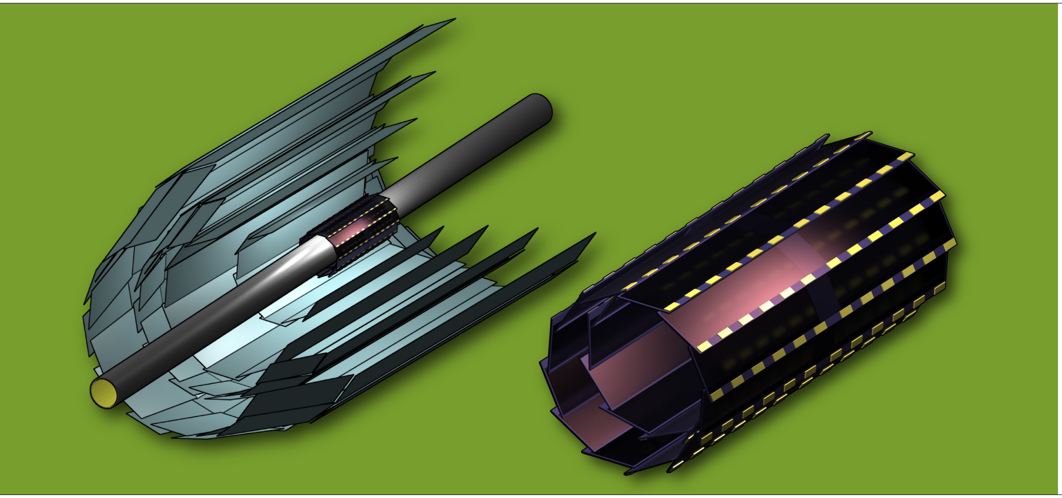
Track-Based alignment

for Belle/Belle II



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On behalf of the work of Martin Ritter

Excellence Cluster Universe

3rd Open Meeting of the Belle II Collaboration
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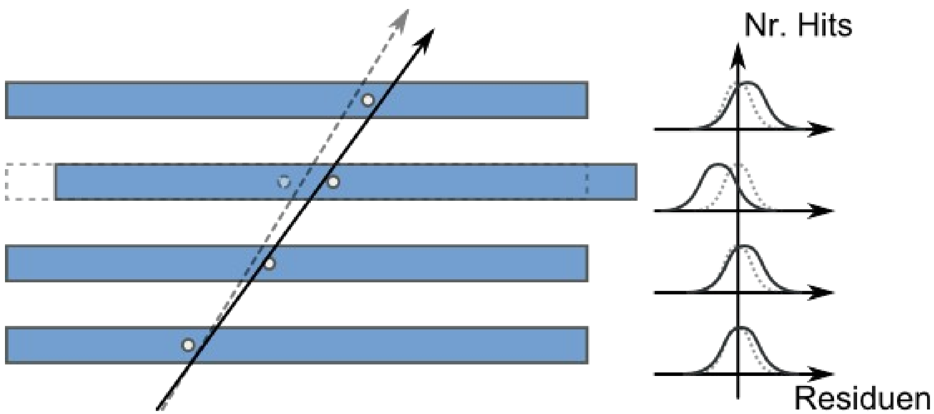
Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)

- Short introduction to track based alignment
- Track based alignment during runs
- Alignment strategy
- The Millepede 2 algorithm
- New BASF module for alignment

Residual: distance of hit with intersection point of track in a module.

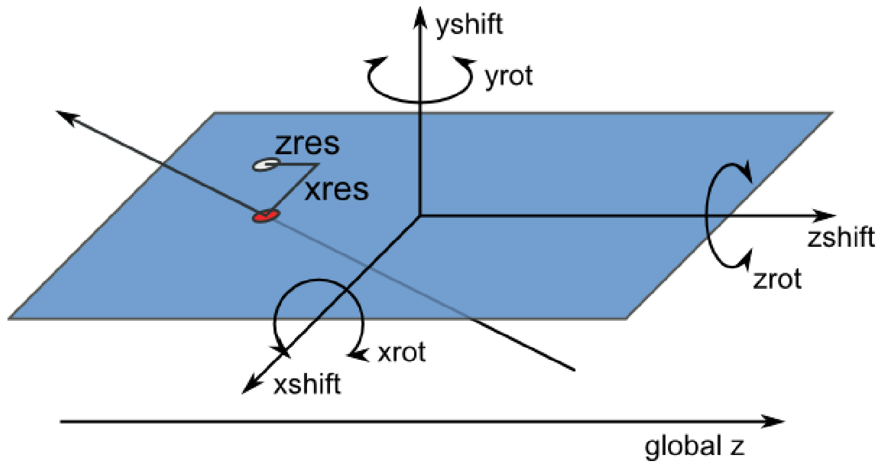


Ideal: Exact positions of modules are known.

- Residuals follow a gaussian distribution

In reality: Known positions of modules are ±100 µm

- Residual is shifted because hit position is shifted.



Solution: calculate correction parameters for each module

Translation 3 parameters
Rotation 3 parameters
…

by using residuals of a large number of tracks.

Minimize: $\chi^2 = \sum_{i \in tracks} \vec{r}_i^{\,T} V_i^{-1} \vec{r}_i$

$$\frac{d\chi^2(\vec{p})}{d\vec{p}} = 0 \qquad (1)$$

$$\chi^2(\vec{p}) = \chi^2(\vec{p}_0) + \left.\frac{d\chi^2(\vec{p})}{d\vec{p}}\right|_{\vec{p}=\vec{p}_0} (\vec{p}-\vec{p}_0) \qquad (2)$$

V: covariance matrix

the **residual** $\vec{r}_i(\vec{p}, \vec{q}_i)$ is a function of

alignment parameters $\vec{p}$ and of

the track parameters $\vec{q}_i$

For the sake of notation the dependence of χ^2 on $\vec{q}_i$ will not be written here.

Rewrite as a Taylor expansion.

Linear least square minimization:
expand up to first order

$\vec{p}_0$ is the vector of initial alignment parameters

(1) in (2) with $\Delta\vec{p} = (\vec{p} - \vec{p}_0)$ yields:

$$\underbrace{(J^T V_i^{-1} J)}_{C} \; \Delta\vec{p} \; = \; \underbrace{J^T V_i^{-1} \; \vec{r}_i(\vec{p}_0)}_{b}$$

$$C \; \Delta\vec{p} \; = \; \vec{b}$$

J: Jacobi Matrix

Task: Invert the Matrix C to find alignment corrections $\Delta\vec{p}$

Global alignment

Use a single χ^2 for all modules and all degrees of freedom.

- ✓ correlations between different modules are taken into account
- ✗ a huge matrix equation has to be solved

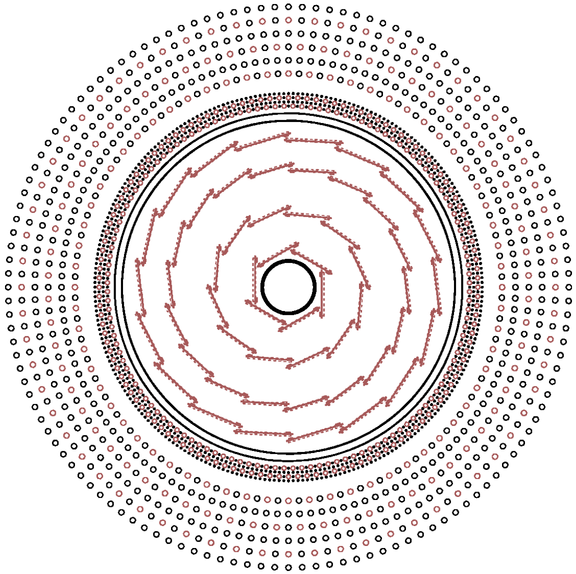
Local alignment

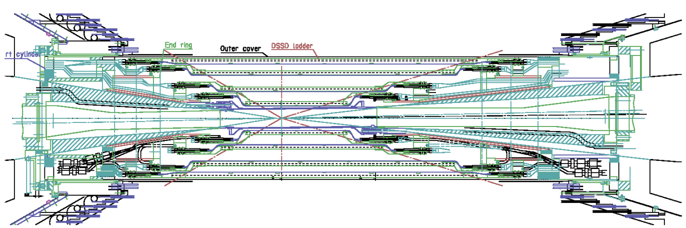
Use a χ^2 for each module

- ✓ small matrices (typically 6x6)
- ✓ solve iteratively
- ✗ correlations between different modules are not taken into account.

Internal alignment alignment of individual modules

External alignment alignment of subdetector structures (regarded as rigid bodies)





SVD 2

- 4 layer DSSD
- 246 modules in total

Strategy

- Two times a year: Alignment using **cosmics** with the magnetic field being turned **off**.
- Lorentz correction using **cosmics** with the magnetic field being turned **on**.
- One set of alignment parameters **per experiment**.
- Current alignment precision: 10 µm

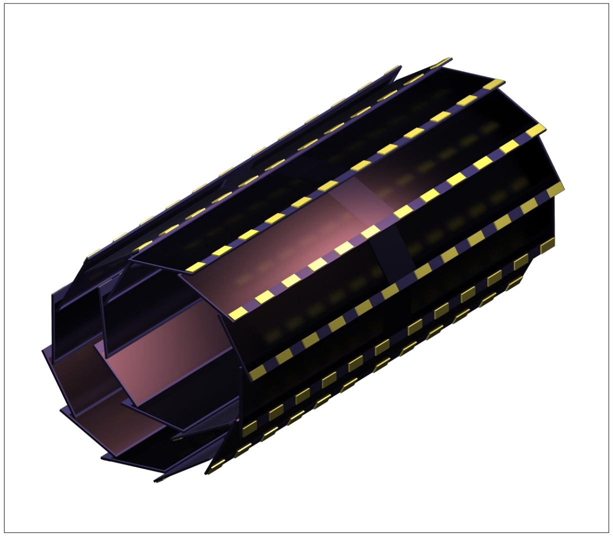
- Internal local alignment for each module
- External local alignment for the whole SVD2 (rigid body) w.r.t. the CDC

Idea: implement a **new** alignment process ?

BELLE

Improve **physics analysis** by a better alignment.

Still some Systematics in current Alignment [Belle Note 715]



BELLE II

A **high precision** PXD detector will be part of the upgraded Belle detector:

2 layer DEPFET (34 modules)

Requirements:

- Need high precision alignment < 10 µm
- PXD is **not** mechanically **connected** to the SVD

Need alignment data on a week-to-week basis

Time dependent alignment

1 Implementation of an **track based** alignment system in BASF for the Belle SVD in **preparation** for the upgraded detector.

Use **muon-pairs** and **cosmics** from actual **run data**.

2 Implement a global alignment strategy for BELLE / BELLE II using the **Millepede 2** [1] approach:

- Used at H1, CDF and CMS
- Non-iterative linear least squares algorithm
- Fits both, track and alignment parameters simultaneously
- Optimized for large matrices

EXP	ALIGN. PARAM	Matrix to invert
BELLE	1476	1476x1476
BELLE II	2974	2974x2974
CMS	47655	47655x47655

[1] http://www.desy.de/~blobel/mptalks.html

Remember from slide 4:

$$\underbrace{\left(J^T V_i^{-1} J\right)}_{C} \, \Delta\vec{p} = \underbrace{J^T V_i^{-1} \, \vec{r}_i(\vec{p}_0)}_{b}$$

$$C \, \Delta\vec{p} = \vec{b} \;\Rightarrow\; \Delta\vec{p} = C^{-1}\vec{b}$$

Millepede approach:

Correlations of alignment parameter

$$C_{total} = \left(\begin{array}{ccc||cc|cc|cc|c}
x & & & & & x & x & & & \cdots \\
 & x & & x & x & & & x & x & \cdots \\
 & & x & x & x & x & x & & & \cdots \\
\hline\hline
 & x & x & x & x & & & & & \cdots \\
 & x & x & x & x & & & & & \cdots \\
\hline
x & & x & & & x & x & & & \cdots \\
x & & x & & & x & x & & & \cdots \\
\hline
 & x & & & & & & x & x & \cdots \\
 & x & & & & & & x & x & \cdots \\
\hline
\vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots
\end{array}\right)$$

correlations of track parameter

Reduce matrix → **Matrix for the alignment parameters only**

Size of matrix C: $\mathrm{Num}_{tracks} * \mathrm{Num}_{track\ parameter} + \mathrm{Num}_{modules} * \mathrm{Num}_{alignment\ parameter}$

$$C \; \Delta\vec{p} = \vec{b}$$

Partition matrix and vectors

$$\begin{pmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{pmatrix} \begin{pmatrix} \Delta\vec{p}_1 \\ \Delta\vec{p}_2 \end{pmatrix} = \begin{pmatrix} \vec{b}_1 \\ \vec{b}_2 \end{pmatrix}$$

Schur complement

$$S = C_{11} - C_{12} C_{22}^{-1} C_{21}$$

$$\begin{pmatrix} \Delta\vec{p}_1 \\ \Delta\vec{p}_2 \end{pmatrix} = \begin{pmatrix} S^{-1} & -S^{-1} C_{21}^T C_{22}^{-1} \\ -C_{22}^{-1} C_{21} S^{-1} & C_{22}^{-1} - C_{22}^{-1} C_{21} S^{-1} C_{21}^T C_{22}^{-1} \end{pmatrix} \begin{pmatrix} \vec{b}_1 \\ \vec{b}_2 \end{pmatrix}$$

$\begin{pmatrix} \Delta\vec{p}_1 \\ \Delta\vec{p}_2 \end{pmatrix}$ ← **alignment parameter corrections** ($\Delta\vec{p}_1$) ← track parameter corrections ($\Delta\vec{p}_2$)

$$\Delta\vec{p}_1 = S^{-1} \left(\vec{b}_1 - C_{21}^T C_{22}^{-1} \vec{b}_2 \right)$$

✓ Since the matrix **S** is much smaller than **C** and $\mathbf{C_{22}}$ is "*easy*" to invert, computing time is drastically reduced !

BASF module procedure:

- **Loop** over all tracks
  - Select suitable subset (High momentum, many measurements)
  - **Loop** over all hits per track
    - **Calculate** residual: track ⟷ current hit
    - **Calculate** derivatives w.r.t. alignment parameters and track parameters
    - **Store** residual, error and derivatives for Pede (Subprogram of Millepede) in suitable format

Millepede procedure:

- Define set of inputfiles
- **Constrain** Global translations and rotations using Lagrange Multipliers
- Obtain List of Alignment-parameter corrections
- Possibility to check for weak-constrained modes using Eigenvalue-spectrum of the Matrix C

- Current alignment-procedure sufficient, but not optimal
- Enhancement of current Alignment using global Alignment strategy
- Basic implementation of Alignment-code almost finished
- Evaluation and fine-tuning still to be done
- First results expected for October