THE BELLE II PIXEL DETECTOR
STATUS AND PERFORMANCE

FLORIAN LÜTTICKE ON BEHALF OF THE BELLE II PXD/DEPFET COLLABORATION
Universität Bonn, Physikalisches Institut, Nussallee 12
- **Phase 1**
  - Accelerator commissioning. No Belle II detector, no final focus system, no collisions.

- **Phase 2**
  - Accelerator tuning, detector integration. Belle II with BEAST II detector, final focus system.

- **Phase 3**
  - Physics runs. Full Belle II detector.

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**Goal of Belle II**

- 9 months/year
- 20 days/month
Asymmetric energy (4 GeV, 7 GeV) $e^+e^-$ collider at the $E_{cm}=m(\Upsilon(4S))$

Final luminosity $8 \cdot 10^{35}$ cm$^{-2}$ s$^{-1}$, 40 times higher than KEKB

Precision measurements using B Mesons (+ Charm, + Tau)

- CKM parameters
- Search for rare decays
- Search for physics beyond the standard model
- CP Violation
- 30 kHz event rate
- 50 MeV - 4 GeV momentum range
- Acceptance between 17°-155°
**Belle II Vertex Detector (SVD)**

- 4 layer double sided Strips

**DEPFET PiXel Detector (PXD)**

### Table

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Occupancy (L1)</td>
<td>0.4 hits/µm²/s</td>
</tr>
<tr>
<td>Radiation (L1)</td>
<td>20kGy/year</td>
</tr>
<tr>
<td>$2 \cdot 10^{12}$ 1 MeV $n_{eq}$ per year</td>
<td></td>
</tr>
<tr>
<td>Frame time</td>
<td>20 µs</td>
</tr>
<tr>
<td>Material budget</td>
<td>0.2% $X_0$ per layer</td>
</tr>
<tr>
<td>Resolution ($\sigma_{z_0}$)</td>
<td>15 µm (50x75 µm²)</td>
</tr>
</tbody>
</table>

**PXD**: DEPFET Pixels at R = 14 mm and R = 22 mm

**SVD**: Double Sided Strips
BELLE II VERTEX DETECTOR
IMPACT PARAMETER

Material budget

\[ \sigma_{d0} \approx a \oplus \frac{b}{p \sin^3 \theta} \]

- Modest resolution (15 μm), dominated by multiple scattering (Pixel size 50 x 75 μm²)
- Lowest possible material budget (0.2% \(X_0/\text{layer}\))

a: Geometry, governs at high momentum
b: Multiple Scattering, dominates at low momentum

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DEPFET BELLE II PXD MODULE

Switcher

DEPFET pixel matrix

DHP

DCD

Kapton

cooling block

silicon support structure
- FET in saturation: \( V_{GS} > V_{th} \) and \( V_{DS} \geq (V_{GS} - V_{th}) \)

\[ I_d = \kappa \left( V_{GSS} + \left(\frac{aq}{C}\right)^2 - V_{th} \right)^2 \]

- Charge modulates drain current
  - Conversion factor:
  \[ g_q = \frac{dI_d}{dq} = \alpha \frac{g_m}{C} \]
  - Internal amplification
  \[ g_q \approx 700 \frac{pA}{e^-} \]

\( I_d \): source-drain current
\( C \): gate capacitance
\( \kappa \): device constant
\( V_{GSS} \): gate voltage
\( V_{th} \): threshold voltage
\( g_m \): transistor gain

\( e^- \): electron
\( h \): hole

\( p+ \): p+ backside
\( p-channel \)

\( \text{top view of a DEPFET} \)
DEPFET – DEPLETED P-CHANNEL FIELD EFFECT TRANSISTOR

- Nondestructive readout
- Charge needs to be cleared
- Clear contact attractive for electrons
- Collect charge: low clear potential
- Remove charge: high clear potential

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DEPFET READOUT

- Single transistor
- Transistor array
- Steering connected row wise
- Drain connected column wise
- Reading one row
- Clearing one row

Drain Current Digitizer (DCD)
BELLE II COMMISSIONING

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**Goal of Belle II**

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

- 9 months/year
- 20 days/month
One segment of VXD, FANGS, CLAWS, PLUME, (+ He3, TPC, and diamonds outside VXD).
- Radiation monitoring and feedback for accelerator tuning.
- Slow control / DAQ integration

See talk of J. Baudot, Tuesday, Session 8
- Narrow Pedestal current distribution
  Stable over time

- Noise ~0.8 LSB (100e ENC)

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- SNR > 50 for all sensors, 10% spread
- Sensitivity to low keV Photons
- Threshold ~900e-
- Inner layer absorbs most photons
- PXD successfully integrated in Belle II DAQ
- $\sigma_{68}^{meas} = 12.1 \, \mu m \pm 0.2 \, \mu m (stat) \pm 0.1 \, \mu m (sys)$
- $\sigma_{68}^{exp} = 9.9 \, \mu m \pm 0.2 \, \mu m (stat)$

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PHASE 2 PXD TID

- TID changes transistor threshold
- $MPV \sim g_q \sim \sqrt{I_D} \sim U_{GS} - U_{th}$
- Higher Background than simulated
- Discrepancy between diamond and radiochromic foil
- PXD at different position than diamond

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BELLE II COMMISSIONING

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STATUS OF PHASE 3

Full layer 1 and 2 layer 2 ladders installed

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Largest Problem: Gluing modules to a ladder

- Stopped due to low yield

PXD2020:

- Replace current PXD in 2020 with completely new PXD
- New gluing approach
  - More tooling
  - Modules face up
- Keep working steps
- Extensive test program
PHASE 3 - TIMELINE

- 21.08. & 04.09 Half shells arrived at KEK
- 05.09 Combining half shells with beam pipe
- 12.09. Module operation of two half shells. All Modules working.
- 03.10. Mating with SVD half shells
- End of October: Cosmic ray test. All Modules working.
- 21.11. Installation into Belle II
- 07.12. Digital parts working, analog tests pending

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CONCLUSION

- Phase 2:
  - Good PXD performance
  - Successful integration into global Belle II DAQ and global slow control
  - Background more than 10x higher than expected

- Phase 3:
  - Full layer 1 and partial layer 2 installed
  - VXD inserted into Belle II
  - Digital tests successful, analog tests this week.
Thank you for listening. Questions?
- Estimation for finding/resolution
UPDATED LUMINOSITY PROFILE

![Graph showing the updated luminosity profile with data points from 2019 to 2025. The graph indicates a steady increase in luminosity over time.]
TOTAL IONIZING DOSE FOR PXD

- Estimated TID from threshold voltage shift: ~2-5 kGy
- Factor 50-100 larger than estimate from diamonds
  - diamonds have only little sensitivity to ~10keV photons
  - different location on beam pipe in z and rφ
- Radio-chromic foils @ diamonds see factor 5-10 higher dose than diamonds and a soft radiation component (<100keV)
- Ratio of PXD dose rate (sens. Si volume) to diamond dose rate gives factor 10-100 depending on run condition

B. Schwenker, Vertex 2018
SR RADIATION BACKGROUND IN PHASE 2

- $R_{sr} = E^2 B^2$ – dominant contribution expected from HER
- Energy of SR photons expected to be from few keV to tens of keV
- Inner surface of beryllium beam pipe coated with Au layer to absorb SR photons
- Ridge structures of incoming pipes to avoid hits from forward reflected SR photons in beam pipe
- Direct hits stopped by tapered shape of incoming beam pipes
- PXD (+X) and FANGS (-X) observed soft photon peaks for both beam around 6-10keV
- "Postdicted" in new MC simulations with more precise Geant4 physics list

Rate of soft photon hits in PXD scales just with current + offset

B. Schwenker,
Vertex 2018
- Layer 1 important for physics parameters
- Layer 2 important to extrapolate the SVD track to the correct layer 1 PXD hit.
  - No Background: Negligible performance difference with full PXD.
  - Design Background: 2% Efficiency loss, slightly degraded time resolution
  - Higher Background: Much worse performance
LADDER ASSEMBLY
NEW METHOD

T Ackermann, E Töpper, H.G. Moser:

1) Module on transport & test jig

2) Take off and put on glue jig
   Glue jig almost identical with test jig, just shorter
   Held by vacuum (balcony and EOS)
   Similar procedure as after kapton soldering

3) Cover with protective cover & clamp

4) Dispense glue (modules & stiffeners)
5) Place on alignment stage

6) Add table with ceramic stiffeners

7) Place 2\textsuperscript{nd} module on stage

8) Align and join together

H.G. Moser
Ceramic stiffeners placed in slots in a table exactly under the grooves.
Pushed inside grooves by lifting guided lifters.
Stops to prevent over-travel.
Self alignment due to triangular geometry (to be checked).
9) Place stiffeners, cure for 48h

10) Add lift off jig

11) Lift off and place on ladder jig
    Same procedure as for ladder mounting

12) Remove lift off jig