CLIC Main Linac Beam Dynamics

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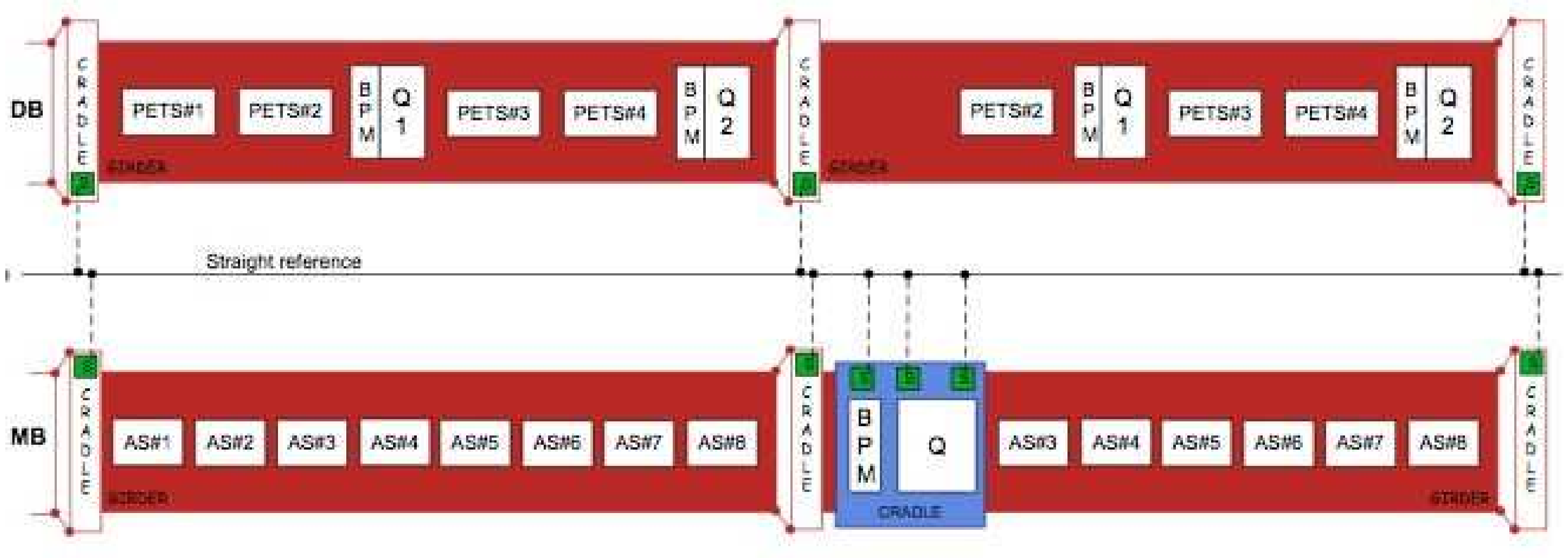
Main Beam Emittance Budgets and Luminosity

- For the vertical emittance a budget has been established
  - $\epsilon_y \leq 5\,\mathrm{nm}$ after damping ring extraction
  - $\Delta\epsilon_y \leq 5\,\mathrm{nm}$ during transport to main linac
  - $\Delta\epsilon_y \leq 10\,\mathrm{nm}$ in main linac
- For the horizontal emittance the old design gave
  - $\epsilon_x = 500\,\mathrm{nm}$ after damping ring extraction
  - $\epsilon_x = 600\,\mathrm{nm}$ before main linac
  - $\epsilon_x = 660\,\mathrm{nm}$ before the beam delivery system with the growth mainly in the RTML
- The emittance budget
  - includes design, static and dynamic effects
  - requires 90% of the machines to perform better than the target
- For the main linac one requires
  - for static imperfections $\Delta\epsilon_y \leq 5\,\mathrm{nm}$ for 90% of the machines
  - for dynamic imperfections $\Delta\epsilon_y \leq 5\,\mathrm{nm}$ on average
    - short and long-term effects

Module Layout



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

Lattice Design Considerations

- Linac lattice is a trade-off

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

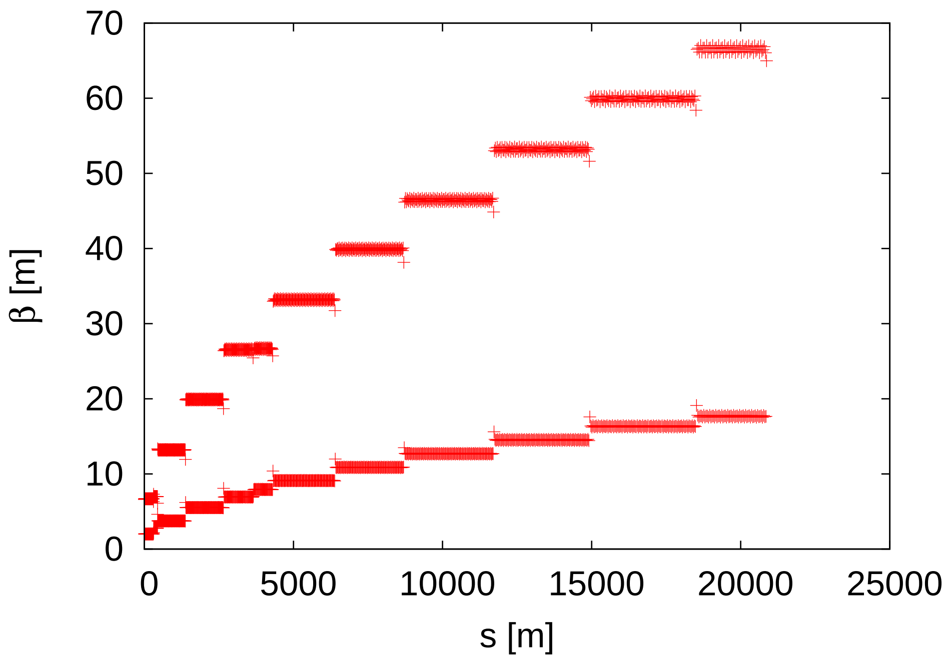
- weak focusing
  - high sensitivity to wakefields
  - dispersive effects smaller
- small correlated energy spread
  - beam is less stable
  - dispersive effects are reduced

- First need to consider beam stability

  $\Rightarrow$ look at allowed energy spread

Lattice Design

- Used $\beta \propto \sqrt{E}$, $\Delta\Phi = \text{const}$
  - 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 about 21km
  - fill factor more than 78%

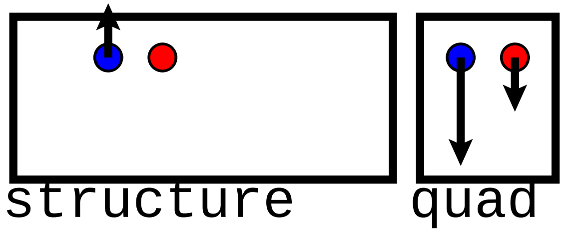


- 12 different sectors used
- Matching between sectors using 7 quadrupoles to allow for some energy bandwidth

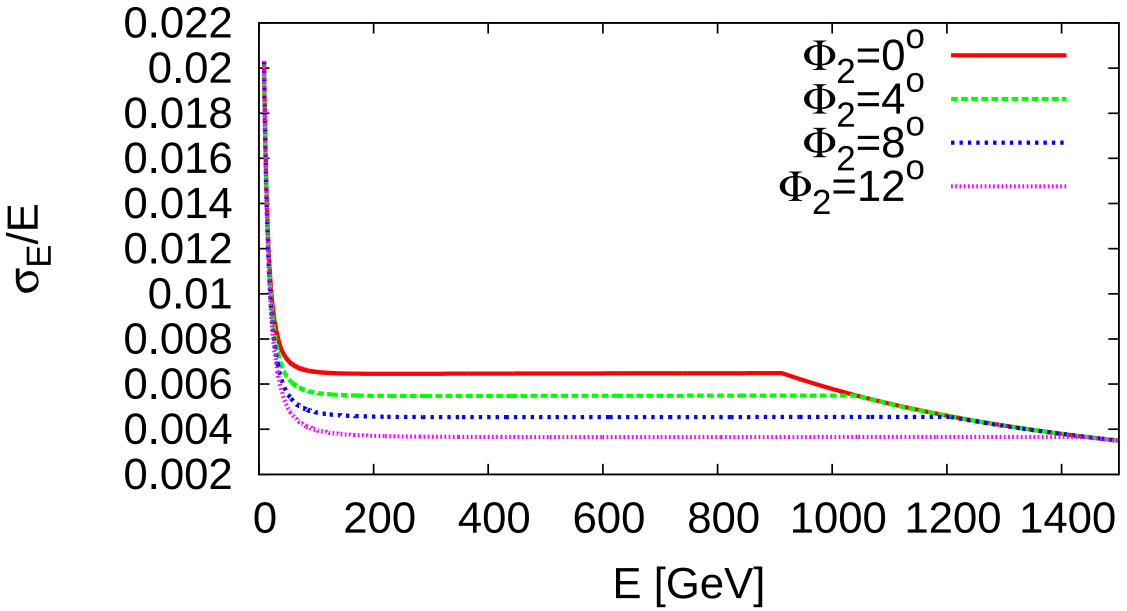
Energy Spread and Beam Stability

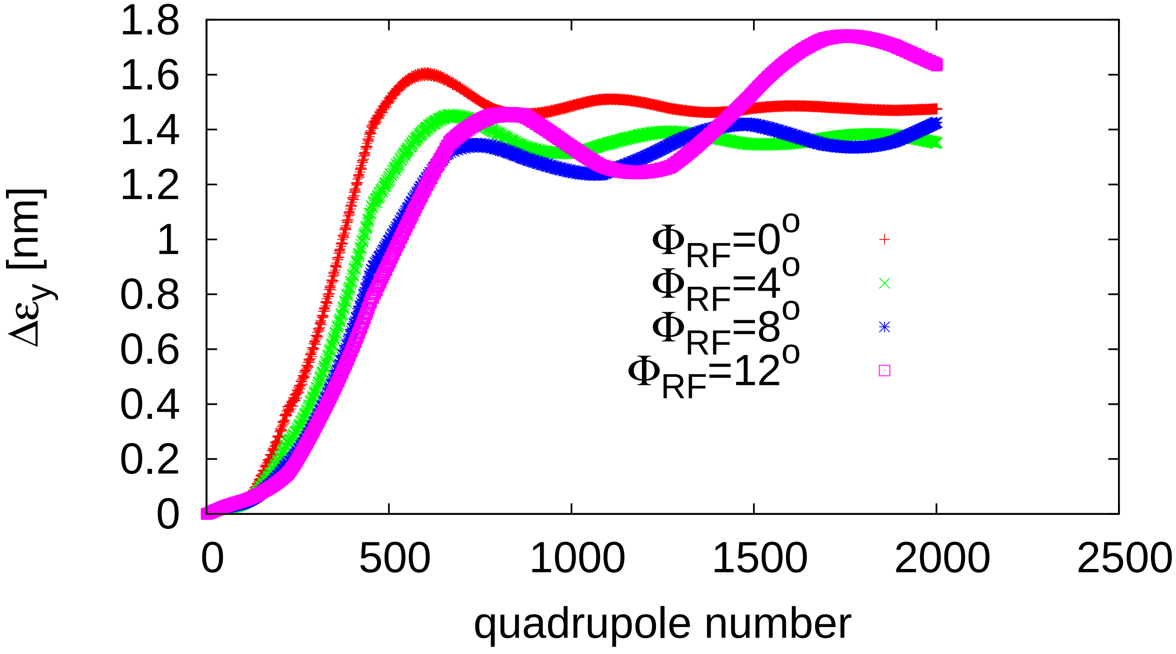
- Trade-off in fixed lattice
  - large energy spread is more stable
  - small energy spread is better for alignment

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



- Some reserve for single bunch wakefields



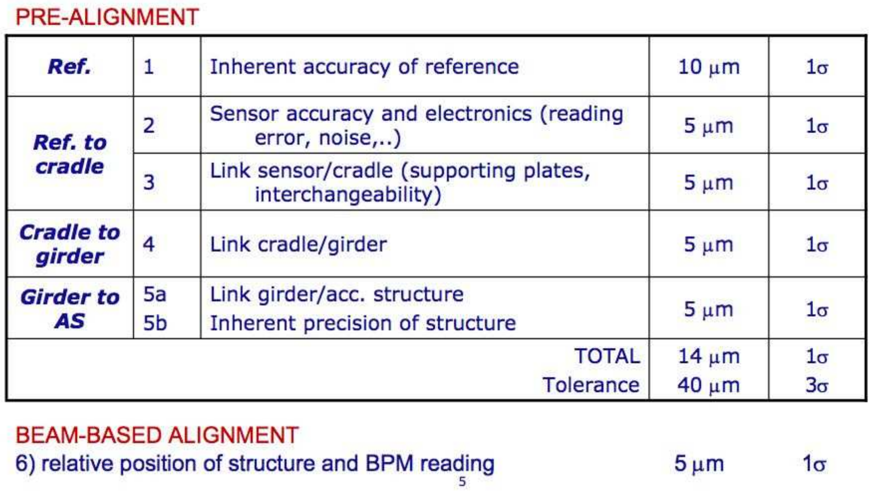


Indicative Static Main Linac Tolerances

Element	error	with respect to	tolerance	
			CLIC	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 simple one-to-one steering
  - note: assume quadrupoles are moved for correction
- CLIC emittance budget is two times smaller than for NLC
- Tighter tolerances for BPM due to stronger focusing in CLIC
  - but therefore more relaxed tolerances for structures

Assumed Pre-Alignment Performance



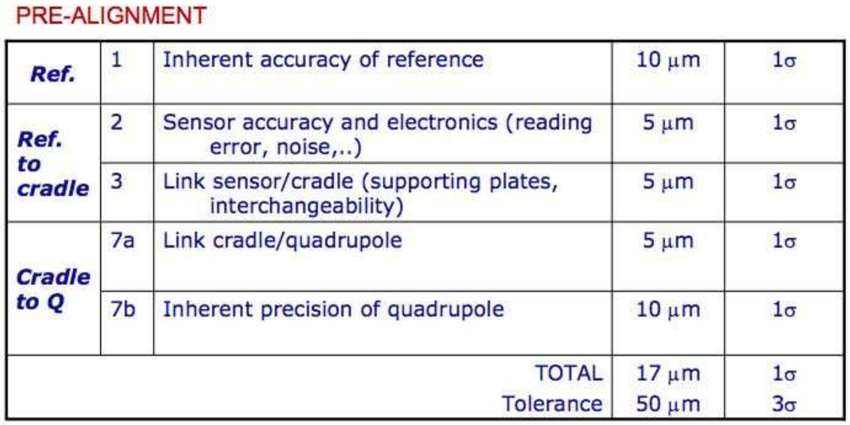
PRE-ALIGNMENT

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	14 μm	1σ
		Tolerance	40 μm	3σ

BEAM-BASED ALIGNMENT

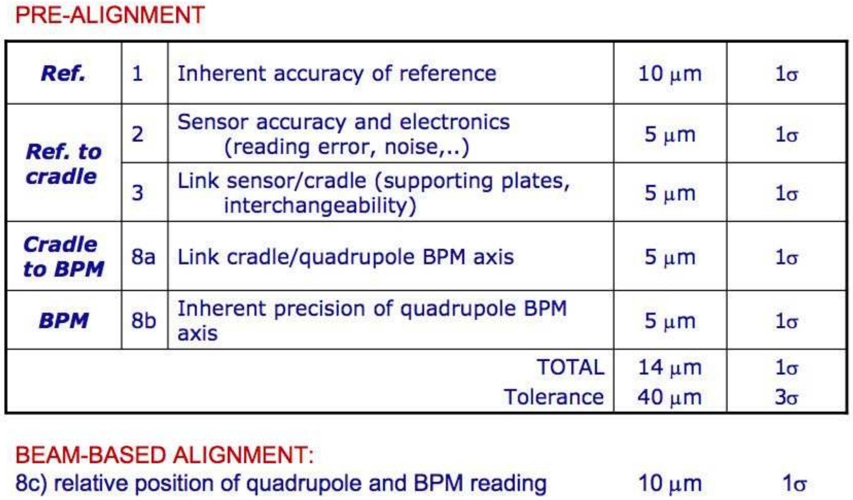
6) relative position of structure and BPM reading 5 μm 1σ

H. Mainaud Durand



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



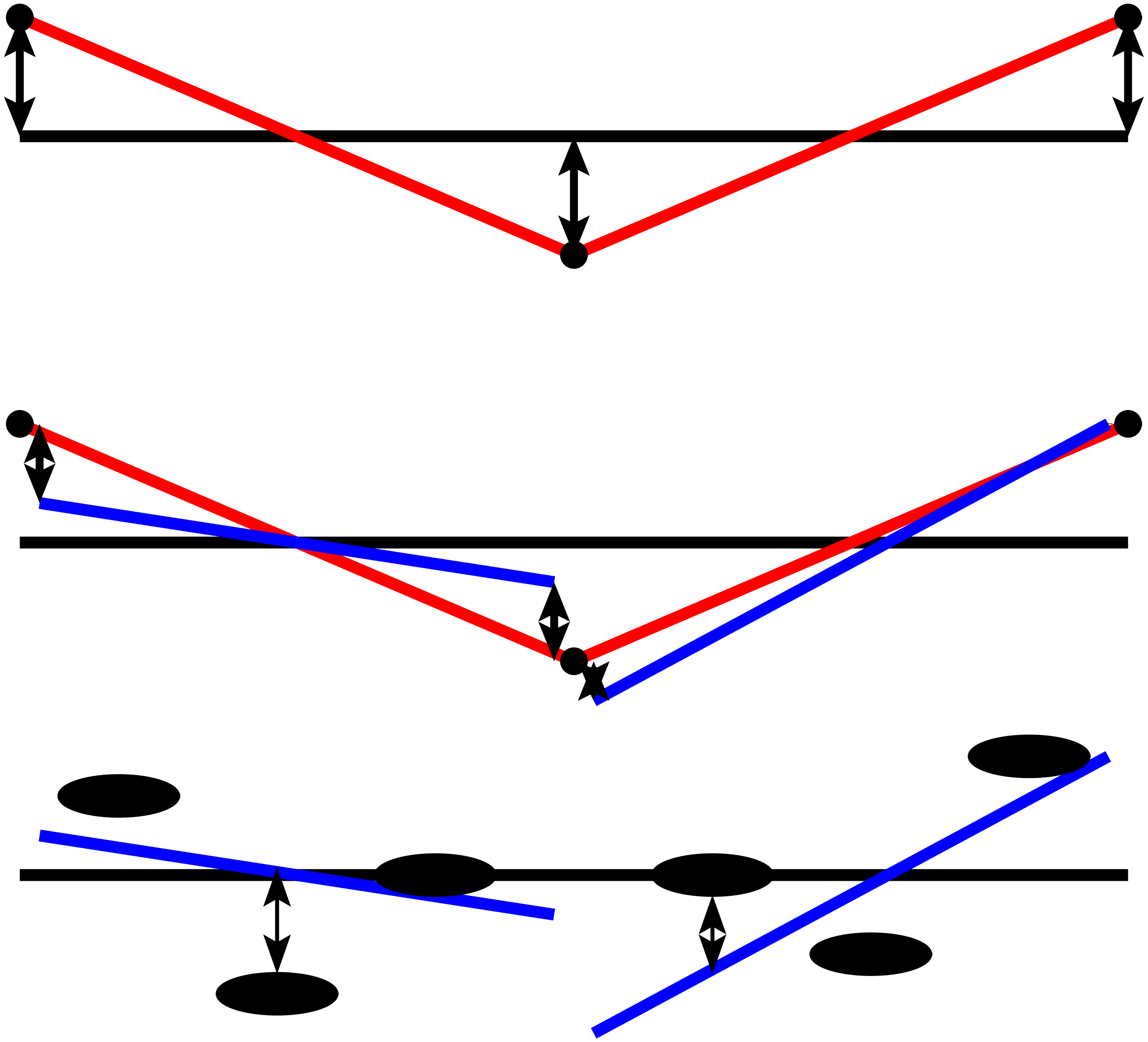
PRE-ALIGNMENT

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

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	$0.1(0.05)\,\mu$m
Wakefield mon.	offset	wake center	$5\,\mu$m	$5\,\mu$m

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

⇒ Better alignment and BPM resolution foreseen in CLIC ($0.1\,\mu$m for alignment)

⇒ Similar wakefield monitor performance

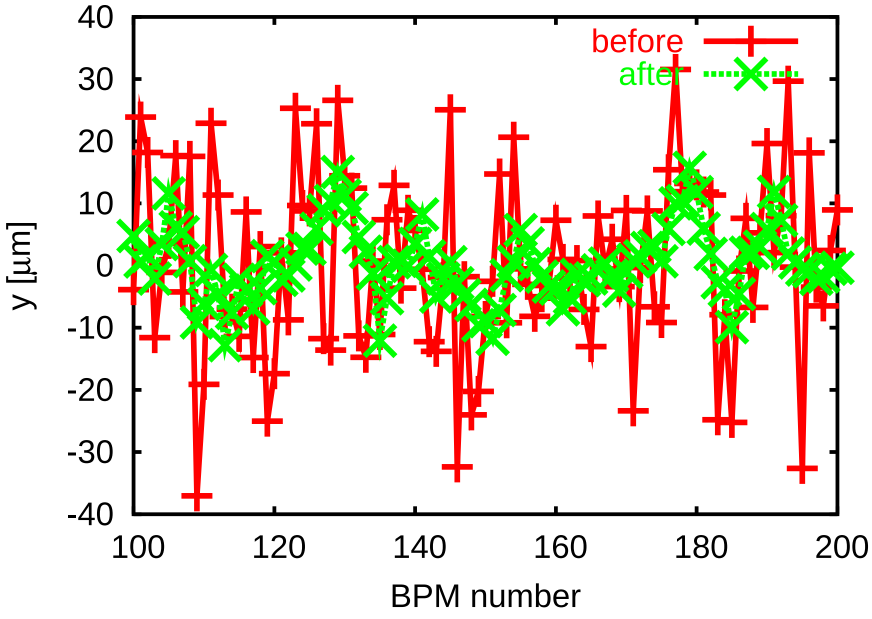
- Structure tilt is dominated by shift of quadrants effective tilt is given by shift as $\theta \approx \Delta z/(2a)$

  in our case $\Delta z = 1\,\mu$m corresponds to $\theta \approx 180\,\mu$radian

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
  - energies done by manipulation of bunch compressor

    demonstrated by A. Latina and P. Eliasson

  $\Rightarrow$ probe beam bunch length $\approx 70\,\mu\mathrm{m}$
- 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

- For stability want to use two parts of one pulse

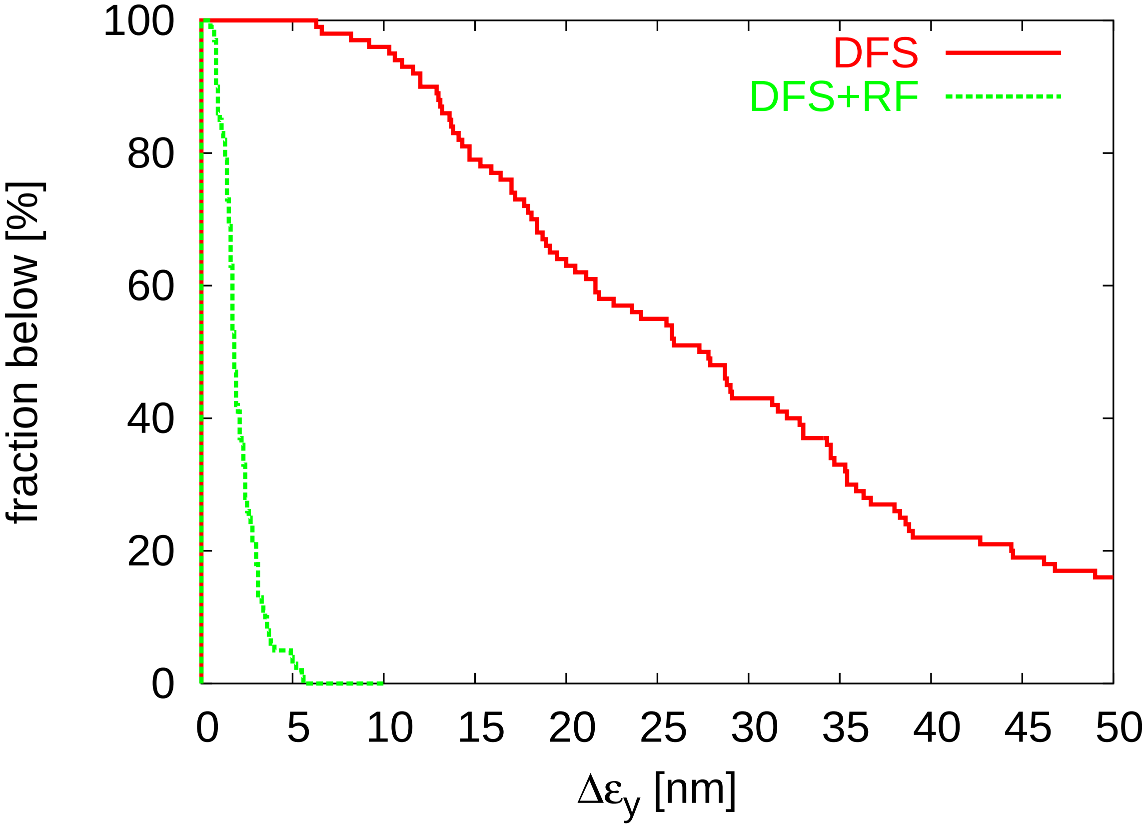
Impact of Structure Alignment

- Slightly older parameters for illustration

⇒ Average emittance growth is still quite large

- Aligning the accelerating structures with RMS accuracy of $5\,\mu\mathrm{m}$ to the beam drastically improves the performance

⇒ Need to move girders



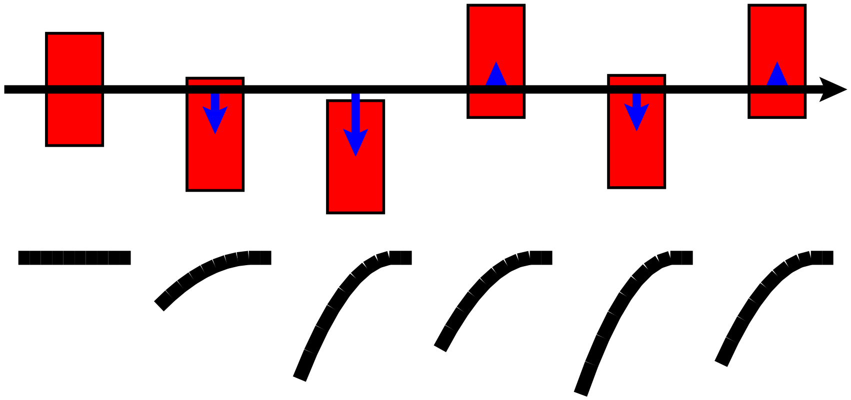
Beam-Based Structure Alignment

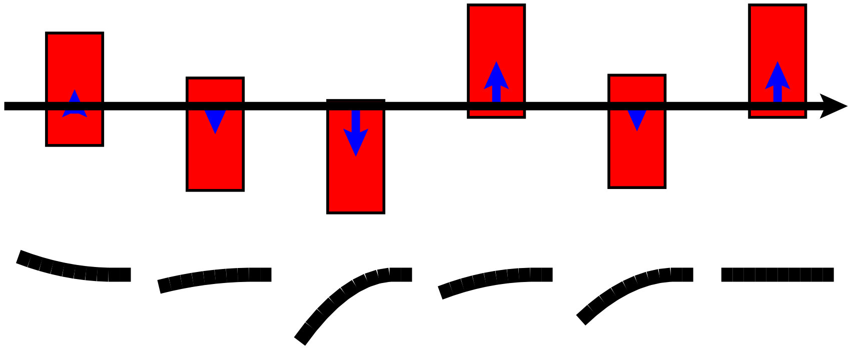
- Each structure is equipped with a wakefield monitor (RMS position error $5\,\mu\mathrm{m}$)
- Up to eight structures on one movable girders

⇒ 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

  ⇒ negligible additional effect if additional articulation point exists at quadrupoles



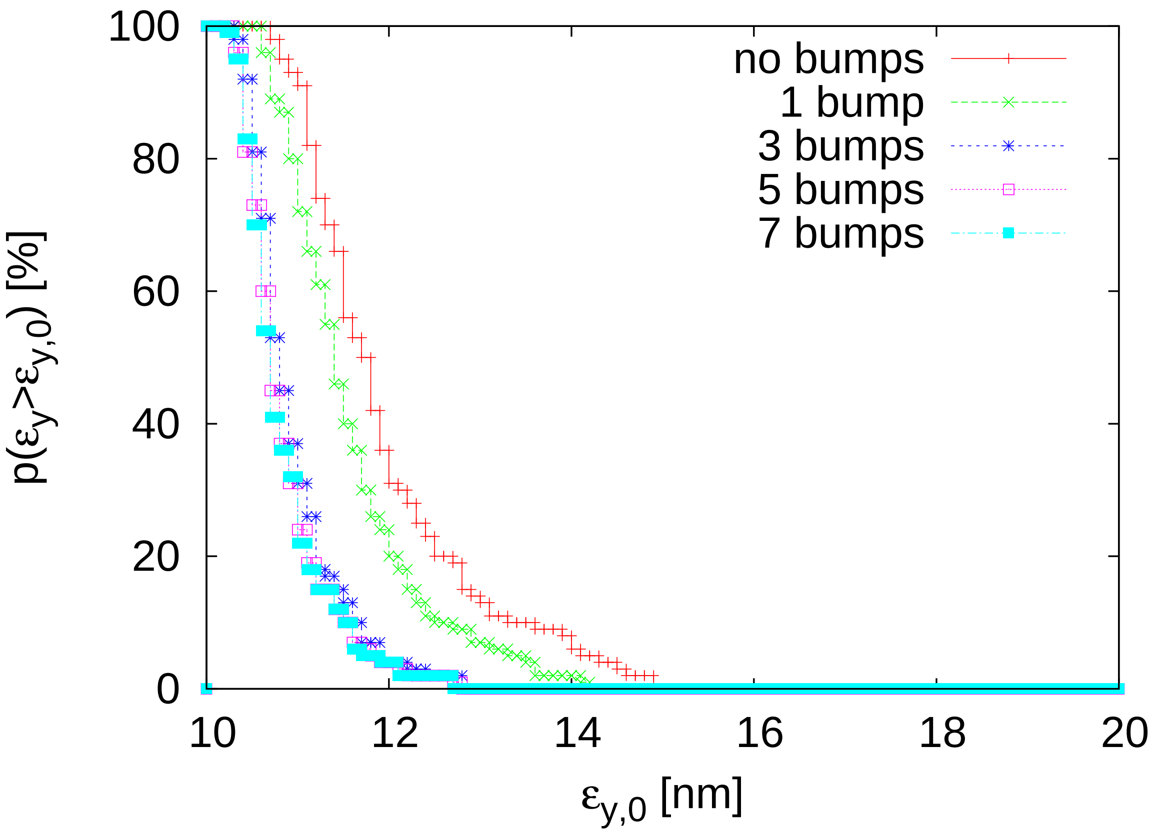


- For our tolerance $\sigma_{wm} = 5\,\mu\mathrm{m}$ we find $\Delta\epsilon_y \approx 0.5\,\mathrm{nm}$
  - some dependence on alignment method

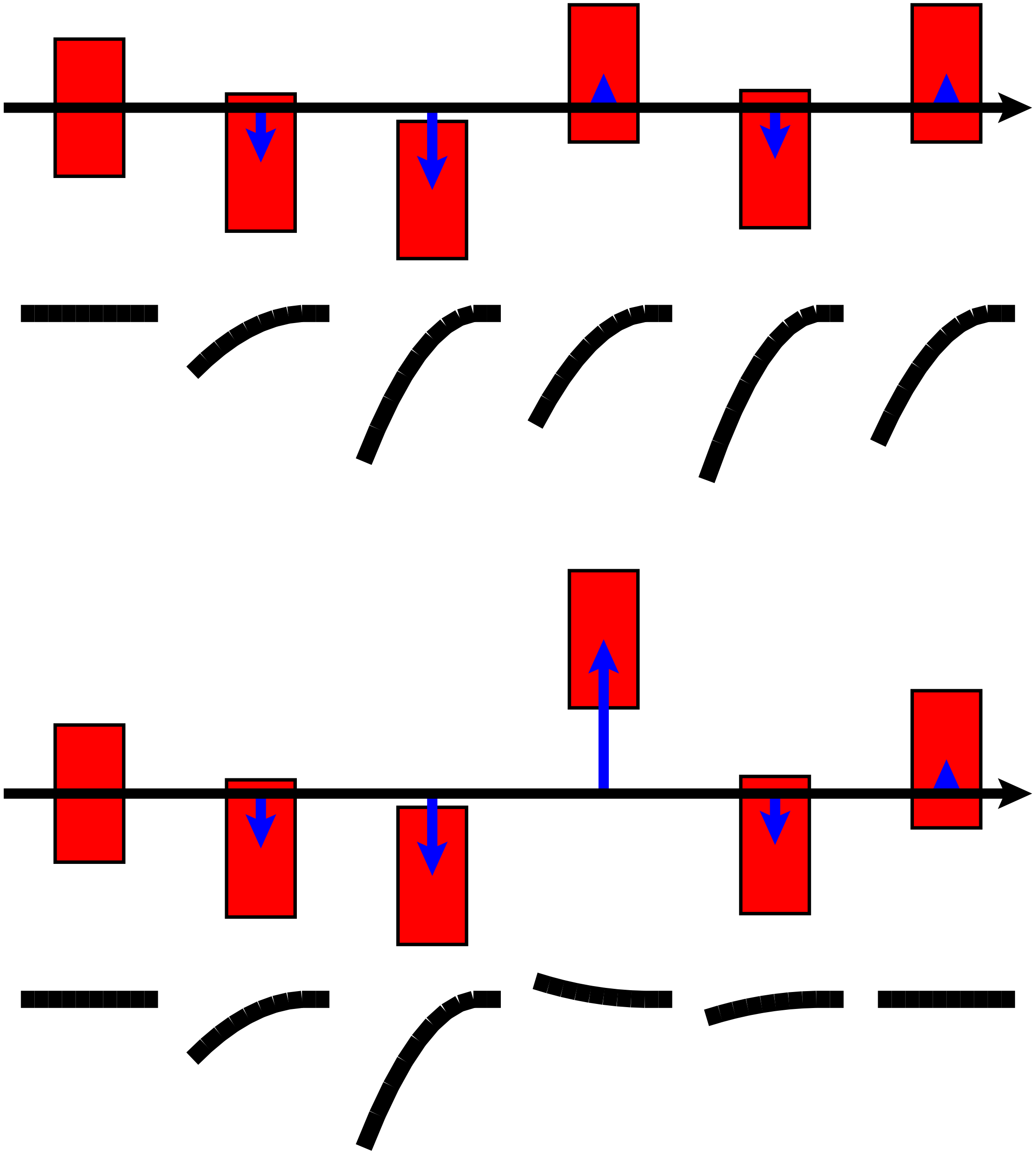
Final Emittance Growth

- Different implementations of DFS have different sensitivities to imperfections
  - values for examples (M1–M4) in nm
  - based on PLACET simulations
  - simplified model for varying bunch compressor
- Case M2 shown in figure

	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



Emittance Tuning Bumps



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

Luminosity Simulator

- Conventionally use laser wire that is smaller than the beam size
  - scan beam
  - fit relevant size
- Proposed use of luminosity simulator
  - laser wire can have roughly Gaussian transverse profile
  - collide beam with laser beam that has transverse dimension corresponding roughly to the target beam size
  - optimise beam-photon luminosity
- P. Eliasson has demonstrated this with simulations
  - using two wires at 90° phase advance
  - 3% RMS luminosity error per measurement
  - incorrect laser spot size does not compromise performance strongly
  - need to steer beam with BPM
  - need to optimise beam position in the BPM once in a while
- Further studies to optimise the design

Structure-To-Girder Tolerance

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

  $\Rightarrow$ 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

  $\Rightarrow$ 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
    $\Rightarrow$ found to give little effect
  - non-identical wakefields or identical wakefields not aligned with single bunch wakes
    $\Rightarrow$ can give an effect