Effects of Accelerating Cavities on On-Line Dispersion Free Steering in the Main Linac of CLIC

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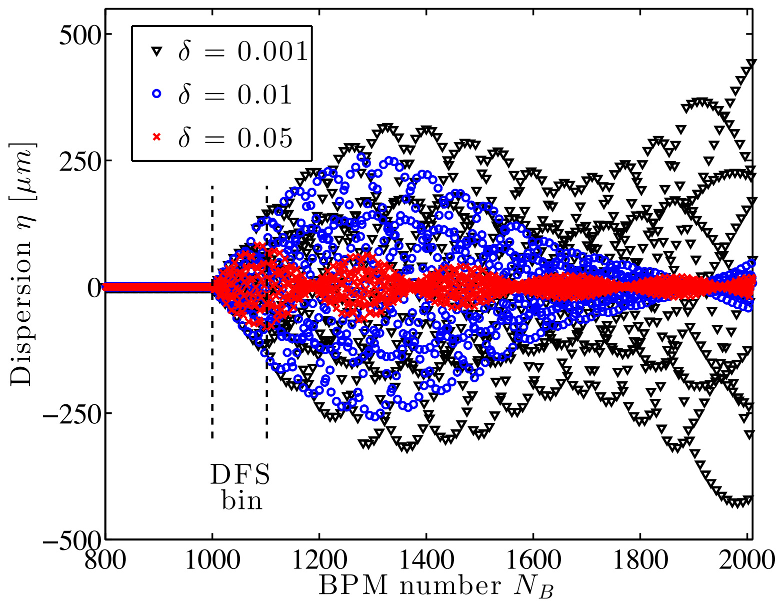
Outline

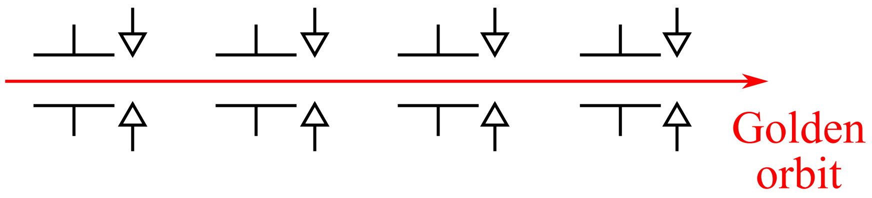


1. On-line DFS.
2. Issues due to wake fields.
3. Issues due to cavity tilts.
4. Conclusions.

1. On-line DFS

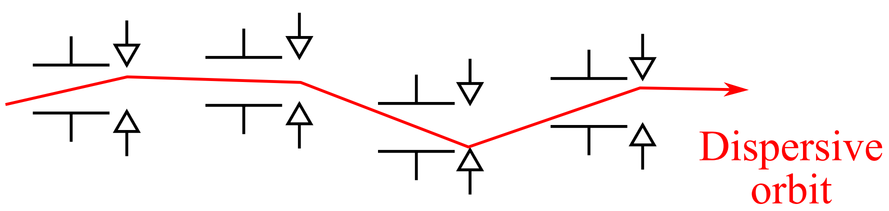
Motivation: Long-term ground motion

- **Initial beam-based alignment:**



Orbit feedback steers beam onto golden orbit.

- **Long-term ground motion (> 1 minutes):**



Orbit feedback steers beam onto dispersive orbit.

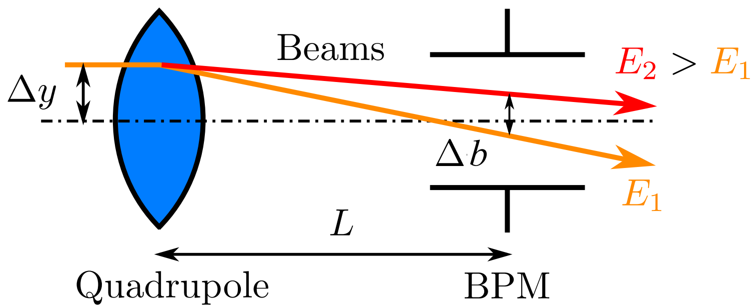
- **Effects on the main linac of CLIC:**
  - Ground motion model: *ATL law* [1] with constant *A* of 10^{-5} *µm/m/s*.
  - Emittance increase $\Delta\varepsilon_y \approx$ 7.5% / hour (scaling law from simulation).
  - E.g. $\Delta\varepsilon_y$ of 100% in 13 hours.

Dispersion free steering (DFS)

- **Method** [2,3]:

  Step 1: The dispersion *η* at the BPMs is measured by varying the beam energy.

  Step 2: Corrector actuations Δy_1 (quadrupole movements) are calculated to minimise dispersion *η* and the beam orbit *b*.



$$\eta = \frac{\Delta b}{\delta} = \frac{b_2 - b_1}{\delta} \quad \text{with}$$

$$\delta = \frac{E_2 - E_1}{E_1}$$

- Considering many BPMs and quadrupoles leads to linear system of equations [4]:

$$\begin{bmatrix} b - b_0 \\ \omega(\eta - \eta_0) \\ 0 \end{bmatrix} = \begin{bmatrix} R \\ \omega D \\ \beta I \end{bmatrix} \Delta y$$

Corrections Δy are computed in least square sense.

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

On-line DFS

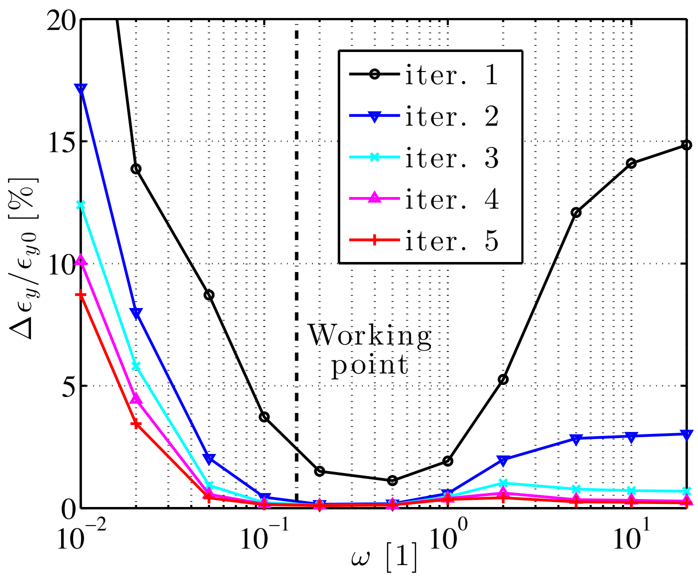
- **Goal:** Perform DFS parasitically during physics data taking.
- **Problem:**
  - Only very small beam energy variation δ acceptable (< 1 per mil).
  - Measurement are strongly influenced by BPM noise and usual energy jitter.
- **Solution:**
  - Many measurements are averaged.
  - Use of a Least Squares estimate (pseudo-inverse), which can be significantly simplified by the choice of the excitation:

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

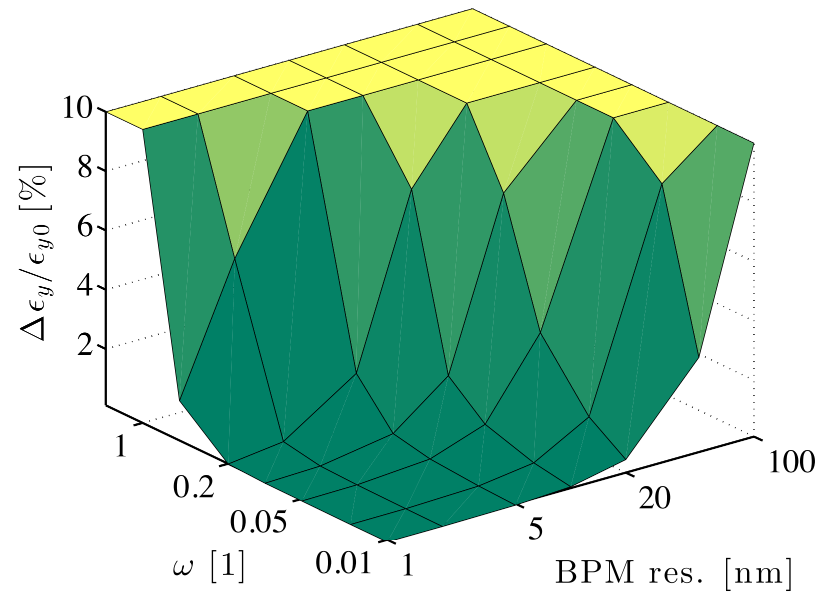
$$\boldsymbol{E} = \begin{bmatrix} -\Delta E \\ +\Delta E \\ \dots \\ -\Delta E \\ +\Delta E \end{bmatrix} \qquad T_N = \sum_{i=1}^{N} (-1)^i b_i$$

Performance of on-line DFS

1. **ATL motion** (13h) correction for different ω:



2. **BPM noise** sensitivity for different ω:



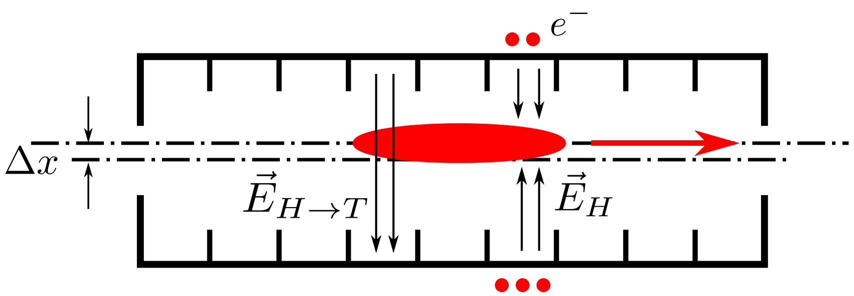
3. **Correction performance:**
   - ATL motion: $\Delta\epsilon_y$ = 0.2% after 3rd iteration.
   - BPM noise: $\Delta\epsilon_y$ = 0.2% (BPM noise 10nm).
   - Averaging time: 144s x 3 iter. (7 minutes)

4. **Robustness:**
   - Robust to all envisioned imperfections apart from two.
   - Accuracy of wake field monitors.
   - Tilt of accelerating structures.

2. Issues due to wake fields

Wake fields and DFS

Wake field kicks



- In cavity with offset Δx, head beam creates asymmetric mirror currents.
- Resulting wake fields apply dipole kicks to beam.
- Kick is zero at the head and rises towards the tail.

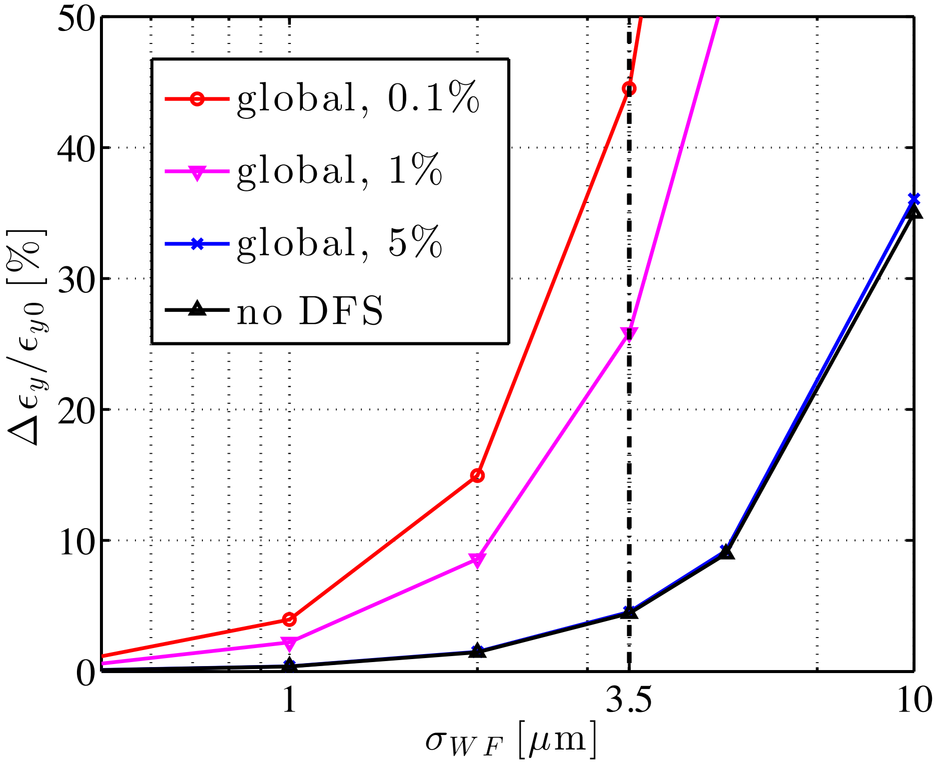
Dispersion from wake fields

- Since wake fields create dipole kicks, they also create dispersion.
- Dispersion profile:
  - Quadrupoles: uniform along beam.
  - Wake fields: stronger towards tail.

> Hence, dispersion from wake fields cannot be compensated all along the beam by dispersion from quadrupole magnets (DFS).

- DFS can only cancel the dispersion on average
- Dispersion of opposite sign remains in head and tail.

Wake fields and DFS performance



- At CLIC, cavities are aligned to the beam to reduce the wake fields (RF alignment):
  - σ_{WF} = 3.5 μm.
  - $\Delta\varepsilon_y$ = 5%.
- Remaining wake fields causes problems for DFS.
- For the target energy change δ of 0.1% the DFS correction is insufficient.
- DFS works only for large energy changes δ.

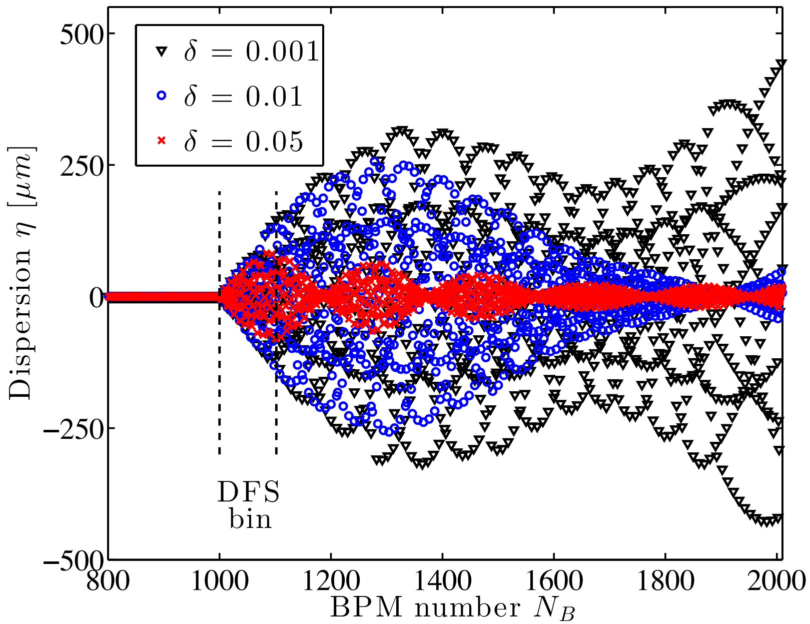
Analysis of wake field sensitivity

Dispersion from wake fields

- Dispersion from wake fields is small and can be neglected for emittance growth.
- However, wake field dispersion deteriorates the DFS correction:
  - Dispersion from wake fields, can only be compensated by DFS (quadrupoles) on average along the beam.
  - Dispersion with opposite sign remains in head and tail.
  - Wake field dispersion is added from many cavities upstream.
  - This wake field dispersion creates large measured signals in the correction bin.

Energy dependence of dispersion

- Dispersions of the same dipole kick depends is larger for smaller energy change δ :

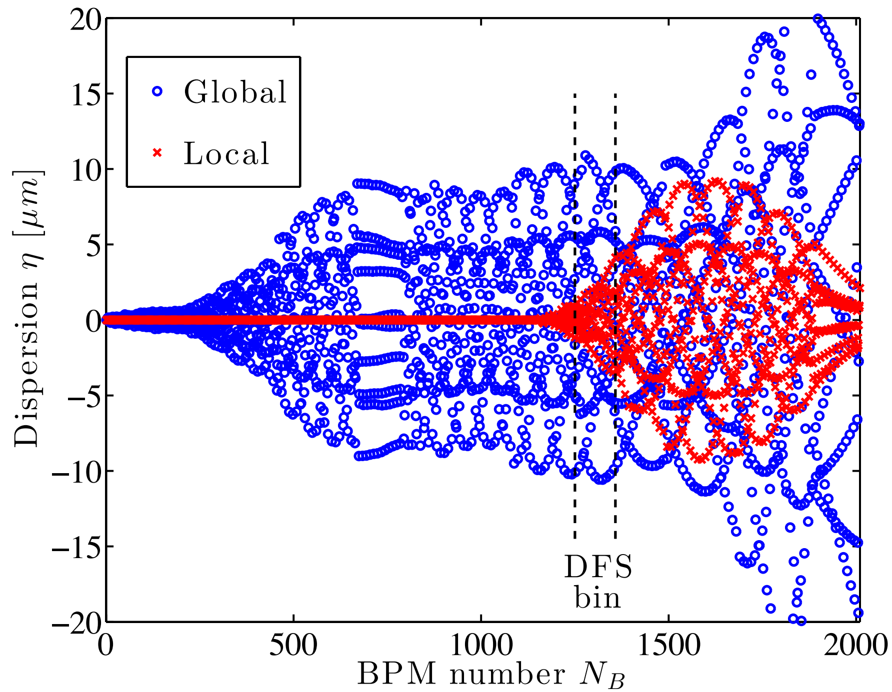


Counter-measure against wake field sensitivity

- Properties of dispersion (for small δ):
  - Only grows to large values far downstream of kick.
  - But stays small just after the kick.

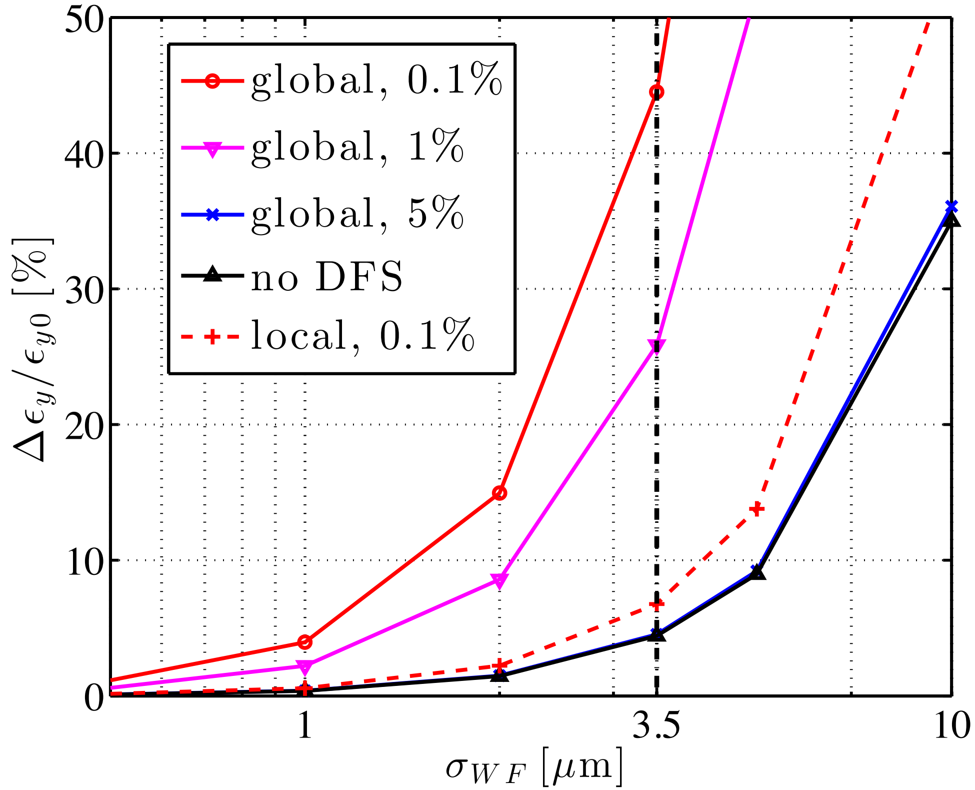
> Hence, dispersion from wake fields can be kept small, if δ is produced just shortly before the bin to be corrected.

- Baseline for CLIC: global δ creation (via change of drive beam charge).
- But a local δ creation can be implemented in different ways, e.g.:
  - Switch off structures with On/Off mechanism of PETS.
  - De-phasing of drive beam bunches.



- Dispersion of wake fields after RF alignment for global and local energy change δ. No DFS applied upstream of DFS bin.

Improvement due to wake field counter-measure



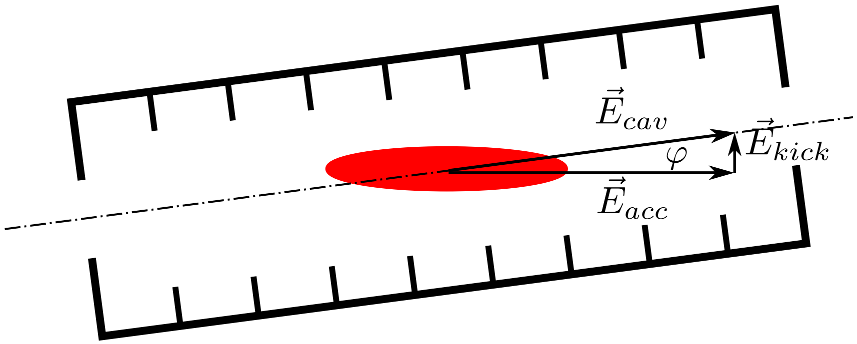
- Local δ creation decreases wake field sensitivity significantly:
  - Wake fields: $\Delta\varepsilon_y$ = 7.0%
  - ATL motion: $\Delta\varepsilon_y$ < 0.2% after 3rd iteration.
  - BPM noise: $\Delta\varepsilon_y$ = 0.2%.
  - Averaging time: 144s x 3 iterations.
- Wake fields are the dominant $\Delta\varepsilon_y$ source.

3. Issues due to cavity tilts

Cavity tilts and dispersion

Kicks due to cavity tilts:

- Field of a tilted cavity has also a transverse field component E_{kick}.
- Resulting kick deflects whole bunch.

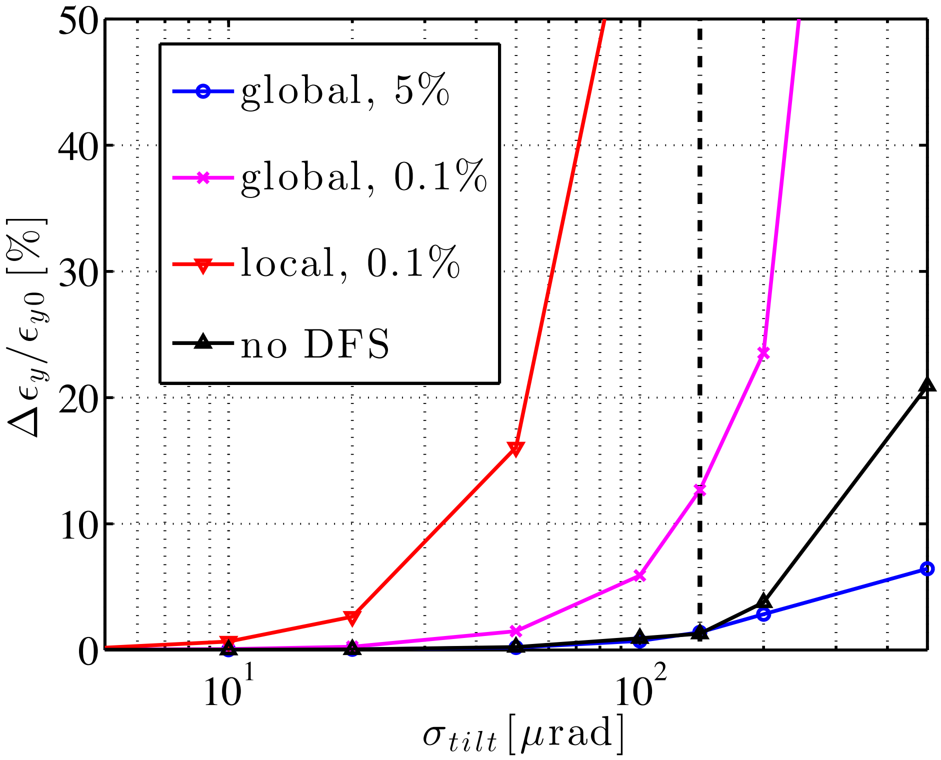


$$\Delta x'_{\varphi} = \vec{E}_{cav} \sin\varphi \approx \vec{E}_{cav}\varphi \quad \text{for} \quad \varphi \ll 1$$

Mitigation of cavity tilt effects:

- Kicks are corrected by BPM steering.
  - σ_{φ} = 140 μrad.
  - $\Delta\varepsilon_y$ = 3%.
- Remaining dispersion is small and can be neglected for DFS.
- Remaining emittance growth due to a "wake field-like" effect:
  - Longitudinal wake fields weaken E_{cav} towards beam tail.
  - Hence, transverse kick is stronger for head than for tail.

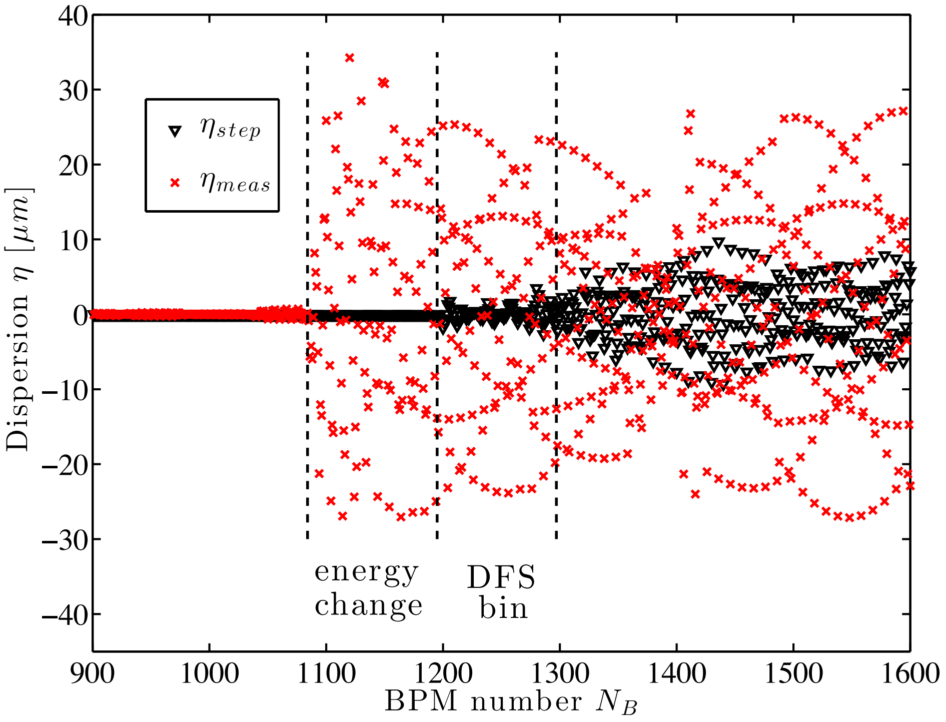
Cavity tilts and DFS performance



- After 1-2-1 steering, remaining emittance growth is due to "wake field-like" effect:
  - σ_{tilt} = 140 µrad.
  - $\Delta\varepsilon_y$ = 3%.
- For global large energy changes δ, DFS correction is not influenced by cavity tilts.
- Small δ worsen DFS performance.
- But especially local δ changes destroy the correction completely.

Analysis of cavity tilt sensitivity

- For dispersion measurement, a beam energy change δ has to be created:
  - Energy change δ is created by changing cavity gradients.
  - Gradient change also causes change of transverse tilt kicks.
  - Beam orbit is changed.



- Orbit change overlaps with dispersion signal in DFS bin.

- Orbit change signal is interpreted as dispersion and destroys correction.

- Higher relative gradient changes make the problem worse:
  - Local scheme is worse than global one.
  - This is not only true for small δ, but also for ordinary DFS.

Counter-measures against cavity tilt sensitivity

- **Goal:** Remove orbit change due to tilt kick change from measured dispersion.
- **Problem:** Mixture of orbit change and dispersion in DFS bin.
- **Solution:** Predict orbit change Δb_{bin} in DFS bin from BPM measurements in upstream bin Δb_{up}:

  1. Fit orbit change Δb_{up} in upstream DFS bin by virtual quadrupole offsets Δx_{up}.

$$\Delta x_{up} = R_{up}^{\dagger} \Delta b_{up} = (U \Sigma V^T)^{\dagger} \Delta b_{up}$$
$$= V \Sigma U^T \Delta b_{up}$$

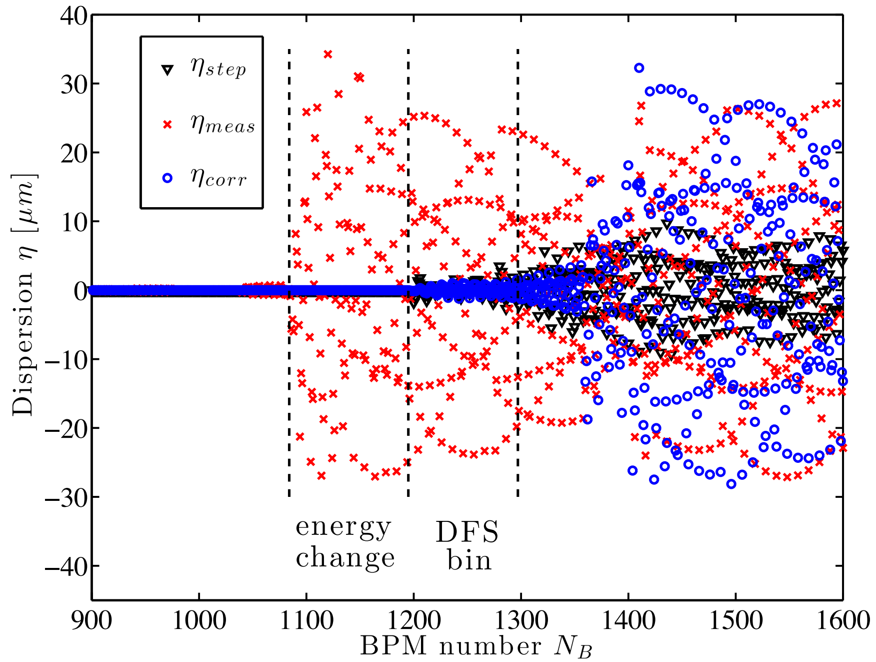
  2. Use only few singular values for the SVD inversion to improve robustness.

  3. Predict orbit changes Δb_{bin} in DFS bin via the corresponding orbit response matrix:

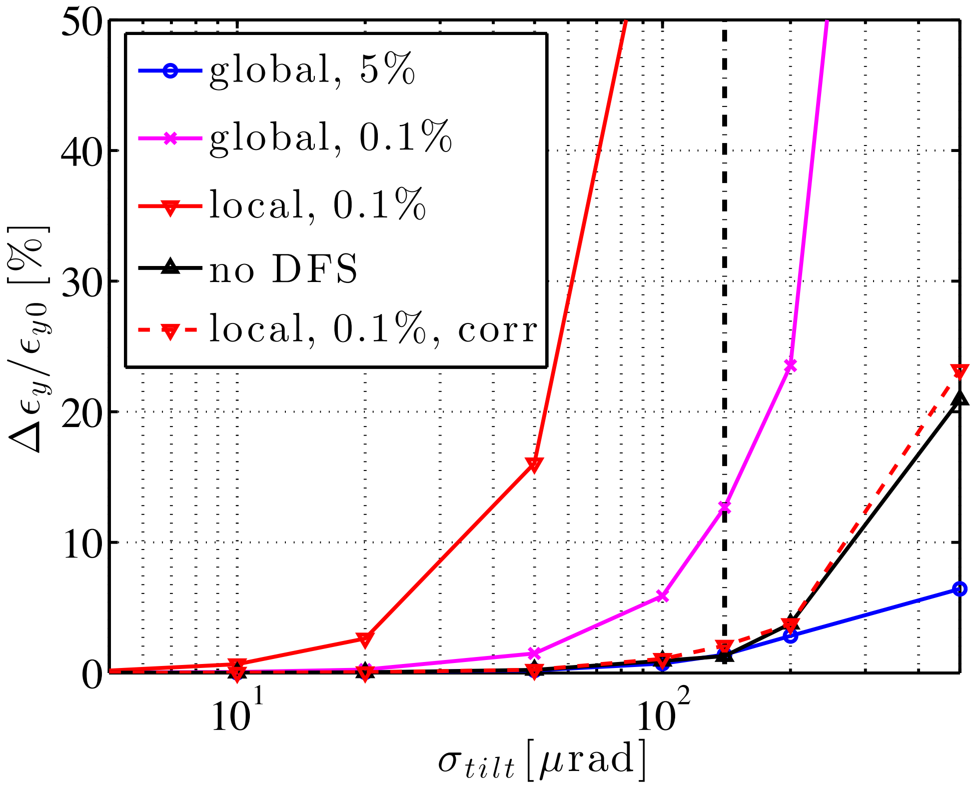
$$\Delta b_{bin} = R_{up \to bin} \Delta x_{up}$$

  4. Finally, the predicted orbit can be removed:

$$\eta_{corr} = \eta_m - \Delta b_{bin}$$



Improvement due to cavity tilt counter-measure



- Removal of the orbit change decreases tilt sensitivity significantly:
  - Tilts: 2.5%
  - Wake fields: $\Delta\varepsilon_y$ = 9.0%
  - ATL motion: $\Delta\varepsilon_y$ < 0.2% after 3rd iteration.
  - BPM noise: $\Delta\varepsilon_y$ = 0.2%.
  - Averaging time: 144s x 3 iterations.
- Wake field effect is worsened, because removal technique also acts on wake field signals.

4. Conclusions

- On-line DFS is necessary to suppress ground motion effects on the time scale of hours.
- The scheme can compensates ground motion effects on-line despite of BPM noise.
- Two imperfections cause problems:
  1. Resolution of wake field monitors.
  2. Tilt of acceleration cavities.
- Effect of these imperfection on DFS has been analysed and counter-measures have been successfully implemented.
- The emittance growth due to dispersion can now be corrected during physics data taking to the same level as with off-line DFS.
- The necessary energy change δ of only 0.1% is 50 times smaller than before, which is also very interesting for the application of DFS in the BDS.

Thank you for your attention!

References:

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[3] A. Latina et al. *Experimental demonstration of a global dispersion-free steering correction at the new linac test facility at SLAC*, Phys. Rev. ST Accel. Beams 17, 042803 (2014).

[4] A. Latina and P. Raimondi, *A novel alignment procedure for the final focus of future linear colliders*, In Proc. of the 25th Linear Accel. Conf. (LINAC10), MOP026 (2010).