Geometry alignment of the BM@N detectors: new approach

Review of ongoing progress

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Geometric alignment: problem statement

Even the best efforts at precise detectors placement and direct geometry measurements are not sufficient to achieve the desired experimental precision. **Additional numerical estimation of residual imperfections in detectors geometry is mandatory**.

We search for the best estimation of: [1]

δx_i, δy_i, δz_i : 3-axis shifts of each i-th detector element;

ϕ_i, θ_i, ψ_i : 3-axis rotations of each i-th detector element [2].

[1] Hereafter, symbols shown in red are being introduced or defined.

[2] Particular rotation order and axes arrangement must be defined; see **App. A**.

Geometric alignment: visual representation [3]

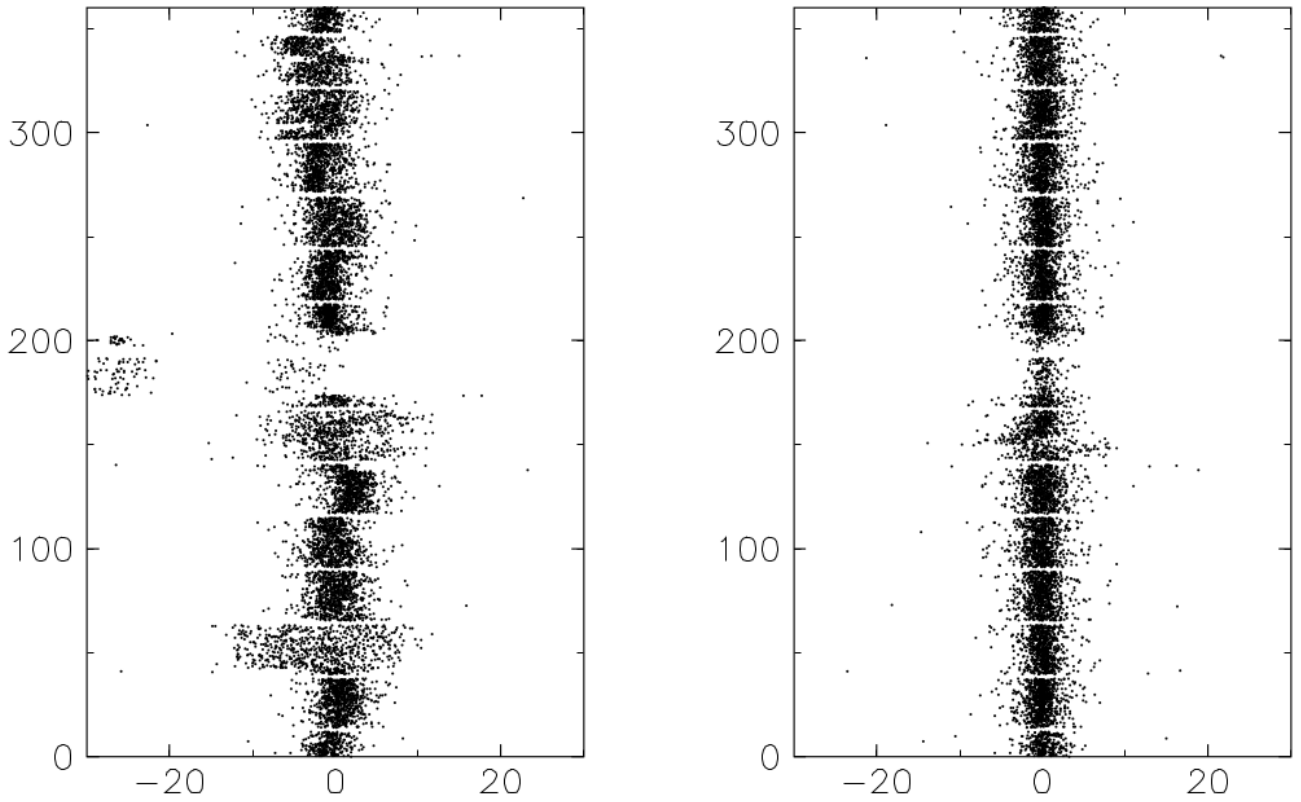


Fig. 1: Residuals between tracks and hits of a silicon tracker are shown as a function of the azimuthal angle (vertical axis, in degrees) before and after an alignment. The residual on the horizontal axis is given in units of 10 μm.

[3] Illustration is taken from [1, Sec. 1]

BM@N: current solution for the alignment problem

- Fixed alignment correction values are introduced into the track reconstruction algorithm.
- These fixed values are obtained from labor-intensive, semi-manual procedures.
- For every experimental run all the work must be repeated from scratch.
- With every new run, time consumption rises considerably due to the increase in detectors complexity.

An alternative solution is highly desirable.

Classical approach: MSE track based alignment

Mean square error (MSE) minimization [4]:

$$S(\alpha, a) = \sum_{\{\vec{v}\}} \|\vec{v} - \vec{f}(\alpha, a)\|^2; \quad S(\alpha, a) \to \min_{\{\alpha, a\}};$$

$\{\vec{v}\}$: set of measured values;

$\vec{f}(\alpha, a)$: physical model of measurements; see **App. B**;

$\{\alpha, a\}$: set of alignment parameters.

Task dimension issue: $\alpha \in \mathbb{R}^N$, where $N \propto |\{\vec{v}\}|$. [5]

In practical cases, including BM@N, $N \sim 10^7$ or higher [6].

[4] Unweighted MSE criterion is shown for simplicity.

[5] α are the so-called "local" parameters; see below for details.

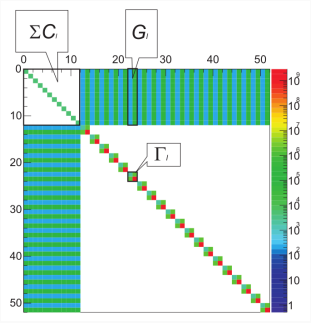
[6] $\approx$ 2.5M suitable tracks in Run-8 alignment dataset $\times$ 4 params/track is 10^7.

Dimension reduction: "Millepede trick" [7]

1. To solve the $S \to \min$ task, use the **matrix of normal equations (MNE) inversion** method.

2. Distinguish between "local" and "global" parameters:
local (α) – parameters of **individual track approximation**;
global (a) – parameters of **detectors geometry alignment**.

3. A special block structure of the MNE emerges. Exploit it to perform the full inversion as a series of small inversion tasks.



Pic. 3.2. from [3]

[7] V. Blobel, C. Kleinwort. *A new method for the high-precision alignment of track detectors*. arXiv:hep-ex/0208021 (2002). See also [2].

BM@N alignment: the current goals

- **Replace the existing approach** with a semi-automatic procedure based on a Millepede-like algorithm.
- Implement the algorithm **using the CERN ROOT framework** – native to the BM@N experiment.
- Achieve an alignment **quality level exceeding the current one**.

What has been done so far

1. **Alignment algorithm utilizing the ROOT framework [6]**:
   - Millepede-like dimension-reduction scheme;
   - iterative procedure for the non-linear measurement model with Levenberg–Marquardt regularization;
   - arbitrary linear equality constraints using Lagrange multipliers.
2. **Test-task generation tool**:
   - synthetic tracks derived from real-track data;
   - actual BM@N detectors geometry (FSD and GEM stations).
3. **Alignment quality evaluation criteria** based on further physical analyses requirements; alignment comparison tool.
4. Preliminary computational results of the Run-8 alignment.
5. Preliminary investigation of PyTorch as an alternative framework for the alignment algorithm implementation.

Ongoing work: main practical issues

1. Intrinsic **underdetermination** of the $S \to \min$ task: entire hypersurface $\vec{f}(\alpha, a) = C$ yields the same MSE value.
2. High detectors **error level** [8] : $\sigma(y) \sim 1\,\mathrm{mm}$.
3. The non-linear minimization is susceptible to the **local-minima** problem.

These obstacles require extensive numerical investigation, which is currently in progress.

[8] An average error of 0.12 cm in the y coordinate was observed in the Run-8 field-free data. Further investigation may be required.

Task underdetermination: some details

Two invariants of $\vec{f}(\alpha, a)$ were identified [9]:

$$\begin{bmatrix} \delta x_1 \\ \vdots \\ \delta x_n \end{bmatrix} \rightarrow \begin{bmatrix} \delta x_1 \\ \vdots \\ \delta x_n \end{bmatrix} + C_1 \begin{bmatrix} 1 \\ \vdots \\ 1 \end{bmatrix}, \quad \begin{bmatrix} \delta x_1 \\ \vdots \\ \delta x_n \end{bmatrix} \rightarrow \begin{bmatrix} \delta x_1 \\ \vdots \\ \delta x_n \end{bmatrix} + C_2 \begin{bmatrix} z_1 \\ \vdots \\ z_n \end{bmatrix}, \ \forall\, C_1, C_2 \in \mathbb{R}.$$

Both are fixed by linear constraints that pin down the overall position and orientation of the detector assembly.

Yet some **MNE eigenvalues remain close to zero** – indicating **extra degrees of freedom still to be fixed**.

[9] The same applies to the y coordinate.

Improvement strategies under consideration

	UD[10]	ER[11]	LM[12]
Appropriate task constraints	✓		
Multi-stage alignment scheme	✓		✓
Simulated annealing regularization scheme			✓
ML-inspired regularization techniques	✓	?	✓
Yet unknown approach		✓	

Among the three issues, ER is the least understood.

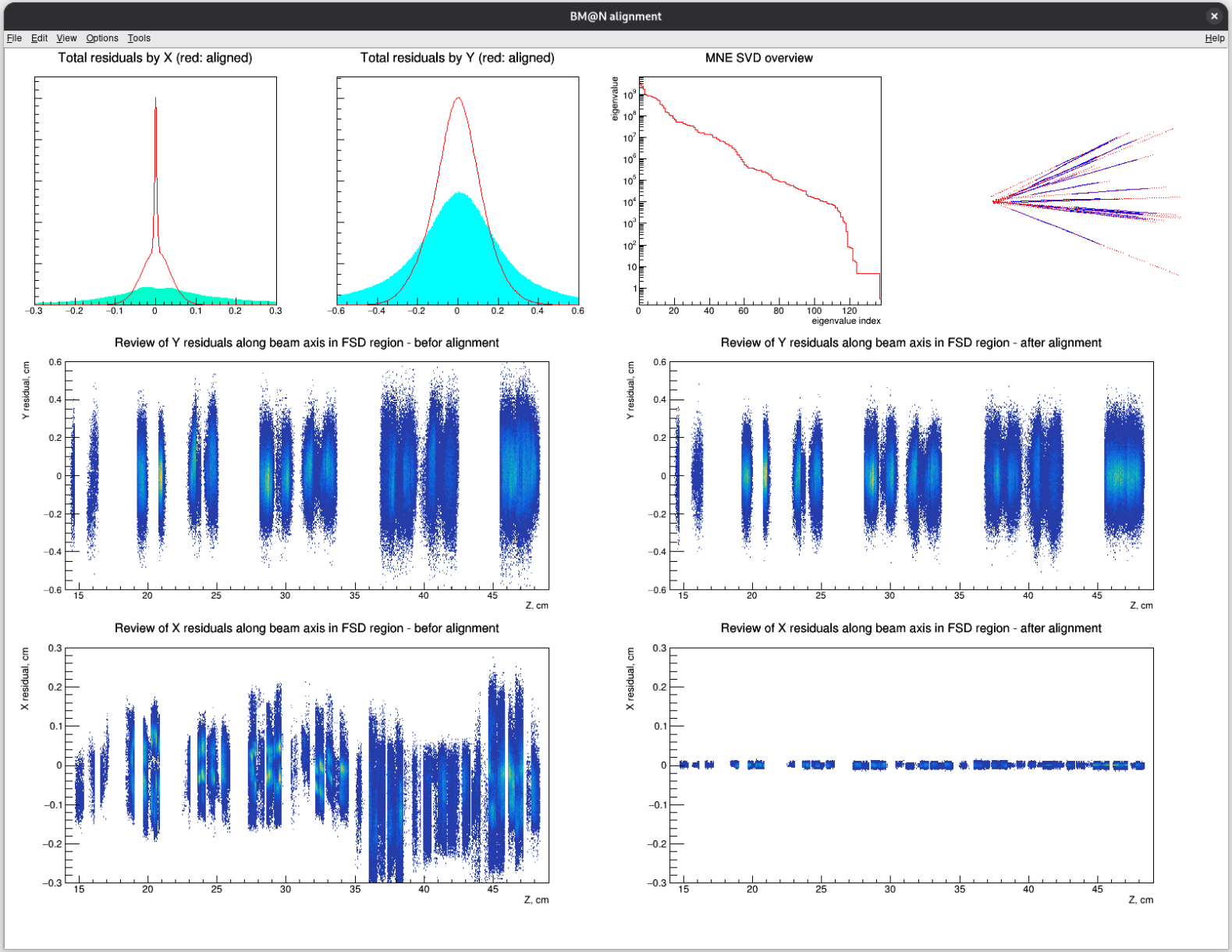
Any advice is welcome.

[10] UD = task underdetermination

[11] ER = high error level

[12] LM = local-minima problem

Computational results: Session 7466 of Run-8



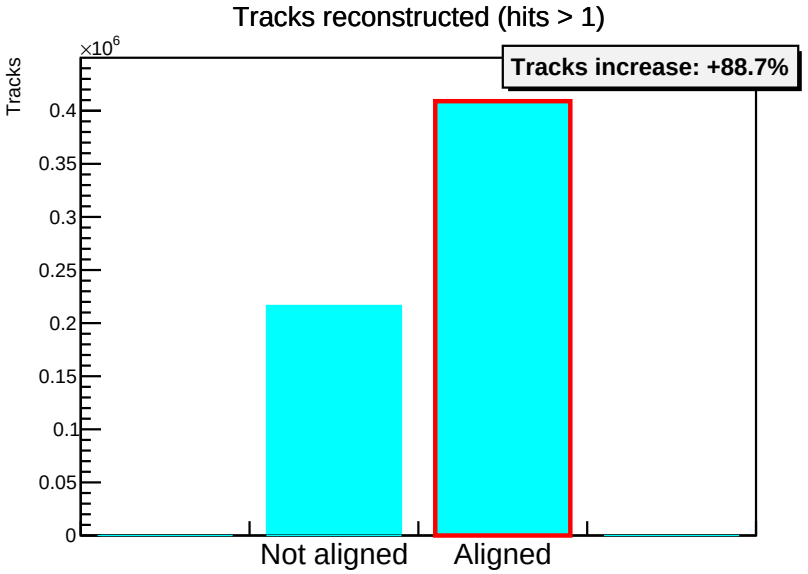
Alignment quality evaluation: criteria

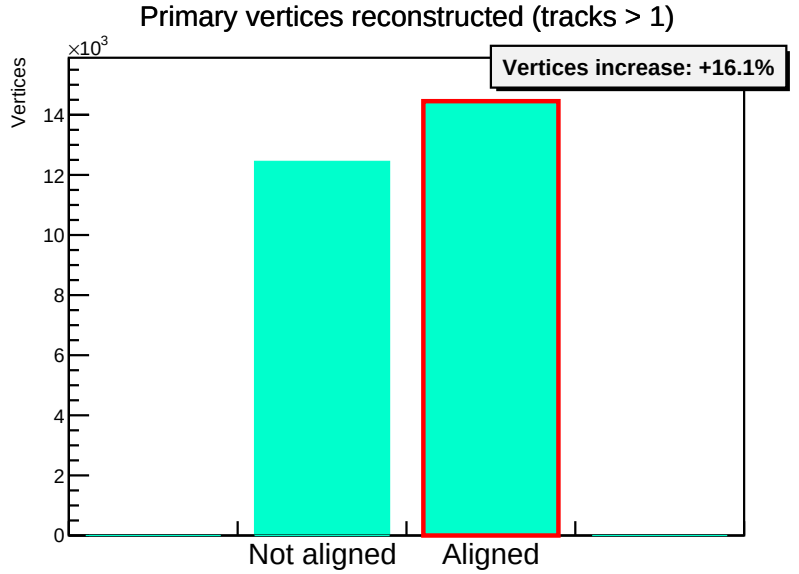
Based on the needs of further physical analyses, four criteria were selected:

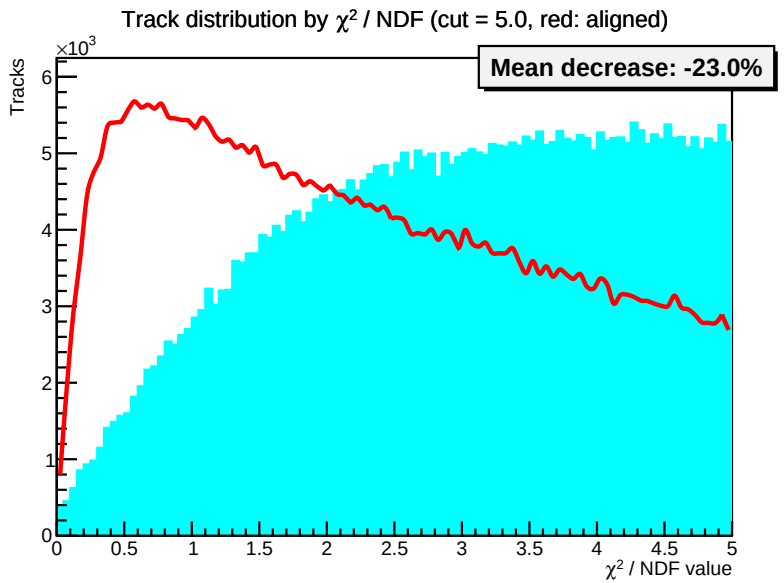
- **Number of reconstructed tracks** with at least two hits – expected to grow.
- **Number of reconstructed primary vertices** with at least two tracks – expected to grow.
- **Track χ^2/NDF distribution** – expected to shift toward smaller values.
- **Primary-vertex distribution along the beam axis** – expected to narrow around the target Z.

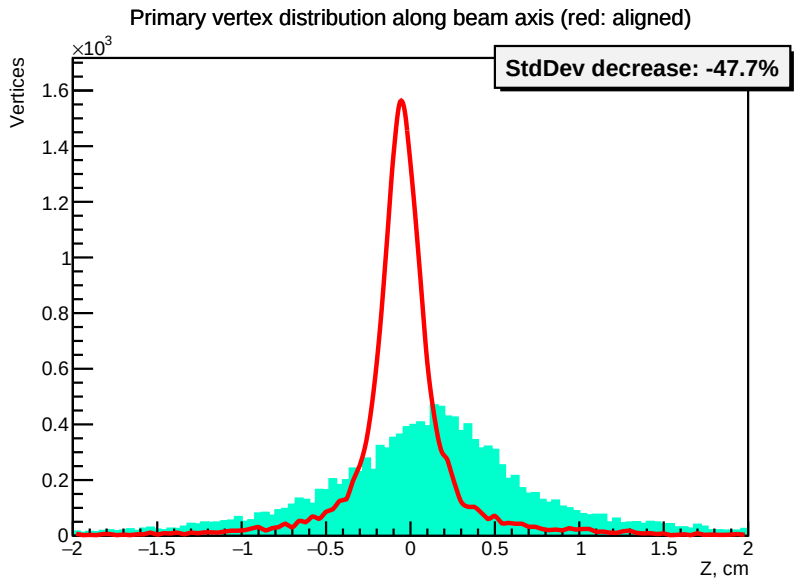
The example below clearly illustrates these criteria "in action".

Alignment quality evaluation: example

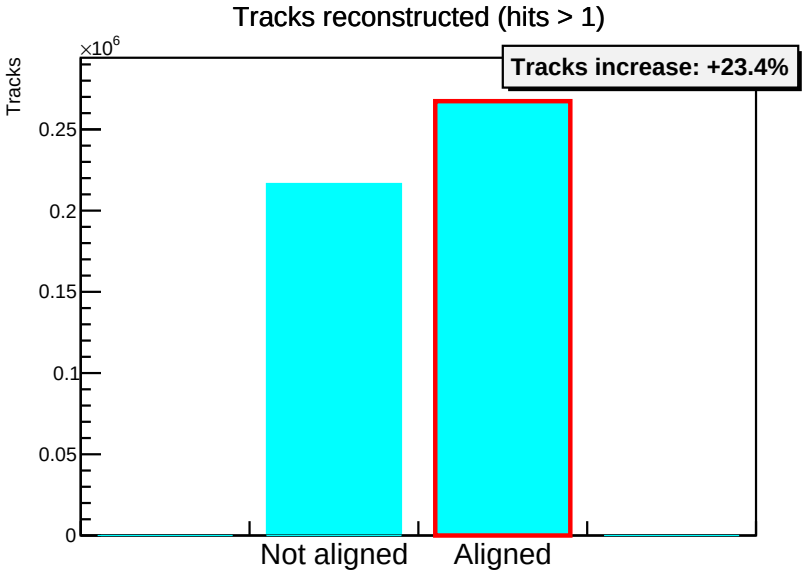


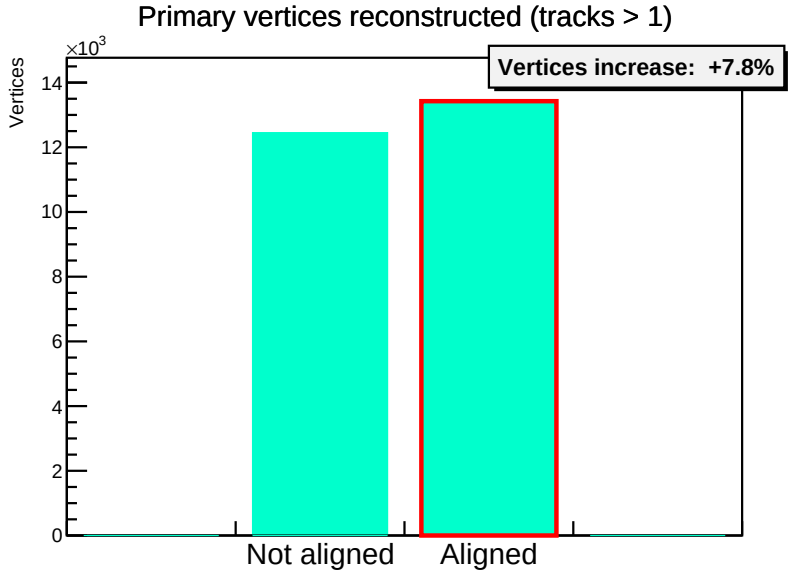


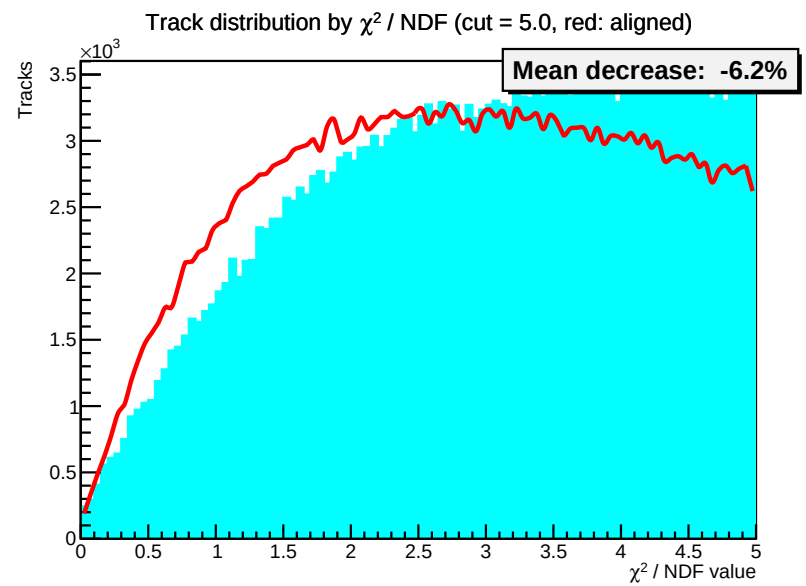


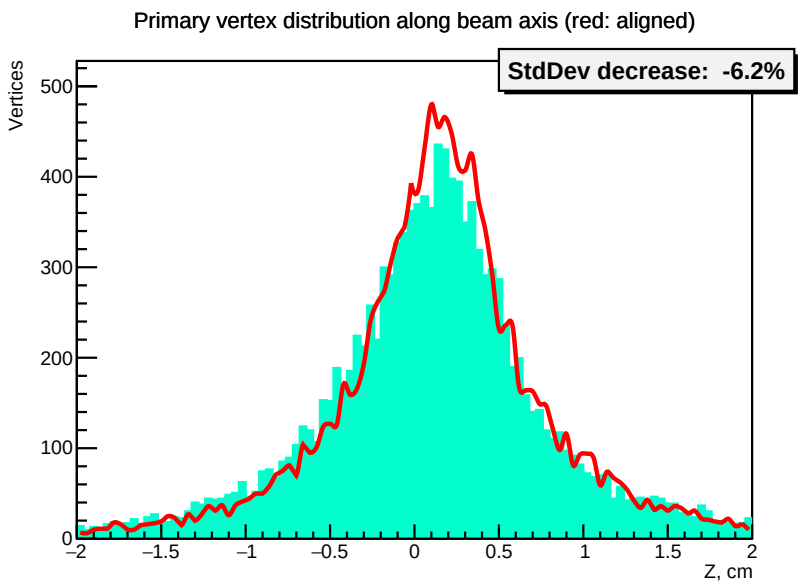


New technique: tracks reconstruction improvement









PyTorch: an alternative framework

The alignment task $S \to \min$ is very similar to the neural-network (NN) training task. [13] Therefore, it is very tempting to utilize well-developed NN toolkits to overcome practical alignment issues.

Such an attempt is in progress in collaboration with the **Big Data and Information Retrieval School at HSE University**. This work is still at an early stage.

[13] The depth of similarity between the two tasks is subject to discussion.

Remote perspective: alignment beyond geometry

A more general formulation of the alignment task is possible: parameters not related to geometry can be added. Examples from the H1 experiment alignment [1, Sec. 4, Table 1]:

- drift-velocity corrections in drift chambers ($\delta v_{\text{drift}} / v_{\text{drift}}$);
- Lorentz angle in drift chambers (α_{Lor});
- time-zero offsets per wire group (δT_0).

Further examples from CMS and Belle II can be found in [4, 5].

The prospects of this approach for the BM@N experiment are subject for discussion.

Thank you for your attention!

Questions and suggestions are always welcome!

Feel free to get in touch: `polev@jinr.int`

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References

1. V. Blobel, C. Kleinwort. *A new method for the high-precision alignment of track detectors*. arXiv:hep-ex/0208021 (2002).
   http://arxiv.org/abs/hep-ex/0208021
2. V. Blobel. *Millepede-II – draft manual*.
   http://www.desy.de/~kleinwrt/MP2/doc/html/draftman_page.html
3. I.I. Belotelov. *Influence of tracking-detector modules positioning accuracy on physical signal reconstruction in the Hera-B and CMS experiments and geometric alignment of the Hera-B outer tracker*. PhD thesis, Moscow State University, Faculty of Physics, Moscow, 2006.
4. CMS Collaboration. *Strategies and performance of the CMS silicon tracker alignment during LHC Run 2*.
   Nucl. Instrum. Meth. **A1037**, 166795 (2022). arXiv:2111.08757;
   http://arxiv.org/abs/2111.08757
5. J. Kandra, T. Bilka, L. Kapitanova et al. *Calibration and alignment of the Belle II tracker*. Proc. Connecting the Dots / Workshop on Intelligent Trackers (2019), PROC-CTD19-098. arXiv:1910.06289;
   http://arxiv.org/abs/1910.06289
6. BmnRoot framework, BmnAligner sub-project:
   http://git.jinr.ru/nica/bmnroot/align_new

Appendix A: Alignment transformation definition

$$\begin{bmatrix} x_m \\ y_m \\ \tilde{z}_i \end{bmatrix} = R_{zyx}(i) \begin{bmatrix} x \\ y \\ z - \tilde{z}_i \end{bmatrix} + \begin{bmatrix} \delta x_i \\ \delta y_i \\ \delta z_i + \tilde{z}_i \end{bmatrix}, \quad R_{zyx}(i) = \begin{bmatrix} 1 & -\psi_i & \theta_i \\ \psi_i & 1 & -\phi_i \\ -\theta_i & \phi_i & 1 \end{bmatrix}$$

$(x_m,\ y_m)^T$: measured coordinates of the hit;

$\tilde{z}_i$: nominal z position of the i-th detector element;

$x,\ y,\ z$: true coordinates of the hit in the laboratory coordinate system;

$R_{zyx}(i)$: linearized combined rotation matrix for the i-th detector element;

$\delta x_i,\ \delta y_i,\ \delta z_i$: shifts of the i-th detector element along the X, Y, Z axes;

$\phi_i,\ \theta_i,\ \psi_i$: sines of the i-th detector element rotation angles around X, Y, Z;

a_i : alignment parameters of the i-th detector element;

$a_i = (\delta x_i,\ \delta y_i,\ \delta z_i,\ \phi_i,\ \theta_i,\ \psi_i)^T$.

Appendix B: Measurement model

Starting from a straight-track model [14]:

$$\begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} \alpha_x \\ \alpha_y \end{bmatrix} + z \begin{bmatrix} \beta_x \\ \beta_y \end{bmatrix}, \quad \alpha = (\alpha_x,\ \beta_x,\ \alpha_y,\ \beta_y)^T,$$

transformation model (App. A) leads to the linearized $\vec{f}(\alpha, a) = (x_m,\ y_m)^T$:

$$x_m = \alpha_x + \beta_x \tilde{z} + \delta x - \delta z \bar{\beta}_x - \psi \bar{y} - \phi \bar{\beta}_x \bar{y} + \theta \bar{\beta}_x \bar{x},$$
$$y_m = \alpha_y + \beta_y \tilde{z} + \delta y - \delta z \bar{\beta}_y + \psi \bar{x} - \phi \bar{\beta}_y \bar{y} + \theta \bar{\beta}_y \bar{x},$$
$$\bar{x} = \bar{\alpha}_x + \bar{\beta}_x \tilde{z}, \quad \bar{y} = \bar{\alpha}_y + \bar{\beta}_y \tilde{z},$$
$$\bar{\alpha} = (\bar{\alpha}_x,\ \bar{\beta}_x,\ \bar{\alpha}_y,\ \bar{\beta}_y)^T \text{ – latest local-parameter approximation}$$

with detector and track indices omitted throughout.

[14] BM@N has dedicated data-taking sessions with the magnetic field deactivated for alignment data accumulation.

Appendix C: algorithm log for Session 7466 of Run-8

