Improved imperfection tolerances for an on-line dispersion free steering algorithm

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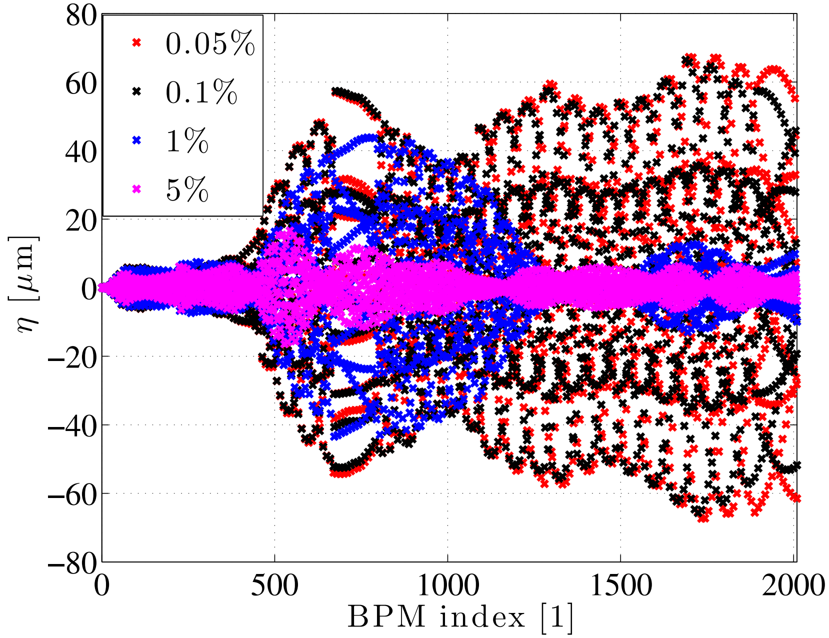

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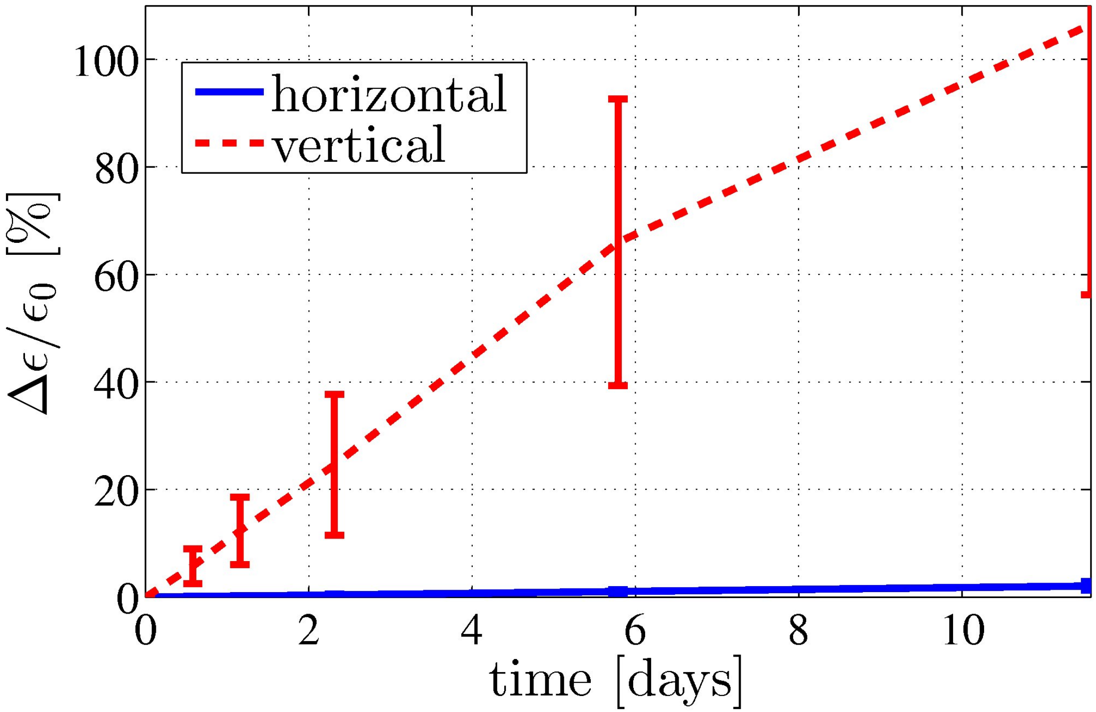
1. Introduction

Long-term ground motion in the CLIC ML



- Start from perfectly aligned machine
- ATL motion and 1-2-1 correction applied
- ε_x = 600nm
  ε_y = 10nm
- 10 samples
- Emittance growth can be corrected with the DFS algorithm.

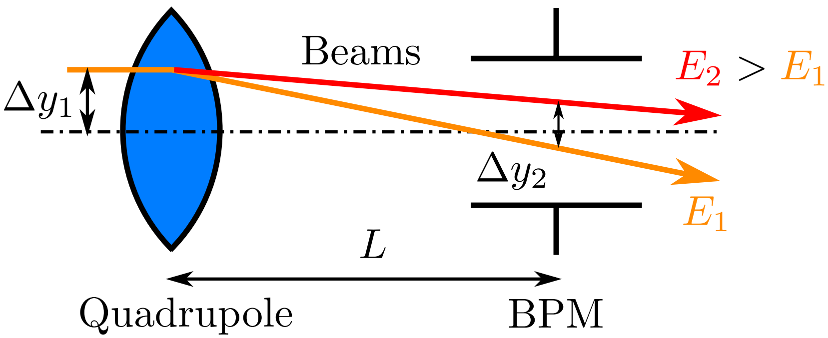
A = 0.5^{-6} $um^2/m/s$

A = 10^{-5} $um^2/m/s$

0h 7h 14h

Dispersion-free steering (DFS)

- Principle:
  1. The dispersion $\boldsymbol{\eta}$ at the BPMs is measured by varying the beam energy.
  2. Corrector actuations Δy_1 are calculated to minimise dispersion $\boldsymbol{\eta}$ and the beam orbit $\boldsymbol{b}$.



- Considering many BPMs and quadrupoles leads to linear system of equations:

$$\begin{bmatrix} \boldsymbol{b} - \boldsymbol{b}_0 \\ \omega(\boldsymbol{\eta} - \boldsymbol{\eta}_0) \\ \boldsymbol{0} \end{bmatrix} = \begin{bmatrix} \boldsymbol{R} \\ \omega \boldsymbol{D} \\ \beta \boldsymbol{I} \end{bmatrix} \Delta y_1$$

- DFS is usually applied to overlapping sections of the accelerator (36 for ML of CLIC).

On-line DFS

- **Problem:** only very small beam energy variation acceptable (< 1 per mil).
- Measurement are strongly influenced by BPM noise and usual energy jitter.
- Therefore, many measurement have to be averaged.
- Use of a Least Squares estimate (pseudo-inverse), which can be significantly simplified by the choice of the excitation:

$$\eta_N = (\boldsymbol{E}^T \boldsymbol{E})^{-1} \boldsymbol{E} \boldsymbol{b} = \frac{T_N}{N \Delta E}$$

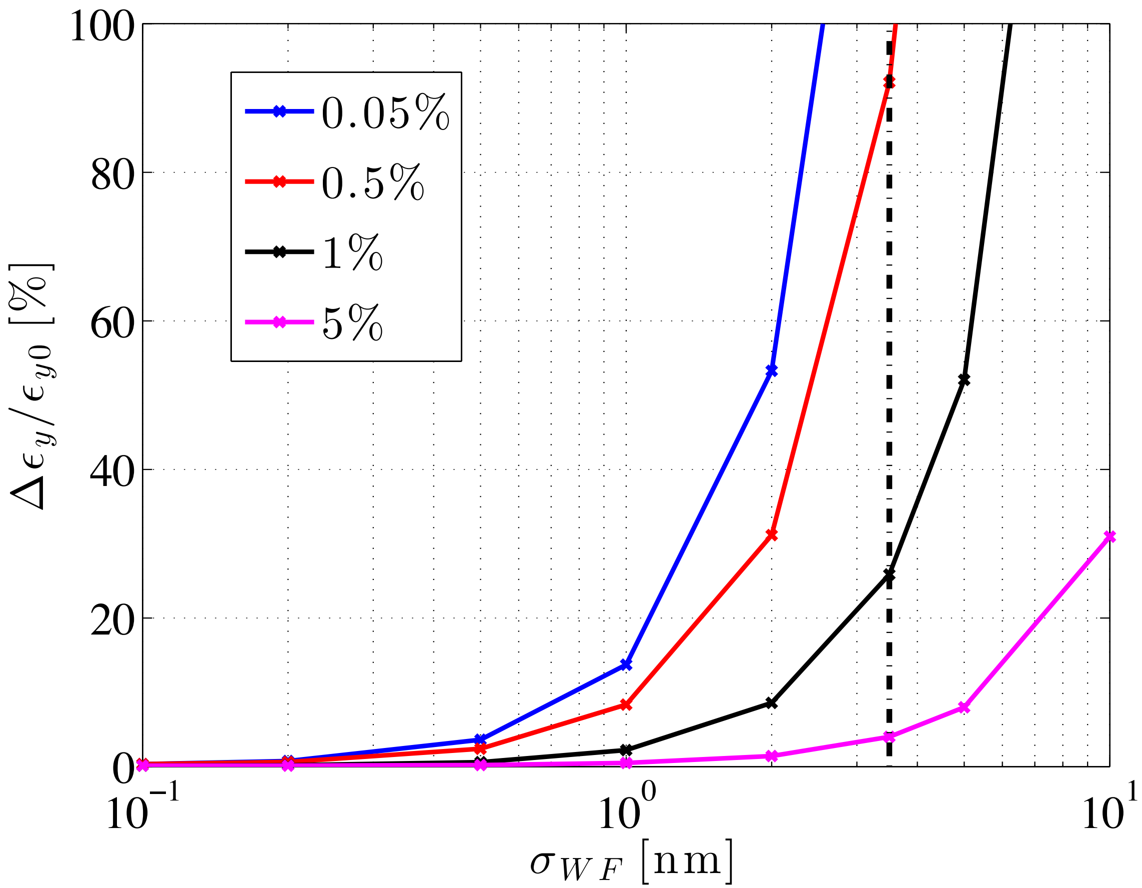
$$\boldsymbol{E} = \begin{bmatrix} -\Delta E \\ +\Delta E \\ \dots \\ -\Delta E \\ +\Delta E \end{bmatrix} \qquad T_N = \sum_{i=1}^{N} (-1)^i b_i$$

Prior results

- On-line DFS showed excellent correction results with respect to ground motion misalignments (ATL motion):
  - Correction to below 10% emittance growth
  - Necessary time about 10 min.
- Also the following imperfections were tested and caused not problems:
  - BPM noise.
  - Coherent and incoherent energy jitter of the acceleration gradients.
  - Different errors in the correction matrices:
    - BPM noise.
    - Energy errors.
  - Linearity errors of BPMs.
  - Quadrupole movers breakdown.
- The algorithm was however too sensitive with respect to two imperfections:
  - Resolution of wakefield monitors.
  - Tilt of accelerating structures.

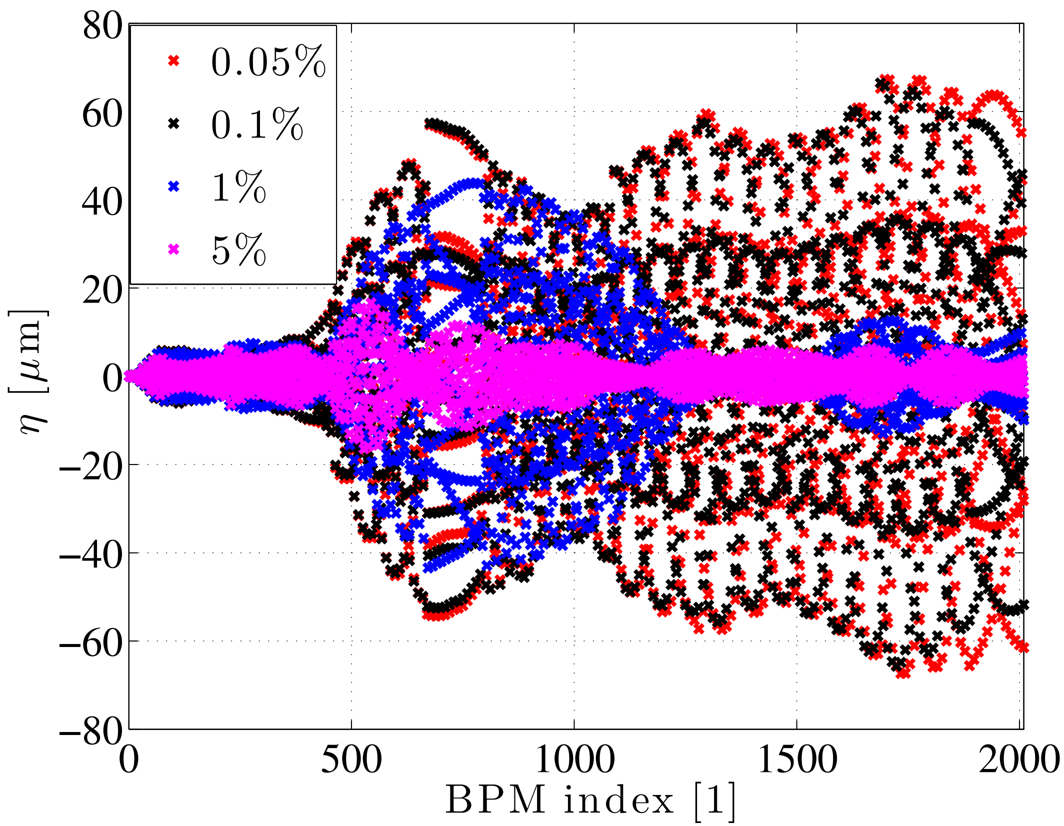
2. Resolution of the wakefield monitors

High sensitivity to remaining wakefields after RF alignment



- Only large energy changes for the dispersion measurement are acceptable.
- For the target energy change of 0.05% the correction performance is unacceptable.

Measured dispersion with only RF alignment.



- No quadrupole misalignment.
- No wakefield produced from head motion (no head motion).
- Only wakefield from structure misalignment (random fashion).
- Tail motion creates average beam offset.
- Offset change is linear with energy change for small ΔE.
- For larger ΔE, effect becomes does not grow and dispersion signature becomes smaller.

Explanation of the effect (2 particle model)

- Motion of head particle (for last experiment on last slide):

$$x_H = 0$$

- Equation of motion for tail particle with reference energy E_0:

$$\frac{\mathrm{d}^2 y_{T,E_0}(s)}{\mathrm{d}s^2} = \frac{eE_y - eB_x}{E_0} = \frac{e^2 N_0 W_t y_{st}(s) - ecg(s) y_{T,E_0}(s)}{E_0}$$

- Equation of motion for tail particle with increased energy $E_0 + \Delta E$:

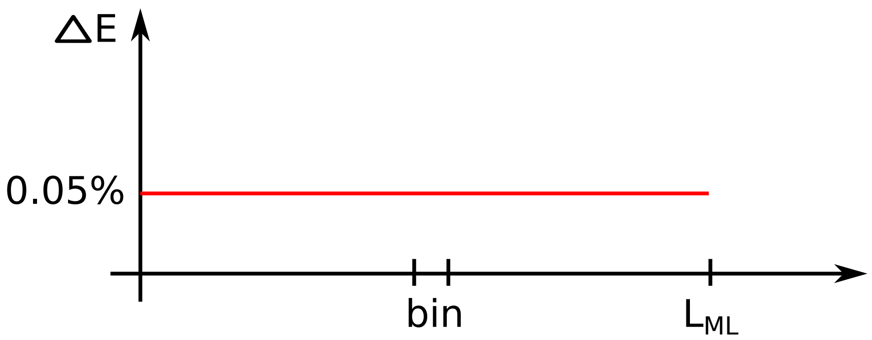
$$\frac{\mathrm{d}^2 y_{T,E_0+\Delta E}(s)}{\mathrm{d}s^2} = \frac{eE_y - eB_x}{E_0 + \Delta E} = \frac{e^2 N_0 W_t y_{st}(s) - ecg(s) y_{T,E_0+\Delta E}(s)}{E_0 + \Delta E}$$

- These equations are clearly different. The tails of the bunches will form differently for different beam energies.
- Since the energy difference is small the differences for only after a certain distance (see last slide).

  - From Newton's law and Lorentz force
  - Ultra-relativistic approximation

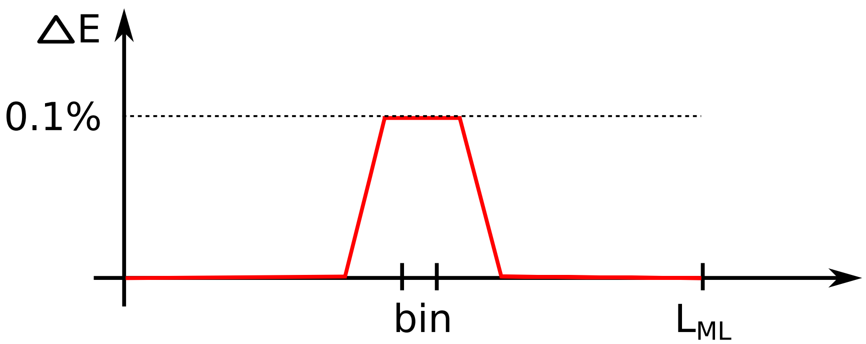
Solution with local energy change

1. Global energy change:



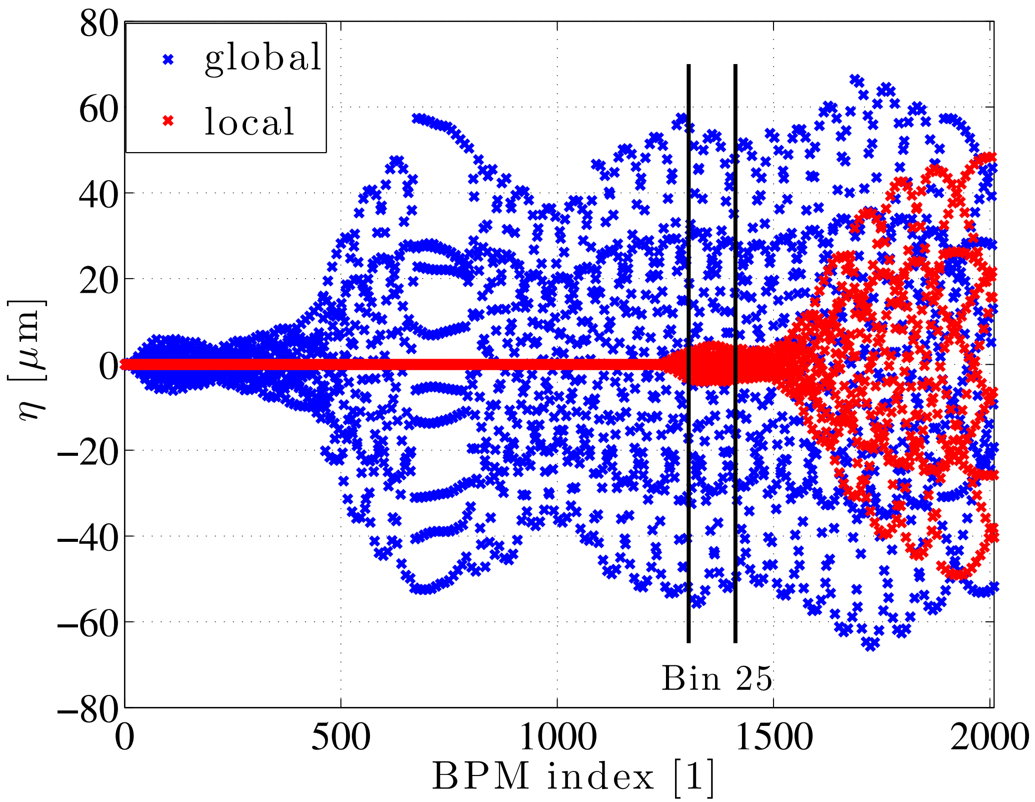
- Simple, since all acceleration gradients are changed equally

2. Local energy change:

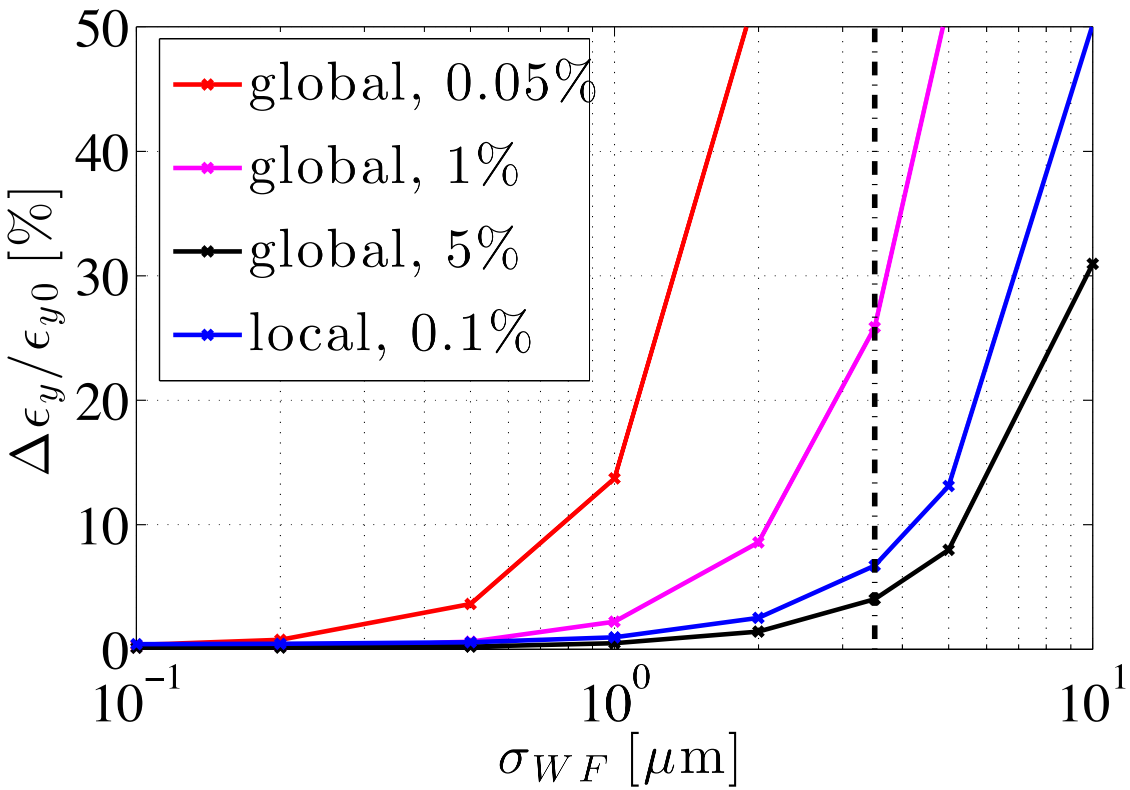


- Change of only the gradients in the decelerators before, at and after the bin to correct
- Beam travels only over a short distance with different energies
- Remove ΔE after corrected bin
- A higher ΔE can be used

Measured dispersion with only RF alignment and local energy changing



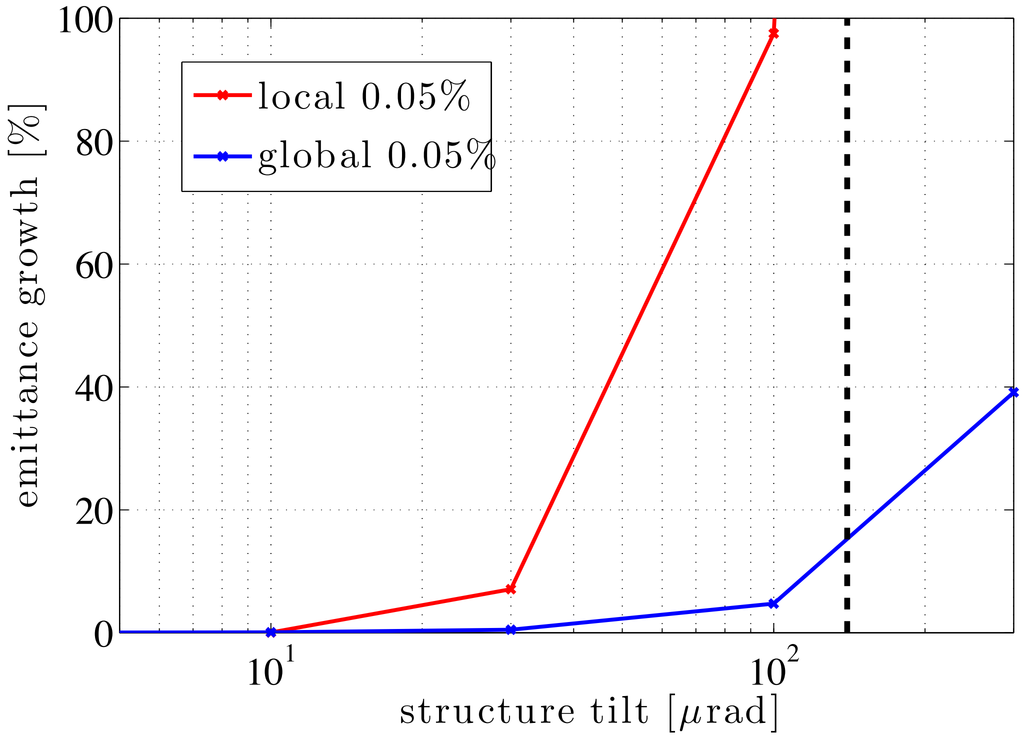
Results with local energy change



- Local scheme with 0.1% shows similar behaviour than global excitation with 5%
- The increase of emittance due to the nominal CLIC wake field monitors resolution is about 6%.

3. Tilt of acceleration structures

High sensitivity to the tilt of the accelerating cavities



- At nominal tilt of 140urad, the performance of local DFS is unacceptable
- The global DFS version is much better, but also creates significant emittance growth.

Singular value filter

- Write calculation of correction with help of singular valued decomposition:

$$\Delta y_{QP} = \begin{bmatrix} R \\ \omega D \end{bmatrix}^{\dagger} m = C^{\dagger} m = V S^{-1} U^T m \qquad \text{with } C = U S V^T$$

- A filter can be easily produced by weighting the different modes or simply by not using time:

$$\Delta y_{QP} = V S^{-1} W U^T m \quad \text{with } W = \mathrm{diag}(w_i) \text{ and } w_i \in \{0,1\}, \forall i \in \{1, \dots, N\}$$

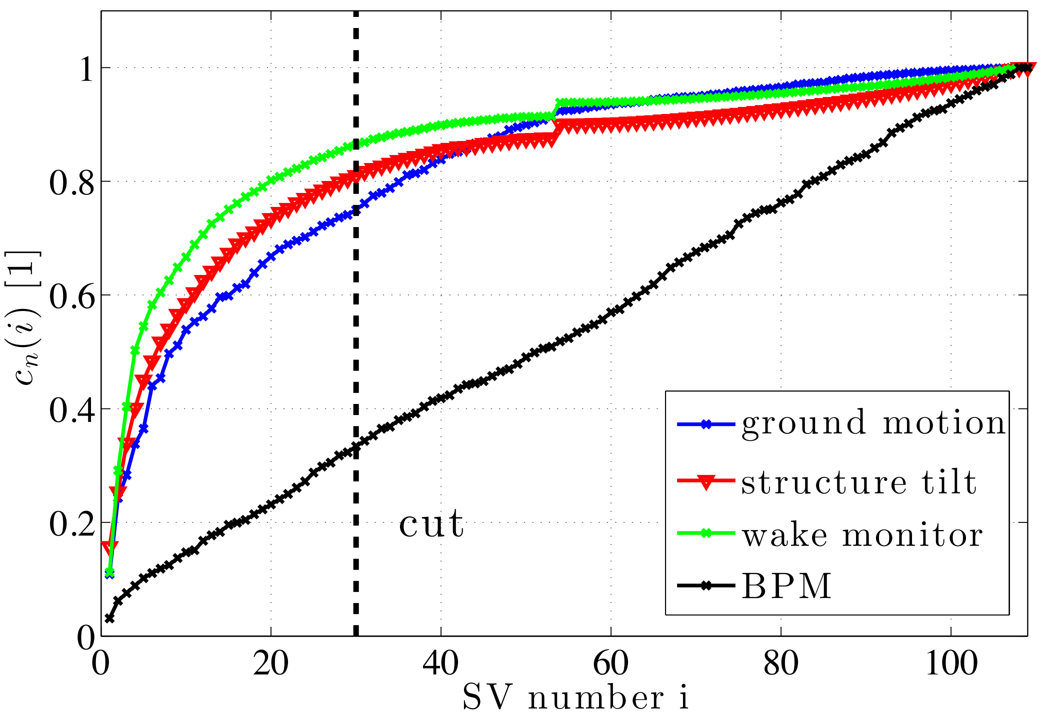
- To identify which modes should be cut away, the projections *p(i)* are studied:

$$\begin{bmatrix} p_1 \\ \vdots \\ p_N \end{bmatrix} = U^T m = \begin{bmatrix} u_1^T \\ \vdots \\ u_N^T \end{bmatrix} m$$

- Easier to interpret is the cumulated sum c(i) of the *p(i)* the normalised version $c_N(i)$:

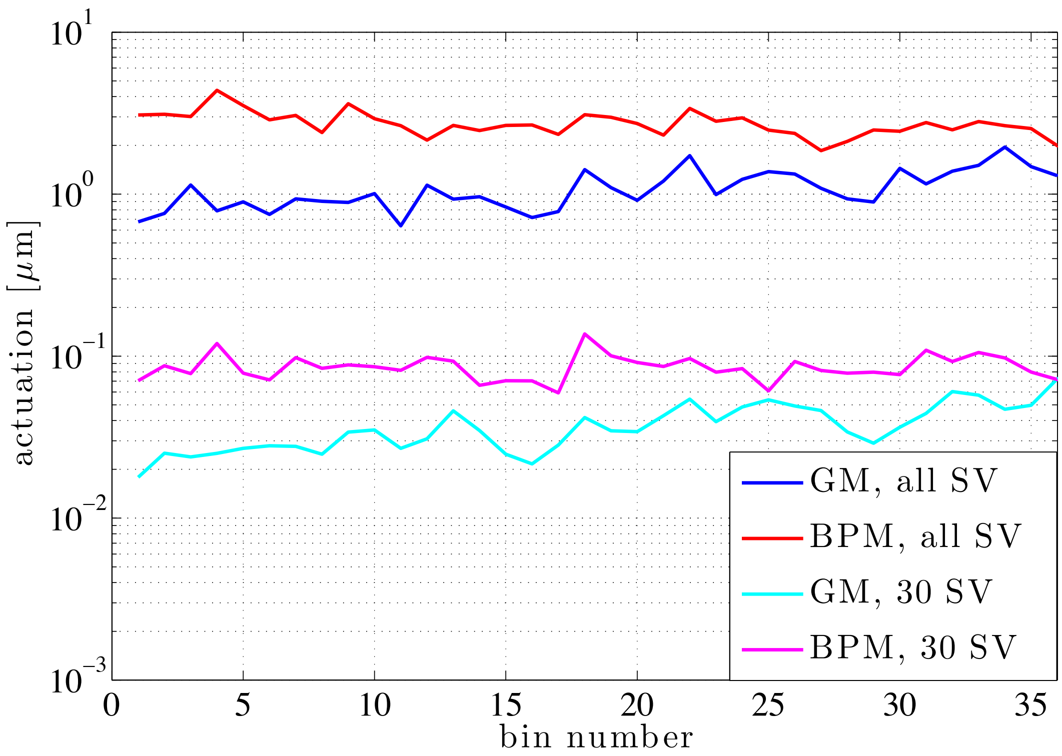
$$c(i) = \sum_{l=1}^{i} p(l) \qquad \text{and} \qquad c_N(i) = \frac{c(i)}{c(N)}$$

Projection of measured dispersion on singular value modes



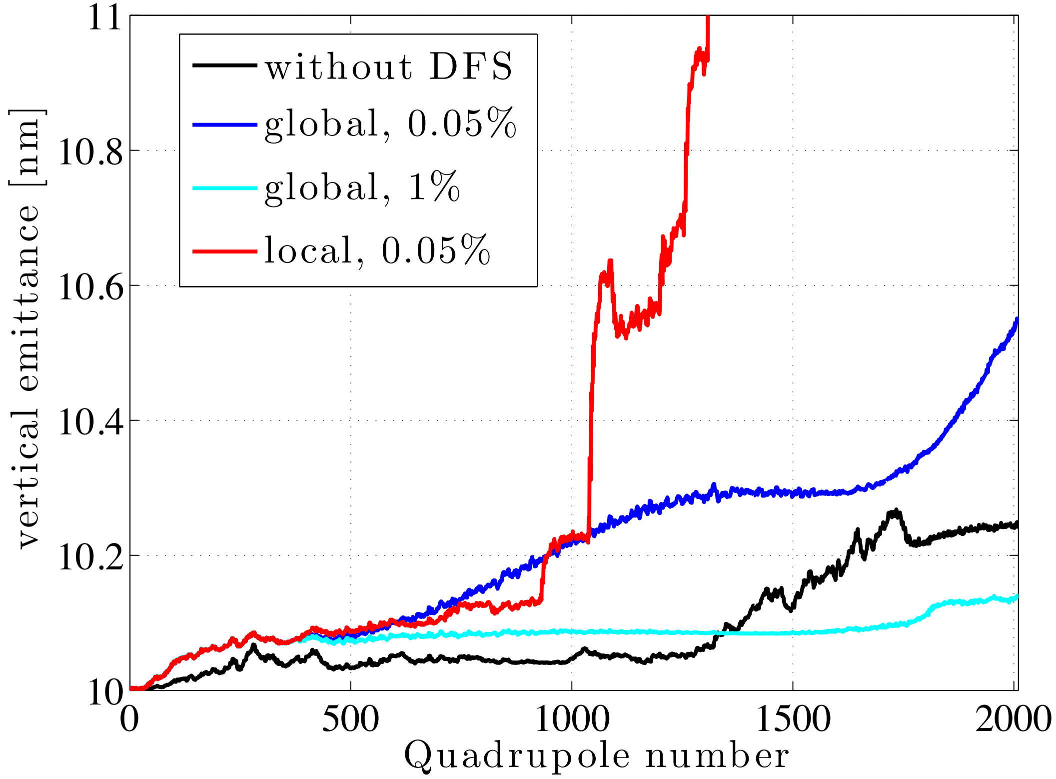
- With cut at SV 30, ground motion correction still very good.
- Unfortunately, influence of structure tilt and wake monitor cannot be reduced.
- Impact only, if SV 1 or 2 are cut, but they are also essential for ground motion correction.

Result with SV filter: Reduction of corrector actuation



- The SV filter is efficient in reducing the amplitude of the calculated corrections:
  - Before: about 3um
  - 30 SV: 0.1um
- Further reduction seems possible.
- Tripod stabilisation system has range of +/- 5um.
- Stabilisation system could be used for DFS.

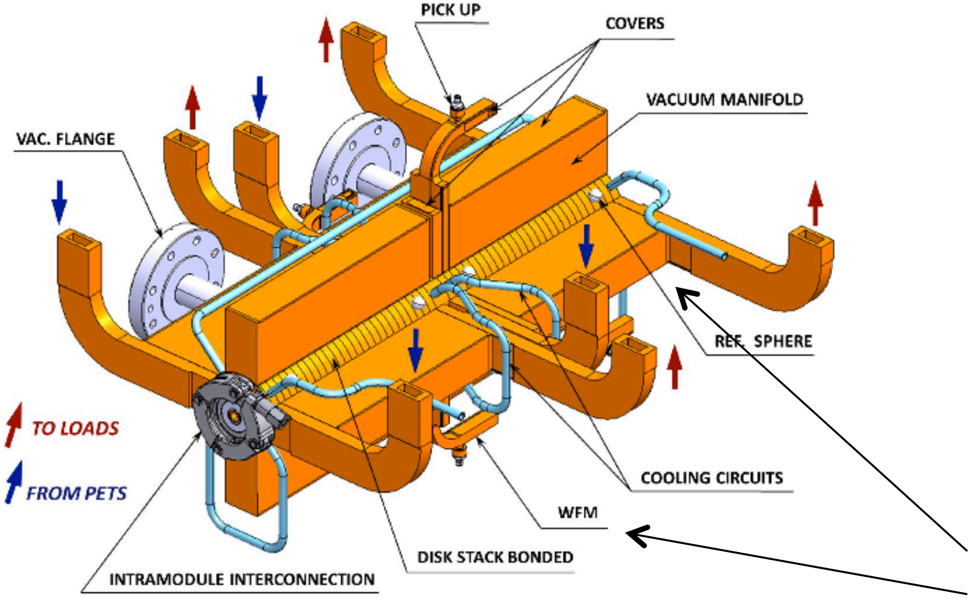
Some observations



- Global DFS works by far better than local one.
- Global DFS works better for larger energies.
- Next steps will be to understand the behaviour of the global DFS, since also there the energy dependence is not understood.

Structure tilt alignment

- In case problem cannot be solved and on-line DFS is wanted, an other option would be a structure tilt alignment.
- An algorithm like tilt-free steering would most likely take to long due to the large number of structures.
- Use two wakefield monitors instead of one:



- Two structures are combined to one unit.
- One wakefield monitor per unit. (beginning of second structure)
- Wakefield monitor also in the first structure.

Wake field monitor

4. Conclusions

- On-line DFS works well to correct emittance increase due to ATL motion.
- Many imperfections have been tested and only two created problems.

- The resolution of the wake field monitors:
  - Cause problems because the bunch tails form different for different energies.
  - Problem could be resolved with local excitation.
  - Still work on analytical model ongoing.

- Tilt of acceleration cavities:
  - Attempts to filter the dispersion signal from cavity tilts with singular value filter were not successful.
  - Many interesting observations, but not solution to the problem yet.

- Tests with the SV filter showed that only actuations in the 0.1um level are necessary for the corrections. Stabilisation system would be largely sufficient.
- Test of the sensitivity to actuator noise have to be performed.

Thank you for your attention!