Upgrade of the CsI calorimeter for the KOTO experiment

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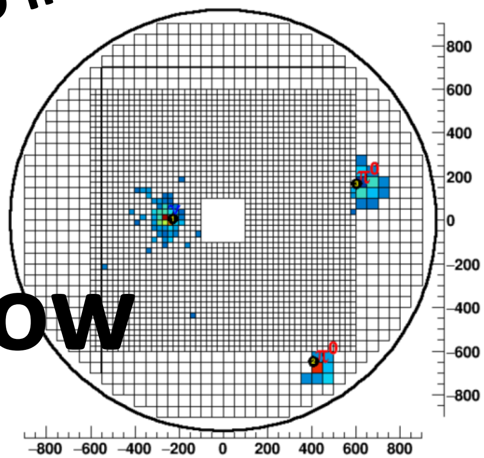
for the KOTO collaboration

CALOR 2018, Eugene, USA, 24th May

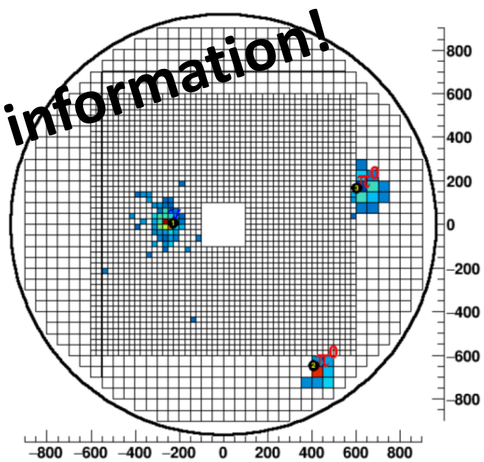
Upgrade of the readout of the CsI output

2D information

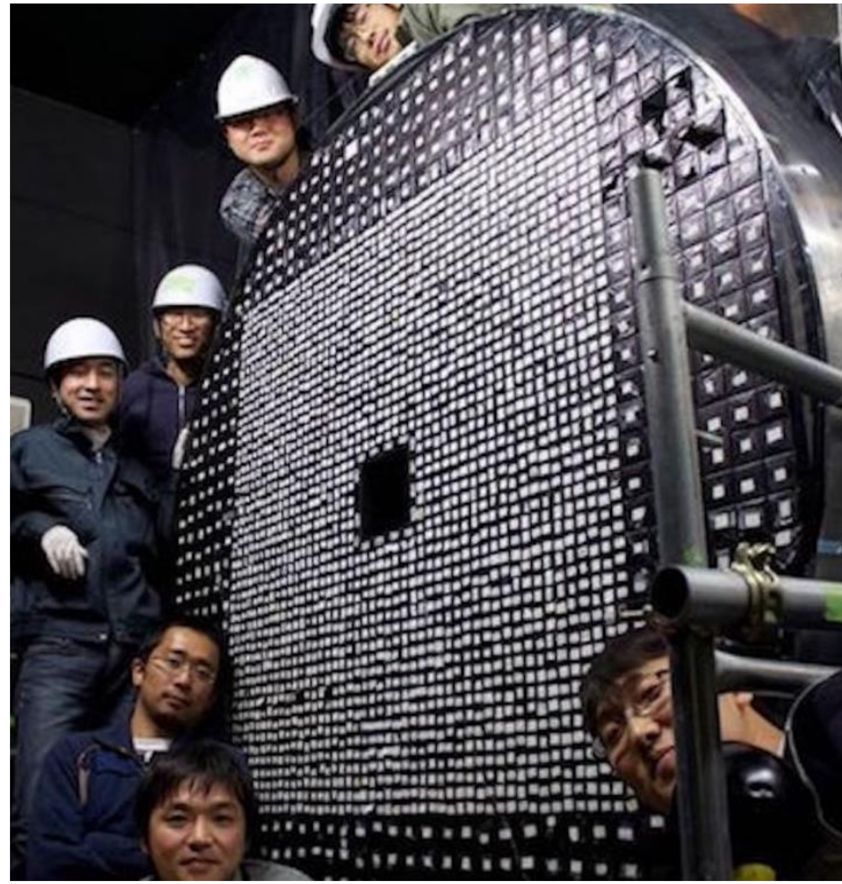


Now

3D information!

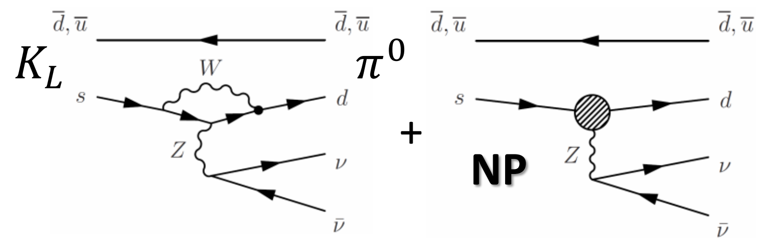


xy + depth $\mathbf{z(from\ \Delta t)}$



γ/n separation power will increase by a factor of 10!

KOTO experiment



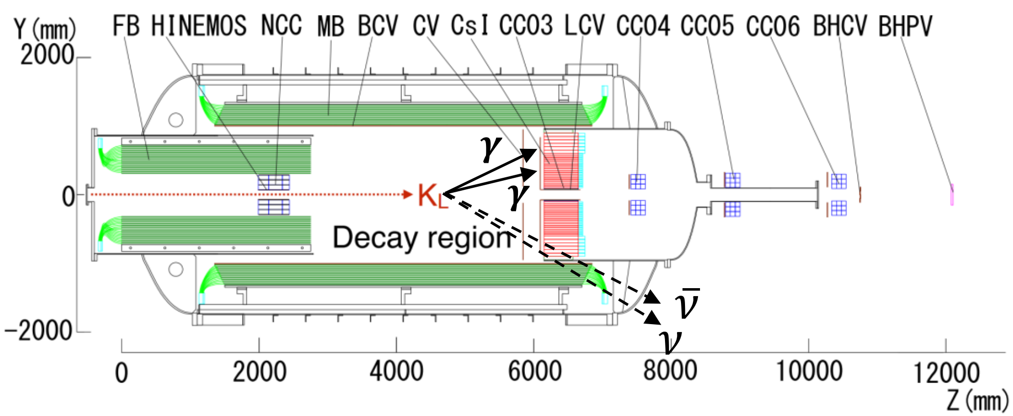
- Rare decay: $K_L \rightarrow \pi^0 \nu \bar{\nu}$

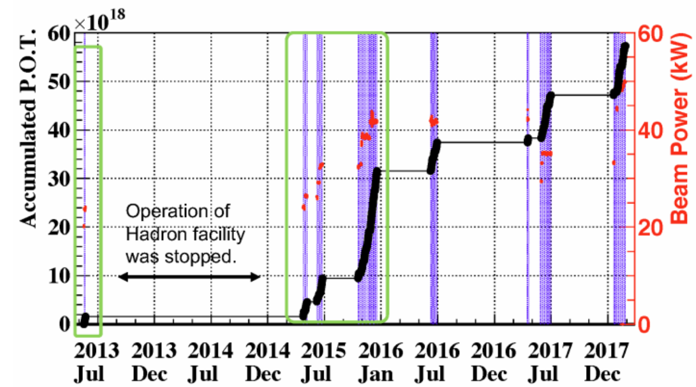
  $\mathcal{B}_{\mathrm{SM}}(K_L \rightarrow \pi^0 \nu \bar{\nu}) = (3.0 \pm 0.3) \times 10^{-11}$ JHEP **11** 033 (2015)

  $\mathcal{B}_{\mathrm{EXP}}(K_L \rightarrow \pi^0 \nu \bar{\nu}) < 2.6 \times 10^{-8}$ (90% C.L.) by E391a

  Useful probe to the New Physics

- Detector





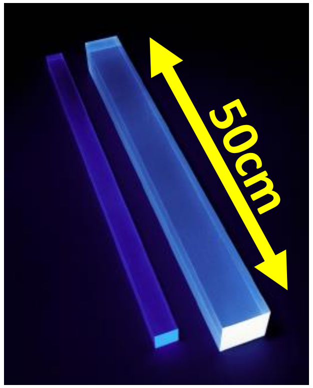
Observed signature: $2\gamma + \mathrm{nothing}$

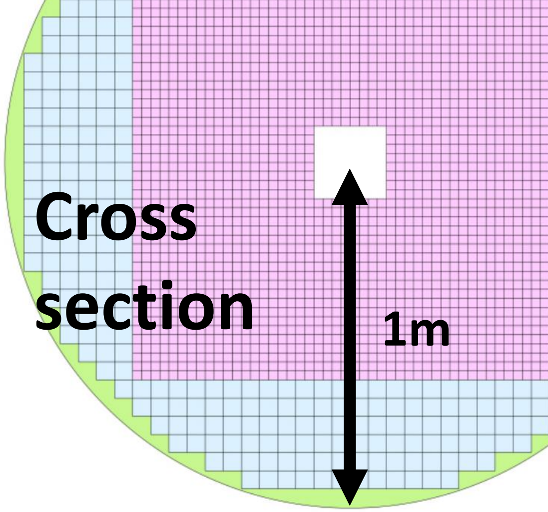
Two electromagnetic showers in CsI and no signal in the hermetic veto counters

Key: avoid missing photons and exclude neutron-induced BG

→ Upgrade CsI calorimeter to reject neutrons in this summer.

CsI calorimeter of the KOTO detector





- CsI crystal
  - Reuse CsI of KTeV experiment
  - undoped CsI (τ~6 ns, 310 nm)

    #crystal = 2716

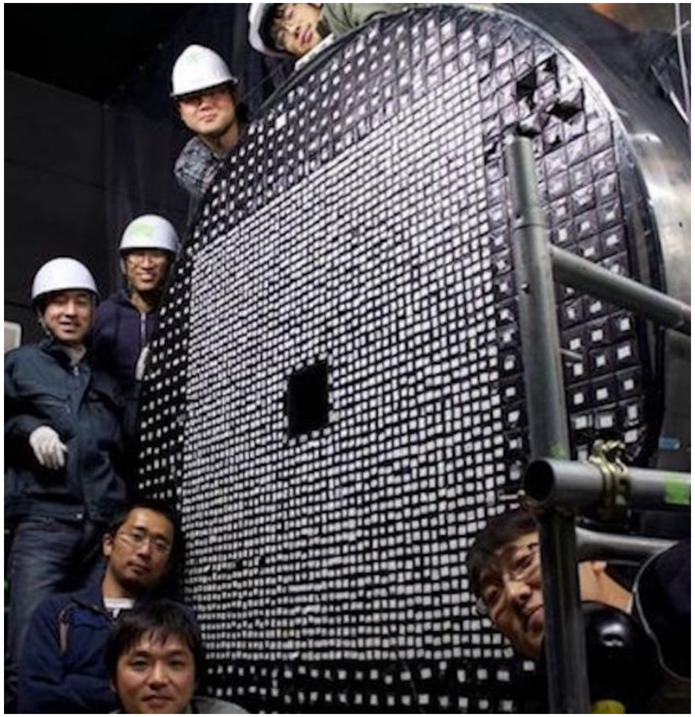
    2240 *small* ($25 \times 25\ \mathrm{mm}^2$)

    476 *large* ($50 \times 50\ \mathrm{mm}^2$)
  - length = $27X_0$ to reduce leakage

- Good performance of resolution
  - $\sigma_E/E = 0.99\% \oplus 1.74\%/\sqrt{E[\mathrm{GeV}]}$

JPS Conf. Proc. 8, 024007 (2015)

- PMT signals are digitized by flash ADC
  - 14 bit 125 MHz sampling
  - 512 ns timing window (64 samples)
  - Tenth-order Bessel filter
  - Timing resolution $\sigma_t \sim$ 1ns



Rejection of neutron BG

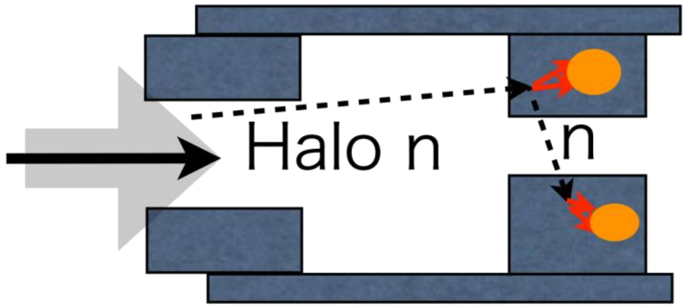
☐ Halo-neutron BG

* Prog. Theor. Exp. Phys. (2017) 021C01

Result of 4 days run: $\mathcal{B}(K_L \to \pi^0 \nu \bar{\nu}) < 5.1 \times 10^{-8}$ (90% C.L.)*

Background source	Number of events
$K_L \to 2\pi^0$	0.047 ± 0.033
$K_L \to \pi^+\pi^-\pi^0$	0.002 ± 0.002
$K_L \to 2\gamma$	0.030 ± 0.018
Pileup of accidental hits	0.014 ± 0.014
Other K_L background	0.010 ± 0.005
Halo neutrons hitting NCC	0.056 ± 0.056
Halo neutrons hitting the calorimeter	0.18 ± 0.15
Total	0.34 ± 0.16

The largest contribution from BG



- We need 3 more magnitudes of suppression

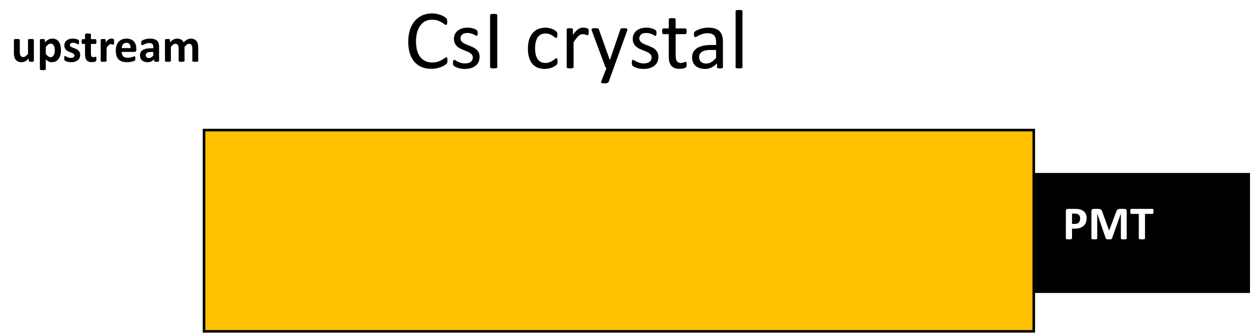
two-dimensional shower envelope → 1/10 ✓ done
Pulse shape likelihood → 1/10 ✓ done

measure shower development (in z)

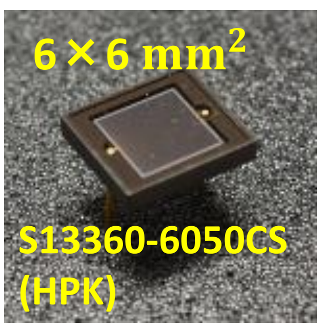
in the calorimeter → O(1/10)

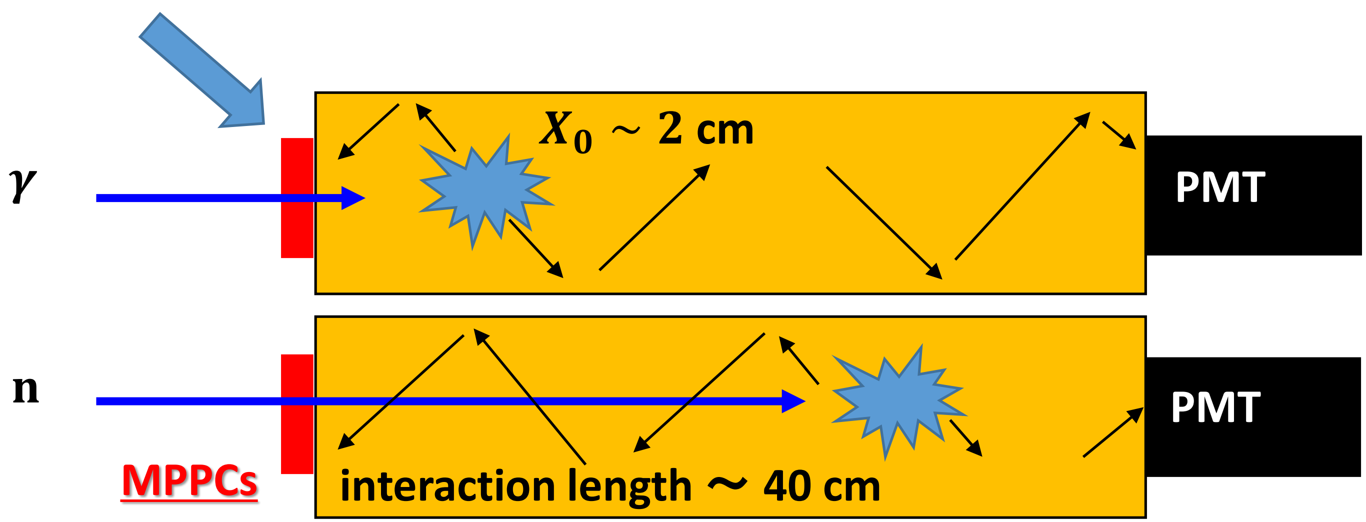
CsI calorimeter upgrade

Now

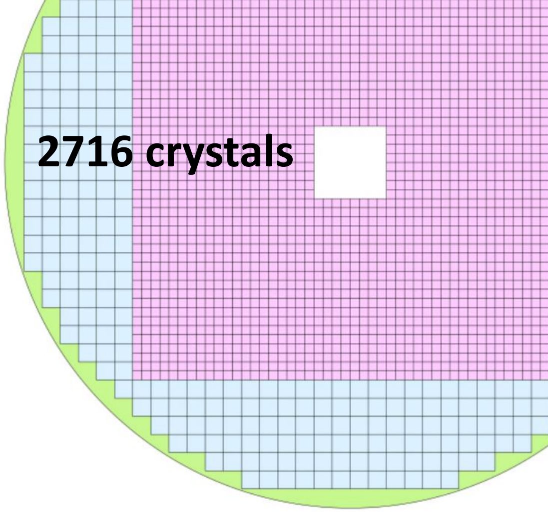


Attach MPPCs in this summer 2018





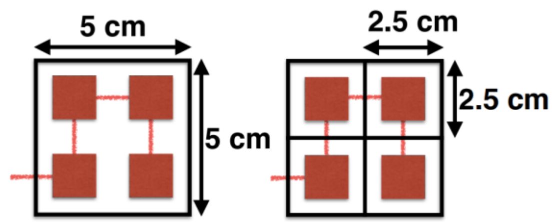
New front-end readout



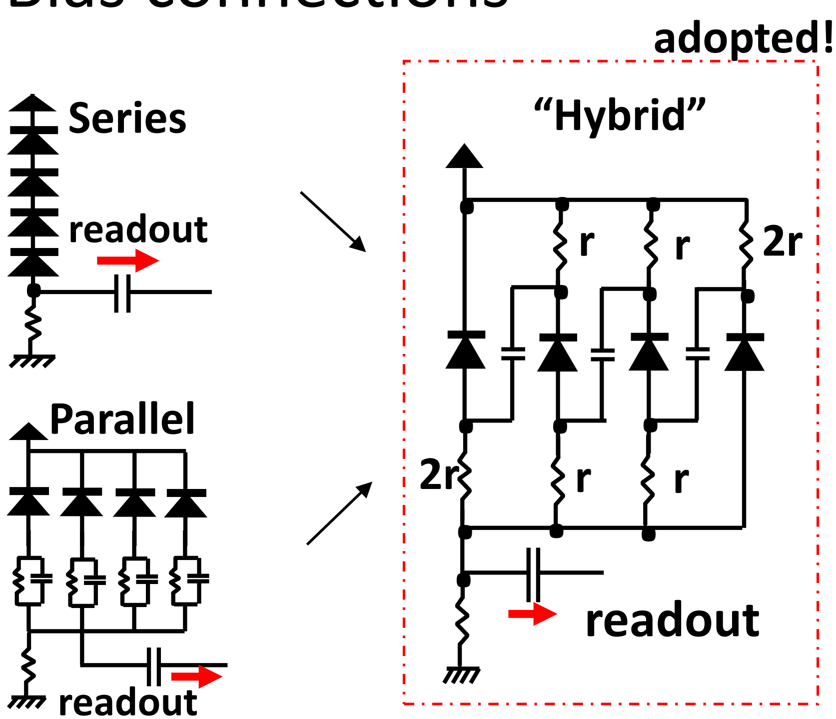
☐ MPPC readout

Issue: **large # of MPPCs: 4096 (>#PMT=#CsI)**

To reduce channels..
4 MPPCs are connected

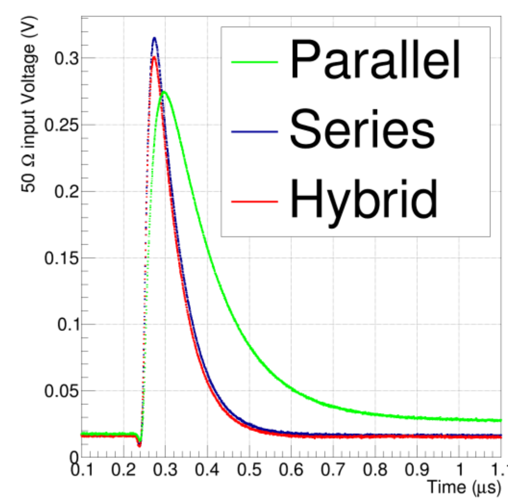


☐ Bias connections

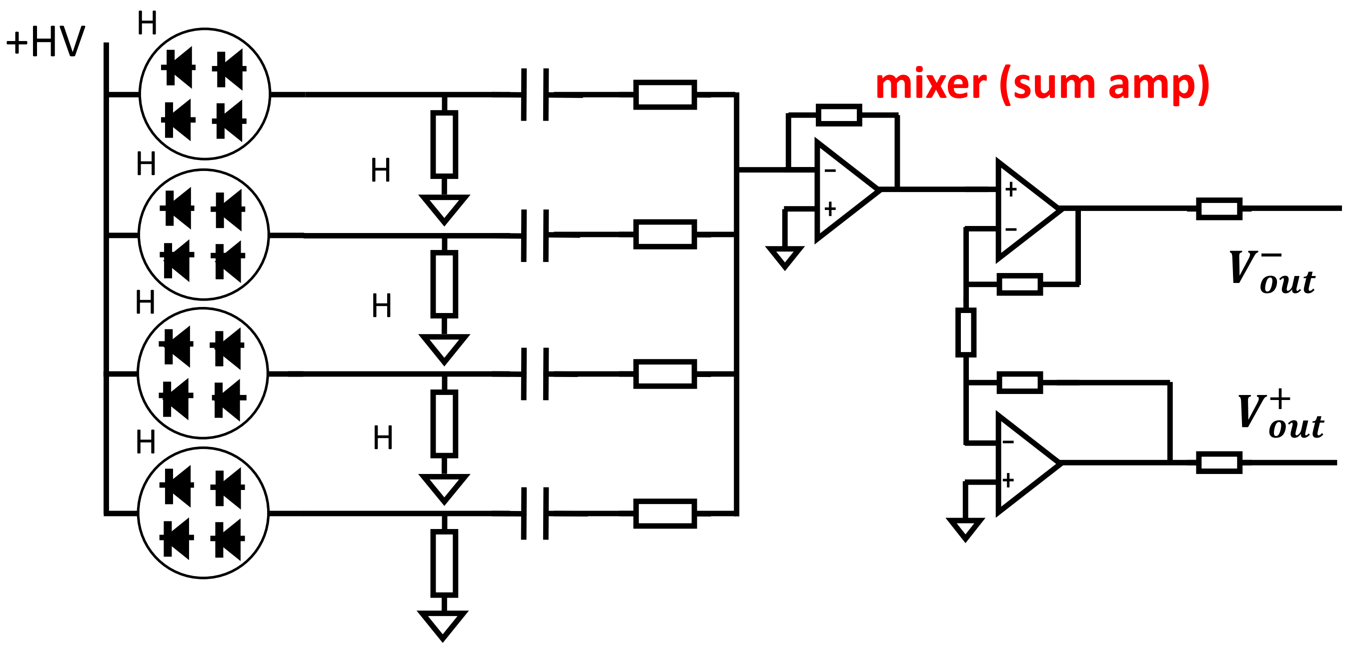


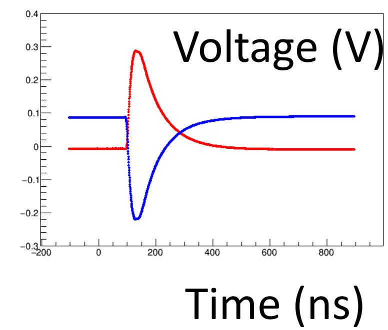
"Hybrid"-connection

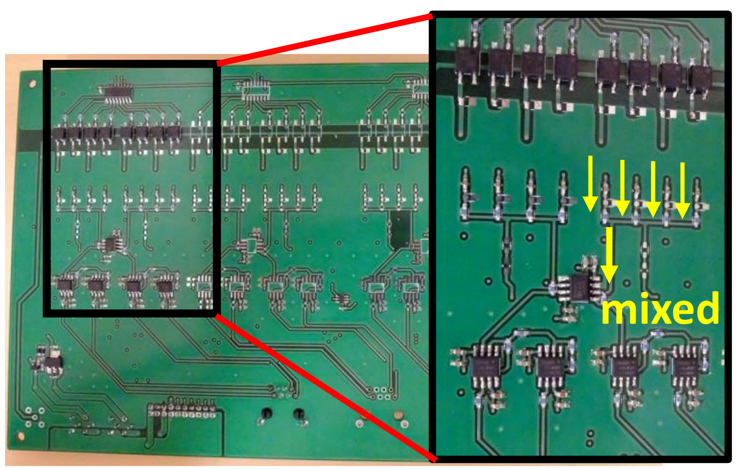
- adopted by MEG II upgrade
- AC line: series
- DC line: parallel
- have both pros



Development of front-end: amplifier







4096 MPPCs

4 MPPCs are connected ×1/4

1024

4 readout is summed × 1/4

256 channels

→**Manageable number of channels**

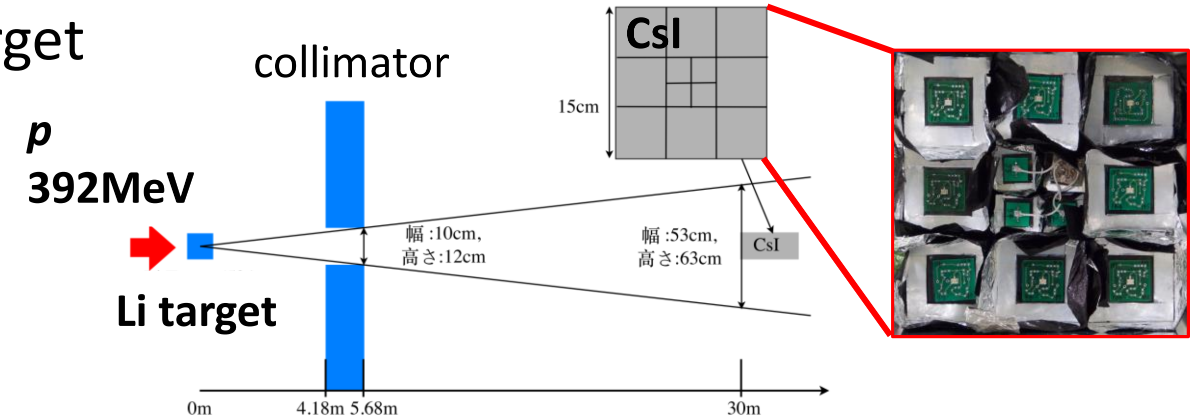
Performance tests (γ/n separation)

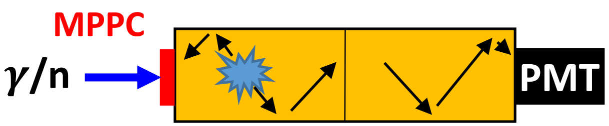
Beam test at RCNP-Osaka cyclotron

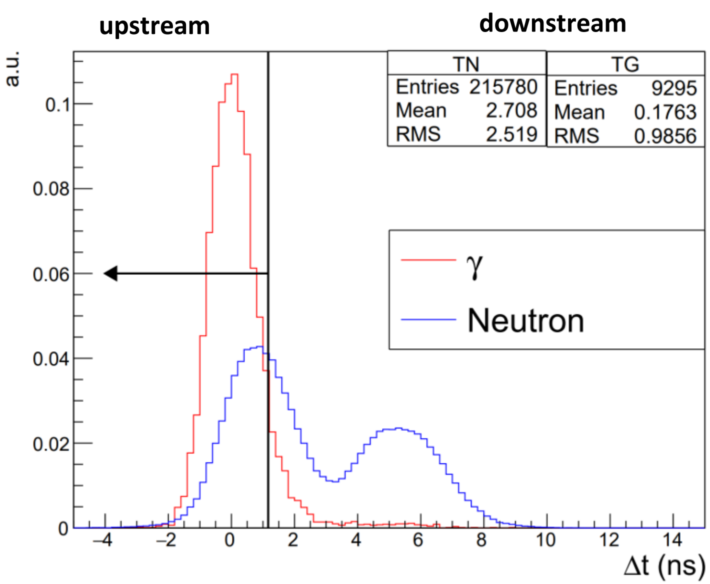
- γ/n beam from Li target

γ: continuous beam up to 392 MeV

n: 392 MeV







Distribution

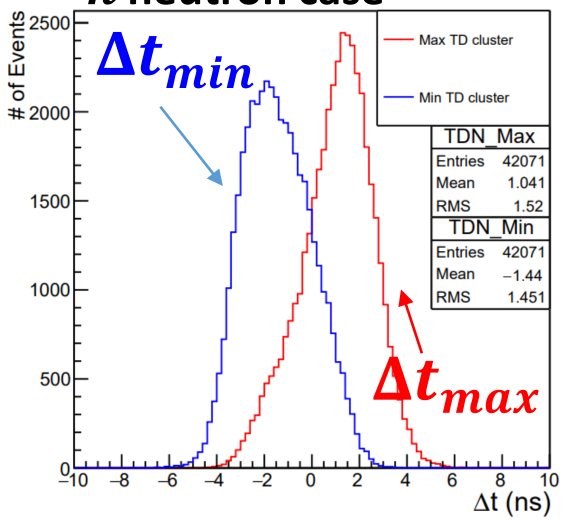
$$\Delta t \equiv T_{MPPC} - T_{PMT}$$

Retain 90% of γ while suppressing n to 34%

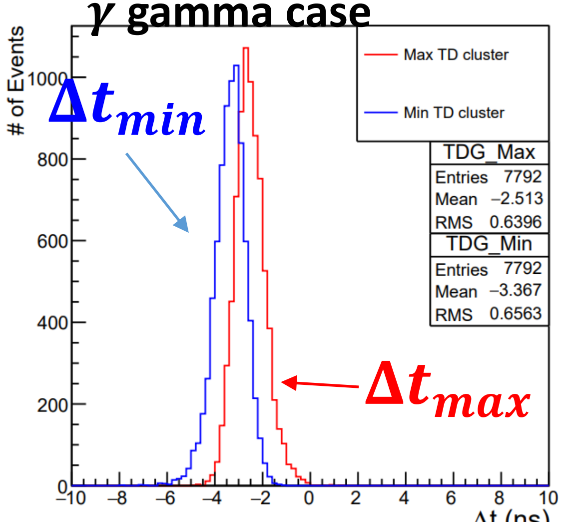
Performance tests (γ/n separation)

MC evaluation of performance for halo neutron events, based on the result of beam test

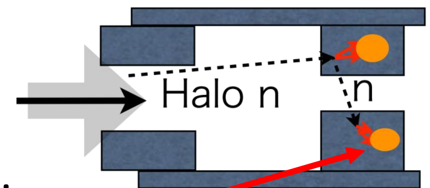
n neutron case



γ gamma case



Taking into account…



① Correlation of two cluster position:

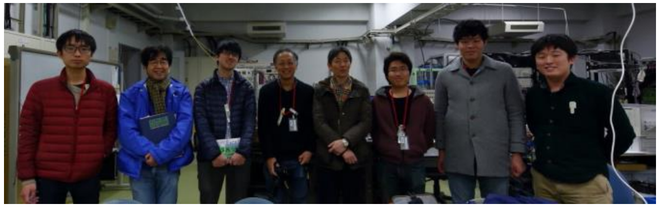
- the second cluster is deeper

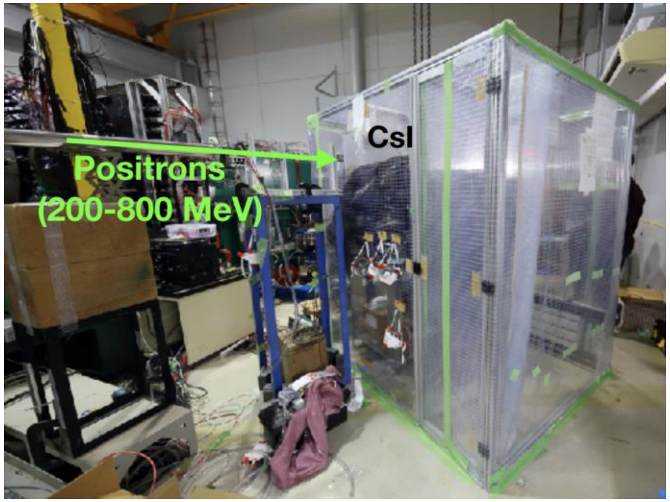
The larger one → Δt_{max}
The smaller one → Δt_{min}

② Other neutron cuts

→ suppresses halo neutron BG to 10% while retaining 90% efficiency of two γ signal events!

Performance tests

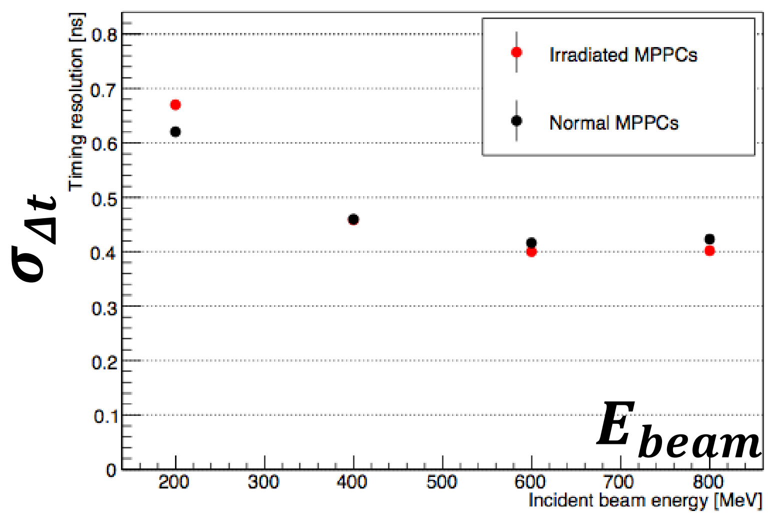


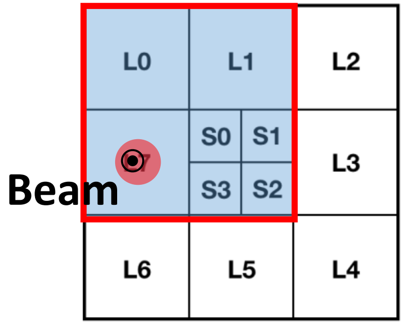


- **Beam test at the ELPH** (Tohoku, Japan) electron synchrotron
  - evaluate $\sigma_{\Delta t}$ (as a func. of E)
    - Monochromatic 200, 400, 600, 800 MeV e^+ beams
  - Used setup as realistic as possible
  - Confirmed MPPC functionality after dose

→Irradiated MPPCs were used

2.4×10^8 1MeV- n/cm^2 (3-years)





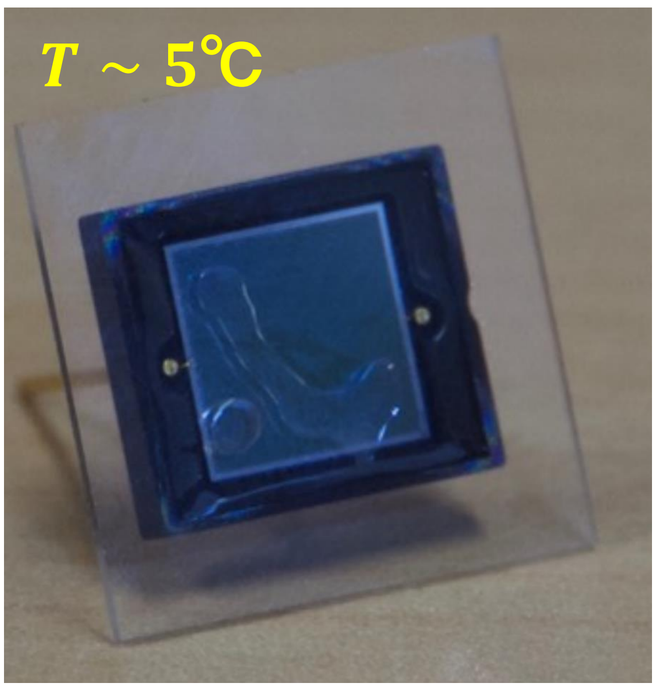
summed $100\times100\ \mathrm{mm}^2$ region

- ✓ **Irradiated MPPCs worked enough**
- ✓ **Readout worked well**

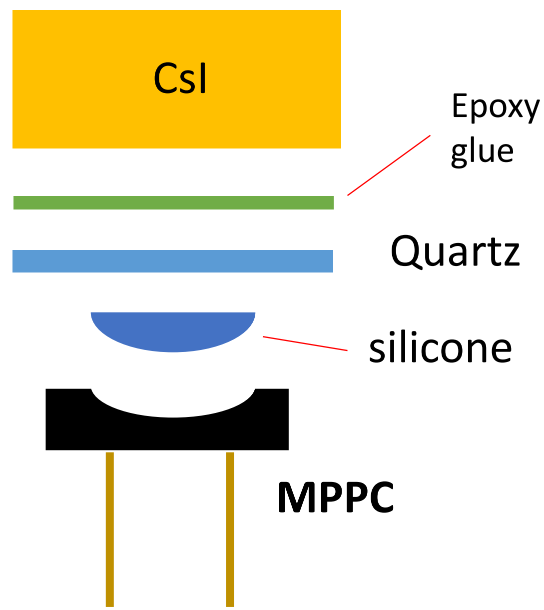
Gluing of MPPC on the CsI surface

Difficulties to glue MPPC

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

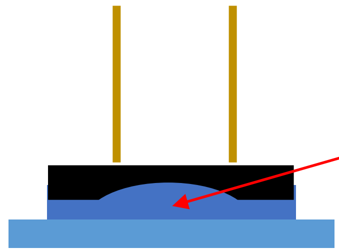


Quartz plate to assure the flatness and transparency in advance

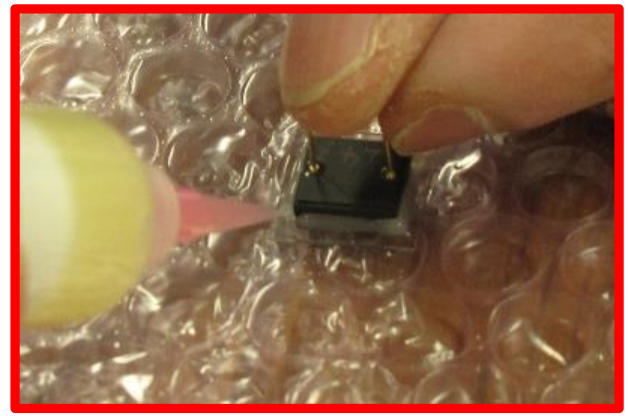


Fabrication of MPPCs

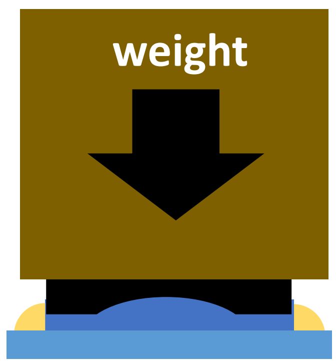
①



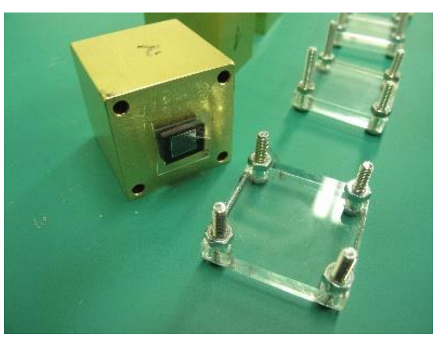
To keep the internal pressure high…



②



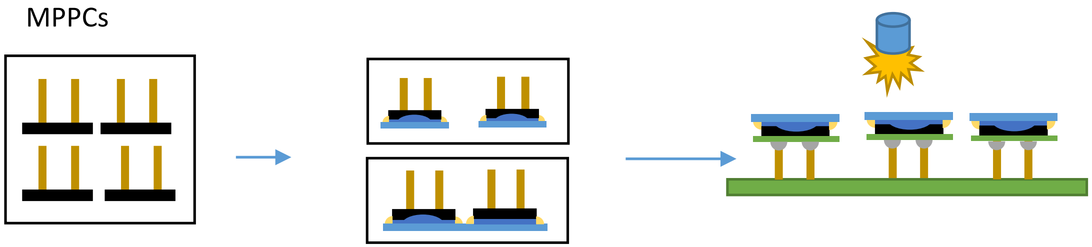
after silicone is cured, **apply pressure and dispense epoxy glue along edges**



→Strong tolerance to low temperature

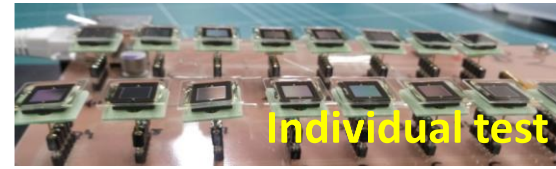
For more detail, see the backup.

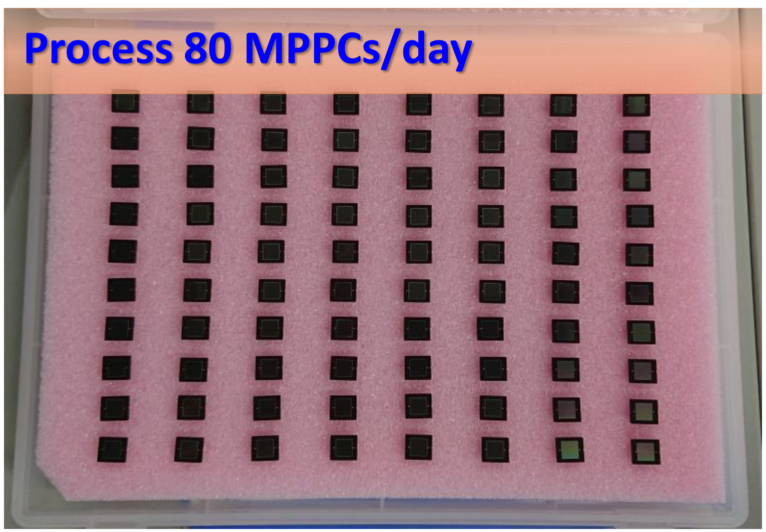
Quality assurance of MPPCs

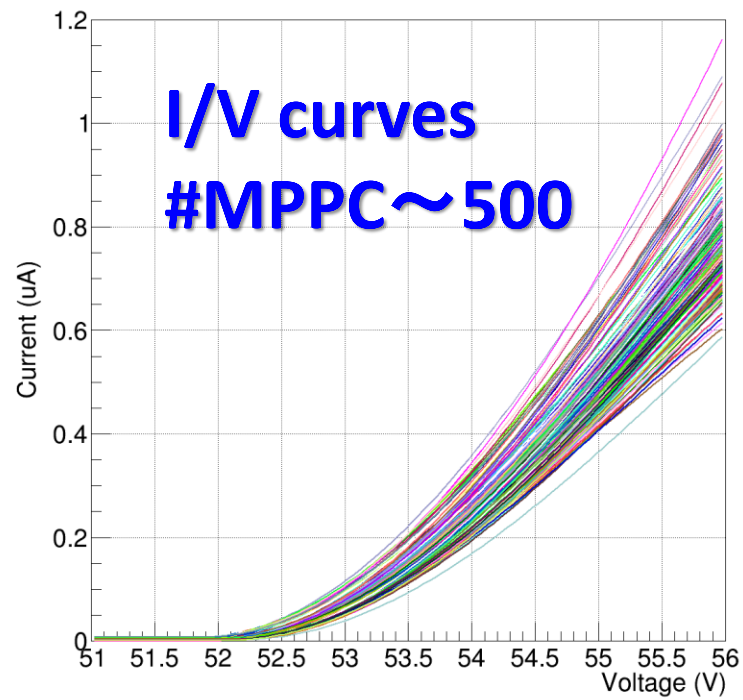


Quartz gluing
Soldering
temperature test

I/V inspection
LED test







Inspect all of MPPCs (#~4000) before installation
→ Start gluing on CsI in this summer

Summary

- KOTO collaboration aims to search for New Physics via very rare decay $K_L \to \pi^0 \nu \bar{\nu}$, $\mathcal{B}_{\mathrm{SM}} = (3.0 \pm 0.3) \times 10^{-11}$.

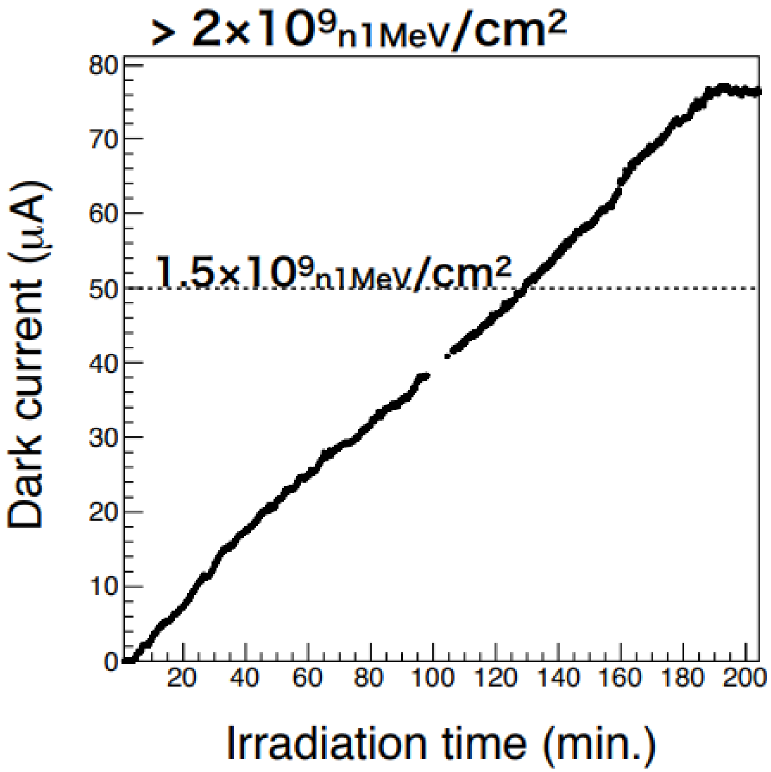
- Attach MPPCs on the front surface of CsI crystal to improve $\boldsymbol{\gamma}$**/n** separation power:

  1/10 suppression of $\boldsymbol{n}$ BG with 90% efficiency of $\boldsymbol{\gamma}$

- In summer 2018, we will start
  - the MPPC installation
  - calorimeter upgrade.

That’s all

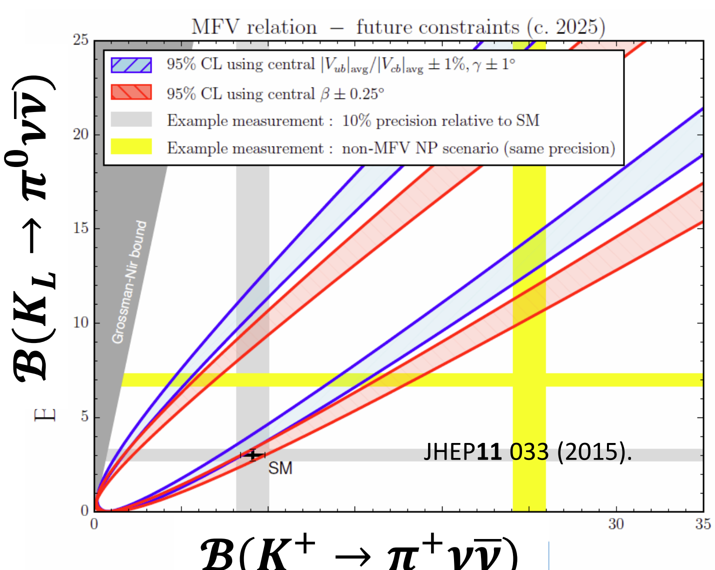
Irradiation of MPPCs



In the innermost part of CsI, $\sim 10^9$ MeV-n/cm^2

$K \to \pi\nu\bar{\nu}$ decay

- Suppressed by FCNC in the SM
- Small QCD uncertainty
  - useful prove to the New Physics
- Two compatible processes
  - $K^+ \to \pi^+\nu\bar{\nu}$: $\mathcal{A} \propto |V_{td}|$
  - $K_L \to \pi^0\nu\bar{\nu}$: $\mathcal{A} \propto \mathrm{Im}V_{td}$



EXP

$\mathcal{B}(K_L \to \pi^0\nu\bar{\nu}) < 2.6 \times 10^{-8}$ (90% C.L.) E391a

$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = 17.3^{+11.5}_{-10.5} \times 10^{-9}$ E949

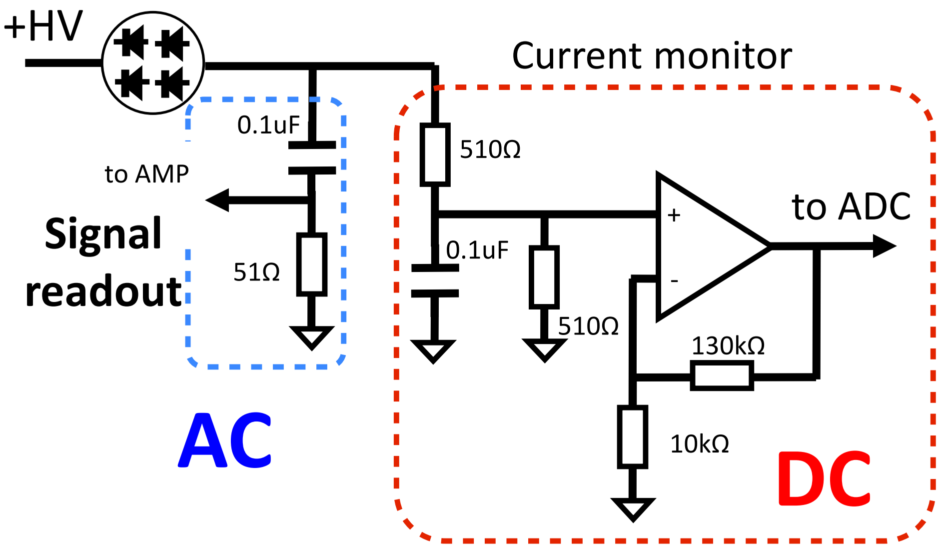
SM prediction

$\mathcal{B}(K_L \to \pi^0\nu\bar{\nu}) = (3.0 \pm 0.3) \times 10^{-11}$

$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = (9.11 \pm 0.72) \times 10^{-11}$

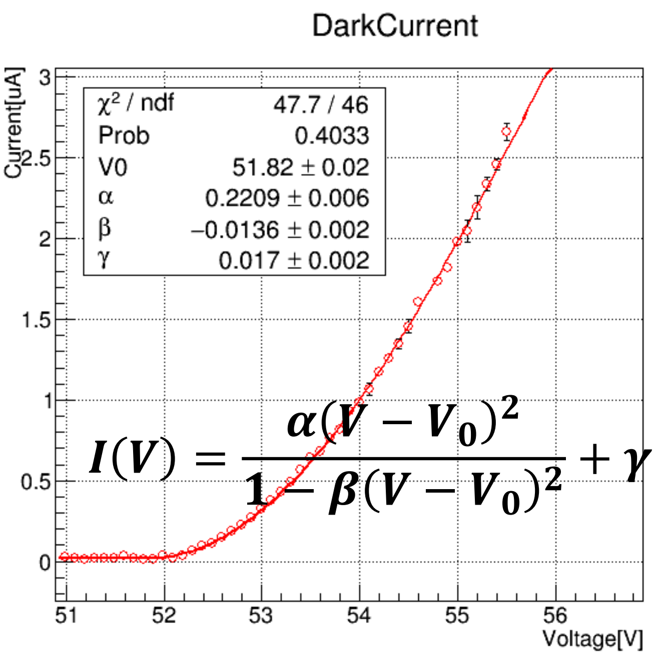
JHEP**11** 033 (2015).

Development of front-end: monitor

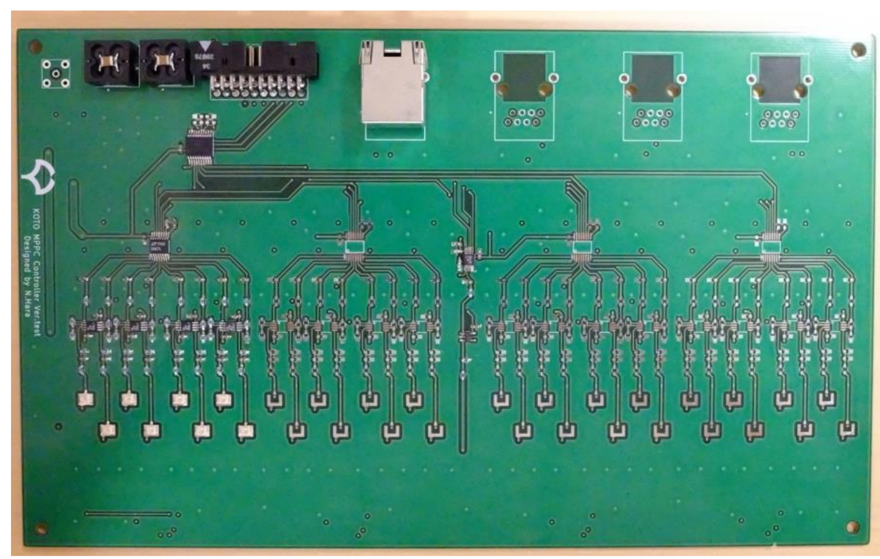


DC dark current is continuously monitored to confirm the functionality and level of radiation damage.

Operation current increases by a factor of 100 in three snowmass year:
$\boldsymbol{I_{op}} = 0.5\mu\text{A} \rightarrow 50\mu\text{A}$

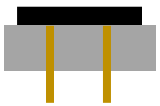


$$\boldsymbol{I(V) = \frac{\alpha(V - V_0)^2}{1 - \beta(V - V_0)^2} + \gamma}$$

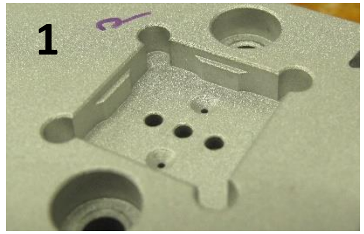


Fabrication of MPPCs

1



Insert MPPC on jig



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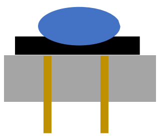
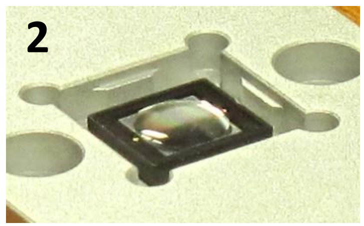


Drop glue



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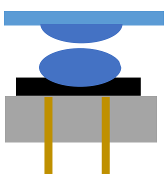
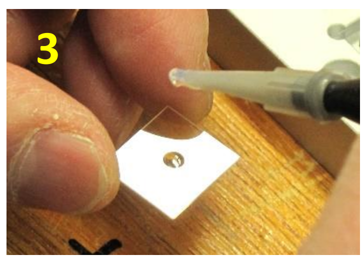
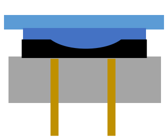


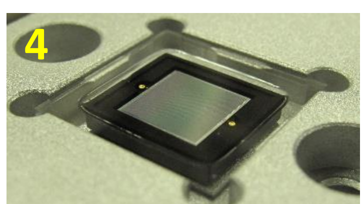
Drop glue on quartz



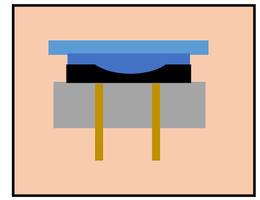
4



wait for cure keeping the quartz floated

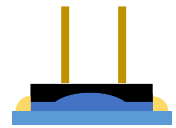


5

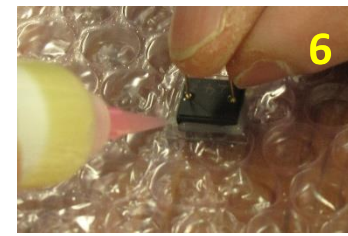


Put MPPCs into oven and wait 24 h (keeping 45 deg)

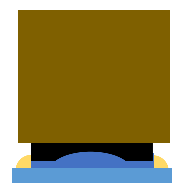
6



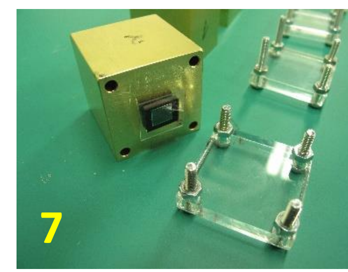
dispense epoxy glue (araldite 2011)



7

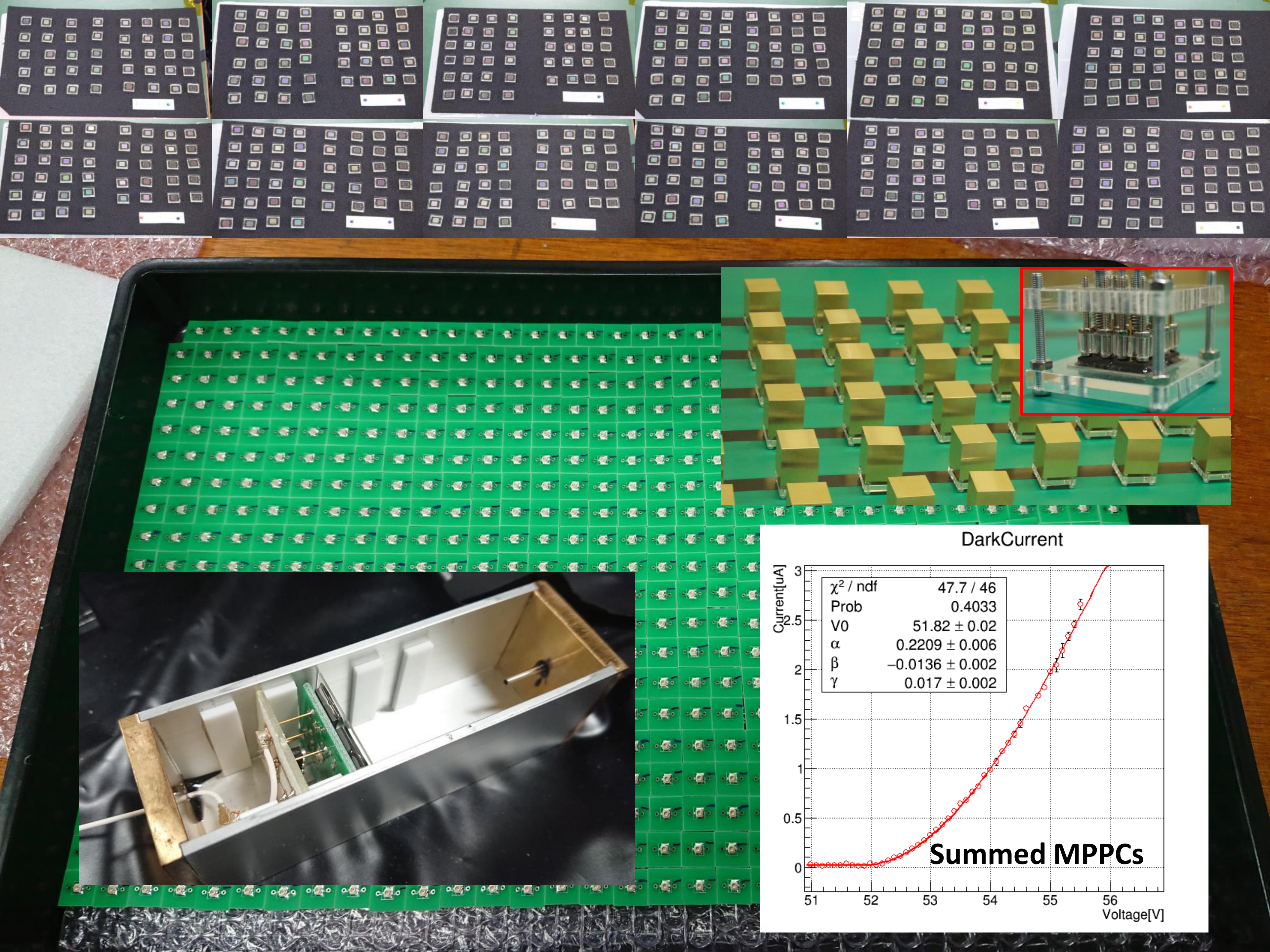


apply weight



8

wait 24 h for cure

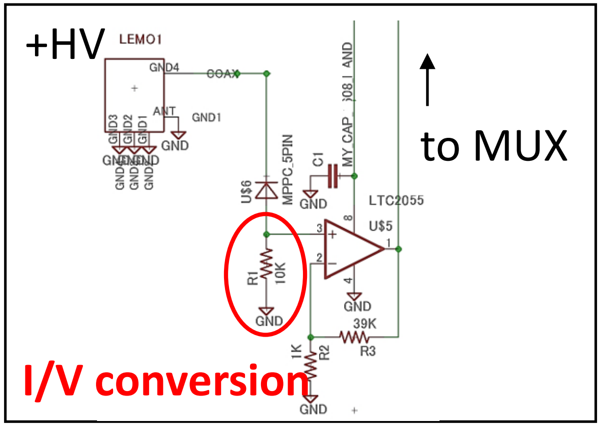

DarkCurrent
χ² / ndf 47.7 / 46
Prob 0.4033
V0 51.82 ± 0.02
α 0.2209 ± 0.006
β −0.0136 ± 0.002
γ 0.017 ± 0.002
Current[uA]
Voltage[V]
Summed MPPCs

Time schedule

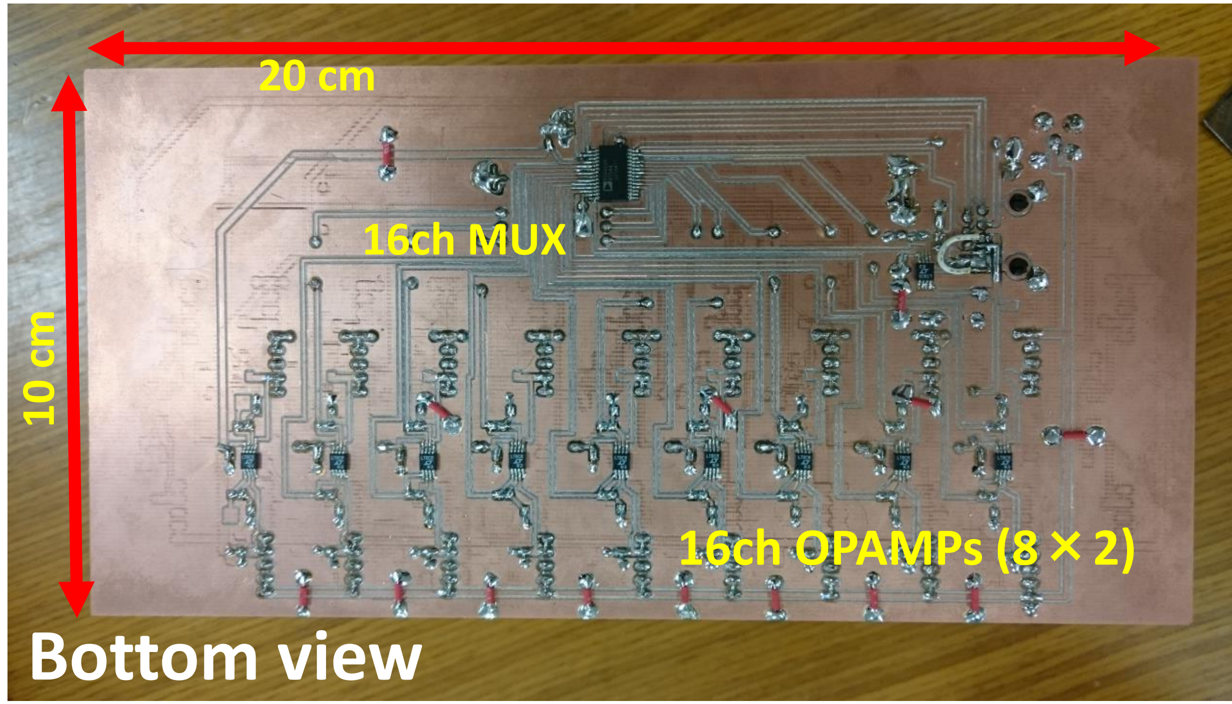
2018-19		
July	Preparation	Move downstream counters
		Open Vacuum tank, Dry room
Aug		Move CV, CsI cover
	MPPC installation	Test installation
Sep		**Install MPPCs and test**
Oct		**2 crystal rows/day (80-140 MPPCs/day)**
Nov	Setup	Setup new CsI cover, CV, cabling
		Close vacuum tank
Dec		Setup downstream counters
		Cabling
Jan	Test run	Test

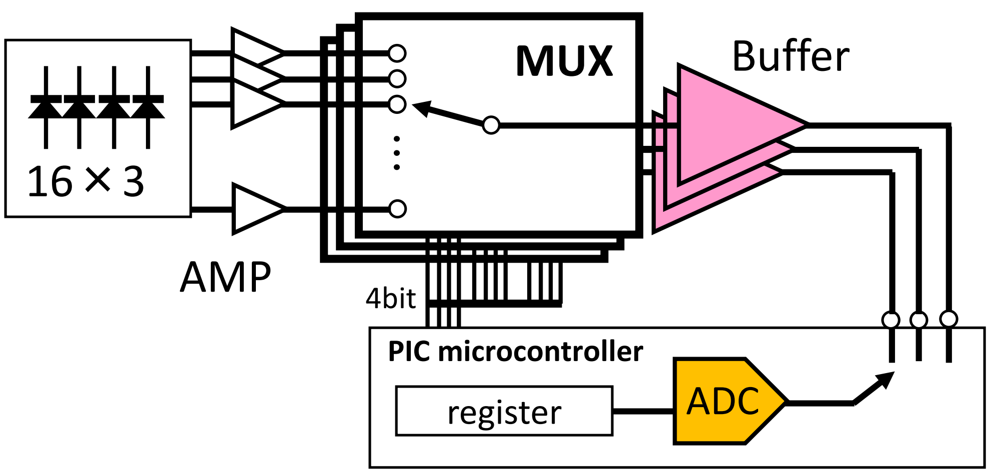
I/V inspection of MPPCs

I/V inspection front end



OPAMP
→FET input（high impedance）
Gain 100

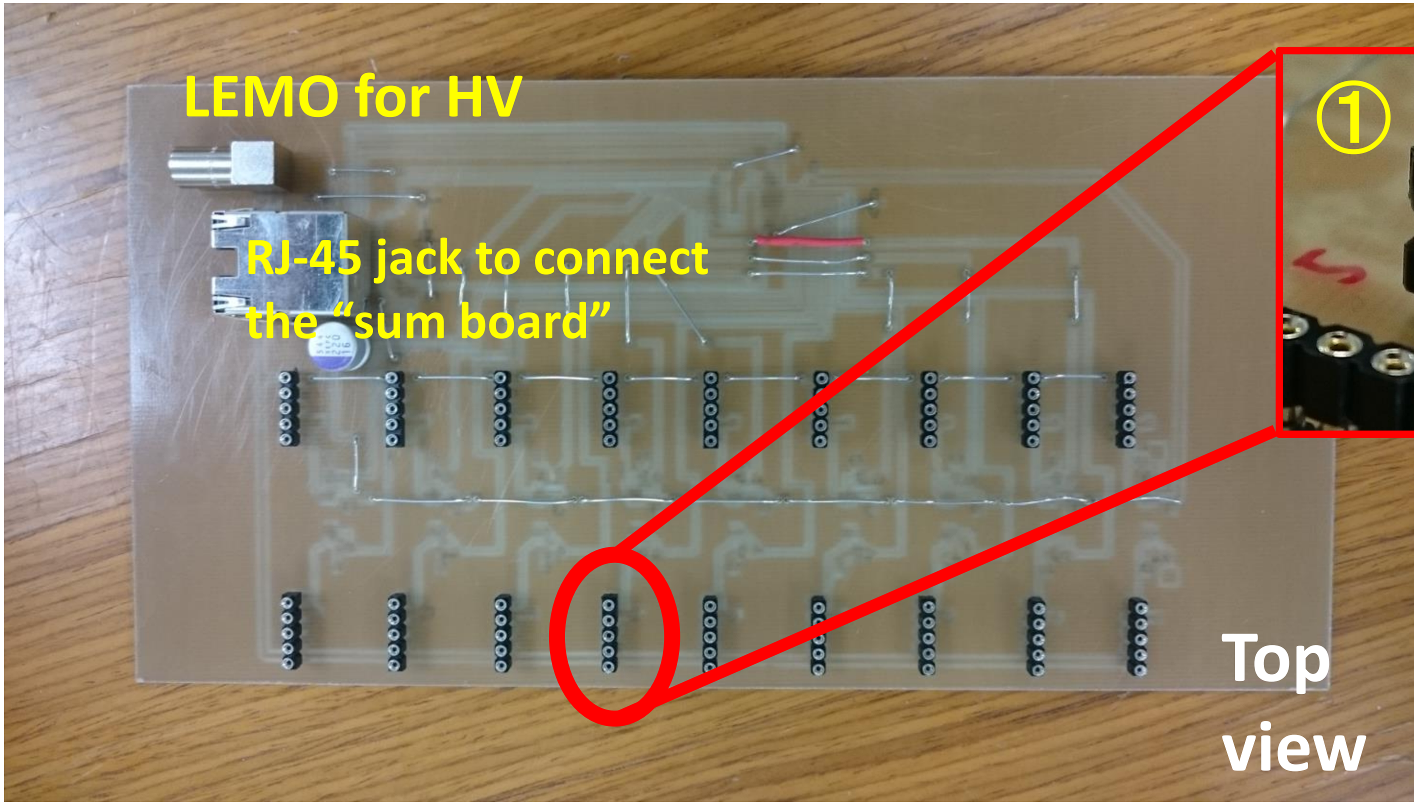


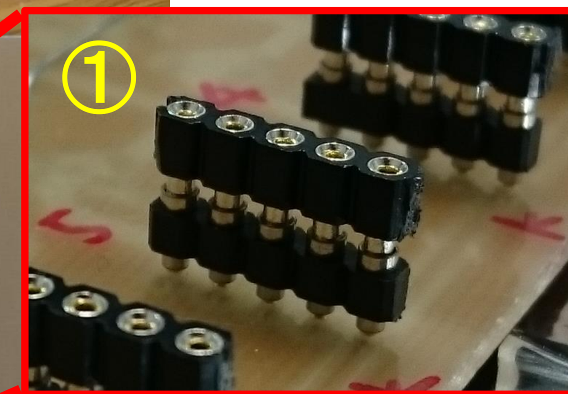


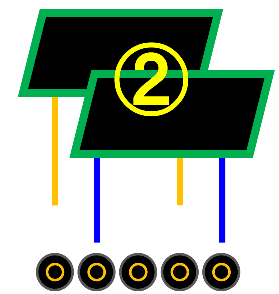
Basic design

- 16ch are chosen by MUX
- DC voltage is buffered by voltage follower after the MUX

Front-end board 1/3 (top)







IC socket

IC socket is used as a connector