The DMAPS upgrade of the Belle II Vertex Detector

Giuliana Rizzo

for the Belle II VTX Upgrade Group

- Belle II @ SuperKEKB
- Upgrade Motivations
- The VTX project: all pixel layers
  - TJ-Monopix2 DMAPS tests
  - OBELIX sensor chip for Belle II
  - Mechanics for inner & outer layers
- Summary & Outlook
Belle II @ SuperKEKB

- Luminosity frontier experiment to search for Physics beyond the Standard Model
- SuperKEKB collider in KEK, Tsukuba - Japan
  - $e^+e^-$ asymmetric collision at the $Y(4S)$ resonance
  - High current / nano-beams
  - Challenging background conditions
- Run 1: 2019 -2022
  - Pixel Detector (PXD): layer 1 + only 20% of layer 2
  - Full 4-layers strip detector (SVD)
  - First physics paper in January 2020
- Long Shutdown 1 (June 2022- end of 2023)
  - several accelerator and detector maintenance & improvements → installation of the complete 2 layers PXD + current SVD
- Run 2: started in Jan 2024
  - Instantaneous luminosity ramping up in next years
  - Path to reach $2 \times 10^{35}$ cm$^{-2}$ s$^{-1}$ identified, but still large factors to reach the target peak luminosity of $6 \times 10^{35}$ cm$^{-2}$ s$^{-1}$

Target
\[
\mathcal{L} = 6 \times 10^{35} \text{ cm}^{-2} \text{ s}^{-1}
\]
\[\int \mathcal{L} \, dt = 50 \text{ ab}^{-1}\]

Achieved
\[
\mathcal{L} = 4.7 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \text{ world record!}
\]
\[\int \mathcal{L} \, dt = 428 \text{ fb}^{-1}\]
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Belle II Upgrade Motivations

• Steep path to higher luminosity
  • x13 in peak luminosity, x2x2 in beam currents, x3 smaller beam size
  • Machine performance and stability
  • Backgrounds in the detector

• Upgrade of accelerator complex required to reach $6 \times 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$
  it may include a major redesign of the Interaction Region (IR)

• Long Shutdown 2 (LS2) ~2027-2028 provides a window of opportunity for a significant detector upgrade

• Belle II Upgrade Program started:
  • To improve detector robustness against backgrounds & provide larger safety factors to run at high luminosity
  • Increase longer term subdetector radiation resistance
  • Develop the technology to cope with a replacement of the VXD, needed in case of major IR redesign
  • Prepare a safety net in case of failure of detector components or accidents
  • Improve physics performance: get more physics per ab-1

• Framework CDR ready: available on arXiv soon
  • several possible detector improvements with different time scales & readiness → New Vertex Detector proposed
**Current Vertex Detector (VXD)**

- Two technology system
  - Low mass ladder design with total material budget of 3.8% X0
  - Spatial resolution 10 - 25 μm

- **PXD**:
  - 2 Layers of DEPFET pixel sensor: R=1.4-2.2 cm
  - Thin sensors (75μm) & air cooling → 0.25% X0/layer
  - Small pixel pitch (50-75 μm) but long integration time (20μs)
  - Occupancy limit 3%
  - Cannot contribute to track finding
  - Delicate detector → damages in high dose beam aborts!

- **SVD**:
  - 4 layers of double sided strip detector: R=3.9 -14 cm
  - DSSD 300 μm + “Origami” chips on sensor design & CO₂ evaporative cooling → 0.75% X0/layer
  - Very good cluster time resolution 3 ns, but long strips (6 cm)
  - Occupancy limit 6%, using also the hit-time for BG rejection
  - Trigger latency limited to 5 μs by readout chip

- Excellent VXD performance in current conditions @ occupancy < 1%
  - Large uncertainty on background extrapolation @ target luminosity & with possible new IR → 3 BG scenarios
  - Limited safety margin & performance degradation possible in the high BG scenario:
    - PXD layer1 up to 2% occupancy (32 MHz/cm² hit rate)
    - SVD layer3 up to 9% occupancy (9 MHz/cm² hit rate)

- May reach limits of current detector @ target luminosity → higher space & time granularity in all layers
VXD upgrade needs

- **Vertex detector upgrade requirements**
  - Radiation levels:
    - TID ~ 100 Mrad
    - NIEL ~ $5 \times 10^{14}$ neq/cm$^2$
  - Hit rate up to 120 MHz/cm$^2$
  - Fast timestamping: 50-100 ns
  - Resolution < 15 um $\rightarrow$ pitch 30-40 um
  - Power dissipation $\leq$ 200 mW/cm$^2$
  - Operation simplicity & reduced services

- **Spec’s match core features of the Depleted Monolithic Active Pixel Sensors (DMAPS) developed for ATLAS**
  - TJ-Monopix sensors, TowerJazz 180 nm process

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- **May reach limits of current detector @ target luminosity $\rightarrow$ higher space & time granularity in all layers**
Vertex detector upgrade: the VTX project

- Concept = 5 straight layers with DMAPS pixel sensors
  - Higher space-time granularity & lower material budget
    - Reduce occupancy to improve tracking in high background
    - Better tracking & vertex resolution at low momentum
  - Lighter services & “easy” geometry
    - adaptable to potential changes of Interaction Region

- Technical choices
  - Identical pixel sensor on all layers: Optimized BELle ll pIXel (OBELIX) chip
    - Thin DMAPS sensor, derived from TJ-Monopix2, with 33 um pitch & 50-100 ns timestamping
    - Operated at room temperature, power consumption 120-200 mW/cm² (hit rate 1-120 MHz/cm²)
  - iVTX: innermost 2 layers, all-silicon, self-supported (PXD-inspired), air cooled (0.2 % X0)
  - oVTX: 3 outer layers, Carbon fiber frame (ALICE-ITS2 inspired), water cooled (0.3 - 0.8% X0)
  - Total material budget reduced to 2.4% X0

Possible VTX layout

R: 1.4 - 14 cm
max length 70 cm -> 1 m²

<table>
<thead>
<tr>
<th>Layer</th>
<th>Radius (mm)</th>
<th># Ladders</th>
<th># Sensors</th>
<th>Expected hit rate*</th>
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<tbody>
<tr>
<td>L1</td>
<td>14.1</td>
<td>6</td>
<td>4</td>
<td>19.6</td>
</tr>
<tr>
<td>L2</td>
<td>22.1</td>
<td>10</td>
<td>4</td>
<td>7.5</td>
</tr>
<tr>
<td>L3</td>
<td>39.1</td>
<td>17</td>
<td>7</td>
<td>5.1</td>
</tr>
<tr>
<td>L4</td>
<td>89.5</td>
<td>40</td>
<td>16</td>
<td>1.2</td>
</tr>
<tr>
<td>L5</td>
<td>140</td>
<td>31</td>
<td>2x24</td>
<td>0.7</td>
</tr>
</tbody>
</table>

*Large uncertainty on BG extrapolation/possible changes in IR region
VTX tracking performance

- VTX performance studies: on benchmark channels, full simulations of signal events overlaying 3 possible background scenarios: optimistic:v1, intermediate:v2, conservative:v3

- Fully pixelated VTX with high space & time granularity in all layers
  - reduction in occupancy by a factor 200
  - all layers included in pattern recognition

- VTX:
  - better tracking efficiency than current VXD for full tracking (VTX tracking combined with Central Drift Chamber)
  - less sensitive to the background level than current VXD
  - better low momentum tracking efficiency than current VXD

  - Reconstruction efficiency for $B^0 \rightarrow D^{*-} l^+ \nu_l$ as a function of the $\pi-$ soft transverse momentum from the decay $D^{*-} \rightarrow D^0 \pi^-$, with $D^0 \rightarrow K^- \pi^+$

![Track finding Efficiency for different Background Scenarios](image1)

![Kπ - Efficiency vs true $p_t$](image2)
TJ-Monopix2

- TJ-Monopix2 as forerunner of OBELIX
  - Developed for ATLAS (ITK outer layers), TJ 180 nm (same as ALPIDE) but modified process to improve rad hardness & faster readout → core features matching Belle II needs
    - 33x33 μm² pitch, 25 ns integration, large matrix 2x2 cm²
    - 7 bit ToT information, 3 bit in-pixel threshold tuning
    - Column drain readout capable to handle >> 120 MHz/cm² → triggerless in TJMP2
    - Various sensing volume thickness (epi-30 um, CZ-bulk)
    - F. Huegging Poster on “Recent results on DMAPS Monopix sensors” # 299 in Solid State Poster session
  - OBELIX design based on the TJMP2 matrix with new digital periphery with trigger logic for Belle II + optional features to allow Track Trigger capability & additional finer timestamping for outer layer hits, low rate.
  - Detailed characterization of TJ-Monopix2 to validate key performance crucial for OBELIX design
TJ-Monopix2 characterization

- Detailed characterisation of TJMP2 to validate key performance
  - **In-laboratory:**
    - Threshold / noise
      → stable operation down to THR~ 250 e- (MIP signal in 30 um Si MPV~2500 e-)
      → THR dispersion 17e-, Noise ~ 8 e-
    - ToT calibration
  - **Several beam test campaigns** (DESY, 5 GeV electrons)
    - July 2022: not-irradiated sensors & high threshold 500 e- (un-tuned chips)
      - Efficiency ~99%
      - Position resolution ~9 μm
    - July 2023: low threshold 250-300 e- & irradiated sensor 5x10^{14} neq/cm²
      - Confirmed good performance & high efficiency after irradiation, increasing bias
    - July 2024: repeat on irradiated sensor with high fluence & TID 100 Mrad

- Biasing for irradiated sensor:
  - Pwell = -6 V
  - Psub = -20 V
  - HV = +30 V (only for AC)

- Irradiated sensor:
  - 5 x 10^{14} neq/cm² (with 24 MeV protons)

- Table: Efficiency (%) for different conditions:
<table>
<thead>
<tr>
<th></th>
<th>Normal</th>
<th>Cascode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency (%)</td>
<td>99.99</td>
<td>99.79</td>
</tr>
<tr>
<td></td>
<td>99.13</td>
<td>98.11</td>
</tr>
</tbody>
</table>

Epi add. p-well: 99.85 %
### OBELIX-1 specifications & layout

<table>
<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pitch</strong></td>
<td>33 µm</td>
</tr>
<tr>
<td><strong>Signal ToT</strong></td>
<td>7 bits</td>
</tr>
<tr>
<td><strong>Time stamping</strong></td>
<td>50 To 100 ns</td>
</tr>
<tr>
<td><strong>Fine time stamping</strong></td>
<td>~5 ns</td>
</tr>
<tr>
<td></td>
<td>for hit rate &lt; 10 MHz/cm²</td>
</tr>
<tr>
<td><strong>Hit rate max for 100% eff.</strong></td>
<td>120 MHz/cm²</td>
</tr>
<tr>
<td><strong>Trigger handling</strong></td>
<td>30 KHz</td>
</tr>
<tr>
<td></td>
<td>with 10 µs delay</td>
</tr>
<tr>
<td><strong>Trigger * Output</strong></td>
<td>~10 ns resolution</td>
</tr>
<tr>
<td></td>
<td>with low granularity</td>
</tr>
<tr>
<td><strong>Power (with hit rate)</strong></td>
<td>120 to 200 mW/cm²</td>
</tr>
<tr>
<td></td>
<td>(1 to 120 MHz/cm²)</td>
</tr>
<tr>
<td><strong>Bandwidth</strong></td>
<td>1 output 320 MHz</td>
</tr>
</tbody>
</table>

*optional features

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**OBELIX-1 design almost completed/verification ongoing ➔ submission in Autumn 2024**

M. Babeluk Poster on OBELIX design

# 225 in Solid State Poster session

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28/05/24 G. Rizzo - The DMAPS Upgrade of Belle II Vertex Detector
**iVTX**

- All-silicon module < 0.2% X0
  - 4 contiguous OBELIX sensors diced as a block from the wafer, thinned to 50 um, except in some border area ~400 um thick, to ensure stiffness
  - Post-process redistribution layer for interconnection
- Prototypes:
  - First real-size ladder at IZM-Berlin with dummy Si & resistive heater to test cooling too

- Air cooling alone might be marginal
  - Non uniform Power: matrix 100 mW/cm², digital periphery ~500 mW/cm² → P_avg ~200 mW/cm²
- Several options under evaluation

<table>
<thead>
<tr>
<th></th>
<th>Ladder only</th>
<th>Ladder only</th>
<th>Ladder + carbon plate</th>
<th>Ladder + carbon plate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T max (°C)</td>
<td>T range (°C)</td>
<td>T max (°C)</td>
<td>T range (°C)</td>
</tr>
<tr>
<td>Contact + air</td>
<td>44</td>
<td>22</td>
<td>41</td>
<td>18</td>
</tr>
<tr>
<td>Contact + water</td>
<td>66</td>
<td>41</td>
<td>34</td>
<td>12</td>
</tr>
<tr>
<td>Contact + air + water</td>
<td>39</td>
<td>17</td>
<td>30</td>
<td>9</td>
</tr>
</tbody>
</table>
oVTX

• Ladder structure (ALICE ITS2-inspired):
  • CF support structure (Ω beam), cold-plate with pipes (2 or 1 pipe) with liquid cooling
  • Chip and Flex circuit for power & signal
• Prototypes:
  • Mechanical & thermal characterization done for the longer ladder ~70 cm (outermost layer)
• Mechanical design already advanced
  • now also exploring a 6 layers option

Modified 6 layers layout
Summary and Outlook

• SuperKEKB will need an upgrade to reach the target Lumi $6 \times 10^{35}$ cm$^{-2}$ s$^{-1}$, including a possible major redesign of the Interaction Region (IR)

• Current VXD has excellent performance now, but limited safety margin in the high BG scenario

• Long Shutdown 2 (~2028) is a good opportunity to upgrade the vertex detector

• Proposed an upgrade (VTX) based on DMAPS pixels in all layers:
  • VTX more performant and resilient against higher machine backgrounds
  • new VTX needed in case of a redesign of the IR
  • replacement of current VXD in case of severe accidents

• Framework CDR ready: available on arXiv soon

• First full scale prototype OBELIX-1 sensor ~ ready $\rightarrow$ submission Autumn 2024

• Next steps: continue R&D and engineering activities $\rightarrow$ prepare VTX Technical Design Reports

• Preliminary schedule: VTX can be ready ~ 3 years after the final sensor (OBELIX-2) is submitted to fabrication

• VTX collaboration is growing, but still a lot to do in many areas
backup
Belle II detector

**KLong and muon detector (KLM)**
- Resistive Plate Chambers (barrel outer layers)
- Scintillator + WLSF + SiPM’s (end-caps, inner 2 barrel layers)

**EM Calorimeter (CDC)**
- Csl(Tl), waveform sampling (barrel+ endcap)

**New**
- Final focusing magnets
- Beryllium beam pipe 2cm diameter
- SuperCond. Solenoid 1.5 T magnetic field
- Vertex Detector (VXD = PXD+SVD) 2 layers DEPFET pixels + 4 layers DSSD
- Particle Identification TOP detector system (barrel) Prox. focusing Aerogel RICH (fwd)

**Upgraded**
- Electrons (7 GeV)
- positrons (4 GeV)

G. Rizzo - The DMAPS Upgrade of Belle II Vertex Detector
SuperKEKB collider

**Recipe to high luminosity**

- **High currents:** $> 1$ A

\[
L = \frac{\gamma_z}{2e_r} \left( 1 + \frac{\sigma_y}{\sigma_x} \right) \frac{B_0}{B_0^*} \gamma_z \gamma_y
\]

- **Nano-scale beam size:**
  - $\sigma_x \times \sigma_y \sim 10 \mu m \times ~60 \ nm$
  - $B_0^* < 1 \ mm$

& specific beam crossing features
- Crossing angle (83 mrad) + crab waist (80%)

**Beam-induced backgrounds**

- Intra-beam scattering
- Beam-gas interaction
- Synchrotron radiation
- Luminosity driven

Radiative Bhabha scattering
2-photon interaction
LS1 activity in a nutshell

- Accelerator improvements:
  - injection system, Non-Linear Collimators, monitoring...
  - additional shielding (e.g. neutron) and increased resilience against beam BG
  - installation of additional loss monitors

- Detector:
  - Replacement of beam-pipe & installation of complete VXD: SVD + PXD2 with 2-layers
  - replacement of 50% of photomultipliers (MCP-PMT) of the central PID detector (TOP) → increased lifespan
  - improvement in CDC gas distribution & monitoring system

- DAQ
  - completed transition to new DAQ boards (PCIe40)
  - improved data-quality monitoring, alarm system, HV control & injection inhibit scheme
Path to high luminosity

• GOAL: higher luminosity while limiting beam beam effects & preserving beam lifetime

• Several modifications are considered to further improve the SuperKEKB performance
  • upgrade of the injection complex
  • new HER beam transport (BT) line
  • increase of the HER RF stations & replacement of various aging components...

• Possible modification of the IR
  • Position of final focusing magnets (QC) closer to IP
  • New QC magnets
  • Additional solenoid for lower emittance while compensating Belle II field
  • Need feed-back from 2024 beam operation
  • Belle II envelope in interaction region still under study & schedule for LS2 is indicative
# Overview of the Upgrade program (CDR table)

Table 1.2: Known short and medium-term Belle II subdetector upgrade plans, sorted by time scale. MDI is the Machine-Detector-Interface, while RMBA is Radiation Monitoring and Beam Abort system. Moving from inner to outer radius, the current Belle II sub-detectors are: Silicon Pixel Detector (PXD), Silicon Strip Detector (SVD), forming the Vertex Detector (VXD), Central Drift Chamber (CDC), Time of Propagation Counter (TOP), Aerogel Rich Counter (ARICH), Electromagnetic Calorimeter (ECL), K-Long Muon System (KLM), Trigger and Data aquisition (TRG/DAQ), including the High Level Trigger (HLT).

<table>
<thead>
<tr>
<th>Subdetector</th>
<th>Function</th>
<th>upgrade activity</th>
<th>time scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>MDI</td>
<td>RMBA</td>
<td>Faster and more performant electronics</td>
<td>medium-term</td>
</tr>
<tr>
<td>VXD</td>
<td>Vertex Detector</td>
<td>all-pixels DMAPS CMOS sensors (VTX)</td>
<td>medium-term</td>
</tr>
<tr>
<td>CDC</td>
<td>Tracking</td>
<td>upgrade front end electronics</td>
<td>short/medium-term</td>
</tr>
<tr>
<td>TOP</td>
<td>PID, barrel</td>
<td>Replace not-life-extended ALD MCP-PMTs</td>
<td>medium-term</td>
</tr>
<tr>
<td></td>
<td></td>
<td>+SiPM option</td>
<td>medium-term</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Front end electronics upgrade</td>
<td>medium-term</td>
</tr>
<tr>
<td>KLM</td>
<td>$K_L, \mu$ ID</td>
<td>replace 13 barrel layers of legacy RPCs with scintillators</td>
<td>medium/long-term</td>
</tr>
<tr>
<td></td>
<td></td>
<td>upgrade of electronics readout and proportional mode RPC readout</td>
<td>medium/long-term</td>
</tr>
<tr>
<td></td>
<td></td>
<td>timing upgrade for K-long momentum measurement</td>
<td>medium/long-term</td>
</tr>
<tr>
<td>Trigger</td>
<td></td>
<td>hardware and firmware improvements</td>
<td>continuous</td>
</tr>
<tr>
<td>DAQ</td>
<td></td>
<td>add 1300-1900 cores to HLT</td>
<td>short/medium-term</td>
</tr>
<tr>
<td>ARICH</td>
<td>PID, forward</td>
<td>replace HAPD with Silicon PhotoMultipliers</td>
<td>long-term</td>
</tr>
<tr>
<td></td>
<td></td>
<td>replace HAPD with Large Area Picosecond Photodetectors</td>
<td>long-term</td>
</tr>
<tr>
<td>ECL</td>
<td>$\gamma$, $e$ ID</td>
<td>Add pre-shower detector in front of ECL</td>
<td>long-term</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Complement ECL PiN diodes with APDs or SiPM</td>
<td>long-term</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Replace Csl(Tl) with pure Csl crystals</td>
<td>long-term</td>
</tr>
</tbody>
</table>
VXD BG scenarios at target $\mathcal{L} = 6 \times 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$

- CAVEAT: Background extrapolation at target luminosity affected by large uncertainty due to SuperKEKB evolution, possible interaction region re-design

- 3 BG scenarios considered in CDR:
  - V1 Optimistic/V2 Nominal/V3 Conservative

<table>
<thead>
<tr>
<th>Layer</th>
<th>Radius (cm)</th>
<th>BG V1 Optimistic hit rate MHz/cm²</th>
<th>BG V2 Nominal hit rate MHz/cm²</th>
<th>BG V3 Conservative hit rate MHz/cm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layer1</td>
<td>1.4</td>
<td>12.1</td>
<td>19.6</td>
<td>32.0</td>
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<td>2.2</td>
<td>4.1</td>
<td>7.5</td>
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<td>3.9</td>
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<td>8.0</td>
<td>0.6</td>
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<td>2.2</td>
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<td>Layer5</td>
<td>10.4</td>
<td>0.3</td>
<td>0.7</td>
<td>1.3</td>
</tr>
<tr>
<td>Layer6</td>
<td>13.5</td>
<td>0.2</td>
<td>0.4</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Occupancy

Hit rate
oVTX Thermomechanics

Ladder structure design inspired by ALICE ITS2, composed of:
CF support structure (truss), cold-plate with pipes for liquid coolant circulation (neg. pressure),
Chip and Flex circuit for power&signal glued on top

Performed mechanical characterization of the L5 prototype:
- Distortion: measurements of sagitta (< 250 µm)
- Vibration: 1st resonance frequency (~250 Hz) (<< earthquake f.)

Thermal characterization:
- Used Kapton heaters, inlet (T=10°C) and outlet on one side
- Uniform temperture along the ladder $\Delta T$ max=3.3 °C

L5 ladder: 70 cm long

This solution saves space in the FWD side, giving more room for the accelerator components!
Transversal T gradient - Cold plate L6 (former L5)

White spots due to a not perfect gluing/contact

NOT fed with coolant

#3 Kapton Heaters
200 mW/cm²
Uniformly distributed

Inlet T = 10 °C
Mass flow = 0.11 kg/min

Pipe position

Results coherent with the geometry

<table>
<thead>
<tr>
<th>ID</th>
<th>Average</th>
<th>Minimum</th>
<th>Maximum</th>
<th>ΔT</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>23.82</td>
<td>22.59</td>
<td>26.46</td>
<td>3.87</td>
</tr>
<tr>
<td>L2</td>
<td>23.84</td>
<td>22.74</td>
<td>27.20</td>
<td>4.46</td>
</tr>
<tr>
<td>L3</td>
<td>26.03</td>
<td>25.22</td>
<td>28.25</td>
<td>3.03</td>
</tr>
<tr>
<td>L4</td>
<td>27.08</td>
<td>25.84</td>
<td>28.53</td>
<td>2.69</td>
</tr>
<tr>
<td>L5</td>
<td>27.37</td>
<td>26.55</td>
<td>28.89</td>
<td>2.34</td>
</tr>
<tr>
<td>L6</td>
<td>27.35</td>
<td>26.33</td>
<td>28.74</td>
<td>2.41</td>
</tr>
<tr>
<td>L7</td>
<td>27.02</td>
<td>26.38</td>
<td>28.41</td>
<td>2.03</td>
</tr>
<tr>
<td>L8</td>
<td>26.66</td>
<td>25.72</td>
<td>29.38</td>
<td>3.66</td>
</tr>
<tr>
<td>L9</td>
<td>27.59</td>
<td>26.10</td>
<td>29.59</td>
<td>3.49</td>
</tr>
</tbody>
</table>

Transversal thermal gradient less than 5 degrees everywhere

Max temperature less than 30 degrees everywhere
Table 5.1: OBELIX sensor specifications, compared to the relevant specification of the TJ-Monopix2 sensor.

<table>
<thead>
<tr>
<th>Specification</th>
<th>OBELIX</th>
<th>TJ-Monopix2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel pitch</td>
<td>&lt; 40 μm</td>
<td>&lt; 33 μm</td>
</tr>
<tr>
<td>Sensitive layer thickness</td>
<td>&lt; 50 μm</td>
<td>30 μm and 100 μm</td>
</tr>
<tr>
<td>Sensor thickness</td>
<td>&lt; 100 μm</td>
<td>-</td>
</tr>
<tr>
<td>Hit rate capability in the matrix</td>
<td>&gt; 600 MHz cm⁻²</td>
<td>&gt; 600 MHz cm⁻²</td>
</tr>
<tr>
<td>Hit rate capability at the sensor output</td>
<td>&gt; 120 MHz cm⁻²</td>
<td>≫ 100 MHz cm⁻²</td>
</tr>
<tr>
<td>Trigger delay</td>
<td>&gt; 10 μs</td>
<td>-</td>
</tr>
<tr>
<td>Trigger rate</td>
<td>30 kHz</td>
<td>-</td>
</tr>
<tr>
<td>Overall integration time</td>
<td>&lt; 100 ns</td>
<td>-</td>
</tr>
<tr>
<td>(optional) Time precision</td>
<td>&lt; 50 ns</td>
<td>-</td>
</tr>
<tr>
<td>Total ionizing dose tolerance</td>
<td>100 Mrad</td>
<td>-</td>
</tr>
<tr>
<td>NIEL fluence tolerance</td>
<td>5 × 10¹⁴ n_{eq}/cm²</td>
<td>1.5 × 10¹⁵ n_{eq}/cm²</td>
</tr>
<tr>
<td>SEU tolerance</td>
<td>frequently (min⁻¹)flash configuration</td>
<td>-</td>
</tr>
<tr>
<td>Matrix dimensions</td>
<td>around 30 × 16 mm²</td>
<td>19 × 19 mm²</td>
</tr>
<tr>
<td>Overall sensor dimensions</td>
<td>around 30 × 19 mm²</td>
<td>20 × 19 mm²</td>
</tr>
<tr>
<td>Powering</td>
<td>through voltage regulators</td>
<td>-</td>
</tr>
<tr>
<td>Outputs</td>
<td>one at &lt; 200 MHz</td>
<td>one at 160 MHz</td>
</tr>
</tbody>
</table>
The Pixel Vertex Detector (PXD) Module

Properties:
- Self-supporting "all-silicon" structure
- Support frame 500 μm thick
- Monolithic active area 75 μm thick
- Low material budget (~0.21% X₀)
- Pixel sizes 50 x 55-85 μm²
  (250 x 768 pixels)

Rolling Shutter Readout:
- Switcher: consecutive row selection for signal digitization of columns (10 MHz)
- DCD: 8-bit AD conversion of signal
- DHP: zero suppression, data formatting
- 20 μs integrated readout time
  (2x beam revolution)

Impact Parameter Resolution:
- Di-muon events (pt > 2 GeV)
  - z₀: 20 – 40 μm
  - d₀: 10 – 22 μm
- MC describes data
  - MC slightly too optimistic
    (z₀ ~3 μm, d₀ ~1.5 μm)
- ~1.5 – 2 times better than Belle

D⁺ Lifetime Resolution:
- Impact of better vertex detector
- Belle II D⁺ lifetime resolution
  ~2 times better

Power Consumption:
- ~9 W per module
  → ~360 W (full detector)
- Cooling
  - 2 phase CO₂: DHP/DCD (8W)
  - N₂ gas: sw.+sensor area (1W)

PXD1:
- PXD1 incomplete (effectively 1 layer)

2 Modules = 1 Ladder:
- Glued together
- In total 20 ladders

10 Ladders = 1 Half-Shell:
- Ladders screwed on cooling block
  - Radii: r₁=14mm, r₂=22mm
- Half-Shell mounted on beam pipe

Belle II lifetime measurements with high PXD impact:

- D⁺: ±σ=3×10⁻⁶ (2002)
- D: ±σ=5×10⁻⁶ (2002)
- B: ±σ=5×10⁻⁶ (2002)
- C: ±σ=1×10⁻⁶ (2002)
**SVD structure**

- Cross-sectional view
- DSSD sensors - Double-sided Silicon Strip Detectors
- Windmill geometry

**Origami chip on sensor concept**
- Readout chips directly on each middle sensor
- Shorter signal propagation length (smaller capacitance and noise)
- Thinned to 100 μm to reduce material budget
- Wrapped flex to read both sides from the same side
- Cool only one side with bi-phase -20 °C CO2

**Front-end electronics**
- APV25 chips in ladder
- Central DSSD sensor connected to front-end APV25 ASICs via flex circuits
- “origami scheme”

- **Total Power 700 W**
- **172 sensors with 1.2 m² se**
- **224k readout strips**

**By default:**
- 6 subsequent samples readout

**Alternative for high luminosity runs:**
- 3/6 mixed acquisition mode
  - allows to reduce data size due to enhanced background occupancy
  - 3 or 6 sample mode depends on the timing precision of the trigger for particular event

- **Frontend ASIC APV25:**
  - 128 channels per chip
  - 50ns shaping time
  - Radiation hardness > 100 Mrad
  - Power consumption: 0.4 W/chip
  - Multi-peak mode at 32 MHz
  - Total Power 700 W