Trigger and Data Acquisition (DAQ) Systems at the Belle II Experiment

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• High instantaneous luminosity
  – Designed peaking luminosity at SuperKEKB: $8 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$ (40 x KEKB)
  – Total physics event rate $\sim 15\text{kHz}$ @ $8 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$

• High beam-induced backgrounds
  – Touschek scattering is dominate
    • Proportional to the inverse of the beam size
    • “Nano-Beam” scheme at Belle II $\rightarrow$ smaller beam size
  – One order higher than Belle

• Huge data flow from pixel detector (PXD) $\sim 1\text{MB/event}$

<table>
<thead>
<tr>
<th>Process</th>
<th>$\sigma$ (nb)</th>
<th>Rate (Hz) @ $L=8 \times 10^{35}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upsilon(4S)</td>
<td>1.2</td>
<td>960.0</td>
</tr>
<tr>
<td>Continuum</td>
<td>2.8</td>
<td>2200.0</td>
</tr>
<tr>
<td>$\mu\mu$</td>
<td>0.8</td>
<td>640.0</td>
</tr>
<tr>
<td>$\tau\tau$</td>
<td>0.8</td>
<td>640.0</td>
</tr>
<tr>
<td>Bhabha $^*$</td>
<td>44.0</td>
<td>350.0</td>
</tr>
<tr>
<td>$\gamma\gamma$ $^*$</td>
<td>2.4</td>
<td>19.0</td>
</tr>
<tr>
<td>Two photon $^{**}$</td>
<td>13.0</td>
<td>10000.0</td>
</tr>
<tr>
<td>Total $^*$</td>
<td>67</td>
<td>$\sim 150000$</td>
</tr>
</tbody>
</table>

* Rate of Bhabha and $\gamma\gamma$ are pre-scaled by factor 100
** Rates are estimated by the luminosity component in Belle L1 trigger rate
Trigger and DAQ Challenges at Belle II (II)

- >99.9% efficient for B and D physics
- **Low multiplicity processes** challenge the trigger due to substantial QED background
  - LFV τ decay: \( \tau \rightarrow e/\mu \gamma \)
  - Leptonic τ decay: \( \tau \rightarrow e/\mu \nu \nu \)
  - Precision electroweak tests: ee and \( \mu \mu \)
  - Precision ISR for g-2: \( \pi\pi/KK/pp/... \) and one photon
  - Searches for Dark Photons and Light Higgs: 0/2/4 charged particles and one photon
  - ......

**LFV tau decay**

\[ \tau \rightarrow \nu_\tau \]

**Leptonic tau decay**

\[ \tau^- \rightarrow W^- + e^-/\mu^- + \nu_\tau \]

**Dark photon search**

\[ e^-(e^-) \rightarrow e^-,\mu^-,\pi^-,\tau^-,\bar{\nu}_e,\bar{\nu}_\mu \]

\[ E_Y = (s - M_{A'}^2) / 2\sqrt{s} \]

**Precision electroweak tests**

\[ A_{\gamma}(e^-e^-\gamma) \sim \frac{\alpha G_F}{4\sqrt{2}\pi s} \frac{M_{A'}}{s^2} \]

[Cortesi, G. et al. (Belle-II Collaboration), JHEP 19 (2019) 052]
Trigger

Scheme: Hardware trigger + Software trigger
• Level 1 (L1): hardware based
• High Level Trigger (HLT): software based
L1 Trigger

• **Requirements**
  – High efficiency for physics processes
  – Maximum trigger rate 30kHz
  – Trigger latency $\sim 5\mu$s
  – Timing precision $\leq 10$ns
  – Two-event separation $\geq 200$ns

• **Scheme**
  – Belle trigger concept: Sub-Triggers + Global Decision Logic
  – Basic idea is the same at Belle II, but each components will be improved
    • Data flow: parallel $\rightarrow$ high-speed serial links
    • Data rate: 16 Mbps $\rightarrow$ 190 Mbps (CDC wire case)
    • Logic: hard-coded $\rightarrow$ FPGA
L1 Trigger Scheme

- CDC
- TSF
- r-φ(2D) Track
- 3D Track
- Neural Net
- ECL
- 4x4 Trigger Cell
- Cluster
- Energy Sum
- BpID
- Hit
- Multiplicity
- Topology
- Fine Timing
- KLM
- μ hit
- Forward
- Backward
- Barrel
- 3D Muon Track
- Hadron Cluster

Global reconstruction logic (GRL)
Global decision logic (GDL)

L1 trigger

New in Belle II
CDC Trigger

- CDC: axial and stereo Track Segments (TS)
- 2D track: axial TS
- 3D trigger
  - 2D tracks in r-\( \phi \) space
  - Combine with stereo TS to determine the z-vertex
- Neural z-vertex trigger
  - Networks of Multi Layer Perceptron (MLP)
  - 2D tracks & stereo TS as input

Hardware test setup of neural trigger
ECL Trigger

- Efficient trigger for both neutral and charged particles
- Total trigger timing latency ~ 3μs
- Upgraded 3D Bhabha-veto logic: higher efficiency for interesting low multiplicity physics

- Divide ECL to forward and backward parts
- Find the most energetic clusters in each part

- 3D Bhabha-veto logic
  - Satisfy the back-to-back topology (look-up table)
  - Cluster energy requirements
• CDC track and ECL cluster matching

• Match in $r$-$\phi$ and $Z$ directions
• $\Delta r$, $\Delta z$: the deviations between cluster position and expected hit position in $r$-$\phi$ and $Z$ directions on ECL, respectively.
• Expected hit position: extrapolate tracks from CDC with 3D tracking information

• Define ($\Delta r$, $\Delta z$) region
• Match track $t0$ to the cluster $c1$ with the smallest $\Delta r$ in its ($\Delta r$, $\Delta z$) region
• The rest are neutral clusters
• Electron ID with E/P
• O(200) L1 bits available $\Rightarrow$ abundant triggers
• Trigger menus for running conditions (i.e. $E_{cm}$, background)
Components:
• Unified data link (Belle2Link)
• Common pipeline platform for electronics readout (COPPER)
• Merge data pieces from all detectors (Event builder)
• High level trigger (HLT): software based
DAQ

**Designed maximum readout rate:** 30kHz

**Data Flow:** L1 → Belle2Link → COPPER → EventBuilder → HLT

- **PXD**
  - FE dig
  - 30kHz 1MB/ev
  - 1/10 size reduction

- **SVD**
  - FE dig tx
  - ~0.5M chan.

- **CDC**
  - FE dig tx

- **PID**
  - FE dig tx

- **ECL**
  - FE dig tx

- **Belle2link**
  - RX

- **PXD readout box**
  - 10kHz 100kB/ev

- **DATCON**
  - ~300 COPPERs
  - ~30 R/O PCs

- **R/O PC**
  - 30kHz 100kB/ev
  - 1/3 rate reduction

- **Event Builder**
  - 10kHz 200kB/ev

- **RAID**
  - ~10 units

- **Express Reco**
  - 10kHz 300kB/ev = 3GB/s

- **Near detector**
  - E-hut

- **DAQ server room**

~MHz before L1
**HLT**

### L3
- dedicated recon. algorithms
  - CDC tracking
  - ECL clustering
- $30\text{kHz} \rightarrow 15\text{kHz}$

### Full reconstruction
- offline software framework (basf2)
- offline recon. algorithm with all detectors except PXD.

### Physics-level event categories
- hadronic physics: B, D...
- low-multi.: $\tau\tau$, DM...
- QED: ee, $\mu\mu$, $\gamma\gamma$...
- trigger menu
- $15\text{kHz} \rightarrow 10\text{kHz}$

### Parallel processing
- allowed in basf2 $\rightarrow$ extended to network cluster in HLT
- $(20 \text{ nodes x } 16 \text{ cores}) / \text{unit}$
- $\geq 5 \text{ units} @ 2 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$, added as luminosity increase
Cosmic ray tests (CRT) of sub-detectors and DAQ has been performed since last November.

- CDC CRT with 6 FEEs was started, more FEEs are added
- Stability of ECL DAQ is improved
- KLM DAQ for CRT is ready

Demonstration on June this year

- ECL and CDC data-taking were run successfully.

Run control
Simplified operations are available (Run start / stop / abort)

Event rate of ECL CRT

CDC DQM
ECL DQM
COPPER rack for KLM
Summary

• Belle II’s trigger/DAQ systems have been much improved, and will capture more low multiplicity physics than Belle ever did, such as dark sectors, precision tests, τ decays.
  – Upgraded electronics
  – 3D CDC tracking, 3D Bhabha-veto
  – Matching between CDC tracking and ECL cluster
  – Low level reconstruction in GRL
  – Trigger Menu

• Trigger/DAQ will be ready before Belle II commissioning (w/o VXD) on May 2017.
Backup
SuperKEKB

• An asymmetric electron-positron collider in Tsukuba, Japan
• Asymmetric beam energies $e^+ \sim 4\text{GeV}$ $e^- \sim 7\text{GeV}$
• Target Luminosity
  $L_{\text{int}} > 50\text{ ab}^{-1}$ by 2020s (50 x Belle)
  $L_{\text{peak}} = 8 \times 10^{35}\text{ cm}^{-2}\text{s}^{-1}$ (40 x KEKB)
Belle II Detector

- **EM Calorimeter:**
  - CsI(Tl), waveform sampling (barrel)
  - Pure CsI + waveform sampling (end-caps)

- **Beryllium beam pipe:**
  - 2 cm diameter

- **Vertex Detector:**
  - 2 layers DEPFET + 4 layers DSSD

- **Central Drift Chamber:**
  - He(50%):C₂H₆(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 (7 GeV)**
- **Positron (4 GeV)**
KLM Trigger

- Important to the detector calibrations and increase the trigger efficiency of low-multiplicity events.
- Data exchange with Aurora core is done and works well.
- Data parser development is started.
- KLM trigger finds muon tracks and $K_L$ clusters.
Event Builder

- Merge data pieces from all detectors to one event
- Large network switch
- Enough large buffers to avoid data loss or retransmission
- Two event builders before and after HLT
  - Builder 1 merge data w/o PXD for HLT
  - Builder 2 merge data from all detectors
PXD Integration

- Large event size from the PXD: 
  ~1MB/event, COPPER can not manage such huge data flow
- ATCA crate receive data from PXD.
- Two ways to reduce PXD data size and rate:
  - RoI selected by ATCA system.
  - The track finding is done with SVD and CDC hit signals, the PXD hits associated with tracks are sent to the event builder.
  - The hit-track association is perform with the track parameters from HLT system.
- RoI selection happens after 5s of HLT processing time
Belle2link

- Unifieddatalink protocol on RocketIO (GTP) technology over optical fibers.
- Data transmission between front-end electronics of detectors to back-end COPPER based on DAQ system.
- Integrated trigger timing system interface.
COPPER Readout System

- A general purpose pipelined readout platform
- FINESSE: Belle2link receiver, receive the data from front-end
- PrPMC: a commercial CPU card, format and reduce data
- Send to event builder through ethernet connection

COPPER board:
4x FINESSE daughter cards, PrPMC
Trigger receiver