Pure CsI calorimeter for Super C-Tau factory

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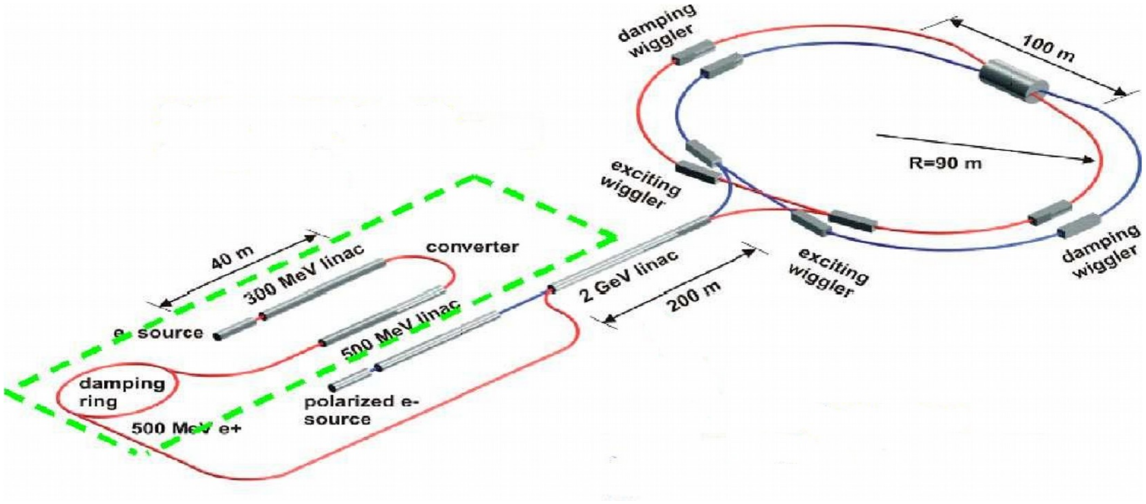
BINP, May 27th 2018



Outline:

- Introduction
- Calorimeters based on CsI(Tl), problems at Super Flavor factories
- Pure CsI endcap calorimeter for Belle II, photopentode/APD options
- Proposal of the calorimeter for Super C-Tau factory
- Summary

Introduction (I)

Large fraction of $\pi^0(\rightarrow\gamma\gamma)$ among the produced hadrons, necessity to reconstruct γ's in such golden modes as $\tau\rightarrow\mu\gamma$ requires a high resolution electromagnetic calorimeter, which detects γ's in the wide energy range: 10 MeV – 3 GeV

The main tasks for the calorimeter

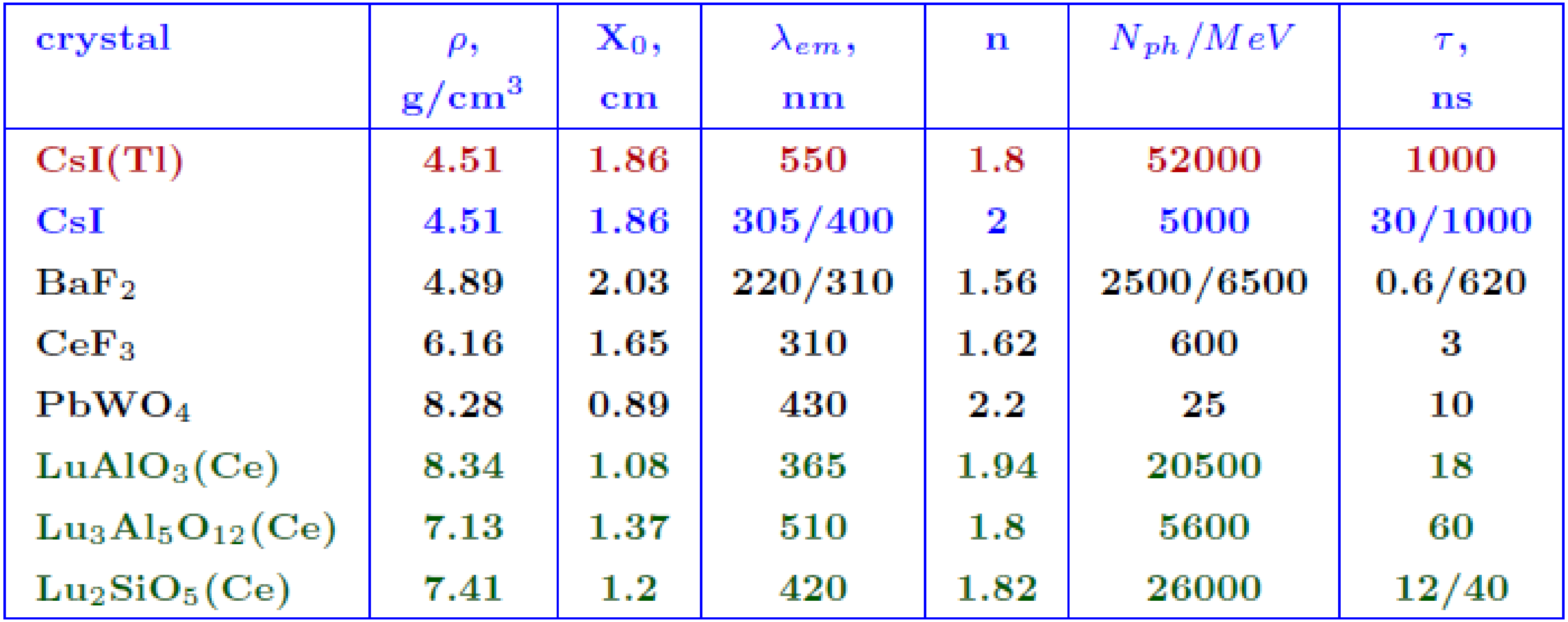
- **High efficiency detection of γ with good energy and coordinate resolutions**
- **Electron/hadron separation**
- **Provides signal for the trigger of the detector**
- **Online/offline luminosity measurement**

Full absorption calorimeter based on the fast scintillation crystals with large light yield (LY) is one of the main approaches

Requirements to the calorimeter

- Thick calorimeter to provide good energy resolution in the wide energy range: $(16 – 18)X_0$
- Minimize the passive material in front of the calorimeter: $< 0.1X_0$
- **Good time resolution to suppress beam background: < 1 ns**
- **Fast scintillator (small shaping time) to suppress pileup noise**

Introduction (II)

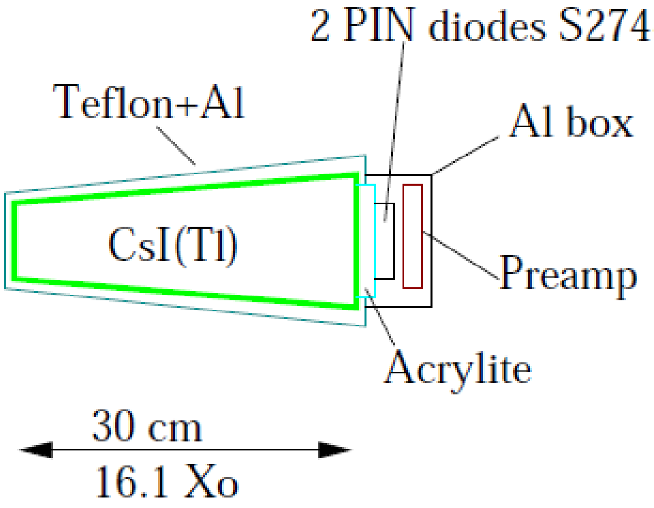


crystal	ρ, g/cm^3	X_0, cm	λ_{em}, nm	n	N_{ph}/MeV	τ, ns
CsI(Tl)	4.51	1.86	550	1.8	52000	1000
CsI	4.51	1.86	305/400	2	5000	30/1000
BaF_2	4.89	2.03	220/310	1.56	2500/6500	0.6/620
CeF_3	6.16	1.65	310	1.62	600	3
$PbWO_4$	8.28	0.89	430	2.2	25	10
$LuAlO_3(Ce)$	8.34	1.08	365	1.94	20500	18
$Lu_3Al_5O_{12}(Ce)$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

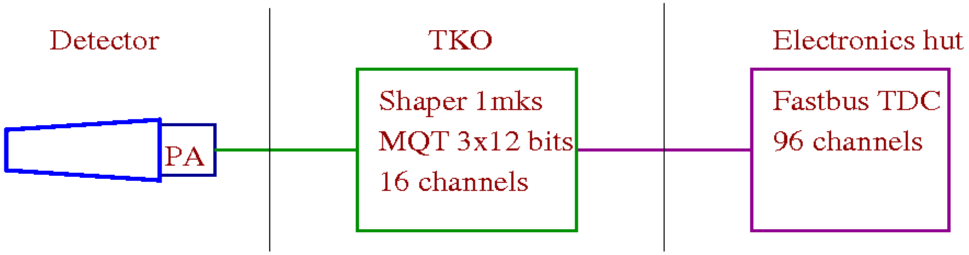
- CsI(Tl) has the largest LY, small scintillation decay time and modest price (~3$/cm^3). It is used in the electromagnetic calorimeters of modern particle detectors: Belle, Belle II, BaBar, BES-III, CMD-3.
- Lu_2SiO_5 (LSO), $LuAlO_3$, LYSO are also very good (and much faster than CsI(Tl)), however 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) → **attractive variant for the Super Flavor factories.**

Belle electromagnetic calorimeter (ECL)

- Calorimeter based on CsI(Tl) scintillating crystals
- Thickness – 16.1 X_0(30 cm)
- Calorimeter is inside magnetic coil
- CDC+ACC is about 0.3 X_0
- 8736 counters (40 tons of CsI(Tl))



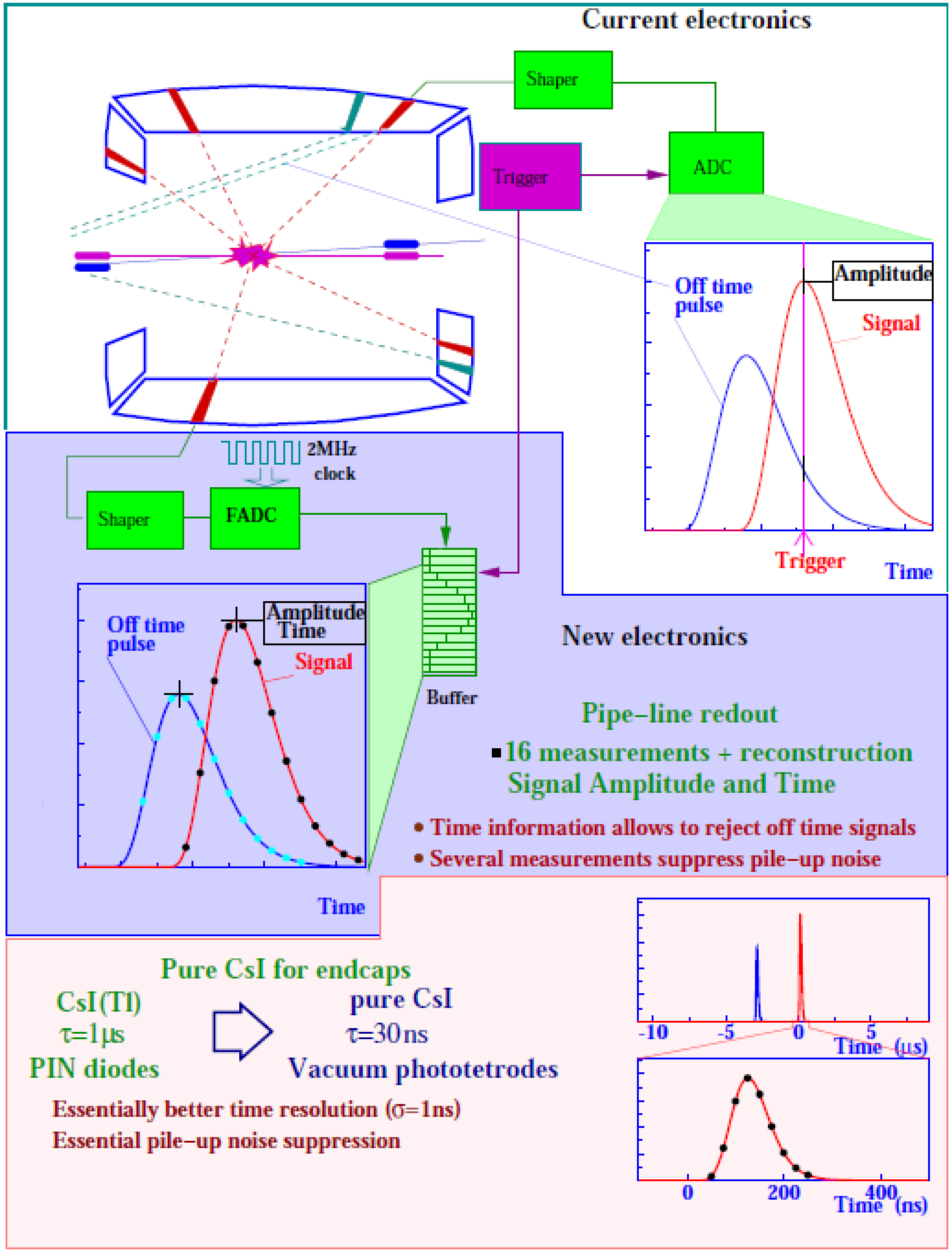
- Crystals 300x(50-80)x(50-80) mm
- Wrapping 200μm teflon+50 μm Al mylar
- Readout 2 10x20 mm PIN diodes
- 2 charge sensitive preamplifiers
- Shaper CR-(RC)^4, τ=1μs
- Lightoutput 5000 p.e./MeV
- Electronic noise 1000$e \approx$ 200 keV



$$\frac{\sigma_E}{E} = \sqrt{\left(\frac{0.066\%}{E}\right)^2 + \left(\frac{0.81\%}{\sqrt[4]{E}}\right)^2 + (1.34\%)^2} \approx 1.8\% (E = 1 GeV)$$

σ_x = 6 mm/√E(GeV)

Belle II ECL



Pipe–line redout

- 16 measurements + reconstruction Signal Amplitude and Time

- Time information allows to reject off time signals
- Several measurements suppress pile–up noise

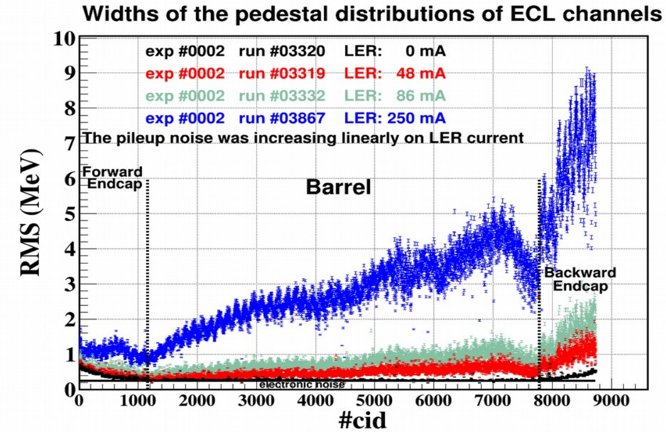
Pure CsI for endcaps

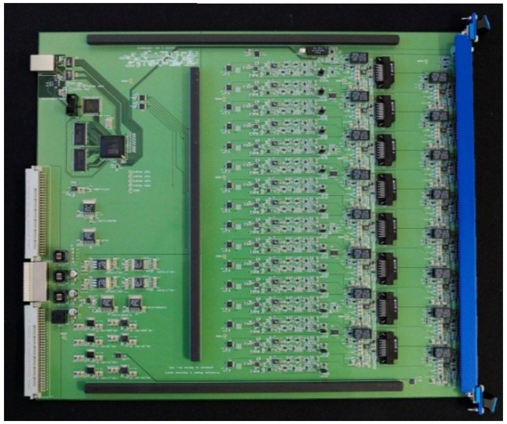
CsI(Tl) τ=1µs PIN diodes ⇨ pure CsI τ=30ns Vacuum phototetrodes

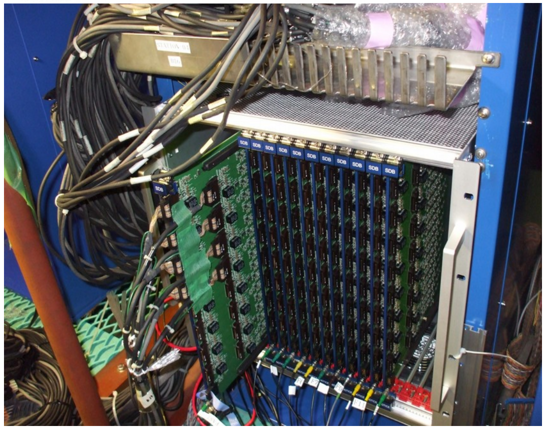
Essentially better time resolution (σ=1ns)

Essential pile–up noise suppression

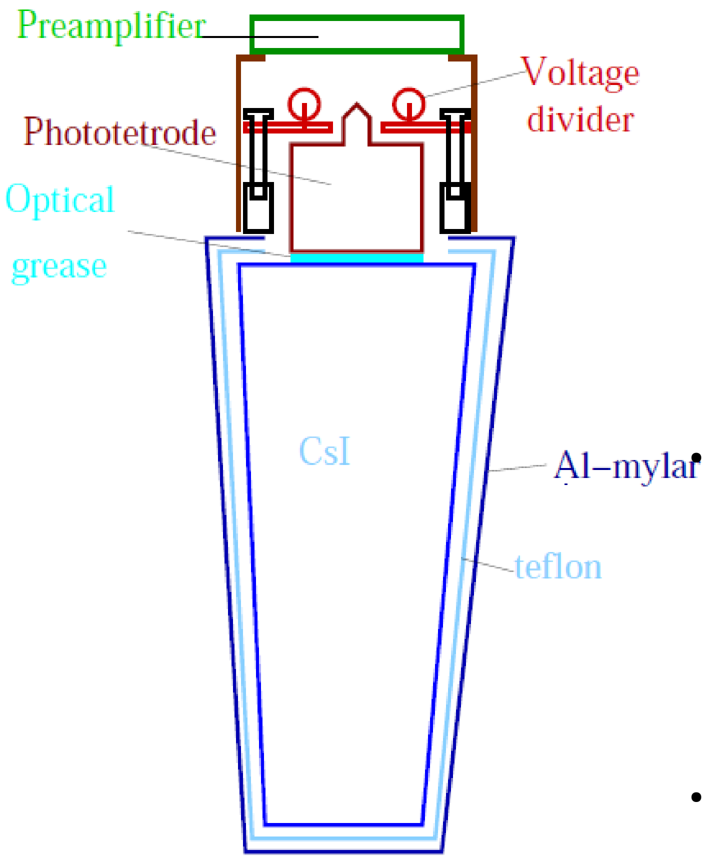
- Belle CsI(Tl) crystals are reused, new electronics with pipe-line readout and waveform analysis (in the 16 ch Shaper-DSP board) has been developed. It is successfully being exploited now at Belle II.
- At least at the first stage of the Belle II experiment endcap part (1152 + 960 channels) will be reused (with new preamplifiers and readout electronics).
- To decrease pileup noise by a factor of √(1000 ns/30 ns)=5.5 in the endcap ECL, CsI(Tl) crystals are planned to be changed to pure CsI crystals: $\sigma_{pileup}[MeV] = \bar{E}_\gamma \cdot \sqrt{\nu \cdot \tau}$

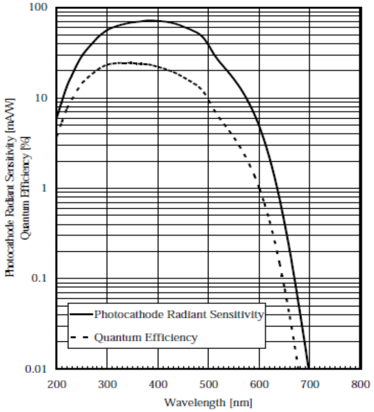






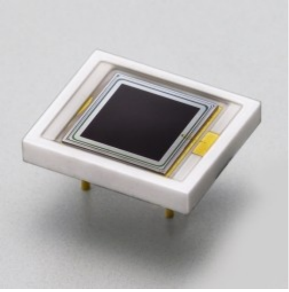
Belle II endcap ECL upgrade

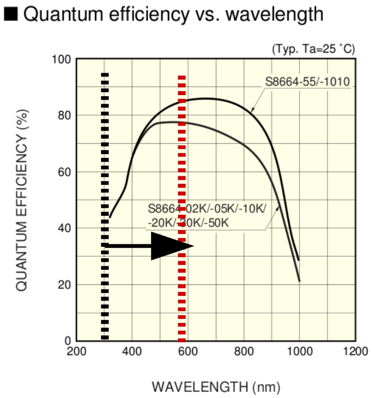




- **The main Belle II endcap ECL upgrade is to use CsI(pure) crystals and Hamamatsu photopentodes (PP) (dedicated R&D showed good results):**
  - Low pileup noise, good energy and spatial resolution
  - Similar physical characteristics (as for CsI(Tl)), better radiation hardness
  - There are several 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 is 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.**

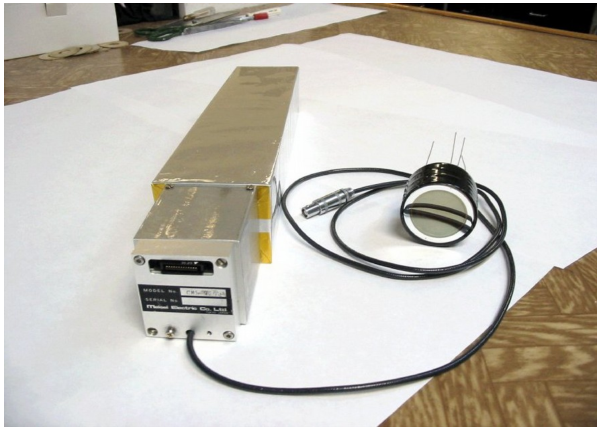
Hamamatsu APD S8664-55

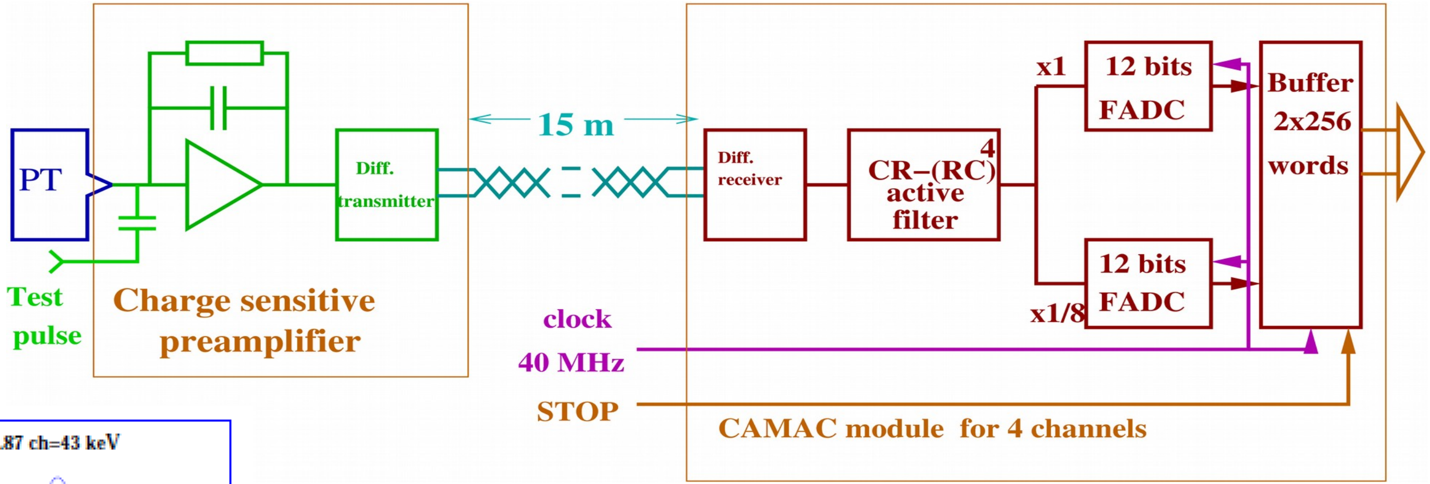


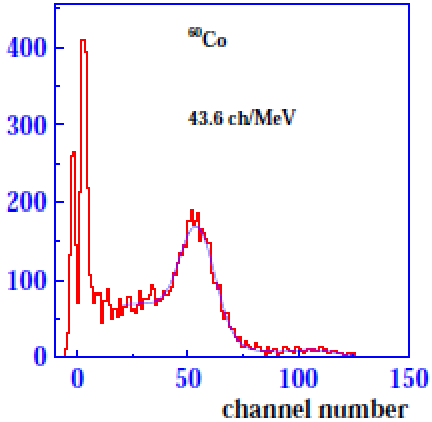


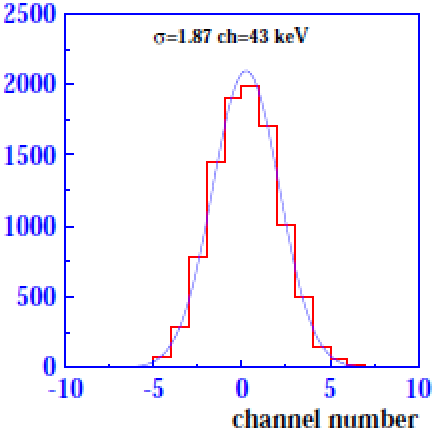
Super C-Tau factory workshop, May 27th, 2018

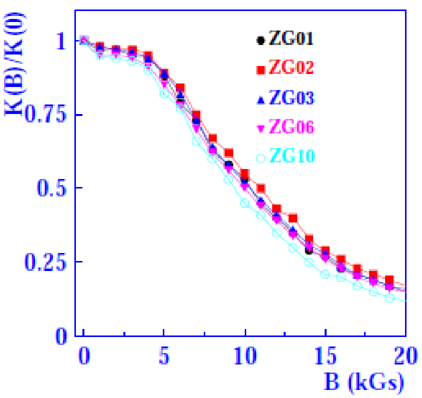
CsI(pure)+PP option (I)

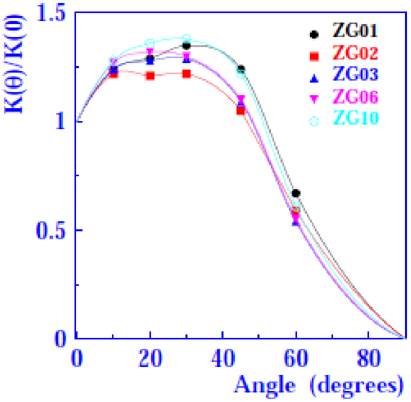




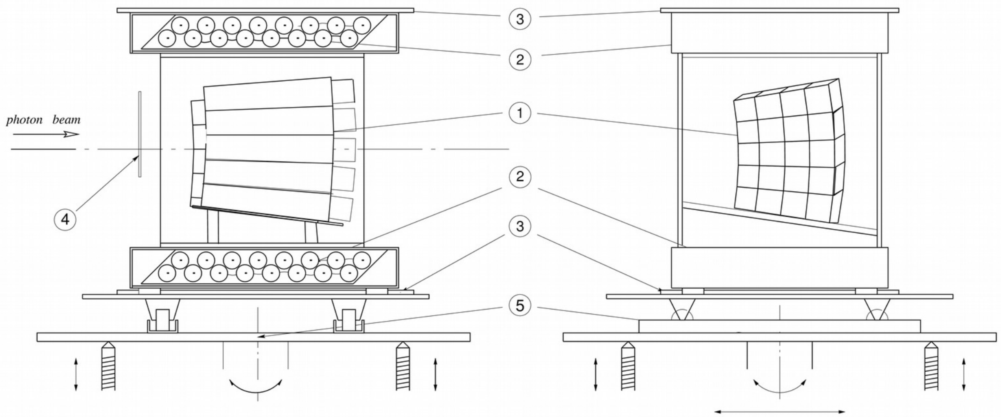




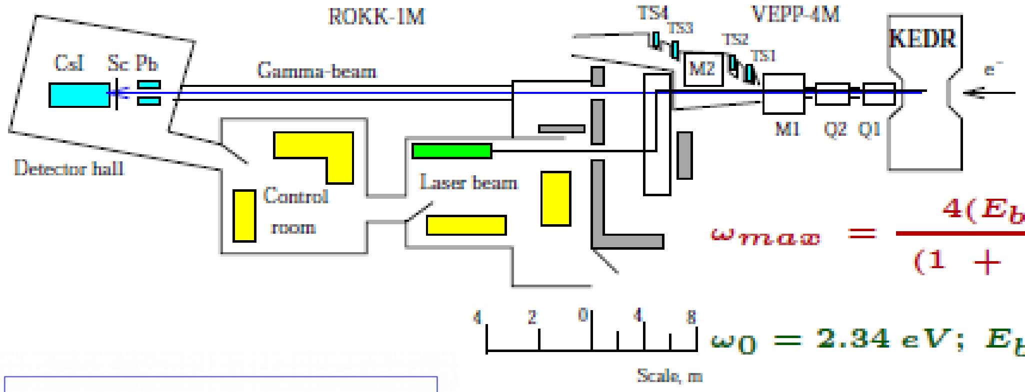


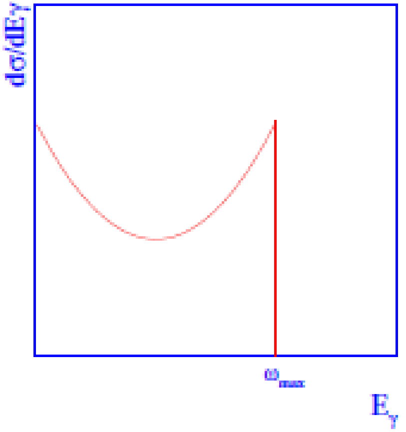


- **The ENE of the CsI(pure)+PP counter is about 50 keV without magnetic field**
- **Due to the drop of the signal in magnetic field of 1.5 T by a factor of ~3, the ENE = 150 keV for B = 1.5 T**
- Prototype was constructed from 20 counters (of 8 geometrical types from FWD ECL). Each counter was based on CsI(pure) crystal (of AMCRYS prod.) and Hamamatsu phototetrode:



CsI(pure)+PP option (II)

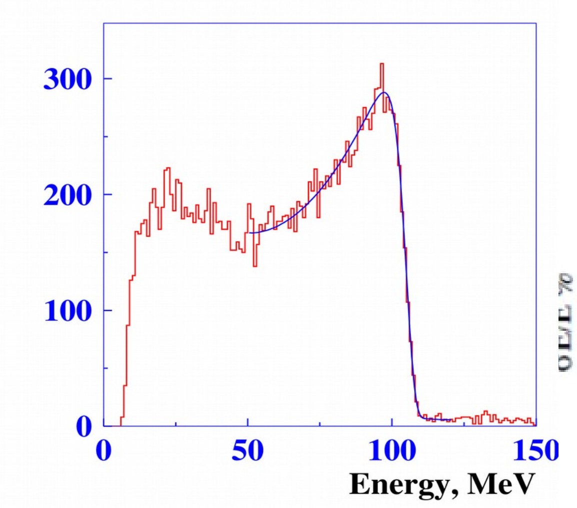


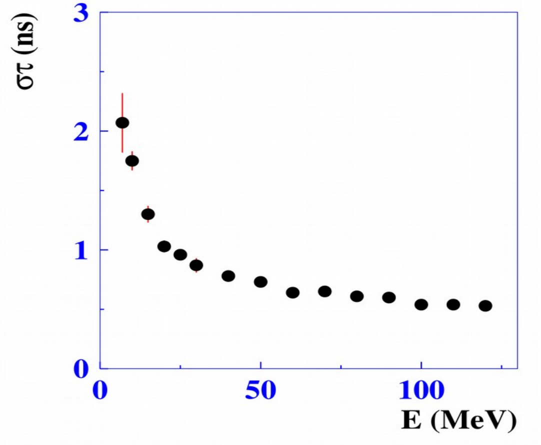


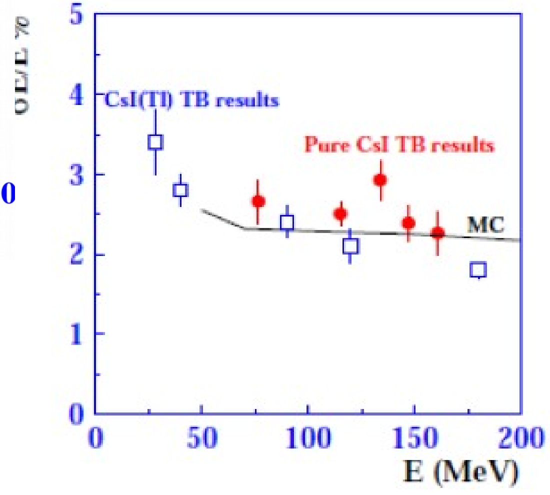
$$\omega_{max} = \frac{4(E_{beam}/m_e)^2\omega_0}{(1 + 4E_{beam}\omega_0/m_e^2)}$$

$$\omega_0 = 2.34\ eV;\ E_{beam} = 1.5 \sim 2.2\ GeV;$$

$$\omega_{max} = 70 \sim 160\ MeV$$







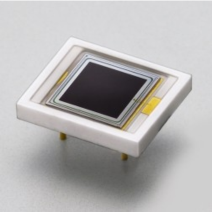
- Energy resolution is obtained from the fit of the edge of the experimental energy distribution by Compton spectrum convoluted with Log-normal function. **It is in good agreement with MC expectation and the resolution obtained with CsI(Tl) based prototype.**
- **Waveform analysis allows us to reach the time resolution of 1 ns for the gamma energies > 20 MeV (60 MeV in magnetic field)**
- Long-term stability, studied with two counters during ~2 years, was found to be better than 2%.
- No essential degradation of the photopentode after absorption of the charge of 140 C

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})**

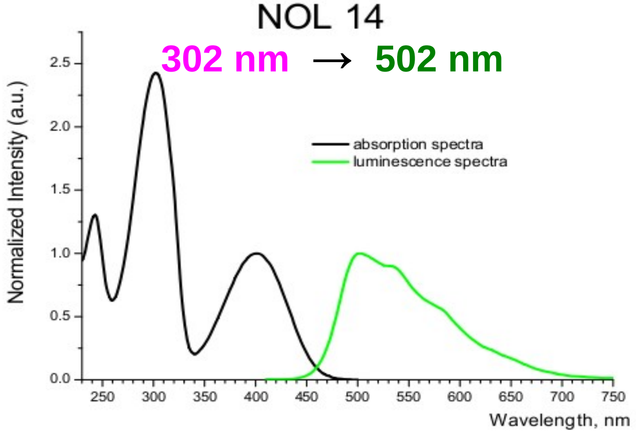


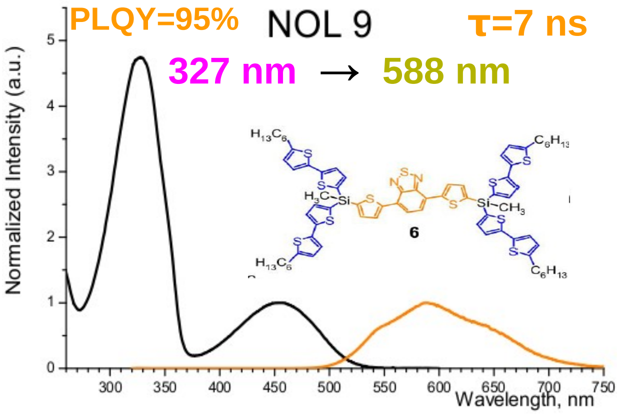
We chose the configuration: CsI(pure) + WLS(nanostructured organosilicon luminophores) + 4APD (Hamamatsu S8664-55)

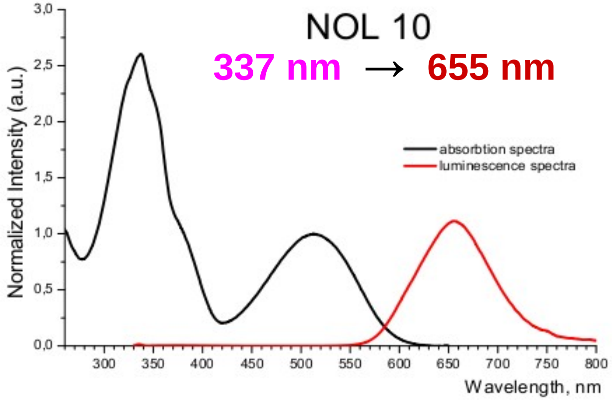
CsI(pure) + WLS + 4APD option (II)

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.

Based on the nanostructured organosilicon luminophores (NOL-9,10,14) from **LumInnoTech Co.**, the WLS plates were developed ((60 x 60 x 5) mm^3).

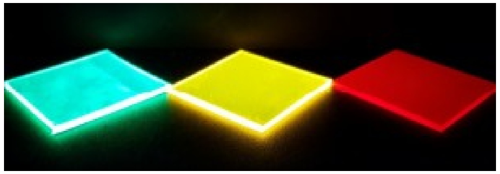




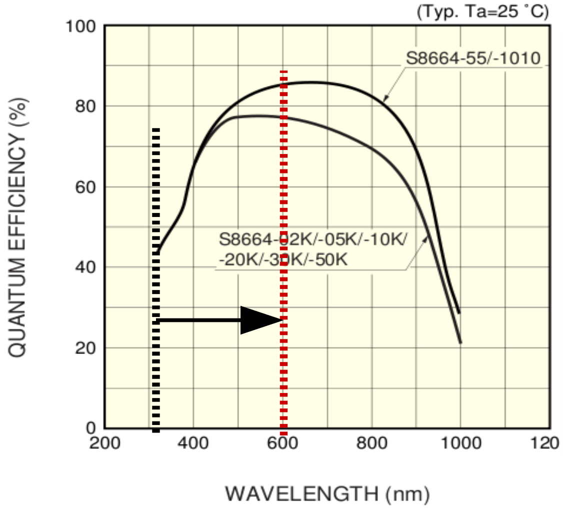


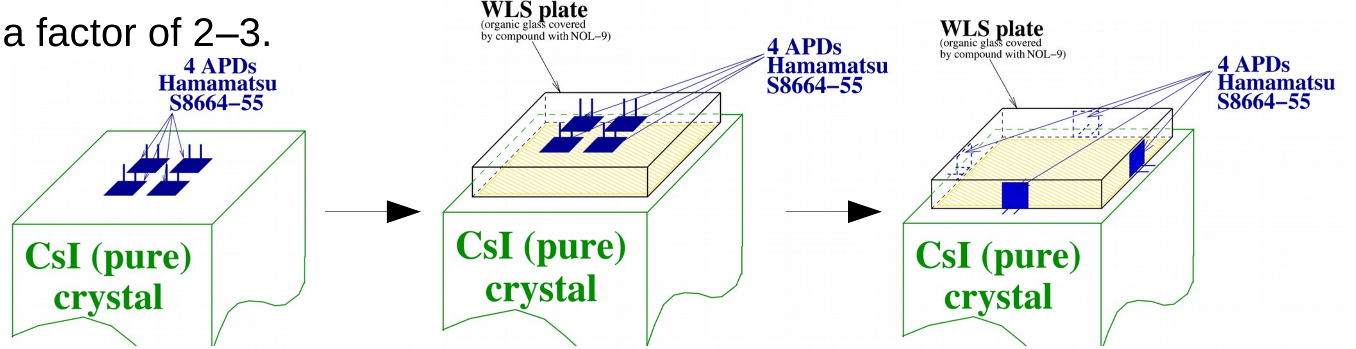
The absorption and emission spectra of these NOL's match our needs very well (**λ_{CsI} = 320 nm**).

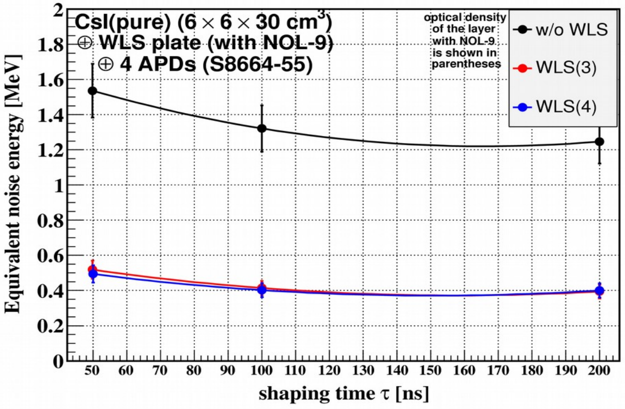
The improvement of the APD QE is by a factor of 2–3.

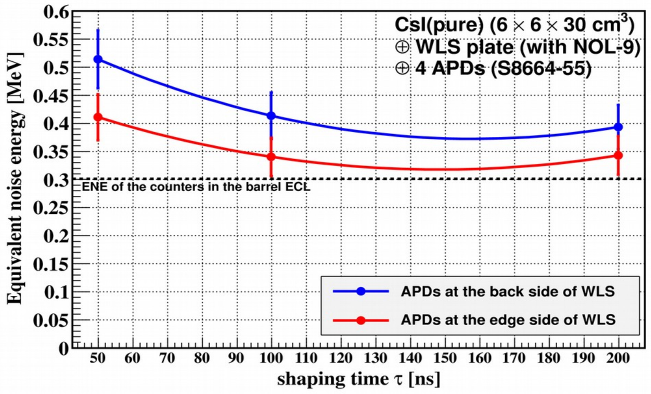


■ Quantum efficiency vs. wavelength

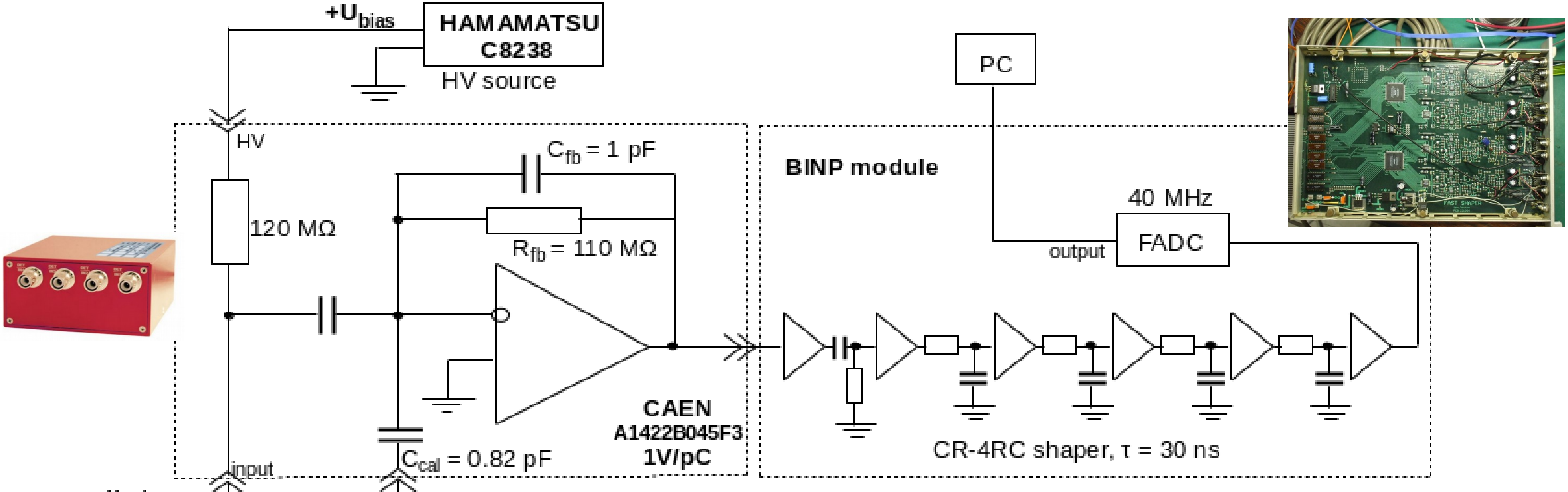


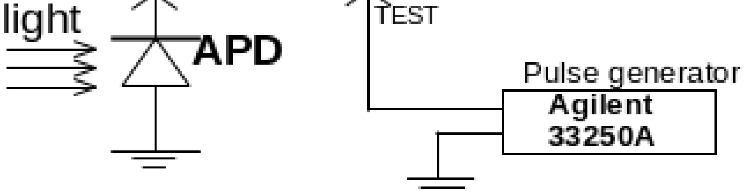




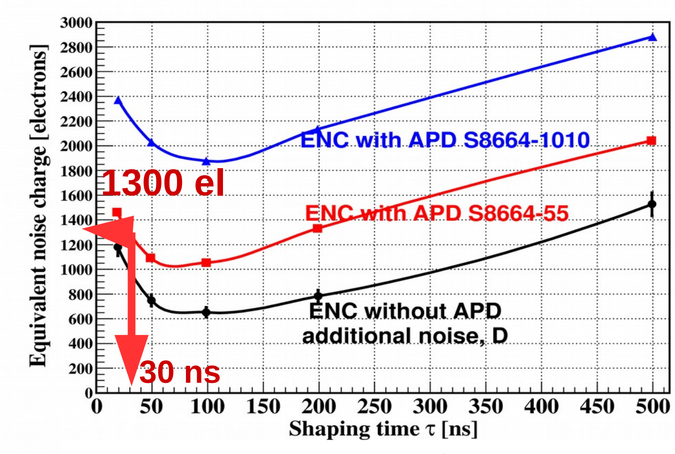


CsI(pure) + WLS + 4APD option (III)



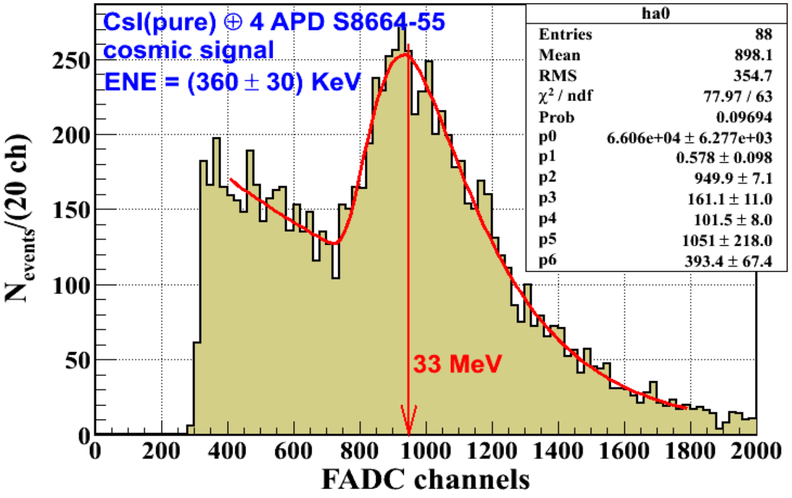


gain(APD) = 50



$$ENC^2 = \frac{2I_d K g F \tau}{e} + (\frac{B^2}{\tau} + E^2)C^2 + D^2$$

Shot noise *Thermal noise* *Additional noise*

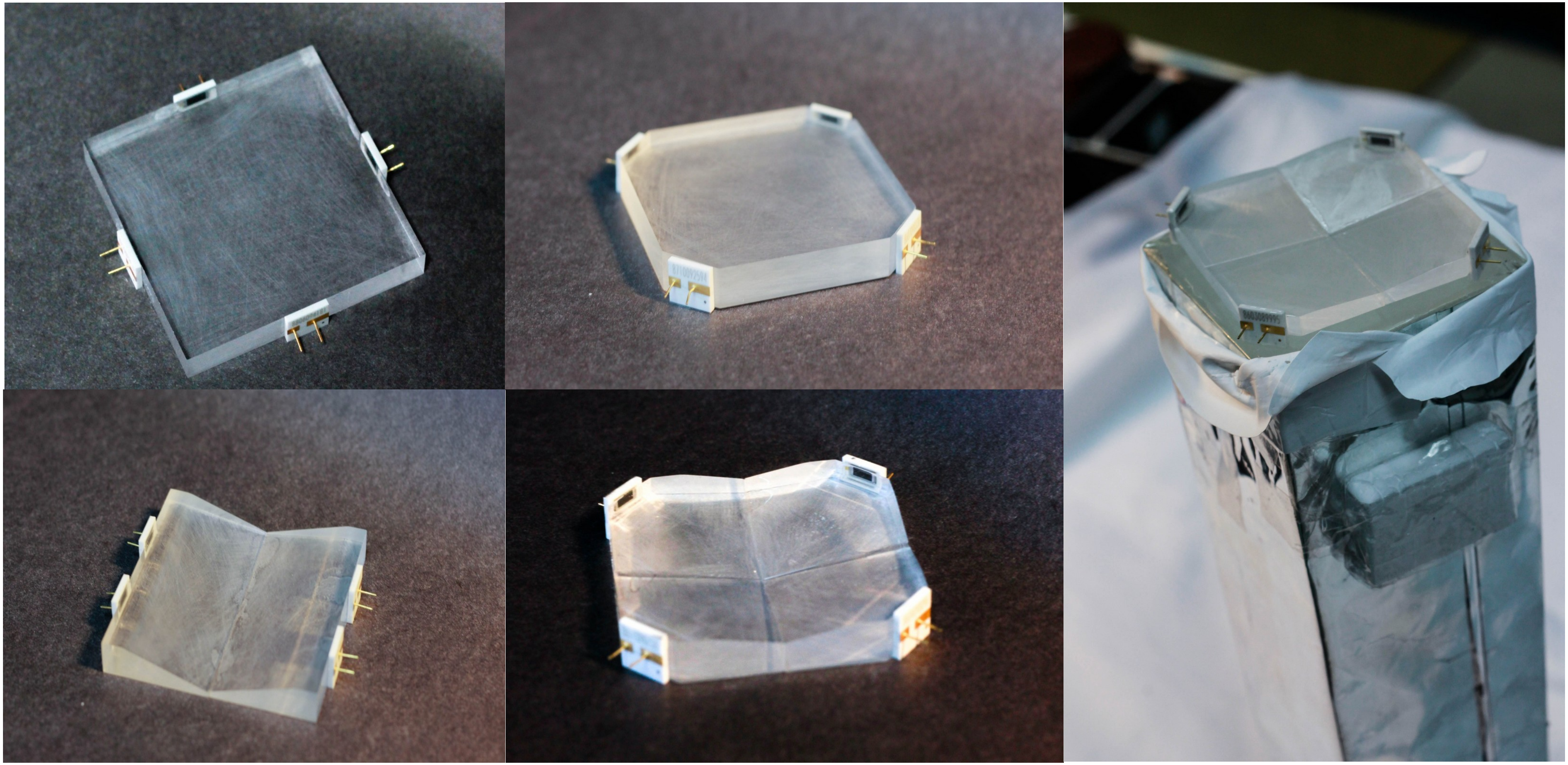


We are developing 4-channel preamplifier

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

Optimization of the shape of the WLS plate was done, signal improvement of 1.6 was achieved

BC-600 optical epoxy resin is used to glue APDs



The achieved light output of the counter is 160 ph.el./MeV

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

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

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

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

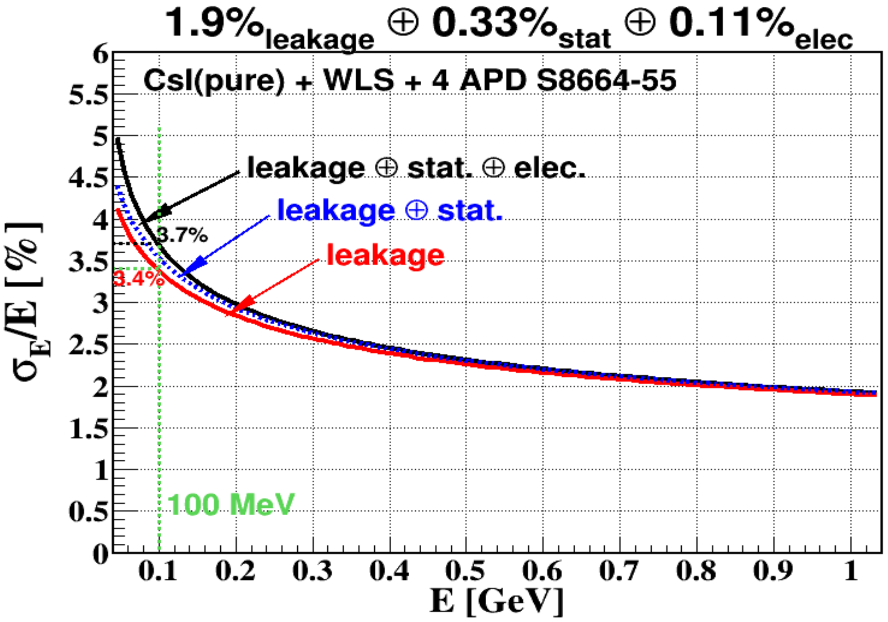
$$Elec = 100\% \cdot \frac{ENE[MeV] \cdot \sqrt{N_{crys}}}{1000}$$

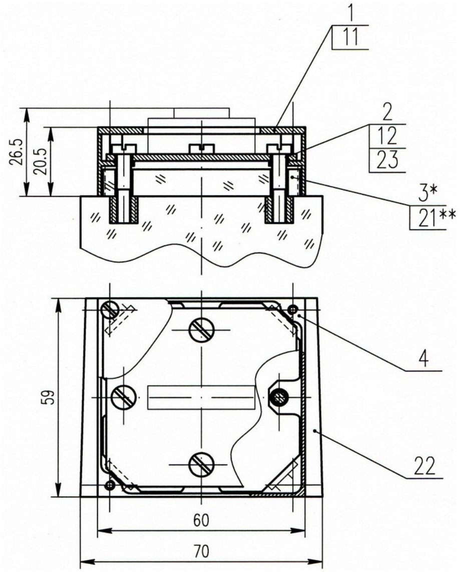
F = 1.69 ± 0.04

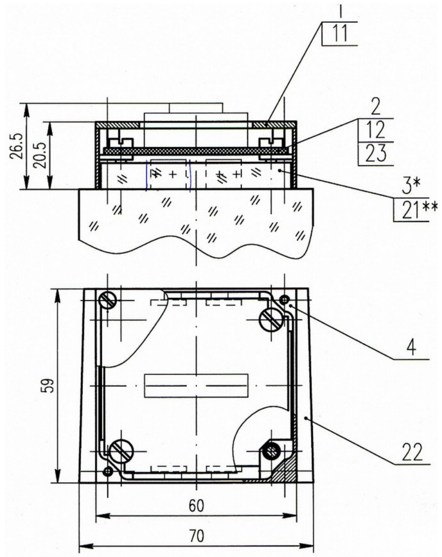
$S \cdot N_{APD}$ = (160 ± 9) ph.el./MeV

ENE = (0.33 ± 0.03) MeV

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

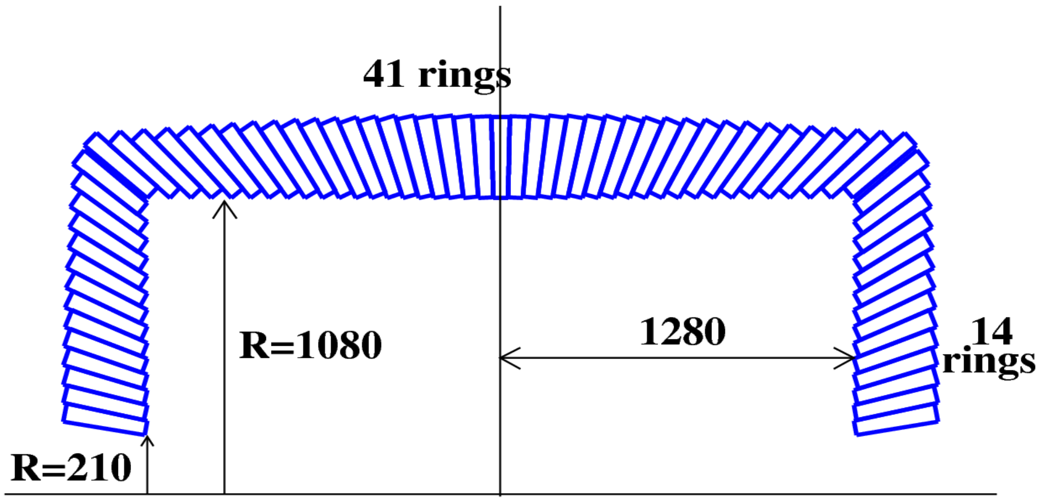


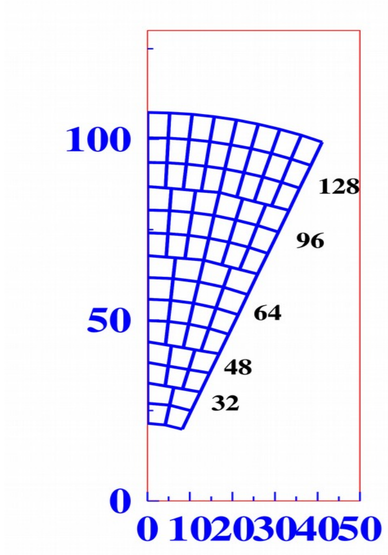




Plan to construct the calorimeter prototype (16 counters) and perform beam tests

Super C-Tau calorimeter layout

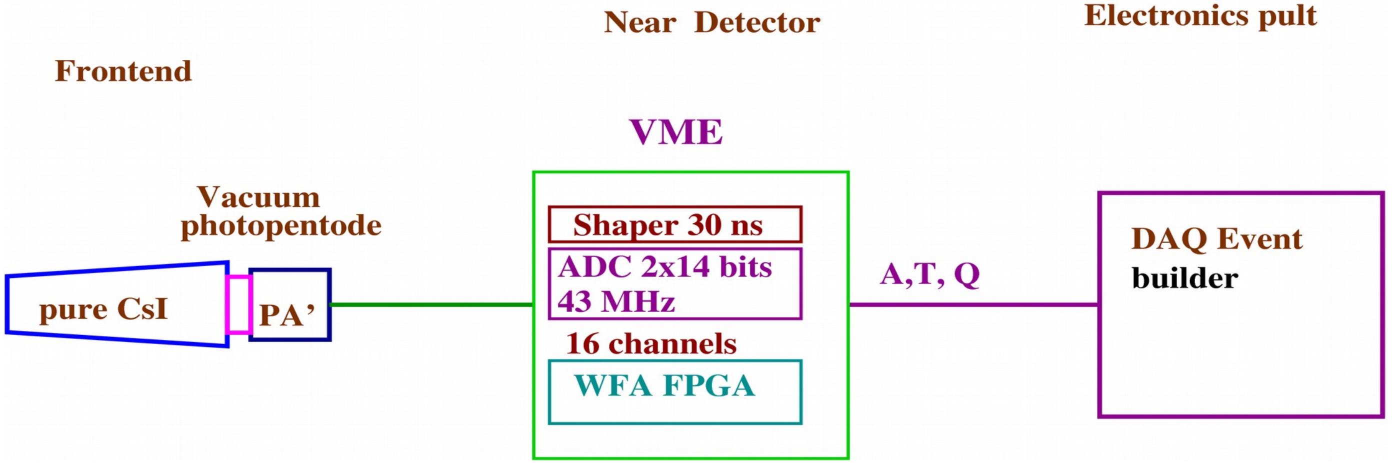




68 counters in 1 sector

- **Crystal of truncated pyramidal form (small facet ~(5.5 x 5.5) cm^2) with the length of 30/34 cm (16/18 X_0)**
- **The barrel part includes 5248 counters = 41 θ-rings x 128 counters, total weight is 26/31 tons**
- **Two endcap parts: 2 x 16 sectors x 68 = 2 x 1088 = 2176 counters, total weight is 10/12 tons**
- **The whole calorimeter: 7424 counters with the total weight of 36/43 tons → 40/47 M$**
- **Photopentodes: 7424 → 7 M$**
- **Electronics: 7424 → 4 M$**
- **Total price: 51/58 M$ (16X_0 / 18X_0)**

Super C-Tau calorimeter electronics



Near Detector

Electronics pult

Frontend

VME

Vacuum photopentode

pure CsI

PA’

Shaper 30 ns

ADC 2x14 bits 43 MHz

16 channels

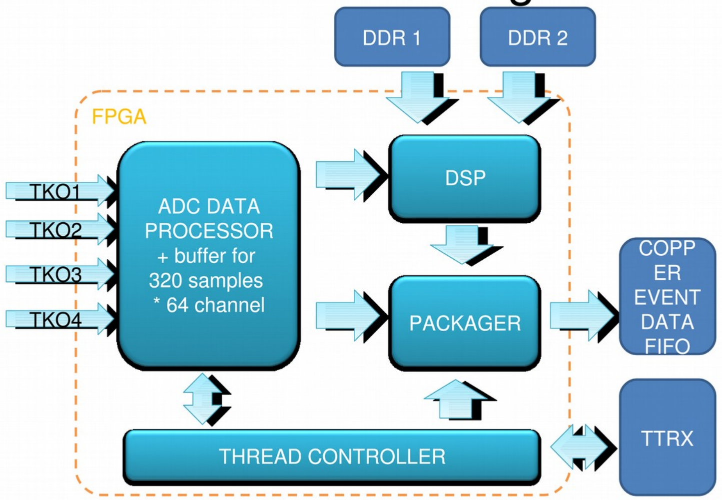
WFA FPGA

A,T, Q

DAQ Event builder

- 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 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

FPGA overall design



DDR 1

DDR 2

FPGA

TKO1

TKO2

TKO3

TKO4

ADC DATA PROCESSOR + buffer for 320 samples * 64 channel

DSP

PACKAGER

COPPER EVENT DATA FIFO

THREAD CONTROLLER

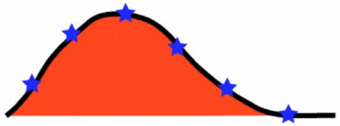
TTRX

Algorithm details

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

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

$f(t)$ – counter response



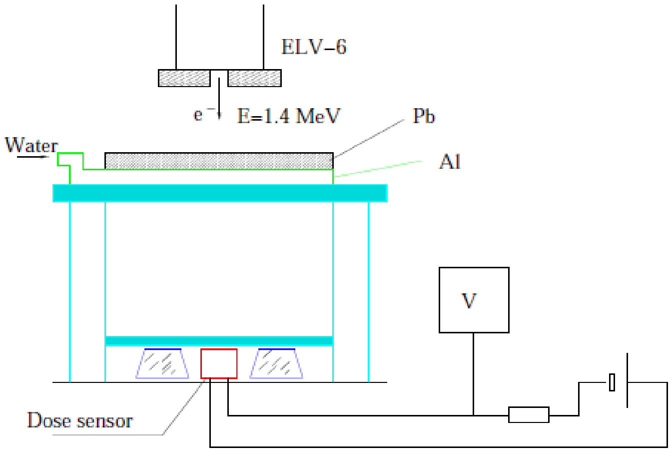
$$Af\left(t_i-t_1-\Delta t\right)=Af\left(t_i-t_1\right)-A\Delta t f'\left(t_i-t_1\right)=Af\left(t_i-t_1\right)+Bf'\left(t_i-t_1\right)$$

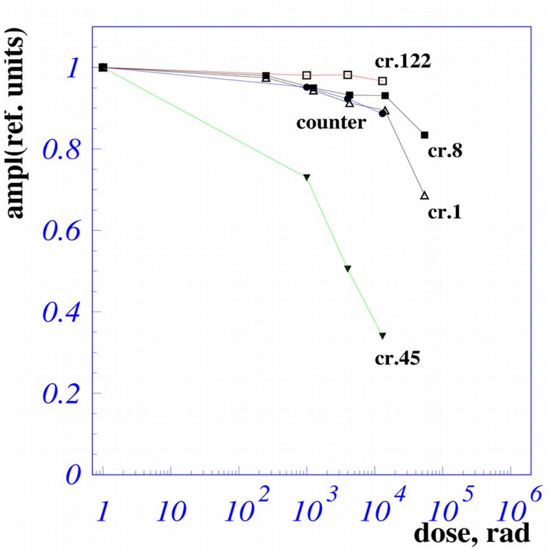
where t_1 – initial time (trigger time)

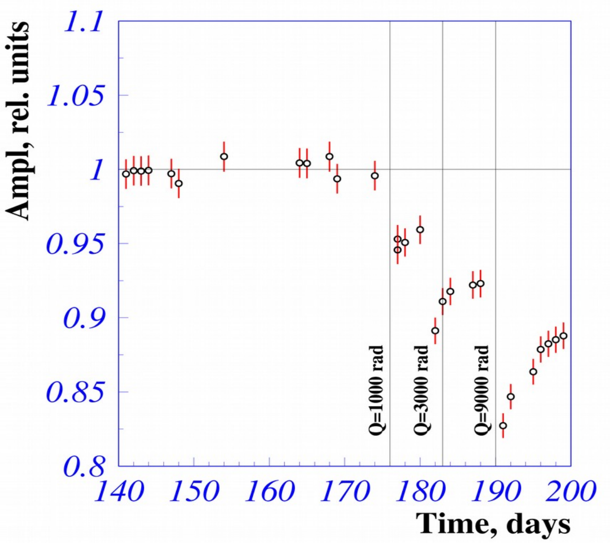
$$\left\{\begin{aligned}&\sum_{i,j} f_i S_{ij}^{-1}\left(y_j-Af_j-Bf_j'-p\right)=0\\&\sum_{i,j} f_i' S_{ij}^{-1}\left(y_j-Af_j-Bf_j'-p\right)=0\\&\sum_{i,j} S_{ij}^{-1}\left(y_j-Af_j-Bf_j'-p\right)=0\end{aligned}\right. \quad\Rightarrow\quad \begin{aligned}&A=\sum_i \alpha_i y_i\\&B=\sum_i \beta_i y_i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

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**

Summary

- CsI(pure) is appropriate material for the calorimeter of the Super C-Tau factory
- The main option is CsI(pure)+photopentode. Beam tests of the prototype showed good energy and spatial resolutions, as well as essential suppression of the pileup noise
- The pipeline readout with on-board waveform analysis (implemented at Belle II) will provide good time resolution (to suppress beam background) and ability to work at high occupancies (up to 30 kHz)
- The second option: CsI(pure)+WLS+4APDs is under development. The problems of the low LO and high ENE have been solved. We are on the way to construct the prototype and perform beam tests