Belle II Track Reconstruction and Results from First Collisions

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Thomas Hauth for the Belle II Collaboration
The Belle II Experiment and its Goal

- KEKB was an electron-positron collider at KEK in Tsukuba/Japan which studied the decay of B mesons at the Y(4S) resonance
- Nobel Prize in Physics 2008 to Kobayashi and Maskawa
- The SuperKEKB collider and the Belle II detector will build on the previous success:
  - Study B meson system in far greater precision
  - Probe for new physics in a wide range of interesting topologies
- The Belle II Collaboration: more than 700 scientists from 100 institutes in 25 countries!

<table>
<thead>
<tr>
<th></th>
<th>KEKB</th>
<th>Super KEKB</th>
<th>Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Instantaneous Luminosity</td>
<td>$2 \times 10^{34}$ cm$^{-2}$s$^{-1}$</td>
<td>$8 \times 10^{35}$ cm$^{-2}$s$^{-1}$</td>
<td>40</td>
</tr>
<tr>
<td>Integrated Luminosity</td>
<td>1 ab$^{-1}$</td>
<td>50 ab$^{-1}$ (projected)</td>
<td>50</td>
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<tr>
<td>Runtime</td>
<td>1998 to 2010</td>
<td>start in 2017</td>
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<tr>
<td>Detector</td>
<td>Belle</td>
<td>Belle II</td>
<td></td>
</tr>
<tr>
<td>Raw Data</td>
<td>1 PB</td>
<td>100 PB (projected)</td>
<td>100</td>
</tr>
</tbody>
</table>
Belle II Detector

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

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)

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

electron (7GeV)

positron (4GeV)
Tracking Detectors - VXD

The Belle II Vertex Detector (VXD) is formed by

- 2 inner DEPFET Pixel Layer (PiXel Detector) : PXD
- 4 outer Silicon Strip Layers (Silicon Vertex Detector) : SVD

- **Very light mechanical structure**: ~0.5% X/X₀ per SVD layer
- DEPFET technology - pixel internal amplification allows for very low material budgeted in PXD layers: ~0.19% X/X₀ per layer
- Compared to Belle: **factor 1.5 improvement** of the impact parameter over a wide range with the new inner tracking system

![Diagram of VXD](<image-url>)

![Graph of σ_z vs pβsin(θ)>0.4][image-url]

**Belle**

**Belle II**

- 30μm
- 15μm

**σ_z [μm]**

**pβsin(θ) [GeV/c]**

0 0.4 0.8 1.2 1.6 2.0

**PXD+SVD**
Tracking Detectors - CDC

- The Belle II Central Drift Chamber is a significant upgrade compared to the drift chamber of the Belle detector

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Belle</th>
<th>Belle II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius of inner cylinder (mm)</td>
<td>77</td>
<td>160</td>
</tr>
<tr>
<td>Radius of outer cylinder (mm)</td>
<td>880</td>
<td>1130</td>
</tr>
<tr>
<td>Radius of innermost sense wire (mm)</td>
<td>88</td>
<td>168</td>
</tr>
<tr>
<td>Radius of outermost sense wire (mm)</td>
<td>863</td>
<td>1111.4</td>
</tr>
<tr>
<td>Number of layers</td>
<td>50</td>
<td>56</td>
</tr>
<tr>
<td>Number of sense wires</td>
<td>8,400</td>
<td>14,336</td>
</tr>
<tr>
<td>Gas</td>
<td>He–C₂H₆</td>
<td>He–C₂H₆</td>
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<tr>
<td>Diameter of sense wire (μm)</td>
<td>30</td>
<td>30</td>
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</table>

- Larger lever arm for precise momentum estimation
- z-component measurement with stereo layers with wires shifted by 2.6 to 4.2 degrees
Tracking Environment & Challenges

- The most widely used event categories for analysis are $Y(4S) \rightarrow B\bar{B}$ decays
- On average: 11 primary tracks / per event (but additional background hits)
- Here: almost all of the beam energy is converted into the $B$-Meson pair
- If all visible decay products of the two $B$-Meson decays can be reconstructed:
  - Very clean topologies with well-known kinematics
  - Search for rare decays by assigning all tracks to a particle candidate

Challenges for Tracking Hard & Software:

- Reconstruct all tracks, also down to very low-pt regions
- Cope with the huge contribution of background hits
- Low fake rate

<table>
<thead>
<tr>
<th>Case</th>
<th>$\gamma(4S)$-only</th>
<th>BG-only</th>
<th>$\gamma(4S) + BG$</th>
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<tbody>
<tr>
<td>Average strips/layer</td>
<td>164.3/122.8</td>
<td>159.4/81.7</td>
<td>200.1/112.3</td>
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<tr>
<td>Total clusters</td>
<td>49.2/48.7</td>
<td>146.0/131.3</td>
<td>194.4/179.6</td>
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<tr>
<td>Total SpacePoints</td>
<td>84.8</td>
<td>534.6</td>
<td>721.3</td>
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CDC Signal & Background Hits

<table>
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<tr>
<th>Hits source</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
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<td>BHWide (HER)</td>
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<td>BHWide (LER)</td>
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<td>Coulomb (HER)</td>
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<td>RBB (HER)</td>
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<td>RBB (LER)</td>
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<tr>
<td>Touschek (HER)</td>
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Belle II Modular Tracking

- The Software Framework of Belle II (basf2) allows to implement processing steps in a so-called Modules which are not coupled and exchange input and output data via a DataStore.
- Due to the very different nature of the two major tracking systems (silicon-based and drift chamber), two different track finders were implemented.
- All stages of the Belle II Tracking software are implemented in independent framework modules which:
  - fits well with our (geographically) distributed development model.
  - allows to re-arrange parts of the tracking software for different use cases (online / offline / beamtest scenarios).
  - A common exchange format class (RecoTrack) is used to transfer pattern recognition and fit results between modules.
  - While the earlier Module (for example VXD Track Finder) are specifically developed for specific hardware, all downstream modules (like TrackFitting) can operate on the common RecoTrack.

Focus of this Talk

CKF = Combinatorial Kalman Filter

Next Talk
Belle II VXD Tracking

- Primary Task: Reconstruct tracks in the 4-layer SVD detector (PXD hits are assigned via CKF later)
- Very large combinatorics, due to huge number of background hits, especially in the innermost layers & ghost hits in the SVD

**SectorMap – Concept to reduce combinatorics**

- Each sensor is split into sectors (~10 per sensor)
- Using tracks from simulated Monte Carlo events, the possibility to hit the next sector is evaluated
- Connections between sectors are stored up to 4 sectors deep
- The SectorMap also stores cut values for two and three-hit filter combinations and is depending on different Pt values

**Cellular Automaton – Graph search for connected Hits**

- A Cellular Automaton (CA) is used to explore the possible combinations of hits to form track candidates
- Quality of the these track candidates is evaluated with a fast fitting method
Belle II CDC Tracking: Background Treatment

- Around 40 percent of all CDC hits are results of machine-induced background
- Background hits have distinctly different properties:
  - Isolated
  - Don’t form larger clusters
- A boosted decision tree classifier is trained on: total and mean number of neighboring clusters, total and mean drift length, super-layer number

The background filter is able to classify background hits reliably
- Reduction of fake rate by 25% and increase of finding efficiency by 2%
CDC Track Finding

Legendre-based Finder

- All axial CDC Hits are transformed to Legendre-space where each forms a sinusoidal curve.
- Fast iterative quad tree algorithm is used to search for areas of high curve densities → parameters shared by one track.
- Takes the drift length and the left/right ambiguity into account.
- **Legendre-based search is a track finder targeting complete tracks originating from the interaction point.**
CDC Track Finding

Local Finder

- **Build segments from individual hits in each super layer**
  - A graph of hits in one CDC super-layer is created
  - Graph search algorithm: cellular automaton searches for connected entries (hits) in the graph which can belong to one track segment
  - All found track segments are fitted with a fast circle fit

- **Build tracks from connected segments**
  - A graph of segments is build
  - Neighboring segment pairs are connected in the graph
  - Loose feasibility cuts first, then judge compatibility by combined $\chi^2$ of the trajectories

Local Finder does not rely on any track origin: designed for displaced tracks and short tracks
Combinatorial Kalman Filter (CKF)

- Very versatile tool which can operate on hits of all tracking detectors: PXD, SVD and CDC
- Implemented using the eigen vectorized library, fast analytical track extrapolations
- Used for multiple improvements of the tracks found by the previous algorithms

**Improve SVD Hit Efficiency**
Search for compatible hits in the SVD detector for tracks which have only CDC hits at the moment

**Search for PXD Hits**
Due to the high occupancy of the two innermost PXD sensors, existing SVD/CDC tracks are used for PXD hit assignment

**In Development: Assign CDC hits to SVD tracks**
Some track segments in the CDC are very short and cannot be found by CDC standalone tracking. Existing SVD tracks can be used to assign these hits to the proper track
First Collisions!

Phase II Started in February 2018 till July 2018
Belle II detector, only one segment of the inner-most silicon-based tracking system
*Primary goals: Quantify accelerator background and commission Belle II detector and associated systems*

Phase III Start in February 2019
Complete Belle II detector
*Goals: Continuous physics run at peak instantaneous luminosity*

One of the first hadronic events recorded with the Belle II Detector at 2:27 a.m.
JST on the 26th April 2018
Tracking with First Data

Track Finding and Fitting is executed during data-taking on the

- **High-Level Trigger farm** (for event filtering, not done in Phase II, SVD&CDC tracking only)
- **ExpressReconstruction** for live event display and data quality monitoring (Full Reconstruction)

Furthermore, multiple offline processings of the Phase II dataset have been completed successfully.

During initial commissioning of the SuperKEKB collider, detector occupancy could vary widely and was sometimes over the background rates expected from simulation.

- For CDC track finding, the background filters worked excellent and the event reconstruction could be completed
- For SVD and CKF track finders, we put local combinatorial limits in place which prevent overly high resource consumption (in case of “hot sensors” etc.)
  This limits will not affect the reconstruction of regular detector signals
Tracking with First Data

- Fast feedback to the SuperKEKB-Accelerator group is important during the early commissioning phase of the accelerator.
- One novel feature to achieve the 40 times higher luminosity is the nano-beam scheme which allows for a very strong focusing at the beam interaction point up to 10 μm (20 times smaller than KEKB)

Within days of first collisions, Belle II Track Reconstruction and Fitting was used for feedback to the accelerator groups. → Here: Confirm the nano-beam scheme works!
The Belle II Pattern Recognition Software supports and integrates two quite distinct detectors:
- Silicon-based PXD & SVD
- Central Drift Chamber

Modular structure of the track finding and fitting algorithms allows for easy replacement and improvement of existing code.

All components of the pattern recognition chain have been successfully used to reconstruct the first collisions of SuperKEKB with the Belle II detector.

The work has just started:
- Data recorded during Phase II (ending in 5 days) is very valuable to further tune the algorithms for Phase III next year.
- Studies of tracking efficiencies using data only are being done right now.

Thank you for your attention!
Backup
Belle II CDC Tracking: Background Treatment

- Around 40 percent of all CDC hits are results of machine-induced background
- Background hits have distinctly different properties:
  - Isolated
  - Don’t form larger clusters
- A boosted decision tree classifier is trained on: total and mean number of neighboring clusters, total and mean drift length, super-layer number

The background filter is able to classify background hits reliably
- With the chosen cut value of 0.2, the finding efficiency and the fake rate can be improved
- Only very small loss in track hit efficiency observed