Construction of the Belle II Pixel-Vertex Detector

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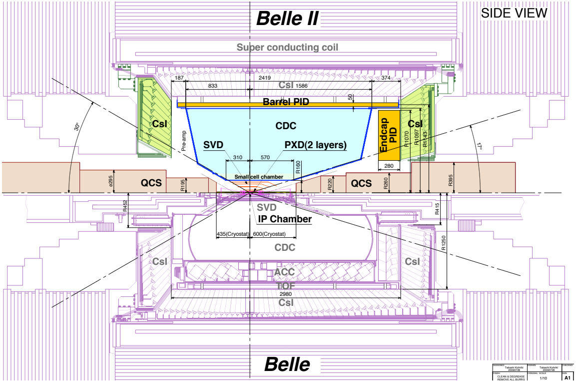
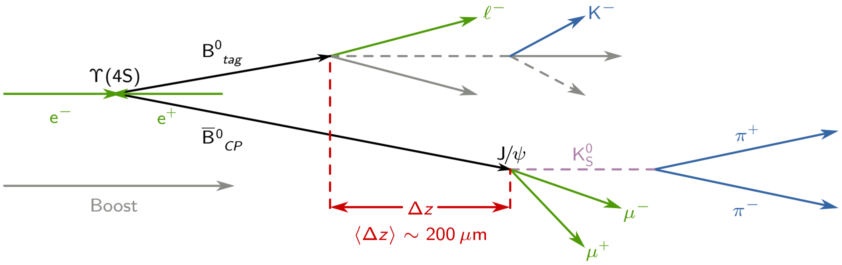
DEPFET
Active Pixel Detector

Belle/Belle II Experiment

- asymmetric e^+e^- experiment mainly at the $\Upsilon(4S)$ resonance (10.58 GeV)
- KEKB peak luminosity of $2.11 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (world record)
- $1023\,\mathrm{fb}^{-1}$ integrated luminosity since 1999 (772 million $B\overline{B}$ pairs)
- upgrade to SuperKEKB/Belle II 2010-2013 (target luminosity: $8 \times 10^{35}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$)



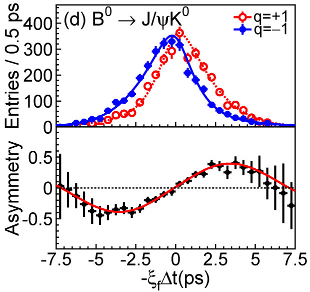
Vertex finding



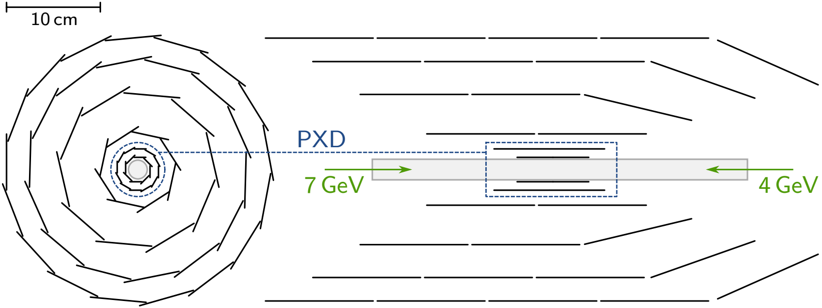
Vertex finding is the Key to CP-Violation measurement:

- CP violation is time dependent ($\langle \Delta t \rangle \sim 1$ ps)
- boost translates lifetime difference into vertex distance ($\langle \Delta z \rangle \sim 200\ \mu$m)

➡ precise silicon vertex detector needed



Belle II Vertex Detector



Will consist of two mechanically independent subdetectors:

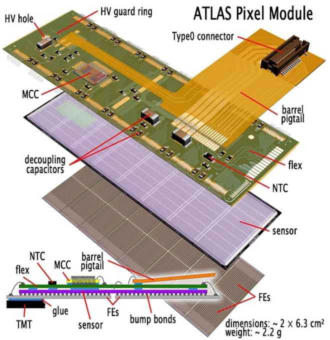
Pixel Vertex Detector

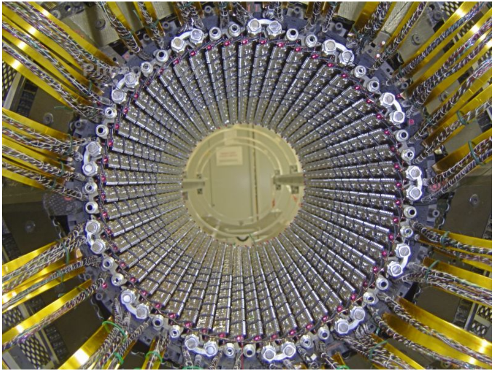
- two layer DEPFET pixel detector
- very low material budget (0.14% X_0 per layer)
- mounted on beampipe
- 40 sensor modules

Strip Vertex Detector

- four layer double sided strip detector
- forward parts will be slanted
- attached to CDC
- 187 sensor modules

Standard Silicon Detector





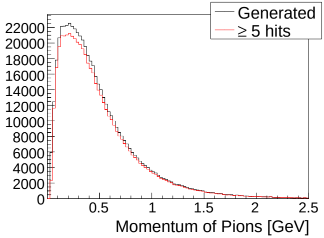
- multiple sensitive modules are glued on support ribs which provide mechanical stability
- support, cooling and cables inside acceptance region
- ➡ too much material for Belle (10 GeV CM energy)

PXD Mechanical Design

Vertex resolution is the key to CP-Violation

➡ low material budget required to minimize energy loss and multiple scattering, leading to a different design compared with existing Silicon detectors

- silicon sensors self supporting
- sensitive area will be thinned down to 75 μm
- almost no additional material inside of the acceptance



Silicon has good mechanical properties (high tensile strength, no plastic deformation, good elasticity)

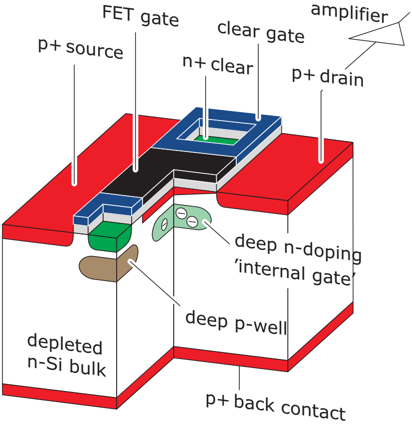
But:

Silicon is very brittle: Once there is a small crack, this crack can grow very easily

No prior experience with this design

➡ additional tests required to make sure nothing breaks

DEPFET Pixel Detector



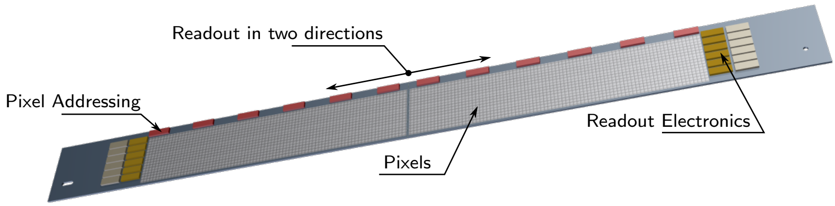
The DEPFET Principle

- FE-Transistor on each pixel
- doped areas beneath transistor form electron trap
- traversing charged particles produces electron hole pairs
- electrons get trapped and act as gate
- integrating device, always active
- collected charge has to be cleared after readout

➡ low noise, fast signal collection, low power consumption

Additional talks on DEPFET on Thursday by Christian Koffmane and Andreas Ritter

Pixel Sensor



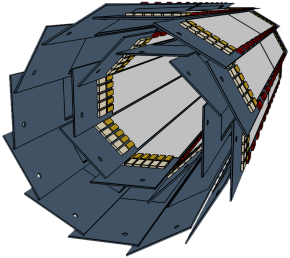
A sensor consists of many pixels in a 2D grid on a silicon module

- some additional electronics needed for addressing and readout of the pixels
- pixels are read out to both sides: one side per half

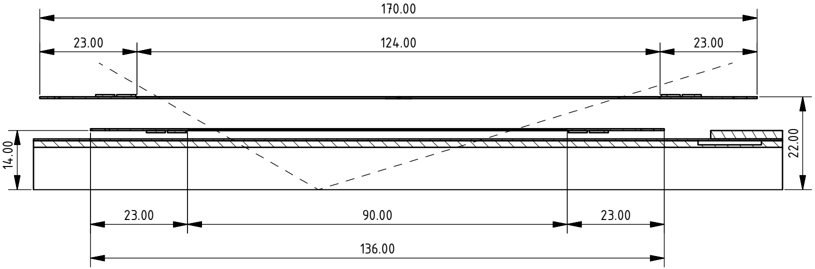
Sensor has to be cooled

- active area produces 0.5 W of heat
- addressing chips produce 0.5 W of heat
- readout electronics produce 8 W of heat per side

Layout of the PXD

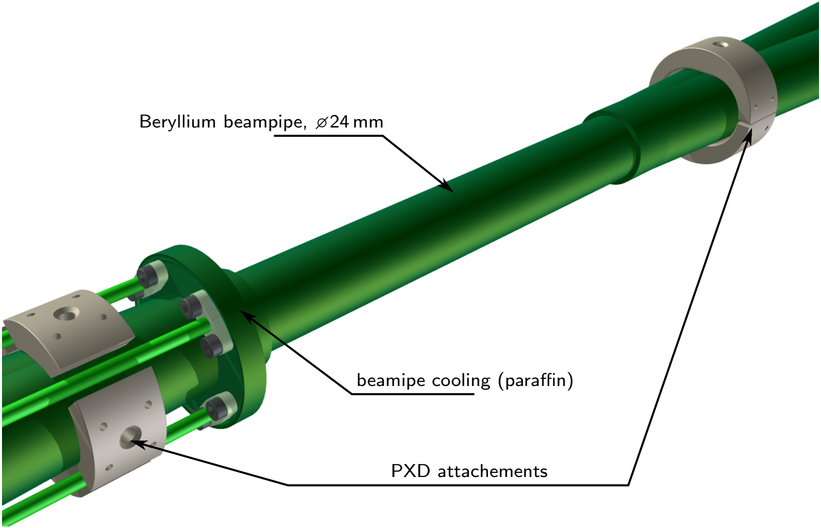


- PXD consists of 20 Modules in 2 layers
- each module has 1600 $\times$ 250 pixels (8 M pixel in total)
- pixel size of 50 $\times$ 50 μm for the inner layer and 75 $\times$ 50 μm in the outer layer
- each pixel readout with 8bit ADC
- total readout time of 20 μs



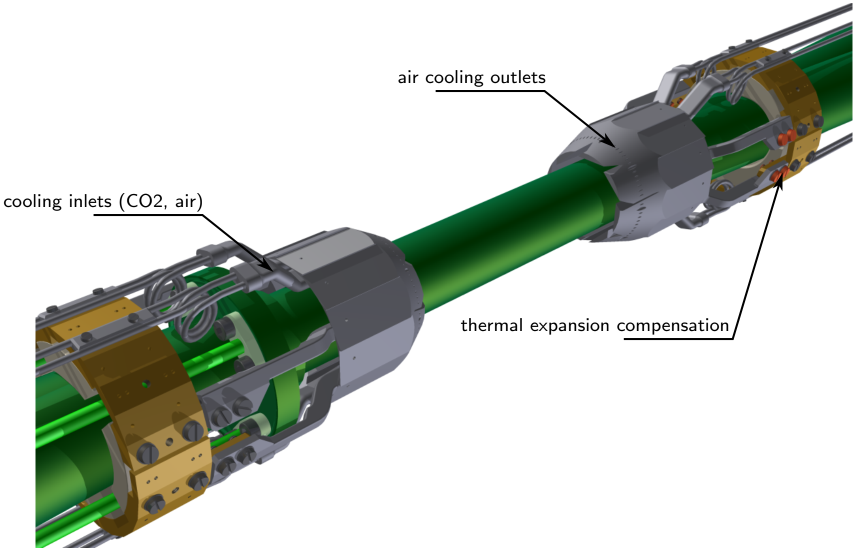
PXD Support

Beampipe including PXD Attachements



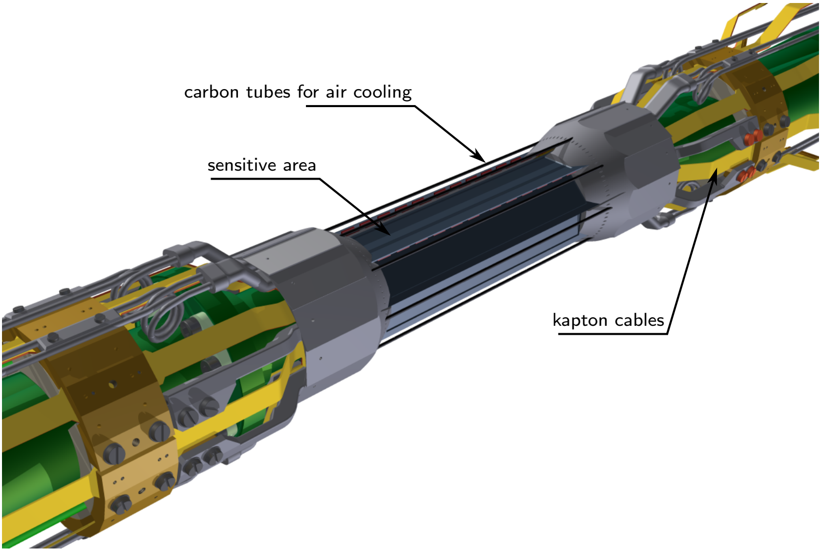
PXD Support

Mechanical Support



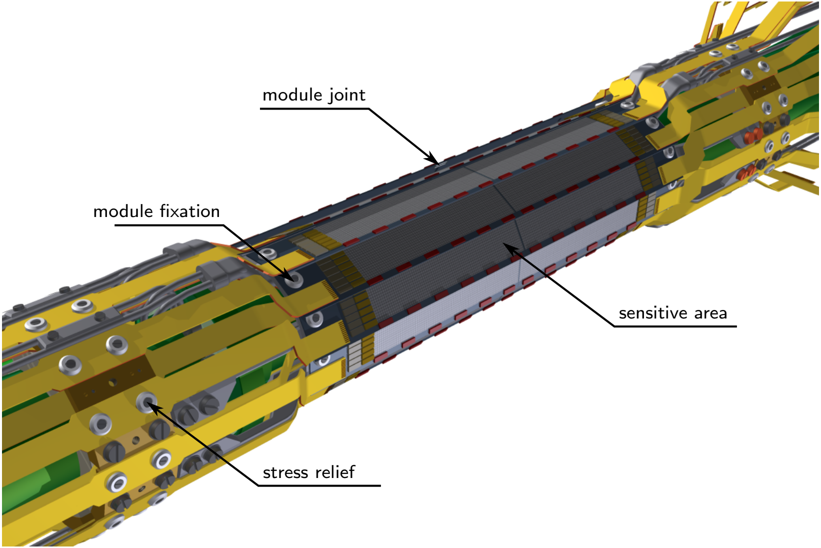
PXD Support

Inner layer and carbon tubes



PXD Support

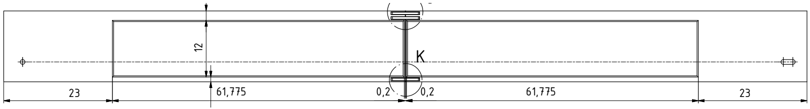
Complete PXD



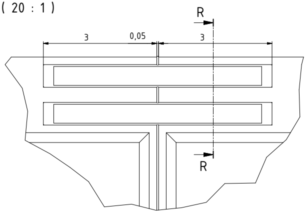
PXD Mockup


Red Bull
ENERGY DRINK
PXD for BELLE - II
DEPFET Collaboration
design and mockup by
MPI Munich

Module Glueing



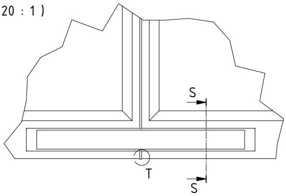
J (20 : 1)

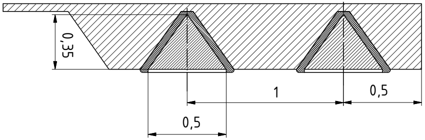


Reinforced front face glueing

- reinforced using ceramic “prisms”
- almost no additional material
- only $\sim 500\,\mu$m of dead area

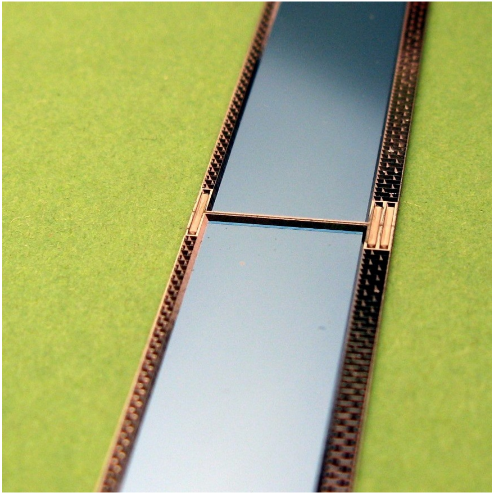
K (20 : 1)



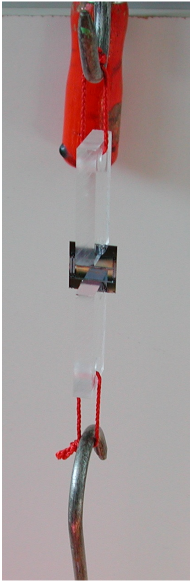


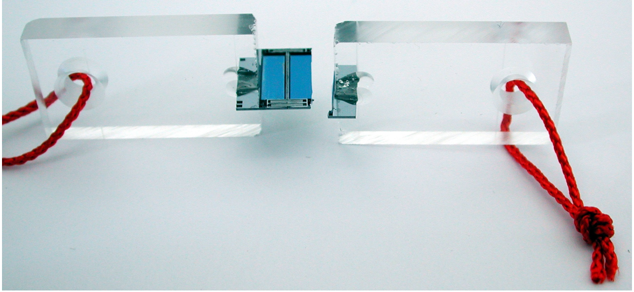
Test Glueing

Test glueing of mechanical dummies thinned to 50 μm to verify design



Tensile Strength Test





Tensile strength test carried out:

- ends of the module fixated
- increasing force applied to pull the pieces apart
- solid 450 μm silicon tested to 7 kg
- unthinned front face glueing achieved $\sim$ 6 kg

Long time test (unthinned, 3 kg) still ongoing: 6 weeks already achieved

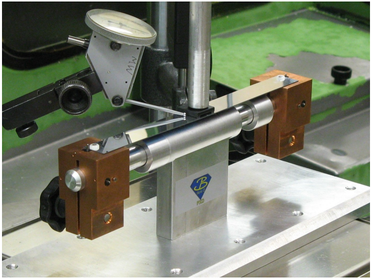
Strengh Test Results

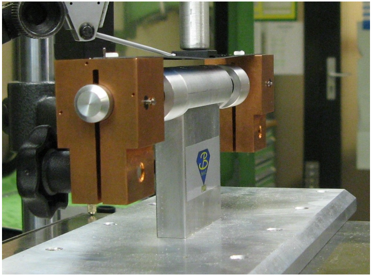
- module broke just above 5 kg
- glue more or less still intact
- silicon seems to be weaker then glue (for 50 μm)
- long time test with 3 kg broke after few hours: silicon again the weak part

Bowing Strength Test

Additional test to study deformation perpendicular to module axis

- module screwed to endplate on both sides
- one endplate fixed, one free to slide along module axis
- applying pressure to module center (0.025 mm every 15 seconds) up to 1 mm deformation

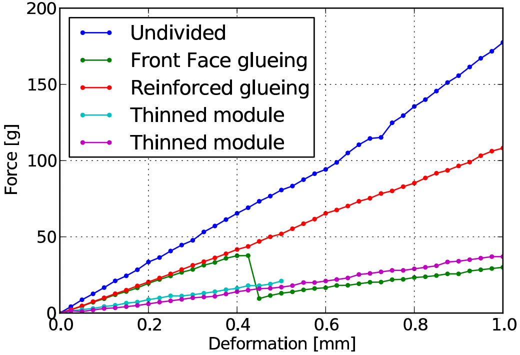




Bowing Test Results

- undivided, inner layer dummy broke at deformation of 1.445 mm (equivalent to a force of 315 g)
- front face glued outer layer module:
  - glueing broke at 0.4 mm deformation (37.7 g)
  - half modules remained in good order, tested to 1 mm deformation ($\sim$ 30 g)
- reinforced glueing successfully tested up to 1 mm deformation (110 g)

- thinned down outer layer dummy tested up to 1 mm deformation (35 g)
- cracks in thinned area: no growing visible

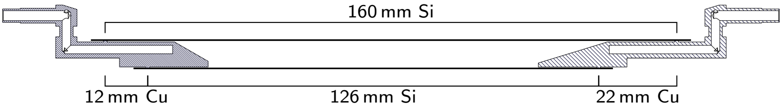


Thermal Mechanical Tests

Goal: Verify Mechanical Design

Baseline: Modules screwed to endflange to ensure good thermal contact and positional stability

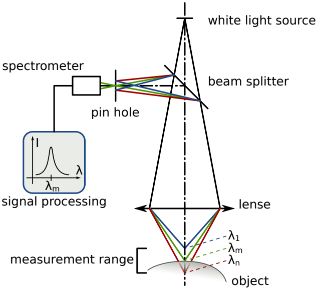
One Issue: Internal stress due to thermal expansion

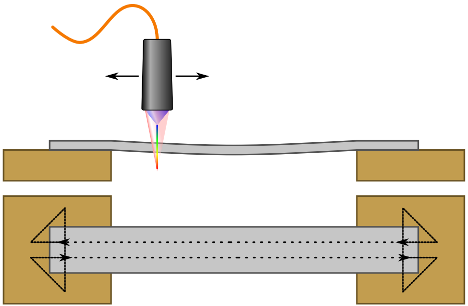


- Difference between thermal expansion of inner and outer layer $\sim 20\,\mu$m for $\Delta T = 40\,^{\circ}$C
- we need to make sure that modules and glue remain stable over the whole temperature range

Precise position/distance measurement over "large" temperature range needed.

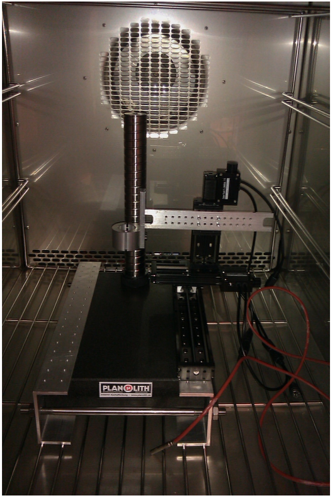
Confocal Chromatic Distance Sensor





- high resolution ($\sim 1\,\mu$m axial, $\sim 10\,\mu$m lateral)
- contact free measurement
- almost independent of material (max. slope depends on reflectivity)
- passive sensor: large temperature range possible
- high measurement rate up to 2 kHz

The Setup



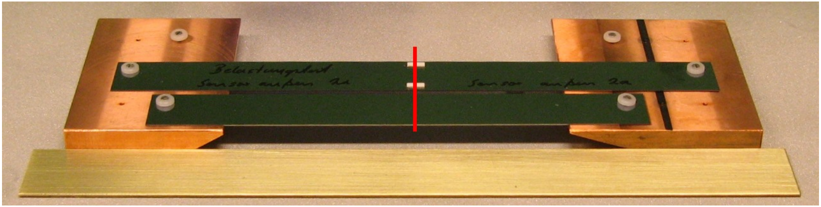
We have prepared a setup to profile modules during temperature cycling

- granite reference plane with $\pm 2\,\mu$m planarity
- range of 200 mm × 50 mm in XY-Plane, $< 2\,\mu$m repeatability
- Z-range of 3 mm, resolution of $< 1\,\mu$m
- possibility to adjust Z-position by 50 mm
- temperature Range from 0 °C to 50 °C

But: No Results Yet

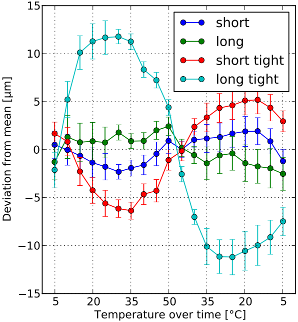
- still calibrating
- technical problems with climate chamber

First tests



Obtained test system to check performance.
But: only measurement in one direction

- measured height of module surface
- covered $\Delta T = 45\,^{\circ}\mathrm{C}$
- first results: most changes are from movement of the stage
- no significant movement after preliminary calibration
- ⇨ additional run with tightened screws
  - movement visible, but not yet understood
  - silicon damaged due to high torque



Conclusions

Belle II will be major upgrade to Belle

- Vertex finding is paramount for CP Violation measurements
- low material budget for vertex detector required due to low momenta

The DEPFET Pixel Vertex Detector can satisfy all requirements

- small size allows to keep support out of acceptance
- silicon as "self supporting structure"
- tests needed to verify feasibility
- so far very promising results

Thank you
for your attention

CP Violation

- CP violated in weak interactions
- represented by non-vanishing complex phase in the weak mixing matrix (CKM model, Nobel Prize 2008 for Kobayashi & Maskawa)

$$\begin{pmatrix} |d'\rangle \\ |s'\rangle \\ |b'\rangle \end{pmatrix} = \underbrace{\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}}_{C_{CKM}} \begin{pmatrix} |d\rangle \\ |s\rangle \\ |b\rangle \end{pmatrix}$$

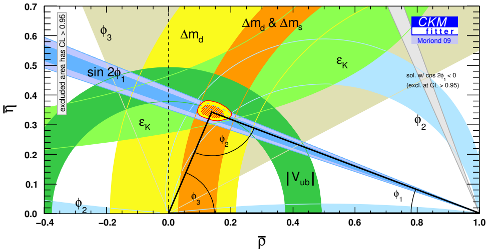
Precision Measurement of CP-Violation

- verification of the CKM model
- search for new sources of CP Violation ⇒ New Physics
- B mesons show large CP-Violation, well suited for CP measurements
- high statistics and precision needed to challenge SM

Unitarity Triangle

- unitarity of CKM matrix leads to column constraints $\sum_k V_{ik} V_{jk}^* = 0$
- triangles in complex space
- almost degenerate in Kaon system, large angles in B meson system

$$\underset{\mathcal{O}(\lambda^3)}{V_{ud} V_{ub}^*} + \underset{\mathcal{O}(\lambda^3)}{V_{cd} V_{cb}^*} + \underset{\mathcal{O}(\lambda^3)}{V_{td} V_{tb}^*} = 0$$



$$\bar{\rho} = \left(1 - \frac{\lambda^2}{2}\right)\rho \qquad \bar{\eta} = \left(1 - \frac{\lambda^2}{2}\right)\eta$$

$$\phi_1 = \arg\left(-\frac{V_{cd} V_{cb}^*}{V_{td} V_{tb}^*}\right) \qquad \phi_2 = \arg\left(-\frac{V_{td} V_{tb}^*}{V_{ud} V_{ub}^*}\right)$$

$$\phi_3 = \arg\left(-\frac{V_{ud} V_{ub}^*}{V_{cd} V_{cb}^*}\right)$$

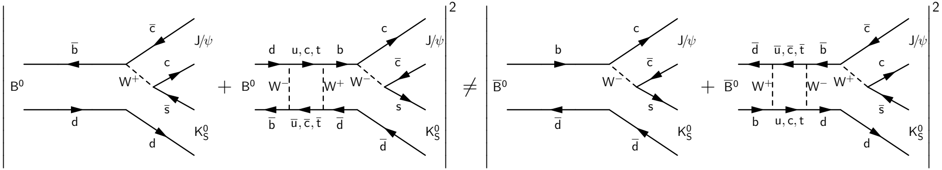
CP Observables

time dependent decay asymmetry

$$a_{CP}(t) = \frac{\Gamma\left(\overline{B}^0 \to f_{CP}; t\right) - \Gamma\left(B^0 \to f_{CP}; t\right)}{\Gamma\left(\overline{B}^0 \to f_{CP}; t\right) + \Gamma\left(B^0 \to f_{CP}; t\right)}$$

3 possible contributions

- CP-Violation in decay (direct)
- CP-Violation in mixing (indirect)
- CP-Violation by interference of mixing and decay (mixing induced)



For B mesons, contributions from indirect CP-Violation are negligible

Measurement of CP-Violation

time dependent decay asymmetry

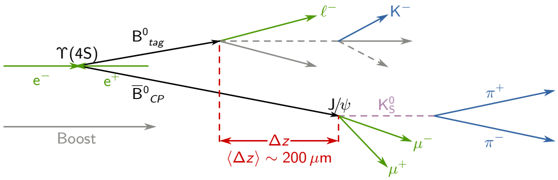
$$a_{CP}(t) = \frac{\Gamma\left(\overline{B}^0 \to f_{CP}; t\right) - \Gamma\left(B^0 \to f_{CP}; t\right)}{\Gamma\left(\overline{B}^0 \to f_{CP}; t\right) + \Gamma\left(B^0 \to f_{CP}; t\right)}$$

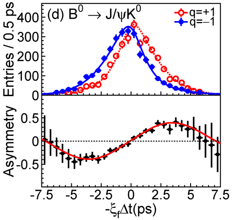
Experimental challenging

- lifetime of B mesons is 1.5 ps
- flavour of B meson has to be known

Solution

- $\Upsilon(4S)$: coherent B-meson pair production
- one B to determine flavour (tag side), other B for CP measurement (CP side)
- boost system using asymmetric beam energies
  $t \to \Delta t = \frac{\Delta z}{\langle \beta\gamma \rangle c}$

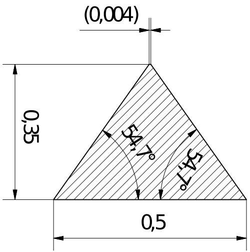


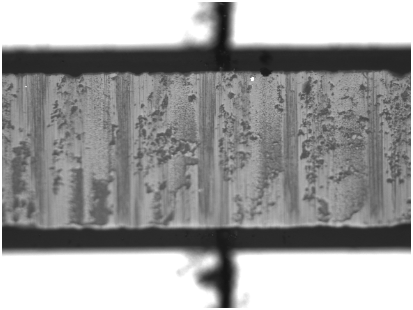


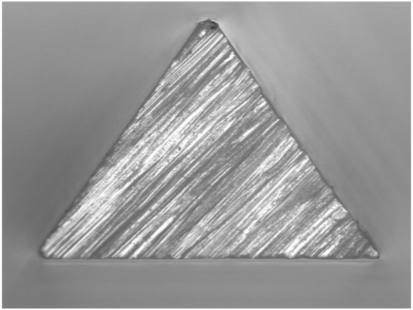
Ceramic Reinforcements

Initial batch of ceramic reinforcements received

- fitting very well into grooves
- manufactured within 42 μm to specification







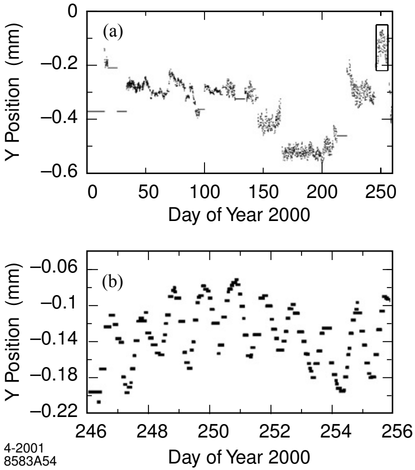
Alignment

Required spatial resolution: $\approx 10\,\mu$m

PXD + SVD

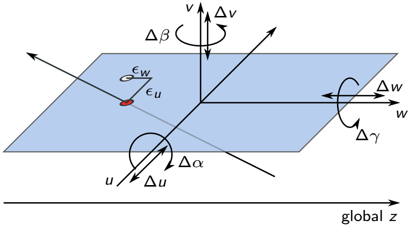
- pixel-detector mounted directly on the beampipe
- double-sided strip-detector attached to the CDC
- mechanically independent subsystems
- frequent and large relative movements possible

⇨ frequent, time-dependent alignment needed



Global alignment of the BABAR SVT

Track-based Alignment



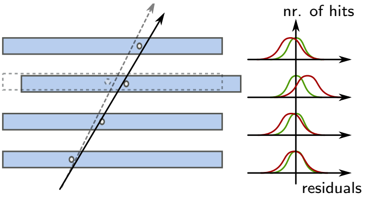
Residual ϵ: Distance hit $\Leftrightarrow$ track

ideal: residuals normal distributed mean 0, width σ_r

but: real wafer position not known assembly precision $\sim 100\,\mu$m, no guaranteed time stability.

Necessary to determine absolute position of every detector module

- wrong positions will distort/degrade residual distribution
- minimize residuals by adjusting module position
- 6 degrees of freedom per module (3 translation + 3 rotation)

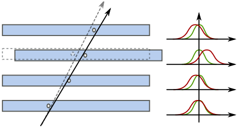


Track-based Alignment

- $\mathbf{a}$ = alignment parameters
- $\boldsymbol{\tau}$ = track parameters

$$\chi^2(\mathbf{a},\boldsymbol{\tau}) = \epsilon(\mathbf{a},\boldsymbol{\tau})^T V^{-1} \epsilon(\mathbf{a},\boldsymbol{\tau})$$

$$\chi^2(\mathbf{a},\boldsymbol{\tau}) = \sum_{i\in tracks} \sum_{j\in hits} \left(\frac{track(\mathbf{a},\boldsymbol{\tau}_i) - hit_j}{\sigma_j} \right)^2$$



Solution for linearized χ^2

$$\underbrace{\left(\mathbf{J}^T \mathbf{V}^{-1} \mathbf{J}\right)}_{\mathbf{C}} \begin{pmatrix} \Delta\mathbf{a} \\ \delta\boldsymbol{\tau} \end{pmatrix} = \underbrace{\left(\mathbf{J}^T \mathbf{V}^{-1} \epsilon(\mathbf{a}_0, \boldsymbol{\tau}_0)\right)}_{\mathbf{b}}$$

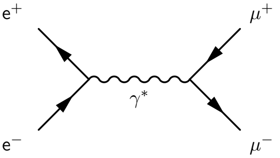
local alignment:

- neglect correlations between modules
- keep track parameters fixed
- χ^2-function per module
- small matrices (6×6)
- iteration needed to account for correlations

global alignment (Millepede):

- one global χ^2-function
- all correlations taken into account
- "large" set of equations (1476×1476 for Belle, similar for Belle II)
- widely used program package available

Alignment with $e^+e^- \to \mu^-\mu^+$



Goal

Implementation of a new alignment procedure for the Belle SVD2 using mainly muon pairs from e^+e^- annihilation as preparation for Belle II

- high statistics

$$\sigma(e^+e^- \to \mu^+\mu^-) \approx 0.77\,\text{nb}$$
$$\sim 15\,\text{s}^{-1} \text{ @ } 2\times10^{34}\,\text{cm}^{-2}\text{s}^{-1}$$
$$\sim 600\,\text{s}^{-1} \text{ @ } 8\times10^{35}\,\text{cm}^{-2}\text{s}^{-1}$$

- large transverse momentum $p_t \gtrsim 2\,\text{GeV}$
- back to back in center of mass system
- not back to back in Lab system (asymmetric energies, crossing angle)

⇒ fit tracks on same vertex, constraining energy and momentum to boost 4-vector.