Pre-Alignment Needs for CLIC

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- Emittance preservation target and lattice design
- Imperfection modelling
- Beam-based alignment
- Consequences for pre-alignment
- Reference line error example
- Conclusion

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Low Emittance Transport Challenges

- Main linac is most important source of emittance growth → best studied
- Static imperfections

  errors of reference line, elements to reference line, elements...

  excellent pre-alignment, lattice design, beam-based alignment, beam-based tuning

- Dynamic imperfections

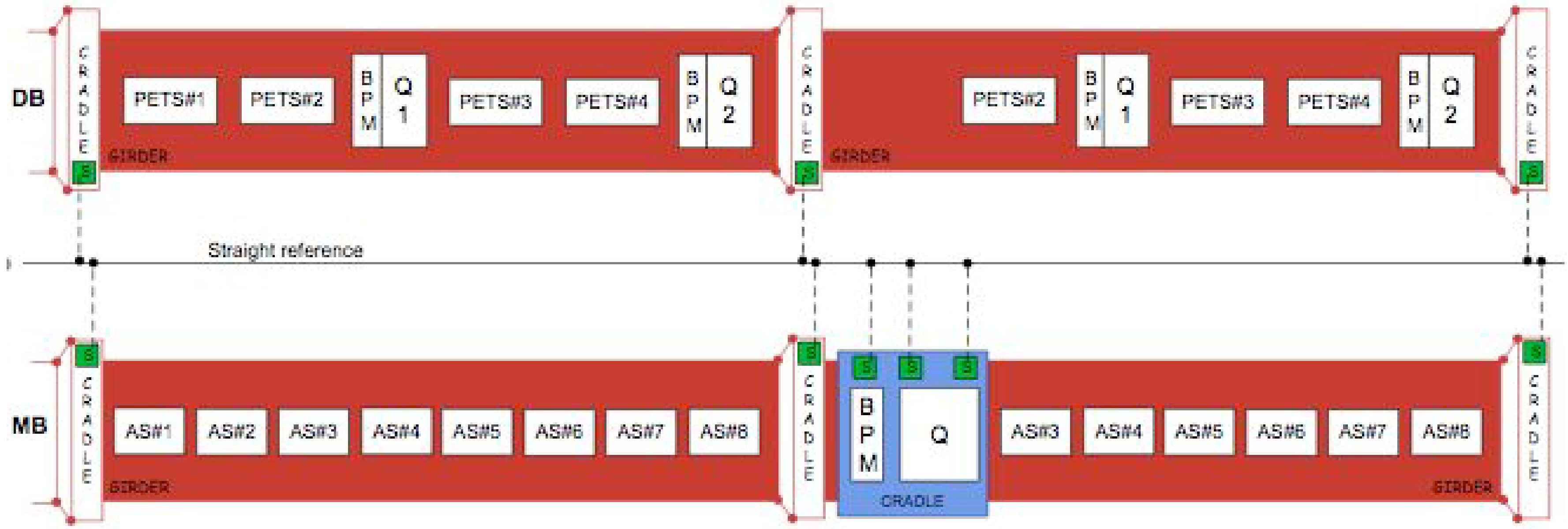
  element jitter, RF jitter, ground motion, beam jitter, electronic noise,...

  lattice design, BNS damping, component stabilisation, feedback, re-tuning, re-alignment

- Combination of dynamic and static imperfections can be severe

- Vertical main linac emittance budget
  - $\Delta\epsilon_y \leq 5\,\mathrm{nm}$ for dynamic imperfections
  - $\Delta\epsilon_y \leq 5\,\mathrm{nm}$ for static imperfections (90% probability)
  - horizontal budget 6 times larger (→ tolerances 2.5 times larger)

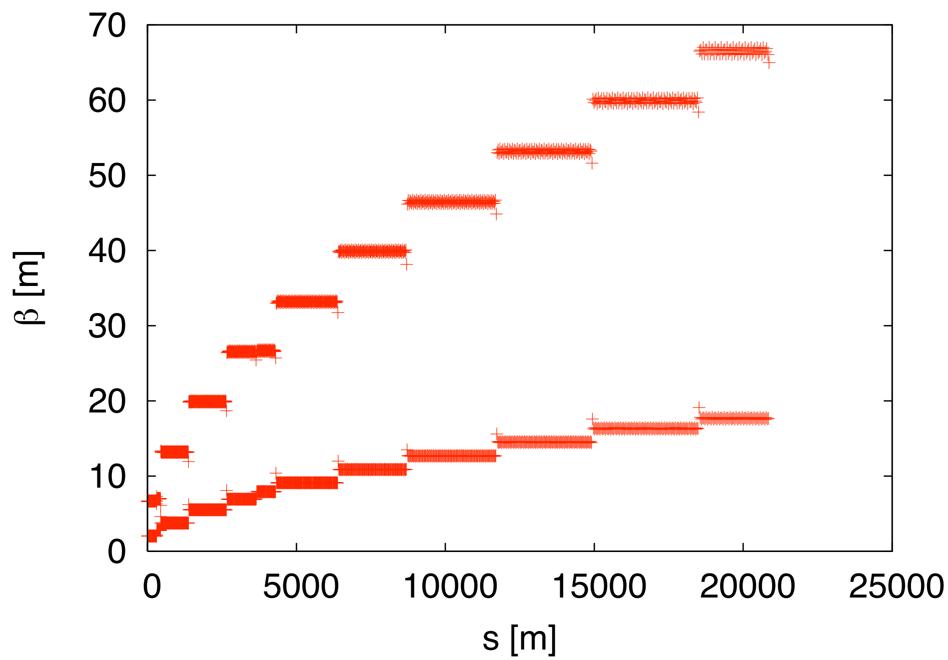
Module Layout



- 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
- Total length 20867.6m
  - fill factor 78.6%
- Jitter tolerance for $\Delta\epsilon_y = 0.4\,\mathrm{nm}$
  - quadrupole position: $1.6\,\mathrm{nm}$
  - structure position: $1.4\,\mu\mathrm{m}$
  - structure angle: $1.1\,\mu\mathrm{radian}$



- 12 different sectors used
- Matching between sectors using 7 quadrupoles to allow for some energy bandwidth

Physics Rational

- 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 complext local model
- The long-distance misalignments are dominated by the wire system

$\Rightarrow$ ignore short-distance misalignments and simulate wire errors only

- Combined studies will come for completeness

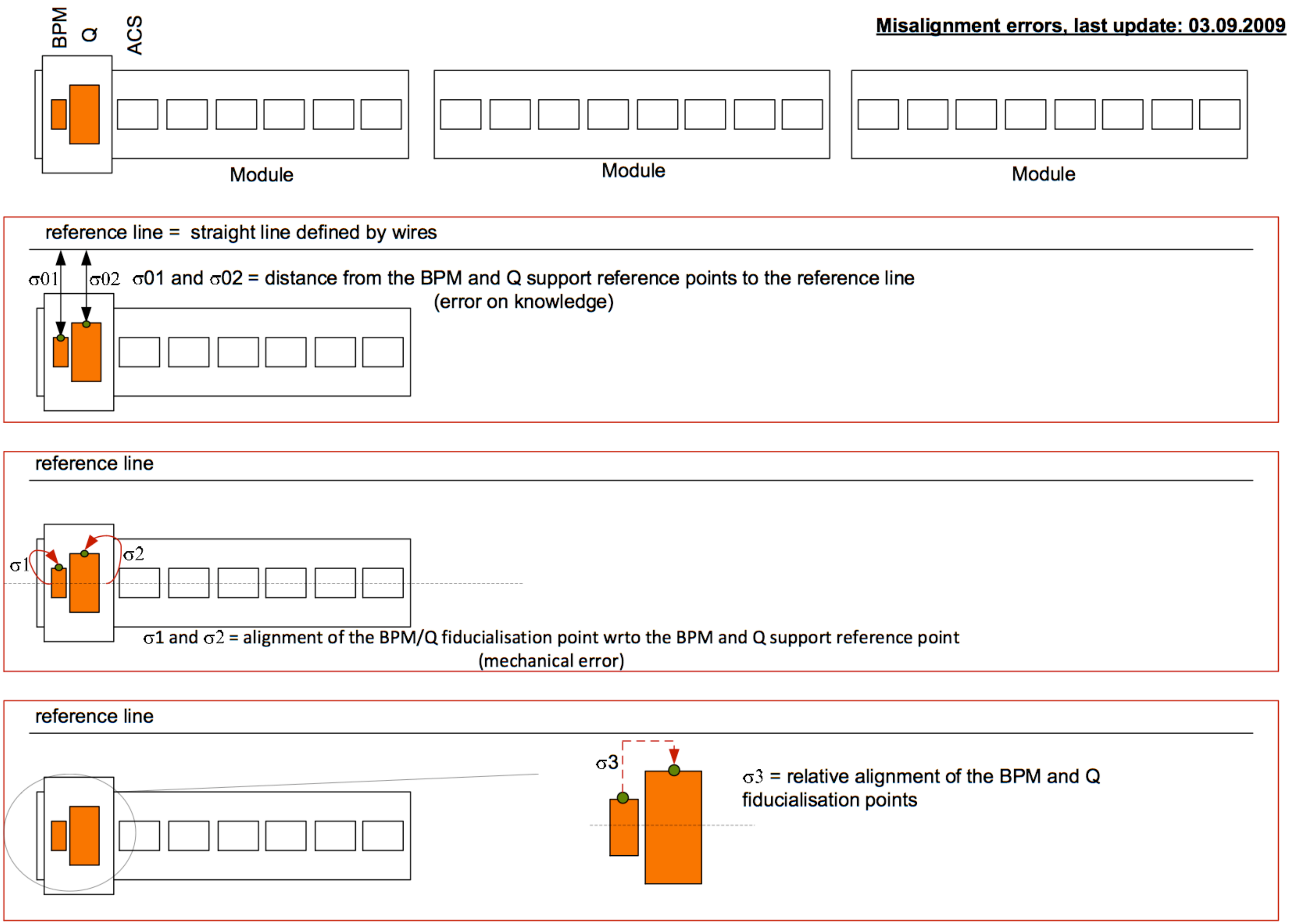
Main Linac Static Tolerances

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

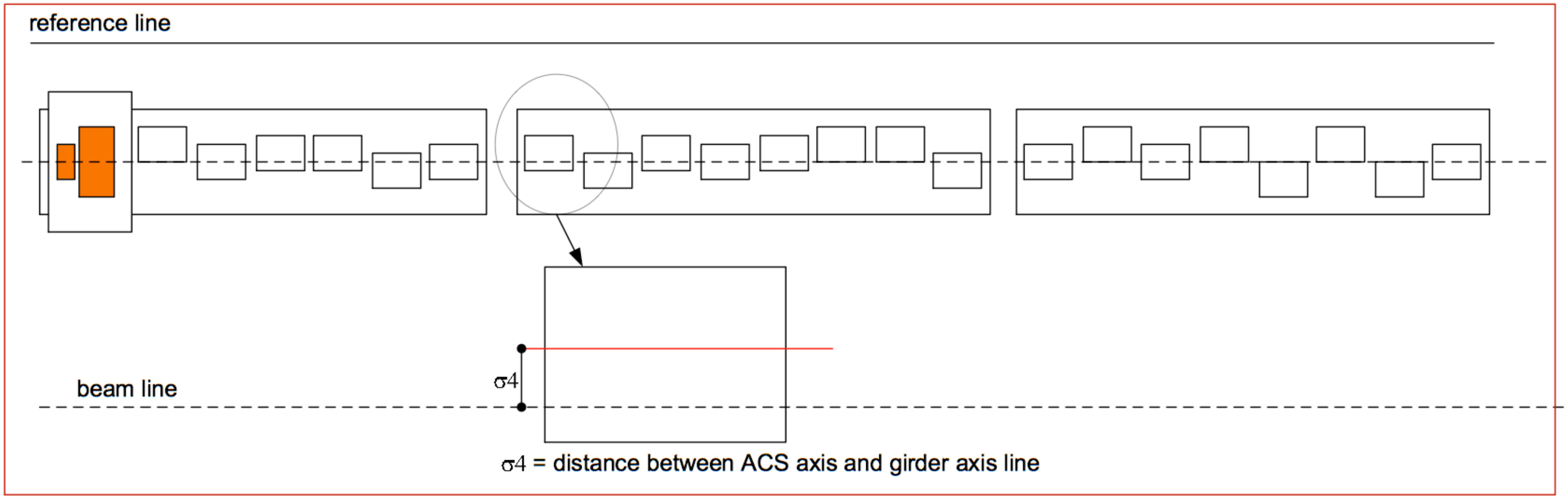
- All tolerances for 1nm growth after one-to-one steering
- CLIC emittance budget is two times smaller than for NLC

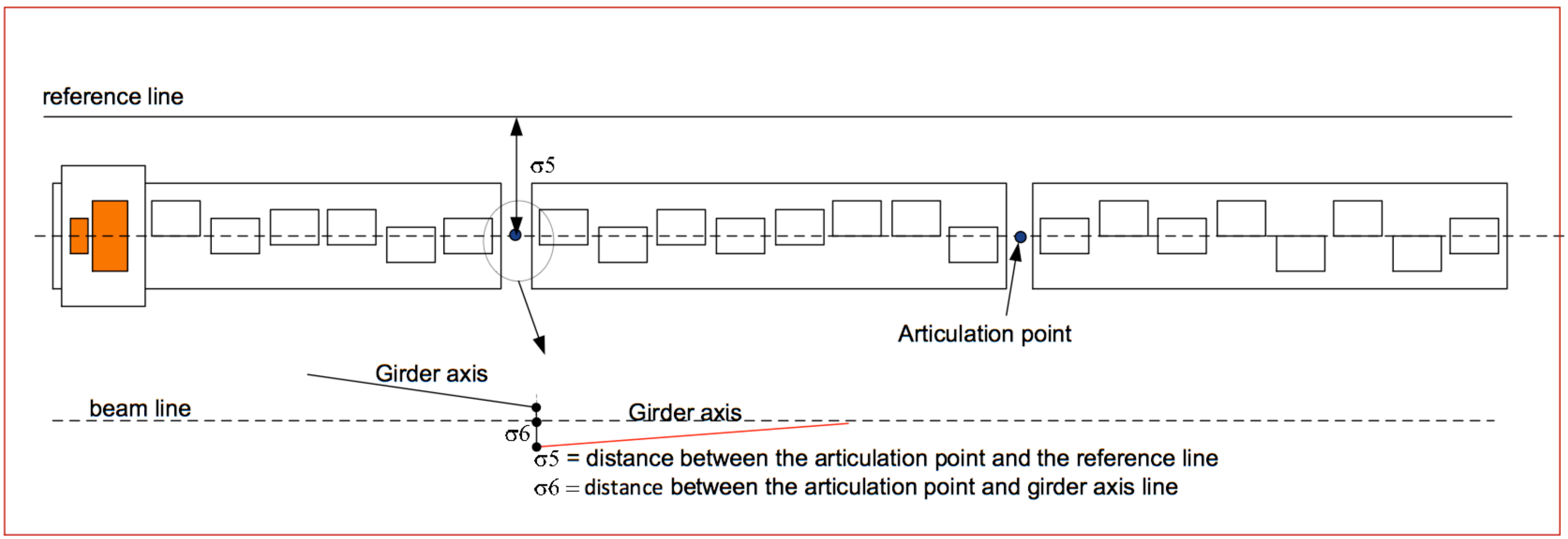
  $\Rightarrow$ for comparison divide tolerances by $\sqrt{2}$
- Goal is to have 90% of the machines achieve an emittance growth due to static effects of less than 5 nm

Alignment Model

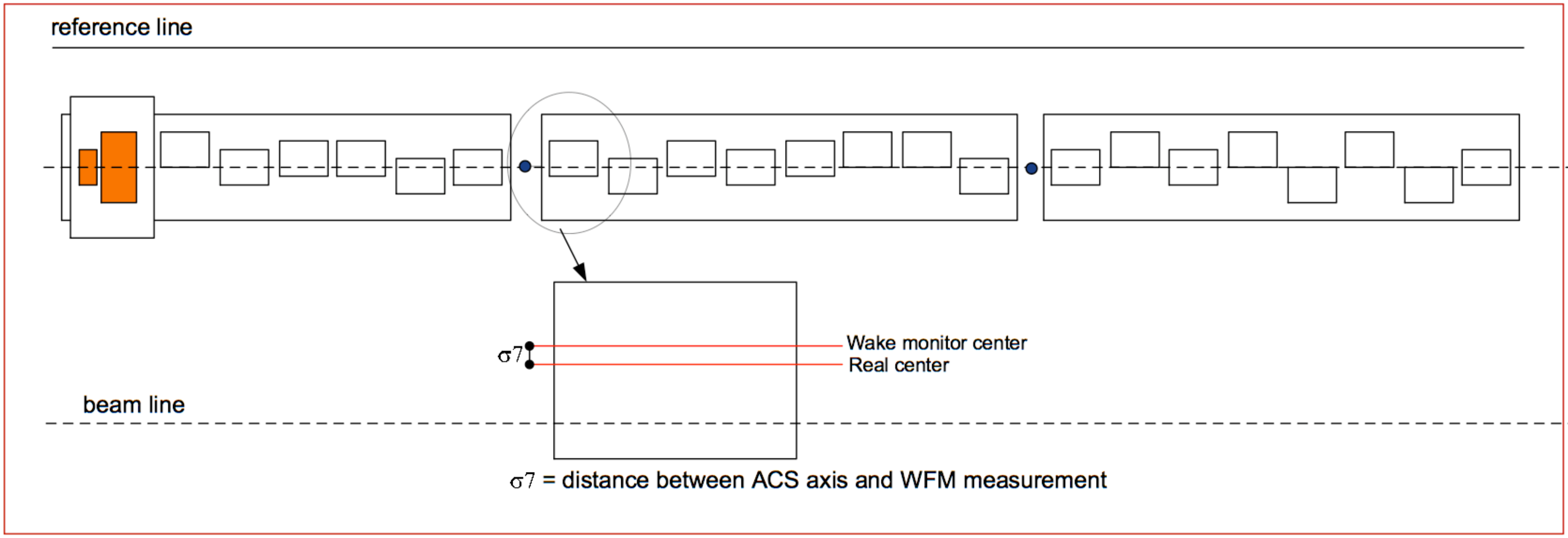


Alignment Model (cont)





Alignment Model (cont)



imperfection	with respect to	symbol	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

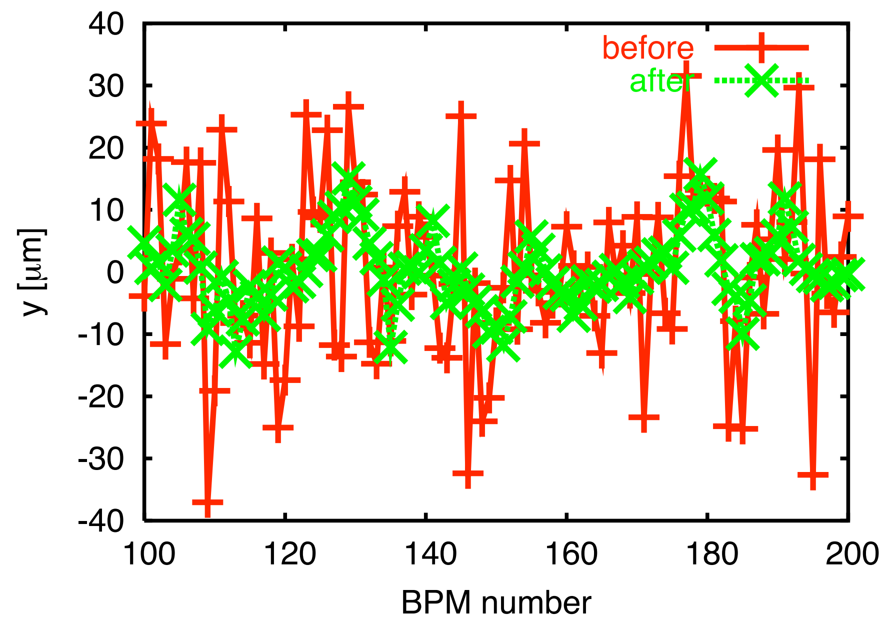
Beam-Based Alignment and Tuning Strategy

- 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

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)



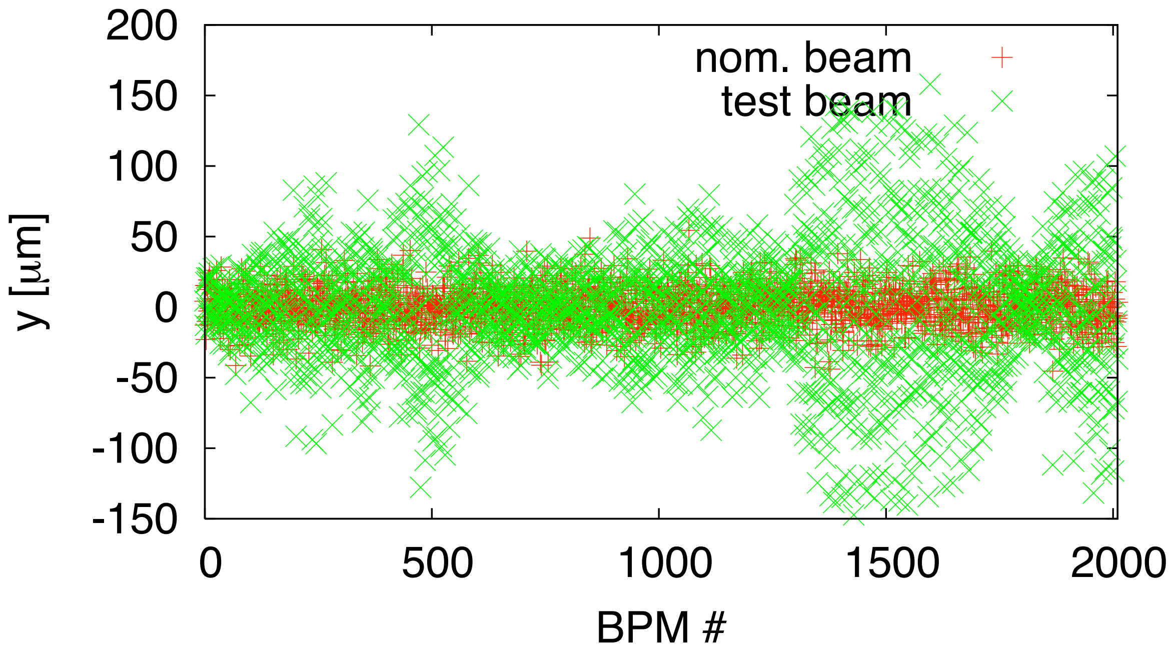
- Optimise trajectories for different energies together:

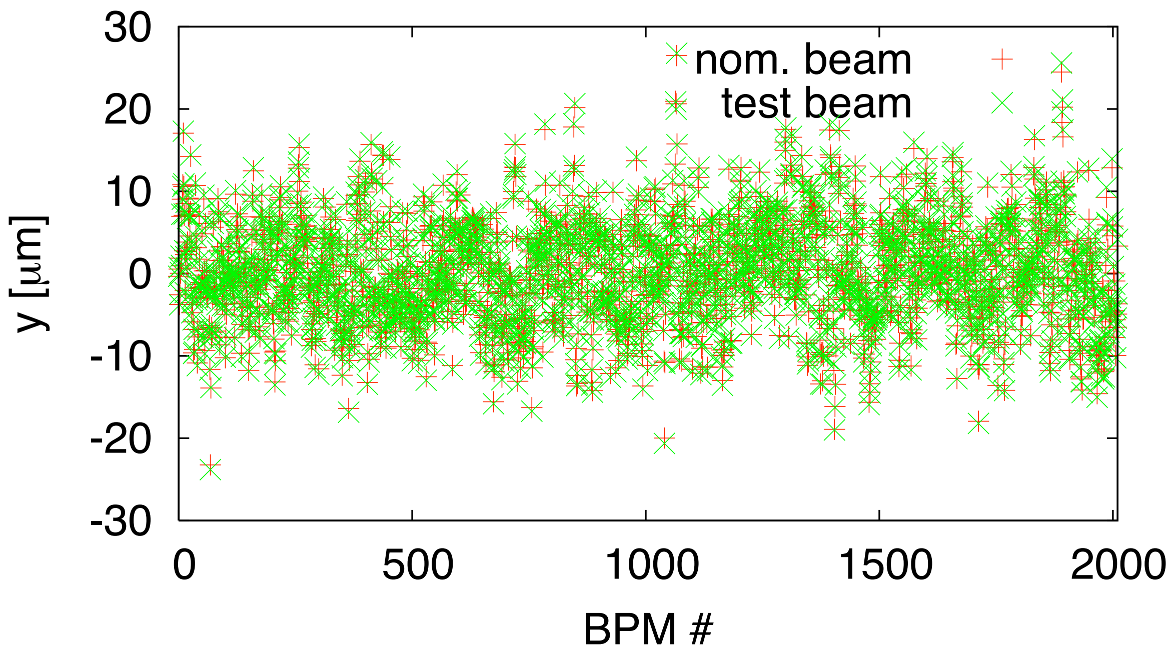
$$S = \sum_{i=1}^{n} \left(w_i (x_{i,1})^2 + \sum_{j=2}^{m} w_{i,j} (x_{i,1} - x_{i,j})^2 \right) + \sum_{k=1}^{l} w'_k (c_k)^2$$

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

Dispersion Free Correction Details

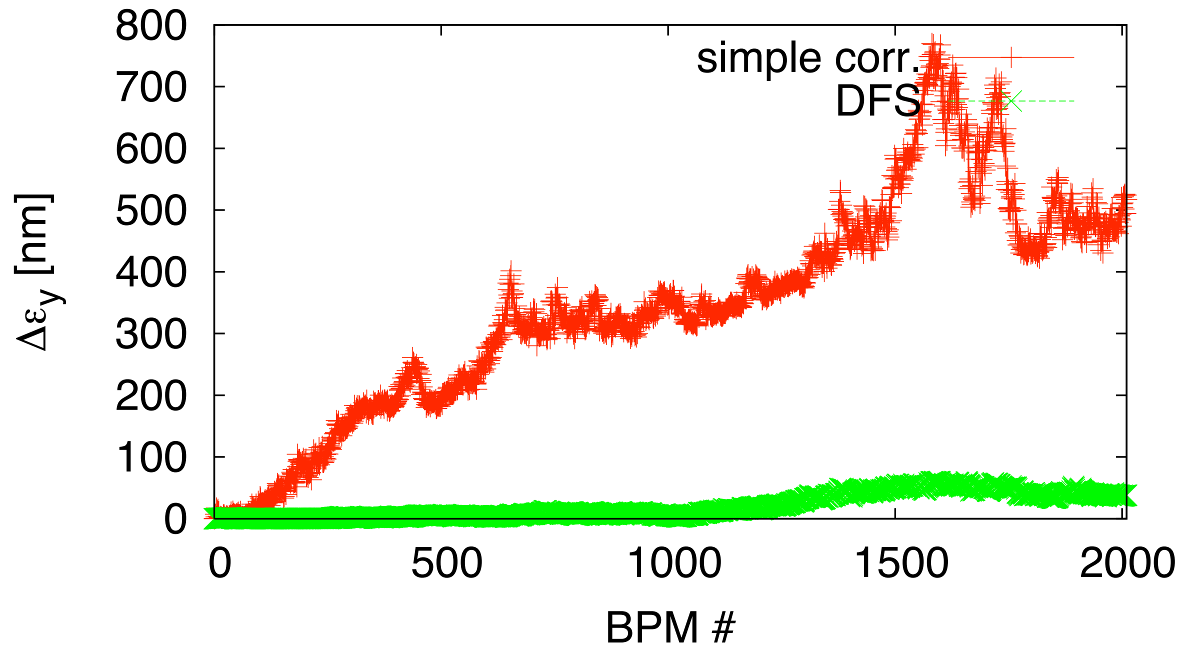
- In the one-to-one corrected machine an off-energy beam takes a very different trajectory
  - this dispersion is visible in the BPMs and is a cause of emittance growth
- After DFS the trajectories of different energy beams are very similar
  - smoother trajectory found

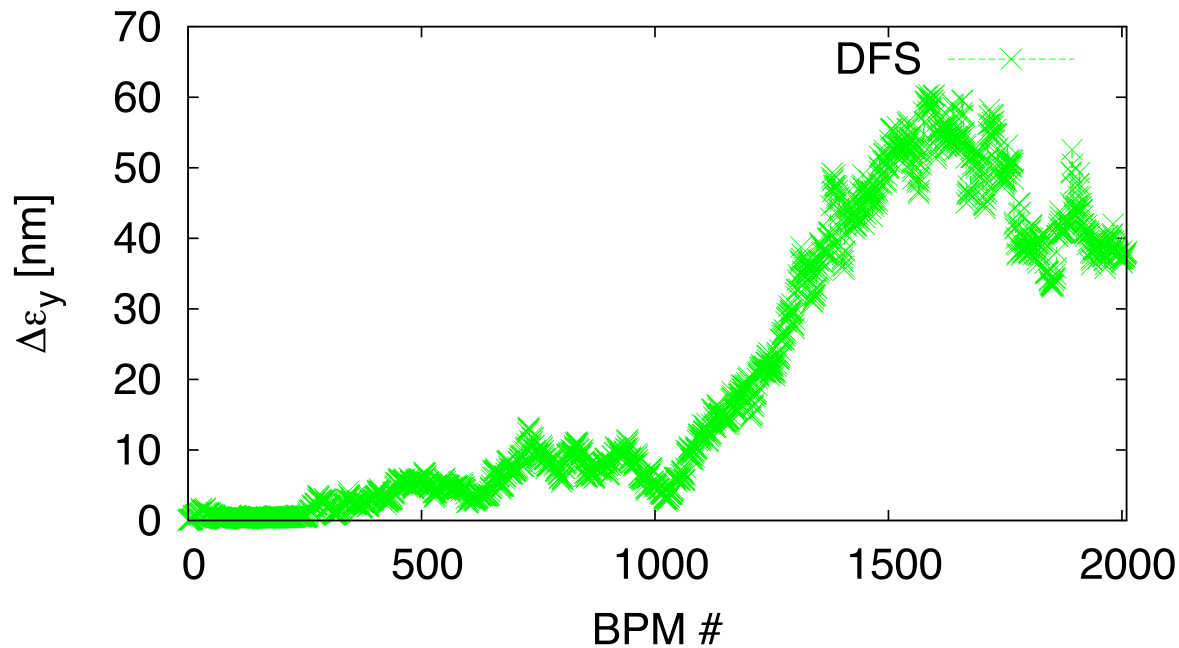




Dispersion Free Correction Details (cont.)

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



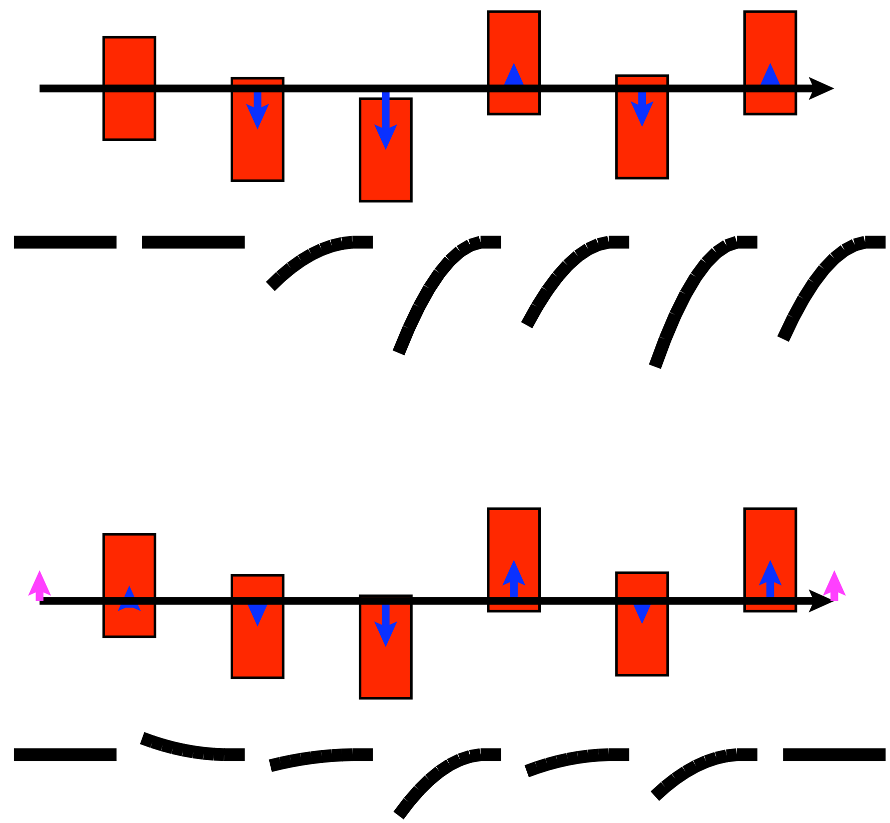


Beam-Based Structure Alignment

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

$\Rightarrow$ Align structures to the beam

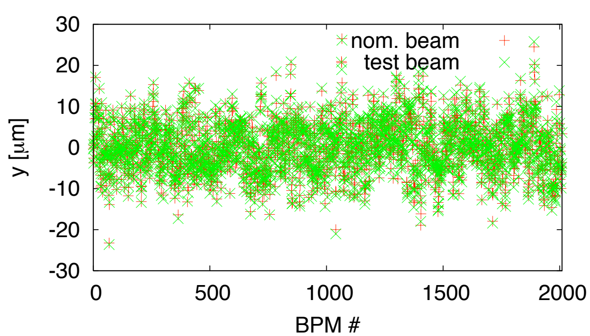
- Assume identical wake fields
  - the mean structure to wakefield monitor offset is most important
  - in upper figure monitors are perfect, mean offset structure to beam is zero after alignment
  - scatter around mean does not matter a lot
- With scattered monitors
  - final mean offset is $\sigma_{wm}/\sqrt{n}$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

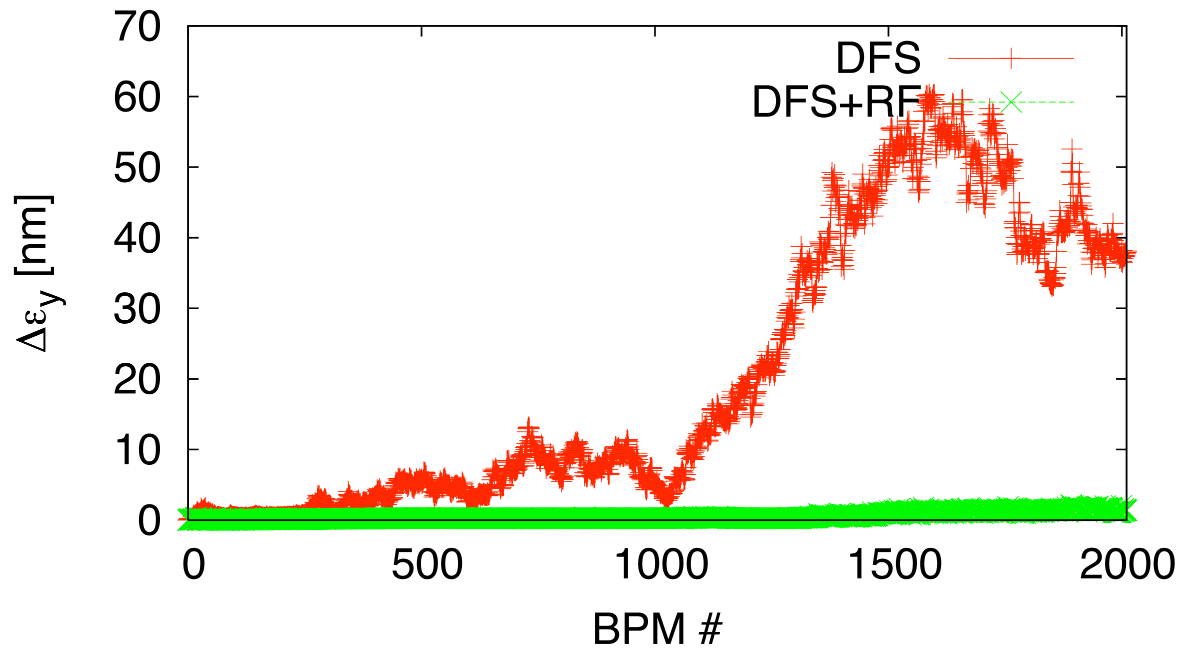


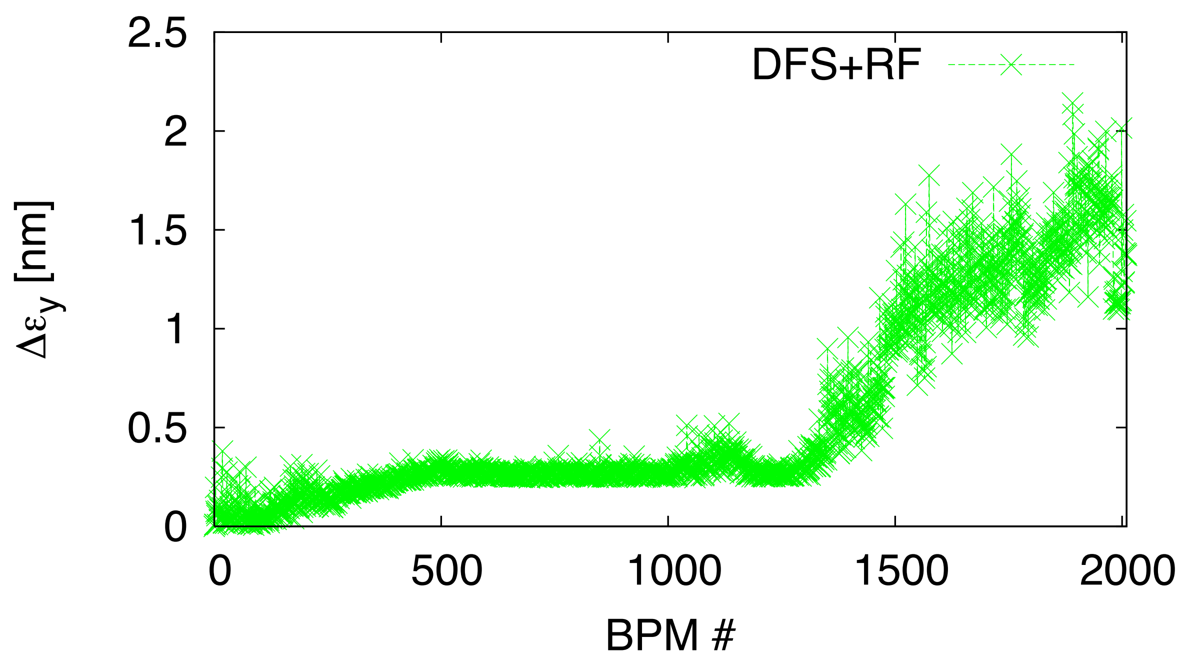
- For our tolerance $\sigma_{wm} = 5\,\mu\mathrm{m}$ we find $\Delta\epsilon_y \approx 0.5\,\mathrm{nm}$
  - some dependence on alignment method

Structure Alignment

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



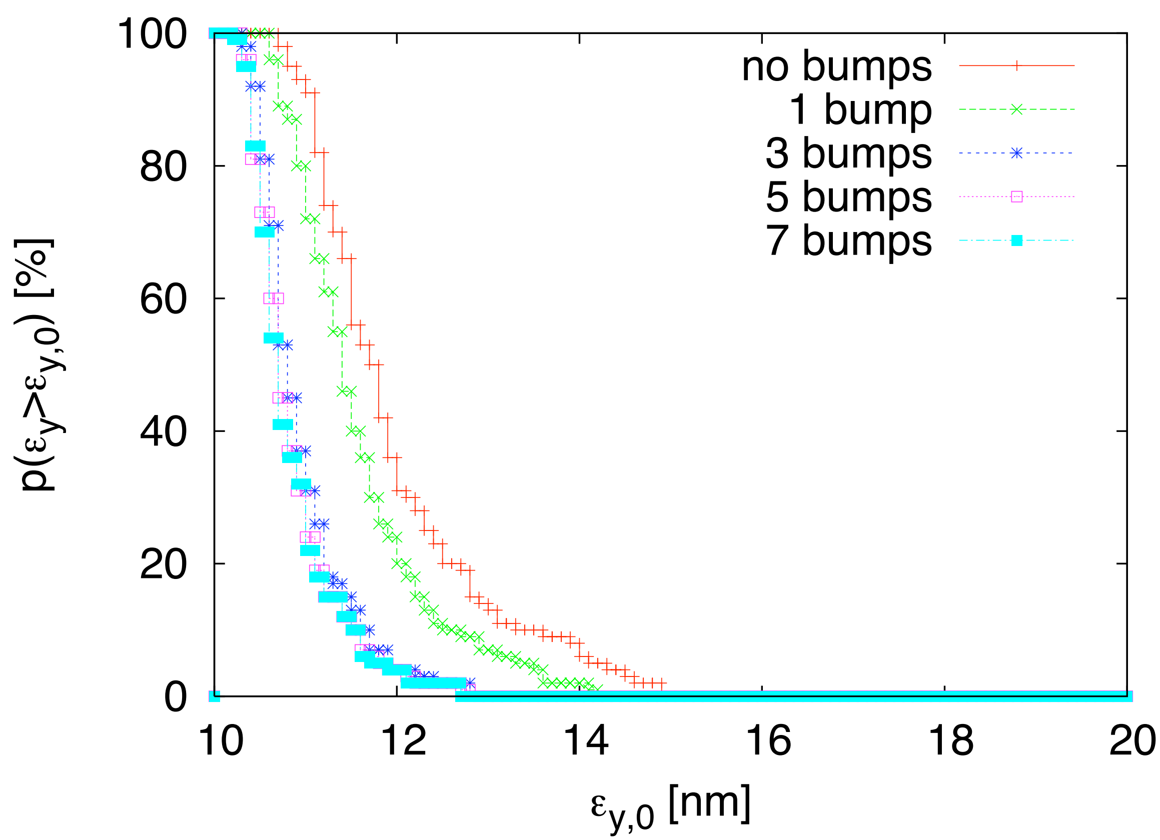




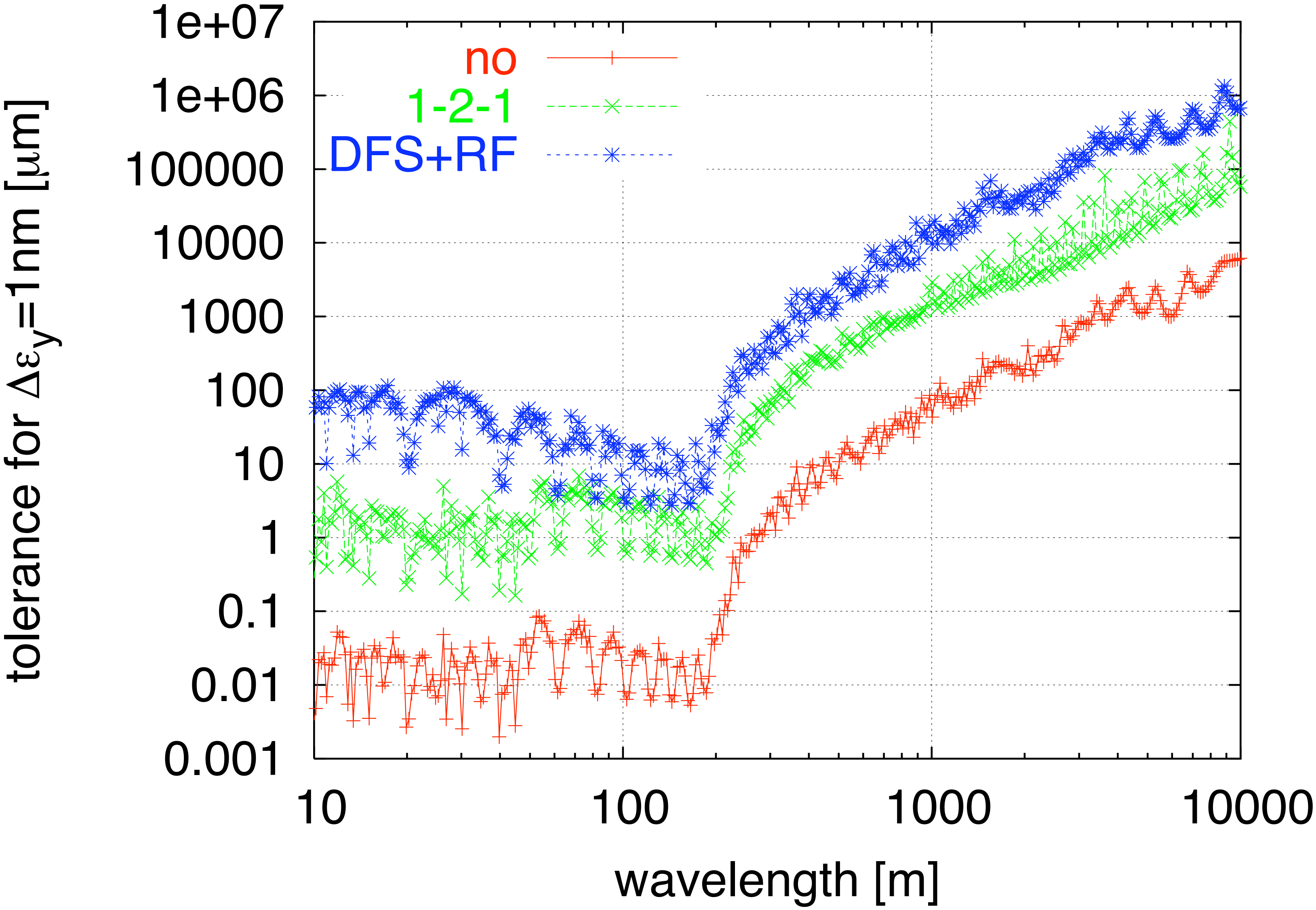
Final Emittance Growth

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	$\approx 0.04\,\mathrm{nm}$
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	$\approx 0.5\,\mathrm{nm}$

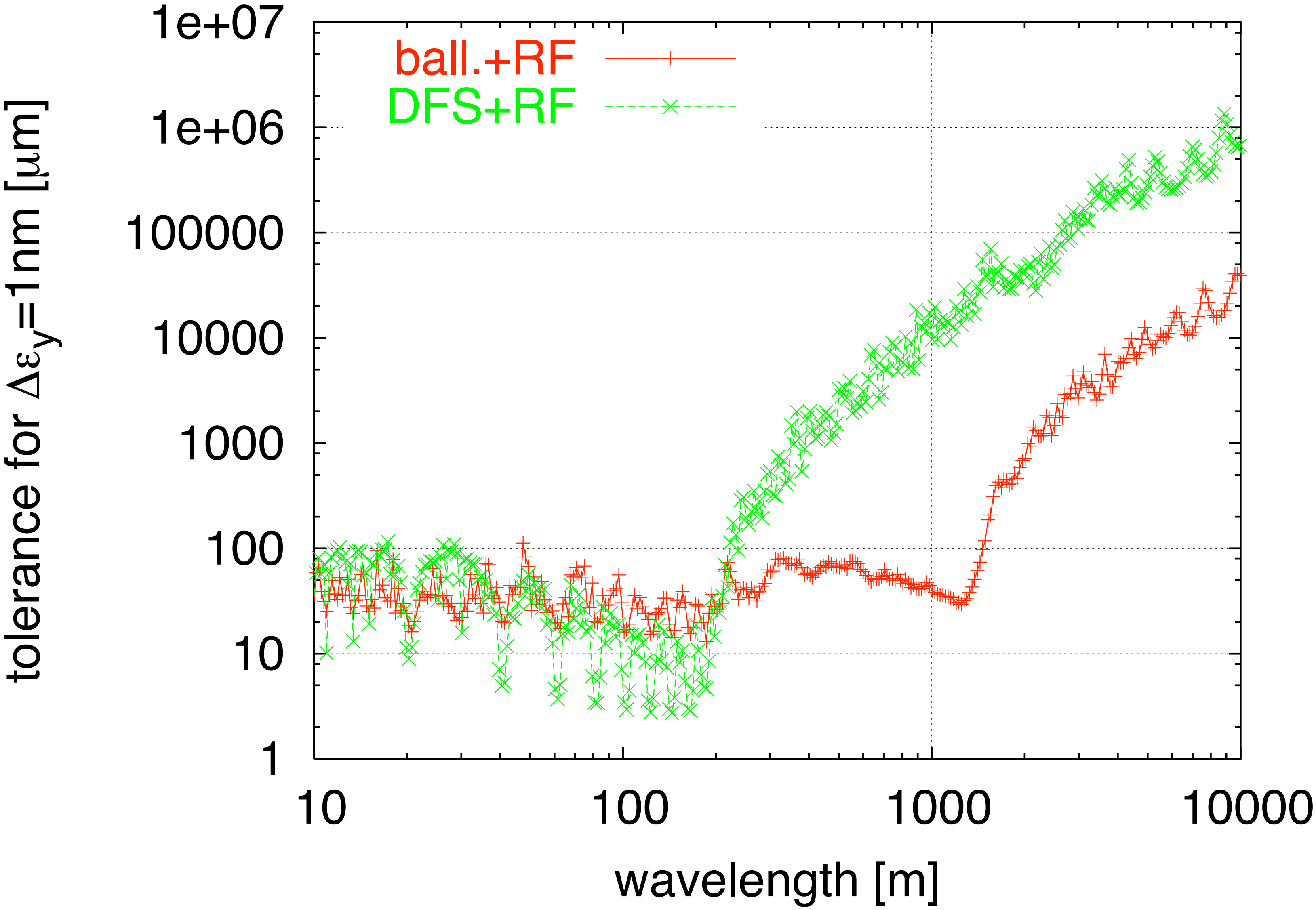
- Different implementations of DFS have different sensitivities to imperfections
  - selected a good method
  - trade-offs are possible



Long Distance Misalignments

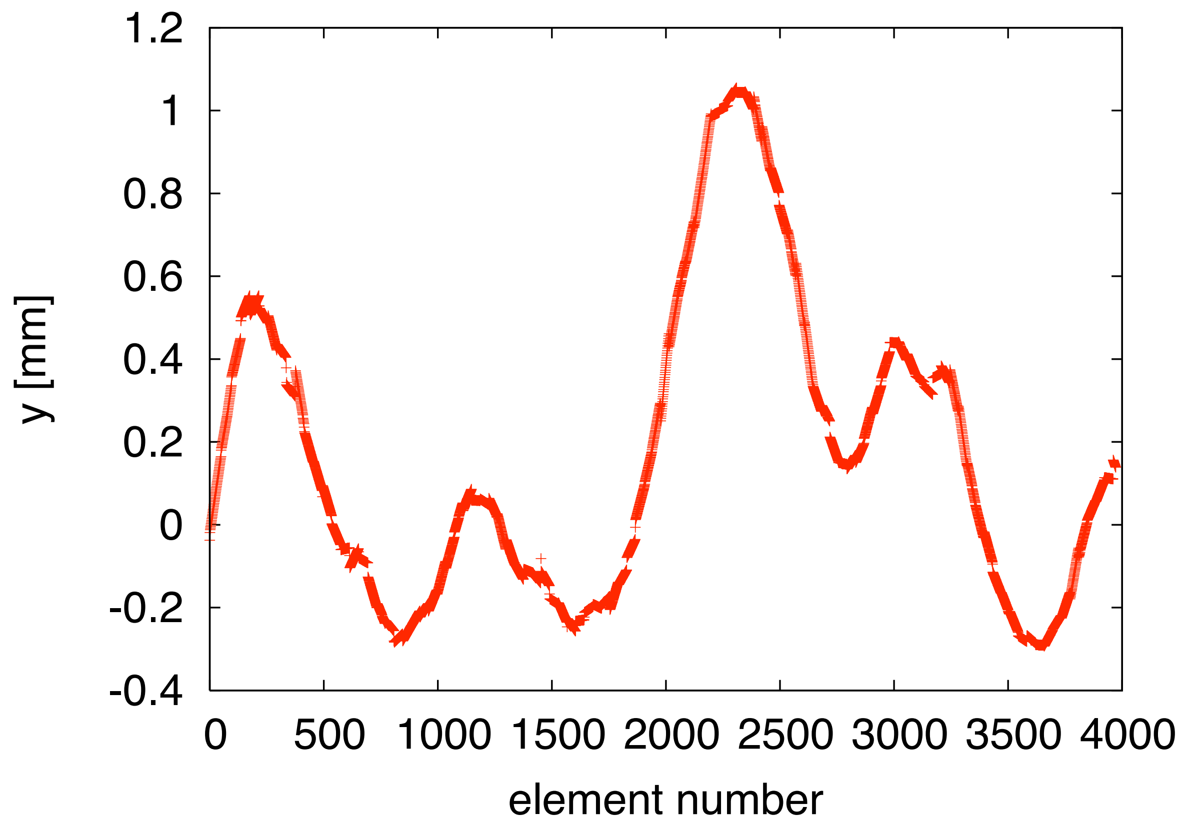


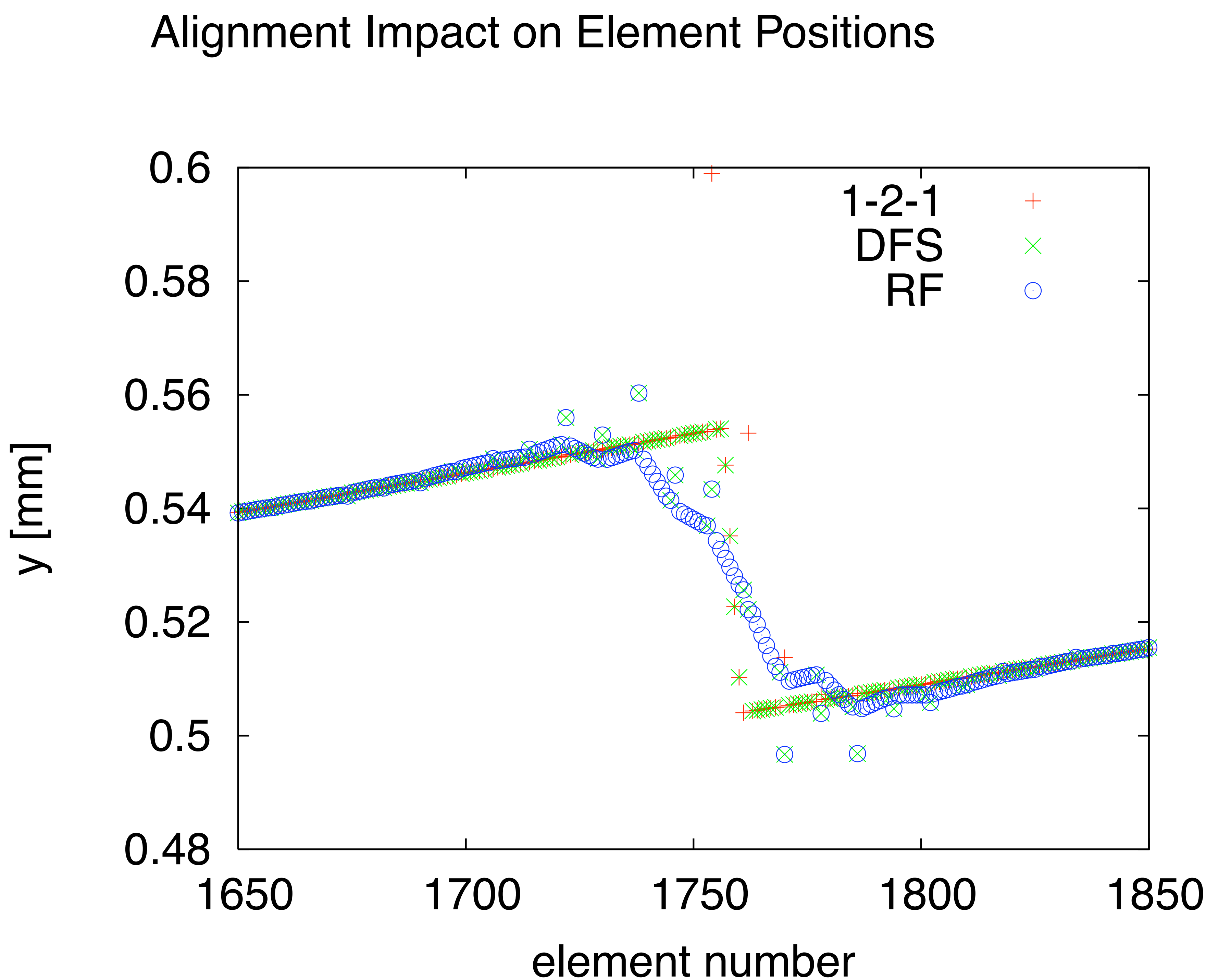
Different Beam-Based Alignment Procedures



Wire System Misalignment Modelling

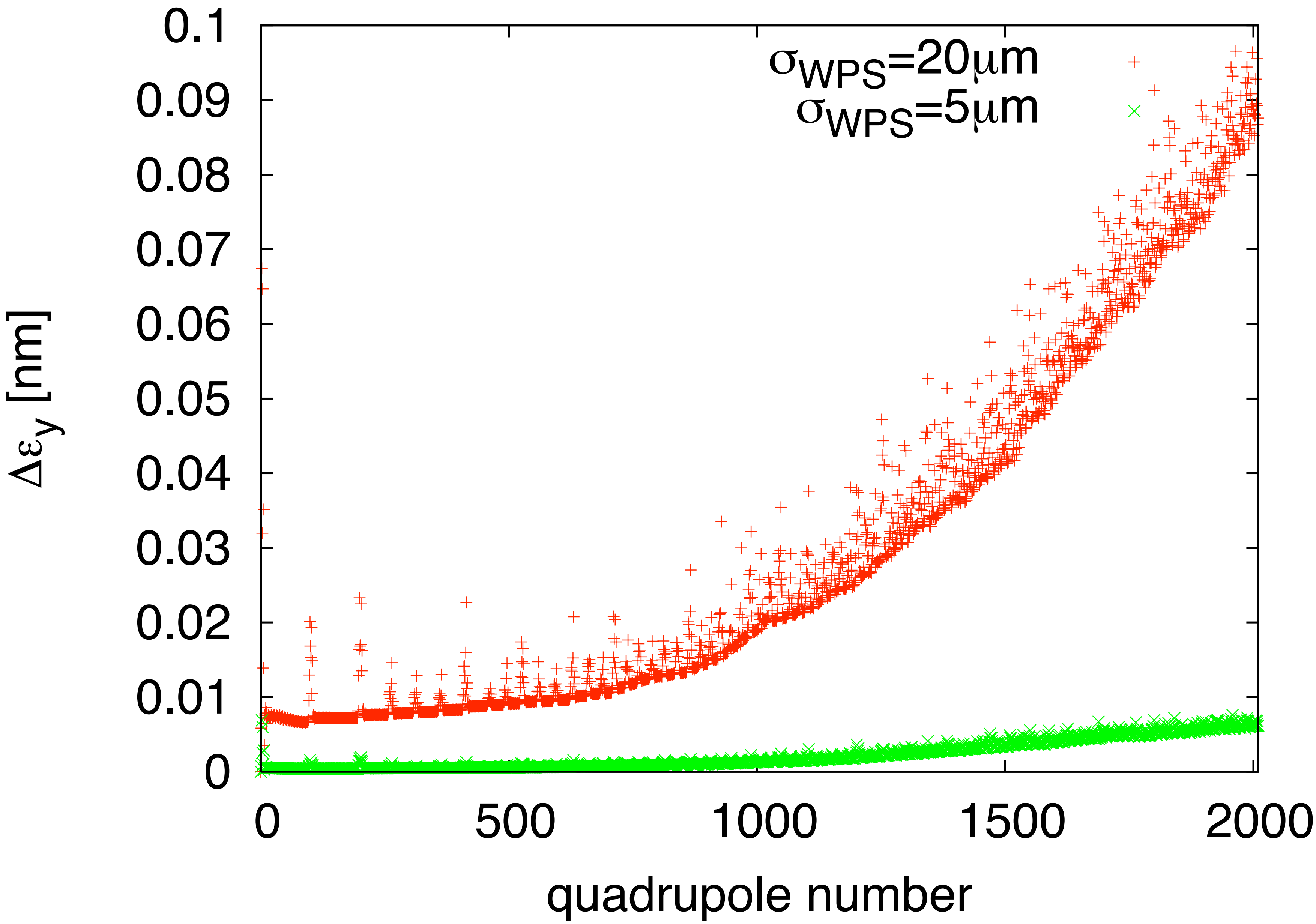
- Received a number of misalignments from Thomas Touzé
- Used 50 seeds for each error set
- Switched from one wire 1 to 2 at end point of 1 and back to 1 at end point of 2
- Used linear interpolation in between wire endpoints
  - no sag error
  - no error of geoid





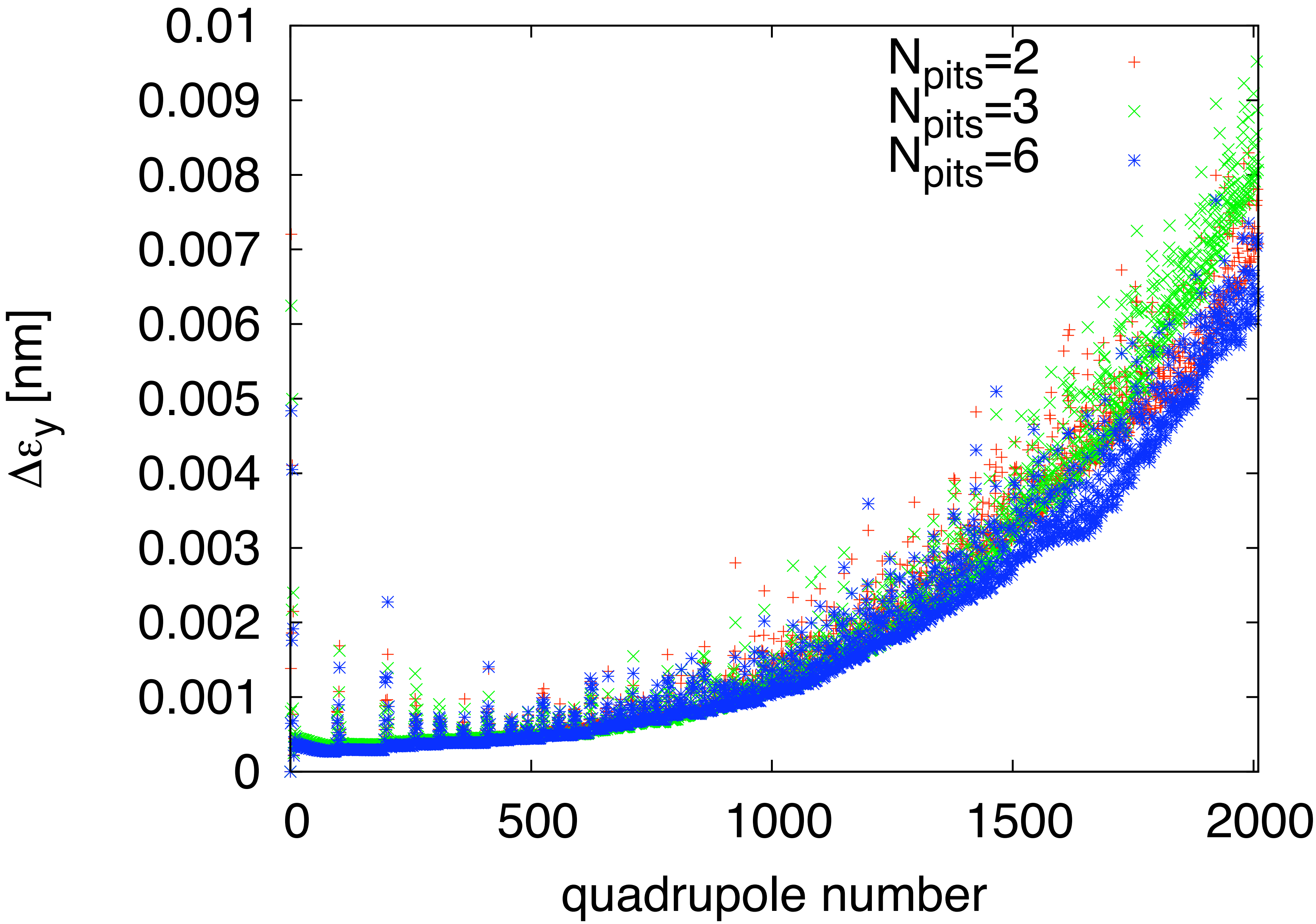
Alignment Impact on Element Positions
0.6
0.58
0.56
0.54
0.52
0.5
0.48
y [mm]
1-2-1
DFS
RF
1650
1700
1750
1800
1850
element number

Accuracy of Wire Position Sensors



⇒ Significant impact of wire position sensor accuracy

Number of Pits (RF Alignment)



⇒ Small impact of number of pits

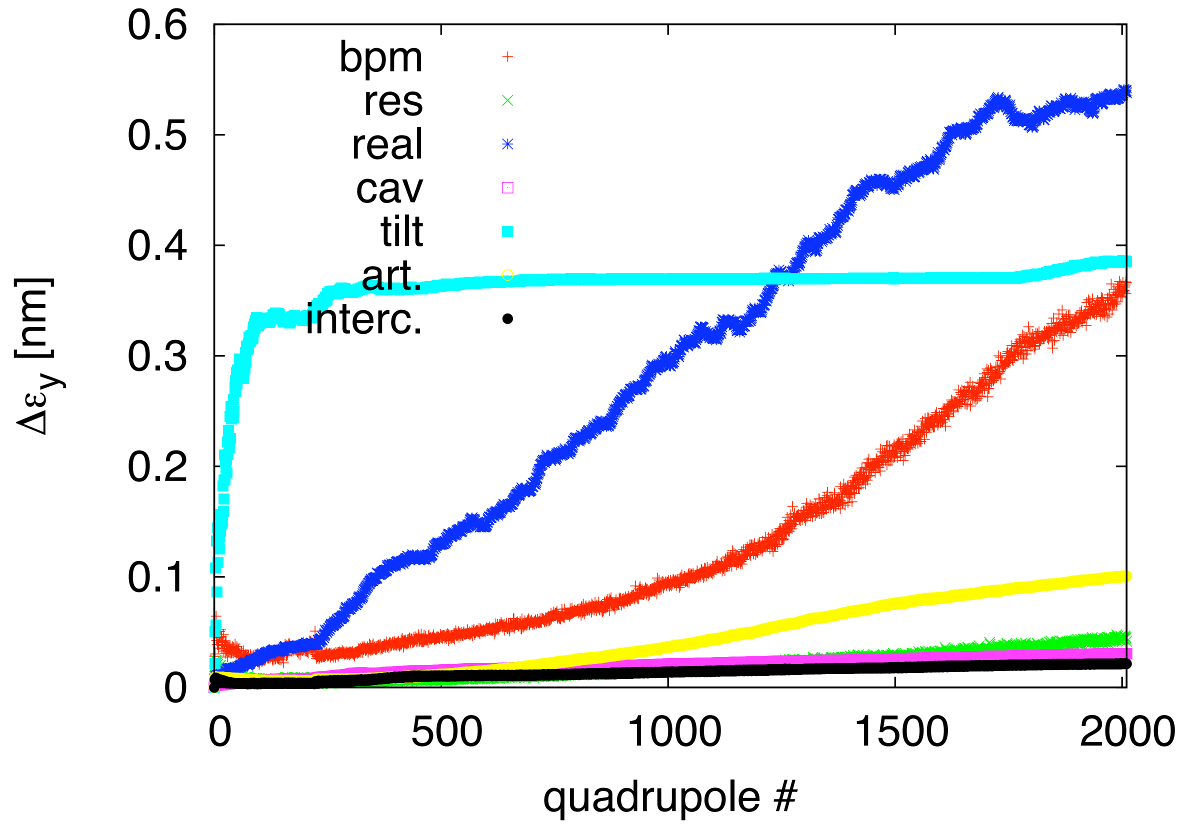
Conclusion

- Typical local alignment tolerances are of the order of $10\,\mu\mathrm{m}$
  - in particular BPM position
- The first results of wire reference system look very promising
  - wire sensor accuracy is important
  - pit number seems to be less important
  - wire length to be checked, may also impact pit number sensitivity
  - more complete beam dynamics studies to follow

Reserve

Growth Along Main Linac

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



Dependence on Weigths (Old Parameters)

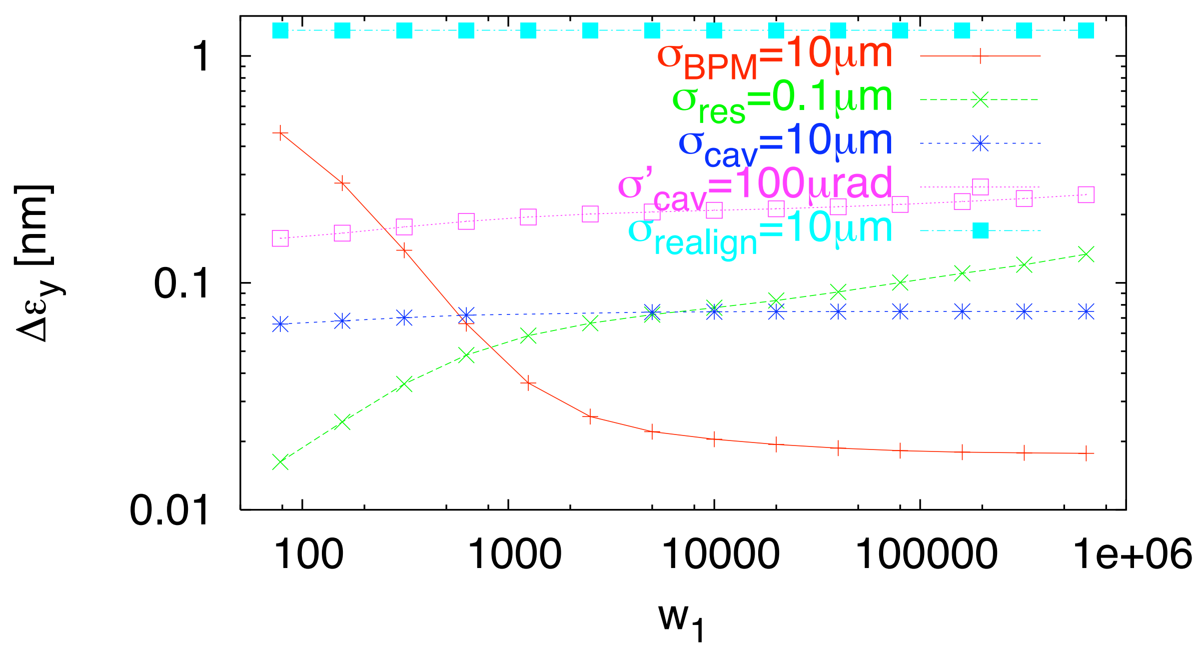
- For TRC parameters set
- One test beam is used with a different gradient and a different incoming beam energy

⇒ BPM position errors are less important at large w_1

⇒ BPM resolution is less important at small w_1

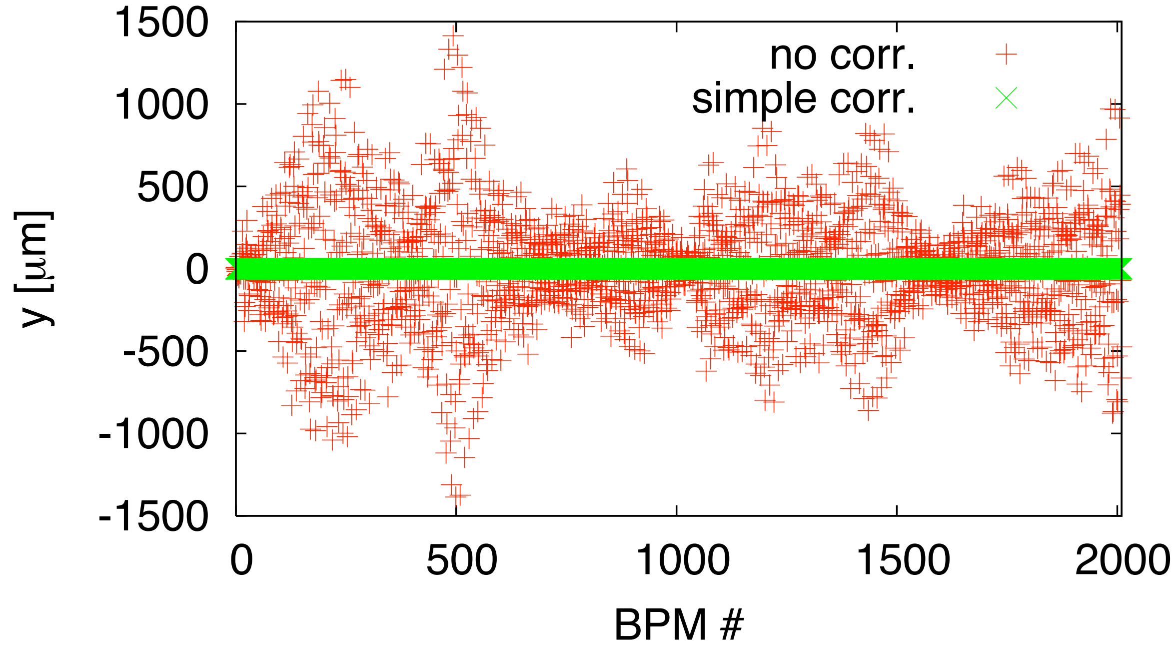
⇒ Need to find a compromise

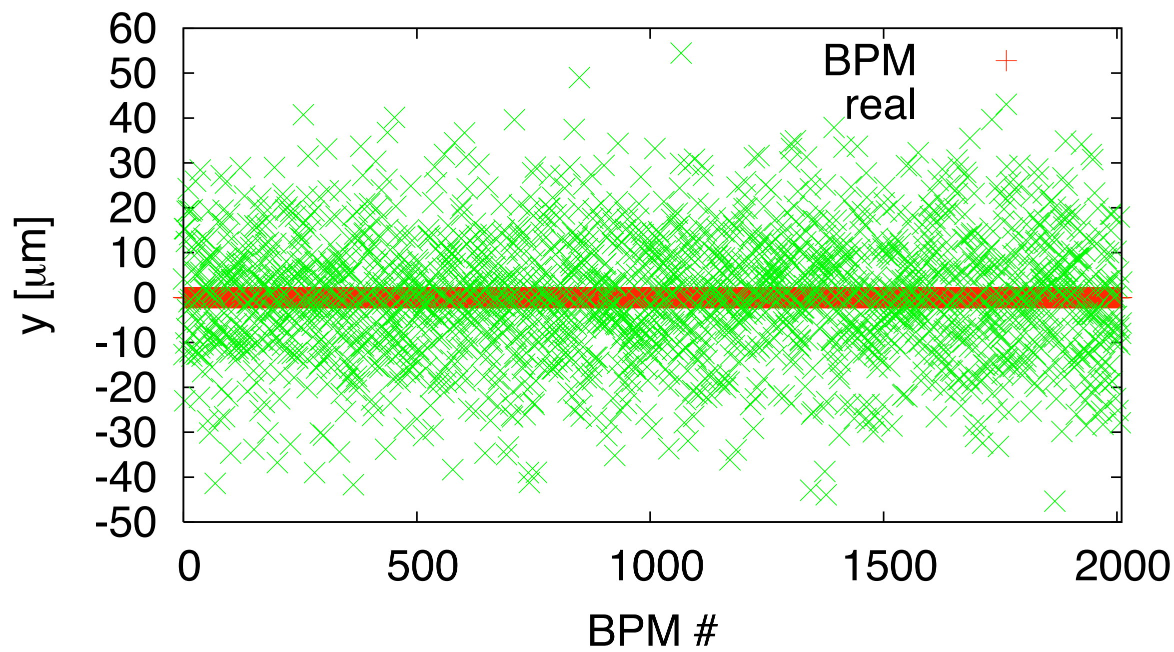
⇒ Cannot give “the” tolerance for one error source



One-To-One Correction

- 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





Assumed Survey Performance

Element	error	with respect to	alignment NLC	alignment 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

$\Rightarrow$ Better BPM alignment and resolution foreseen in CLIC

$\Rightarrow$ Smaller quadrupole roll than in NLC

$\Rightarrow$ Similar wakefield monitor performance

- Structure tilt is dominated by structure fabrication precision