Track based Alignment for the Belle/Belle II vertex detector

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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)

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

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

Measurement of CP-Violation

time dependent decay asymmetry

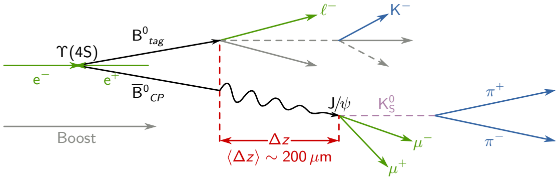
$$a_{CP}(t) = \frac{\Gamma\left(\overline{B}^0 \to f_{CP}; t\right) - \Gamma\left(B^0 \to f_{CP}; t\right)}{\Gamma\left(\overline{B}^0 \to f_{CP}; t\right) + \Gamma\left(B^0 \to f_{CP}; t\right)}$$

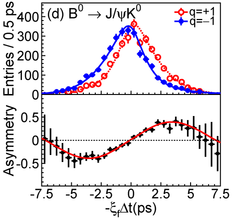
Experimental challenging

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

Solution

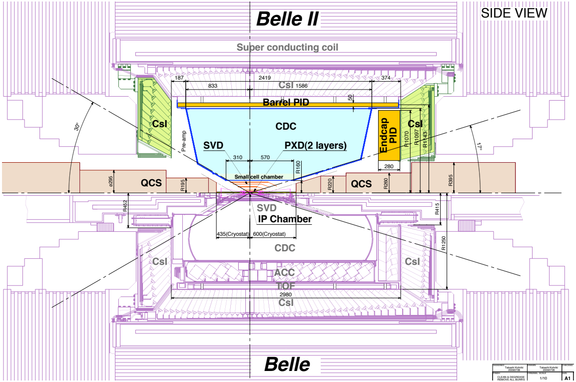
- $\Upsilon(4S)$: coherent B-meson pair production
- one B to determine flavour (tag side), other B for CP measurement (CP side)
- boost system using asymmetric beam energies
  $t \to \Delta t = \frac{\Delta z}{\langle \beta\gamma \rangle c}$



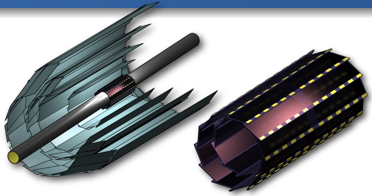


Belle/Belle II Experiment

- asymmetric e^+e^- experiment 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)
- $946\,\mathrm{fb}^{-1}$ integrated luminosity since 1999 (772 million $B\overline{B}$ pairs)
- upgrade to SuperKEKB/Belle II 2010-2013
  (target luminosity: $8 \times 10^{35}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$)



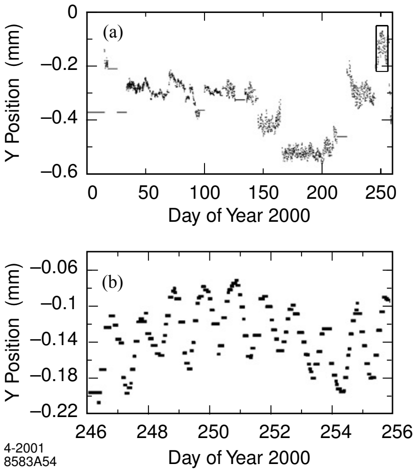
Belle II Vertex Detector



SuperSVD + DEPFET PXD

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

➡ frequent, time-dependent alignment needed

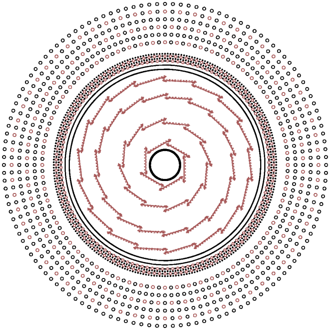


Global alignment of the BABAR SVT

Current Belle Alignment

Current SVD2

- 4 Layer DSSD
- 246 Modules



Belle SVD2

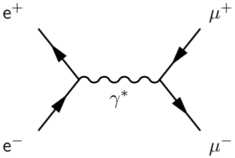
Alignment of the SVD2 using cosmic muons without magnetic field

1. internal alignment of all 246 Modules with respect to each other
2. global alignment of rigid SVD with respect to CDC
3. lorentz-shift correction using run cosmics

Limitations

- dedicated cosmic runs needed
- at most 2 distinct alignment runs a year
- statistics will not increase with luminosity of collider

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



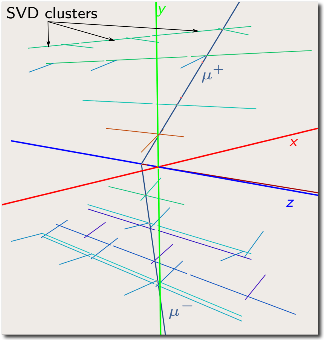
Goal

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

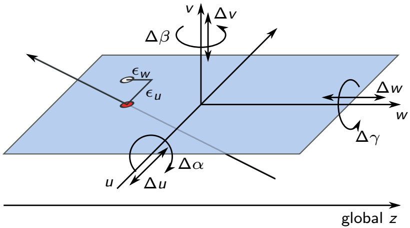
- high statistics

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

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



Track-based Alignment



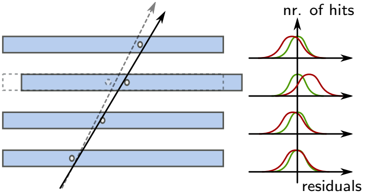
Necessary to determine absolute position of every detector module

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

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.

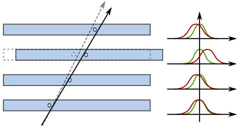


Track-based Alignment

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

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

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



Solution for linearized χ^2

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

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

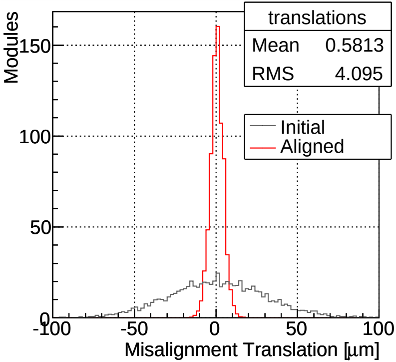
global alignment (Millepede):

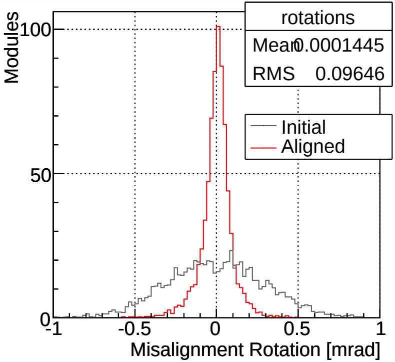
- one global χ^2-function
- all correlations taken into account
- "large" set of equations (1476×1476 for Belle, similar for Belle II)

Internal Alignment

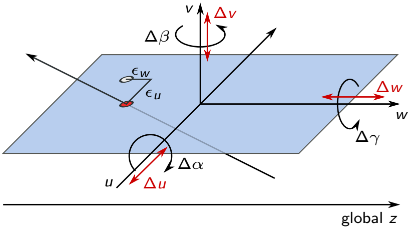
Current Status

- internal alignment of all the 246 Belle SVD2 modules
- no alignment with respect to the CDC yet
- single tracks from muon 10^6 pair events
- simulated misalignment of 30 μm (0.3 mrad) for all modules.

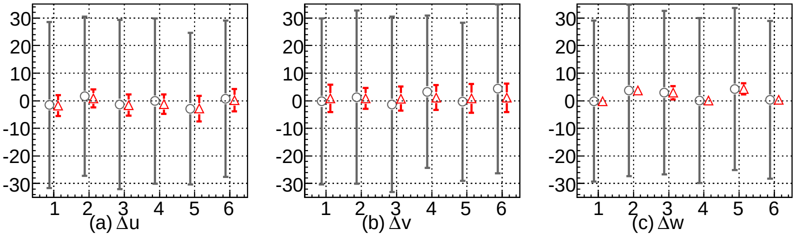




Remaining misalignment per parameter

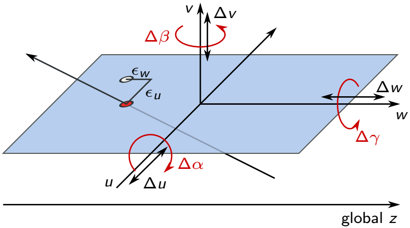


- 6 Monte Carlo studies performed
- significant improvement for all degrees of freedom
- global misalignment remaining
- low sensitivity for rotations around long module axis



remaining misalignment for translations

Remaining misalignment per parameter



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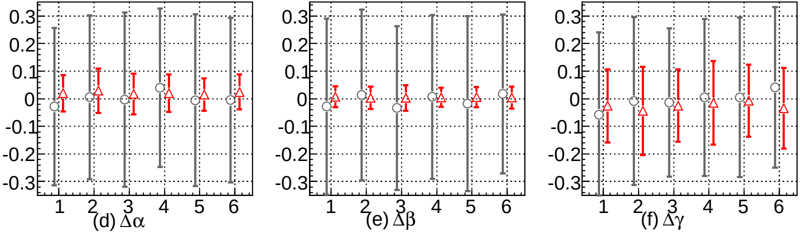
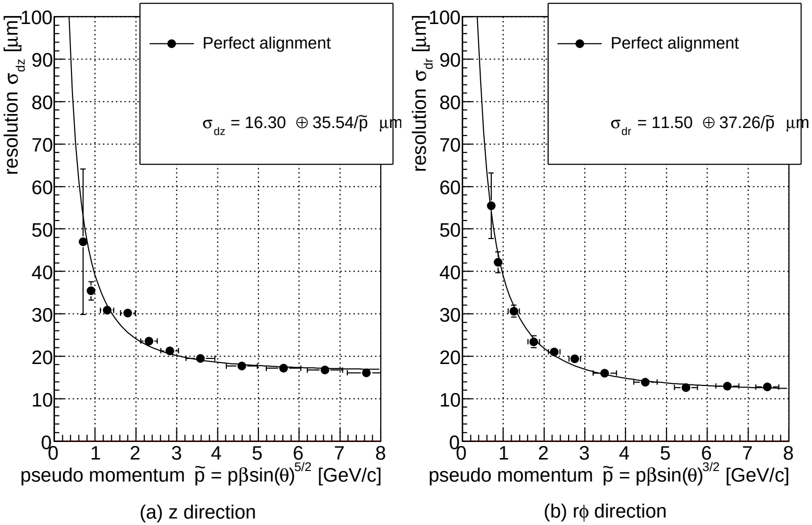


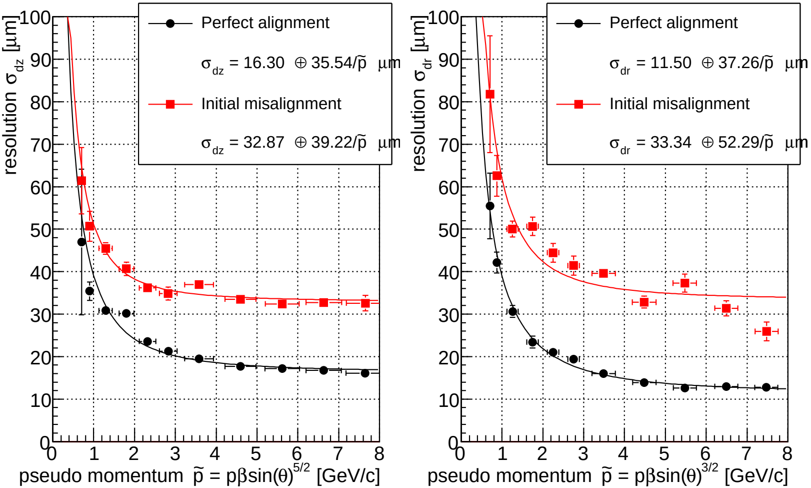
remaining misalignment for rotations

SVD2 Performance



Impact parameters obtained from cosmic muons

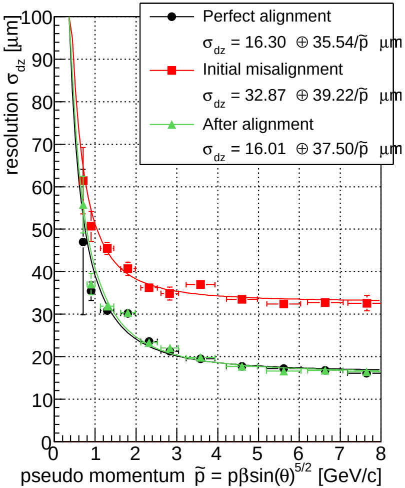
SVD2 Performance



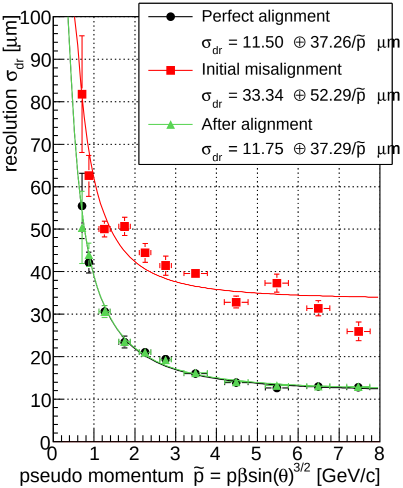
(a) z direction (b) rϕ direction

Impact parameters obtained from cosmic muons

SVD2 Performance



(a) z direction

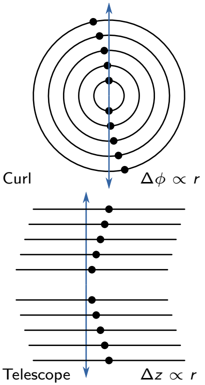


(b) rϕ direction

Impact parameters obtained from cosmic muons

Weak modes

- depending on input: matrix **C** (almost) singular
- undefined (or weak) modes which do not change χ^2 but may introduce physics bias



Further studies needed to optimise stability

- optimization of track sample
- pair fit of muons to improve correlations
- matrix regularisation: minimize alignment parameters in addition to residuals
- additional constraints (prior knowledge, survey data)

Conclusions

- internal alignment working
- low computing requirements
  - $\sim$ 3 h to collect residuals from 10^6 events ($\sim$3 days of data-taking in Belle)
  - $\sim$ 2 min to do the actual alignment
- complete weekly alignment seems possible for Belle
- external alignment much faster (only 6 degrees of freedom)
- increased Belle II luminosity will further decrease time needed for data-taking

plans for the future

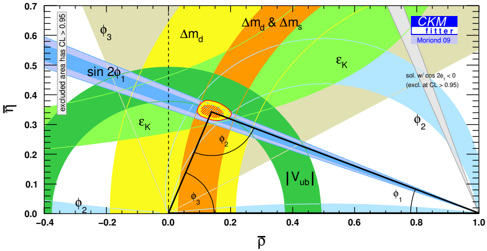
- external alignment with respect to the CDC
- simulation of larger misalignment
- further optimization of track sample selection
- pair-fit of muon pairs

Backup

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

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



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

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

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

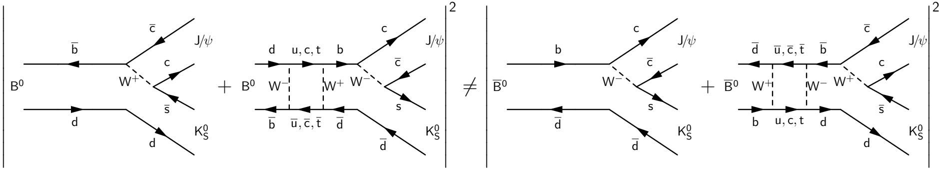
CP Observables

time dependent decay asymmetry

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

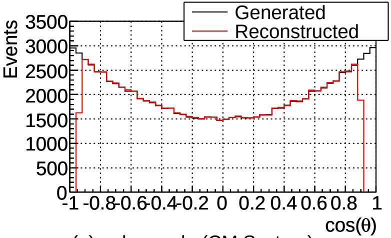
3 possible contributions

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

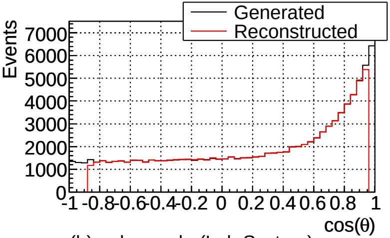


For B mesons, contributions from indirect CP-Violation are negligible

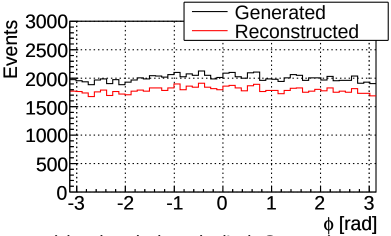
Muon Pair Distributions



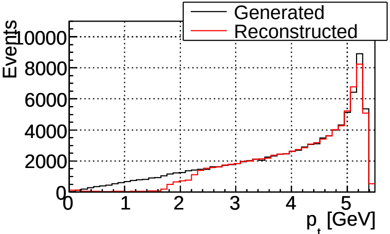
(a) polar angle (CM System)



(b) polar angle (Lab System)



(c) azimuthal angle (Lab System)



(d) transverse momentum (Lab System)

Millepede

Alignment

Solve set of linear equations with large number of parameters

$$\mathbf{C}\begin{pmatrix}\Delta\mathbf{a}\\ \delta\boldsymbol{\tau}\end{pmatrix} = \mathbf{b}$$

- $\mathbf{C} = \mathbf{J}^T\mathbf{V}^{-1}\mathbf{J}$ very large, $\sim$ millions of rows.
- simultaneous minimization of residuals with respect to alignment and track parameters
- not interested in corrections for tracks

Millepede/Millepede II

- program package to solve special χ^2-problems
- used for the alignment by H1, HERA-B, CDF, LHCb and CMS
- optimized for up to $\mathcal{O}(50000)$ parameters
- reduction of matrix size using Schur complement

Matrix reduction

Any set of linear equations with invertible submatrix $\mathbf{C}_{22}$

$$\left(\begin{array}{c|c} \mathbf{C}_{11} & \mathbf{C}_{21}^T \\ \hline \mathbf{C}_{21} & \mathbf{C}_{22} \end{array}\right) \left(\begin{array}{c} \Delta\mathbf{a} \\ \hline \delta\boldsymbol{\tau} \end{array}\right) = \left(\begin{array}{c} \mathbf{b} \\ \hline \boldsymbol{\beta} \end{array}\right)$$

can be solved using the Schur complement $\mathbf{S} = \mathbf{C}_{11} - \mathbf{C}_{21}^T \mathbf{C}_{22}^{-1} \mathbf{C}_{21}$

$$\left(\begin{array}{c} \Delta\mathbf{a} \\ \hline \delta\boldsymbol{\tau} \end{array}\right) = -\left(\begin{array}{c|c} \mathbf{S}^{-1} & -\mathbf{S}^{-1}\mathbf{C}_{21}^T\mathbf{C}_{22}^{-1} \\ \hline -\mathbf{C}_{22}^{-1}\mathbf{C}_{21}\mathbf{S}^{-1} & \mathbf{C}_{22}^{-1} - \mathbf{C}_{22}^{-1}\mathbf{C}_{21}\mathbf{C}_{21}^T\mathbf{S}^{-1}\mathbf{C}_{22}^{-1} \end{array}\right) \left(\begin{array}{c} \mathbf{b} \\ \hline \boldsymbol{\beta} \end{array}\right) \qquad (1)$$

$$\mathbf{C} = \left(\begin{array}{c|cccc} \sum \mathbf{C}_i & \mathbf{G}_1 & \mathbf{G}_2 & \cdots & \mathbf{G}_n \\ \hline \mathbf{G}_1^T & \boldsymbol{\Gamma}_1 & 0 & \cdots & 0 \\ \mathbf{G}_2^T & 0 & \boldsymbol{\Gamma}_2 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \mathbf{G}_3^T & 0 & 0 & \cdots & \boldsymbol{\Gamma}_n \end{array}\right)$$

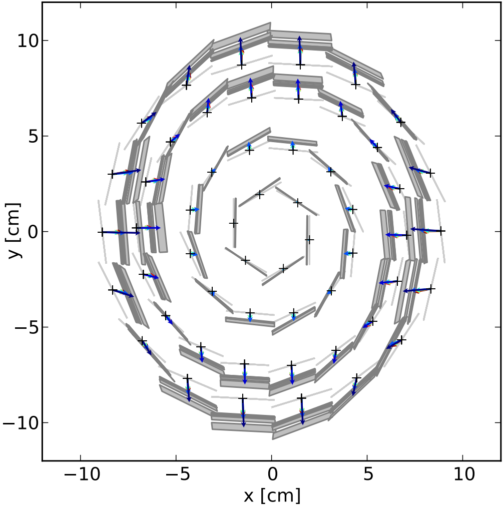
- Top part of Eq. 1 are the desired alignment corrections
- Only $\mathbf{C}_{22}$ has to be inverted, inexpensive since block diagonal
- No approximation, all correlations still included

Final set of equations

$$\left(\sum \mathbf{C}_i - \sum \mathbf{G}_i \boldsymbol{\Gamma}_i^{-1} \mathbf{G}_i^T\right) \Delta\mathbf{a} = \left(\sum \mathbf{b}_i - \sum \mathbf{G}_i (\boldsymbol{\Gamma}_i^{-1} \boldsymbol{\beta}_i)\right)$$

Weak Modes

- weak modes can be estimated from eigenvalue spectrum
- visualisation of current smallest eigenvalue
- would introduce significant bias depending on ϕ



Possible weak deformation in the current alignment procedure