Emittance tuning knobs for CLIC ML

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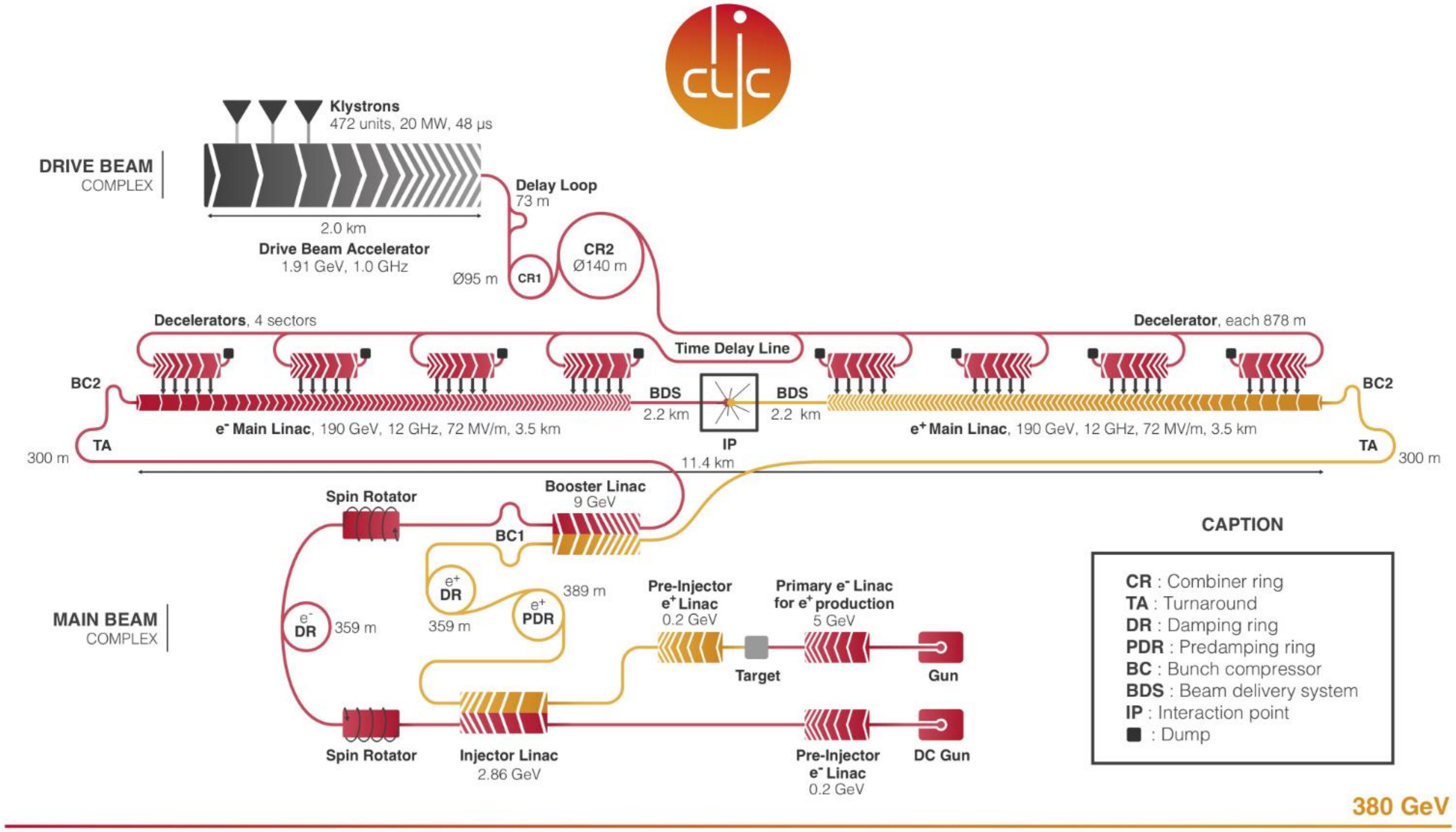
CLIC 380 GeV

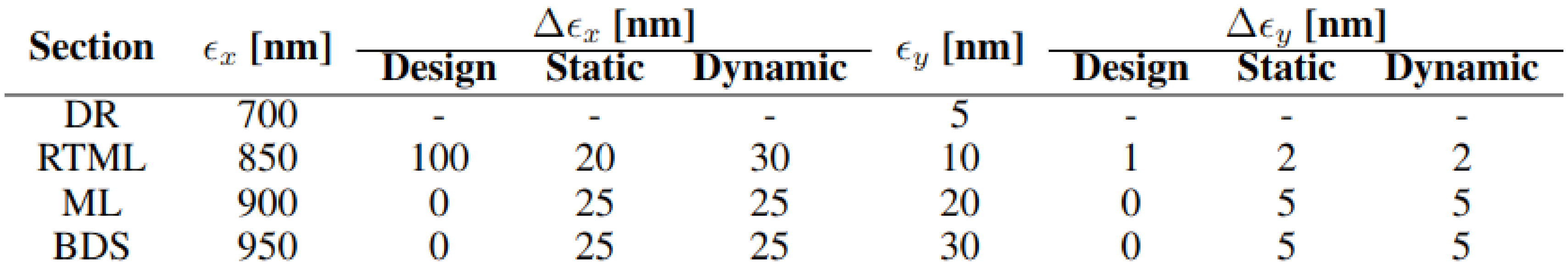


CLIC - Scheme of the Compact Linear Collider (CLIC)

CLIC 380 GeV

Emittance budget

- A nanometer vertical beam size at the IP calls for a very small vertical emittance. **Limiting emittance growth throughout the beamline is crucial.**
- Each CLIC subsystem has allocated emittance growth budget for **static** and **dynamic** imperfections. Respecting these allows CLIC to meet the target luminosity.
- For **ML**, the budget is **5 nm for static imperfections** and **5 nm for dynamic imperfections**.
- The budget is met by utilizing various **Beam Based Alignment** techniques.



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

CLIC 380 GeV

Integrated simulations

- 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:

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

Design luminosity is $1.5\mathrm{x}10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

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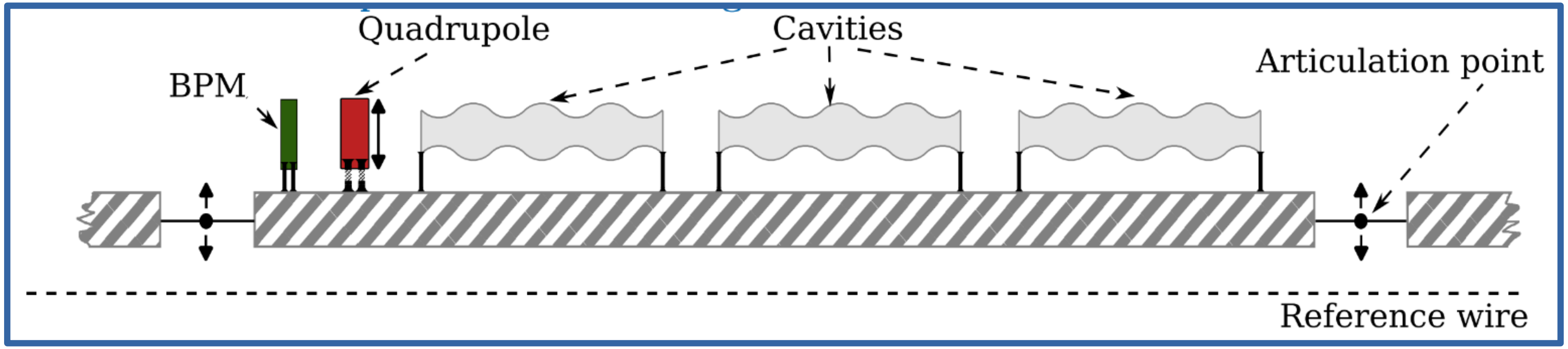
[1] C. Gohil, et. al. "*Luminosity performance of the Compact Linear Collider at 380 GeV with static and dynamic imperfections*", 2020

CLIC ML alignment



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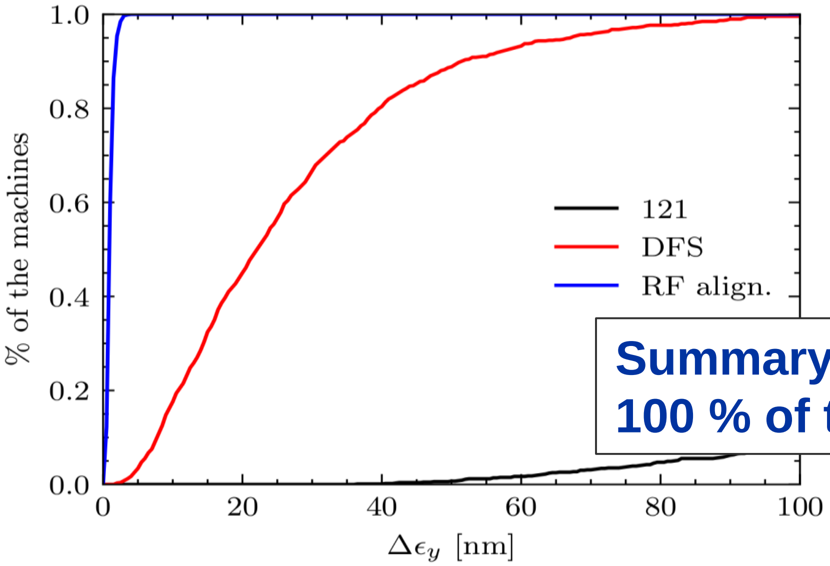
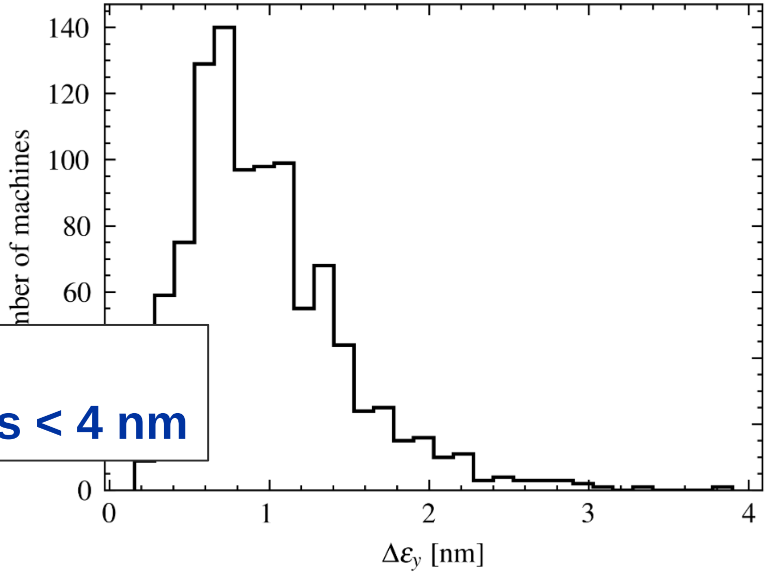
ım]		
	FS	RF
Girder en	27	0.07
Girder en	21	0.02
Quadrup	05	0.05
BPM o	05	0.18
Cavity		
Cavity		
BPM res		
Wake m	77	0.41

RF





Summary[2]:
100 % of the machines < 4 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

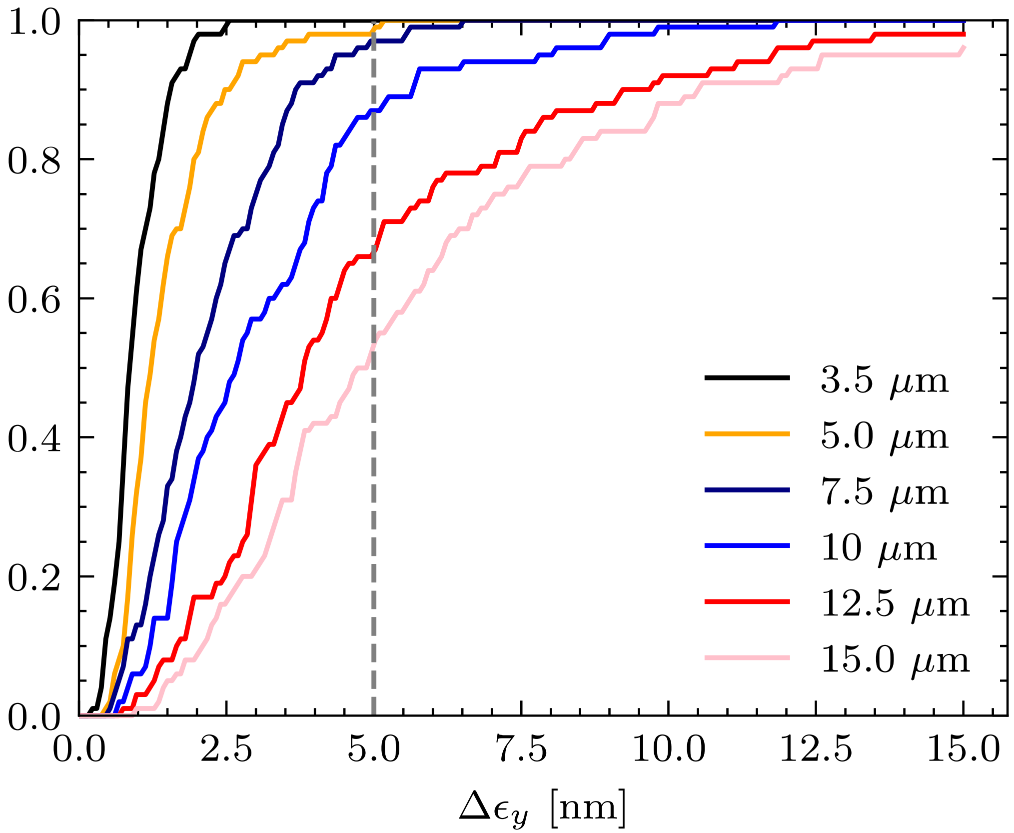
CLIC ML alignment

- **Wakefield monitors (WFMs)** are very important for the RF alignment. So far the accuracy we used is **3.5 µm**. Changes to the accuracy influences the performance:

  *With accuracy **> 7.5 µm**, static error budget is not met!*

  Realistic value so far is 10 µm[3]*.*

- **We need some margin here and tools to reduce the emittance to be within the budget!**



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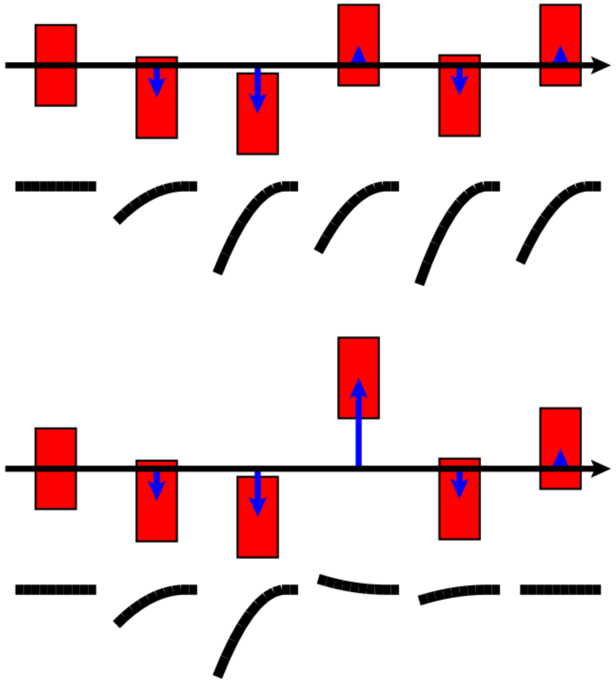
[3] K. N. Sjobak, et. al., "*CLIC Wake Field Monitor as a detuned Cavity Beam Position Monitor: ..*", arXiv:2307.06681

Emittance tuning knobs

Emittance tuning knobs

- Residual emittance growth comes from the wakefields of the misaligned accelerating structures.
- To compensate the unwanted wakefield kicks, we need to offset the beam vertically inside of the cavities. This can be done by **misaligning cavities** (girders) or creating orbit bumps with **displaced quadrupoles.**
- **Emittance tuning knob**[4] – is a set of elements offset that allows to reduce the emittance growth.

$$\epsilon_y = f(\epsilon_{y,0}, A(\mathrm{Y}_1), A(\mathrm{Y}_2), ..)$$



Evaluate potential of using the tuning knobs to: **squeeze down the budget for static errors** and **provide a backup solution for RF alignment.**

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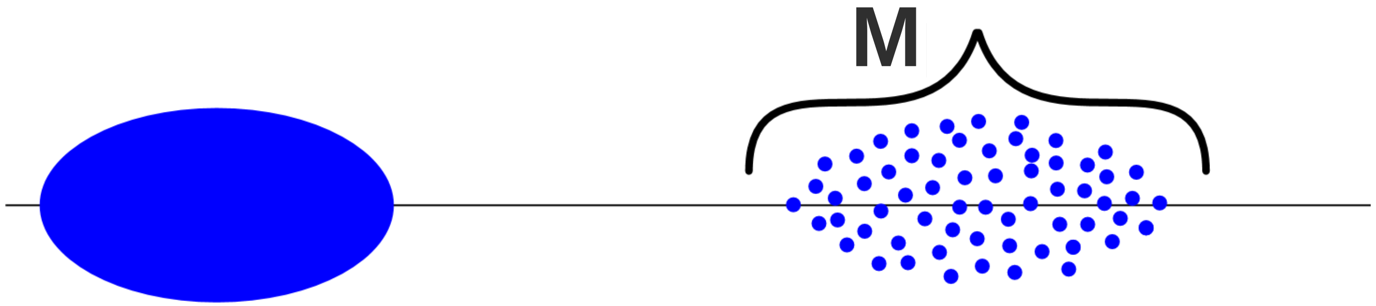
[4] A. Pastushenko, D. Schulte, "*Emittance tuning bumps for the Main Linac of CLIC 380 GeV*", IPAC 2023, THPL087

Emittance tuning knobs

Macroparticle model of the beam

- **The beam is represented by a set of macroparticles.**
- **The beam is cut longitudinaly with multiple macroparticles in each slice. Macroparticles within each slice have different energies to simulate the beam energy spread.**
- **Each macroparticle is characterized with $x, y, x', y', \Delta s, \mathrm{t}$ and also the 2nd momentas, σ_{xy}, σ_{xx}, .. and also with a weight w**

Macroparticle beam simplified:



Emittance tuning knobs

Emittance of the macroparticle beam

- **Emittance of the macroparticle beam** writes:

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

$\boldsymbol{M}$ is the number of macropartiles; $(\boldsymbol{y_i}, \boldsymbol{y'_i})$ – coordinates of the macroparticle; $\boldsymbol{\tilde{\sigma}_{yy}}$, $\boldsymbol{\tilde{\sigma}_{y'y'}}$, and $\boldsymbol{\tilde{\sigma}_{yy'}}$ are the variances, when the macroparticles are transversaly aligned; $\boldsymbol{A_{ij} = w_i\,(\delta_{ij} - w_j)}$ with $\boldsymbol{w_i}$ being the weight of ith macroparticle.

- Expanded without 4th-order terms (*valid for analyzing the data after the RF alignment*), **emittance growth due to transverse motion of macroparticles**:

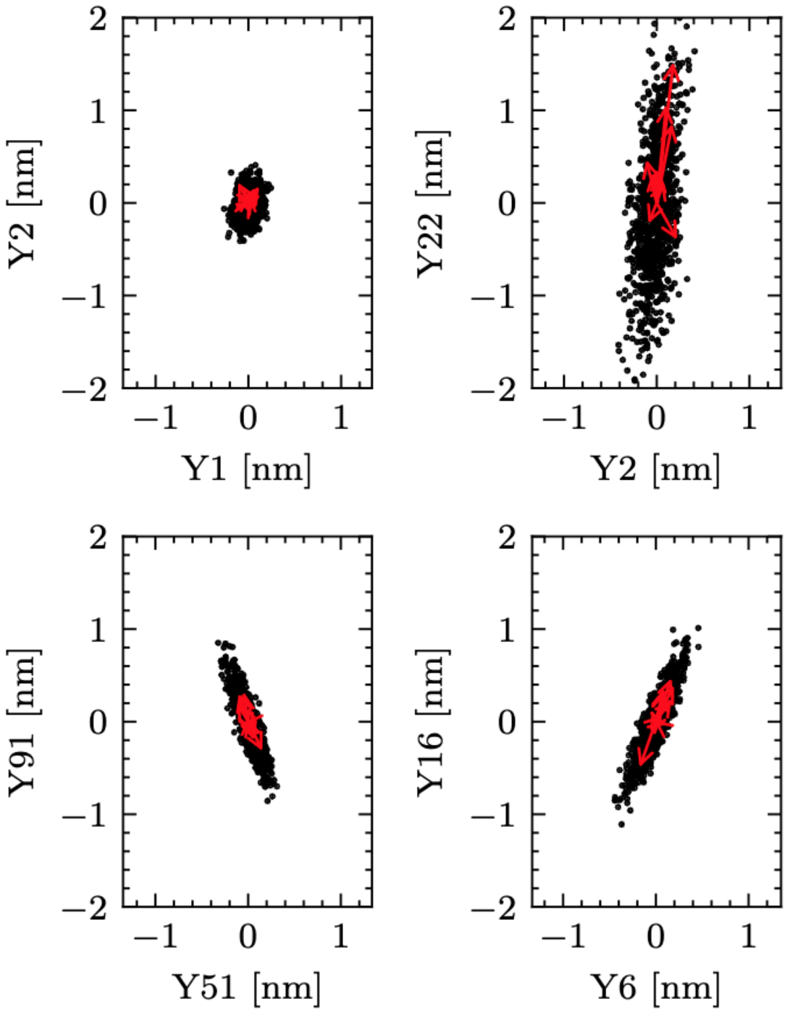
$\epsilon_y^2 - \epsilon_{y,o}^2 = \gamma^2 [\langle y| \quad \langle y'|]\, \widehat{M} \begin{bmatrix} |y\rangle \\ |y'\rangle \end{bmatrix}$, with block-matrix $\widehat{M} = \begin{bmatrix} \tilde{\sigma}_{y'y'}\hat{A} & -\tilde{\sigma}_{yy'}\hat{A} \\ -\tilde{\sigma}_{yy'}\hat{A} & \tilde{\sigma}_{yy}\hat{A} \end{bmatrix}$

- With **Cholesky decomposition**, we establish a set of **normalized coordinates** $|\boldsymbol{y_n}\rangle$:

$\gamma^2 \widehat{M} = \hat{L}\hat{L}^T$, $|Y_n\rangle = \hat{L}^T \begin{bmatrix} |y\rangle \\ |y'\rangle \end{bmatrix}$. Such that emittance growth writes $\boldsymbol{\epsilon_y^2 - \epsilon_{y,o}^2 \sim \langle Y_n | Y_n \rangle}$

Emittance tuning knobs

Emittance of the macroparticle beam



- **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). This gives as a new PCA space, where machine is characterized with $|Y_p\rangle$.**

Emittance growth now writes $\epsilon_y^2 - \epsilon_{y,o}^2 \sim \langle Y_p | Y_p \rangle$

For the study we used the setup with **11 longitudinal slices** and **5 macroparticles** in each slice.

That gives:
- **55** macroparticles in total.
- **110** normalized coordinates.
- **110** principal components.

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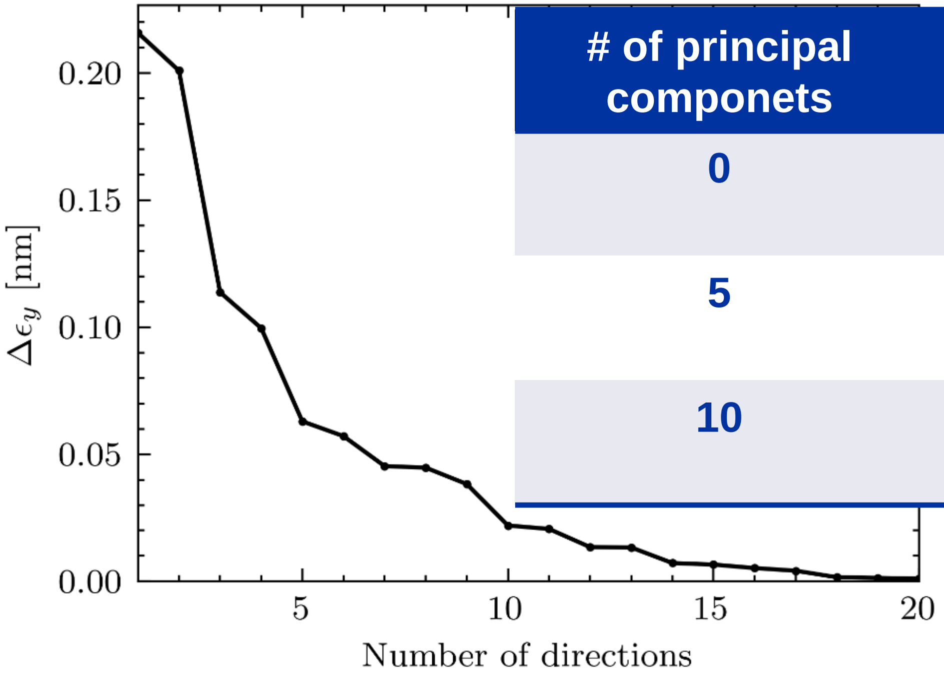
al to the emittance

Emittance tuning knobs

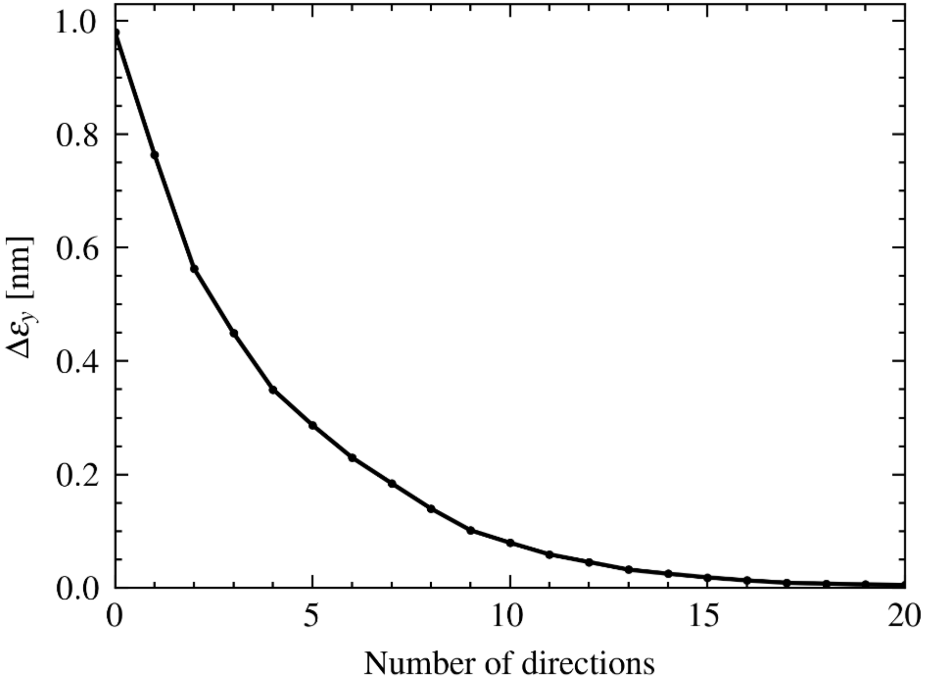
PCA

From **PCA** we can evaluate how much of the emittance growth, each principal direction carries.



# of principal componets	Emittance growth [nm]
0	0.98
5	0.3
10	0.08

Or, if we assume we **can correct first *N* principal components**, what RMS emittance growth we can expect after that:



Emittance tuning knobs

Knobs construction using pseudo-inverse

There are several degrees of freedom when constructing the knobs using pseudo-inverse:

- Elemens to use for the knob construction - **Quads, Girders, Quads+Girders**.
- **Cutoff** in the pseudo-inverse.
  Pseudo-inverse matrix is evaluated with Singular Value Decomposition (SVD):

$$\hat{R}^\dagger = \hat{V}\hat{E}^\dagger\hat{U}^T$$

So, we can set the limit (cutoff) to zero the nonimportant singular values.

- The obvious solution is:

$$|\boldsymbol{\Delta}_{\mathbf{i}}\rangle = \boldsymbol{\lambda}\widehat{\boldsymbol{R}}^\dagger|\boldsymbol{I}_{\boldsymbol{i}}\rangle$$

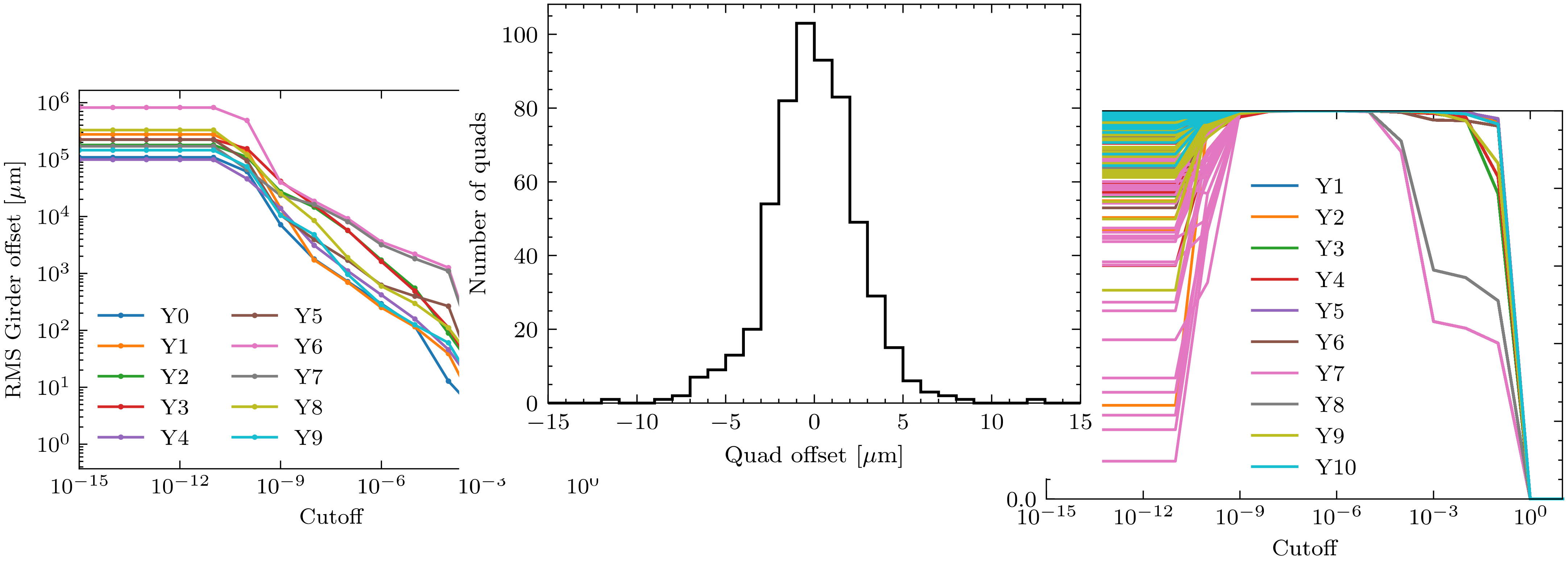
$\widehat{\boldsymbol{R}}^\dagger$ is a pseudo-inverse matrix.

The knob Y_i applies the offsets equal to $|\boldsymbol{\Delta}_{\mathbf{i}}\rangle$.

Emittance tuning knobs

Knobs construction using pseudo-inverse

By finding the balance between the knob performance and offsets we construct



Optimal cutoff is around **10^{-4} – 10^{-3}**. The girders' offsets are around **6 – 20 μm.**
The knobs Y_7 and Y_8 cannot be constructed.

Emittance tuning knobs

Optimal knobs

The optimal knob should:

- *Be based on the offsets of couple tens of girders/quadrupoles.*
- *Have a reasonable offsets associated with it. Offsets at the mm level mechanically are not possible. At the same time, they cannot be too small.*
- *Beam orbit to be controlled. It must stay at the reasonable level.*

The task to be solved:

$$\min\left\| \hat{R}|\Delta\rangle - |I_j\rangle \right\| \quad + \quad \begin{cases} |\Delta_i| \in [\Delta_{min}, \Delta_{max}] \\ \min\left\| \hat{R}_{orbit}|\Delta\rangle \right\| \end{cases}$$

And use the smallest number of quads/structures!

Optimal knobs

We build a model in Tensorflow: linear model with custom regularization:

- The offsets **< 1 μm (< 10 μm** for girders) are penalized ('Zero penalty').
- The large values are clipped to **100 μm**.
- The RMS beam orbit (among all the BPMs) is penalized. Also, to deal with the outliners, additional penalty is added for the BPMs with orbit **> 20 μm**.

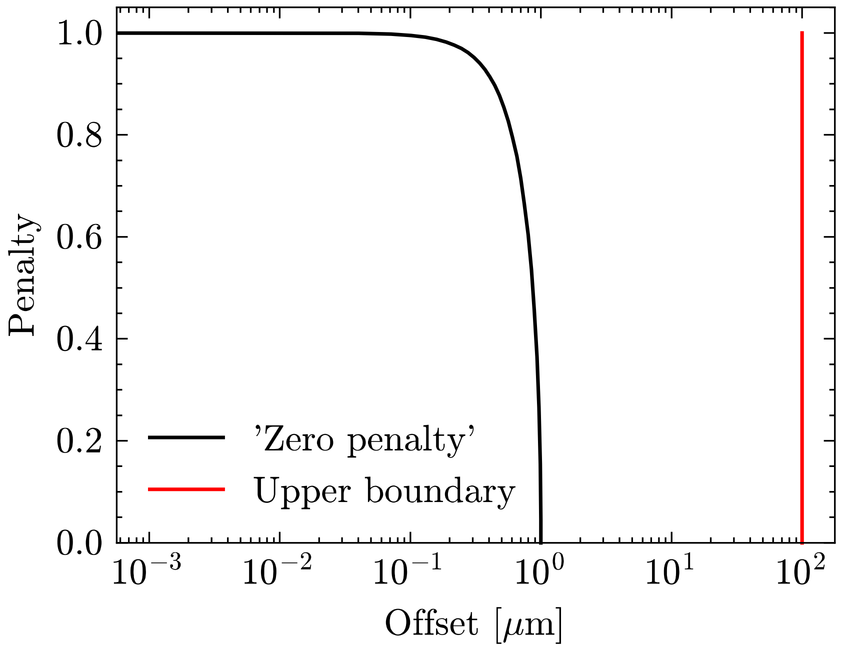
+ no orbit change at the ML exit.

We search for the optimal setup of the quads/girders by applying Forward Feature Selection (FFS).

To quantify the solutions I use the custom score, that I called orthogonality:

$$O(Y_i) = \frac{Y_{p,i}^2}{\sum_{j=1}^{M} Y_{p,j}^2}$$

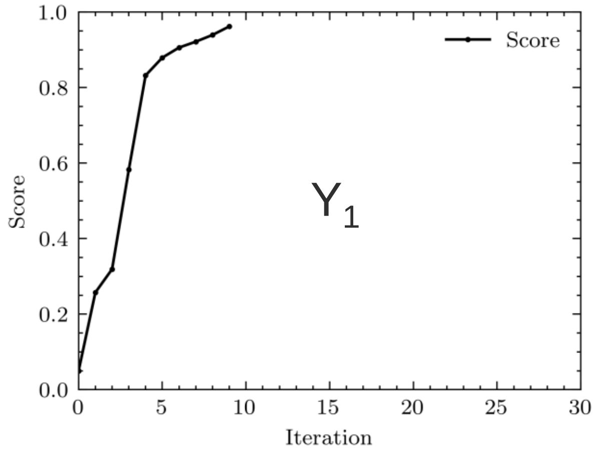
$Y_{p,i}$ - Beam ith coordinate in the PCA space

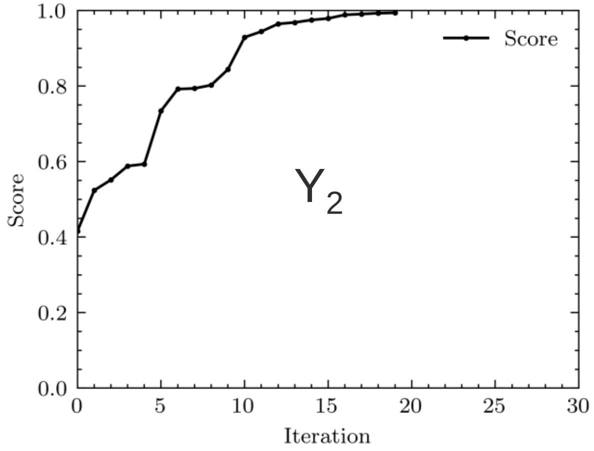


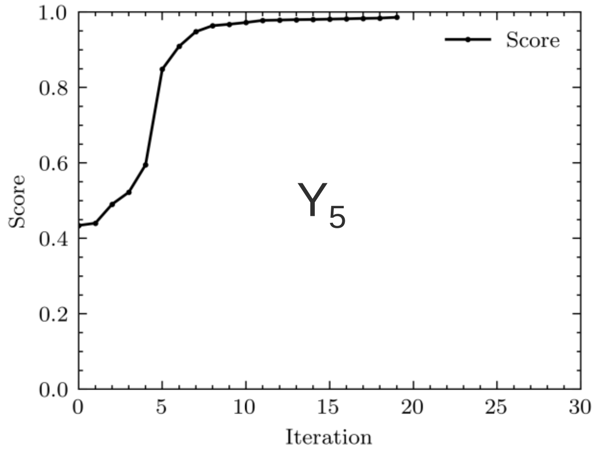
- *$O(Y_i)$ stays in the range [0, 1].*
- *For $O(Y_i) > 0.5$ it is possible to perform emittance tuning – multiple iterations might be needed.*
- *Case $O(Y_i) = 1.0$ is ideal. 1 knob iterations is enough.*

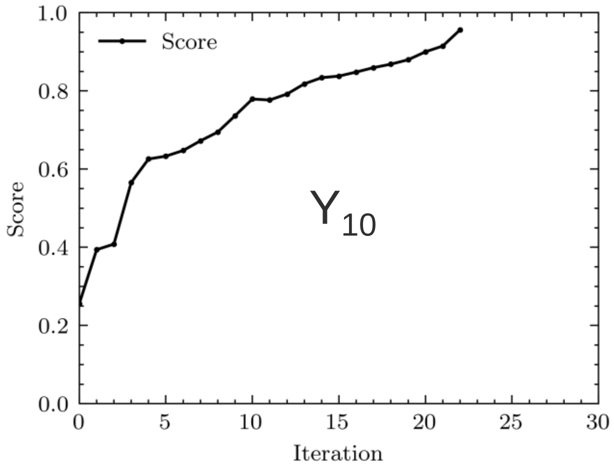
Optimal knobs

Some examples of the Sequential Selection









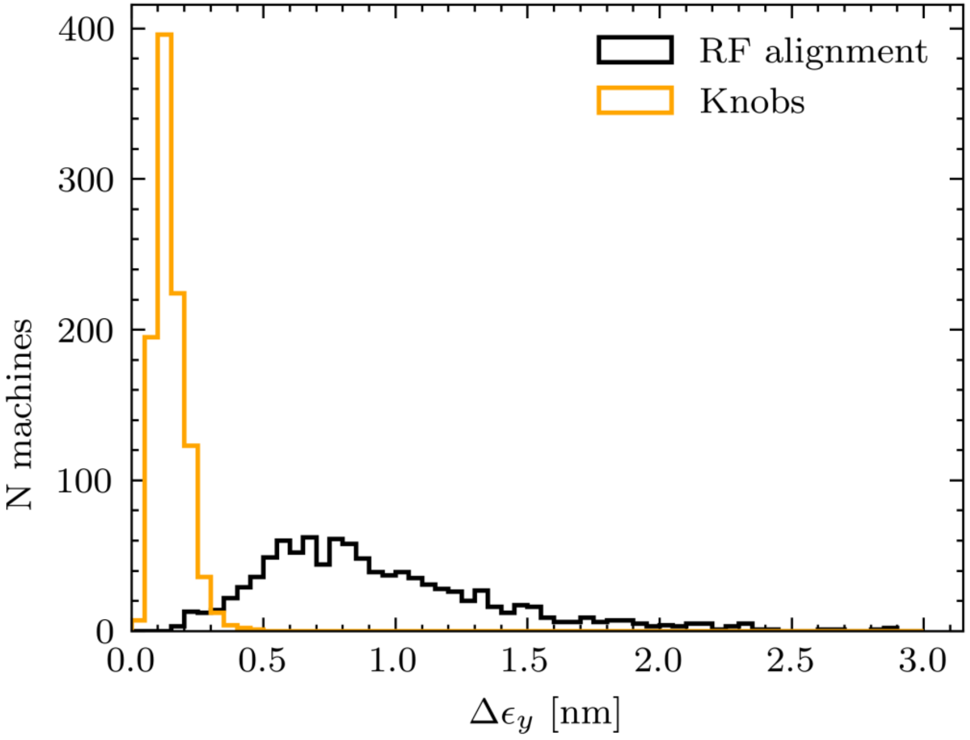
Knobs construction summary

Knob	Score	N_elements
Y1	0.96	12
Y2	0.96	15
Y3	0.97	10
Y4	0.95	9
Y5	0.97	13
Y6	0.96	23
Y7*	0.92	10
Y8*	0.96	19
Y9	0.96	19
Y10	0.96	25

The set is featured here: https://github.com/drozzoff/CLIC380_linac_knobs/tree/2024_03_07

Optimal knobs

Tuning performance



To check the performance of the knobs we simulate the BBA and knobs tuning for in PLACET for 1000 machines

The setup:

1. Distribute randomly the static imperfections after the prealignment.
2. Apply the BBA: 1-2-1 correction, DFS, and RF alignment
3. Scan each knob (Y1 – Y10).

Summary:

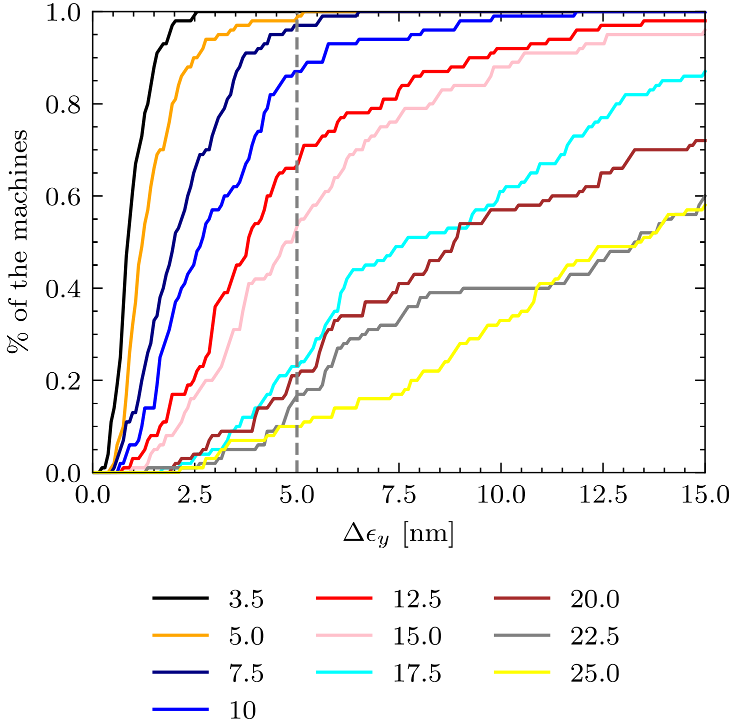
100% of the machines have emittance growth < 0.5 nm.

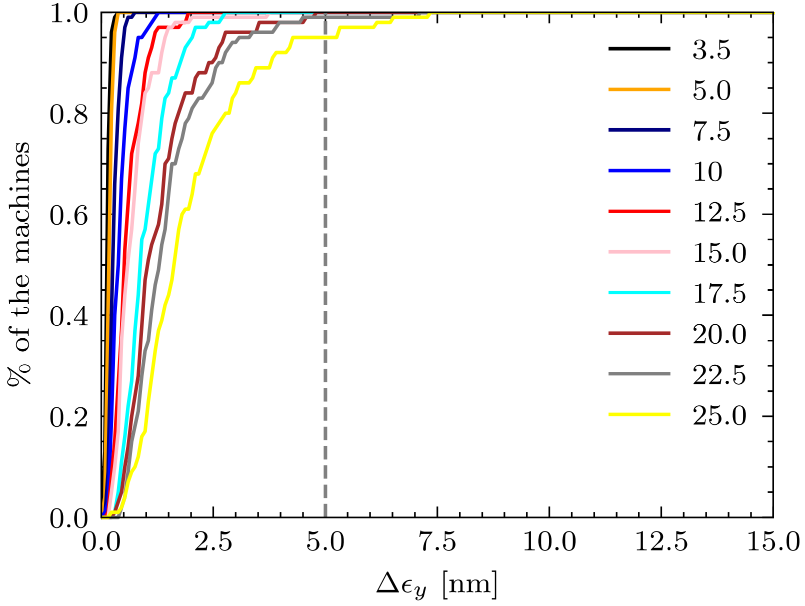
It is possible to squeeze in the budget for static errors down to < 1 nm or even 0.5 nm!

Emittance tuning knobs

Tuning performance

Performance of the knobs when the RF alignment is not perfect (accuracy > 3.5 μm)





The budget is not respected for **> ~7 μm**

All the machines respect the budget for **up to 25 μm.**

Summary

- With a set of emittance tuning knobs it is possible to reduce emittance growth down to < 0.5 nm and consequently increase the luminosity.

- Emittance tuning knobs provide additional margin for the emittance budget.

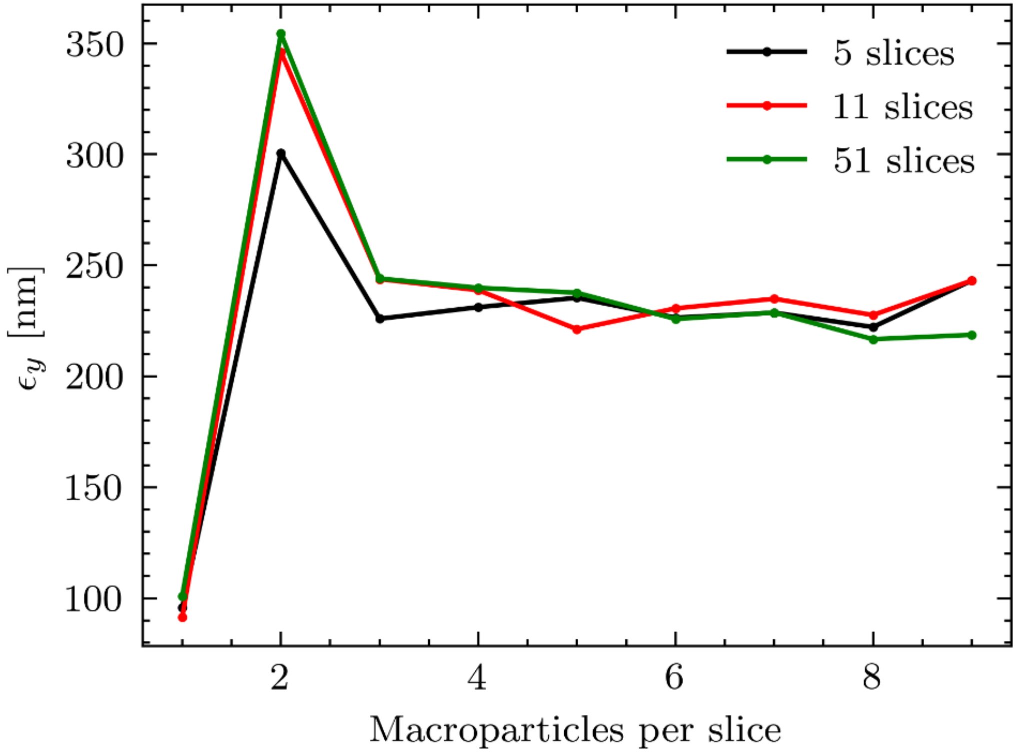
- Such a set of knobs can assist when the RF alignment is not perfect.

Thank you for your attention!

Back-up

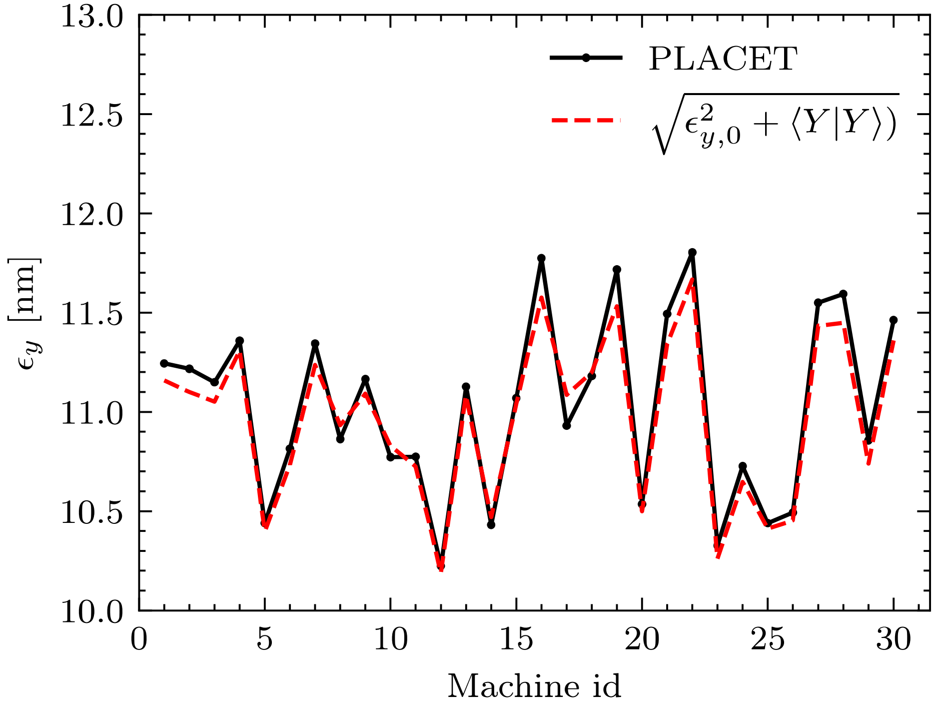
Macroparticle model of the beam

Beam emittance as a function of the number of slices and macroparticles.



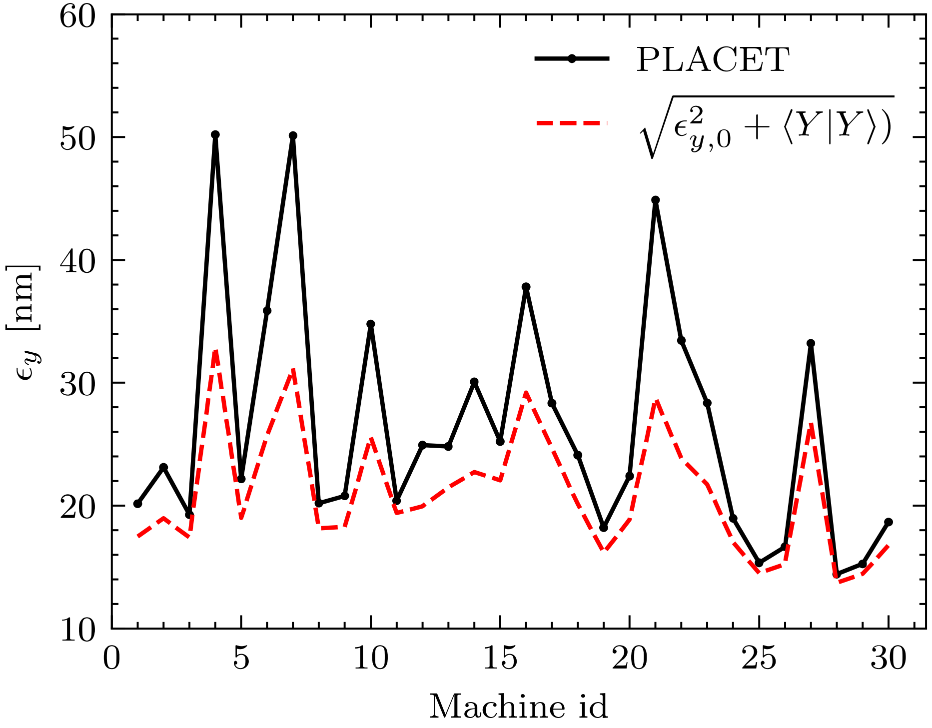
Application range of the emittance simplification

Emittance evaluated after the RF alignment



works well

Emittance evaluated after the DFS

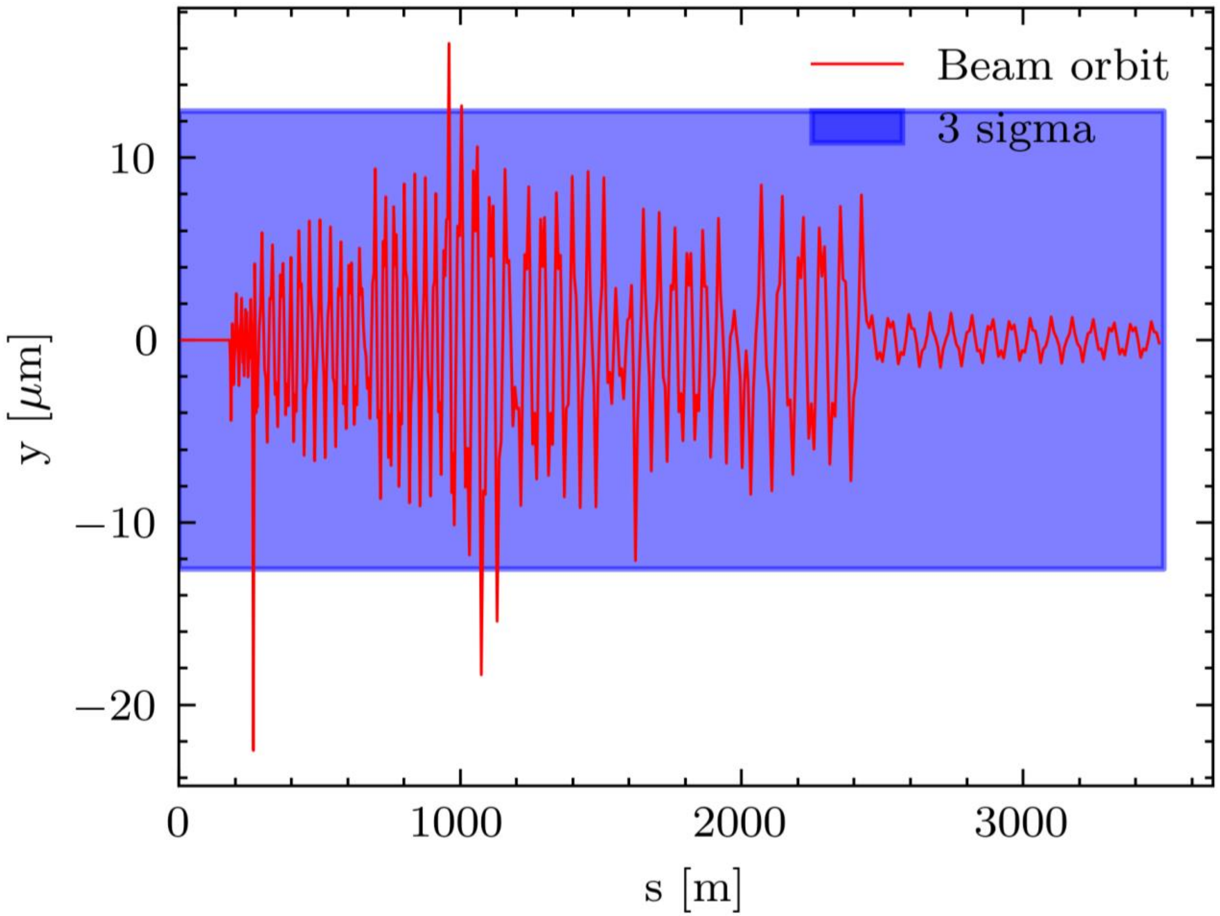


Underestimates the emittance

Optimal knob example

Knob Y6

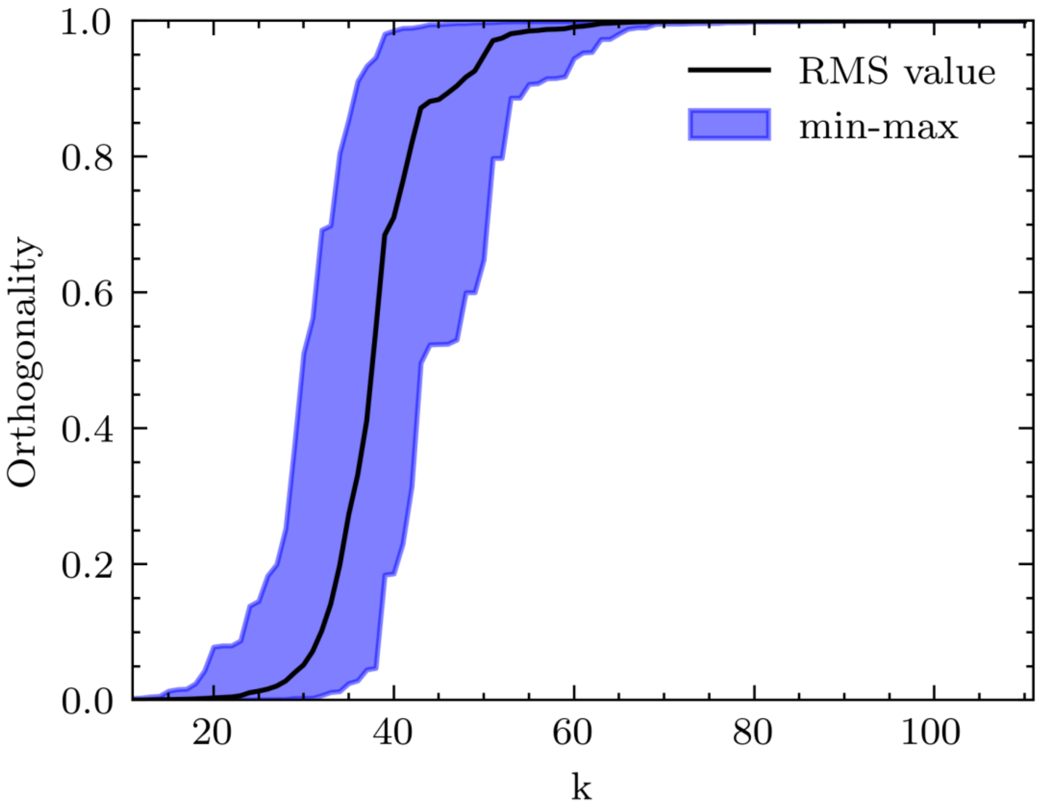
Quads offsets [μm]
13.5
4.3
-1.0
1.1
15.5
3.7
3.1
-1.0
-1.0
10.5
-5.2
1.7



Principal directions

- To simplify the analysis I limit the number of principal directions, skipping those that do not contribute to the score.

- In the knobs constructions, 70 principal directions were used instead of 110.



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