Status of CsI(pure) + APD R&D

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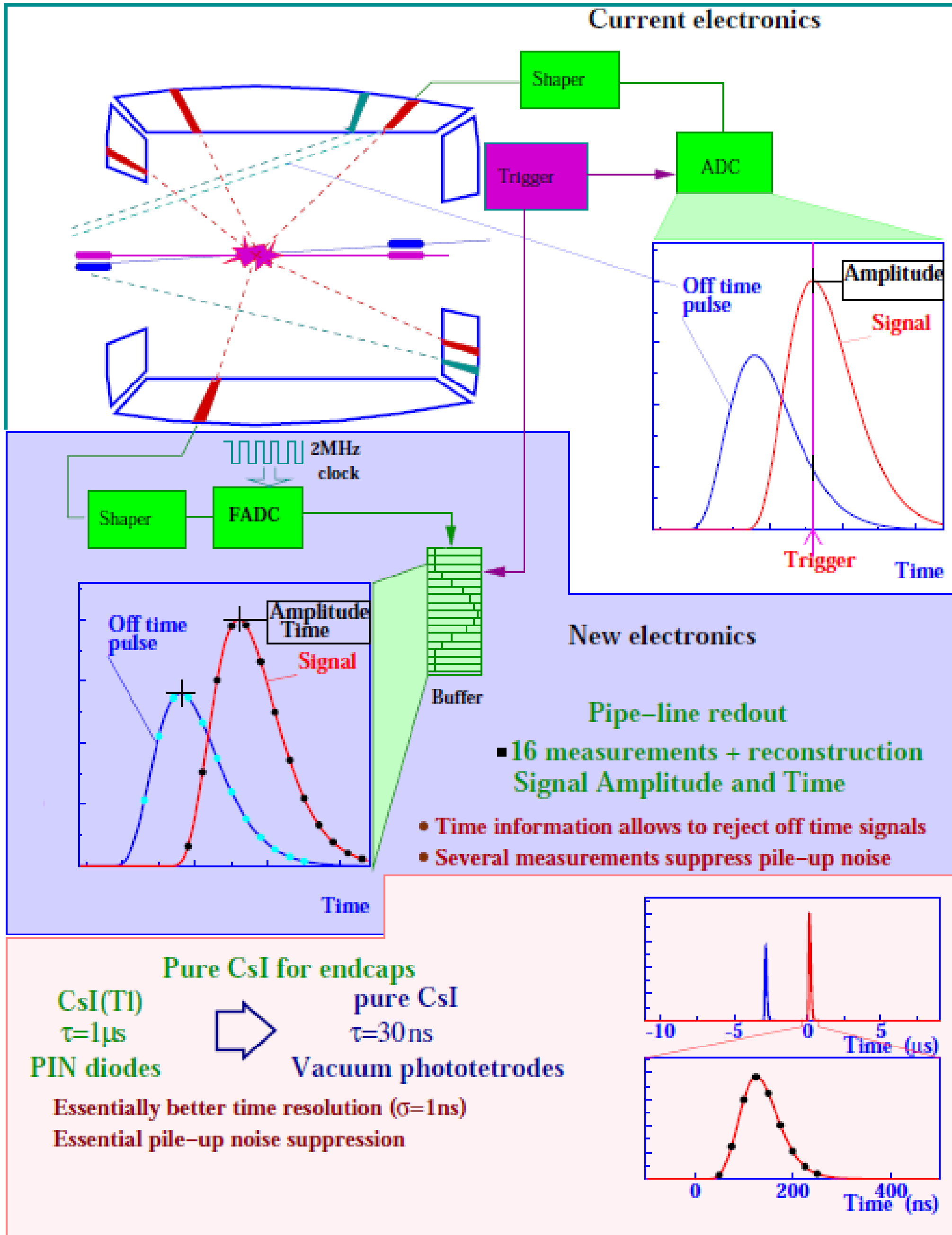
STCF/SCTF meeting, November 17th, 2021

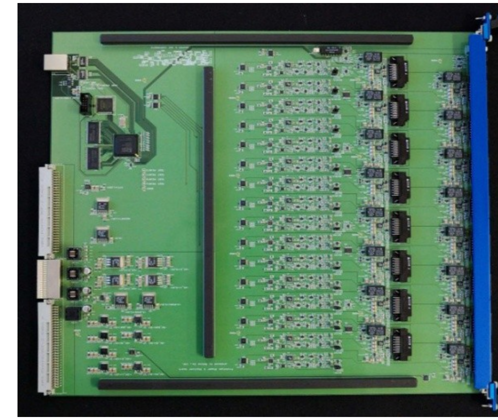
Outline:

- Belle II ECL
- Endcap ECL upgrade: CsI(pure) + photopentode **option I**
- Endcap ECL upgrade: CsI(pure) + WLS(NOL-9) + 4APDs **option II**
- Works on **option II,** current status, 1-year progress
- Summary

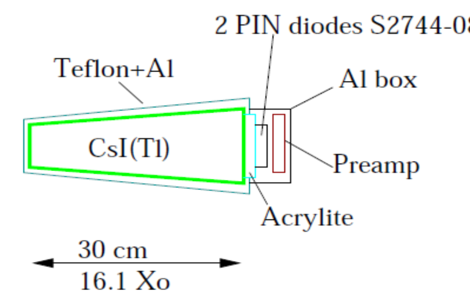
Belle II electromagnetic calorimeter (ECL)

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.





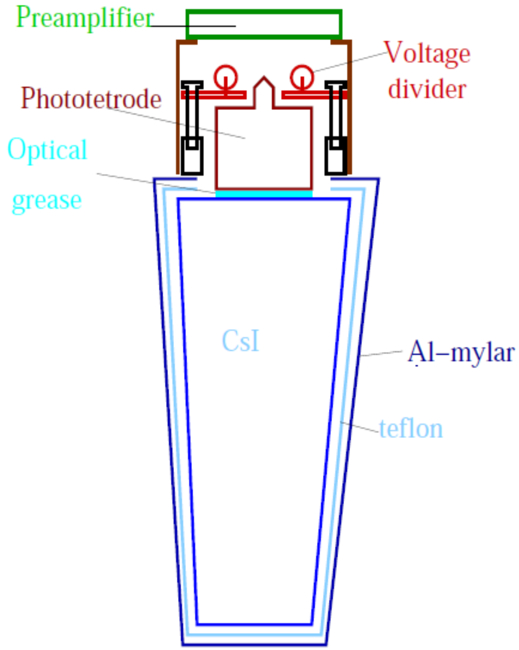
- Crystals 300x(50-80)x(50-80) mm
- Wrapping 200μm teflon+50 μm Al mylar
- Readout 2 10x20 mm PIN diodes
- 2 charge sensitive preamplifiers
- Shaper CR-(RC)^4, τ=1μs
- Lightoutput 5000 p.e./MeV
- Electronic noise 1000e ≈ 200 keV



- 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



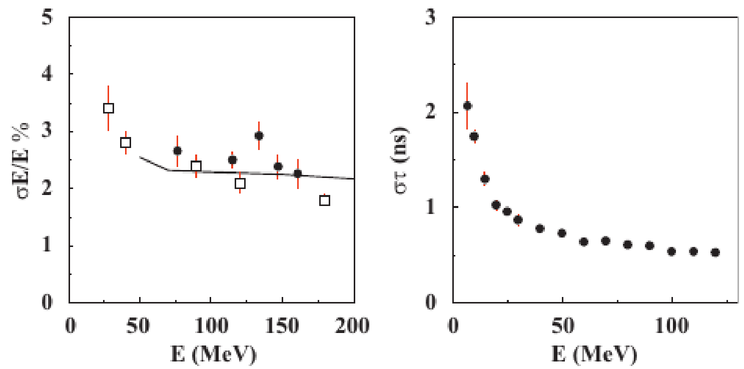
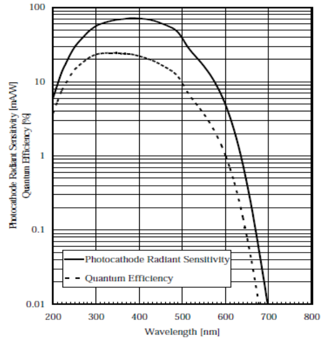
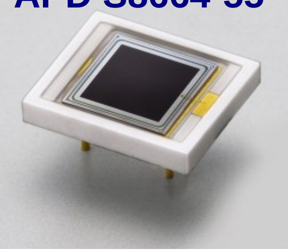
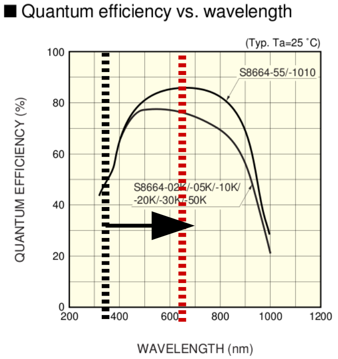


Fig. 5. Energy and time resolution obtained with the test beam (black points). The open squares present the earlier measurements with the CsI(Tl) crystals [7].



Hamamatsu APD S8664-55





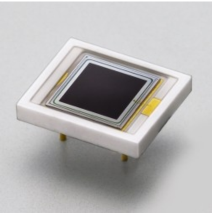
- **To decrease pileup noise by a factor of 5.8 in the endcap ECL, it was suggested to change CsI(Tl) to pure CsI crystals. R&D with CsI(pure) crystals and Hamamatsu photopentodes (PP) showed good results:**
  - Low pileup noise, good energy and spatial resolution
  - Similar physical characteristics (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 cm^2) 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.**

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).

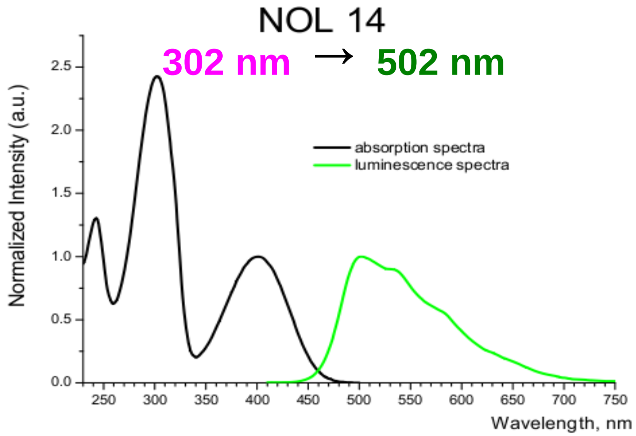
- The ways to improve LO and ENE:
  - Increase the number of APDs (LO ~ N_{APD}, ENE ~ $1/\sqrt{N_{APD}}$) → too expensive
  - **Use smaller area APDs: 4 APDs S8664-55 (0.25 cm^2, C_{APD} = 85 pF) (LO is the same, ENE is smaller by a factor of $1/\sqrt{N_{APD}}$ = 0.5)**
  - **Apply wavelength shifter (320 nm → 600 nm)**
  - **Optimize the input circuit of the preamplifier (increase g_{FET})**

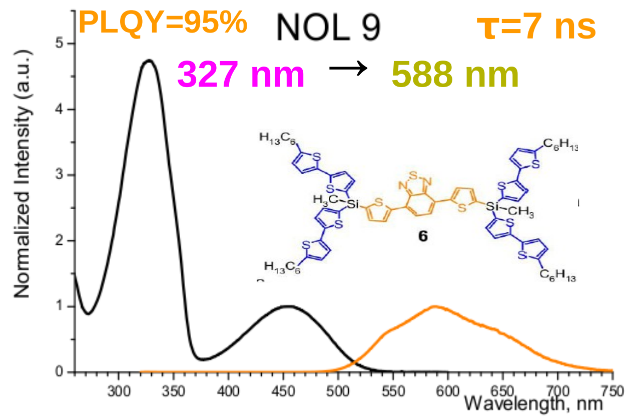


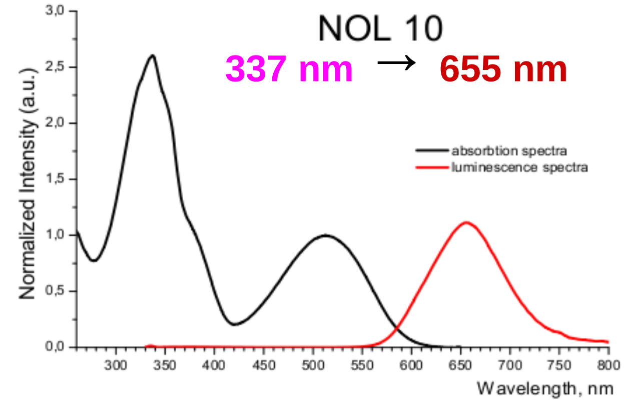
We chose the configuration: CsI(pure) + WLS(nanostructured organosilicon luminophores) + 4APD (Hamamatsu S8664-55)

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).

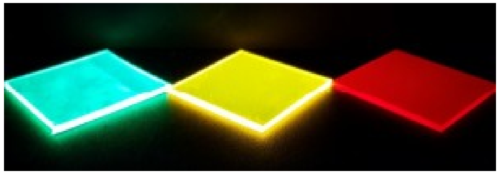


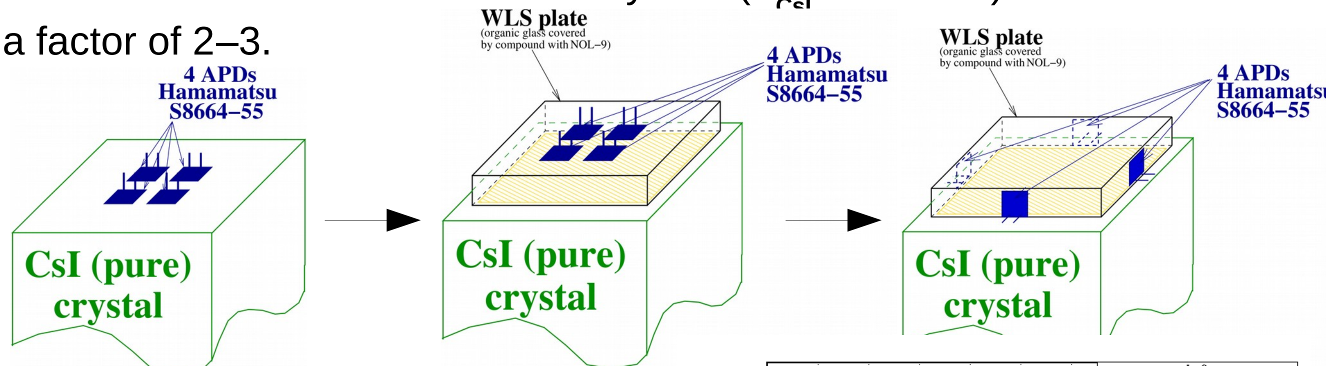




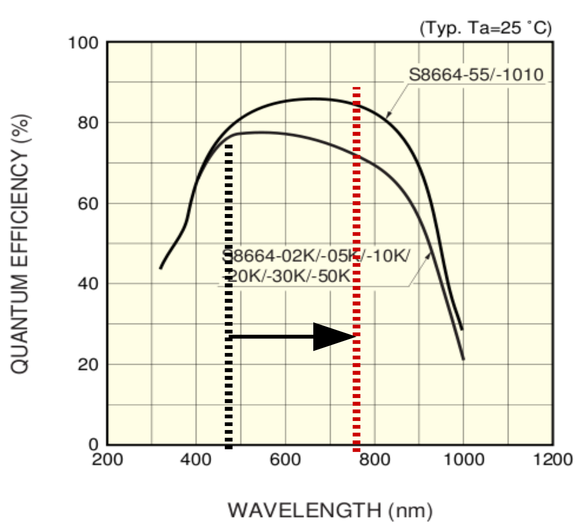
The absorption and emission spectra of these NOL's match our needs very well (**λ_{CsI} = 320 nm**).

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





■ Quantum efficiency vs. wavelength



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

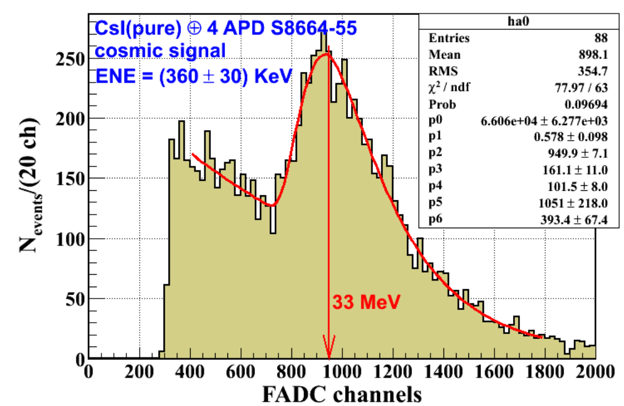
LO = 26 x 4 ≈ 100 ph.el./MeV,

ENE ≈ 0.4 MeV

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

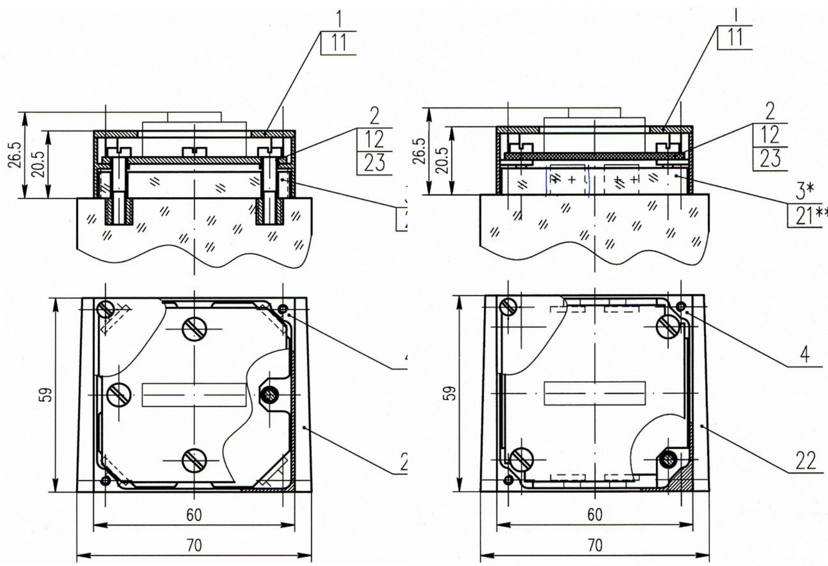
H. Aihara et al., **PoS PhotoDet 2015** (2016) 052.

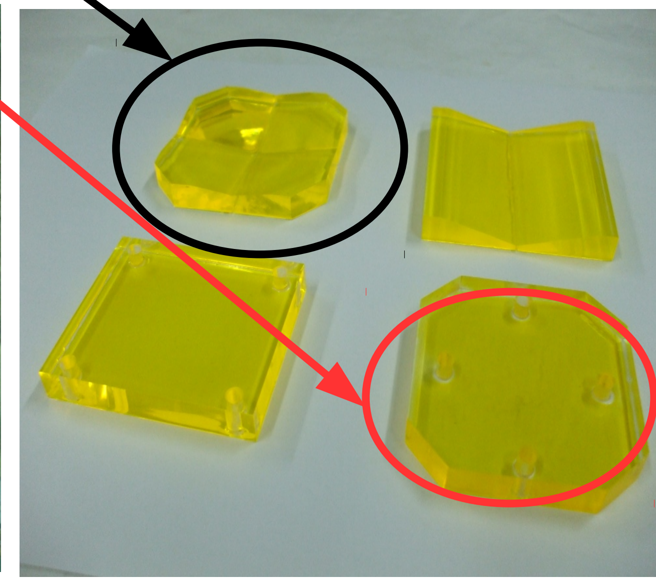
H. Aihara et al., **PoS ICHEP 2016** (2016) 703.



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).
- Currently we use APDs, which have large dark current (Idark = 60 nA) at the working point (gain = 50).



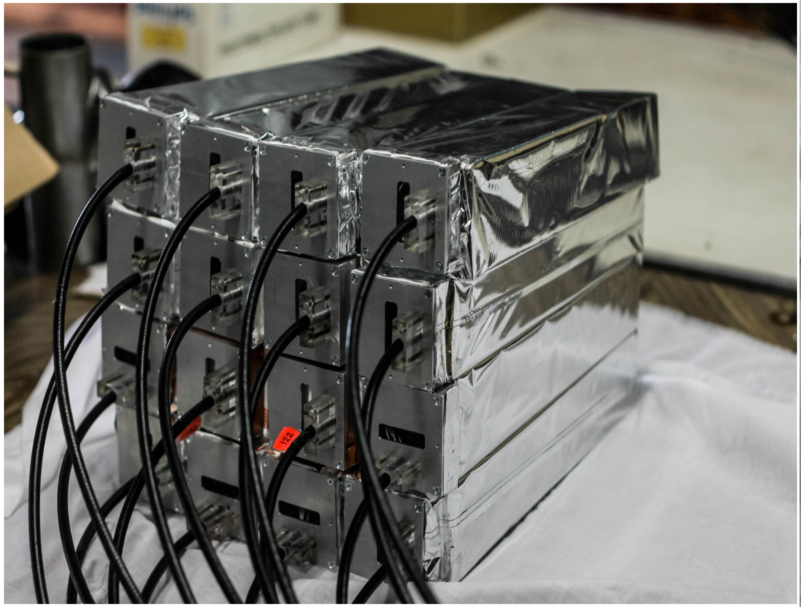



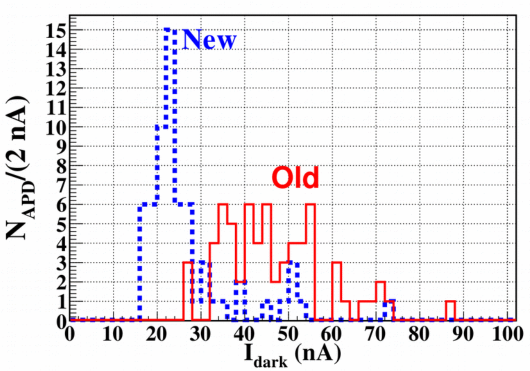
With cosmic particles the light output of the counter was measured to be
LO = (62 ± 3) ph.el./MeV (before APD gain)

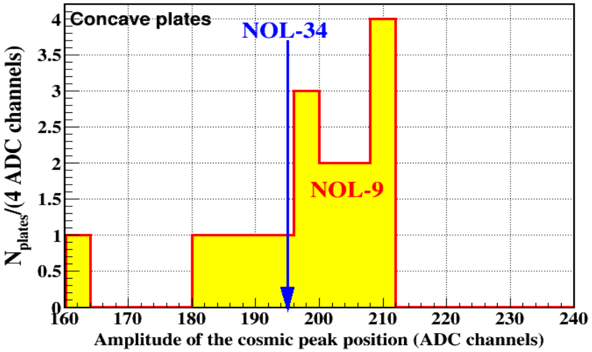
CsI(pure) + WLS + 4APD option (IV)

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.

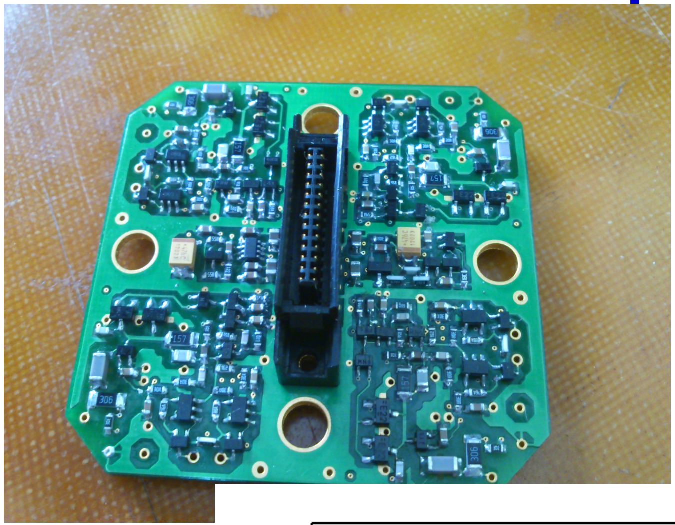




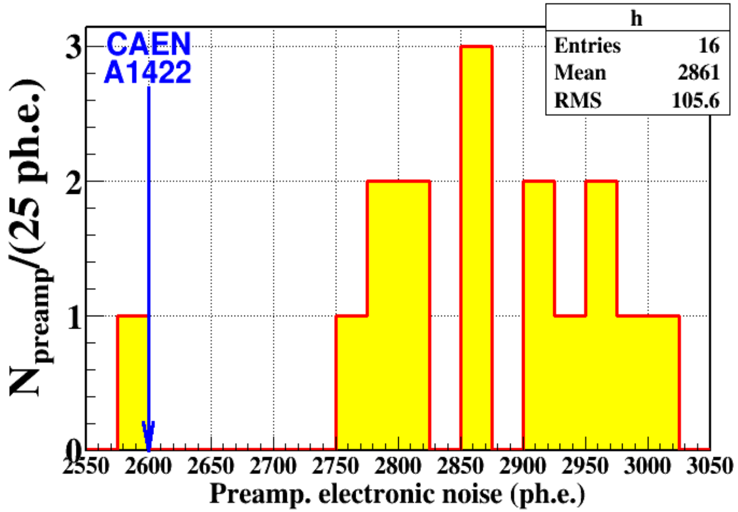


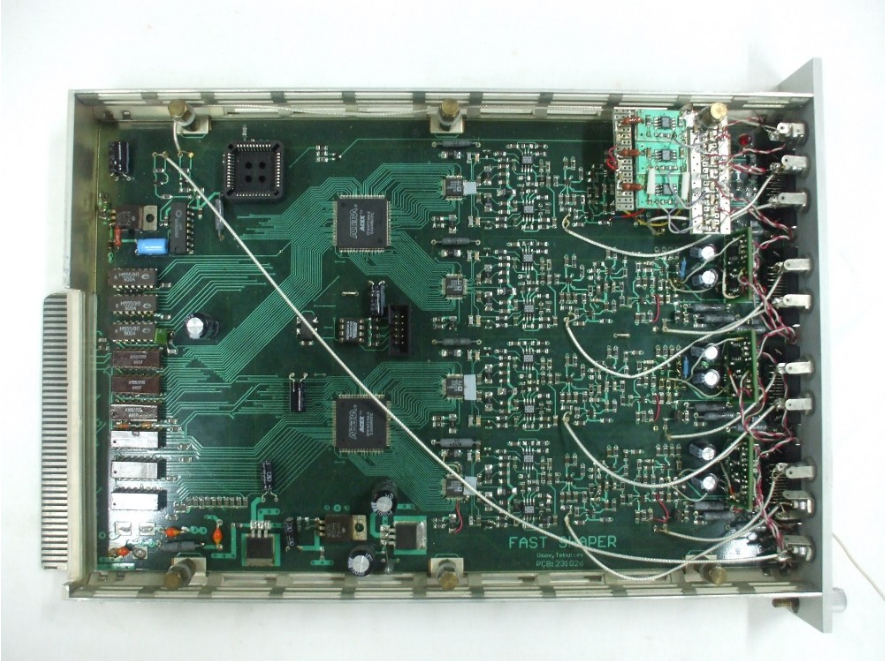
CsI(pure) + WLS + 4APD option (V)

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

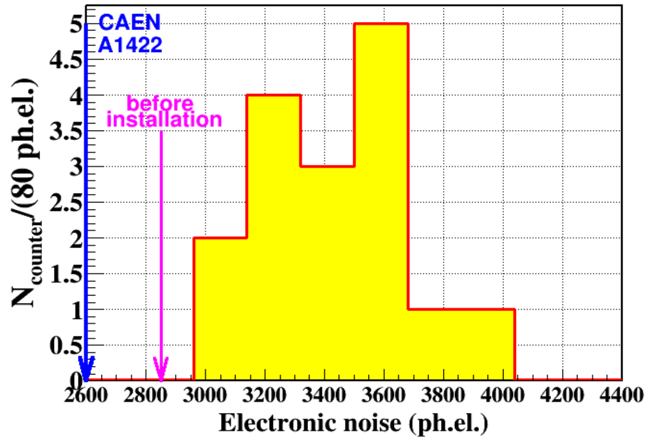


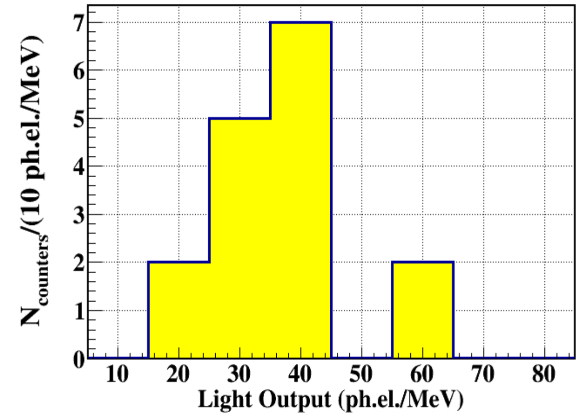


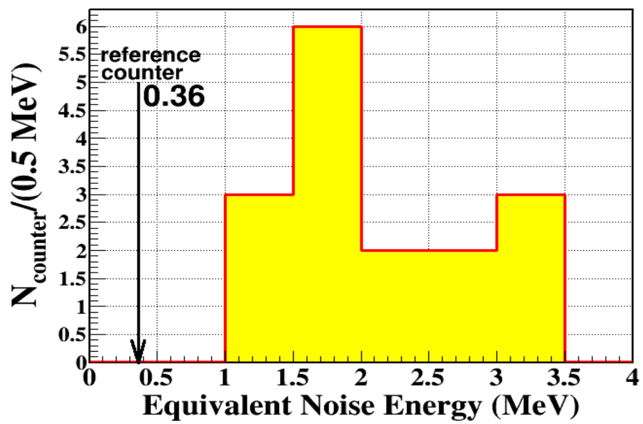
- **4-channel CAMAC Shaper-ADC board**
- CR-$(RC)^4$ filter (τ = 30 ns) + 40 MHz 12-bit pipelined ADC + 256-word circular buffer
- To comply with the new 4-ch preamp additional differential receiver and summator (DRS) boards have been produced and mounted in the Shaper-ADC boards

Prototype

- Assembly of 16 counters of the prototype was done, main characteristics were measured. Cosmic runs with the prototype have been started.



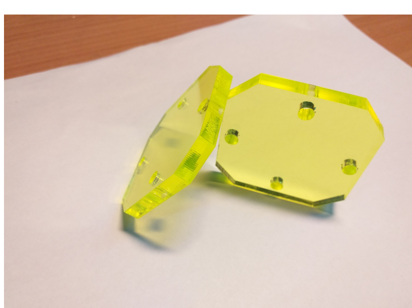
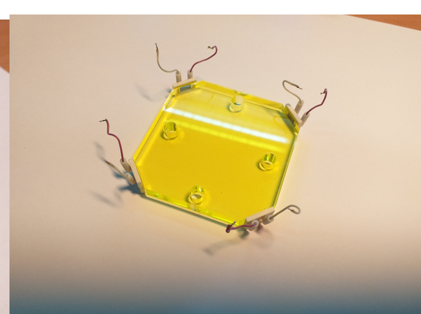
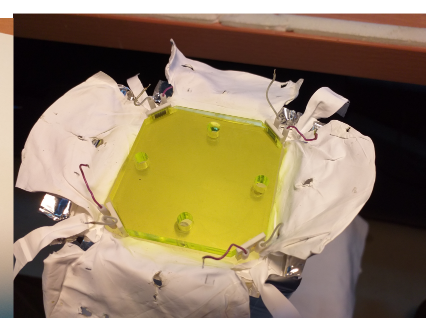
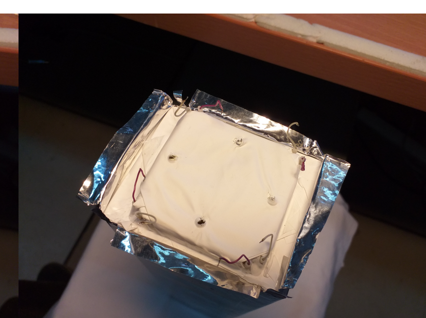
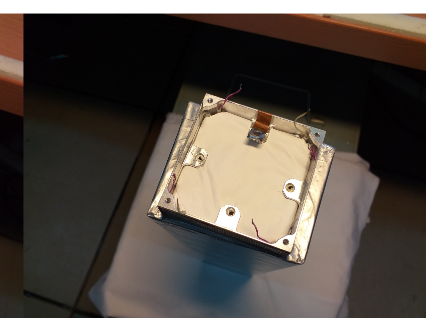




- The best counter has the light output of only LO = 62 ph.el./MeV, it is related to the LO without WLS of only LO = 15 ph.el./MeV, which is **1.7 times** smaller than the LO without WLS of U-Tokyo counter (26 ph.el./MeV).
- Also, the electronic noise of the best counter, ENC = 4000 el., is **1.5 times** 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).

1-year progress in CsI(pure)+WLS+4APD option

- 4 shaper-ADC boards were modified to cope with high current (1.6A @ 12V) consumption by prototype. **Big correlated noises** were suppressed in the electronic setup (additional filters in shaper-ADC boards, bias voltage divider module etc).
- 2 of 16 4ch preamplifiers showed problems with tantalum capacitors.
- Basically, 1 year periodical operation of the prototype showed good performance.
- LumInnoTech company developed the PMMA plate with the **dissolved NOL-9 luminophore** in the bulk of the plate. Two plates were delivered to BINP. Measurement of the LO of the counter with the new plate showed good expectable result.
- Study of the light collection efficiency in the counter in Geant4 has been carried out. It was realized that additional selective reflector on the plate (crystal side) with optical contact of such plate to the crystal will further essentially increase the light collection efficiency. And in this case the plate with the slanted sides will be more efficient.
- The procedure of the calibration of the shape of the signal, as well as the procedure of the fit of the electric signal to extract amplitude, time and fit quality is being developed. Test pulse calibration runs are recorded for that.

Summary & Plans

- CsI(pure) is an appropriate material for the Belle II end cap ECL upgrade.
- **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 ~1.4 larger ENC the LO of the counters are smaller than that of the reference counter (with good CsI(pure) crystal) and ENE is quite high.
- Cosmic runs have been started with the prototype, test beam study of the prototype at ROKK-1M facility in BINP is planned in 2021.
- We could not reanimate the Shaper-DSP board (VME 9U format) with the shaping time of 30 ns.
- LumInnoTech company developed the technology and produced the PMMA plates with dissolved NOL-9. Two plates were delivered to BINP. The counter with the new plate showed expectably good LO. Further improvement of the plate with additional dielectric selective reflective layer is possible.
- Works with several types of SiPM (to improve the counter time resolution) have been started.

Backups

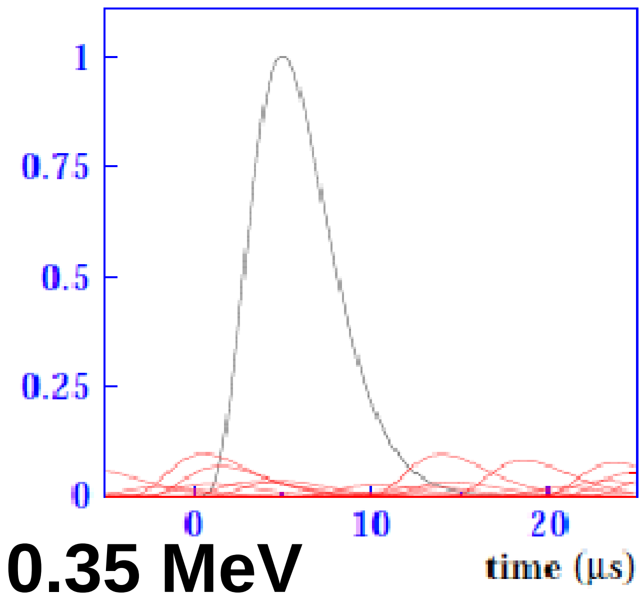
Choice of the crystal

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)$/cm^3), COMET (2000 LYSO crystals).
- Pure CsI has still notable LY, fast decay time component of 30 ns and acceptable price (~5$/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 Super Flavor factories.**

Pile-up noise suppression

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



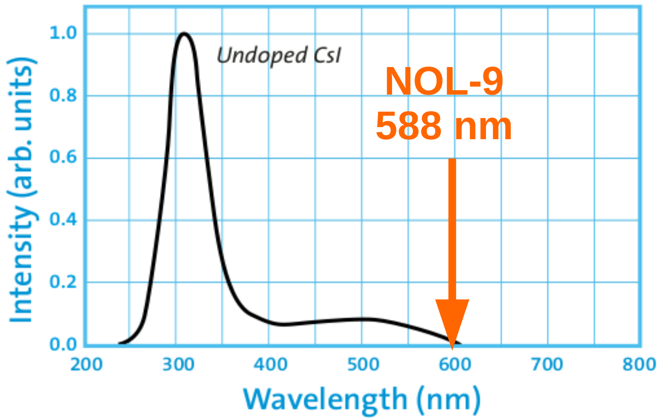
$\bar{E}_\gamma$ = 0.5 MeV – energy of the background photons

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

Expected energy resolution

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

fluctuation of e/m shower leakage | **statistics of photoelectrons** | **electronic noise**

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

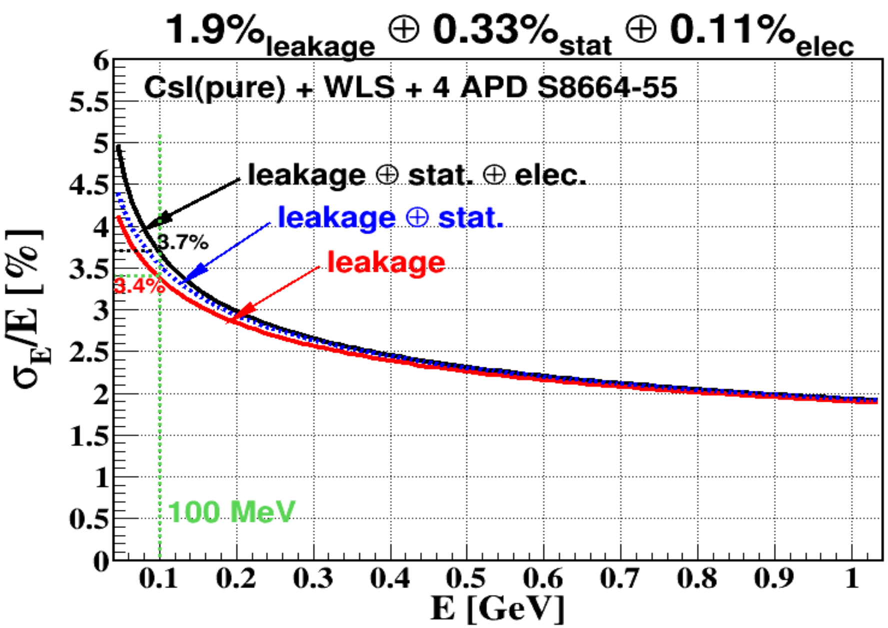
$$Elec = 100\,\% \cdot \frac{ENE[MeV] \cdot \sqrt{N_{crys}}}{1000}$$

F = 1.69 ± 0.04

$S \cdot N_{APD}$ = (160 ± 9) ph.el./MeV

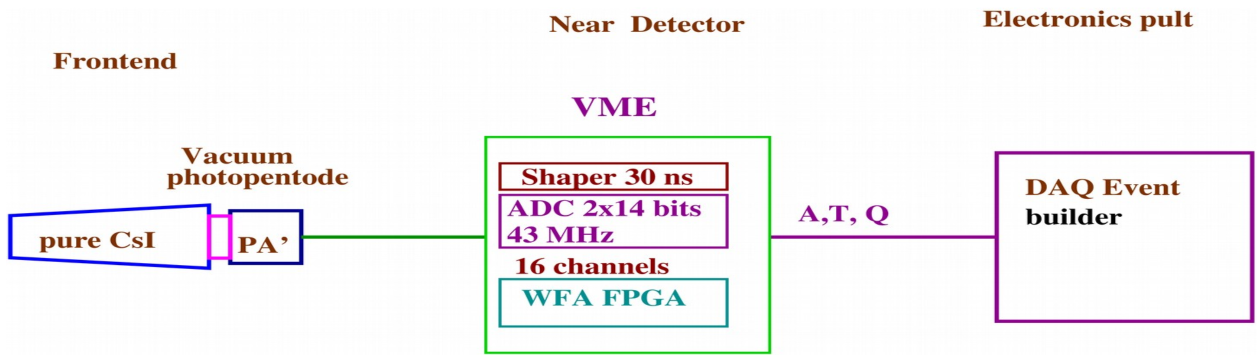
ENE = (0.33 ± 0.03) MeV

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

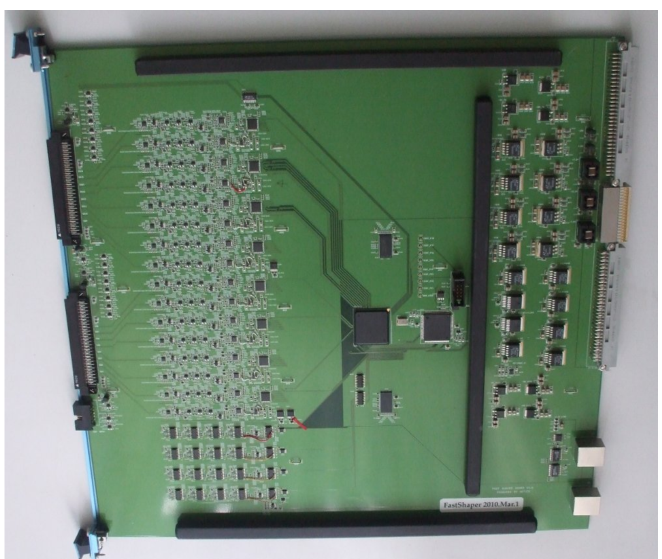


New Shaper-DSP board for CsI(pure) counters

Development of new electronics for the calorimeter



- Pipeline readout, on-board waveform analysis approach (successfully realized at Belle II ECL)
- Preamplifier is located in the counter, shaping digitization and analysis is implemented in the VME 9U Shaper-DSP board located nearby the detector. Shaper: CR + $(RC)^4$ with the **shaping time of 30 ns**. Amplitude, time and pedestal are fitted in FPGA of the Shaper-DSP board. The data from the Shaper-DSP boards are sent to the DAQ via optical link (directly or via intermediate collector board)
- The temperature variation of the LY of CsI(pure) is 1.5%/°C, hence, thermostabilization of the calorimeter is needed, the temperature map should be monitored with the accuracy of (0.1 – 0.2) °C

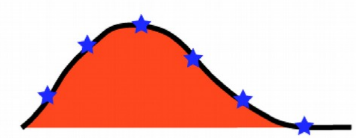


Algorithm details

$$\chi^2(A,p,t_0)=\sum_{i,j}\left(y_i-Af(t_i-t_0)-p\right)S_{ij}^{-1}\left(y_j-Af(t_j-t_0)-p\right)\to \min$$

$$S_{ij}=\overline{(y_i-\bar{y})(y_j-\bar{y})}$$

$f(t)$ – counter response



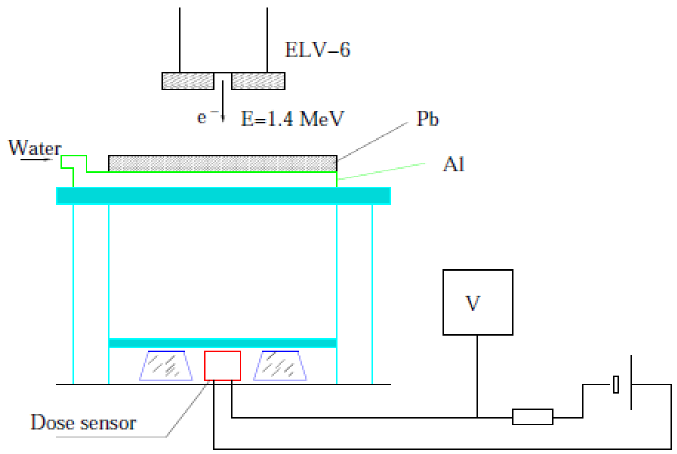
$$Af(t_i-t_1-\Delta t)=Af(t_i-t_1)-A\Delta t f'(t_i-t_1)=Af(t_i-t_1)+Bf'(t_i-t_1)$$

where t_1 – initial time (trigger time)

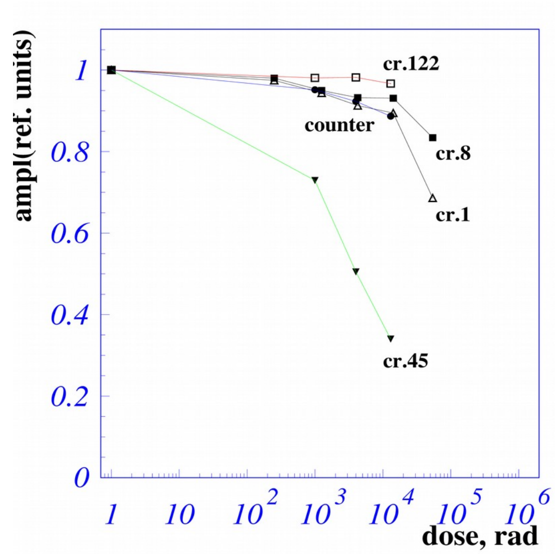
$$\begin{cases}\sum_{i,j} f_i S_{ij}^{-1}\left(y_j-Af_j-Bf'_j-p\right)=0\\ \sum_{i,j} f'_i S_{ij}^{-1}\left(y_j-Af_j-Bf'_j-p\right)=0\\ \sum_{i,j} S_{ij}^{-1}\left(y_j-Af_j-Bf'_j-p\right)=0\end{cases}\Rightarrow\quad \begin{aligned}A&=\sum_i \alpha_i y_i\\ B&=\sum_i \beta_i y_i \Rightarrow \Delta t=-B/A\\ p&=\sum_i \gamma_i y_i\end{aligned}$$

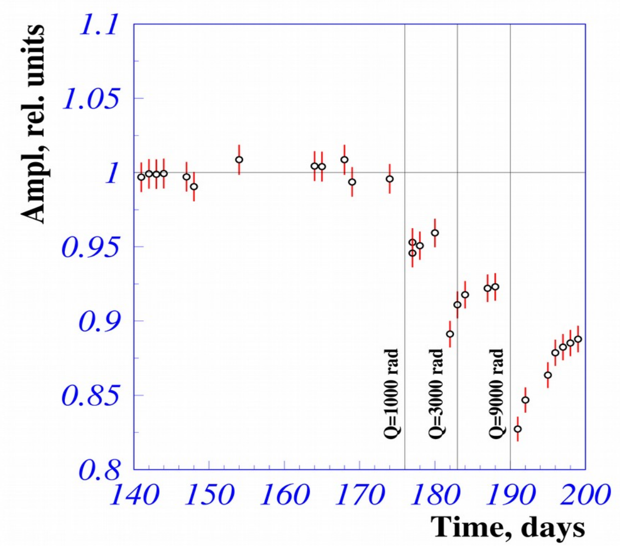
Study of radiation hardness of CsI(pure) crystals

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 $E_\gamma < 1.4$ 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**