Design of main linac emittance tuning bumps

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Motivation

- Remaining misalignments after prealignment cause unacceptable emittance growth.
- Beam-based alignment (one-to-one correction, Dispersion Free Steering) not sufficient to achieve acceptable emittance growth.
- Emittance tuning bumps have to be used to reduce the remaining emittance growth.
- Potential problems of tuning bumps include: slow convergence, need for large structure displacements, and finite mover stepsize.
- A general strategy for bump design has been developed.
- The new bumps are optimal in terms of emittance reduction capability and convergence speed, and can be chosen such that structure displacements are limited.

Prealignment and Beam-Based Alignment (BBA)

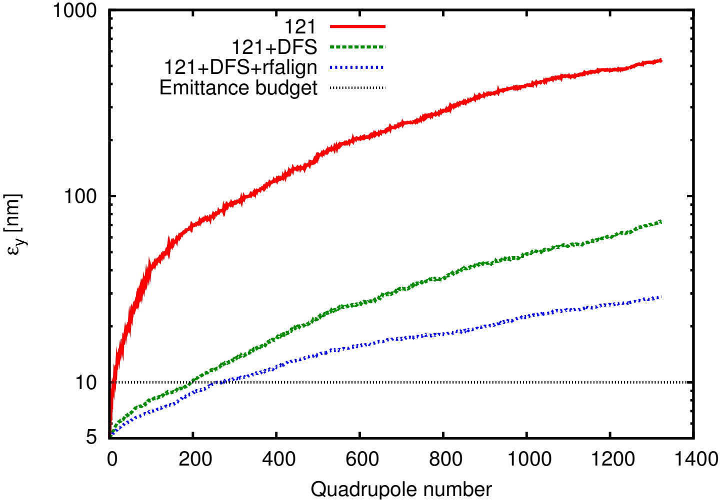
- Prealignment is assumed to be done with precision according to the CLIC yellow report.
- PLACET used to create 100 machines (seeds) with elements scattered according to a Gaussian distribution.
- Then one-to-one correction and Dispersion Free Steering is used for further alignment.
- Finally structures are aligned to the beam (with a finite precision.)

Element	σ
Quads	50 μm
Acc. struct.	10 μm
Acc. struct. realign.	10 μm
Acc. struct. vert. angle	10 μ
Bpms	10 μm
Bpm res.	0.1 μm
Bpm scale error	10%

Beam-Based Alignment Performance

Using 121, DFS and aligning structures

- After BBA emittance is 28.8 nm, still far above the target of 10 nm.

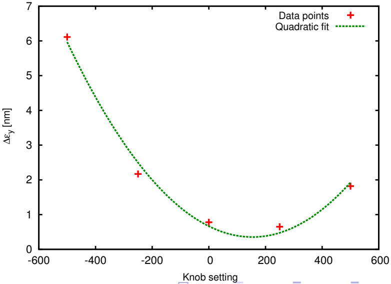


Emittance Tuning Bumps

General Description

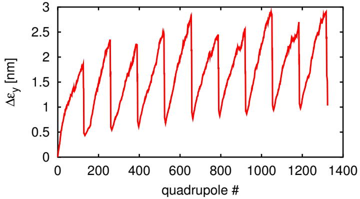
- Consist of tuning knobs and emittance measurement station.
- Each knob controls the vertical displacements of a number of accelerating structures. 121 steering assumed after knob change.
  - Optimal displacement patterns should be identified and assigned to the knobs.
- Structure displacements give rise to wakefields which cancel unwanted wakefields caused by misalignments remaining after BBA.
  - Wakefield-induced emittance growth is the main source of emittance growth after BBA.

- Tuning carried out by testing a few knob settings and finding optimum by a quadratic fit to the obtained emittance readings.
- Knobs are tuned one by one. Procedure may have to be iterated.



Emittance Tuning Bumps

Local vs global



Local bumps

- Each knob controls the displacements of a pair of structures. Emittance in station close to structures measured.

\+ No iterations needed if one knob after the other (from the beginning to the end) is tuned.

\- Local emittance minima do not guarantee minimised emittance at the end of the linac.

Global bumps

- Emittance measured at the end of the linac. Each knob may control a large number of structures.

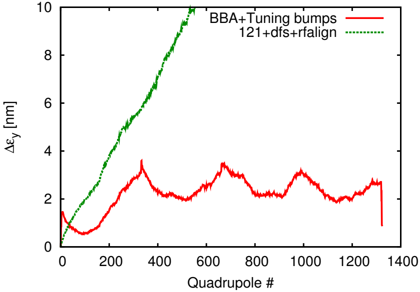
\+ More powerful than local measurements since the most relevant value is measured.

\- More complex since knobs in general are dependent and the iteratations of the tuning procedure may be required.

Basic Global Tuning Bumps

Performance

- 10 knobs each controlling vertical displacements of a pair of structures.
- The structures of a pair are positioned after 2 consecutive focusing quadrupoles. Pairs are equidistant in terms of number of quadrupoles.

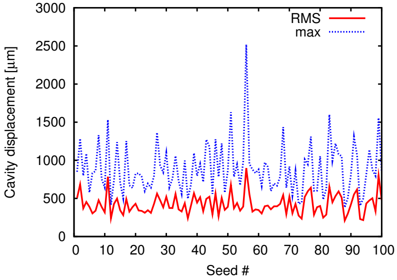


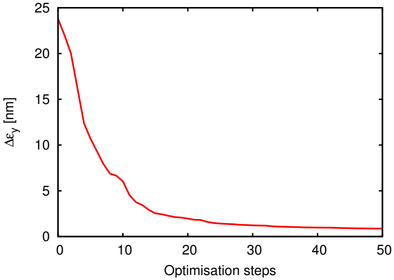
- Using these 10 knobs the emittance growth can be reduced to acceptable levels ($\Delta\epsilon_y \approx 0.9$nm).
- Final emittance growth of these 10 structures is slightly lower than for the 20 structures and local emittance measurements.

Basic Global Tuning Bumps

Problems

- Unacceptably large structure displacements required (same problem for local tuning bumps).
- Convergence problem: many iterations needed to reach minimum (dependent knobs). Not a big problem when only 10 knobs are used.

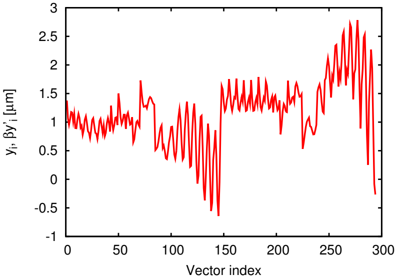


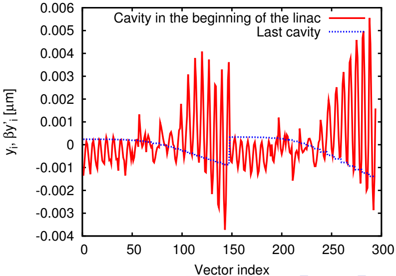


Bump Design Strategy

Notation

- For a given machine (after BBA) the beam (represented by p macroparticles) at the end of the linac can be represented by a vector
$$\tilde{\mathbf{s}}_i = (y_{1,i}, y_{2,i}, \ldots, y_{p,i}, y'_{1,i}, y'_{2,i}, \ldots, y'_{p,i})^T. \tag{1}$$
- Assuming that particle positions and angles are linear in the knob adjustments (true for eg. acc. struture or quadrupole displacements), each knob can be represented by
$$\tilde{\mathbf{k}}_j = (\Delta y_{1,j}, \ldots, \Delta y_{p,j}, \Delta y'_{1,j}, \ldots, \Delta y'_{p,j})^T. \tag{2}$$





Bump Design Strategy

Coordinate normalization

Emittance of macro-particle beam:

$$\begin{aligned}\epsilon &= [(\sum_k w_k(y_k-\bar{y})^2+\bar{\sigma}_{yy})(\sum_k w_k(y'_k-\bar{y}')^2+\bar{\sigma}_{y'y'})- \\ &- (\sum_k w_k(y_k-\bar{y})(y'_k-\bar{y}')+\bar{\sigma}_{yy'})^2]^{1/2} \qquad (3)\end{aligned}$$

Taylor expansion ⇒ second order approximation:

$$\Delta\epsilon = \epsilon-\epsilon_0 \approx \frac{1}{2}\tilde{\mathbf{y}}^T\mathbf{H}\tilde{\mathbf{y}}, \qquad (4)$$

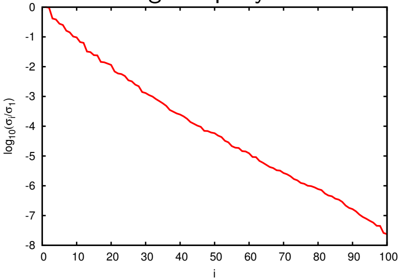
H is a function of Twiss parameters and the ideal beam distribution at the end of the linac. Eigenvalue decomposition of **H** ⇒ coordinate normalization):

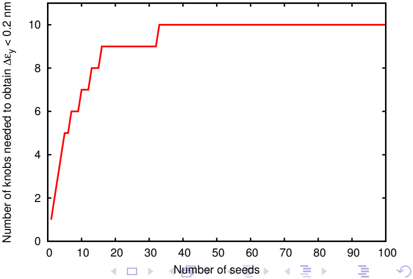
$$\begin{aligned}\Delta\epsilon &\approx \frac{1}{2}\tilde{\mathbf{y}}^T\mathbf{Q}\mathbf{D}\mathbf{Q}^T\tilde{\mathbf{y}} = \\ &= \left(\frac{1}{\sqrt{2}}\mathbf{D}^{1/2}\mathbf{Q}^T\tilde{\mathbf{y}}\right)^T\left(\frac{1}{\sqrt{2}}\mathbf{D}^{1/2}\mathbf{Q}^T\tilde{\mathbf{y}}\right) = \\ &= (\mathbf{M}\tilde{\mathbf{y}})^T\mathbf{M}\tilde{\mathbf{y}} = \mathbf{y}^T\mathbf{y} = |\mathbf{y}|^2. \qquad (5)\end{aligned}$$

Bump Design Strategy

Principal directions

- If a large number of random machines (aligned with BBA) are studied it turns out that a few directions in normalized space are particularly important.
- These principal directions are identified by singular value decomposition.
- Square of singular value is proportional to the emittance reduction along corresponding vector (direction). Singular values of normalized seed matrix $\mathbf{S} = (\mathbf{s}_1, \mathbf{s}_2, \ldots, \mathbf{s}_n)$ decrease rapidly.
- Consequently, the number of knobs required to obtain $\Delta\epsilon_y < 0.2$ nm converges rapidly for an increasing number of seeds.

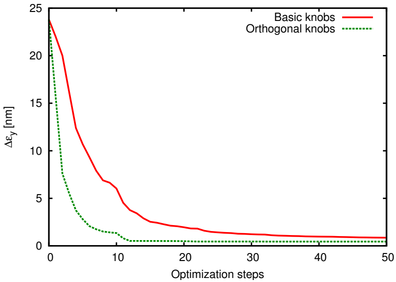


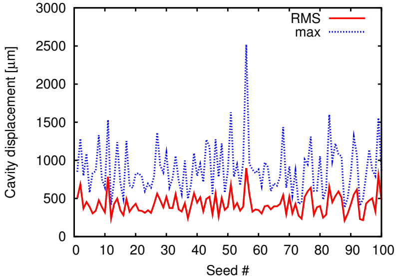


Bump Design Strategy

Knob Construction

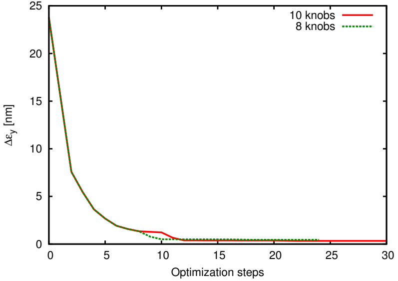
- By constructing the principal directions as linear combinations of the existing knob vectors, optimal knobs are obtained.
    - The obtained knobs are the ones with the greatest emittance reduction capability.
    - The knobs are also non-interfering (in the regime where the second order emittance approximation is accurate).
- Using the same ten structures as before, but with optimal knob design, performance is clearly improved. Convergence is excellent.
- Structure displacements are unacceptable.

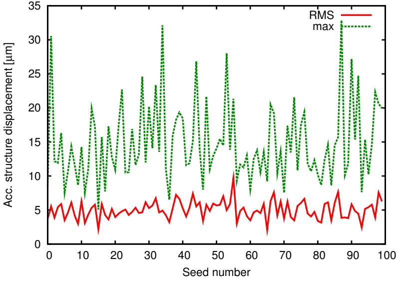




Performance of new bumps

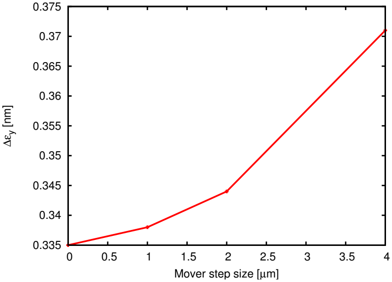
- Large number of accelerating structures has to be used to reduce the required displacements.
- As before linear combinations of the corresponding knob vectors are used to create new optimal knobs.
- By SVD of the knob matrix $\mathbf{K} = (\mathbf{k}_1, \mathbf{k}_2, \ldots, \mathbf{k}_m)$ the strongest directions of the old set of knobs is obtained. Using only the strongest directions, the required displacements may be kept at a minmimum (compare to solving $\mathbf{A}\mathbf{x} = \mathbf{b}$ using SVD and truncation of small singular values.)



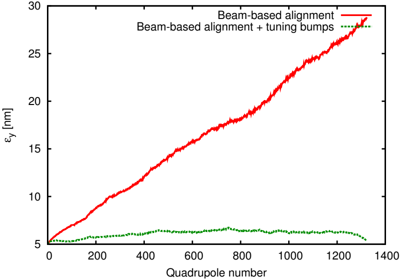


Performance of new bumps

- The new bumps are relatively tolerant to mover step size imperfections.



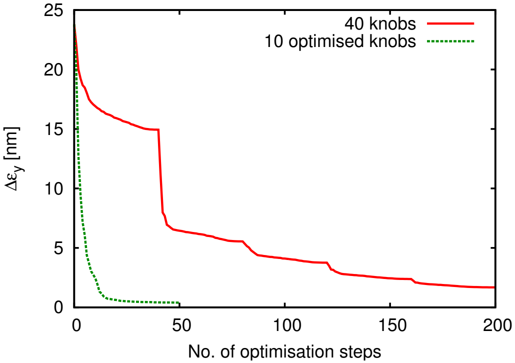
- A plot of emittance growth along the main linac shows that the bumps are very useful as a complement to BBA.



Performance of new bumps

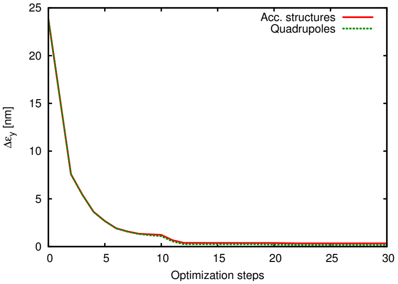
A more extreme example

- If 40 structures each controlled by its own knob for some reason would be used for tuning the convergence would be terrible.
- New optimal knobs may be constructed using the method already outlined. The ten best directions are identified and new knobs constructed.
- Convergence is improved a lot.



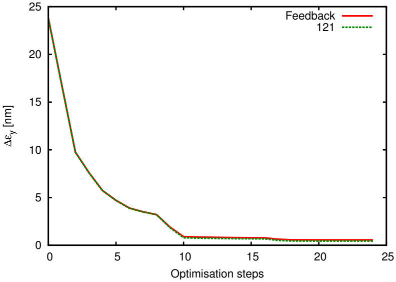
Knobs based on quadrupole displacements

- 10 knobs controlling vertical displacements of all focusing quadrupoles of the CLIC main linac.
- Result is nearly identical to that of accelerating structures.
- However, these bumps are very sensitive to mover step size.
  - Step size of 0.1 nm ⇒ bumps are of no use.
  - Only the 20 most important quads controlled by ten knobs $\Rightarrow \Delta\epsilon_y = 6.6$ nm for 0.1 nm step size (0.55 nm for ideal movers).
  - Only the 20 most important quads controlled by five knobs $\Rightarrow \Delta\epsilon_y = 4.6$ nm for 0.1 nm step size (2.0 nm for ideal movers).



Dynamic imperfections

- Simulations described so far assumed that tuning bumps were used on static misaligned machines and that the beam was resteered using 121 steering after each knob change.
- 121 steering would be slow and instead the feedback correctors are assumed to steer the beam back based on expected change due to knob change. Eight knobs ⇒ 0.56 nm emittance growth (0.45 nm in case of 121 steering) if the dynamic effects are neglected.

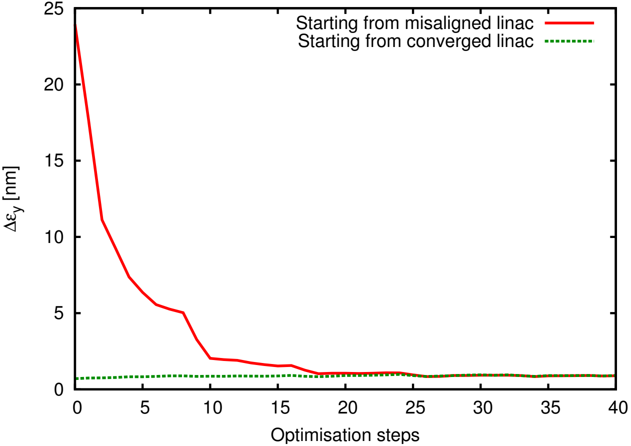


Dynamic imperfections

- In reality many dynamic effects influence performance. Recently the effect of the following imperfections have been included in the tuning bumps simulations:
  - ATL Ground motion ($A = 0.5 \cdot 10^{-6} \mu\text{m}^2/\text{s}/\text{m}$), trajectory feedback system (gain=0.05, $\sigma_{BPM} = 0.1\mu\text{m}$), quadrupole jitter (1 nm), acc. structure jitter (1 nm), beam jitter (0.1 μm)
  - In addition it was assumed that the structure movers had a limited speed of $1\mu\text{m/s}$ and (rather arbitrarily)that emittance could be measured with a precision of 10%.
- The direct effect of the imperfections (on emittance growth) was determined (theoretically and via simulations). This effect was seen to be stronger than the indirect emittance growth caused by the tuning bumps themselves in a dynamic environment.
- Total emittance growth after bump tuning while taking the dynamical imperfections into account was ≈1 nm. Initial tests with two-dimensional power spectrum ground motion model give ≈2 nm

Dynamic imperfections

Result



Summary

- A strategy for design of tuning knobs has been developed
    - New knobs have optimal emittance reduction capabililty
    - and are optimal in terms of convergence speed.
- For static misaligned machines ten knobs could be designed based on accelerating structure or quadrupole displacements.
    - Quadrupole version very sensitive to limited mover step size.
- The ten acc. structure knobs reduce emittance growth to very low levels (0.34 nm) and converge almost instantly. They were designed such that acceptable displacements could be used and were shown to have good tolerance to mover step size.
- Taking dynamic imperfections into account the performance is worse, but still seems acceptable (≈1 nm).