Fast calorimeter on the pure CsI crystals for the modern $e^+ e^-$ Super Factories

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1. Introduction

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 – 6 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**

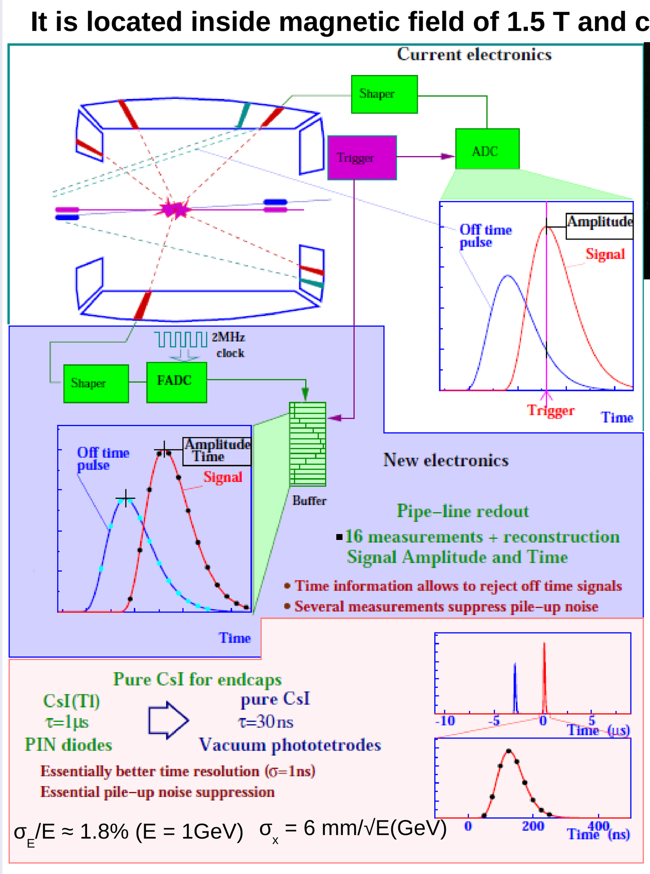
2. Inorganic scintillation crystals

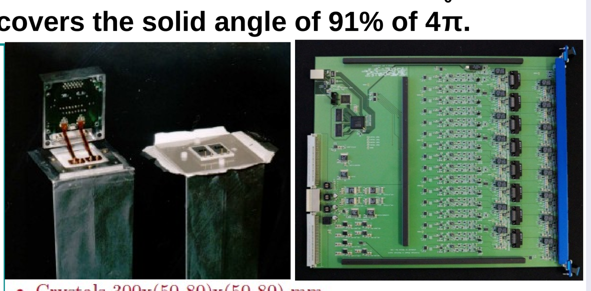
crystal	ρ, g/cm^3	X_0, cm	λ_{em}, nm	n	N_{ph}/MeV	τ, ns
CsI(Tl)	4.51	1.86	550	1.8	52000	1000
CsI	4.51	1.86	305/400	2	5000	30/1000
BaF_2	4.89	2.03	220/310	1.56	2500/6500	0.6/620
CeF_3	6.16	1.65	310	1.62	600	3
$PbWO_4$	8.28	0.89	430	2.2	25	10
$LuAlO_3$(Ce)	8.34	1.08	365	1.94	20500	18
$Lu_3Al_5O_{12}$(Ce)	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, small scintillation decay time and modest price (~3\$/cm³). 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)\$/cm³), COMET (2000 LYSO crystals).
- Pure CsI has still notable LY, fast decay time component of 30 ns and acceptable price (~5\$/cm³). 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.**

3. Belle II electromagnetic calorimeter

Calorimeter 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.

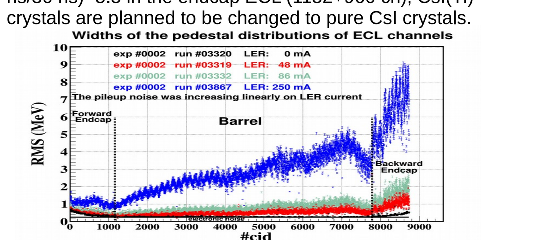




- Crystals 300x(50-80)x(50-80) mm
- Wrapping 200μm teflon+50 μm Al mylar
- Readout 2 10x20 mm PIN diodes
- 2 charge sensitive preamplifiers
- Shaper CR-(RC)⁴, τ=1μs
- Lightoutput 5000 p.e./MeV
- Electronic noise 1000e ≈ 200 keV

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.

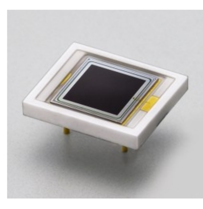
To decrease **notable pileup noise** by a factor of √(1000 ns/30 ns)=5.5 in the endcap ECL (1152+960 ch), CsI(Tl) crystals are planned to be changed to pure CsI crystals.



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

4. CsI(pure) + WLS + 4 APDs option

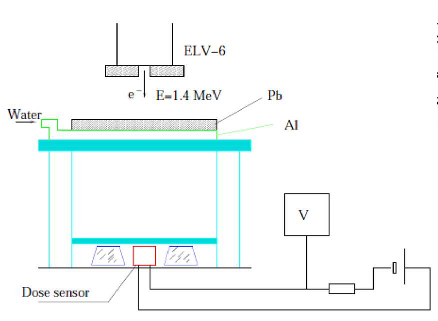
- The first tests showed that for the counter, based on the 6 x 6 x 30 cm³ CsI(pure) crystal (AMCRYS) and 1 APD Hamamatsu S8664-1010 (1 cm², C_{APD} = 270 pF) coupled to the back facet of the crystal with optical grease (OKEN-6262A) has the light output LO = 26 ph.el./cm²/MeV (for the shaping time of 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 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 (WLS) (320 nm → 600 nm)**
  - **Optimize the input circuit of the preamplifier (increase g_{FET})**

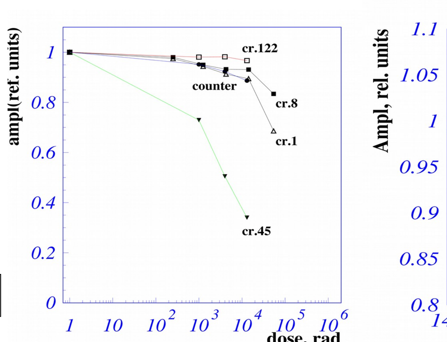


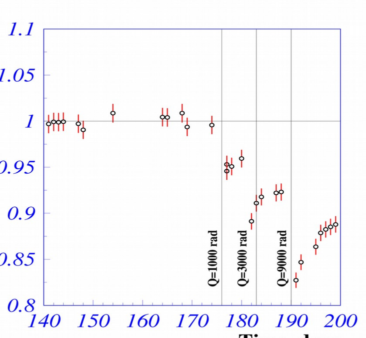
We chose the configuration: CsI(pure) + WLS (nanostructured organosilicon luminophores) + 4 APDs (Hamamatsu S8664-55)

5. Radiation hardness of CsI(pure) crystals

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





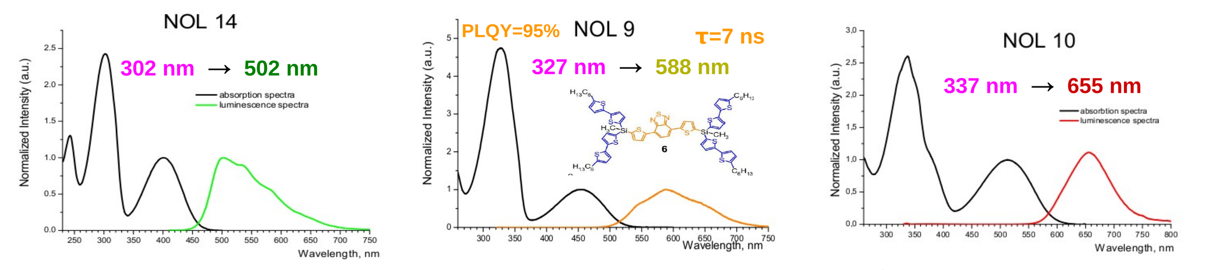


- We studied the radiation hardness of 4 CsI(pure) crystals and 1 counter (CsI(pure) + photopentode), they were irradiated by bremsstrahlung γ's with E_γ < 1.4 MeV
- The dose rate was controlled by ELV-6 current and measured by a special dosimeter made of CsI(Tl) crystal and PIN PD
- For the dose of 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 10¹² 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**

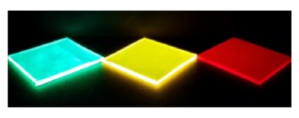
6. Nanostructured organosilicon luminophores (NOL)

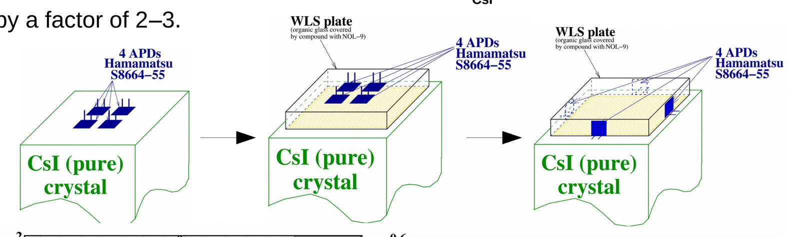
Y. Jin et al., **NIMA 824** (2016) 691. H. Aihara et al., **PoS PhotoDet 2015** (2016) 052. H. Aihara et al., **PoS ICHEP 2016** (2016) 703.

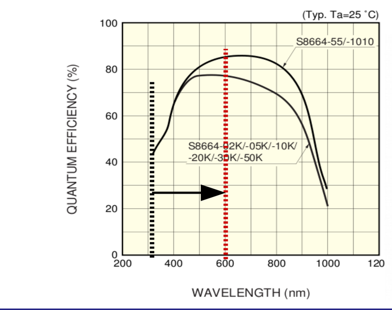
Based on the nanostructured organosilicon luminophores (NOL-9,10,14) from **LuMInnoTech Co.**, the WLS plates were developed ((60 x 60 x 5) mm³).

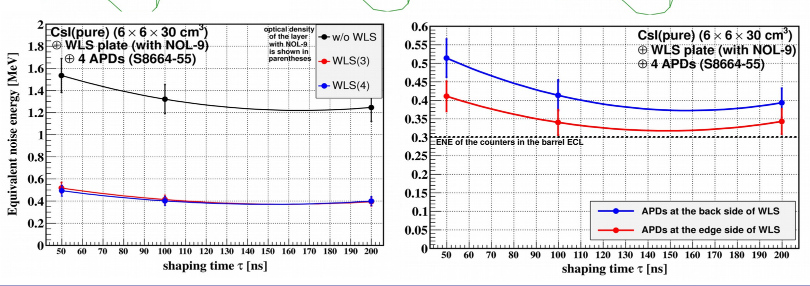


The absorption and emission spectra of these NOL's match our needs very well (λ_{CsI} = 320 nm). The improvement of the APD QE is by a factor of 2–3.



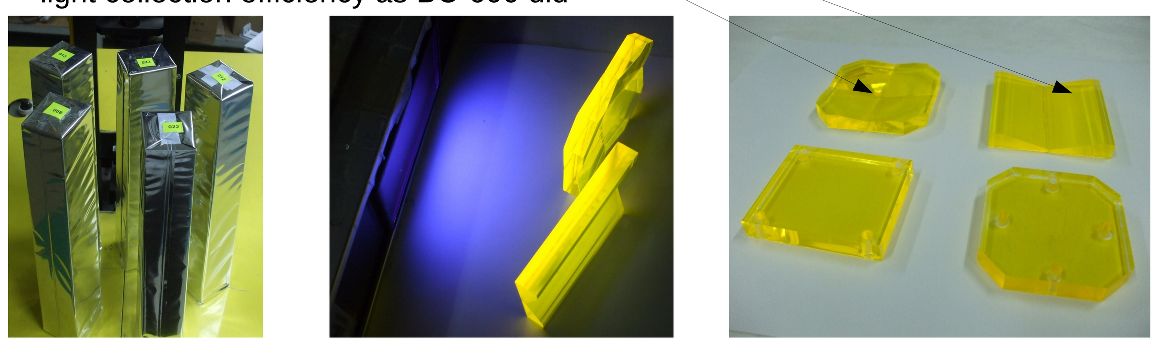


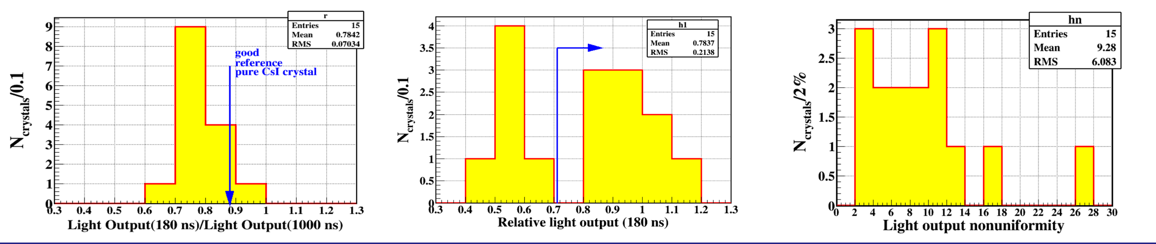




7. CsI(pure) crystals and WLS(NOL-9) plates

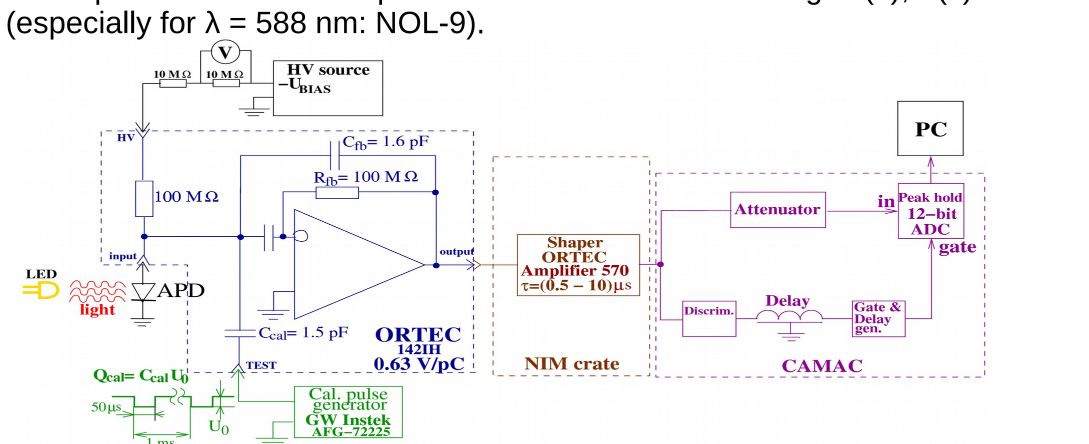
- **We plan to construct calorimeter prototype made of 16 counters**, the parameters of available 18 crystals (of 6 x 6 x 30 cm³ size) were measured
- Optimization of the shape of the WLS plate was done, further signal improvement of 1.6 was achieved
- 10 WLS plates of different shapes were purchased, 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





8. Spectral characteristics of Hamamatsu APD S8664-55

- In the counter based on the CsI(pure) crystal, WLS plate and APD(s) (Hamamatsu S8664-55), the statistical noise, ~√F (F – excess noise factor of APD), provides notable contribution to the evaluated energy resolution at the energies E_γ < 0.3 GeV.
- It is important to measure spectral characteristics of APD: gain(λ), F(λ) (especially for λ = 588 nm: NOL-9).



$$G(U_{BIAS}) = \frac{I_{light}(U_{BIAS}) - I_{dark}(U_{BIAS})}{I_{light}(10V) - I_{dark}(10V)} = \frac{I_{photo}(U_{BIAS})}{I_{photo}(10V)}$$

The RMS of the peak in the amplitude spectrum of the calibration signal is a measure of the equivalent noise charge (ENC) in the scheme with APD.

LED type	U, V	λ, nm
RED: ARL-3214URC-6cd	1.9 – 2.3	620 – 635
ORANGE: ARL-3214UYC-6cd	1.9 – 2.3	580 – 595
GREEN: ARL-3214PGC-6cd	2.9 – 3.3	520 – 530
BLUE-GREEN: ARL-3214BGC-15cd	2.9 – 3.3	495 – 510
BLUE: ARL-3214UGC-6cd	2.9 – 3.3	460 – 470
UV: L-7104UVC	3.9 – 4.2	385 – 405

9. Measurement of gain(λ) and F(λ)

$$ENC^2_{light}(U_{BIAS}) = 2e\tau(I_{photo} + I_{dark}) \cdot g \cdot F \cdot K_{shaper} + ENC^2_{other}(U_{BIAS})$$

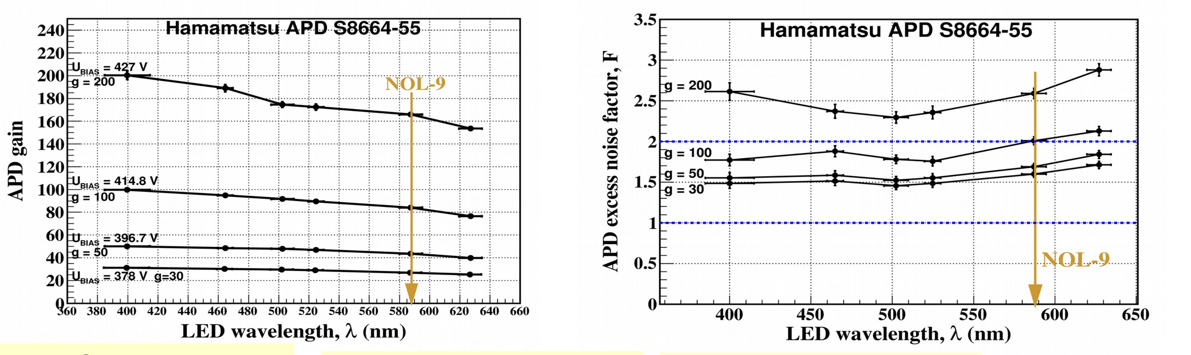
$$ENC^2_{dark}(U_{BIAS}) = 2e\tau I_{dark} \cdot g \cdot F \cdot K_{shaper} + ENC^2_{other}(U_{BIAS})$$

$$F(U_{BIAS}) = \frac{ENC^2_{light}(U_{BIAS}) - ENC^2_{dark}(U_{BIAS})}{2e\tau I_{photo}(U_{BIAS})\, g(U_{BIAS})\, K_{shaper}}$$

♦ $ENC_{other}(U_{BIAS})$ – thermal (~APD capacitance) + additional noise. ♦ e – positron charge;

♦ K_{shaper} = 1.55 ± 0.06 – shape factor of ORTEC Amplifier 570; ♦ τ – shaping time;

♦ $I_{photo}(U_{BIAS})$ – photocurrent; ♦ $g(U_{BIAS})$ – APD gain;



For λ = 588 nm: F(g=30) = 1.59 ± 0.04 F(g=50) = 1.69 ± 0.04 F(g=100) = 2.00 ± 0.05 F(g=200) = 2.58 ± 0.06

10. 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

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

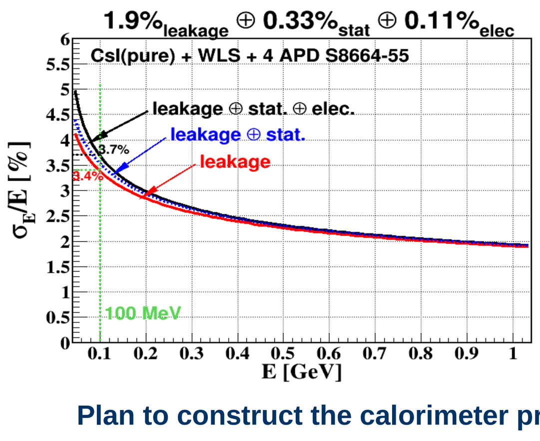
$$Elec = 100\% \cdot \frac{ENE[MeV] \cdot \sqrt{N_{crys}}}{1000}$$

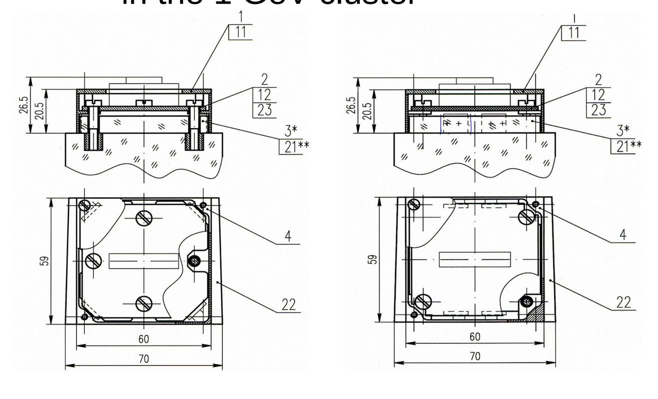
F = 1.69 ± 0.04

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

ENE = (0.33 ± 0.03) MeV

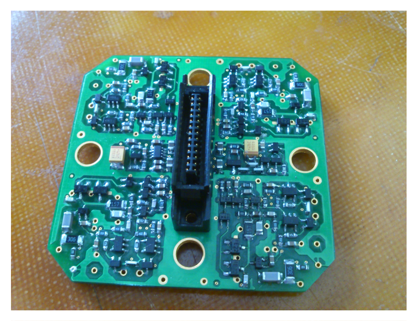
N_{crys} = 10 – number of crystals in the 1 GeV cluster



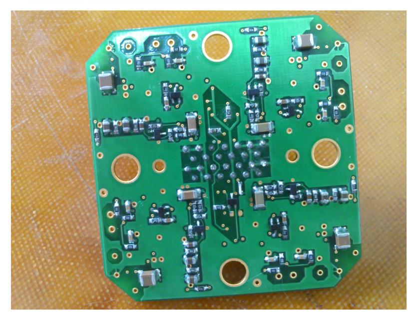


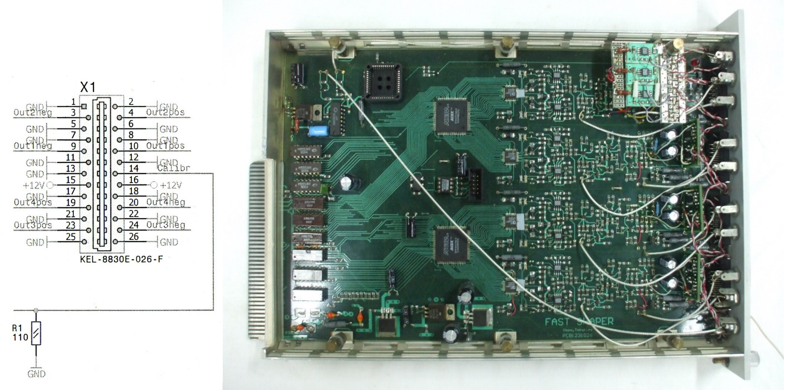
Plan to construct the calorimeter prototype (16 counters) and perform beam tests

11. Electronics for the prototype



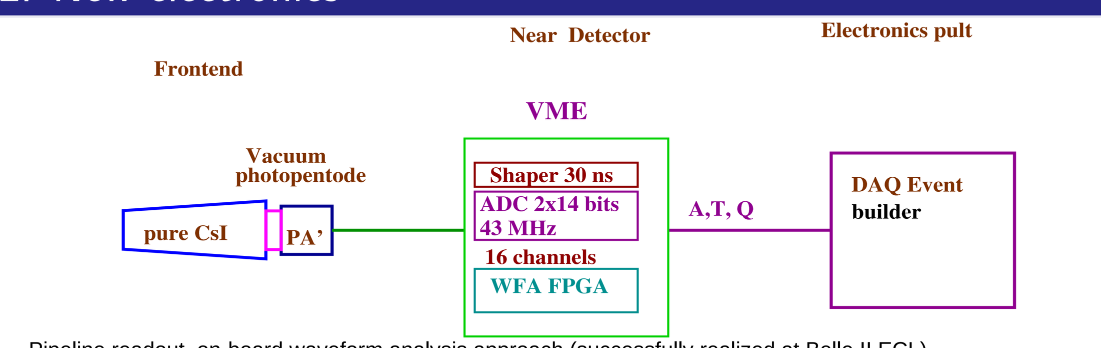
- **4-channel charge sensitive preamplifier** on 53 x 55 mm² PCB
- Each channel: sensitivity of 0.2 V/pC, 2 input FET 2SK932 (high transconductance), differential output, HV bias circuit, test pulse input



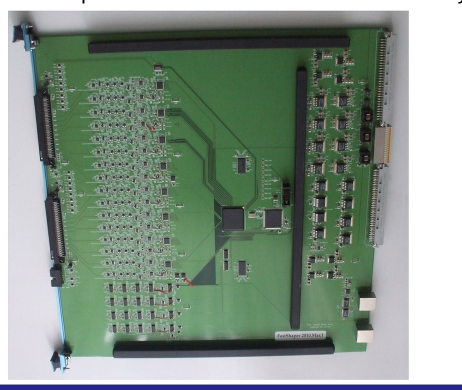


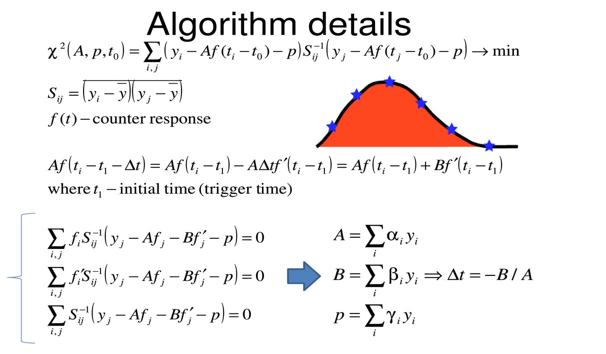
- **4-channel CAMAC Shaper-ADC board**
- CR-(RC)⁴ filter (τ = 30 ns) + 40 MHz 12-bit pipelined ADC + 256-word circular buffer
- To comply with the new 4-ch preamp additional differential receiver and summator (DRS) boards have been produced and mounted in the Shaper-ADC boards

12. New electronics



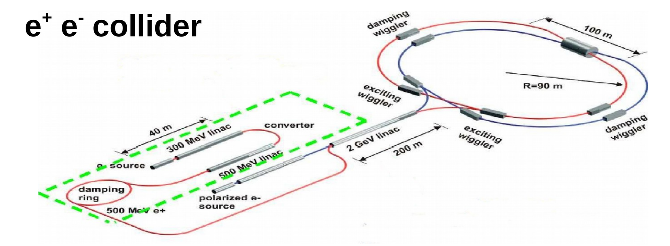
- Pipeline readout, on-board waveform analysis approach (successfully realized at Belle II ECL)
- Preamplifier is located in the counter, shaping digitization and analysis is implemented in the VME 9U Shaper-DSP board located nearby the detector. Shaper: CR + (RC)⁴ with the **shaping time of 30 ns**. 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





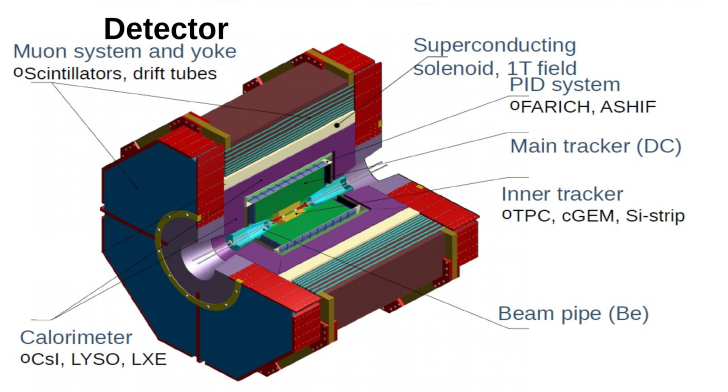
13. Super Charm-Tau Factory in Novosibirsk

- Double ring collider with crab waist
- CM energy from 2 to 6 GeV
- L = 10³⁵ at 2 GeV
- Beam size at IP: 20 x 0.2 μm
- Longitudinal polarization of e⁻

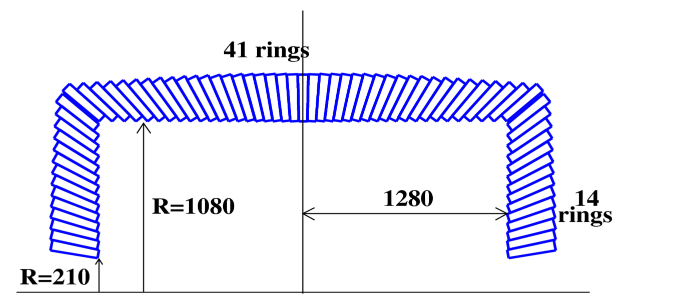


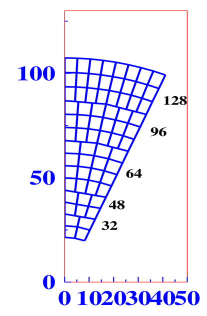
Requirements

- Occupancy up to 300 kHz
- Good energy and momentum resolution
- High reconstruction efficiency to soft tracks
- Perfect π/K and π/μ separation
- Minimal $\mathcal{CP}$ detector asymmetry



14. Sketch of the calorimeter for Super Charm-Tau Factory





68 counters in 1 sector

- **Crystal of truncated pyramidal form (small facet ~(5.5 x 5.5) cm²) 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\$**

15. Summary

- CsI(pure) inorganic scintillation crystal is an appropriate material for the electromagnetic calorimeter of the modern e⁺e⁻ Super factories.
- Compact, insensitive to magnetic field and modest price Hamamatsu APD S8664-55 is an appropriate photosensitive element, several APDs in one counter provide necessary signal readout redundancy.
- An essential increase (x 6 times) of the light output of the CsI(pure)+APDs counter was achieved with WLS plates of special shape made of PMMA and the nanostructured organosilicon luminophores (NOL-9).
- The ENE of the counter based on CsI(pure) + WLS(NOL-9) + 4 APDs was measured to be ENE = (0.33 ± 0.03) MeV, which allows one to achieve high energy resolution (σ_E/E = 3.7%) even for the small energy gammas with E = 100 MeV.
- The pipeline readout with on-board waveform analysis (already implemented in Belle II calorimeter) will provide good time resolution (to suppress beam background) and ability to work at high occupancies.
- The calorimeter prototype of 16 counters based on CsI(pure) crystals, WLS(NOL-9) plates and Hamamatsu S8664-55 APDs is under construction. All necessary electronics (preamplifiers, preliminary Shaper-ADC boards) have been developed and produced. It will be studied on the test beam facility in 2019 in Budker Institute of Nuclear Physics.

5th International Workshop on New Photon-Detectors PD18