CLIC Beam Dynamics, Alignment, Stability and Luminosity

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Luminosity

- The luminosity is given by

$$\mathcal{L} = H_D \frac{N^2 f_{rep} n_b}{4\pi\sigma_x\sigma_y}$$

$$\mathcal{L} \propto H_D \frac{N}{\sqrt{\beta_x\epsilon_x}\sqrt{\beta_y\epsilon_y}} \eta P$$

- Efficiency η depends on beam current that can be transported

  $\Rightarrow$ decrease bunch distance $\Rightarrow$ long-range transverse wakefields in main linac

  $\Rightarrow$ increase bunch charge $\Rightarrow$ short-range transverse and longitudinal wakefields in main linac, other effects

- Horizontal beam size σ_x
  beam-beam effects, final focus system, damping ring, bunch compressors

- Vertical beam size σ_y
  need to collide beams, beam delivery system, main linac, beam-beam effects, damping ring, bunch compressor

- Will go from IP to damping ring

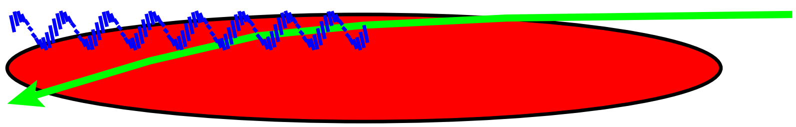
  $\Rightarrow$ logical order

Beam Size Limit at IP

- The vertical beam size had been $\sigma_y \approx 1\,\mathrm{nm}$ (BDS)

  $\Rightarrow$ challenging, cannot be reduced much

- Fundamental limit on horizontal beam size arises from beamstrahlung

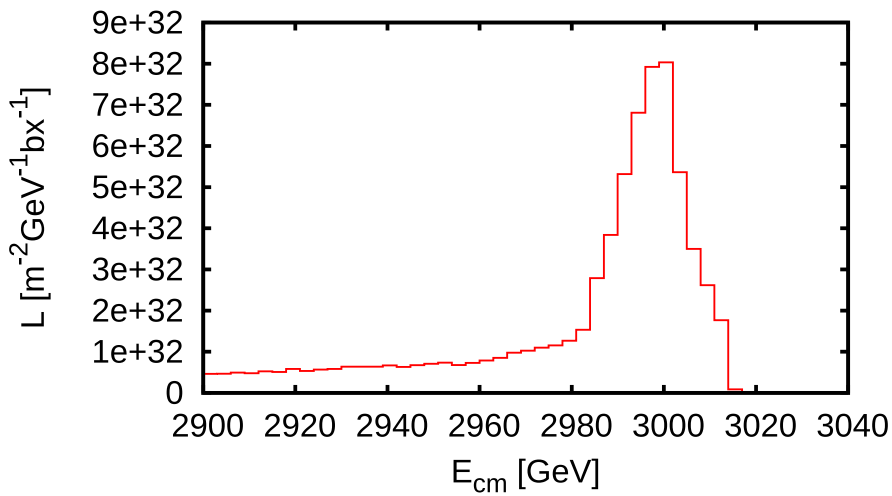


Photon emission grows with beam-strahlung parameter

$$\Upsilon = \frac{2}{3}\frac{\hbar\omega_c}{E_0} \propto \frac{N\gamma}{(\sigma_x + \sigma_y)\sigma_z}$$

$\Rightarrow$ Lower limit for σ_x

- In addition, horizontal emittance and beam delivery system make it difficult to achieve small σ_x

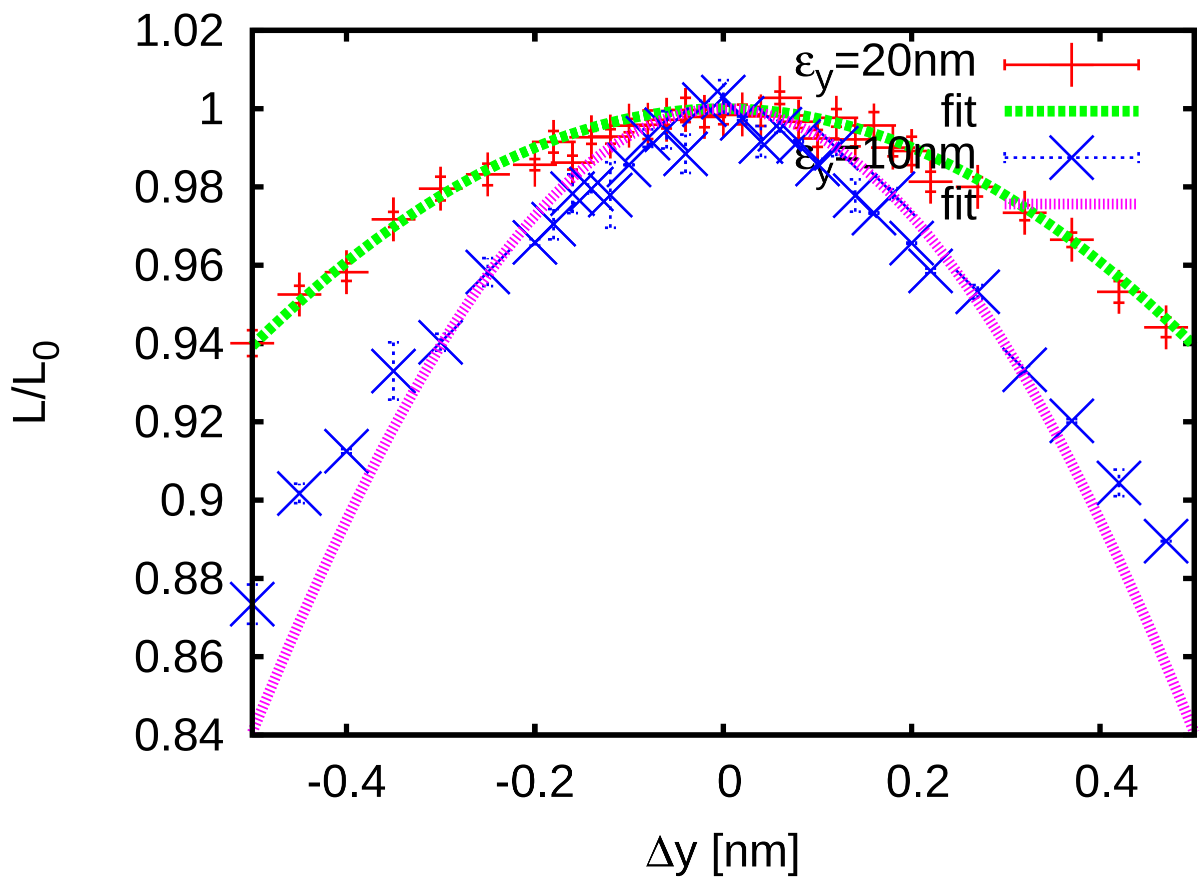


$\Rightarrow$ Relevant is luminosity in the peak

Beam-Beam Jitter Tolerance

- $0.2\,\mathrm{nm}$ beam-beam vertical position jitter leads to 1.0% luminosity loss
- Inclusion of beam-beam effects finds almost the same values
  - 0.28 nm yields about 2%

  $\Rightarrow$ tolerance on beam-beam jitter is $\approx 0.28\,\mathrm{nm}$



- Limit value for enhancement of coherent beam jitter is

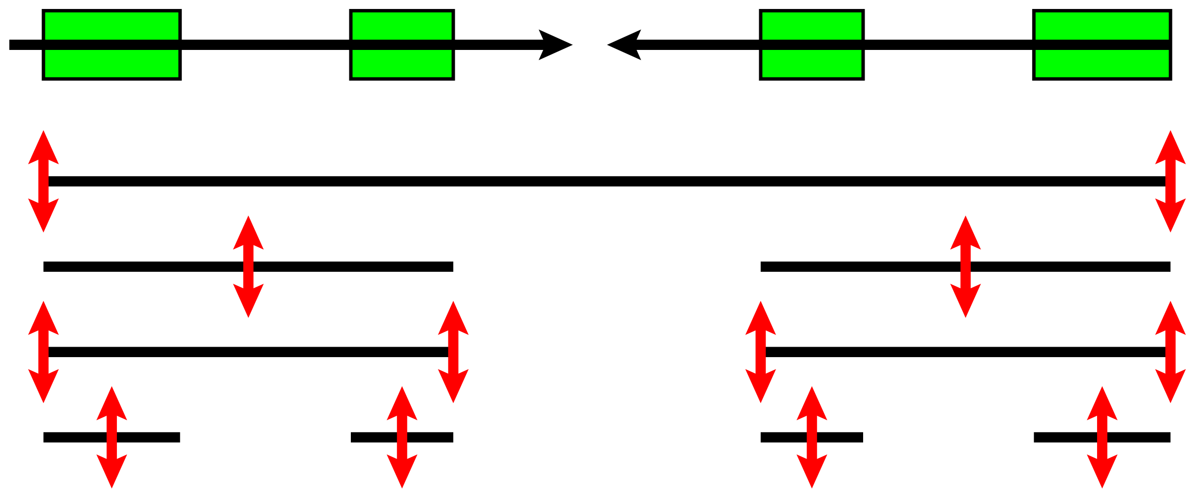
$$\Delta y = \frac{\Delta y_0}{1 - n_c \frac{4Nr_e}{\gamma\theta_c^2} \frac{\delta y'}{\delta \Delta y_0}}$$

- $\Delta y = 1.09 \Delta y_0$

Final Doublet Jitter

- Final doublet jitter is most relevant source for beam jitter at IP
- One support structure
  - relative tolerance on end points $\approx$ 4–$5\sigma_{beam-beam}$
- Two support structures
  - relative tolerance of mid points $\approx 0.7\sigma_{beam-beam}$
  - relative tolerance of end points $\approx 0.64\sigma_{beam-beam}$
- Four support structures
  - relative tolerance of mid points $\approx 0.5\sigma_{beam-beam}$

$\Rightarrow$ Only one support seems excluded



$\Rightarrow$ Chose two or four supports

- four is conservative ($\Rightarrow 0.14\,\mathrm{nm}$)
- two needs additional tolerance of motion on support ($\Rightarrow 0.18\,\mathrm{nm}$)

Main Linac Wakefield Effects

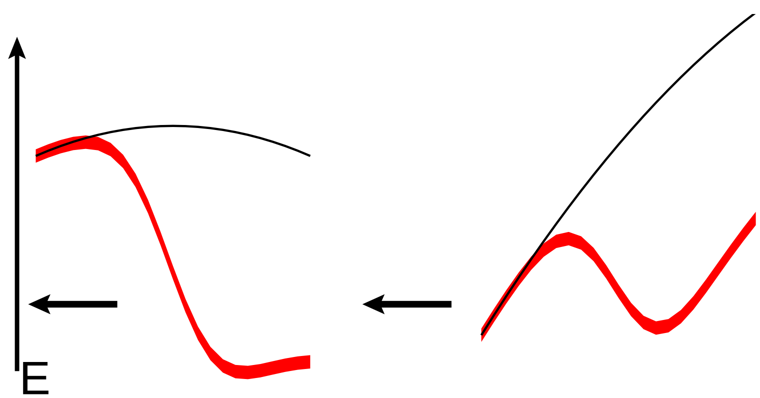
- Emittance growth scales as

$$\Delta\epsilon_y \propto (W_\perp \sigma_z)^2 (\Delta y)^2 L_{typical} 1/G$$

  $\Rightarrow$ aim for shortest possible bunch

- 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

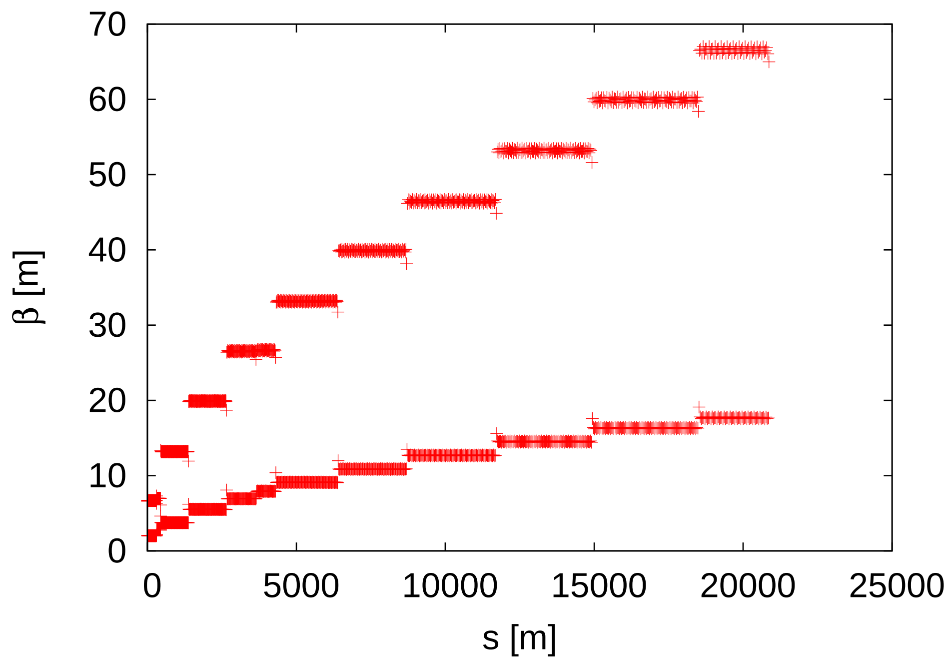


- Limit around average $\Delta\Phi \leq 12^\circ$

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

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 $N = 5.2 \times 10^9$
  - 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

Single Bunch Dynamic Tolerances

- For jitters we assumed no correction

  $\Rightarrow$ 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: $0.55\,\mu\mathrm{radian}$

$\Rightarrow$ Tolerances are very tight

  - in particular for quadrupole

- ATL-model 1.2 nm for $10^5\,\mathrm{s}$ with $A = 0.5 \times 10^{-6}\,\mu\mathrm{m}^2\mathrm{s}^{-1}\mathrm{m}^{-1}$ using one-to-one steering

  $\Rightarrow$ tuning bumps are needed

  - for three bumps $0.45\,\mathrm{nm}$, for seven $0.25\,\mathrm{nm}$

  $\Rightarrow$ realignment every few days

Static Error Sources

- Most important are
  - BPM position errors
  - BPM resolution
  - structure to beam offset
  - structure to beam angle
  - quadrupole roll
- 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

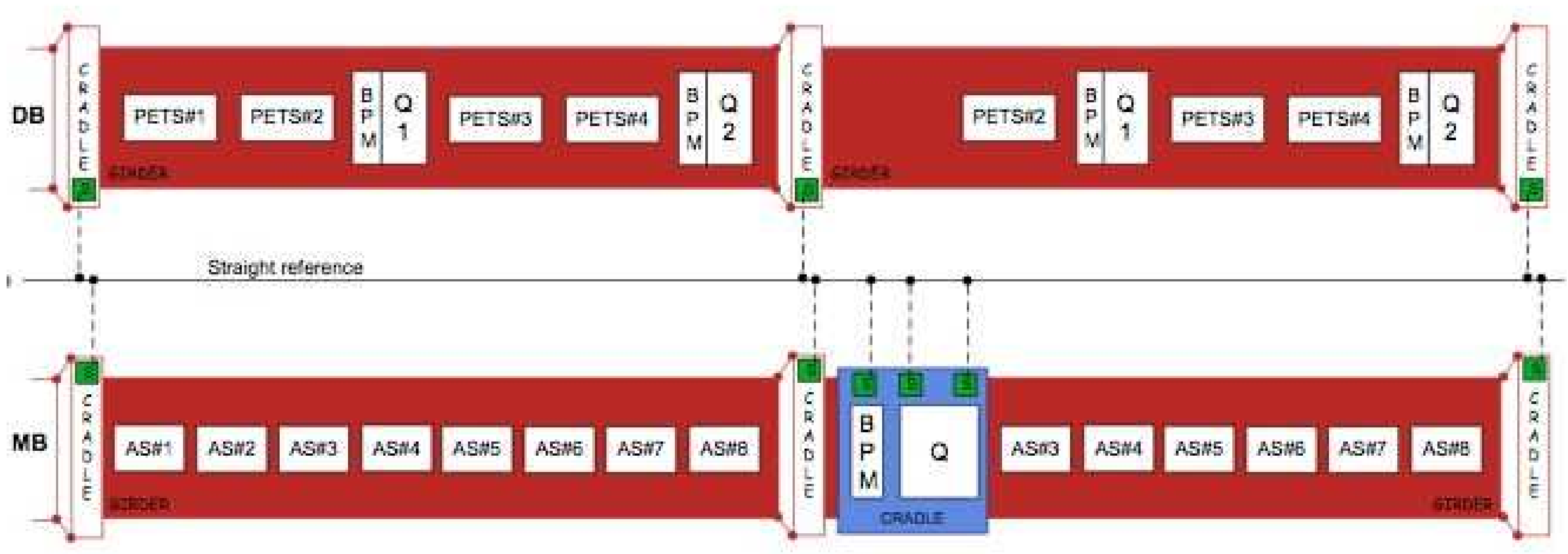
    could matter for long-range wakefields

Main Linac Sensitivities

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	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 sensitivities for 1nm growth after one-to-one steering
- Using DFS relaxes BPM position but constrains BPM resolution (example case 57 μm and 0.18 μm)
- Bumps help
- A bookshelfing of $1\ \mu$m corresponds roughly to an angle error of $170\ \mu$radian

Misalignment Model: Module



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

(G. Riddone, module working group)

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 Tolerance	14 μm 40 μm	1σ 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 Tolerance	17 μm 50 μm	1σ 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 Tolerance	14 μm 40 μm	1σ 3σ

BEAM-BASED ALIGNMENT:

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

Summary of Assumed Alignment 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	RF structures
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
Structure BPM	offset	wake center	$5\ \mu$m	$5\ \mu$m

- Tolerances depend on the beam based alignment method
  - e.g. can trade-off BPM resolution against BPM alignment
- Budgets need a trade-off between different effects

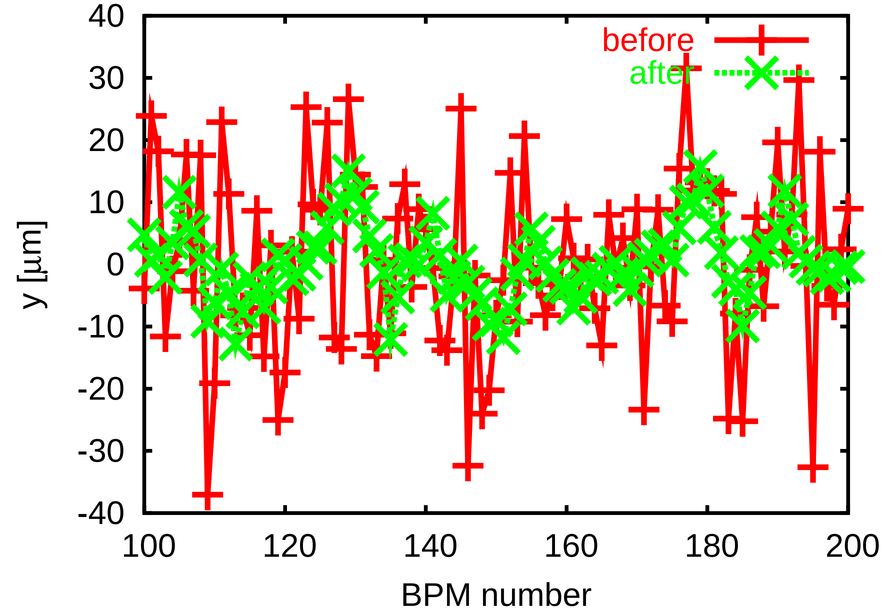
Beam-Based Alignment and Tuning Strategy

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

\- Tune luminosity
  - tuning knobs
- currently noise during correction is being studied (e.g. beam or quadrupole jitter)

Dispersion Free Correction

- Basic idea: use different beam energies
- Accelerate beams with different gradient and initial energy

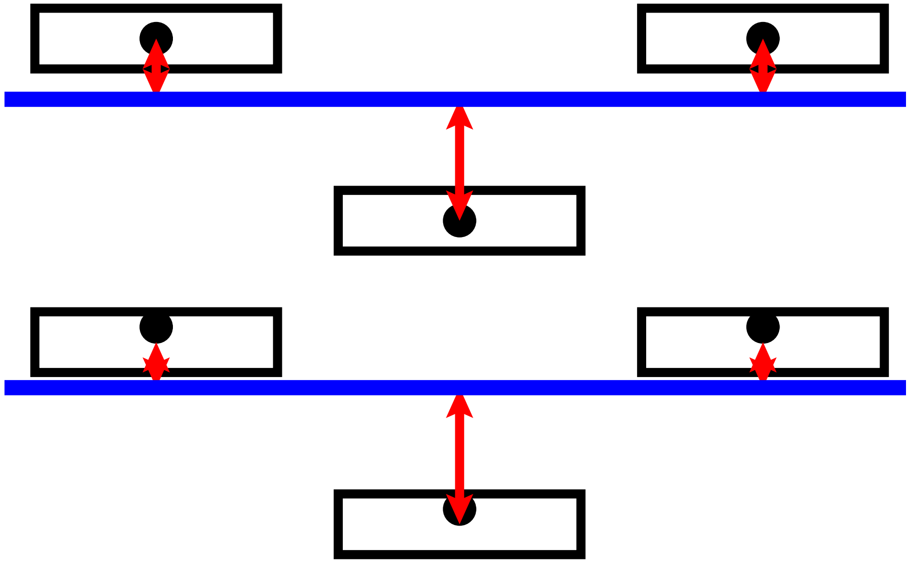


- Optimise trajectories for different energies together:

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

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

Beam-Based 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

- A study had been performed to move the articulation points

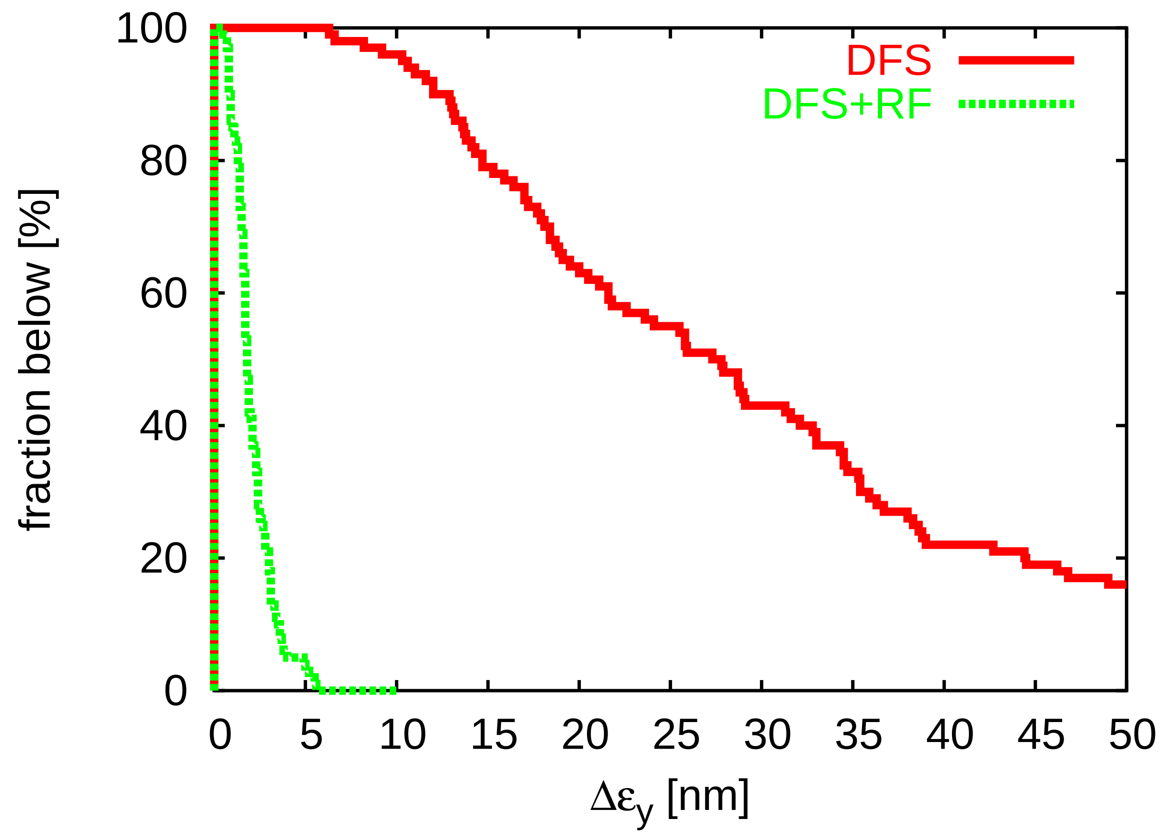
  $\Rightarrow$ negligible additional effect if additional articulation point exists at quadrupoles

- For wakes that are identical in each structure
  - relevant is error of structure BPM to structure centre
- For wakes that differ from structure-to-structure
  - relevant is structure to beam offset

DFS Results

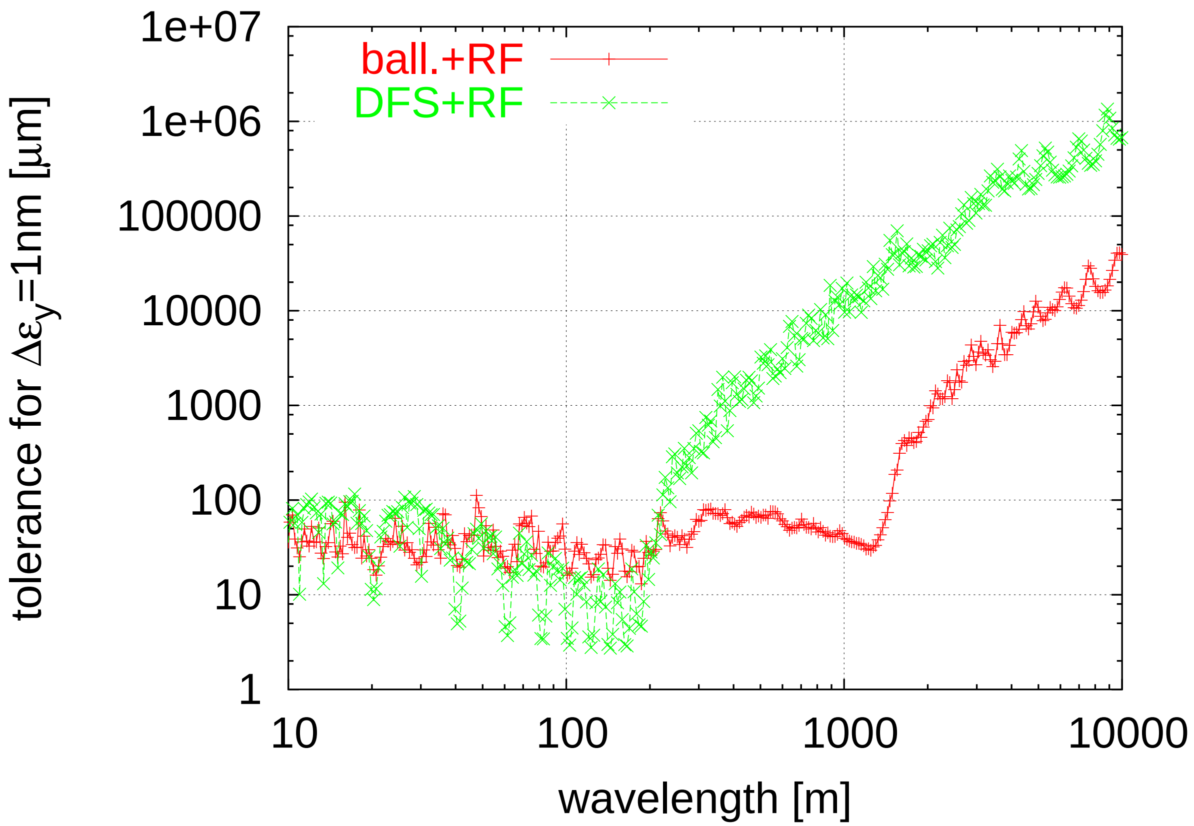
⇒ With RF alignment we can have more then 90% of the machines below 5nm

⇒ But not much margin



Long Distance Alignment

- Beam line elements are more difficult to align over long distances
  - we are investigating the alignment performance for this case
  - testing good material for long distance wires
- Simulation results to illustrate the point



⇒ The alignment tolerance depends on the correction method

Conclusion

- Element stability is vital for CLIC
  - very tight tolerance at interaction point
  - nanometer tolerance on all main linac quadrupoles
- Pre-alignment of beam line elements is vital
  - in particular good survey line over long distance
  - good alignment of BPMs to survey
  - good alignment of BPM to quadrupole (cost)
  - good alignment of structures on girder
  - precise structure fabrication
  - good structure BPM precision