Main Linac Design and Alignment

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Lots of contributions from G. Riddone, H. Mainaud-Durand and A. Latina

Introduction

- The main linac is an important driver of the structure design
  - the wakefields can render the beam instable
  - they introduce energy spread
- The linac beam dynamics limits the bunch charge and beam current and consequently the efficieny and the luminosity
- Challenges for the linac design are to
  - ensure beam stability
  - limit emittance growth
- Will introduce lattice design for new CLIC parameters (not finished)
  - structure design from A. Grudiev
- Currently want to verify that there is a solution
  - next step will be to find best solution

Low Emittance Transport Challenges

- 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

Lattice Design Considerations

- Linac lattice is a trade-off

- strong focusing
  - small sensitivity to wakefields
  - dispersive effects important
- large energy spread
  - beam is more stable
  - dispersive effects are increased

- weak focusing
  - high sensitivity to wakefields
  - dispersive effects smaller
- small energy spread
  - beam is less stable
  - dispersive effects are reduced

- First need to consider beam stability

  $\Rightarrow$ look at allowed energy spread

Beam Stability

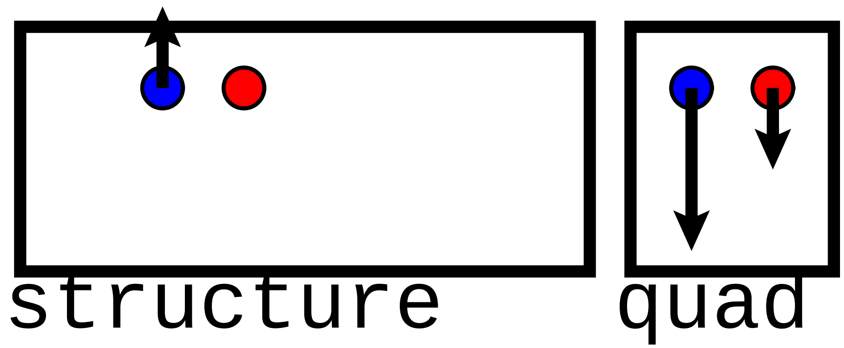
- Transverse wakes act as defocusing force on tail

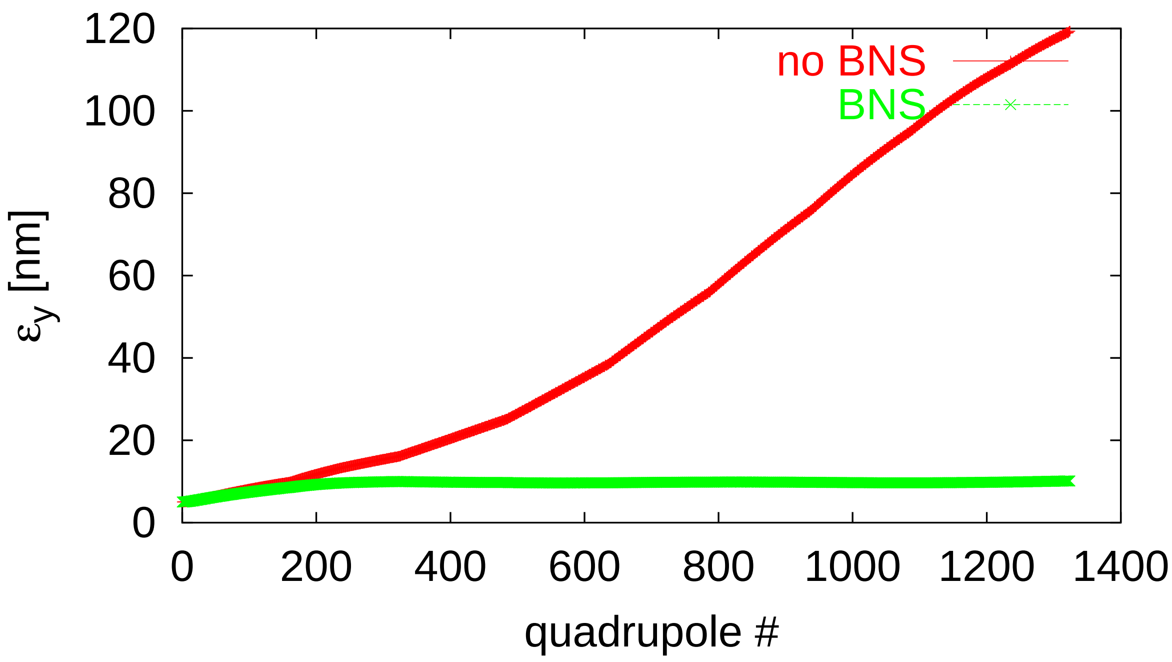
  ⇒ beam jitter is exponentially amplified

- BNS damping prevents this growth

  - manipulate RF phases to have energy spread

  - take spread out at end





Emittance Preservation

- $\epsilon_x \gg \epsilon_y \Rightarrow$ consider only ϵ_y
- Current main linac target: $\Delta\epsilon_y \le 5\,\mathrm{nm}$
  - initial $\epsilon_y \le 5\,\mathrm{nm}$
  - may need review to allow for large growth in RTML
- Budget is shared with other effects

  $\Rightarrow$ assume $2.5\,\mathrm{nm}$

  Large spread in emittance growth as function of initial distribution

  $\Rightarrow$ need to define probability level (we require 90%)

- Emittance growth is dominated by wakefields
  - even dispersive growth since BNS damping is used

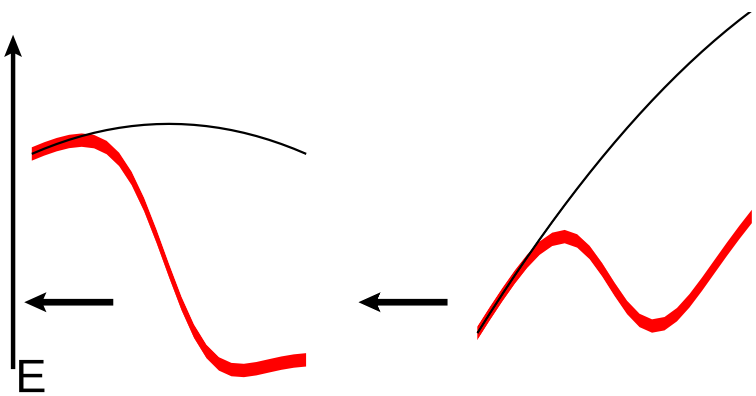
$$\Delta\epsilon_y \propto (W_\perp N \sigma_z \Delta y)^2$$

$W_\perp$	large a (iris radius)
Δy	very good prealignment sophisticated beam-based alignment
N	trivial, but $\eta \propto N$
σ_z	large a, small N

Beam Loading and Bunch Length

- Aim for shortest possible bunch (wakefields)
- Energy spread into the beam delivery system should be limited to about 1% full width or 0.35% rms
- Multi-bunch beam loading compensated by RF
- Single bunch longitudinal wakefield needs to be compensated

  $\Rightarrow$ accelerate off-crest

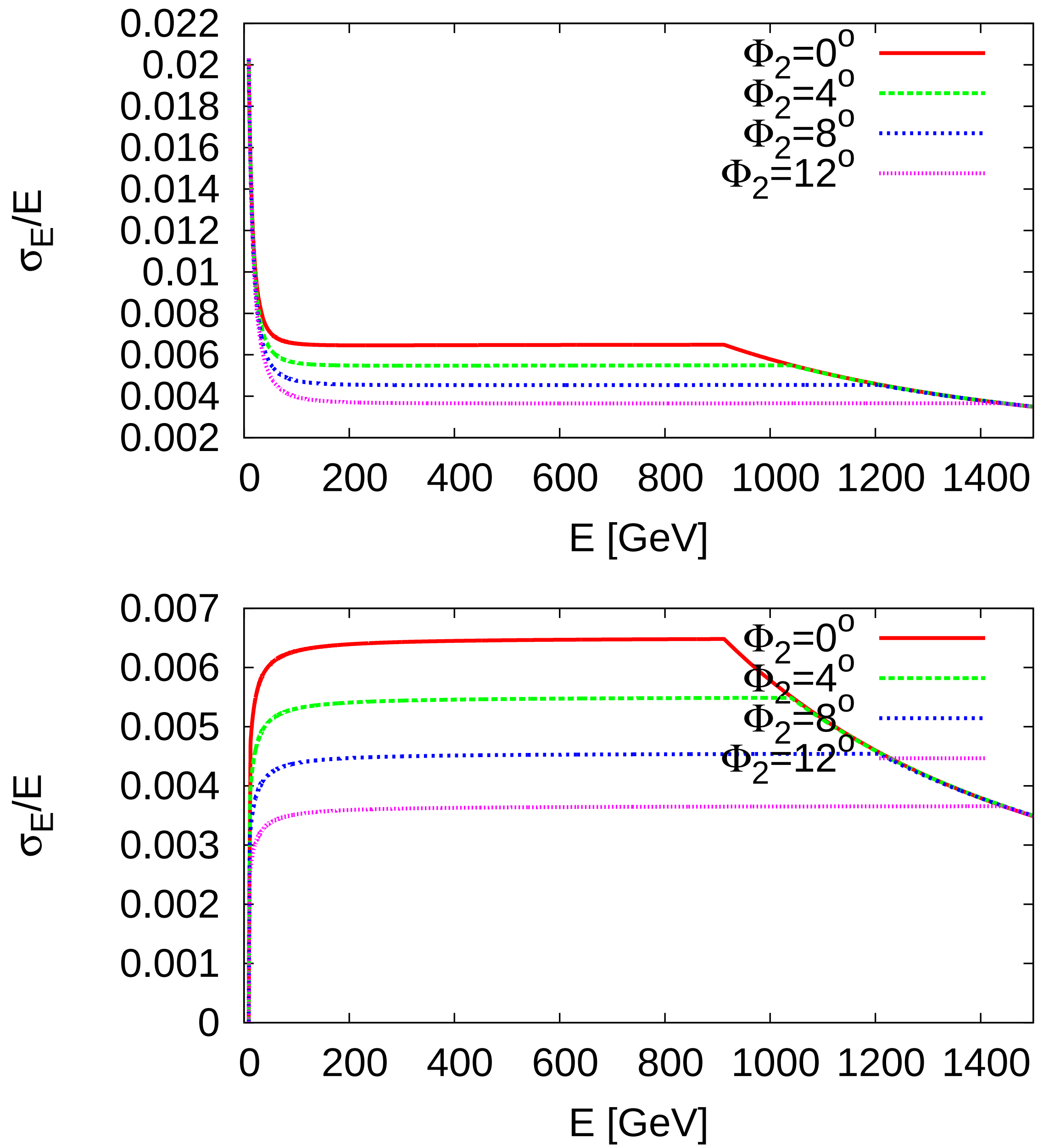


- Limit around average $\Delta\Phi \leq 12^\circ$

  $\Rightarrow \sigma_z = 65\,\mu\mathrm{m}$ for $N = 5.2 \times 10$

Energy Spread

- Three regions
  - generate
  - maintain
  - compress
- Configurations are named according to RF phase in section 2
- Trade-off in fixed lattice
  - large energy spread is more stable
  - small energy spread is better for alignment



Lattice Design Strategy

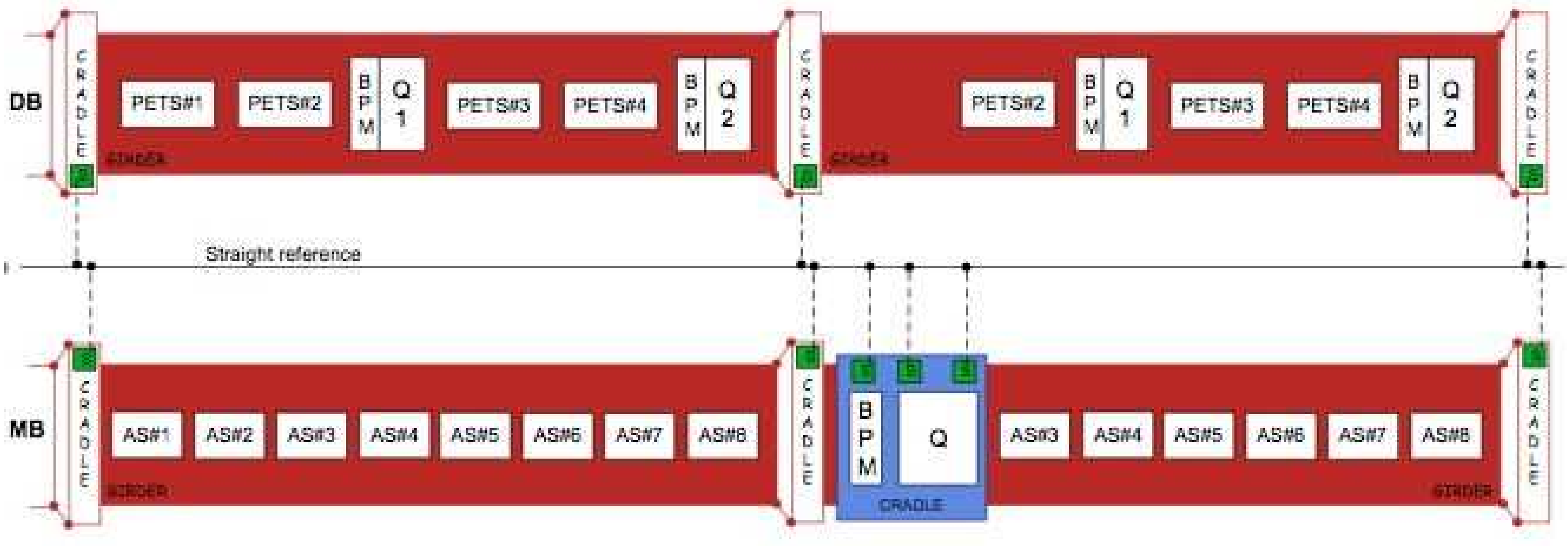
- Chose a strength that ensures beam stability (same as in old lattice)
- At higher energies beam is less sensitive to wakefields

  $\Rightarrow$ increase beta-function along machine

$$\beta \propto \sqrt{E},\ \Delta\phi = \mathrm{const}$$

- In practice sectors with constant FODO cells are used
- Scaling ensures roughly constant fill factor
  - magnet strength (and length) is proportional to $E/\beta \propto \sqrt(E)$
  - spacing is proportional to $\beta \propto \sqrt(E)$
- Phase advance in cells is chosen as compromise of fill factor and stability with respect to ground motion
- Review will be needed
  - we might be able to reduce the focusing strength a bit
  - the phase advance optimum might have moved a bit

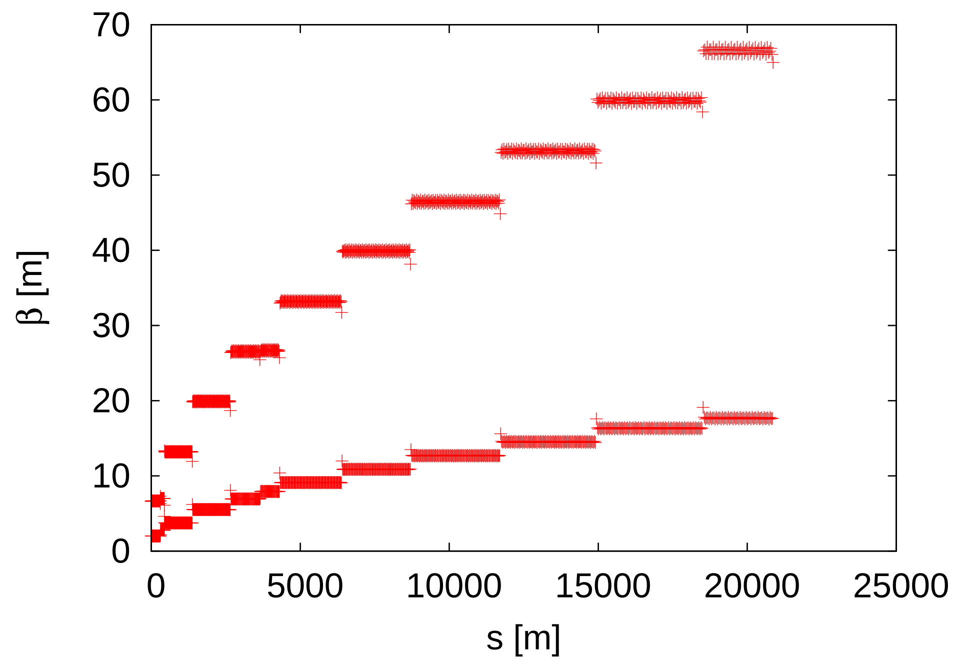
Module Layout



- The articulation point and the quadrupoles can be moved
- Maybe need sheer point before quadrupole

Lattice Design

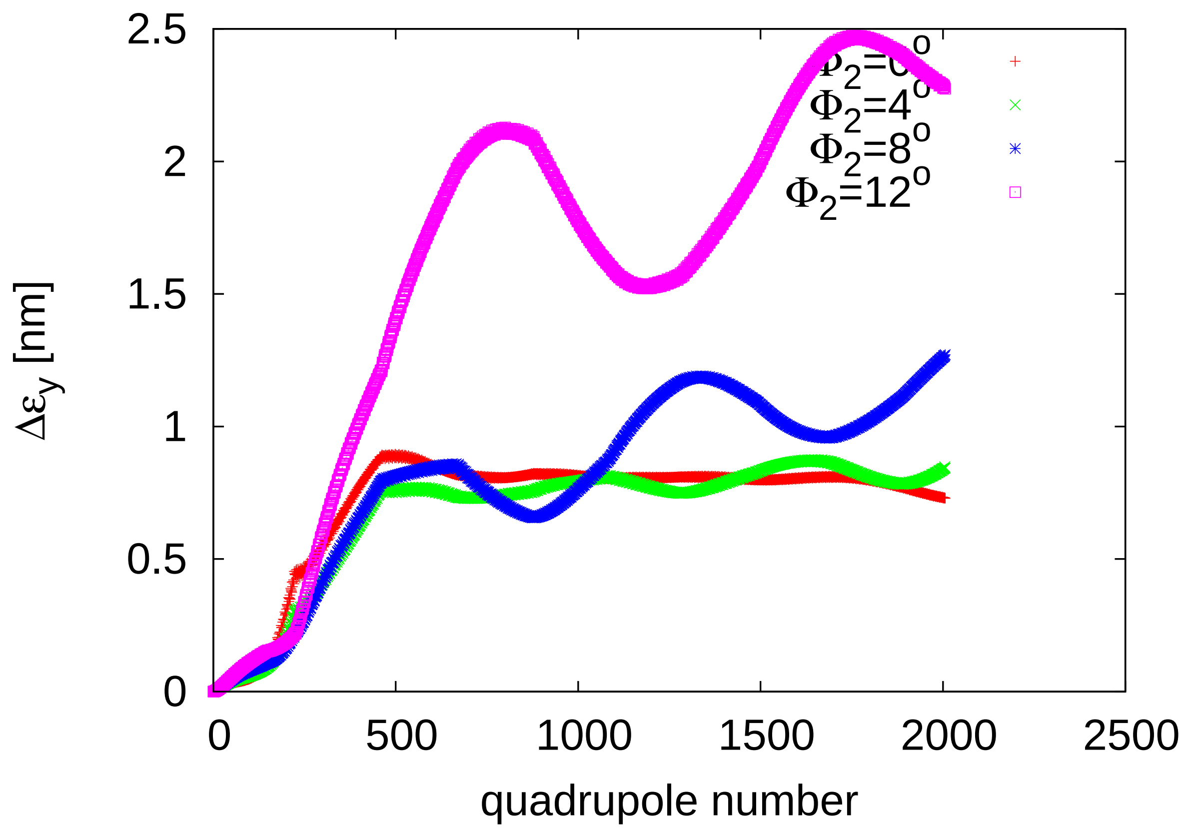
- Preliminary lattice
  - quadrupoles need to be confirmed
  - some optimisations remain to be done
- Total length 20867.6m
  - fill factor 78.6%
- 12 different sectors used
- Matching between sectors using 5 quadrupoles to allow for some energy bandwidth



Beam Stability

- The beam is stable if the energy spread is large enough
  - at $\Phi_2 = 8^\circ$ the stability is marginal
- Seems acceptable but cannot relax focusing very much

$\Rightarrow$ have to live with it



Single Bunch Jitter Tolerances

- Assumed no correction

  ⇒ multi-pulse emittance is important

- Value is given for 0.1 nm emittance growth

  - quadrupole position: $0.8\,\mathrm{nm}$

  - structure position: $0.7\,\mu\mathrm{m}$

  - structure angle: $0.55\,\mu\mathrm{radian}$

⇒ Tolerances are very tight

  - in particular for quadrupole

Different Error Contributions

- The main linac can be treated as a linear system
- For the same beam-based alignment method

  $\Rightarrow$ emittance growth scales as the square of the errors

  $\Rightarrow$ emittance growth for different errors can be calculated seperately (in most cases)
- But the choice of weights for DFS affects the results

  - large BPM position error pushes towards large weights
  - bad BPM resolution pushes towards small weights

  $\Rightarrow$ compromise

  $\Rightarrow$ cannot specify a tolerance easily, depends on other errors

Error Sources

- Most important are
  - BPM position errors
  - BPM resolution
  - structure to beam misalignment
- BPM position errors and resolution determine the final dispersion left in the beam
- Structure offsets determine the final wakefield effect in the beam
  - if the wakefields are identical in two consecutive structures, the mean offsets is important
  - if wakefields are different, scattering of structures around mean value matters

    should not matter for short-range wakefields

    could matter for long-range wakefields

Beam-Based Correction Strategy

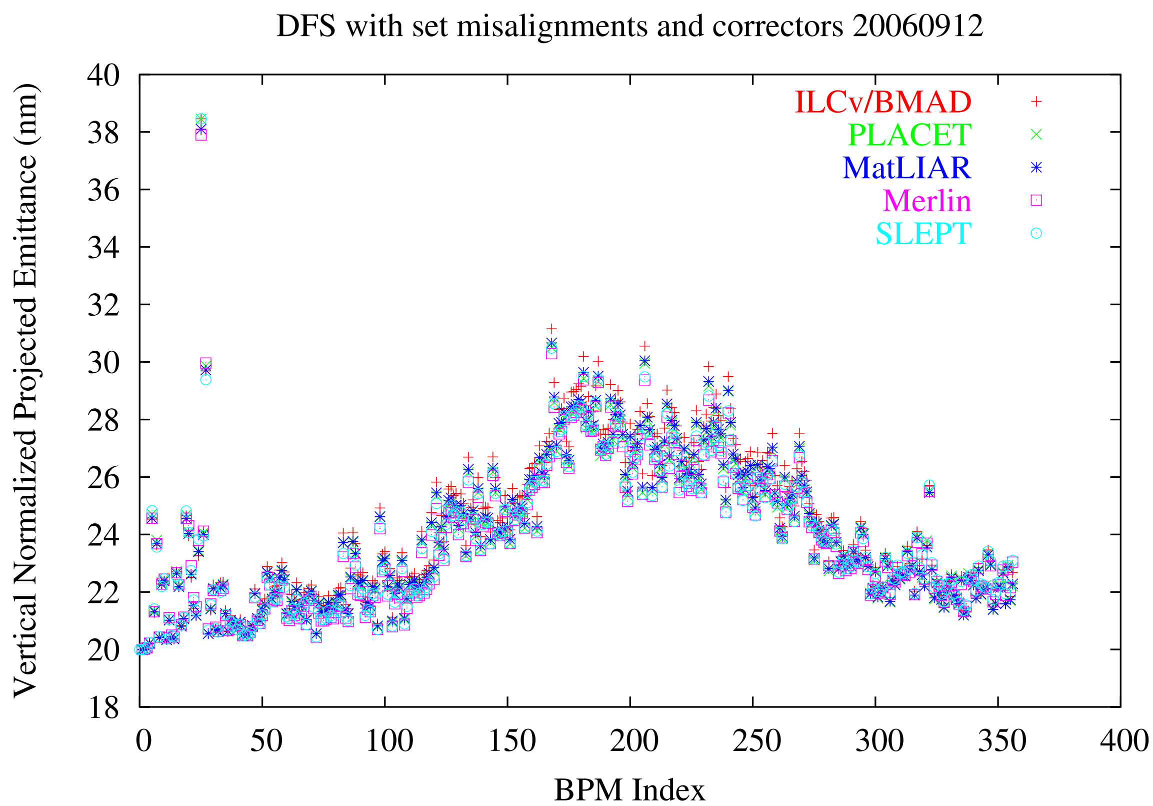
- Make beam pass linac
  - one-to-one correction
- Remove dispersion
  - dispersion free steering
  - ballistic alignment
- Remove wakefield effects
  - accelerating structure alignment
  - emittance tuning bumps

- Tune luminosity
  - tuning knobs

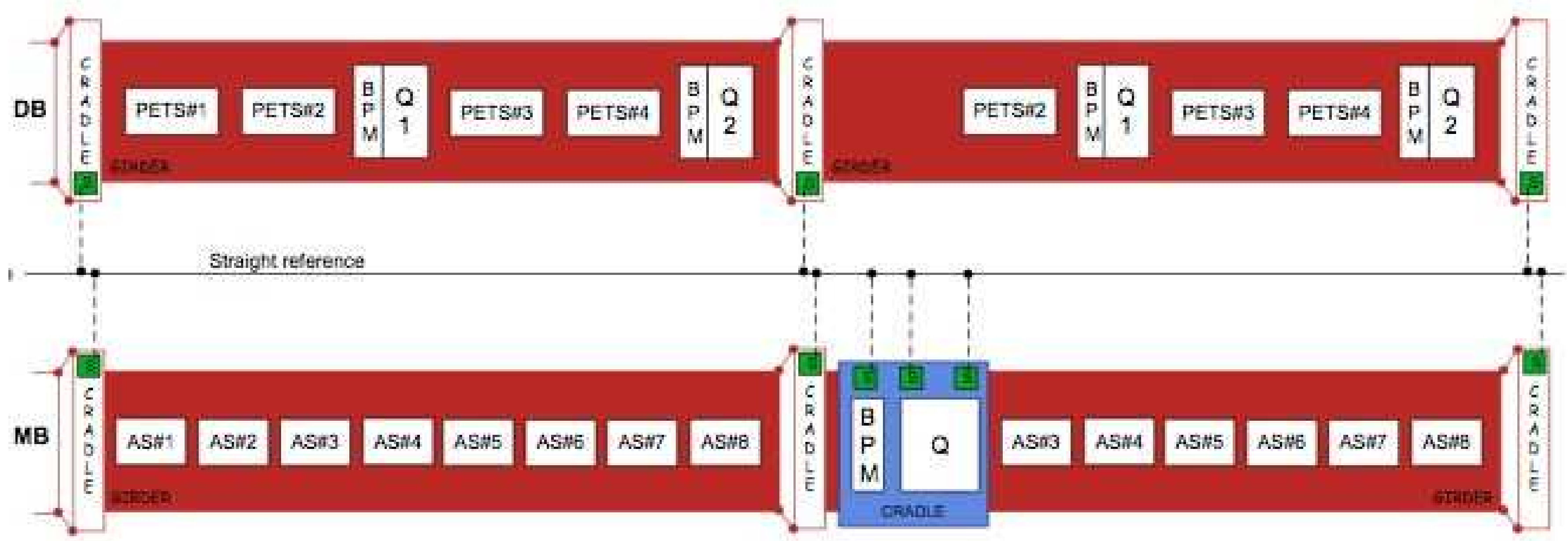
- currently noise during correction is only taken into account in simplified way (e.g. beam jitter)

Simulation Procedure and Benchmarking

- All simulation studies are performed with PLACET
  - based on 100 different machines
- Benchmarking of tracking codes is essential
- Comparisons performed in ILC framework
  - tracking with errors
  - alignment methods

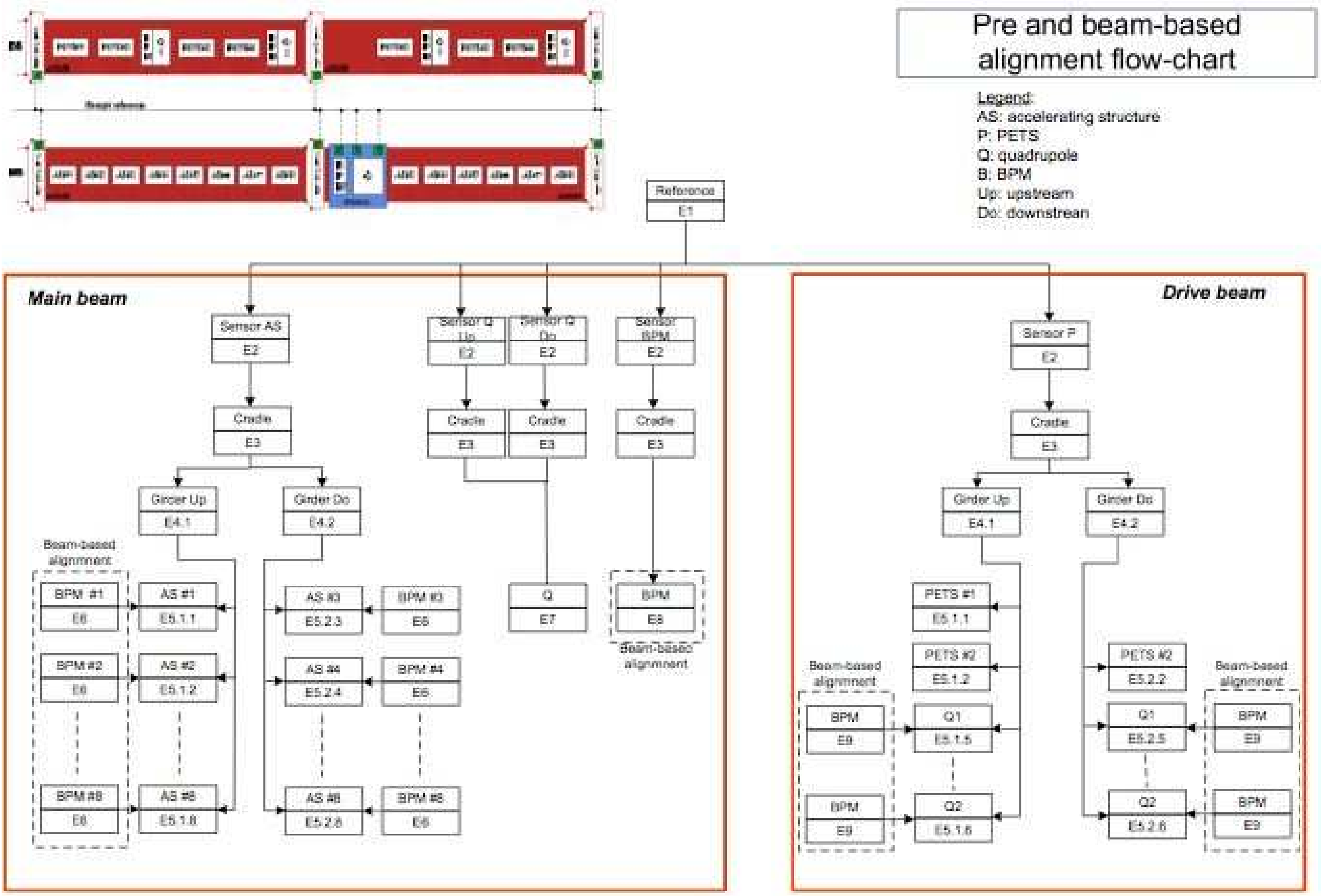


Misalignment Model: Module



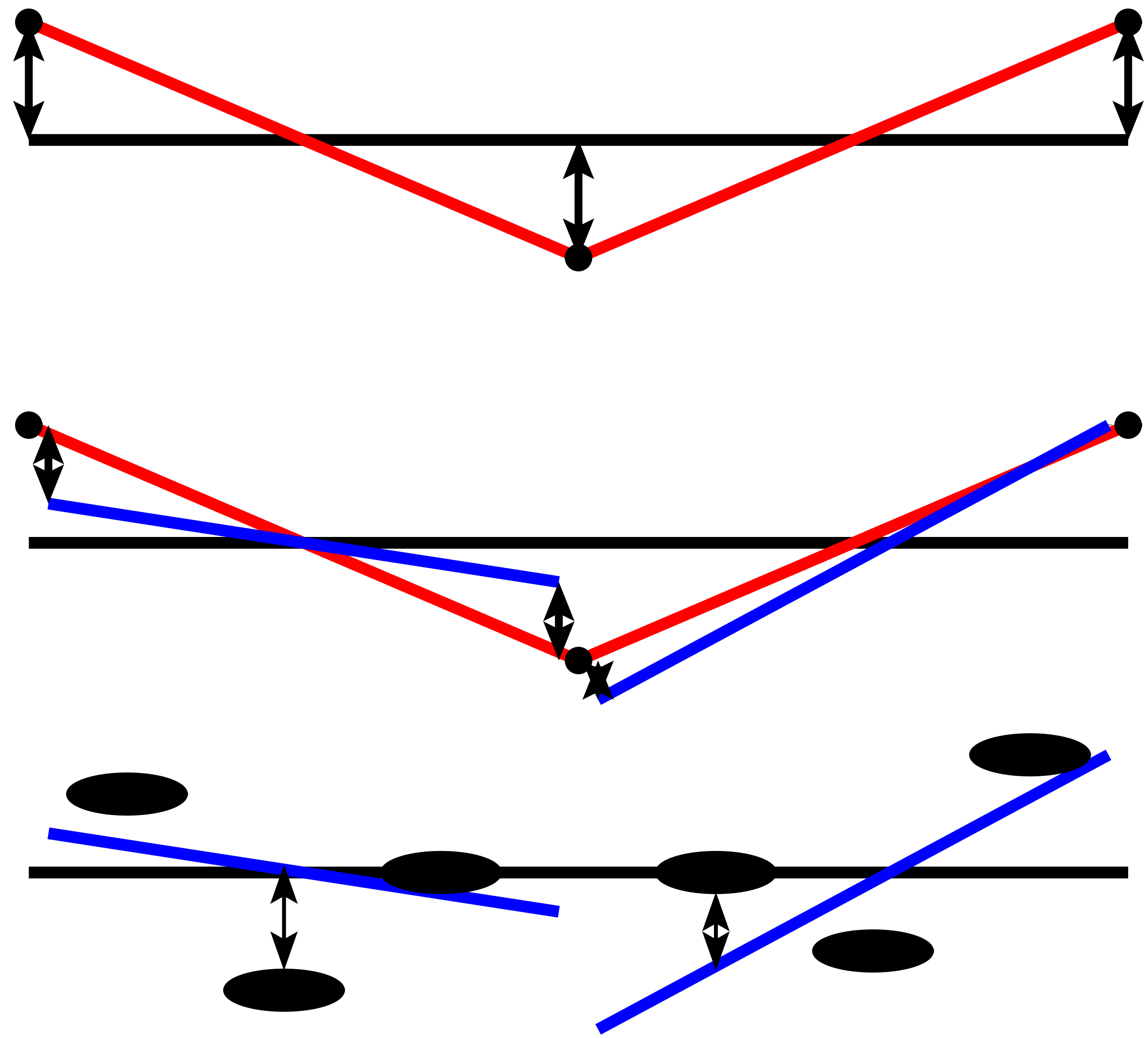
- Sensors connect beam line to reference system
- Excellent prealignment of elements on the girders

Misalignment Model: Flow Diagram



Misalignment Model: Simplified Version

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



Accelerating Structure Alignment

PRE-ALIGNMENT

Ref.	1	Inherent accuracy of reference	10 μm	1σ
Ref. to cradle	2	Sensor accuracy and electronics (reading error, noise,..)	5 μm	1σ
	3	Link sensor/cradle (supporting plates, interchangeability)	5 μm	1σ
Cradle to girder	4	Link cradle/girder	5 μm	1σ
Girder to AS	5a 5b	Link girder/acc. structure Inherent precision of structure	5 μm	1σ
		TOTAL Tolerance	14 μm 40 μm	1σ 3σ

BEAM-BASED ALIGNMENT

6) relative position of structure and BPM reading 5 μm 1σ

Quadrupole Alignment

PRE-ALIGNMENT

Ref.	1	Inherent accuracy of reference	10 μm	1σ
Ref. to cradle	2	Sensor accuracy and electronics (reading error, noise,..)	5 μm	1σ
	3	Link sensor/cradle (supporting plates, interchangeability)	5 μm	1σ
Cradle to Q	7a	Link cradle/quadrupole	5 μm	1σ
	7b	Inherent precision of quadrupole	10 μm	1σ
		TOTAL	17 μm	1σ
		Tolerance	50 μm	3σ

BPM Alignment

PRE-ALIGNMENT

Ref.	1	Inherent accuracy of reference	10 μm	1σ
Ref. to cradle	2	Sensor accuracy and electronics (reading error, noise,..)	5 μm	1σ
	3	Link sensor/cradle (supporting plates, interchangeability)	5 μm	1σ
Cradle to BPM	8a	Link cradle/quadrupole BPM axis	5 μm	1σ
BPM	8b	Inherent precision of quadrupole BPM axis	5 μm	1σ
		TOTAL	14 μm	1σ
		Tolerance	40 μm	3σ

BEAM-BASED ALIGNMENT:

8c) relative position of quadrupole and BPM reading 10 μm 1σ

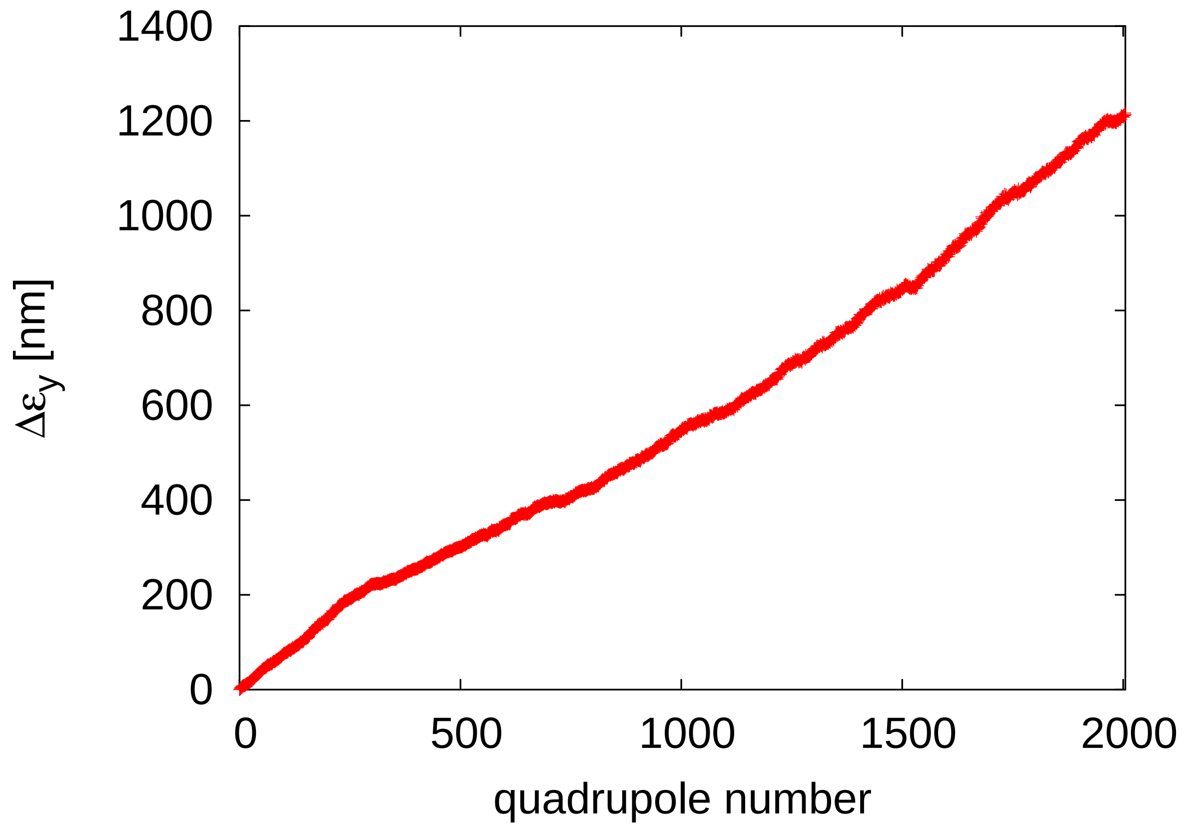
Assumed Alignment Performance

Element	error	with respect to	alignment NLC	alignment CLIC
Structure	offset	girder	$25\,\mu$m	$7\,\mu$m
Structure	tilts	girder	$33\,\mu$radian	?(cost)
Girder	offset	survey line	$50\,\mu$m	$9.4(6.2)\,\mu$m
Girder	tilt	survey line	$15\,\mu$radian	$9.4(6.2)\,\mu$radian
Quadrupole	offset	survey line	$50\,\mu$m	$17(13)\,\mu$m
BPM	offset	quadrupole/survey line	$100\,\mu$m	$14\,\mu$m
BPM	resolution	BPM center	$0.3\,\mu$m	$0.1\,\mu$m
Structure bpm	resolution	wake center	$5\,\mu$m	$5\,\mu$m

One-To-One Correction

- The beam is made to pass through the centres of the BPMs

⇒ The result is very far from the target



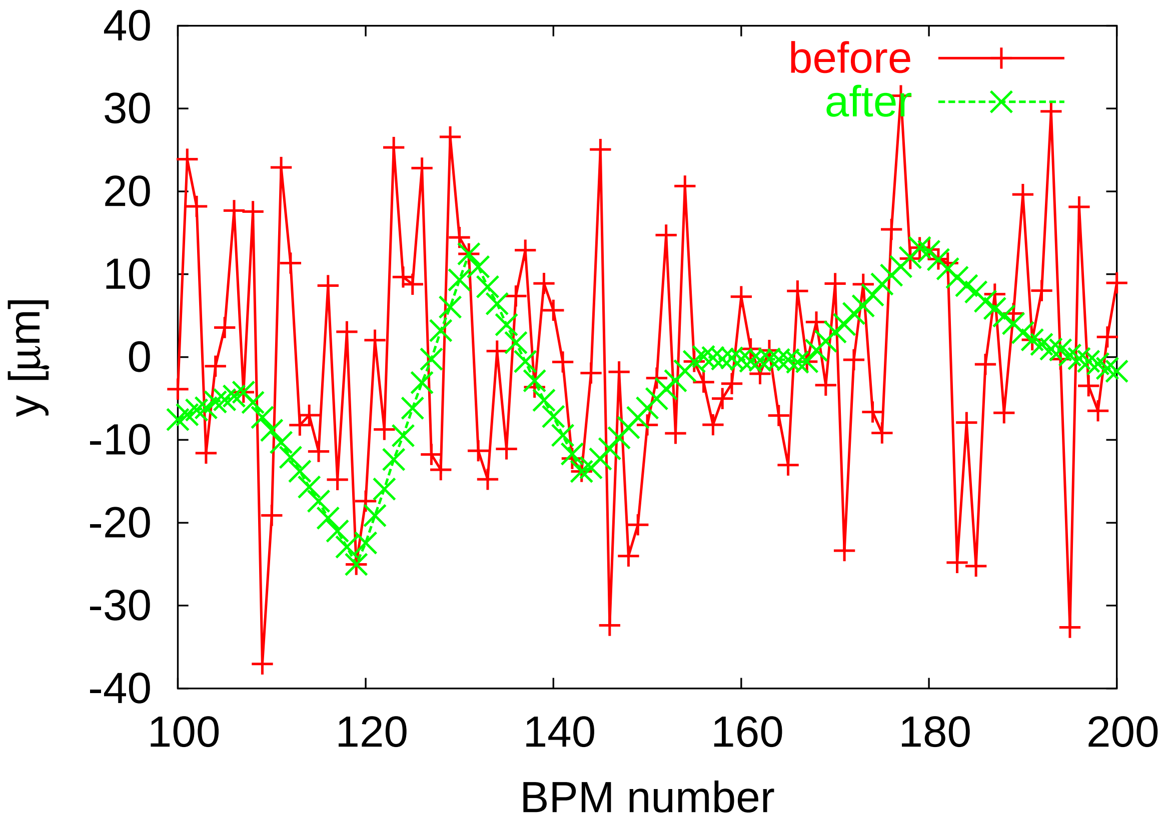
Tolerances

Element	error	with respect to	tolerance CLIC	tolerance NLC
Structure	offset	beam	$4.3(5.8)\,\mu$m	$5.0\,\mu$m
Structure	tilt	beam	$220\,\mu$radian	$135\,\mu$radian
Quadrupole	offset	straight line	—	—
Quadrupole	offset jitter	straight line	$13\,$nm	—
Quadrupole	roll	axis	$240(240)\,\mu$m	$280\,\mu$radian
BPM	offset	straight line	$0.4(0.44)\,\mu$m	$1.3\,\mu$m
BPM	resolution	BPM center	$0.4(0.44)\,\mu$m	$1.3\,\mu$m
Art. point	offset	straight line	$1.7(3)\,\mu$m	
End point	offset	Art. point	$2.0(3.8)\,\mu$m	

- All tolerances are given after one-to-one steering, except quadrupole jitter
- In brackets low charge version

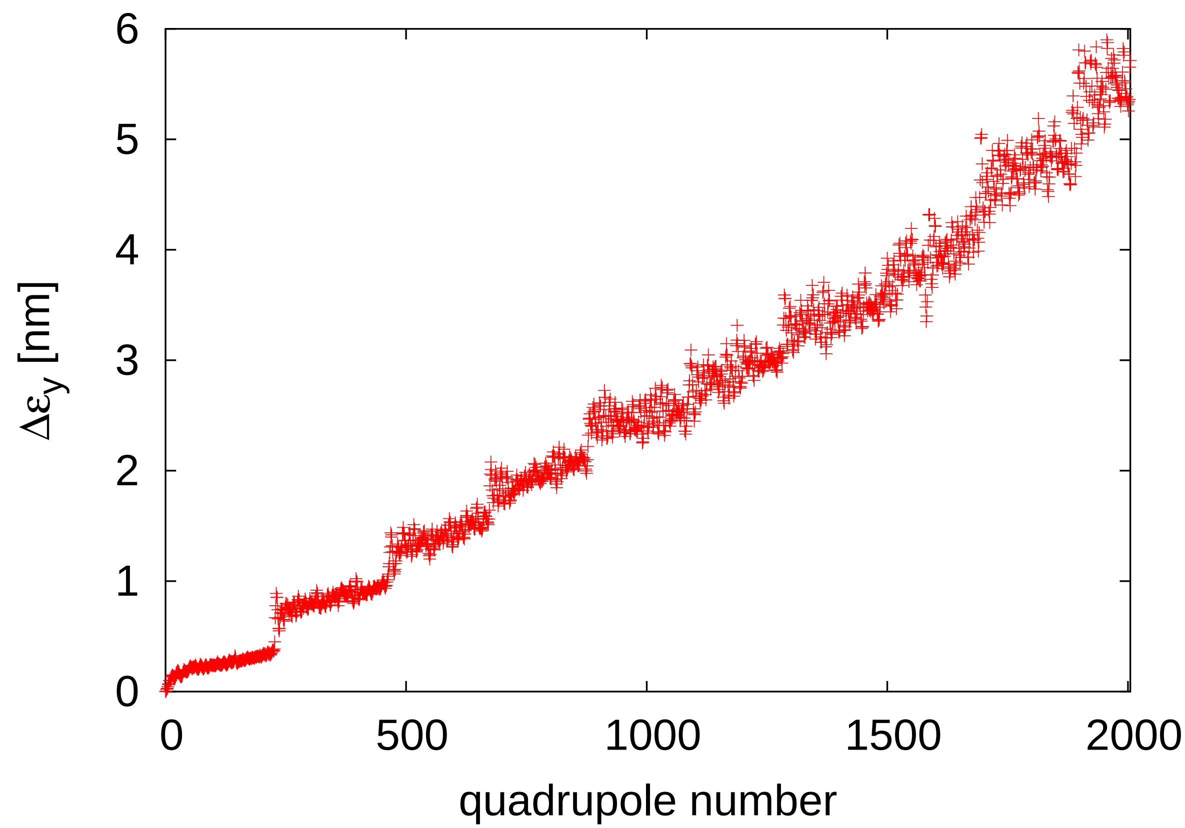
Ballistic Alignment

- 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



Results for Ballistic Alignment

- The result is not satisfactory
- But much better compared to one-to-one
- Previous results showed that the earth magnetic field already has an influence



Dispersion Free Correction

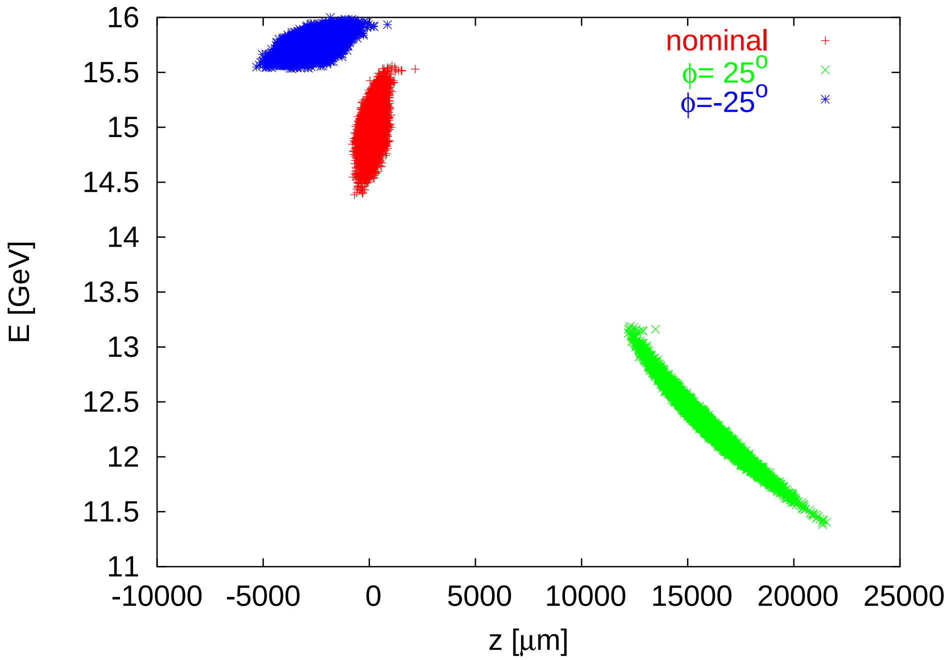
- Basic idea: use different beam energies
- NLC: switch on/off different accelerating structures
- CLIC (ILC): accelerate beams with different gradient and initial energy
- Optimise trajectories for different energies together:

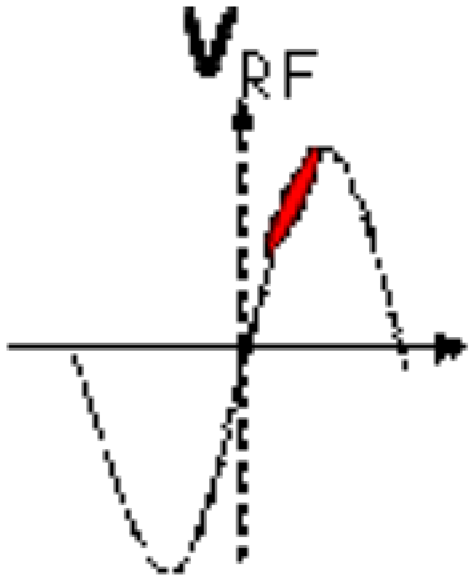
$$S = \sum_{i=1}^{n} \left(w_i (x_{i,1})^2 + \sum_{j=2}^{m} w_{i,j} (x_{i,1} - x_{i,j})^2 \right) + \sum_{k=1}^{l} w'_k (c_k)^2$$

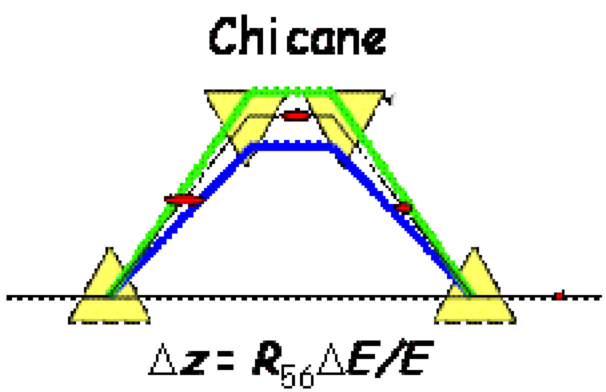
- Last term can be omitted
- Idea is to mimic energy differences that exist in the bunch with different beams

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)

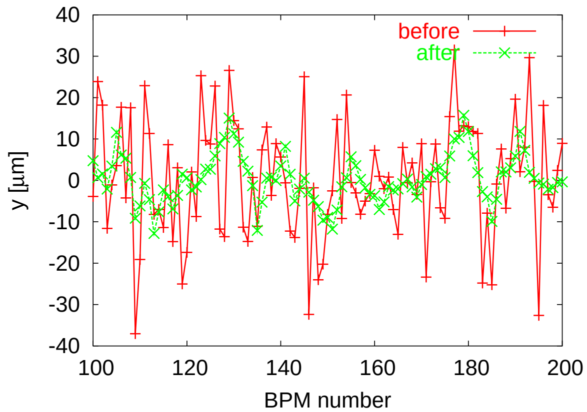


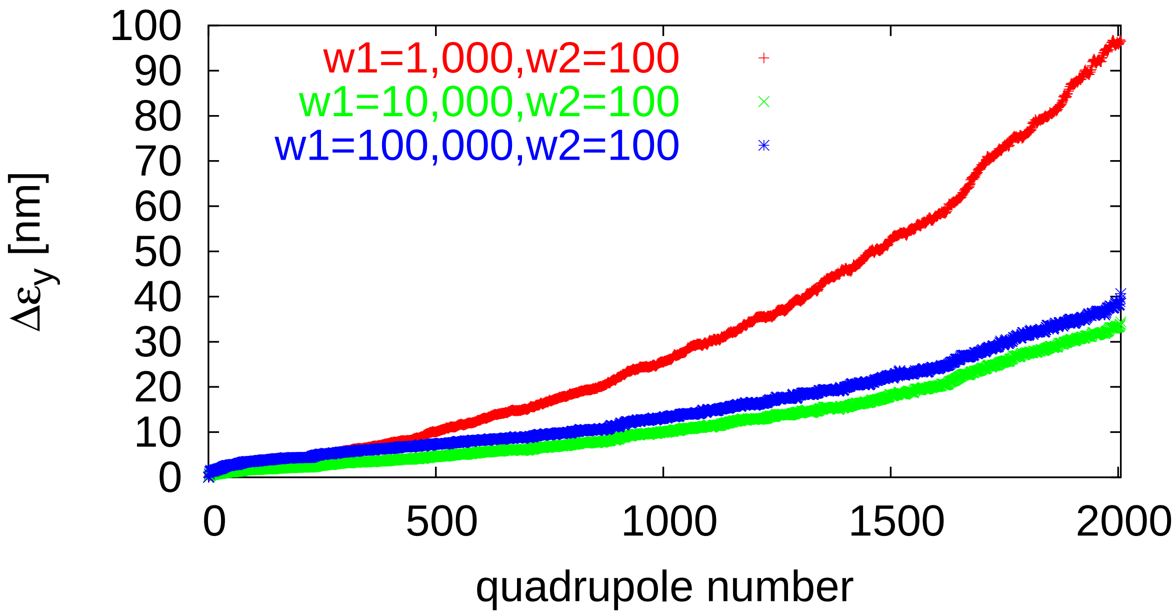


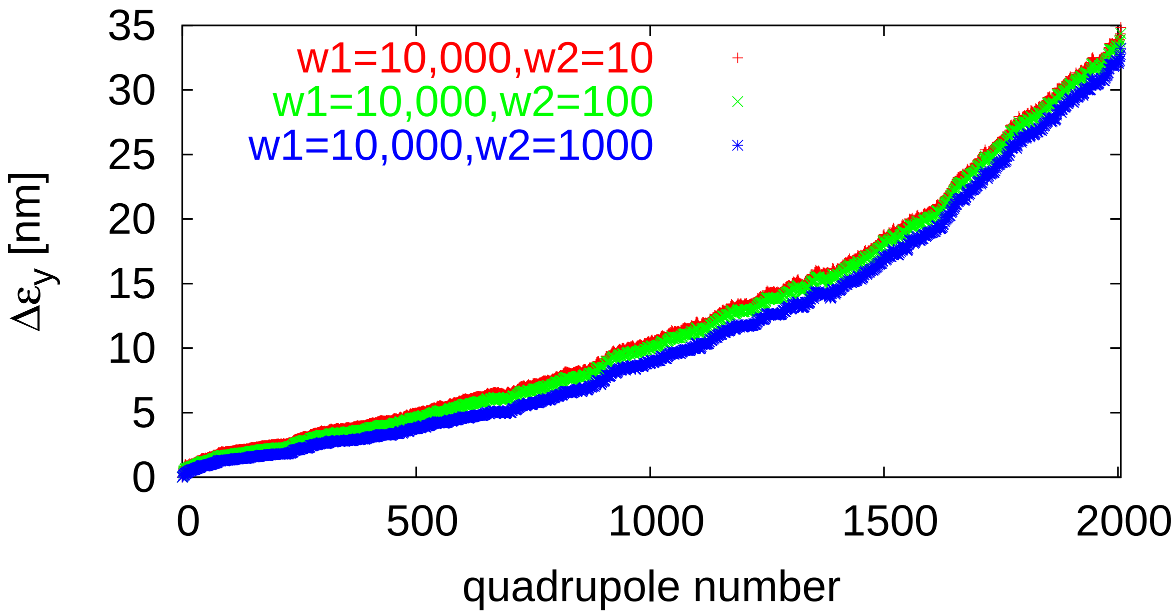


DFS Results

- Optimum combination of w_1 and w_2 found
- Average emittance growth about is not acceptable







Structure Alignment

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

$\Rightarrow$ Align structures to the beam

- In the current simulation each structure is moved independently
- A study had been performed to move the articulation points (N. Leros, D.S.)

  $\Rightarrow$ small effect if chain is continuous

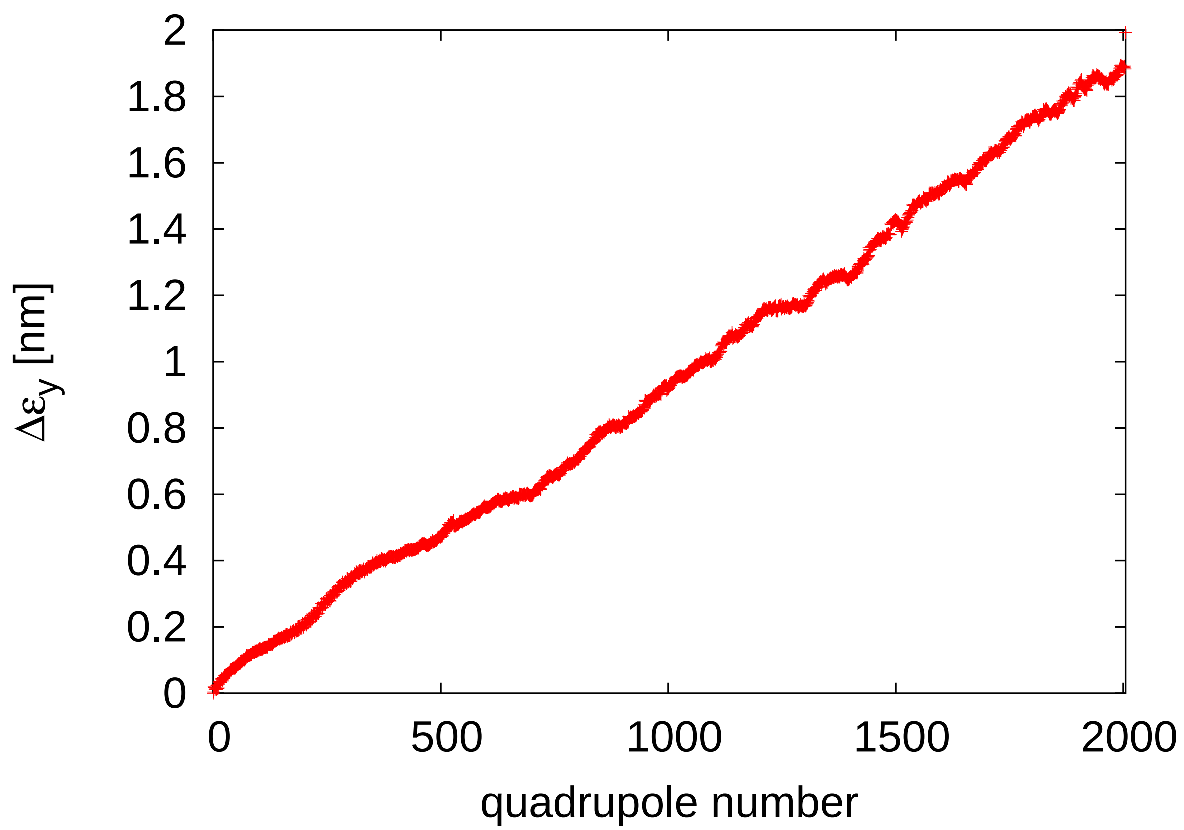
  $\Rightarrow$ negligible additional effect if additional articulation point exists at quadrupoles

$\Rightarrow$ Would like to revisit the problem to get rid of sheer point at quadrupoles

Result for Ballistic Alignment

- Structure alignment is very efficient
  - large misalignments between BPMs and structures existed
  - they are removed by structure alignment

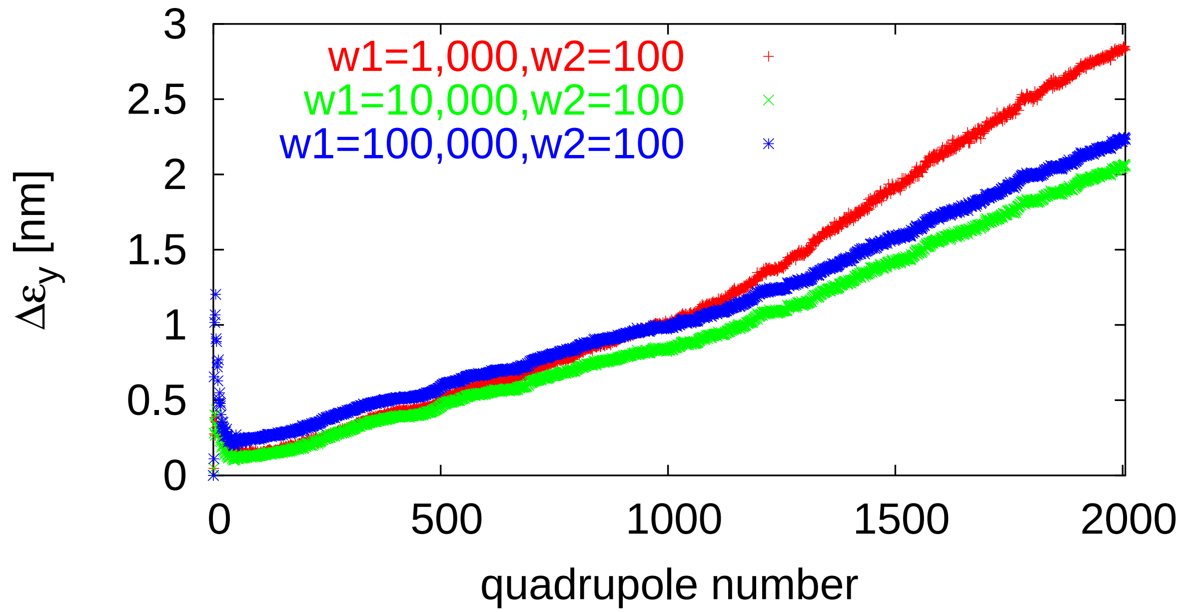
⇒ The performance is almost satisfactory

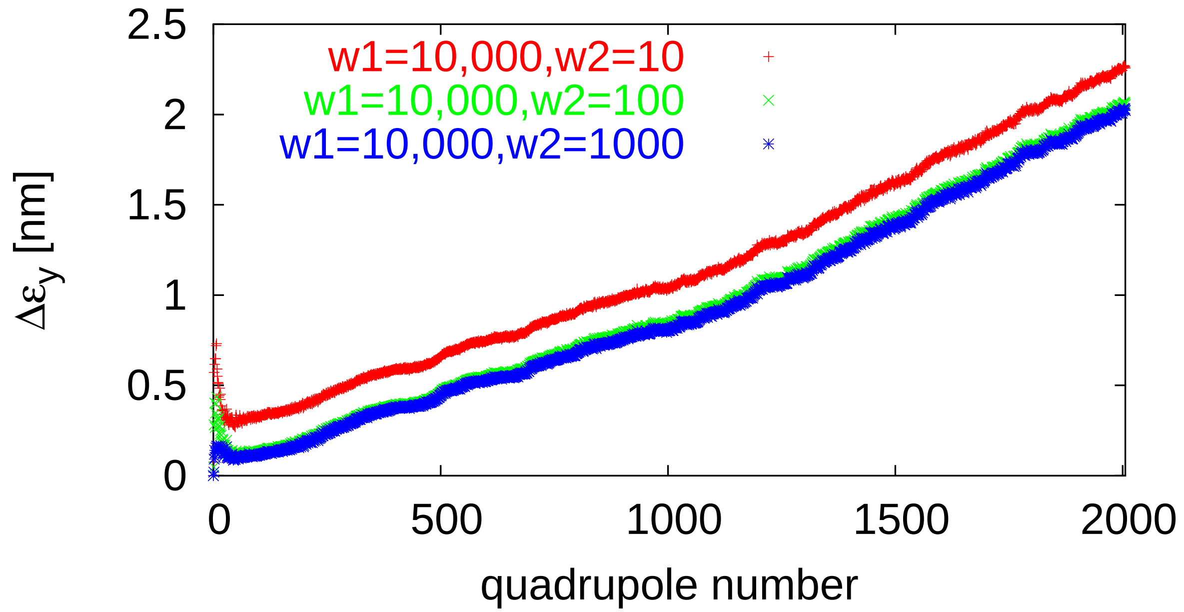


DFS Results

- Also DFS profits from structure alignment

⇒ Almost satisfactory performance

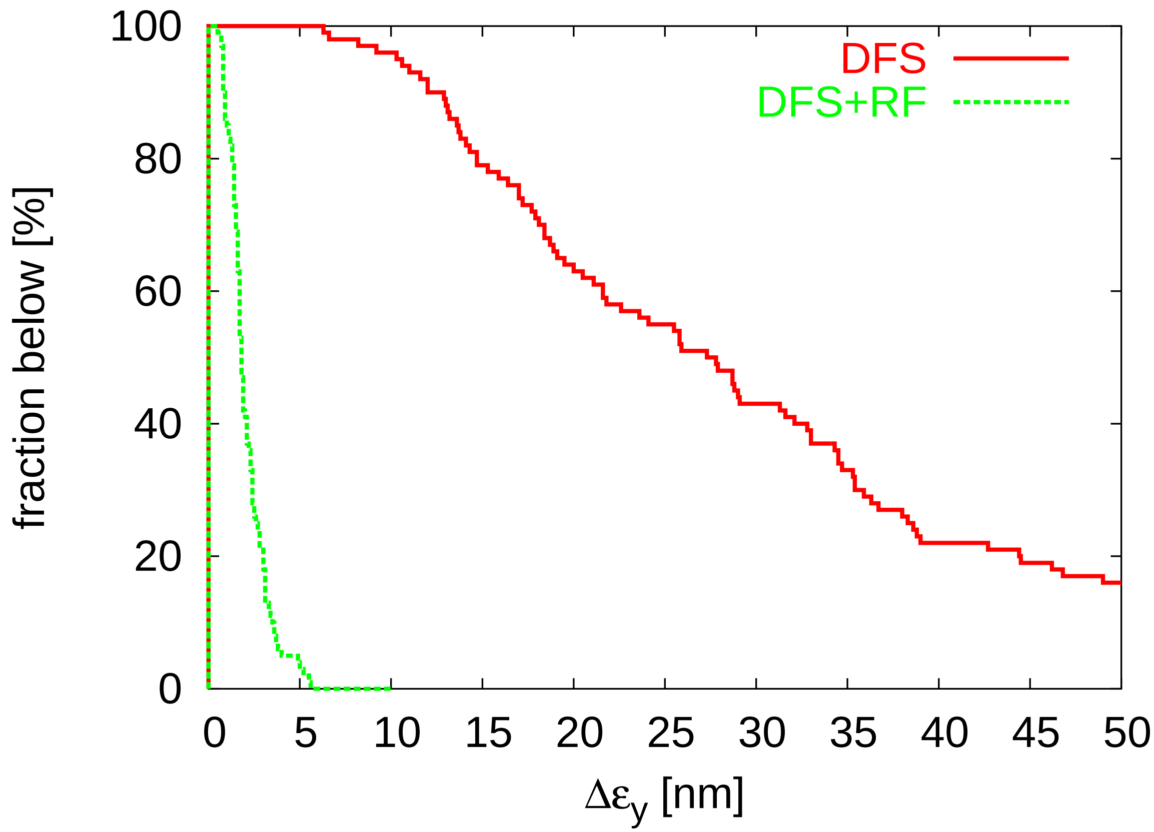




DFS Results

⇒ With RF alignment we can have more then 90% of the machines below 5nm

⇒ But not much margin



Tuning Bumps

- Tuning bumps will be used to reduce the wakefield effects

  the beam accumulates wakefield kicks as

$$F(z) = w_\perp(z) \sum_{i=1}^{n} A_i y_i$$

  the bump is used to zero the sum

$$F'(z) = w_\perp(z) \left(\sum_{i=1}^{n} A_i y_i + A_j \Delta y_j \right)$$

  Residual remains

  - energy spread in the beam (slight z-dependence of A)
  - imperfect measurement/correction

- Bumps are simulated by moving a single structure transversely

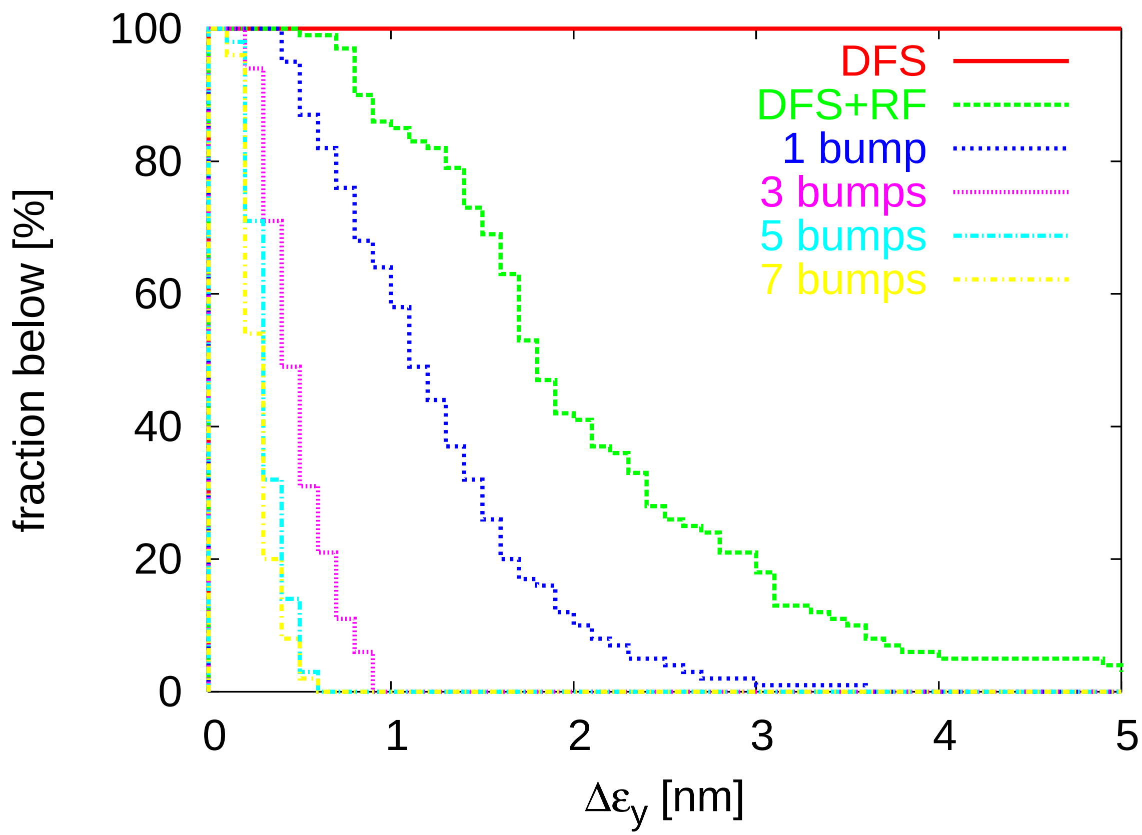
  - previous studies showed that this is a good enough model (P. Eliasson, D.S.)

Results for DFS

- Bumps are efficient
- Already a single bump (two degrees of freedom) is satisfactory
  - but we would use 3 or 5

⇒ Need to optimise taking into account convergence

- Final average emittance in nm (bumps): 1.6 (0), 0.9 (1), 0.3 (3), 0.18 (5), 0.13 (7)



Dependence on Weigths (Old Parameters)

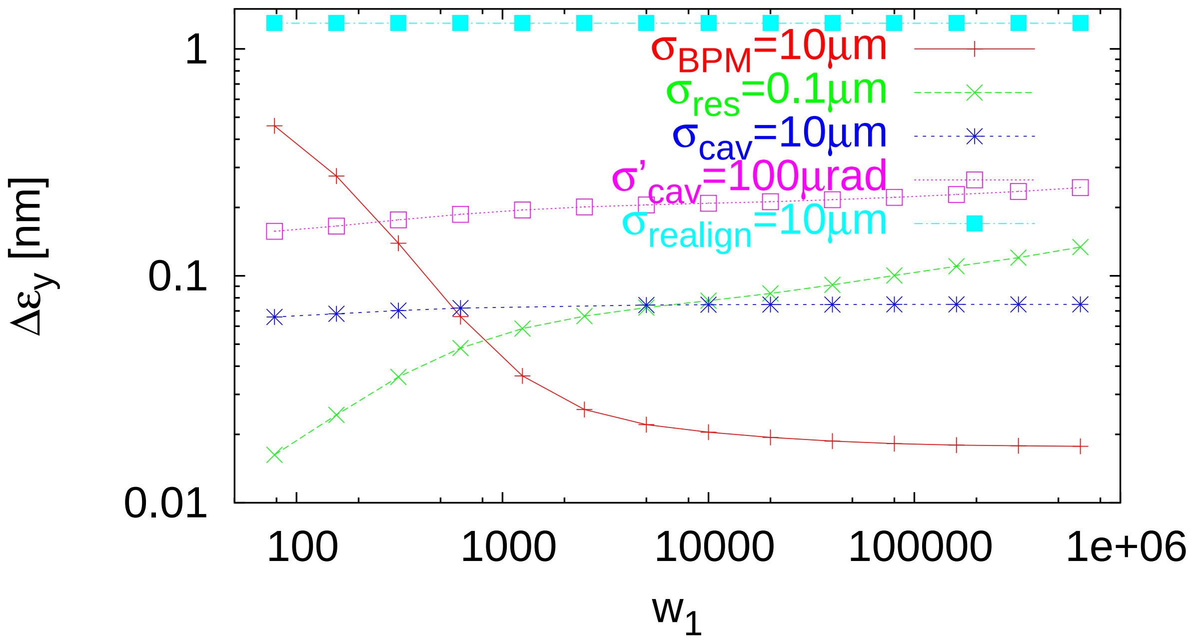
- For TRC parameters set
- One test beam is used with a different gradient and a different incoming beam energy

⇒ BPM position errors are less important at large w_1

⇒ BPM resolution is less important at small w_1

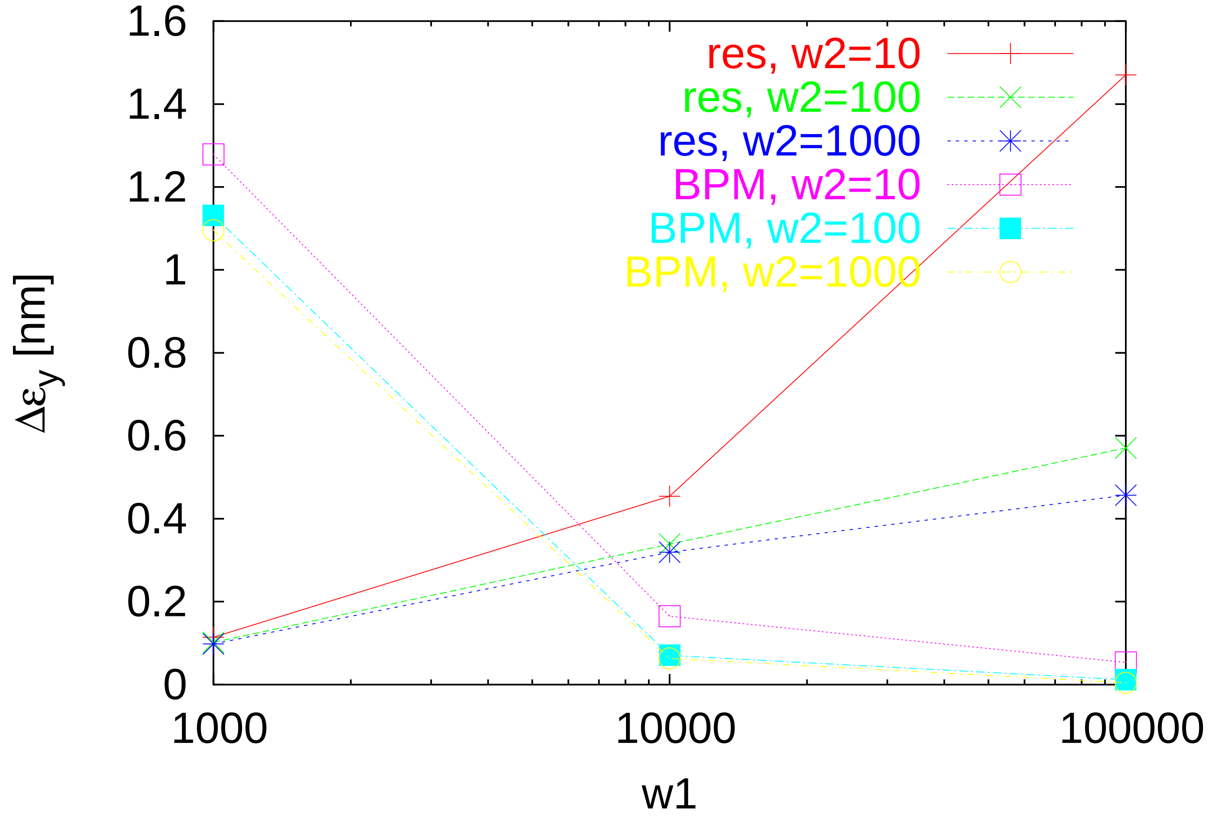
⇒ Need to find a compromise

⇒ Cannot give “the” tolerance for one error source



New Parameters

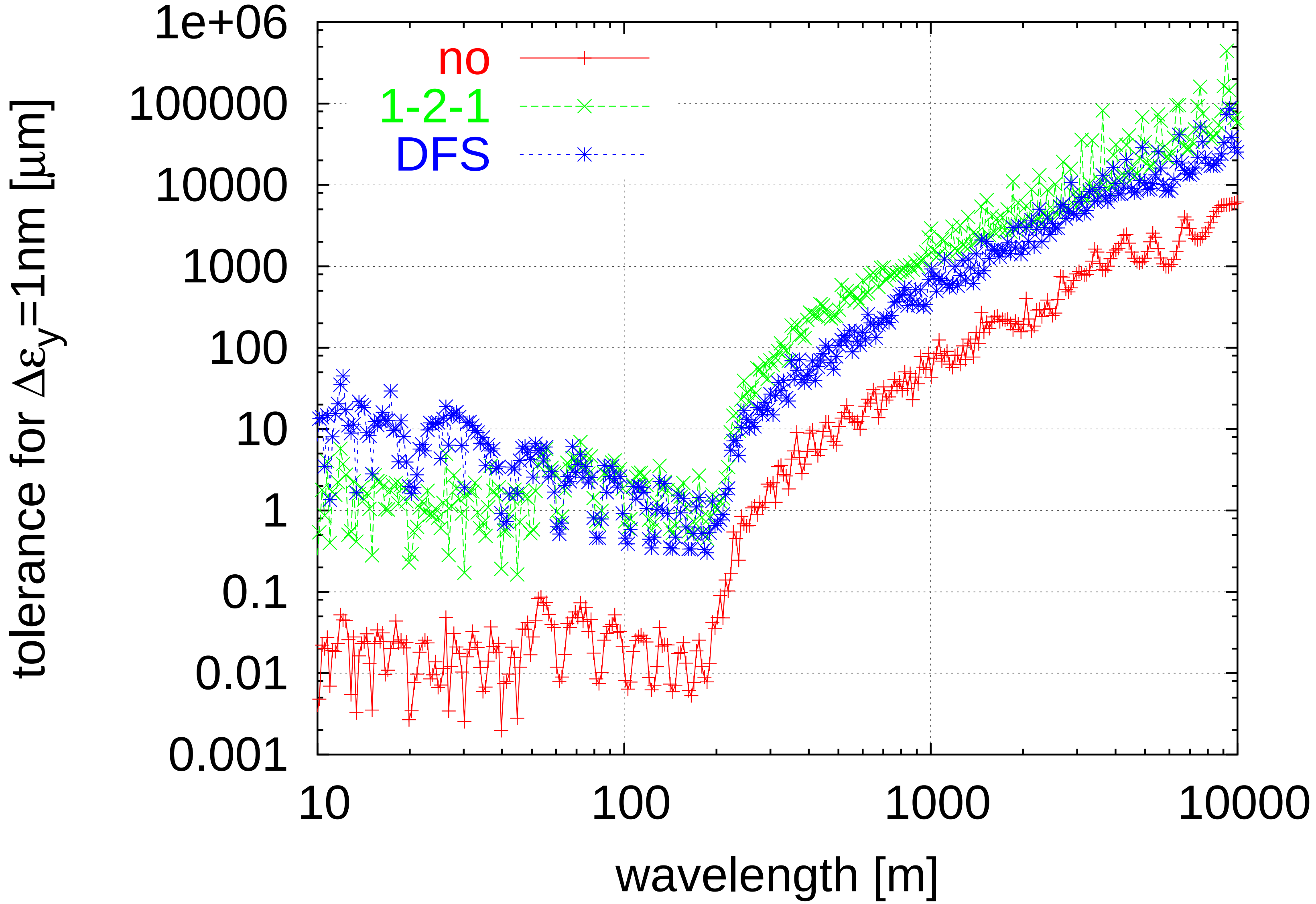
- For new parameters similar dependence is found (as expected)
- can achieve
  - $\Delta\epsilon_y \approx 0.05$–$0.3\,\mathrm{nm}$ for BPM misalignments
  - $\Delta\epsilon_y \approx 0.3$–$0.05\,\mathrm{nm}$ for BPM resolution



Long Distance Alignment

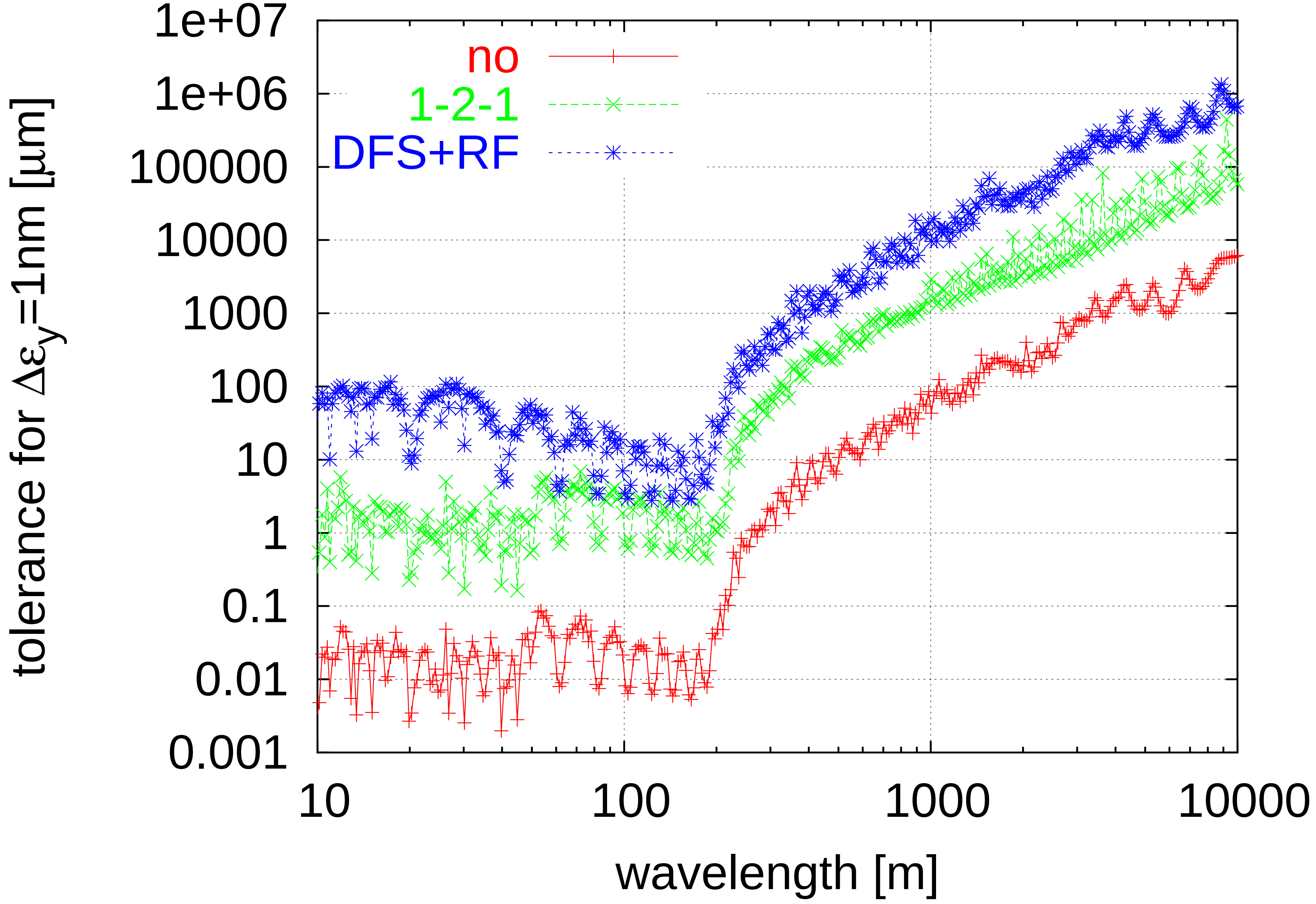
- In most simulations elements are scattered around a straight line
- In reality, the relative misalignments of different elements depends on their distance
- To be able to simulate this, PLACET can read misalignments from a file
  - simulation of pre-alignment is required
- To illustrate long-wavelength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

Results 1

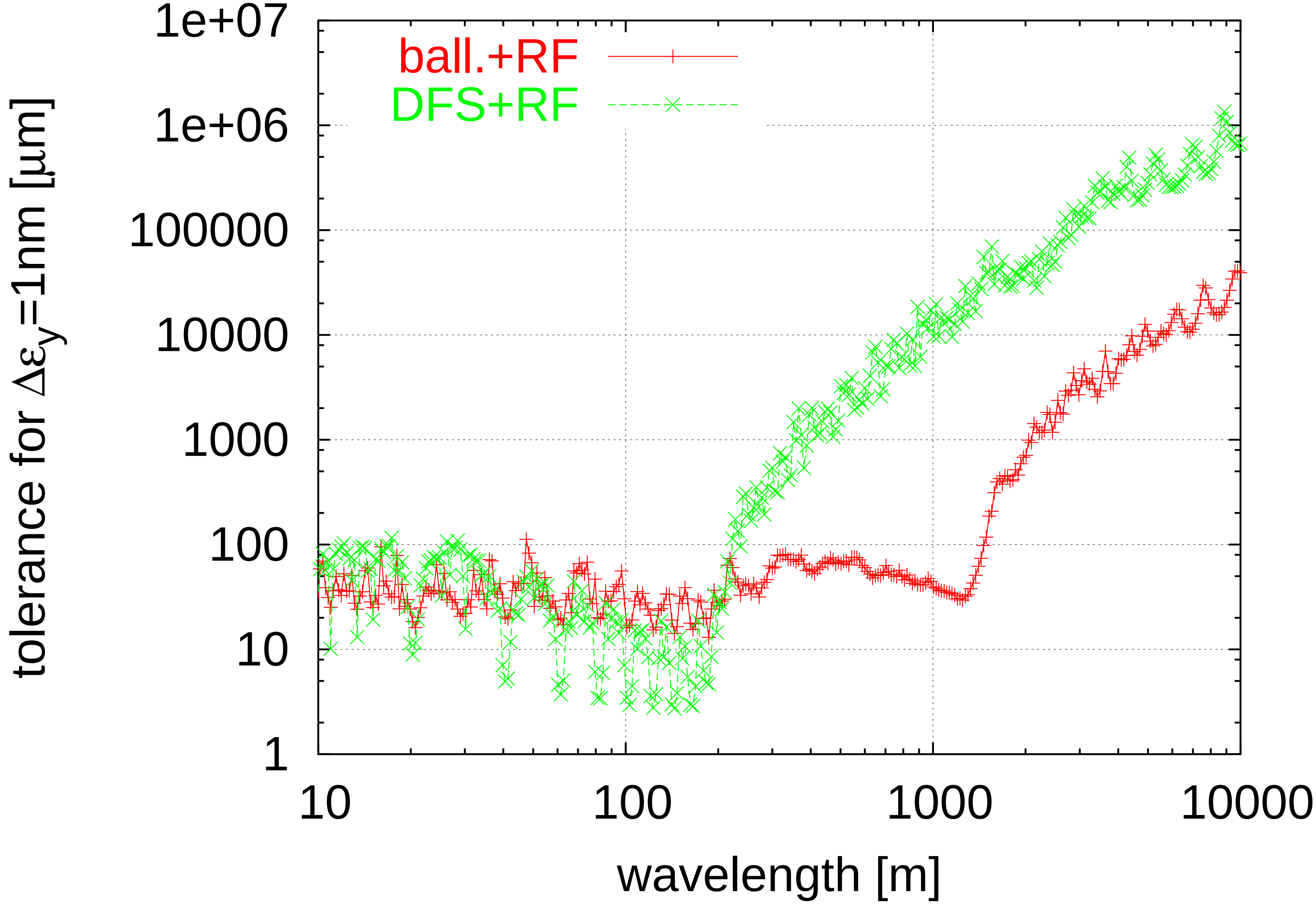


no
1-2-1
DFS
1e+06
100000
10000
1000
100
10
1
0.1
0.01
0.001
10
100
1000
10000
tolerance for Δε_y=1nm [μm]
wavelength [m]

Results 2


tolerance for $\Delta\epsilon_y$=1nm [µm]
wavelength [m]
no
1-2-1
DFS+RF
1e+07
1e+06
100000
10000
1000
100
10
1
0.1
0.01
0.001
10
100
1000
10000

Results 3



ball.+RF
DFS+RF
tolerance for $\Delta\varepsilon_y$=1nm [µm]
wavelength [m]
1e+07
1e+06
100000
10000
1000
100
10
1
10
100
1000
10000

Long-Range Wake Fields

- Wake-fields are know in time or frequency domain
- Time domain is time consuming:

$$F_n = e \sum_{i=1}^{n} W_\perp(z_n - z_i)(x_i q_i)$$

$\Rightarrow$ use FFT (convolution theorem)

$\Rightarrow$ or mode model (in linacs often sufficient):

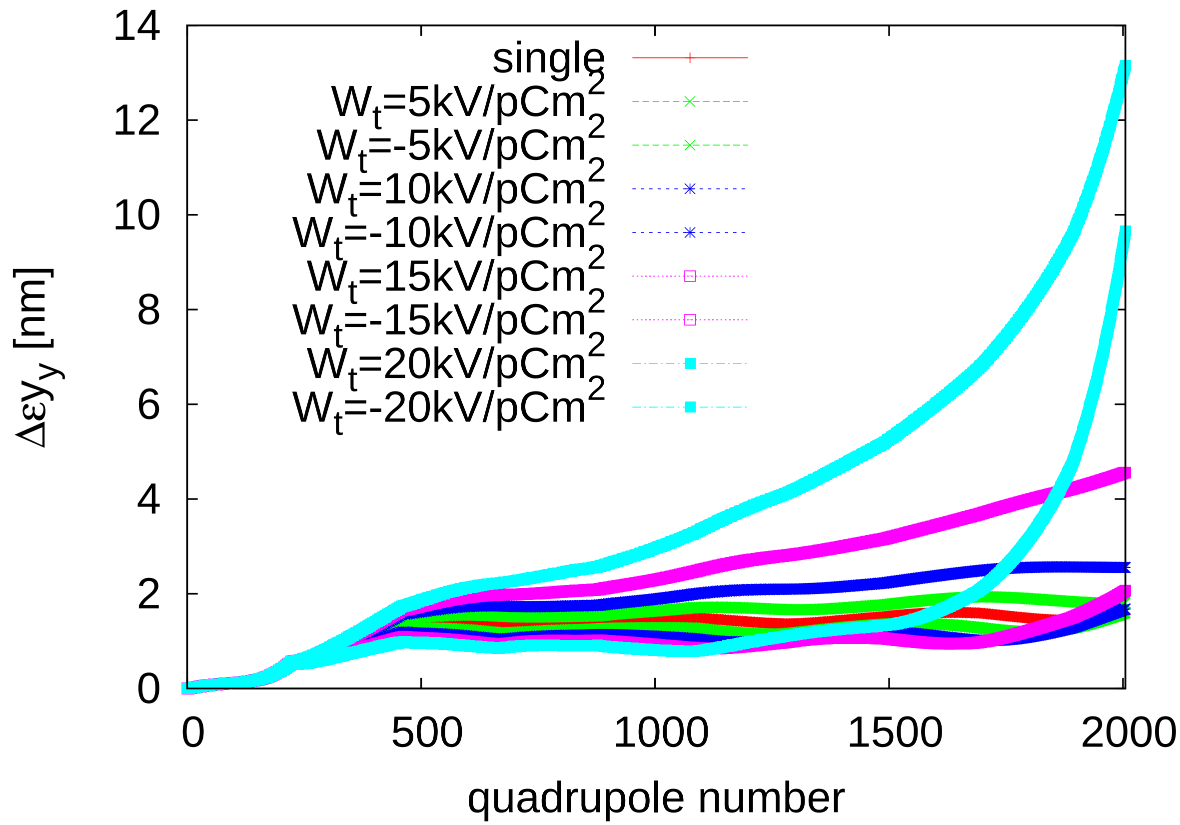
$$W_\perp(z) = \sum_{j=0}^{n} a_j \sin\left(\frac{2\pi z}{\lambda_j}\right) \exp\left(-\frac{\pi z}{\lambda_j Q_j}\right)$$

can be evaluated very efficiently

CLIC Longrange Wakefields

- Long-range wakefields are important
- Simulation of emittance growth due to beam jitter
  - no energy spread (pessimistic)
- Allowed wake at second bunch is $\approx 4.5\,\mathrm{kV/pCm^2}$

  $\Rightarrow$ seems acceptable



Static Effects

- If all structures have the same long-range wake, the tuning bumps are curing short- and long-range efeects at the same time

  ⇒ simulations indicate small additonal effects in other lattices

- For different longrange wakes the compensation is not guaranteed

  ⇒ need to develop a model for long-range wakes with errors

- Wakefield tolerance given is for the wake envelope

  ⇒ spread is wakes should lead to lower average kick

- We could develop special long-range bumps e.g. based on train straightener

Conclusion

- New lattice design is waiting for confirmation of quadrupole lengths
  - final optimisation will be performed once this is done
- Performance corresponds to expected values from scaling
- A model for the alignment has been developed in the module working group
  - needs continuation
  - a complex data transfer between alignment and beam dyanmics is required
- Static tuning study needs to be repeated (in more complete version) for final lattice
- Dynamic effects and feedback need to be included
- Multi-bunch effects need to be treated
- For a number of these studies the strategy is know and needs to be applied
  - in some cases more development remains to be done