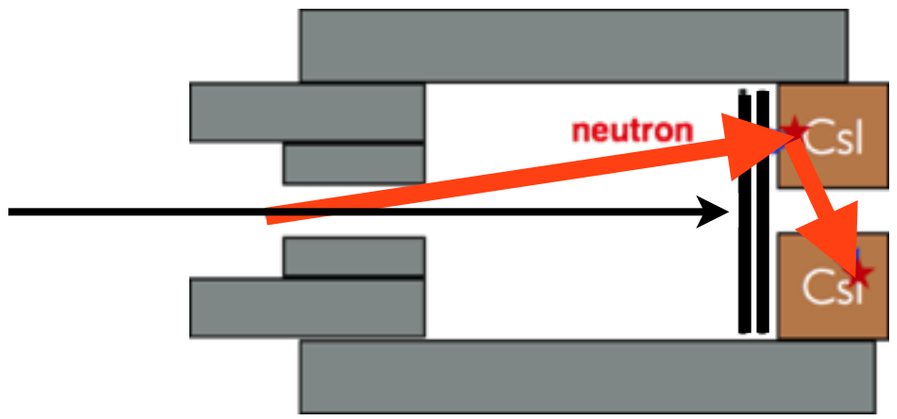






90% γ acceptance

50% n rejection



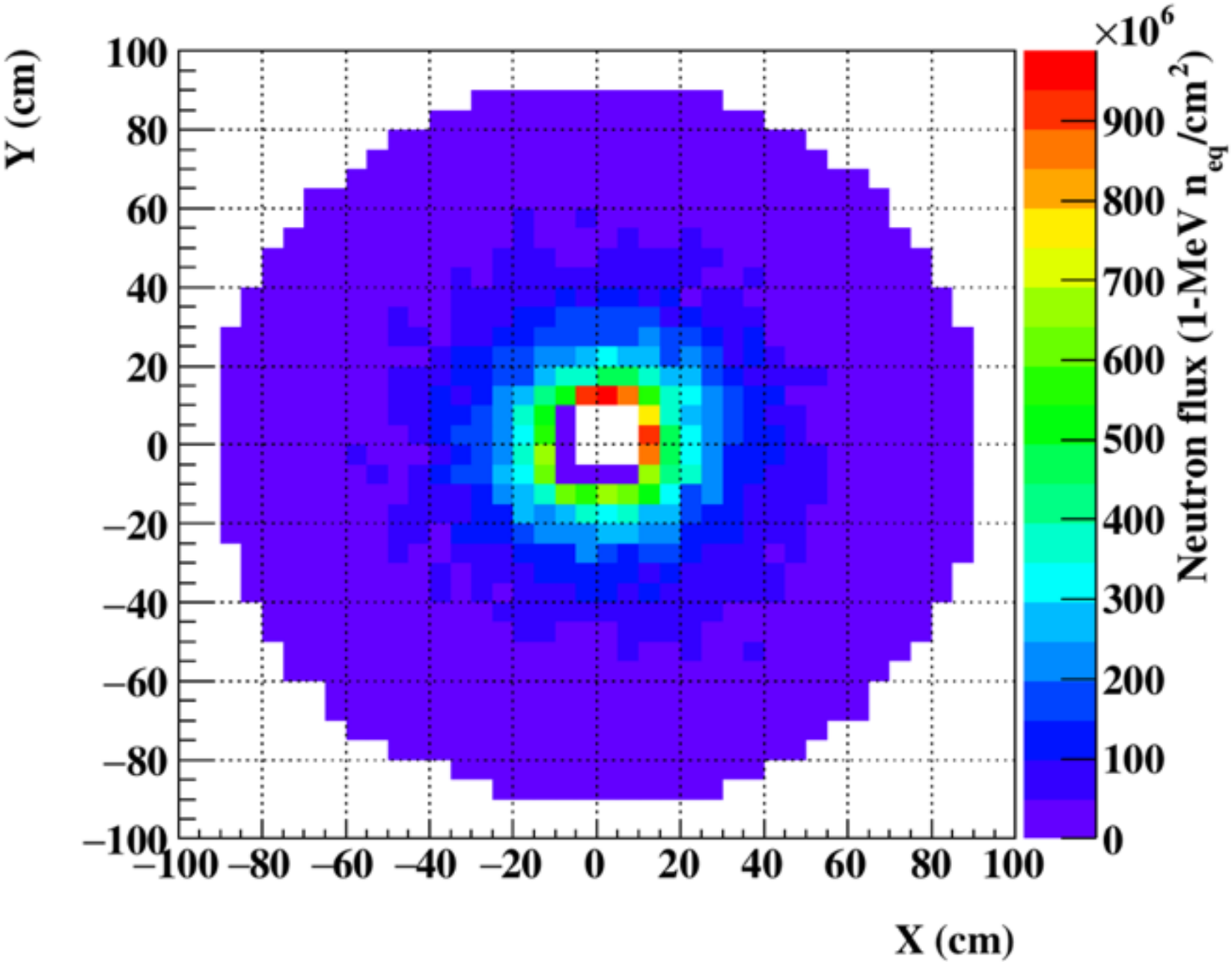
most of 2nd cluster is detected at the downstream.

➡ 90% n rejection.

Neutrons on KOTO CsI (MC)

3 Snowmass years (3×10^7 s)
with 100kW beam(nowadays 40-60kW)

implemented a shift of beam center (conservative) : x 6mm, y 2mm.

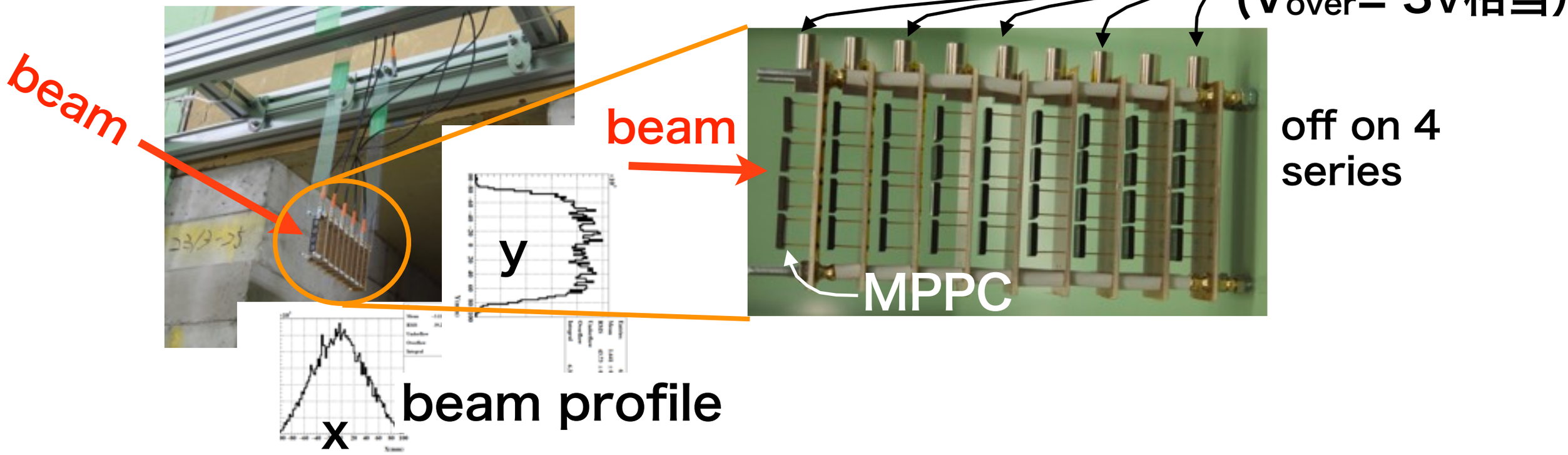


max
10^9 n_{1MeV}/cm^2

Irad @ KOTO beam dump hole, 25th June 17

36 MPPC samples

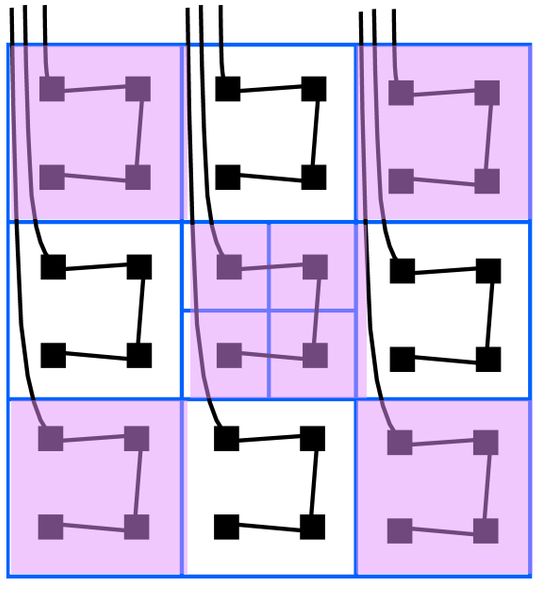
Bias on : 5 series
(V_{over}= 3V相当)



beam profile

1.5×10^9 n_{1MeV}/cm^2 (1.5 × 3 snowmass Y)

For test beam at ELPH (Tohoku U)

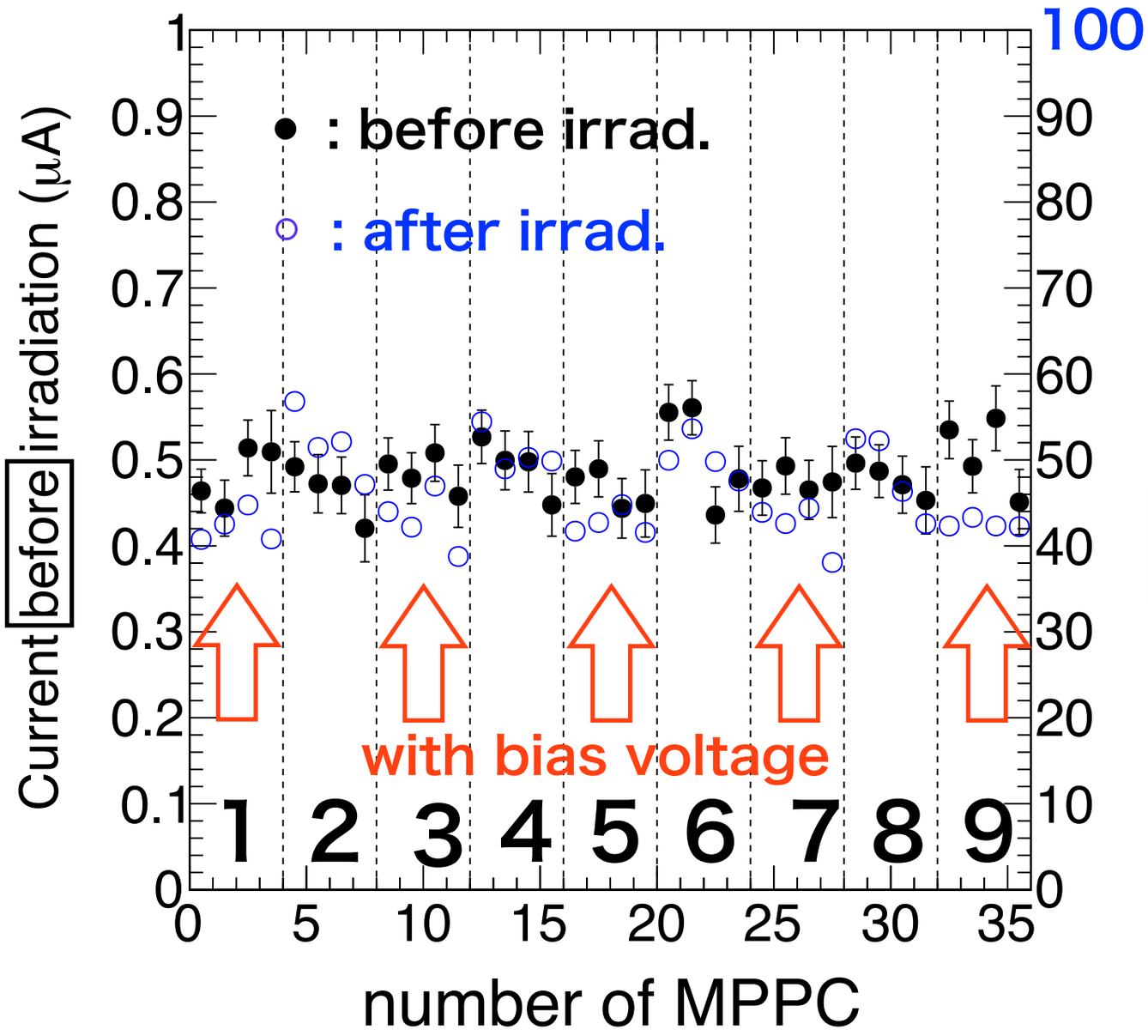


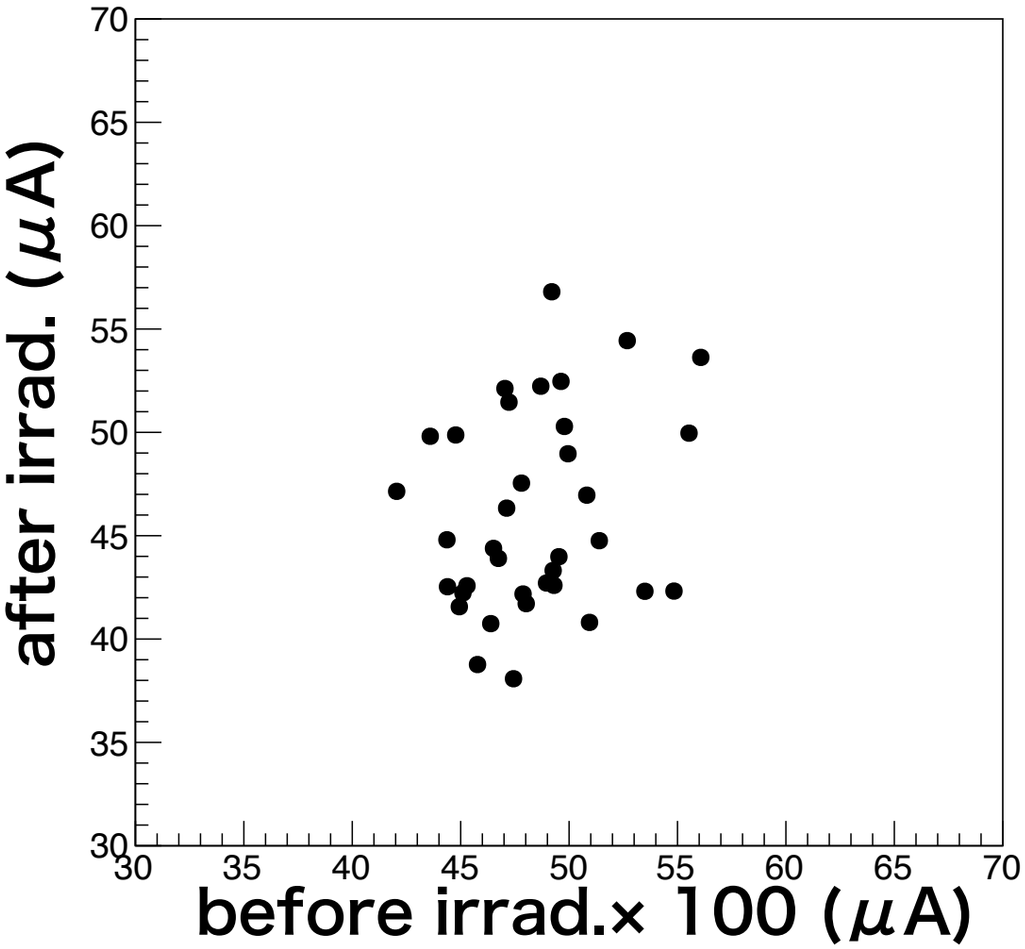
200 - 800 MeV electron

from 9th December 2017

Dark current @ V_{over}=3V

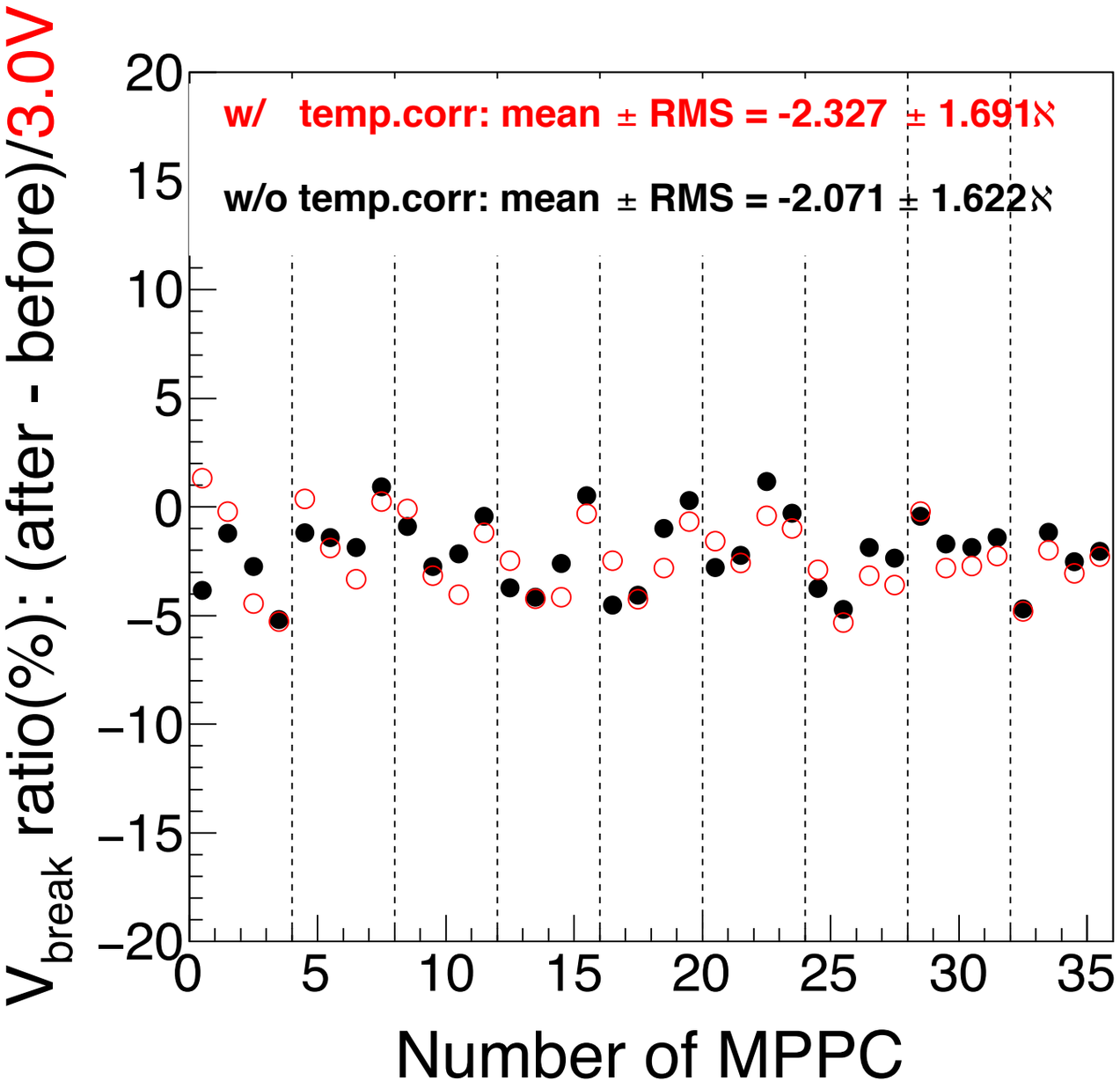
- Before vs after irradiation





- 1.5 × 3 Snowmass Year (100kW) irradiation ➡ ~ x 100 倍 dark current.
- There is no difference among devices.
- There no affects by existence of bias.

V_{break} の変化



- no change of V_{break}

  $\Delta V/V_{over}(3V) \sim -2\%$.

- no effect by the temp. correction

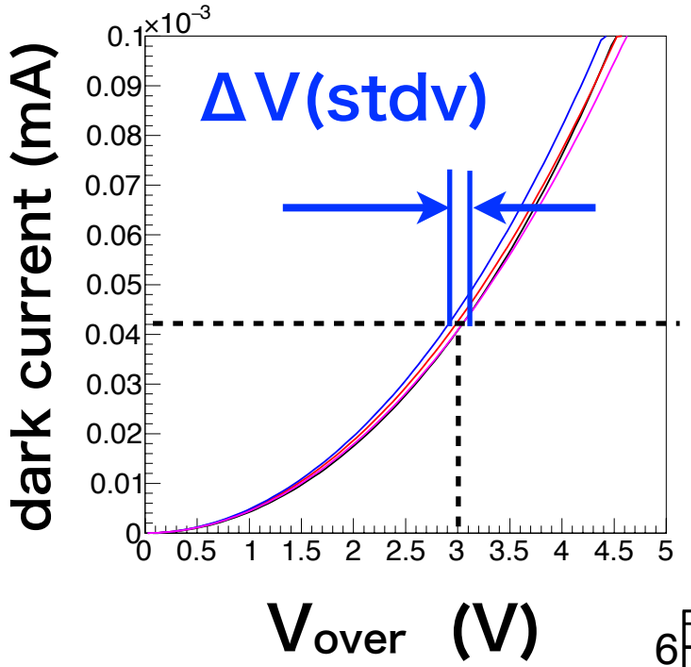
  54 mV/K

↓

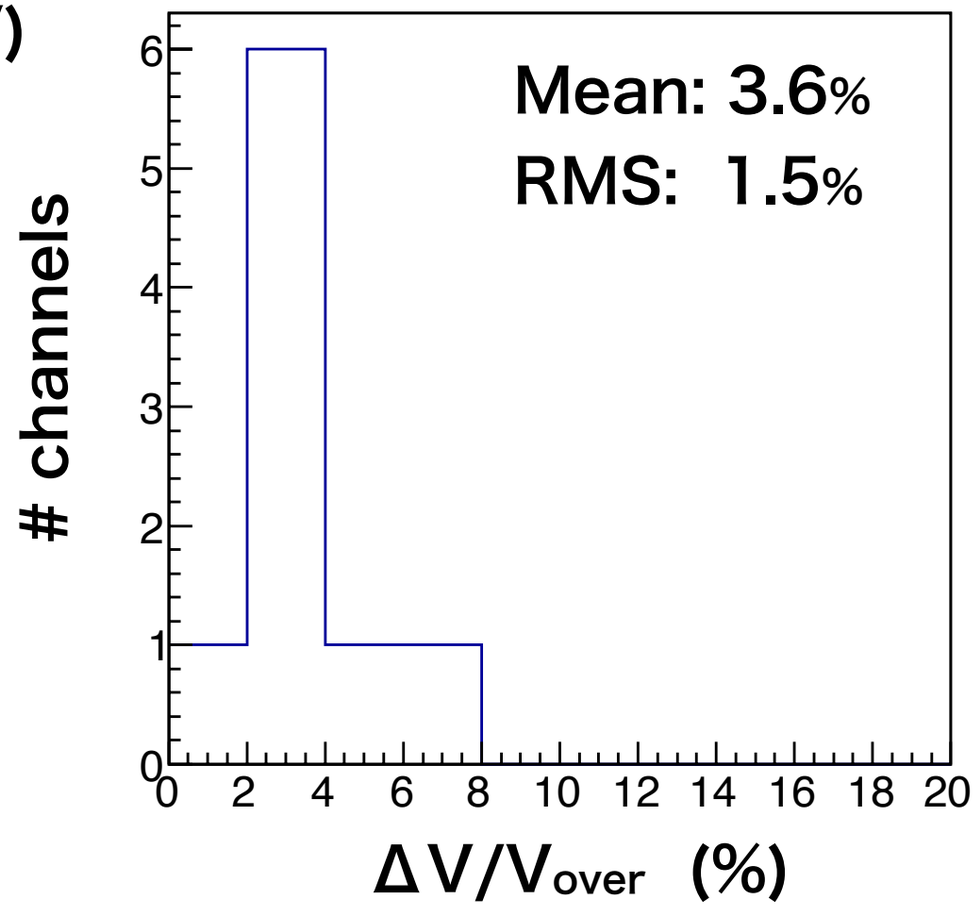
Difference among MPPCs ➡ not by temperature variation.

$\Delta V_{(stdv)}/V_{over}$(%) of 4 MPPCs

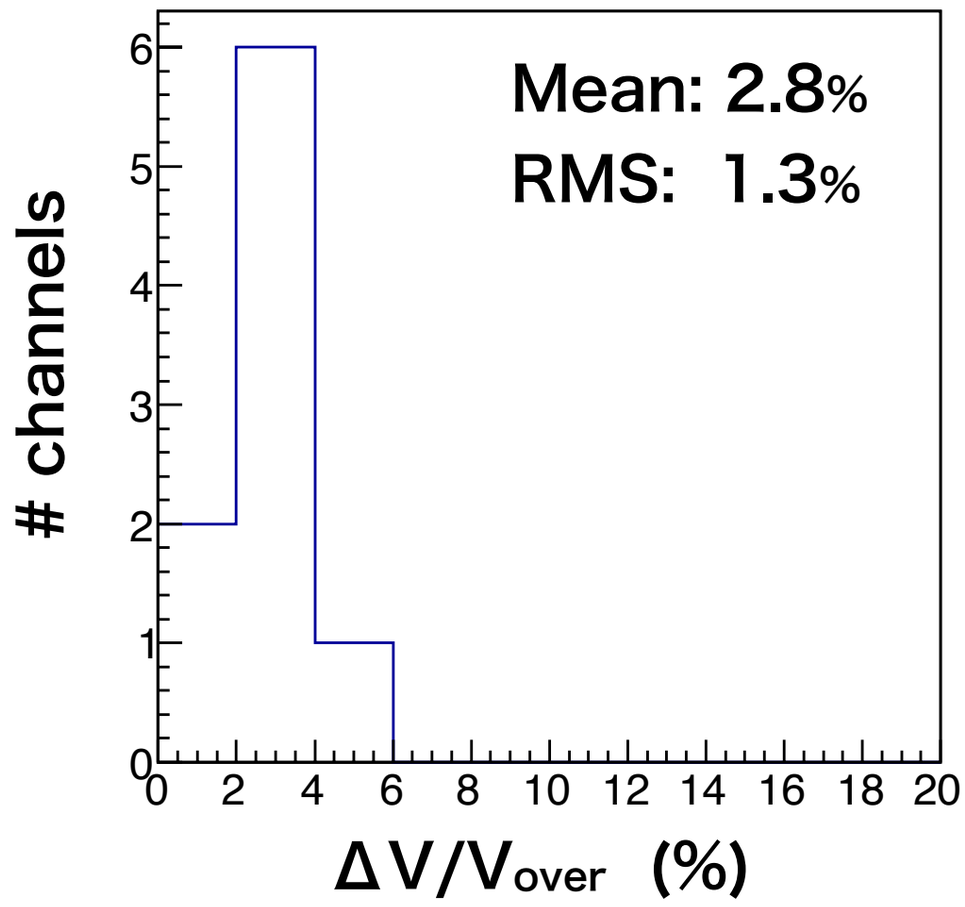
difference of V_{over} in s 4-series



Before



After



no degradation by irrad.

Sensitivity

- Before vs after irradiation

measurement

LED @ V_{over} = 3V

before after individual MPPC,

Result

Befor: 9.9±1.0(RMS) × 10^2 p.e.

After: 9.7±0.7(RMS) × 10^2 p.e.

(after-before)/before = -1.8±1.5%

No change of light response with 100 times dark noise

task: S/N at lower limit of energy

Summary

- KOTO is special experiment to search for $K_L \to \pi^0 \nu\bar{\nu}$.

- Amplitude of $K_L \to \pi^0 \nu\bar{\nu}$ can determine the height of CKM unitary triangle.

- Key issue of KOTO experiment is to prevent BG.

- Plane to upgrade using MPPCs to make both-end readout of CsI calorimeter to reduce neutron BG.

- Rejection power of neutron BG is promising.

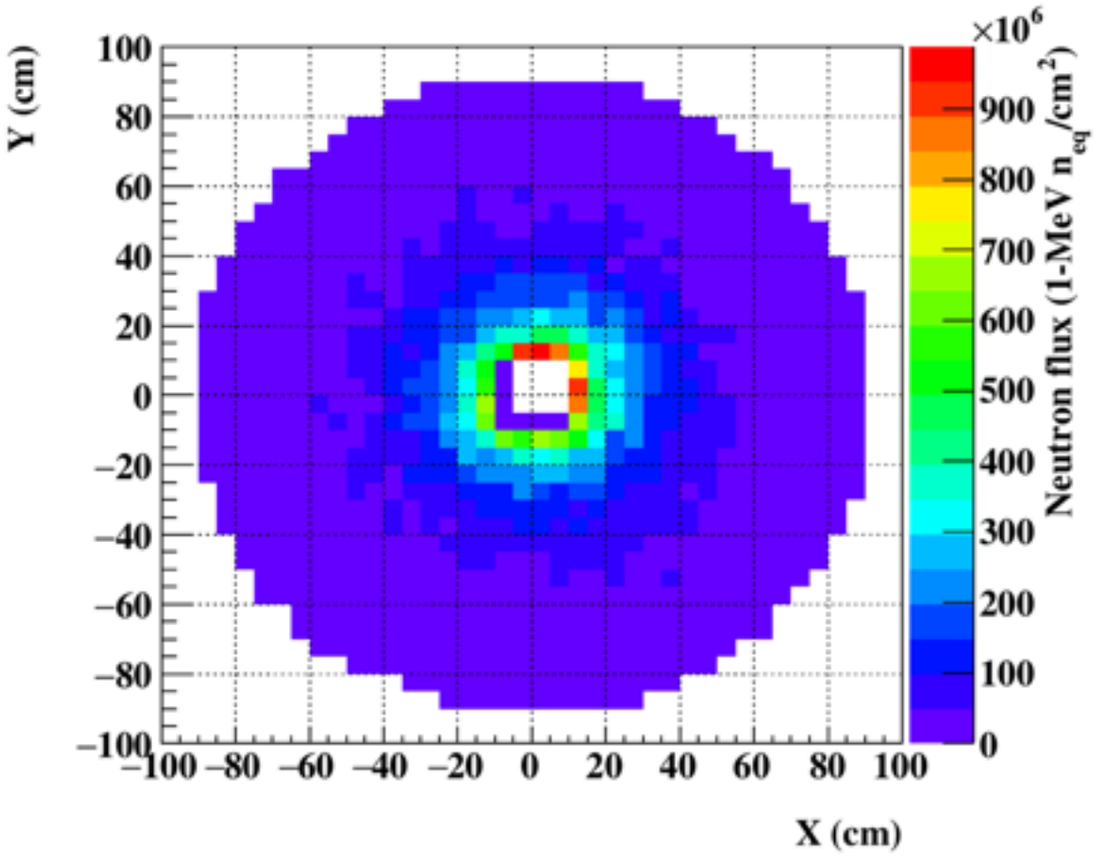
- Even 100 times larger dark current after 3 snowmass Y irradiation, variation of V_{break} is 2% of 3V V_{over}

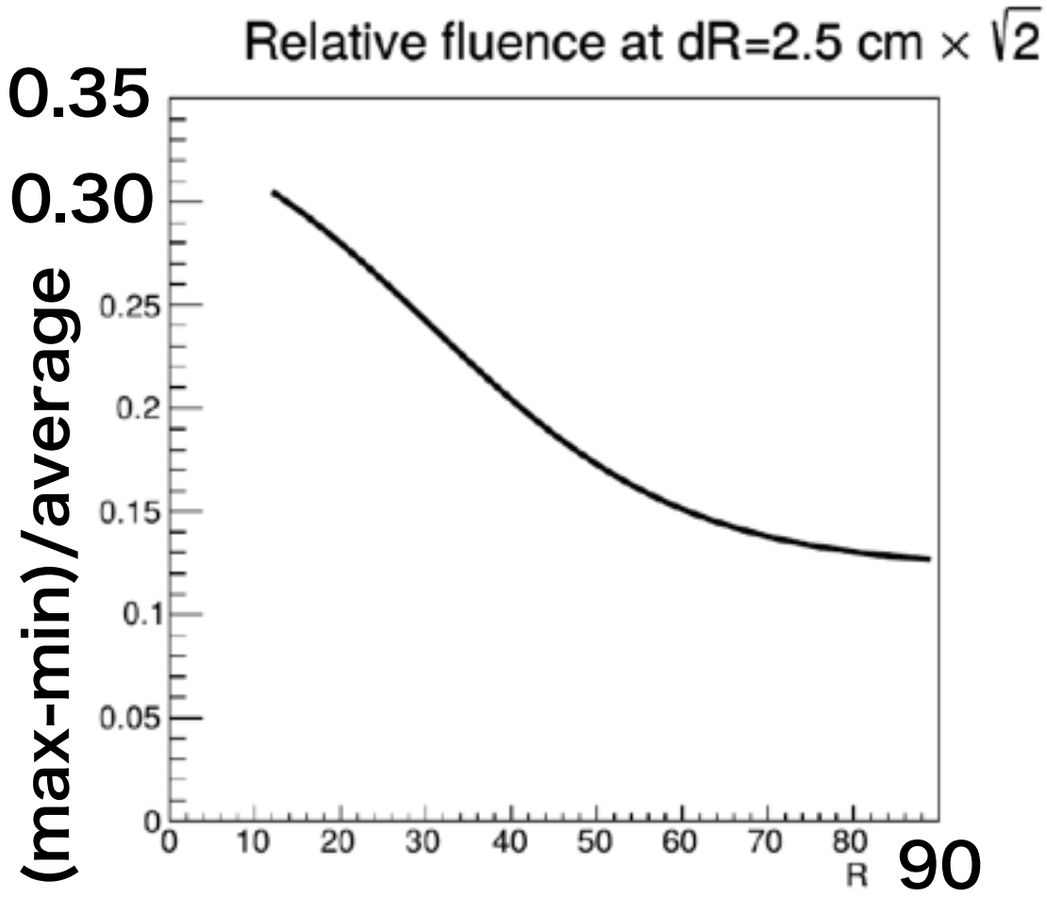
- Sensitivity to photon also does not degrade.

Backup

at JPS meeting

W. Ootani asked us:
“if difference of radiation is too large for a set of 4 MPPCs?”





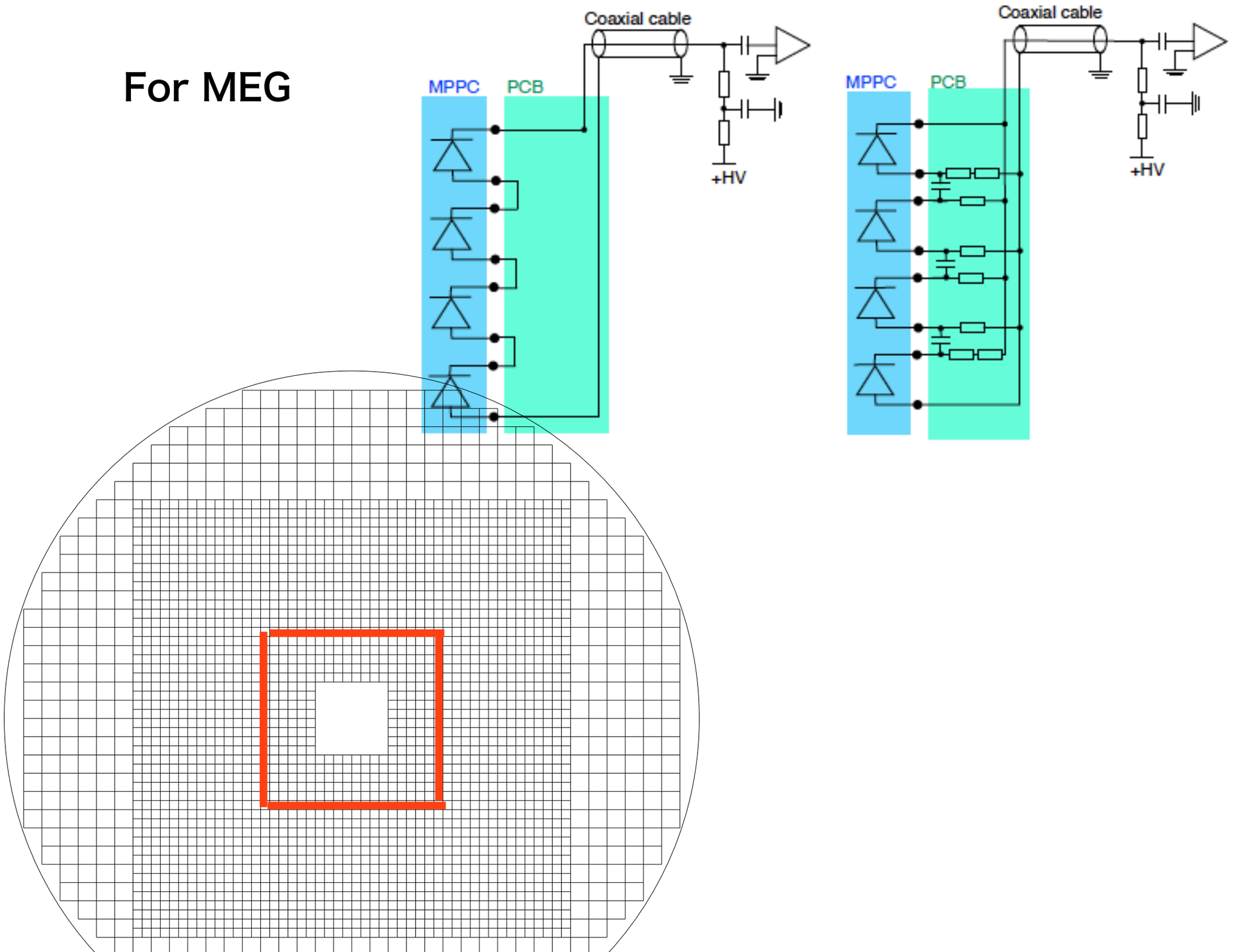
R: position from center(cm)

Slope is not so small

Hybrid connection

From S. Ogawa's (U Tokyo) Master thesis

For MEG



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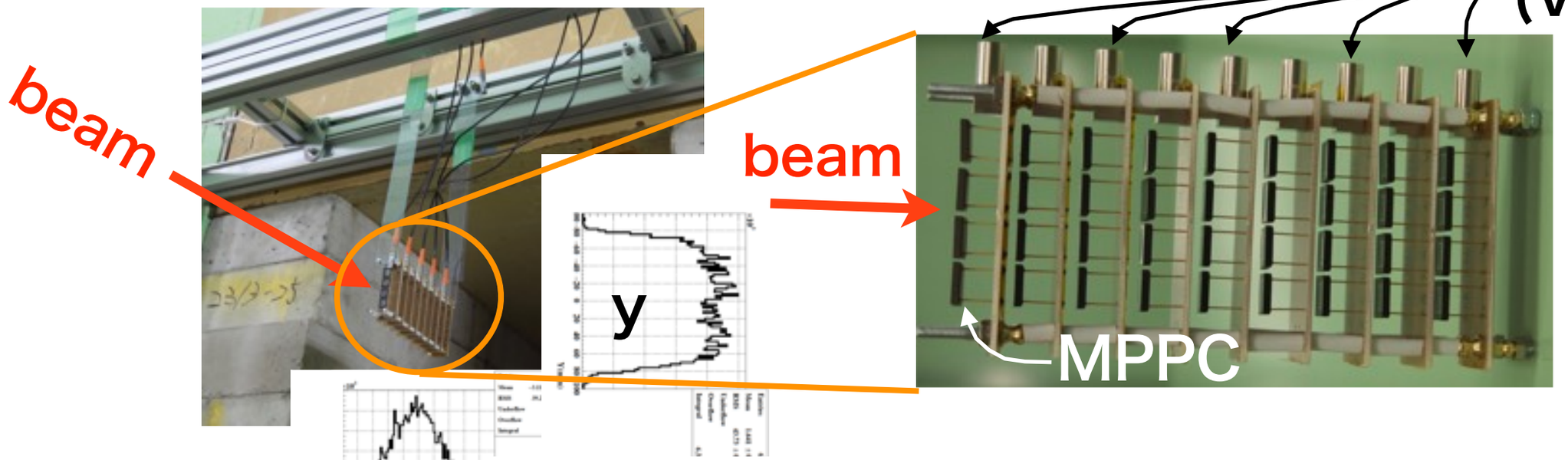
(V_{over}= 3V相当)

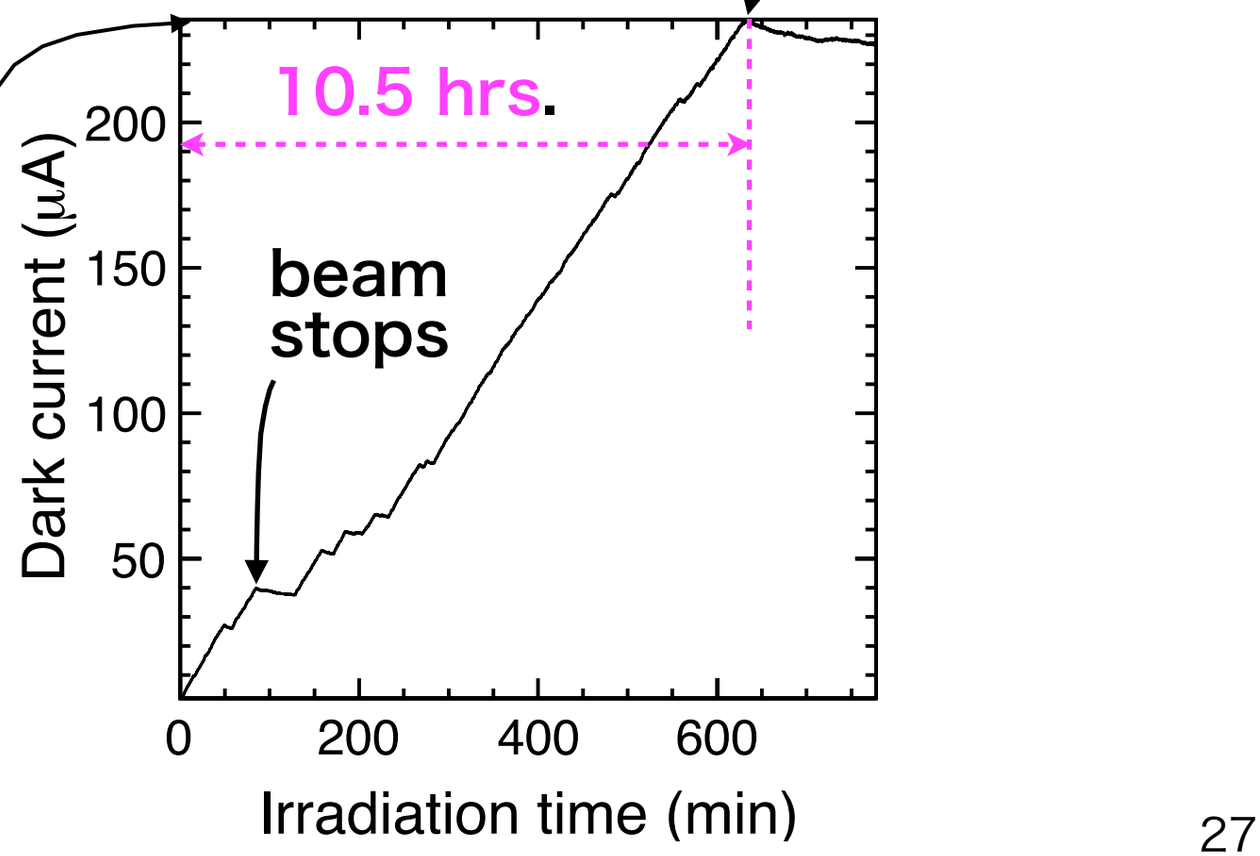


beam profile

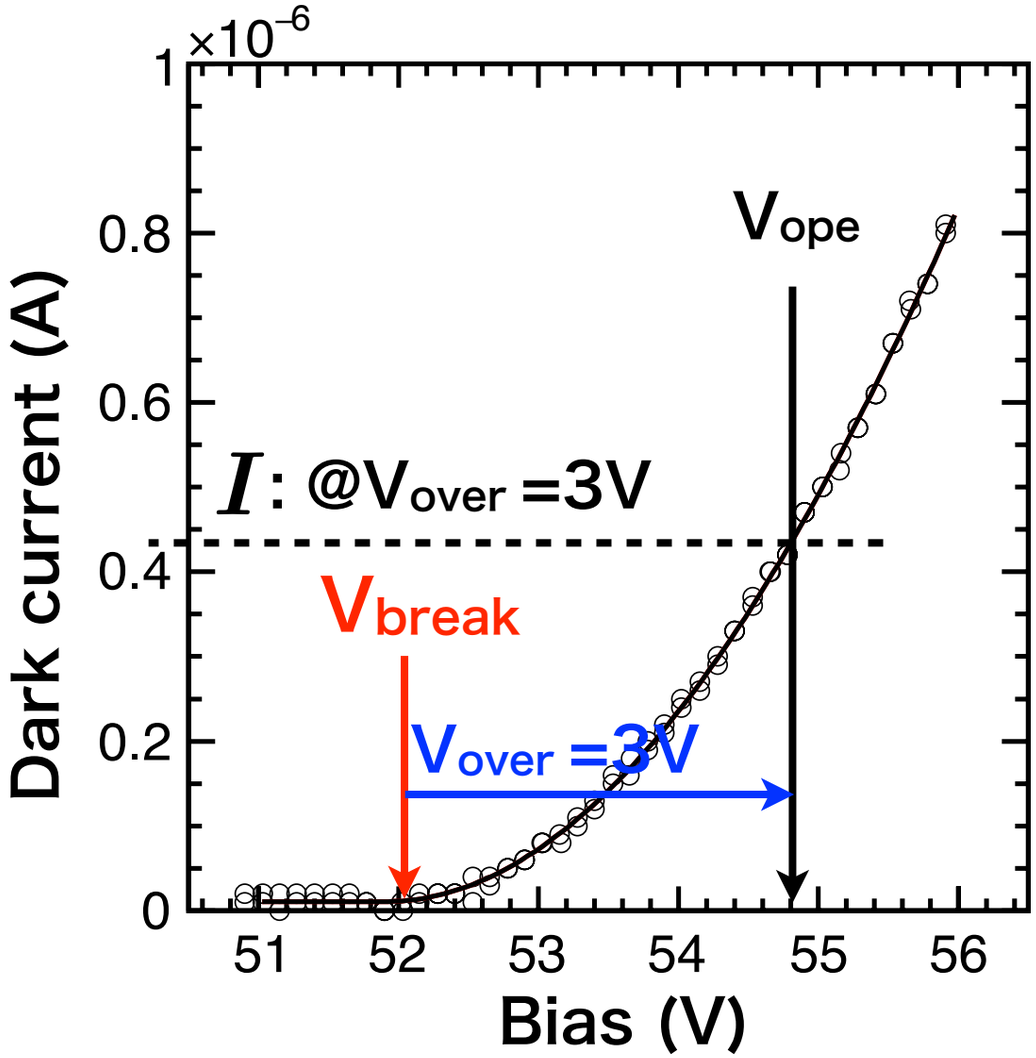
Dark current for
1.5× 10^9 n_{1MeV}/cm^2 相当
= 235μA

Dark current : irradiation determined @ RCNP

consistent T. Matsumura et al NIMA 603, pp301 (2009)



Concern radiation hardness



Raising point: V_{break},

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

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

Gain is proportional to V_{over}.

Lattice defects

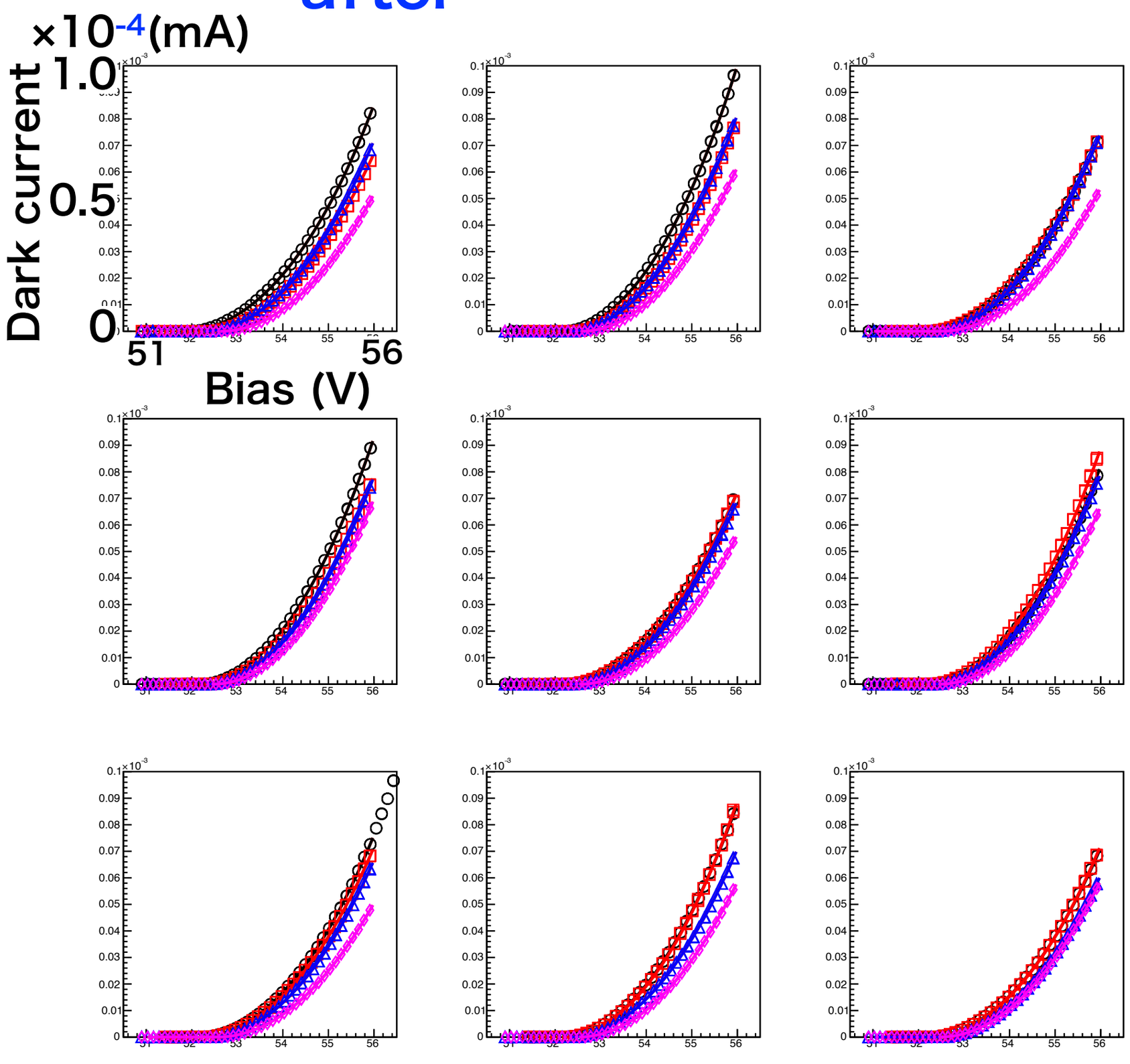
Increase drak current ➡

- **variation of V_{break},**
- **variation of gain,**
- **Change of IV property**

Result of irradiation test

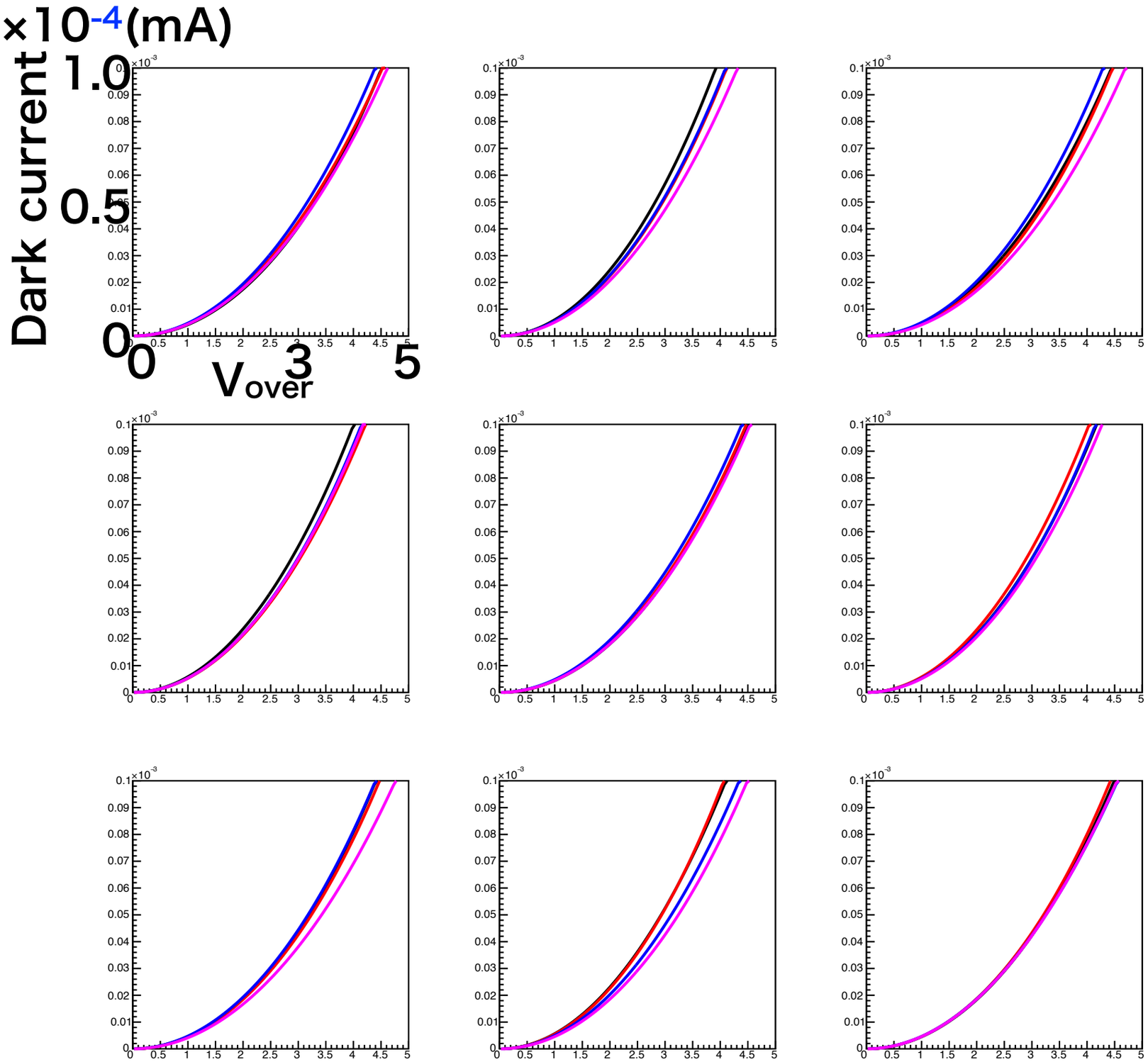
IV curve 36 MPPCs

after



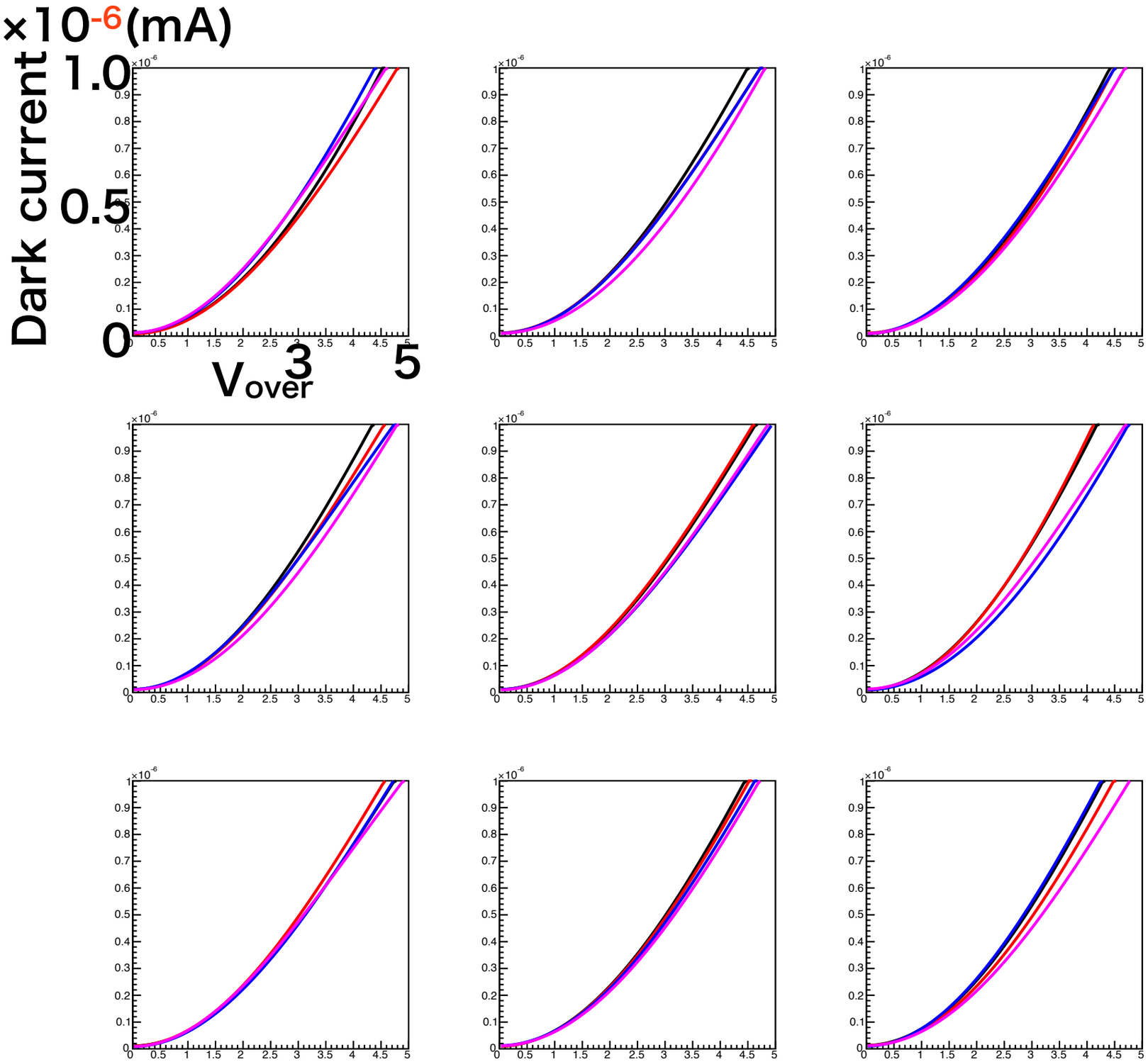
Fitting results (plot V_{over})

after



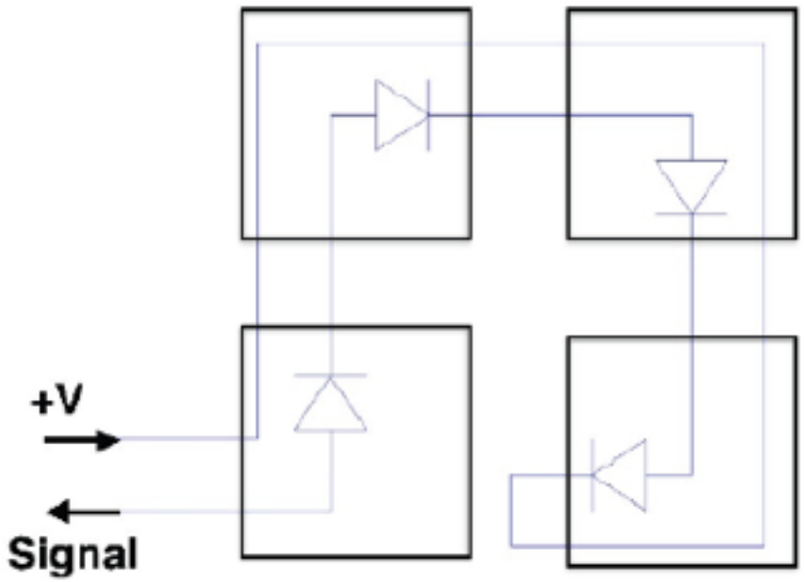
Fitting results (plot V_{over})

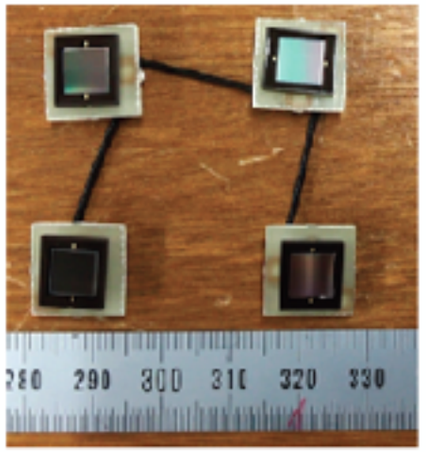
before

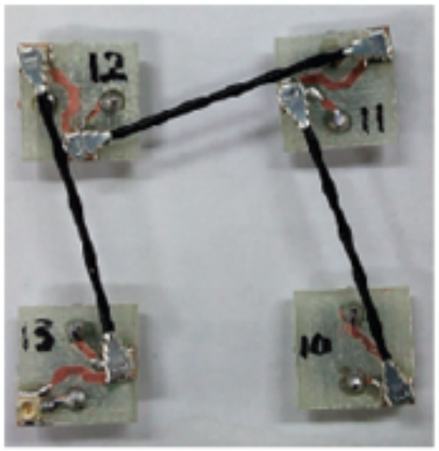


Readout

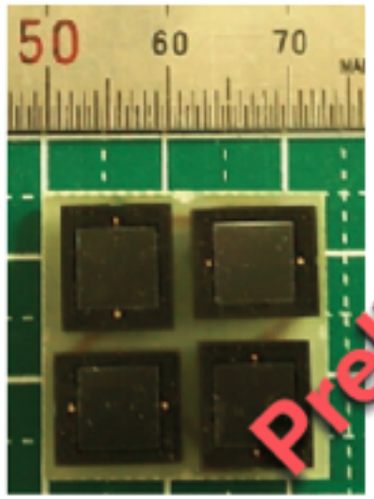
- MPPCの配線







For small crystals: 13 mm角基板×4



For large crystals: 23 mm角基板×1

- 電源供給と信号読み出しを一本の同軸ケーブル（φ1.13 mm)で行う

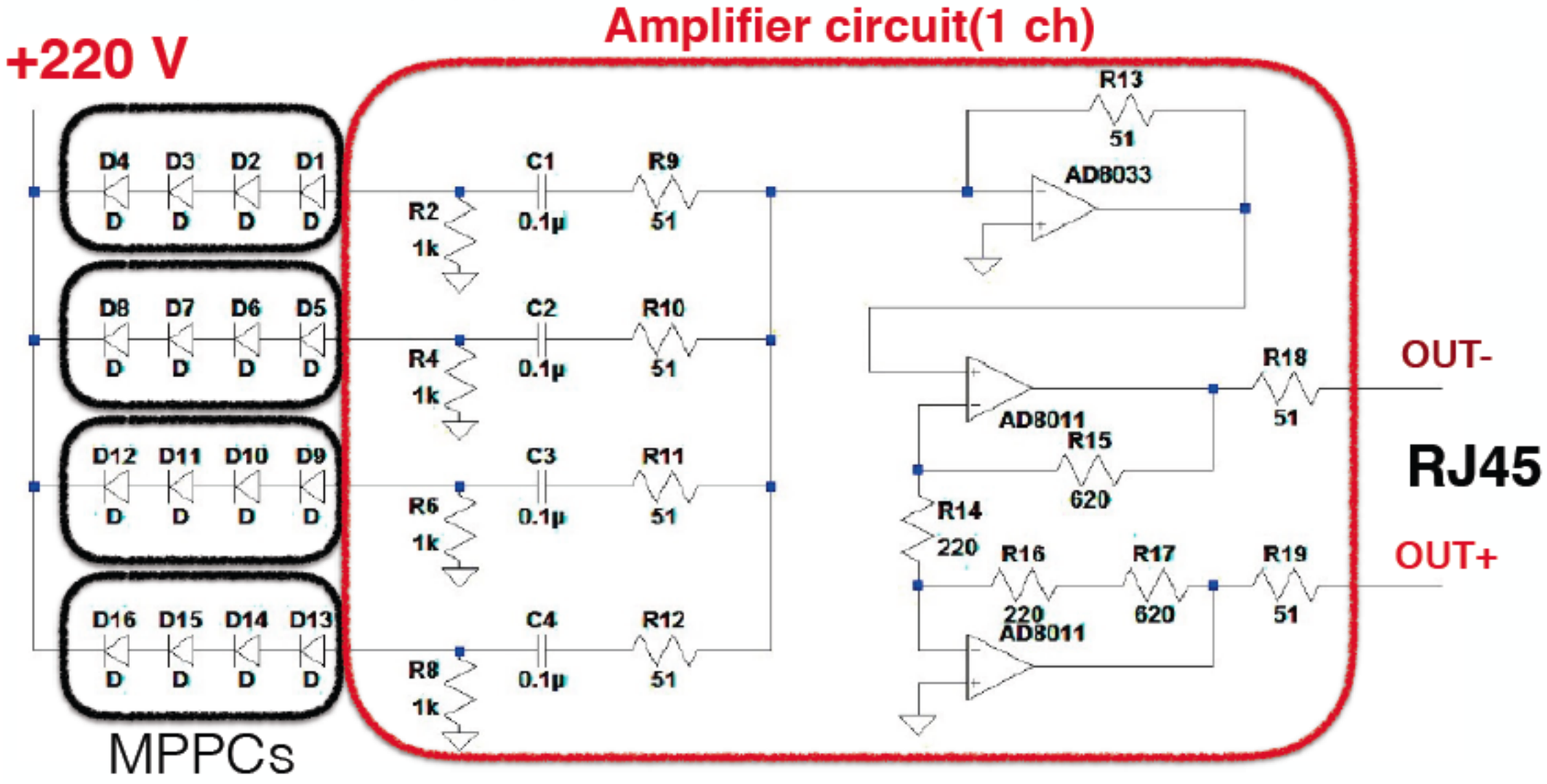
- MPPC一つずつに独立な基板を付け、それらをケーブルで接続する

9

低物質量

Readout

- 読み出し回路



消費電力：1 ch当たり55 mW

→ 260 chで14 W

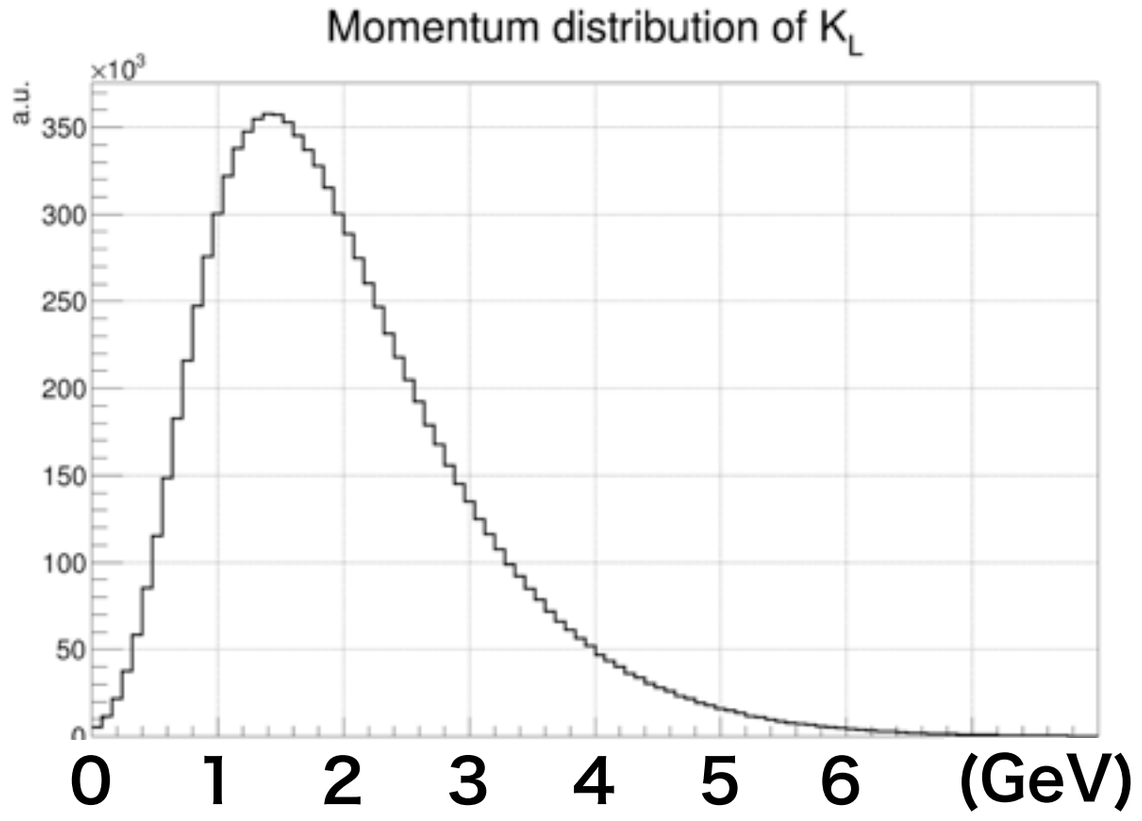
低消費電力

- 周波数帯域
- クロストーク
- 線形性

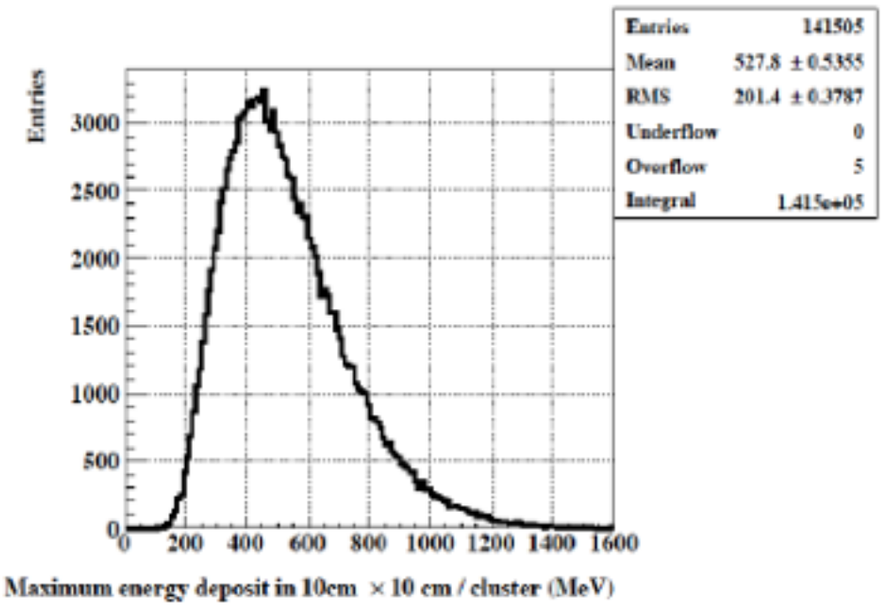
Energy range

30 GeV proton,
2sec/6sec extraction.

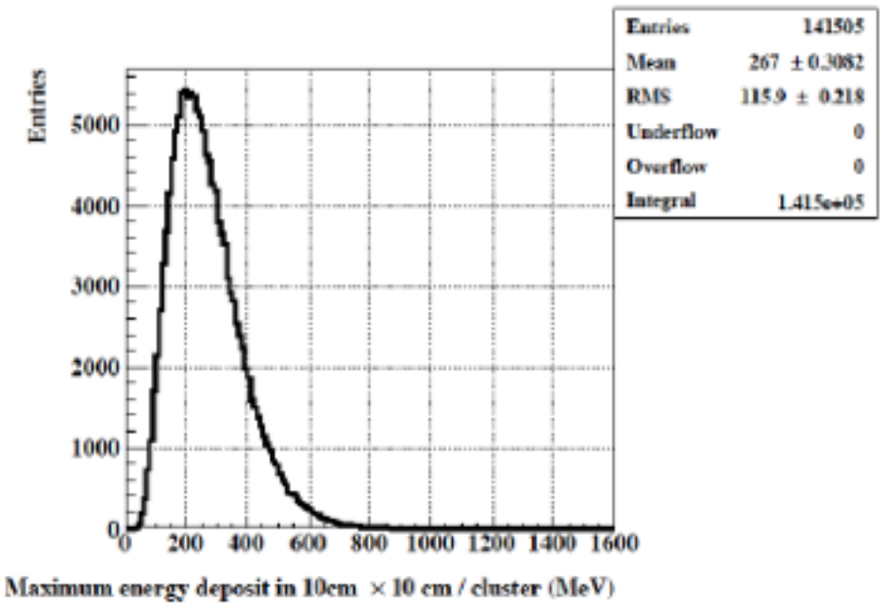
gold target
➡16° extraction.



1st cluster



2nd Cluster

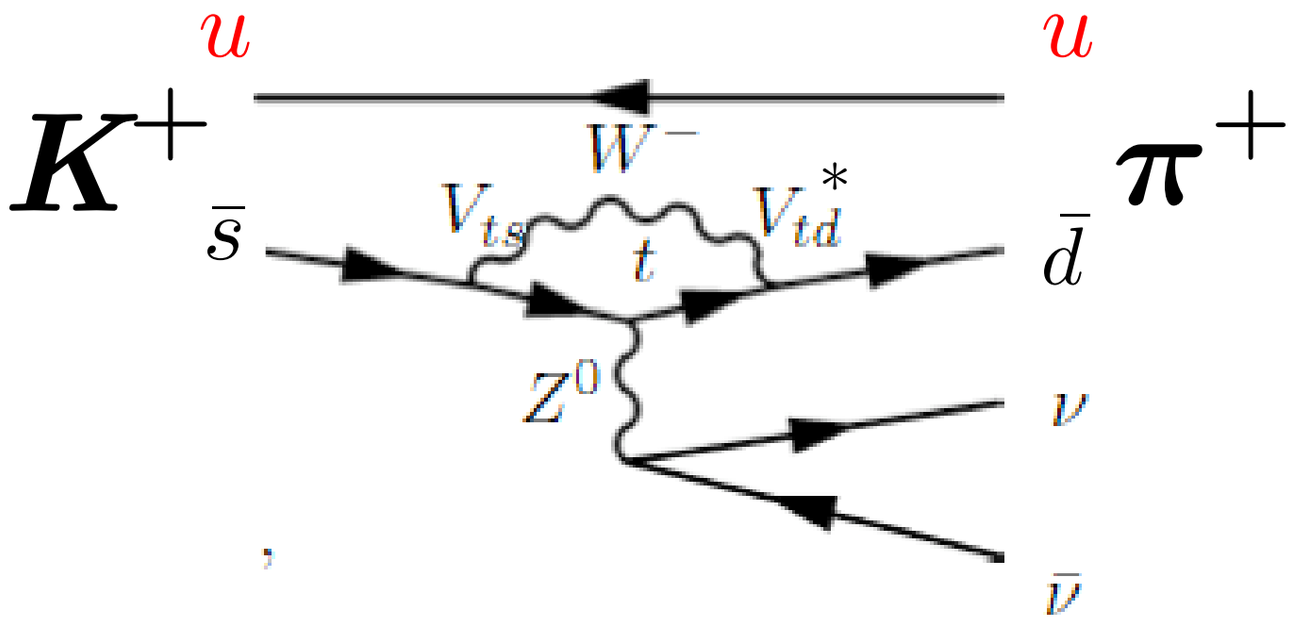


Energy range : 50MeV – 1.5GeV

Final: goal find 100 $K_L \to \pi^0 \nu\bar{\nu}$:(3.0±0.3)×10^{-11}

First milestone

Grossman-Nir Limit



Observation $K^+ \to \pi^+ \nu\bar{\nu}$: (1.7±1.1)× 10^{-10}

⬇ iso-spin rotation

1.5 × 10^{-9} :Limitation of $K_L \to \pi^0 \nu\bar{\nu}$

Pencil beam

To reconstruct π^0 from two γ: no track!

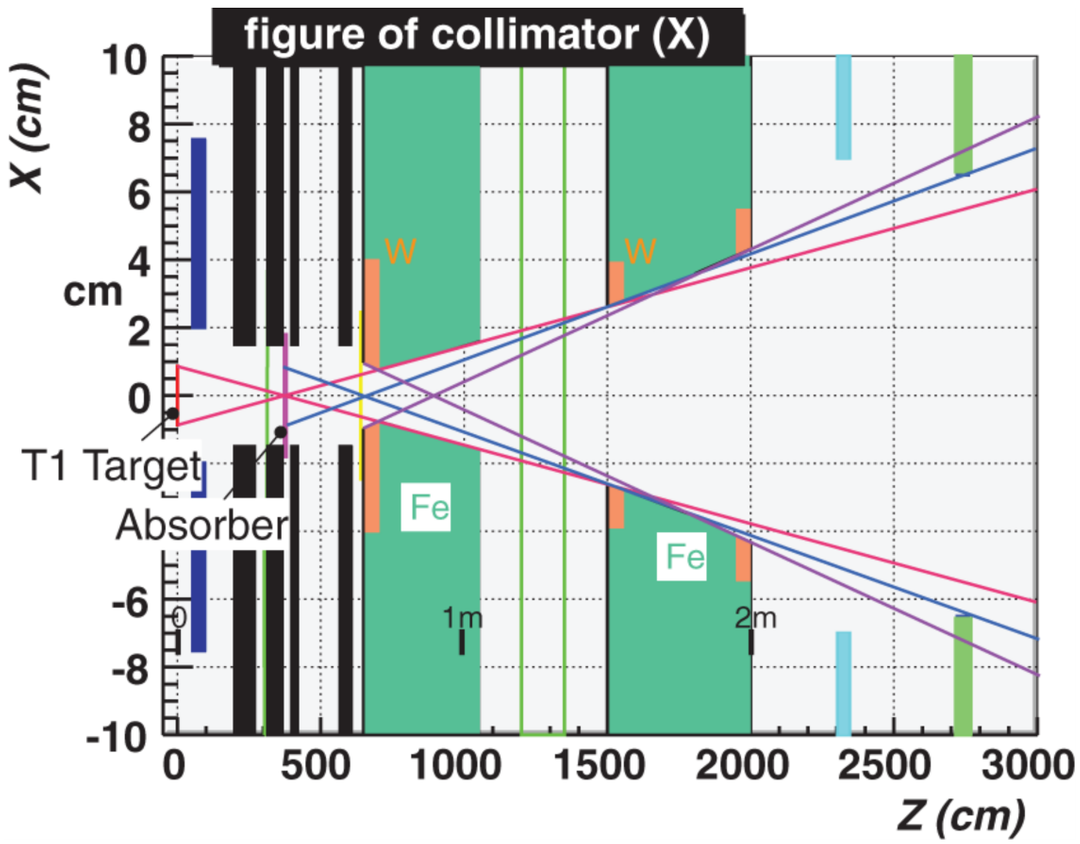
assumption of π^0 on the beam line is necessary

$$p^{\mu}_{\gamma_1} p_{\gamma_2 \mu} = m^2_{\pi}$$

we have $p_{\gamma_{(1,2)}} \perp$

$$2E_1E_2(1-\cos\theta) = m^2_{\pi^0}$$

for a fine reconstruction need narrow beam



10cm□ at CsI cal.

A neutron is source of BG.
reduce halo neutron.

Halo neutron/K_L = 0.07%
1/240 of previous

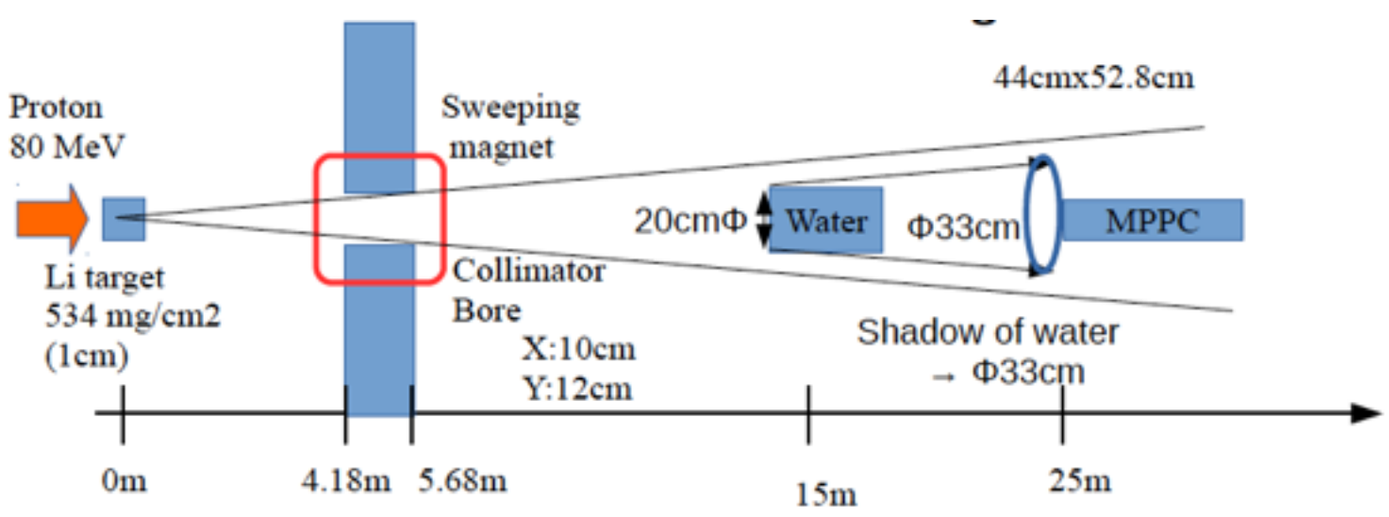
照射量と暗電流

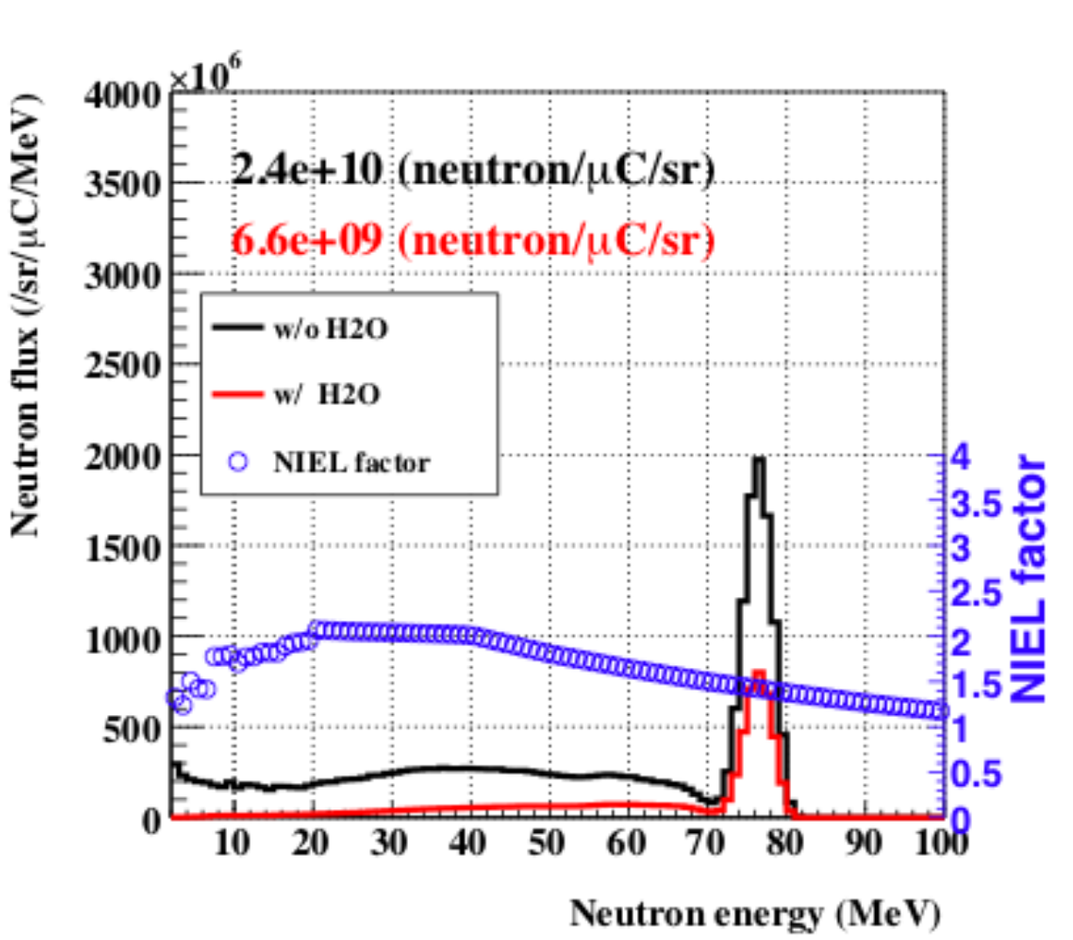
80MeV neutron @ 大阪大学核物理研究センター

2017年３月27日

Neutron energy distribution × NIEL factor

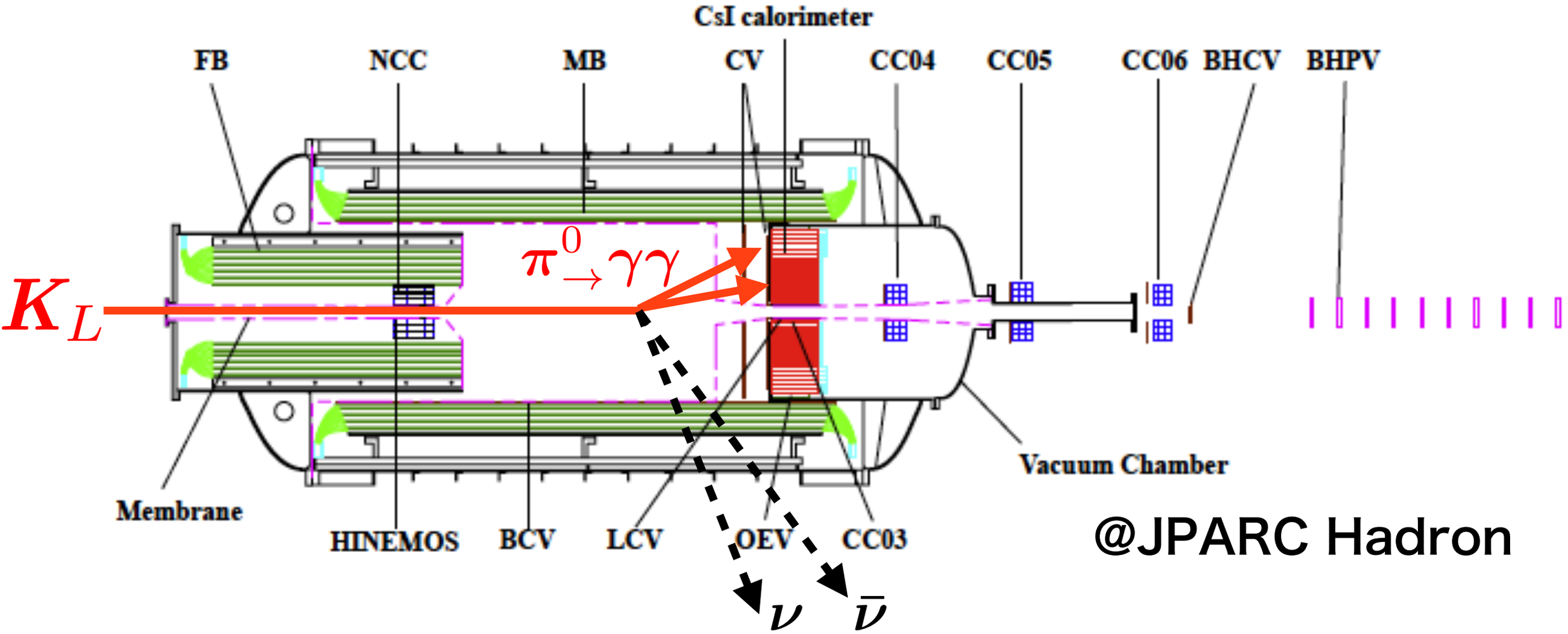
$2 \times 10^7\ n_{1MeV}/cm^2$ ➡ $0.6\,\mu A$





KOTO experiment

$K_L \to \pi^0 \nu\bar{\nu}$: Br=(3.0±0.3)×10^{-11} S.M.



@JPARC Hadron

Only signal $\pi^0 \to \gamma\gamma$ ➡ found on CsI Cal

Key: prevent background