CLIC Tuning Bump Strategies

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Outline

- Introduction
  - Motivation
  - Prealignment and BBA
  - BBA performance
- Emittance Tuning Bumps
  - General description
  - Performance
  - Potential problems
- Tuning Bump Convergence
  - Linear knobs
  - SVD
- Orthogonal knobs
  - Construction
  - Performance
- Conclusions
- (ILC)

Motivation

- In CLIC remaining misalignments after prealignment cause unacceptable emittance growth.
- Beam-based alignment methods such as one-to-one correction, Dispersion Free Steering and Ballistic Alignment are not enough to achieve acceptable emittance growth.
- Emittance tuning bumps have to be used to reduce the remaining emittance growth
- Potential problems for the CLIC bump implementation include: finite mover stepsize, crosstalk between bumps and limited range for structure displacements.
- A general method for bump implementation has been developed.
- A fast routine for bump tuning has been implemented.

Prealignment and Beam-Based Alignment

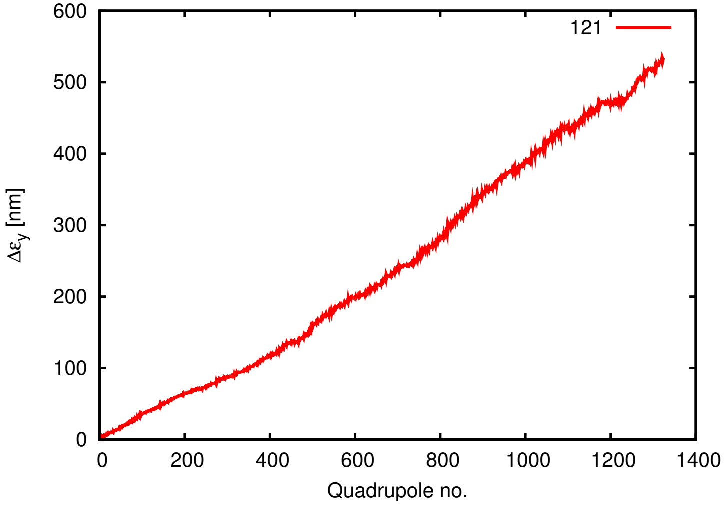
- Prealignment is assumed to be done with precision according to the CLIC yellow report.
- PLACET used to create 100 machines (seeds) with elements scattered according to a Gaussian distribution.
- Then one-to-one correction and Dispersion Free Steering is used for further alignment.
- Finally structures 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 only 121 correction

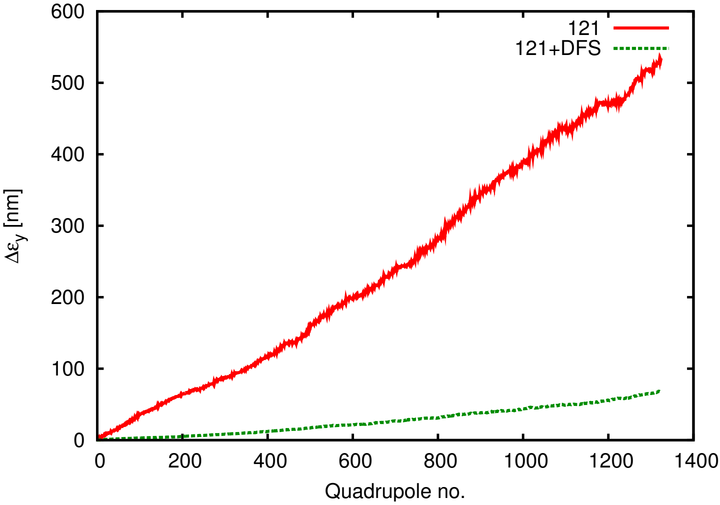
- Far above the emittance growth target of 5nm.



Beam-based Alignment Performance

Using 121 and DFS

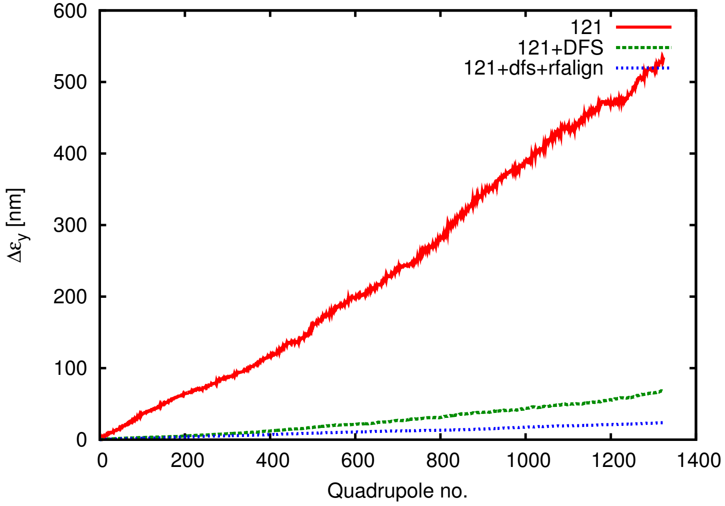
- Better, but far from 5nm.



Beam-based alignment performance

Using 121, DFS and aligning structures

- Even better. At the end of the linac emittance growth is 23.8nm.



Emittance Tuning Bumps

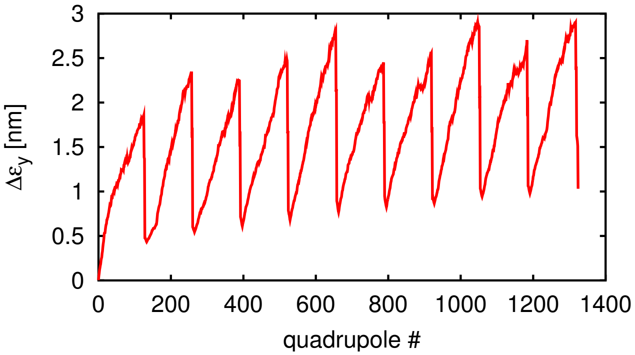
General Description

- Consist of tuning knobs and measurement station.
- The term tuning knob is quite general. In this case a knob corresponds to displacement of one or several structures or quads.
- For CLIC main contribution to remaining emittance growth after beam-based alignment is wakefields from misaligned structures.
- The idea is to use vertical structure displacements to give rise to wakefield kicks that cancel the unwanted wakefield kicks.

Emittance Tuning Bumps

Measurement station 1

- Previous studies used local emittance measurements.
  - Each knob corresponded to a displacement of one single structure.
  - No iterations are needed if one knob after the other (from the beginning to the end) is corrected.
  - Problem is that local emittance minima do not guarantee minimised emittance at the end of the linac.



Emittance Tuning Bumps

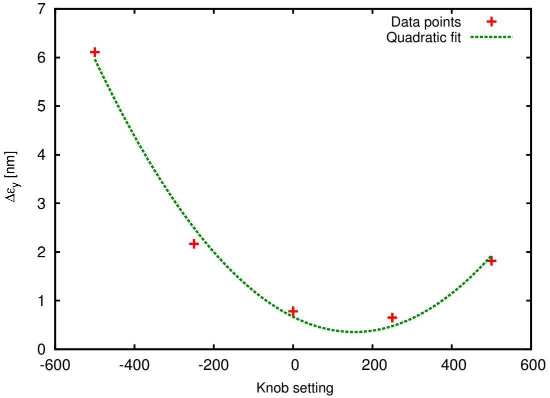
Measurement station 2

- In this case the measurement station measures emittance at the end of the linac.
  - More powerful than local measurements since the most relevant value is measured.
  - More complex since knobs in general become dependent and the crosstalk makes it necessary to iterate the tuning procedure.
- Simulations with promising results have also been carried out where two laserwires separated by a phase advance of 90° were used to get a tuning signal. The laserwires were assumed to have gaussian transverse profile of the same size as a perfect target beam, thereby measuring the profile of the studied beam weighted with a gaussian distribution representing the target beam size.
  - See for example: P. Eliasson, D. Schulte, "Luminosity Tuning Bumps in the CLIC Main Linac", EUROTeV-Report-2005-007-1, 2005

Emittance Tuning Bumps

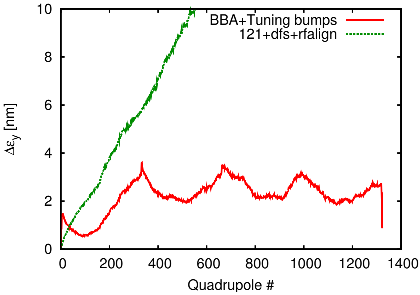
Optimisation procedure

- Knobs are tuned by testing different knob settings and recording the measurement station readings. Optimum knob setting is determined with a quadratic fit.
- All knobs are tuned one by one. This procedure in general has to be iterated.



Basic Tuning Bumps Performance

- 10 knobs each corresponding to a vertical displacement of one single structures.
- Structures are arranged in pairs (the structures of a pair being positioned after 2 consecutive focusing quadrupoles). Pairs are equidistant in terms of number of quadrupoles.

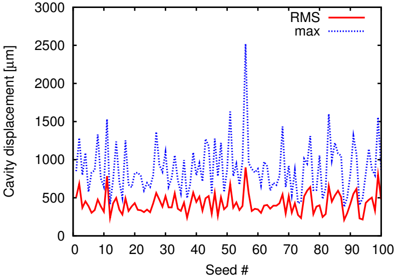


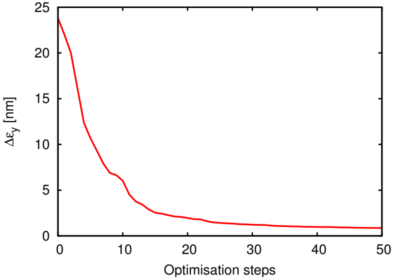
- Using these 10 knobs the emittance growth can be reduced to acceptable levels ($\Delta\epsilon_y \approx 0.9$nm).
- Observe that the final emittance growth these 10 structures is similar to using 20 structures and local emittance measurements.

Basic Tuning Bumps Performance

Potential problems 1

- Potential problems:
  - Unacceptably large structure displacements necessary.
  - Convergence: many iterations needed to reach minimum (due to “crosstalk” between the knobs). With only 10 knobs this is not a big problem.

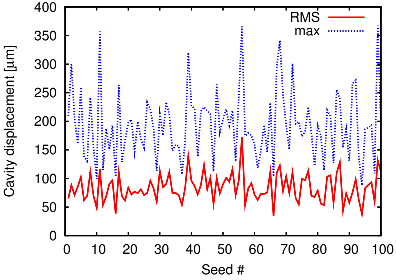


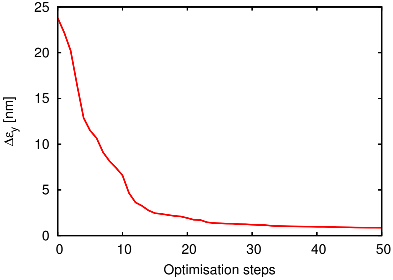


Basic Tuning Bumps Performance

Potential problems 2

- Potential problems:
  - The large structure displacements can be reduced by using more structures (40 in this case).
  - Each knob is now controlling a group of four structures all close to one focusing quadrupole.





Convergence and degrees of freedom

Vector representation 1

- Our system is linear as long as the knobs correspond to structure displacements.
- For a given seed the final beam after BBA can be represented by a vector

$$\mathbf{s}_i = (y_i^1, y_i^2, \ldots, y_i^p, \beta y_i^{'1}, \beta y_i^{'2}, \ldots, \beta y_i^{'p}) \quad (1)$$

- And each knob can be represented by

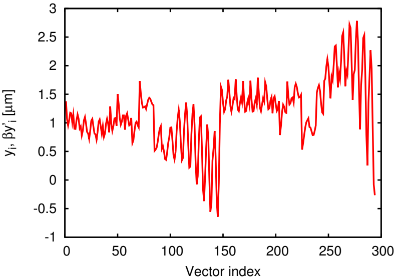
$$\mathbf{k}_i = (\Delta y_i^1, \Delta y_i^2, \ldots, \Delta y_i^p, \beta \Delta y_i^{'1}, \beta \Delta y_i^{'2}, \ldots, \beta \Delta y_i^{'p}) \quad (2)$$

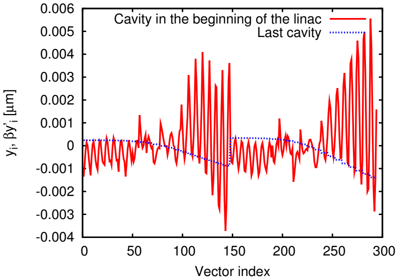
- In other words $\mathbf{s}_i$ contains the p particle positions and p particle angles at the end of the linac. Similarly $\mathbf{k}_i$ contains changes in particle positions and angles for a unit change of knob i.
  - We will as an example use the 662 knob vectors representing each structure immediately following a focusing quadrupole). We also produce 100 seeds corrected by BBA.
- In our case, vectors are 294-dimensional (the beams used during simulations consisted of $np = 147$ macroparticles.

Convergence and degrees of freedom

Vector representation 2

- The vectors can be depicted by 2D-plots. To the left $\mathbf{s}_1$. To the right $\mathbf{k}_{40}$ and $\mathbf{k}_{662}$





- To minimise the emittance we should try to turn the left plot into a straight line by using the knobs $\mathbf{k}_i$

Convergence and degrees of freedom

Vector representation 3

- The 100 seed vectors $\mathbf{s}_i$ span a subspace of the 294-dimensional space. If they are linearly independent this subspace is of dimension 100.
- The 662 knob vectors are of course not linearly independent
- If the knobvectors span the subspace of the 100 seed vectors, knob settings $\mathbf{x}_i$ exist such that

$$\mathbf{s}_i - \mathbf{K}\mathbf{x}_i = 0, \qquad \forall i \tag{3}$$

- where

$$\mathbf{K} = (\mathbf{k}^1, \mathbf{k}^2, \ldots, \mathbf{k}^{662}) \tag{4}$$

Singular Value Decomposition (SVD)

- The 100 seed vectors point in 100 independent directions. Only a few of these are of importance though.
- This can be shown in a number of ways. Easiest might be to study the singular values of the matrix

$$\mathbf{S} = (\mathbf{s}^1, \mathbf{s}^2, \ldots, \mathbf{s}^{100}) \tag{5}$$

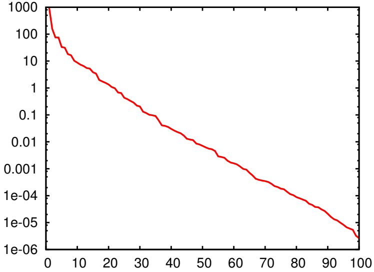
- The SVD algorithm decomposes the matrix $\mathbf{S}$ into the product

$$\mathbf{S} = \mathbf{U}_s \mathbf{W}_s \mathbf{V}_s^T \tag{6}$$

- Here $\mathbf{U}_s$ is an orthonormal matrix spanning the same space as $\mathbf{S}$. $\mathbf{W}_s$ is a diagonal matrix with the singular values (importance of directions) of $\mathbf{S}$ in decreasing order in the diagonal. $\mathbf{V}_s^T$ is a square orthonormal matrix

Singular Value Decomposition

- The singular values of $\mathbf{S}$ decrease rapidly.



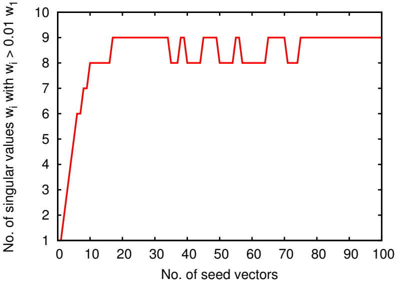
- If we truncate $\mathbf{W}_s$ by setting the n diagonal elements w_i for which $w_i < 0.01 w_1$ (or some other truncation limit) to $w_i = 0$ we obtain the matrix

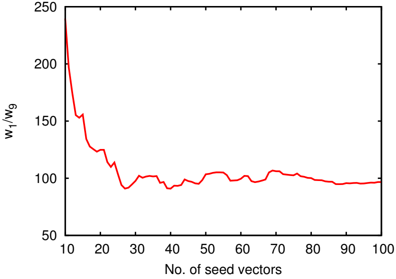
$$\tilde{\mathbf{S}} \approx \mathbf{U}_s \tilde{\mathbf{W}}_s \mathbf{V}_s^T \tag{7}$$

- $\tilde{\mathbf{S}}$ is a good approximation to $\mathbf{S}$. Consequently we can use n of the columns of $\mathbf{U}_s$ to span the same space as $\mathbf{S}$.

Singular Value Decomposition

- Even though the seed vectors span a 100-dimensional space, 9 knobs might be sufficient to correct all 100 machines (truncation limit=1%)
- It is unlikely that a larger set of machines would be more difficult to correct. The plots below show the development of singular values as one seed vector after the other is added.





Singular Value Decomposition

- SVD can also be used to study the knob vector space.

$$\mathbf{K} = \mathbf{U}_k \mathbf{W}_k \mathbf{V}_k^T \tag{8}$$

- where

$$\mathbf{K} = (\mathbf{k}^1, \mathbf{k}^2, \ldots, \mathbf{k}^{662}) \tag{9}$$

- The same arguments as before show that the 662 knob vectors only have 16 relevant directions (truncation limit $= 1\%$)

Orthogonal knobs

Construction

- Observe that $\mathbf{U}_k$ gives an orthonormal base for the knob vector space. In particular its first 16 columns span the 16-dimensional subspace mentioned above.
- Eq. 8 may be rewritten as

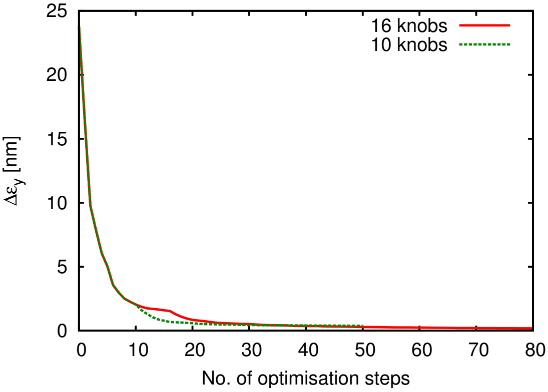
$$\mathbf{U}_k = \mathbf{K}\mathbf{V}\mathbf{W}_k^{-1} \tag{10}$$

- First 16 columns of $\mathbf{V}\mathbf{W}_k^{-1}$ describe the linear combinations of $\mathbf{K}$ which form an orthonormal base for the 16-dimensional subspace.
- We have thus managed to construct 16 orthogonal knobs, each corresponding to a pattern of displacements of all 662 structures. Do they work?

Orthogonal knobs

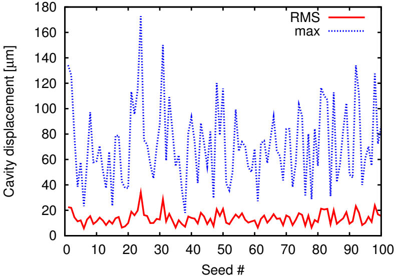
Performance

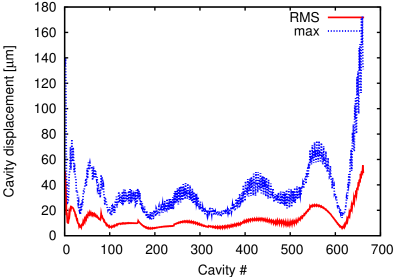
- Emittance redcution is excellent with 16 knobs
  - Faster convergence with 10, slightly worse final emittance.
- In principle 2 iterations enough
- What about structure displacements for optimum knob settings?



Structure displacements

- Structure displacements are not too far from being acceptable.

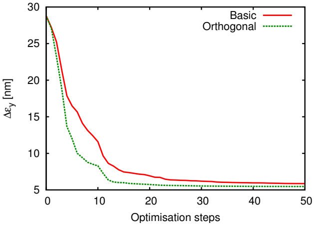


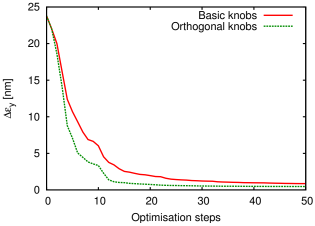


Orthogonal knobs

10, 40 structures

- As another example of the orthogonalisation of knobs we look at the 10 and 40 structures again. Fewer structures means:
  - Fewer movers. A limited number of structures could be put on special movers that are faster and more precise than the prealignment movers.
  - Larger displacements needed.
- Orthogonalisation of the knob vectors as before.
- In both cases a significant improvement of the convergence is obtained. To the left 40 structures, to the right 10.

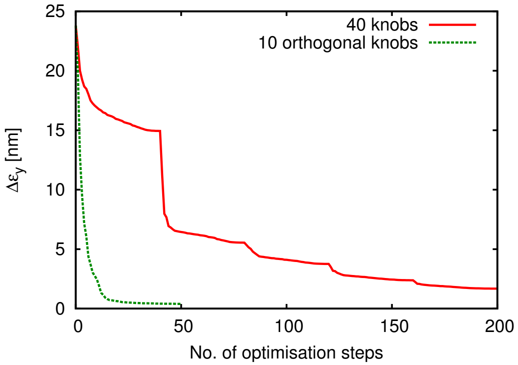




Orthogonal knobs

Another example

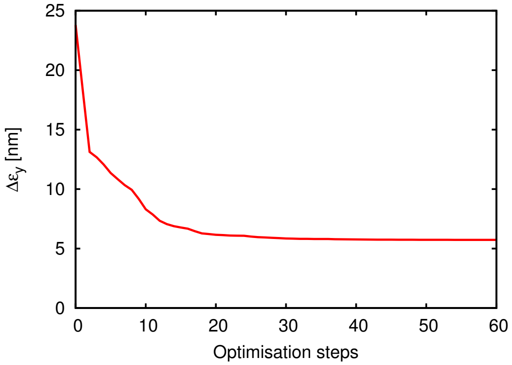
- If 40 structures each controlled by its own knob for some reason would be used for tuning the convergence would be terrible.
  - As we concluded earlier no more than 10-16 knobs makes sense.
- The SVD strategy can be used to reduce the number of knobs to 10 orthogonal ones.
- Convergence is improved a lot.



Orthogonal knobs

One last example

- 12 knobs constructed using all focusing quadrupoles in CLIC.
- Result is not as good as with accelerating structures.
  - Difficult to cancel wakefields without introducing dispersion with the quads.
- Besides mover sensitivity will be an issue, see two last slides.

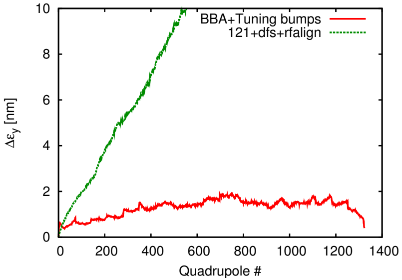


Comment on the "tracking" procedure

- Previous simulations of the bumps were relatively time consuming and . PLACET was used to track the beam through the whole line for every single knobsetting tested.
- Since I implemented a new PLACET routine which can be used for linear knobs the time consumption for a certain simulation was reduced from a few hours to a few minutes.
- The routine simply stores the seed vectors and calculates the knob vectors by normal PLACET tracking. When these vectors have been calculated no more tracking is needed until the quadratic fit routine has calculated the optimal knob settings.
- For a person who wants to study the effect of different BBA methods for CLIC the use of tuning bumps is of importance to get the final picture. A fast and easy way to simulate the tuning bumps is very important. The new routines also simplifies life a lot for someone who wants to study different tuning bump strategies.

Final comments on CLIC tuning bumps

- Already the 10 basic knobs gave very good emittance reduction.
  - 10 knobs might be just enough since the seed space had 9 degrees of freedom.
  - Very large structure displacements necessary though.
- With 40 structures in groups of 4 controlled by 10 orthogonal knobs, we got
  - Lower final emittance
  - Same convergence speed.
  - Reduced structure displacements.

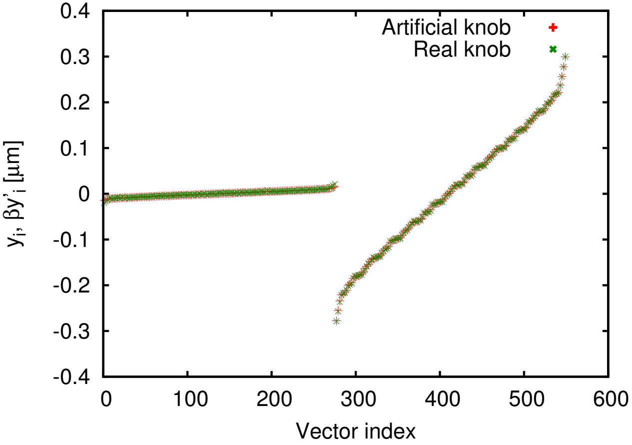


Some comments on ILC

- A few slides to show that this kind of treatment of the implementation of bumps is also very useful for ILC.
- With very similar methods as described earlier a set of quadrupoles (structures are not foreseen to be on movers) have been used to create knobs. Problem is that by moving a quadrupole both dispersion and wakefields are introduced.
- The knobs were constructed as linear combinations of the quadrupole knob vectors in such a way that they were identical to the knob vectors of structure displacements and also to the knob vectors of artificial dispersion bumps.
- The use of the artificial dispersion bumps and the bumps based on structure displacements had already been shown to be very efficient.

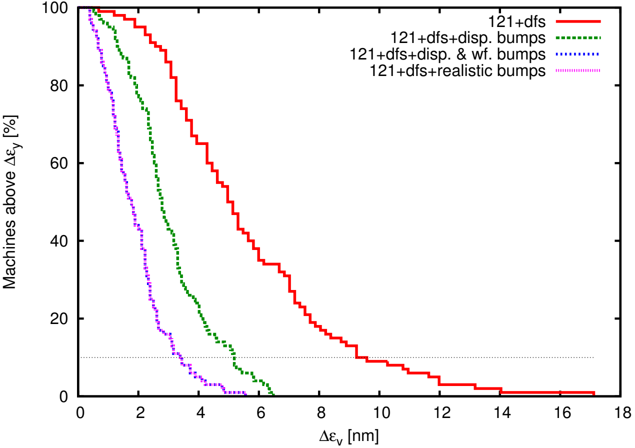
Some comments on ILC

- The right linear combination of quadrupole vectors has almost exactly the same effect on y_i and y_i' as an artificial dispersion bump positioned at the end of the linac.



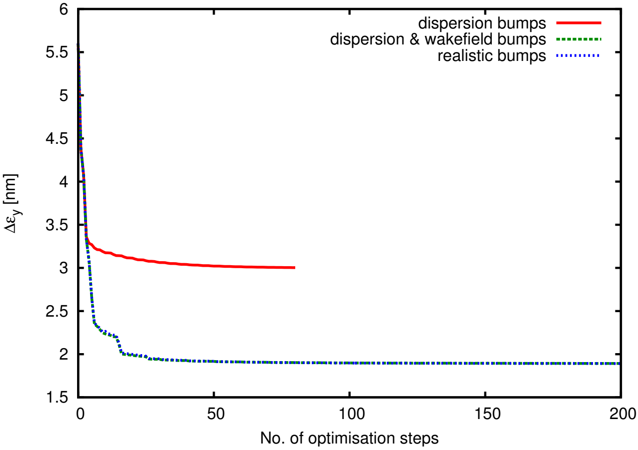
Emittance growth histogram

- The realistic bumps give almost exactly the same final emittance as the artificial ones. For ILC the target for emittance growth is maximum 10% of all machines above 10nm.



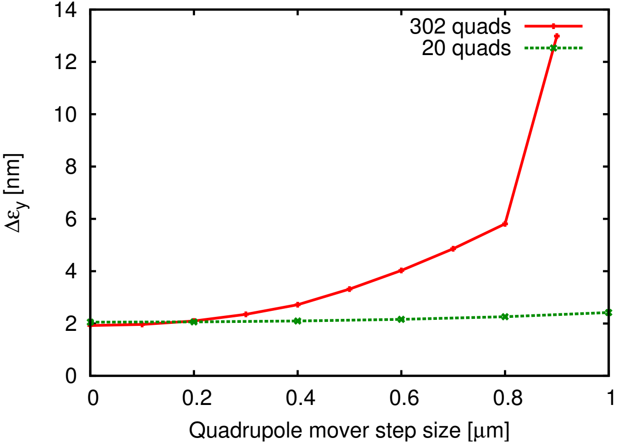
Tuning bumps convergence speed

- Emittance growth vs optimisation steps for the different bumps.



Some comments on ILC

- If all quadrupoles are used to construct knobs with the same effect as the artificial ones, the tuning gets sensitive to the mover step size. This problem is much less severe in case a few "good" quadrupoles are chosen.



Some more comments on ILC

- The step size problem is similar to what is experienced when quadrupoles are used as feedback correctors.
  - In that case the MICADO algorithm is used to choose the "optimal" subset of quads. These quads perform as well as all together, but the system becomes less sensitive to mover step size.
- A few different approaches to find a subset of quads for the bumps have been tested
  - "MICADO": The single quad that does the job best is chosen and moved to its optimal position. Then one by one quad that best optimises the problem is chosen in the same way.
  - Reoptimised "MICADO": Similar, but when each new quad is being tested both this quad and the previously chosen are optimised.
  - LA solution: The quad vector with the longest projection on the seed or knob space is chosen and then one by one quad orthogonal to the previous ones is selected in the same way.
- Especially the second approach was efficient and clearly improved the results compared to using equidistant quads.