A concept of neutrino scintillation detector with threshold below 1 keV

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GOALS:

Main Goal:

- Setting new constraints for neutrino magnetic moment from $\beta -$ decay of ^{3}H $(E_\nu = 17\ keV)$;

Tasks:

- Development of scintillation detector of recoil electrons;
- Development of detector's module prototype;
- Tests of detector's module prototype;

Importance:

- Current threshold of recoil electron detection is >1 keV;
- Feasible threshold of SrI_2 at temperature of $-60\ °C$ is $\sim$ 100 eV.

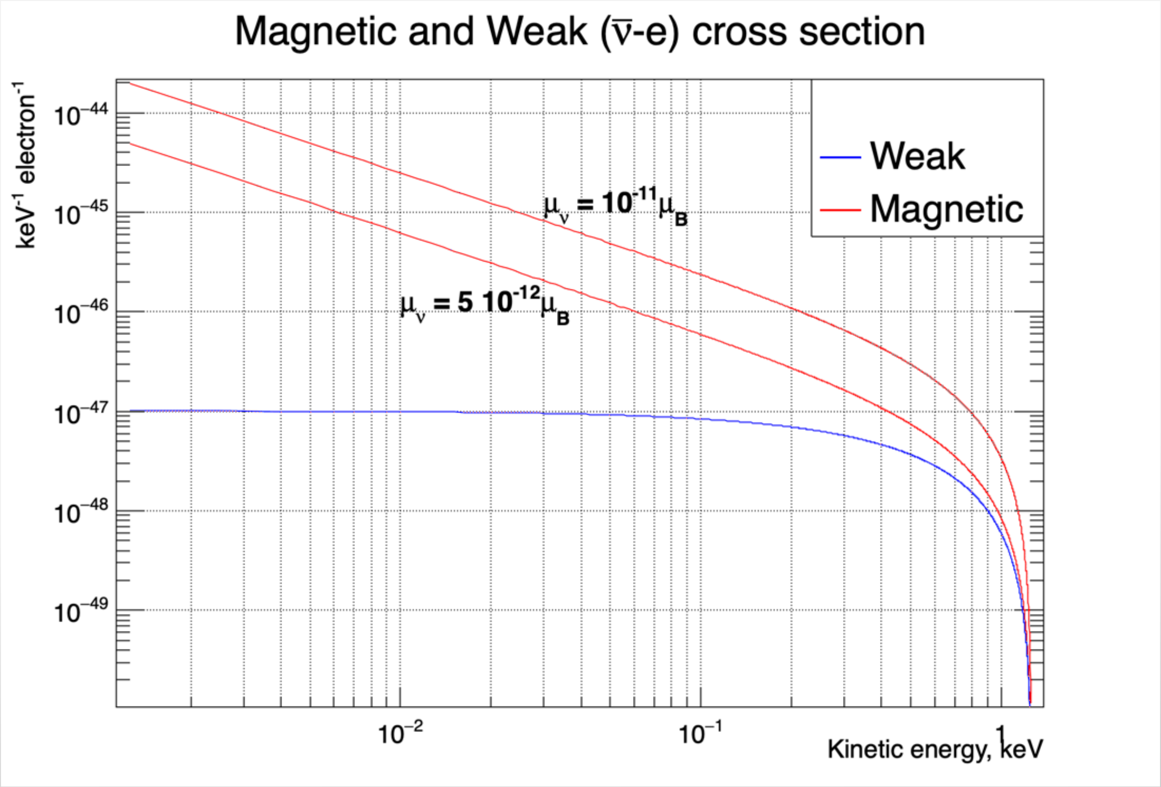
Magnetic and Weak elastic neutrino scatterings on recoil electron

Scattering on free electron:

$$\sigma_W(T,E) = \frac{G_F^2}{2\pi} m_e \cdot \left(g_R^2 + g_L^2 \left(1 - \frac{T}{E}\right)^2 - g_L^2 g_R^2 \frac{m_e T}{E^2} \right)$$

$$\sigma_M(T,E) = \pi r_e^2 \frac{\mu_\nu^2}{\mu_B^2} \cdot \left(\frac{1}{T} - \frac{1}{E} \right)$$

T – kinetic energy of the recoil electron
E – neutrino energy



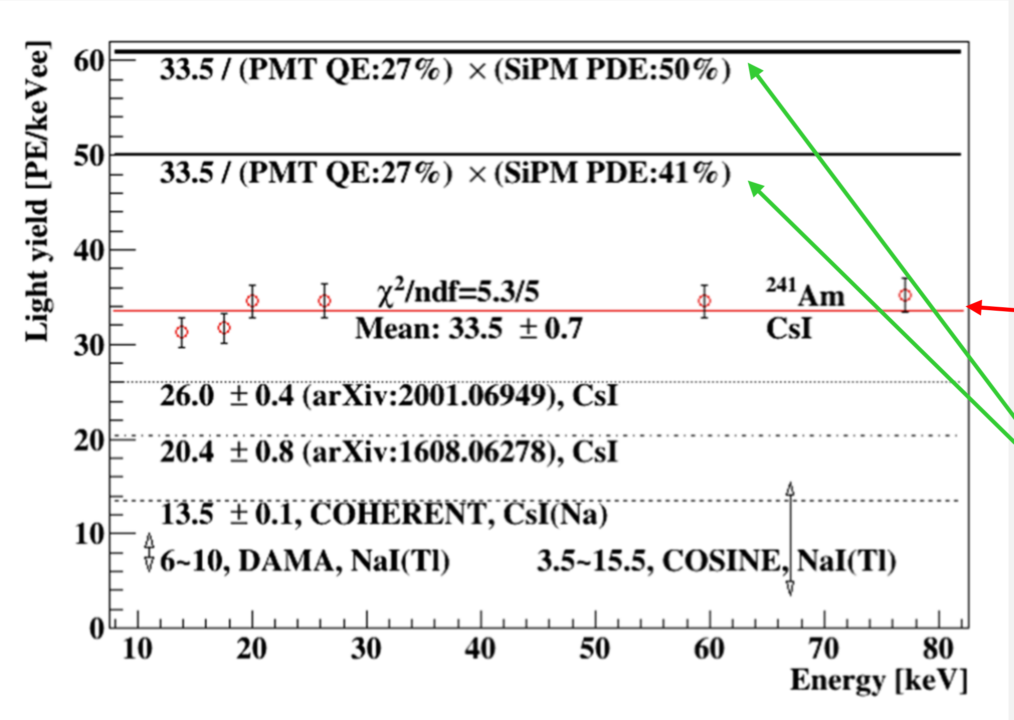
Expected event rate for electromagnetic interactions:

Mass of prototype $SrI_2(Eu)$ detector $m_{SrI_2(Eu)} = 14\ kg$
Mass of source of ^{3}H $m_{source} = 1\ kg$
$A_{^3H}(m = 1\ kg) = 9.65 MCi$

Energy threshold $\boldsymbol{E_{Threshold} = 100eV}$
Calculated event rate $\sim \mathbf{25}\frac{\boldsymbol{events}}{\boldsymbol{year}}$
Estimated constraint for 1 year of data acquisition

$$\boldsymbol{\mu_\nu < 2 \cdot 10^{-12} \mu_B}$$

Previous prototypes of detectors



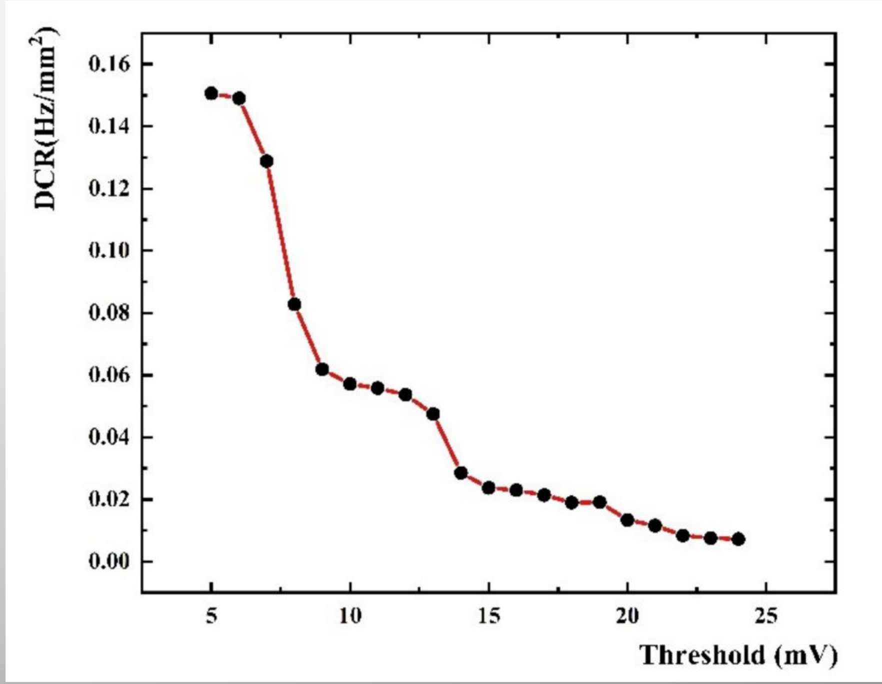
Several experimental groups tested light yields of CsI scintillator at LN_2 temperatures with PMT readout.

In recent article *Keyu Ding, Dmitry Chernyak, Jing Liu, Eur. Phys. J. C (2020) 80: 1146* authors published obtained light collections with PMT readout.

Better light collection for SiPM readout was *predicted* based on higher SiPM efficiency of photon detection compared to PMT.

In *Fang Liu et al Sensors 2022, 22(3), 1099* parameters of SiPMs were tested at LN_2 temperatures. The main drawback of SiPMs – dark current rate (DCR) was found to be low.

Authors claim that low threshold experiments are feasible if $DCR < 0.1$



Reasons for selecting $SrI_2(Eu)$

- *Light yield of* $\boldsymbol{SrI_2(Eu)}$ can reach $LY_{SrI_2(Eu)} = 120\ ph/keV$ even at room temperature.
- If light collection efficiency is ~50%, the 100 eV threshold corresponds to 6 photons.
- Photon detection efficiency (PDE) of SiPMs can reach ~50% !

main $SrI_2(Eu)$ advantages

Internal radioactivity	none
Scintillation wavelength	430 nm (close to SiPM maximum efficiency)
Operating temperature	T ~ -60 ^{0}C (SiPM noise suppression)

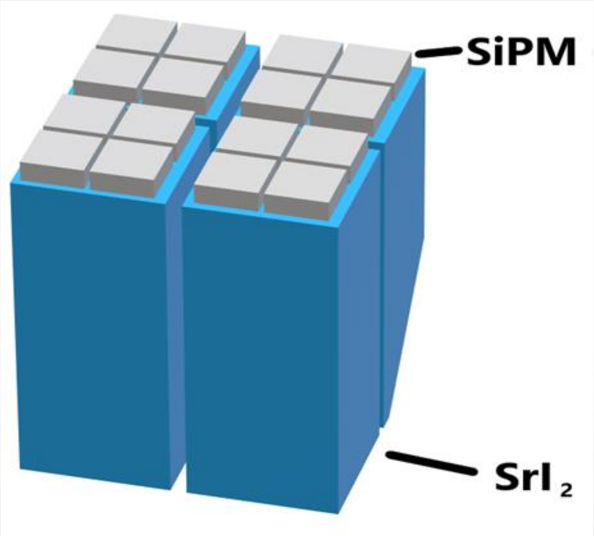
Optimal optical contact at operating temperature

Basic detector cell is a crystal with SiPM matrix light readout from one of the ends.
Cross dimension ~15x15 mm^2 is close to SiPM matrix size.
Length ~25 mm.

SrI_2(Eu) has many advantages for low threshold scintillation detectors.
However, it is very hygroscopic and requires innovative manufacturing.

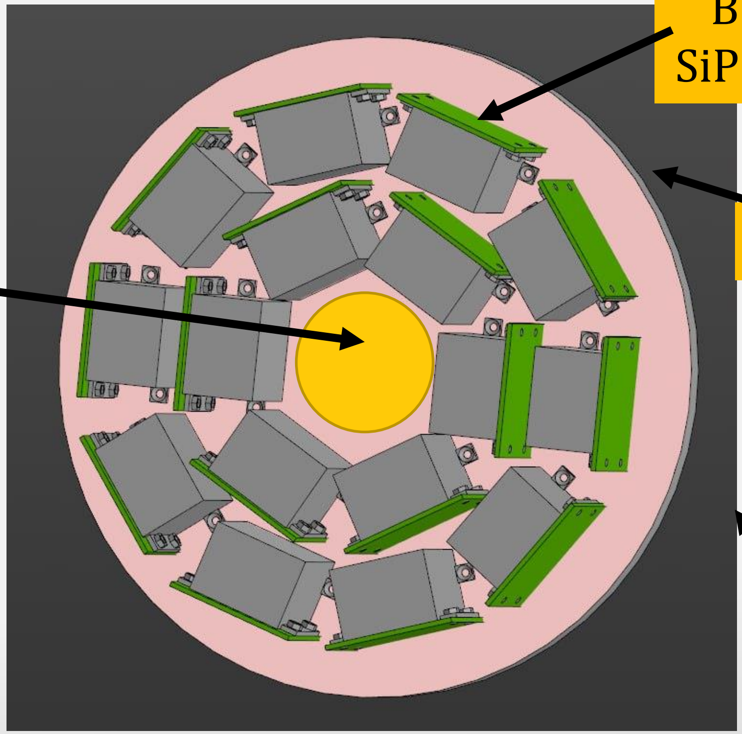
Concept of $SrI_2(Eu)$ scintillation detector

Module:
Base element consists of 4 $SrI_2(Eu)$ crystals, placed in plastic container.
16 SiPM matrix is used to read signals.



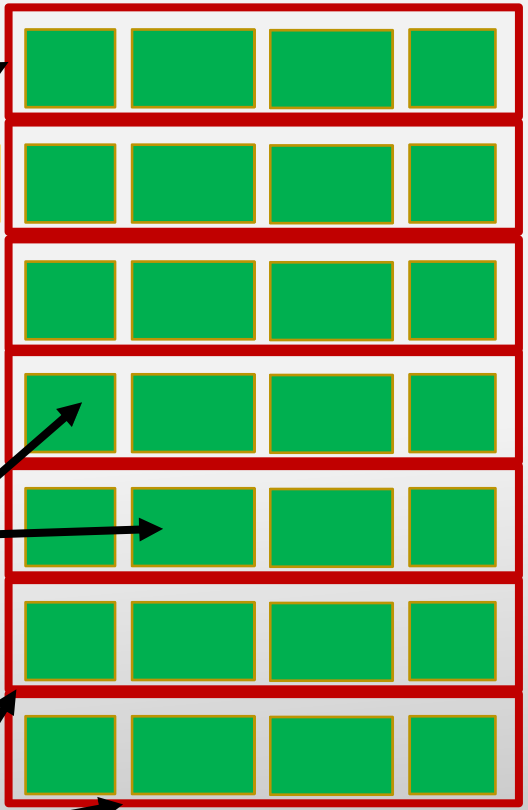
Mass of a $SrI_2(Eu)$ crystal $\sim$ 25 g
Mass of crystals in single module $\sim$ 100 g

Detector layer



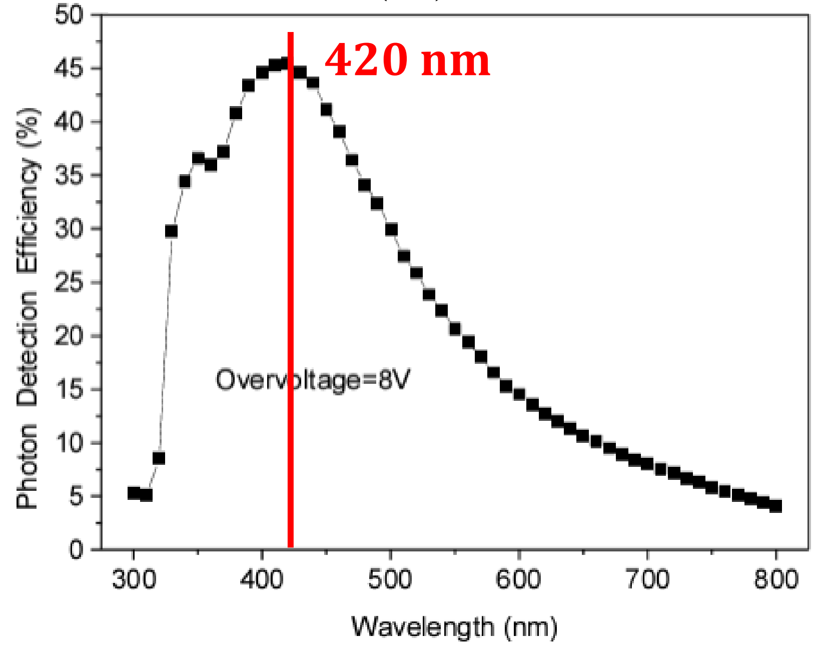
- Detector layer consists of 16 modules.
- Each modules layer has 64 channel readout
- Mass of crystals in one detector layer is $m_{SrI_2(Eu)} = 1.6\ kg$

Detector layer structure

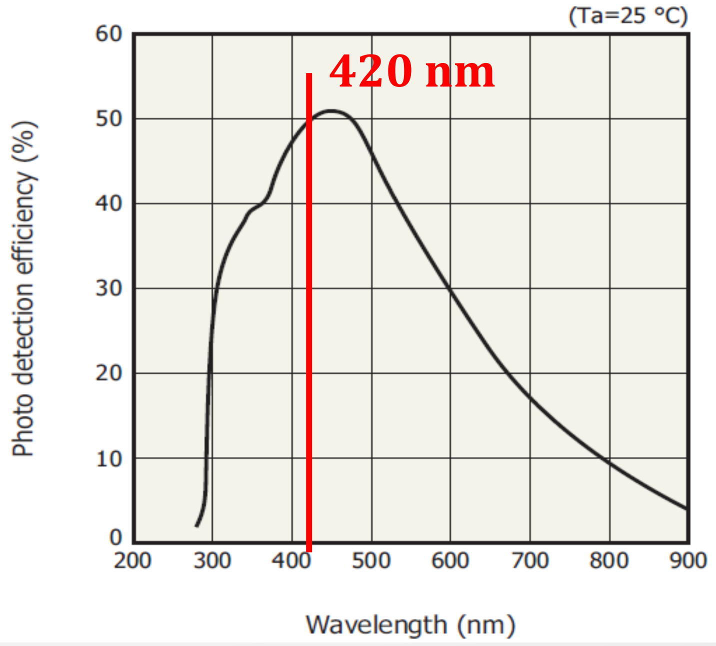


Considered SiPM matrixes

NDL EQR15(20) *11-6060D-S*



Hamamatsu MPPC *S14161-3050HS-04*



Parameters of ***NDL EQR15*** *11-6060D-S*

- 4 independent $6 \times 6mm^2$ $SiPMs$
- Size 15×15 mm^2
- High PDE (~45% at 420 nm)
- High gain $\sim 4 \cdot 10^5$
- Breakdown voltage is low ($\approx$ 30 V for room temperature)
- Relatively high DCR

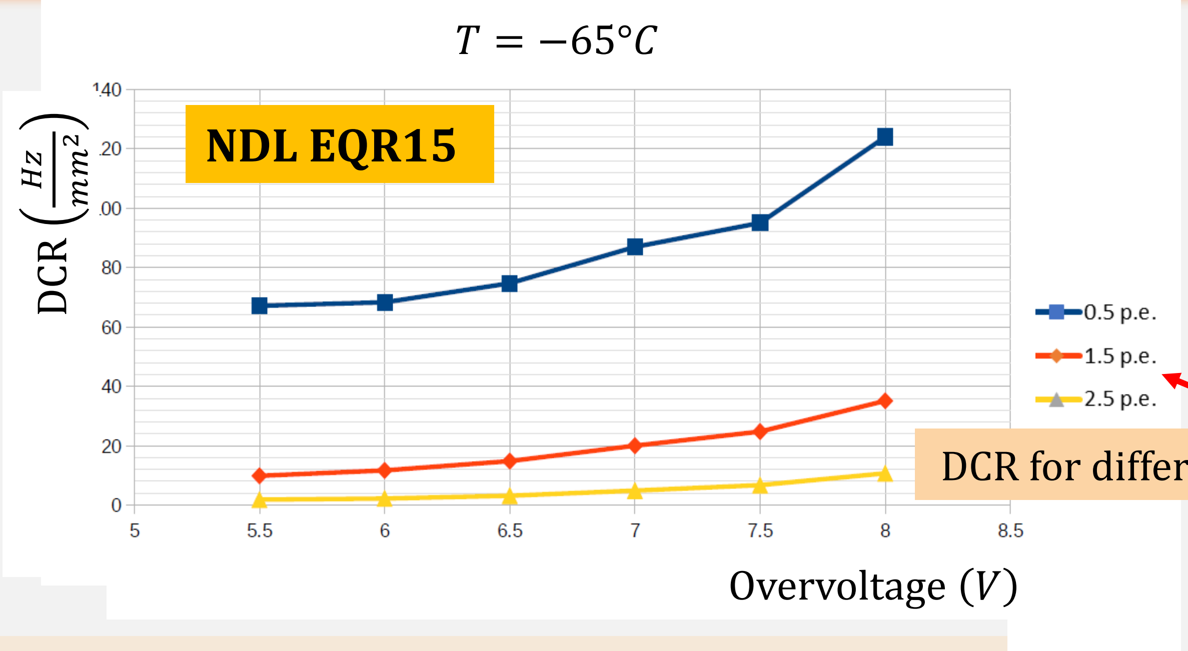
Parameters of ***NDL EQR20*** *11-6060D-S*

- 4 independent $6 \times 6mm^2$ $SiPMs$
- Size 15×15 mm^2
- High PDE (~46% at 420 nm)
- High gain $\sim 8 \cdot 10^5$
- Breakdown voltage is low ($\approx$ 27.5 V for room temperature)
- Relatively high DCR

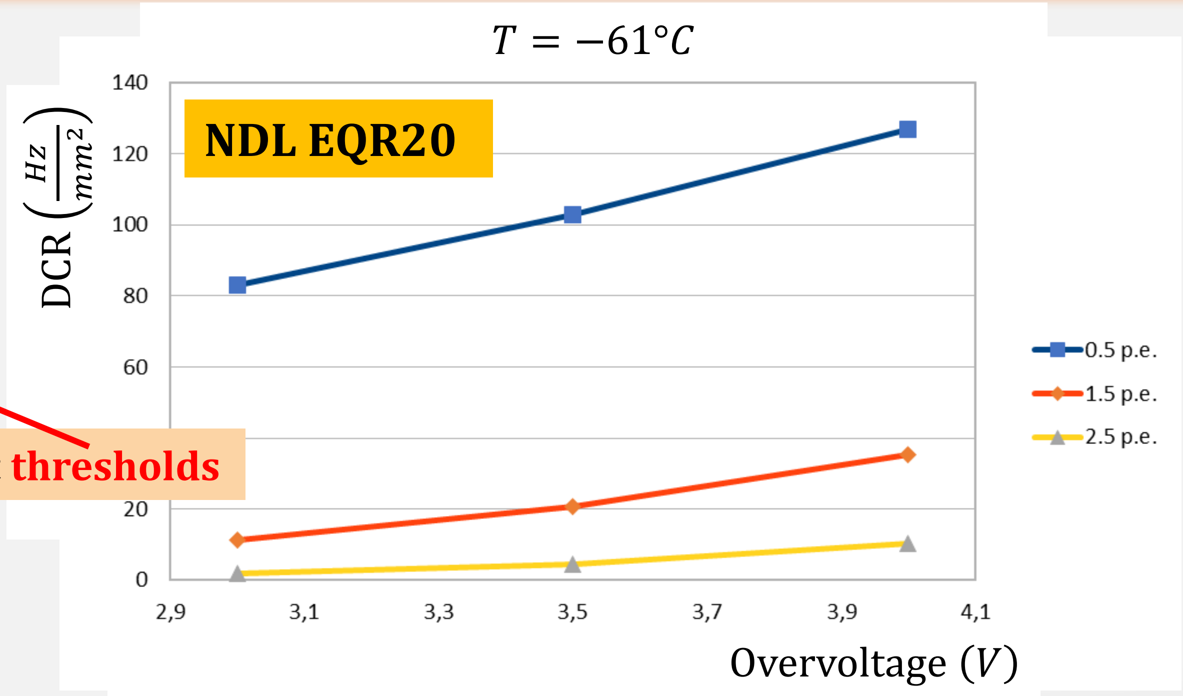
Parameters of ***Hamamatsu MPPC*** *S14161-3050HS-04*

- 16 independent $3 \times 3mm^2$ $SiPMs$
- Size 13×13mm^2
- High PDE (~50% at 420 nm)
- High gain $\sim 10^6$
- Breakdown voltage is low ($\approx$ 38 V for room temperature)
- Relatively low DCR

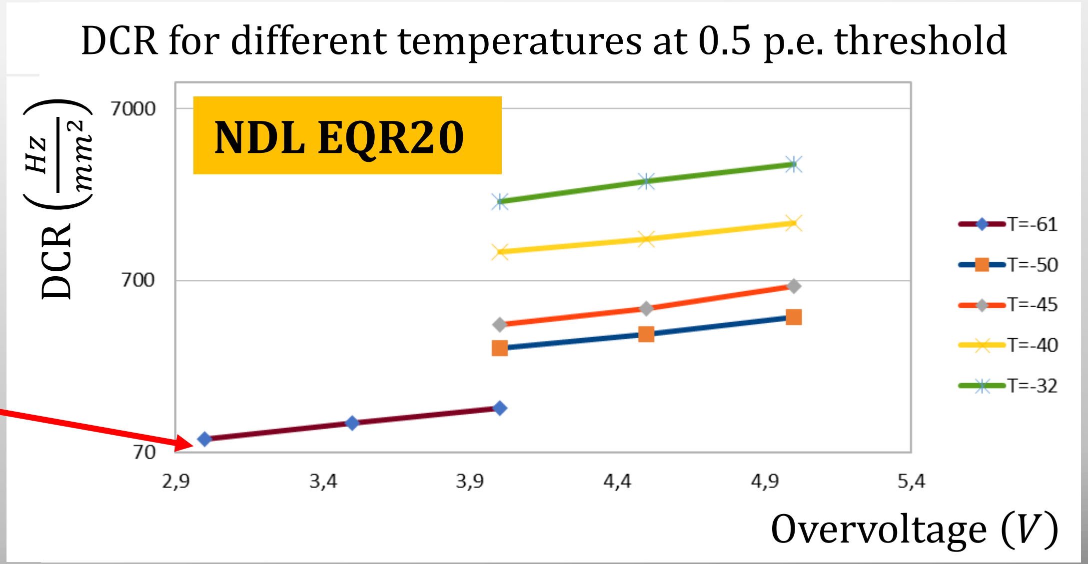
Dark current rate (DCR) of NDL SiPM matrixes



DCR for different **thresholds**

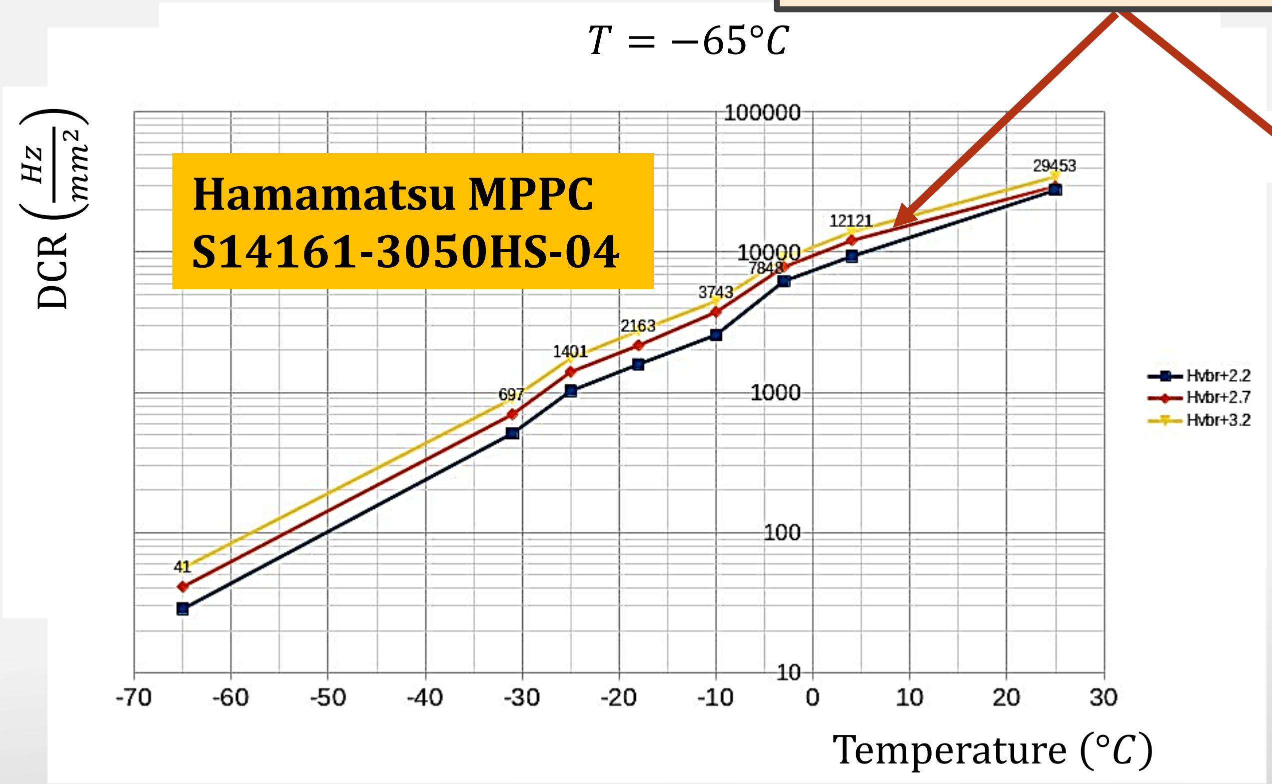


- *NDL EQR20 and EQR15* have similar DCR despite datasheet claiming 2 times lower for *EQR20*
- High DCR $\sim\frac{70Hz}{mm^2}$ at $T = -65°C \Rightarrow$ temperature should as low as -100 $°C$!
- *NDL15* can operate at low temperatures
- **NDL20 is unstable at low temperatures (higher than 100% crosstalk)**

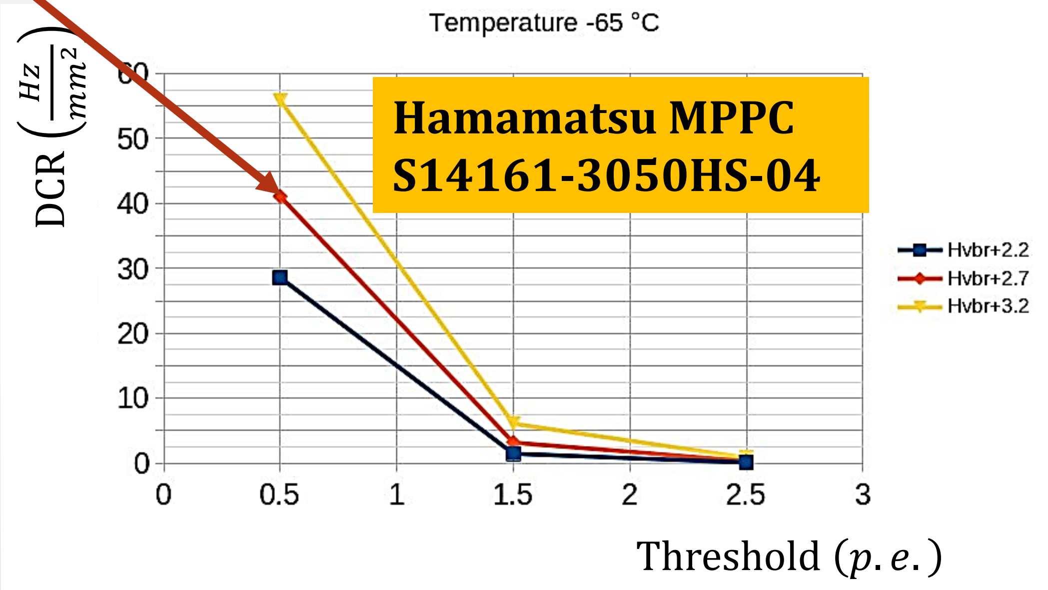


Dark current rate (DCR) of Hamamatsu SiPM matrixes

$Overvoltage = 2.7V$ is recommended by Hamamatsu for maximum efficiency



DCR for different overvoltages OV ($OV = 2.7V$ default)

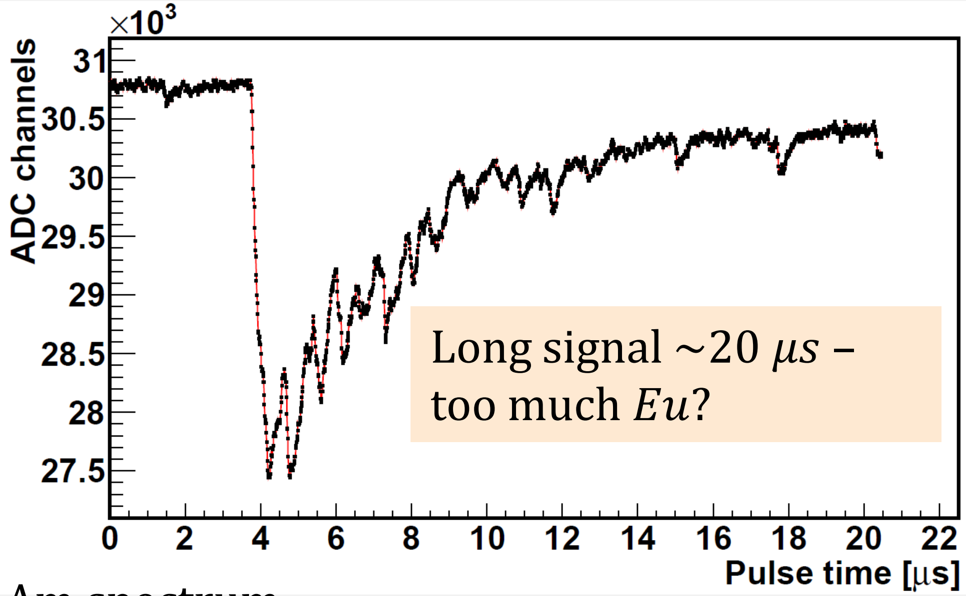


For temperature $T = -65°C$ an upper limit of Crosstalk (CT) value was calculated:

$CT < 7\%$

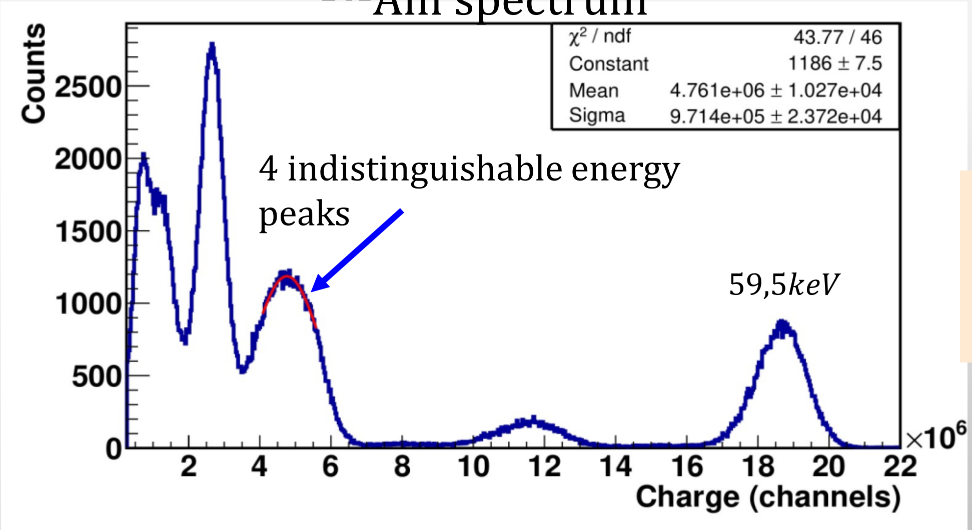
Hamamtsu SiPMs are considered as the main option for future detector

Commercial sample of $SrI_2(Eu)$ scintillation detector



- Scintillation detector sample CapeSym (USA).
- Crystal size 13x13x13 mm^3 corresponds to SiPM matrix size

^{241}Am spectrum



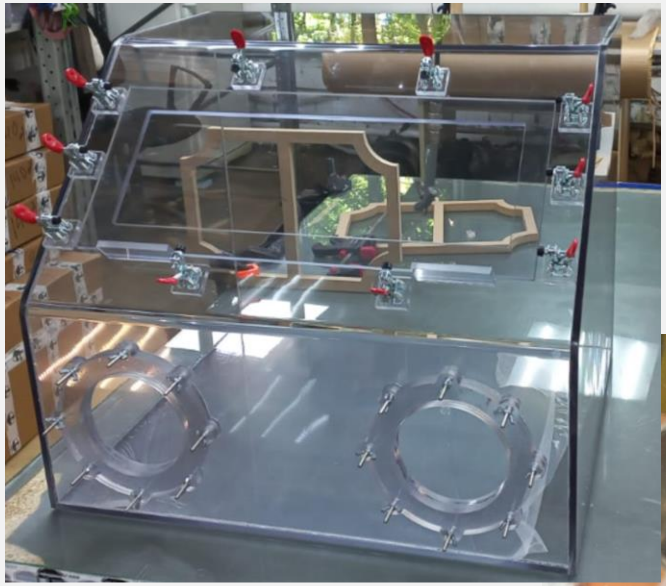
SiPM matrix Sensl ArrayC-60035-4P-EVB
- Matrix size 13x13мм^2.
- 4 independent 6x5 SiPMs.
- PDE (~40% at 420 nm)
- High gain $\sim 3 \cdot 10^6$
- Breakdown voltage is low ($\approx$ 24.7 V for room temperature)
- High DCR

- Light Collection $= \mathbf{33.4}\ \frac{\boldsymbol{p.e.}}{\boldsymbol{keV}}$
- No information about SiPM crosstalk

Packing of $SrI_2(Eu)$ crystals at INR RAS

$SrI_2(Eu)$ is highly hygroscopic.
Treatment in dry box is essential.

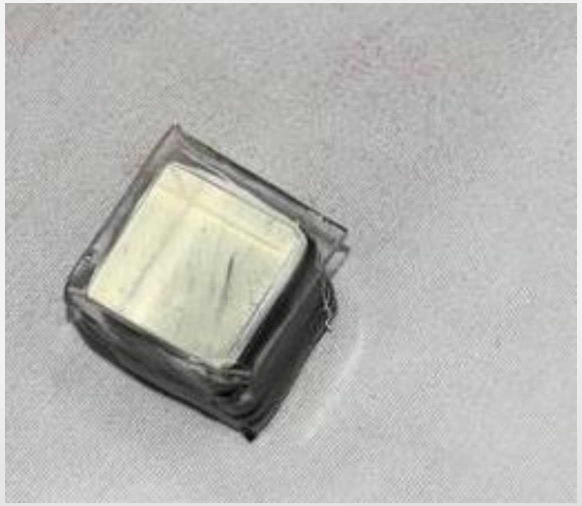
Recently, crystals started being produced in Nikolaev Institute of Inorganic Chemistry, Siberian Branch of Russian Academy of Sciences (NIIC SB RAS, Novosibirsk)



Dry box

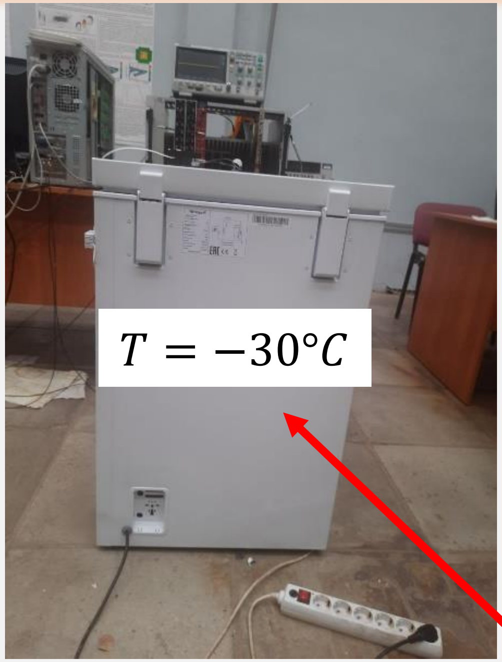
Polishing and wrapping crystal in Teflon tape

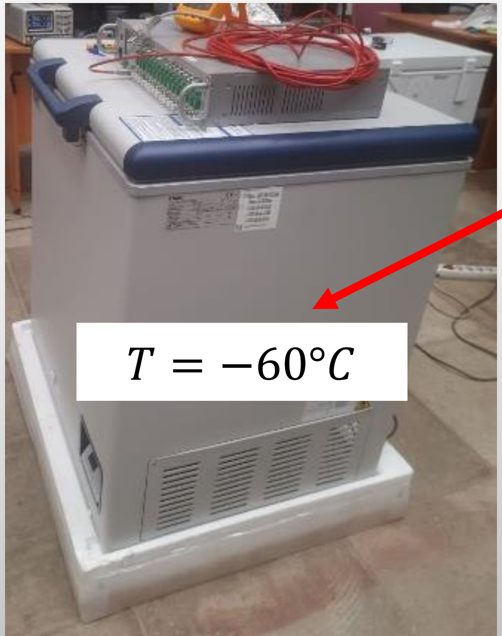
Crystal is polished. Looks opaque due to fast hydration.

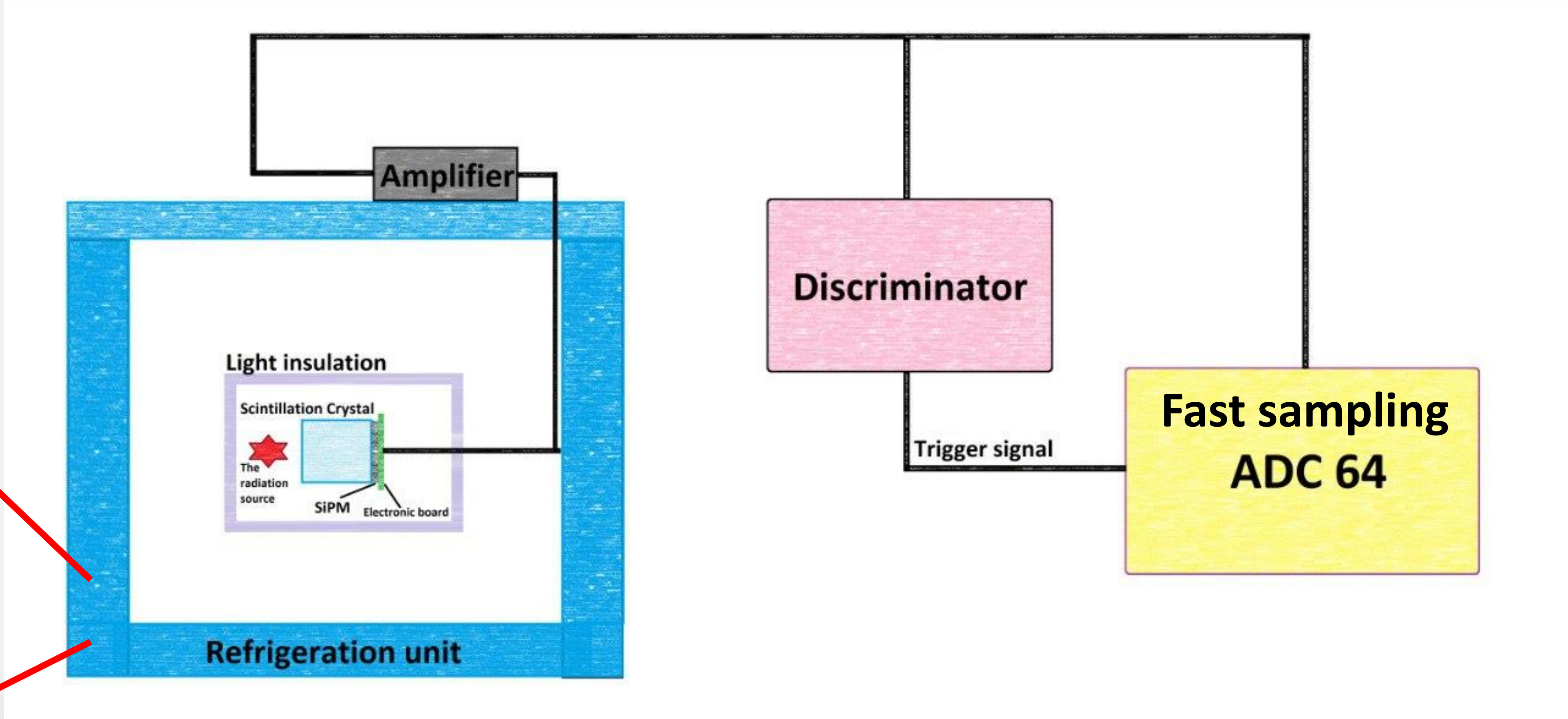


Crystal is wrapped in highly reflective Teflon tape and covered by transparent tape for optical contact

Experimental setup for testing module parameters



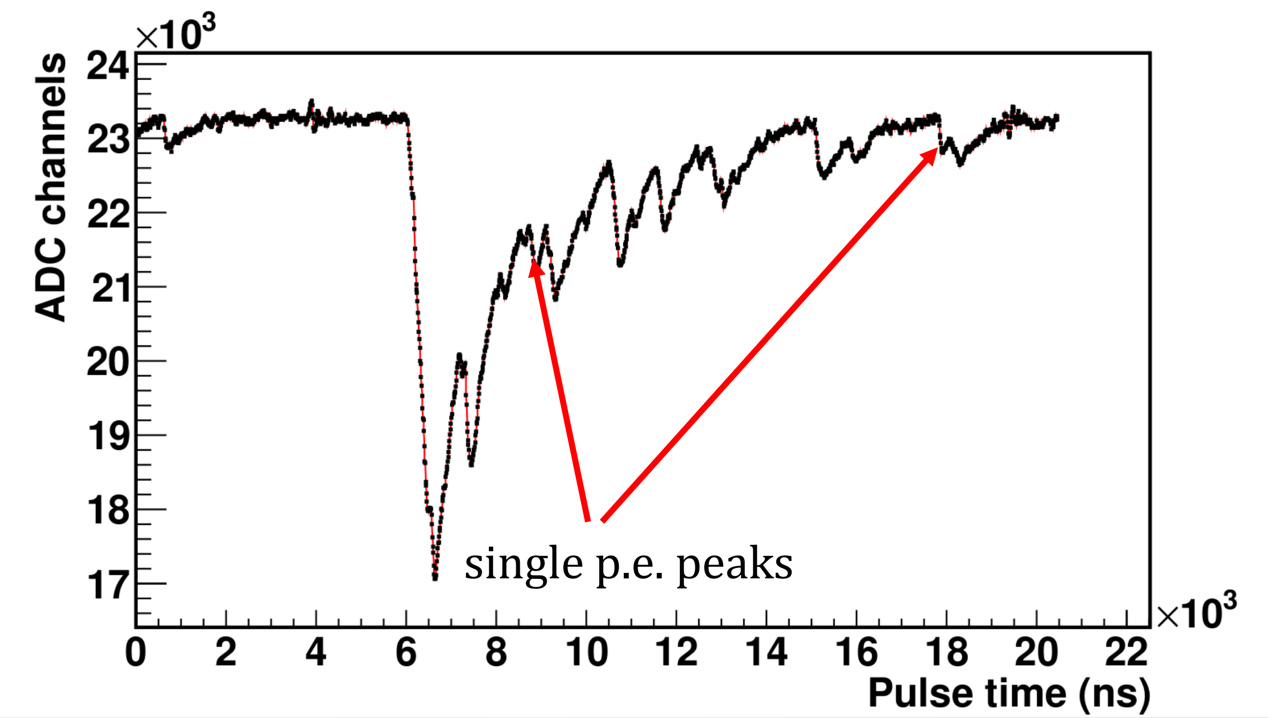




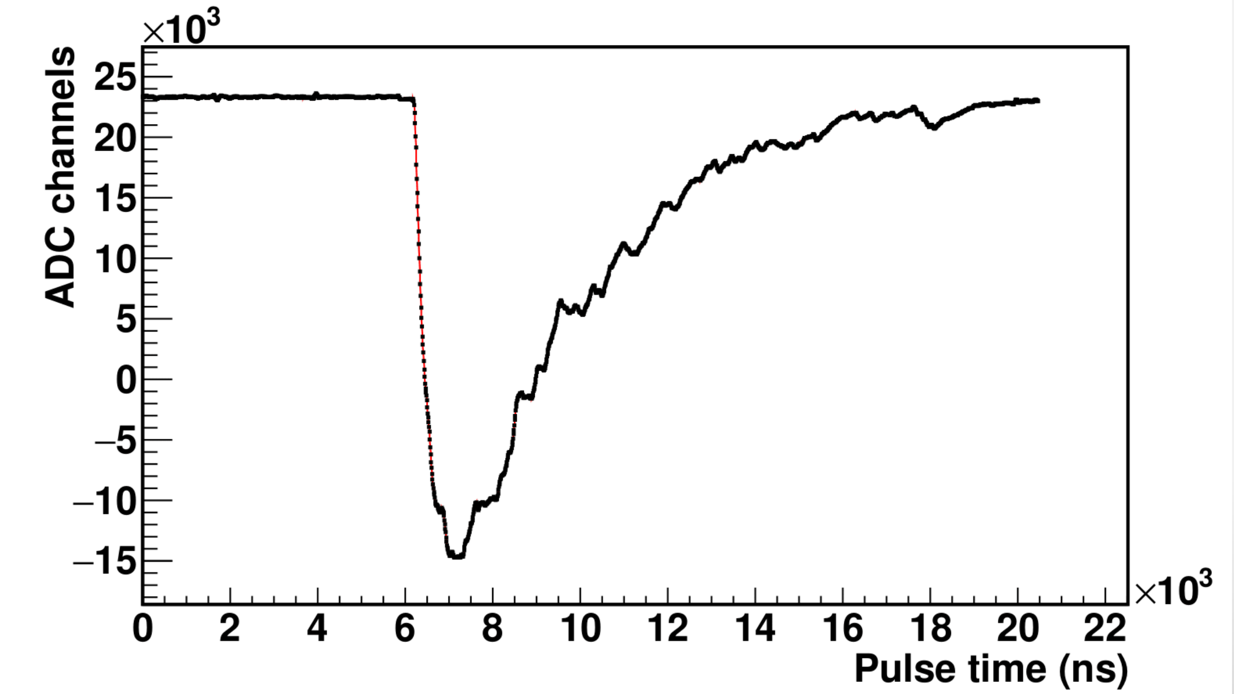
- $SrI_2(Eu)$ scintillation crystal is wrapped in Teflon fluoroplastic tape.
- Several γ sources were used to test modules in wide energy range (Am241, Co57, Cs137, Na22)
- $SrI_2(Eu)$ crystals of two different sizes were tested ($15 \times 15 \times 15mm^3$ and $15 \times 15 \times 25mm^3$)

Typical signals

Signals acquired during ^{241}Am tests of scintillation detector



Low (few keVs) amplitude signal



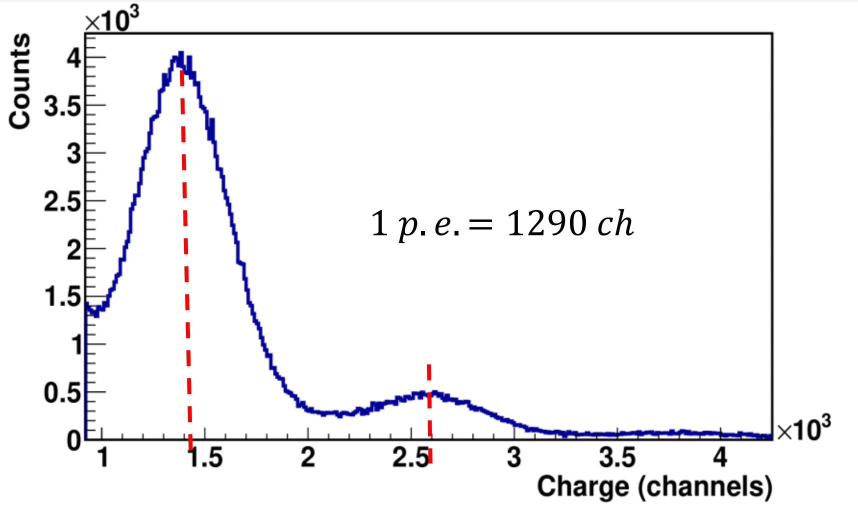
High (tens of keVs) amplitude signal

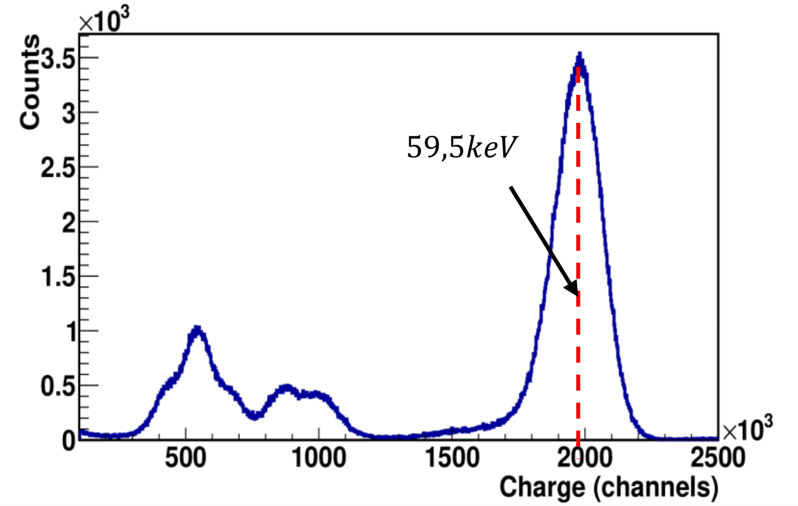
- Typical analyzed signal time ~8μs is much lower than for commercial CapeSym sample (20 μs)
- Integrating over signal waveform yields lesser noise impact on charge

$SrI_2(Eu)$ light collection for NDL SiPM matrixes

$15 \times 15 \times 15mm^3$ crystal

$\boldsymbol{NDL\ EQR15}$; $U_{op} = 30.15\ V$; $241Am$; $T = -61°C$



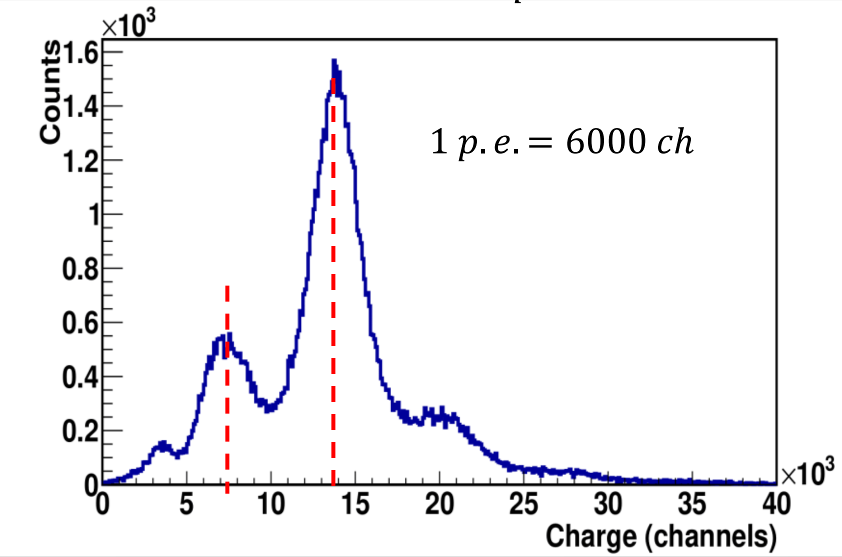


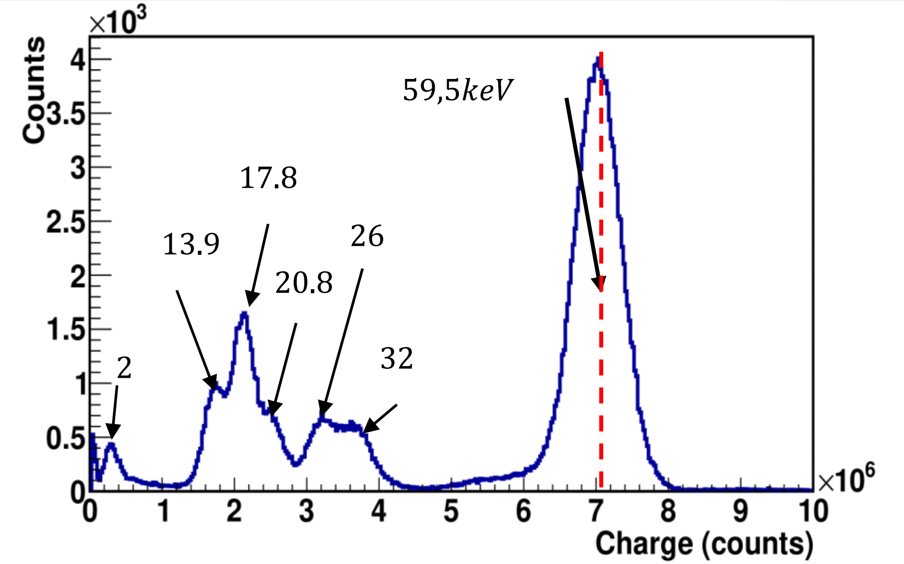
Light Collection $\boldsymbol{LC} = \mathbf{25.8}\ \boldsymbol{\frac{p.e.}{keV}}$

Crosstalk $\boldsymbol{CT} = \mathbf{35\%}$

Corrected LC $= \mathbf{19.1}\ \boldsymbol{\frac{p.e.}{keV}}$

$\boldsymbol{NDL\ EQR20}$; $U_{op} = 29\ V$; $241Am$; $T = -50°C$ (does not function at $T = -60°C$)





Light Collection $\boldsymbol{LC} = \mathbf{39.6}\ \boldsymbol{\frac{p.e.}{keV}}$

Crosstalk $\boldsymbol{CT} = \mathbf{30\%}$?
(unstable)

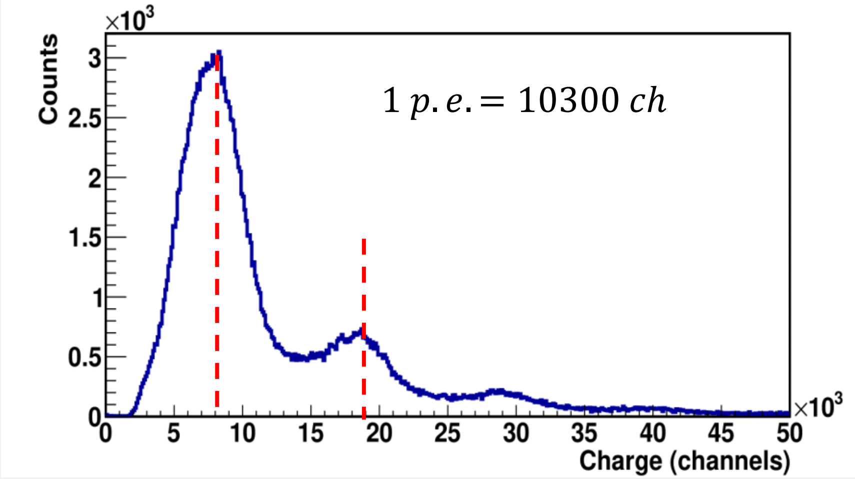
Corrected LC $= \mathbf{30.5}\ \boldsymbol{\frac{p.e.}{keV}}$

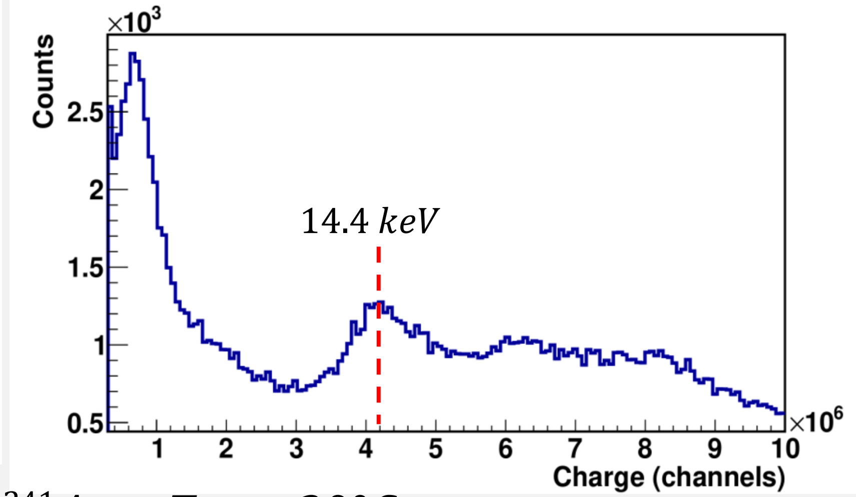
Much higher light collection and much better energy resolution.
2 keV peak is visible!

$SrI_2(Eu)$ light collection for Hamamatsu SiPM matrixes

$15 \times 15 \times 15 mm^3$ crystal

S14161−3050HS−04; ^{57}Co; $T = -30°C$



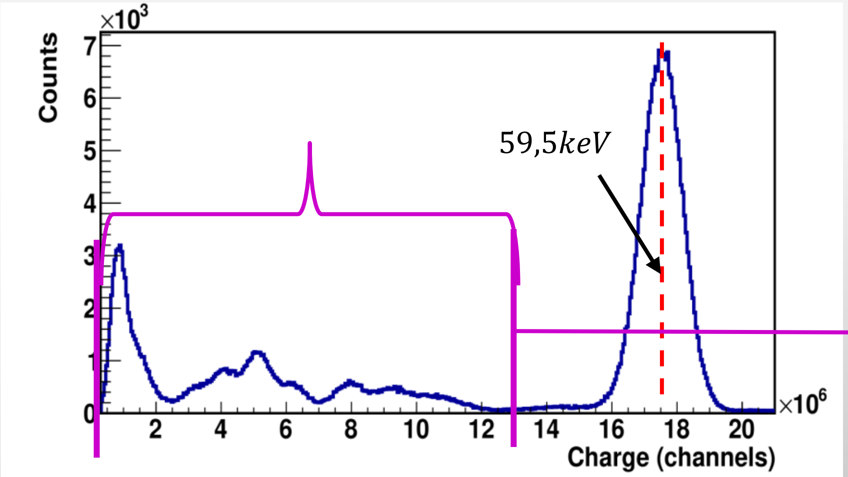


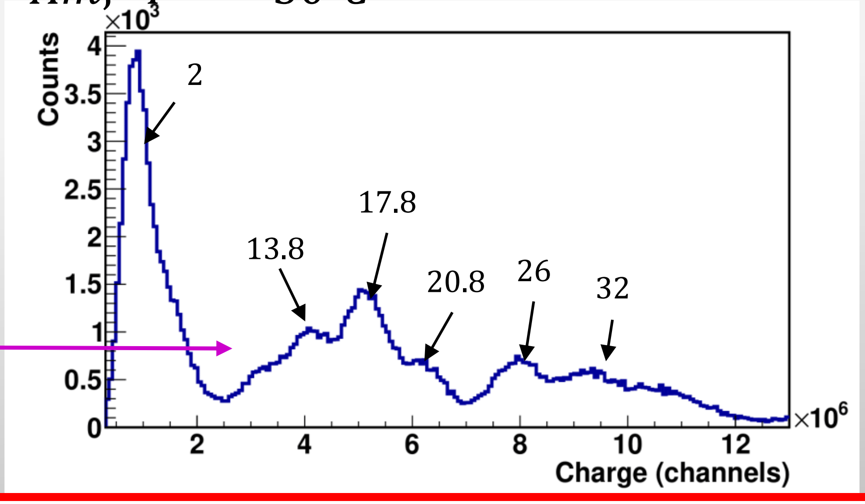
Light Collection $\boldsymbol{LC = 28.3\ \frac{p.e.}{keV}}$

Crosstalk $\boldsymbol{CT = 3\%}$

Corrected LC $= \boldsymbol{27.5\frac{p.e.}{keV}}$

S14161−3050HS−04; ^{241}Am; $T = -30°C$





Light Collection $\boldsymbol{LC = 28.5\ \frac{p.e.}{keV}}$

Crosstalk $\boldsymbol{CT = 3\%}$

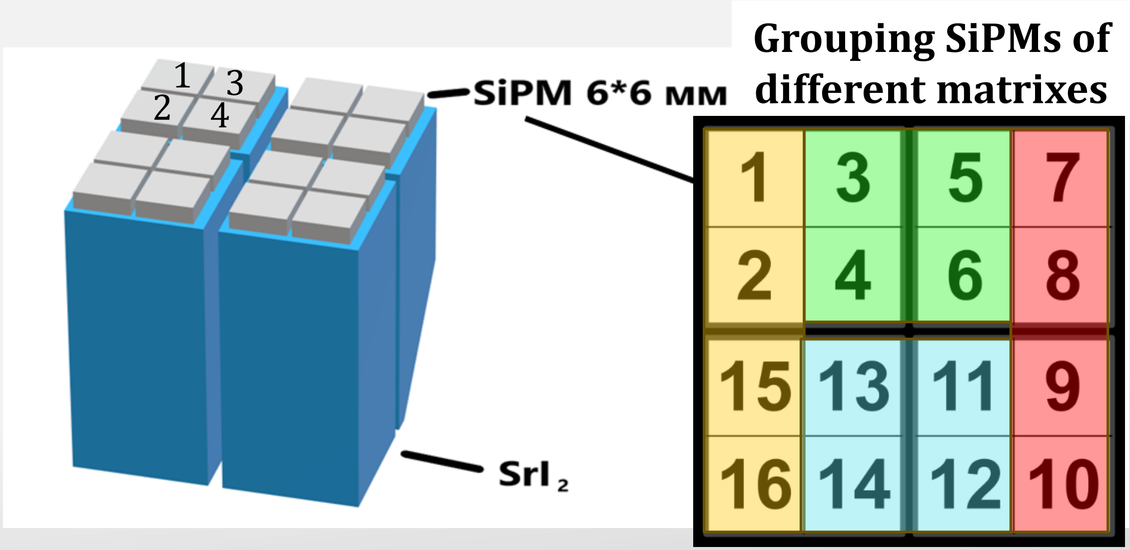
Corrected LC $= \boldsymbol{27.7\frac{p.e.}{keV}}$

- **Hamamatsu matrixes readout yields better resolution due to lower crosstalks**
- **Hamamatsu matrixes are more stable at lower temperatures**

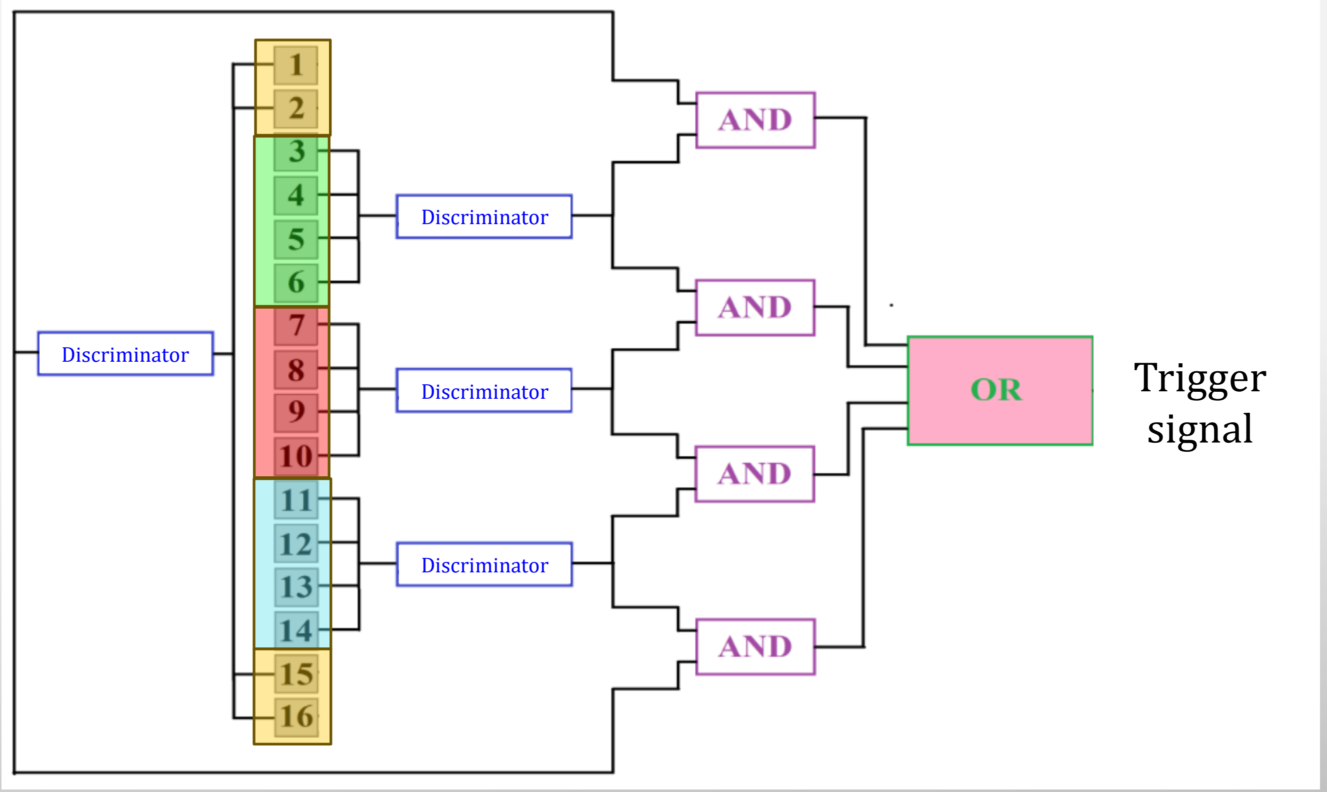
Additional suppression of DCR (double coincidence)

Dark current rate (DCR) still high ($\sim 1\ Hz/mm^2$) even at $T = -60°C$. Additional DCR suppression is needed.
Signal double coincidence in each crystal would suppress DCR for a few orders.

Above results acquired by signal integration and threshold about 1 keV was achieved.
To achieve 100 eV threshold, photoelectron counter regime will be used.



Signal readout from detector module



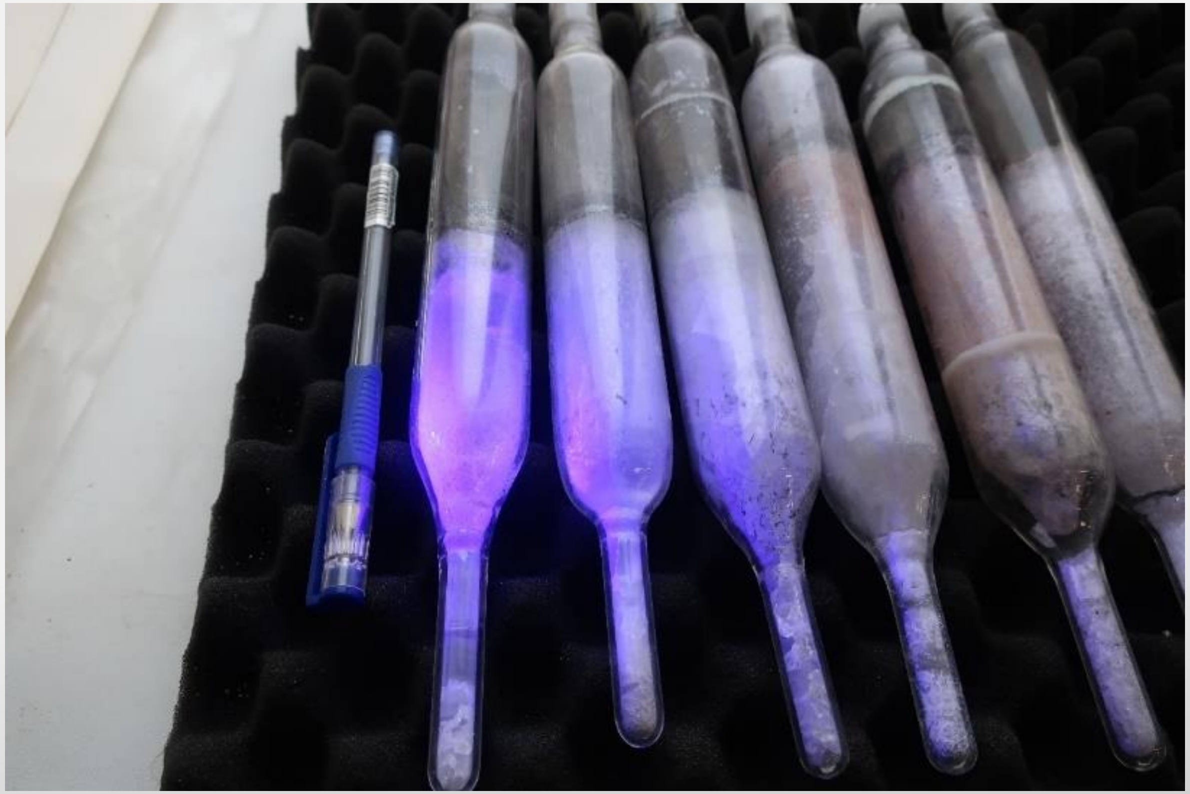
Trigger logic

Conclusion

- New concept of ultralow threshold neutrino $SrI_2(Eu)$ scintillation detector was suggested;
- Preliminary test of $SrI_2(Eu)$ prototype confirms that signal could achieve 30 p.e./keV;
- Detector can operate at relatively convenient temperature of $-60°C$;
- 2 keV signals corresponding to Sr atom excitation are nicely visible;
- Low threshold of ~100 eV can be achieved by photoelectron counter regime;
- Due to NDL SiPMs higher DCR value and instability at lower temperatures Hamamatsu MPPC will be used for light detection;

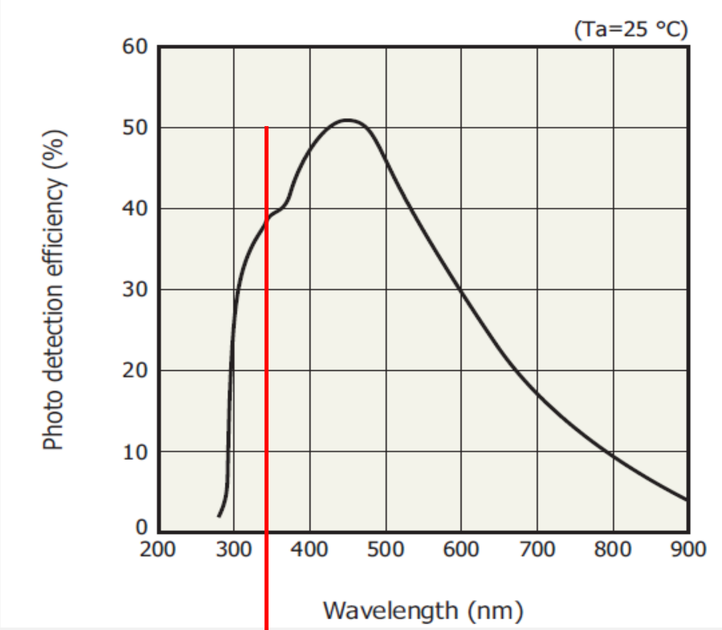
Thank you for your attention

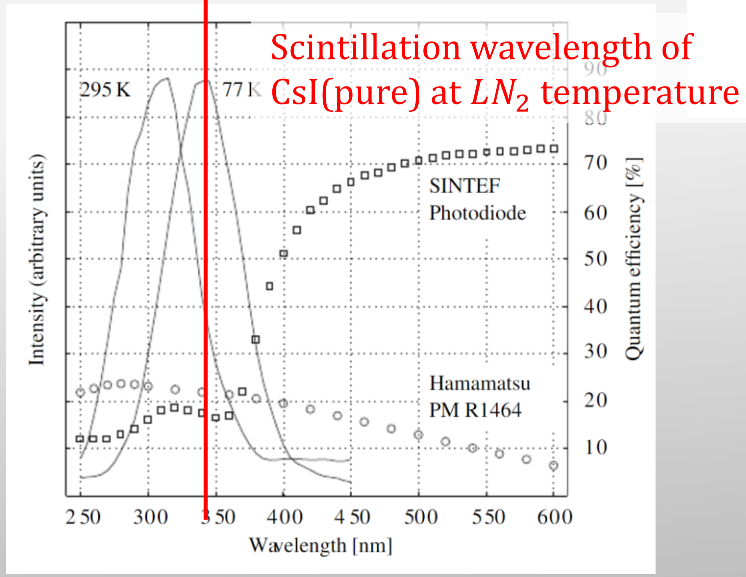
$SrI_2(Eu)$ production



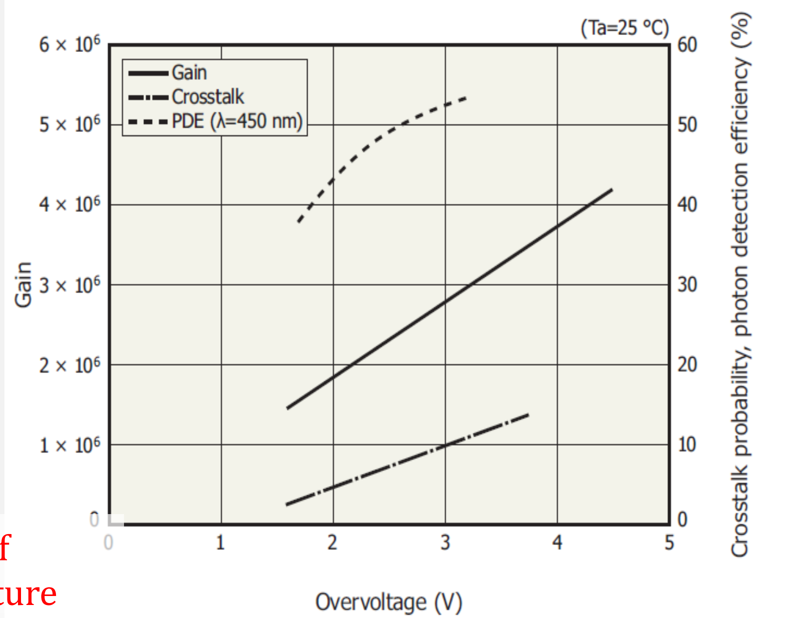
SiPM matrixes

FEE board with soldered SiPM matrix





Emission spectrum of CsI (pure) at room and LN_2 temperatures

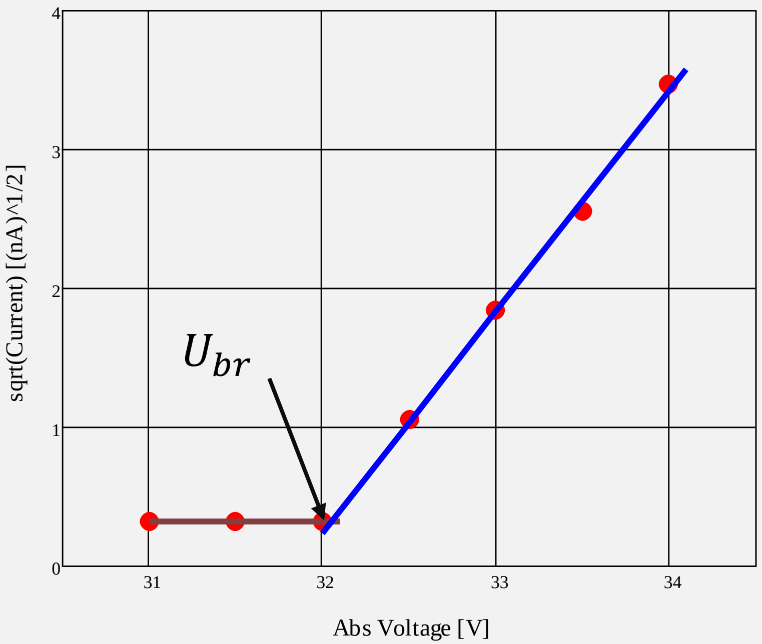


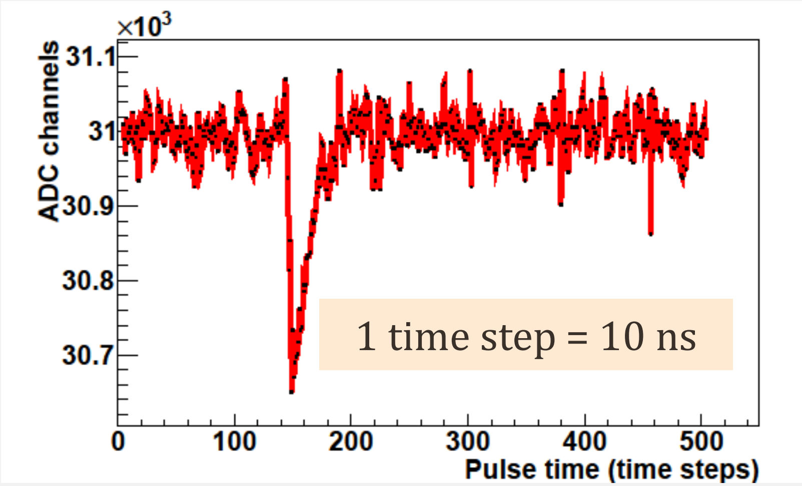
Dependence of Gain and PDE on overvoltage for the SiPM matrixes

Parameters of *Hamamatsu MPPC S14161-3050HS-04*

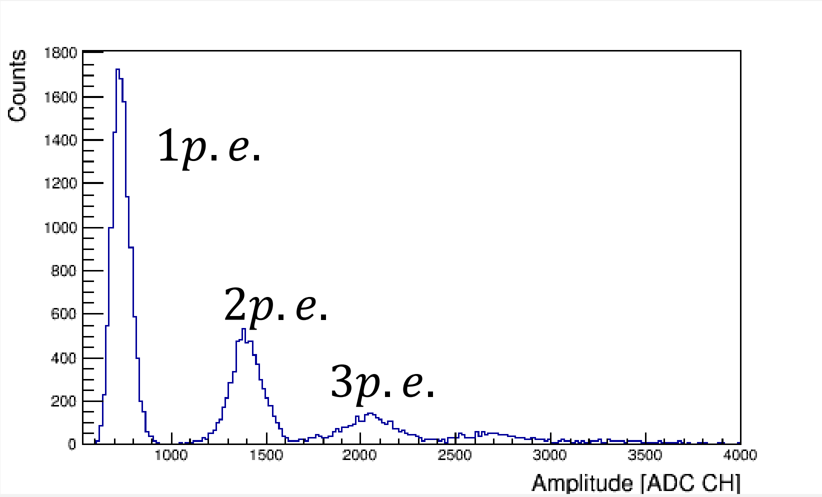
- 16 independent $3 \times 3mm^2$ *SiPMs*
- Size $13 \times 13\text{mm}^2$
- High PDE (~40% at 350 nm)
- High gain $\sim 10^6$
- Breakdown voltage is low ($\approx$ 38 V for room temperature)

MPPC parameters at LN_2 temperature





Single photoelectron signal from SiPM



Electron noise amplitude spectrum

Breakdown voltage at LN_2 temperature (77K):

$$U_{br_{LN_2}} = 32\ V;$$

Breakdown voltage at room temperature (293K):

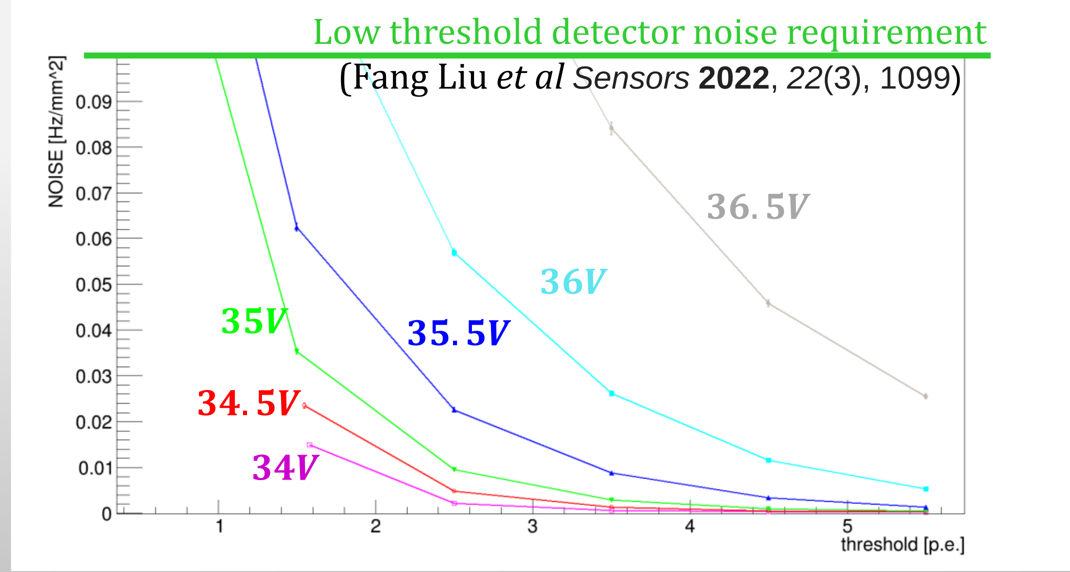
$$U_{br_{room}} = 38\ V;$$

In a large temperature range breakdown voltage depends on environment temperature linearly.

Temperature coefficient $\frac{\Delta U}{\Delta T} = 0.027 \frac{mV}{K}$

According to Hamamatsu $\frac{\Delta U}{\Delta T} = 0.034 \frac{mV}{K} \Rightarrow$

Non-linearity of U_{br} at cryogenic temperature?

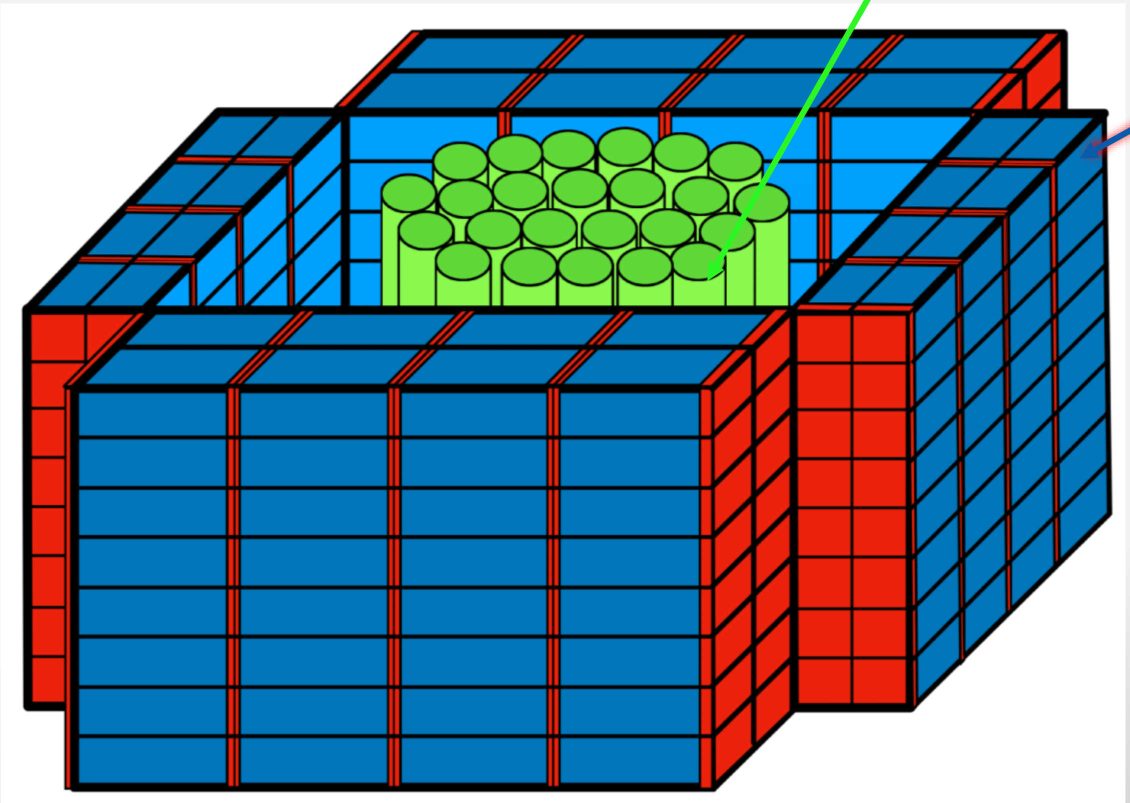


Noise event rate vs threshold dependence for different operating voltages

Possible variant of the Setup

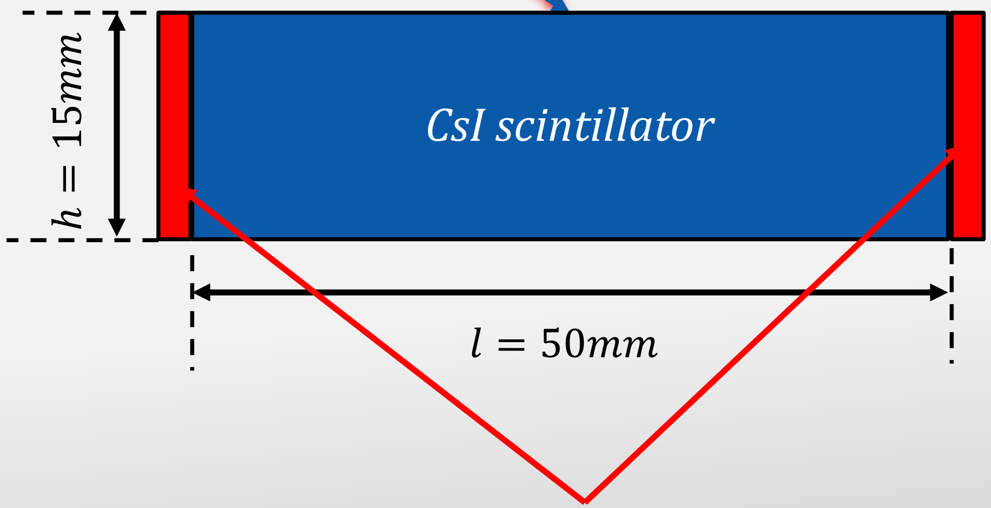
Source - *Ti* tubes with ^{3}H gas

$m_{^3H} = 1kg; A = 9.65\ kCi$



Design of the experimental setup`s prototype

detector module

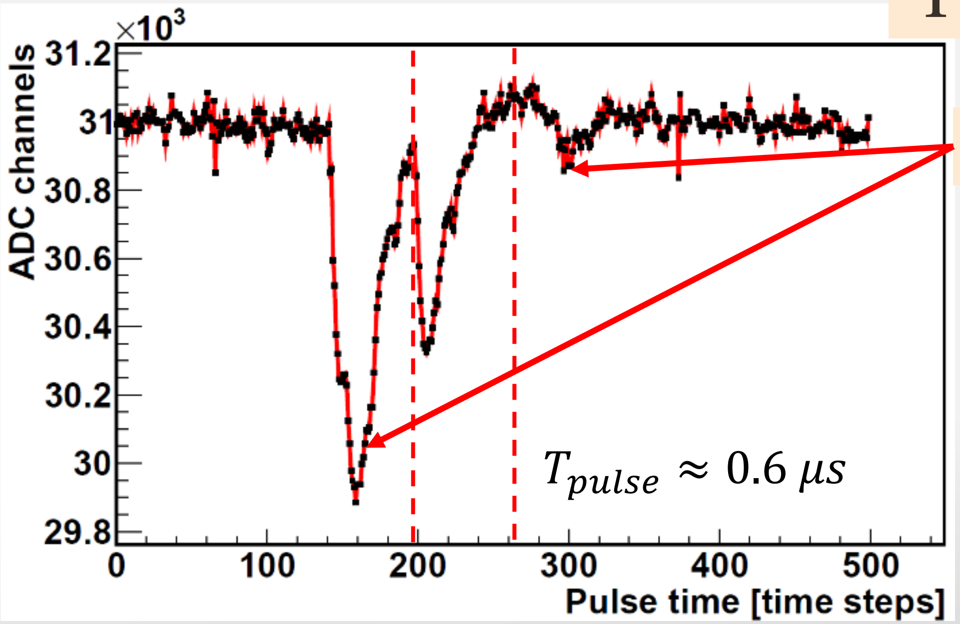


HAMAMATSU MPPC S14161-3050HS-04

Each module has 2 channel SiPM readout
Expected number of channels ~2000

Typical waveforms for different amplifiers

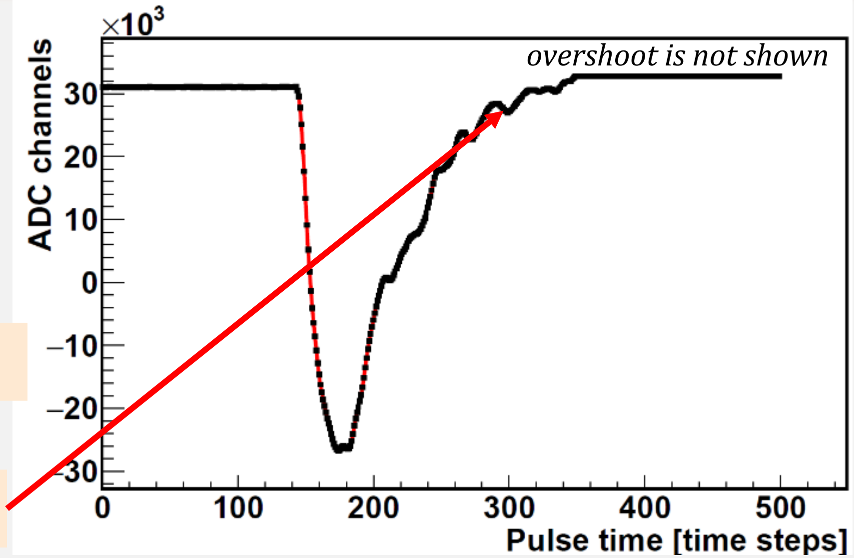
Scintillation length of CsI (pure) crystal at LN2 temperatures is long ($\sim 10 \mu s$). Baseline is unstable during the scintillation time. Decay time for higher signals is much longer than for few photoelectrons.



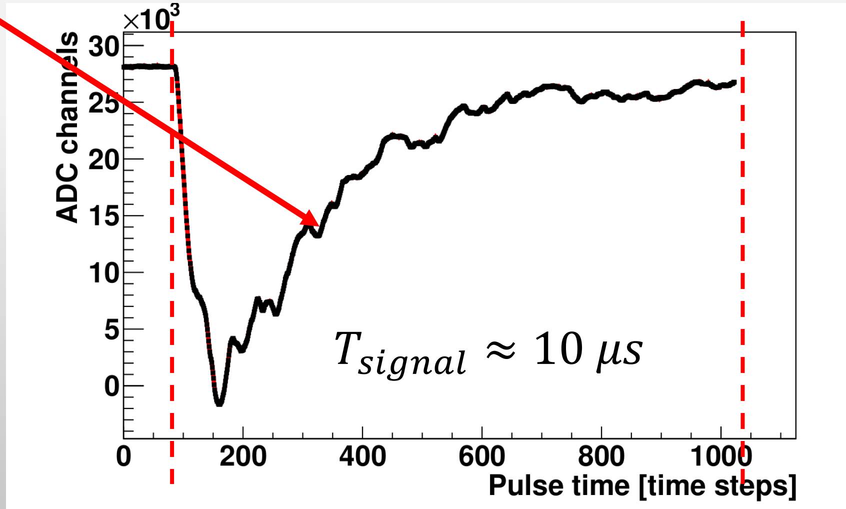
Low amplitude waveform (different peaks correspond to a certain number of photoelectrons)

1 time step = 10 ns

a few $p.e.$ pulses



*High amplitude waveform for **charge sensitive** amplifiers*



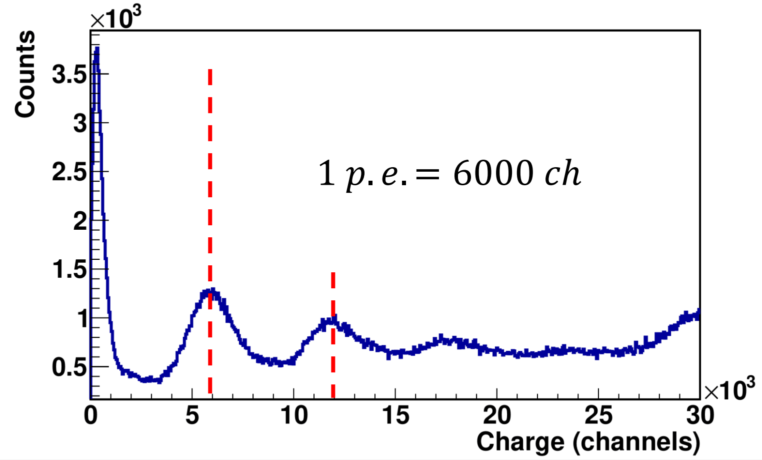
*High amplitude waveform for **current** amplifiers*

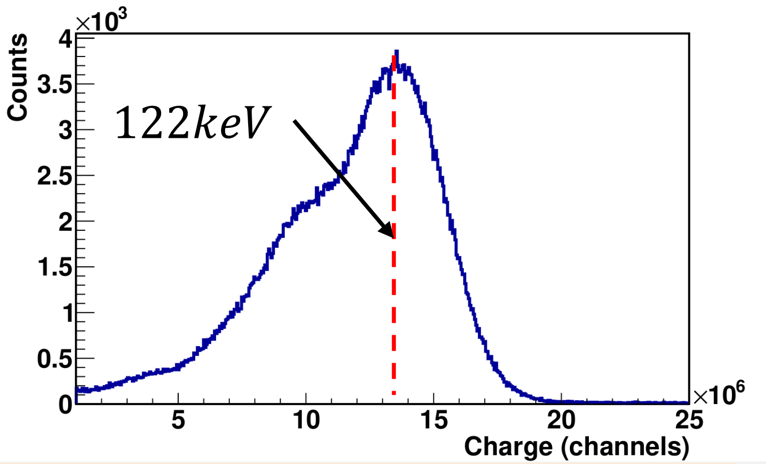
$T_{pulse} \ll T_{signal} \Rightarrow$ Charge should be used to correctly estimate number of photoelectrons

Spectra for small vs large CsI crystal (current amplifiers)

Double SiPM readout	Low charge spectrum range	High charge spectrum range	*Light Collection* (LC)

$U_{op} = 36\,V, Co57$
Small CsI crystal
$(15 \times 15 \times 15mm^3)$
Spectra for SiPM1

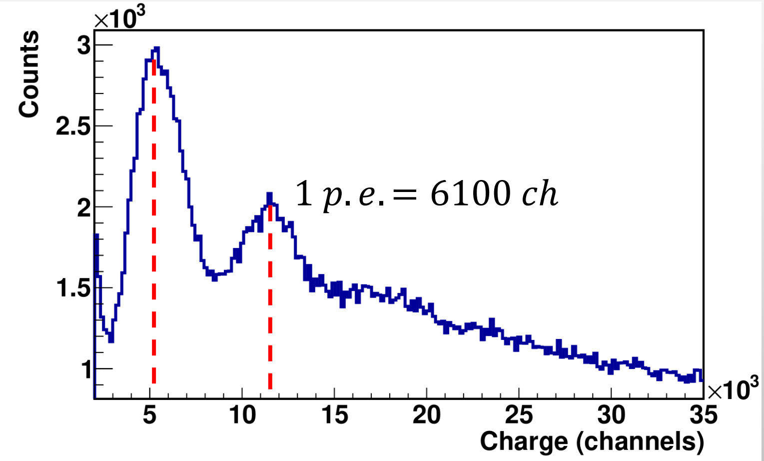


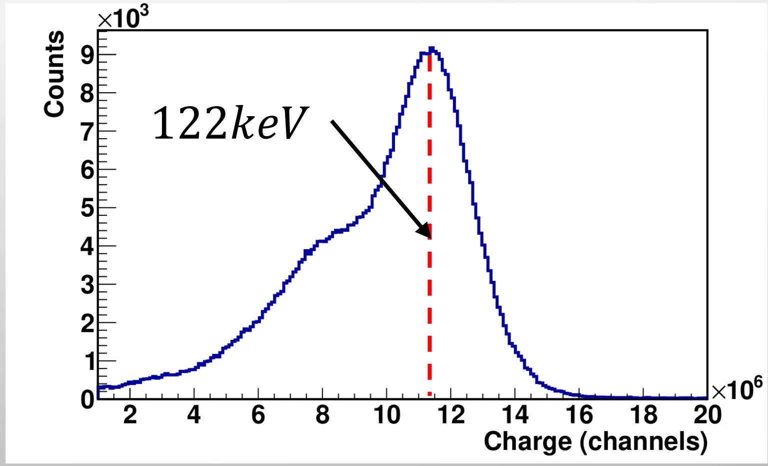


$$LC_{SiPM1} = 18.5\,\frac{p.e.}{keV}$$
$$LC_{SiPM2} = 16\,\frac{p.e.}{keV}$$
$$LC_{total} = 34.5\,\frac{p.e.}{keV}$$

Current amplifier allow to increase light collection by 50%

$U_{op} = 36\,V, Co57$
Large CsI crystal
$(15 \times 15 \times 25mm^3)$
Spectra for SiPM1





$$LC_{SiPM1} = 15.2\,\frac{p.e.}{keV}$$
$$LC_{SiPM2} = 14.1\,\frac{p.e.}{keV}$$
$$LC_{total} = 29.3\,\frac{p.e.}{keV}$$

Larger crystal slightly decreases light collection

Spectra for single vs double SiPM readout (current amplifiers)

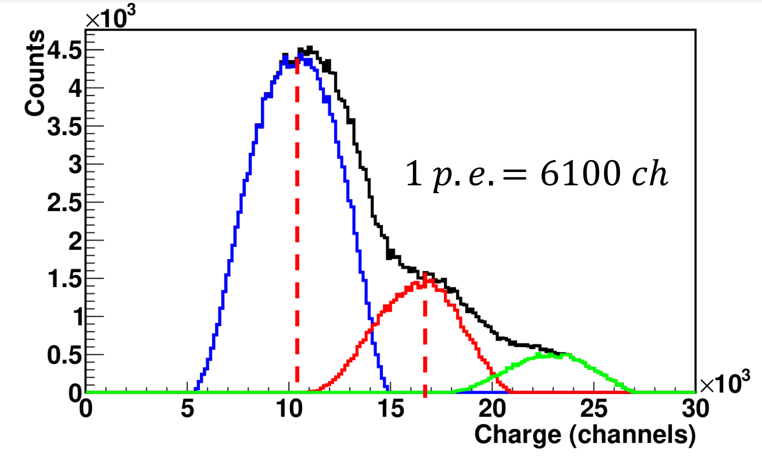
$15 \times 15 \times 25 mm^3$
CsI crystal

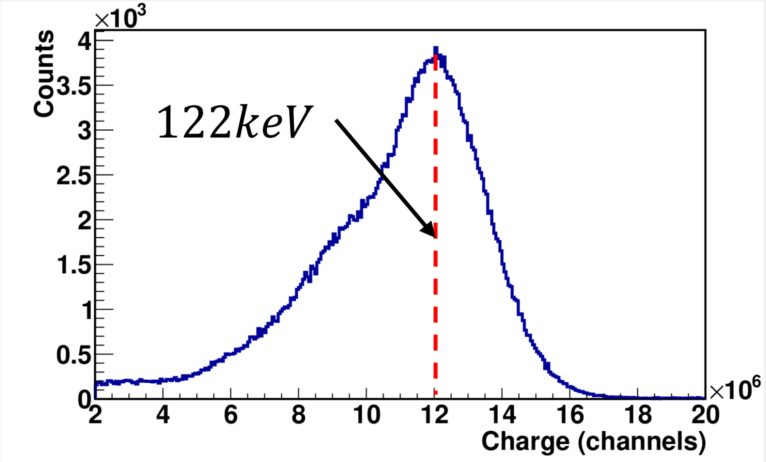
Low charge spectrum range

High charge spectrum range

$Light\ Collection\ (LC)$

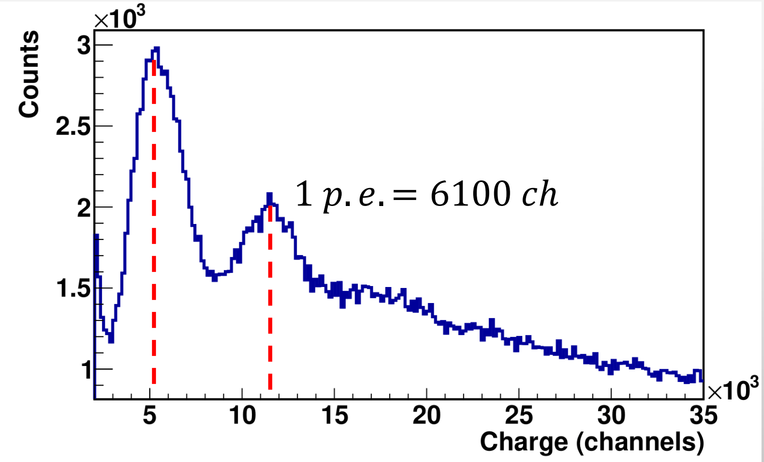
$U_{op} = 36\ V, Co57$
single SiPM readout

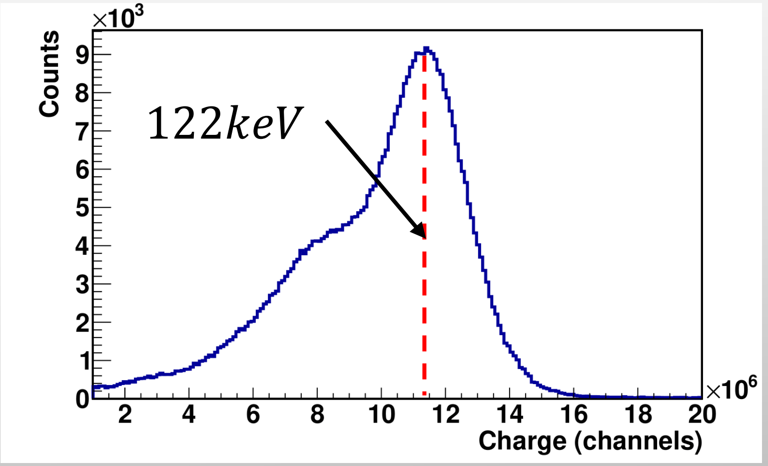




$$LC = 16.1 \frac{p.e.}{keV}$$

$U_{op} = 36\ V, Co57$
double SiPM readout
Spectra for SiPM1





$$LC_{SiPM1} = 15.2 \frac{p.e.}{keV}$$

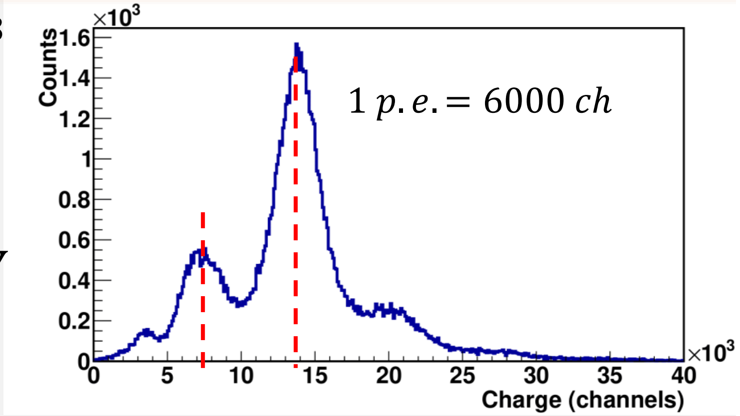
$$LC_{SiPM2} = 14.1 \frac{p.e.}{keV}$$

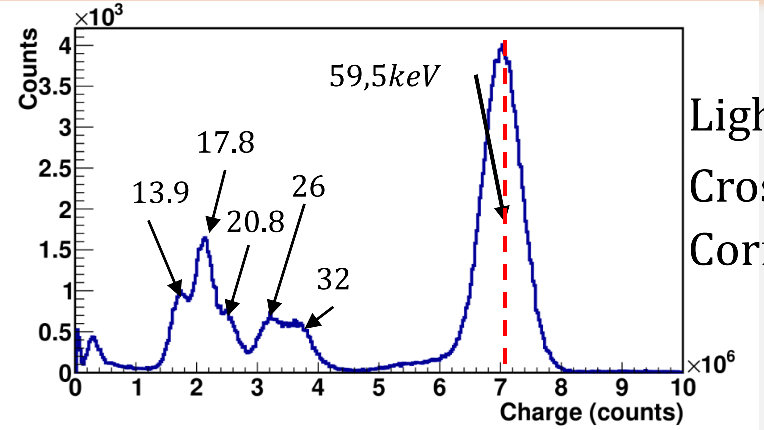
$$LC_{total} = 29.3 \frac{p.e.}{keV}$$

Two SiPM readout significantly increases light collection.

Light collection for NDL SiPM matrixes

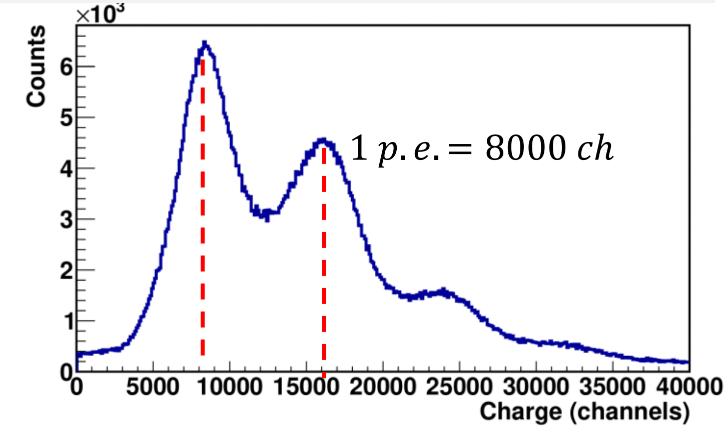
$\mathbf{15 \times 15 \times 15 mm^3}$
$\boldsymbol{SrI_2(Eu)}$ **crystal**
$\boldsymbol{NDL\ EQR20}$
$U_{op} = 29\ V$
$Overvoltage = 3{,}85V$
$^{241}Am, T = -50°C$

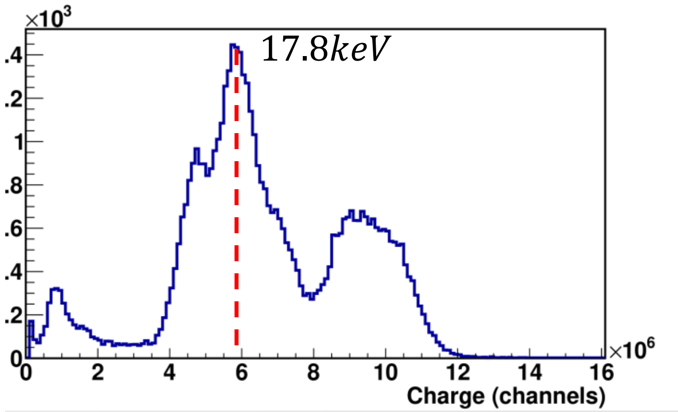




Light Collection $\boldsymbol{LC = 39.6\ \frac{p.e.}{keV}}$
Crosstalk $\boldsymbol{CT = 30\%}$
Corrected LC $\boldsymbol{CLC = 30.5\frac{p.e.}{keV}}$

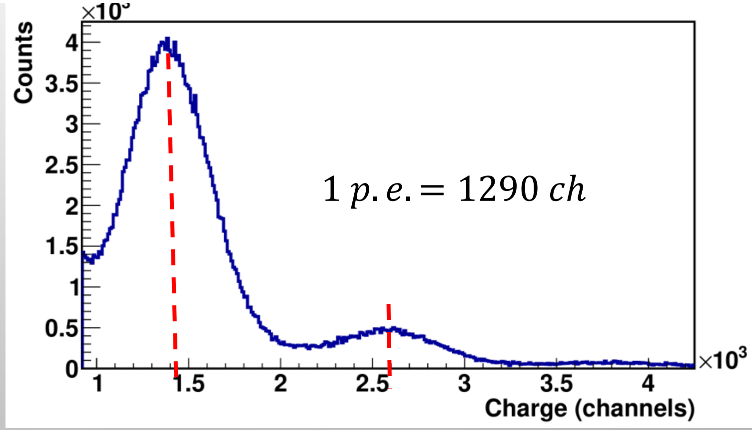
$\boldsymbol{NDL\ EQR20}$
$U_{op} = 30.15\ V$
$Overvoltage = 4{,}5V$
$^{241}Am, T = -32°C$

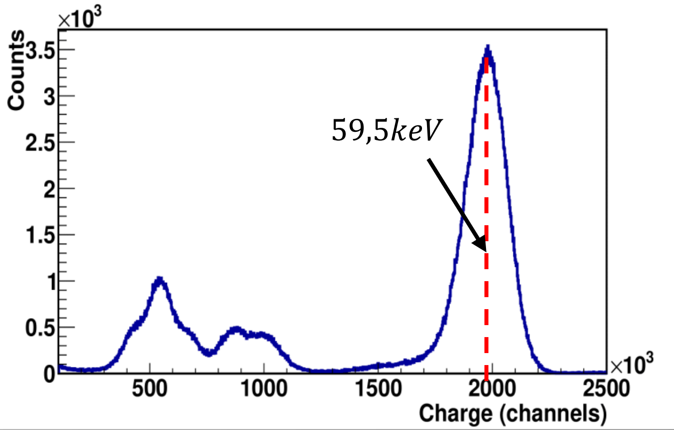




$\boldsymbol{LC = 42.4\ \frac{p.e.}{keV}}$
$\boldsymbol{CT = 50\%}$
$\boldsymbol{CLC = 28.2\frac{p.e.}{keV}}$

$\boldsymbol{NDL\ EQR15}$
$U_{op} = 30.15\ V$
$Overvoltage = 4{,}5V$
$^{241}Am, T = -61°C$



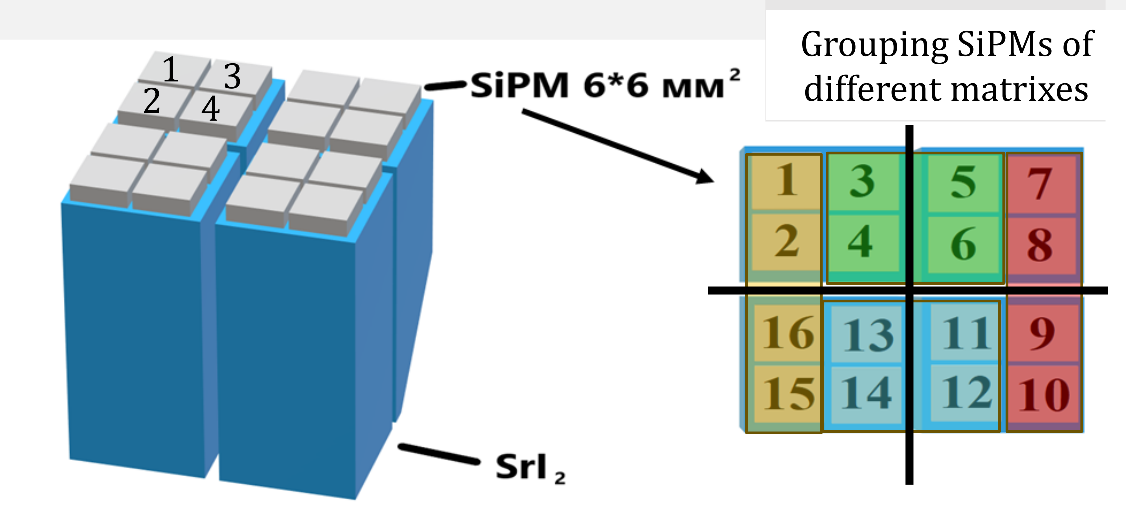


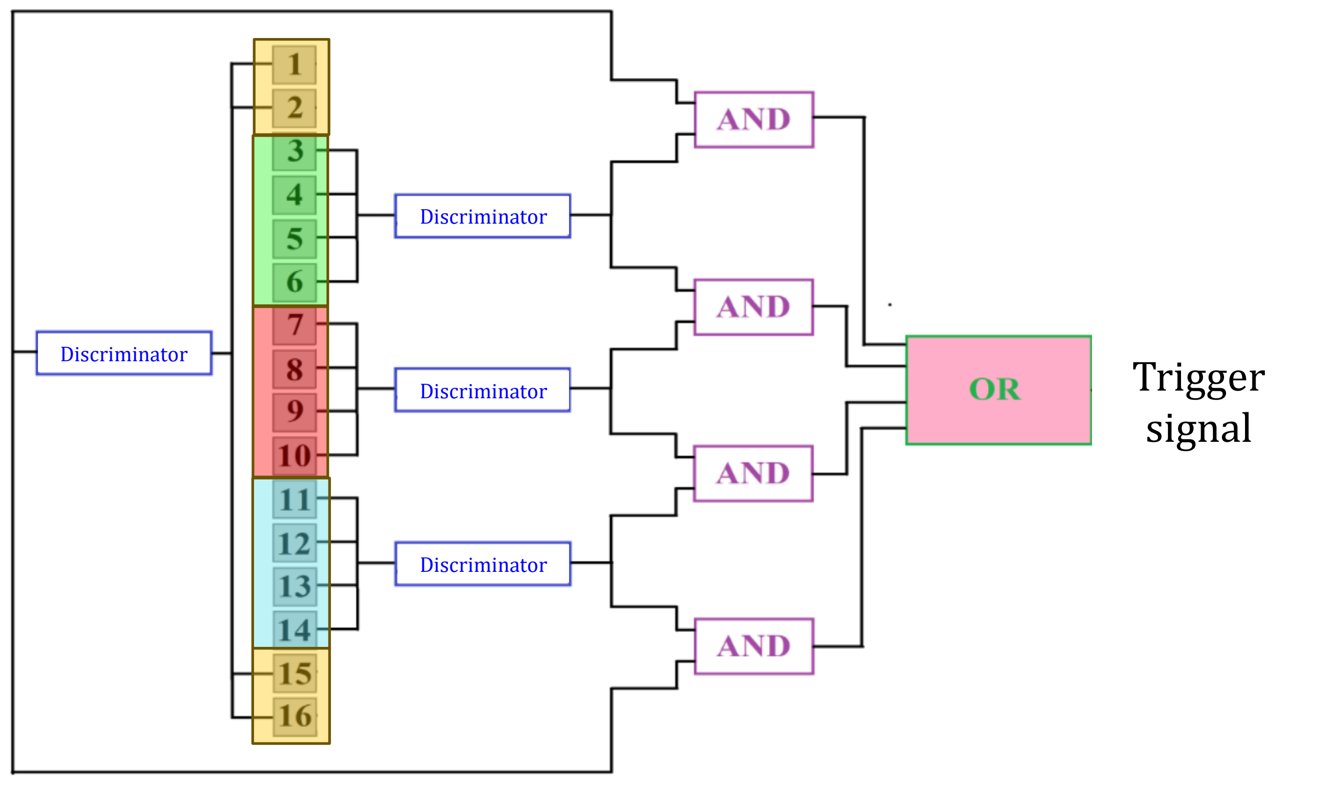
$\boldsymbol{LC = 25.8\ \frac{p.e.}{keV}}$
$\boldsymbol{CT = 35\%}$
$\boldsymbol{CLC = 19.1\frac{p.e.}{keV}}$

Additional suppression of DCR (double coincidence)

- DCR still high even at $T = -60°C$
- Additional suppression needed

Above results acquired by signal integration and threshold below 1 keV was achieved.





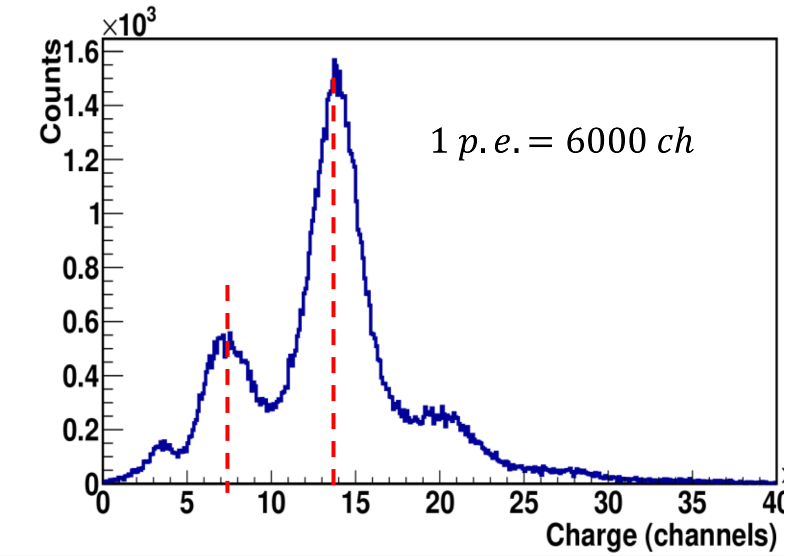
- Developed readout scheme does not change total channel’s number
- Information of triggered channels allows to find fired crystal

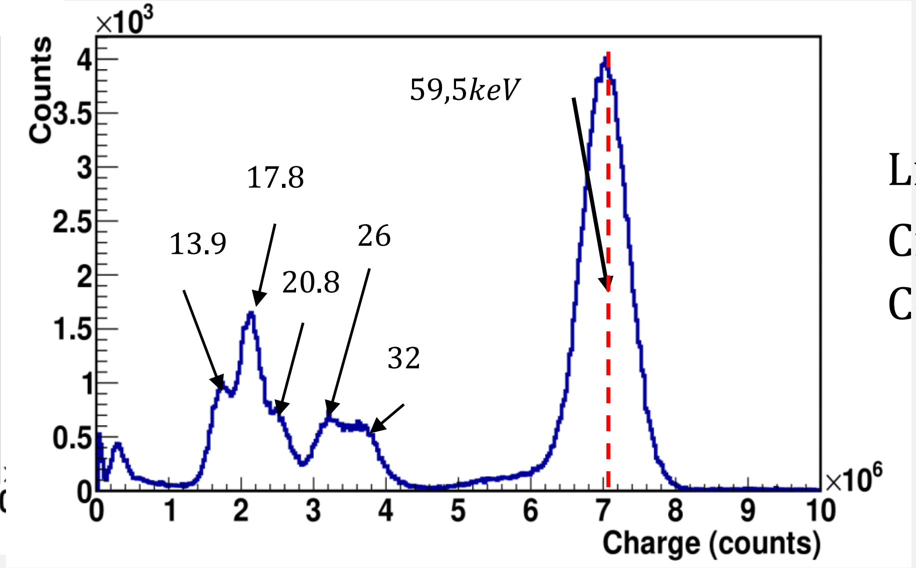
With developed trigger and 2 photoelectrons threshold in SiPM noise rate is $\boldsymbol{noise \sim 30 \frac{events}{year}}$ for the whole detector

$SrI_2(Eu)$ light collection for NDL SiPM matrixes

$15 \times 15 \times 15 mm^3$ crystal

$\boldsymbol{NDL\ EQR20}\ U_{op} = 29\ V\ \ 241Am, T = -50°C$



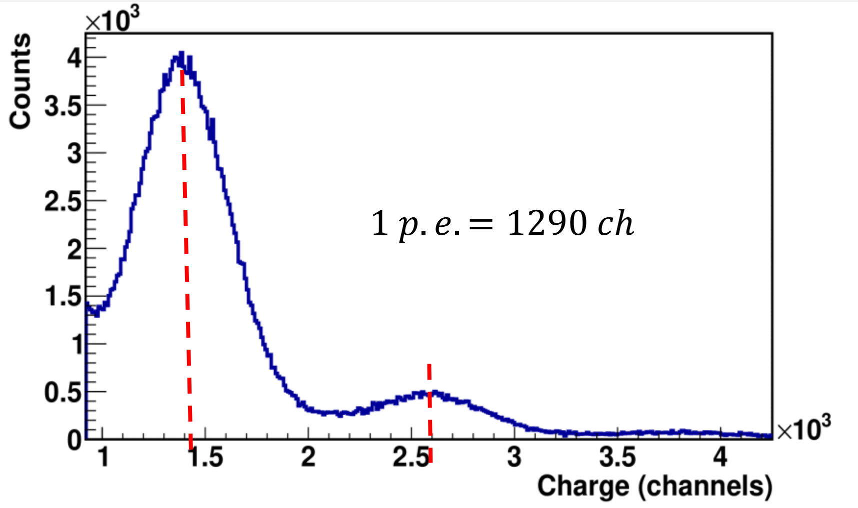


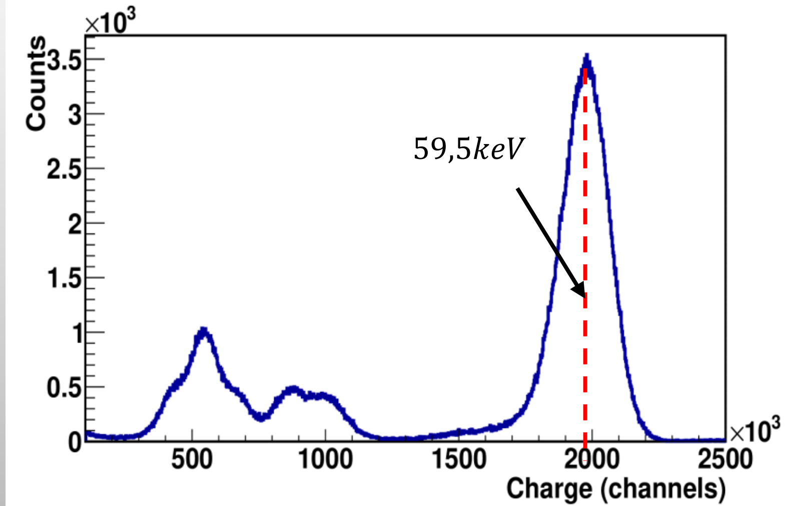
Light Collection $\boldsymbol{LC = 39.6\ \frac{p.e.}{keV}}$

Crosstalk $\boldsymbol{CT = 30\%}$

Corrected LC $\boldsymbol{CLC = 30.5\ \frac{p.e.}{keV}}$

$\boldsymbol{NDL\ EQR15};\ U_{op} = 30.15\ V\ \ 241Am, T = -61°C$





$\boldsymbol{LC = 25.8\ \frac{p.e.}{keV}}$

$\boldsymbol{CT = 35\%}$

$\boldsymbol{CLC = 19.1\ \frac{p.e.}{keV}}$