Botho Paschen (University of Bonn) on behalf of the Belle II PXD collaboration

PERFORMANCE OF FINAL BELLE II PIXEL DETECTOR MODULES

Vienna Conference of Instrumentation
19th February 2019
INTRODUCTION

- The SuperKEKB Accelerator
- Belle II
- Commissioning
SUPERKEKB

- Located at KEK, Japan
- Upgrade of KEKB accelerator
- Asymmetric e+e- collider
- Peak luminosity $L = 8 \times 10^{35}$ /cm$^2$/s (40 times higher than KEKB)
- $E_{cm} = m(Y(4S)) = 10.58$ GeV → super B-factory
The Belle II Detector

- Upgrade of Belle for higher luminosity
- Higher trigger rate (30 kHz)
- Higher machine induced background
- Radiation damage
- Occupancy
- All sub-detectors replaced or upgraded
- New vertex detector
COMMISSIONING OF SUPERKEKB + BELLE II

- Stepwise commissioning in three phases
  - Phase 1 finished in 2016
    results published Jan 2019
    [Link to paper](https://doi.org/10.1016/j.nima.2018.05.071)
  - Phase 2 finished 2018
  - Phase 3 (physics run) about to start

Goal of Belle II

- Phase 1: Accelerator commissioning
- Phase 2: BEAST and partial Belle II commissioning
- Phase 3: Full Belle II detector

P.M. Lewis, I. Jaegle, H. Nakayama et al. “First Measurements of Beam Backgrounds at SuperKEKB”
THE PIXEL DETECTOR

- Belle II Vertex Detector
- Pixel Detector
- Working Principle and Design
THE BELLE II VERTEX DETECTOR (VXD)

- 4 layers double sided silicon strip (SVD)
  - $R = 3.9$ cm, 8.0 cm, 10.4 cm, 13.5 cm
  - Area $\sim 1$ m$^2$

- 2 layers DEPFET pixel detector (PXD)
  - $R = 1.4$ cm, 2.2 cm
  - Area $\sim 0.03$ m$^2$
**PXD SPECIFICATIONS**

- Very low material budget (0.2% X₀/layer)
- Self supporting ultra-thin detectors
- Resolution dominated by multiple scattering

### Belle II PXD

- **Occupancy**: 0.4 hits/µm²/s (< 3%)
- **Radiation**: 2 Mrad/year
- **Frame time**: 20 µs
- **Momentum range**: Low momentum (< 1 GeV)
- **Acceptance**: 17°-155°
- **Material budget**: 0.2% X₀ per layer
- **Resolution**: 15 µm (50x75 µm²)
THE DEPFET MODULE

- Highly integrated monolithic silicon module (HLL)
  - Three regions:
    - Sensor (thinned, 75 μm)
    - Frame and balcony (525 μm thick + grooves)
    - End Of Stave (EOS) outside acceptance
  - Three metal layers for interconnection
    - 2 Al + 1 Cu
- Three types of ASICs bump-bonded to module
  - 14 chips, ~3000 bumps in total
PXD MECHANICS/COOLING

- 3D printed metal support cooling blocks (SCB)
- mounted directly onto the beam pipe
THE DEPFET

- Field Effect Transistor (FET) on top of fully depleted silicon bulk
- Fast charge collection (~ns)
- Charges collected in “internal gate”
- Readout of modulated drain current
  → internal amplification

\[ g_q = \frac{\partial I}{\partial q} \approx 500 \frac{pA}{e^-} \]

- Periodical clearing of “internal gate” required
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SENSOR READOUT CONCEPT

- Row-wise readout (four-fold rolling shutter)
- Charge collection in “off-state”
  → Low sensor power consumption (0.5 W/mod)
- Readout electronics outside of detector acceptance
- Trickle injection in SuperKEKB causes noisy bunches 
  ~ every 50 Hz
- Sensor can be periodically blinded during bypass (100 KHz)
- Newly created charges are not collected
- Charges in internal gate are preserved
  -> still mostly sensitive to clean bunches
PERFORMANCE OF THE PXD

- Phase 2 Vertex Detector
- PXD during Phase 2
- PXD at the Test Beam
PHASE 2 SETUP

Final Silicon Vertex Detector (VXD)

The BEAST II Detector

60 cm

~7.5 m
Motivation for **BEAST II**:
- Machine commissioning
- Radiation safe environment for the VXD
- DAQ integration of Belle II pixel and strip detectors
- For more on BEAST II see Luka Santelj’s poster
THE BEAST II VERTEX DETECTOR (VXD)

- 4x SVD: Belle II double sided strips
- 2x PXD: Belle II DEPFET pixel
- 3x FANGS: hybrid pixels ATLAS IBL modules
- 2x CLAWS: scintillator tiles
- 2x PLUME: monolithic CMOS pixel
PHASE 2 PXD PERFORMANCE

- Good pedestal distribution throughout run
- Compression with variable current source
- Noise \(\sim 0.8\) ADU

\[ \Rightarrow 100e^{-}\text{ENC} \]
PHASE 2 PXD PERFORMANCE

- SNR of charged particle peak ~ 50 for all sensors
- Low energy photon peaks
- Threshold ~900 e
PHASE 2 PXD PERFORMANCE

- FET threshold changed by radiation over time
- Adjustments of gate voltages necessary to recover amplification
- Background radiation unexpectedly high and TID uncertain
PHASE 2 PXD PERFORMANCE

- $\sigma(d_0) = 12 \, \mu m$ (10 $\mu m$ expected)
- $\sim$ factor 2 better than at Belle
PHASE 2 PXD PERFORMANCE

- Tracks from CDC + SVD
  - > 2 SVD hits
  - $P > 4$ GeV
- Efficiency $\geq 97\%$
- ADCs at default parameters
- DEPFET working point possibly not optimal
- Beam test at DESY in Nov. 2018
- Task: Find optimal working parameters to maximize efficiency
  - 3 GeV electrons
  - Mimosa beam telescope for tracking
  - FEI4 plane for timing (25 ns)
MODULE BEAM TEST PERFORMANCE

- Two modules large-area-illuminated
- 10-100 tracks per pixel (to be improved, recover more data)
- Known electrical issues on certain drain, gate, clear lines
- Raw efficiencies 96-98 %
- Efficiencies of working regions: 99.5 %
STATUS OF BELLE II PXD
PRESENT AND FUTURE

- Problems during the ladder assembly (glueing)
- De-scoped PXD was installed
  - Full layer 1
  - 2/12 layer 2 ladders
- PXD 2020:
  - Current PXD to be replaced during summer 2020
  - Production of sensors already started a year ago
  - Revised glueing procedure for better yield
PHASE 3 COMMISSIONING

- Cosmic tests with combined VXD end of last year
- Pre-insertion DAQ and alignment studies
- Currently global commissioning of full Belle II
- Accelerator start in March
SUMMARY

- Belle II PXD modules have been integrated into the Belle II experiment (phase 2+3)
  -> High Energy DEPFET in action!

- Performance during phase 2 satisfactory
  - Preliminary vertexing results close to expectation

- Partial PXD (L1 + partial L2) installed for beginning of Belle II physics run (phase 3)

- Replacement with full Belle II PXD planned in summer 2020
Thank you
BELLE II CONTRIBUTIONS AT VCI 2019

- Alexander Kuzmin, „Belle II electromagnetic calorimeter“, Tue 16:30, calorimeter
- Leonid Burmistrov, „Belle II aerogel RICH detector“, Wed 11:30, cherenkov
- Giulia Casarosa, „Commissioning of the Belle II Silicon Vertex Detector“, Thu 09:25, semiconductor detectors
- Matrin Bessner, „Performance of the Belle II imaging Time-Of-Propagation (iTOP) detector in first collisions“, Fri 14:50
- Luka Santelj, „Measurements of Beam Backgrounds at SuperKEKB“, poster B
- Christian Irmler, „Run and Slow Control System of the Belle II Silicon Vertex Detector“, poster A
- Richard Thalmeier, „Series Production Testing, Commissioning and Initial Operation of the Belle II Silicon Vertex Detector Readout System“, poster B
PRODUCTION TESTING – WAFER LEVEL

- 6 modules per wafer
  module sizes: 1.5 x 6.8/8.5 cm²
  (+ additional test structures)
- 3 pilot run wafers → modules tested 2016
- 4 pre-production wafers → modules tested 2017
- 21 final production wafers → processing finished

- Needle testing for shorts and basic IV-curves
  with dedicated fan-out structure before dicing
- Module yield ca. 60 % grade A (>99% working pixels)

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<tr>
<td>Inner Forward</td>
<td>8</td>
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<tr>
<td>Outer Forward</td>
<td>12</td>
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PRODUCTION TESTING – MODULE LEVEL

ASIC ↔ backend communication: 1.6 Gbps links via
50 cm Kapton + 1.5 m copper cable
+ 15 m optical for data / 15 copper for steering signals
ASIC ↔ ASIC communication: 300 MHz on-module signals

ADC optimization
1000 active ADCs/module
Transfer curves:
- dynamic range
- gain
- linearity

Radioactive
source scans
- dead pixel test
- working point
optimization
Table 2.1: Geometrical layout of the DEPFET vertex detector modules.

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<thead>
<tr>
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<th>inner layer</th>
<th>outer layer</th>
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<tbody>
<tr>
<td>radius</td>
<td>14 mm</td>
<td>22 mm</td>
</tr>
<tr>
<td>pixel size 1-256 (RΦ)</td>
<td>50 μm × 55 μm</td>
<td>50 μm × 70 μm</td>
</tr>
<tr>
<td>pixel size 257-768 (RΦ)</td>
<td>50 μm × 60 μm</td>
<td>50 μm × 85 μm</td>
</tr>
<tr>
<td>sensitive area (module)</td>
<td>12.5 mm × 44.8 mm</td>
<td>12.5 mm × 61.4 mm</td>
</tr>
<tr>
<td>sensor thickness</td>
<td>75 μm</td>
<td>75 μm</td>
</tr>
<tr>
<td>max. occupancy</td>
<td>0.9 %</td>
<td>0.55 %</td>
</tr>
</tbody>
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L=3.6 μm, W=11 μm
EPICS AND SLOW CONTROL

- Experimental Physics and Industrial Control System (EPICS)
- Control System Studio (CSS)
- Smooth integration of GUIs, plots and archiver functionality

EPICS