Optimization studies of the Pixel Vertex Detector (PXD)

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Overview

- Motivation for Optimization studies
- Simulation framework (ILC)
- Results on pixel arrangements
- Comparison of PXD Geometries for Highcurrent and Nanobeam options
- Summary
Aim of studies

- PXD Optimization for best physics performance
- Parameters to be varied
  - Beampipe radius (Nanobeam / Highcurrent option)
  - Pixel size (pitch) (10 or 20μs readout)
  - Pixel shape: constant pixel size (CPS), variable pixel size (VPS), bricked pixels (BP)
- Material budget
  - Beampipe (influence of gold layer)
  - Thickness of active material (PXD sensors) [to be done]
- Studies in two frameworks (full / fast simulation)
PXD Geometry

Windmill structure
Support structure challenging
(see talk Frank Simon)

<table>
<thead>
<tr>
<th></th>
<th>R [mm]</th>
<th>ladders</th>
<th>support</th>
</tr>
</thead>
<tbody>
<tr>
<td>PXD 1</td>
<td>18</td>
<td>10</td>
<td>no</td>
</tr>
<tr>
<td>PXD 2</td>
<td>22</td>
<td>12</td>
<td>yes</td>
</tr>
</tbody>
</table>

PXD Layer 2 must be divided (size)
Idea to divide PXD Layer 1 (ground loops)
The ILC Framework

Simulation
- Pythia
  Generator
- HEPEvt (ASCII)
  Generated events

Reconstruction
- Mokka
  (Geant4)
- GEAR (XML)
  Geometry information
- Marlin
  - MaterialDB
  - Digitization
  - Tracking
  - Optimization
- LCIO (persistency data model)
- LCCD
- LCIO
- ROOT

08.07.2009
3rd Open Meeting of the Belle II Collab.
Mokka – Belle II Geometry - 1

• Mokka model: *complete Belle II Tracker*
  (beam pipe + PXD + SVD + CDC)

• **Beam pipe**: cylindrical onion-like structure
  - inner golden layer + inner Be wall + cooling gap (paraffin) + outer Be wall

• **PXD**: 2 layers of Si pixel detectors – DEPFETs
  - active part: layers → ladders → Si sensors (50µm)
  - passive part: Si rims (450µm) + 12 switchers (300µm) +
    Si support bridge @ 2nd layer (400 µm)
Mokka – Belle II Geometry - 2

- **SVD:** 4 layers of Si strip detectors (DSSDs) in barrel part
  - organized in stagger-like structure
  - active part: layers → ladders → Si sensors (300µm)

- **CDC:** Al cylinder with cone-shaped inner parts (as Belle)
  - active medium: gas He/C\textsubscript{2}H\textsubscript{6} (50:50)
  - uses Gaussian smearing as digitization
  - geometry as of December 2008
MarlinReco – Digitization for Belle II

- Chain of Marlin reconstruction tools:
  - **MaterialDB**: (defines all materials – required by Kalman filter in the tracking code)
  - **PXDDigitizer**: (detailed PXD digitizer – both CPS & VPS options possible)
  - **SiStripDigi**:  
    - implemented (→ Zbynek Drasal)
  - **CDCDigitizer**: (digitizes data from central drift chamber)
    - simple gaussian smearing
Details of simulation and reconstruction

- Particle gun: muons from origin
  - \( \phi \in [0^\circ, 360^\circ] \)
  - \( \theta: 20^\circ, 40^\circ, 60^\circ, 80^\circ \)
  - Energies: 0.1, 0.2, 0.4, 0.6, 1.0, 1.5, 2.0 GeV
- Stand alone tracking in PXD and SVD
- Stand alone tracking in CDC
- Refit of CDC and SVD/PXD tracks
- Detailed simulation including realistic PXD/SVD and material budget!
4 Procedures to obtain the resolution

Cut at ±500µm

RMS: 65µm

Cut tails (90%) remain

RMS: 48µm

Start cut from mean?
Start cut from zero?

RMS: 60µm

RMS: 56µm
Data analysis for the spatial resolution

Clustering based on Center of Gravity algorithm
→ see talk Z.Drasal at last B2GM

Residual plot is created (Monte-Carlo hit – reconstructed hit)

**RMS** of the residuals is used as the spatial resolution (pessimistic case)
Data analysis for Impact parameter resolution

- Histogram of the D0 and Z0 Track parameters
  - D0: distance of closest approach in R-Phi
  - Z0: distance to point of closest approach in Z
- using **RMS 90** as a measure for the Impact Parameter Resolution (optimistic)
Variations of the pixel layout

- Variable pixel size
  - Bricked pixel structure
  - Improvement in r-phi with minimal additional work
  - Bricked structure only in R-Phi direction possible (readout lines)
  - 50µm unbricked option (baseline)
  - 70µm in max. for bricked option

- Idea: partition the PXD in steps of equal solid angle

\[ \text{Radius axis} \]

\[ \text{Z axis} \]
VPS and CPS resolutions in Z

<table>
<thead>
<tr>
<th>Configuration</th>
<th>R [mm]</th>
<th>L [mm]</th>
<th>P0 [µm]</th>
<th>Pn [µm]</th>
<th>Pm [µm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPS2000 l1</td>
<td>18</td>
<td>98</td>
<td>49.0</td>
<td>49.0</td>
<td>49.0</td>
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<tr>
<td>CPS2000 l2</td>
<td>22</td>
<td>117.4</td>
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<td>58.7</td>
<td>58.7</td>
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<tr>
<td>VPS2000 l1</td>
<td>18</td>
<td>98</td>
<td>21.9</td>
<td>93.9</td>
<td>177.2</td>
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<tr>
<td>VPS2000 l2</td>
<td>22</td>
<td>117.4</td>
<td>35.6</td>
<td>91.9</td>
<td>174.0</td>
</tr>
</tbody>
</table>

Effect of VPS (1st layer) starts at:
- 1600: $\theta = 52.6^\circ$
- 2000: $\theta = 66.3^\circ$
- for 2nd layer even smaller angles
VPS and CPS resolutions in R-phi

Resolution in R-0: SuperBelle - 1st pixel layer

Resolution in R-0: SuperBelle - 2nd pixel layer
VPS or CPS

- VPS Z resolution better for $\theta > 50^\circ$
- CPS R-Phi resolution better for $\theta < 40^\circ$

- Technical challenges
  - Pixel size can only be varied in steps of 4 pixels
  - Pixels bigger than 150$\mu$m have long drift times
- Constant pixel size is the favored option
Bricked Pixels (BP)
spatial resolution in Z

Resolution in Z: Belle II - 1st pixel layer

Resolution in Z: SuperBelle - 2nd pixel layer
Bricked Pixels (BP)
spatial resolution in R-phi

Resolution in R-φ: Belle II - 1st pixel layer

Resolution in R-φ: Belle II - 2nd pixel layer
Impact parameter resolution using the 1600 pixel Highcurrent model

Fitting curve with multiple scattering formula

Parameter $a$: mostly geometry, pixel sizes ...
Parameter $b$: mostly material budget

$$a + \frac{b}{p\beta \sin(\theta)^{5/2}}$$
Bricked Pixels discussion

- Technically possible:
  - 50µm unbricked / 70µm bricked

- Bricked pixels
  - R-phi resolution
    - Unbricked 50 µm pixel option always better
    - Bricked 70 µm pixel option only better for $\theta \leq 30^\circ$
      everywhere else resolution is worse

- Z resolution
  - No effect

- Unbricked Pixels is the favored option
Nanobeam and Highcurrent option
2000 pixel

PXD Cluster Size: Belle II - High-Current x Nano-Beam Option

0.5GeV muon: 2000 pixels - 50μm Si, CPS, unbricked

- 1st layer - high-current option
- 2nd layer - high-current option
- 1st layer - nano-beam option
- 2nd layer - nano-beam option

Cluster size vs θ [deg]
Nanobeam and Highcurrent option

2000 pixel
Conclusion

- Full simulation of PXD, SVD ready in the ILC framework
- Vienna LicDetectorToy running for rapid answers to design changes (not show)
- Optimization studies sorted out important parameters for the production
  - Favored option no bricked structure with constant pitch
- Nanobeam option will improve the PXD resolution because of reduced beam pipe radius
- Better background and error estimation
Backup
Impact parameter resolution compared for different angles and energies

Data points is simulated data

Solid lines taken from Impact Parameter fits
Dashed lines correspond to Belle resolution taken from Belle note 715
Lic Detector Toy 2.0 (LDT)

- Vienna Fast Simulation Tool for Charged Tracks
- Authors: Meinhard Regler, Manfred Valentan and Rudolf Frühwirth
- Geometry approximated as cylinders
- dE/dx and resolution specified for every layer
- Simulation: Gaussian smearing according to given resolutions
- Kalman tracking
- we wrote a module to convert the track parametrization to our common(LCIO) track model
- very fast / ideal for rapidly changing models
- impossible to study details of the detector implementation
LDT: The Nanobeam Option

- Effects on PXD
  - smaller beampipe → reduced PXD radius → improves resolution
  - changed background (not yet simulated)

![Graphs showing D0 and Z0 resolution vs. particle momentum](image)

- nano beam options
LDT: Beampipe variations

- influence of gold foil on vertex resolution
  - replace with low Z material
- big win for low momentum tracks
Global track parameterization

- $P_r$: arbitrary pivot point
- $P_0$: point of closest approach (p.c.a.) to $P_r$ in x-y plane

**Helix Parameters**
- $d_0$: distance $P_0$ to $P_r$
- $\Phi_0$: angle at $P_0$
- $\Omega$: $1/R$
- $\tan \lambda = \cot \theta$: slope in s-z projection
- $z_0$: distance to p.c.a. in s-z projection
Nanobeam and Highcurrent option
1000 pixel

PXD Cluster Size: Belle II - High-Current x Nano-Beam Option

0.5GeV muon: 1000 pixels - 50μm Si, CPS, unbricked
- 1st layer - high-current option
- 2nd layer - high-current option
- 1st layer - nano-beam option
- 2nd layer - nano-beam option

Cluster size vs. θ [deg]
Nanobeam and Highcurrent option
1000 pixel
Nanobeam and Highcurrent option
1000 pixel
Different models tested

- VPS – variable pixel size
- CPS – constant pixel size

<table>
<thead>
<tr>
<th>Configuration</th>
<th>$R$ [mm]</th>
<th>$l$ [mm]</th>
<th>$N_{\text{pixels}}$</th>
<th>$p_0$ [µm]</th>
<th>$p_n$ [µm]</th>
<th>$p_m$ [µm]</th>
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<tbody>
<tr>
<td>CPS0800_B_layer1</td>
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<td>122.5</td>
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<td>2000</td>
<td>35.6</td>
<td>91.9</td>
<td>174.0</td>
</tr>
</tbody>
</table>

- $R =$ layer radius
- $l =$ ladder length
- $p_0 =$ minimal pixel size in $Z$
- $p_n =$ minimal pixel size in -$Z$
- $p_m =$ minimal pixel size in +$Z$
- for CPS $p_0 = p_n = p_m$
- for VPS $p_0 \neq p_n \neq p_m$
# Lic Detector Toy parameters and analysis

<table>
<thead>
<tr>
<th></th>
<th>Beampipe</th>
<th>PXD</th>
<th>SVD</th>
<th>CDC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Layers</td>
<td>1</td>
<td>2</td>
<td>4</td>
<td>35</td>
</tr>
<tr>
<td>Radii (mm)</td>
<td>15</td>
<td>18/22</td>
<td>45/70/100/137</td>
<td>356/1155</td>
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<tr>
<td>Thickness per Layer (% of X0)</td>
<td>0.0065</td>
<td>0.000468</td>
<td>0.003 avg.</td>
<td>0.0000125</td>
</tr>
</tbody>
</table>

50 µm silicon

300 µm silicon
Comparison ILC and LDT

- PXD Model CPS 1600 pixel 18/22mm radius

<table>
<thead>
<tr>
<th>Model</th>
<th>Energy (GeV)</th>
<th>D0 (µm)</th>
<th>Z0 (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ILC frame</td>
<td>0.2</td>
<td>69</td>
<td>75</td>
</tr>
<tr>
<td>ILC frame</td>
<td>0.4</td>
<td>39</td>
<td>47</td>
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<tr>
<td>ILC frame</td>
<td>1.0</td>
<td>23</td>
<td>23</td>
</tr>
<tr>
<td>LDT</td>
<td>0.2</td>
<td>75</td>
<td>83</td>
</tr>
<tr>
<td>LDT</td>
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<td>42</td>
</tr>
<tr>
<td>LDT</td>
<td>1.0</td>
<td>21</td>
<td>23</td>
</tr>
</tbody>
</table>

Difference LDT to ILC Frame

<table>
<thead>
<tr>
<th>Energy (GeV)</th>
<th>D0</th>
<th>Z0</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>-10.0%</td>
<td>-10.6%</td>
</tr>
<tr>
<td>0.4</td>
<td>-5.3%</td>
<td>9.3%</td>
</tr>
<tr>
<td>1.0</td>
<td>6.2%</td>
<td>0.5%</td>
</tr>
</tbody>
</table>

Big differences at low momentum are due to differences in the reconstruction software.
Comparison of Mokka/Marlin with Lic Detector Toy results

**D0 residuals**

\[ \theta = 80^\circ \]

**Z0 residuals**

\[ \theta = 80^\circ \]
Comparison of Belle note 715 with Lic Detector Toy

<table>
<thead>
<tr>
<th>Energy (GeV)</th>
<th>D0 (µm)</th>
<th>Z0 (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>37</td>
<td>40</td>
</tr>
<tr>
<td>2.0</td>
<td>21</td>
<td>25</td>
</tr>
<tr>
<td>8.0</td>
<td>13</td>
<td>18</td>
</tr>
</tbody>
</table>

Beampipe | PXD | SVD | CDC
---|----|----|----|
Number of Layers | 1 | 2 | 4 | 35
Radii (mm) | 15 | 18/22 | 45/70/100/137 | 356/1155
Thickness per Layer (X0) | 0.0065 | 0.000468 | 0.003 | 0.0000125

Z0 residuals

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38