Study of a scintillation counter consisting of a pure CsI crystal and APD

JIN Yifan

Aihara Lab

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Outline

- Belle II calorimeter upgrade
- Electronics noise in the scheme with APD
- CsI(pure)+(1-4)APDs light output and equivalent noise energy
- Improvement of the light output
- Novel wavelength shifters with nanostructured organosilicon luminophores
- Summary and Plans
Belle and Belle II

Belle experiment operated at KEKB accumulated the world's largest statistics of B meson decays. CPV was observed in B decays at Belle. CKM mechanism was confirmed. And plenty of other fruitful results were achieved at Belle.

At Belle, we are searching for New Physics in many processes (B decays, D decays, $\tau$ decays), for example, decay mode $B \rightarrow \tau \nu$ was studied [PRL 110 131801 (2013)]. This mode is sensitive to the BSM with charged Higgs (2HDH).

\[
\frac{r_H}{Br(B^+ \rightarrow \tau^- \bar{\nu}_\tau)} = \left(1 - \frac{M_B^2}{M_H^2} \tan^2 \beta \right)^2
\]

\[
Br(B^+ \rightarrow \tau^- \bar{\nu}_\tau) = (0.72 \pm 0.27^{(\text{stat})} \pm 0.11^{(\text{syst}}) \times 10^{-4}
\]

The statistical error is still large, so higher luminosity is needed.

Belle II, as an upgrade of Belle, planned to increase the luminosity by a factor of 40, will be capable to test several BSM. Belle II is complementary to the current and coming energy frontier experiments (LHC).
Belle II detector

- **EM Calorimeter:** Csl(Tl), waveform sampling (barrel), Pure CsI + waveform sampling (end-caps)
- **Beryllium beam pipe:** 2cm diameter
- **Vertex Detector:** 2 layers DEPFET + 4 layers DSSD
- **Central Drift Chamber:** He(50%):C$_2$H$_6$(50%), Small cells, long lever arm, fast electronics
- **KL and muon detector:** Resistive Plate Counter (barrel), Scintillator + WLSF + MPPC (end-caps)
- **Particle Identification:** Time-of-Propagation counter (barrel), Prox. focusing Aerogel RICH (fwd)

**Electron (7GeV)**

**Positron (4GeV)**
Upgrade of end cap ECL

- As the luminosity gets increased of 40 times, the pile-up noise produced by the high rate low energy background photons will be very notable and severe, especially in end cap electromagnetic calorimeter (ECL).

\[ \sigma_{E_{\text{Pile up}}} \sim \bar{E}_\gamma \sqrt{\nu \tau} \]

\( \bar{E}_\gamma \), average energy of background photon; \( \nu \), background event frequency; \( \tau \), shaping time

- Reducing shaping time only will reduce the signal (CsI (Tl)) at the same time.

- Fast scintillators with as small as possible scintillation decay time are needed.

- We chose pure CsI, due to its fast scintillation time, moderate cost, radiation hardness and handy mechanical property. Therefore, shaping time is set to be 30ns. A factor of \( \sqrt{\frac{\tau_{\text{CsI(Tl)}} = 1\, \mu s}{\tau_{\text{CsI(pure)}} = 30\, \text{ns}}} \approx 5.5 \) is earned to reduce the pile up noise with pure CsI.

- However, the light yield of pure CsI is only 10% of that of doped one. Therefore, PIN-photodiode (without internal amplification) is no longer sufficient. New photosensors with internal amplification, like vacuum photopentodes, silicon photo multiplier (SiPM) and avalanche photodiodes (APD), are under consideration.
End cap ECL upgrade (option 1)

The main end-cap ECL upgrade option is to use pure CsI crystals readout by Hamamatsu photopentodes R11283MOD-A (ENE ~ 200 keV [1]).

However, there are some difficulties: no redundancy, notable dependence on magnetic field, long term stability, new mechanical support is needed.

In the CsI(pure) + Si APD option, APDs from Hamamatsu Photonics are investigated. The advantages of APD are:
1. compactness; 2. insensitivity to magnetic field; 3. demanding of bias voltage and low dark current of ~ nA.

The main problem with APD is to reach desirable level of electronic noise. With the actual size crystal and 1 APD (1 x 1 cm$^2$) Hamamatsu S8664-1010, we obtained ENE $\approx$ 2 MeV, while the required ENE $\leq$ 0.5 MeV.
# Photopentode VS APD

<table>
<thead>
<tr>
<th></th>
<th>Photopentode</th>
<th>APD S8664-55</th>
<th>APD S8664-1010</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U_{\text{operating}}$ (V)</td>
<td>$&gt; 800$</td>
<td>400</td>
<td>400</td>
</tr>
<tr>
<td>Gain</td>
<td>20</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Sensitive area (cm$^2$)</td>
<td>20</td>
<td>0.25</td>
<td>1</td>
</tr>
<tr>
<td>QE(%)</td>
<td>15</td>
<td>30 ± 10</td>
<td>30 ± 10</td>
</tr>
<tr>
<td>Capacitance (pF)</td>
<td>~ 10</td>
<td>85</td>
<td>270</td>
</tr>
<tr>
<td>$(1/G)(dG/dT)$ @G=50</td>
<td>&lt;&lt; 1%</td>
<td>3%</td>
<td>3%</td>
</tr>
</tbody>
</table>

The low capacitance and large sensitive area provide photopentode low noise. However, at bias voltage and QE, APD's performance is better. **In the case of photopentode, the stochastic noise is the dominant term. However, for APD, the situation is reverse. Electronics noise is dominant, and stochastic noise can be neglected.**
Layout of setup

- Aluminized mylar
- APD
- Csl crystal 6 x 6 x 30 cm³
- Teflon

CAEN preamp.
CP 4467A Fast Shaping Amplifier (NIM)
τ = (20—500) ns

4ch preamplifier
CAEN A1422B045F3
45 mV/MeV (1 V/pC)

Hoshin C008 16ch peak hold ADC (CAMAC)

PC
Study of electronic noise

\[ \text{ENC}_{\text{best}}^2 = 2ABC + E^2C^2 + D^2 \]

\[ \tau_{\text{best}} = \frac{BC}{A} \]

Shot noise coefficient, \( A = \sqrt{2 I_{\text{dark}}} K_1 g F/e \)

Thermal noise coefficient, \( B = \frac{\sqrt{4 k_B T R_s K_3}}{e} \)

1/f noise coefficient, \( E = \sqrt{K_2 A_f} \)

\( A_f \) is a noise coefficient of order \( 10^{-10} - 10^{-12} \) V^2

\[ e \] – positron charge;

\[ I_d \] – dark current;

\( F \) – excess noise factor;

\( C \) – APD junction capacitance;

\( \tau \) – shaping time;

\( g \) – APD gain;

\( K_1 K_2 K_3 \) – shaper factor;

\( R_s \) – equivalent serial resistance of preamp

\( D \) – additional noise.
Measurement of total ENC and addition noise (D)

- At the shaping times from 20 ns to 500 ns, D is not constant. It varies strongly, which is explained by the relatively large additional parallel (i_{na}) and serial (e_{na}) noises.

- Fast shaper of better quality (like ORTEC 474, 579) might be helpful to decrease D.

\[
1 - \frac{\sqrt{1850^2 - 650^2}}{1850} = 6\%
\]

\[
1 - \frac{\sqrt{1050^2 - 650^2}}{1050} = 21\%
\]
Measurement of thermal noise B, 1/f noise E

Two well known capacitors $C_1$ and $C_2$ were used to measure $B$ and $E$.

$$B^2/T + E^2 = (Q_1^2 - Q_2^2)/(C_1^2 - C_2^2)$$

$$B = (26.2 \pm 0.8 \pm 4.8) \sqrt{\text{ns/pF}}$$

$$E = (6.1 \pm 0.1 \pm 0.4) 1/\text{pF}$$

$$B^2/T = (4k_B T R_S)/\tau e^2$$

$R_S$, equivalent serial resistance, is dominated by reversal transconductance of the CAEN preamp's FET (BF862).

$R_S \approx 50 \Omega$ was also measured with additional serial resistance at the CAEN preamp input.

Therefore, we tried FET 2SK932-23, one of the best FET at short shaping times, with intention to get lower $R_S$. However, no obvious improvement is obtained.

**There is no potential to reduce B and E!**
Shot noise, excess noise factor $F$

$$Q^2_{\text{no } \text{photo}} = 2 \cdot e \cdot I_d \cdot \tau \cdot g \cdot F \cdot K + (B^2/\tau + E) \cdot C_d^2 + D^2$$

$$Q^2_{\text{with } \text{photo}} = 2 \cdot e \cdot (I_d + I_{\text{photo}}) \cdot \tau \cdot g \cdot F \cdot K + (B^2/\tau + E) \cdot C_d^2 + D^2$$

$$F = \frac{(Q^2_{\text{with } \text{photo}} - Q^2_{\text{no } \text{photo}})}{(2 \cdot e \cdot I_{\text{photo}} \cdot \tau \cdot g \cdot K)}$$

$K_2(\text{EXP}) = 0.44 \pm 0.02$  $K_2(\text{CR-4RC}) = 0.45$

measured by PIN-photodiode

S8664-55: $g = 50$, $F = 5.1 \pm 0.5$

S8664-1010: $g = 50$, $F = 3.4 \pm 0.4$

Excess noise refers to the additional noise due to avalanche fluctuation, and can be expressed as: $F = h^* g + (2-1/g)(1-h)$

where $h$ is the ratio of the hole impact ionization rate to that of electrons.
ENC vs. shaping time

\[ \text{ENC}^2 - D^2 = A^2 \tau + (B^2/\tau + E^2)C^2 \]

\[ A = \sqrt{(2 I_{\text{dark}} K_1 g F/e)} \quad B = \sqrt{(4 k_B T R_S K_2)} / e \quad E = \sqrt{(K_3 A_f C^2)} \]

Discrepancy between calculated and measured \( \sqrt{\text{ENC}^2 - D^2} \) is due to the uncertainty in \( C_{\text{APD}} \).

The agreement between the measured noise and noise calculated by the formula indicates good suppression of the correlated noises.
Light output (LO) and ENE

Cosmic muons are used to calibrate ADC channels in units of energy (MeV)

\[ E_{\text{peak (cosmic)}} \approx 33 \text{ MeV} \]

**ENE = \sigma_{\text{cal}} \times \text{Conversion}_{\text{ADC}}**

The light output is measured by comparison of the signal from cosmic muons \((A_{\text{cosmic}})\) with calibration signal \((A_{\text{cal}})\).

\[ N_{\text{cosm}} \text{ (ph.e.)} = (C_{\text{cal}} \times U_0 / e) \times (A_{\text{cosm}} / A_{\text{cal}}) \]

Sensitivity = \( N_{\text{cosm}}^{MC} / E_{\text{peak}}^{MC} / \text{(APD gain = 50)} / (S_{\text{APD}} [\text{cm}^2]) \)

Sensitivity = \( 26 \pm 2 \text{ ph.e. / MeV / cm}^2 \)
ENE, several APDs per crystal

1 APD S8664-1010 has essentially larger dark current (26 nA) in comparison with the average one (8 nA), we introduce correction to ENE.

<table>
<thead>
<tr>
<th>ENE</th>
<th>Measured</th>
<th>Estimated</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 S8664-1010 (same (I_{\text{dark}}))</td>
<td>1.1 + 0.11 MeV</td>
<td>0.97 + 0.09 MeV</td>
</tr>
<tr>
<td>2 S8664-55</td>
<td>1.7 + 0.17 MeV</td>
<td>2.05 + 0.18 MeV</td>
</tr>
<tr>
<td>4 S8664-55</td>
<td>1.2 + 0.12 MeV</td>
<td>1.36 + 0.12 MeV</td>
</tr>
</tbody>
</table>

The ENEs of the counter are far away from our goal. Further studies are needed.
To increase the light output

The light collection coefficient is strongly depending on the quality of APD coupling to crystal and reflectivity of the wrapping material.

1, Three types of optical grease were tested, OKEN-6262A, BC-630 and TSF451-50M. However, we didn't find anything better than OKEN-6262A.

2, White porous Gore-Tex teflon was confirmed as the best reflector at UV range [1]. The thickness of the white teflon was studied. It is shown that 200 μm is sufficient, further increase on thickness provides no more than 5% improvement on signal.


Wavelength shifters with organosilicon luminophores

Based on the nanostructured organosilicon luminophores (NOL-9,10,14) from LumInnoTech Co., the WLS plates were developed ((60 x 60 x 2) mm$^3$).

The absorption and emission spectra of these NOL's match our needs very well ($\lambda_{\text{Csl}} = 320$ nm). The improvement of the APD QE is by a factor of 2–3.
Results with WLS plates

NOL-9 turns out to be the best WLS that provides an enhancement on signal by a factor of about 3.

It is important to cover the whole $6 \times 6 \text{ cm}^2$ plate by optical grease!
However, the largest signal is achieved w/o optical grease between crystal and WLS plate!

\[
\text{ENE}(2 \text{ S8664-1010}) = (0.53 \pm 0.05) \text{ MeV} \\
\text{ENE}(4 \text{ S8664-55}) = (0.45 \pm 0.05) \text{ MeV} \\
\text{(one APD was operated with gain>50)}
\]

Error originates from the relative temperature gain variation \((1/G)(dG/dT)\), accuracy of simulation of cosmic peak position and statistical accuracy of the data.
Summary & Plans

- Hamamatsu APDs of S8664 series provide a promising option for Belle II end cap ECL upgrade.
- Several APDs per crystal allow us to decrease further ENE and provide readout redundancy.
- Essential increase of the light output of the CsI(pure)+APD(s) counter was achieved with WLS plates based on the nanostructured organosilicon luminophores (NOL-9).
- The ENE of the counter with 2 S8664-1010 APDs was measured to be ENE = (0.53 ± 0.05) MeV, which is close to project requirements.
- Radiation hardness of WLS plates is under investigation.
- We are testing the scheme where APDs are mounted to the side edge of the thick WLS plate.
- We will test pipeline readout scheme with a special shaper-FADC board.
- The preliminary results have been already reported at 13th Pisa Meeting and PhotoDet-2015 conferences.
Finally, I would like to thank Prof. Aihara and Dr. Epifanov for their instruction on this study.
Back up
Evaluation of the desirable noise level (0.5 MeV)

Energy resolution can be expressed as:

$$\frac{\sigma_E}{E} = \sqrt{\left(\frac{1.9\%}{\sqrt{E(\text{GeV})}}\right)^2 + \left(\frac{A}{E(\text{GeV})}\right)^2 + B^2}$$

- shower leakage
- electronics noise

small additional noise from: stability of counter, stochastic noise and non-uniformity.

Taken into account the typical threshold of the energy of photon in data analysis of Belle, 100 MeV, the first term gives an energy resolution 3.4%, in other words, $\sigma_{E(\text{shower})} = 3.4$ MeV.

Electronics noise contributes $< 10\%$ total noise

$$\frac{\sigma_{E(\text{ele})}^2}{3.4^2 + \sigma_{E(\text{ele})}^2} \leq 10\% \quad (1.13 \text{ MeV})$$

At Belle, a 100 MeV photon shower involves five crystals. And we assume these channels are uncorrelated.

$$\sigma_{E(ele)} \approx \frac{1.13}{\sqrt{5}} \approx 0.5 \text{MeV}$$
## Improvement of the LO

<table>
<thead>
<tr>
<th></th>
<th>Refraction index</th>
<th>Transparency @315 nm from the producer</th>
<th>Light collection efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>OKEN-6262A</td>
<td>1.453 (@ 590 nm)</td>
<td>85%</td>
<td>1.00</td>
</tr>
<tr>
<td>TSF451-50M</td>
<td>1.404 (@ 590 nm)</td>
<td>98%</td>
<td>0.85</td>
</tr>
<tr>
<td>BC-630</td>
<td>1.465</td>
<td>95%</td>
<td>0.95</td>
</tr>
</tbody>
</table>

Three types of optical grease were tested ($\Delta = 100 \, \mu m$), **OKEN-6262A** provide the largest light output.

Effect of the thickness of white porous Gore-Tex teflon was studied, thickness of **200 $\mu m$** was found to be optimal.

![Graph](image.png)

Characteristics of APD

APD is a dominant source of the signal temperature variations, which have to be compensated \((1/G)(dG/dT)\ [%/°C]\)

To compensate temperature variations of APD gain, we can organize temperature sensor - bias voltage feedback.