Status of the R&D on the calorimeter based on pure CsI crystals for the Super Charm-Tau factory

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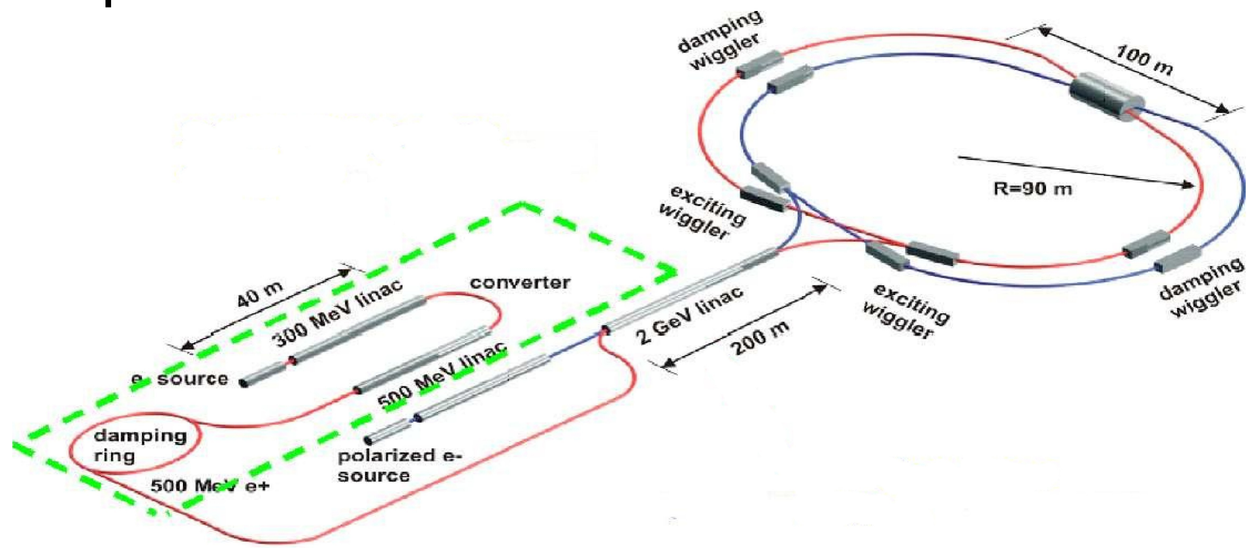
Moscow, September 25th 2019



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 Charm-Tau factory
- Summary

Introduction (I)

Large fraction of $\pi^0(\to\gamma\gamma)$ among the produced hadrons, necessity to reconstruct γ's in such golden modes as $\tau\to\mu\gamma$ 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)

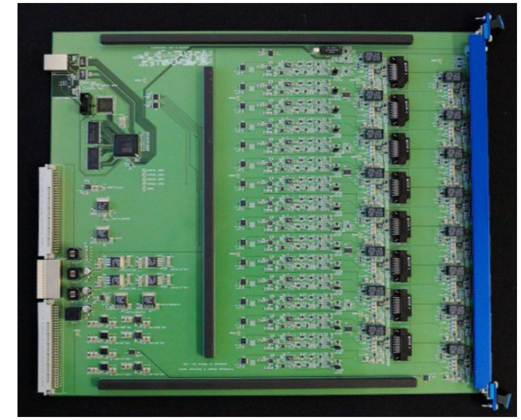
crystal	ρ, g/cm^3	X_0, cm	λ_{em}, nm	n	N_{ph}/MeV	τ, ns
CsI(Tl)	4.51	1.86	550	1.8	52000	1000
CsI	4.51	1.86	305/400	2	5000	30/1000
BaF_2	4.89	2.03	220/310	1.56	2500/6500	0.6/620
CeF_3	6.16	1.65	310	1.62	600	3
$PbWO_4$	8.28	0.89	430	2.2	25	10
$LuAlO_3(Ce)$	8.34	1.08	365	1.94	20500	18
$Lu_3Al_5O_{12}(Ce)$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

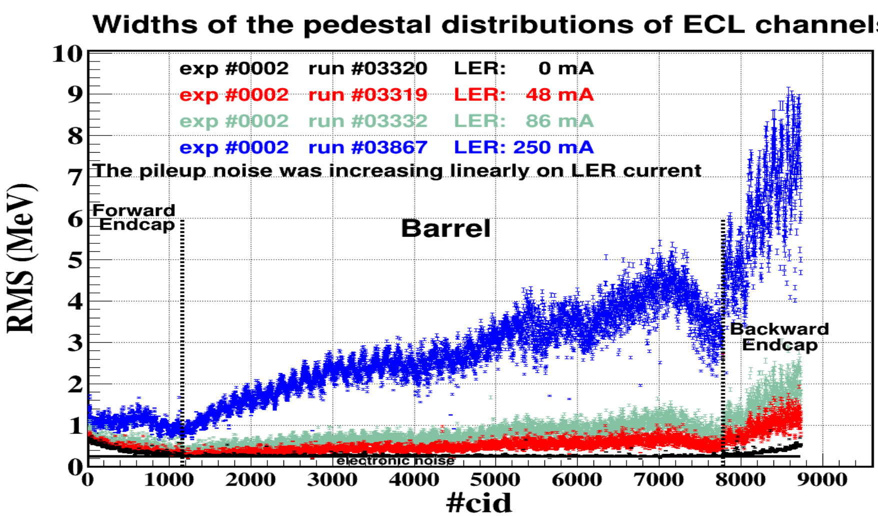
Belle II electromagnetic calorimeter (ECL)

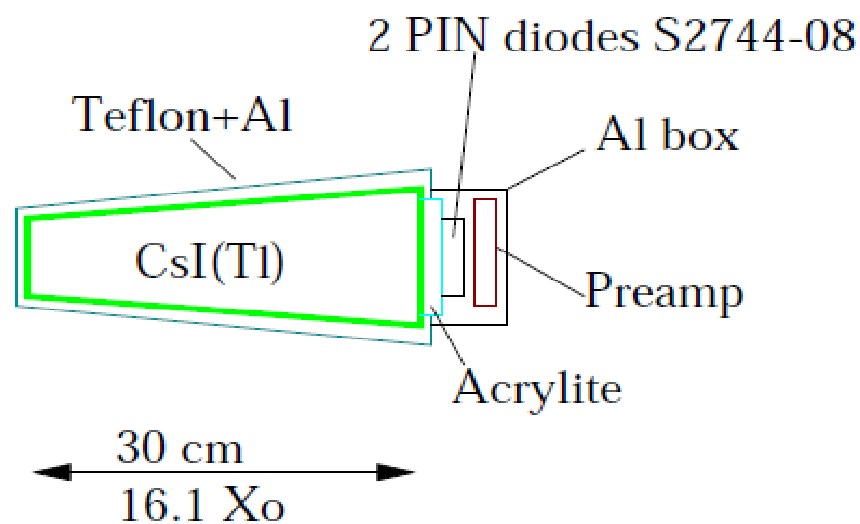
Belle II ECL is based on 8736 CsI(TI) crystals (40 tons) with the thickness of $16X_0$ (30 cm). It is located inside magnetic field of 1.5 T and covers the solid angle of 91% of 4π.

- 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 1000$e \approx$ 200 keV



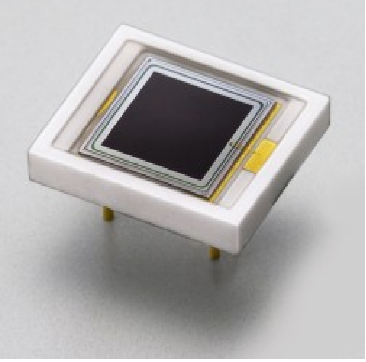
$\sigma_E/E \approx 1.8\%$ (E = 1GeV) **$\sigma_x = 6$ mm/√E(GeV)**

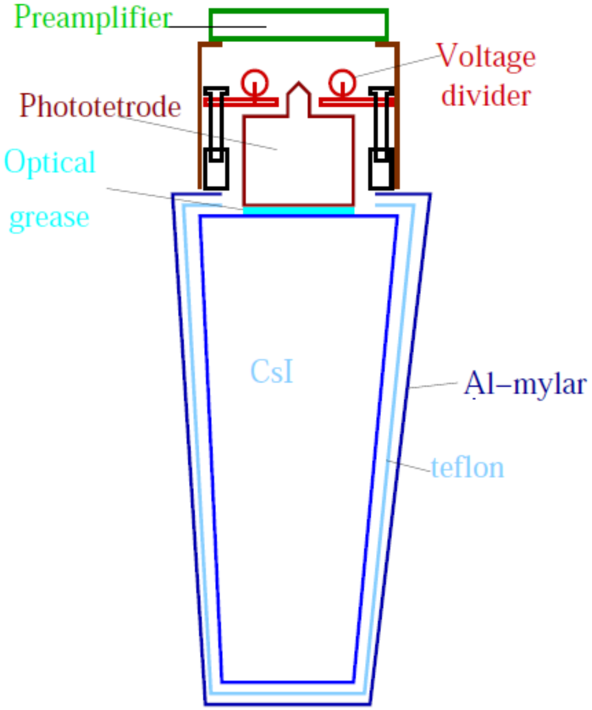




Belle II endcap ECL upgrade

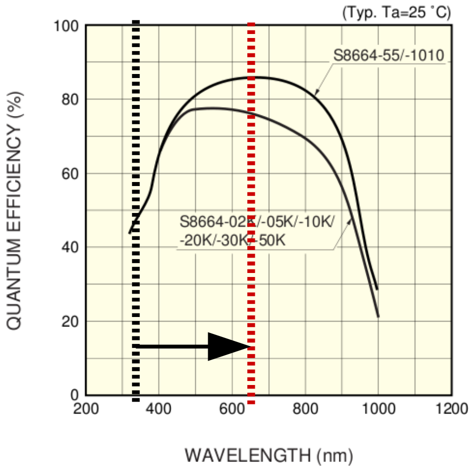
Hamamatsu
APD S8664-55





- **To decrease pileup noise by a factor of 5.5 in the endcap ECL, CsI(Tl) are planned to be changed 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
- However there are some difficulties: **no redundancy**, **strong dependency on magnetic field, completely.** 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.**

■ Quantum efficiency vs. wavelength

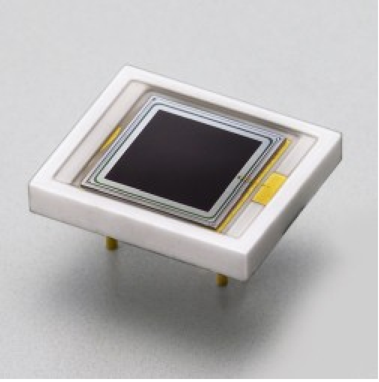


CsI(pure)+WLS+4APD option (I)

- 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})**

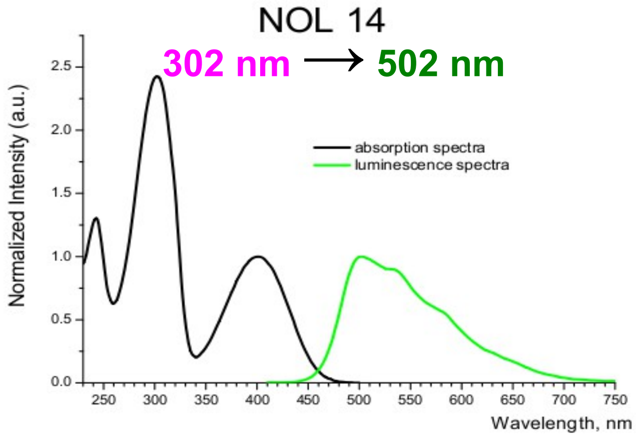


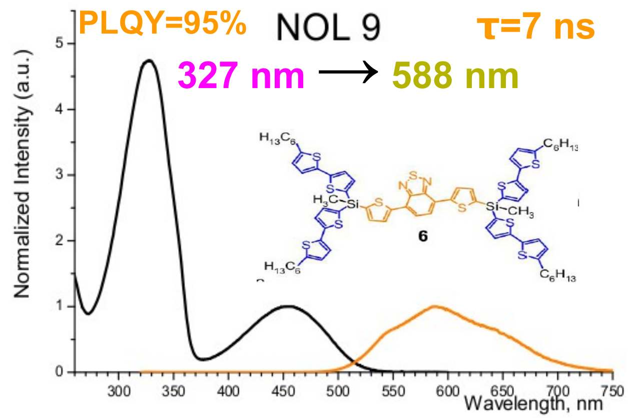
We chose the configuration: CsI(pure) + WLS(nanostructured organosilicon luminophores) + 4APD (Hamamatsu S8664-55)

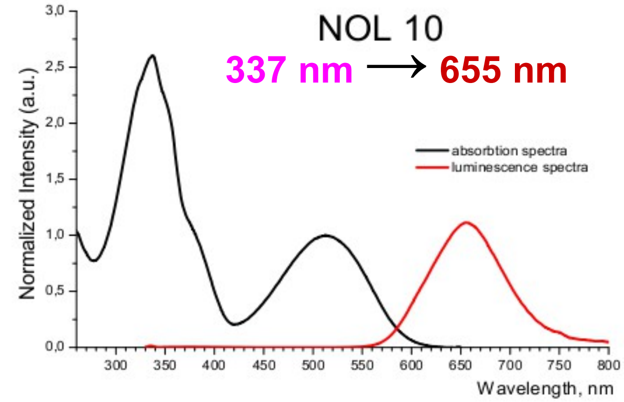
CsI(pure) + WLS + 4APD option (II)

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.

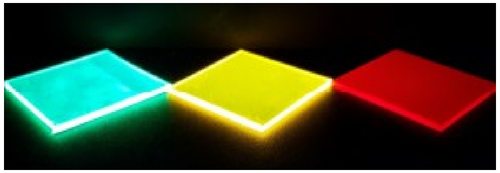
Based on the nanostructured organosilicon luminophores (NOL-9,10,14) from **LumInnoTech Co.**, the WLS plates were developed ((60 x 60 x 5) mm^3).



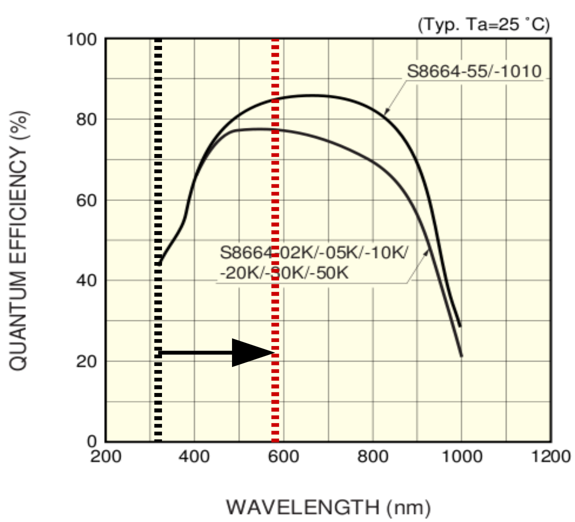


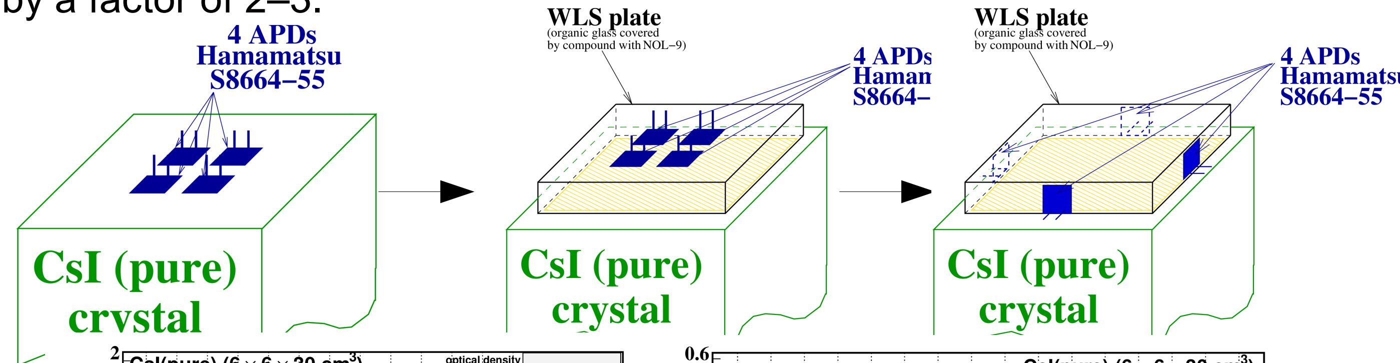


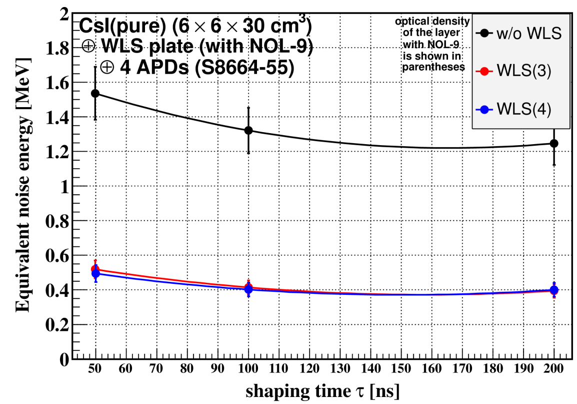
- The absorption and emission spectra of these NOL's match our needs very well (λCsI = 320 nm).
- The improvement of the APD QE is by a factor of 2–3.

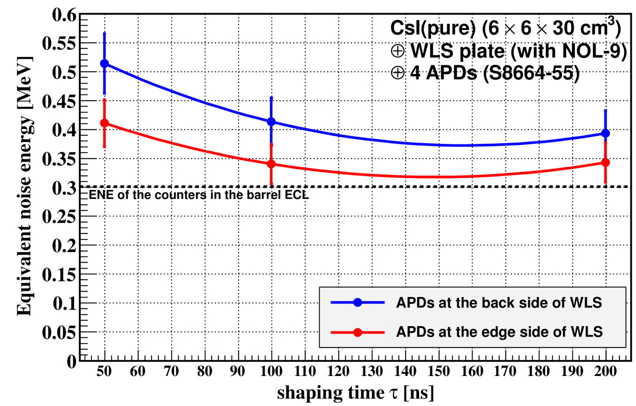


■ Quantum efficiency vs. wavelength

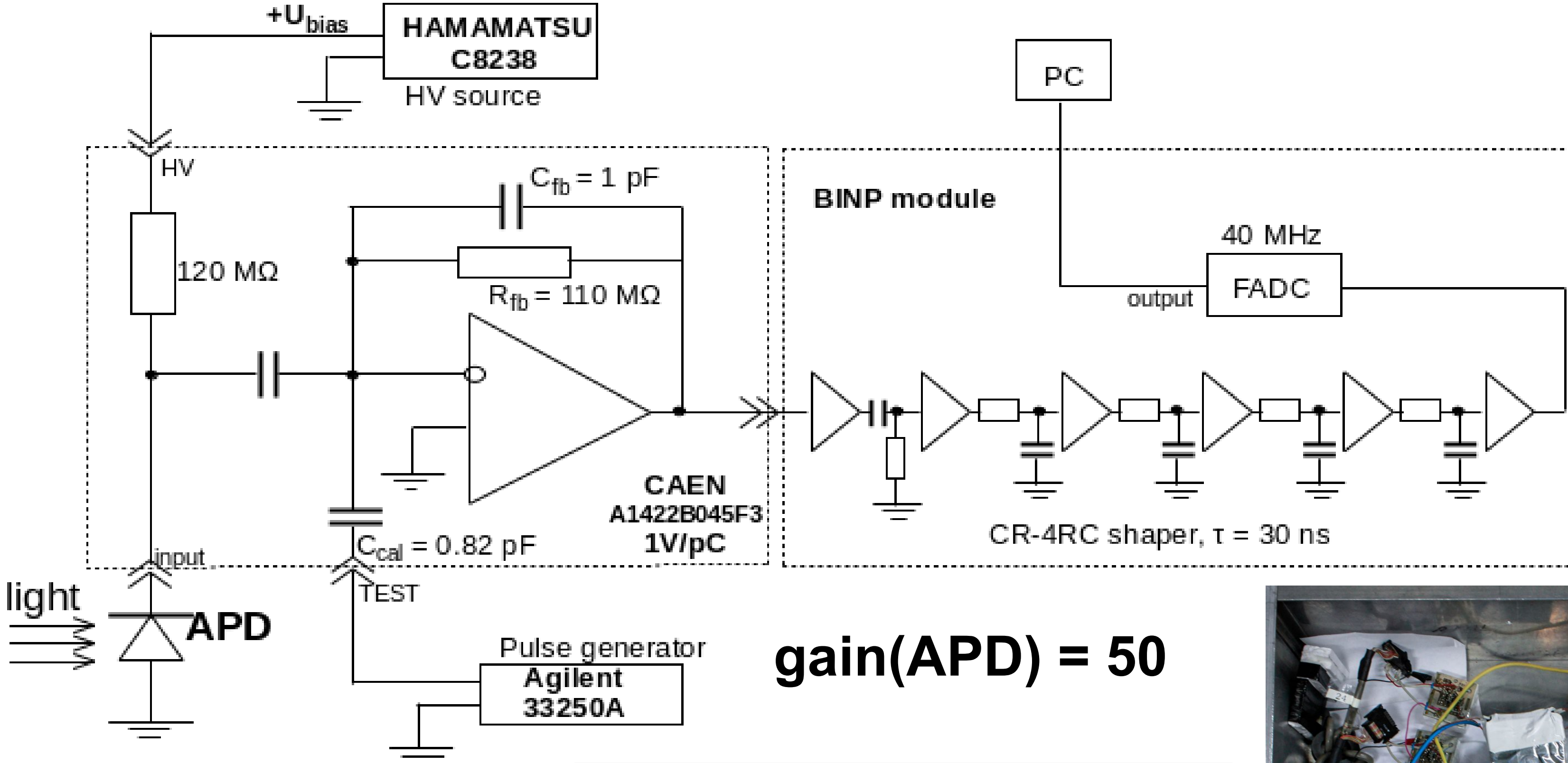




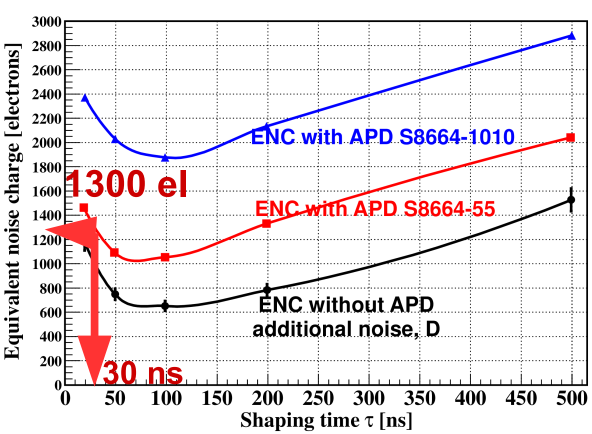


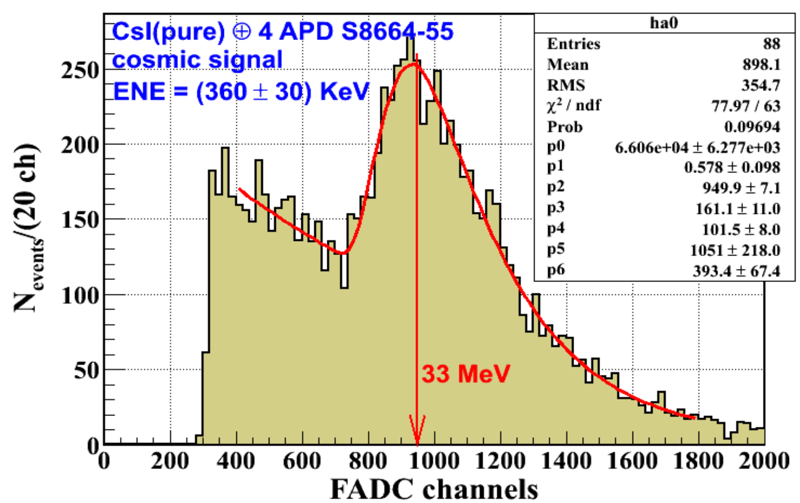


CsI(pure) + WLS + 4APD option (III)



gain(APD) = 50





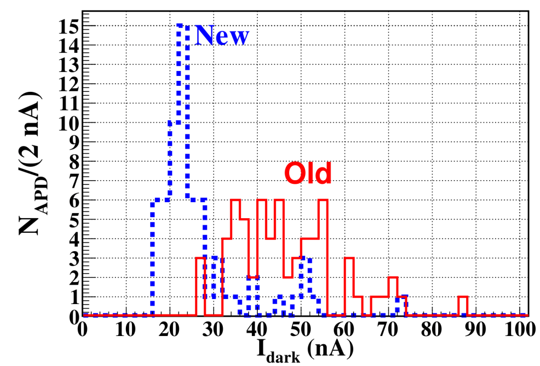
$$ENC^2 = \frac{2I_d K g F \tau}{e} + \left(\frac{B^2}{\tau} + E^2\right)C^2 + D^2$$

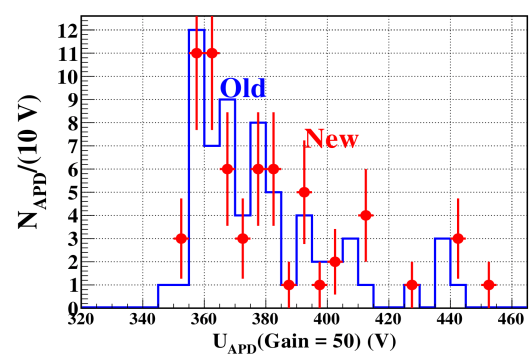
Shot noise *Thermal noise* *Additional noise*

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

Crystals, WLS plates and APDs

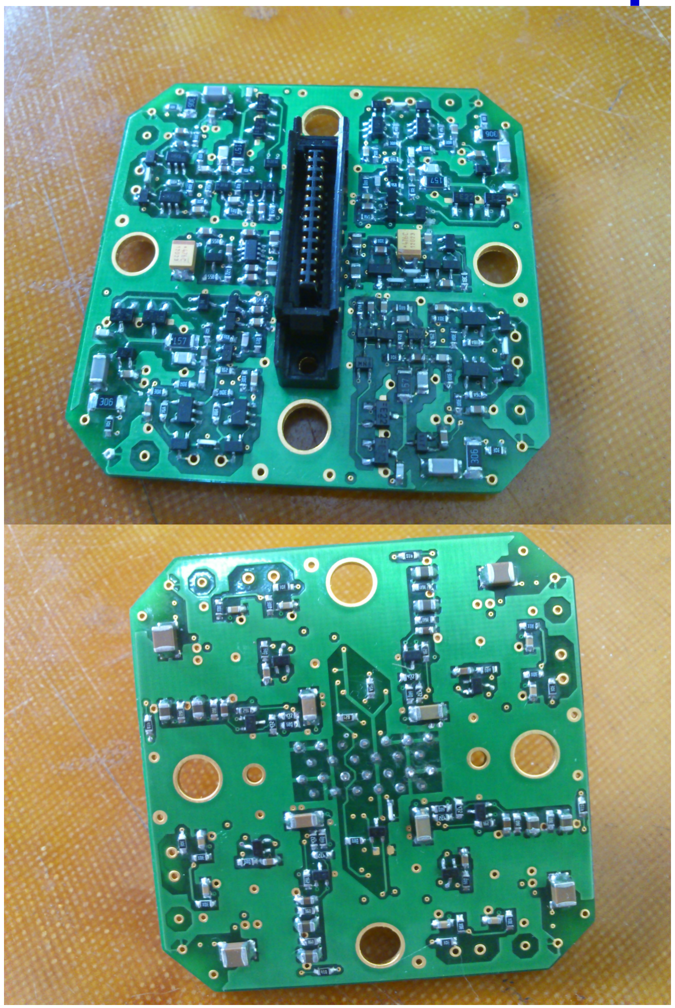
- **We are constructing calorimeter prototype made of 16 counters**, the parameters of available 18 crystals (of 6 x 6 x 30 cm^3 size) were measured, mechanics was developed, produced and assembled.
- Optimization of the shape of the WLS plate was done, further signal improvement of 1.6 was achieved, 16 WLS plates of optimal shape were purchased, tests are in progress.
- BC-600 optical epoxy resin is used to couple APDs to the side edges of the WLS plate.
- 64 Hamamatsu S8664-55 APDs were purchased from LHC CMS calorimeter group, baking procedure was held at CERN to decrease the dark current of CMS APDs. Main characteristics of all APDs were measured.



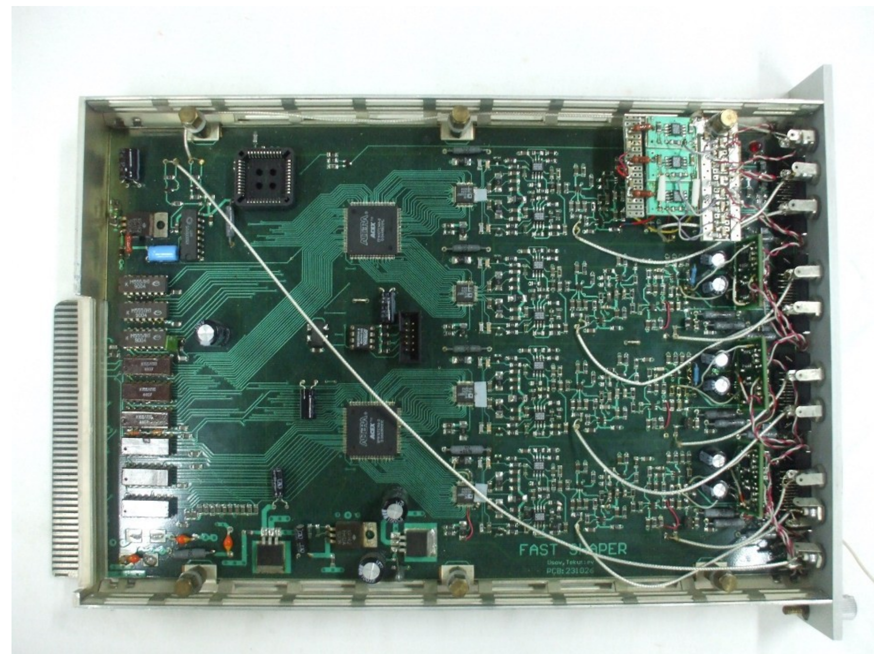


CsI(pure) + WLS + 4APD option (V)

4-channel preamplifier and Shaper-ADC board



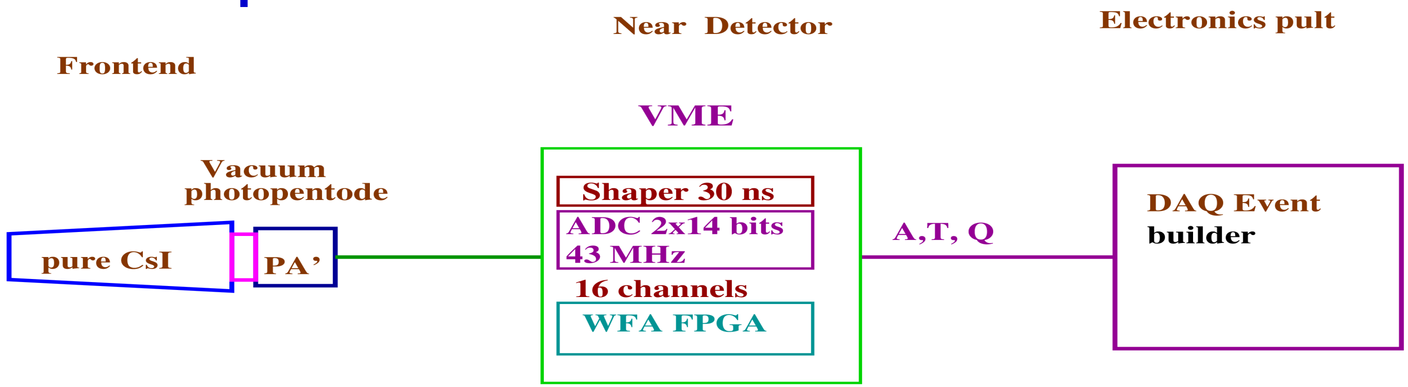
- **4-channel charge sensitive preamplifier** on 53 x 55 mm^2 PCB
- Each channel: sensitivity of 0.2 V/pC, 2 input FET 2SK932 (high transconductance), differential output, HV bias circuit, test pulse input



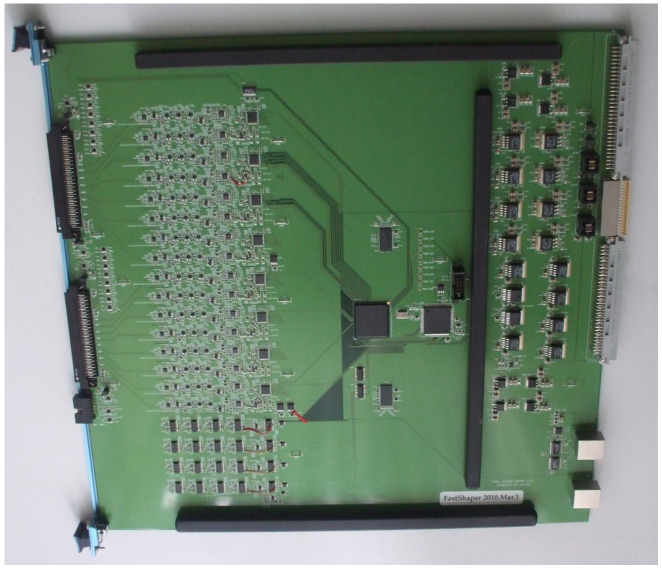
- **4-channel CAMAC Shaper-ADC board**
- CR-$(RC)^4$ filter (τ = 30 ns) + 40 MHz 12-bit pipelined ADC + 256-word circular buffer
- To comply with the new 4-ch preamp additional differential receiver and summator (DRS) boards have been produced and mounted in the Shaper-ADC boards

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

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%/ ^{o}C, hence, thermostabilization of the calorimeter is needed, the temperature map should be monitored with the accuracy of (0.1 – 0.2) oC

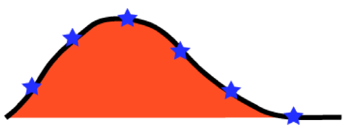


Algorithm details

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

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

$f(t)$ – 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)

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

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

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

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

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

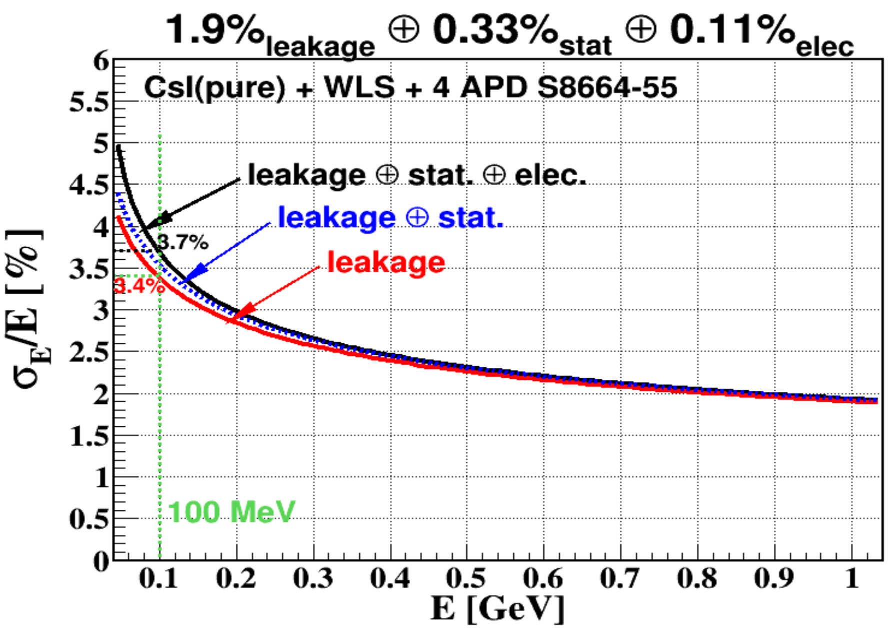
$$Elec = 100\% \cdot \frac{ENE[MeV] \cdot \sqrt{N_{crys}}}{1000}$$

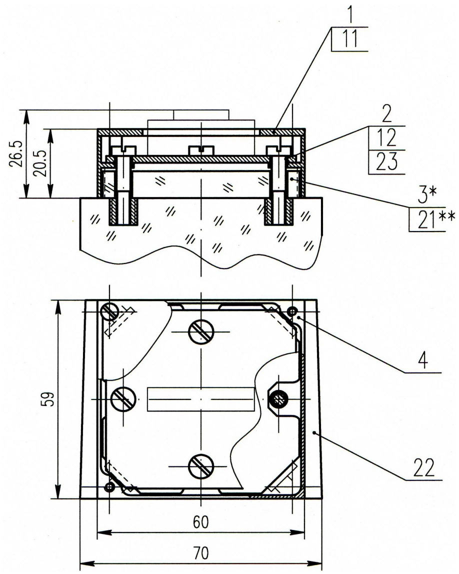
$F = 1.69 \pm 0.04$

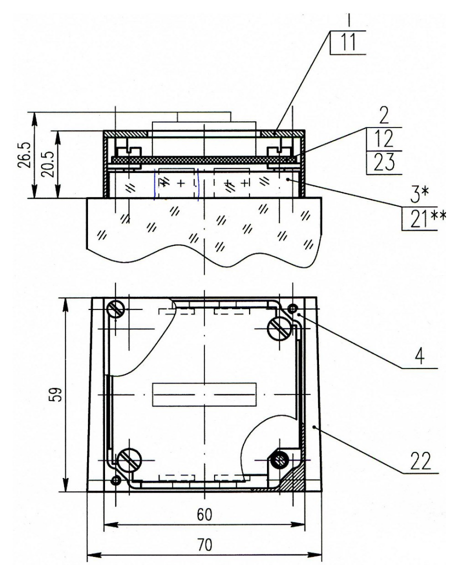
$S \cdot N_{APD} = (160 \pm 9)$ ph.el./MeV

$ENE = (0.33 \pm 0.03)$ MeV

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

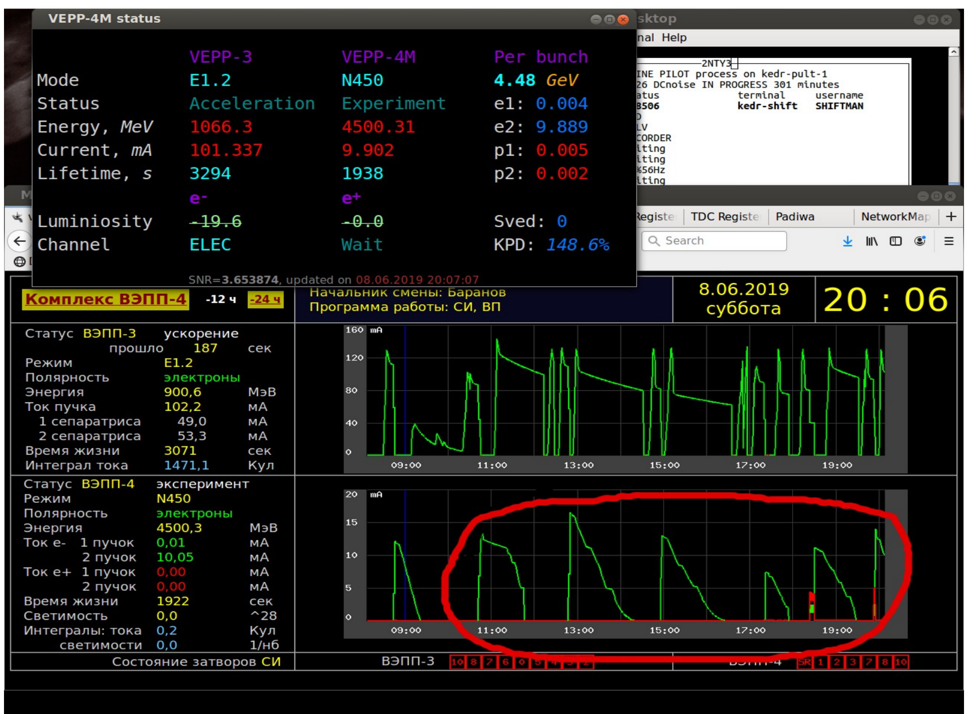


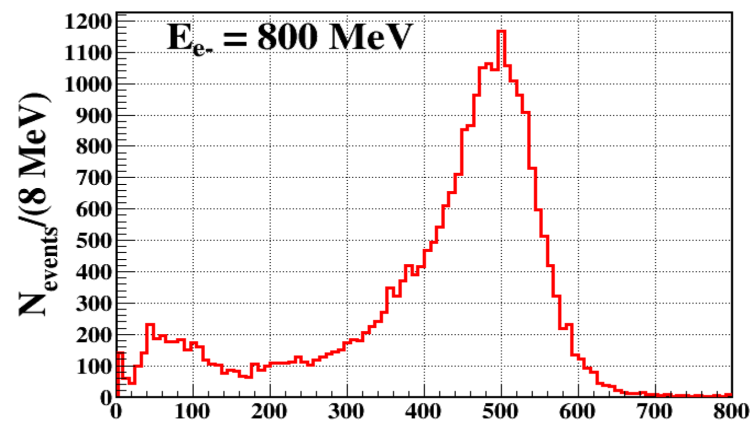


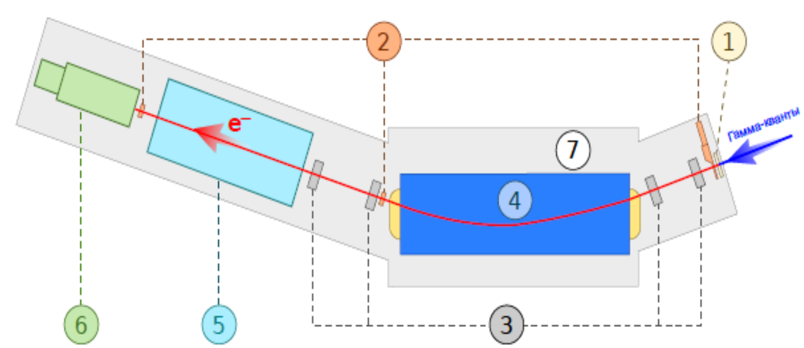


Test beam study of 1 counter

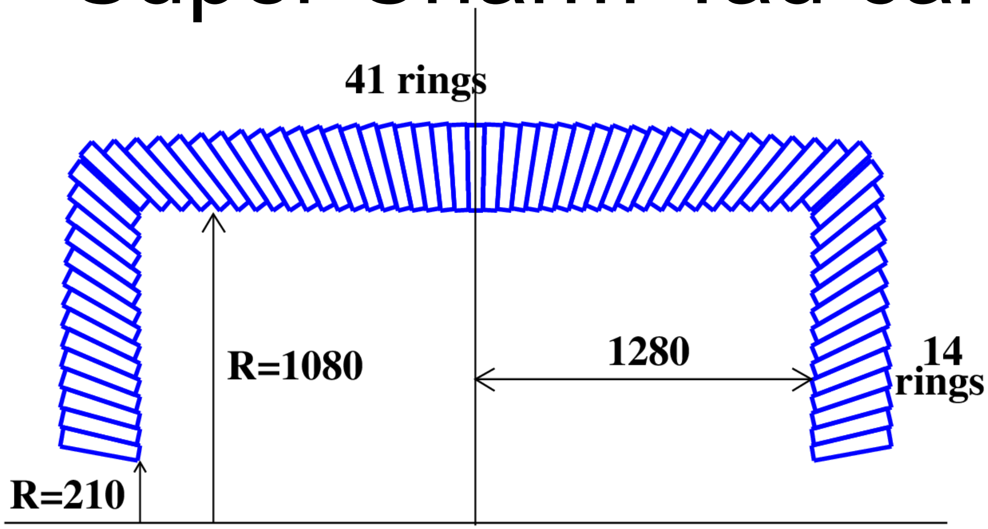
- In June 2019 we performed test beam studies with 1 fully assembled CsI counter.
- Electron beam with the energies 0.8, 1.5, 2.0, 2.5 and 3.0 GeV hit the center of the pure CsI crystal. Signals from the counter were recorded with the trigger from the external plastic scintillation detector and from CsI counter itself.
- In total about 1.2M events were recorded, got expected energy deposition spectra from the counter.

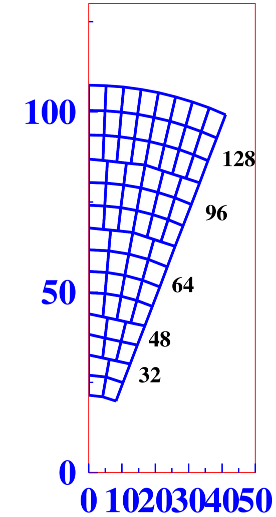






Super Charm-Tau calorimeter layout





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$**
- **Photodiodes: 7424 → 2 M$**
- **Electronics: 7424 → 4 M$**
- **Total price (16X_0 / 18X_0): 46/53 M$**

9 month progress in CsI(pure)+WLS+4APD option

- Mechanics (16 crystals with aluminum shielding cases) of the calorimeter prototype is ready.
- 16 WLS plates of the optimal shapes with NOL-9 were purchased, measurement of their characteristics is in progress.
- 64 APDs Hamamatsu S8664-55 from LHC CMS group were baked, the dark current was decreased by a factor of about 2.
- 17 4-channel preamplifiers and 5 4-channel shaper-ADC boards are ready.
- Study of 1 fully assembled counter was performed at the electron test beam facility in BINP. Expected results were obtained.
- Assembly of all counters of the prototype will start soon, test beam study of the prototype is planned this year in BINP.

Summary

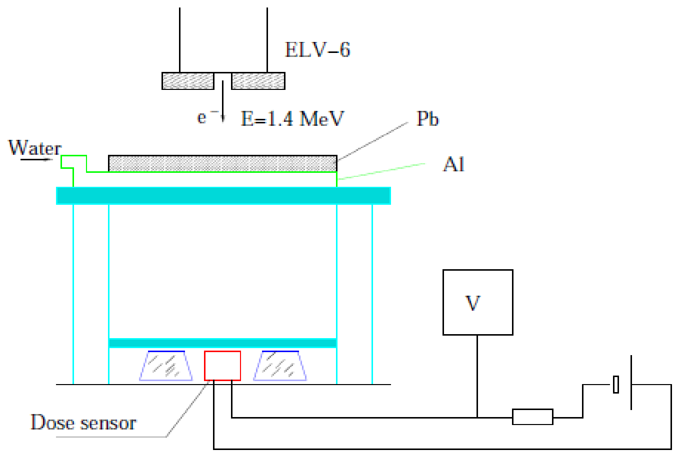
- CsI(pure) is an appropriate material for the calorimeter of the Super Charm-Tau factory.
- Beam tests of the prototype based on CsI(pure) crystals and vacuum photopentodes showed good energy and spatial resolutions, as well as essential suppression of the pileup noise.
- The CsI(pure)+WLS+4APDs option is considered to be the main one now. The problems of the low LO and high ENE have been solved, beam tests of one fully assembled counter showed expected results.
- The mechanics of the 16-counter prototype is ready, all WLS plates and preamplifiers are available in lab. Assembly of the prototype will start soon.

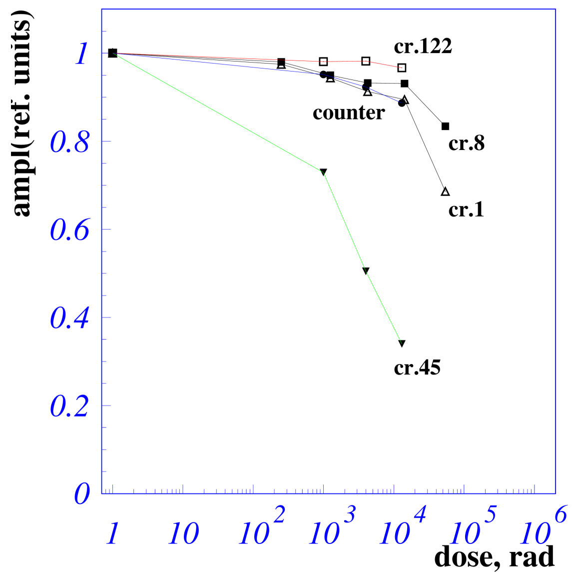
Backups

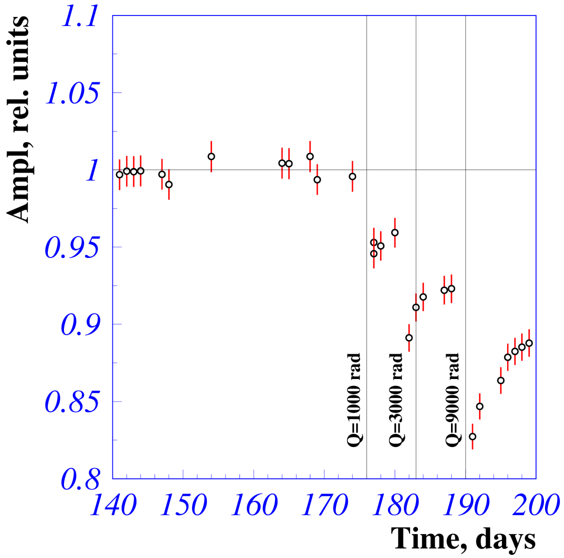
Study of radiation hardness of CsI(pure) crystals

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_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**