Status of orbit correction studies at PITZ

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HELMHOLTZ

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Transfer matrix

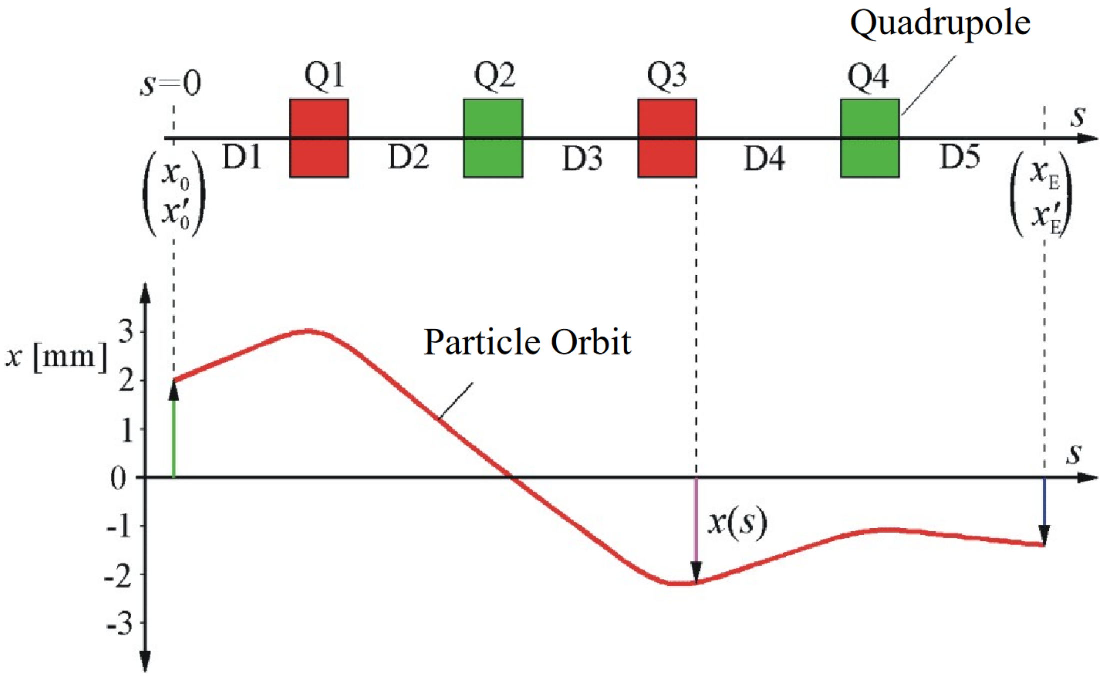
Trajectory of the center of the beam from point A to point B

- Drift
  - $R = \begin{bmatrix} 1 & L \\ 0 & 1 \end{bmatrix}$
- Quadrupole in thin lens approximation
  - $R_x = \begin{bmatrix} 1 & 0 \\ -\frac{1}{f_x} & 1 \end{bmatrix}$
- 6D transfer matrix

$$\begin{pmatrix} x \\ x' \\ y \\ y' \\ z \\ \Delta p/p_0 \end{pmatrix}_{final} = R \begin{pmatrix} x \\ x' \\ y \\ y' \\ z \\ \Delta p/p_0 \end{pmatrix}_{initial} = \begin{pmatrix} R_{11} & R_{12} & R_{13} & R_{14} & R_{15} & R_{16} \\ R_{21} & R_{22} & R_{23} & R_{24} & R_{25} & R_{26} \\ R_{31} & R_{32} & R_{33} & R_{34} & R_{35} & R_{36} \\ R_{41} & R_{42} & R_{43} & R_{44} & R_{45} & R_{46} \\ R_{51} & R_{52} & R_{53} & R_{54} & R_{55} & R_{56} \\ R_{61} & R_{62} & R_{63} & R_{64} & R_{65} & R_{66} \end{pmatrix} \begin{pmatrix} x \\ x' \\ y \\ y' \\ z \\ \Delta p/p_0 \end{pmatrix}_{initial}$$

Courtesy: Maria Elena Castro Carballo,
ORBIT CORRECTION IN THE EUROPEAN XFEL, 31.03.2017

Example: FODO cell:



$$\vec{X}_E = \mathbf{M}_{D5} \cdot \mathbf{M}_{Q4} \cdot \mathbf{M}_{D4} \cdot \mathbf{M}_{Q3} \cdot \mathbf{M}_{D3} \cdot \mathbf{M}_{Q2} \cdot \mathbf{M}_{D2} \cdot \mathbf{M}_{Q1} \cdot \mathbf{M}_{D1} \cdot \vec{X}_0$$

Courtesy: Wolfgang Hillert, Transverse Beam Dynamics, CAS 2018

Response matrix

Responses of the BPMs to the change of current of steerers before them

- The response of **i-th** BPM to the change of current of the **j-th** steerer
  - $H_{ij} = \Delta I_j \rightarrow \Delta x_i = \frac{\Delta x_i}{\Delta \theta_j} \rightarrow R_{12}$ of transfer matrix from steerer to BPM

- If there is only drift between the BPM and the steerer, then
  - $R = \begin{bmatrix} 1 & L \\ 0 & 1 \end{bmatrix} \rightarrow R_{12} = L$

- If there are also other non-steerer magnets (e.g., quadrupoles), then R_{12} should be calculated using transfer matrix considering all m elements between them:
  - $R = R_m R_{m-1} \dots R_1$

Trajectory prediction

From change of currents to change of positions

- Workflow
  - User defines a list of elements
  - Get the number of steerers (M) and BPMs (N) and initiate the response matrix H [N x M]
  - For each BPM (i<N), get each steerer (j<M) before it and calculate the H_{ij}
  - Predict new positions of the beam at chosen BPMs (N)

- Prediction
  - Get strengths of steerers, $k_{xx,} k_{yy}$ (we decided to calculate X and Y axis independently)
  - Get the changes of angles from the new currents of steerers: $\begin{bmatrix} \Delta\theta_x \\ \Delta\theta_y \end{bmatrix} = \begin{bmatrix} k_{xx} & k_{xy} \\ k_{yx} & k_{yy} \end{bmatrix} \begin{bmatrix} \Delta I_x \\ \Delta I_y \end{bmatrix}$
  - Calculate the new positions: $\Delta x = H\Delta\theta$

Trajectory correction

From desired change of positions to necessary change of currents

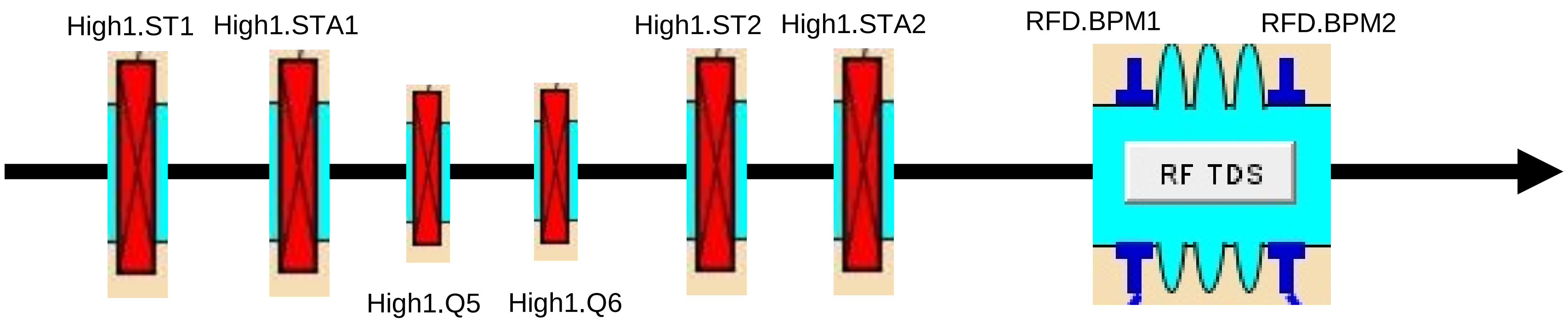
- Workflow
  - User defines a list of elements
  - Get the number of steerers (M) and BPMs (N) and initiate the response matrix H [N x M]
  - For each BPM (i<N), get each steerer (j<M) before it and calculate the H_{ij}
  - Do SVD for the response matrix: $H = U\Sigma V^T$ (needed for pseudo-opposite matrix to H)
  - Correct the current orbit at BPMs (N) by changing currents at steerers (M)

- Correction
  - Get strengths of steerers, k_{xx}, k_{yy} (we decided to calculate X and Y axis independently, k_{xy} and k_{yx} = 0)
  - Solve the angles: $\Delta\theta = V\Sigma^{-1}U^T\Delta x$
  - Solve the currents of steerers: $\begin{bmatrix}\Delta I_x \\ \Delta I_y\end{bmatrix} = \begin{bmatrix}k_{xx} & k_{xy} \\ k_{yx} & k_{yy}\end{bmatrix}^{-1} \begin{bmatrix}\Delta\theta_x \\ \Delta\theta_y\end{bmatrix}$

First experiments

The idea of an experiment

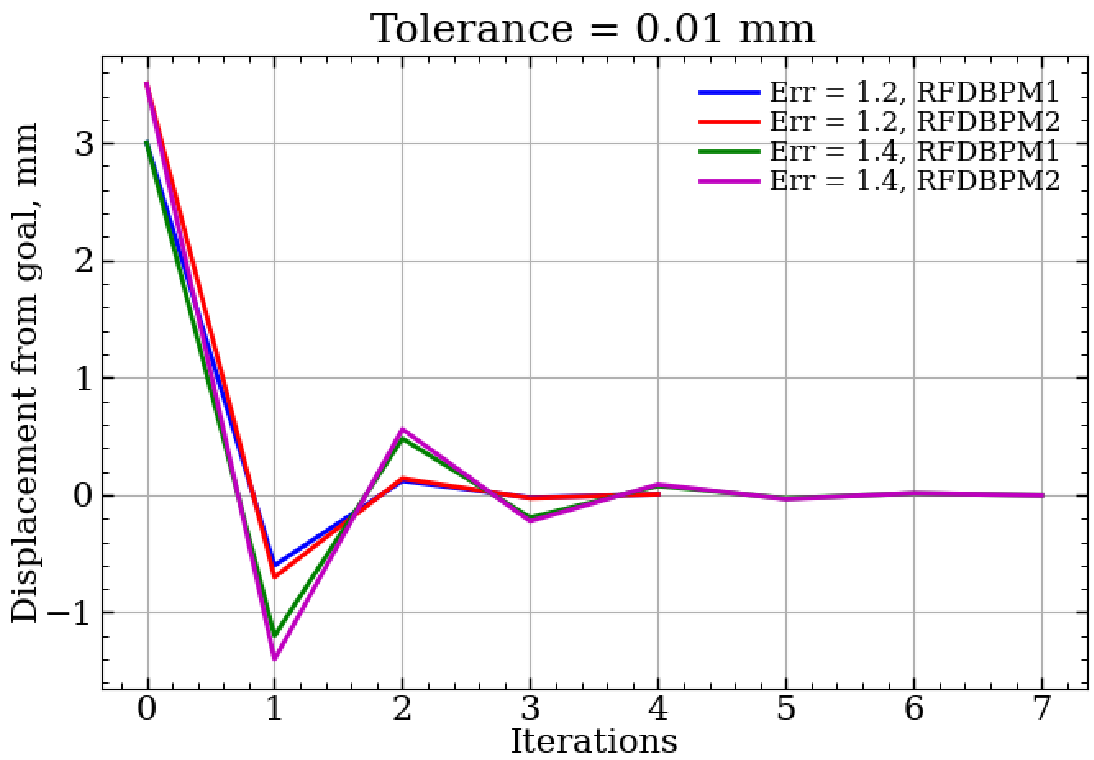
- → High1.ST1, High1.STA1, High1.ST2, High1.STA2
  → Get the steerer strength in the steering plane.
- Define an orbit correction model (the above steerers + RFD.BPM1 & RFD.BPM2)

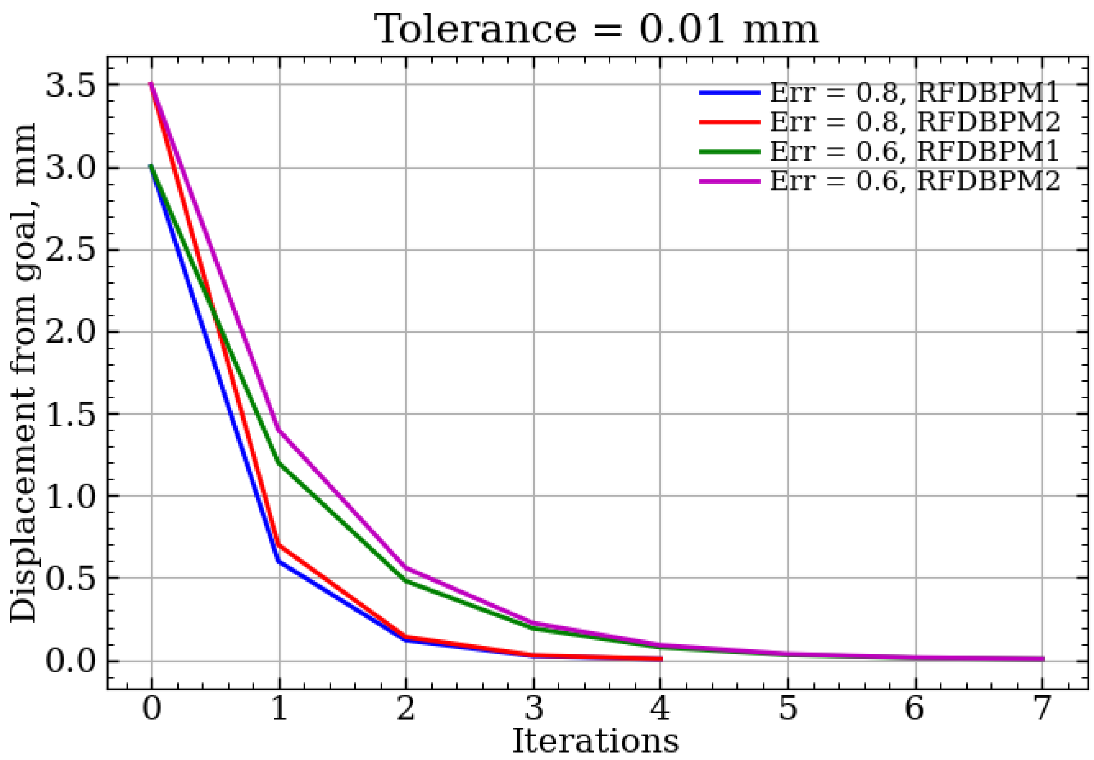


- Experimentally check the trajectory correction（e.g., center the beam at the BPMs）
  - Add quadrupoles to the model (High1.Q5, High1.Q6, High1.Q7)
- Robustness of the algorithm (e.g. does it work when the steerer strength estimated with an error?)

First experiments

Robustness test





- User defines desired position **change** at chosen BPMs
- Needed currents changes are calculated for all steerers
- Position change is simulated based on the calculated currents change
- If the difference between desired position change and actual position change < tolerance, then break

First experiments

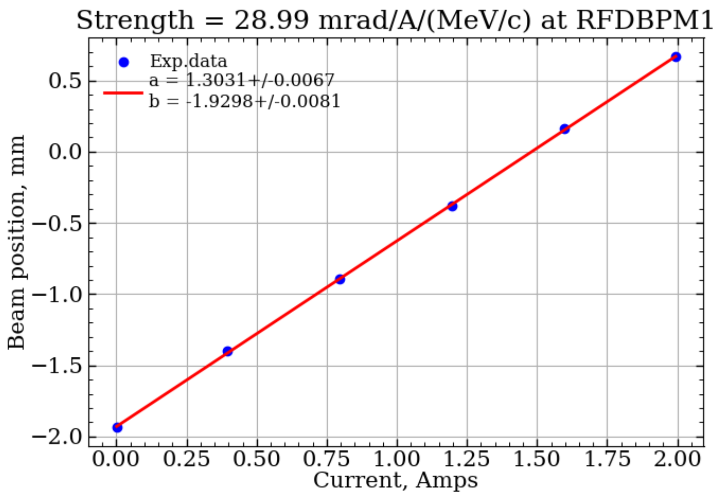
Shift results (Xiangkun + Dima, 09.08.2023 afternoon)

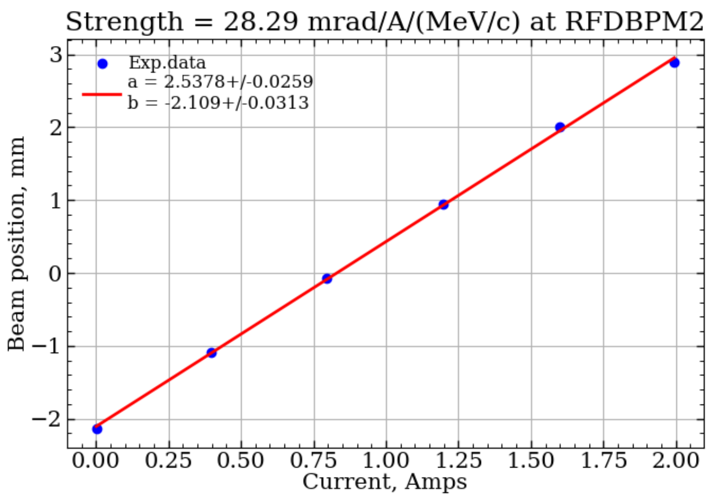
Achievements

- Calibrated steerers with new script: HIGH1.ST1, HIGH1.ST2, HIGH1.ST3, **HIGH1.ST4(shown on slide)** HIGH1.STA1, HIGH1.STA2

Difficulties

- Several booster IL due to sparks with counter. Tests were conducted without booster.
- Orbit correction can have large error due to the beam jitter (at least at RFD.BPM1&2)





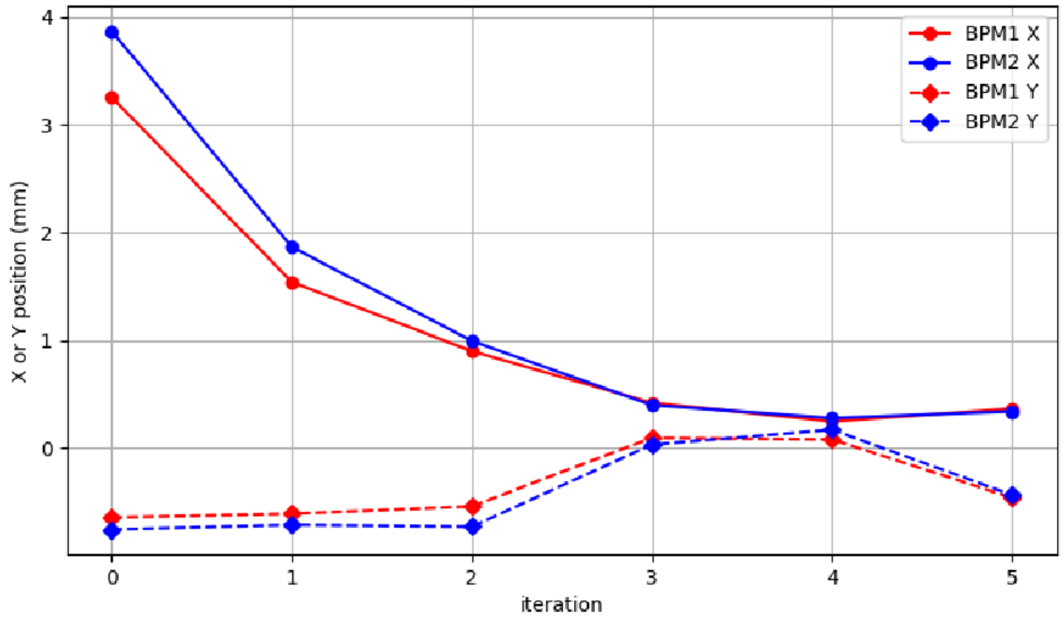
	Meas Str 09082023	
Device	RFDBPM1	RFDBPM2
HIGH1.ST1	29.69	31.11
HIGH1.STA1	27.13	26.56
HIGH1.ST2	11.67	11.41
HIGH1.STA2	56.69	55.79
HIGH1.ST3	11.45	11.24
HIGH1.ST4	28.99	28.29

First experiments

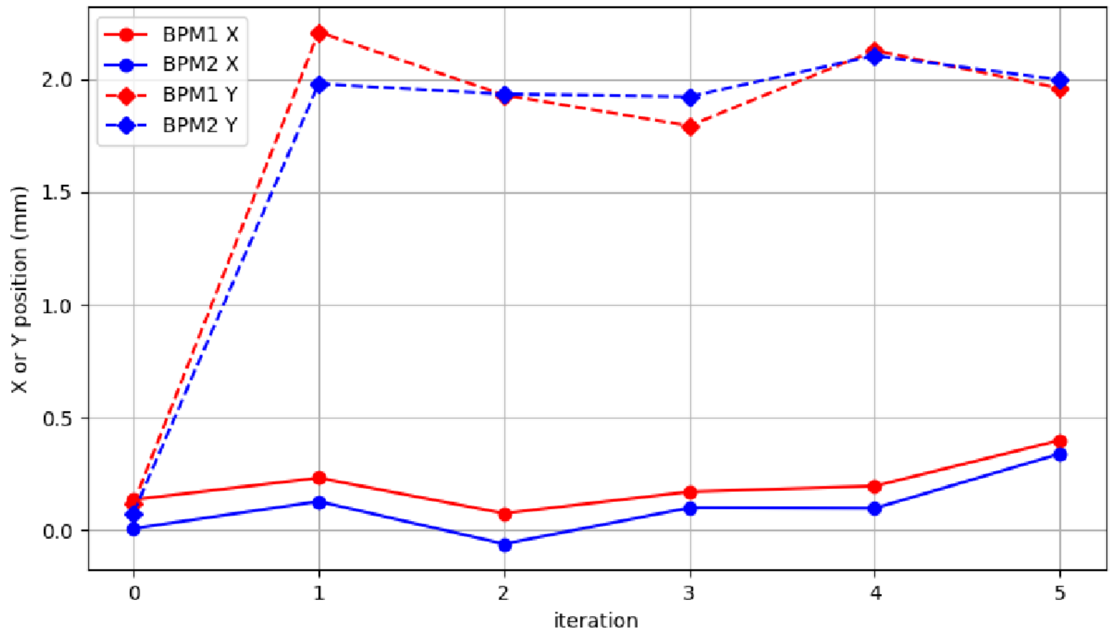
Shift results (Xiangkun + Dima, 09.08.2023 afternoon)

- Tested orbit correction (High1.ST1&2 for x and High1.STA1&2 for y at both RFD.BPM1&2) and ran successfully.

Goal x = 0 mm



Goal x = 2 mm



Development plans

- Add quads to models and test (simulation+measurement)

- Steering free tuning of combination of quadrupoles
  - Response matrices with and without quads are **different**
  - When all quads are made steering free → response with and without quads will be **same**

- Test of the tool for different parts of the beamline
  - Low, High1, PST, THz matching/FLASH beam focusing

- Beautification of the code (separate classes for different routines)
- User Interface + understandable documentation

First simulation test to make quads steering free

- Idea
  - Response matrices with and without quads are **different**
  - When all quads are made steering free
    → response with and without quads will be **same**
  - By minimizing the difference (e.g., simplex method), the trajectory inside the quads can be optimized

- Test
  - Upper, tuning with two quads (perfect case)