Cryogenic scintillation CsI(pure) detector of low energy neutrino

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TASKS:

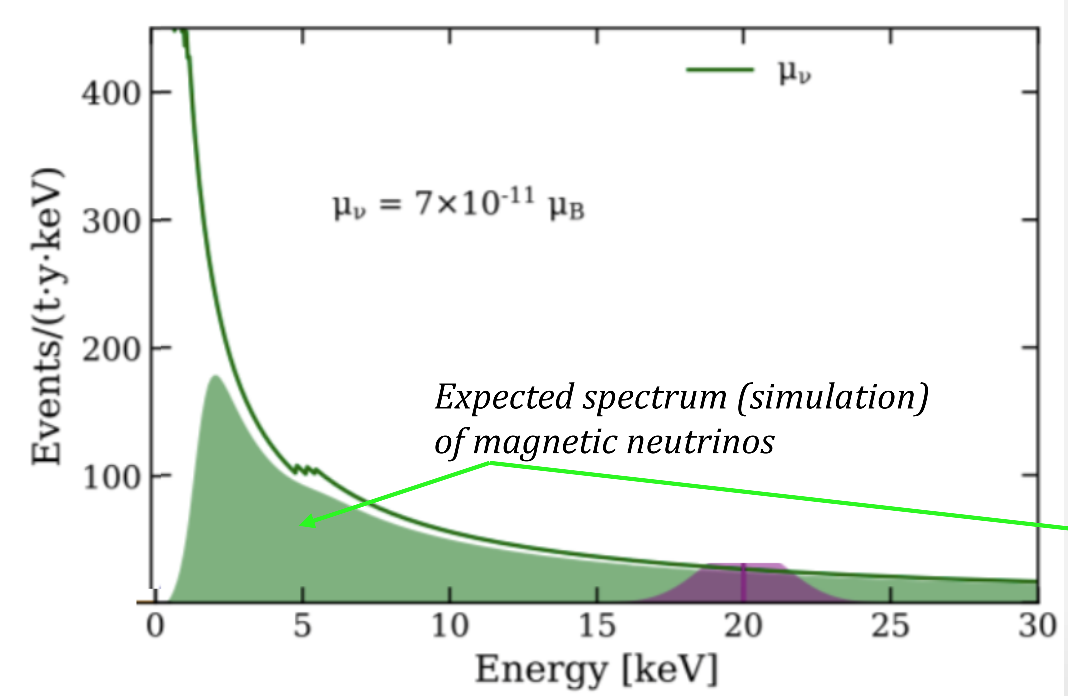
- Development of CsI cryogenic LN_2 detector of recoil electrons with SiPM readout;
- Development of prototype of detector`s module;
- Tests of detector`s module prototype;

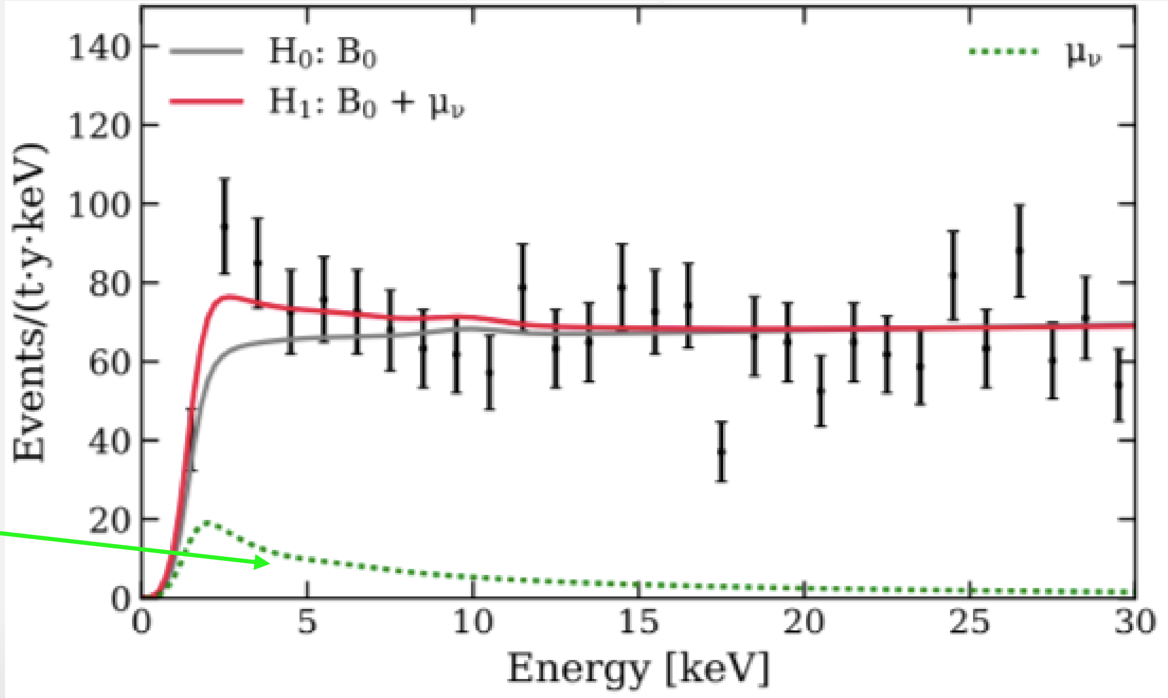
Importance:

- In 2017 XENON1T collaboration published an article, where an abundance of recoil electrons in low energy range is noted;
- One of the possible explanations is non-zero magnetic moment of solar neutrino;
- Current threshold of recoil energy detection is several keVs;
- Possible threshold of CsI cryogenic LN_2 detector is ~ 100 eV.

XENON1T energy spectrum in low energy range

The XENON is the dark matter research underground facility comprising several experiments aimed at dark particles detection. One of them is XENON1T, which was constructed in 2017.





E. Aprile et al., Phys.Rev.D 102 (2020) 7, 072004

A discrepancy in low energy spectrum was detected. Possible explanations:

- ^3H contamination which is not detected by other means
- Solar axions
- Solar neutrino with non-zero magnetic momentum
- 3.5σ statistical fluctuation

Magnetic and Weak elastic neutrino scatterings on recoil electron

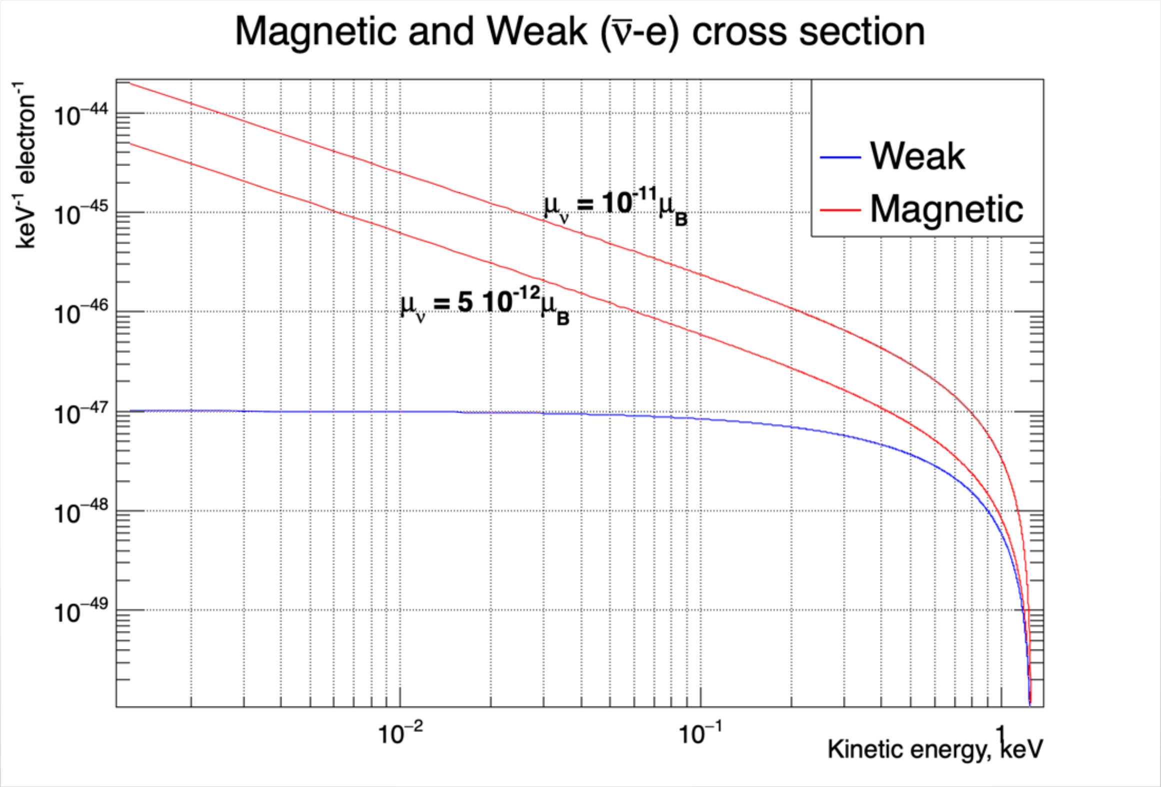
Scattering on free electron:

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

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

T – kinetic energy of the recoil electron

E – neutrino energy



Expected event rate for electromagnetic interactions:

$$\mu_\nu = 10^{-11}\mu_B$$

Mass of CsI(pure) detector $m_{CsI} = 100\ kg$.

Mass of source of ^{3}H $m_{source} = 1\ kg$.

$A_{^3H}(m = 1\ kg) = 9.65 kCi$

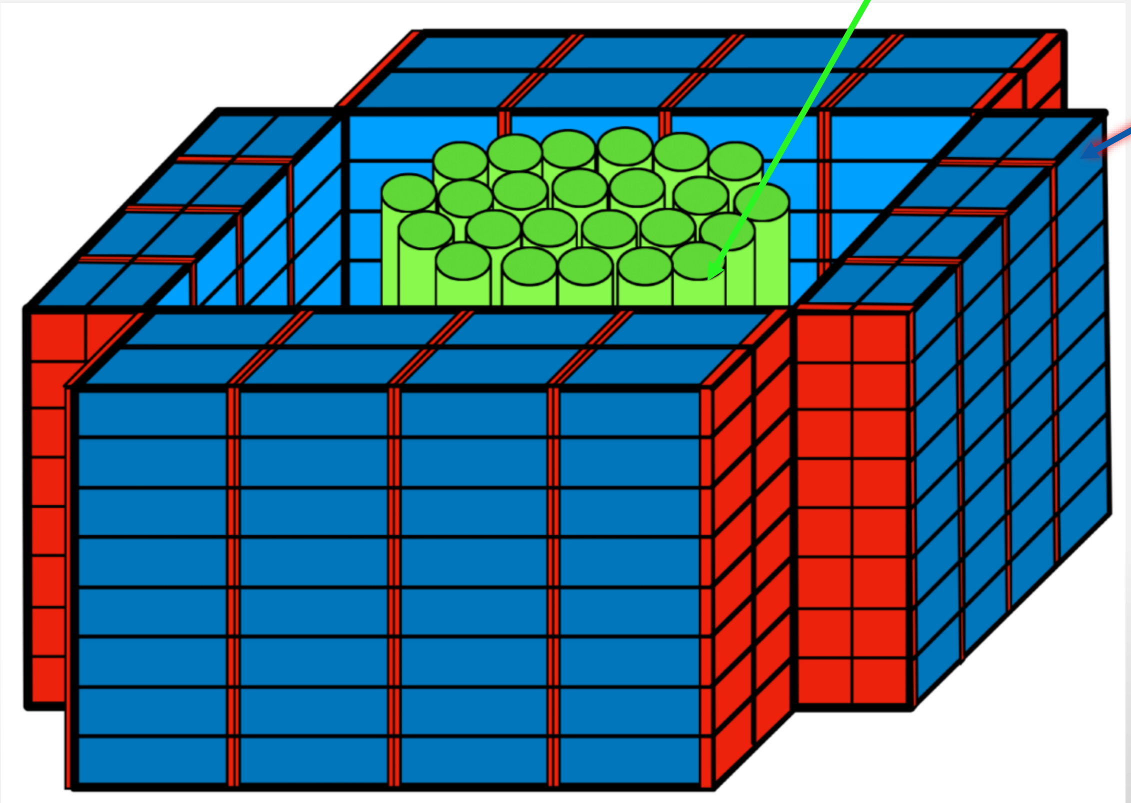
Threshold energy $E_{Threshold} = 100 eV$.

Calculated event rate $\sim \mathbf{600} \frac{\boldsymbol{events}}{\boldsymbol{year}}$

Possible variant of the Setup

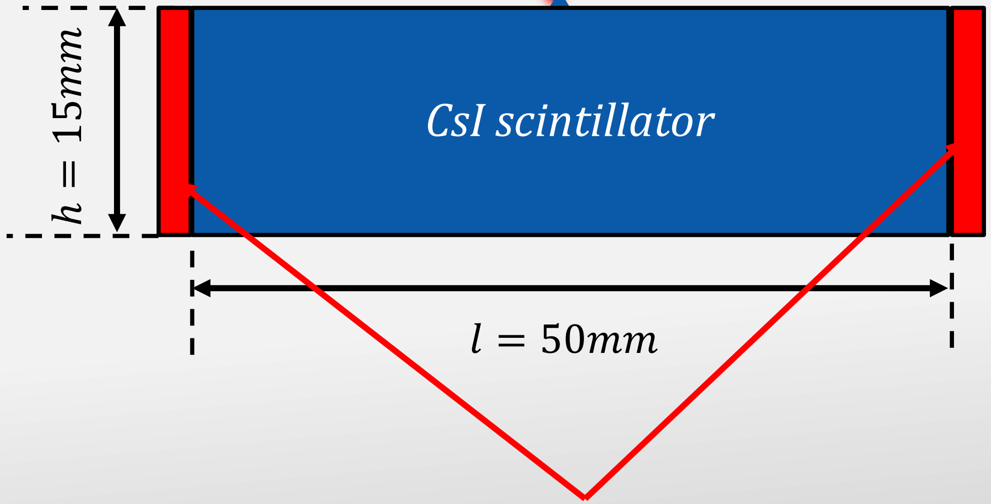
Source - *Ti* tubes with ^{3}H gas

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



Design of the experimental setup`s prototype

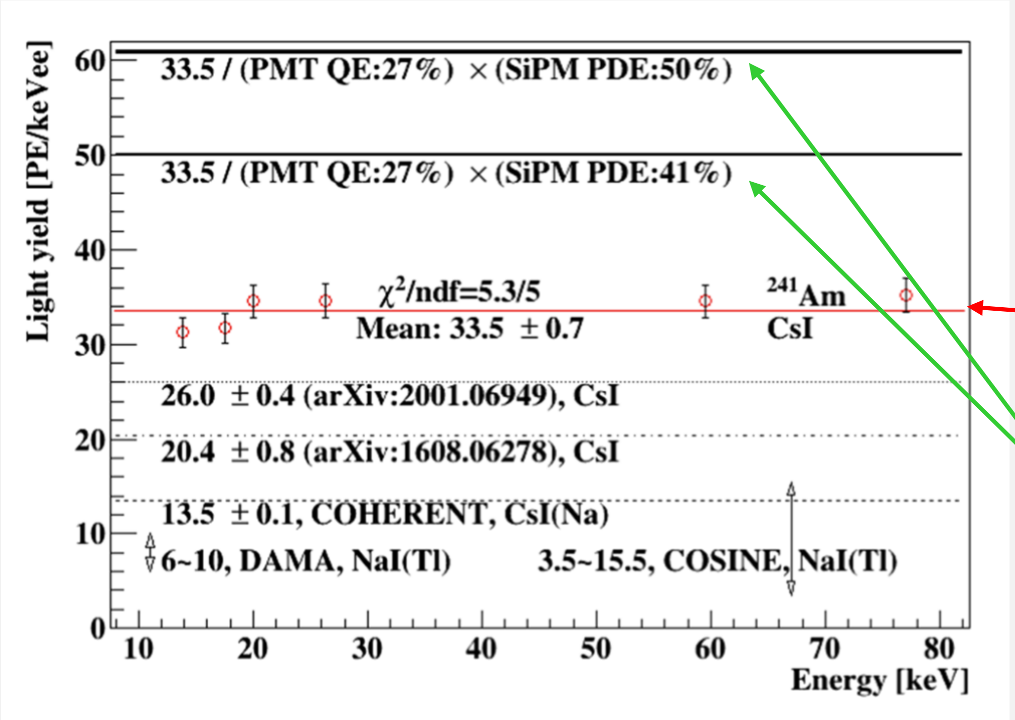
detector module



HAMAMATSU MPPC S14161-3050HS-04

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

Previous Results



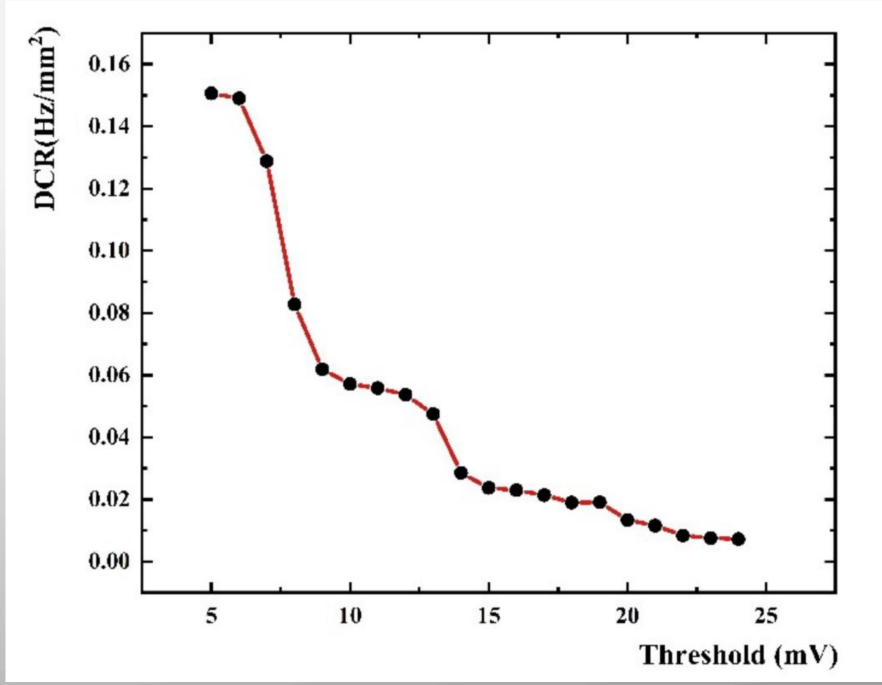
Several experimental groups tested light yields of CsI scintillator at LN_2 temperatures with PMT readout.

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 PDE than QE of PMTs.

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.

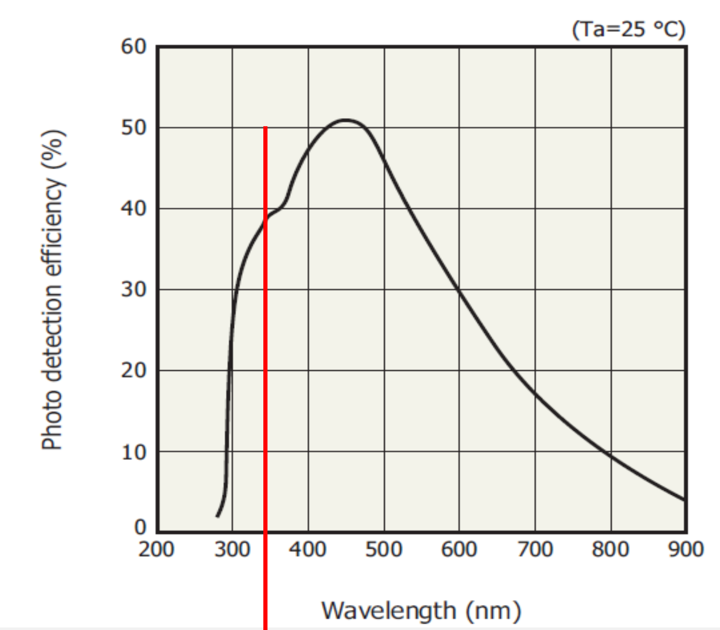
Authors claim that low threshold experiments are feasible if $DCR < 0.1$

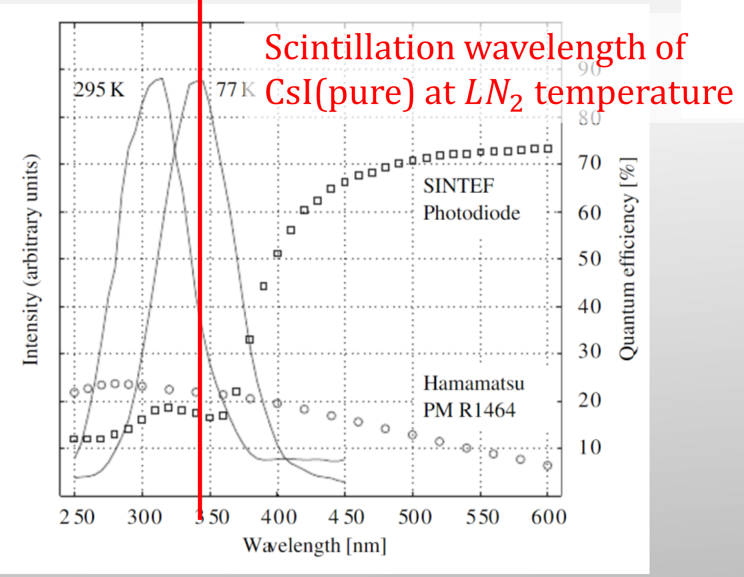


Instead of cryogenic PMTs we use Hamamatsu MPPC S14161-3050HS-04

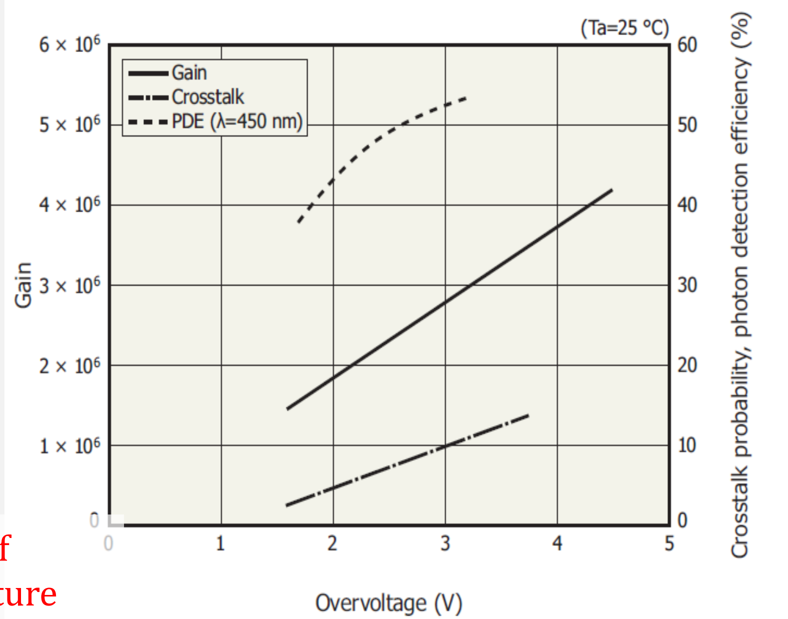
FEE board with soldered SiPM matrix

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)



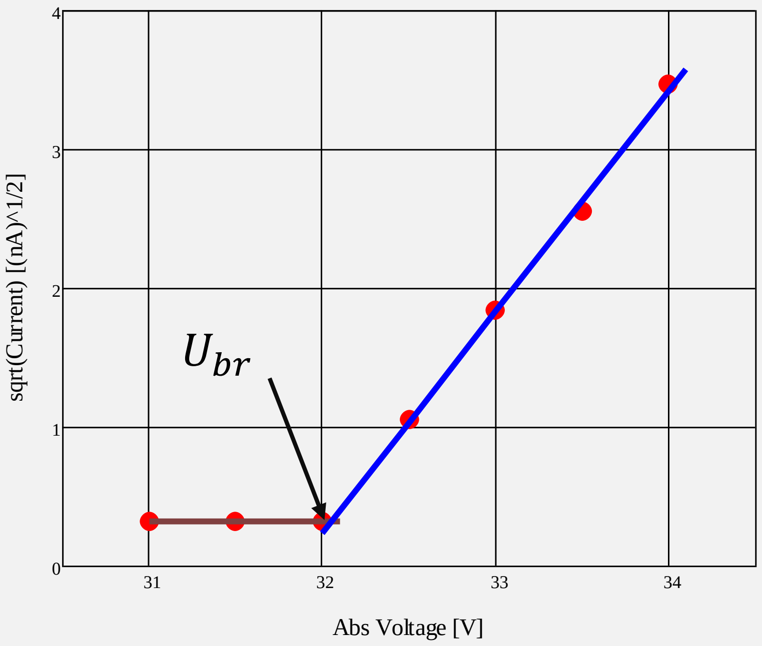


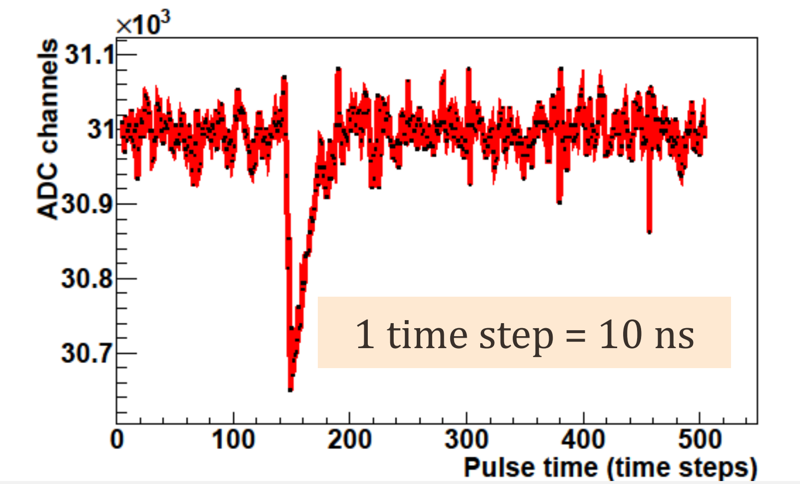
Emission spectrum of CsI (pure) at room and LN_2 temperatures



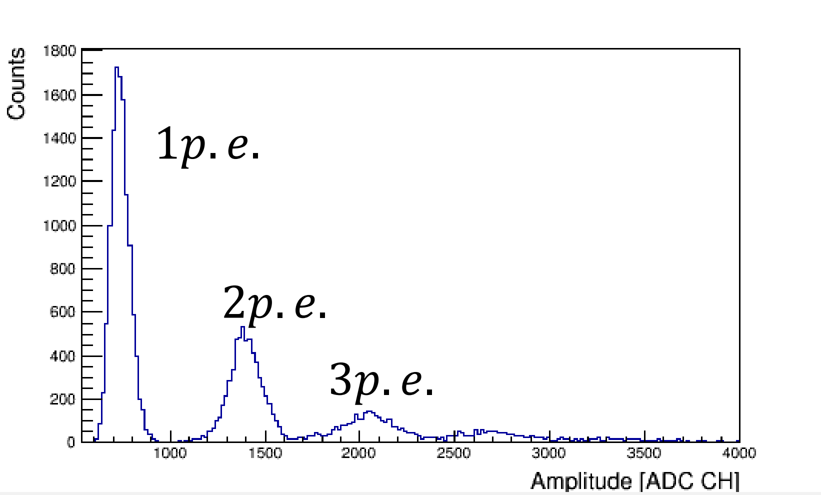
Dependence of Gain and PDE on overvoltage for the SiPM matrixes

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):

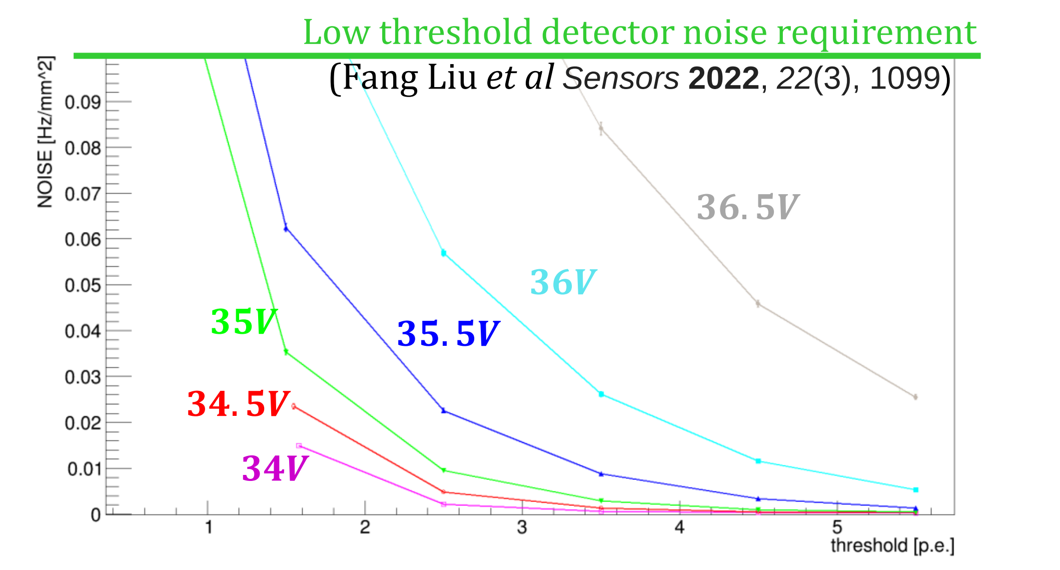
$$U_{br_{room}} = 38\ V;$$

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

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

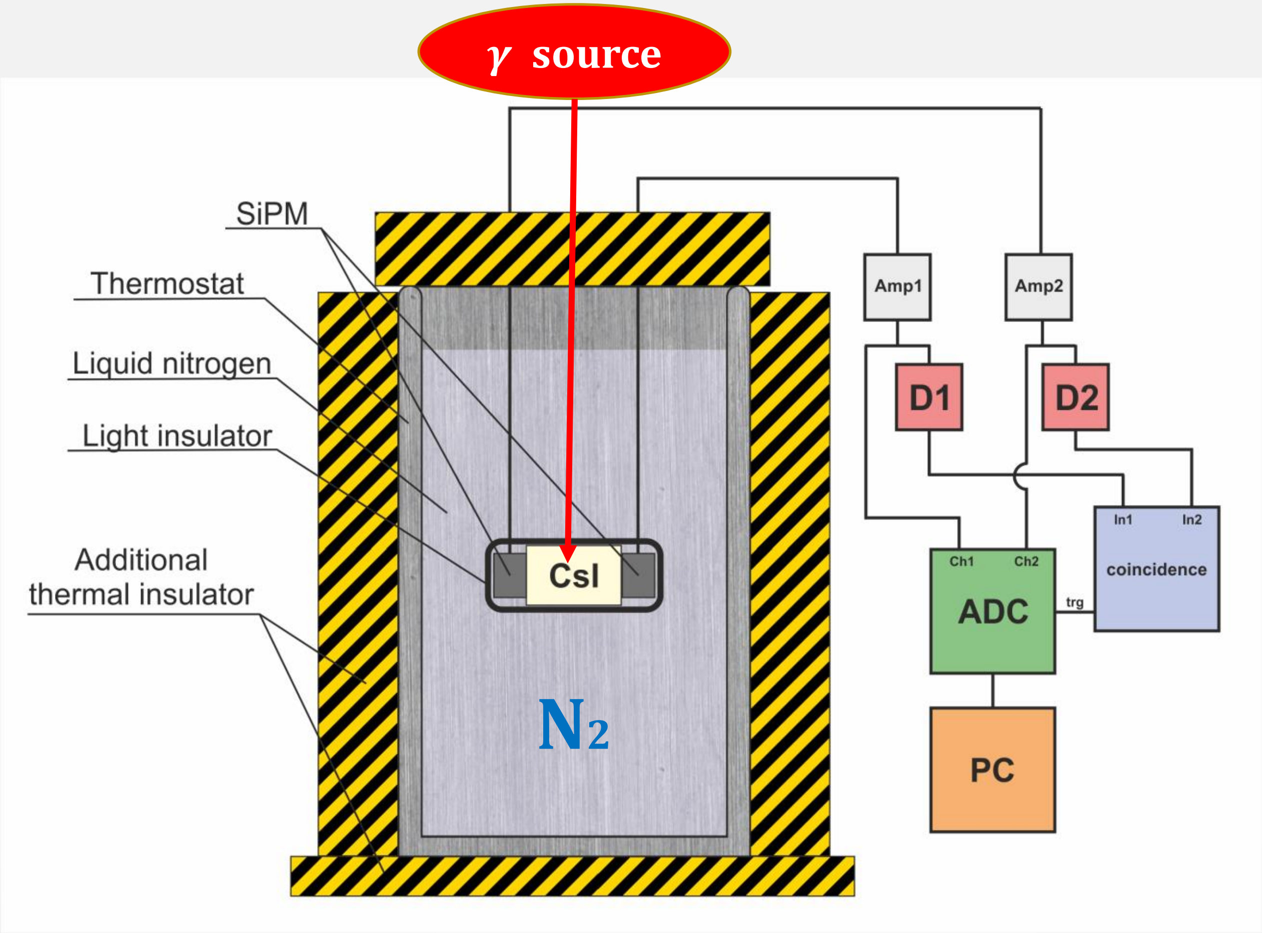
According to Hamamatsu $\frac{\Delta U}{\Delta T} = 0.034 \frac{mV}{K} \Rightarrow$

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



Noise event rate vs threshold dependence for different operating voltages

Experimental Setup for testing module parameters



D1, D2 – discriminators (used in the coincidence scheme)

- CsI (pure) scintillation crystal is wrapped in Teflon tape.

- First tests were conducted with *one* and *two* SiPM readouts.

- Several γ sources were used to test modules in wide energy range (Am241, Co57, Cs137, Na22)

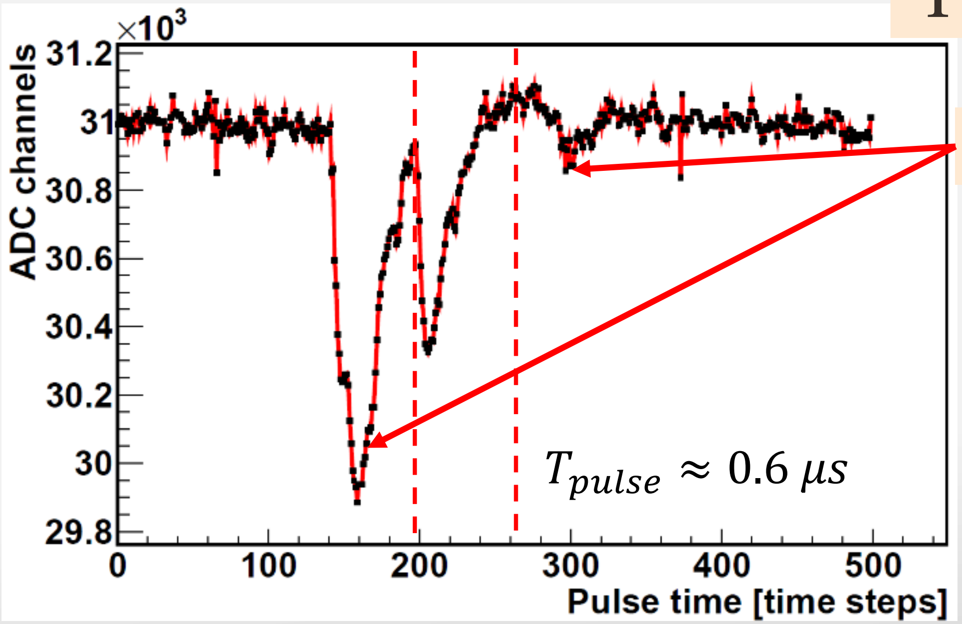
- CsI crystals of two different sizes were tested ($15 \times 15 \times 15 mm^3$ and $15 \times 15 \times 25 mm^3$)

Typical waveforms for different amplifiers

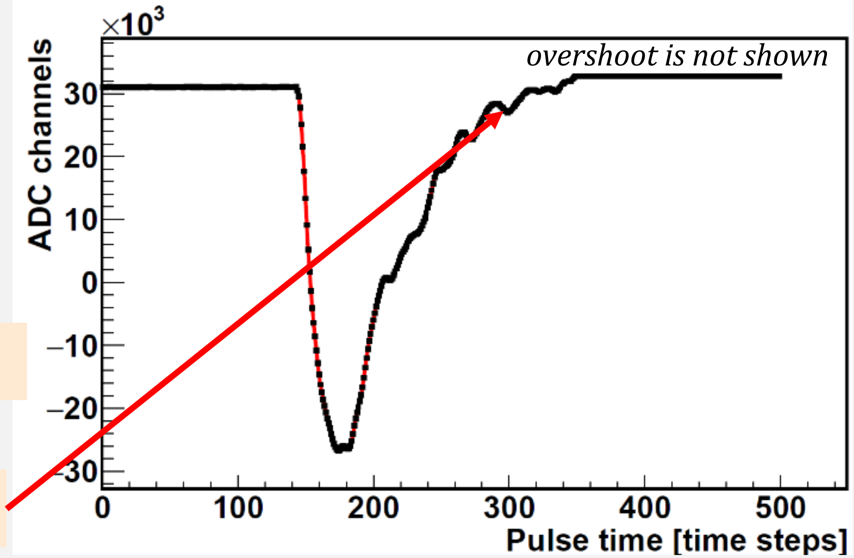
Scintillation length of CsI (pure) crystal at LN2 temperatures is long ($\sim 10\mu s$). Baseline is unstable during the scintillation time. Decay time for higher signals is much longer than for few photoelectrons.

1 time step = 10 ns

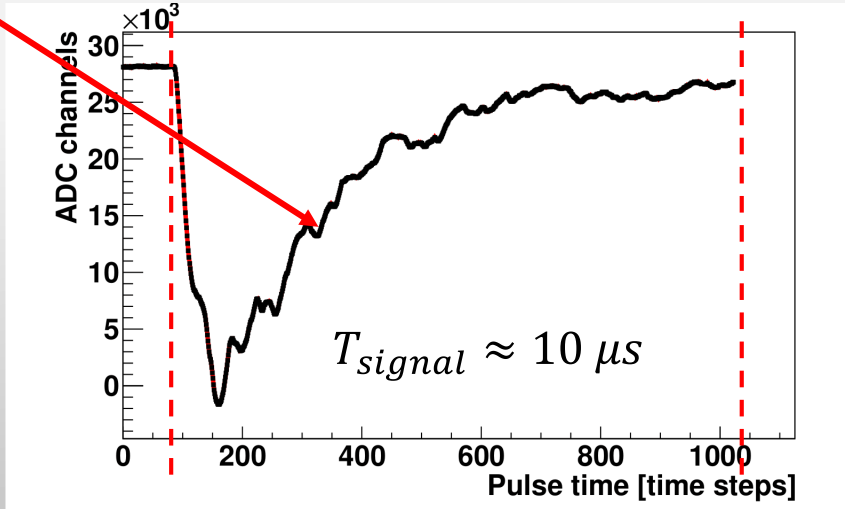
a few $p.e.$ pulses



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



*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 different operating voltages (single SiPM matrix, charge sensitive amplifiers)

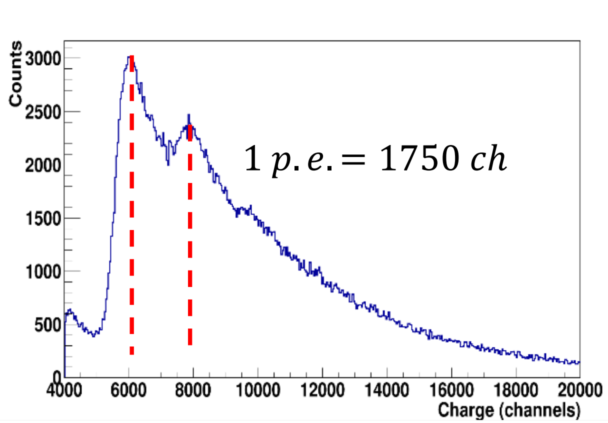
$15 \times 15 \times 15 mm^3$ CsI crystal

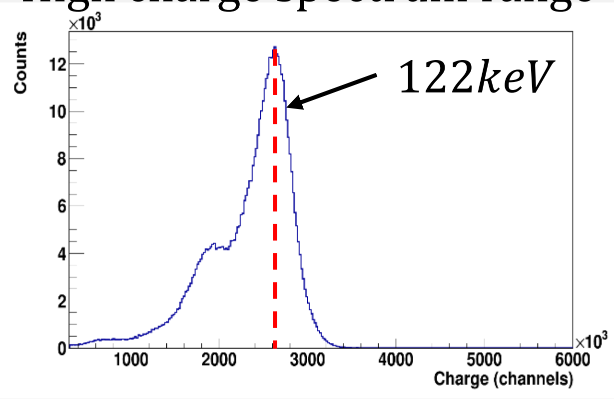
Low charge spectrum range

High charge spectrum range

Light Collection (*LC*)

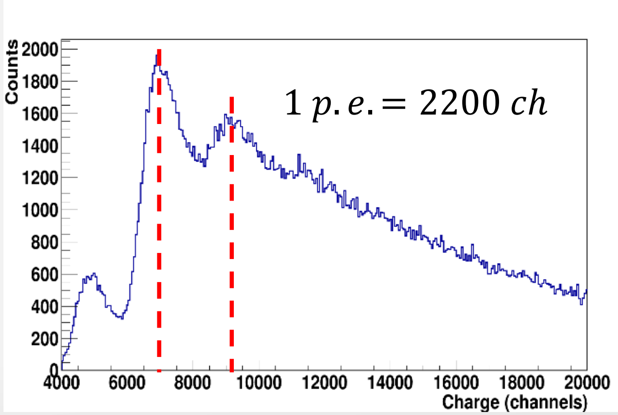
$U_{op} = 35.5\ V, Co57$

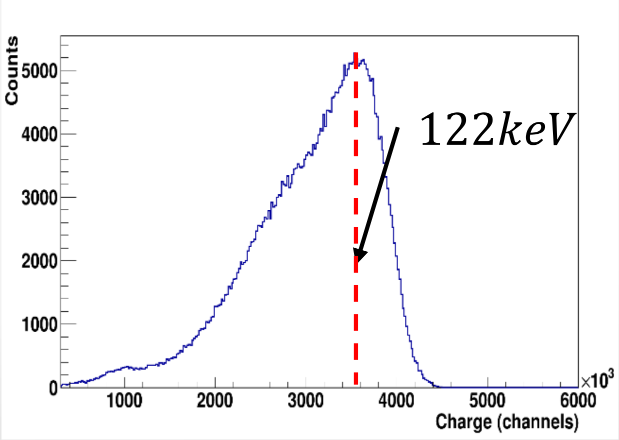




$LC = 13 \frac{p.e.}{keV}$

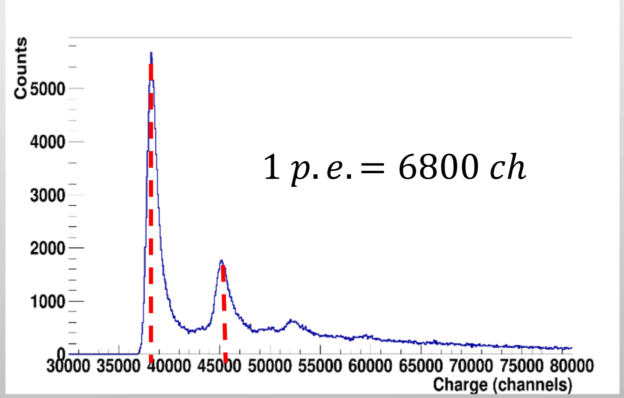
$U_{op} = 36\ V, Co57$

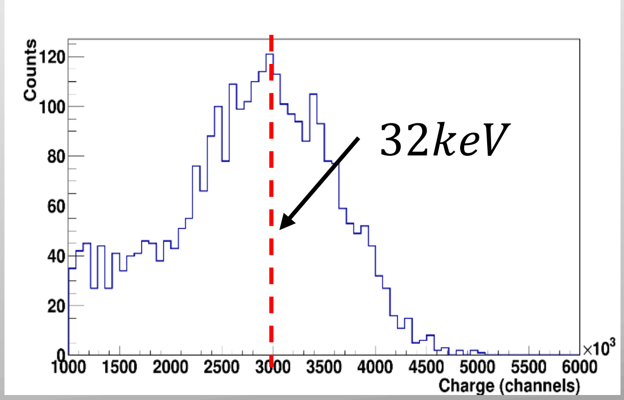




$LC = 14.1 \frac{p.e.}{keV}$

$U_{op} = 36\ V, Cs137$





$LC = 13.8 \frac{p.e.}{keV}$

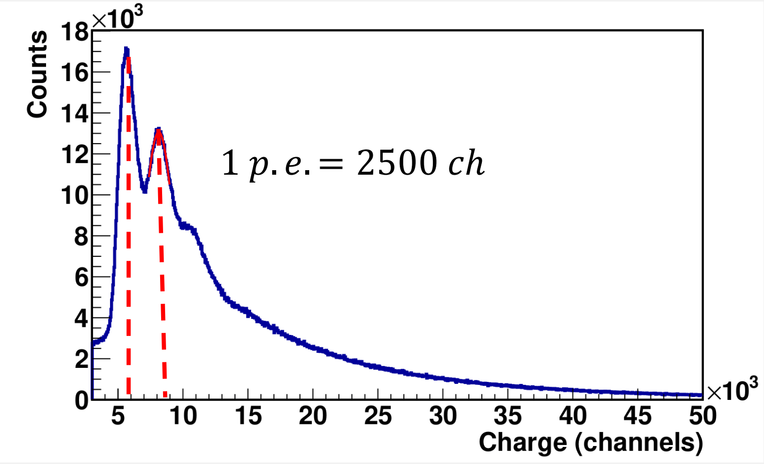
Spectra for single vs double SiPM readout (charge sensitive amplifiers)

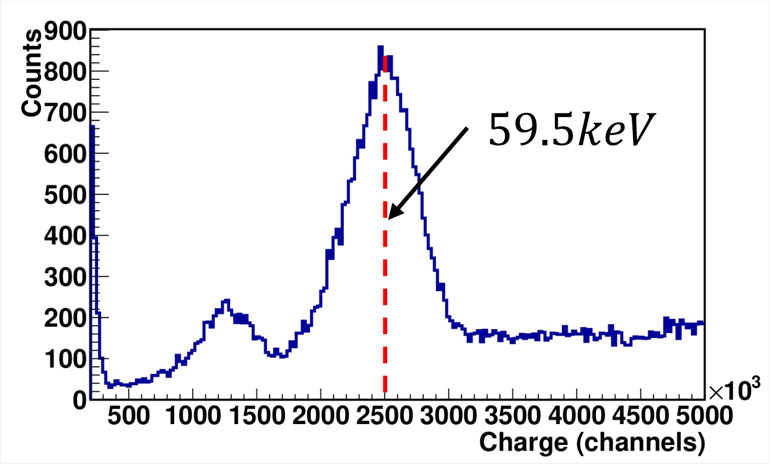
$15 \times 15 \times 15 mm^3$ CsI crystal

Low charge spectrum range | High charge spectrum range | *Light Collection (LC)*

$U_{op} = 36\,V, Am241$

Single SiPM readout

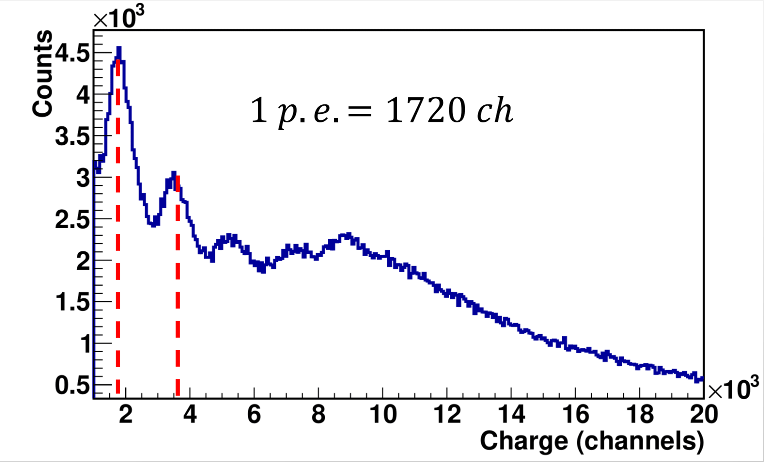


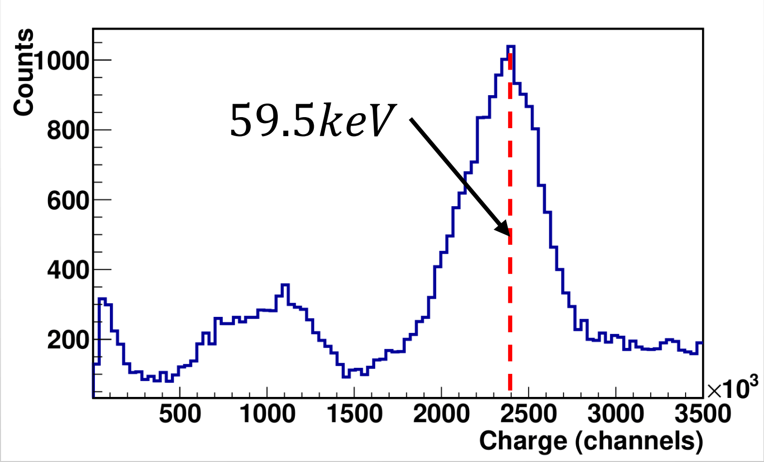


$$LC = 16 \frac{p.e.}{keV}$$

$U_{op} = 36\,V, Am241$

Double SiPM readout





$$LC = 23.2 \frac{p.e.}{keV}$$

Imperfect light collection due to not full charge integration.
Two SiPM readout gives 50% increased light collection.

Spectra for small vs large CsI crystal (current amplifiers)

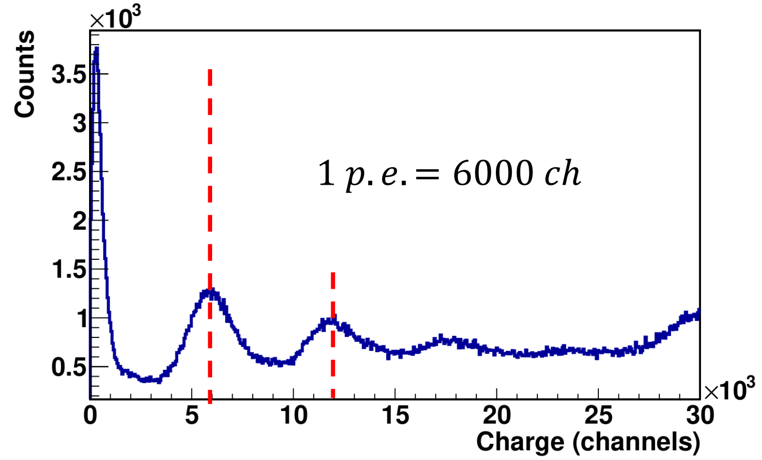
Double SiPM readout	Low charge spectrum range	High charge spectrum range	*Light Collection (LC)*

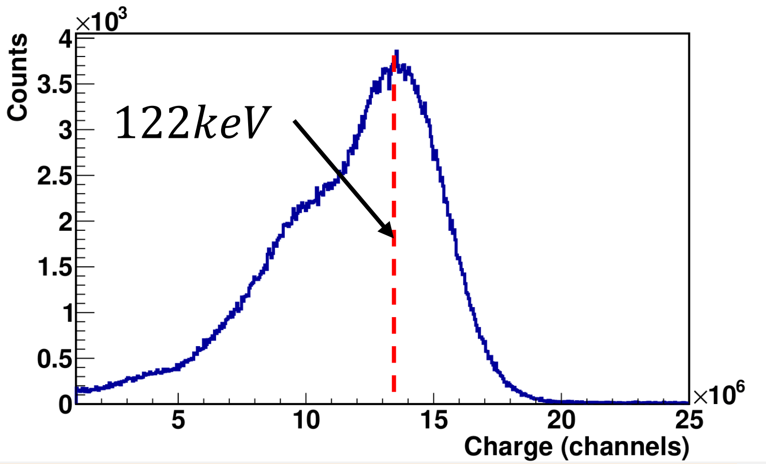
$U_{op} = 36\,V, Co57$

Small CsI crystal

($15 \times 15 \times 15mm^3$)

Spectra for SiPM1





$$LC_{SiPM1} = 18.5\,\frac{p.e.}{keV}$$

$$LC_{SiPM2} = 16\,\frac{p.e.}{keV}$$

$$LC_{total} = 34.5\,\frac{p.e.}{keV}$$

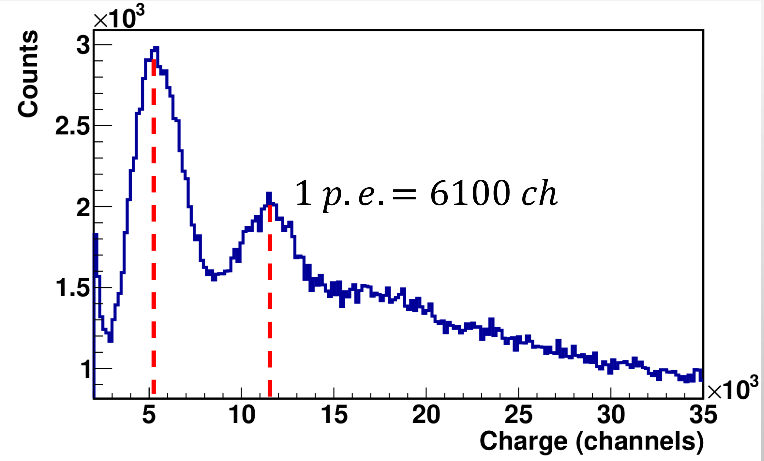
Current amplifier allow to increase light collection by 50%

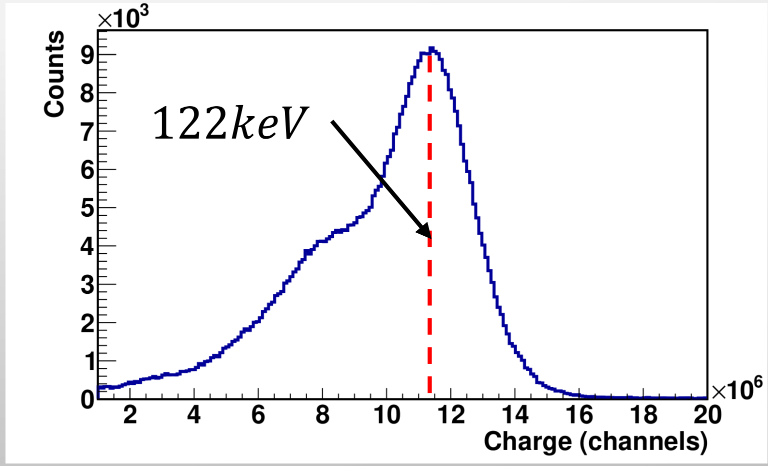
$U_{op} = 36\,V, Co57$

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)

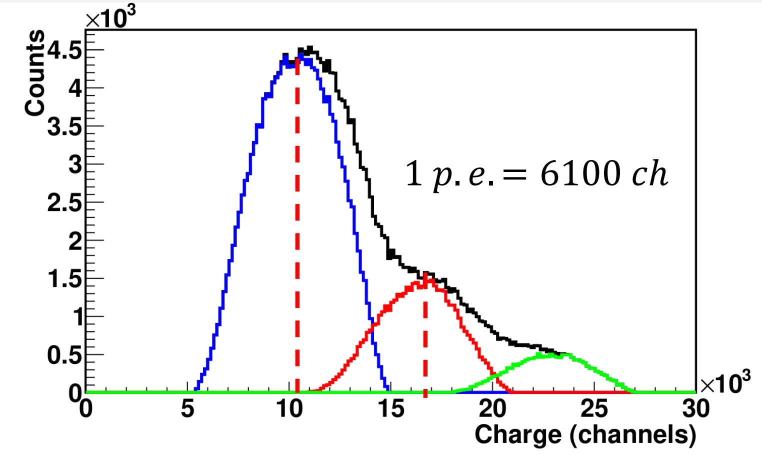
$15 \times 15 \times 25mm^3$
CsI crystal

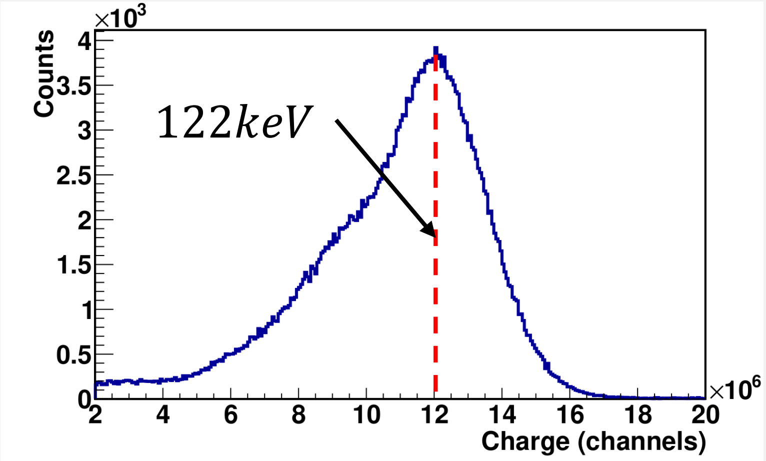
Low charge spectrum range

High charge spectrum range

$Light\ Collection\ (LC)$

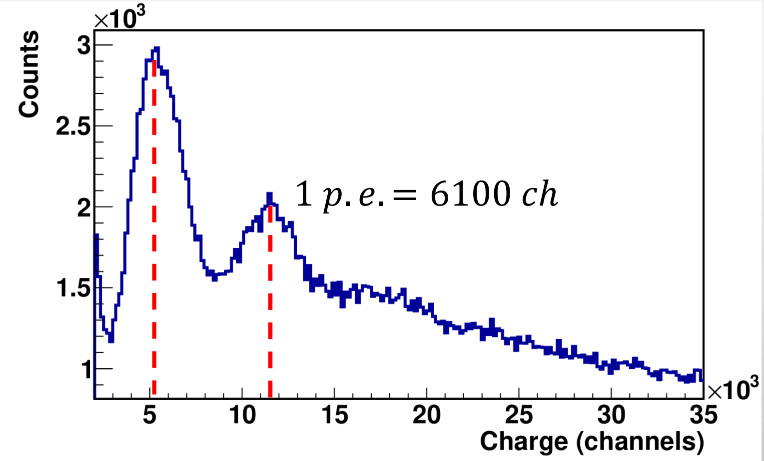
$U_{op} = 36\ V, Co57$
single SiPM readout

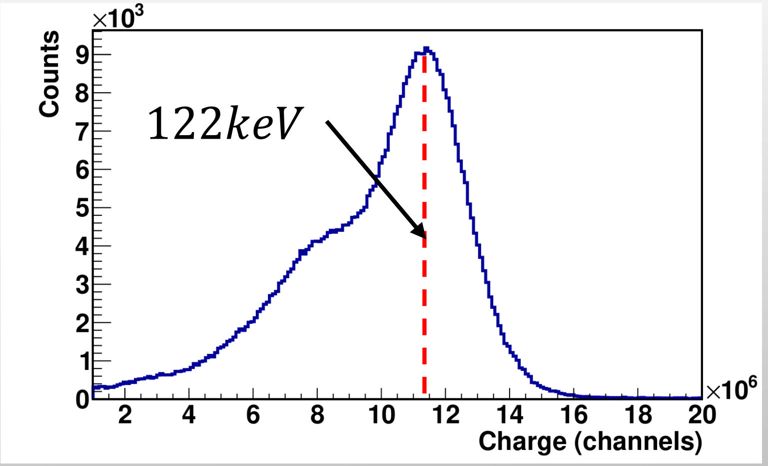




$$LC = 16.1 \frac{p.e.}{keV}$$

$U_{op} = 36\ V, Co57$
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.

Conclusion

- A design of detector`s prototype was developed;
- Experimental setup to test SiPM parameters was constructed;
- Parameters of HAMAMATSU MPPC S14161-3050HS-04 were tested at cryogenic temperatures;
- Experimental setup to test CsI at cryogenic temperature was constructed;
- Light collection for different types of amplifiers and readout configurations was obtained;
- The best light collection of 34.5 $\frac{ph.e.}{keV}$ was obtained.

Thank you for your attention