Electromagnetic calorimeter for Belle II

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on behalf of BELLE calorimeter group

Budker Institute of Nuclear Physics Novosibirsk,
Novosibirsk State University
KEKB and Belle at KEK
From 1999 to 2010

Peak lumi record at KEKB:
$L = 2.1 \times 10^{34} \text{cm}^2/\text{sec}$ with crab cavities
**SuperKEKB**

- **e⁻ 7 GeV 2.6 A**
- **e⁺ 4 GeV 3.6 A**

*New superconducting/permanent final focusing quads near the IP*

*Add / modify RF systems for higher beam current*

- **Belle II**
- **New IR**

*Colliding bunches*

- **New beam pipe & bellows**
- **Replace short dipoles with longer ones (LER)**
- **Redesign the lattices of both rings to reduce the emittance**
- **TiN-coated beam pipe with antechambers**
- **Inject low emittance positrons**
- **Damping ring**
- **Inject low emittance electrons**

*Positron source*

- **New IR**
- **New positron target / capture section**

*New IR*

**x 40 Increase in Luminosity**

\[
L = \frac{\gamma}{2\epsilon} \left(1 + \frac{\sigma_y^*}{\sigma_x^*}\right) \left(\frac{I_{\pm \pm \pm \pm}}{\beta_y R_L} \frac{R_L}{R_y}\right)
\]
Belle II Detector (in comparison with Belle)

SVD: 4 DSSD lyr → 2 DEFPET lyr + 4 DSSD lyr
CDC: small cell, long lever arm
ACC+TOF → TOP+A-RICH
ECL: waveform sampling (+pure CsI for end-caps)
KLM: RPC → Scintillator +MPPC(end-caps)
Role of electromagnetic calorimeter

Measurement of
- Energy/angle of photon (20MeV~8GeV)
- Electron identification
- $K_L$ detection together with KLM
- Redundant trigger
- Neutral trigger

Measurement of the luminosity
- Online/offline luminosity

Very important: high resolution for low energy photons are needed
BELLE Electromagnetic Calorimeter for KEKB energy asymmetric B-factory

CsI(Tl) crystals

\[ L_{er} = 30 \text{ cm} = 16.2X_0 \]

Number of crystal: 8736
Total weight is \(~43\text{ton}\)

2/3 of these crystals were provided by the Kharkov&BINP,

Others – Crismatec and Shanghai

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CALOR 2014, Giessen
Belle ECL

- Calorimeter successfully worked for more than 10 years since 1999 to 2010
- All 8736 channels are operable
- It demonstrated high resolution and good performance.

**Test beam**

Light output - 5000 ph.el./MeV
Electronics noise $\sigma \sim 200$ keV
Calorimeter performance in a view of the luminosity increase.

At $L \sim 10^{34}\text{cm}^{-2}\text{s}^{-1}$ and $\int L dt \sim 700\text{fb}^{-1}$

Radiation damage of the crystals

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

Basically – no problem.

Increase of the PD dark current

Small increase of the dark current in barrel

Essential increase of the dark current in endcaps

Caused by neutrons flux

Results in $\sigma_d \sim 0.2-0.3\text{ MeV}$, still not the most annoying problem.
Fake clusters

(E>20 MeV) 6 fake clusters, 3 in barrel 3 in endcaps background

Pile-up noise

$$\sigma_{\text{pile-up}} = E_\gamma \sqrt{f_{\text{bkg}} \cdot \tau_{\text{eff}}} \propto \sqrt{I \cdot P}$$
The obvious solution is to replace CsI(Tl) crystals by the other scintillators with

\[ L \sim L_{\text{CsI(Tl)}}, \ \tau \sim \tau_{\text{CsI(Tl)}/10} \text{ and zero afterglowing.} \]

Lu\(_2\)SiO\(_5\)(Ce), LuAlO\(_5\)(Ce), LaBr\(_3\)(Ce) ……  ?

Problems - cost and mass production

**We needed in a reasonable compromise…**

- To keep existing CsI(Tl) crystals in the barrel part.
- To keep existing CsI(Tl) crystals in the end caps at the initial stage.
- To modify all readout electronics.
- To replace CsI(Tl) to pure CsI crystals in the end caps at later stage.
- To keep the present mechanical structure.
- Belle II can get advantage in \( \pi^0 \) and soft photon-detection efficiency and resolution in comparision with LHCb experiment
- Modify electronics for the barrel.
- Pipe-line readout with waveform analysis:
  - 16 points within the signal are fitted by the signal function \( F(t) \):
    \[
    F(t) = A f(t - t_0)
    \]
    \( A \) - amplitude of the signal and \( t_0 \) - time of the signal,
    \[
    \chi^2 = \sum (y_i - A f(t_i - t_0)) S^{-1}_{ij} (y_i - A f(t_i - t_0))
    \]
- Both amplitude and time information are reconstructed:
- Next stage: Replace the CsI(Tl) by the pure CsI crystals in endcaps.
Expected improvement

- Time information allows to suppress the fake clusters by a factor of 7 for the barrel by rejecting wrong time clusters.
- For endcaps the suppression is by a factor of 7x30=200 due to shorter decay time of the pure CsI.

- The pileup noise will be reduced factor $\sim 1.5$ for barrel and factor 5 for endcaps.
There are 52 ECL VME crates
We don’t plan to install VME controller at the crates

The crates have non-standard power supplies:
7.5 V (instead of 5.0V)
15 V (instead of 12V)
FPGA algorithm

- Fit of several measurements to response function taking into account correlation between measurements \( \rightarrow A, T, \text{Quality} \)
- Correlation matrix is obtained from the data

FPGA overall design

Algorithm details

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

\[
S_{ij} = \left( y_i - \bar{y} \right) \left( y_j - \bar{y} \right)
\]

\[ f(t) - \text{counter response} \]

\[ Af(t_i - t_i - \Delta t) = Af(t_i - t_i) - A \Delta t f(t_i - t_i) = Af(t_i - t_i) + B f(t_i - t_i) \]

For some fraction of data both input and output informations are sent to DAQ for test
Shaper DSP module status

The design of ShaperDSP modules has been finalized. We need ~450 modules for barrel and ~150 modules for endcap.

Most of the modules were produced and delivered to KEK, remaining should be delivered during this year.

- Shaping of the signal with time 0.5 µs
- Waveform sampling with 2 MHz
- Waveform fitting in FPGA => A,T
- Providing fast sum signal for trigger (FAM)

In full range ~260 000 bins nonlinearity < 2 \times 10^{-3}

Trigger output

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To test modules of ShaperDSP, the test benches have been mounted in Hanyang University and at KEK.

It allows to test both barrel and endcap modules.

The set of tests:
- Signal shape
- FAM signal shape
- Channel workability
- Slope and linearity
- Noise
- FPGA logic
- Attenuation
Neutral trigger

- Basic element (576): Trigger Cell (4x4 crystal sum)
- Main physics event triggers
  - Energy trigger: $E_{TOT} > 1$ GeV & Bhabha
  - Cluster trigger: ICN > 3
- ECL TRG output to GDL

<table>
<thead>
<tr>
<th>Item</th>
<th>Number of bits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trigger timing (Final, Fwd, Barrel, Bwd)</td>
<td>4</td>
</tr>
<tr>
<td>Total Energy (&gt;0.5, 1.0, 3.0 GeV)</td>
<td>3</td>
</tr>
<tr>
<td>Isolated cluster</td>
<td>4</td>
</tr>
<tr>
<td>Bhabha-type</td>
<td>11</td>
</tr>
<tr>
<td>OR ed Bhabha</td>
<td>1</td>
</tr>
<tr>
<td>Barrel Bhabha</td>
<td>1</td>
</tr>
<tr>
<td>Prescale Bhabha</td>
<td>1</td>
</tr>
<tr>
<td>Cosmic veto</td>
<td>1</td>
</tr>
<tr>
<td>TC hit pattern</td>
<td>576</td>
</tr>
<tr>
<td>Total</td>
<td>26 + 576</td>
</tr>
</tbody>
</table>
Neutral trigger

The fast trigger output is digitized in FAM module with 10 MHz. TMM module generates flexible logic by FPGA using FAM outputs in order for neutral trigger as well as luminosity measurement.
Cosmic ray check of all barrel ECL elements after earthquake 2011

- VME crate
  +12 Shaper DSP
  +collector
  +FAM
- Computer

-- Test of barrel counters
-- Test of electronics

All 6624 channels are operable!
Still performance of the end caps is questionable

The obvious solution is to replace CsI(Tl) crystals by the other scintillators with

\[ L \sim L_{\text{CsI(Tl)}} \text{, } \tau \sim \tau_{\text{CsI(Tl)}}/10 \text{ and zero afterglowing.} \]

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Properties of pure CsI and CsI(Tl) scintillation crystals

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<tr>
<th></th>
<th>(\rho), g/cm(^3)</th>
<th>(X_0), cm</th>
<th>(\lambda_{\text{em}}, \text{nm})</th>
<th>(N(\lambda_{\text{em}}, \text{nm}))</th>
<th>(N_{\text{ph}}/\text{MeV})</th>
<th>(T), ns</th>
<th>(dL/dT), %/° @20°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure CsI</td>
<td>4.51</td>
<td>1.85</td>
<td>550</td>
<td>2</td>
<td>2000</td>
<td>20/1000</td>
<td>- 1.3</td>
</tr>
<tr>
<td>CsI(Tl)</td>
<td>4.51</td>
<td>1.85</td>
<td>305</td>
<td>1.8</td>
<td>52000</td>
<td>1000</td>
<td>0.4</td>
</tr>
</tbody>
</table>
Photodetector

Baseline option:

2" UV sensitive photopentods (PP), Hamamatsu Photonics
Q ~ 20%, C ≈ 10 pF.
PP gain factor 120-240.
(we need > 30 in mag.eld)

The gain factor drops down 3.5 times for B=15 kGs
About 20-30 % improvement for angle 20-45°

Alternative options with silicon APD are under study

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Beam test at BINP back scattered Compton beam

20 crystals of 8 geometrical types (part of FWD) produced in Kharkov, coupled with Hamamatsu phototetrodes.

Energy resolution is consistent with MC and previous beam test results.

Time resolution
Waveform analysis allows to determine time with accuracy better than 1 ns for $E > 20$ MeV (60 MeV in magnetic field).
Bremsstrahlung photons, \( E = 0 \div 1.4 \text{ MeV} \) from ELV-6, BINP

Absorbed doses 0.250, 1, 4, 10, 30 krad

14 full size crystals in total

- Most of the crystals has drop less than 20\% for 14 krad
- 3 crystals drop 20-35\%
- There is clear correlation lightoutput drops for small (0.3 krad) and full dose
Belle II Collaboration

23 countries/regions, 94 institutions, >500 collaborators

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### SuperKEKB/Belle II schedule

**→ construction started in 2010!**

**Ground breaking ceremony in November 2011**

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<td>✷ low emittance beam tuning</td>
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<td>✷ vacuum scrubbing</td>
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<td>✷ At least one month at beam currents of 0.5~1A.</td>
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**Phase 2: with final quads and Belle II, but no VXD**

- low beta* beam tuning
- small x-y coupling tuning
- collision tuning
- study beam background
- careful checks beam background before VXD installation.

**Phase 3: with QCS and full Belle II**

- physics run
- luminosity increase

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**Commissioning in three phases:**

- **Phase 1:** Start of commissioning
  - w/o final quads
  - w/o Belle II
  - basic machine tuning
  - low emittance beam tuning
  - vacuum scrubbing
  - At least one month at beam currents of 0.5~1A.

- **Phase 2:** With final quads and Belle II, but no VXD
  - low beta* beam tuning
  - small x-y coupling tuning
  - collision tuning
  - study beam background
  - careful checks beam background before VXD installation.

- **Phase 3:** With QCS and full Belle II
  - physics run
  - luminosity increase
Summary

- Belle calorimeter worked for more than 10 years and showed good performance
- New electronics was developed. Considerable part of the boards are already produced.
- All barrel counters have been tested and all are alive
- Option with pure CsI+PP is well developed and can solve the background problems in end cap parts
- Pure CsI crystals produced in Kharkov show good radiation resistance