The Central Drift Chamber of Belle 2

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Brief introduction

Aims:
- Introduction to the Central Drift Chamber (CDC) of Belle 2.
- Familiarise with the terminology of the CDC.
- Show some performance numbers.

Goal:
- Lay the groundwork to understand CDC tracking and software better. (Later sessions)
The Belle 2 detector
CDC structure

CDC is the main tracker of Belle 2:

- Measures particle momenta.
- Used in triggering.
- Particle identification.
CDC in Belle 2

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The particles in the travel in helices:

\[
\frac{d\vec{p}}{d\tau} = q\gamma[\vec{\beta} \times \vec{B}]
\]  

(1)

Covers $17^\circ < \theta < 150^\circ$ (polar angle).
CDC and CDC wires

CDC is composed of:

- 9 super layers
  which consist of
  - 56 layers (grouped to 1x8 and 8x6)
  - 14336 wires (160 - 384 wires in a layer).
Drift chambers in general

Drift chamber measures the trajectory of traversing particles through secondary ionisation it leaves:

- Primary particle **ionises** gas molecules.
- Secondary electrons create **avalanches**.
- Readout wires measure **drift time**.

\[ pA \rightarrow pA^+ e^-, pA^{2+} e^- e^- ... \]  \hspace{1cm} (2)

or in gas mixtures e.g.,

\[ pA \rightarrow pA^*, \quad \text{and} \quad A^* B \rightarrow AB^+ e^-, \]  \hspace{1cm} (3)

Ionisation

Bethe-Bloch formula:

\[
\frac{dE}{dx} = \frac{4\pi Ne^4}{mc^2\beta^2} z^2 \left( \ln \frac{2mc^2\beta^2\gamma^2}{I} - \beta^2 + \text{corr} \right)
\]  

(4)
Drift chambers in general

To induce the drift electric field is needed.
→ Accelerated electrons create avalanches

Field wires generate electric field.
Sense wires “sense” the signal

\[ E \sim \frac{U}{r} \quad (5) \]
Drift chambers in general

Once the electron avalanche reaches the sense wire a signal is generated. (CDC Hit)

The signal is readout by electronics: the signal is digitised by ADCs and TDCs.

Drift radius extracted from drift velocity:
Drift chambers in general

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The signal is readout by electronics: the signal is digitised by ADCs and TDCs.

Drift radius extracted from drift velocity:
Typical event in the CDC

An example typical event of $\Upsilon(4S)$ decay (no beam background)

Can already easily get important info about particles:

$$|\vec{p_T}| = R \cdot B \cdot |q| \quad \&\& \quad q > 0 \text{ if clockwise, otherwise } q < 0.$$
Axial and Stereo layers

If wire is along $z$ (the beamline): how to differentiate between $z = z_1$ and $z = z_2$?
Axial and Stereo layers

If wire is along the beamline:
how to differentiate between $z = z_1$ and $z = z_2$?

(a) An axial wire layer - sense wires are parallel to the beamline

(b) A stereo wire layer - sense wires are skewed to the beamline (exaggerated)

→ different combinations of wires are hit for different $z$, due to skew.
### Layer structure

<table>
<thead>
<tr>
<th>Superlayer</th>
<th>Type</th>
<th># of layers</th>
<th># of wires/layer</th>
<th>Radius, mm</th>
<th>Stereo angle, mrad</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A</td>
<td>8</td>
<td>160</td>
<td>168.0 – 238.0</td>
<td>0 – 0</td>
</tr>
<tr>
<td>2</td>
<td>U</td>
<td>6</td>
<td>160</td>
<td>257.0 – 348.0</td>
<td>45.4 – 45.8</td>
</tr>
<tr>
<td>3</td>
<td>A</td>
<td>6</td>
<td>192</td>
<td>365.2 – 455.7</td>
<td>0 – 0</td>
</tr>
<tr>
<td>4</td>
<td>V</td>
<td>6</td>
<td>224</td>
<td>476.9 – 566.9</td>
<td>-55.3 – -64.3</td>
</tr>
<tr>
<td>5</td>
<td>A</td>
<td>6</td>
<td>256</td>
<td>584.1 – 674.1</td>
<td>0 – 0</td>
</tr>
<tr>
<td>6</td>
<td>U</td>
<td>6</td>
<td>288</td>
<td>695.3 – 785.3</td>
<td>63.1 – 70.0</td>
</tr>
<tr>
<td>7</td>
<td>A</td>
<td>6</td>
<td>320</td>
<td>802.5 – 892.5</td>
<td>0 – 0</td>
</tr>
<tr>
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<td>6</td>
<td>352</td>
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<td>384</td>
<td>1020.9 – 1111.4</td>
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The diagram illustrates the layer structure with labels for each superlayer and the distribution of wires per layer.
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### Diagram

- **SL 0**: Axial, stereo
- **SL 1**: 46 mrad, stereo
- **SL 2**: 60 mrad, stereo
- **SL 3**: 67 mrad, stereo
- **SL 4**: Axial
- **SL 5**: 67 mrad, stereo
- **SL 6**: Axial
- **SL 7**: -71 mrad, stereo
- **SL 8**: Axial

**IP**

- **Wires per layer**: 160, 160, 192, 224, 256, 288, 320, 352, 384
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![Diagram of layer structure](image)
basf2 objects for CDC

Some important quantities that you actually “see” that characterise hits.

- **Analog-to-Digital-Converter (ADC).**
  → related to integrated charge deposited on the wire.
- **Time-over-Threshold (TOT).**
  → threshold for a hit to be registered as non-background/noise.
- **Time-to-Digital-Converter (TDC).**
  → related to drift time.

Very important in track reconstruction and correct hit selection!
Belle II has a two-level trigger system.

1st-level trigger implemented in FPGAs:
- Return trigger signal for data acquisition
- Trigger rate: 30 kHz, latency: 5 µs.

Consists of subtrigger systems:
- track (CDC) trigger & ECL trigger.
- additional TOP & KLM triggers.
dE/dx measurements and PID

Ionisation is $\sim$ distance traversed, so charge/distance is used:

- Charge in each layer summed.
- Distance approximated as straight line to next layer.

$$dE/dx$$ - extracted as avg ionisation:

electrons, muons, pions, kaons, protons.

$\rightarrow$ PID possible by comparing with distributions. & combining with $dE/dx$ from PXD/SVD.
Expected CDC Performance

Majority of charged particles below 2 GeV

$$\left( \frac{\sigma_{pT}}{pT} \right)_{\text{meas}} \rightarrow \text{measurement error}$$

Dominating:

$$\left( \frac{\sigma_{pT}}{pT} \right)_{\text{MS}} \rightarrow \text{error due to multiple scattering}$$
Expected CDC Performance

Majority of charged particles below 2 GeV
→ mom. resolution will be dominated by multiple scattering.

- low-Z gas (50% He, 50%-C₂H₆).
- low-mass Au plated, W sense wires.
- low-mass Al field wires.

→ assuming \( \sigma_{r\phi} \sim 100 \, \mu m \):

Ideally, measurement error:

\[
\left( \frac{\sigma_{p_T}}{p_T} \right)_{\text{meas}} \approx 0.1\% p_T \quad \text{(Belle 1: } \approx 0.2\% p_T ) \tag{6}
\]

Ideally, error due to multiple scattering:

\[
\left( \frac{\sigma_{p_T}}{p_T} \right)_{\text{MS}} \approx 0.2\% / \beta \quad \text{(Belle 1: } \approx 0.3\% / \beta ) \tag{7}
\]

for equations and Belle numbers see: https://doi.org/10.1016/S0168-9002(00)00513-1
Expected CDC Performance

Calculated resolution: \( \delta k \)

\[(\delta k)^2 = (\delta k_{\text{res}})^2 + (\delta k_{\text{ms}})^2 \]

\( (\delta k_{\text{res}}) \): multiple scattering
\( (\delta k_{\text{res}}) \): measurement resolution

\[ P_t \text{ resolution [\%]} \]

\[ P_t \text{ [GeV/c]} \]

Simulation
Fitting
Material: only CDC generated muon
Summary

- CDC is the main tracker of the Belle 2 experiment.
- It is used in tracking, triggering and for PID.
- The resolution is expected to improve over Belle.

See how this CDC geometry and outputs are used in tracking
→ upcoming seminars
Further reading

About drift chambers in general:


About Belle2:

- Belle 2 TDR: arXiv:1011.0352
- Belle 2 Expected CDC performance: N. Taniguchi 2017 JINST12 C06014
- Belle literature: https://belle.kek.jp/ (still relevant)
- Belle 2 Physics Book: BELLE2-PAPER-2018-001
- Technical/CDC software PhD Theses, e.g. IEKP-KA/2013-06, BELLE2-PTHESIS-2018-001, IEKP-KA/2012-9
- Belle 2 examples and software documentation!
Backup: Hit selection

Selected based on ADC/TOT requirements, depending on experiment/run:

<table>
<thead>
<tr>
<th>ADC (outer SLs/inner SL)</th>
<th>TOT</th>
<th>ADC/TOT</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\geq 15/ \geq 12$</td>
<td>$\geq 2$</td>
<td>$\geq 4$</td>
</tr>
<tr>
<td>$\geq 18/ \geq 15$</td>
<td>$\geq 2$</td>
<td>$\geq 3$</td>
</tr>
</tbody>
</table>
Backup: Readout

[Diagram showing the components of a readout system, including ASDs (ASIC), ADCs, DAC, Network Proc., Ring Buffer, Data suppressor, TDC 1nsec, Aurora I/F, ASD, FADC, and FPGA.]
Backup: particle fractions

Top to bottom:
- pion
- kaon
- electron
- muon
- proton
The numbering scheme is conventionalised: numbering starts at 0!

<table>
<thead>
<tr>
<th>ID</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superlayer ID</td>
<td>0 – 8</td>
</tr>
<tr>
<td>Layer ID</td>
<td>0 – 7, for superlayer 0</td>
</tr>
<tr>
<td></td>
<td>0 – 5, for superlayer 1–8</td>
</tr>
<tr>
<td>Continuous layer ID</td>
<td>0 – 55</td>
</tr>
<tr>
<td>Wire ID</td>
<td>0 – [159;191..;383] for superlayers [0 and 1;2;...;8]</td>
</tr>
<tr>
<td>Encoded wire ID</td>
<td>0 – 35711 (discontinuous!)</td>
</tr>
</tbody>
</table>
CDCHit objects in basf2

https://b2-master.belle2.org/software/development/classBelle2_1_1TrackFindingCDC_1_1CDCWireHit.html
https://b2-master.belle2.org/software/development/classBelle2_1_1CDCHit.html
https://b2-master.belle2.org/software/development/classBelle2_1_1CDCRawHit.html