Some Remarks on Beam-Based Alignment and Stabilisation

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- Will just mention some important tolerances
- Focus on alignment and stabilisation procedure
  - step size of correctors

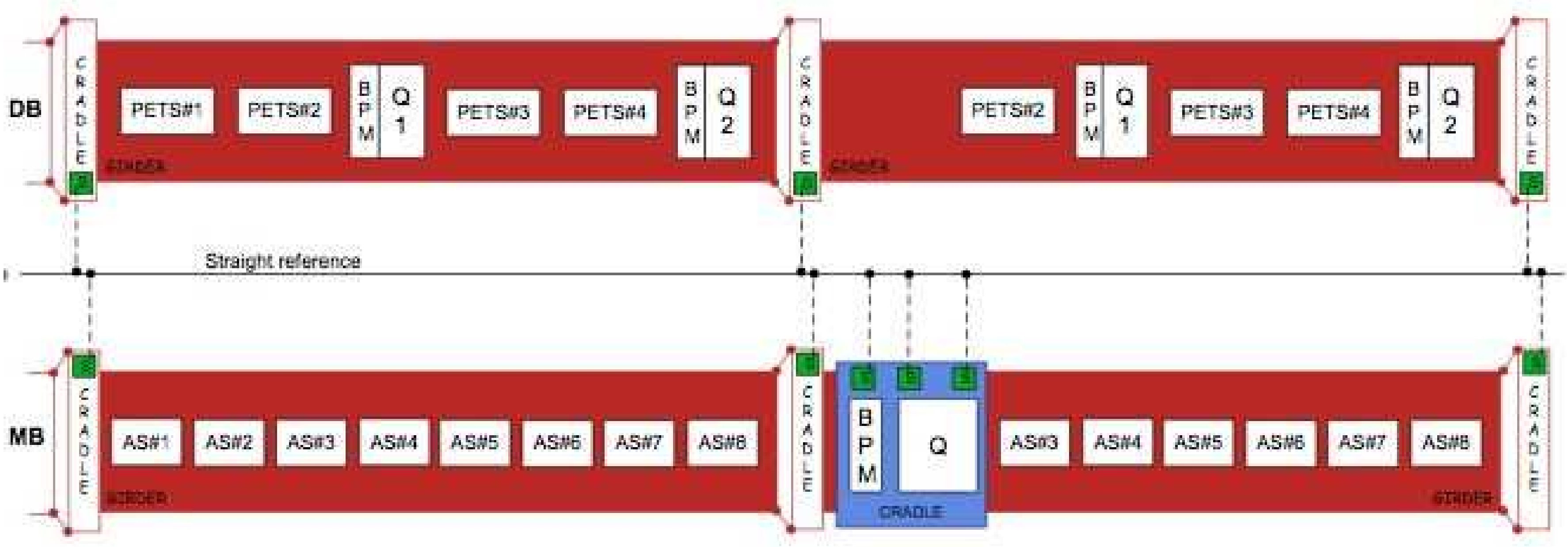
Quantities and their Constraints

- Quadrupole mover range
  - initial misalignment
- Girder mover range
  - initial misalignment
- Quadrupole mover step size
  - feedback requirement
- Girder mover step size
  - final static error
- BPM resolution
  - static and dynamic effects

Main Linac Emittance Growth

- The vertical emittance is most important since it is much smaller than the horizontal one (10 nm vs 550 nm)
- For a perfect implementation of the machine the main linac emittance growth would be negligible
- Two main sources of emittance growth exist
  - static imperfections
  - dynamic imperfections
- The emittance growth budget is 5 nm for static imperfections
  - i.e. 90% of the machines must be better
- For dynamic imperfections the budget is 5 nm
  - but short term fluctuation must be smaller to avoid problems with luminosity tuning

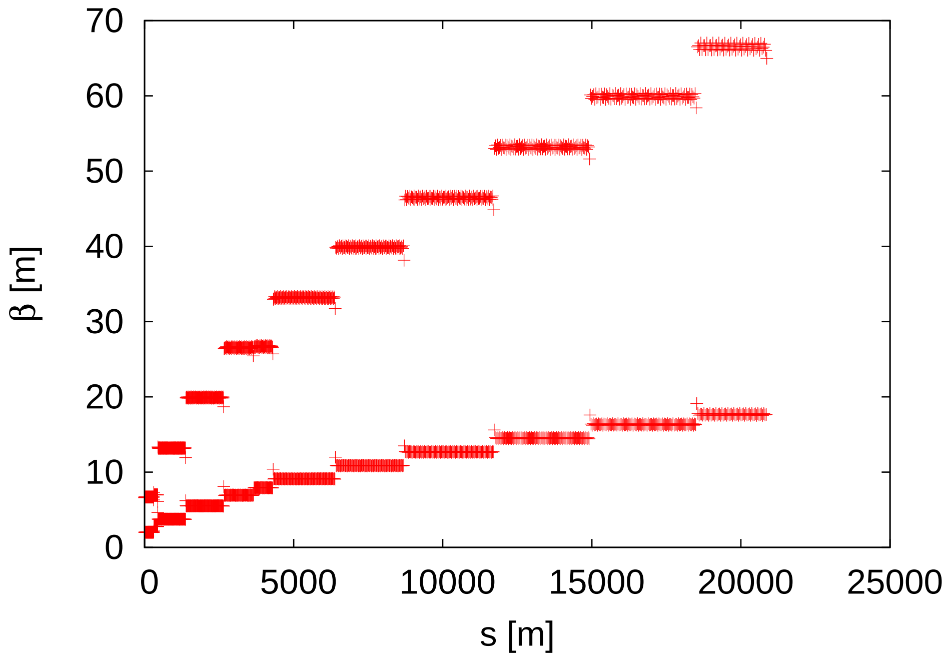
Module Layout



- Five types of main linac modules
- Drive beam module is regular

Lattice Design

- Used $\beta \propto \sqrt{E}$, $\Delta\Phi = \mathrm{const}$
  - balances wakes and dispersion
  - roughly constant fill factor
  - phase advance is chosen to balance between wakefield and ground motion effects
- Preliminary lattice
  - made for $N = 3.7 \times 10^9$
  - quadrupole dimensions need to be confirmed
  - some optimisations remain to be done
- Total length 20867.6m
  - fill factor 78.6%

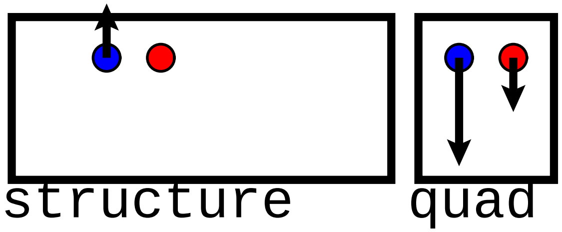


- 12 different sectors used
- Matching between sectors using 5 quadrupoles to allow for some energy bandwidth

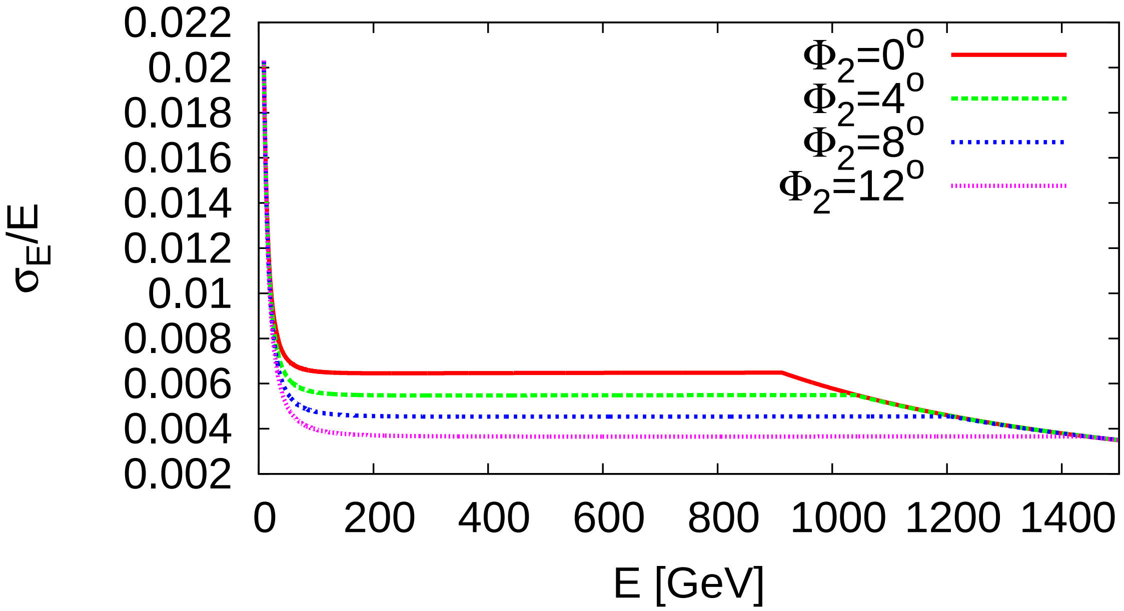
Energy Spread and Beam Stability

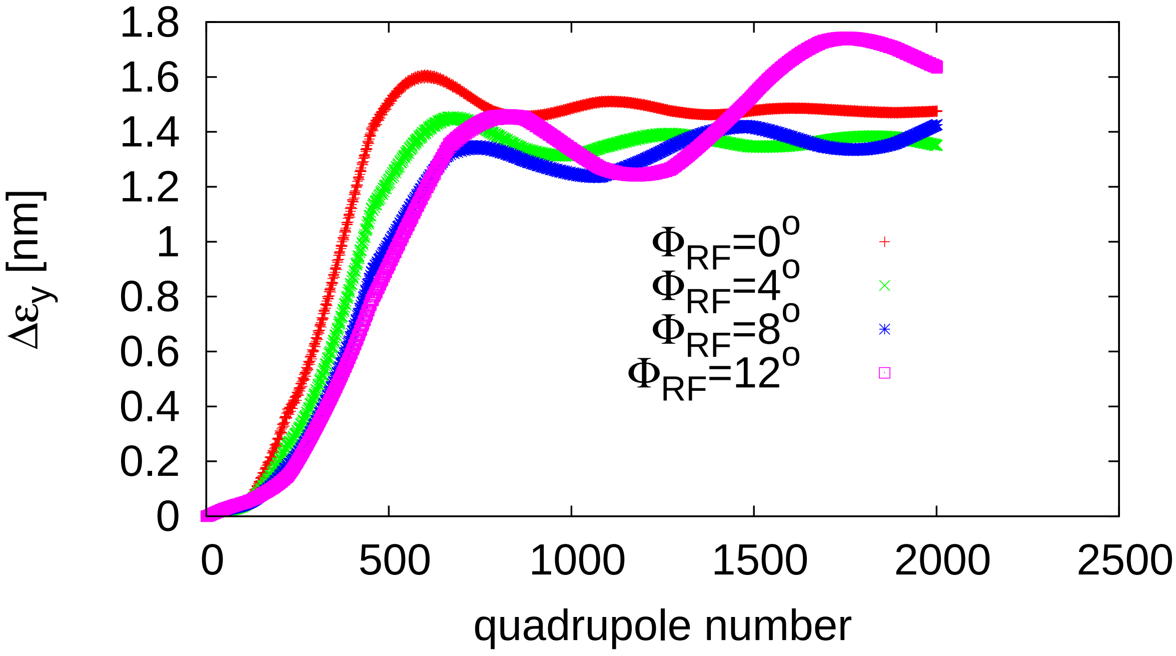
- Trade-off in fixed lattice
  - large energy spread is more stable
  - small energy spread is better for alignment

⇒ Beam with $N = 3.7 \times 10^9$ can be stable



⇒ Tolerances are not a unique number





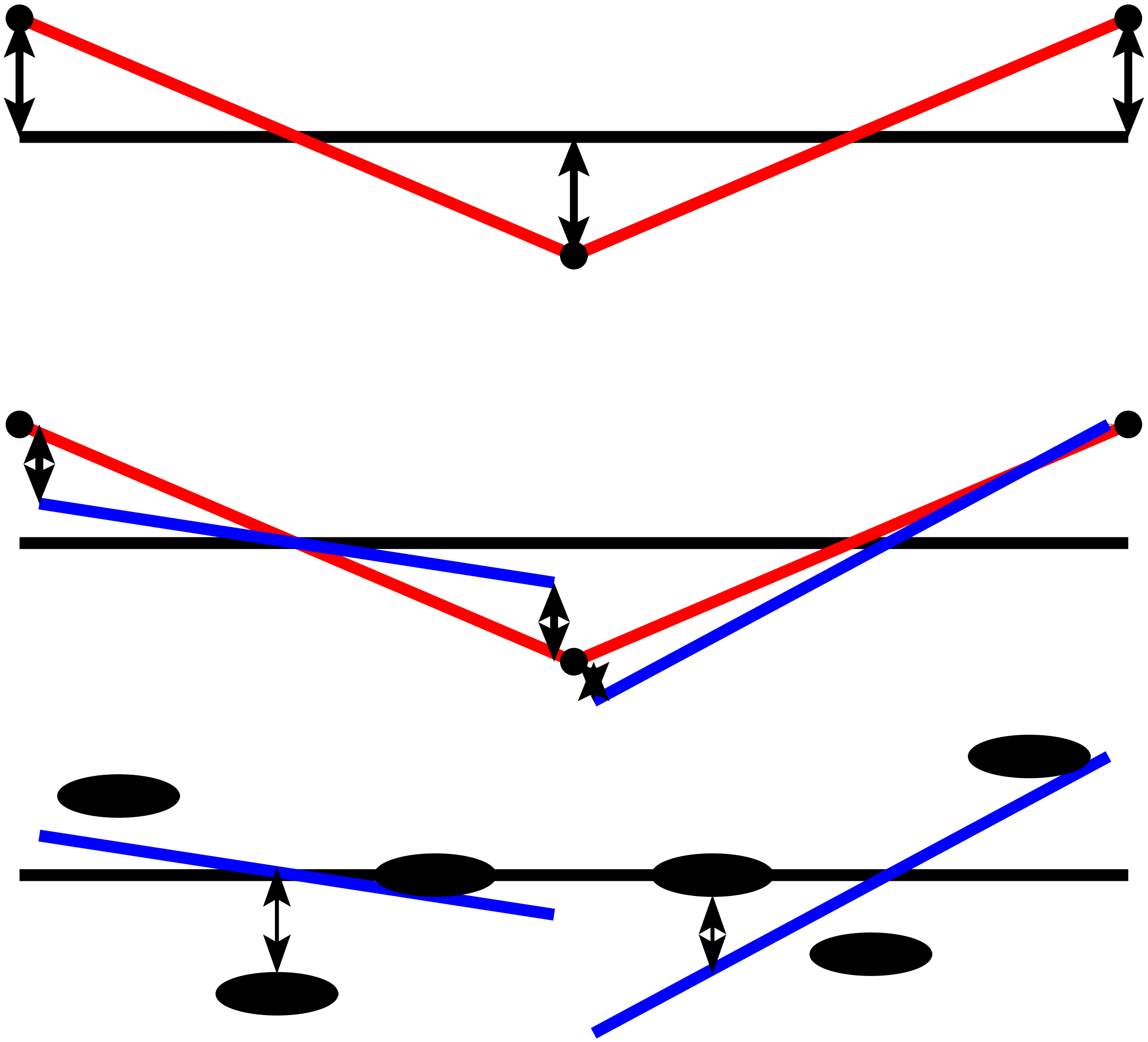
Main Linac Tolerances

Element	error	with respect to	tolerance	
			CLIC	NLC
Structure	offset	beam	$5.8\,\mu\mathrm{m}$	$5.0\,\mu\mathrm{m}$
Structure	tilt	beam	$220\,\mu\mathrm{radian}$	$135\,\mu\mathrm{radian}$
Quadrupole	offset	straight line	—	—
Quadrupole	roll	axis	$240\,\mu\mathrm{m}$	$280\,\mu\mathrm{radian}$
BPM	offset	straight line	$0.44\,\mu\mathrm{m}$	$1.3\,\mu\mathrm{m}$
BPM	resolution	BPM center	$0.44\,\mu\mathrm{m}$	$1.3\,\mu\mathrm{m}$

- All tolerances for 1nm growth after one-to-one steering
- CLIC emittance budget is two times smaller than for NLC

  $\Rightarrow$ for comparison divide tolerances by $\sqrt{2}$
- Goal is to have 90% of the machines achieve an emittance growth due to static effects of less than 5 nm

Misalignment Model: Simplified Version



- In PLACET consider three types of misalignment
  - articulation point (cradle)
  - articulation point to girder
  - structure centre to girder
- Error of reference line may contain systematics

Assumed Survey Performance

Element	error	with respect to	alignment	
			NLC	CLIC
Structure	offset	girder	$25\,\mu$m	$5\,\mu$m
Structure	tilts	girder	$33\,\mu$radian	$200(*)\,\mu$m
Girder	offset	survey line	$50\,\mu$m	$9.4\,\mu$m
Girder	tilt	survey line	$15\,\mu$radian	$9.4\,\mu$radian
Quadrupole	offset	survey line	$50\,\mu$m	$17\,\mu$m
Quadrupole	roll	survey line	$300\,\mu$radian	$\leq 100\,\mu$radian
BPM	offset	quadrupole/survey line	$100\,\mu$m	$14\,\mu$m
BPM	resolution	BPM center	$0.3\,\mu$m	$0.1\,\mu$m
Wakefield mon.	offset	wake center	$5\,\mu$m	$5\,\mu$m

- In NLC quadrupoles contained the BPMs, they are seperate for us

⇒ Better BPM alignment and resolution foreseen in CLIC

⇒ Smaller quadrupole roll than in NLC

⇒ Similar wakefield monitor performance

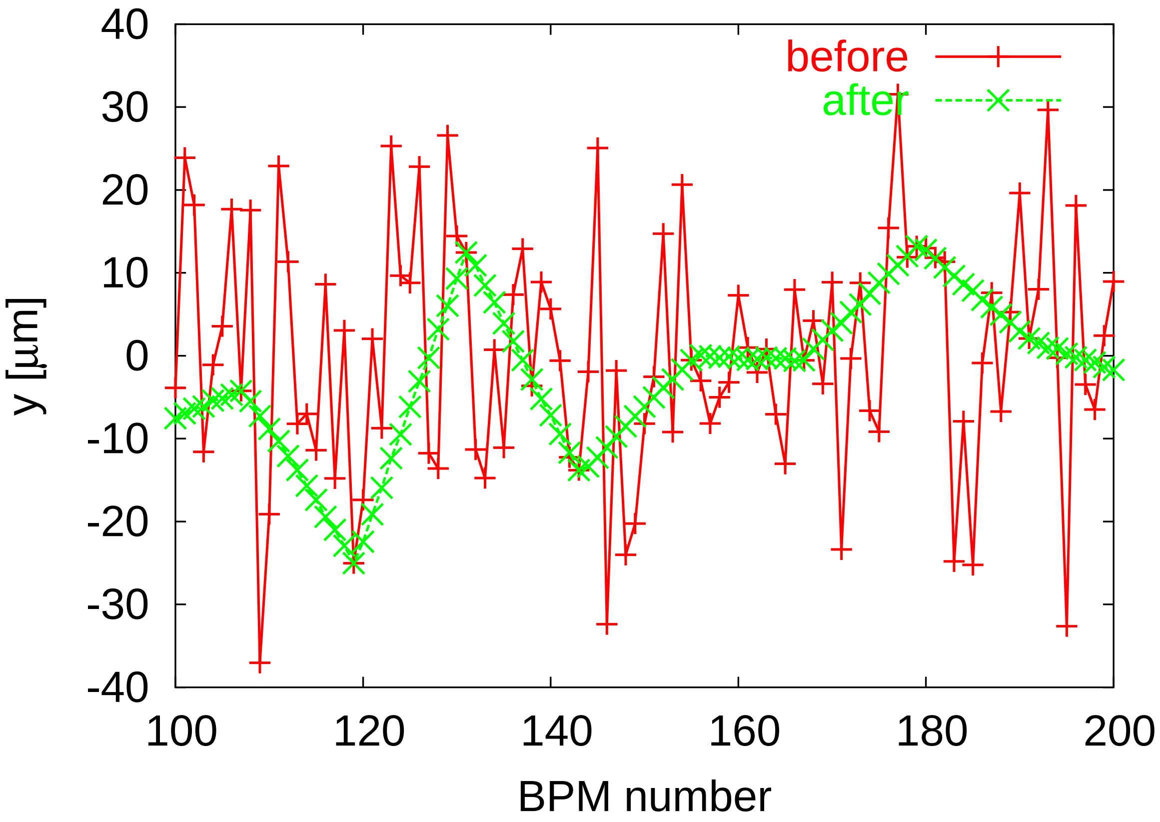
- Structure tilt is dominated by structure fabrication precision

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 wakefield effects
  - accelerating structure alignment
  - emittance tuning bumps
- Tune luminosity
  - tuning knobs

Ballistic Alignment

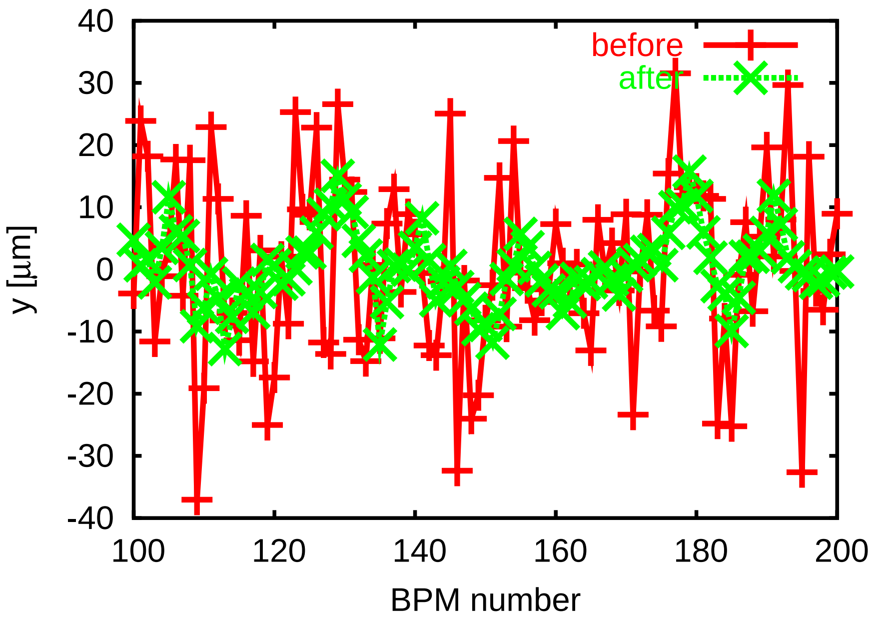
- Beamline is divided into bins (12 quadrupoles)
- Quadrupoles in a bin are switched off
- Beam is steered into last BPM of bin
- BPMs are realigned to beam
- Quadrupoles are switched on
- Few-to-few steering is used



- Typical problems are residual fields

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

Kick Minimisation

- First align BPMs to quadrupoles
  - shunt quadrupole field
  - observe beam motion
  - move quadrupole/beam to a position that shuting 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

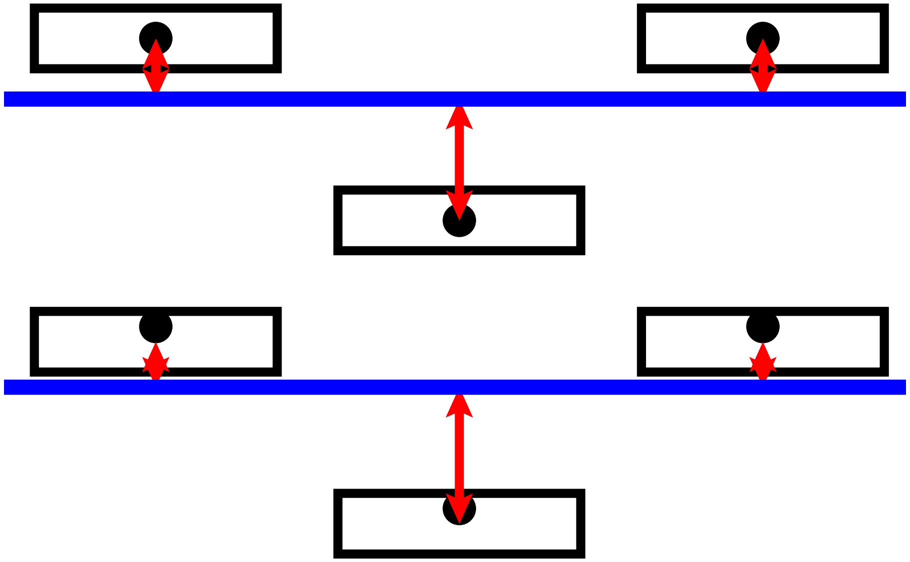
Beam-Based Structure Alignment

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

$\Rightarrow$ 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 $\sigma_{wm}/\sqrt{n}$
- Error of final articulation point position must be $\sigma_{art} \ll 5\,\mu\mathrm{m}/\sqrt{8} \approx 1.5\,\mu\mathrm{m}$

$\Rightarrow$ step size $\Delta_{art} < 1\,\mu\mathrm{m}$



- Tolerance and performance prediction are similar for CLIC and NLC
- For our tolerance $\sigma_{wm} = 5\,\mu\mathrm{m}$ we find $\Delta\epsilon_y \approx 0.5\,\mathrm{nm}$
  - some dependence on alignment method

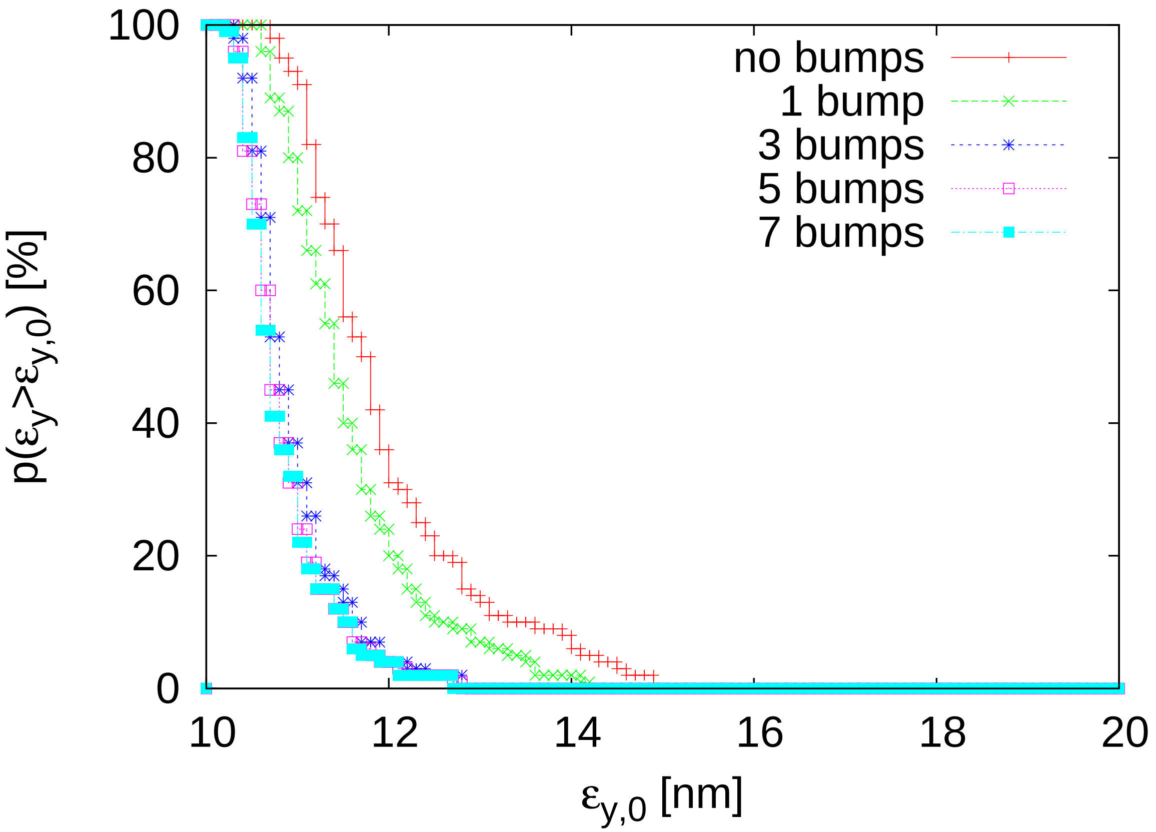
Final Emittance Growth

- Different implementations of DFS have different sensitivities to imperfections
  - values for examples (M1–M4) in nm
- Static uncorrelated phase and gradient errors of the structures can lead to emittance growth
  - no attempt made to correct lattice information

⇒ a 2% gradient error leads to $\Delta\epsilon_y \approx 0.3\,\mathrm{nm}$

⇒ a 1 degree phase error leads to $\Delta\epsilon_y \approx 0.3\,\mathrm{nm}$

	M1	M2	M3	M4
beam jitter	0.57	0.67	0.51	0.57
BPM resolution	0.19	0.17	0.17	0.16
struct. tilt	2.64	0.43	0.4	0.48
struct. real.	0.14	0.53	0.53	0.44
struct. scatter	0.18	0.06	0.05	0.04
sum	3.8	1.6	1.8	1.8



Generic Alignment Procedure

- Split the beam line into bins
- Foreach bin
  - use beam to determine new BPM and quadrupole positions
  - if movement is large do it mechanically and iterate
    need to maintain BPM position reference (precision better than position error)
  - correct BPM position electronically
  - correct quadrupole position electronically
  - iterate, if needed
- Foreach set of girders between quadrupoles
  - measure beam offset in wakefield monitors
  - move articulation points
  - recentre beam in next BPM moving quadrupole electronically
  - iterate, if needed

Structure-To-Girder Tolerance

- The mean offset of the structures to the beam is corrected
  - this corrects almost all effects due to identical wakefields

  ⇒ a limit will come from non-identical wakefields
  - some impact on the alignment procedure can exist
- Single bunch wakefield limit
  - assume relative slope of wakefields scatters by σ_w

  ⇒ alignment tolerance is $\sigma_{cav,girder} = \sigma_{wm}/\sigma_w = 5\,\mu\mathrm{m}/\sigma_w$
- Multi-bunch wakefield limits
  - additional kicks for identical wakes aligned with single bunch wakes

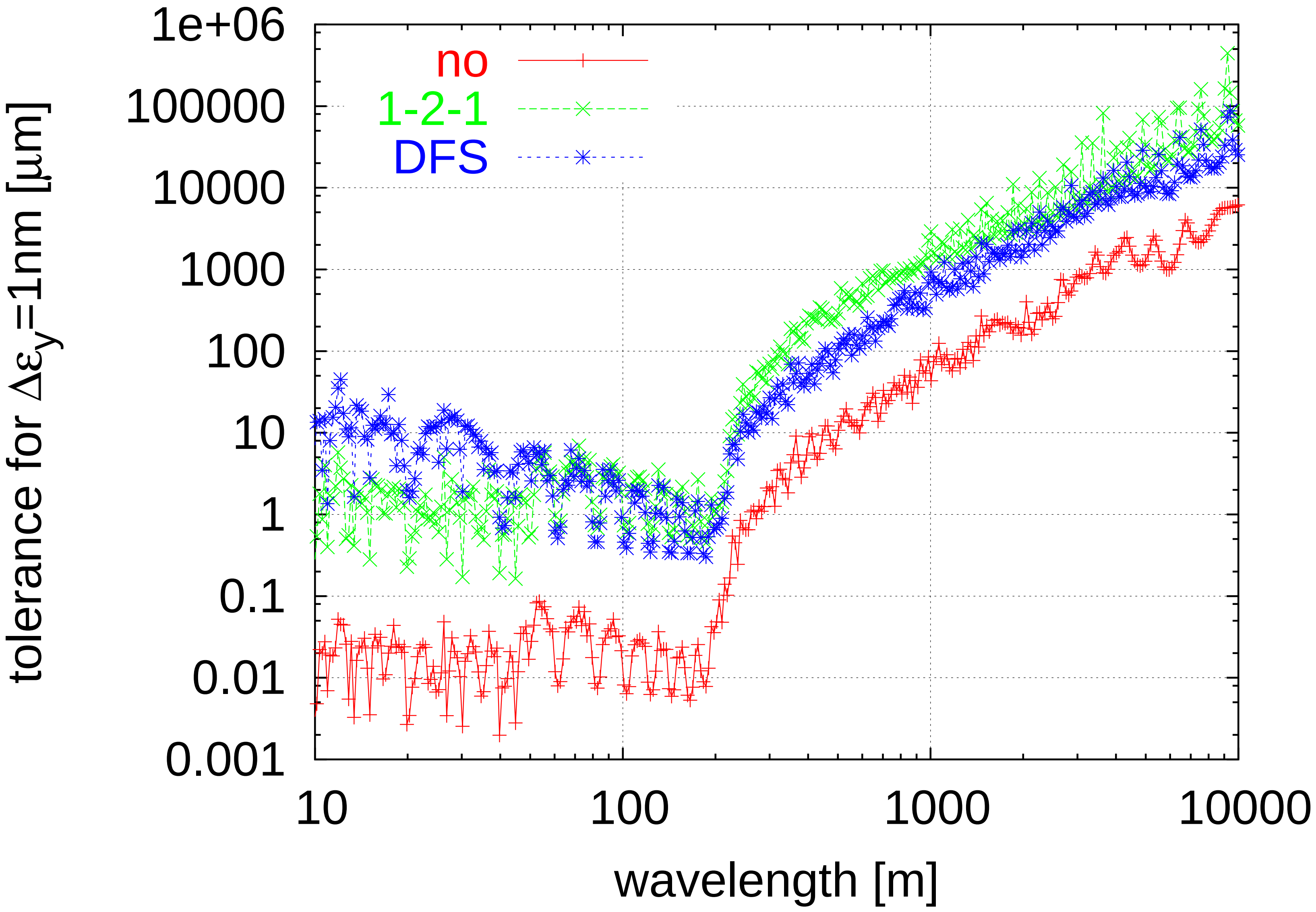
    ⇒ found to give little effect
  - non-identical wakefields or identical wakefields not aligned with single bunch wakes

    ⇒ can give an effect

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, PLACET 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

Results 1


no
1-2-1
DFS
1e+06
100000
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10
1
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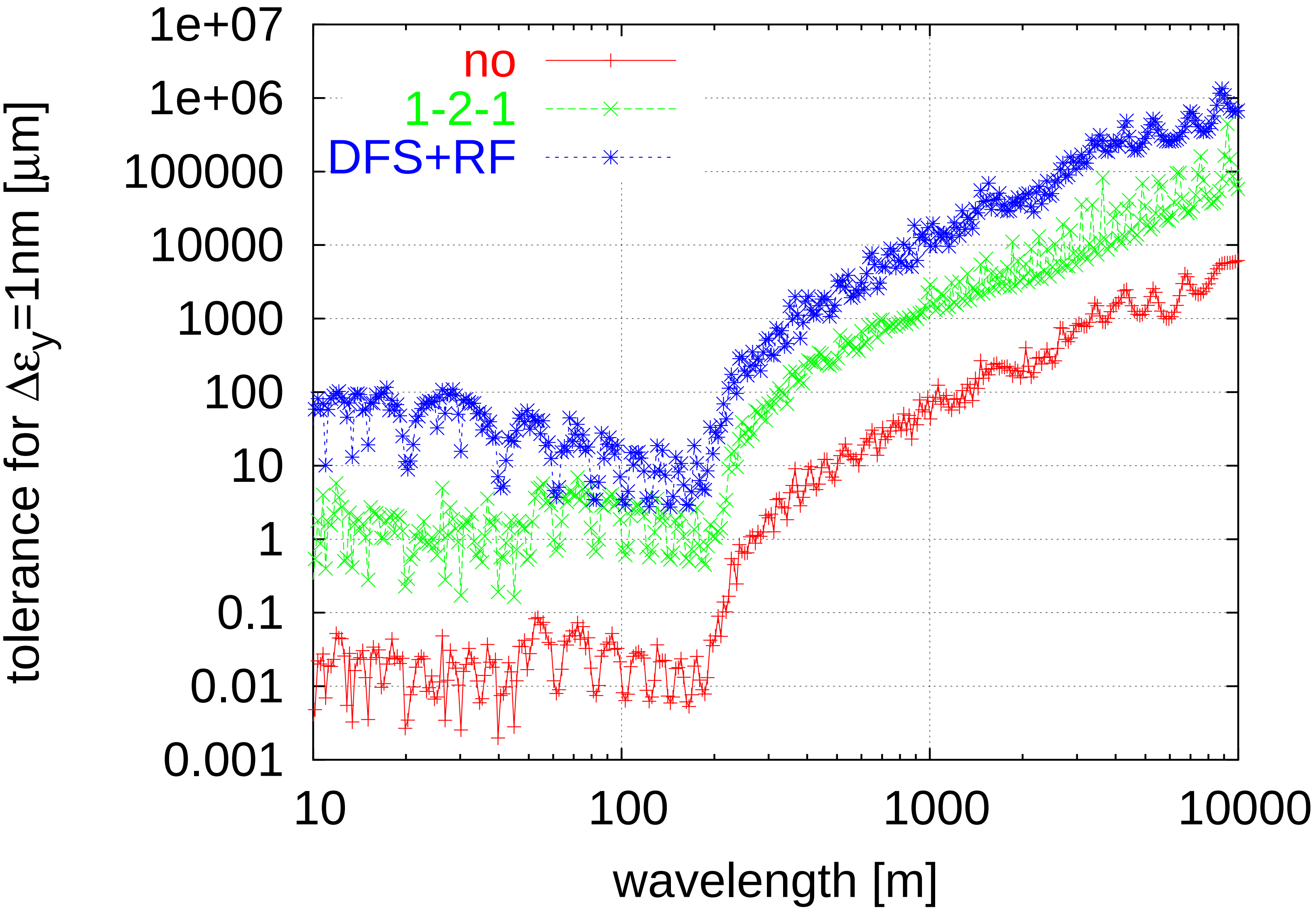
tolerance for $\Delta\varepsilon_y$=1nm [µm]
wavelength [m]

Results 2



no
1-2-1
DFS+RF
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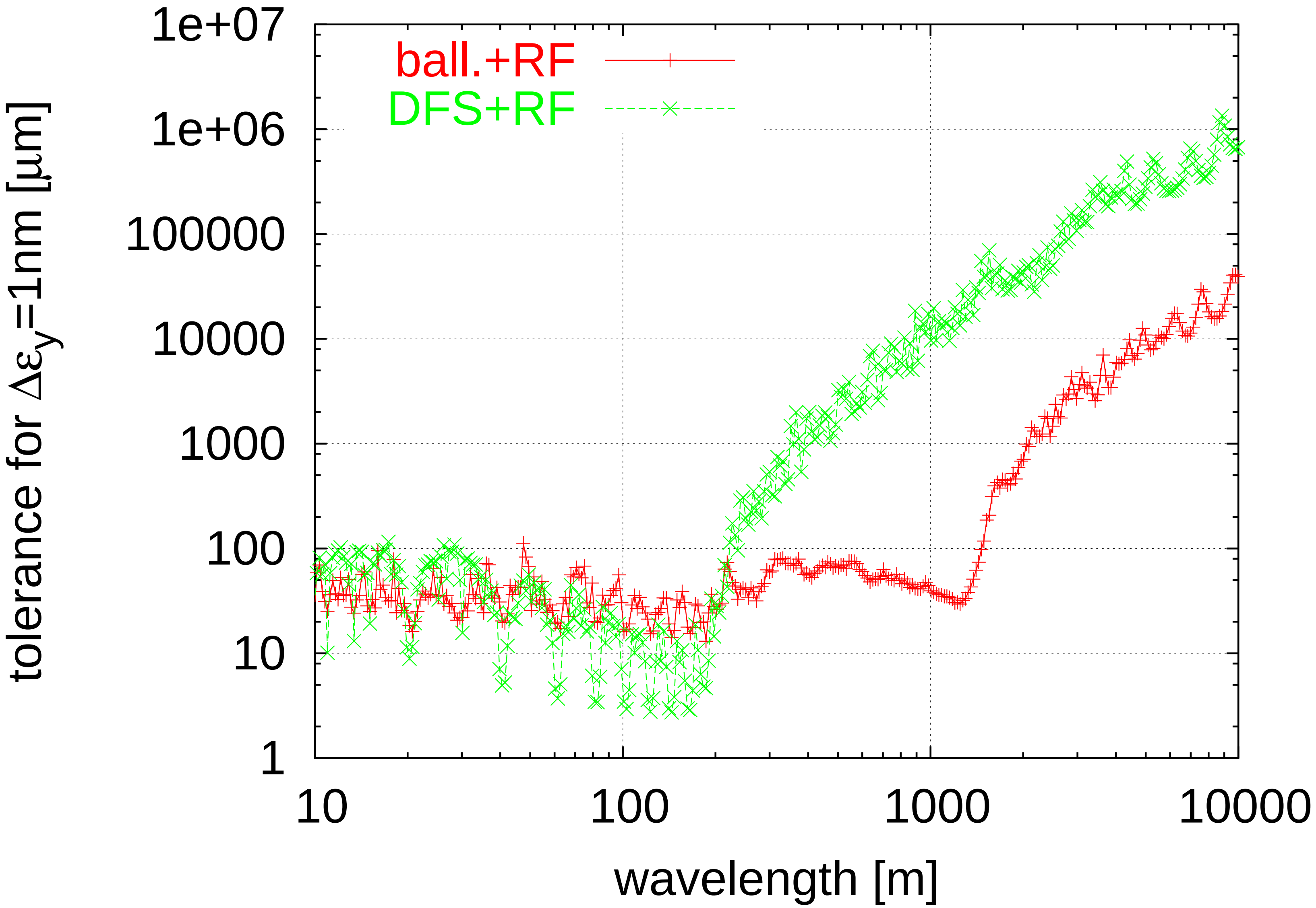
tolerance for $\Delta\varepsilon_y$=1nm [μm]
wavelength [m]

Results 3



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tolerance for $\Delta\varepsilon_y$=1nm [μm]
1e+07
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10000
wavelength [m]

Dynamic Imperfections

- A large number of dynamic imperfections exist

  e.g. ground motion, RF phase and amplitude jitter, element transverse jitter, magnet strength jitter, . . .

- These imperfections need to be adressed across the whole machine

  - but can start looking at individual components

- Imperfection can lead to direct luminosity reduction

  e.g. quadrupole transverse jitter in main linac

- They can lead to indirect luminosity loss

  - the required feedback impacts the beam

  - impact on static alignment and tuning procedures

Main Linac Feedback Strategy

- Stabilisation of elements using local mechanical feedback
- Information from survey system is only recorded, not used directly
- Intra-pulse beam feedback
  - hardly possible in main linac
- Pulse-to-pulse feedback
  - main linac orbit feedback
- Retuning
  - slow process in the main linac
- Complex beam-based alignment and tuning
  - not in normal running conditions
- Other feedback systems (e.g. tunenl temperatur)
- Independent feedbacks on the same property will have to share the overall feedback bandwidth

  ⇒ try to combine as much as possible

  - but need to know response

Stability and Feedback

- Stability is required to avoid luminosity degradation of a tuned machine
  - beam-based feedback will be used for low-frequency motion
  - typical luminosity with feedback is loss

$$\Delta\mathcal{L}_{total} = \Delta\mathcal{L}_{uncorr}(g) + \Delta\mathcal{L}_{noise}(g) + \Delta\mathcal{L}_{residual}(t)$$

  $\Delta\mathcal{L}_{uncorr}$ actual dynamic effect that is not yet corrected/amplified

  $\Delta\mathcal{L}_{noise}$ feedback tries to correct dynamic effect that is faked by diagnostics noise

  $\Delta\mathcal{L}_{residual}$ local feedback cannot correct all global effects

- Often a value that leads to 2% luminosity loss is quoted as a tolerance, but many values add up
- Stability is also required to be able to tune the machine
  - e.g. luminosity fluctuations may impact quality of tuning procedure
  - currently under investigation

$\Rightarrow$ Tolerances may change

Some Sources

- Draft guess of a luminosity sources (for $\epsilon_y = 10\,\mathrm{nm}$)

  losses are per side

  numbers need to be reviewed, just to illustrate that many sources exist

Source	budget	tolerance
Damping ring extraction jitter	1%	
Magnetic field variations	?%	
Bunch compressor jitter	1%	
Quadrupole jitter in main linac	1%	$\Delta\epsilon_y = 0.4\,\mathrm{nm}$ $\sigma_{jitter} \approx 1.5\,\mathrm{nm}$
Structure pos. jitter in main linac	0.1%	$\Delta\epsilon_y = 0.04\,\mathrm{nm}$ $\sigma_{jitter} \approx 200\,\mathrm{nm}$
Structure angle jitter in main linac	0.1%	$\Delta\epsilon_y = 0.04\,\mathrm{nm}$ $\sigma_{jitter} \approx 170\,\mathrm{nradian}$
RF jitter in main linac	1%	
Crab cavity phase jitter	1%	$\sigma_\phi \approx 0.01^\circ$
Final doublet quadrupole jitter	1%	$\sigma_{jitter} \approx 0.1\,\mathrm{nm}$
Other quadrupole jitter in BDS	1%	
$\cdots$	?%	

Time Dependent Emittance Growth

- The residual emittance growth determines for how long the feedback is sufficient
- The simplest feedback is to use

$$\Delta y_{n+1} = \Delta y_n - g \times \Delta y_n + \gamma_n$$

- For the different dynamic imperfection types we find

  - pulse-to-pulse jitter

$$\Delta \mathcal{L}_{resid} = a \times \Delta \mathcal{L}_0$$

  - ATL like motion

$$\Delta \mathcal{L}_{resid} = a \times n \Delta \mathcal{L}_0$$

  - slow drifts

$$\Delta \mathcal{L}_{resid} = a \times n^2 \Delta \mathcal{L}_0$$

- Luminosity loss per timestep is $\Delta \mathcal{L}$

- Feedback reduces emittance growth per time step by factor a

  $a = 1$ for no feedback

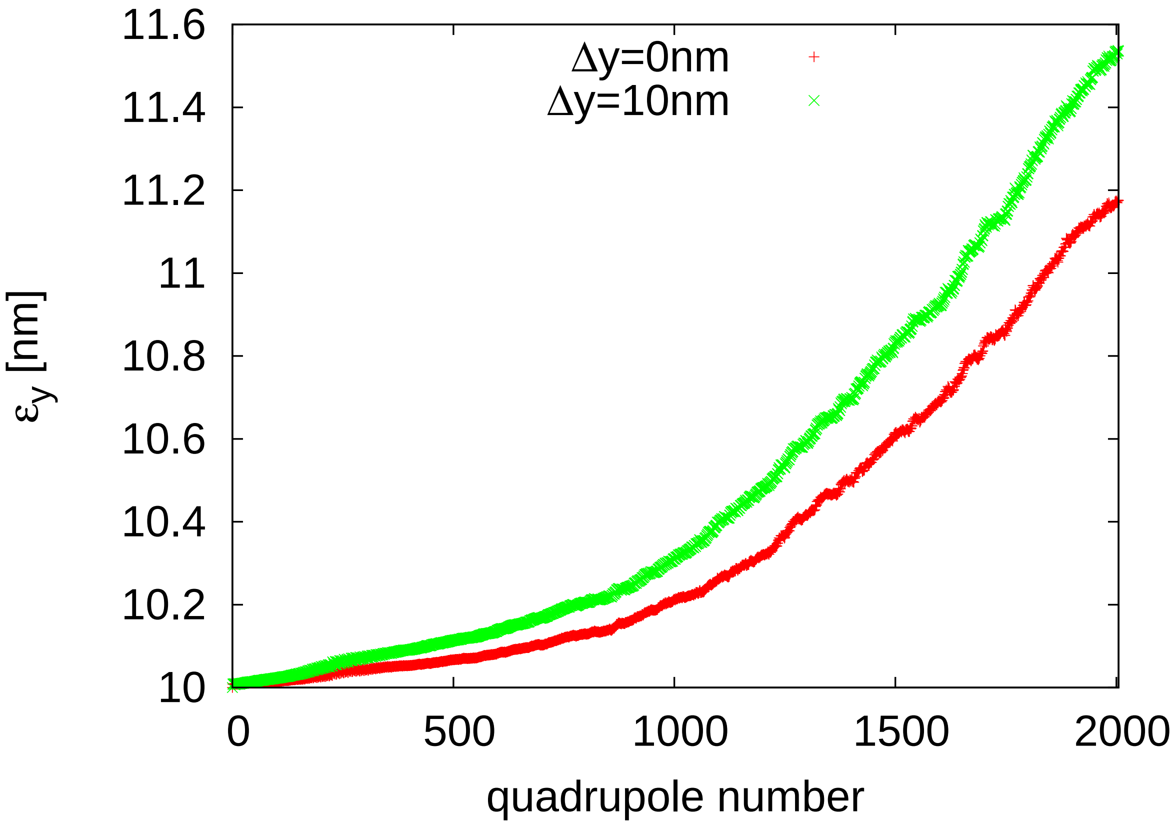
Main Linac Orbit Feedback

- All quadrupoles could be stabilised
  - But in the long run they follow the ground motion
- ATL-model used

  ⇒ emittance growth is linear with time
  - one day simulated
- All focusing quadrupoles used for feedback in one-to-one correction

⇒ Emittance growth is $\Delta\epsilon_{y,residual} = 1\,\mathrm{nm}$ per day

- If we were using local feedback the growth rate would be larger



Simple Feedback Algorithm

- The simplest feedback is to use

$$\Delta y_{n+1} = \Delta y_n - g \times \Delta y_n + \gamma_n$$

- For the different noise types we find
  - pulse-to-pulse jitter

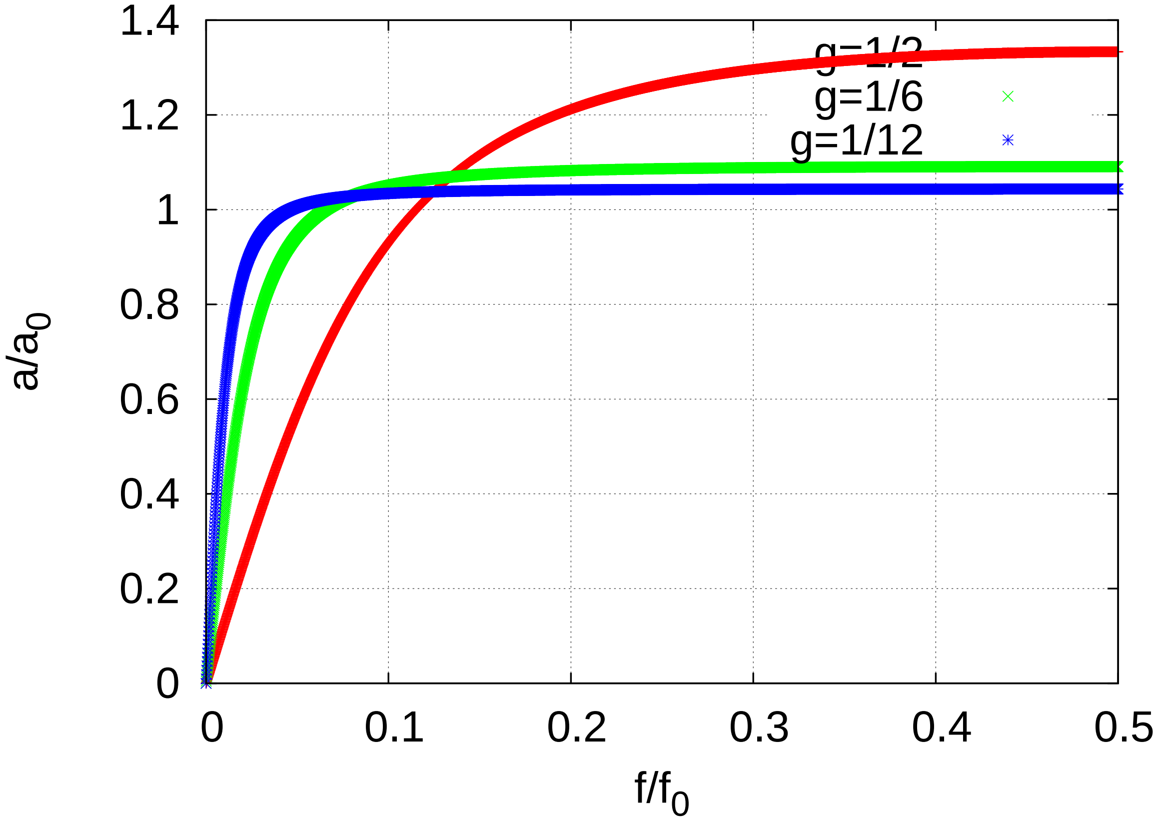
$$\Delta L_{uncorr} = \Delta L_0 \frac{2}{2-g}$$

  - ATL like motion

$$\Delta L_{uncorr} = \Delta L_0 \frac{1}{g(2-g)}$$

  - slow drifts

$$\Delta L_{uncorr} = \Delta L_0 \frac{1}{g^2}$$



- Frequency response can be calculated from impulse response
  - for CLIC at $1\,\mathrm{Hz}$ amplification is 0.86 (g=1/12), 0.62 (g=1/6), 0.25 (g=1/2)
  - at 4 Hz g=1/2 is marginal

Other Feedback Algorithm

- Summation feedback

$$\Delta a_n = \frac{1}{m} \times \Delta y_n + \left(1 - \frac{1}{m}\right) \times a_{n-1}$$
$$\Delta y_{n+1} = \Delta y_n - a_n$$

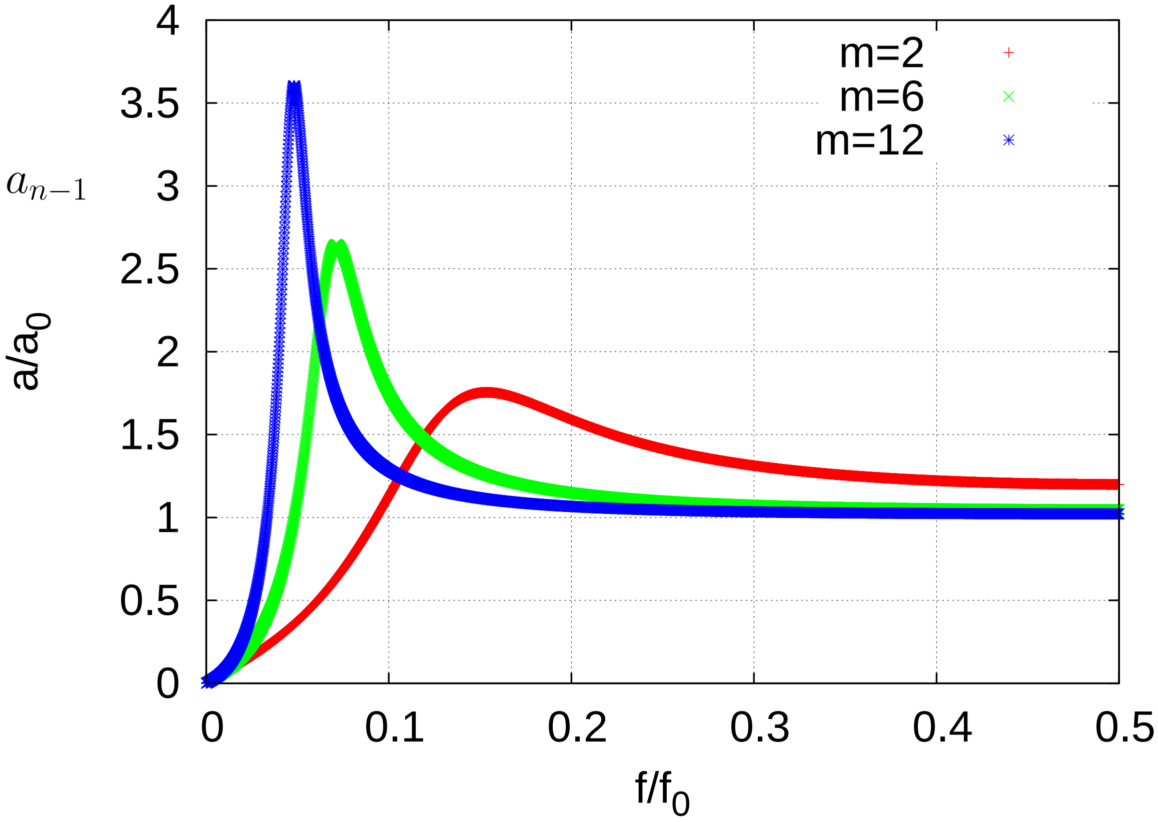
- For slow drifts

$$\Delta \mathcal{L}_{uncorr} = \Delta L_0$$

$\Rightarrow$ good low frequency behaviour

- For jitter for large m

$$\Delta \mathcal{L}_{uncorr} \approx 1.5 \Delta L_0$$



- For CLIC at $1\,\mathrm{Hz}$ amplification is 0.27 (m=12), 0.16 (m=6), 0.13 (m=2)
- At 4 Hz m=2 is marginal
- Will have to fold with ground motion/transfer function

Main Linac BPM Resolution

- The BPM resolution will limit the feedback bandwidth
- Assume pulse-to-pulse uncorrelated BPM readout jitter
- Emittance growth (correspoding to $\Delta\mathcal{L}_{noise}$) can be estimated as function of gain g by

$$\begin{aligned}\Delta\epsilon &= \Delta\epsilon_0\left(g^2\sum_{i=0}^{\infty}(1-g)^{2i}\right)\\ \Delta\epsilon &= \Delta\epsilon_0\left(\frac{g}{2-g}\right)\end{aligned}$$

- For 100 nm resolution, the emittance growth is $\Delta\epsilon_0 = 0.1\,\mathrm{nm}$

⇒ Even for large gains the emittance growth should be small

- BPM resolution is determined by need to see beam jitter
  - beam jitter is measured in vertically focusing quadrupoles
  - beam is smallest at the end of the linac
  - with $\beta_y \approx 65\,\mathrm{m}$ and $\epsilon_y \approx 10\,\mathrm{nm}$ we find $\sigma_y \approx 465\,\mathrm{nm}$

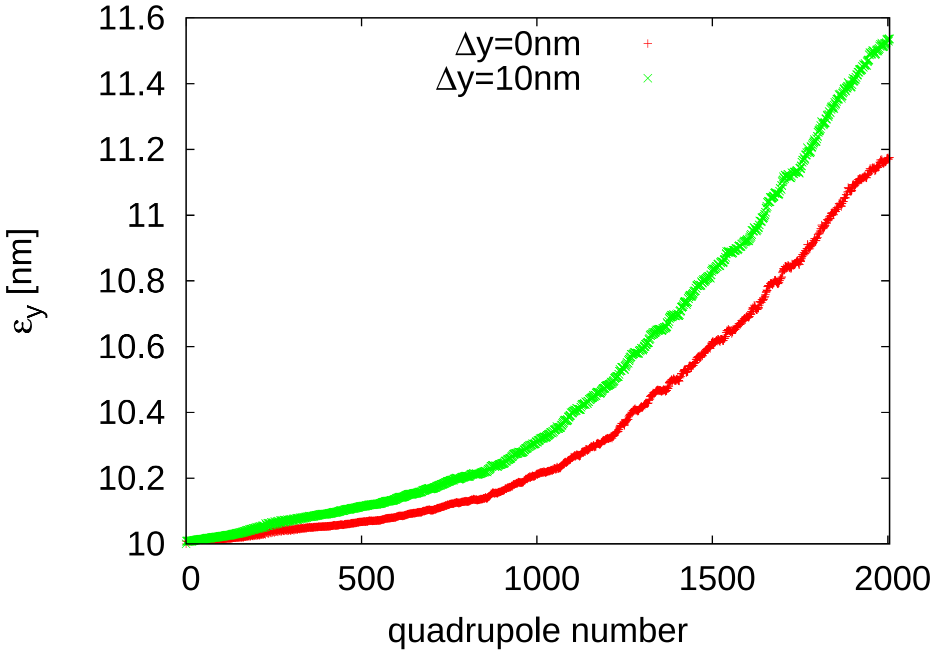
  ⇒ require BPM resolution of about $50\,\mathrm{nm}$

Quadrupole Correctors

- Two types of correctors for the quadrupoles exist
  - movers
  - dipole corrector coils
- Reason for movers is to avoid quadrupole jitter
  - power supply riples for quadrupoles or dipoles would introduce transverse quadrupole jitter
  - typical quadrupole offset with no active alignment is 100 $\mu\mathrm{m}$
  - quadrupole power supply ripple of $\Delta K/K = 10^{-5}$ leads to 1 nm effective quadrupole jitter
  - same effect for dipole power supplies
- Reason for corrector coils is to allow for small steps sizes
  - the smallest corrector step must be a fraction of the beam size
  - require $\mathcal{O}(10\,\mathrm{nm})$

Smallest Corrector Step

- Even a step size of $10\,\mathrm{nm}$ leads to noticeable additional emittance growth
  - already use focusing quadrupoles only
  - leads to 1% luminosity loss
- Depending on the feedback algorithm effective step size would be larger than real one
- The situation can be improved by using a few correctors only



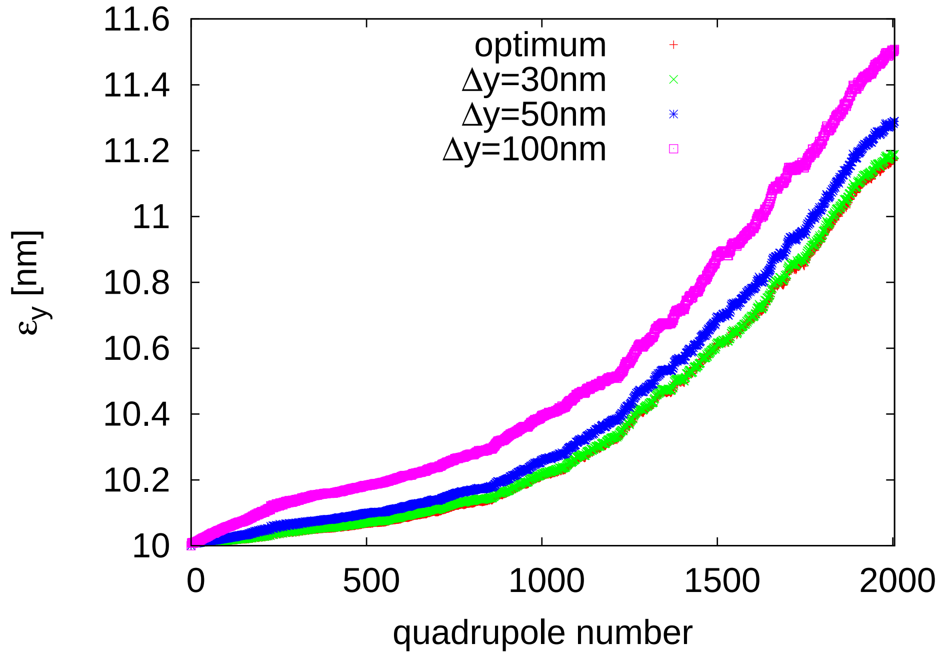
- Different options exist to reduce number of correctors among them
  - localised feedback systems

    $\Rightarrow$ would need to be complemented with one-to-one steering after a while
  - MICADO

Use of MICADO

- Try to find a small number m of most effective correctors
- Simulation performed using
  - one-to-one correction with given step size
  - then some iterations of MICADO

⇒ Significantly larger corrector step size are allowed



- In principle, MICADO can replace the one-to-one steering
  - speed of correction should be largely unaffected
- The main problem is to have an accurate enough model of the beamline
  - problem shared with other integrated feedback methods

Corrector Step Error

- The steps performed by the correctors may not be predictable
  - will lead to additional emittance growth
- A random error in the corrector step can be regarded as quadrupole jitter
- A simple estimate of allowed error is given by

$$\sigma_{step} \approx \sigma_{jitter}\sqrt{\frac{N_{quad}}{N_{corrector}}}$$

$N_{corrector}$ is the number of correctors used

- To be negligible for $N_{corrector} = 80$ we require $\sigma_{step} < 5\,\mathrm{nm}$

$\Rightarrow$ Should use minimum step size of $\Delta = 5\,\mathrm{nm}$ to reduce impact of step size to much less than quadrupole jitter

- Typical movements are some $100\,\mathrm{nm}$ (but site dependent)
  - we require convergence between pulses

Quadrupole Correctors

- Range is given by possible initial misalignment
  - for conventional survey $\sigma = 100\,\mu\mathrm{m}$
  - range needs to be $\geq 300\,\mu\mathrm{m}$

Breakdown Rate

- Direct limit to breakdown rate
  - 1% luminosity loss budget
  - assuming that a pulse with breakdown leads to no luminosity
  - have 7×10^4 structures per linac

  $\Rightarrow$ breakdown rate $0.01/14 \times 10^4 \approx 0.7 \times 10^{-7}$
- Assumed strategy is to switch off corresponding PETS and slowly go up to power again
- Indirect luminosity loss exists due to switching off of PETS
  - if structures are tilted this deflect the beam

$$\frac{\Delta y'}{\sigma_{y'}} = \frac{\theta G L e}{2E} \sqrt{\frac{\gamma \beta_y}{\epsilon}}$$

- Due to the tilt, switching off a pair of structures leads to a transverse deflection of

$$\left\langle \frac{\Delta y'^2}{\sigma_{y'}^2} \right\rangle \approx 0.16$$

$\Rightarrow \Delta\epsilon_y \approx 0.8\,\mathrm{nm}$, time to recover from switching off structure is important

- Need to study full effects

Summary of Accelerating Structure Tolerances

- Structure tilts
  - structure precision
  - $\sigma_{ang} \leq 200\,\mu\mathrm{radian}$ corresponds to $\sigma_{\Delta z} \leq 1\,\mu\mathrm{m}$
- Mean transverse misalignment of relevant groups of structure to the beam
  - wake monitors
  - $\sigma_{wm} \leq 5\,\mu\mathrm{m}$
- RMS transverse misalignment of the individual structures to the beam
  - structure mechanical alignment on girder
  - $\sigma_{cav,rms} \leq 10\,\mu\mathrm{m}$
- Misalignment of the structure pieces to the beam
  - depends on details of long-range wake, but likely $\sigma_{cav,part} \leq 5\,\mu\mathrm{m}$ is sufficient
- Static gradient and phase error
  - $\sigma_G/G \leq 2\%$, $\sigma_\Phi \leq 1^\circ$
- Mover stet granularity
  - $\Delta_{acc} = 1\,\mu\mathrm{m}$

Summary for Quadrupoles and BPMs

- Quadrupole corrector
  - range 1 mm
  - ideal step size would be 0.5 nm
  - practical smallest step size should be 5 nm
  - but can have combination of two step sizes
- BPM movers
  - range 1 mm
  - step size not much larger than σ_{res},
    i.e. 1 $\mu\mathrm{m}$ might be tolerable
  - need to track BPM position with resolution of about 1 $\mu\mathrm{m}$
- BPM resolution
  - aim for 50 nm
- BPM center stability
  - aim for 100 nm over days
- Girder mover step size 1 $\mu\mathrm{m}$

Mover Requirements

- Coarse mechanical motion
  - structure girders, quadrupoles and BPM support
  - range: $\approx 1\,\mathrm{mm}$
  - resolution: $\Delta \approx 1\,\mu\mathrm{m}$
  - precision: $\approx 0.5\,\mu\mathrm{m}$
  - speed: may take a few pulses, but controlled
- Fine quadrupole motion
  - resolution: $\Delta \approx 5\,\mathrm{nm}$
  - range: $\approx 20\,\mu\mathrm{m}$
  - precision: $\approx 2\,\mathrm{nm}$
  - speed: from pulse to pulse
- Very fine quadrupole motion
  - resolution: $\Delta \approx 0.1\,\mathrm{nm}$?
  - range and precision: tbd
  - speed: works in intervall between pulses
- Precision could be defined as function of step size