Emittance tuning bumps for CLIC ML at 380 GeV

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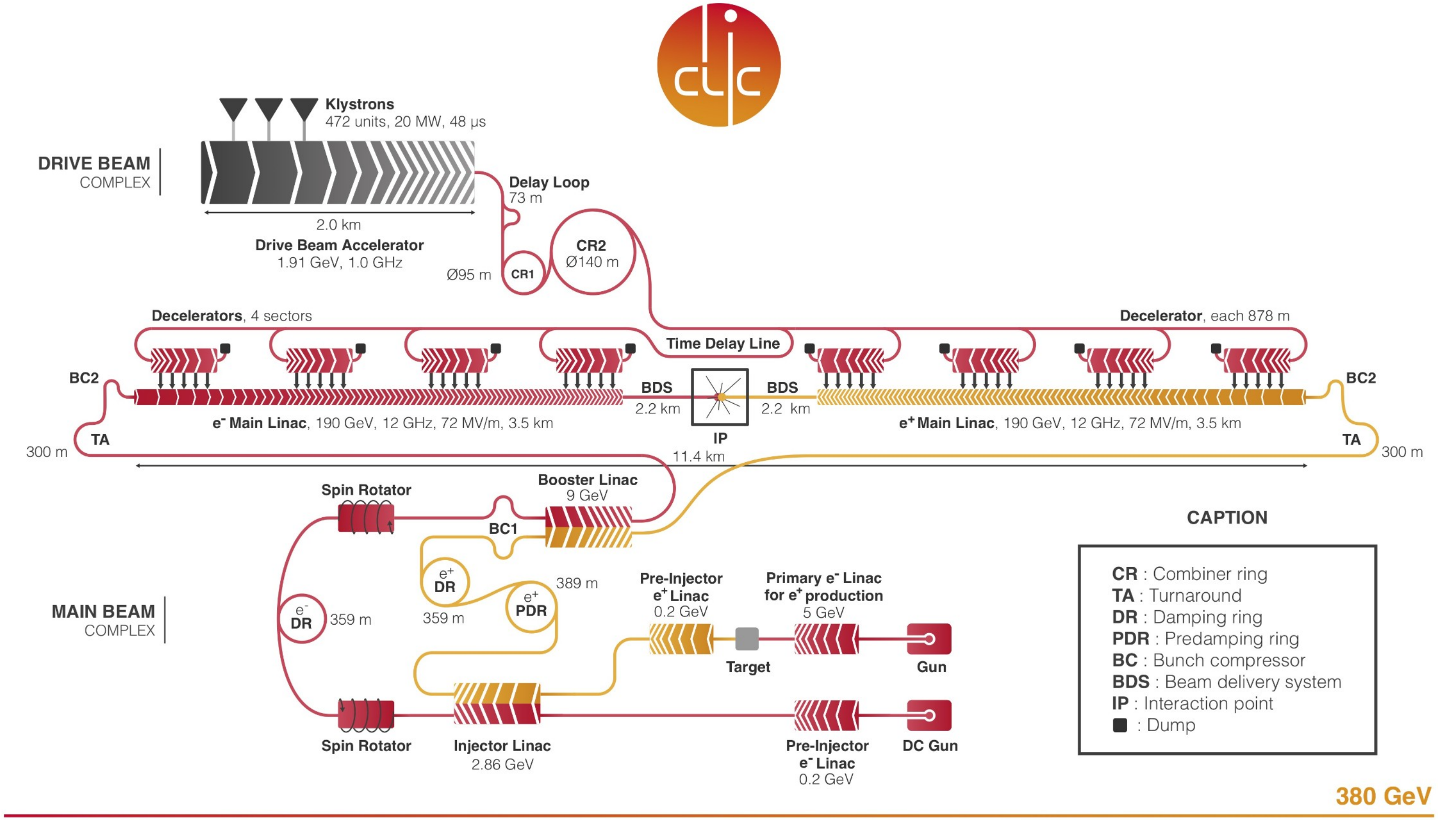
Outline

- **Introduction**
  - CLIC performance goals
  - ML current performance and motivation
- **Emittance tuning knobs construction**
  - Knobs definition
  - Identifying the principle directions
  - Orthogonal knobs construction
- **Tuning simulations**
- **Conclusions**

Introduction

CLIC schematic layout



CLIC - Scheme of the Compact Linear Collider (CLIC)

Introduction

Performance goals

- Each section has design emittance value, that includes the growths coming from static and dynamic errors.

Section	ϵ_x [nm]	$\Delta\epsilon_x$ [nm]			ϵ_y [nm]	$\Delta\epsilon_y$ [nm]		
		Design	Static	Dynamic		Design	Static	Dynamic
DR	700	-	-	-	5	-	-	-
RTML	850	100	20	30	10	1	2	2
ML	900	0	25	25	20	0	5	5
BDS	950	0	25	25	30	0	5	5

- **Perfect machine** $\mathcal{L} = 4.3 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- **Static imperfections** $\mathcal{L} = 2.3 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- **Static and dynamic imperfections** $\mathcal{L} = 1.55 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

Introduction

Performance goals

- The vertical budgets are the similar to the 3 TeV design. Typically, it is easier to meet the budget for 380 GeV.
- Integrated simulations starting from the exit of the DR to the IP including static errors give the average luminosity of [1]:

$$\mathcal{L} = (3.0 \pm 0.4) \times 10^{34} \mathrm{cm}^{-2} \mathrm{s}^{-1}$$

- With ground motion included:

$$\mathcal{L} = (2.8 \pm 0.3) \times 10^{34} \mathrm{cm}^{-2} \mathrm{s}^{-1}$$

90% of the machines reach the lumi of:

$$\mathcal{L} = 2.35 \times 10^{34} \mathrm{cm}^{-2} \mathrm{s}^{-1}$$

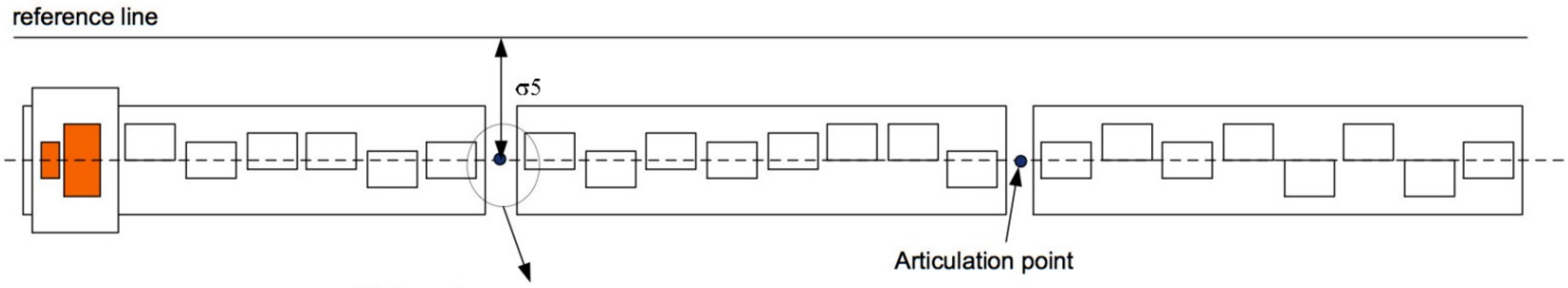
[1] C. Gohil, et. al. "*Luminosity performance of the Compact Linear Collider at 380 GeV with static and dynamic imperfections*", 2020,PhysRevAccelBeams.23.101001

ML current performance and motivation

- Current design foresees 10 nm vertical normalized emittance with 5 + 5 nm budget for static and dynamic imperfections.
- The budget is respected with the usage of **1-2-1 correction**, **Dispersion Free Steering**, and **RF structures alignments**.
- **Emittance tuning bumps/knobs** are designed to control the residual emittance → potential to reduce the budget dedicated for the static imperfections → higher lumi at the IP.

ML current performance and motivation

Imperfections overview



	With respect to	Error value	$\Delta\epsilon_y$ [nm] 1-2-1	DFS	RF
Girder end point	Wire reference	12 μm	12.38	12.27	0.07
Girder end point	Articulation point	5 μm	1.22	1.21	0.02
Quadrupole roll	Longitudinal axis	100 μrad	0.05	0.05	0.05
BPM offset	Wire reference	14 μm	208.82	7.05	0.18
Cavity offset	Girder axis	14 μm	5.01	4.98	0.04
Cavity tilt	Girder axis	141 μrad	0.14	0.41	0.29
BPM resolution		0.1 μm	0.03	0.75	0.05
Wake monitor	RF structure center	3.5 μm	0.02	0.77	0.41

Accelerating elements, quadrupoles, BPMs, wake monitors

Prealignment and BBA techniques

Beam-based alignment

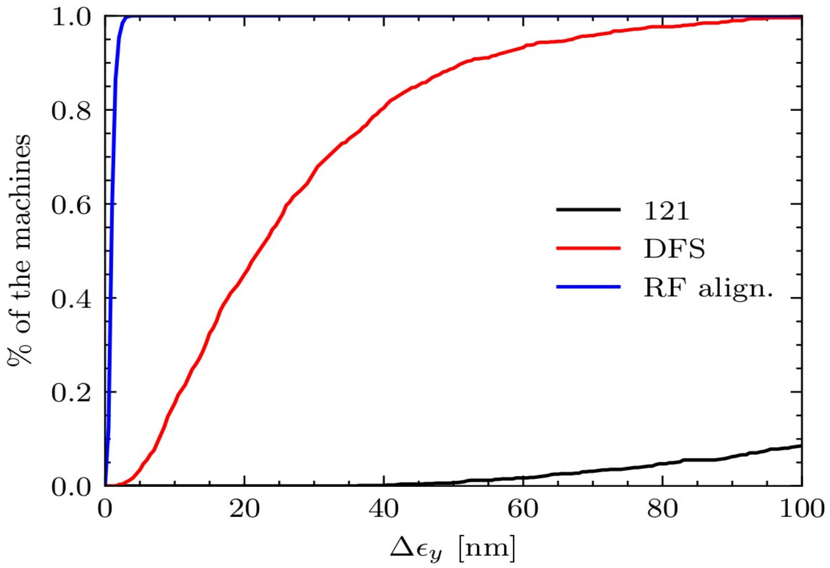
Current ML alignment routines consist of:

1) **One-to-one correction**
   The quadrupoles are moved to steer the beam through the BPM centers.
2) **Dispersion free steering**
   The quadrupoles are moved to minimize the orbit and dispersion simultaniously.
3) **Accelerating structures realignment with the wake monitors**
   The girders' supports are moved to minimize the wake monitors reading in the structures.

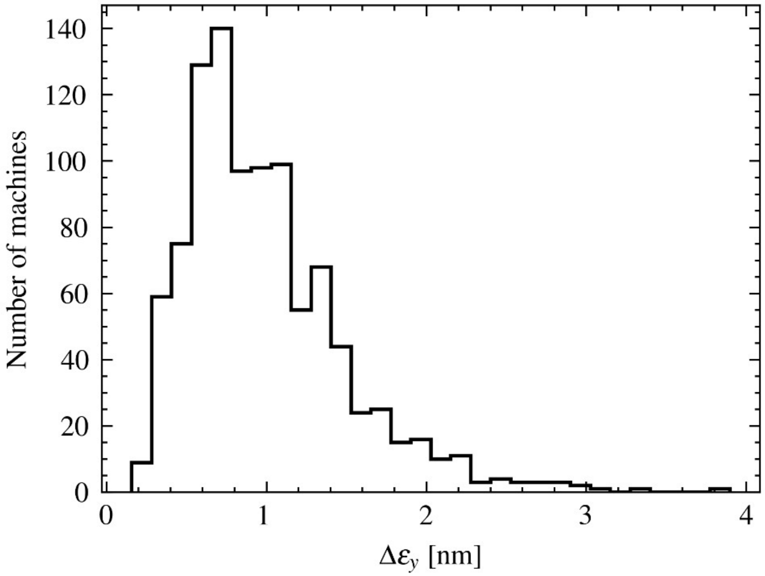
Prealignment and BBA techniques

Simulation of the BBA

Rms emittance growth:
- 1-2-1: 235.09 nm
- DFS: 25.84 nm
- RF align.: 0.98 nm



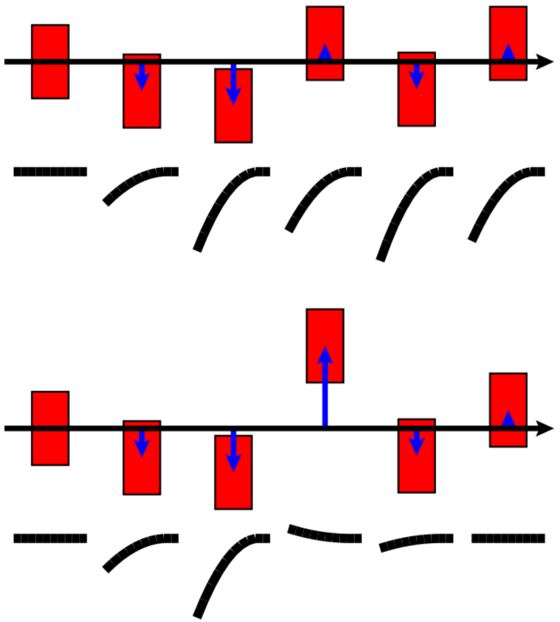
Summary (results from [2] are well reproduced):
100% of the machines < 4 nm
95% of the machines < 2 nm
Rms of 0.98 nm



[2] N. Blaskovic Kraljevic, D. Schulte, "*Beam-based beamline element alignment for the main linac of the 380 GeV stage of CLIC*", IPAC 2019, http://jacow.org/ipac2019/papers/mopmp018.pdf

Knobs definition

- The term knob is used for the set of changes that can be applied to the lattice (offsets, ..) to modify it.
- The remaining emittance growth after beam based alignment is due to the wakefields of the misaligned accelerating structures.
- The key idea is to add the vertical displacement to compensate the unwanted wakefield kicks.



Identifying the principle directions

Identifying the remaining emittance growth after the BBA

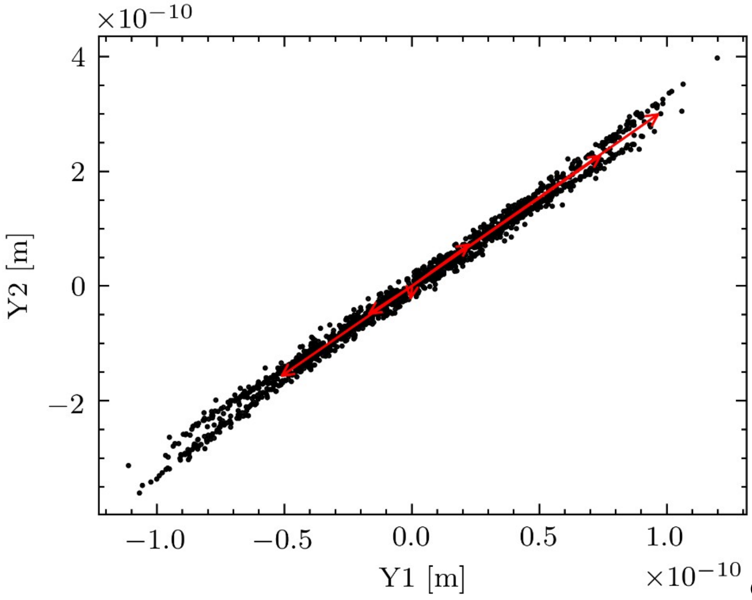
- We simulate the BBA (1-2-1 → DFS → RF align.) for 1000 machines with different error seeds and evaluate the macroparticles coordinates and angles at the ML exit.
- We use the macroparticle model of the beam.
- For each seed we calculate the corresponding vector in the normalized phase space. The length of that vector is the emittance growth $\Delta\epsilon_y^2$ [3].
- For the calculations we use the bunch of 11 slices with 5 macroparticles per slice (55 total).
- The tracking is done with **Placet**.
- To identify the key directions in the normalized phase space that statistically contribute to the emittance growth the most, we use **Principal Component Analysis (PCA)**.

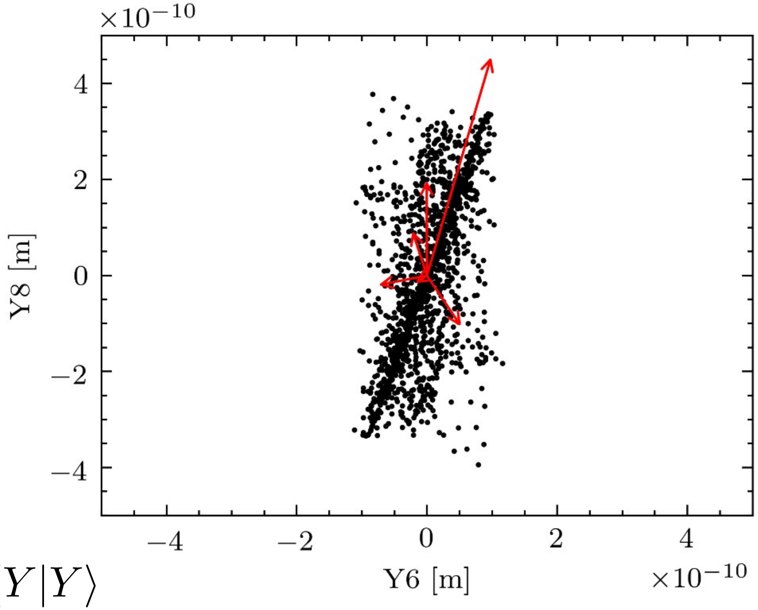
[3] P. Eliasson, D. Schulte, "*Design of main linac emittance tuning bumps for the Compact Linear Collider and the International Linear Collider*", 2008, 10.1103/PhysRevSTAB.11.011002

Identifying the principle directions

PCA

Example of the **PCA** applied to the data.
For the data analysis further on, utilizying Python modules, such as Pandas, Sklearn, and Numpy.



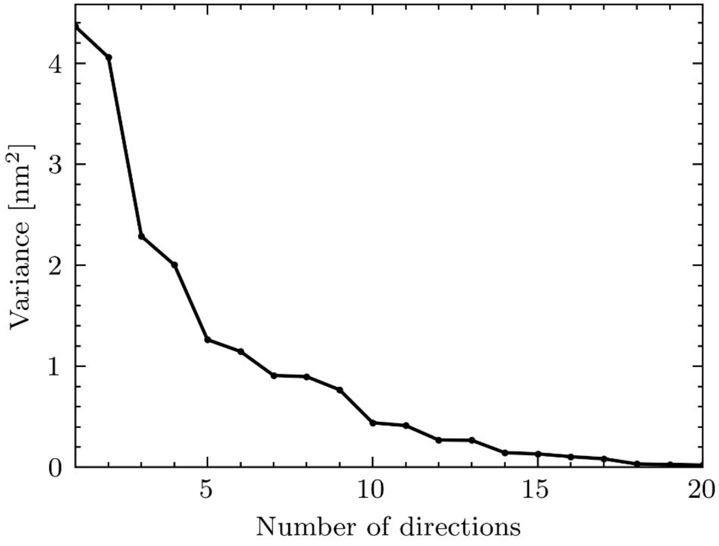


$$\epsilon_y^2 - \epsilon_{y,0}^2 = \langle Y|Y \rangle$$

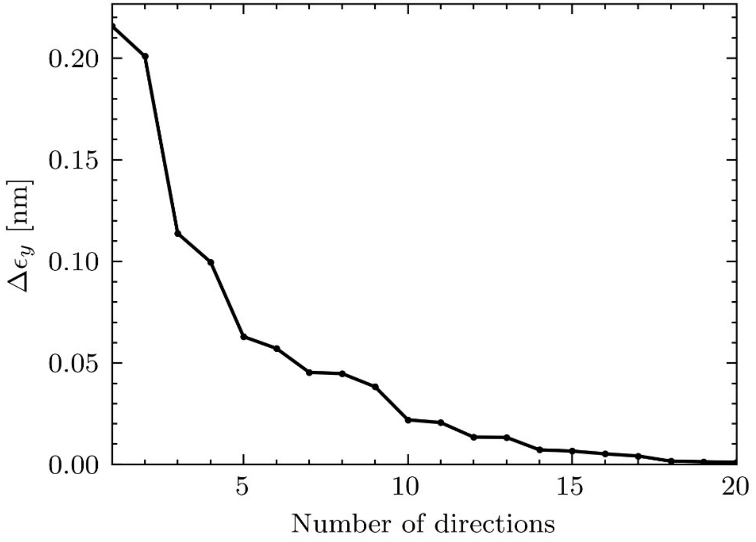
Identifying the principle directions

PCA

Each principal direction is characterized with its variance.



..or it can be transformed to the emittance growth.



$$\epsilon_y^2 - \epsilon_{y,0}^2 = \langle Y|Y\rangle$$

Identifying the principle directions

PCA

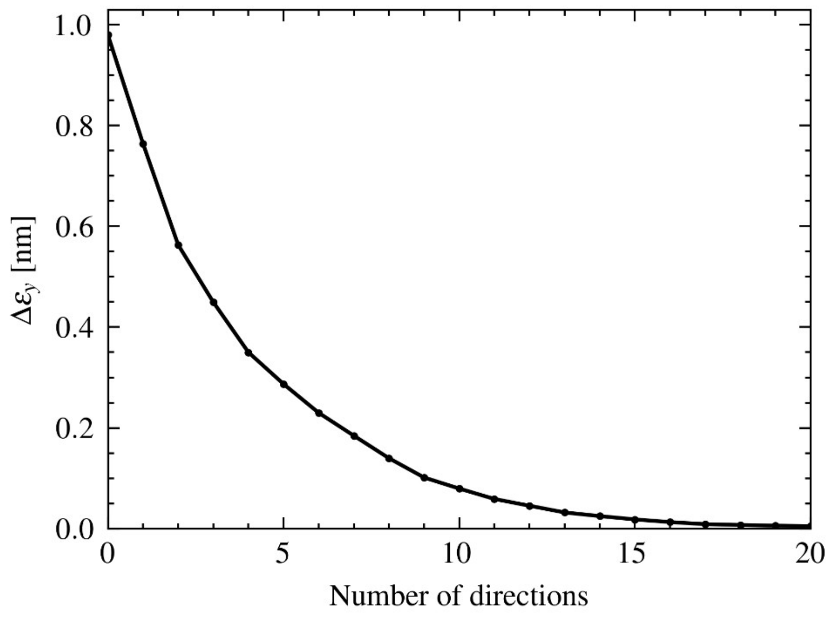
Based on this data we build the function of the residual emittance growth as the function of the number of the principle directions we correct.

For example:

- We correct 0 directions → ~0.98nm (what we have after rf alignment)
- 5 directions → ~0.3 nm
- 10 directions → ~0.08 nm

..

For the further analysis, 10 principle directions was taken.



Orthogonal knobs construction

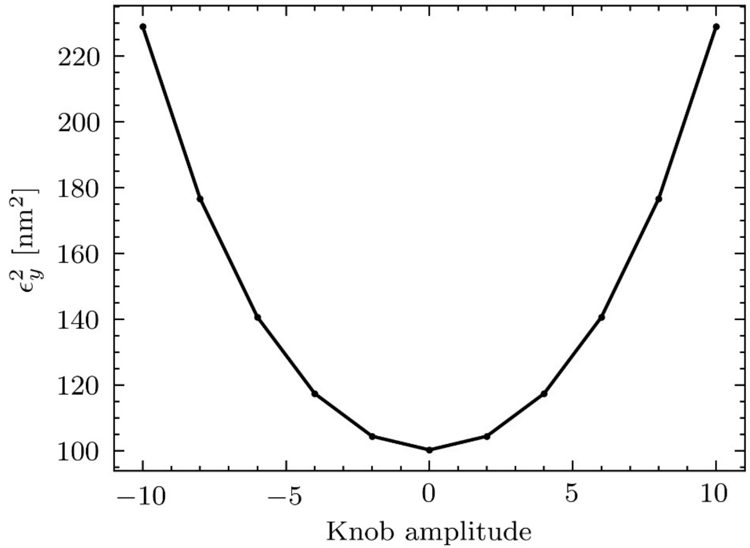
- To correct the coordinates along the principal directions we want to offset the girder with the accelerating structure on it. (We used all the girders/quads in the lattice)
- Also, we want to adjust the quads to compensate for the orbit change.

We build the response matrix as $$R_{ij} = \frac{\Delta Y_{p,i}}{\Delta y_{offset,j}}$$

- We want to find the sets of the girders/quads offsets that form the basis that corresponds to the principal directions. We will call these sets the tuning knobs.
- The solution are the columns of $\lambda\hat{R}^{\dagger}$. $\hat{R}^{\dagger}$ - is the pseudo-inverse of the response matrix. λ - is the target value (set to 1 nm).

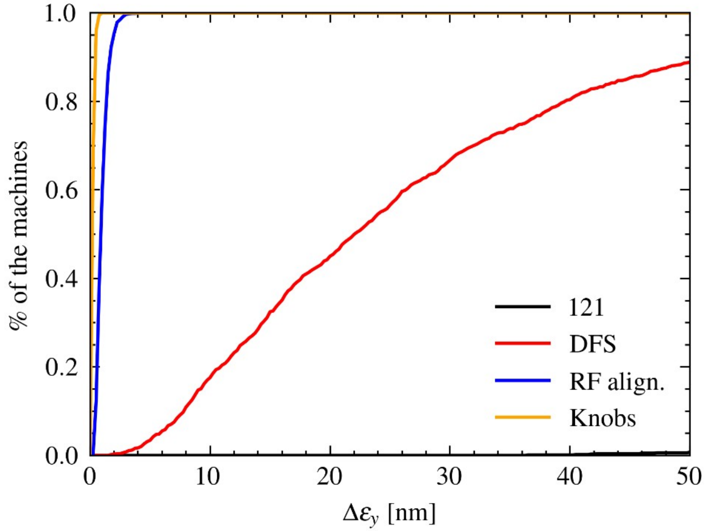
Orthogonal knobs construction

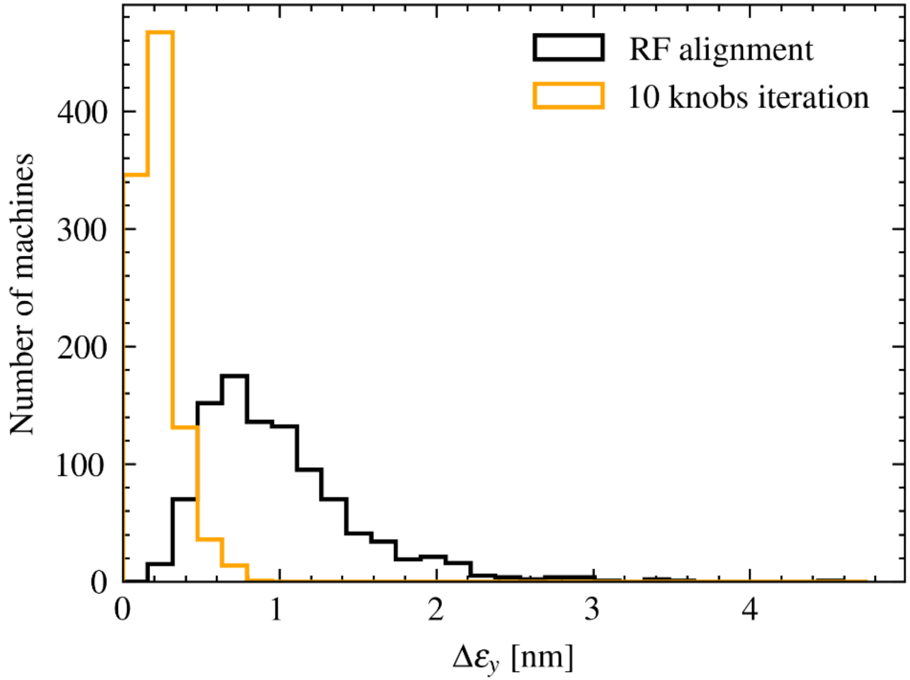
- When we apply the knob, the function is quadratic:
  $\epsilon_y^2 - \epsilon_{y,0}^2 = \langle Y_p | Y_p \rangle$
- For small changes, could be also aproximated as
  $\epsilon_y \propto \langle Y_p | Y_p \rangle$



Tuning simulations

- We perform the knob scans after the RF alignment
- Each knob is scanned once.
- **After the knobs tuning:**
  100% of the machines - < 0.8 nm
  95% of the machines - < 0.5 nm
  RMS 0.12 nm

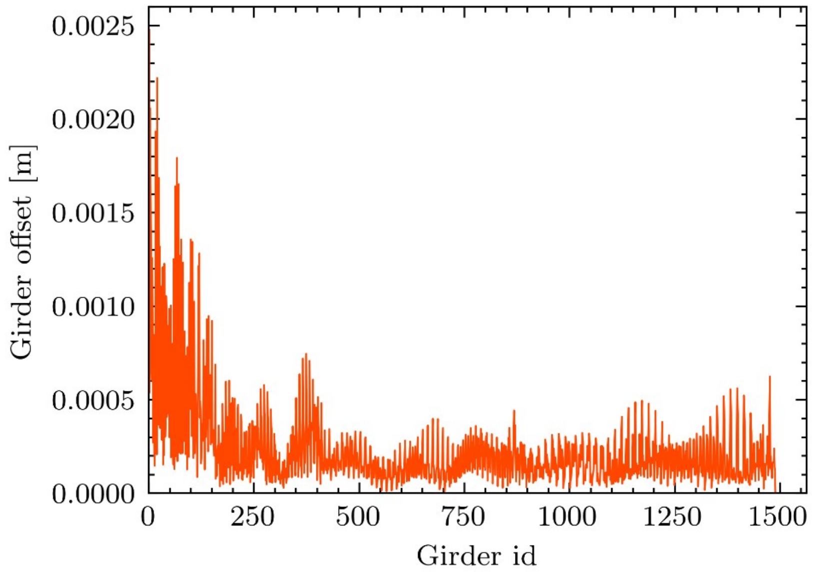




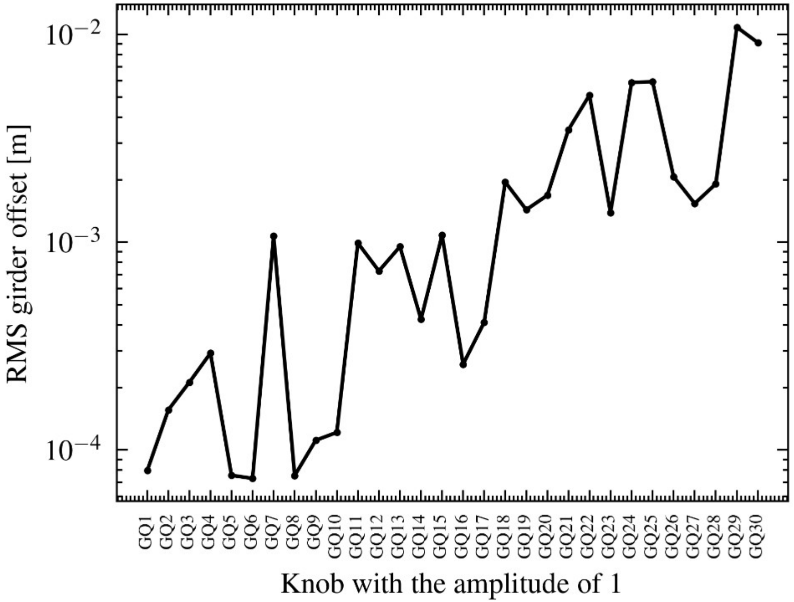
Tuning simulations

Structures displacements

- Fast convergence, but large structure displacements.



Unacceptably large structure displacements, especially in the first 150 elements



Tuning simulations

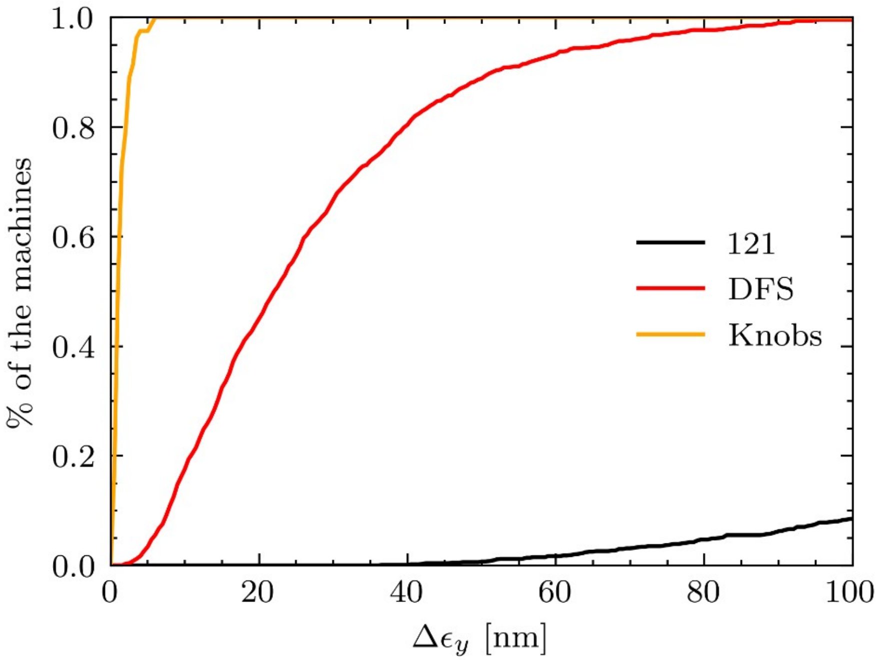
Things to address

- Reduce the number of the structures involved. Some structures are uninvolved in the tuning.
- Limit the structures offsets.
- We constructed the knobs on the girders vertical offsets. Instead, the movement of the articulation points should be investigated.

Tuning simulations

without RF alignment

- Similarly we built the set of the knobs to be used after the DFS in the event some/all wake monitors fail to work.



With 10 knobs, 95% of the machines reached < 3.5 nm.
With larger number of knobs, it is possible to reduce that value and even reduce the budget.

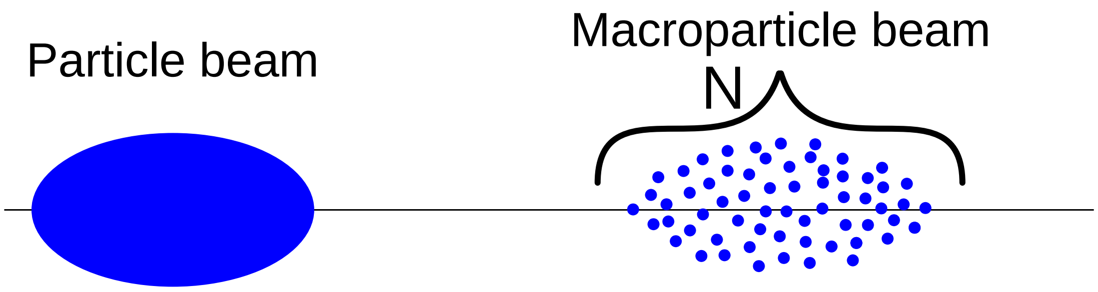
Conclusions

- The tuning bumps are promising to reduce the emittance budget for static errors.
- The realistic value of the budget to be evaluated taking into account the issues like large structures offsets,
- The tuning bumps constructed this way can also be used to reduce the emittance in the case of some/all wake monitors failure.

Thanks for your attention!

Back-up slides

Macroparticle model of the beam



- The beam is represented by a set of macroparticles.
  - The beam is cut longitudinaly into slices with 1 or more macroparticles in it to represent the energy distribution.
- Each macroparticle has typical set of coordinates as normal particle, but also the variations such as σ_{yy}, $\sigma_{yy'}$, etc., and also the weight.

Macroparticle model of the beam

Beam emittance

- In the macroparticle model of the beam, vertical emittance writes as:

$$\epsilon_y^2 = \gamma^2[(\sum_{i,j=1}^{M} r_{i,j} y_i y_j + \widetilde{\sigma}_{yy})(\sum_{i,j=1}^{M} r_{i,j} y'_i y'_j + \widetilde{\sigma}_{y'y'}) - (\sum_{i,j=1}^{M} r_{i,j} y_i y'_j + \widetilde{\sigma}_{yy'})^2]$$

  M is the number of macroparticles, **(y_i, y'_i)** are coordinates of i-th macroparticle, and $\widetilde{\sigma}_{yy}$, $\widetilde{\sigma}_{yy'}$,$\widetilde{\sigma}_{y'y'}$ are the variances, when the all macroparticles are centered.

  \+ $r_{ij} = w_i(\delta_{ij} - w_j)$

- Dropping the 4th order terms in this eq:

$$\epsilon_y^2 - \epsilon_{y,0}^2 = \gamma^2 \left[\langle y| \quad \langle y'|\right] \hat{M} \begin{bmatrix} |y\rangle \\ |y'\rangle \end{bmatrix} \text{ with } \hat{M} = \begin{bmatrix} \widetilde{\sigma}_{y',y'}\hat{R} & -\widetilde{\sigma}_{y,y'}\hat{R} \\ -\widetilde{\sigma}_{y,y'}\hat{R} & \widetilde{\sigma}_{y,y}\hat{R} \end{bmatrix}$$

- Each seed is represented by the vector composed of coordinates and angles of M macroparticles $[y_1, y_2, y_3, .. y'_1, y'_{2, ..}]^T$.

Macroparticle model of the beam

Beam emittance

- Matrix $\hat{M}$ is real, symmetric, and positive definite → applying Cholesky decomposition:

  $$\gamma^2 \hat{M} = \hat{L}\hat{L}^T$$

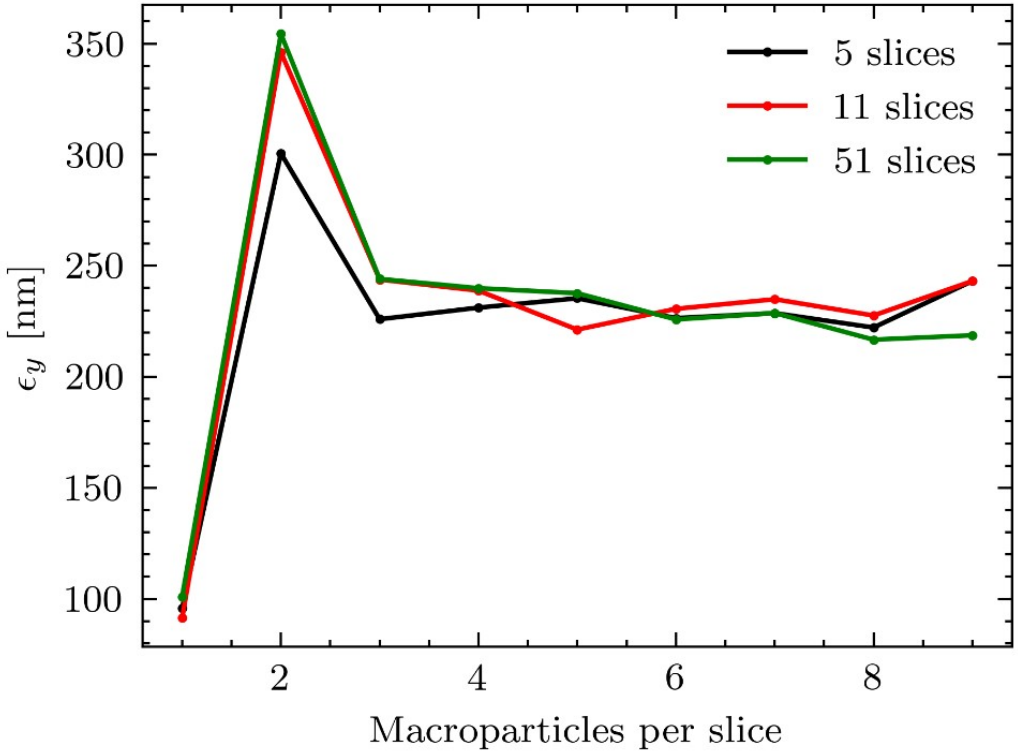
  We have the normalized set of coordinates $|Y\rangle$, so the emittance growth is:

  $$\epsilon_y^2 - \epsilon_{y,0}^2 = \langle Y|Y\rangle$$

- Further, in the data analysis, we will be using the normalized coordinates.

Macroparticle model of the beam

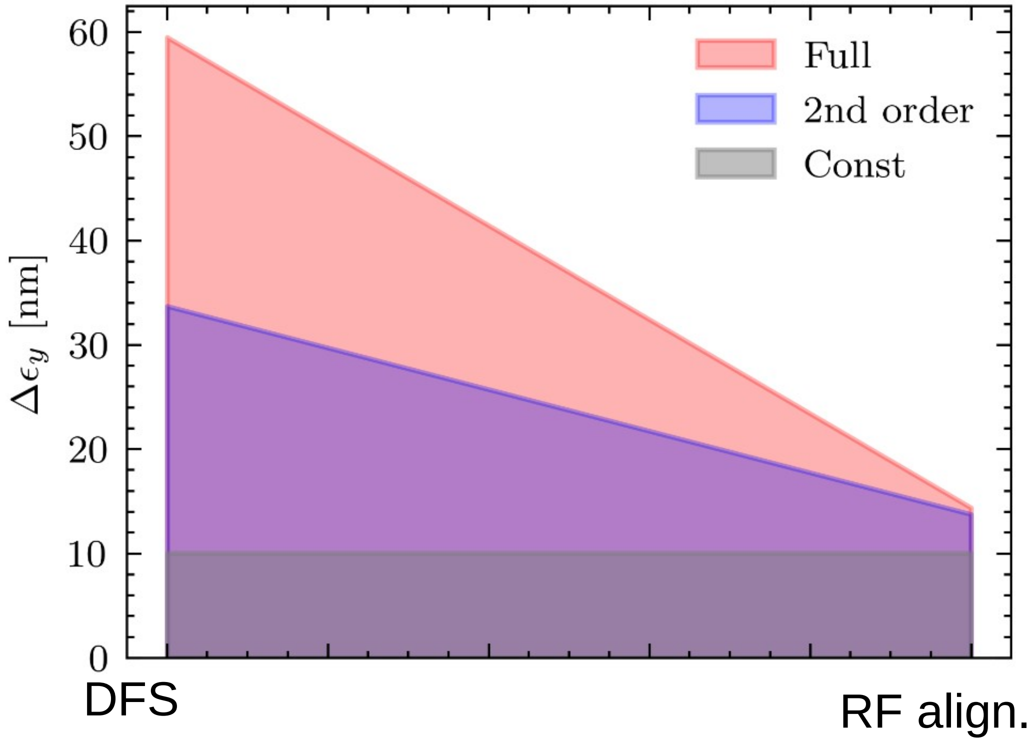
Emittance for several configurations of number of slices and macroparticles



Macroparticle model of the beam

Beam emittance

Emittance contributions:



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