Pure CsI calorimeter for Super C-Tau factory

A. Kuzmin/D.Epifanov
(BINP, NSU)

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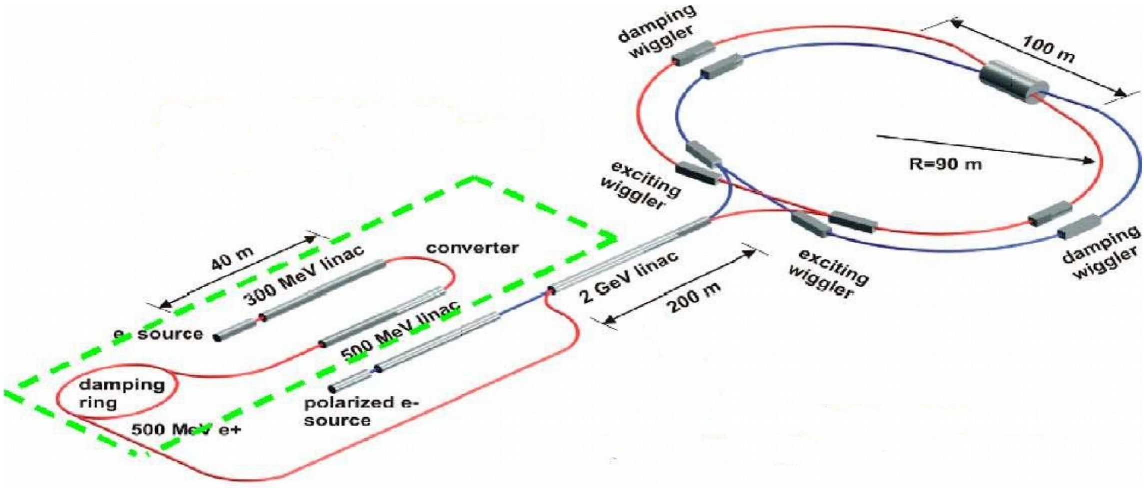


Outline:

- 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
- Current status of R&D
- Summary

The main tasks for the calorimeter

- **High efficiency detection of γ with good energy and position resolutions**
- **Electron/hadron separation**
- **Signal for neutral trigger**
- **Online/offline luminosity measurement**

-Low energy γ from radiation transitions
-intermediate energies γ from $\pi^0(\rightarrow\gamma\gamma)$ decay
-high energy photons from golden modes as $\tau\rightarrow\mu\gamma$, ee->γγ
Energy range: 10 MeV – 3 GeV

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**
- **Good time resolution to suppress beam background: < 1 ns**
- **Fast scintillator (small shaping time) to suppress pileup noise**
- **Minimize the passive material in front of the calorimeter: < 0.1X_0**

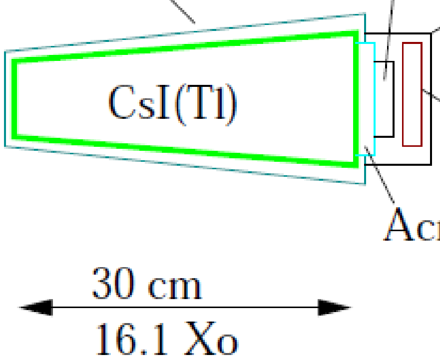
Scintillatimg crystals

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

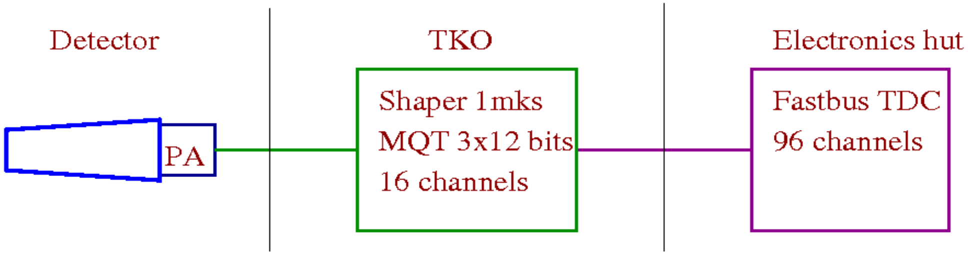
- CsI(Tl) has the largest LY, reasonable scintillation decay time and modest price (~3\$/cm^3). It is used in the electromagnetic calorimeters of modern particle detectors: Belle, Belle II, BaBar, BES-III, CMD-3.
- Lu_2SiO_5 (LSO), $LuAlO_3$, LYSO are also very good (and much faster than CsI(Tl)), however 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). There are several crystal-growing companies which are able to produce necessary number of large size crystals (~40 tons): AMCRYS(Ukraine), Saint Gobain (France), HPK (Japan-China), SICAS(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))



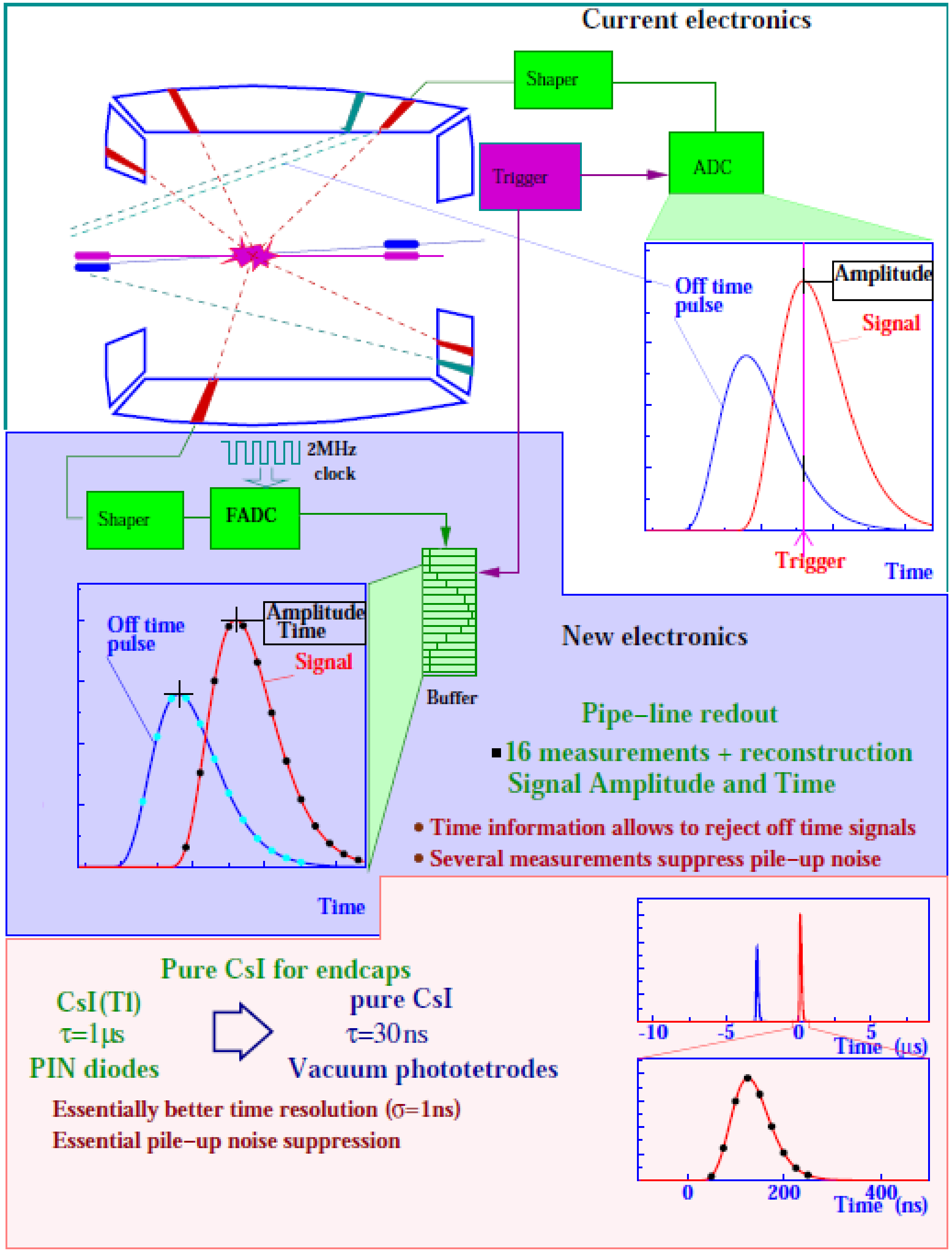
- Crystals 300x(50-80)x(50-80) mm
- Wrapping 200μm teflon+50 μm Al mylar
- Readout 2 10x20 mm PIN diodes
- 2 charge sensitive preamplifiers
- Shaper CR-(RC)^4, τ=1μs
- Lightoutput 5000 p.e./MeV
- Electronic noise 1000$e \approx$ 200 keV



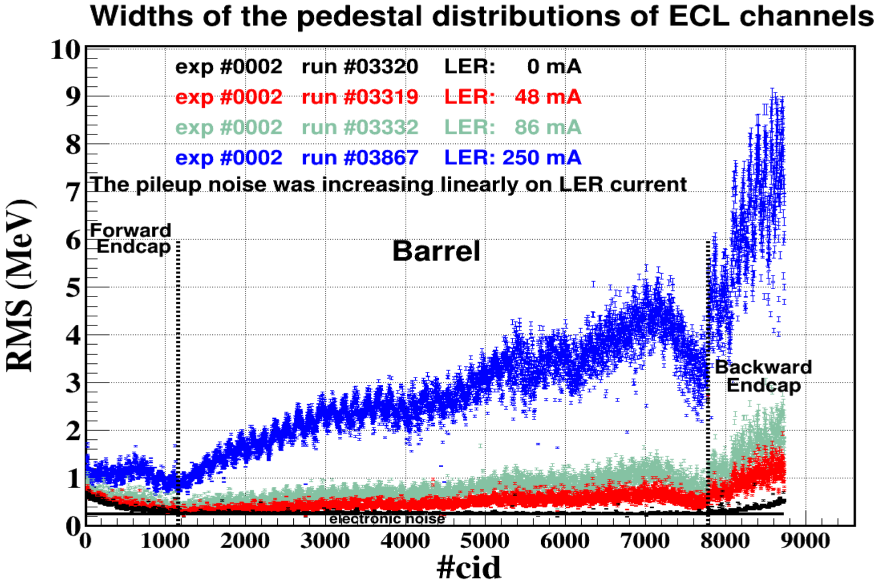
$$\frac{\sigma_E}{E} = \sqrt{\left(\frac{0.066\%}{E}\right)^2 + \left(\frac{0.81\%}{\sqrt[4]{E}}\right)^2 + (1.34\%)^2} \approx 1.8\% (E = 1 GeV)$$

$$\sigma_x = 6\ mm/\sqrt{E(GeV)}$$

Belle II ECL

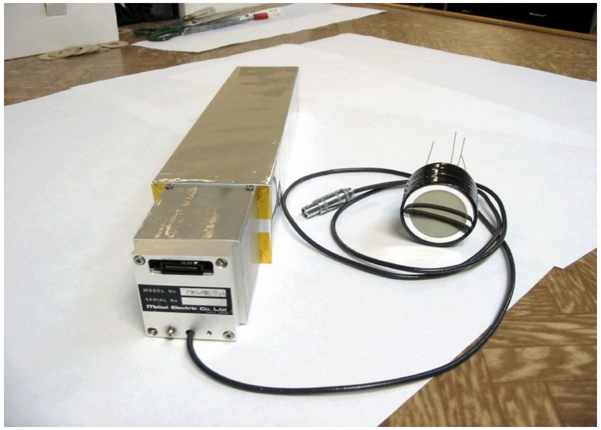


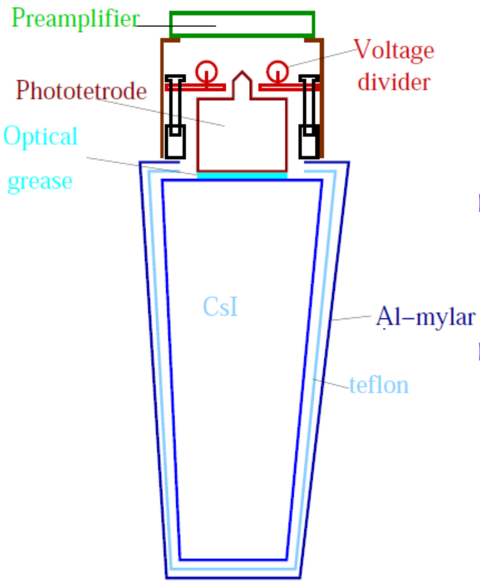
- **CsI(Tl) crystals, PIN diodes and preamplifiers are kept from Belle.**
- **New electronics with pipe-line readout and waveform analysis**
- **In case too large noise, endcaps (or part of endcaps) can be replaced by pure CsI crystals.**

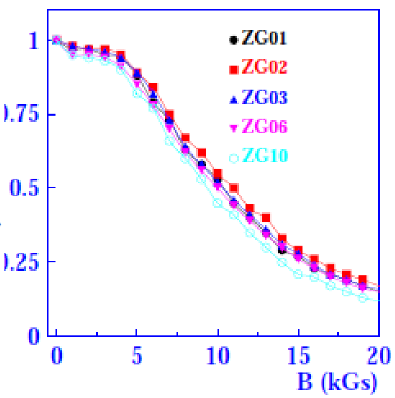


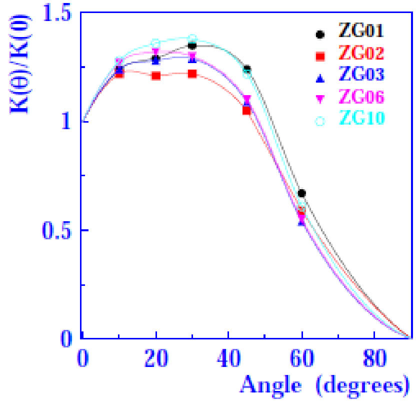
CsI(pure)+PP option

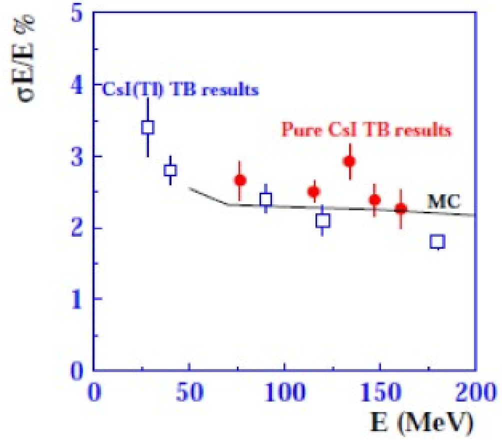
- **The main stream pure CsI endcap ECL upgrade is to use Hamamatsu photopentodes (PP) (dedicated R&D showed good results.**



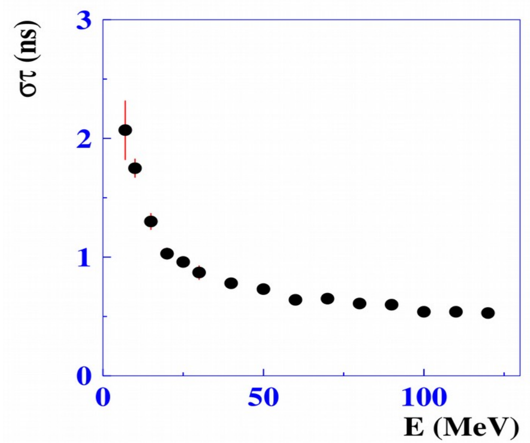




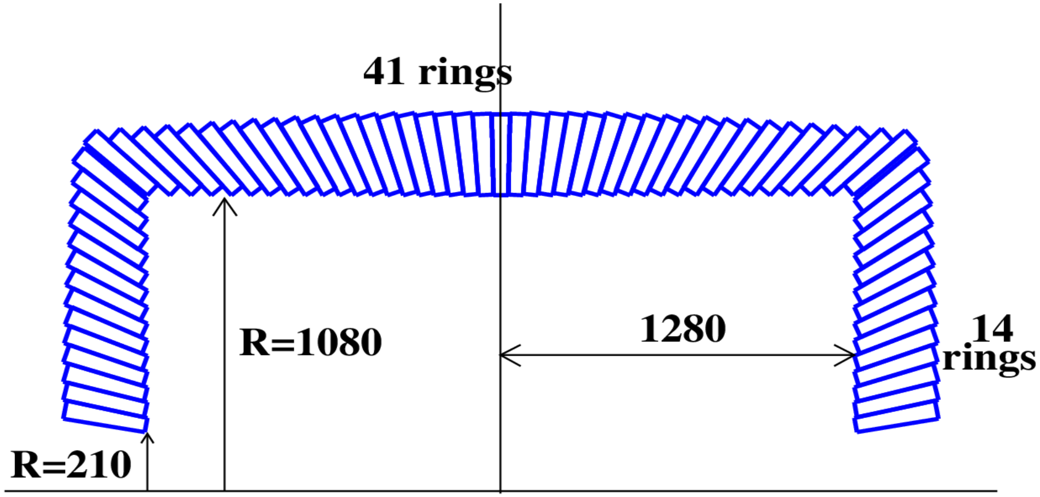


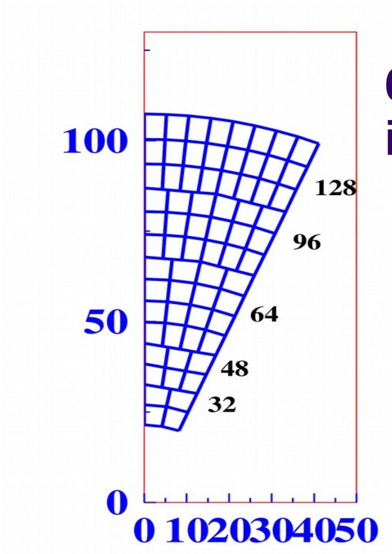


- **The ENE of the CsI(pure)+PP counter is about 50 keV without magnetic field**
- **Due to the drop of the signal in magnetic field of 1.5 T by a factor of ~3, the ENE = 150 keV for B = 1.5 T**
- **Prototype was constructed from 20 counters (of 8 geometrical types from FWD ECL). Each counter was based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



Super C-Tau calorimeter layout





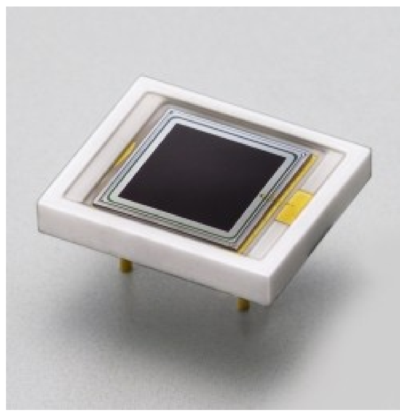
68 counters in 1 sector

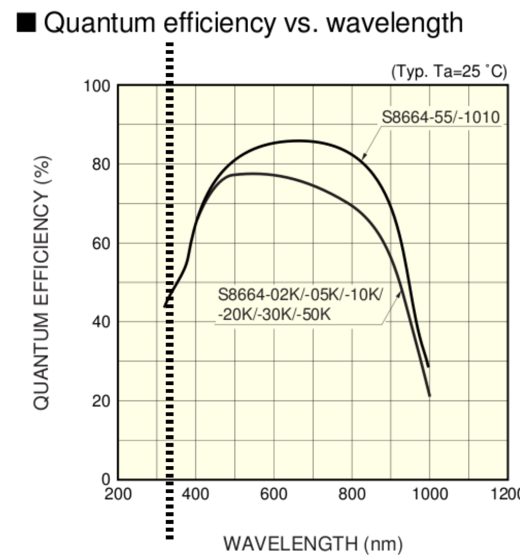
- Crystal of truncated pyramidal form (small facet ~(5.5 x 5.5) cm^2) with the length of **30/34 cm (16/18 X_0)**
- The barrel part includes 5248 counters = 41 θ-rings x 128 counters, total weight is **26/31 tons**
- Two endcap parts: 2 x 16 sectors x 68 = 2 x 1088 = 2176 counters, total weight is **10/12 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)**

CsI(pure)+APD option

- **There are some problems: no redundancy, strong dependency on magnetic field, complex mechanical design.**
- **To solve these difficulties second R&D option was developed: CsI(pure) + Si APD. Hamamatsu APD: S8664-1010 and S8664-55.**

Hamamatsu APD S8664-55





- **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 degrades the energy resolution of the calorimeter (σ_E/E (100 MeV) ≈ 8%).**

CsI(pure)+APD option

- **The reason of the small LO:**

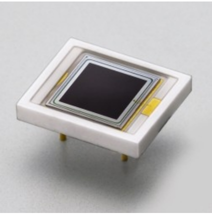
  -small sensitive area of APD (1/36 of the area of the crystal facet),

  -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).**

  To get ENE < 0.4 MeV → σ_E/E (100 MeV) = 3.7% (3.4% from the fluctuations of the shower leakage) → LO ≥ 150 ph.el./MeV.

- **Possible 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 cm², 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})**

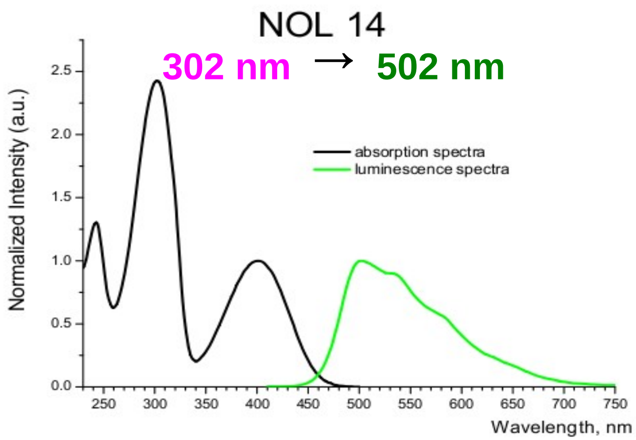


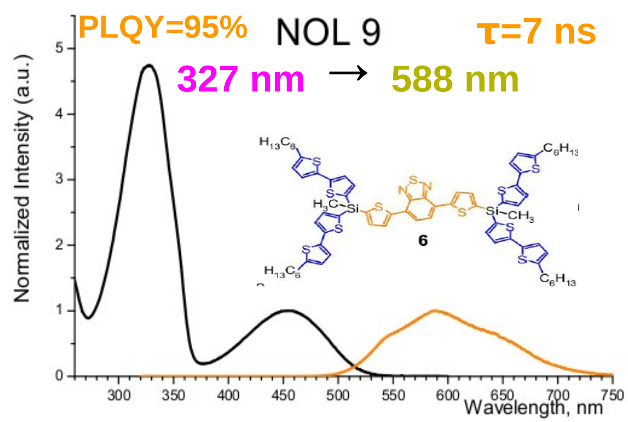
We chose the configuration: CsI(pure) + WLS(nanostructured organosilicon luminophores) + 4APD (Hamamatsu S8664-55)

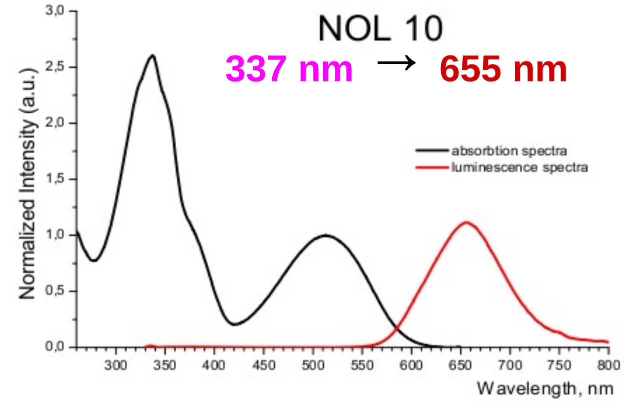
CsI(pure) + WLS + 4APD option (II)

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).

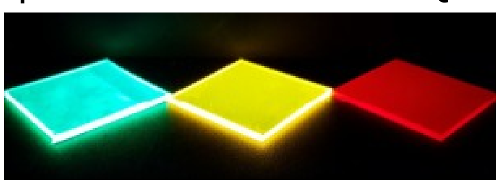


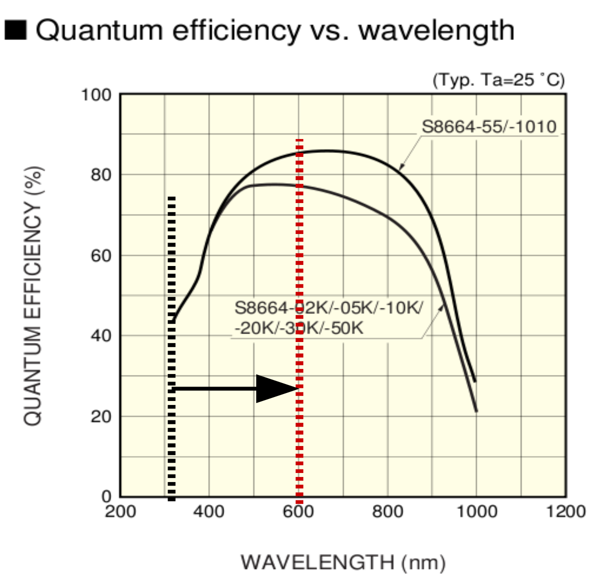


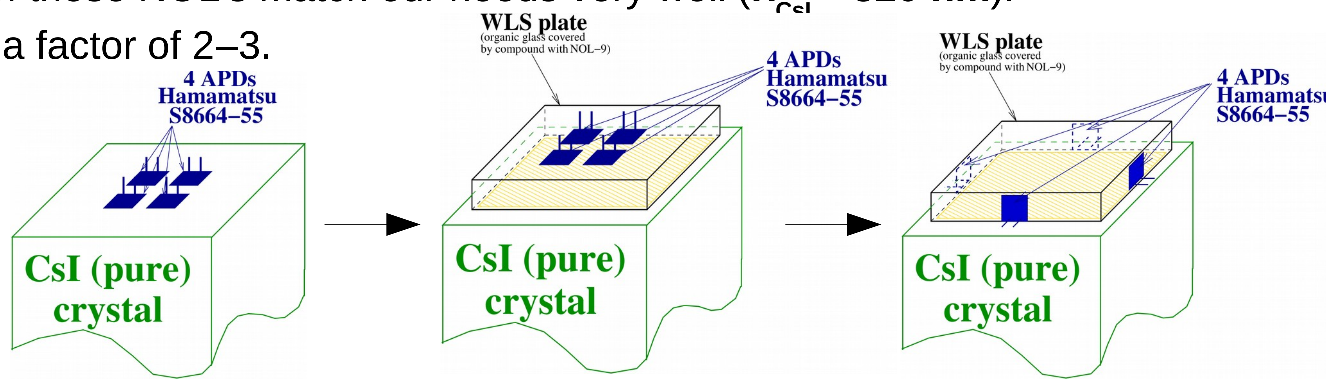


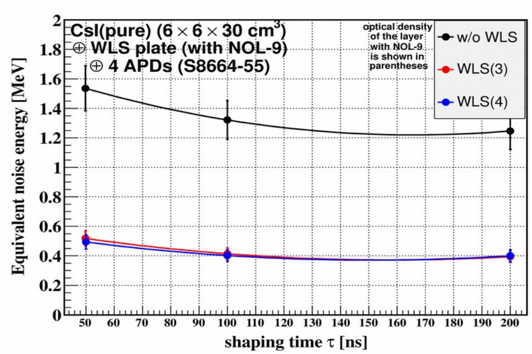
The absorption and emission spectra of these NOL's match our needs very well (**λ_{CsI} = 320 nm**).

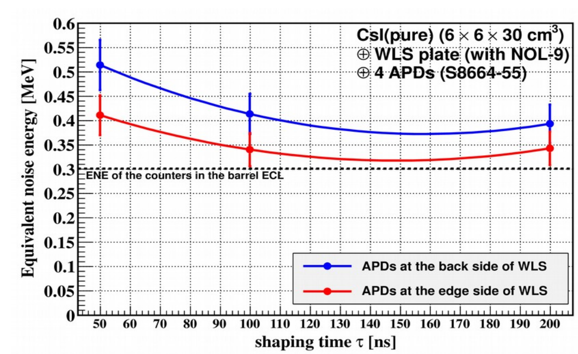
The improvement of the APD QE is by a factor of 2–3.











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

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

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

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

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

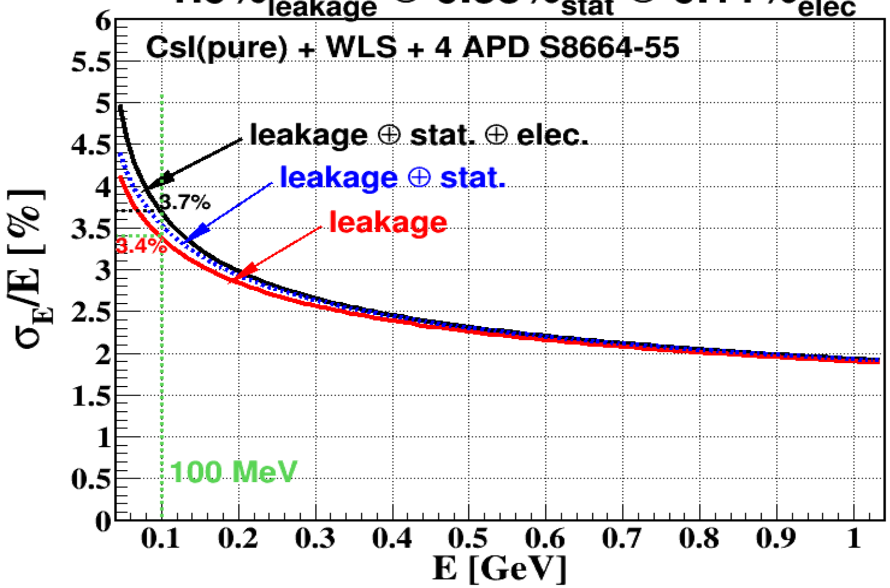
F = 1.69 ± 0.04

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

ENE = (0.33 ± 0.03) MeV

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

$1.9\%_{leakage} \oplus 0.33\%_{stat} \oplus 0.11\%_{elec}$



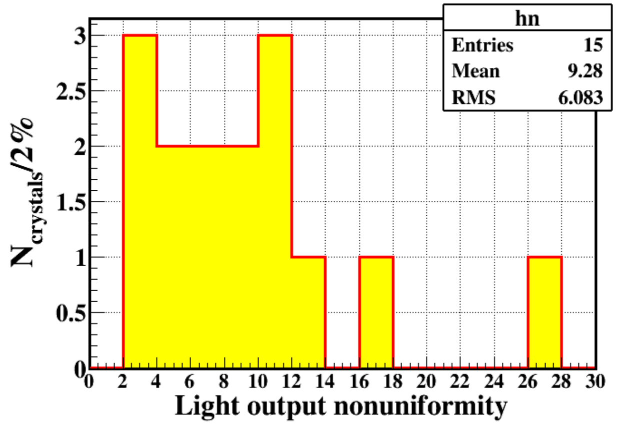
Plan to construct the calorimeter prototype (16 counters) and perform beam tests

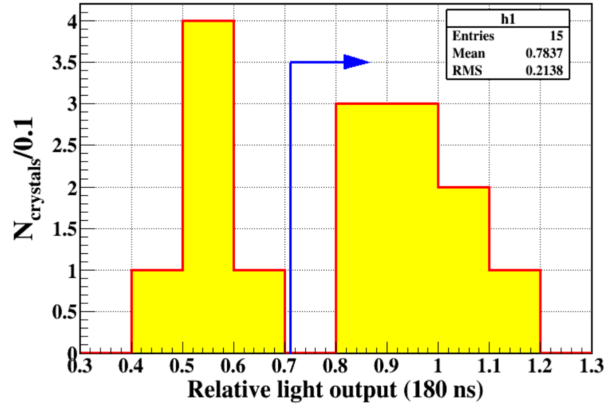
Half a year progress in CsI(pure)+WLS+4APD option

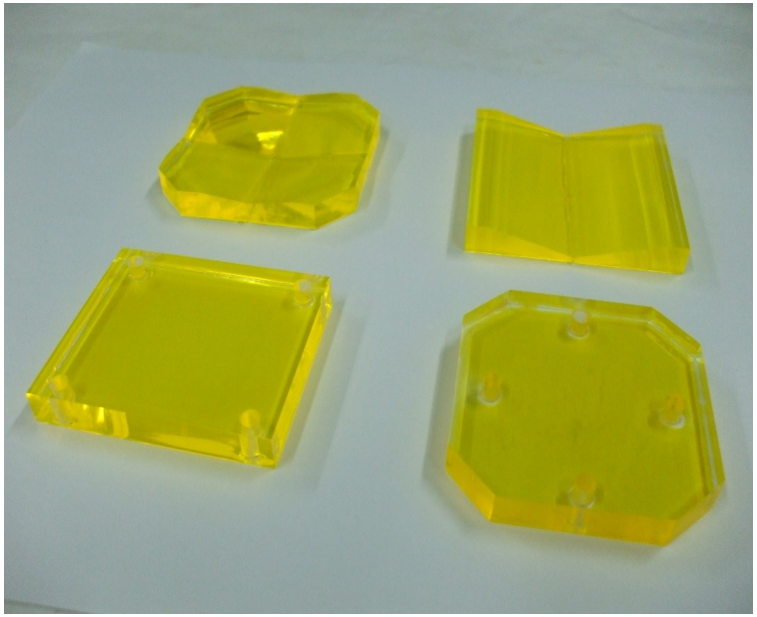
CsI(pure) + WLS + 4APD option

Crystals, WLS plates and APDs

- Parameters of available 18 crystals were measured
- 10 WLS plates of different shapes were purchased, studies are going on
- BC-600 optical epoxy resin is used to couple APDs to the side edges of the WLS plate, we tested additional 3 types of the optical epoxy resin, they showed as high light collection efficiency as BC-600 did
- 65 Hamamatsu S8664-55 APDs were purchased for the prototype

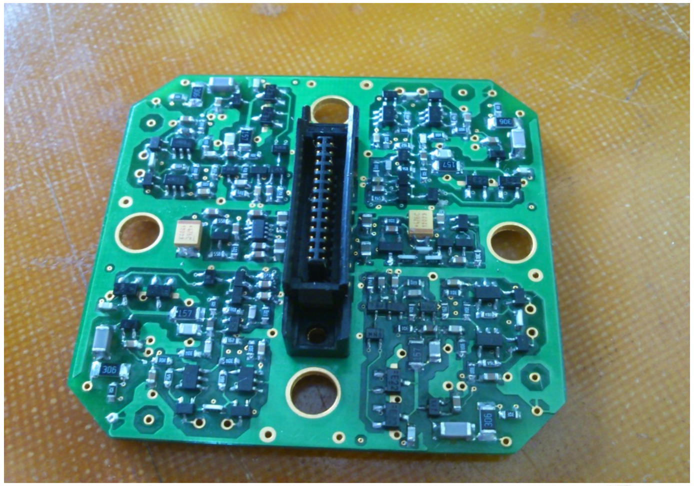


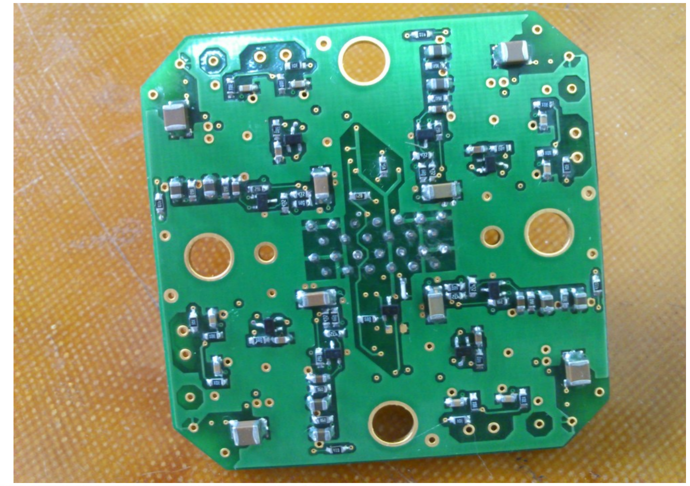


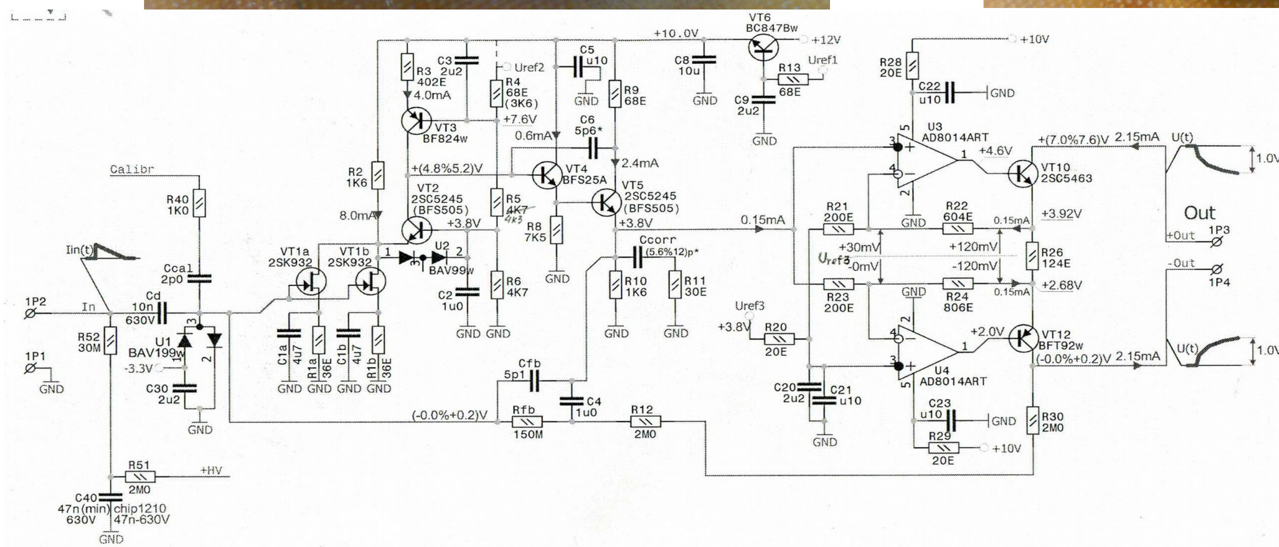


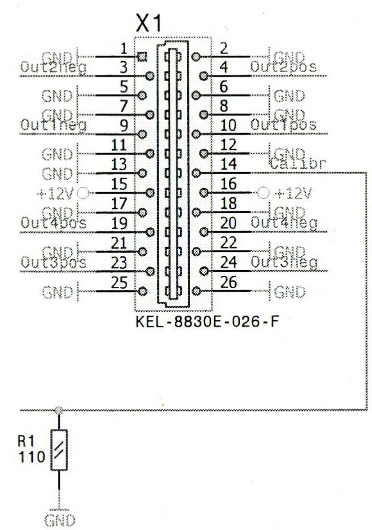
CsI(pure) + WLS + 4APD option

New 4-channel preamplifier



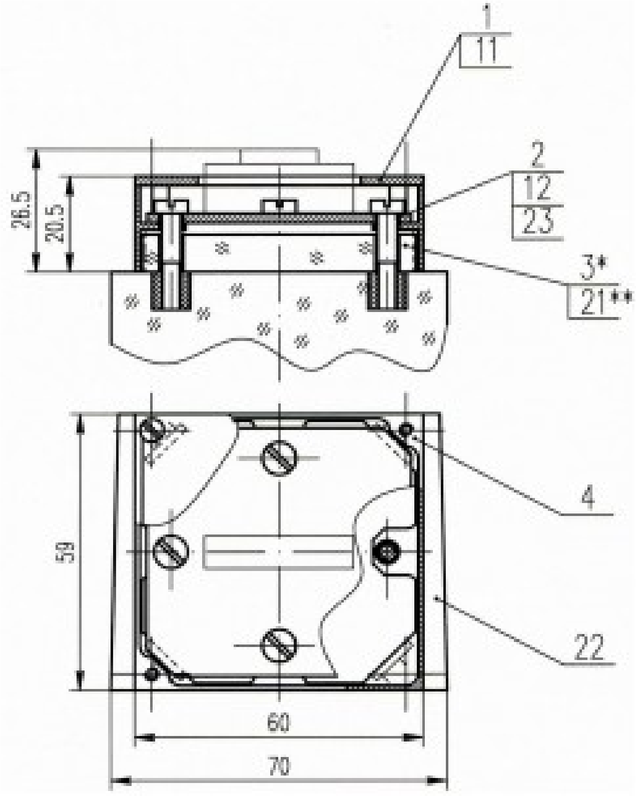


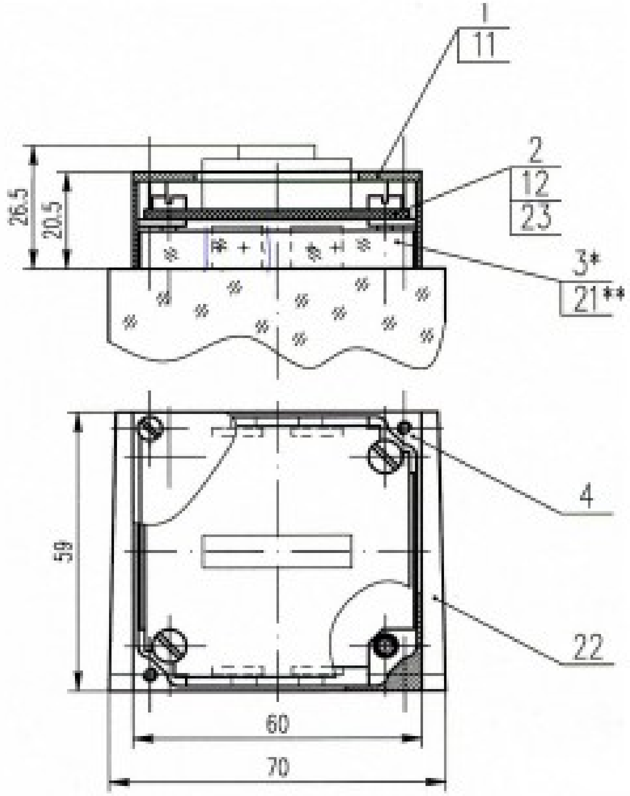




- 4 channels on 53 x 55 mm² PCB
- Each channel: sensitivity of 0.2 V/pC, 2 input FET 2SK932 (high transconductance), differential output, HV bias circuit, test pulse input

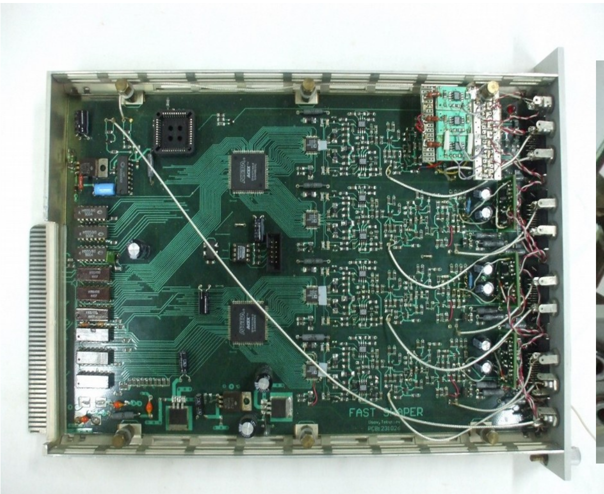
- The scheme of the counter was revised

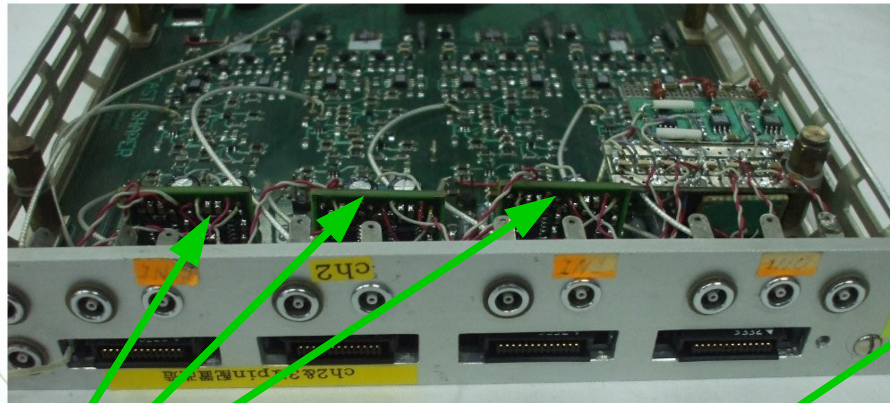


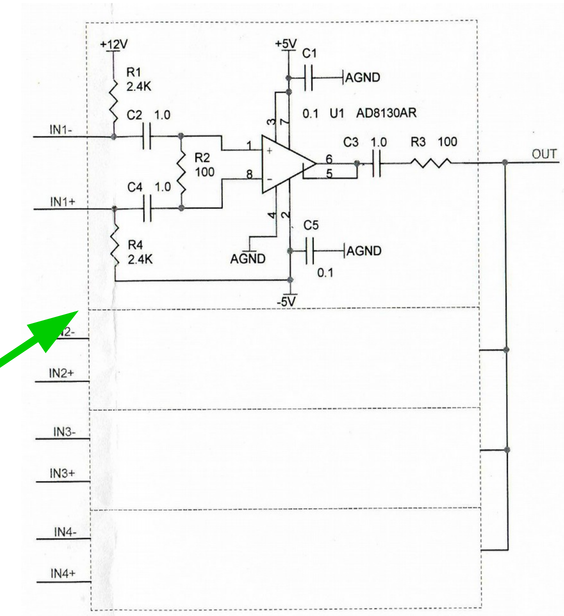


CsI(pure) + WLS + 4APD option

4-channel Shaper-ADC board







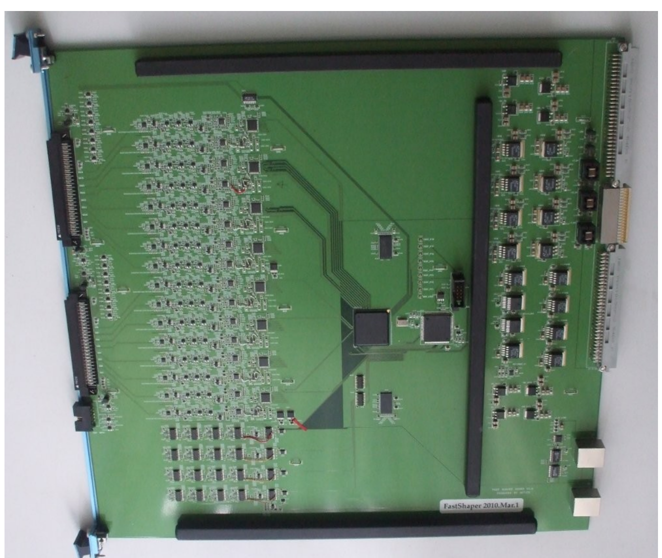
new differential receiver and summator board

- 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

CsI(pure) + WLS + 4APD option

Development of new electronics for the calorimeter

- **Pipeline readout, on-board waveform analysis approach (successfully realized at Belle II ECL)**
- **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**

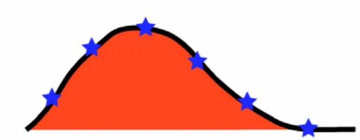


Algorithm details

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

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

$f(t)$ – 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)

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

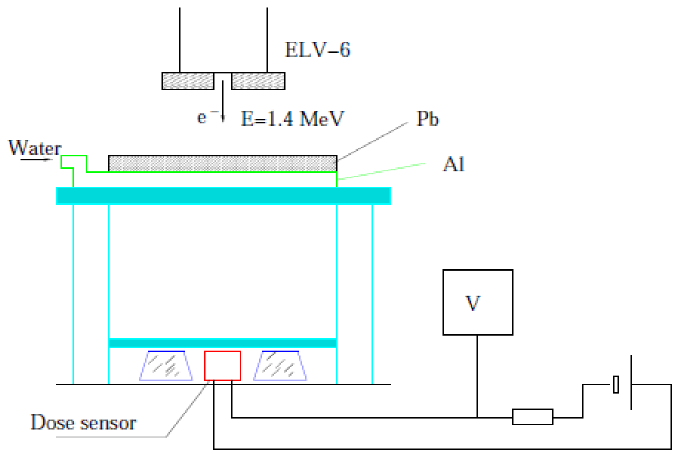
Summary

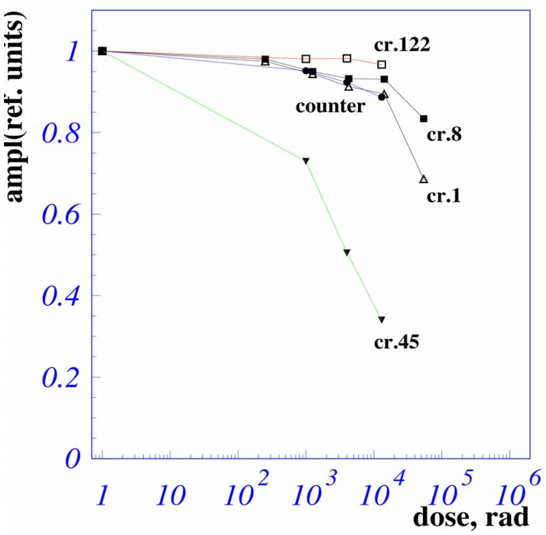
- CsI(pure) is appropriate material for the calorimeter of the Super C-Tau factory
- The main option is CsI(pure)+photopentode. Beam tests of the prototype showed good energy and spatial resolutions, as well as essential suppression of the pileup noise
- The pipeline readout with on-board waveform analysis (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.
- Notable progress on the CsI(pure)+WLS+4APDs option during half a year, we are on the way to construct the prototype and perform beam tests

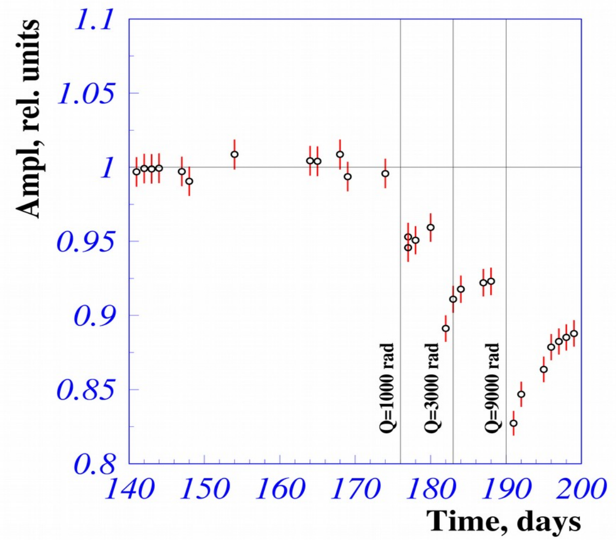
Backups

Study of radiation hardness of CsI(pure) crystals

I. Bedny et al., **NIMA598** (2009) 273. A. Boyarintsev et al., **JINST11** (2016) P03013.

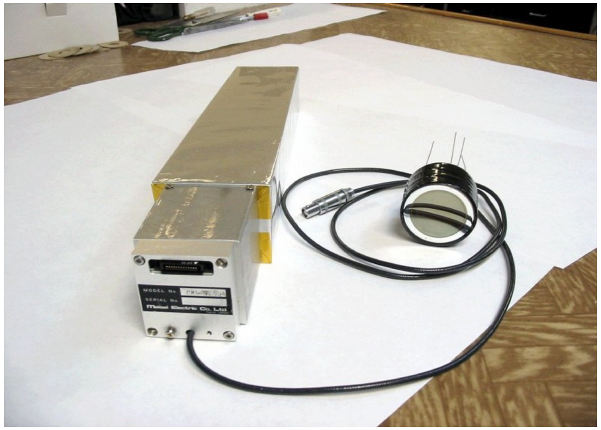


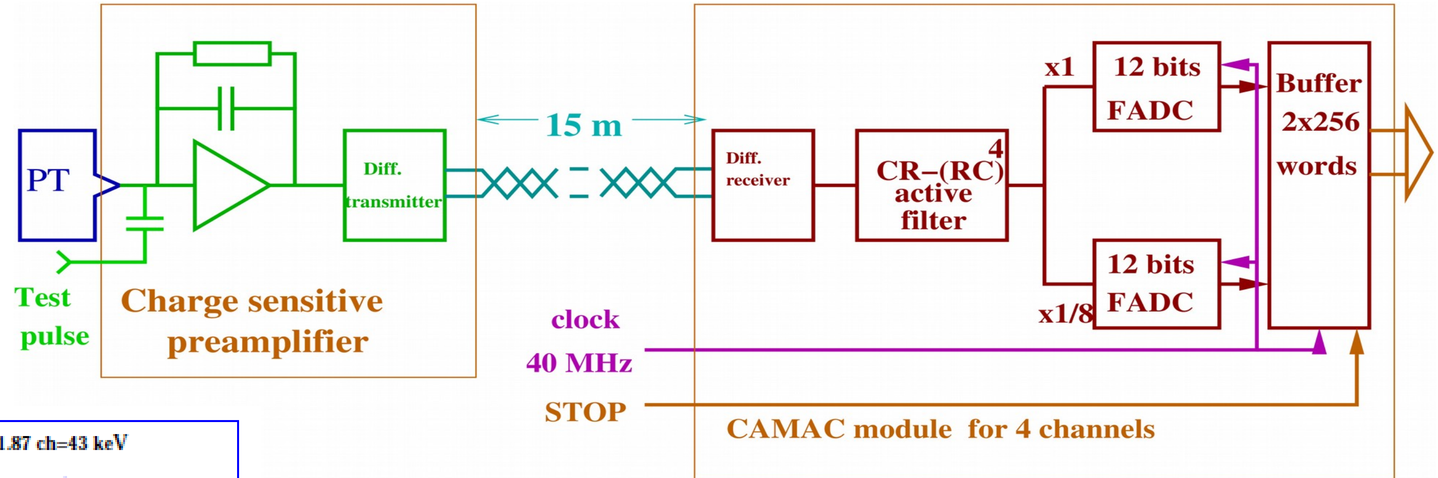


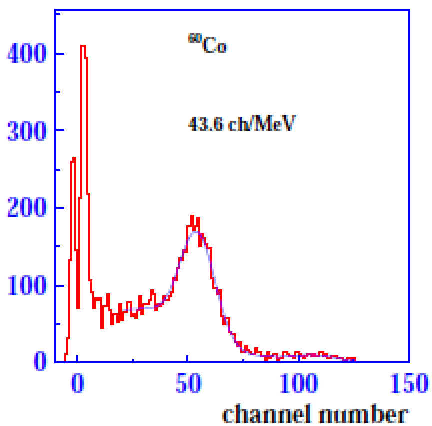


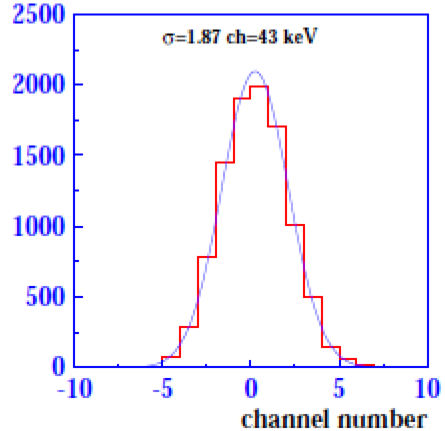
- We studied the radiation hardness of 4 CsI(pure) crystals and 1 counter (CsI(pure) + photopentode), they were irradiated by bremsstrahlung γ's with $E_\gamma < 1.4$ MeV
- The dose rate was controlled by ELV-6 current and measured by a special dosimeter made of CsI(Tl) crystal and PIN PD
- For the dose 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/cm²), 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**

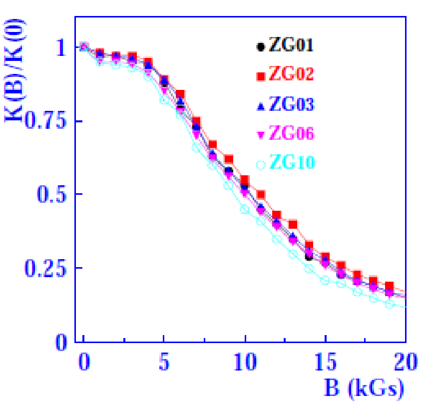
CsI(pure)+PP option (I)

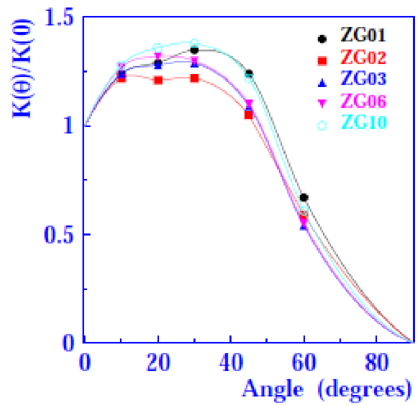




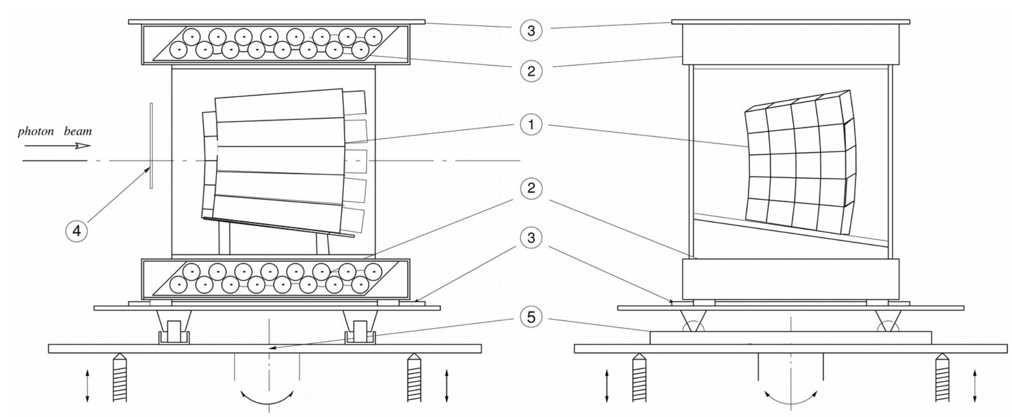




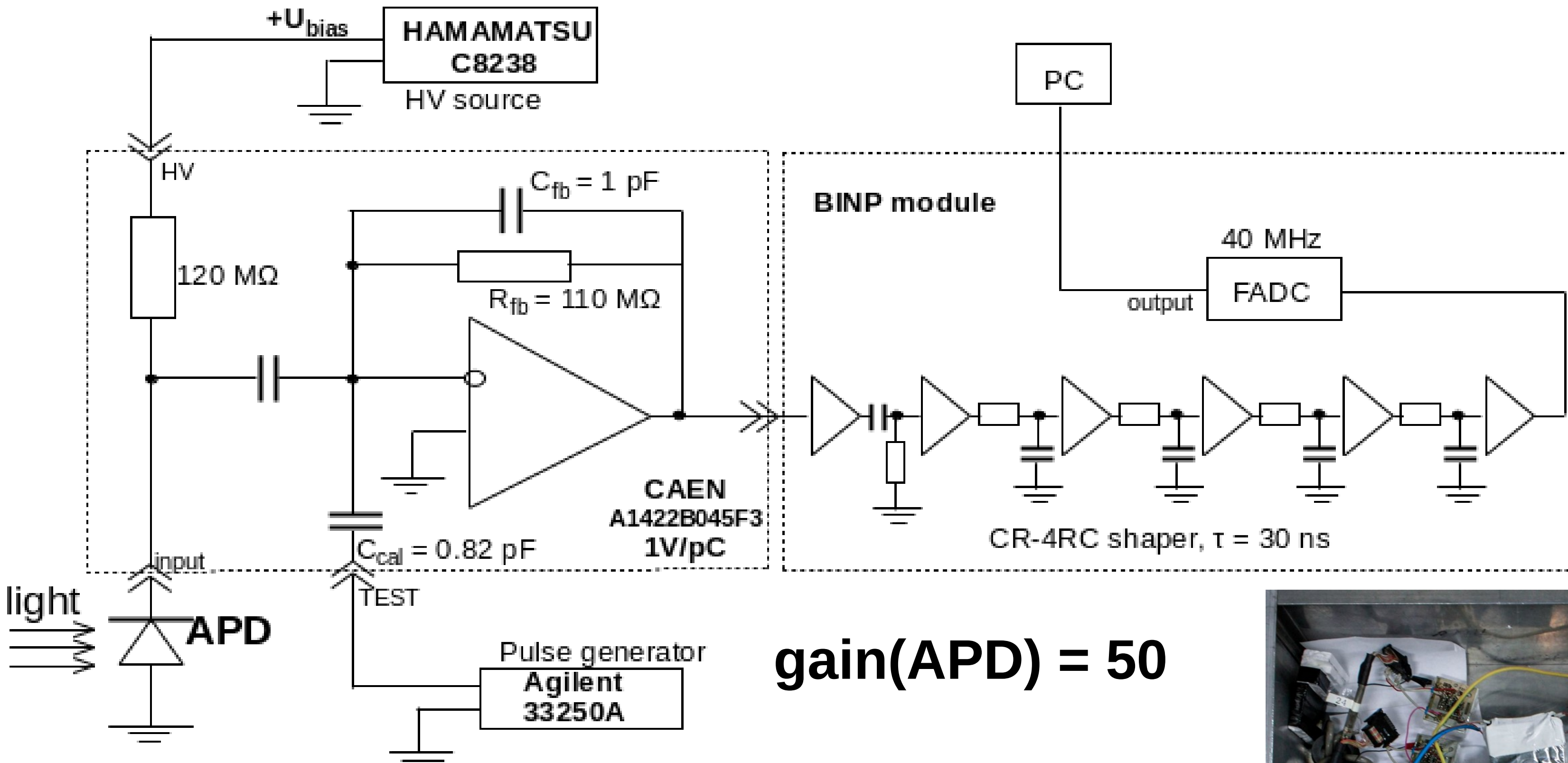




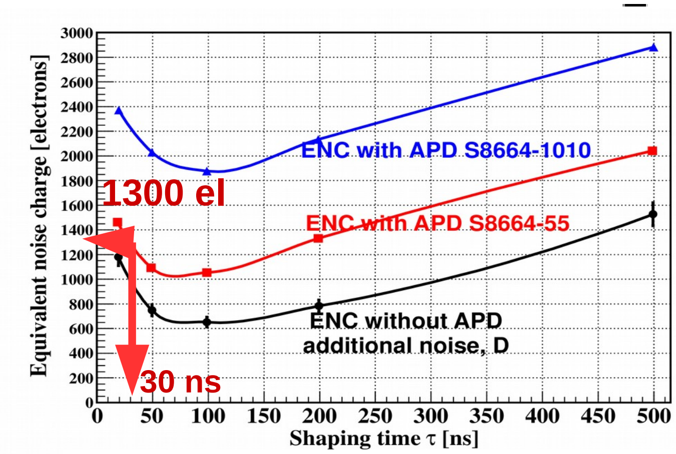
- **The ENE of the CsI(pure)+PP counter is about 50 keV without magnetic field**
- **Due to the drop of the signal in magnetic field of 1.5 T by a factor of ~3, the ENE = 150 keV for B = 1.5 T**
- Prototype was constructed from 20 counters (of 8 geometrical types from FWD ECL). Each counter was based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

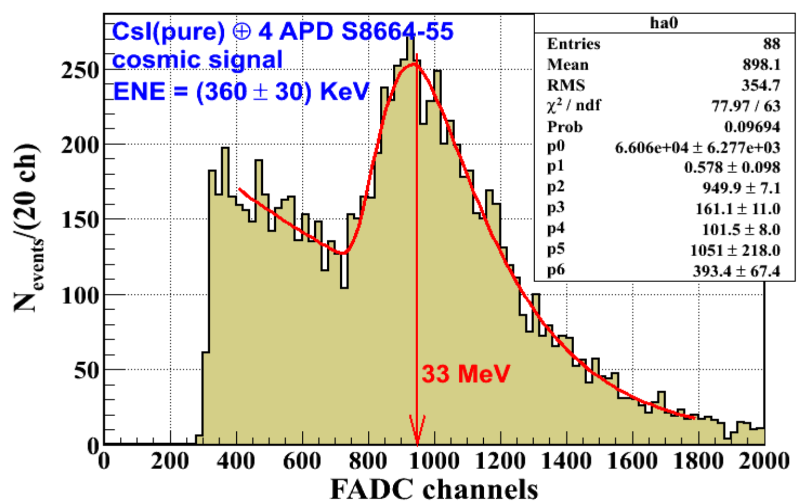


CsI(pure) + WLS + 4APD option (III)



gain(APD) = 50



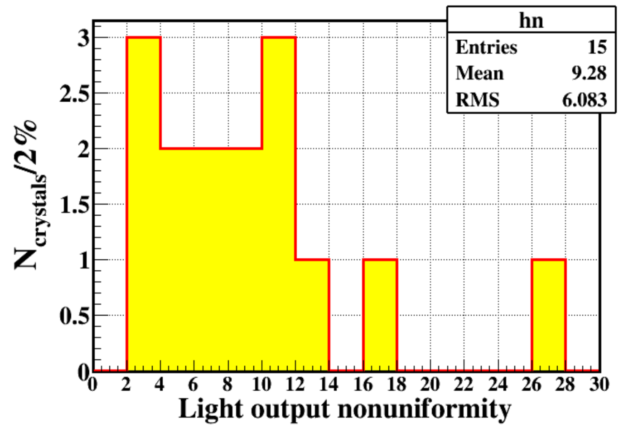


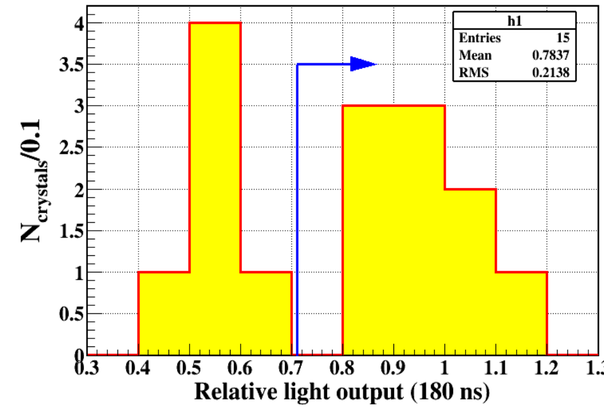
$$ENC^2 = \frac{2I_dKgF\tau}{e} + \left(\frac{B^2}{\tau} + E^2\right)C^2 + D^2$$

Shot noise *Thermal noise* *Additional noise*

Half a year progress in CsI(pure)+WLS+4APD option

- **Parameters (LO, longitudinal LO nonuniformity, fast/total) of 18 pure CsI crystals were measured, it was confirmed that we can construct 16-crystal calorimeter prototype. All crystals are being rewrapped now, holes with plastic insets to mount the shielding cases will be made soon.**





- **In addition to BC600 3 more optical glues (PEO-210KE, PEO-510KE-20/0, PEO-610KE-20/0) were tested, they showed as high light collection efficiency as BC600.**