

Static Imperfections and Beam-Based Correction

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Low Emittance Transport Challenges

- Main linac is one of the most important sources of emittance growth
- Static imperfections
 - errors of reference line, elements to reference line, elements. . .
 - excellent pre-alignment, lattice design, beam-based alignment, beam-based tuning
- Dynamic imperfections
 - element jitter, RF jitter, ground motion, beam jitter, electronic noise, . . .
 - lattice design, BNS damping, component stabilisation, feedback, re-tuning, re-alignment
- Combination of dynamic and static imperfections can be severe
- Lattice design needs to balance dynamic and static effects

Emittance Budget

- CLIC

- the initial emittance has to stay below $\epsilon_x = 600$ nm and $\epsilon_y = 10$ nm
- for static imperfections an emittance budget of $\Delta\epsilon_x = 30$ nm and $\Delta\epsilon_y = 5$ nm exists, which 90% of the machines have to meet
- for dynamic imperfections an emittance budget of $\Delta\epsilon_x = 30$ nm and $\Delta\epsilon_y = 5$ nm exists

- ILC

- the initial emittances have to stay below $\epsilon_x = 8400$ nm and $\epsilon_y = 24$ nm
- the final emittances have to stay below $\epsilon_x = 9400$ nm and $\epsilon_y = 34$ nm

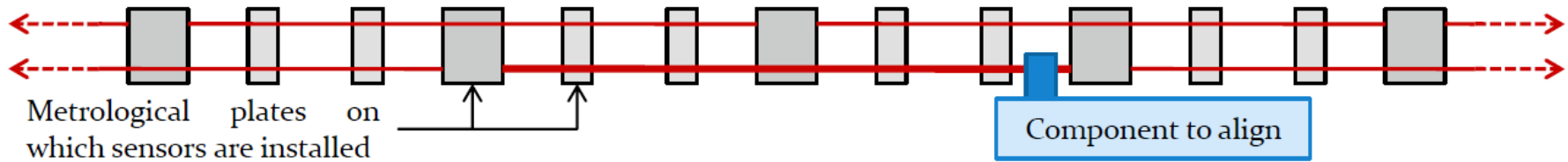
- We will limit our discussion to the vertical plane

Imperfections

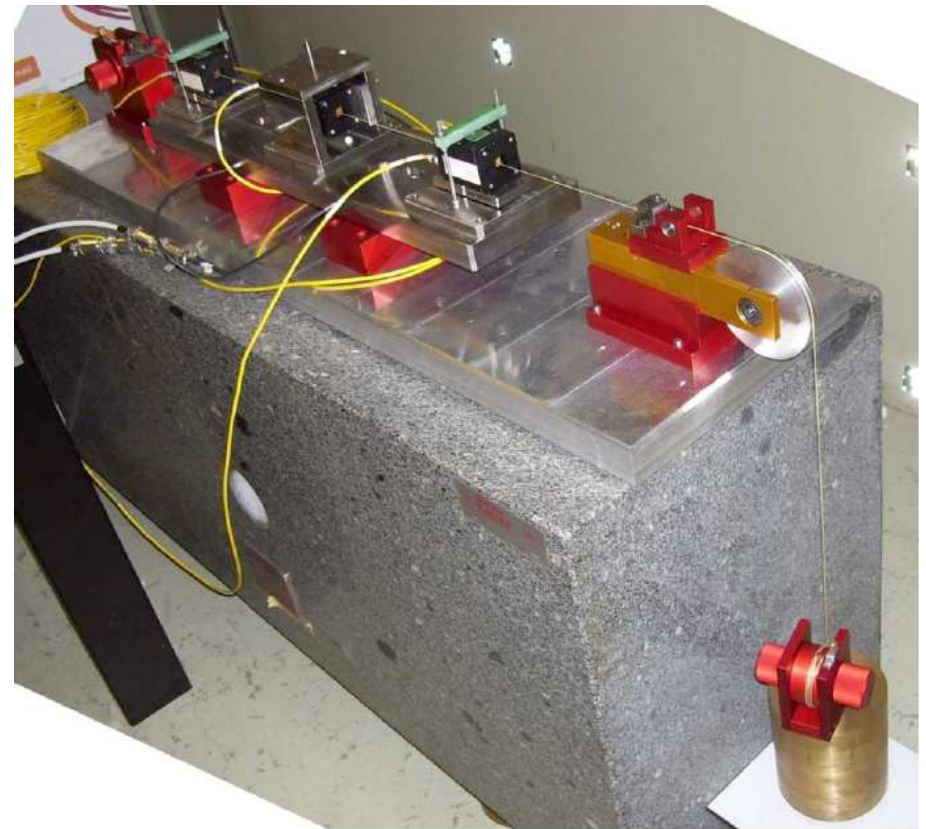
- Pre-Alignment imperfections can be roughly categorised into **short-distance** and **long-distance** errors
 - To first order, the imperfections can be treated as independent
 - as long as a linear main linac model is sufficient
 - The short-distance misalignments give largest emittance contribution
 - misalignment of elements is largely independent
 - simulated by scattering elements around a straight line
 - or slightly more complex local model
 - The long-distance misalignments are dominated by reference line system, e.g. the wire or laser tracking system
- ⇒ ignore short-distance misalignments and simulate wire errors only
- Combined studies are mainly for completeness

Example: Residual Alignment Errors due to Pre-Alignment System

Wire System for CLIC

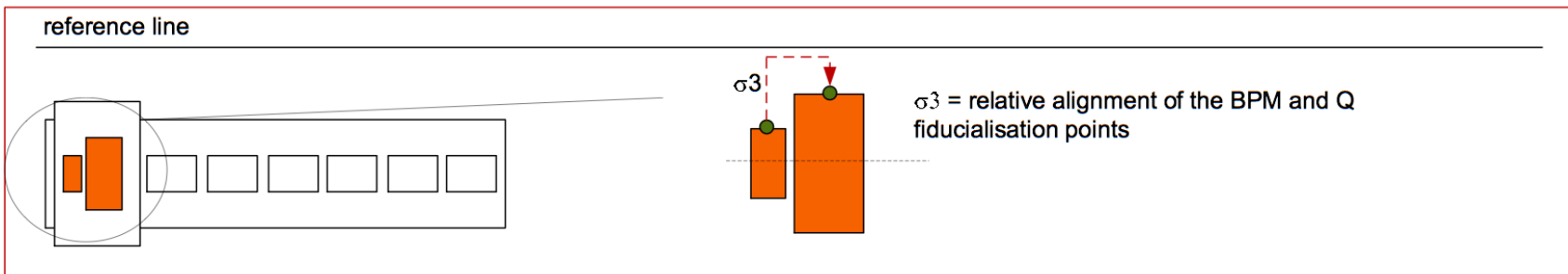
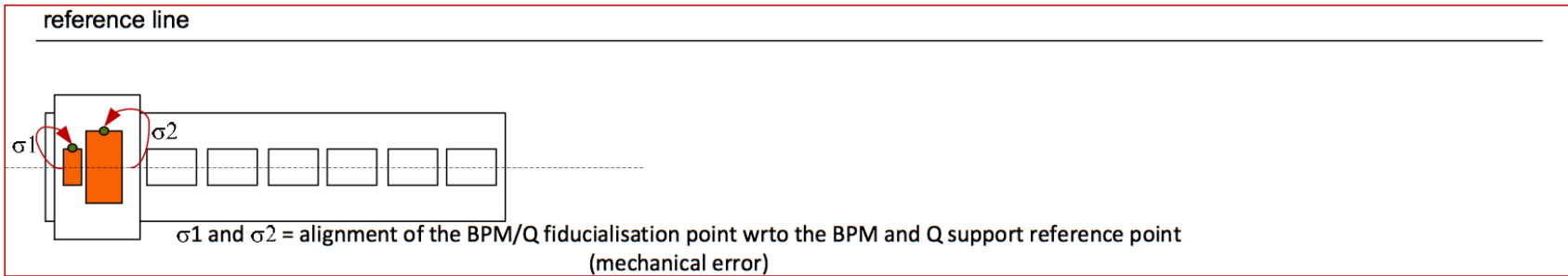
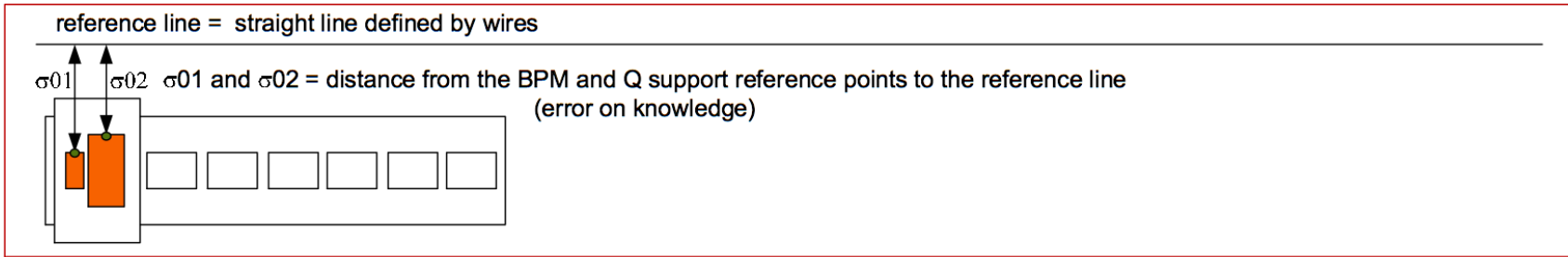
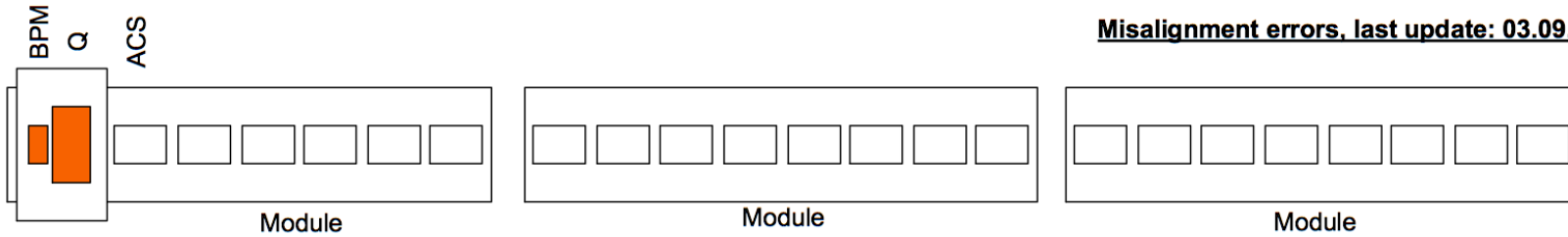


- Reference method for CLIC
 - has been used in the LHC insertions
- A system of overlapping wires that form straight lines
- Alternative is optical measurements

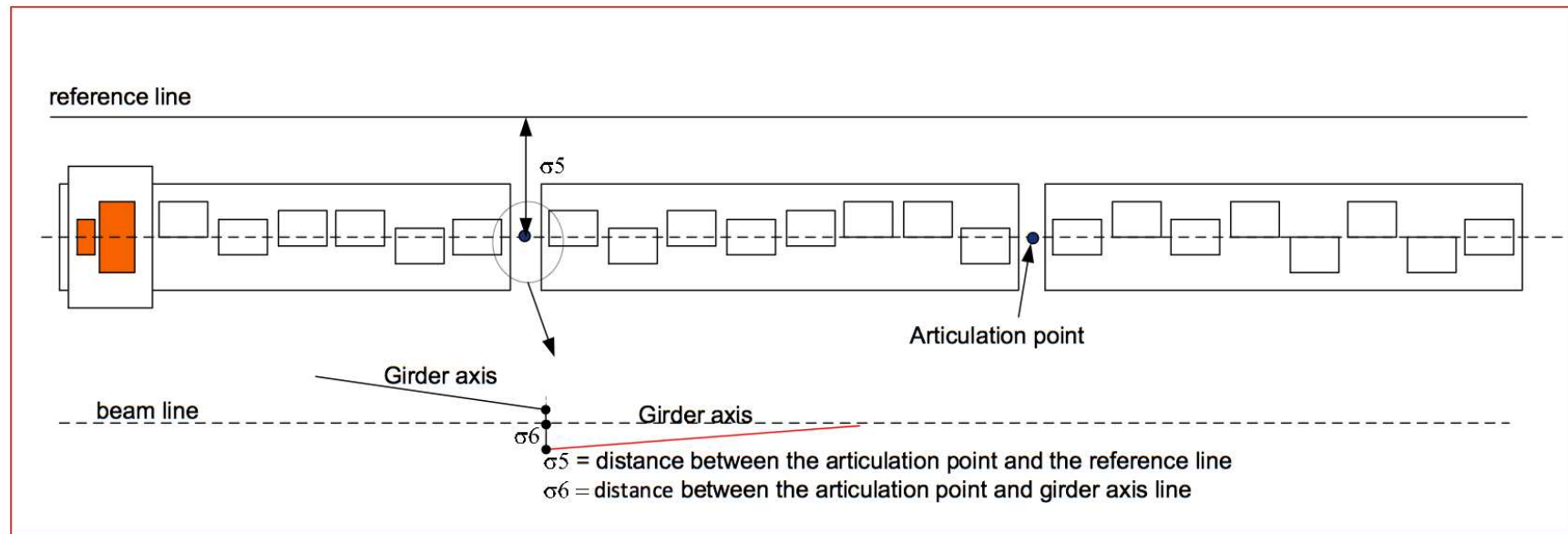
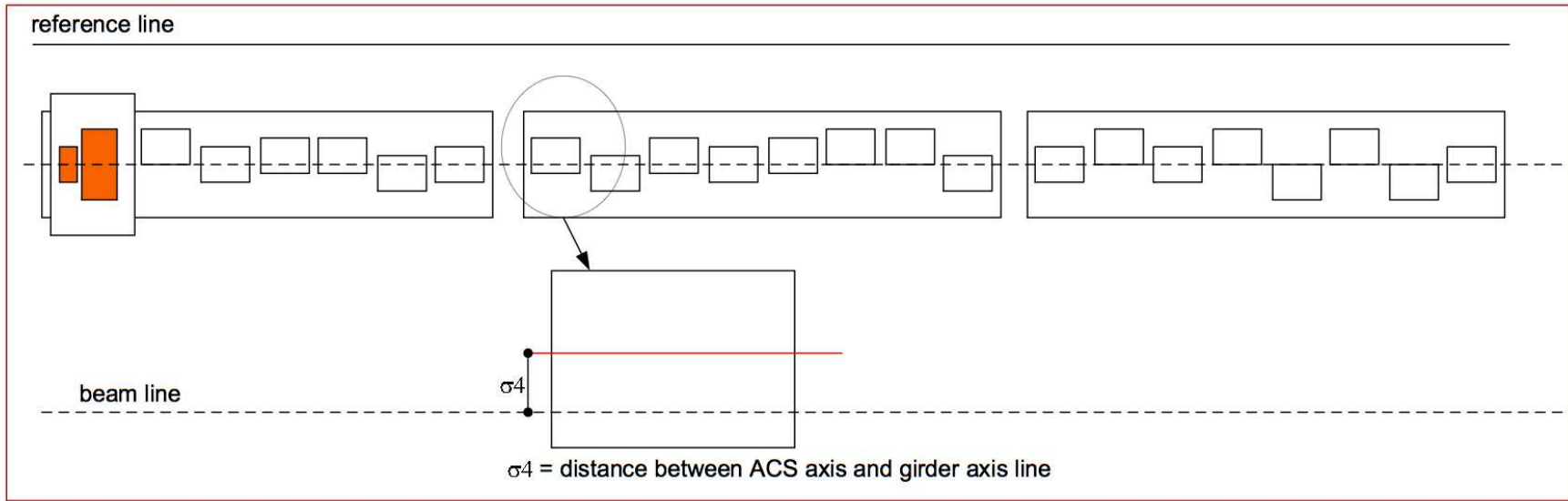


Alignment Model (CLIC)

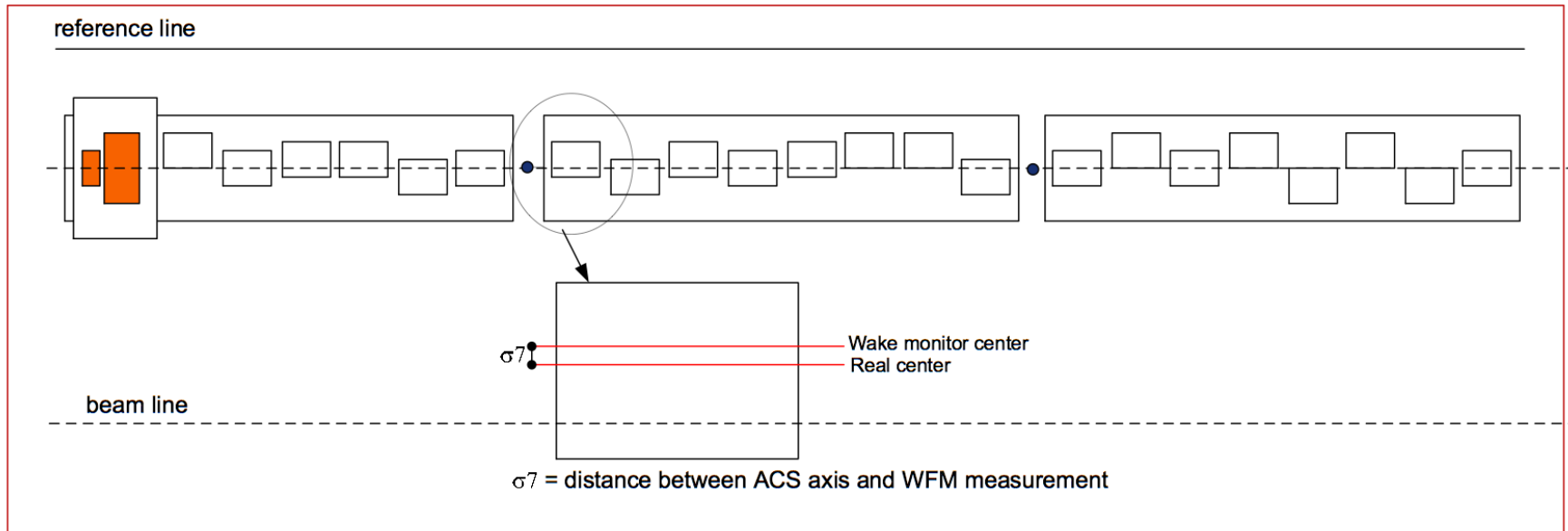
Misalignment errors, last update: 03.09.2009



Alignment Model (cont)



Alignment Model (cont)



imperfection	with respect to	symbol	target value
BPM offset	wire reference	σ_{BPM}	14 μm
BPM resolution		σ_{res}	0.1 μm
accelerating structure offset	girder axis	σ_4	10 μm
accelerating structure tilt	girder axis	σ_t	200 μradian
articulation point offset	wire reference	σ_5	12 μm
girder end point	articulation point	σ_6	5 μm
wake monitor	structure centre	σ_7	5 μm
quadrupole roll	longitudinal axis	σ_r	100 μradian

Assumed Survey Performance

Element	error	with respect to	alignment	
			ILC	CLIC
Structure	offset	girder	300 μm	10 μm
Structure	tilts	girder	300 μradian	200(*) μm
Girder	offset	survey line	200 μm	9.4 μm
Girder	tilt	survey line	20 μradian	9.4 μradian
Quadrupole	offset	girder/survey line	300 μm	17 μm
Quadrupole	roll	survey line	300 μradian	$\leq 100 \mu\text{radian}$
BPM	offset	girder/survey line	300 μm	14 μm
BPM	resolution	BPM center	$\approx 1 \mu\text{m}$	0.1 μm
Wakefield mon.	offset	wake center	—	5 μm

- In ILC specifications have much larger values than in CLIC
 - more difficult alignment in super-conducting environment
 - dedicated effort for CLIC needed
- Wakefield monitors are currently only foreseen in CLIC
 - but could be an option also in ILC

Impact on the Beam

Misalignment and Wakefields

- We use a two particle model to determine the trajectory change of the second particle for an offset structure (two particles do not occupy any area in phase space)
 - same energy particles for simplicity

- The kick of the wakefield is for an offset δ

$$\Delta y' = \frac{W_{\perp}(z) N e^2 L}{E} \delta$$

- We calculate the kick in normalised phase space

$$\Delta y'_N = \sqrt{\beta\gamma} \frac{W_{\perp}(z) N e^2 L}{E} \delta$$

- The impact on the emittance is

$$\Delta \epsilon_y \propto \beta\gamma \left(\frac{W_{\perp}(z) N e^2 L}{E} \delta \right)^2$$

- The emittance growth per unit length is

$$\Delta \epsilon_y \propto \beta\gamma \left(\frac{W_{\perp}(z) N e^2 L}{E} \delta \right)^2 L$$

- Summing over many elements gives the final normalised positions

$$y_N = \sum_i \sin(\phi_f - \phi_i) \sqrt{\frac{\beta_i}{\gamma_i}} W_{\perp}(z) N e^2 L_i \delta_i$$

$$y'_N = \sum_i \cos(\phi_f - \phi_i) \sqrt{\frac{\beta_i}{\gamma_i}} W_{\perp}(z) N e^2 L_i \delta_i$$

⇒ Worst case is $\delta_i = \delta_0 \sin(\phi_i + \phi_0)$

Misalignment and Spurious Dispersion

- We use a two particle model to determine the trajectory change of the second particle with respect to the first
 - Note: In this case both particles are kicked, but since we look at the static effect we can remove the average kick
 - by the way the same is true for the wakefield kick
- A particle at nominal energy is kicked by

$$\Delta y'_0 = \frac{y_q}{f}$$

a particle with a different energy $E = E_{nom}(1 + \delta)$ is kicked as

$$\Delta y'_1 = \frac{y_q}{f(1 + \delta)}$$

the difference is

$$\Delta y'_1 - \Delta y'_0 \approx -\frac{y_q}{f}\delta$$

Impact of Element Offset (ILC)

- Consider case with no correction

Error	with respect to	value	$\Delta\gamma\epsilon_y$ [nm]
Cavity offset	module	300 μm	3.5
Cavity tilt	module	300 μradian	2600
BPM offset	module	300 μm	0
Quadrupole offset	module	300 μm	700000
Quadrupole roll	module	300 μradian	2.2
Module offset	perfect line	200 μm	250000
Module tilt	perfect line	20 μradian	880

⇒ Need to do much better

⇒ Will align with the beam

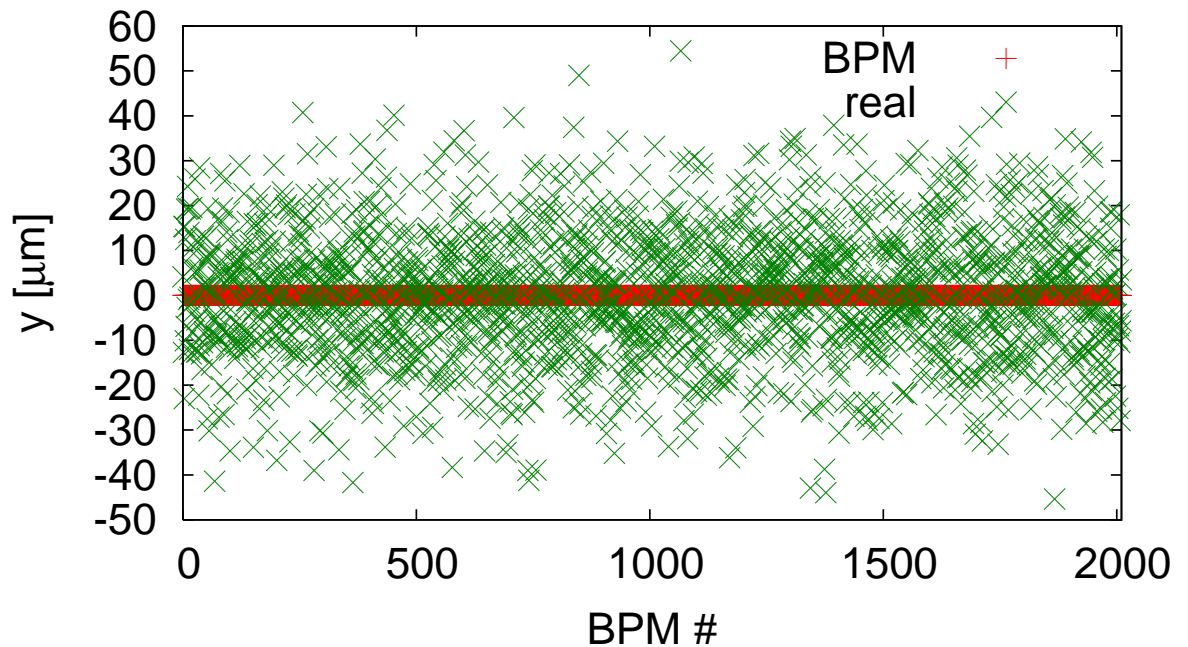
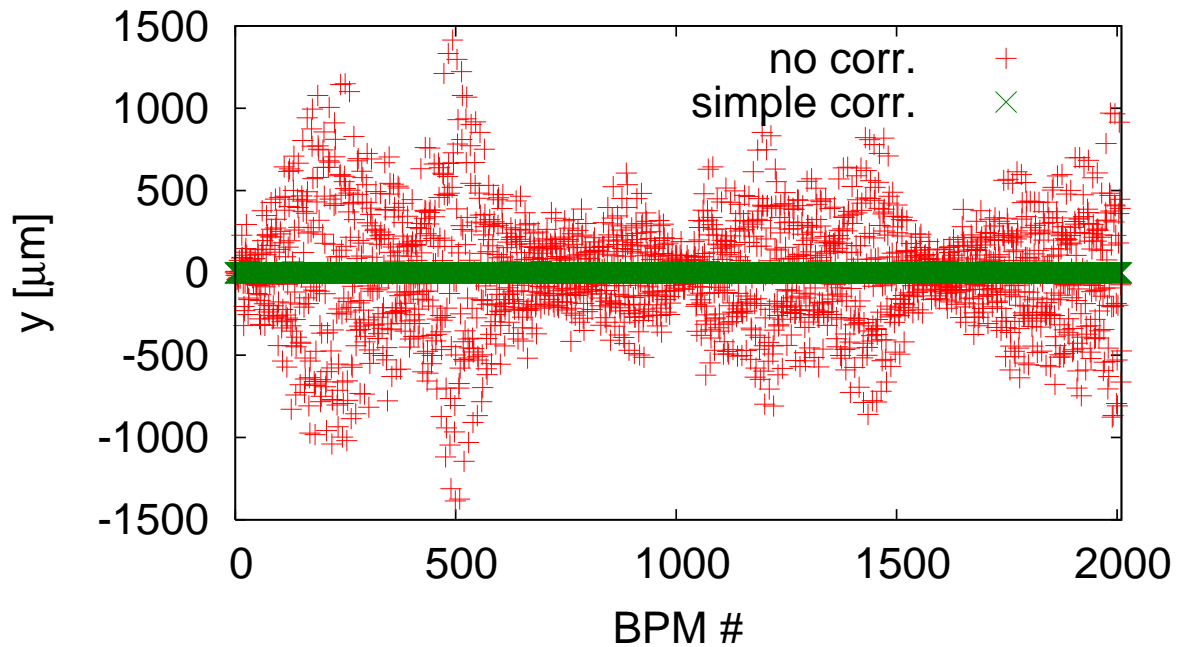
Beam-Based Tuning

Beam-Based Alignment and Tuning Strategy

- Make beam pass linac
 - one-to-one correction
- Remove dispersion, align BPMs and quadrupoles
 - dispersion free steering
 - ballistic alignment
 - kick minimisation
- Remove residual dispersive and wakefield effects
 - accelerating structure alignment (CLIC only)
 - emittance tuning bumps
- Tune luminosity
 - tuning knobs

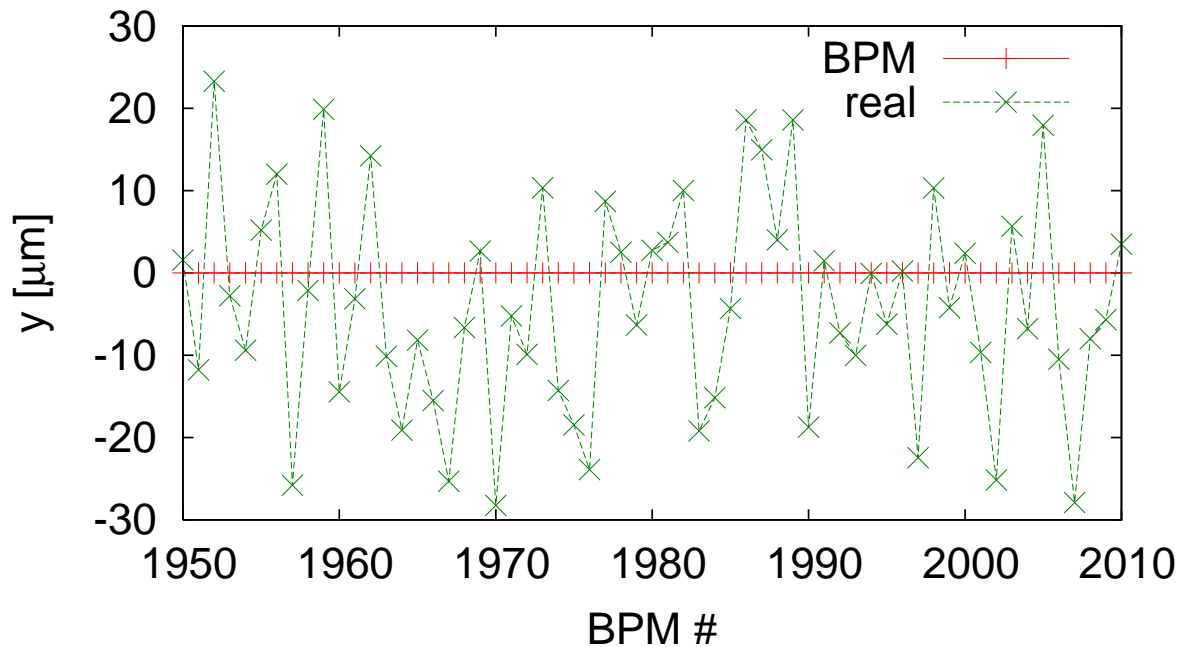
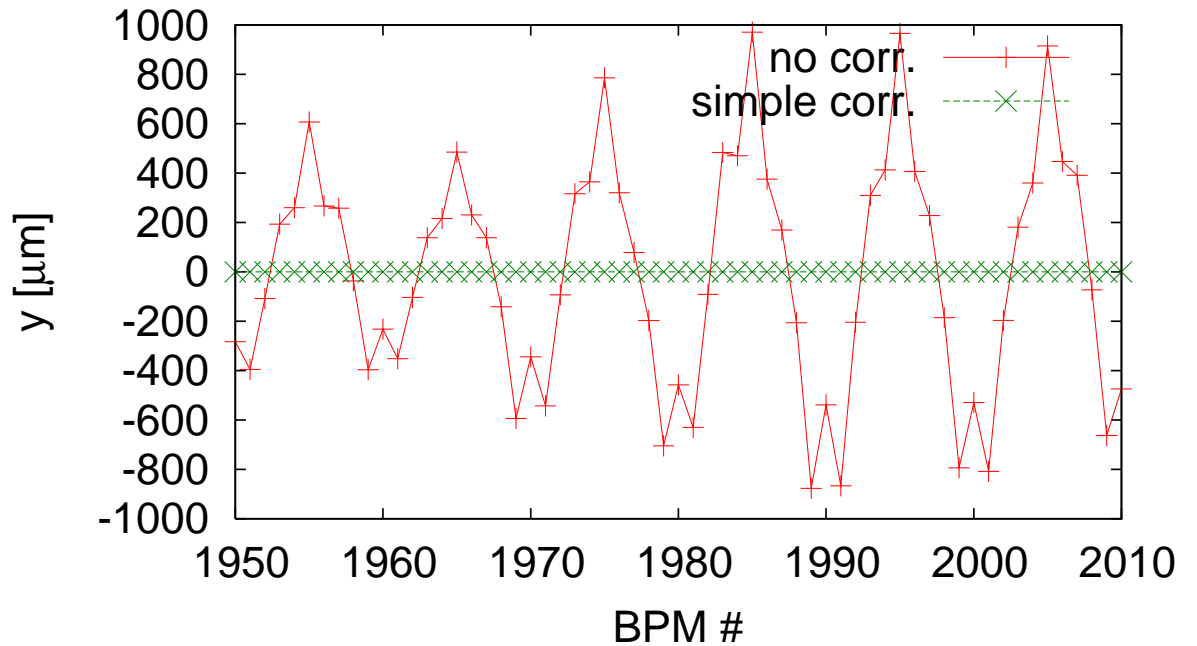
BPM Readings in One-To-One Correction (CLIC)

- Beam position in BPMs before and after one-to-one correction shown
 - after corrections no offsets remain
- Real position of beam shown in lower plot
 - BPMs are misaligned



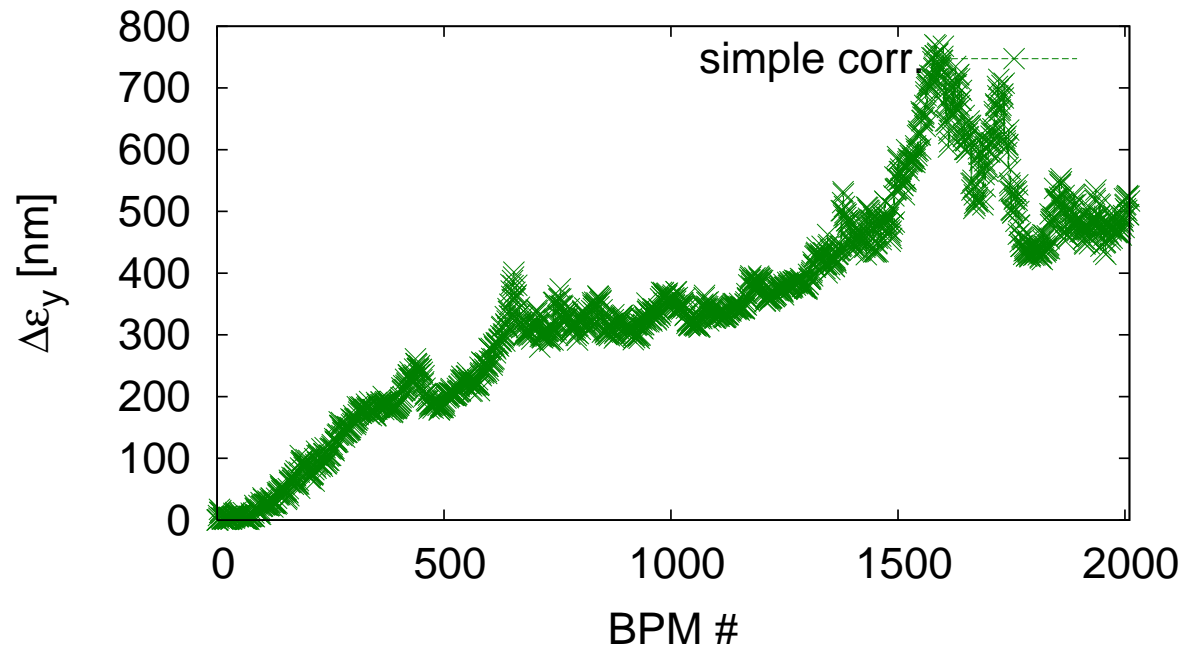
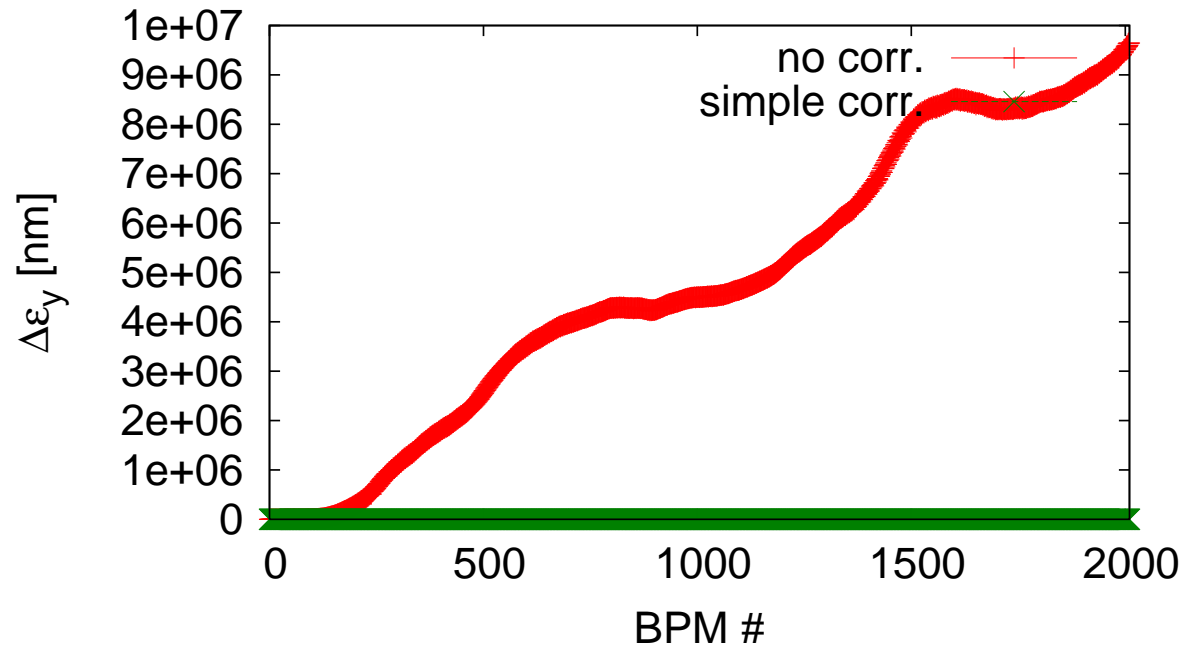
BPM Readings

- Beam position in BPMs before and after one-to-one correction shown
 - after corrections no offsets remain
- Real position of beam shown in lower plot
 - BPMs are misaligned



Emittance Growth

- Initial emittance growth is enormous
- After one-to-one correction growth is still large



Comparison Before and After One-To-One (ILC)

- The huge impact of the quadrupoles is mitigated using one-to-one alignment
 - each corrector is used to centre the beam in the next BPM downstream

⇒ The problem of the quadrupoles is solved but now we have a BPM problem

Error	with respect to	value	$\Delta\gamma\epsilon_y$ [nm]	$\Delta\gamma\epsilon_{y,121}$ [nm]
Cavity offset	module	300 μm	3.5	0.2
Cavity tilt	module	300 μradian	2600	< 0.1
BPM offset	module	300 μm	0	360
Quadrupole offset	module	300 μm	700000	0
Quadrupole roll	module	300 μradian	2.2	2.2
Module offset	perfect line	200 μm	250000	155
Module tilt	perfect line	20 μradian	880	1.7

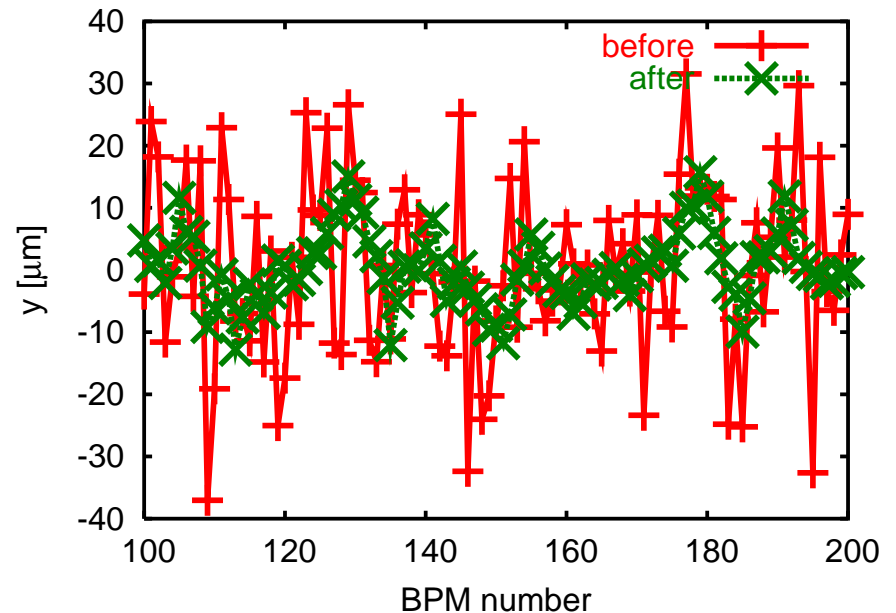
Static Tolerances and Accuracies for One-To-One Correction

Element	error	with respect to	tolerance	
			CLIC	ILC
Structure	offset	beam	$5.8 \mu\text{m}$	$\approx 700 \mu\text{m}$
Structure	tilt	beam	$220 \mu\text{radian}$	$\approx 1000 \mu\text{radian}$
Quadrupole	offset	straight line	—	—
Quadrupole	roll	axis	$240 \mu\text{radian}$	$190 \mu\text{radian}$
BPM	offset	straight line	$0.44 \mu\text{m}$	$15 \mu\text{m}$
BPM	resolution	BPM center	$0.44 \mu\text{m}$	$15 \mu\text{m}$

Element	error	with respect to	alignment	
			ILC	CLIC
Structure	offset	girder	$300 \mu\text{m}$	$10 \mu\text{m}$
Structure	tilts	girder	$300 \mu\text{radian}$	$200(*) \mu\text{m}$
Girder	offset	survey line	$200 \mu\text{m}$	$9.4 \mu\text{m}$
Girder	tilt	survey line	$20 \mu\text{radian}$	$9.4 \mu\text{radian}$
Quadrupole	offset	girder/survey line	$300 \mu\text{m}$	$17 \mu\text{m}$
Quadrupole	roll	survey line	$300 \mu\text{radian}$	$\leq 100 \mu\text{radian}$
BPM	offset	girder/survey line	$300 \mu\text{m}$	$14 \mu\text{m}$
BPM	resolution	BPM center	$\approx 1 \mu\text{m}$	$0.1 \mu\text{m}$
Wakefield mon.	offset	wake center	—	$5 \mu\text{m}$

Dispersion Free Correction

- Basic idea: use different beam energies
- NLC: switch on/off different accelerating structures
- CLIC (ILC): accelerate beams with different gradient and initial energy
 - try to do this in a single pulse (time resolution)



- Optimise trajectories for different energies together:

$$S = \sum_{i=1}^n \left(w_i (x_{i,1})^2 + \sum_{j=2}^m w_{i,j} (x_{i,1} - x_{i,j})^2 \right) + \sum_{k=1}^l w'_k (c_k)^2$$

- Last term is omitted
- Idea is to mimic energy differences that exist in the bunch with different beams

Simple DFS Example

- BPM in the centre is misaligned by y_0
 - first corrector moves beam by $c = L\delta$ in this position
 - second (-2δ) and third (δ) correctors remove oscillation

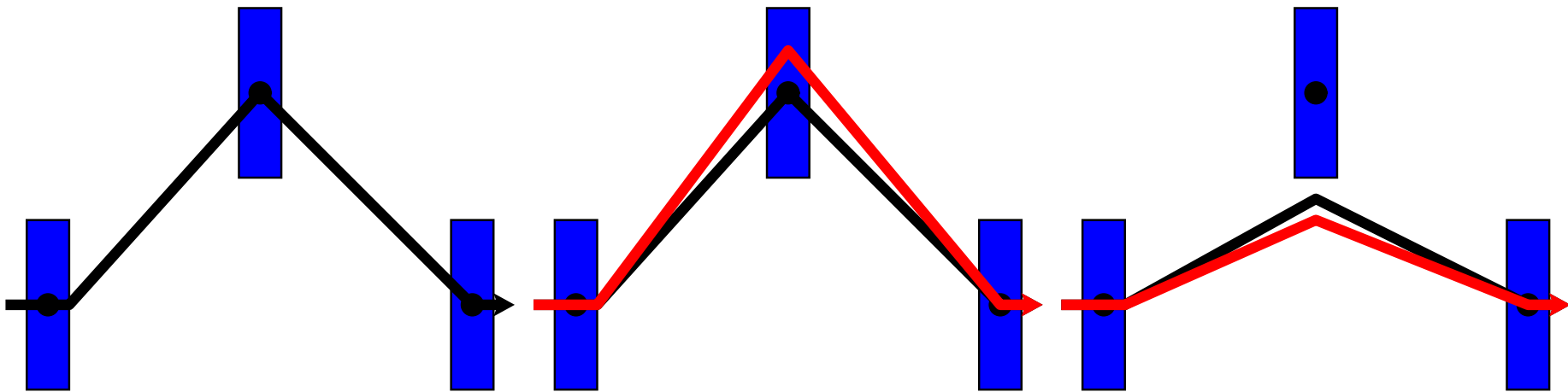
- We minimise

$$(c - y_0)^2 + w \left(c \frac{\Delta E}{E} \right)^2$$

which yields

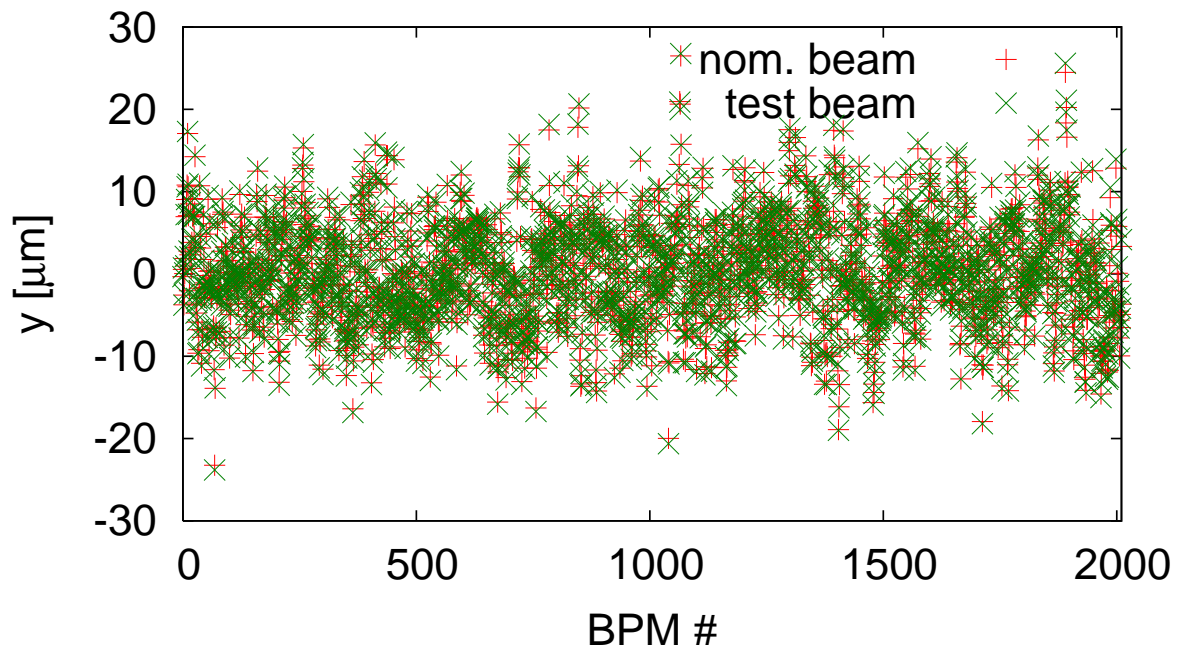
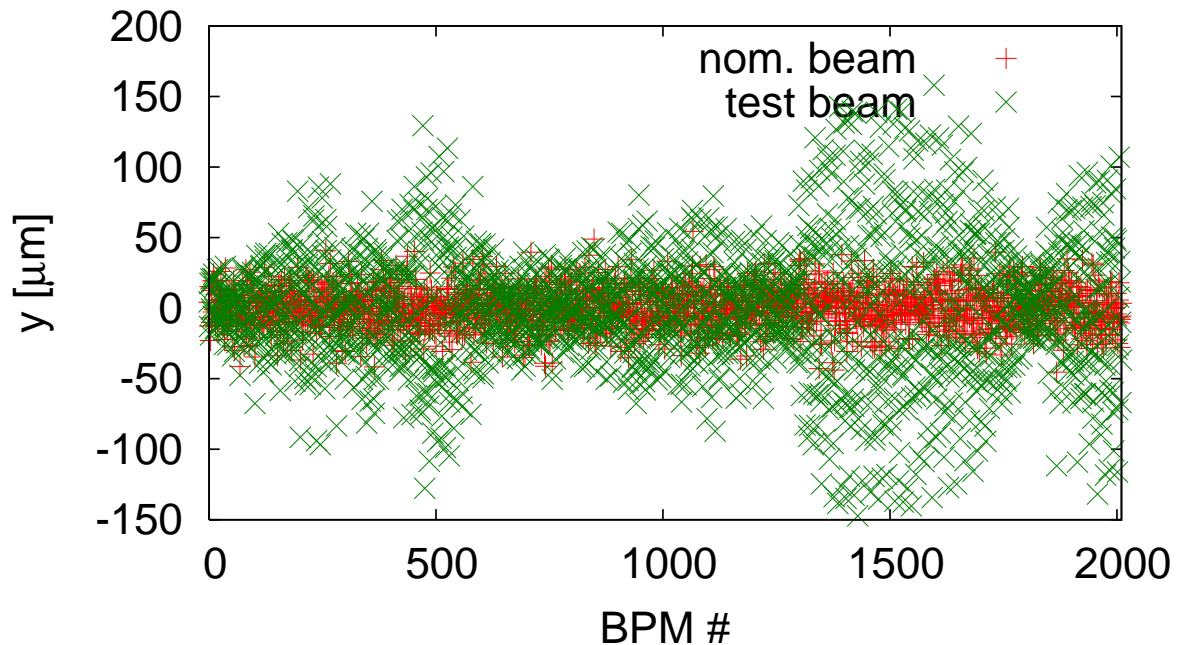
$$0 = \frac{\partial}{\partial c} (c - y_0)^2 + w \left(c \frac{\Delta E}{E} \right)^2 \quad (1)$$

$$c = \frac{y_0}{1 + w \left(\frac{\Delta E}{E} \right)^2} \quad (2)$$



Dispersion Free Correction BPM Readings

- In the one-to-one corrected machine an off-energy beam takes a very different trajectory
 - this dispersion is visible in the BPMs and is a cause of emittance growth
- After DFS the trajectories of different energy beams are very similar
 - smoother trajectory found



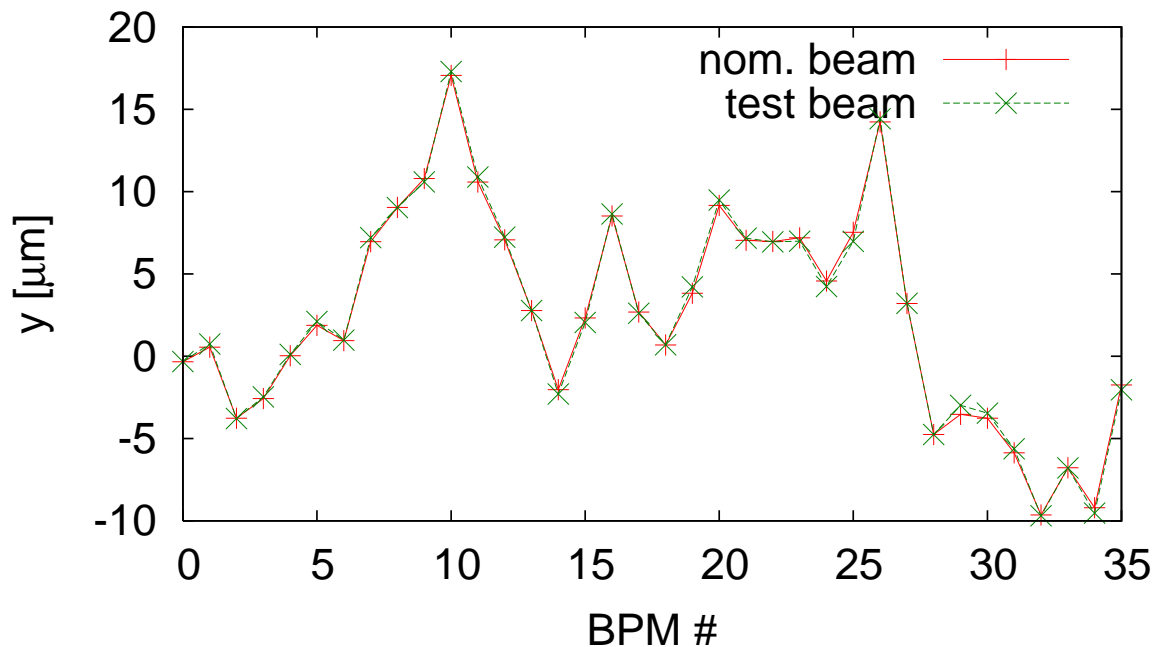
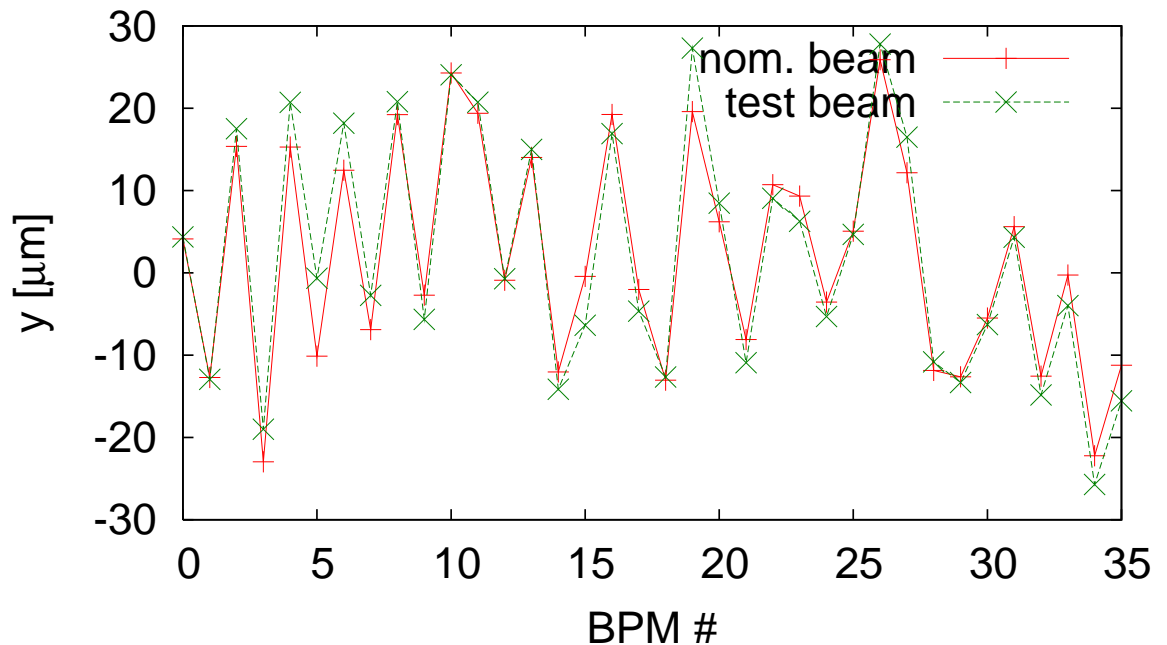
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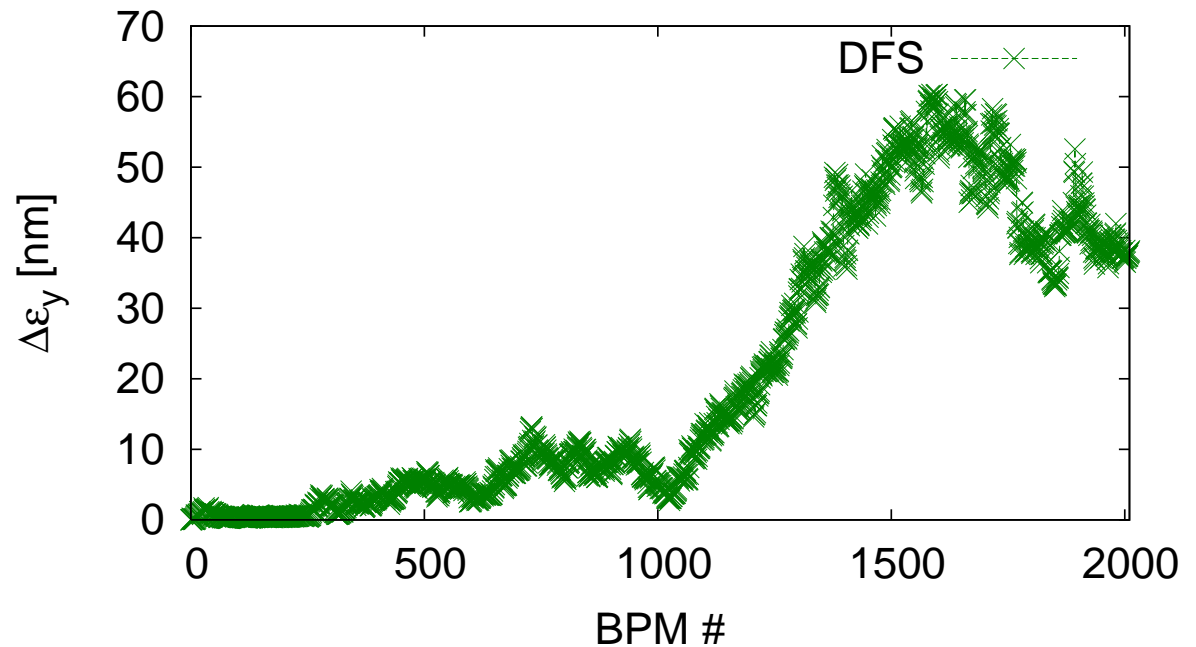
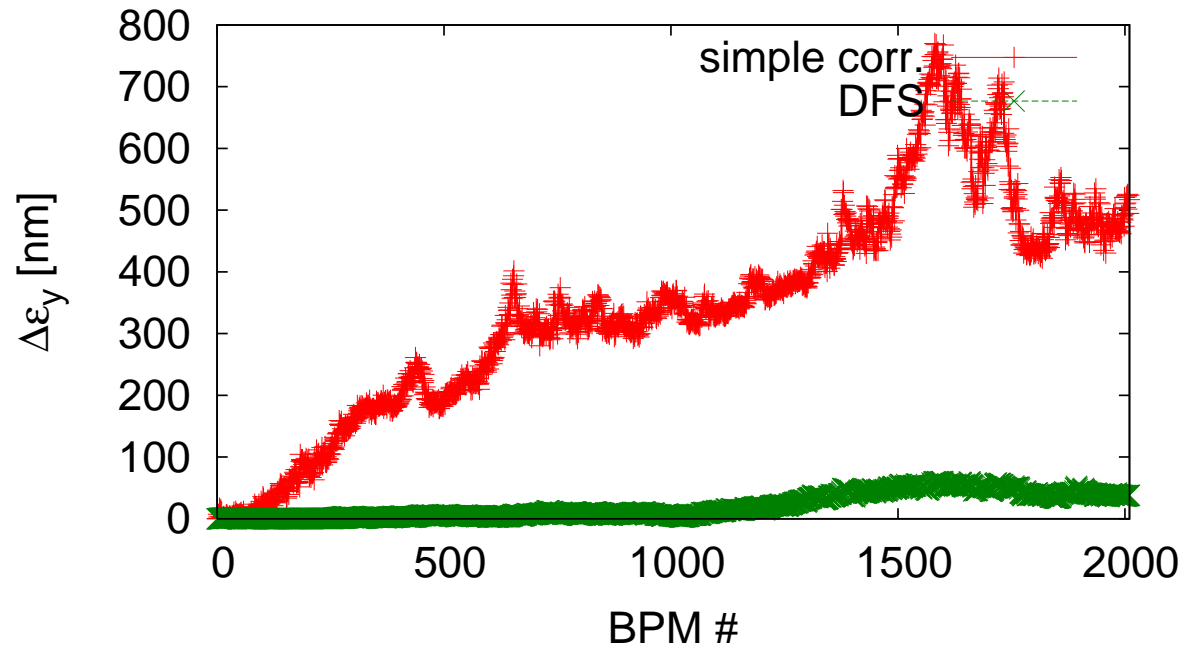
- After DFS the trajectories of different energy beams are very similar

- smoother trajectory found



Dispersion Free Correction Emittance

- The emittance growth is largely reduced by DFS
 - but still too large
- Main cause of emittance growth
 - trajectory is smooth but not well centred in the structures
 - effective coherent structure offset
 - structure initial scatter remains uncorrected



Emittance Growth (ILC)

Error	with respect to	value	$\Delta\gamma\epsilon_y$ [nm]	$\Delta\gamma\epsilon_{y,121}$ [nm]	$\Delta\gamma\epsilon_{y,dfs}$ [nm]
Cavity offset	module	300 μm	3.5	0.2	0.2(0.2)
Cavity tilt	module	300 μradian	2600	< 0.1	1.8(8)
BPM offset	module	300 μm	0	360	4(2)
Quadrupole offset	module	300 μm	700000	0	0(0)
Quadrupole roll	module	300 μradian	2.2	2.2	2.2(2.2)
Module offset	perfect line	200 μm	250000	155	2(1.2)
Module tilt	perfect line	20 μradian	880	1.7	—

- The results of the reference DFS method is quoted, results of a different implementation in brackets
- Note in the simulations the correction the quadrupoles had been shifted, otherwise some residual effect of the quadrupole misalignment would exist

Beam-Based Structure Alignment (CLIC only)

- Each structure is equipped with a wakefield monitor (RMS position error $5 \mu\text{m}$)

- Up to eight structures on one movable girders

⇒ Align structures to the beam

- Assume identical wake fields
 - the mean structure to wakefield monitor offset is most important

- in upper figure monitors are perfect, mean offset structure to beam is zero after alignment

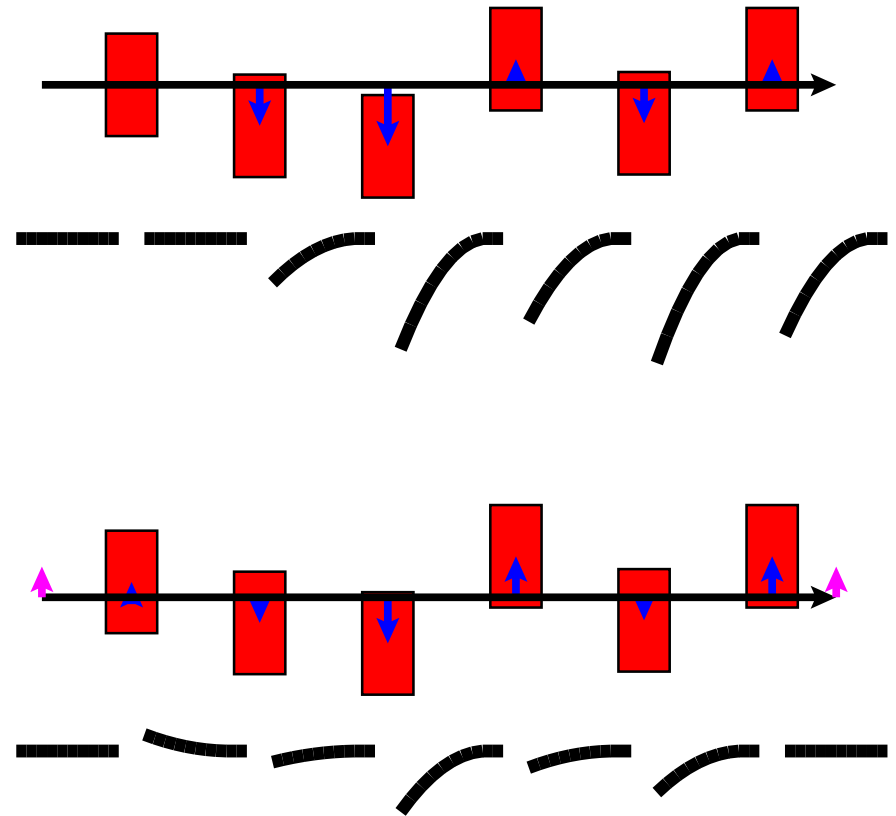
- scatter around mean does not matter a lot

- With scattered monitors

- final mean offset is σ_{wm}/\sqrt{n}

- In the current simulation each structure is moved independently

- A study has been performed to move the articulation points

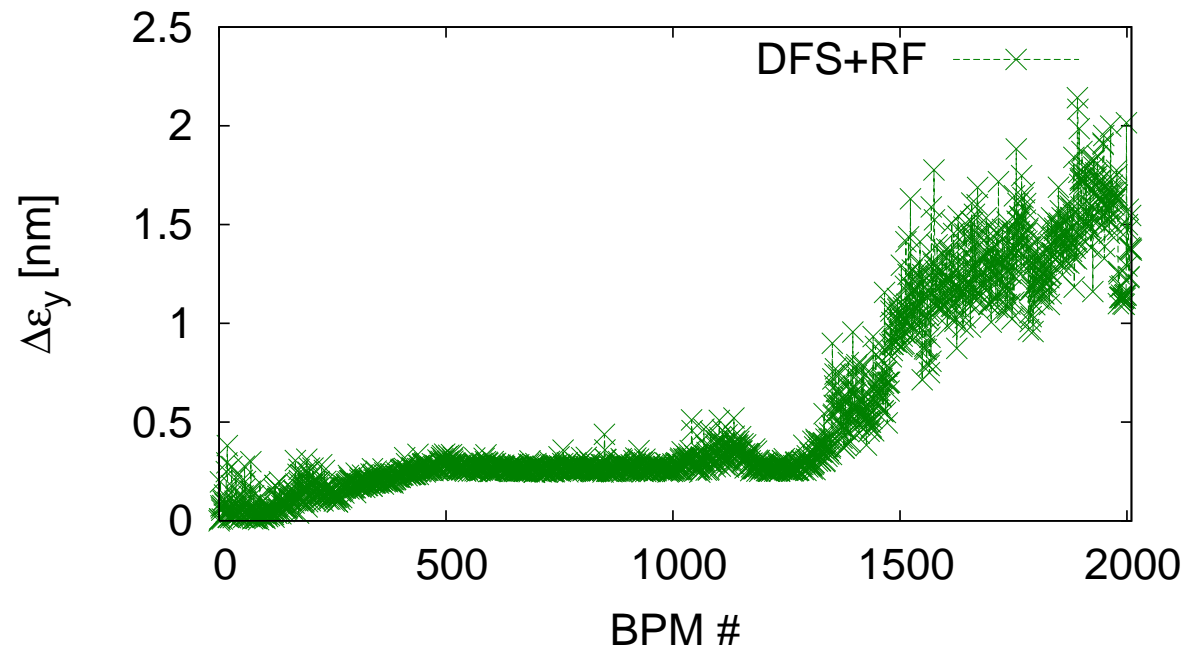
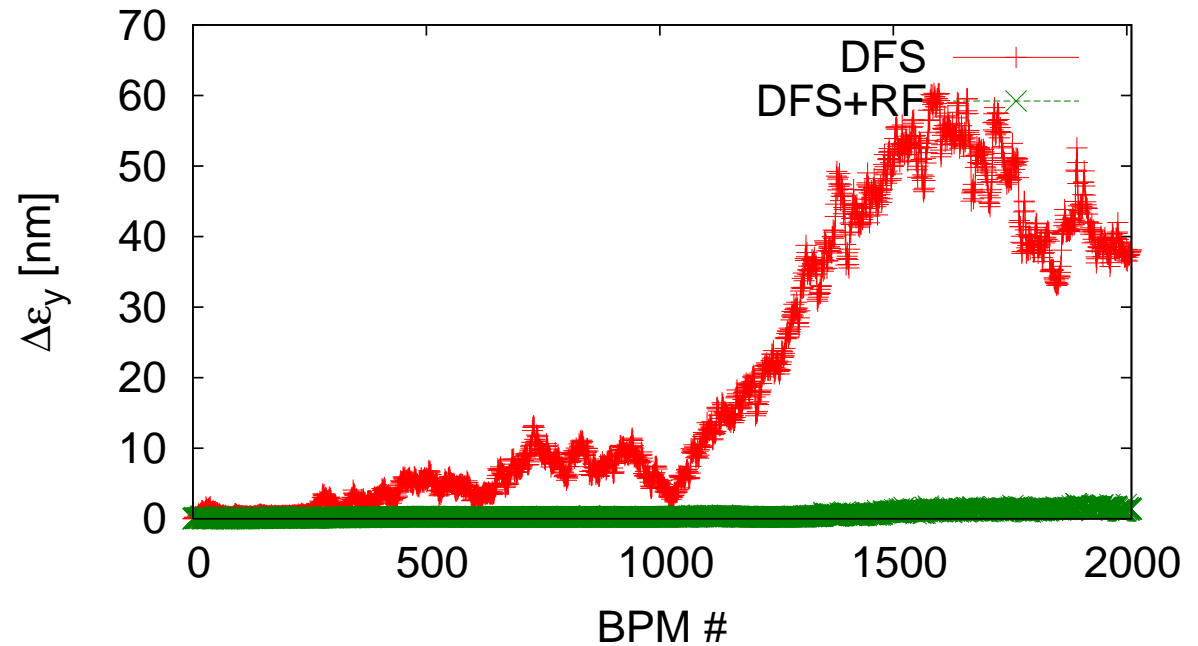
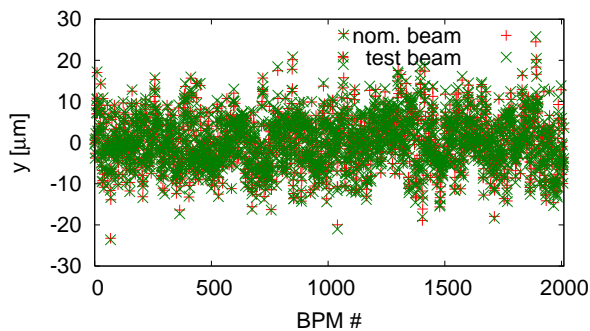


- For our tolerance $\sigma_{wm} = 5 \mu\text{m}$ we find $\Delta\epsilon_y \approx 0.5 \text{ nm}$

- some dependence on alignment method

Structure Alignment

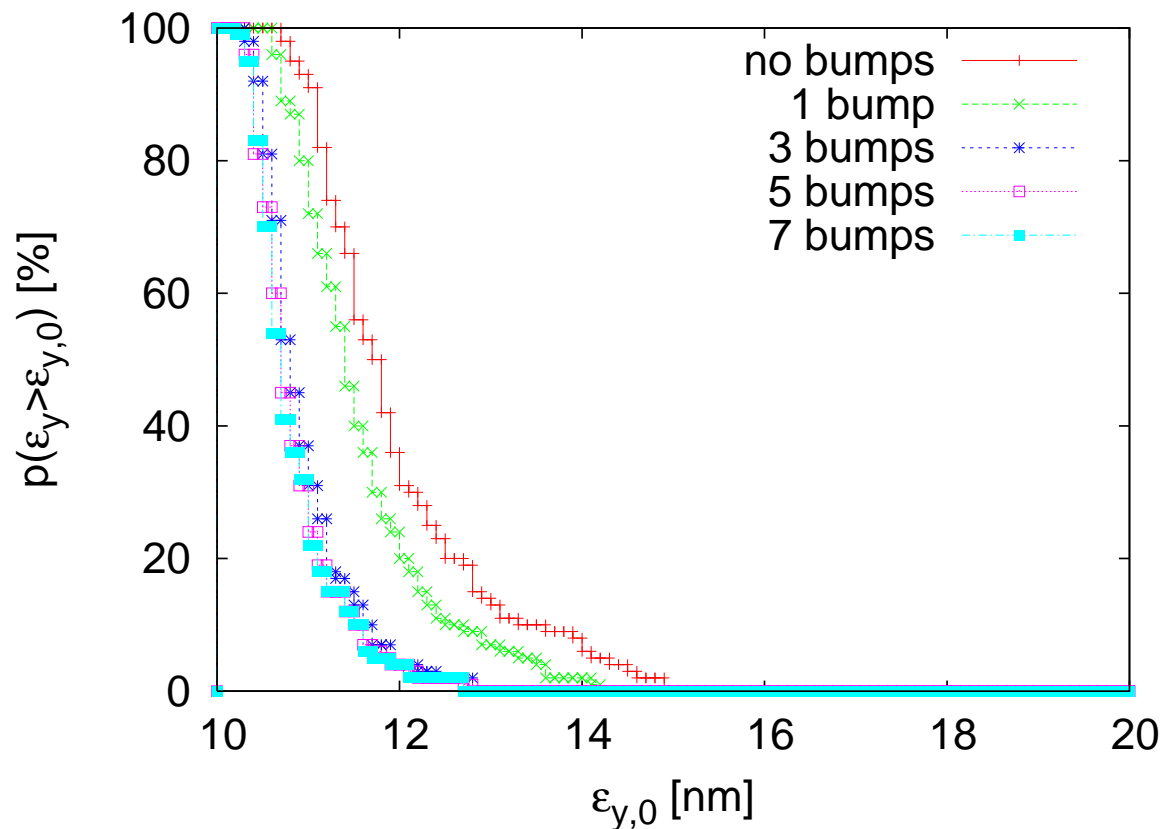
- Beam trajectory is hardly changed by structure alignment
 - beam is re-steered into BPMs
- But emittance growth is strongly reduced



Final Emittance Growth (CLIC)

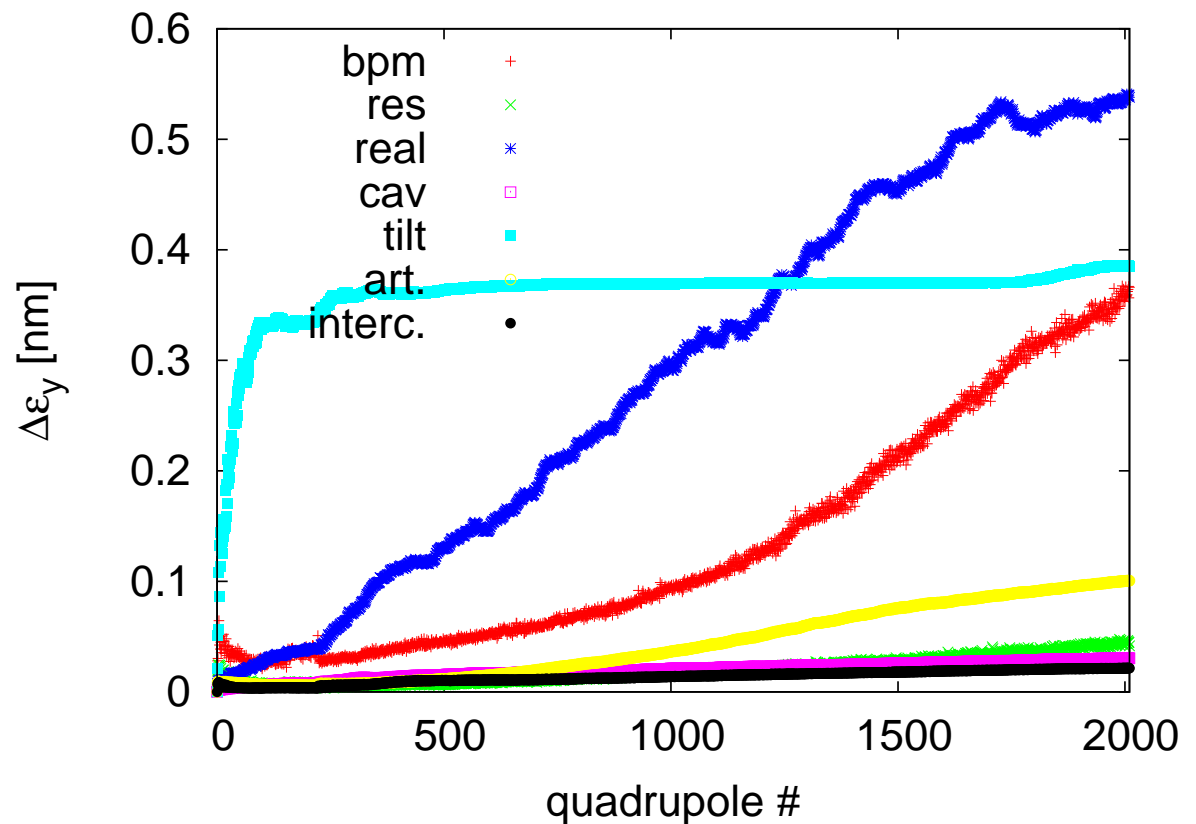
imperfection	with respect to	symbol	value	emitt. growth
BPM offset	wire reference	σ_{BPM}	14 μm	0.367 nm
BPM resolution		σ_{res}	0.1 μm	0.04 nm
accelerating structure offset	girder axis	σ_4	10 μm	0.03 nm
accelerating structure tilt	girder axis	σ_t	200 μradian	0.38 nm
articulation point offset	wire reference	σ_5	12 μm	0.1 nm
girder end point	articulation point	σ_6	5 μm	0.02 nm
wake monitor	structure centre	σ_7	5 μm	0.54 nm
quadrupole roll	longitudinal axis	σ_r	100 μradian	≈ 0.12 nm

- Selected a good DFS implementation
 - trade-offs are possible
- Multi-bunch wakefield misalignments of 10 μm lead to $\Delta\epsilon_y \approx 0.13$ nm
- Performance of local pre-alignment is acceptable



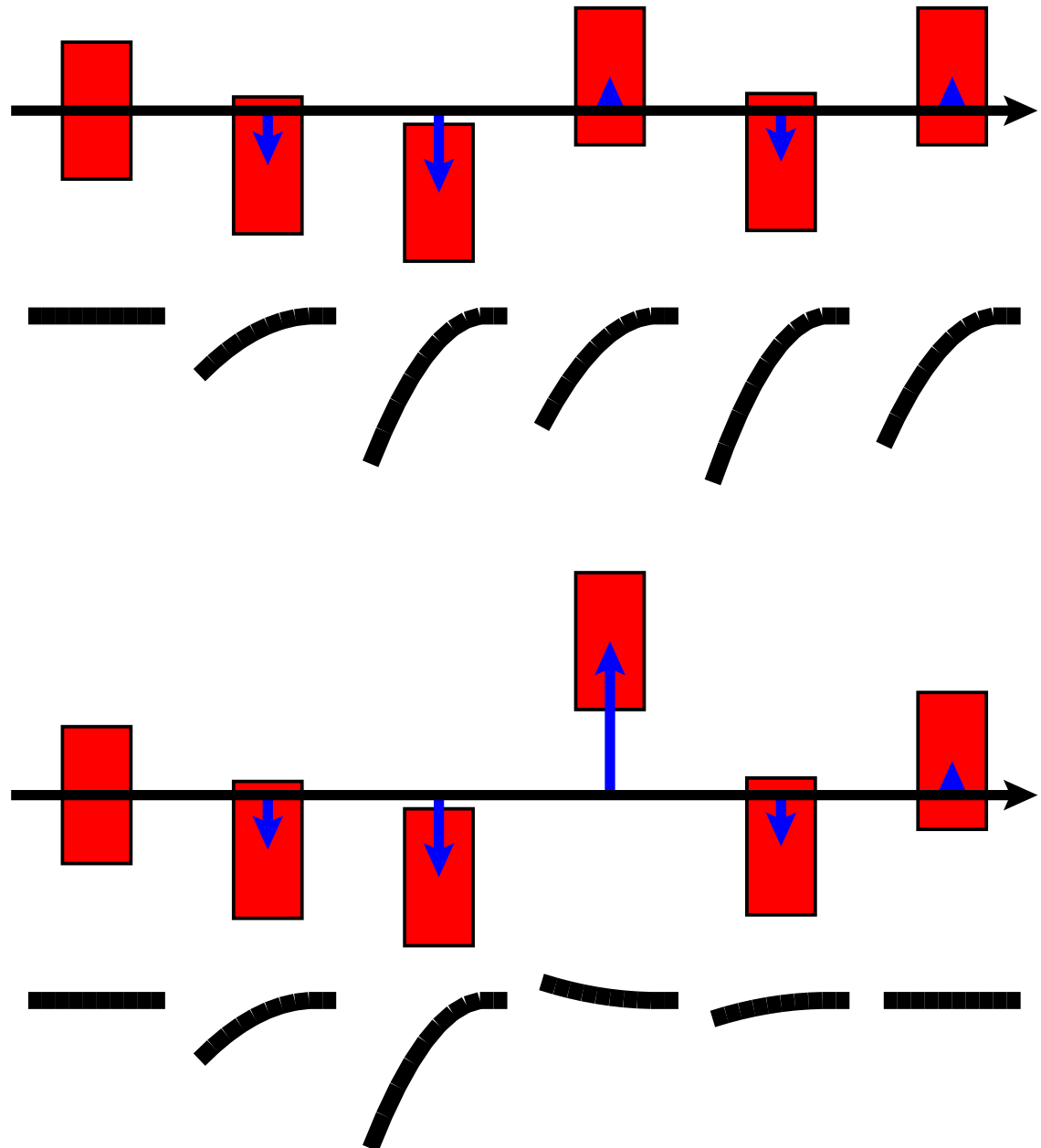
Growth Along Main Linac

- Emittance growth along the main linac due to the different imperfections
- Growth is mainly constant per cell
 - follows from first principles applied during lattice design
- Exception is structure tilt
 - due to uncorrelated energy spread
 - flexible weight to be investigated
- Some difference for BPMs
 - due to secondary emittance growth



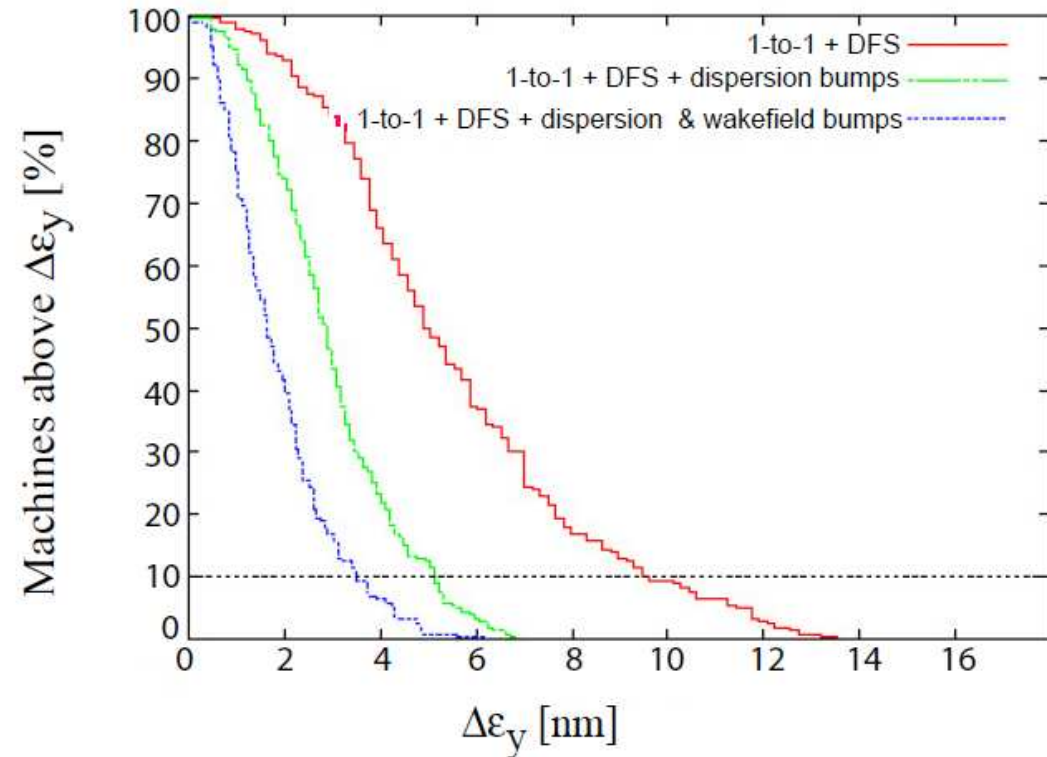
Emittance Tuning Bumps

- Emittance (or luminosity) tuning bumps can further improve performance
 - globally correct wake-field by moving some structures
 - similar procedure for dispersion
- Need to monitor beam size
- Optimisation procedure
 - measure beam size for different bump settings
 - make a fit to determine optimum setting
 - apply optimum
 - iterate on next bump



Tuning Bumps (ILC)

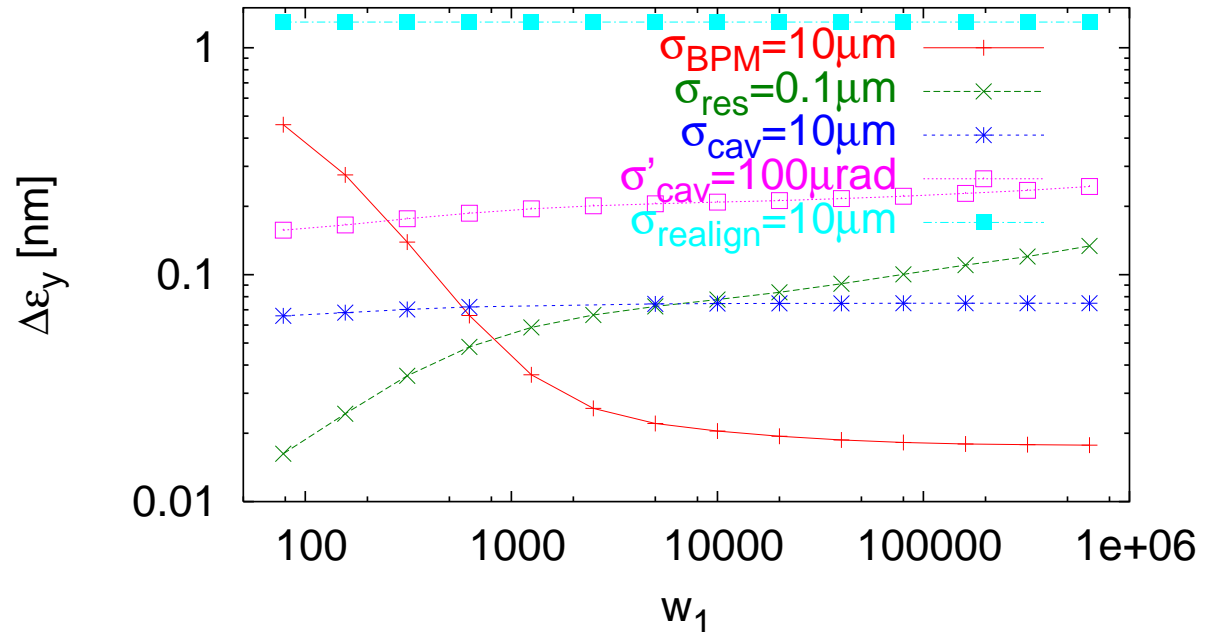
- The emittance growth after dispersion steering is still too large
 - ⇒ further improvement needed
- Possible solutions are emittance tuning bumps
 - measure the beam size after the main linac, i.e. with a laser wire
 - modify the beam dispersion at the beginning and end of the main linac to minimise beam size



P. Eliasson et al.

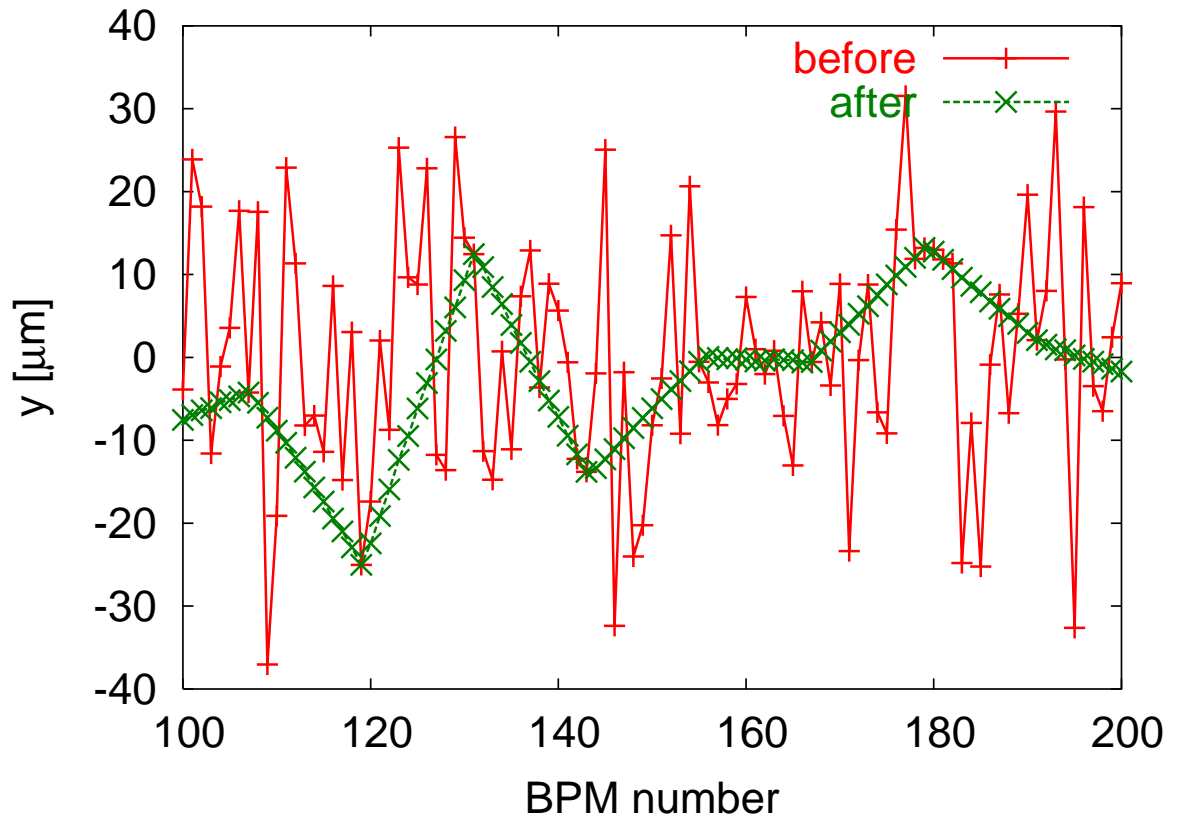
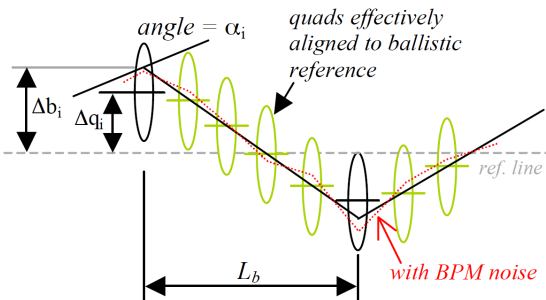
Remark: Dependence on Weights (Old CLIC Parameters)

- For TRC parameters set
 - One test beam is used with a different gradient and a different incoming beam energy
- ⇒ BPM position errors are less important at large w_1
- ⇒ BPM resolution is less important at small w_1
- ⇒ Need to find a compromise
- ⇒ Cannot give “the” tolerance for one error source



Ballistic Alignment

- Beam-line is divided into bins (12 quadrupoles)
- Quadrupoles in a bin are switched off
- Beam is steered into last BPM of bin
- BPMs are realigned to beam
- Quadrupoles are switched on
- Few-to-few steering is used



- Typical problems are residual fields

Kick Minimisation

- First align BPMs to quadrupoles
 - shunt quadrupole field
 - observe beam motion
 - move quadrupole/beam to a position that shunting does not kick beam any more
 - beam now defines BPM target reading in quadrupole
- Now minimise target function

$$S = \sum_{i=1}^n (c_i^2 + wx_i^2)$$

- Main problem shift of quadrupole centre with strength

Misalignment of BPM to Quadrupole due to Centre Motion

Initial deflection

$$x'_0 = Kx_0$$

deflection for shunted quadrupole

$$x'_1 = (K + \Delta K)(x_0 + \delta)$$

beam does not move if

$$x'_0 = x'_1$$

hence

$$\begin{aligned} Kx_0 &= (K + \Delta K)(x_0 + \delta) \\ \Rightarrow x_0 &= -\delta \frac{K + \Delta K}{K} \end{aligned}$$

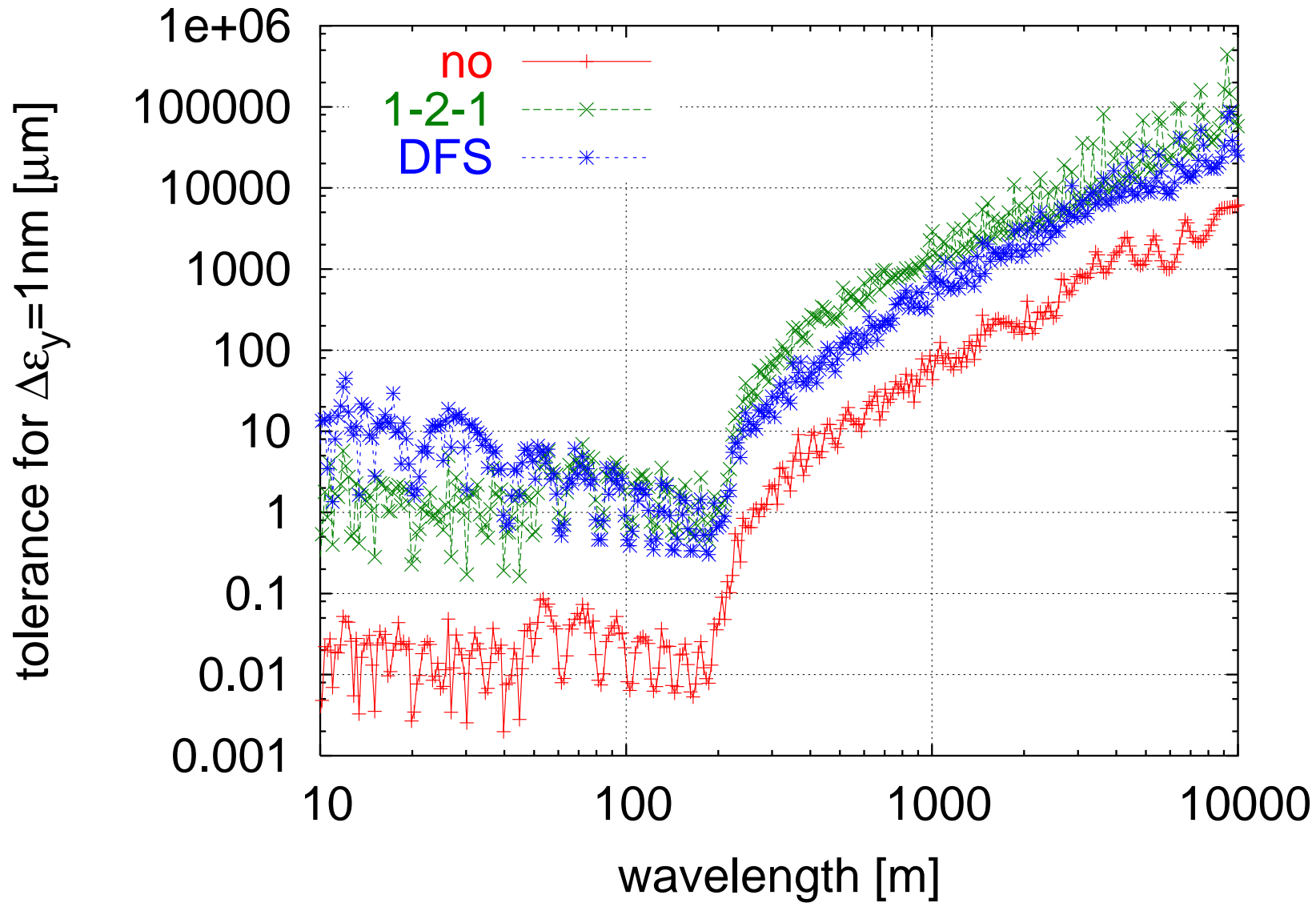
\Rightarrow As long as ΔK is small and $\delta \approx a\Delta K/K$

$$x_0 \approx -a$$

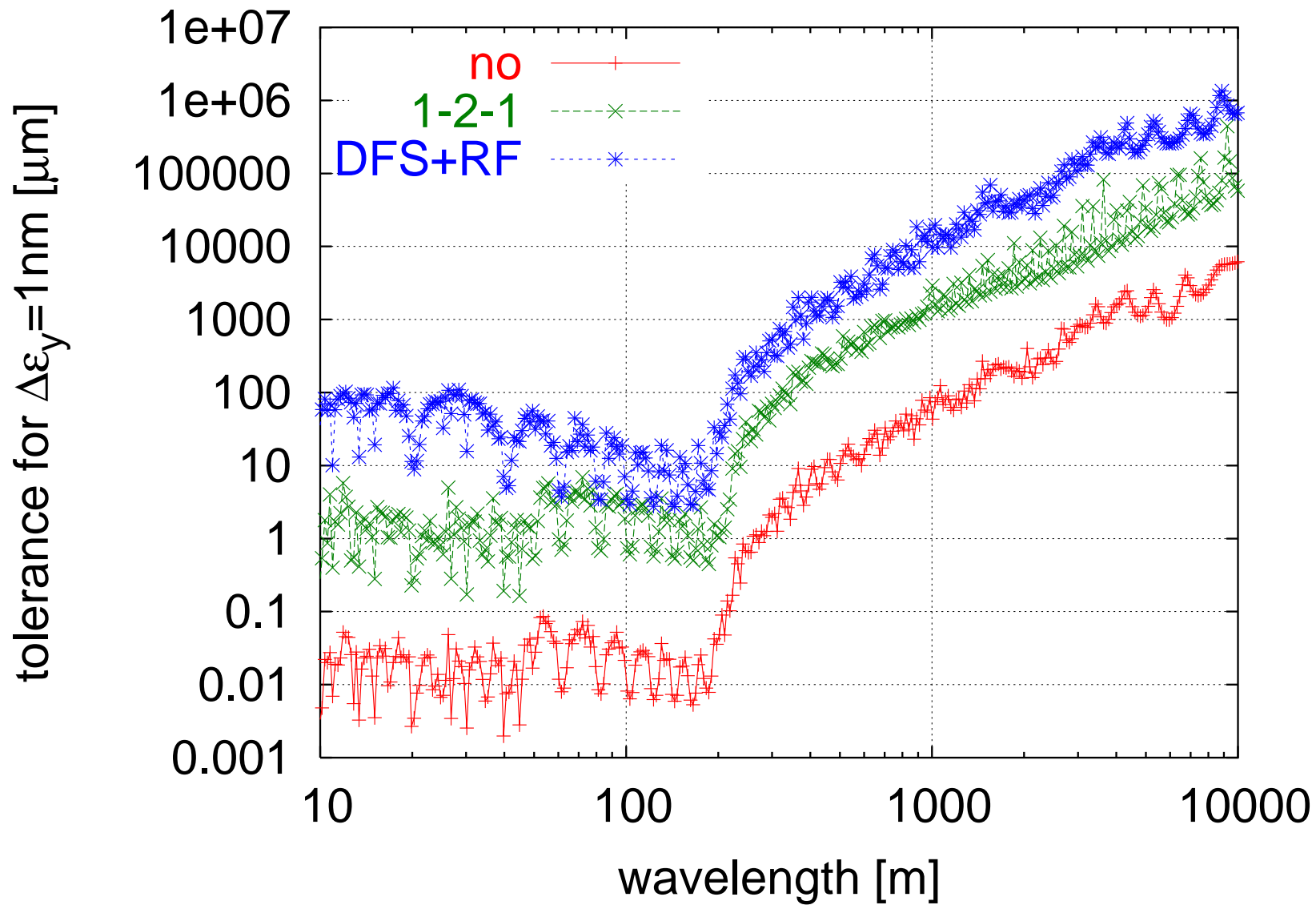
Long Distance Alignment

- In most simulations elements are scattered around a straight line
- In reality, the relative misalignments of different elements depends on their distance
- To be able to simulate this, our simulation code can read misalignments from a file
 - simulation of pre-alignment is required
- To illustrate long-wavelength misalignments, simulations have been performed
 - cosine like misalignment used

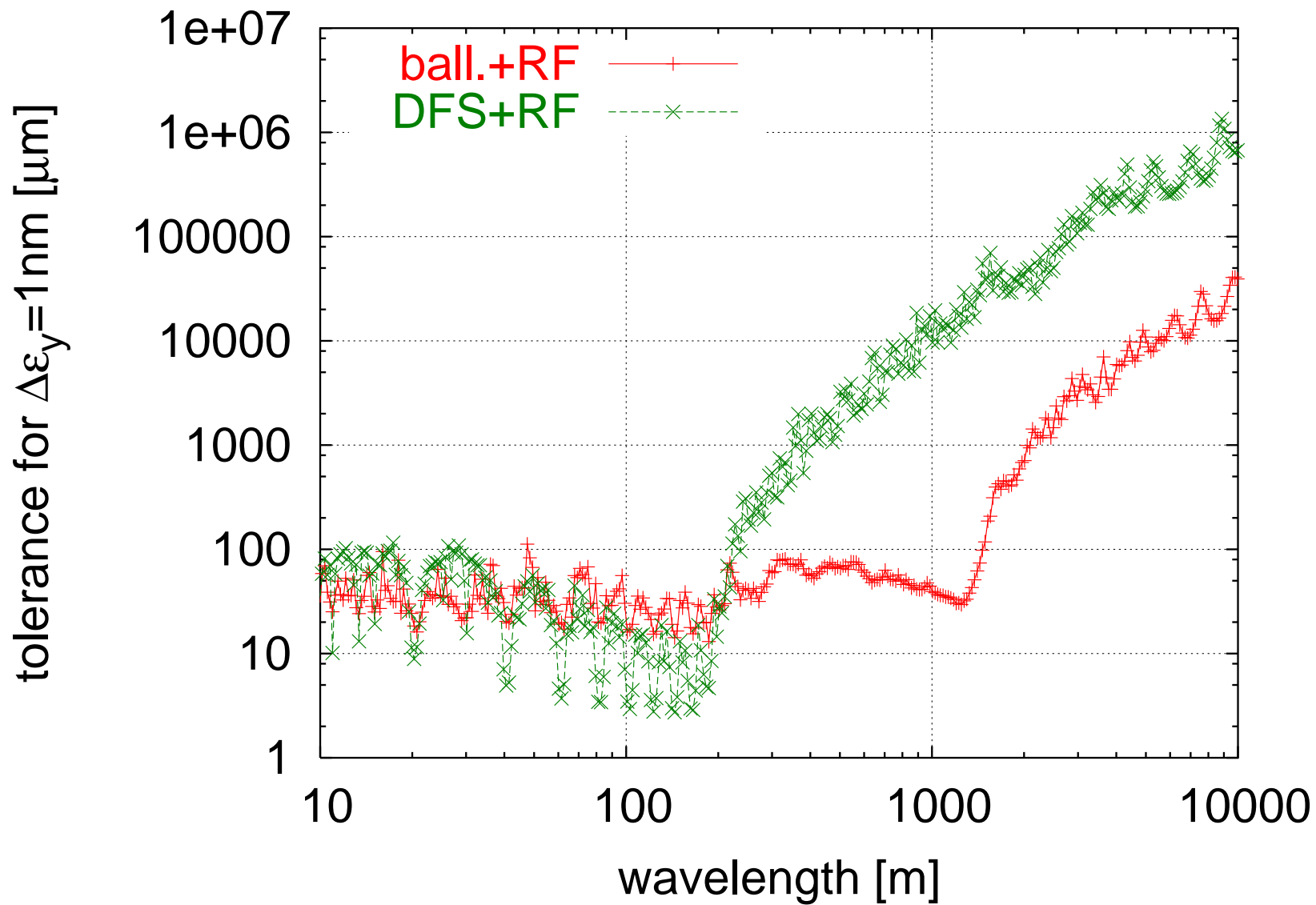
Long Wavelength Tolerance I (Old CLIC)



Long Wavelength Tolerance II (Old CLIC)

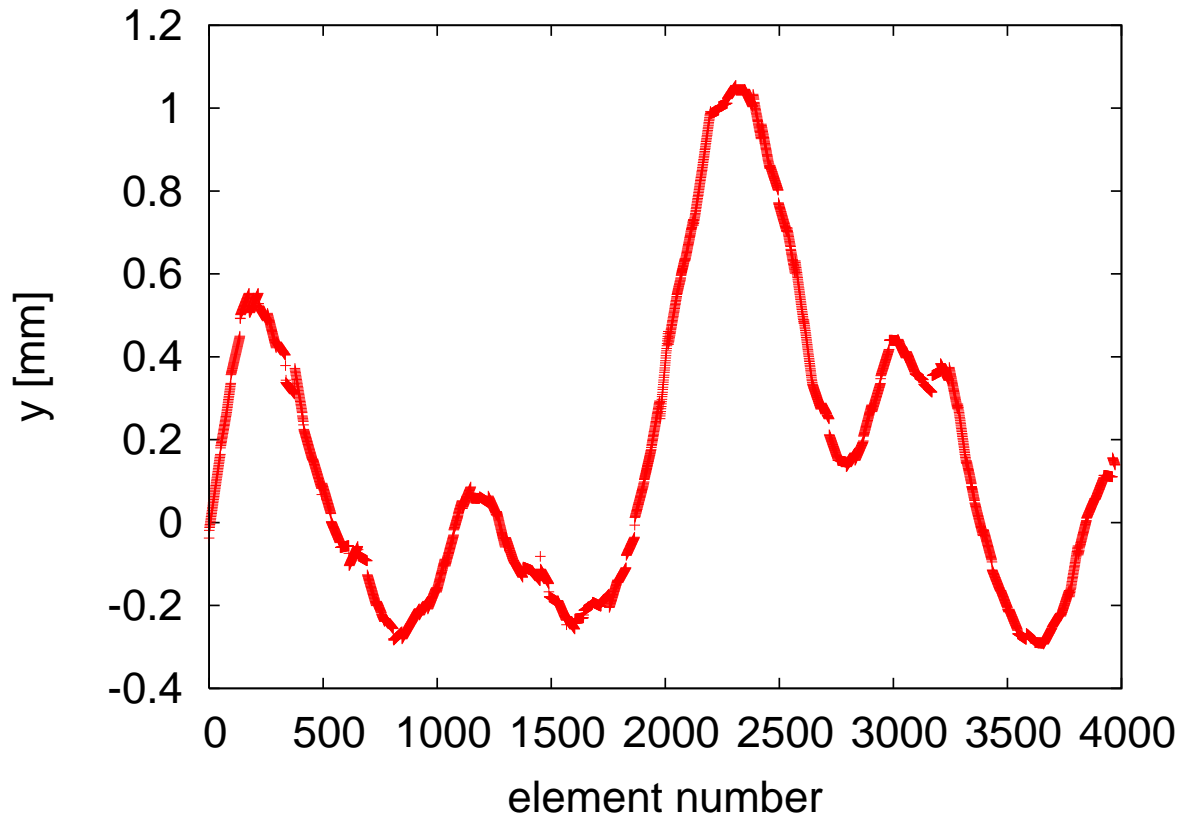


Long Wavelength Tolerance III (Old CLIC)



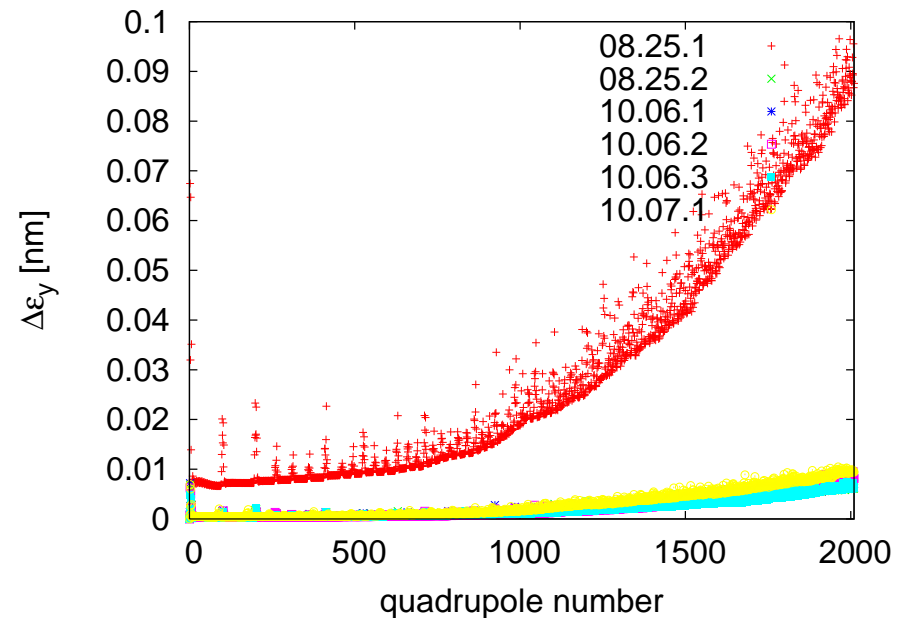
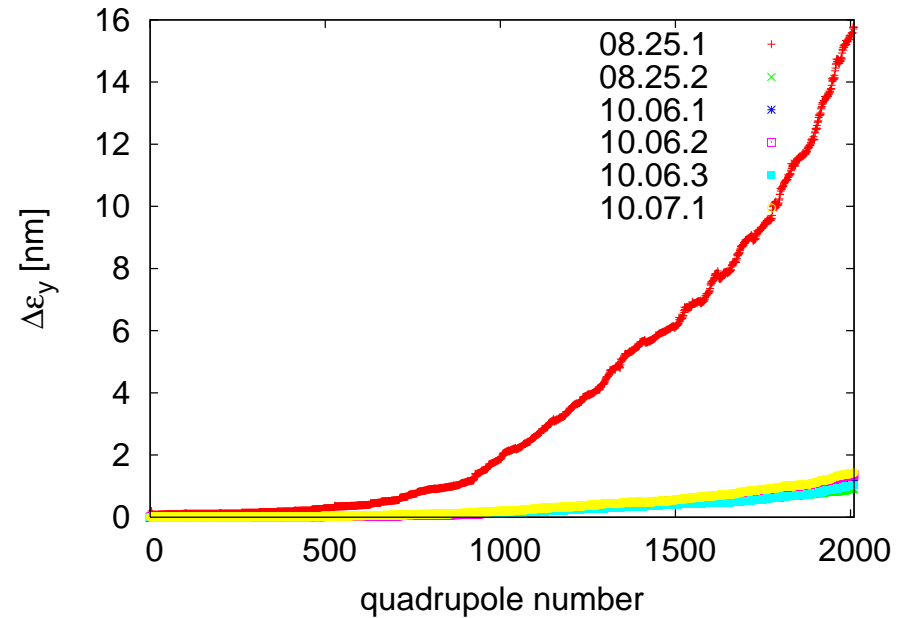
Wire System Misalignment Modelling

- Received a number of misalignments from Thomas
- Used 50 seeds for each error set
- Switched from one wire 1 to 2 at end point of 1 and back to 1 at end point of 2
- Used linear interpolation in between wire endpoints
 - no sag error
 - no error of geoid

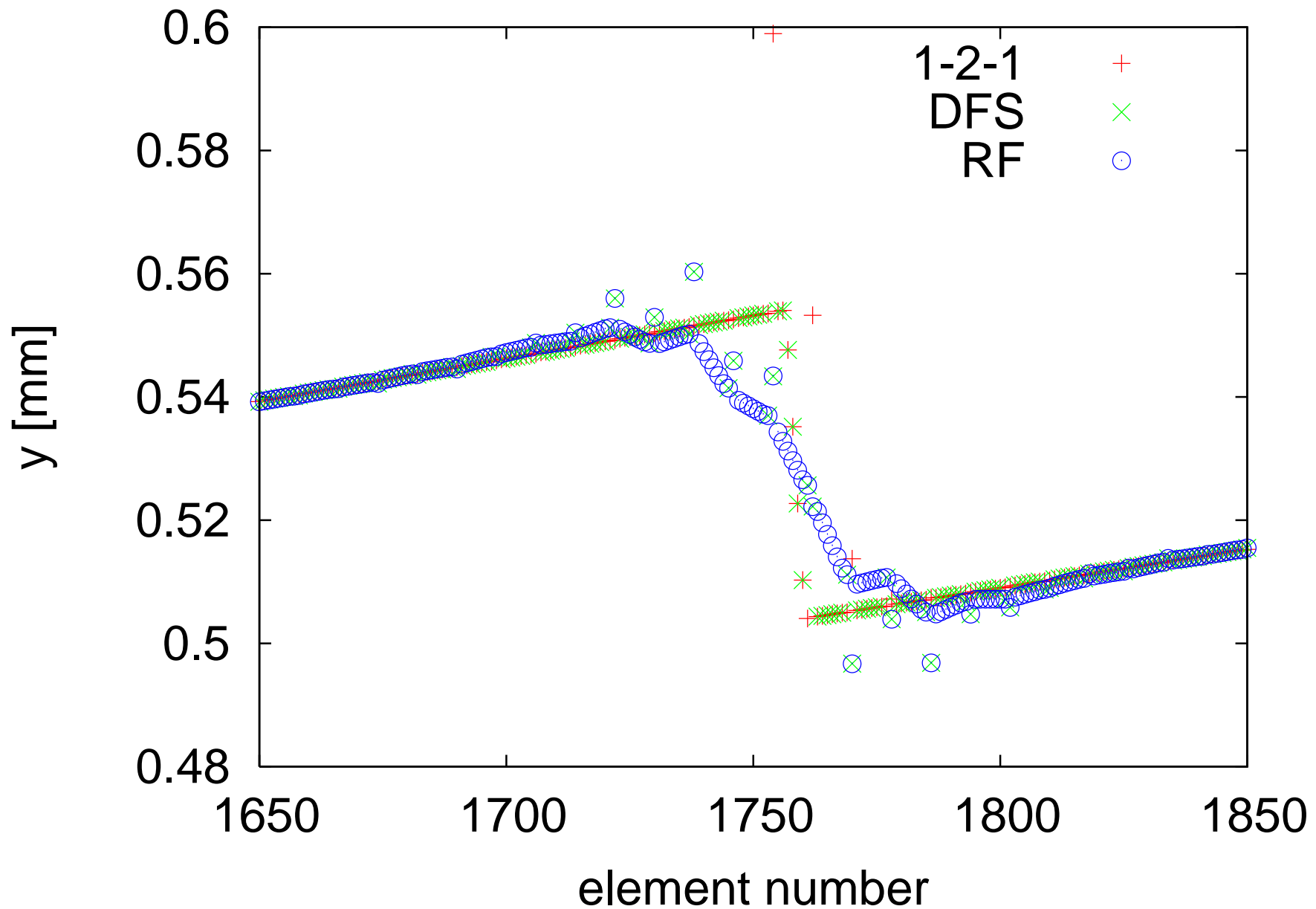


Beam-Based Alignment

- Flat steering used first
 - Dispersion free steering using settings from baseline algorithm
 - RF structure alignment
 - Different cases marked by date
- ⇒ RF Alignment is very important

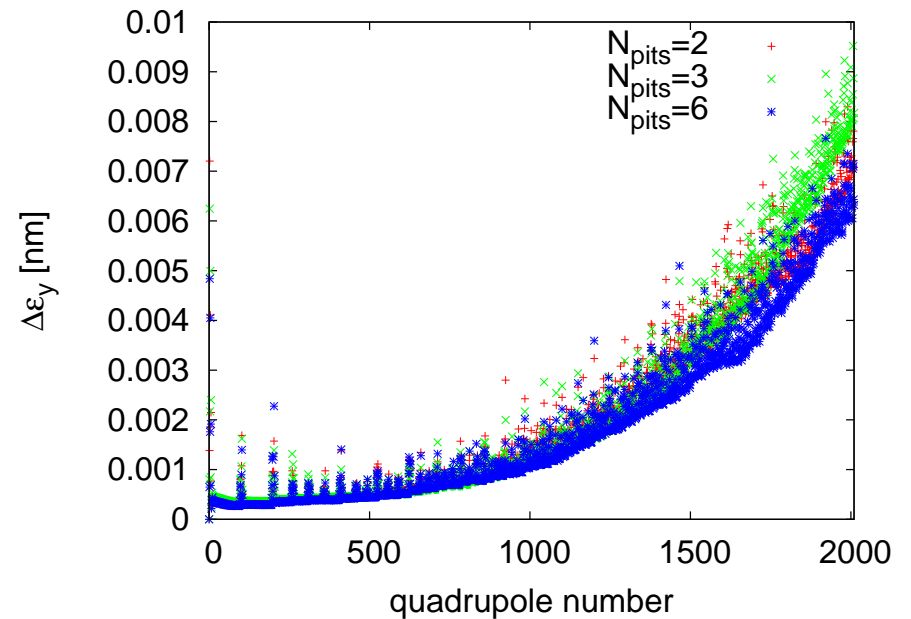
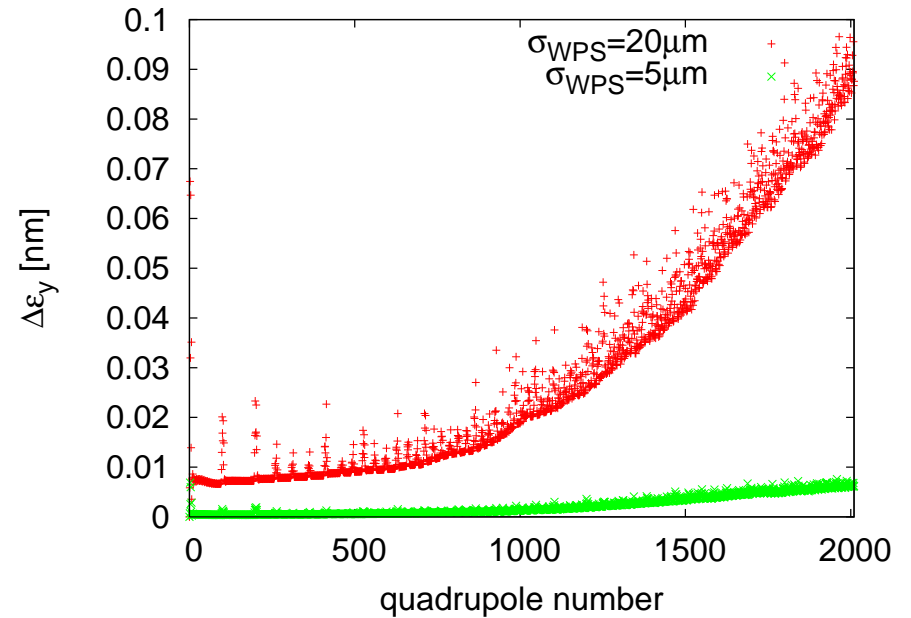


Impact on Element Positions



Preliminary Results

- ⇒ Significant impact of wire position sensor accuracy
- ⇒ Small impact of number of pits
- ⇒ The first results look very promising but more complete model being developed



Curved Main Linac (ILC)

Two main reasons why one might want to have a tunnel that follows the earth curvature

- one can stay close to the surface everywhere (but site dependent)
- in ILC, the helium level will follow the equipotential of the gravity

But there are some problems for the beam dynamics

- one needs to guide the beam on a curved orbit this requires introduction of dispersion
- the dispersion makes the machine operation more difficult

In ILC the arguments for the cryogenics were considered important, so a curved tunnel is chosen

In CLIC there was no benefit to go to a curved tunnel, so the laser-straight option is preferred.

Dispersion

- We deflect a particle of energy E_1 with a dipole corrector (offsetting a quadrupole has exactly the same effect)
the resulting deflection angle is

$$\delta'_1 \approx 0.3 \frac{\text{GeV}}{\text{Tm}^2} \frac{BL}{E_1}$$

If we have a second particle at a different energy E_2 it is deflected differently

$$\delta'_2 \approx 0.3 \frac{\text{GeV}}{\text{Tm}^2} \frac{BL}{E_2}$$

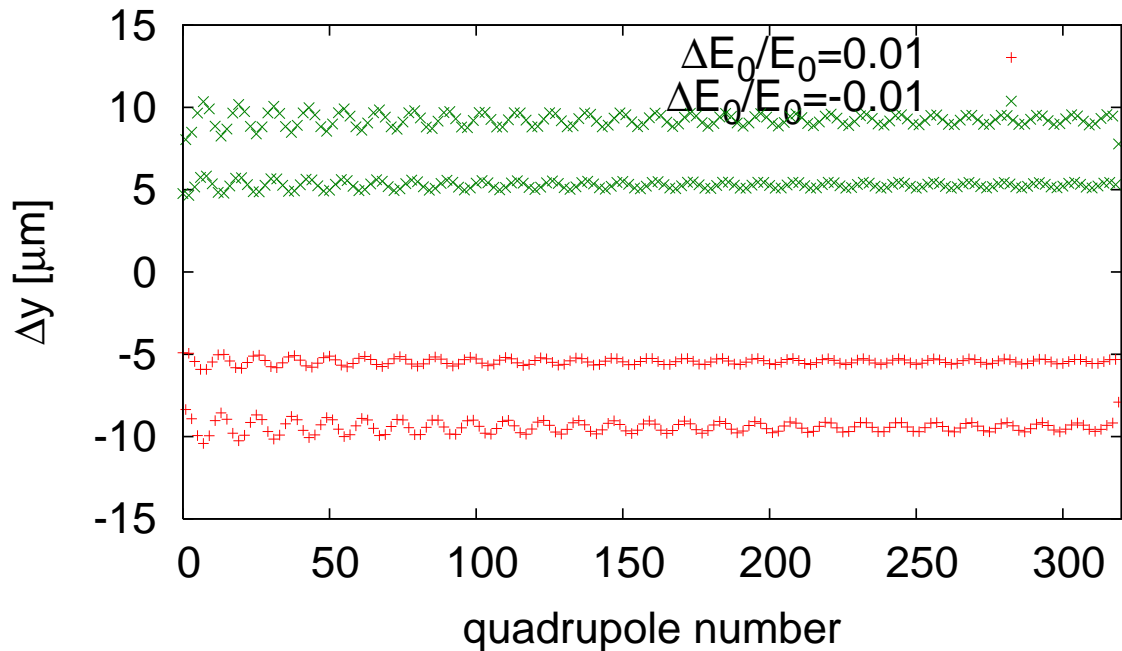
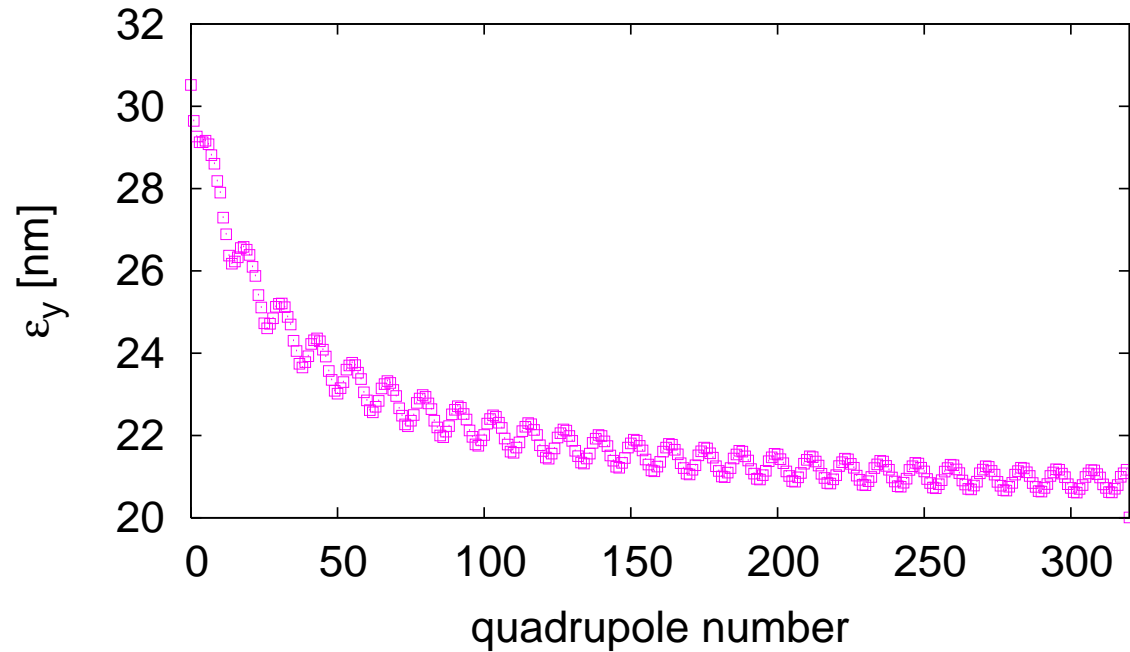
so the two particles will take different trajectories

The difference is described by the dispersion $D_{x,y}$ with

$$D_x = \frac{\partial x}{\partial \delta} \quad D_y = \frac{\partial y}{\partial \delta}$$

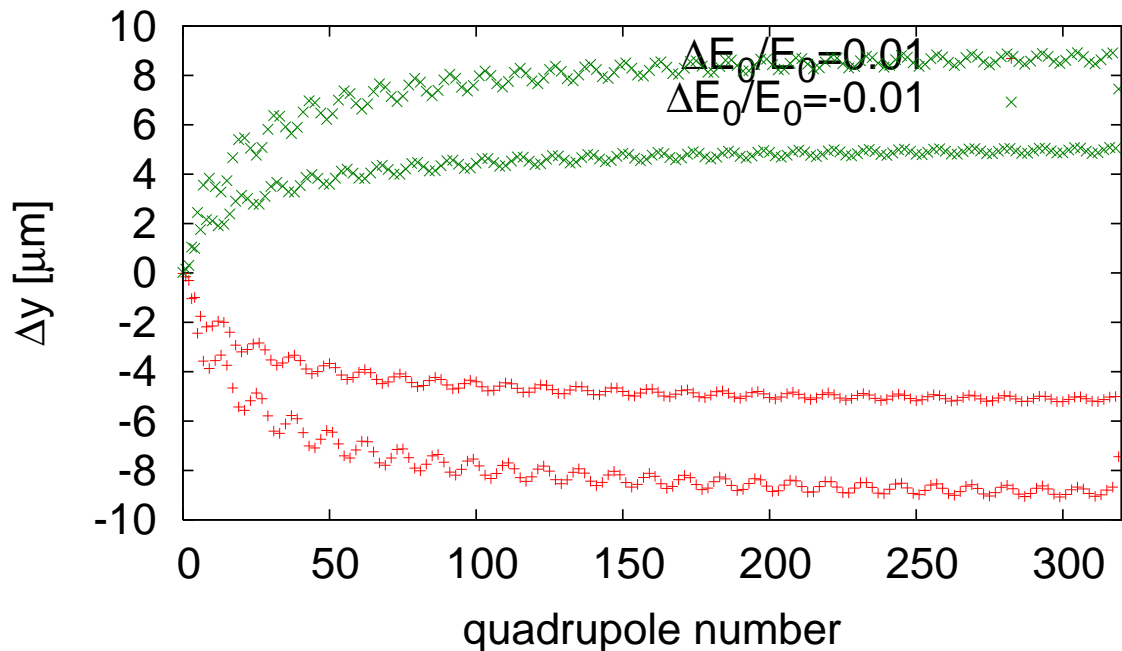
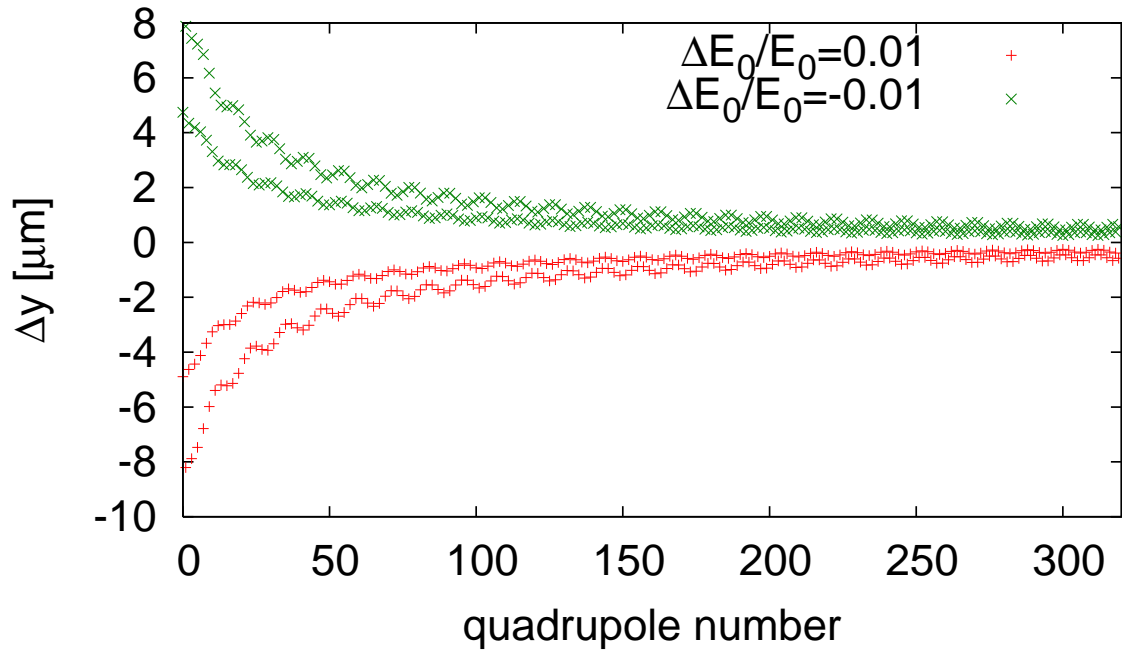
Dispersion in ILC

- Find a periodic solution for the dispersion
- ⇒ Projected emittance is varying but final value is good
- good example of projected emittance
- Particles with constant 1% energy difference shown
 - Dispersion is 100 times larger



Initial Energy vs. Gradient

- The incoming beam has an energy spread
 - Different longitudinal slices of the beam are accelerated with different gradients
- ⇒ These path difference need not be the same



Impact of a Curved Tunnel

- If the tunnel follows the earth curvature one needs to introduce dispersion along the main linac
⇒ beams of different energy will take different paths

The dispersion is measured using

$$D \approx \frac{y_1 - y_2}{E_1 - E_2}$$

the error of the measured value is given by the BPM resolution

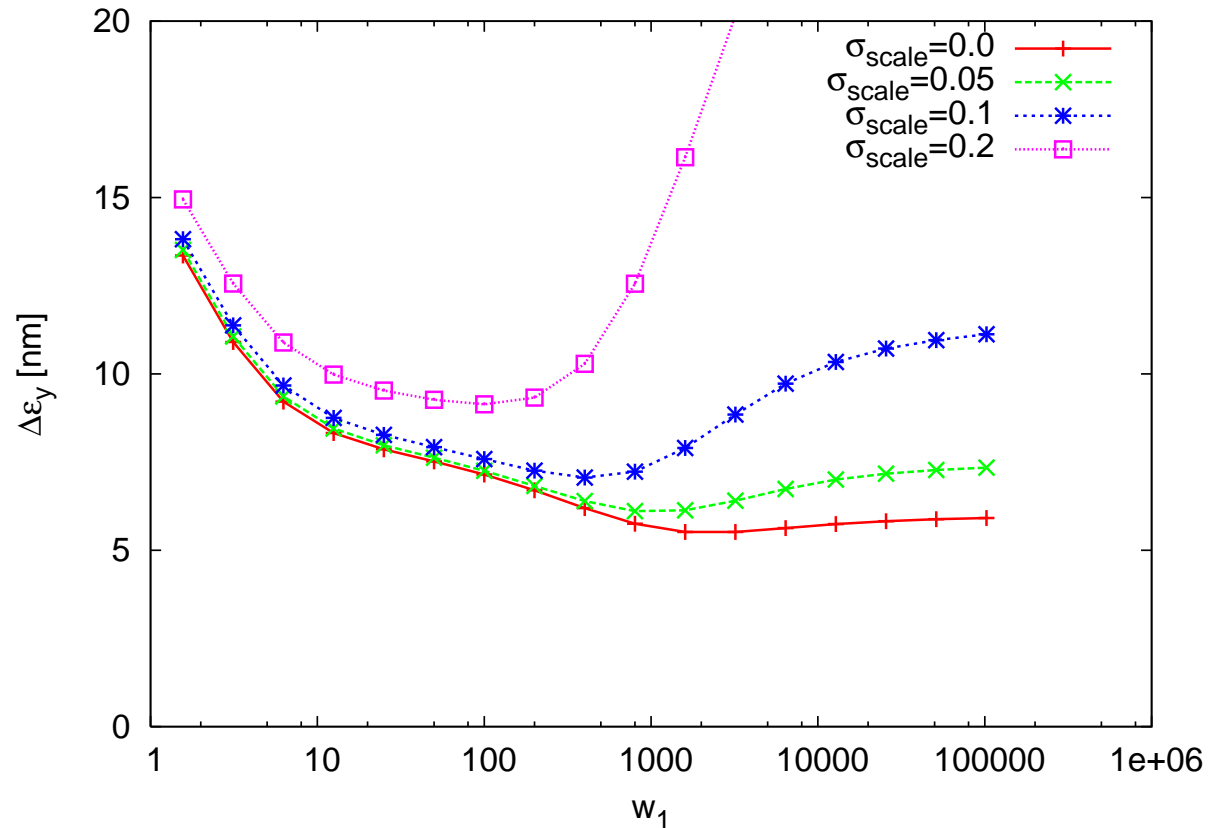
$$\sigma_D^2 \approx \frac{2\sigma_{res}^2}{(E_1 - E_2)^2}$$

If we introduce an BPM calibration error a such that the measured position y_{meas} is $y_{meas} = (1 + a)y_{real}$ and assume σ_a we get

$$\sigma_D^2 \approx \frac{2\sigma_{res}^2}{(E_1 - E_2)^2} + \frac{\sigma_a^2}{E_1}$$

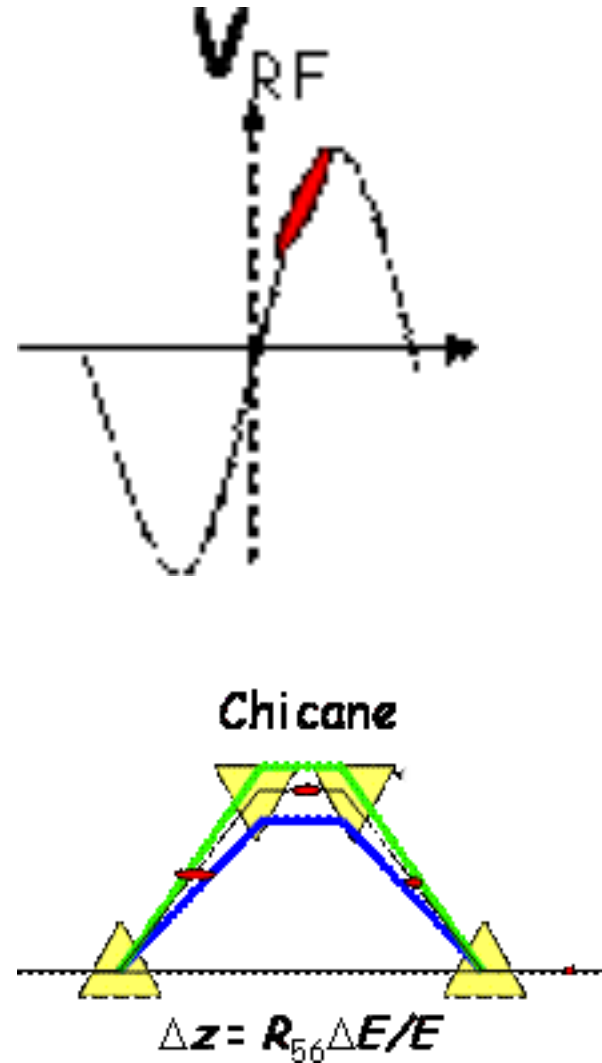
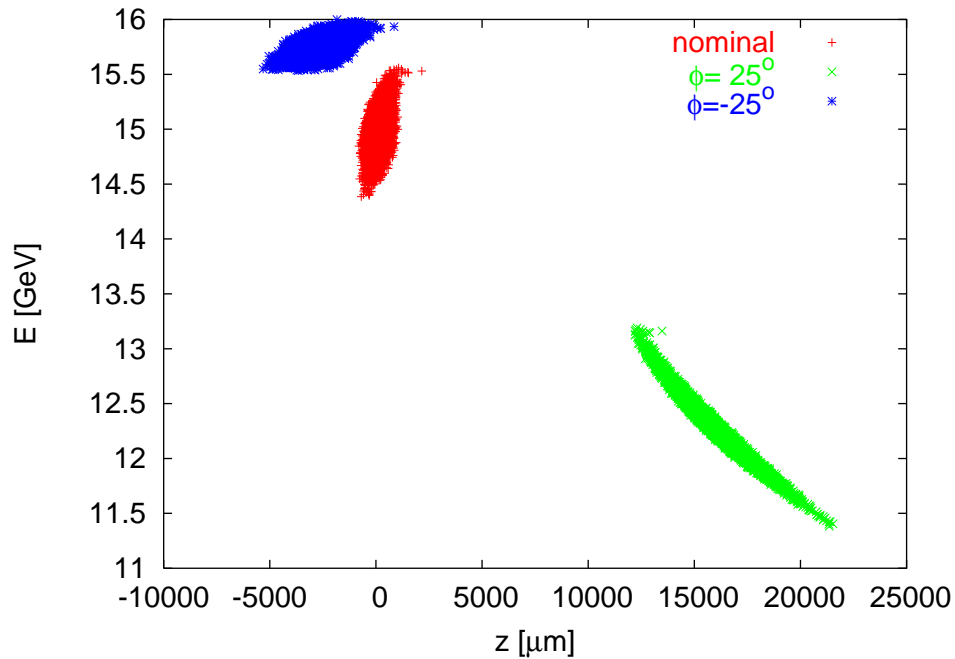
Single Bunch Dispersion Steering Simulations

- Aim is 90% of machines at $\Delta\epsilon_y \leq 10$ nm
- P. Eliasson, K. Kubo, A. Latina, P. Lebrun, F. Poirier, K. Ranjan, D. Schulte, J. Smith, N. Soljak, N. Walker...
- Not all results are benchmarked against others
 - small differences in the assumptions etc.
- Consensus is:
 - beam-based alignment is close to the target but not quite sufficient
 - some further improvement needed with other means



Alignment of Beginning of Main Linac

- Use bunch compressor (ILC shown)
- Only energy change modelled
 - simulations with realistic distribution showed even better performance (A. Latina)



Performing the Correction

We determine the response matrix of our bin with m BPMs and n correctors
First we measure the response matrix B with $b_{i,k}$ the change of beam position in BPM i due to a change of corrector k

$$\Delta\vec{y} = B\delta\vec{c}$$

If $m = n$ one can solve this by inversion, if $m > n$ one can use the pseudo inverse or calculate

$$\vec{c} = (BbB^T)^{-1}B^T\vec{y}$$

If we use more than one beam (DFS) we can use

$$B = \begin{pmatrix} B_0 \\ \sqrt{w_1}(B_1 - B_0) \\ \dots \\ \sqrt{w_k}(B_k - B_0) \end{pmatrix}$$

Other options are to use a SVD decomposition or a MICADO type algorithm

MICADO

- One employs MICADO if one wants to limit the number of correctors to be used
- The algorithm
 - for each corrector calculate how much it would improve the figure of merit
 - chose the most efficient one
 - for each corrector calculate how much it would improve the figure of merit with the first corrector
 - chose the most efficient one
 - continue to add correctors until predefined number is reached
 - apply the correction
- MICADO is very good if the correction steps tend to be small compared to the minimum step size

Summary

- We realised that static imperfections can have dramatic impact on the luminosity
- The most important imperfection for the main linac are the misalignment of elements in the tunnel due to the limited accuracy of the pre-alignment system
- Simple one-to-one steering can correct the impact of quadrupole misalignments
- Dispersion free steering can cure the impact of BPM misalignment
- Structure alignment with wake monitors can reduce the impact of structure misalignments
- Emittance tuning bumps can also be used