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 $\epsilon_x = 600\,\mathrm{nm}$ and $\epsilon_y = 10\,\mathrm{nm}$
  - for static imperfections an emittance budget of $\Delta\epsilon_x = 30\,\mathrm{nm}$ and $\Delta\epsilon_y = 5\,\mathrm{nm}$ exists, which 90% of the machines have to meet
  - for dynamic imperfections an emittance budget of $\Delta\epsilon_x = 30\,\mathrm{nm}$ and $\Delta\epsilon_y = 5\,\mathrm{nm}$ exists
- ILC
  - the initial emittances have to stay below $\epsilon_x = 8400\,\mathrm{nm}$ and $\epsilon_y = 24\,\mathrm{nm}$
  - the final emittances have to stay below$\epsilon_x = 9400\,\mathrm{nm}$ and $\epsilon_y = 34\,\mathrm{nm}$
- We will limit our discussion to the vertical plane

Imperfections

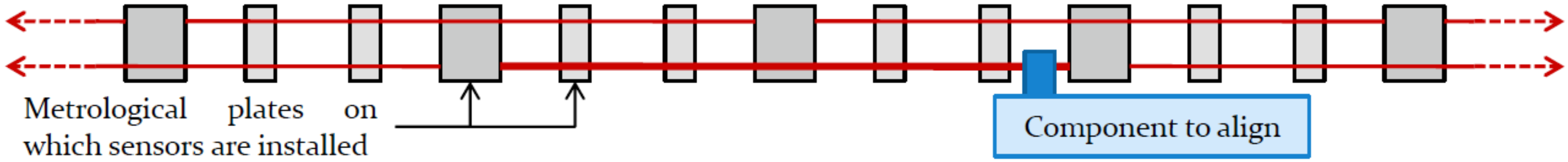
- Pre-Alignment imperfections can be roughly categorised into short-distance and long-distance errors
- To first order, the imperfections can be treated as independent
  - as long as a linear main linac model is sufficient
- The short-distance misalignments give largest emittance contribution
  - misalignment 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

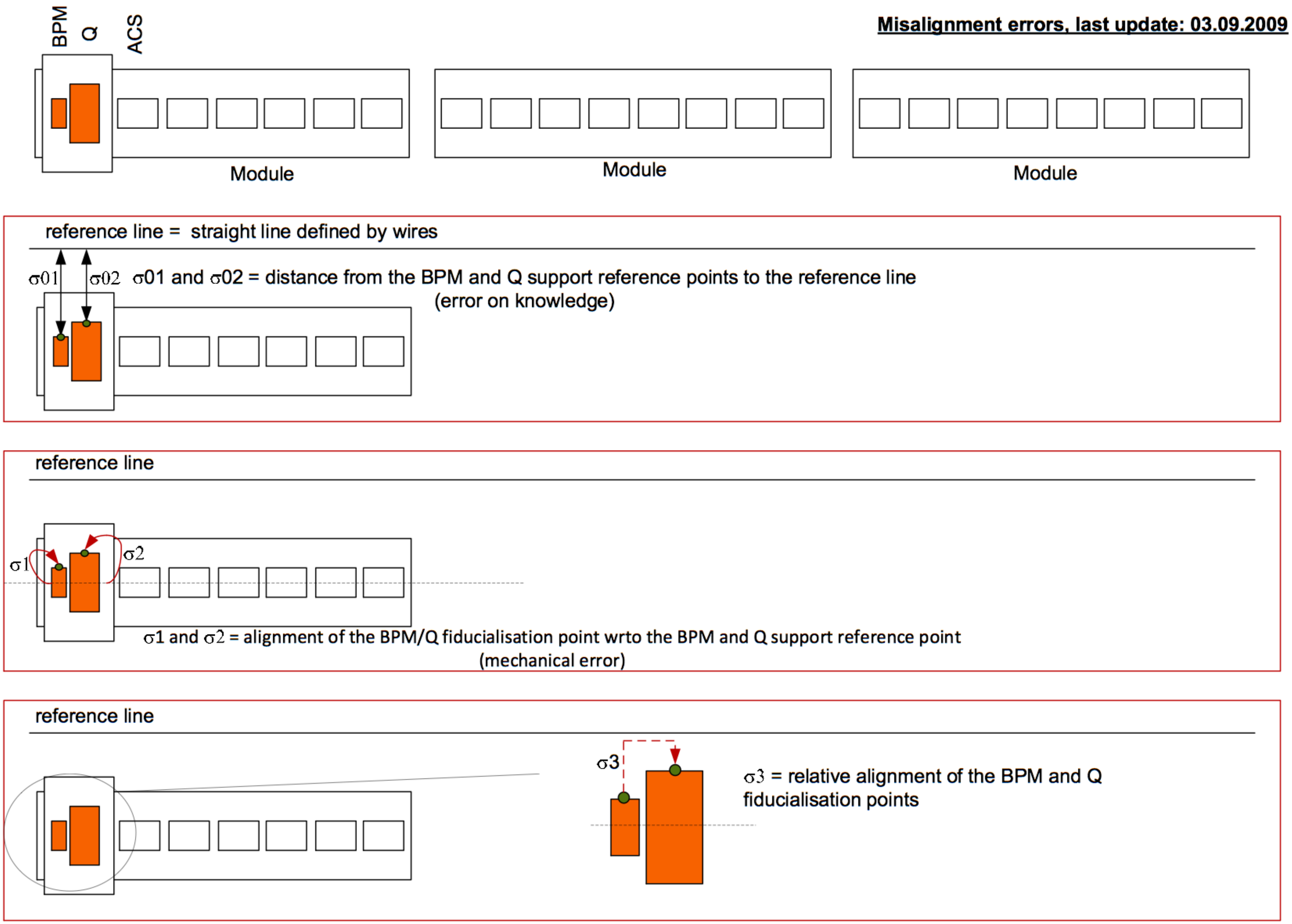
Example: Residual Alignment Errors due to Pre-Alignment System

Wire System for CLIC

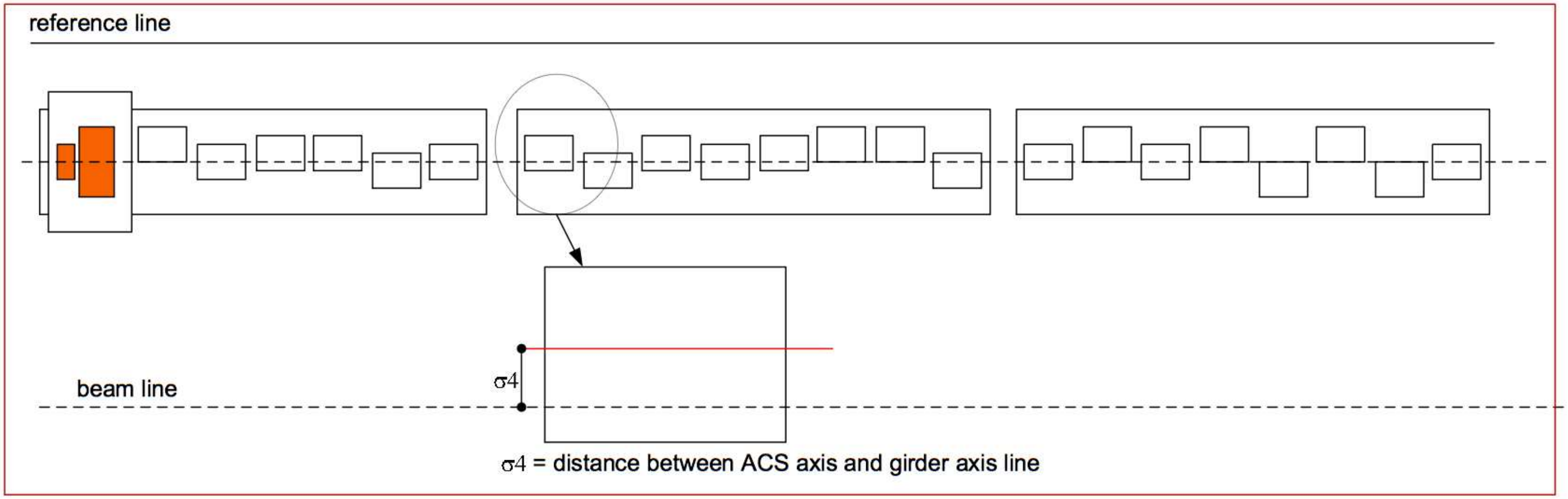


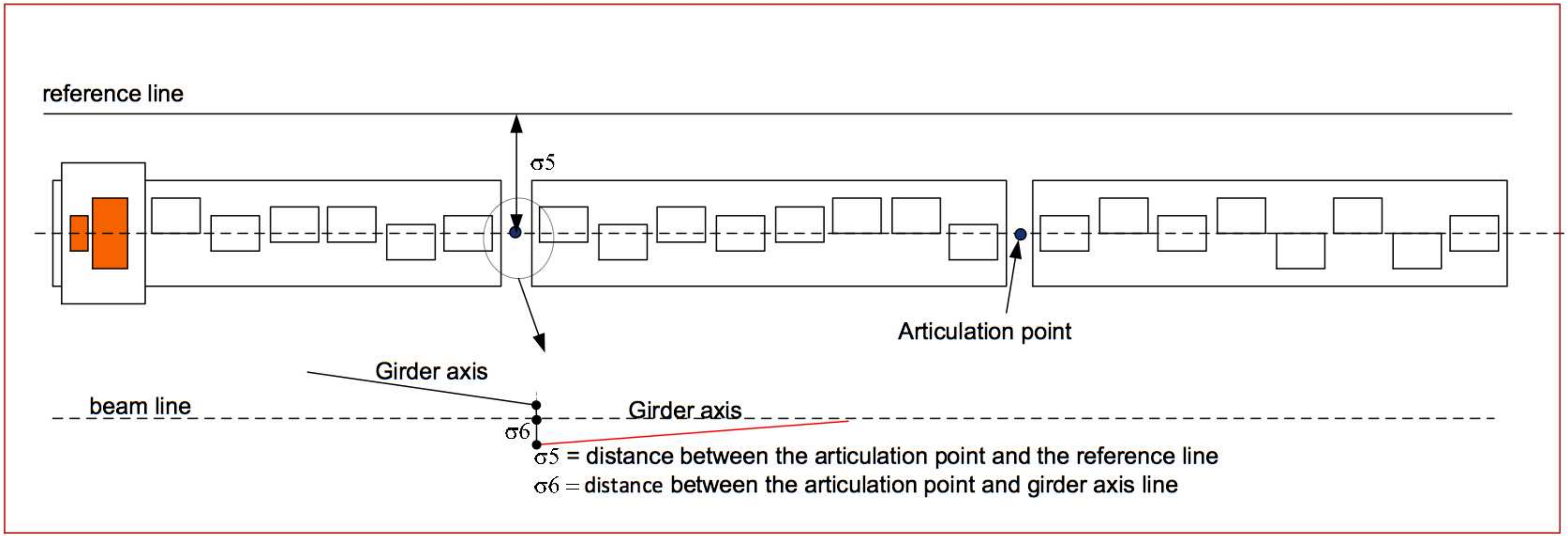
- Reference method for CLIC
  - has been used in the LHC insertions
- A system of overlapping wires that form straight lines
- Alternative is optical measurements

Alignment Model (CLIC)

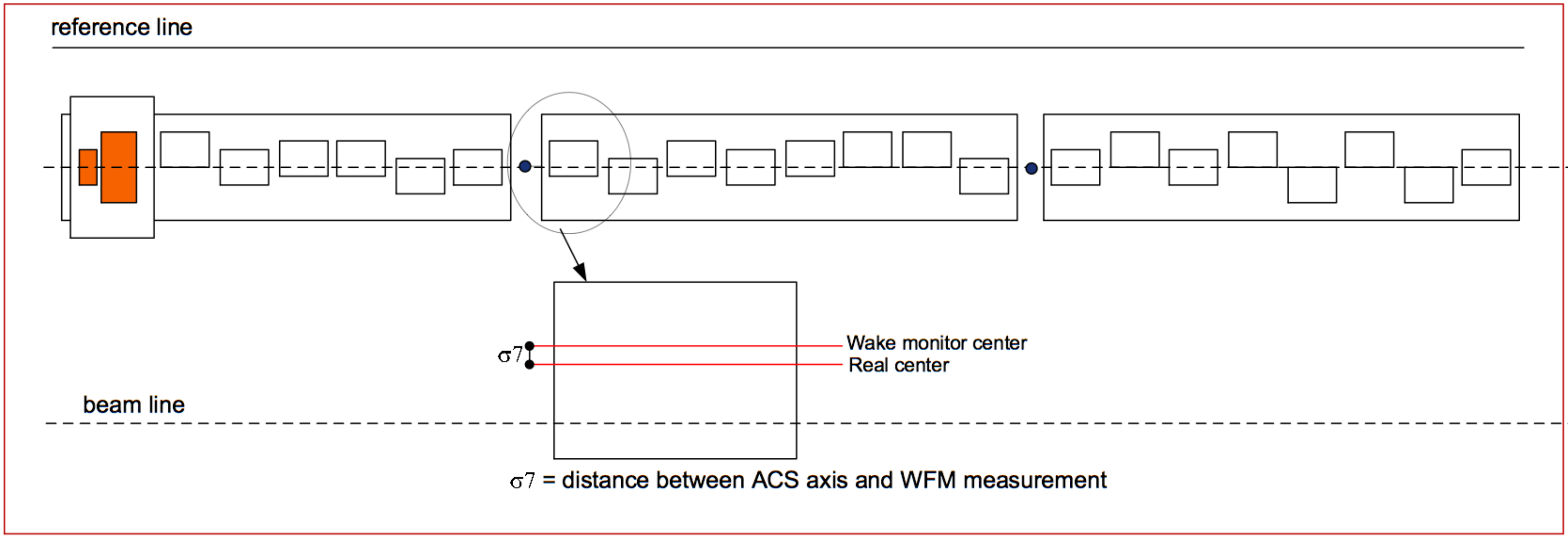


Alignment Model (cont)





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

- 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 particle 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

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

- Summing over many elements gives the final normalised positions

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

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

$\Rightarrow$ 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	$300\ \mu$m	3.5
Cavity tilt	module	$300\ \mu$radian	2600
BPM offset	module	$300\ \mu$m	0
Quadrupole offset	module	$300\ \mu$m	700000
Quadrupole roll	module	$300\ \mu$radian	2.2
Module offset	perfect line	$200\ \mu$m	250000
Module tilt	perfect line	$20\ \mu$radian	880

$\Rightarrow$ Need to do much better

$\Rightarrow$ Will align with the beam

Beam-Based Tuning

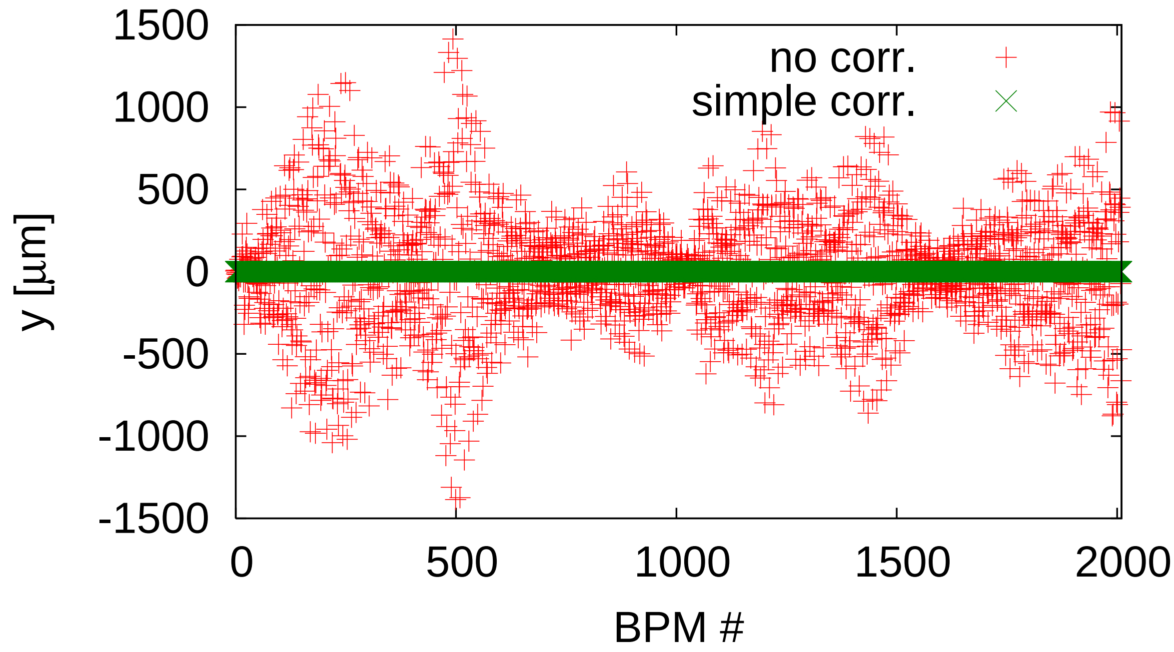
Beam-Based Alignment and Tuning Strategy

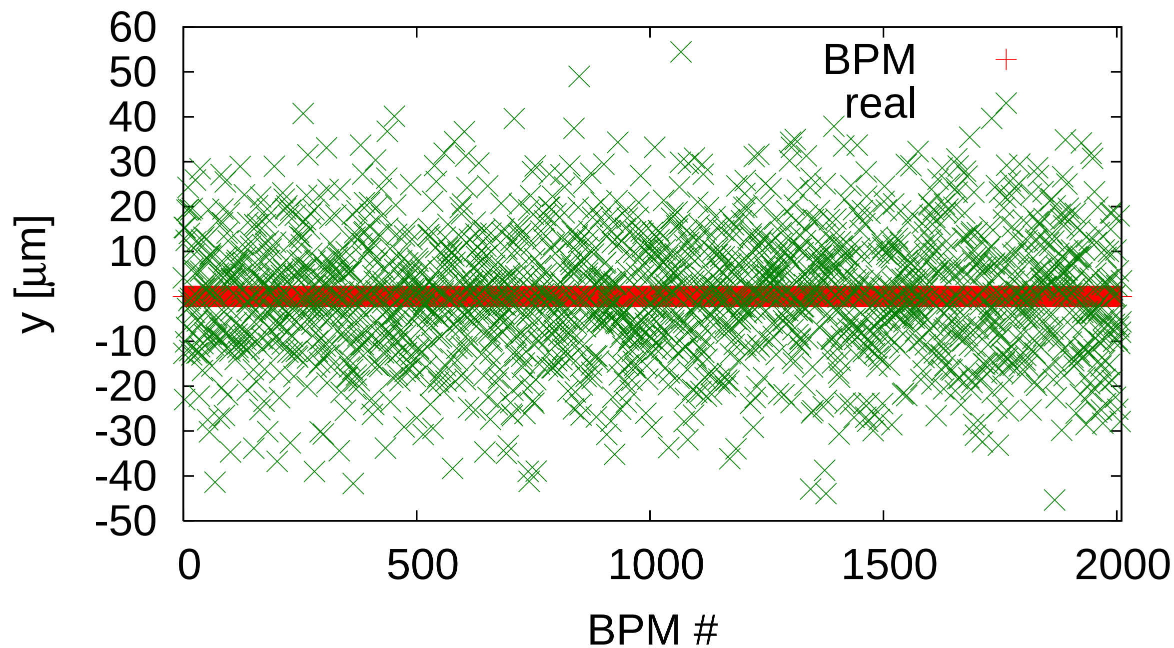
- Make beam pass linac
  - one-to-one correction
- Remove dispersion, align BPMs and quadrupoles
  - dispersion free steering
  - ballistic alignment
  - kick minimisation
- Remove residual dispersive and wakefield effects
  - accelerating structure alignment (CLIC only)
  - emittance tuning bumps

\- 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 off-sets remain
- Real position of beam shown in lower plot
  - BPMs are misaligned





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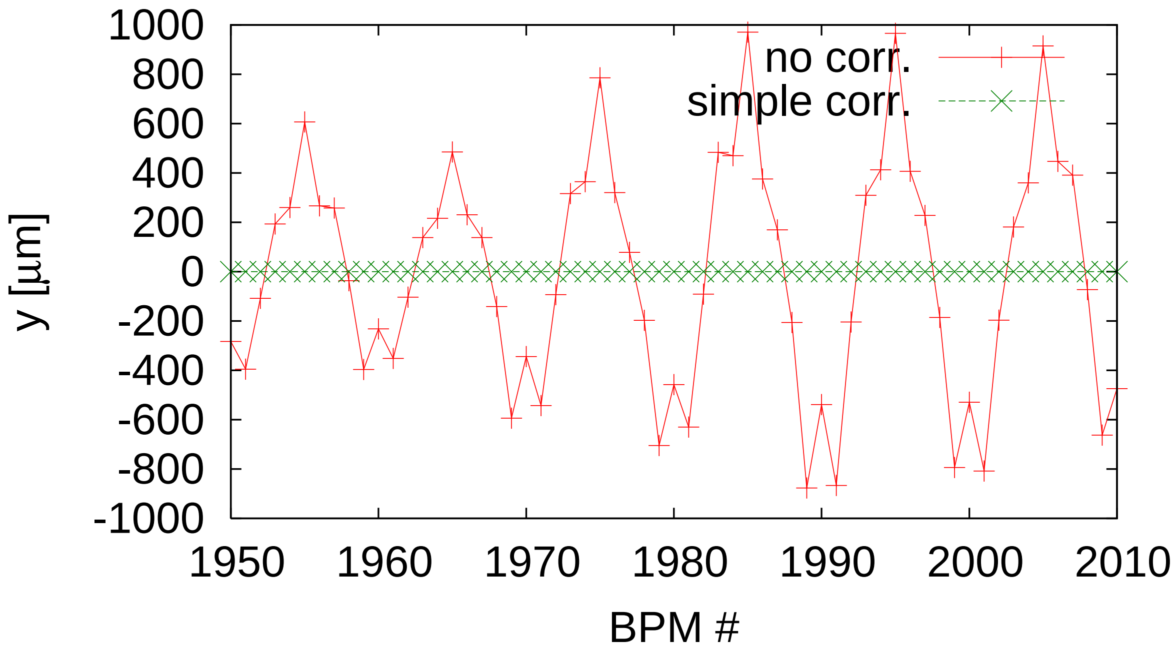
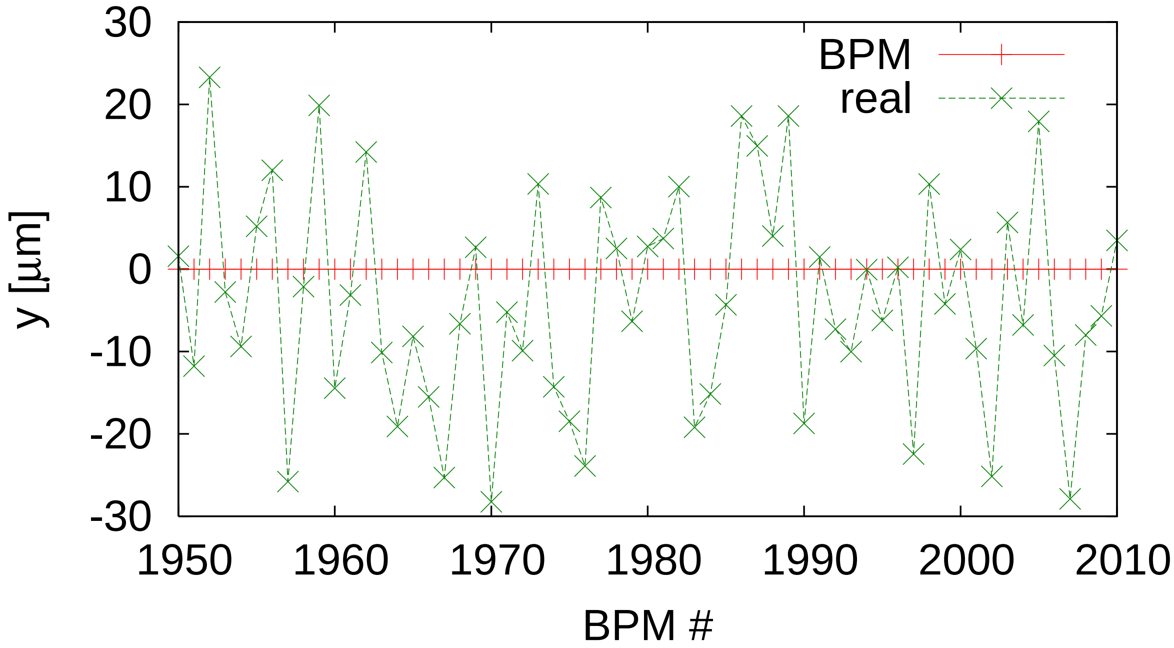
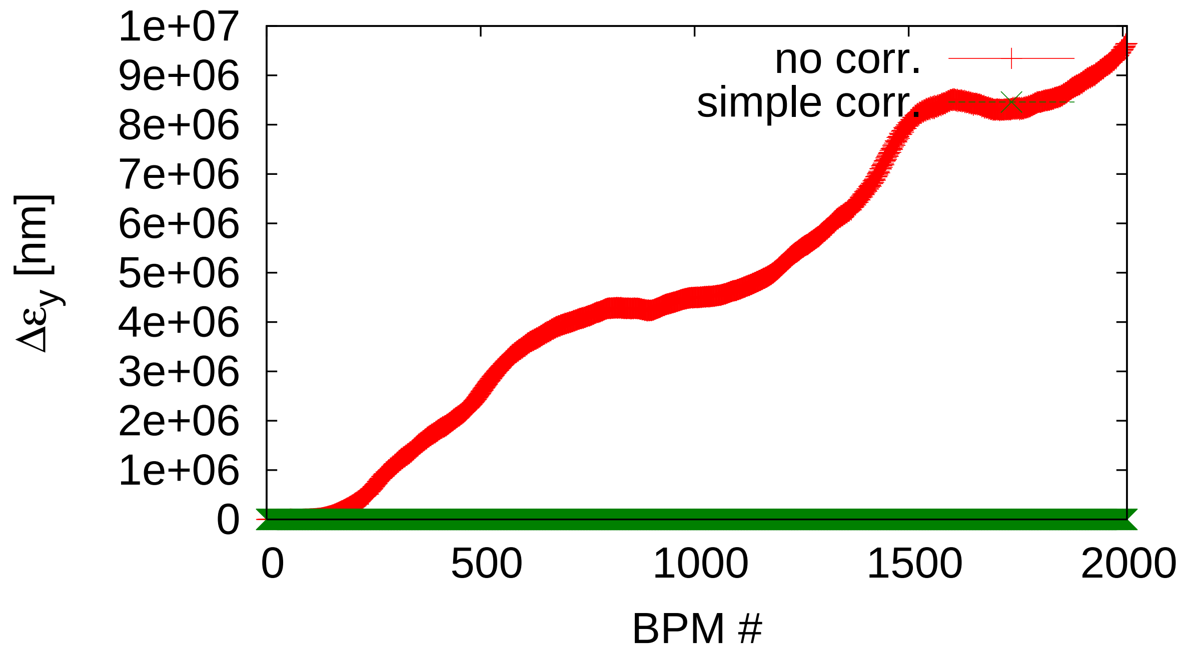
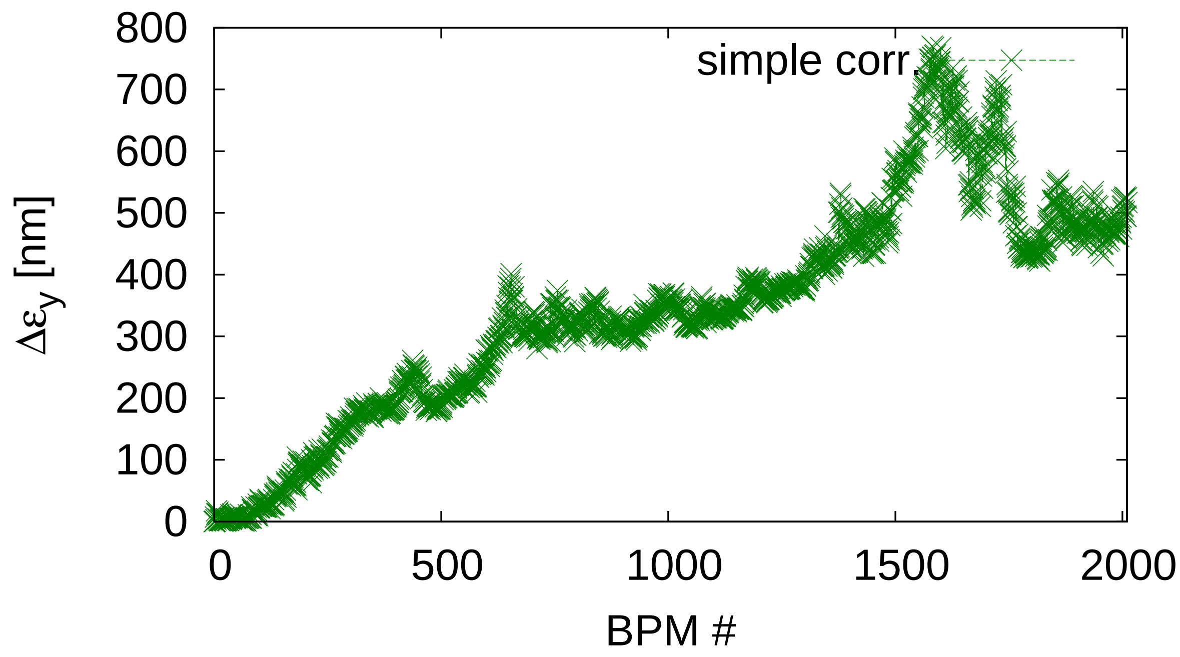




Emittance Growth



- 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

$\Rightarrow$ The problem of the quadrupoles is solved but now we have a BPM problem

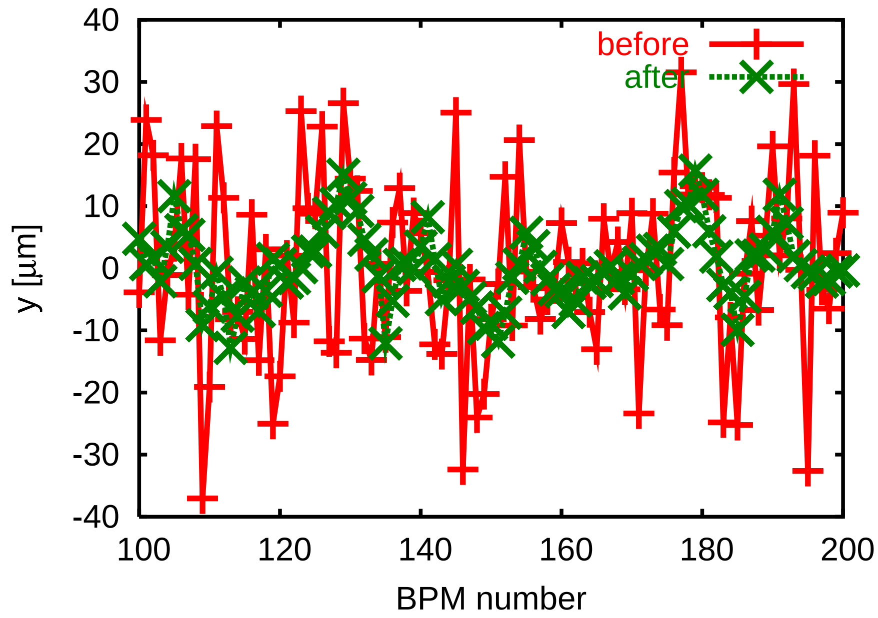
Error	with respect to	value	$\Delta\gamma\epsilon_y$ [nm]	$\Delta\gamma\epsilon_{y,121}$ [nm]
Cavity offset	module	$300\ \mu$m	3.5	0.2
Cavity tilt	module	$300\ \mu$radian	2600	< 0.1
BPM offset	module	$300\ \mu$m	0	360
Quadrupole offset	module	$300\ \mu$m	700000	0
Quadrupole roll	module	$300\ \mu$radian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

Static Tolerances and Accuracies for One-To-One Correction

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

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

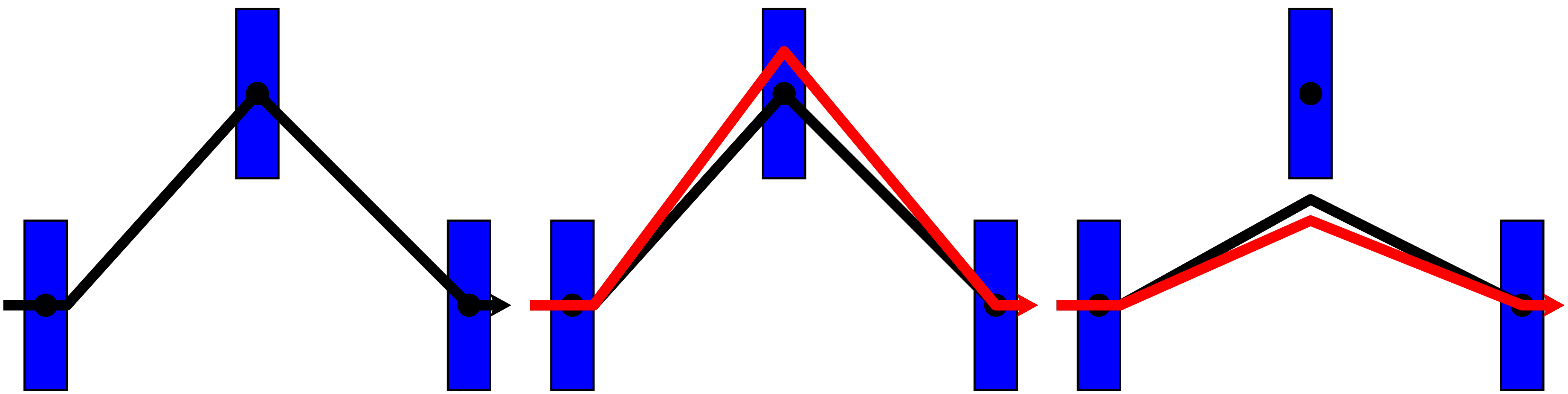
- We minimise

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

which yields

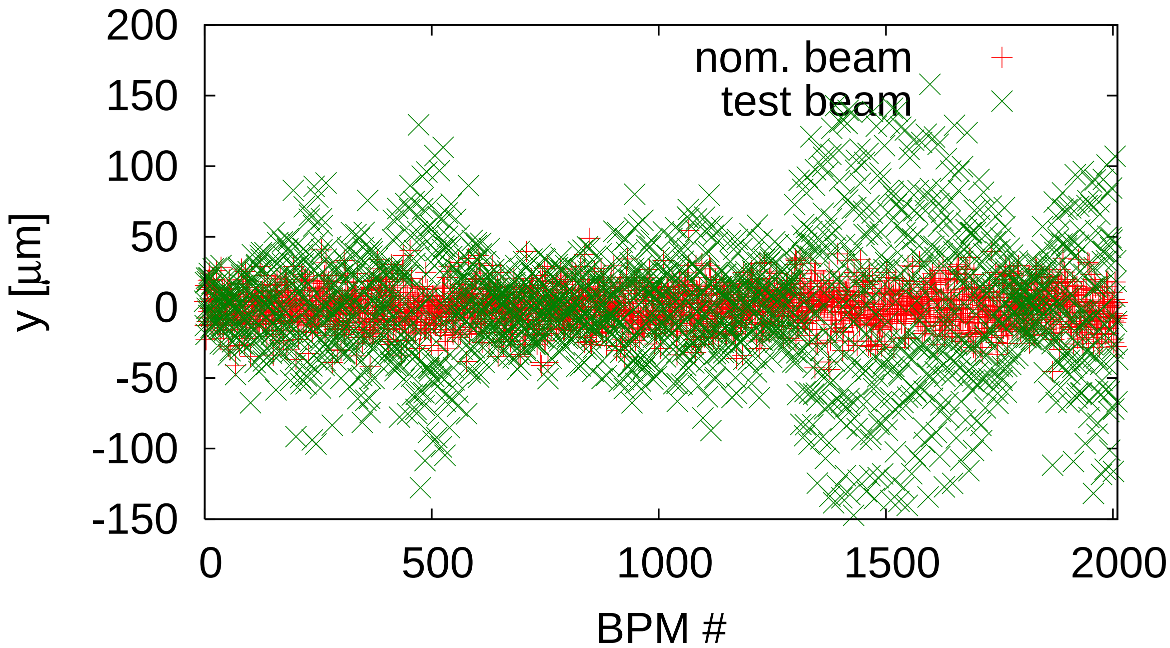
$$0 = \frac{\partial}{\partial c}(c - y_0)^2 + w\left(c\frac{\Delta E}{E}\right)^2 \quad (1)$$

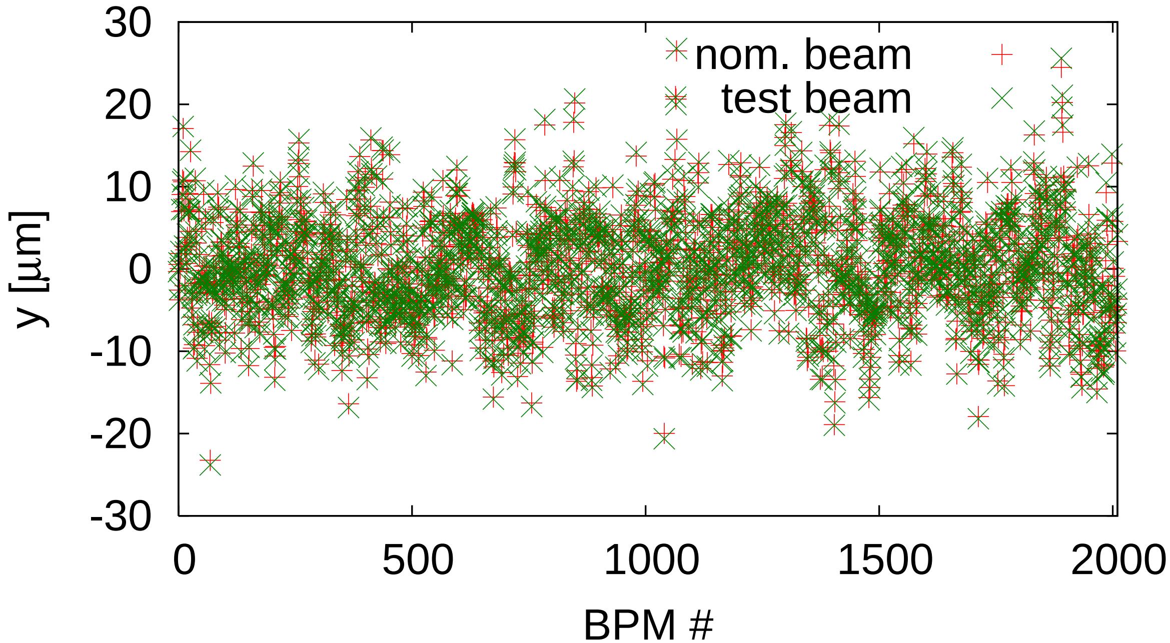
$$c = \frac{y_0}{1 + w\left(\frac{\Delta E}{E}\right)^2} \quad (2)$$



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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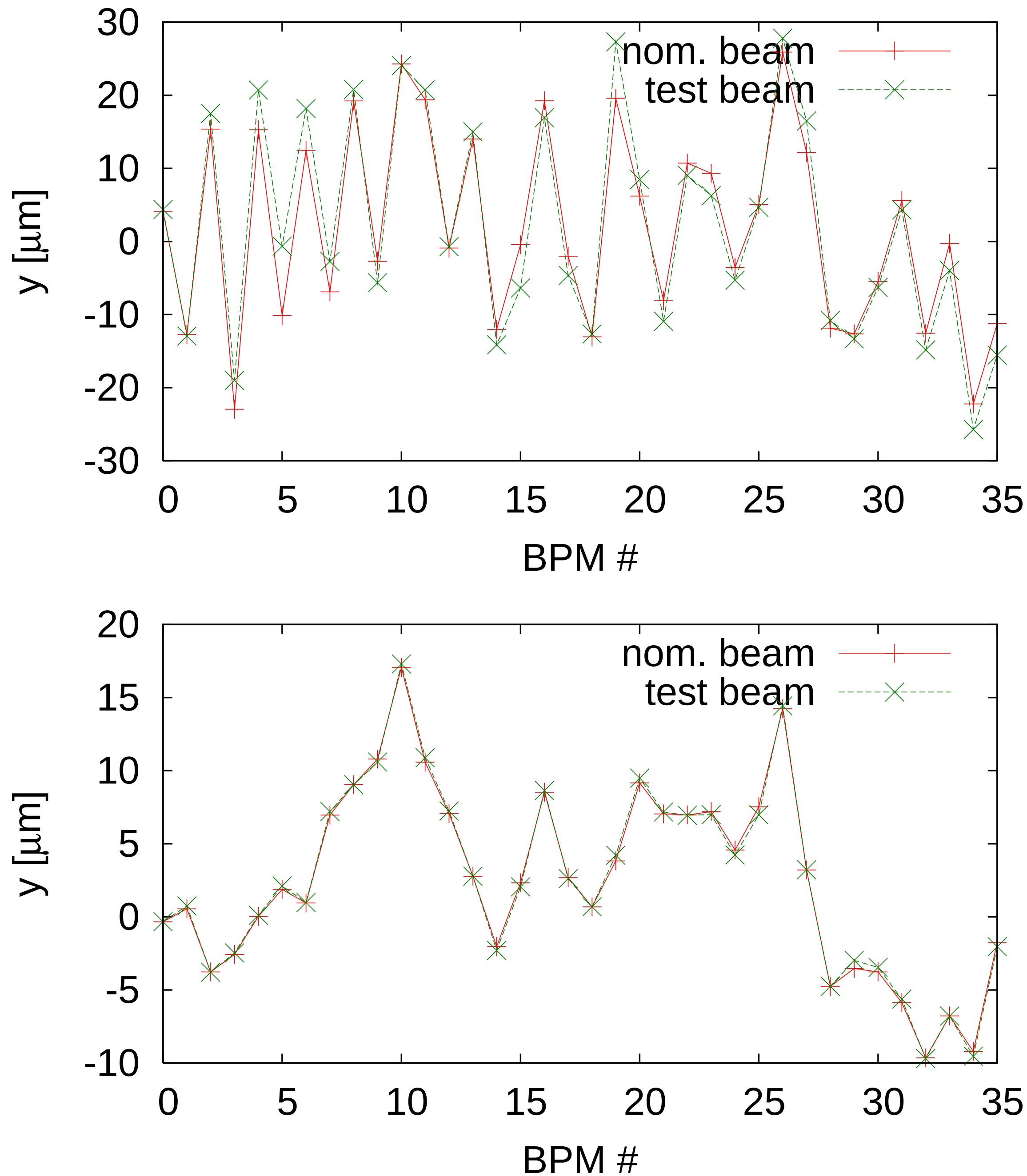
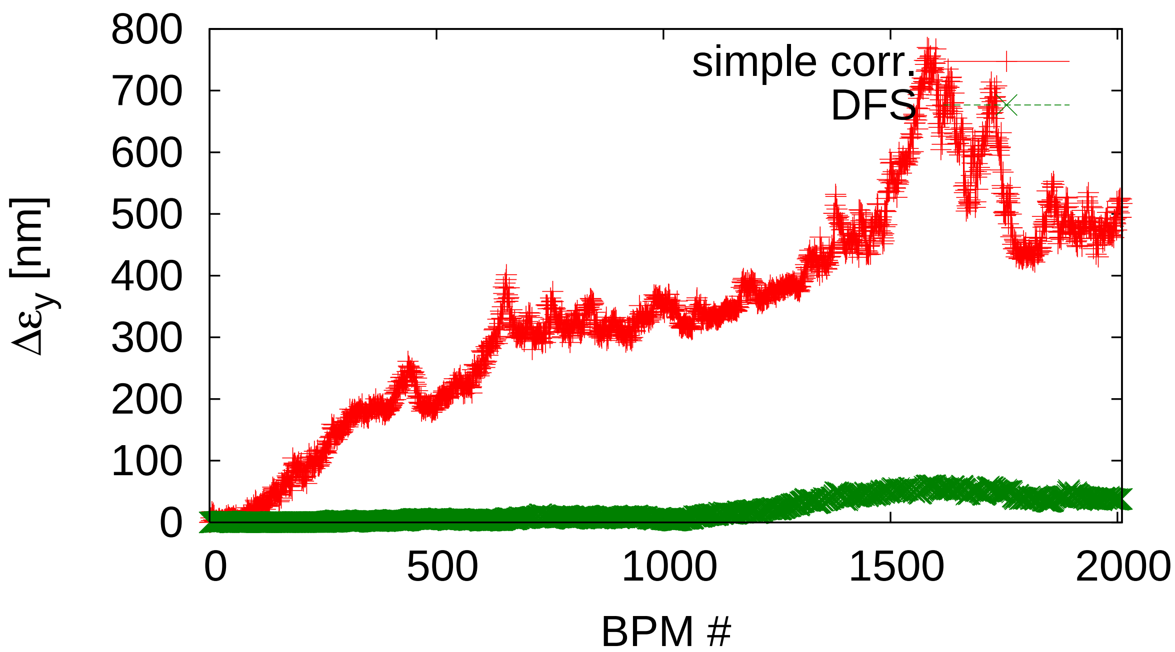
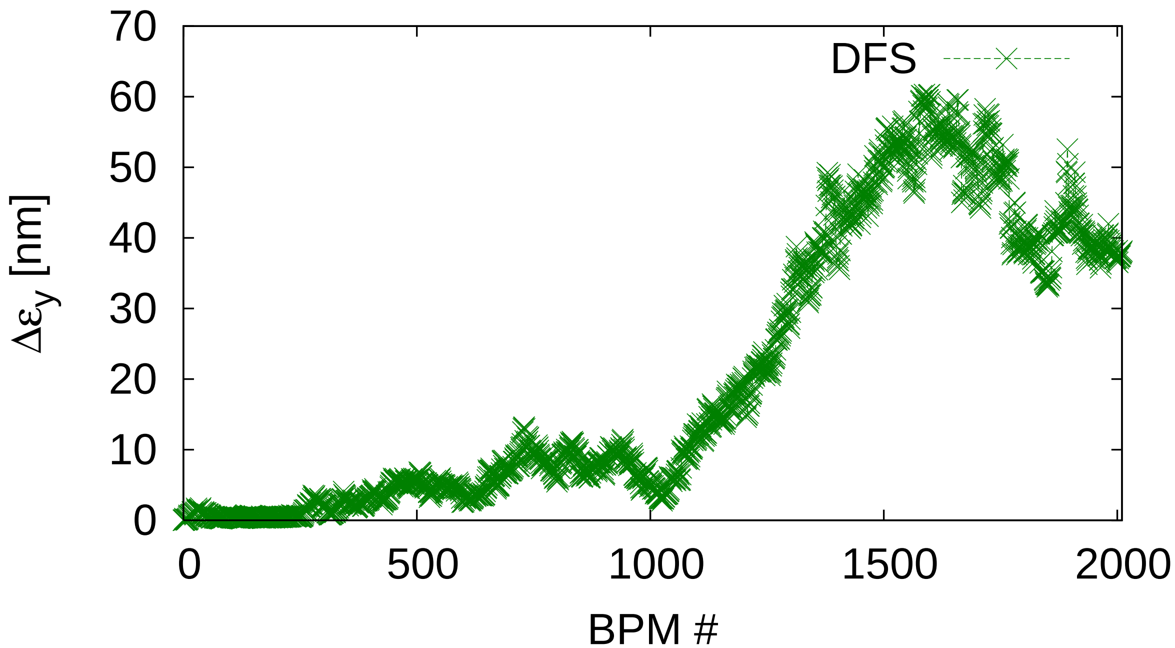


Dispersion Free Correction Emittance

- 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	$300\ \mu$m	3.5	0.2	$0.2(0.2)$
Cavity tilt	module	$300\ \mu$radian	2600	< 0.1	$1.8(8)$
BPM offset	module	$300\ \mu$m	0	360	$4(2)$
Quadrupole offset	module	$300\ \mu$m	700000	0	$0(0)$
Quadrupole roll	module	$300\ \mu$radian	2.2	2.2	$2.2(2.2)$
Module offset	perfect line	$200\ \mu$m	250000	155	$2(1.2)$
Module tilt	perfect line	$20\ \mu$radian	880	1.7	—

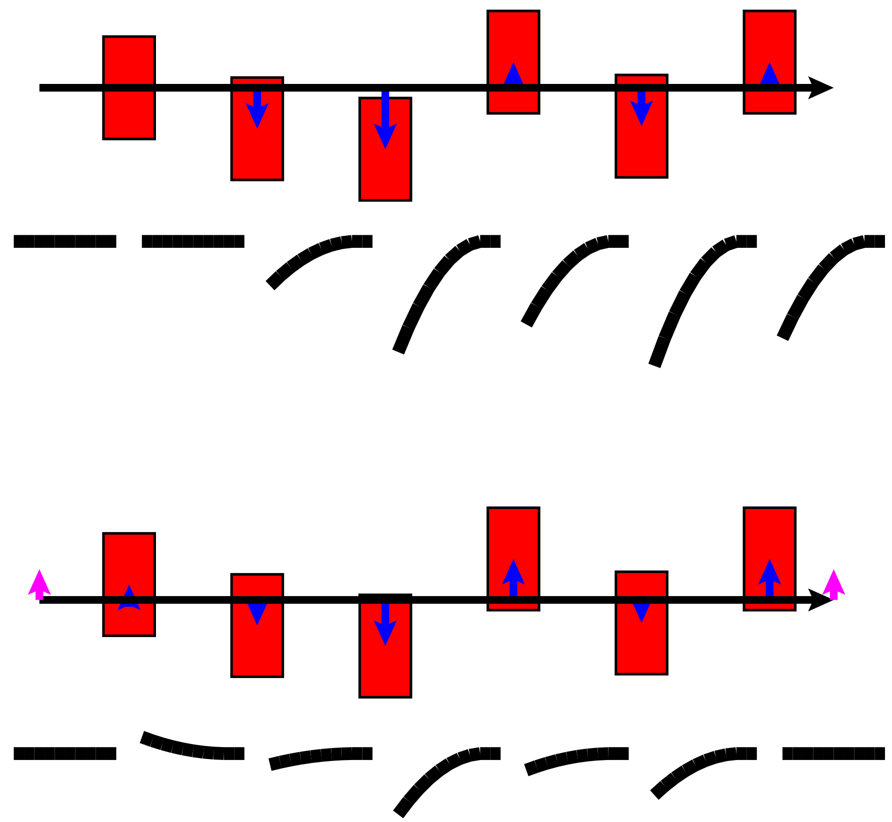
- The results of the reference DFS method is quoted, results of a different implementation in brackets
- Note in the simulations the correction the quadrupoles had been shifted, other wise some residual effect of the quadrupole misalignment would exist

Beam-Based Structure Alignment (CLIC only)

- Each structure is equipped with a wake-field monitor (RMS position error $5\,\mu\mathrm{m}$)
- Up to eight structures on one movable girders

⇒ Align structures to the beam

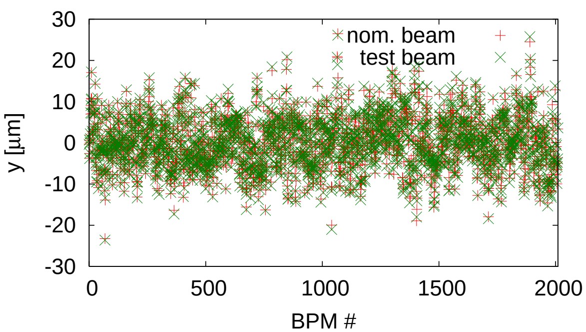
- Assume identical wake fields
  - the mean structure to wakefield monitor offset is most important
  - in upper figure monitors are perfect, mean offset structure to beam is zero after alignment
  - scatter around mean does not matter a lot
- With scattered monitors
  - final mean offset is $\sigma_{wm}/\sqrt{n}$
- In the current simulation each structure is moved independently
- A study has been performed to move the articulation points

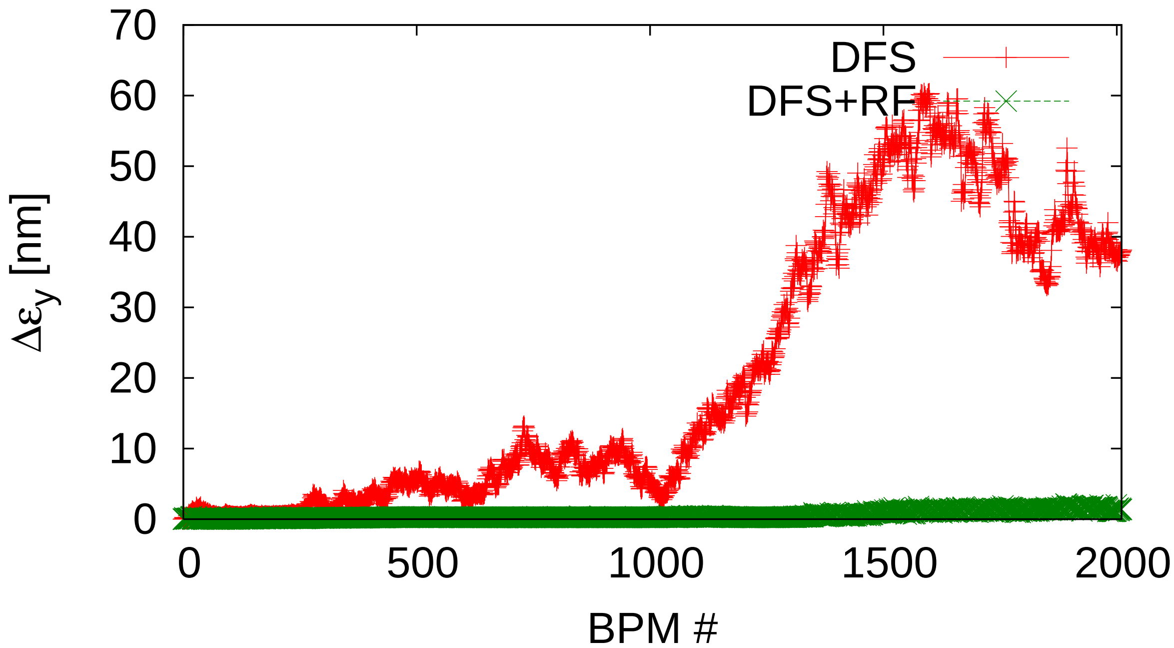


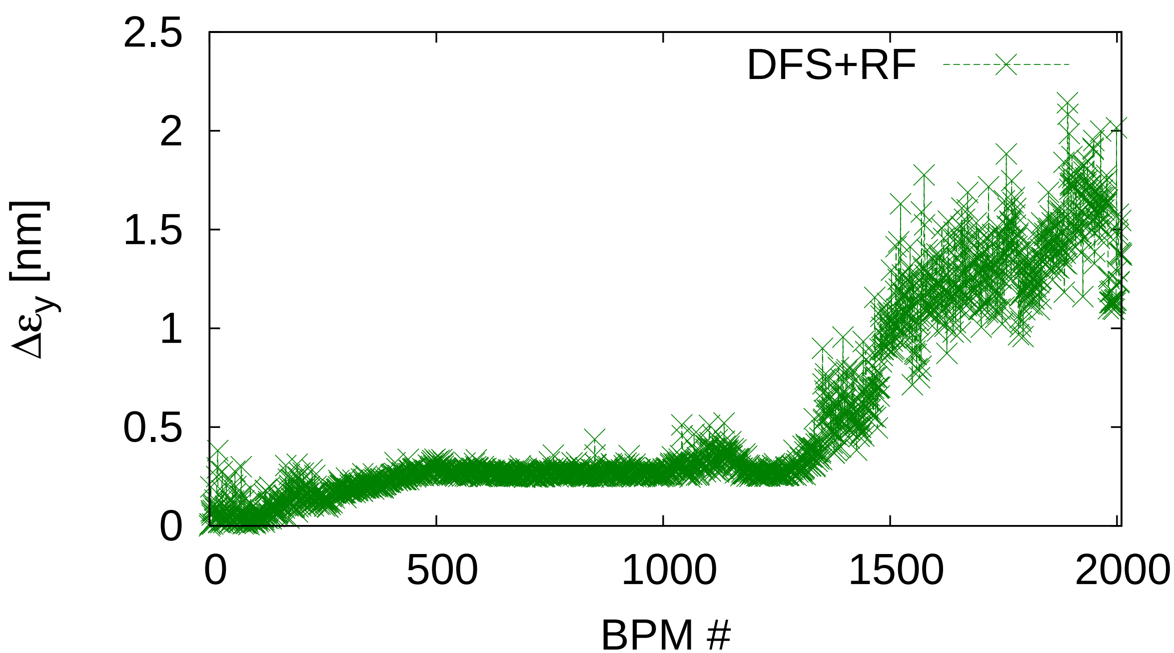
- For our tolerance $\sigma_{wm} = 5\,\mu\mathrm{m}$ we find $\Delta\epsilon_y \approx 0.5\,\mathrm{nm}$
  - some dependence on alignment method

Structure Alignment

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



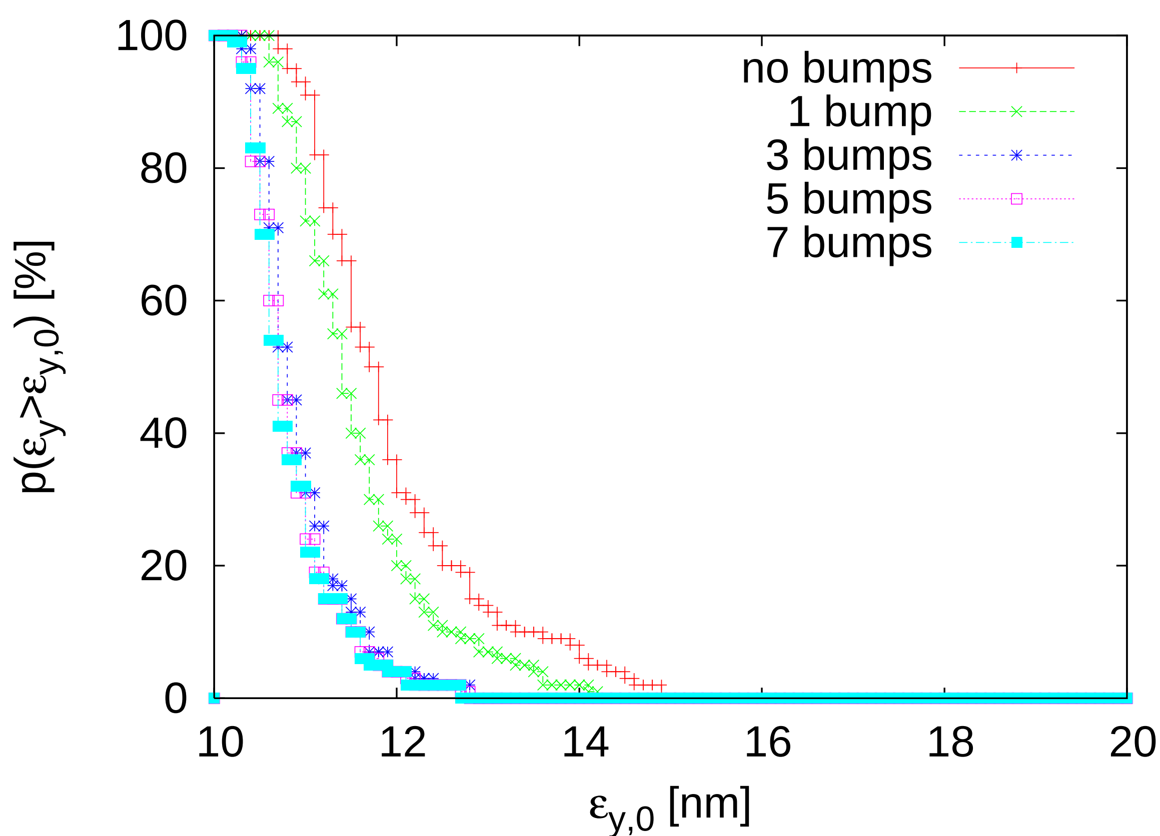




Final Emittance Growth (CLIC)

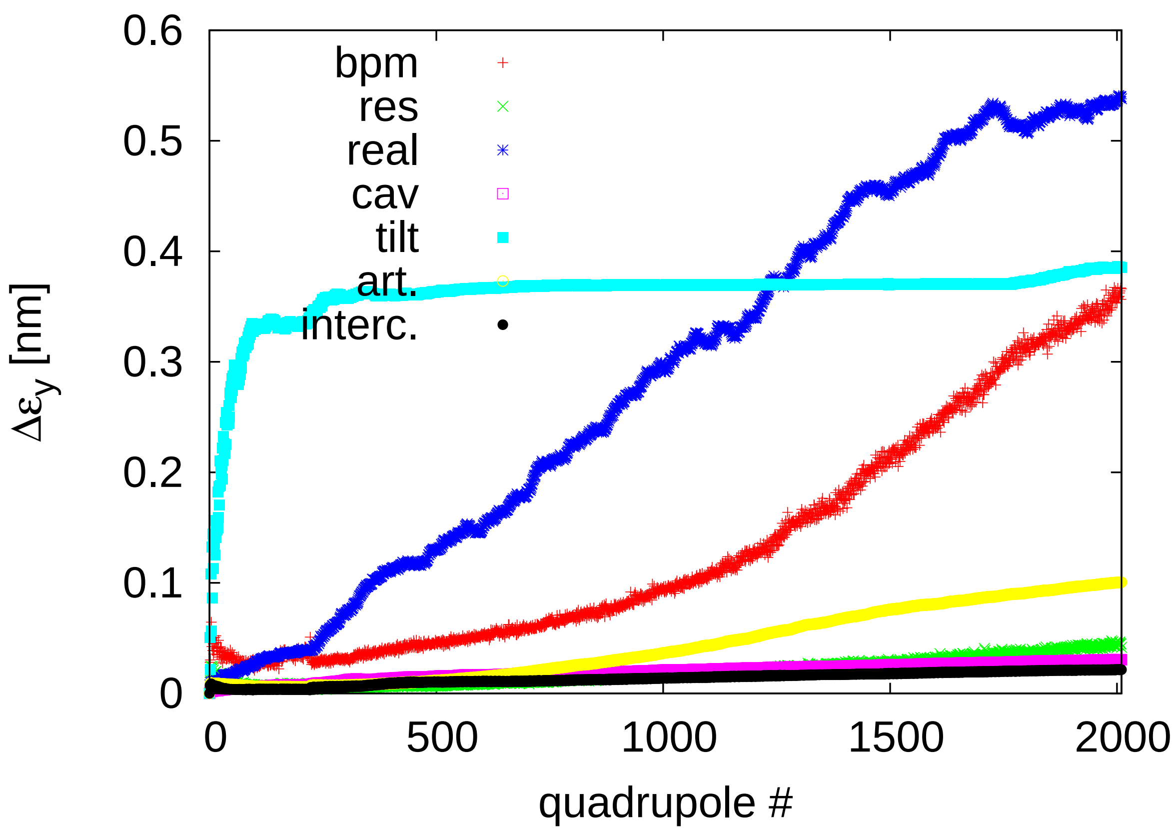
imperfection	with respect to	symbol	value	emitt. growth
BPM offset	wire reference	σ_{BPM}	14 μm	$0.367\,\mathrm{nm}$
BPM resolution		σ_{res}	0.1 μm	$0.04\,\mathrm{nm}$
accelerating structure offset	girder axis	σ_4	10 μm	$0.03\,\mathrm{nm}$
accelerating structure tilt	girder axis	σ_t	200 μradian	$0.38\,\mathrm{nm}$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

- Selected a good DFS implementation
  - trade-offs are possible
- Multi-bunch wakefield misalignments of $10\,\mu\mathrm{m}$ lead to $\Delta\epsilon_y \approx 0.13\,\mathrm{nm}$
- Performance of local prealignment is acceptable



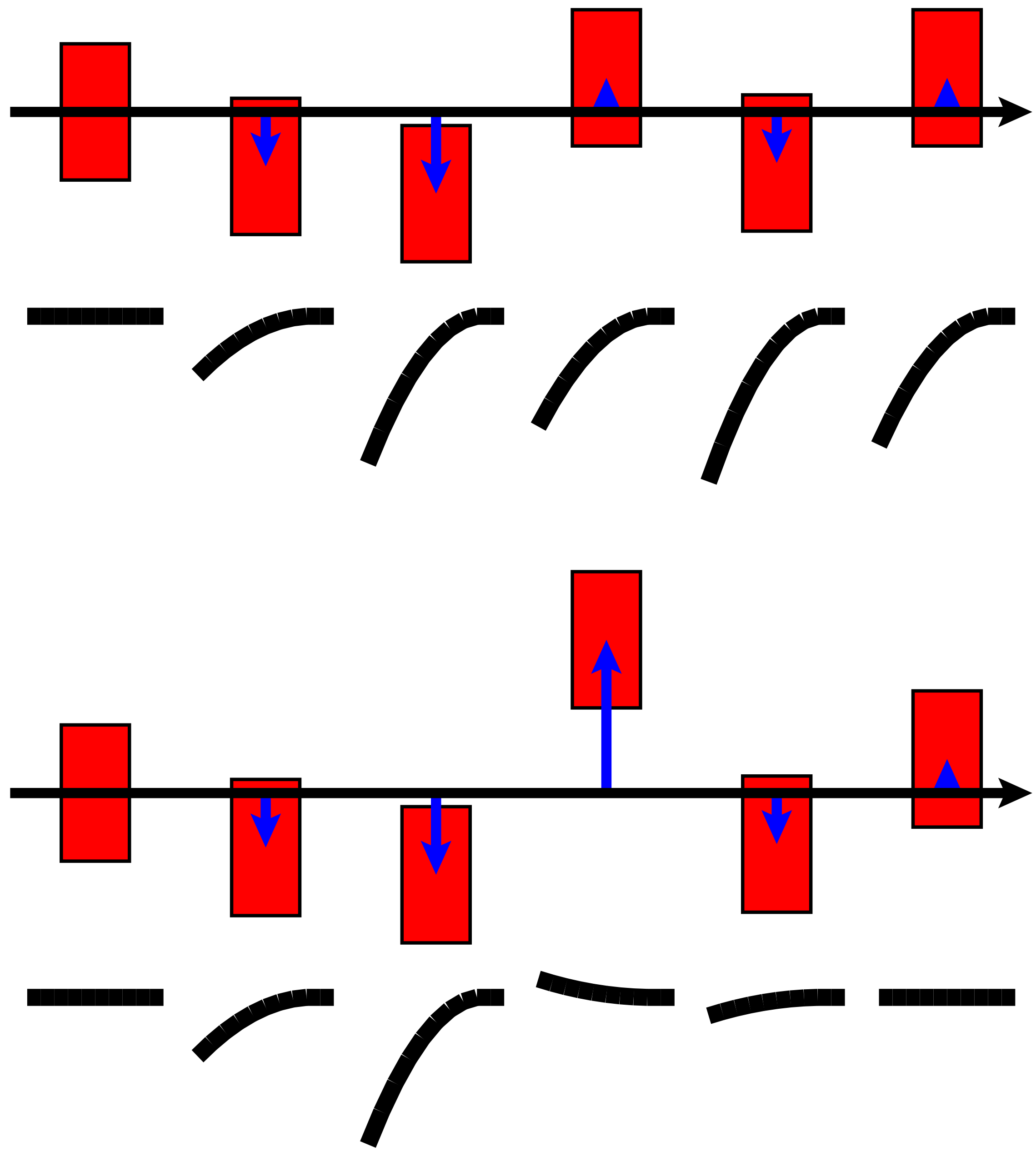
Growth Along Main Linac

- 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)

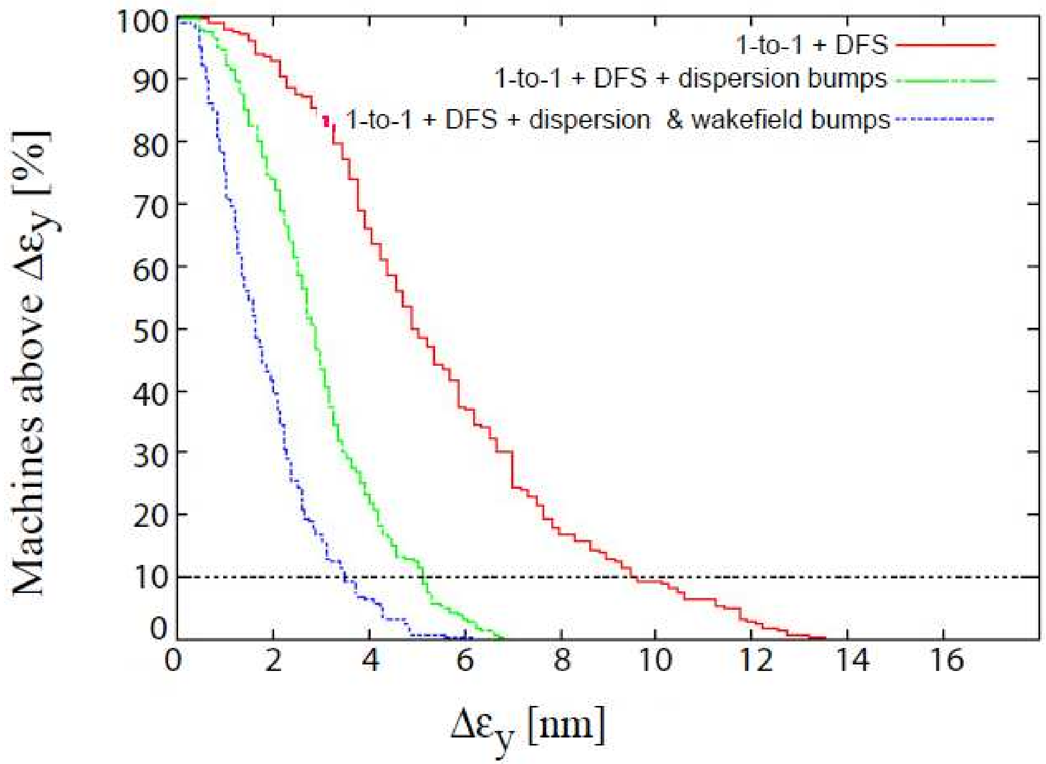
- The emittance growth after dispersion steering is still too large

  ⇒ further improvement needed

- Possible solution 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



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Remark: Dependence on Weights (Old CLIC Parameters)

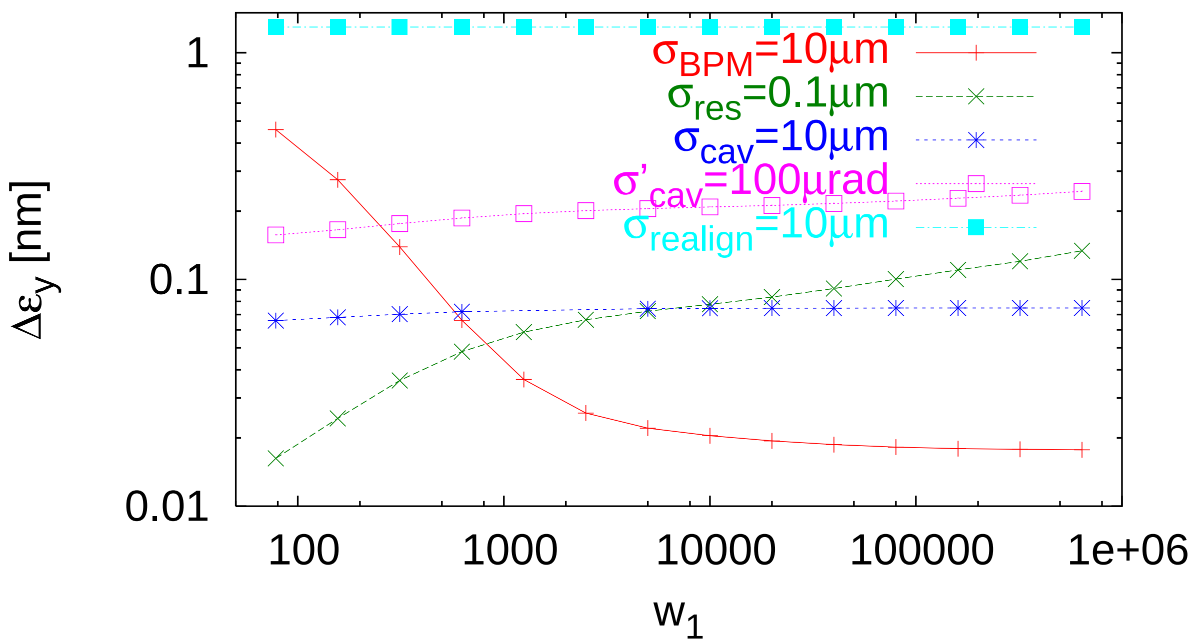
- For TRC parameters set
- One test beam is used with a different gradient and a different incoming beam energy

⇒ BPM position errors are less important at large w_1

⇒ BPM resolution is less important at small w_1

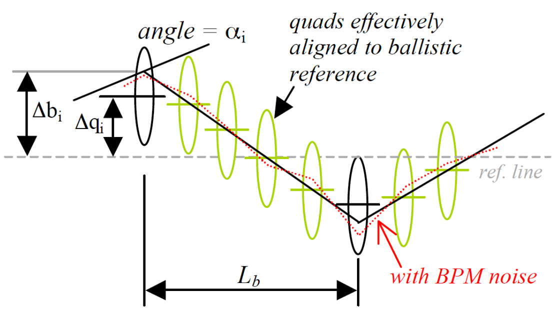
⇒ Need to find a compromise

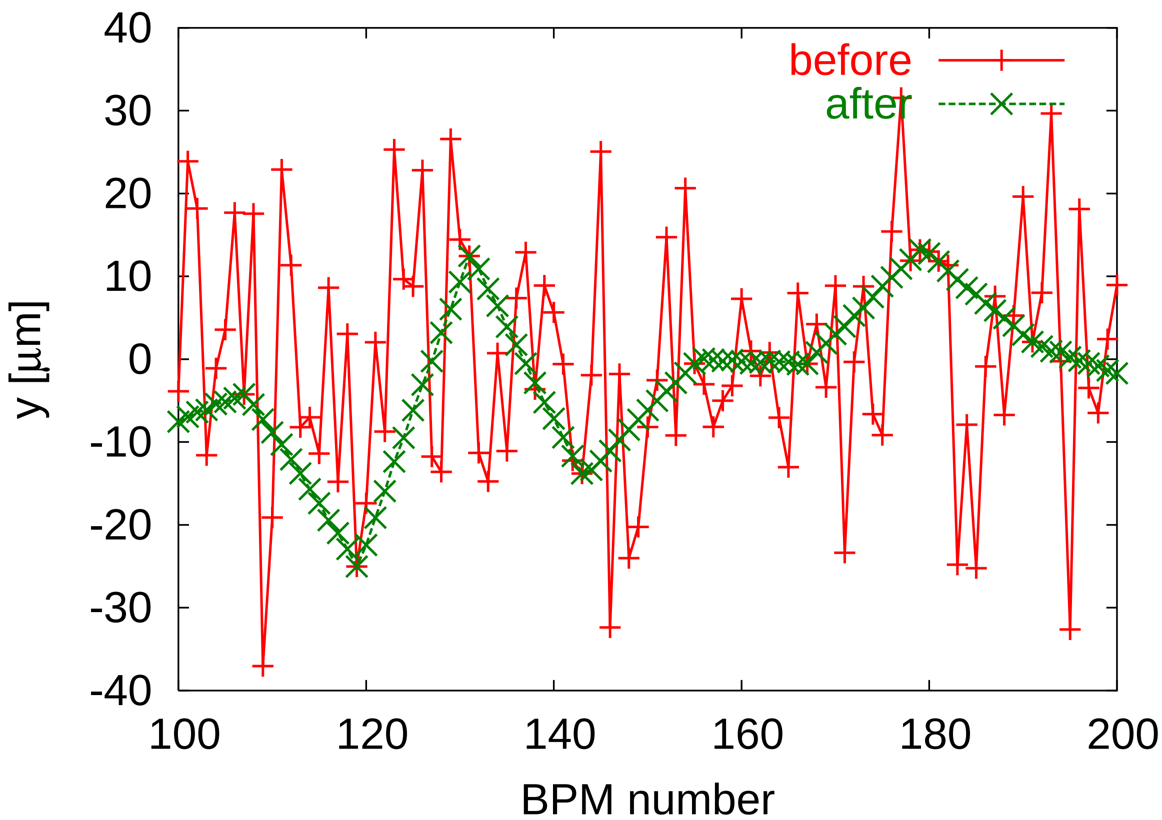
⇒ Cannot give “the” tolerance for one error source



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

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

- 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

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

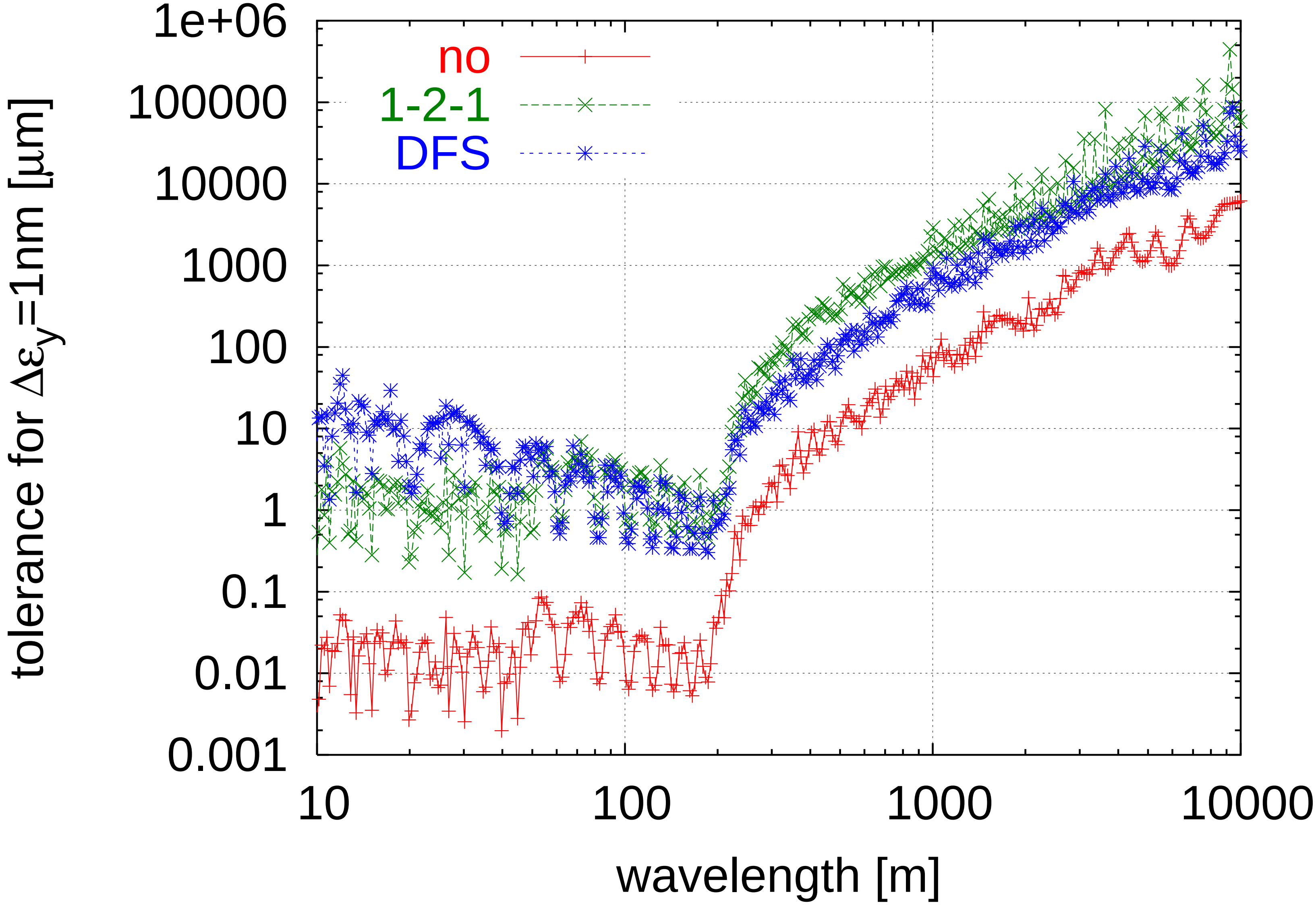
$\Rightarrow$ As long as ΔK is small and $\delta \approx a\Delta K/K$

$$x_0 \approx -a$$

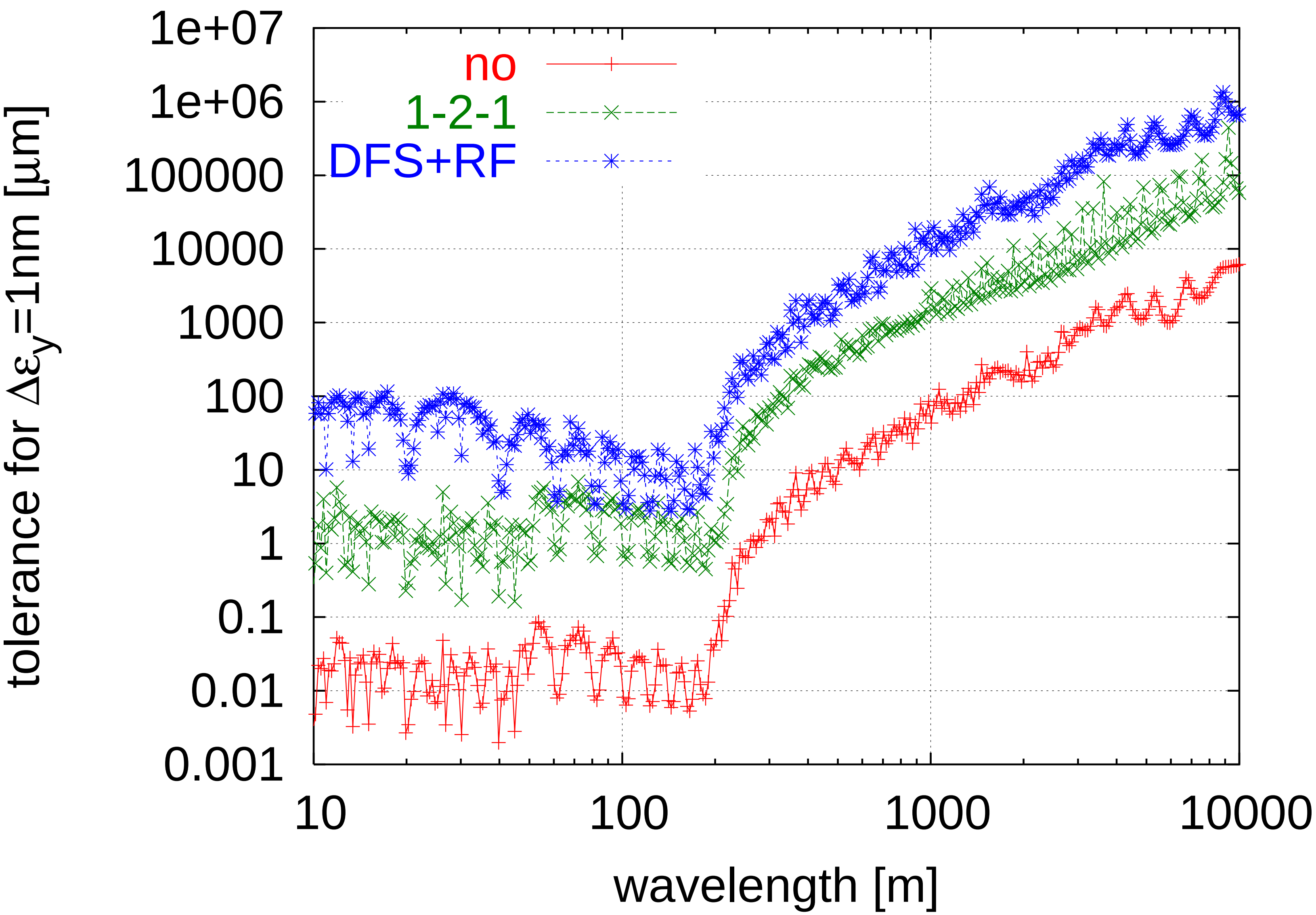
Long Distance Alignment

- 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

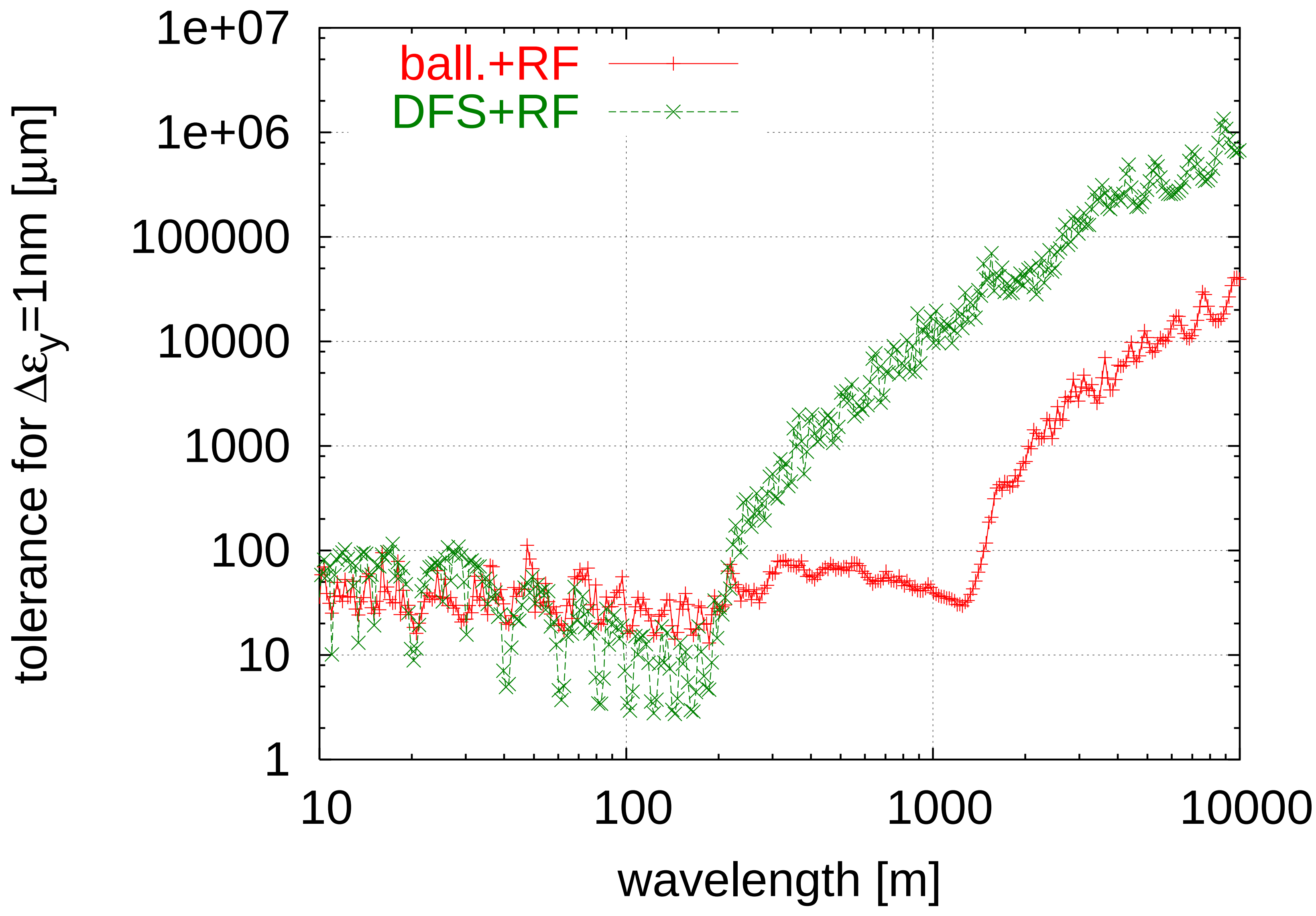
Long Wavelength Tolerance I (Old CLIC)



Long Wavelength Tolerance II (Old CLIC)

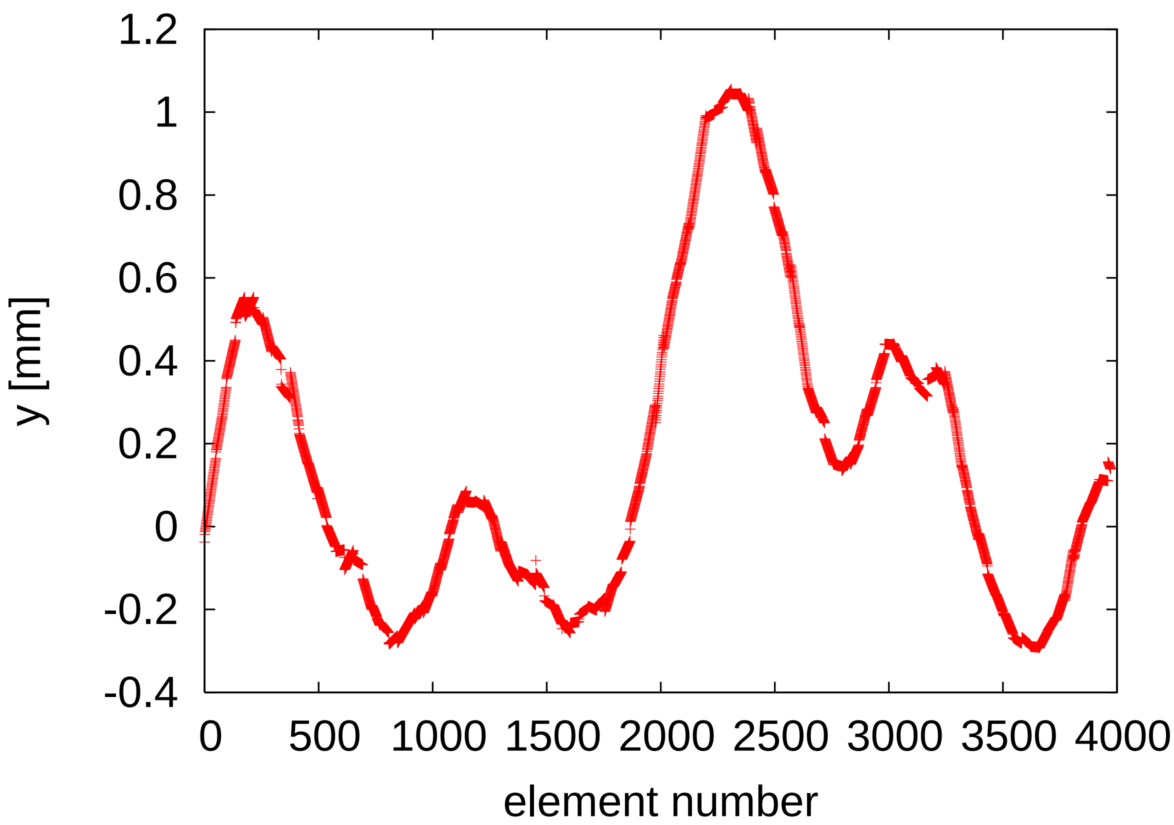


Long Wavelength Tolerance III (Old CLIC)

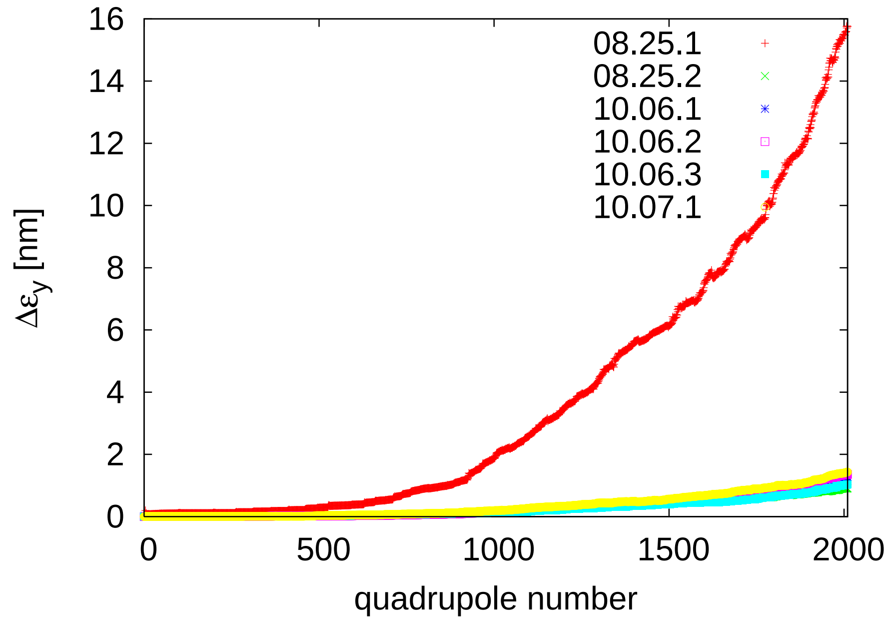


Wire System Misalignment Modelling

- 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

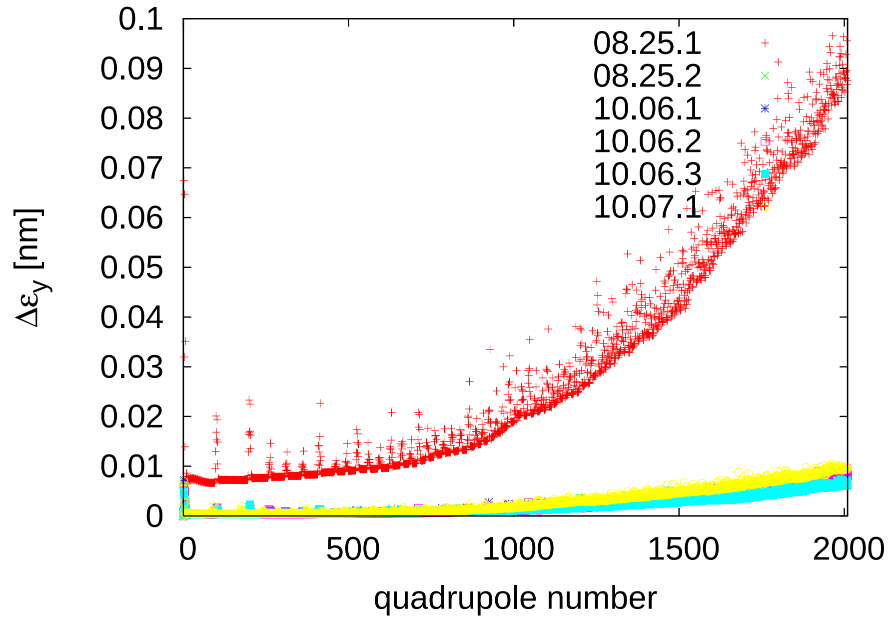


Beam-Based Alignment

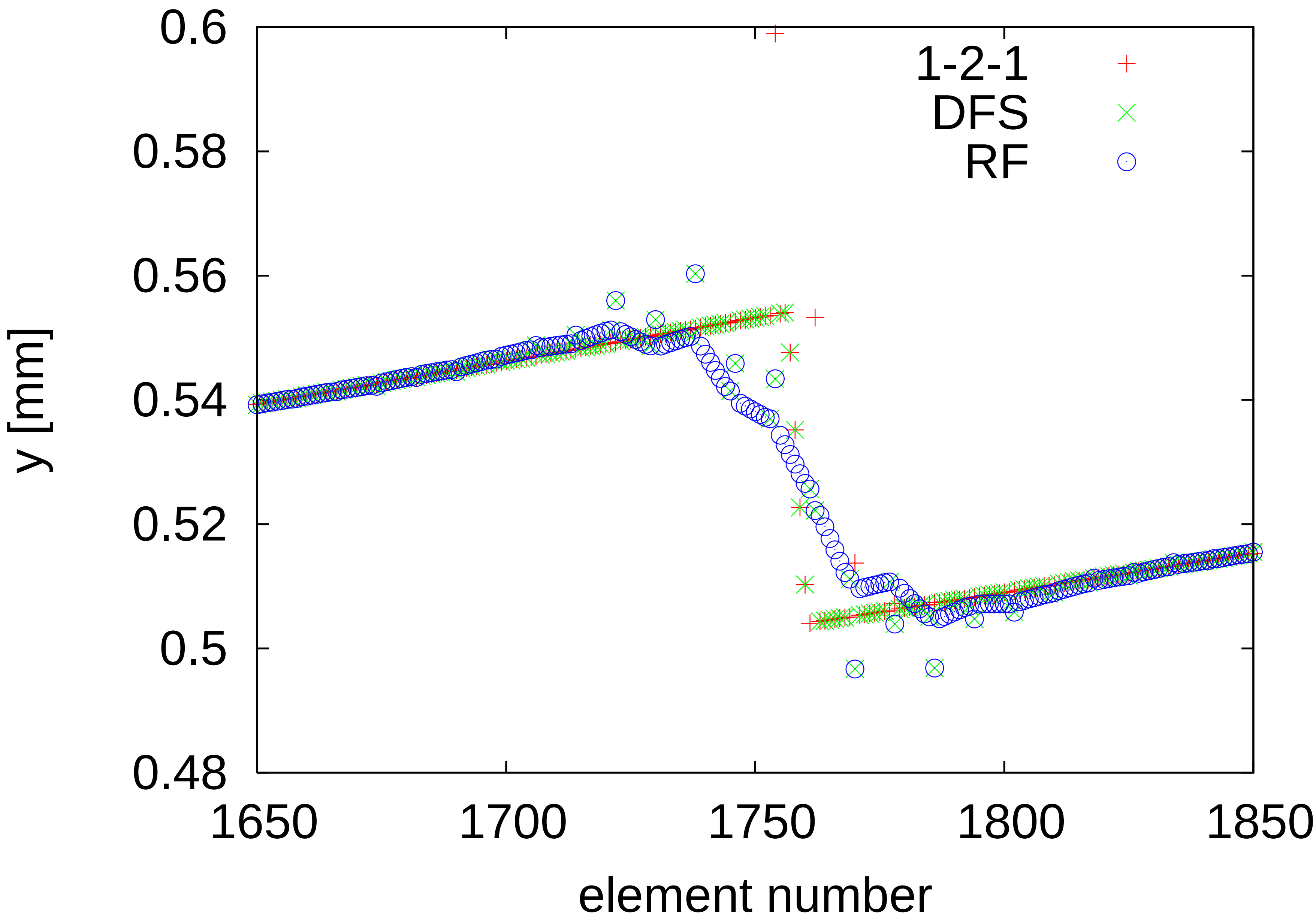


- Flat steering used first
- Dispersion free steering using settings from baseline algorithm
- RF structure alignment
- Different cases marked by date

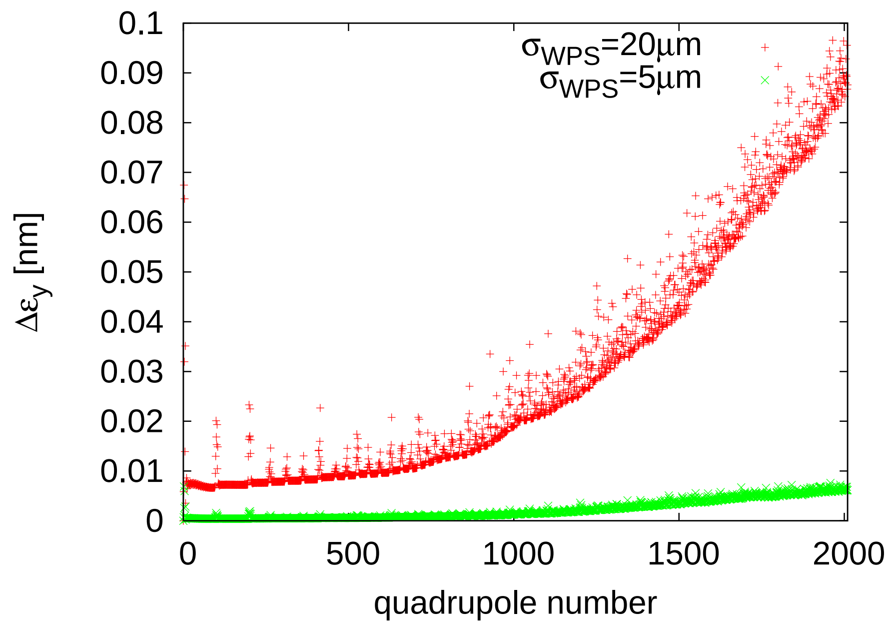
⇒ RF Alignment is very important



Impact on Element Positions



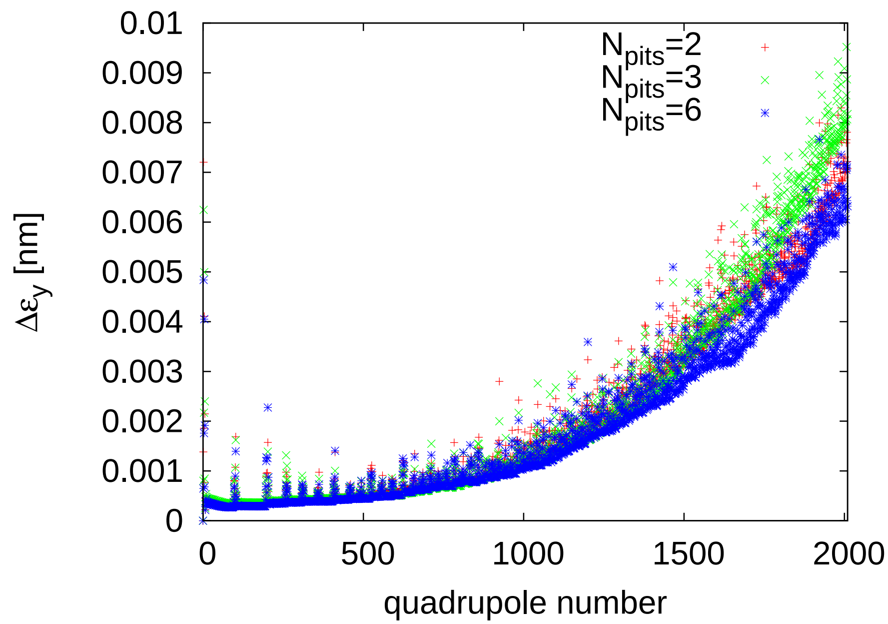
Preliminary Results



⇒ 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 equipontential 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 where 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
  $$\delta'_1 \approx 0.3 \, \frac{\mathrm{GeV}}{\mathrm{Tm}^2} \frac{BL}{E_1}$$
  If we have a second particle at a different energy E_2 it is deflected differently
  $$\delta'_2 \approx 0.3 \, \frac{\mathrm{GeV}}{\mathrm{Tm}^2} \frac{BL}{E_2}$$
  so the two particles will take different trajectories
  The different is described by the dispersion $D_{x,y}$ with
  $$D_x = \frac{\partial x}{\partial \delta} \qquad D_y = \frac{\partial y}{\partial \delta}$$

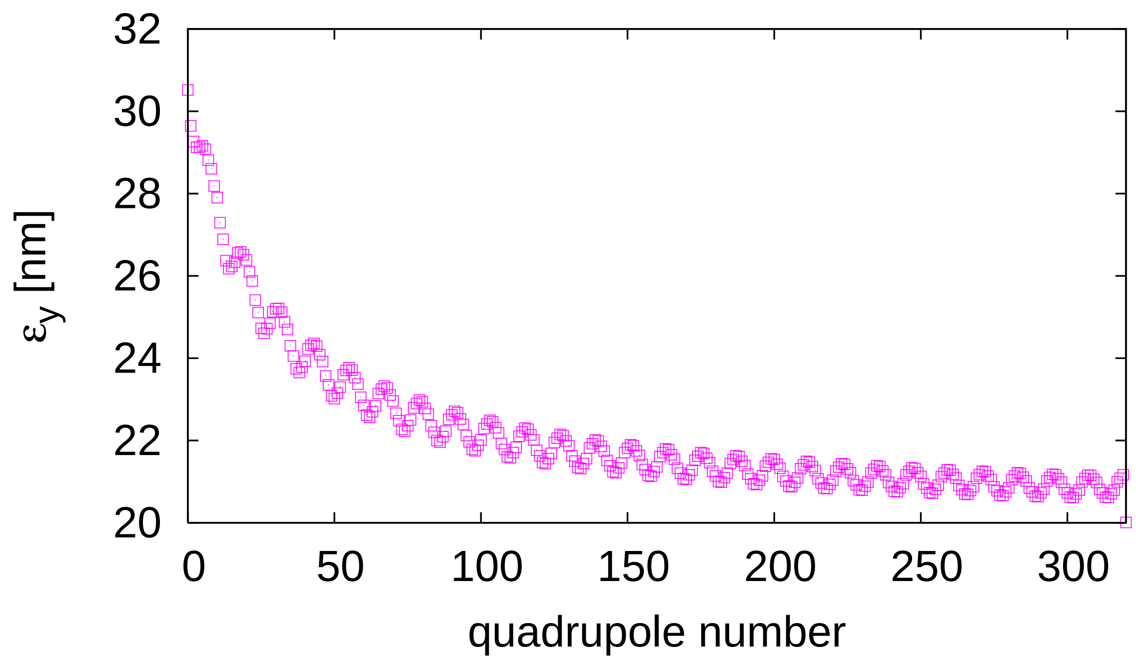
Dispersion in ILC

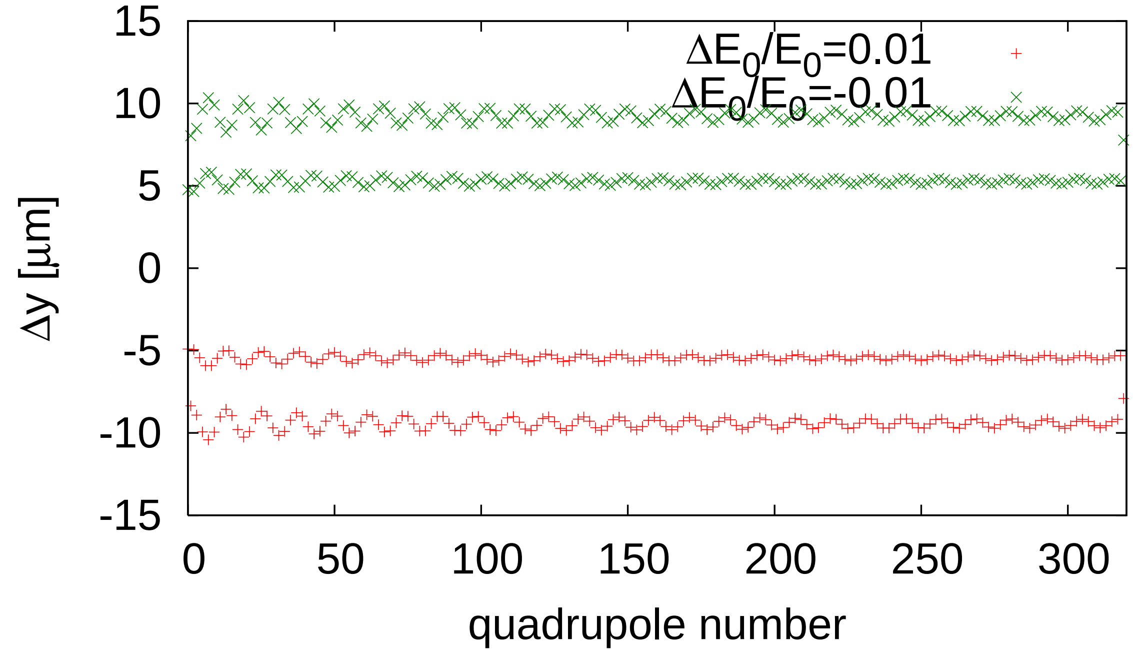
- Find a periodic solution for the dispersion

⇒ 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

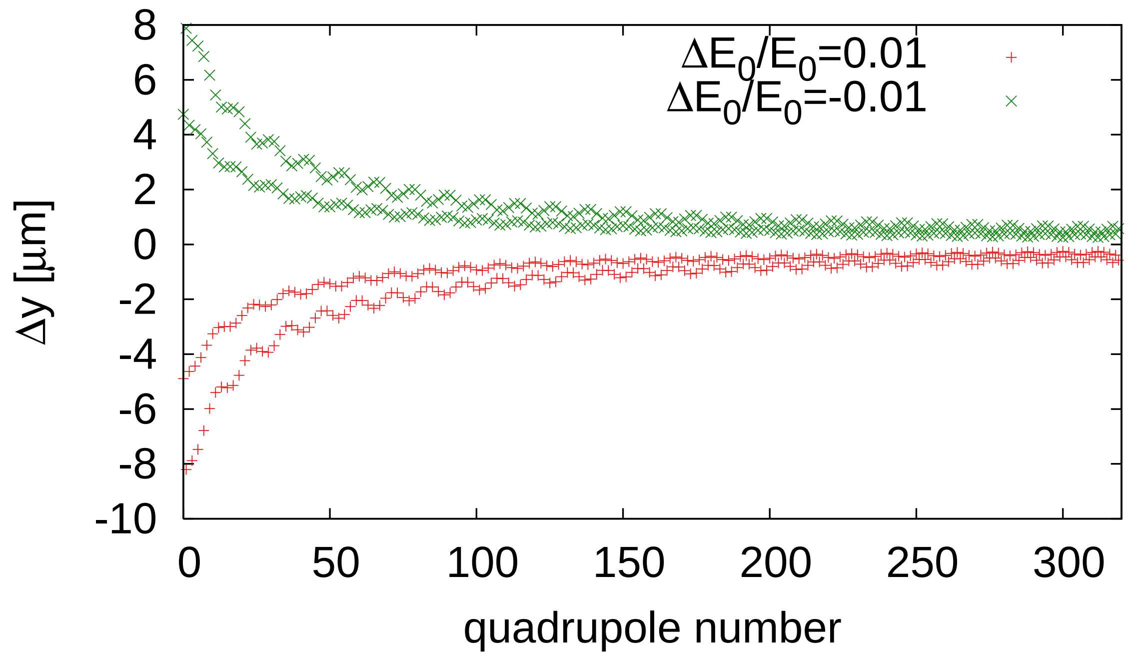


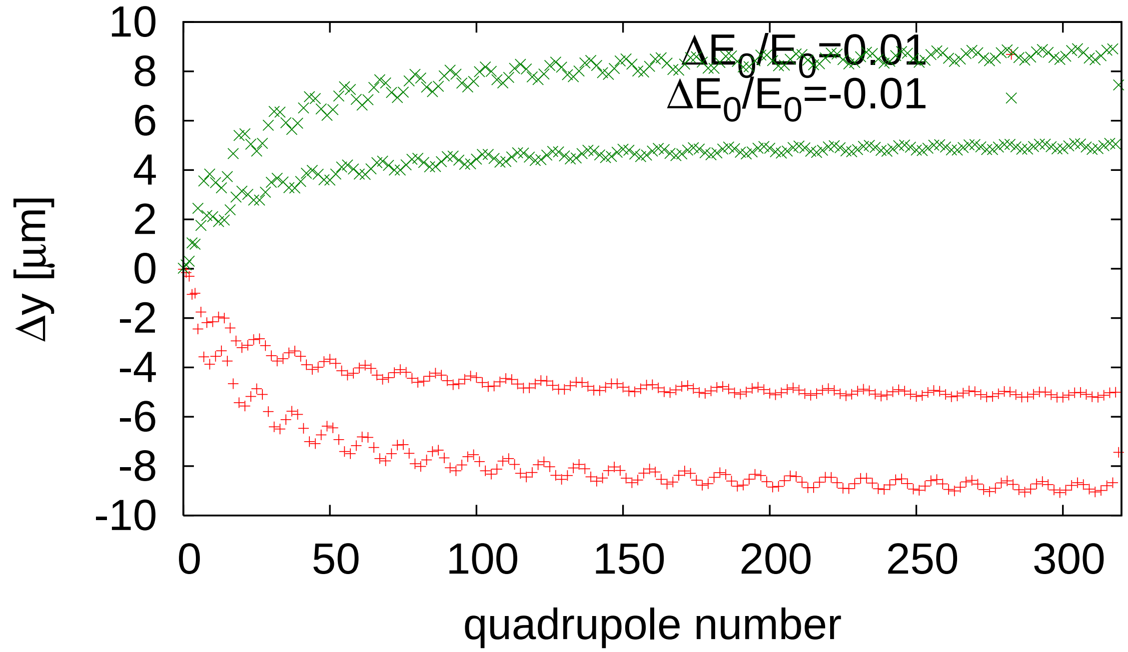


Initial Energy vs. Gradient

- 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

  $\Rightarrow$ 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

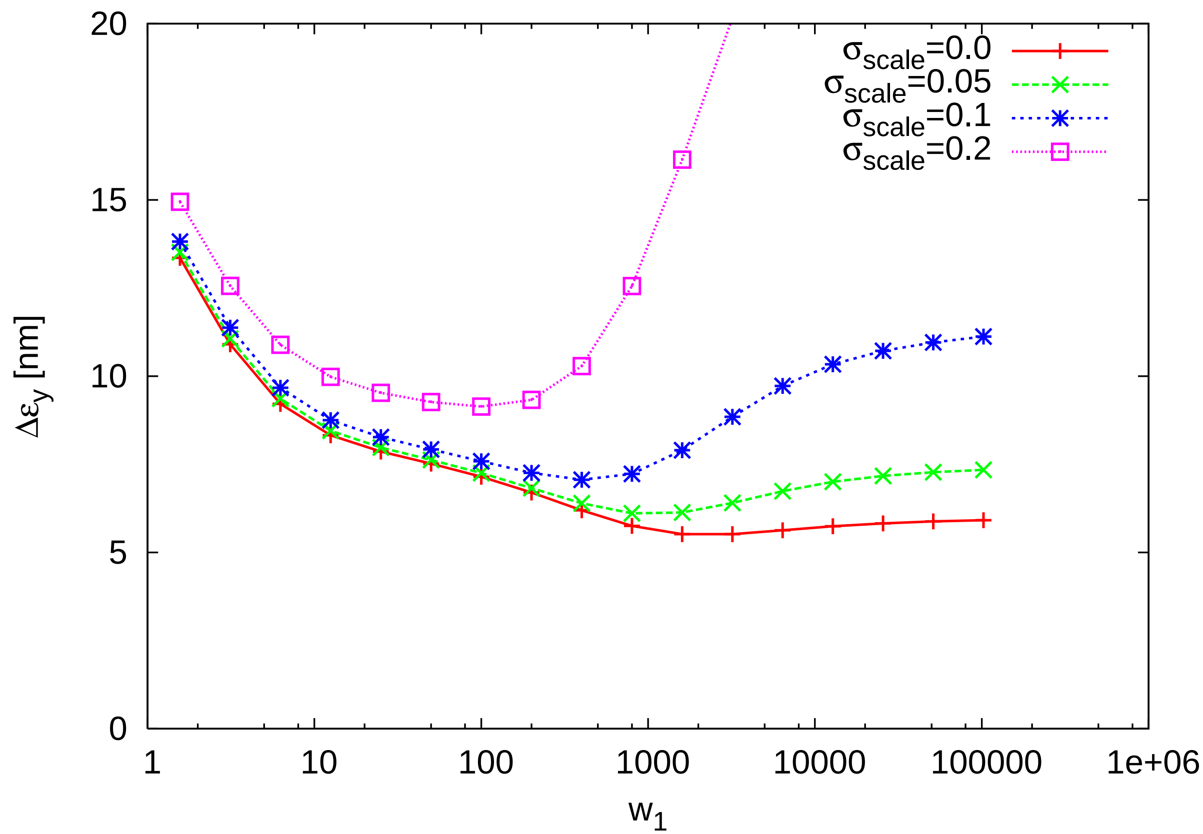
$$\sigma_D^2 \approx \frac{2\sigma_{res}^2}{(E_1 - E_2)^2}$$

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

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

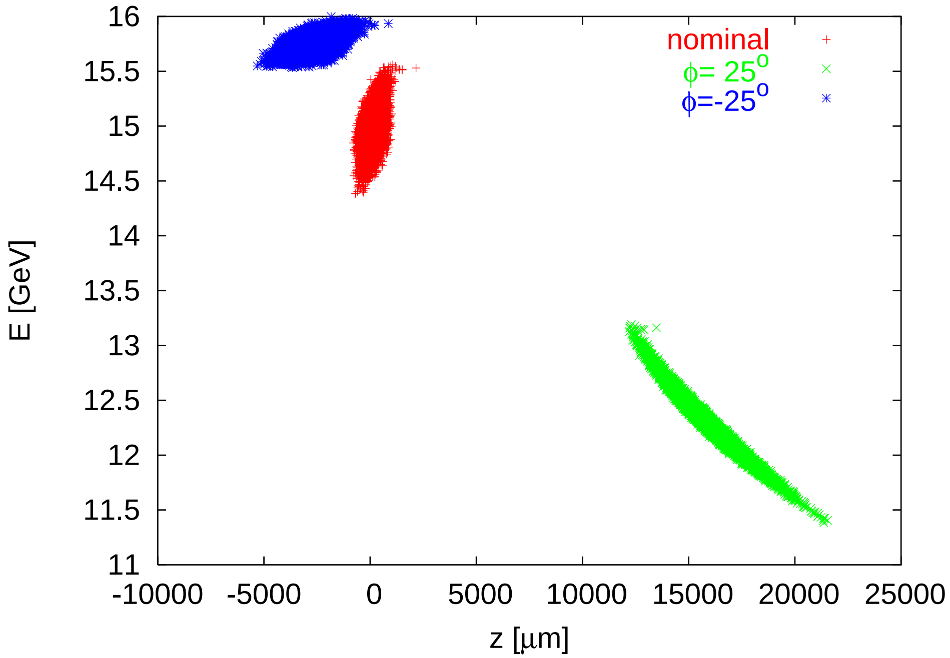
Single Bunch Dispersion Steering Simulations

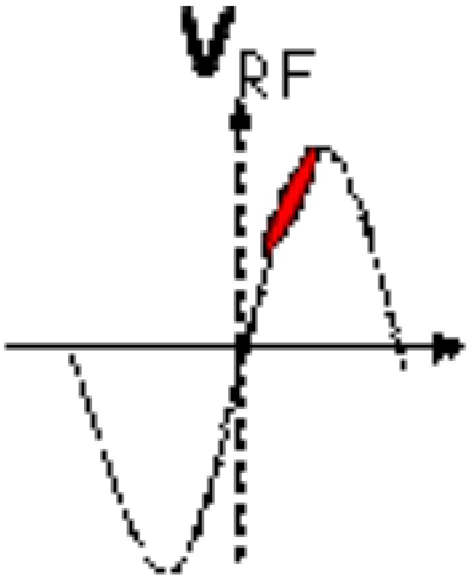
- Aim is 90% of machines at $\Delta\epsilon_y \leq 10\,\mathrm{nm}$
- P. Eliasson, K. Kubo, A. Latina, P. Lebrun, F. Poirier, K. Ranjan, D. Schulte, J. Smith, N. Soljak, N. Walker...
- Not all results are bench-marked against others
  - small differences in the assumptions etc.
- Consensus is:
  - beam-based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

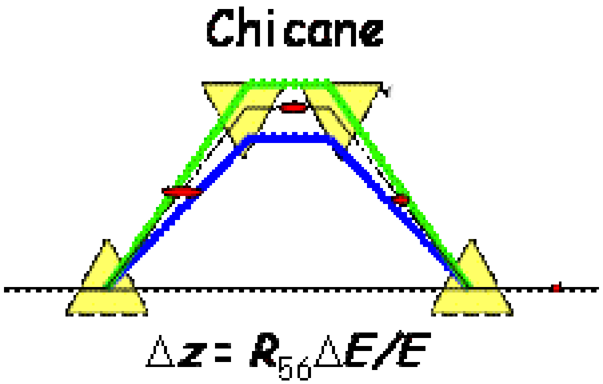


Alignment of Beginning of Main Linac

- 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 misalinement of elements in the tunnel due to the limited accuracy of the pre-aligment 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