Status of CsI(pure) + APD R&D

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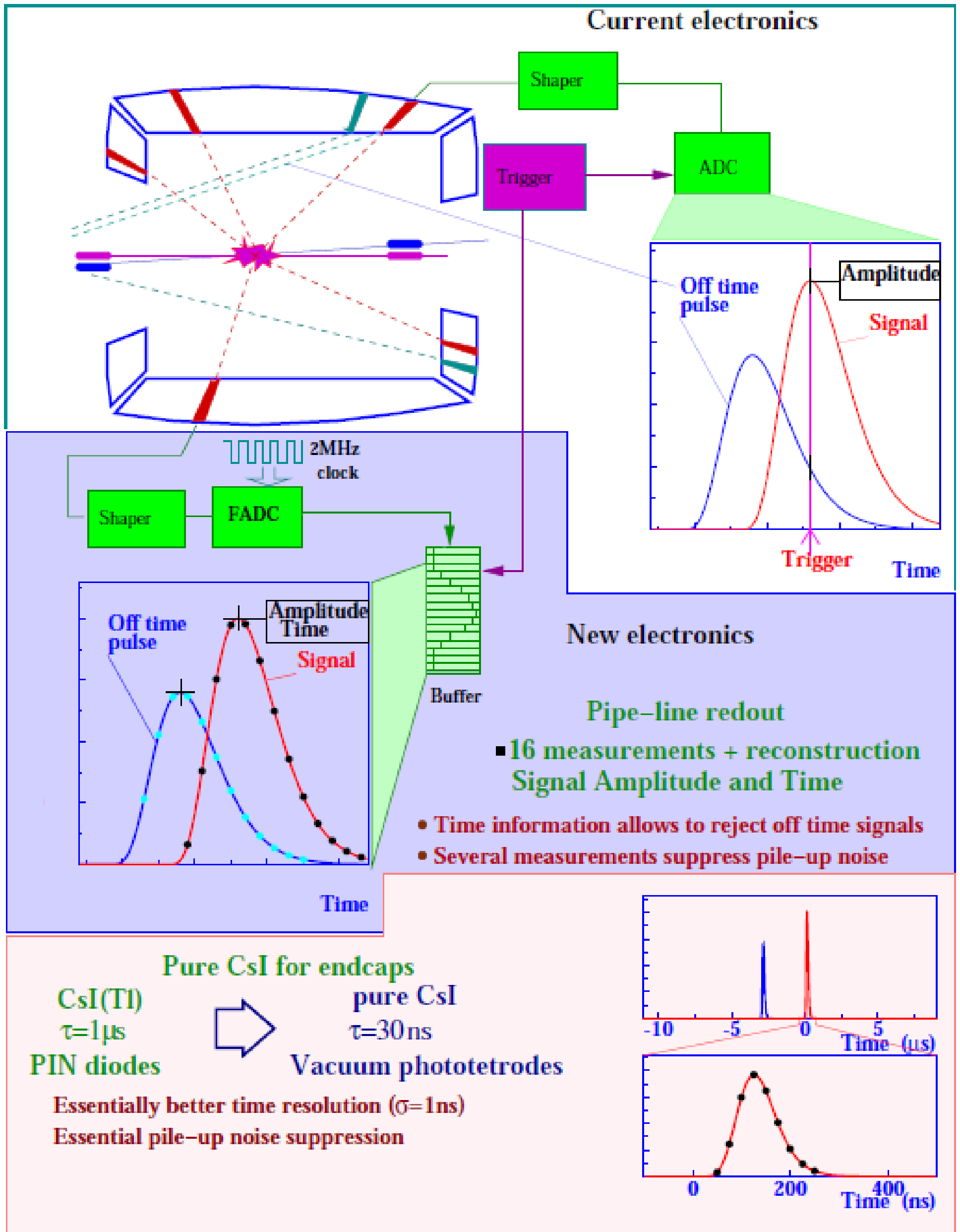
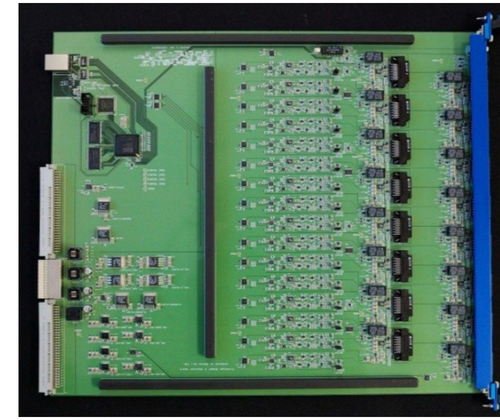
Outline:

- CsI(pure) for the Belle II ECL upgrade → STCF/SCTF
- CsI(pure) + photopentode **option I**
- CsI(pure) + WLS(NOL-9) + 4APDs **option II**
- Works on **option II,** γ-beam test of the prototype, current status
- Summary

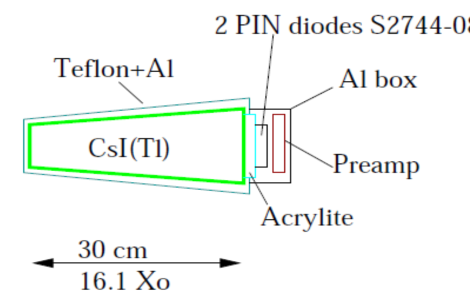
Belle II electromagnetic calorimeter (ECL)

Belle II ECL is based on 8736 CsI(Tl) crystals (40 tons) with the thickness of $16X_0$ (30 cm). It is located inside magnetic field of 1.5 T and covers the solid angle of 91% of 4π.





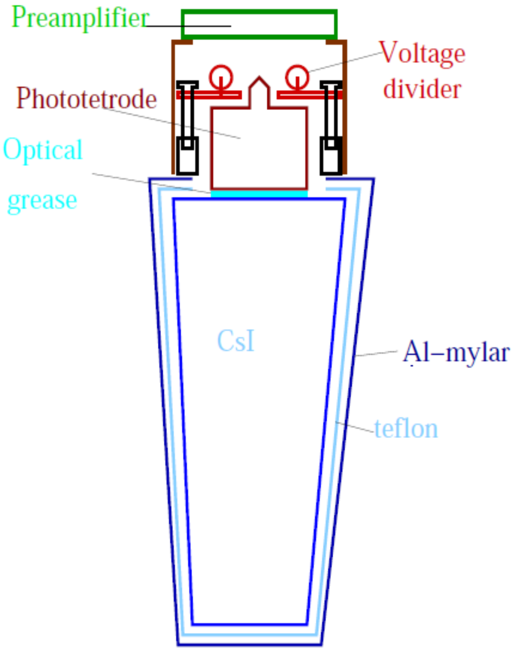
- Crystals 300x(50-80)x(50-80) mm
- Wrapping 200μm teflon+50 μm Al mylar
- Readout 2 10x20 mm PIN diodes
- 2 charge sensitive preamplifiers
- Shaper CR-(RC)^4, τ=1μs
- Lightoutput 5000 p.e./MeV
- Electronic noise 1000e ≈ 200 keV



- Electronics with pipe-line readout and waveform analysis (in the 16-ch Shaper-DSP board) has been developed. It is successfully being exploited now at Belle II.
- To decrease **notable pileup noise** by a factor of √(1000 ns/30 ns)=5.8 in the endcap ECL (1152+960 ch), CsI(Tl) crystals are planned to be changed to pure CsI crystals.

$\sigma_E/E \approx 1.8\%$ (E = 1GeV) **σ_x = 6 mm/√E(GeV)**

Belle II endcap ECL upgrade



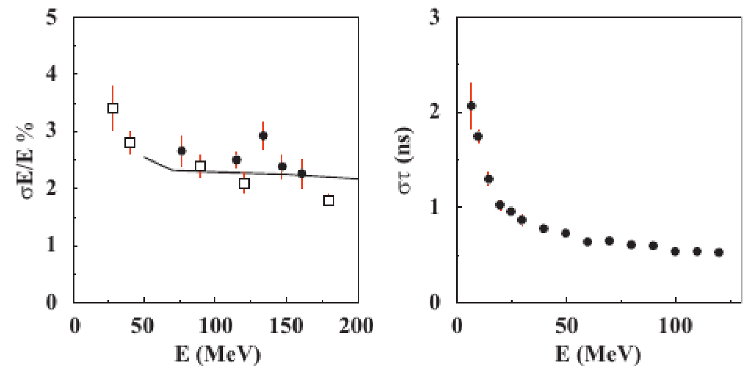
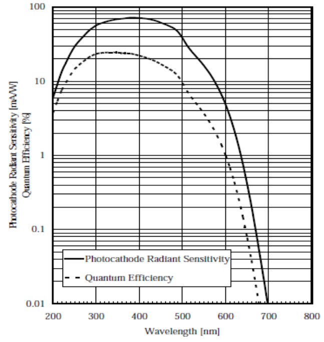
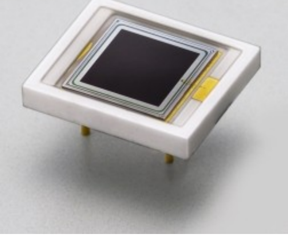


Fig. 5. Energy and time resolution obtained with the test beam (black points). The open squares present the earlier measurements with the CsI(Tl) crystals [7].

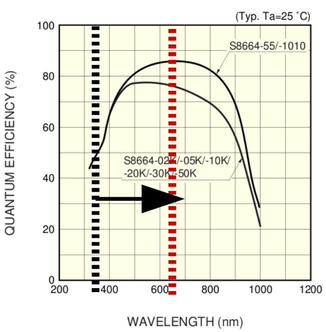
- **To decrease pileup noise by a factor of 5.8 in the endcap ECL, it was suggested to change CsI(Tl) to pure CsI crystals. R&D with CsI(pure) crystals and Hamamatsu photopentodes (PP) showed good results:**
  - Low pileup noise, good energy and spatial resolution
  - Similar physical characteristics (as for CsI(Tl)), better radiation hardness
  - There are several crystal producers, acceptable price
- However there are some difficulties: **no redundancy**, **strong dependency on magnetic field, completely new mechanical support is needed.** To solve these difficulties **second R&D option was suggested: CsI(pure) + Si APD**
- In the CsI(pure) + Si APD option we investigated Hamamatsu APD: S8664-1010 and S8664-55.
- **With the actual size crystal and 1 APD (1 x 1 cm²) Hamamatsu S8664-1010 we obtained ENE ≈ 2 MeV, while the required ENE ≤ 0.4 MeV**
- **The main task was to reach admissible level of the electronic noise and the light output of the counter. The wavelength shifter with the nanostructured organosilicon luminophore (NOL-9) is used to improve the light output of the counter by a factor of ~4.**



Hamamatsu APD S8664-55



■ Quantum efficiency vs. wavelength

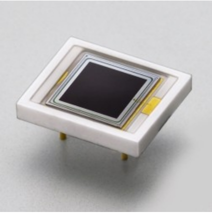


CsI(pure)+WLS+4APD option (I)

- The first tests showed that for the counter, based on the 6 x 6 x 30 cm^3 CsI(pure) crystal (AMCRYS) and 1 APD Hamamatsu S8664-1010 (1 cm^2, C_{APD} = 270 pF) coupled to the back facet of the crystal with optical grease (OKEN-6262A) has the light output **LO = 26 ph.el./cm^2/MeV** (for the shaping time of 30 ns), which corresponds to ENE ≈ 2 MeV. Such a small LO and large ENE substantially degrade the energy resolution of the calorimeter (σ_E/E (100 MeV) ≈ 8%). The acceptable parameters are:
  LO ≥ 150 ph.el./MeV, ENE < 0.4 MeV → σ_E/E (100 MeV) = 3.7% (3.4% from the fluctuations of the shower leakage)

- The reason of the small LO: small sensitive area of APD (1/36 of the area of the crystal facet), small quantum efficiency ((20 – 30)%) for the UV scintillation light (320 nm). The reason of large ENE = ENC/LO: small LO and large ENC (large capacitance of Hamamatsu S8664-1010, small shaping time τ = 30 ns → thermal noise ~$C_{APD}/(\sqrt{\tau} * g_{FET})$ dominates).

- The ways to improve LO and ENE:
  - Increase the number of APDs (LO ~ N_{APD}, ENE ~ $1/\sqrt{N_{APD}}$) → too expensive
  - **Use smaller area APDs: 4 APDs S8664-55 (0.25 cm^2, C_{APD} = 85 pF) (LO is the same, ENE is smaller by a factor of $1/\sqrt{N_{APD}}$ = 0.5)**

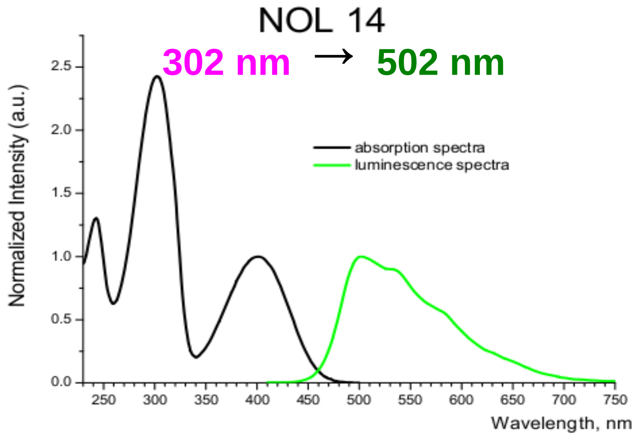


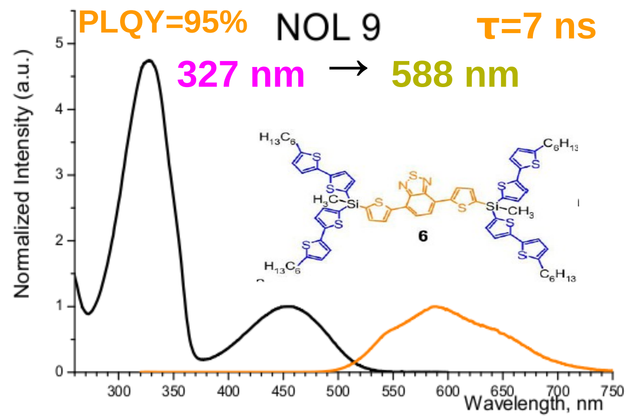
  - **Apply wavelength shifter (320 nm → 600 nm)**
  - **Optimize the input circuit of the preamplifier (increase g_{FET})**

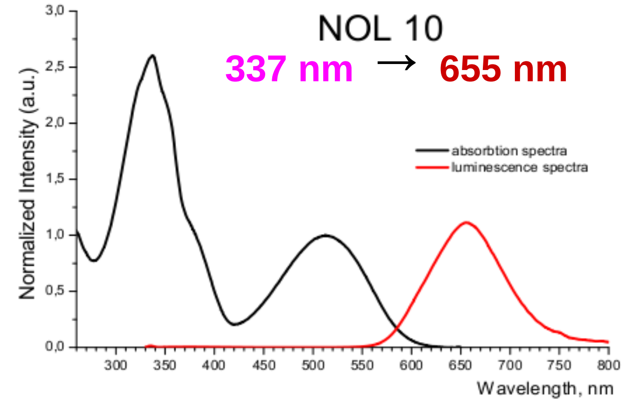
We chose the configuration: CsI(pure) + WLS(nanostructured organosilicon luminophores) + 4APD (Hamamatsu S8664-55)

CsI(pure) + WLS + 4APD option (II)

Based on the nanostructured organosilicon luminophores (NOL-9,10,14) from **LumInnoTech Co.**, the WLS plates were developed ((60 x 60 x 5) mm³).

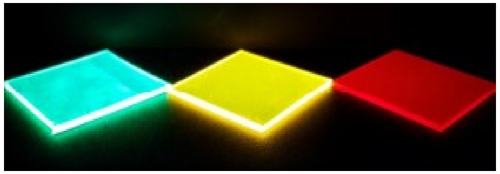


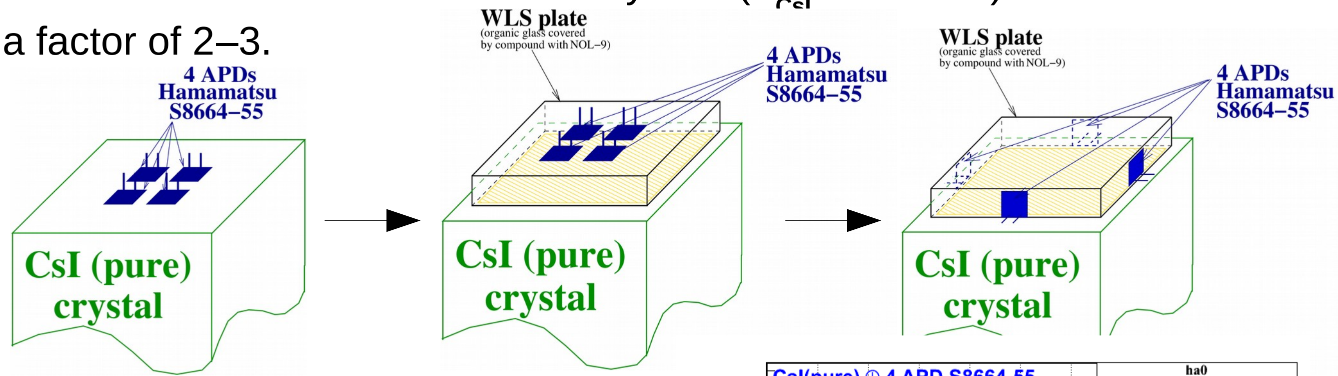


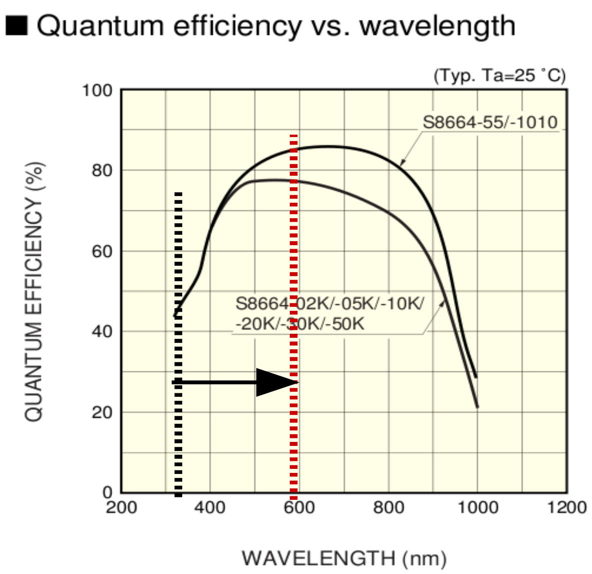


The absorption and emission spectra of these NOL's match our needs very well (**λ_{CsI} = 320 nm**).

The improvement of the APD QE is by a factor of 2–3.

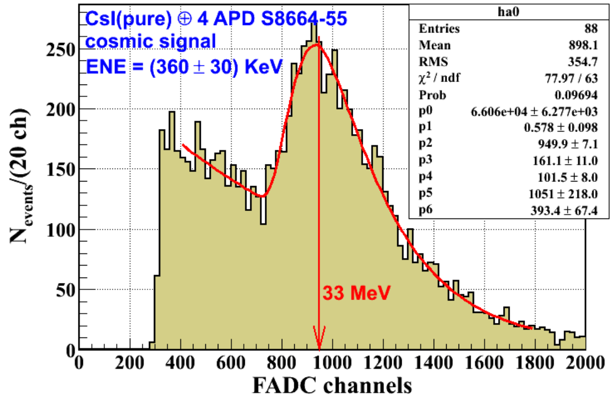






Finally, the increase of the LO by a factor of 4 was reached:

LO = 26 x 4 ≈ 100 ph.el./MeV,
ENE ≈ 0.4 MeV



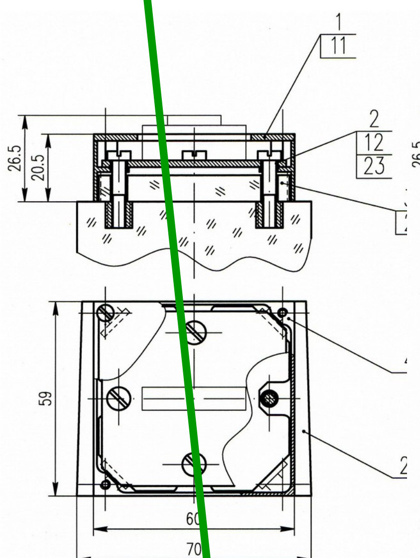
Y. Jin et al., **NIMA 824** (2016) 691.

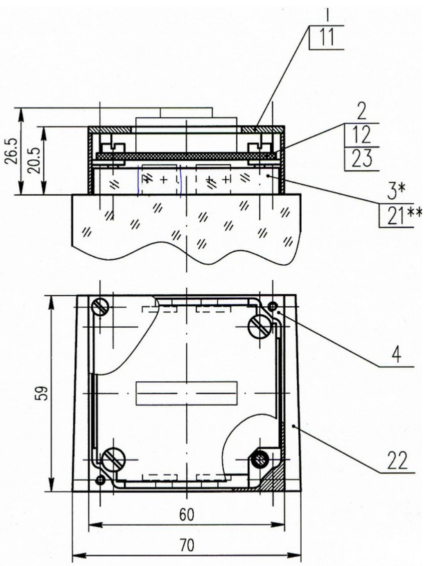
H. Aihara et al., **PoS PhotoDet 2015** (2016) 052.

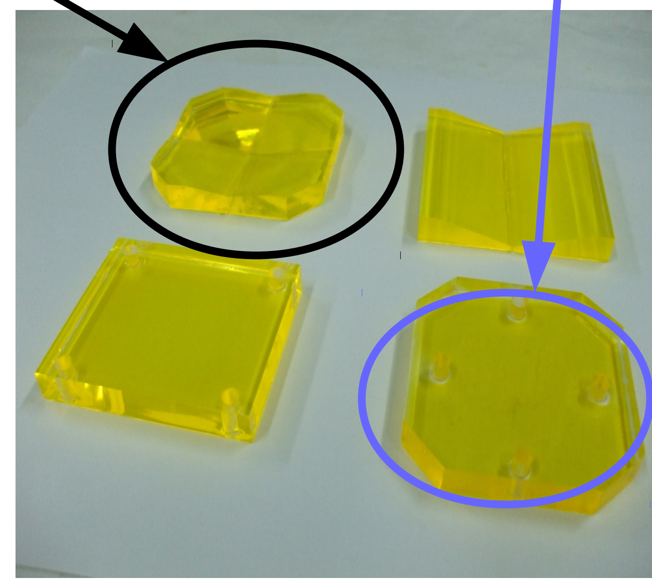
H. Aihara et al., **PoS ICHEP 2016** (2016) 703.

CsI(pure) + WLS + 4APD option (III)

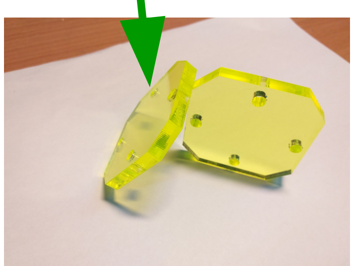
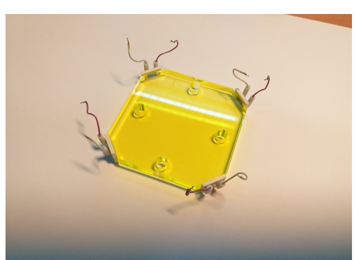
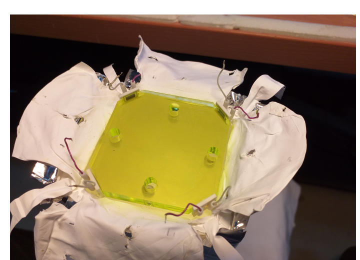
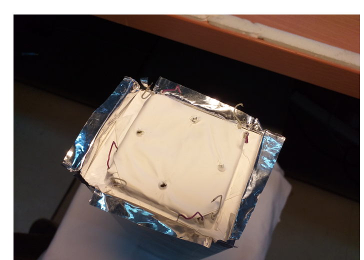
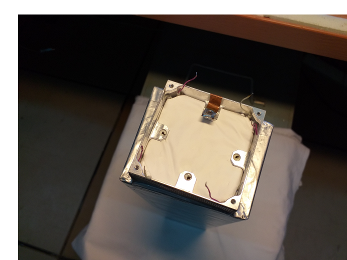
- Two types of mechanical construction of the counter were tested, the first variant was chosen**.**
- Electronic mounting of the counter was elaborated.
- WLS (NOL-9) plate of special shape was chosen (later, experimentally and with Geant4 MC we confirmed that ordinary flat plate is the best).
The flat plates with the dissolved (in the bulk) NOL-9 luminophore will be used.
- Currently we use APDs, which have large dark current (Idark = 60 nA) at the working point (gain = 50).







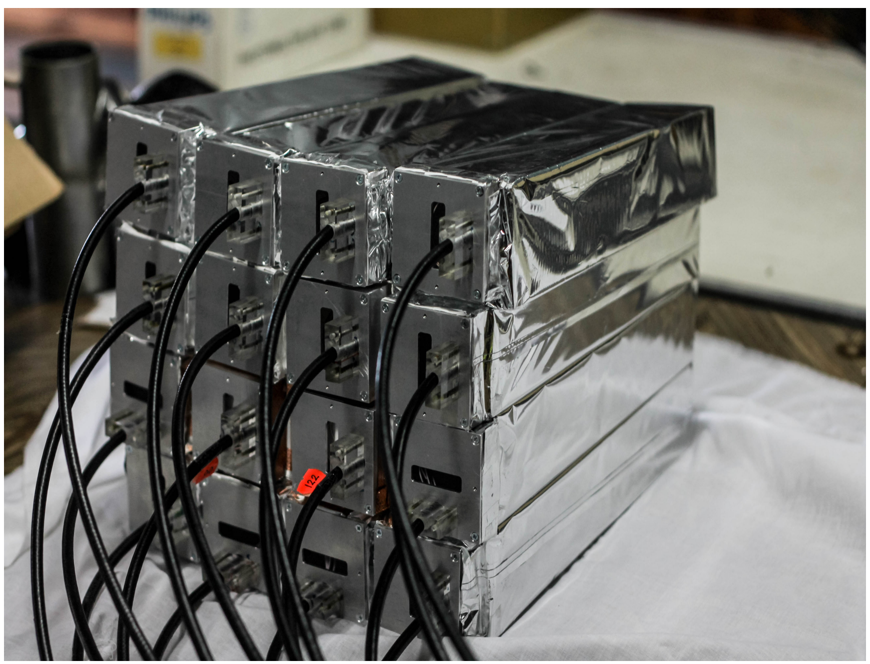
With cosmic particles the light output of the counter was measured to be
LO = (62 ± 3) ph.el./MeV (before APD gain)

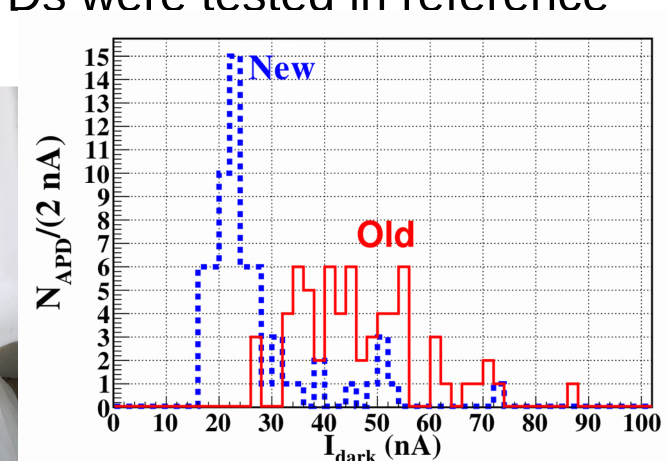






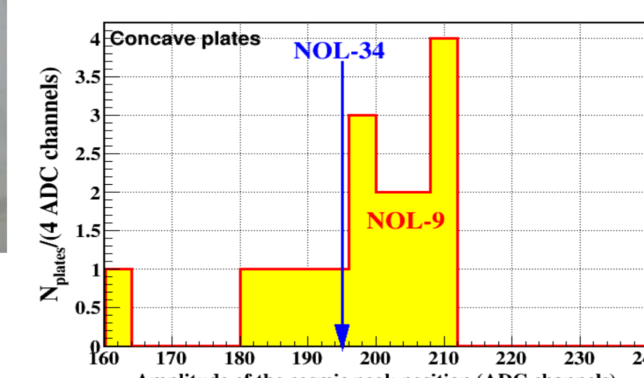
CsI(pure) + WLS + 4APD option (IV)

Crystals, WLS plates and APDs

- **We constructed calorimeter prototype made of 16 counters**, the parameters of available crystals (of 6 x 6 x 30 cm^3 size) were measured, mechanics was developed, produced and assembled.
- 64 Hamamatsu S8664-55 APDs were purchased from LHC CMS calorimeter group, baking procedure was held at CERN, the dark current was decreased by a factor of about 2.
- 16 WLS plates were purchased, APDs were coupled to the side edges of WLS plates with help of BC-600 optical epoxy resin. The WLS plates with APDs were tested in reference counter.

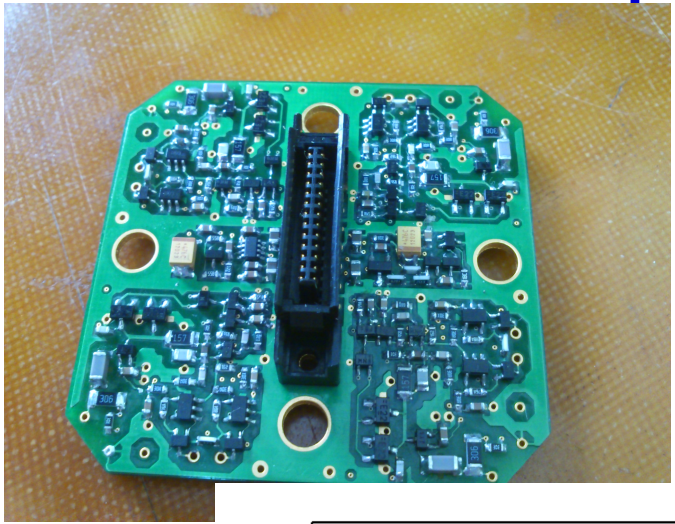




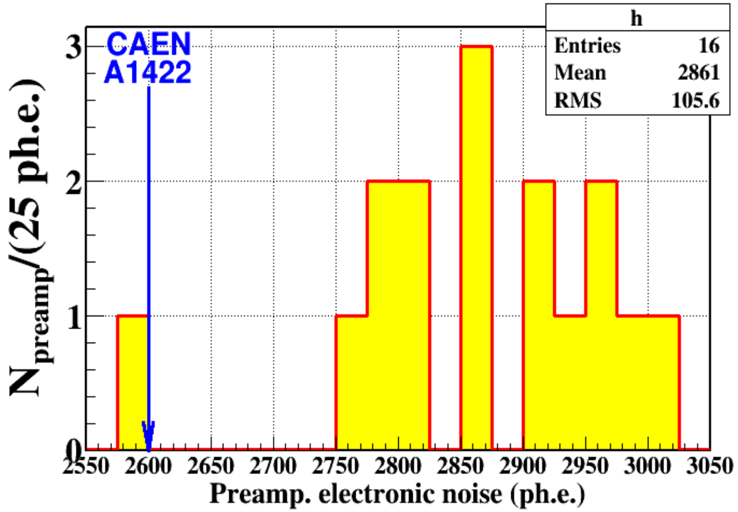


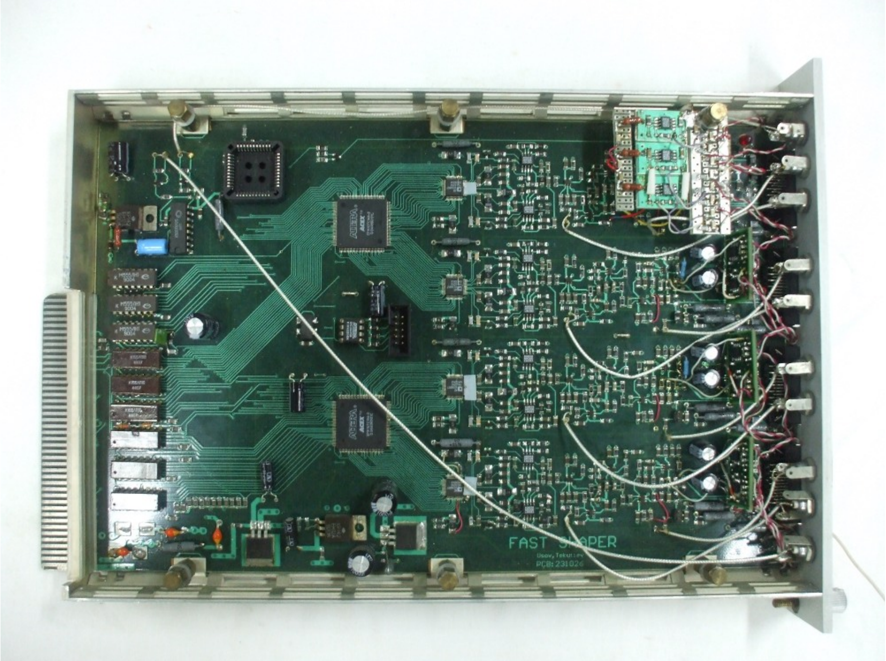
CsI(pure) + WLS + 4APD option (V)

4-channel preamplifier and Shaper-ADC board



- **4-channel charge sensitive preamplifier** on 53 x 55 mm^2 PCB
- Each channel: sensitivity of 0.2 V/pC, 2 input FET 2SK932 (high transconductance), differential output, HV bias circuit, test pulse input

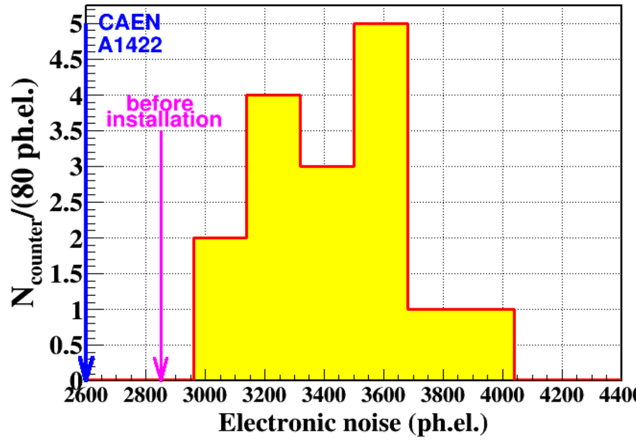


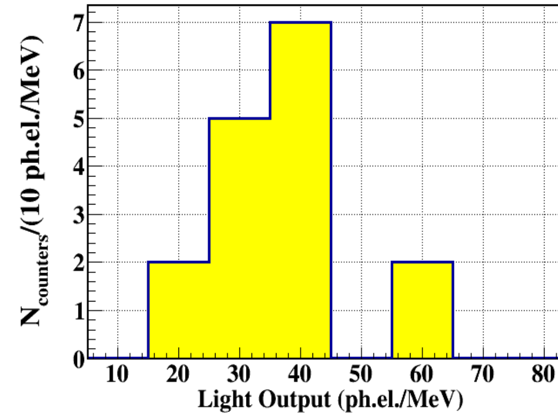


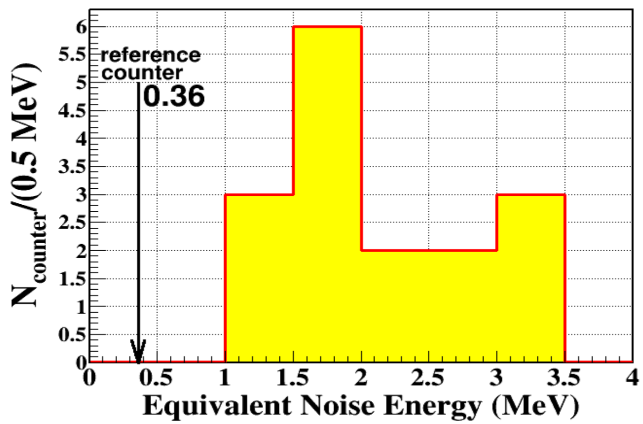
- **4-channel CAMAC Shaper-ADC board**
- CR-(RC)^4 filter (τ = 30 ns) + 40 MHz 12-bit pipelined ADC + 256-word circular buffer
- To comply with the new 4-ch preamp additional differential receiver and summator (DRS) boards have been produced and mounted in the Shaper-ADC boards

Prototype

- Assembly of 16 counters of the prototype was done, main characteristics were measured. Cosmic and pulse generator runs with the prototype are used for the calibration.







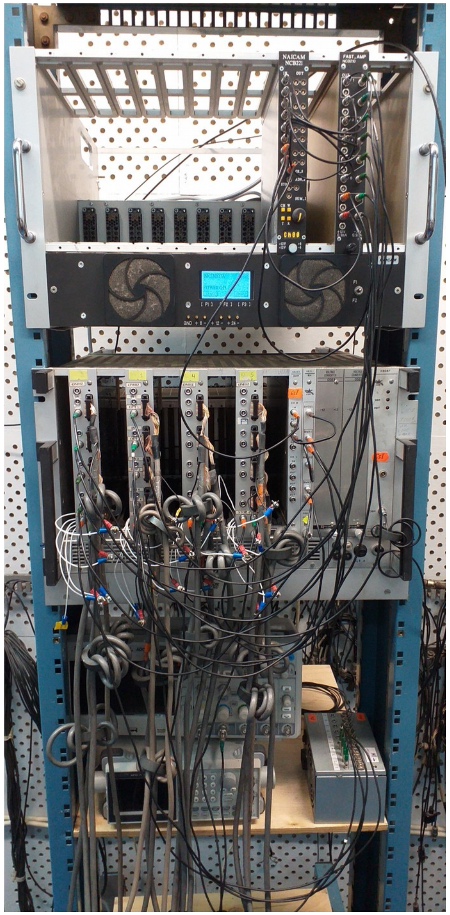
- The best counter has the light output of only LO = 62 ph.el./MeV, it is related to the LO without WLS of only LO = 15 ph.el./MeV, which is **1.7 times** smaller than the LO without WLS of U-Tokyo counter (26 ph.el./MeV).

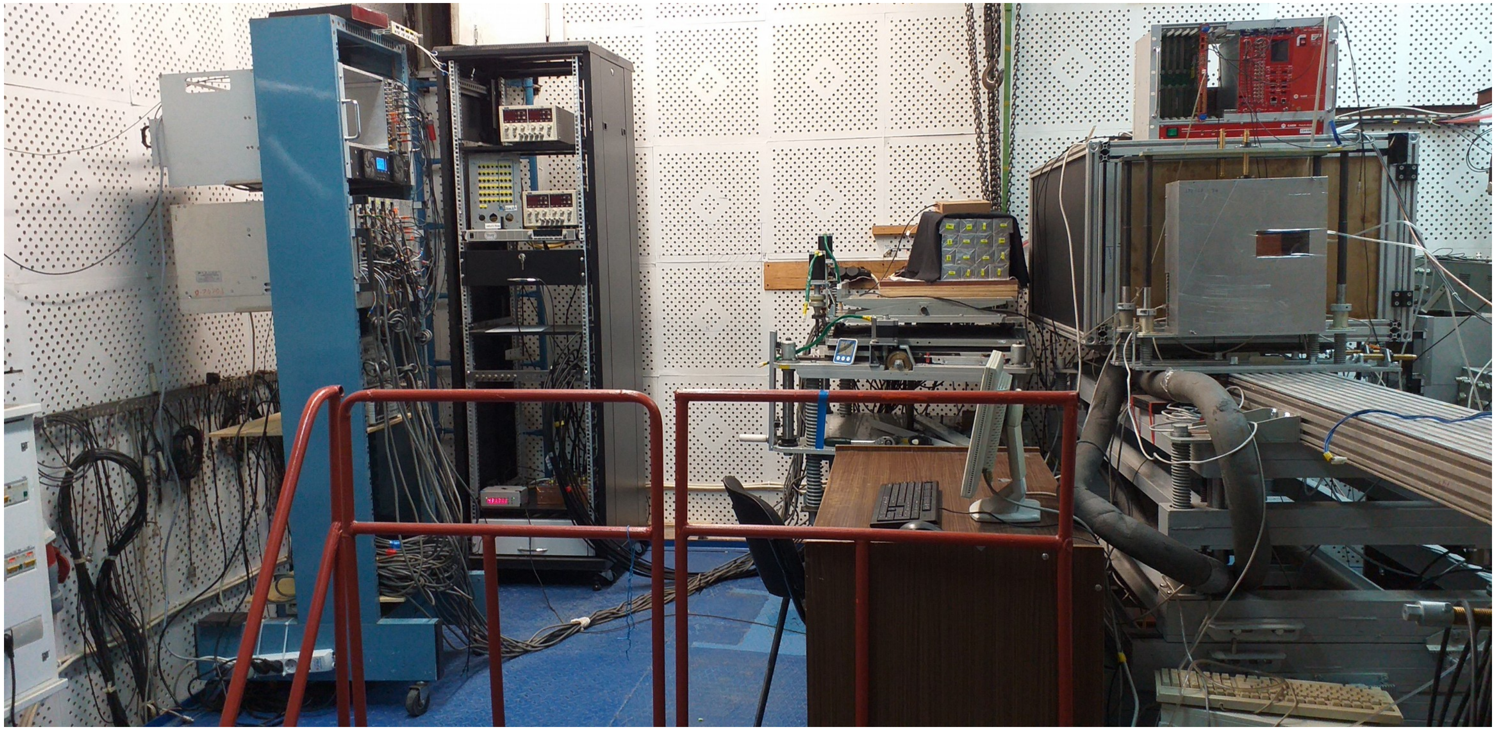
- Also, the electronic noise of the best counter, ENC = 4000 el., is **1.5 times** larger than that of U-Tokyo counter (ENC = 2600 el.) because of the large APD dark current (Id = 260 nA), and, hence large shot noise (becoming similar to the thermal noise).

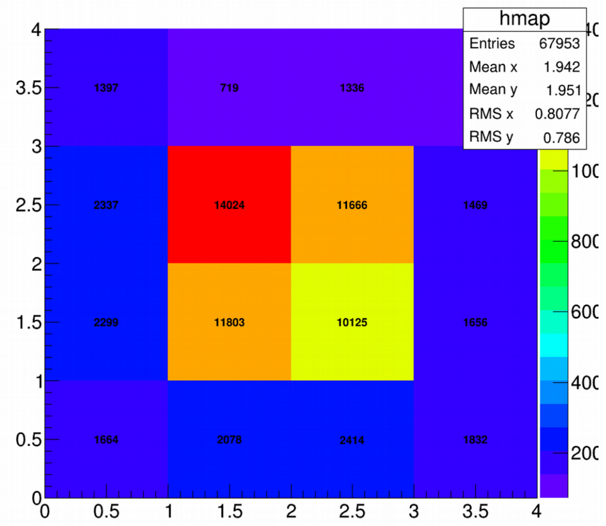
- These two factors explain why the ENE of the best counter is now about ENE = 1 MeV (to be compared with ENE of U-Tokyo counter ENE = 0.4 MeV).

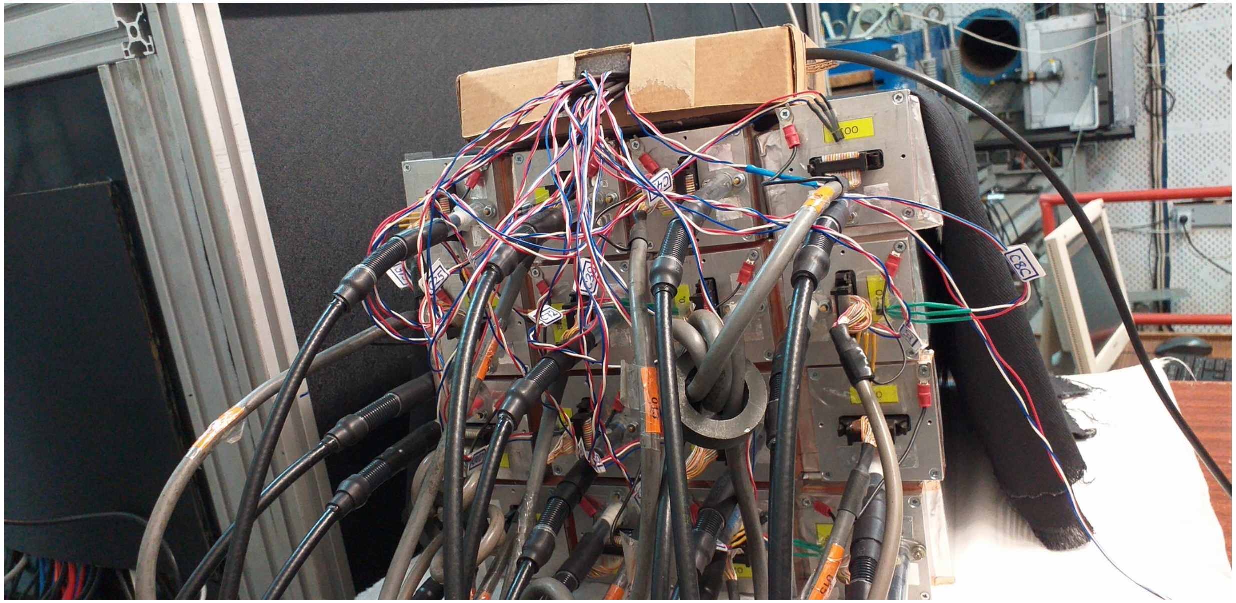
Beam test of the prototype (I)

Was held in June 2023 at the ROKK-1M test beam facility in BINP



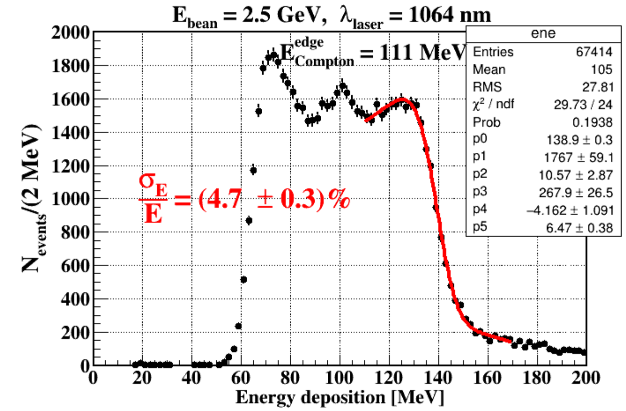


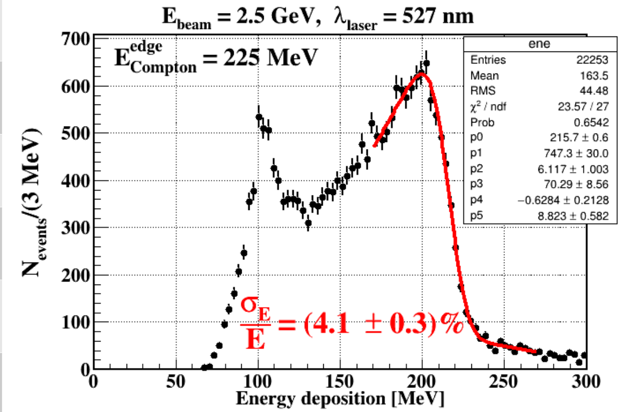


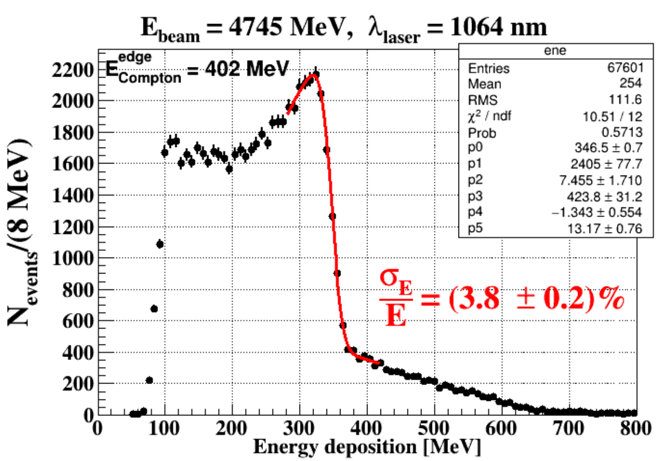


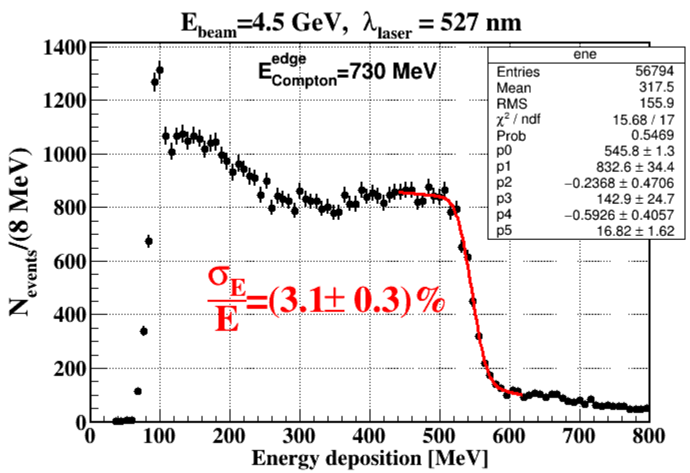
Beam test of the prototype (II)

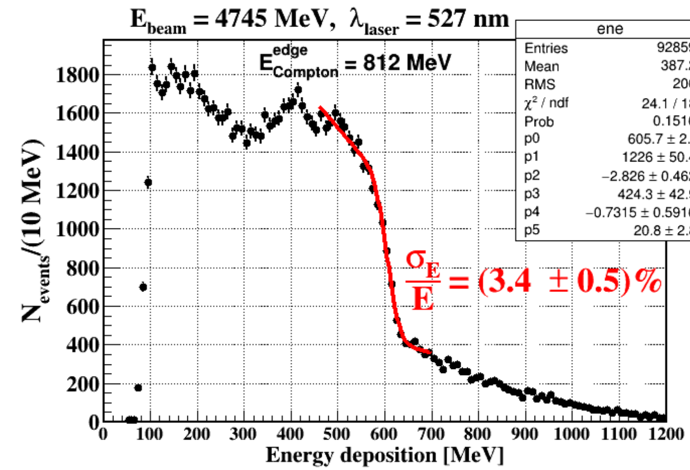
VEPP-4M e-beam energy, MeV	Laser mode, nm	Energy of the Compton edge, MeV	# events
1900	1064	**64**	880k
2500	1064	**111**	1060k
2500	527	**225**	1550k
4500	1064	**361**	630k
4745	1064	**402**	800k
3500	527	**441**	900k
4500	527	**730**	1350k
4745	527	**812**	800k
		Total:	**8M**





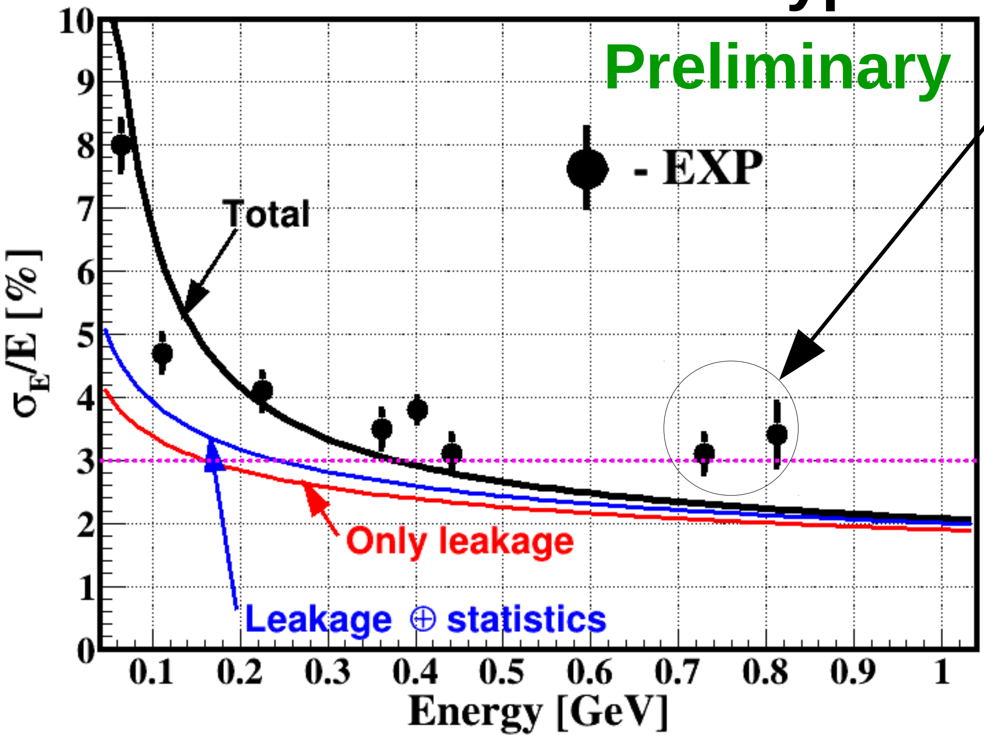






Beam test of the prototype (III)

Prototype energy resolution



There is remaining ~3% contribution to the energy resolution due to the *rough cosmic calibration* of the counters in the prototype (will be improved).

It is seen that at the energies <~0.2 GeV the *contribution of the electronic noise* of the counters to the prototype energy resolution *dominates.*

Works to decrease electronic noises are going on.

$$\frac{\sigma_E}{E} = \frac{1.9\%}{\sqrt[4]{E[GeV]}} \oplus \frac{Stat}{\sqrt{E[GeV]}} \oplus \frac{Elec}{E[GeV]}$$

$$Stat = 100\% \cdot \sqrt{\frac{F}{S[ph.e/MeV] \cdot N_{APD} \cdot 1000}} = 0.63\%$$

$$Elec = 100\% \cdot \frac{ENE[MeV] \cdot \sqrt{N_{crys}}}{1000} = 0.54\%$$

F = 1.69 ± 0.04

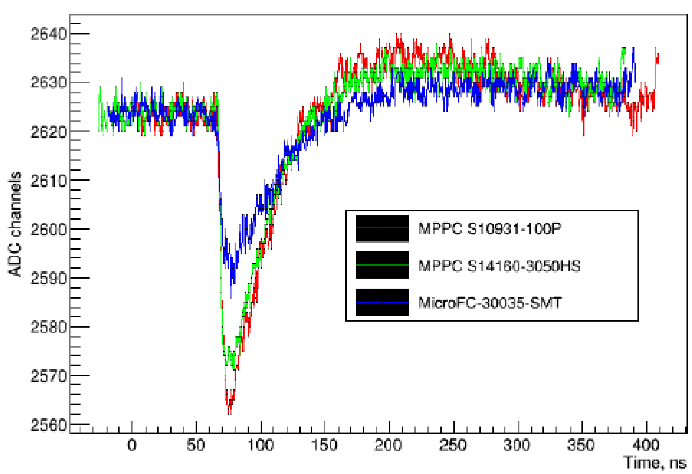
$S \cdot N_{APD}$ = 42 ph.el./MeV

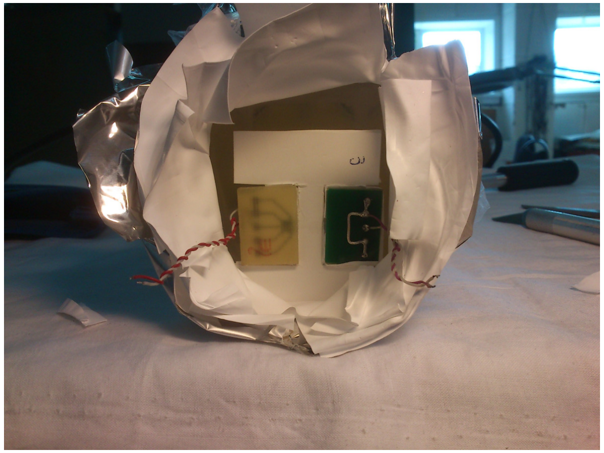
ENE = 1.7 MeV

N_{crys} = 10 – number of crystals in the 1 GeV cluster

Works with SiPM

- For the precise time measurement it is suggested to install several SiPMs in the counter in addition to the APD-based spectrometric channel.
- In the perspective this scheme will allow one to measure the incident angle of γ-quantum as well as its production point in the detector.
- One counter of the prototype was equipped by two SiPMs Hamamatsu MPPC S14160-3050HS (3 x 3 мм^2). The signals from SiPMs were digitized by CAEN V1742B. The obtained light output is 10 ph.e./MeV/cm^2, the time resolution was measured to be 23 ns/MeV $\oplus$ 70 ps.
- Plan to install 16 SiPMs (Broadcom AFBR-S4N66C013 6x6 mm^2) into 4 counters of the prototype and measure time resolution.





Summary & Plans

- **CsI(pure) is an appropriate material for the STCF/SCTF calorimeter.**
- Beam tests of the 20-counter prototype based on CsI(pure) crystals and vacuum photopentodes showed good energy and spatial resolutions, as well as essential suppression of the pileup noise.
- The CsI(pure)+WLS+4APDs option is also quite promising. The 16-counter calorimeter prototype has been constructed. Due to the small light yield of the utilized CsI(pure) crystals and big electronic noises (ENC) the ENE is still quite high, which results in the low energy resolution of the prototype at small energies $E_\gamma <\sim 0.3$ GeV.
- Test beam study of the prototype at the ROKK-1M facility in BINP was performed in June 2023. The preliminary result on the energy resolution of the prototype agrees with the expectations. Plan to complete the data analysis and publish the result.
- Further improvement of the light output of the counter (to reduce ENE) with an additional selective mirror is possible. The work is going on.
- Works with SiPMs (to improve time resolution) are going on.

Backups

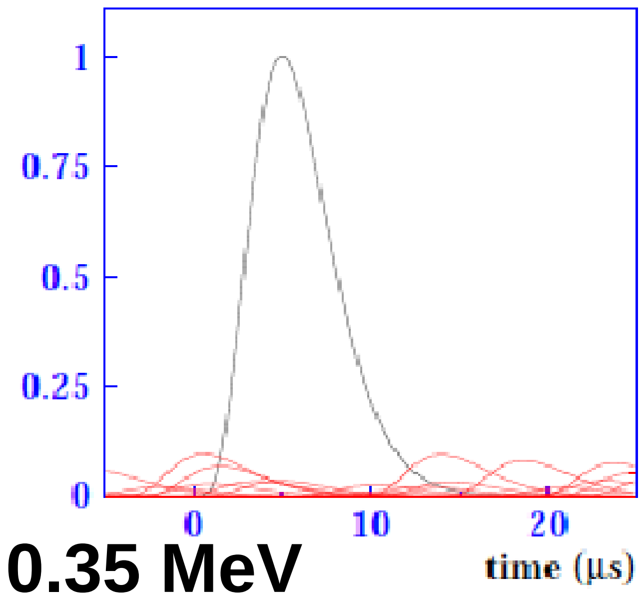
Choice of the crystal

crystal	ρ, g/cm^3	X_0, cm	λ_{em}, nm	n	N_{ph}/MeV	τ, ns
CsI(Tl)	4.51	1.86	550	1.8	52000	1000
CsI	4.51	1.86	305/400	2	5000	30/1000
BaF_2	4.89	2.03	220/310	1.56	2500/6500	0.6/620
CeF_3	6.16	1.65	310	1.62	600	3
$PbWO_4$	8.28	0.89	430	2.2	25	10
$LuAlO_3$(Ce)	8.34	1.08	365	1.94	20500	18
$Lu_3Al_5O_{12}$(Ce)	7.13	1.37	510	1.8	5600	60
Lu_2SiO_5(Ce)	7.41	1.2	420	1.82	26000	12/40

- CsI(Tl) has the largest LY, small scintillation decay time and modest price (~3$/cm^3). It is used in the electromagnetic calorimeters of modern particle detectors: Belle, Belle II, BaBar, BES-III, CMD-3.
- Lu_2SiO_5 (LSO), $LuAlO_3$, LYSO are also very good (and much faster than CsI(Tl)), however they are essentially more expensive ((15 – 30)$/cm^3), COMET (2000 LYSO crystals).
- Pure CsI has still notable LY, fast decay time component of 30 ns and acceptable price (~6$/cm^3). The are several crystal-growing companies which are able to produce needed number of large size crystals (~40 tons): AMCRYS(Ukraine), Saint Gobain (France), HPK (Japan-China), SICCAS (China) → **attractive variant for the STCF/SCTF factories.**

Pile-up noise suppression

$$\sigma_{pile-up}[MeV] = \bar{E}_\gamma \cdot \sqrt{\nu \cdot \tau}$$



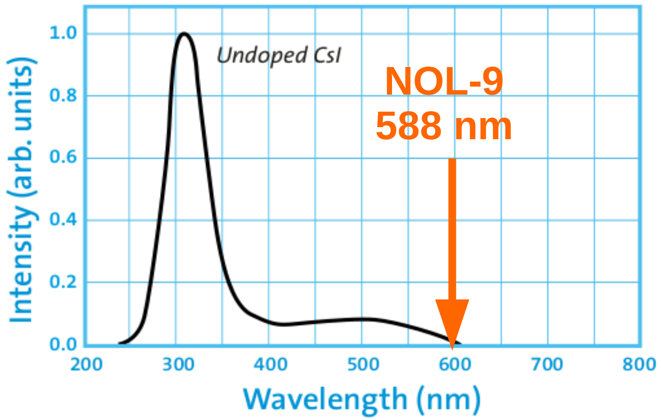
$\bar{E}_\gamma$ ***= 0.5 MeV*** – energy of the background photons

ν ***= 16 MHz*** – rate of background photons at the project SuperKEKB luminosity

τ – scintillation decay time

σ_{pileup}(τ = 1 μs) = 2 MeV, σ_{pileup}(τ = 30 ns) = 0.35 MeV

Long scintillation light decay time component of CsI(pure) is notable (up to 50%) with τ ≥ 1 μs. It has larger wavelength (in the visible range: (400 – 600) nm). So, there is additional pile-up noise due to these long tails of the previous pulses (from both, signal and background).



Solution (KTeV experiment): *additional optical filter to cut this long decay time component*

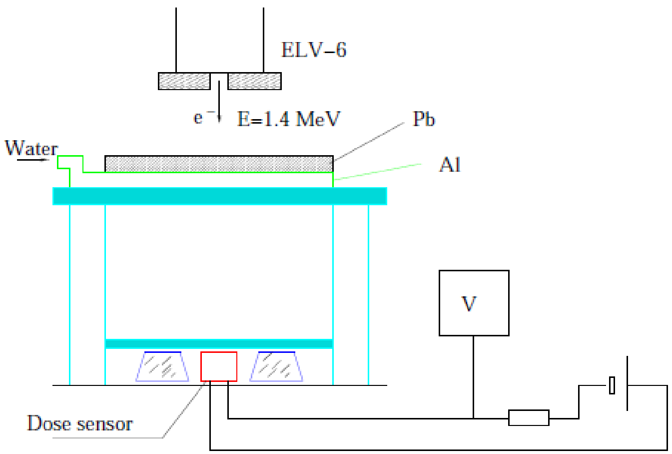
We can add filter between CsI(pure) crystal and WLS plate. In case of NOL-9, half of the re-emitted light will be rejected by the filter. We can change WLS and use, for example, NOL-10. Or use narrower filter ((400 – 540) nm)

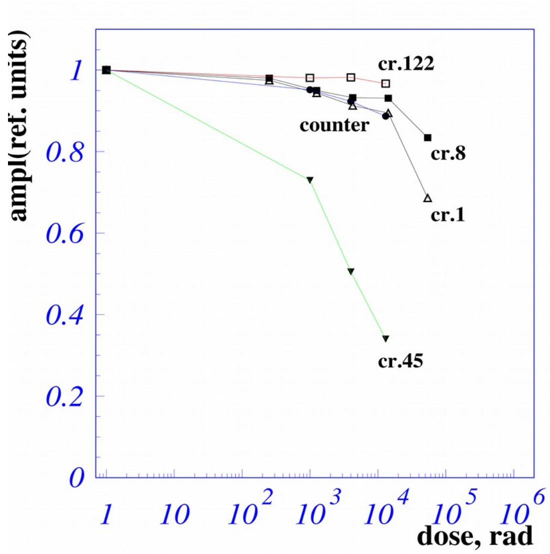
Spectral characteristics of the long decay time component of CsI(pure) should be studied to choose optimal scheme

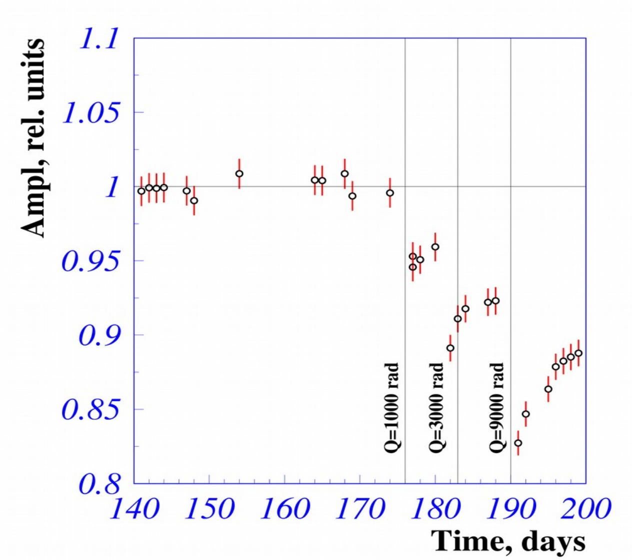
Study of radiation hardness of CsI(pure) crystals

I. Bedny et al., **NIMA598** (2009) 273.

A. Boyarintsev et al., **JINST11** (2016) P03013.

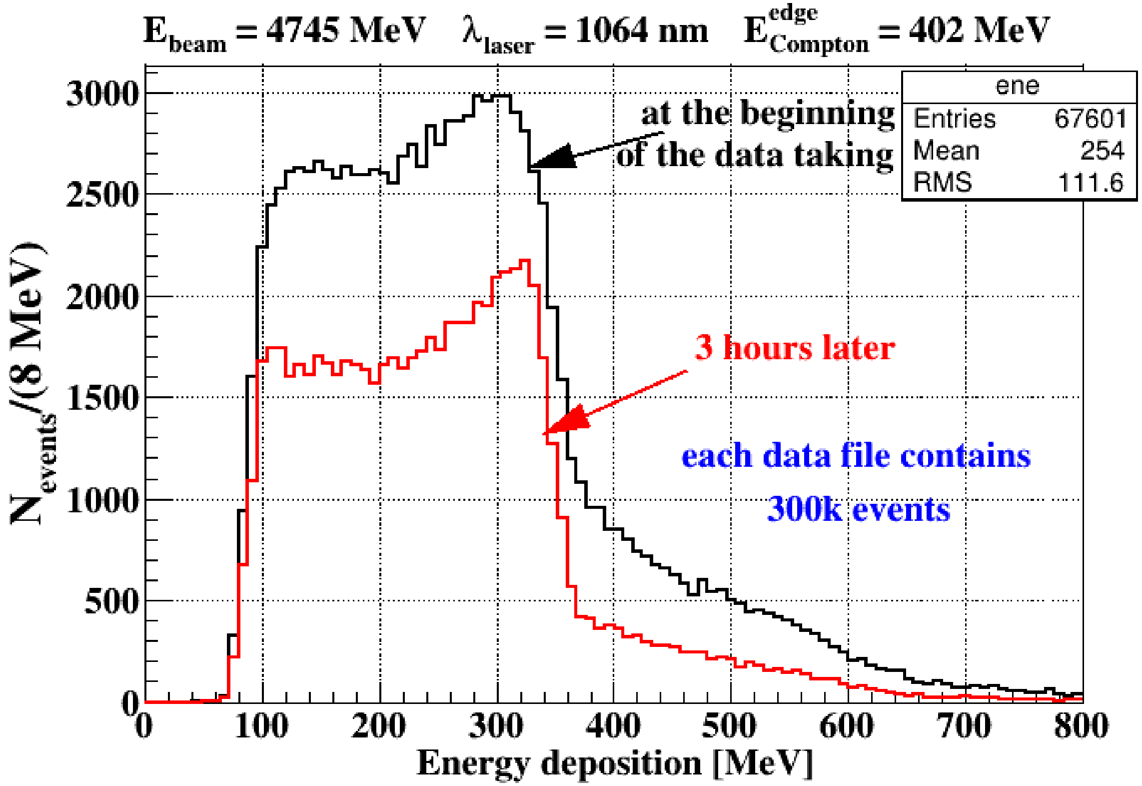






- We studied the radiation hardness of 4 CsI(pure) crystals and 1 counter (CsI(pure) + photopentode), they were irradiated by bremsstrahlung γ's with E_γ < 1.4 MeV
- The dose rate was controlled by ELV-6 current and measured by a special dosimeter made of CsI(Tl) crystal and PIN PD
- For the dose of 15 krad the degradation of the LO of 3 crystals and counter was less than 15%, **but the degradation of the LO of one counter turned out to be about 60%, it was recovered to about 80% within one year. No change if the Fast/Total-ratio was detected within the accuracy of 3%.**
- **CsI(pure) crystals were also irradiated by neutrons (up to 10^{12} 1/cm^2), we didn't detect any LO degradation within the accuracy of 5%**
- **The procedure to reject CsI(pure) crystals with poor radiation hardness should be developed**

1-γ regime in the test at ROKK-1M



- Laser frequency – 4 kHz, rate of the scattered electrons was kept at the 1.2 kHz level using focusing system of the laser light. I.e. average number of the laser photon interaction with electron beam = 1.2/4 = 0.3. Hence, the number of gammas in an event obeys Poisson distribution with μ=0.3. P(0) = exp(-0.3) = 0.74, P(1) = 0.3*exp(-0.3) = 0.22, P(>1) = 0.04. Therefore, the fraction of background from multi-gamma events for μ=0.3: 0.04/(0.22+0.04) = 15%. For the μ=0.1 the fraction of background from multi-gamma events is already 5%.

- During data taking e- beam current was decreasing, the rate of the scattered electrons descended (μ became smaller) as a result events became cleaner, but at the same time the fraction of signal 1-γ events decreased substantially.

- For the demonstration we choose 1/3 fraction of the run data in the middle of run, where μ = 0.15 – 0.20.