The BELLE Electromagnetic Calorimeter and its upgrade to BelleII

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Outline:
- BELLE CsI(Tl) calorimeter
- SUPERKEKB and BelleII
- Front End electronics upgrade for BelleII
- Commissioning of ECL for phase 2 and 3
- Upgrade of the CsI(Tl) to pure CsI
- Summary and Conclusions
• Large dynamic range: 20MeV~8GeV
  – 1/3 of B decays have $\pi^0$, most of $\gamma \sim 100$MeV.
  – Radiative B decays ($B \rightarrow K^* \gamma$, etc.) $\gamma$ up to 4GeV
  – Bhabha, $e^+e^- \rightarrow \gamma \gamma$ calibration, up to 8GeV
• High energy resolution
  – $\sigma_E/E \sim 4\%$ at 100MeV
  – $\pi^0$ Mass resolution $\sim 5$MeV
• High position resolution
  – $\sigma_x : 5\sim 10$mm at the incident point
Belle

Belle II

CsI(Tl) Calorimeter

8736 CsI(Tl) crystals
6624 Barrel
1152 Fwd. Endcap
960 Bwd. Endcap

30cm long
CsI(Tl) = 16.1X0

Light output – 5000 ph/el./MeV
electronics noise σ~200 keV

Lcr = 30 cm = 16.2X0

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η → γγ in hadronic events

\[ \sigma_m = 12.1 \pm 0.2 \text{ (MeV/c}^2) \]

π\(^0\) → γγ in hadronic events

\[ \sigma_m = 4.75 \pm 0.08 \text{ (MeV/c}^2) \]

Test beam

\[ \sigma_E/E = 1.7\% \]
SuperKEKB

Currents $\times 2$, $\beta^*_y \times 1/20$ w.r.t. KEKB to aim $\times 40$ luminosity

See P. Krizan’s talk
ECL in view of luminosity increase

Radiation damage of crystals after BELLE (1 ab⁻¹)

Expected dose in crystal @ Belle-II
FWD ECL: 5-6 Gy/yr x 10 yr of data taking → a factor of 13 higher than in BELLE

In the most loaded part the light output degradation is about 10%

See D.Matvienko’s poster
Background increase: pile-up effect

Scintillation decay time is $\sim 1\mu$s

Signal by physics particle incident

Pileup caused by beam background incident

behaves as noise increase

CsI(Tl):
- very high light output 😊
- very slow device 😞

Need a fast and rad-hard detector

(E$\geq 20$ MeV) 6 fake clusters, 3 in barrel 3 in endcaps background
Background MC campaign

Crystal Radiation Dose vs $\theta_{ID}$

14.5th campaign
maximum dose: 5.52 Gy/yr

15th campaign
maximum dose: 6.27 Gy/yr
**Read-out electronic upgrade**

**EARLY PROTOTYPE TESTED AT BELLE**

- Gate width = 100ns
- Timing (leading/trailing edges) with range information by QtoT converter (MQT300A)
- Digitized by TDC
- Shaper output signal
- 1.76MHz, 18bits digitizer, waveform fit to get energy and timing (i.e. Digital Signal Processing)

Reduction factors:
- ×7 BG showers
- ×1.5~2 pileup noise

Pileup reduction
ECL pulse-shape calibration

- First calibration with very preliminary start coefficients is done by about 130 iterations and takes about 30 min. The next calibrations take about 10 min.
- Whole calibration time (including data taking and copying raw files to KEKCC) takes about 1.5 days.

See A.Bobrov's poster
Endcap Installation

Endcap tested before and after installation → all channels working and all DSP shapers

FWD Endcap installation
September 2017

Barrel and Backward are being monitored and calibrated (barrel) → stability $10^{-3}$
ECL cosmic test

- CDC-ECL cosmic run was performed Feb. 2 2017
- Short runs with total statistic of about 4000 events
- ECL distributions seems to be reasonable
Environment monitoring

See F. Di Capua’s talk
New ECL reconstruction

Written from scratch and optimized for different backgrounds

4.5 MeV
BGX0

5.6 MeV
BGX1

6.3 MeV
BGX2

PDG mass
01/03/2017

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Electronics upgrade may not be sufficient for the forward endcap

<table>
<thead>
<tr>
<th>Crystal</th>
<th>CsI(Tl)</th>
<th>CsI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g/cm³)</td>
<td>4.51</td>
<td>4.51</td>
</tr>
<tr>
<td>Melting Point (°C)</td>
<td>621</td>
<td>621</td>
</tr>
<tr>
<td>Radiation Length (cm)</td>
<td>1.86</td>
<td>1.86</td>
</tr>
<tr>
<td>Molière Radius (cm)</td>
<td>3.57</td>
<td>3.57</td>
</tr>
<tr>
<td>Interaction Length (cm)</td>
<td>39.3</td>
<td>39.3</td>
</tr>
<tr>
<td>Refractive Index</td>
<td>1.79</td>
<td>1.95</td>
</tr>
<tr>
<td>Hygroscopicity</td>
<td>Slight</td>
<td>Slight</td>
</tr>
<tr>
<td>Luminescence (nm)</td>
<td>560</td>
<td>420</td>
</tr>
<tr>
<td>(at Peak)</td>
<td>310</td>
<td></td>
</tr>
<tr>
<td>Decay Time (ns)</td>
<td>1220</td>
<td>30</td>
</tr>
<tr>
<td>Light Yield</td>
<td>165</td>
<td>3.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.1</td>
</tr>
<tr>
<td>d(LY)/dT (%/°CC)</td>
<td>0.4</td>
<td>−1.4</td>
</tr>
</tbody>
</table>

Because of short scintillation decay time, ~30ns, Pure CsI crystal is almost pileup free.
Photo Pentode readout is regarded as a baseline, noise~0.2MeV.

- **same density and radiation length allow to reuse Belle mechanical structure**

- **much lower light yield**
  - fast component of emitted light in the near-UV region

- **much faster light decay time**
  - but slow component is an issue for pile-up

- Use of Pure CsI requires R&D studies on:
  - photodetectors in the near-UV and wavelength shifters
  - radiation hardness of crystals, photodetectors, and wavelength shifters
  - electronics
Pure CsI optical properties: transmittance

- No irradiation
- @ 310 nm: L.T. ~ 50%, T.T. ~ 40% for Optomaterials, lower for Amcrys
- Transverse transmittance at different irradiated doses (7 to 104 Gy)
- Maximum variation @ 310 nm ~ -7%
- Saturation effects
- Completed and fast recovery for doses < 7 Gy (not shown here)
**Pure CsI Optical properties: Light Yield**

- **Optomaterials (Italy), 5x5x30 cm³**
- **Amcrys (Karchov, Ukraine), trapezoidal shape, ~7.5x7.5x30 cm³**

- **Longitudinal LY variation (Irradiated)**
  - before irr.: ~ 6-10%
  - after irr.: ~ 7-15%
  - LY variation before and after irr.: ~1-5%

- **No irradiation**
  - Longitudinal LY variation < 10%

01/03/2017  
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## Photodetector options

Requirement: photodetector ENE < pile-up noise (O(1MeV))

### Photodetector options:

<table>
<thead>
<tr>
<th></th>
<th>PhotoPentodes</th>
<th>Large Area APD (LAAPD)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>C (pF)</strong></td>
<td>10</td>
<td>270</td>
</tr>
<tr>
<td><strong>Gain@V_{op}</strong></td>
<td>150-250 [*]</td>
<td>50 [**]</td>
</tr>
<tr>
<td><strong>Q.E.@310 nm (%)</strong></td>
<td>25</td>
<td>50</td>
</tr>
<tr>
<td><strong>Area (cm²)</strong></td>
<td>20</td>
<td>10x10</td>
</tr>
</tbody>
</table>
| **Comments**         | • [*] gain reduced by 75% in 1.5T magnetic field  
• 1 PP per crystal, no redundancy  
• back plane of the mechanical structure need to be replaced | • [**] special production with G=200  
• 2 LAAPD per crystal |
Extensive R&D has been done on Pure CsI + LAAPD

They meet the experiment requirement \((\text{ENE} O(1\text{MeV}))\)

<table>
<thead>
<tr>
<th>(\sigma [\text{mV}])</th>
<th>Signal [\text{mV}]</th>
<th>S/N</th>
<th>ENE [\text{MeV}]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.80(\pm)0.17</td>
<td>108.6(\pm)0.6</td>
<td>38.8(\pm)2.4</td>
<td>0.77(\pm)0.05</td>
</tr>
</tbody>
</table>

- Study effect of ionizing and non-ionizing radiation:
  - gamma: \(250 \text{ Gy} = 10 \text{ y data taking} \times 10\) safety factor
  - Neutron fluence: \(10^{12} \text{ n/cm}^2 = 10 \text{ y data taking} \times 5\) safety factor

- Quantum efficiency:
  - Decrease after irradiation with \(\gamma\) at 250 Gy

- Gain:
  - almost stable
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- Dark current:
  - 2 orders of magnitude increase after neutrons + gamma
R&D on Wavelength Shifters

- Novel wavelength (WLS) plates containing nanostructured organosilicon luminophores provides essential increase in light output

LuminoTech Co, (60x60x2 mm³) WLS plates

- Results:
  
  - Enhancement on signal of a factor of about 3 (n.b. test performed with G=50 LAAPD)
  
  - Increase in LAAPD Q.E. of a factor of 2-3

- Radiation hardness tests on NOL9 WLS: no irradiation effects on excitation/emission peaks up to 105 Gy
Pile-up study: cosmic+source

- Signal from cosmic rays superimposed to 1.33 and 1.17 MeV produced by $^{60}$Co
  - $1.77 \pm 0.04$ hits/μsec from source

- From the difference in quadrature of the measurements with and without source, pile-up effect can be estimated: CsI(Tl) shows twice the ENE of pure CsI

- [nb: wrt to pag 12 (ENE=0.77MeV), different shaping times and signal window used, optimization of such parameters underway]

The ENE with pile-up is ~2 MeV for pure CsI and ~3 MeV for CsI(Tl)
Conclusions

• Belle CsI(Tl) calorimeter successfully operated for 10 years to bring various physics output

• SuperKEKB is aiming x40 luminosity w.r.t. KEKB.
  - Beam background control is a challenge for the detector and its performances
    Use all the existent CsI(Tl) with waveform sampling readout electronics.
    Full simulation studies for CsI(Tl) deterioration \(\rightarrow\) new reconstruction algorithm

• PureCsI upgrade
  - Extensive R&D on crystals and photodetectors shows that the upgrade represents an improvement in dealing with beam background and pile-up
  - A real estimation of the background is necessary before the decision is taken \(\rightarrow\) after the first run of Belle II for the background measurement