Emittance preservation in the main linacs of ILC and CLIC

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Table of contents

- Main sources of emittance growth in a linac and their cure
- Low emittance transport in the ILC and CLIC main linacs (LET)
- Simulations, Code benchmarking
- Experimental program

Main sources of emittance growth *and their cure*

- Transverse wakefields in the accelerating structures
  - Single-bunch break-up *: careful lattice design / BNS damping*
  - Bunch-to-bunch instabilities : *damping by RF design / detuning*

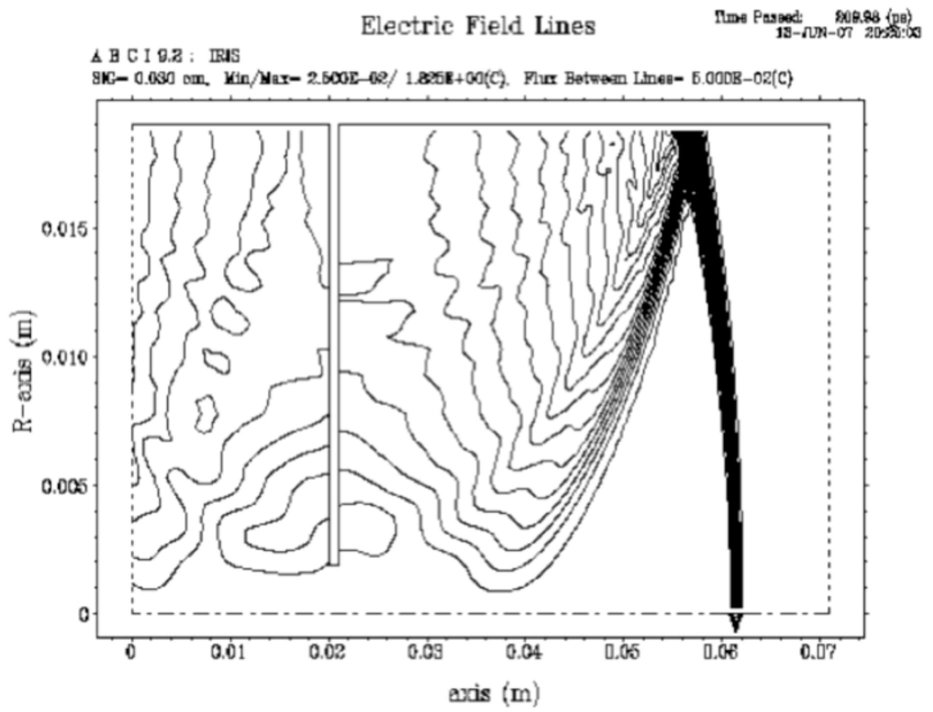
- Static imperfections
  - Quadrupole / BPM misalignments *: pre- and beam-based alignment*

- Others
  - Resistive wall wakes *: strong focusing*
  - Fast beam-ion instability *: high vacuum*
  - RF kicks *: RF design*
  - Ground motion *: feedback loops*
  - BPM scaling errors *: tuning and BBA*

Wakefields

The beam pipe is not a perfectly conducting pipe of constant aperture.

A beam passing through a cavity radiates electromagnetic fields and excites the normal modes of the cavity.



The consequences are:

1) the beam loses energy;
2) energy can be transferred from head to tail of a bunch;
3) the head of the bunch can deflect the tail;
4) energy and deflections can be transferred between bunches if there are normal mode with high *Q* (quality factor).

2) - 4) can give rise to instabilities.

Long-range wakefields

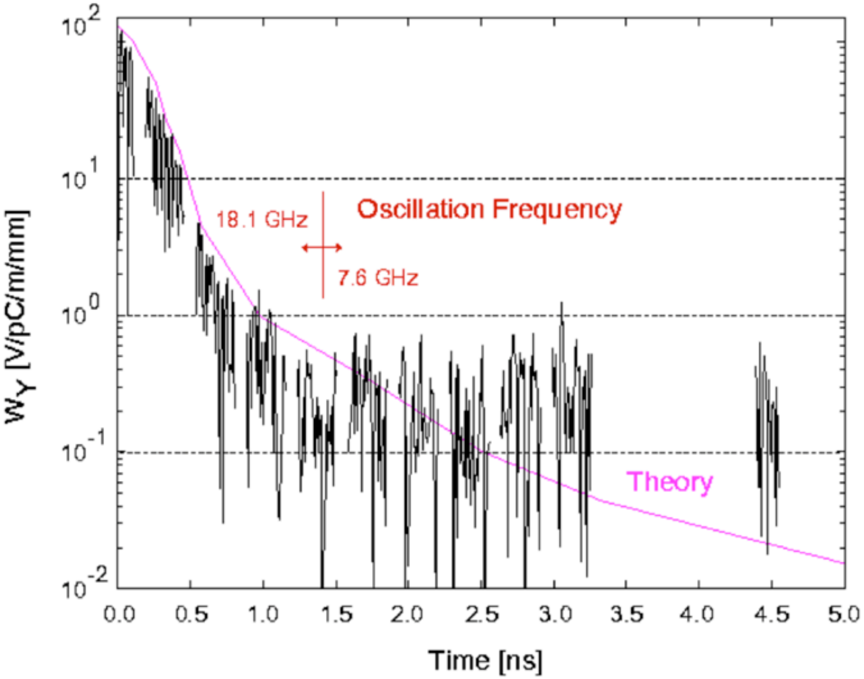
Bunch-to-bunch long-range wakefields can induce transverse instabilities leading to beam break-up.

Long-range wakefields are sine-like functions:

$$W_\perp(z) = \sum_i^\infty 2k_i \sin\left(2\pi \frac{z}{\lambda_i}\right) \exp\left(-\frac{\pi z}{\lambda_i Q_i}\right)$$

They can be reduced by

- damping
- Detuning



Beam-based alignment, tuning strategy

- Make beam pass linac
  - one-to-one correction
- Remove dispersion, align BPMs and quadrupoles
  - dispersion free steering
  - ballistic alignment
  - kick minimisation
- Remove residual dispersive and wakefield effects
  - accelerating structure alignment (CLIC only)
  - emittance tuning bumps
- Tune luminosity
  - tuning knobs

Emittance budgets

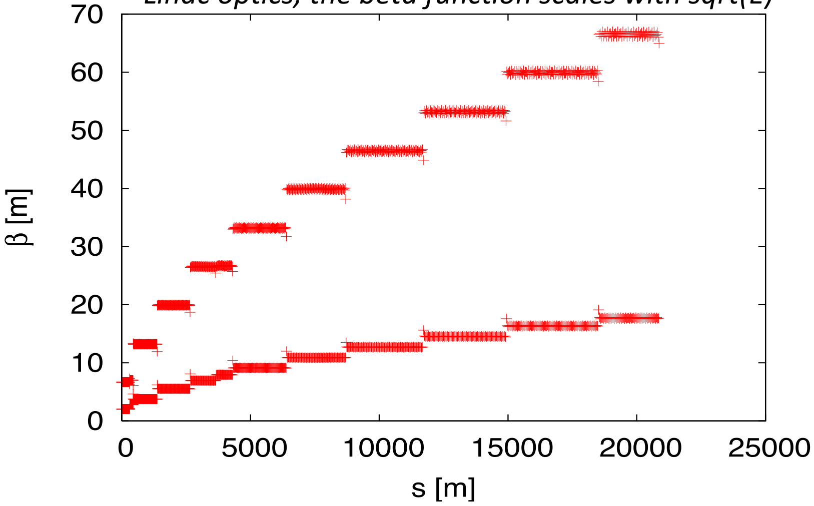
- CLIC
  - the initial emittance has to stay below $\epsilon_x = 600\,\mathrm{nm}$ and $\epsilon_y = 10\,\mathrm{nm}$
  - for static imperfections an emittance budget of $\Delta\epsilon_x = 30\,\mathrm{nm}$ and $\Delta\epsilon_y = 5\,\mathrm{nm}$ exists, which 90% of the machines have to meet
  - for dynamic imperfections an emittance budget of $\Delta\epsilon_x = 30\,\mathrm{nm}$ and $\Delta\epsilon_y = 5\,\mathrm{nm}$ exists
- ILC
  - the initial emittances have to stay below $\epsilon_x = 8400\,\mathrm{nm}$ and $\epsilon_y = 24\,\mathrm{nm}$
  - the final emittances have to stay below$\epsilon_x = 9400\,\mathrm{nm}$ and $\epsilon_y = 34\,\mathrm{nm}$

CLIC main linac lattice design

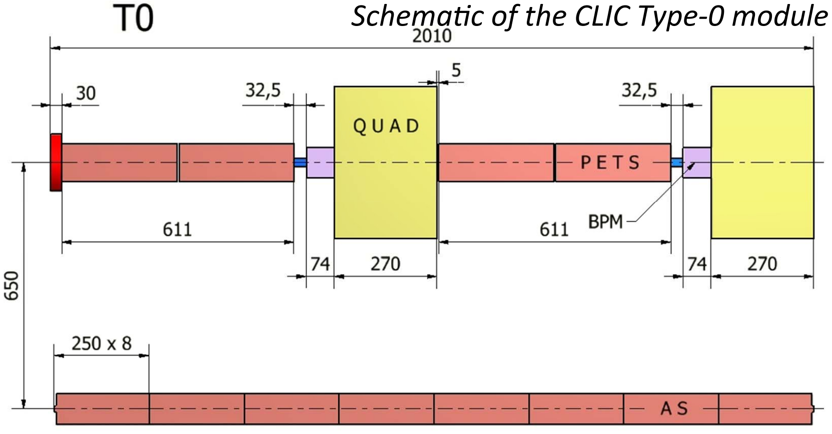
The main linac injection emittances are 600 and 10 nm respectively. The lattice is designed with the following criteria:

- Strong focusing lattice, to balance the impact of the transverse wakefields in the accelerating structures
- Lattice strength is varied along the linac to have an almost constant fill factor
- BNS damping is used to compensate for short-range wakefield effects. The RF phases offset chosen is 8° at the beginning and 30° at the end of the linac
- The linac is composed by five types of modules that accommodate two beams: drive beam and main beam

Linac optics, the beta function scales with sqrt(E)

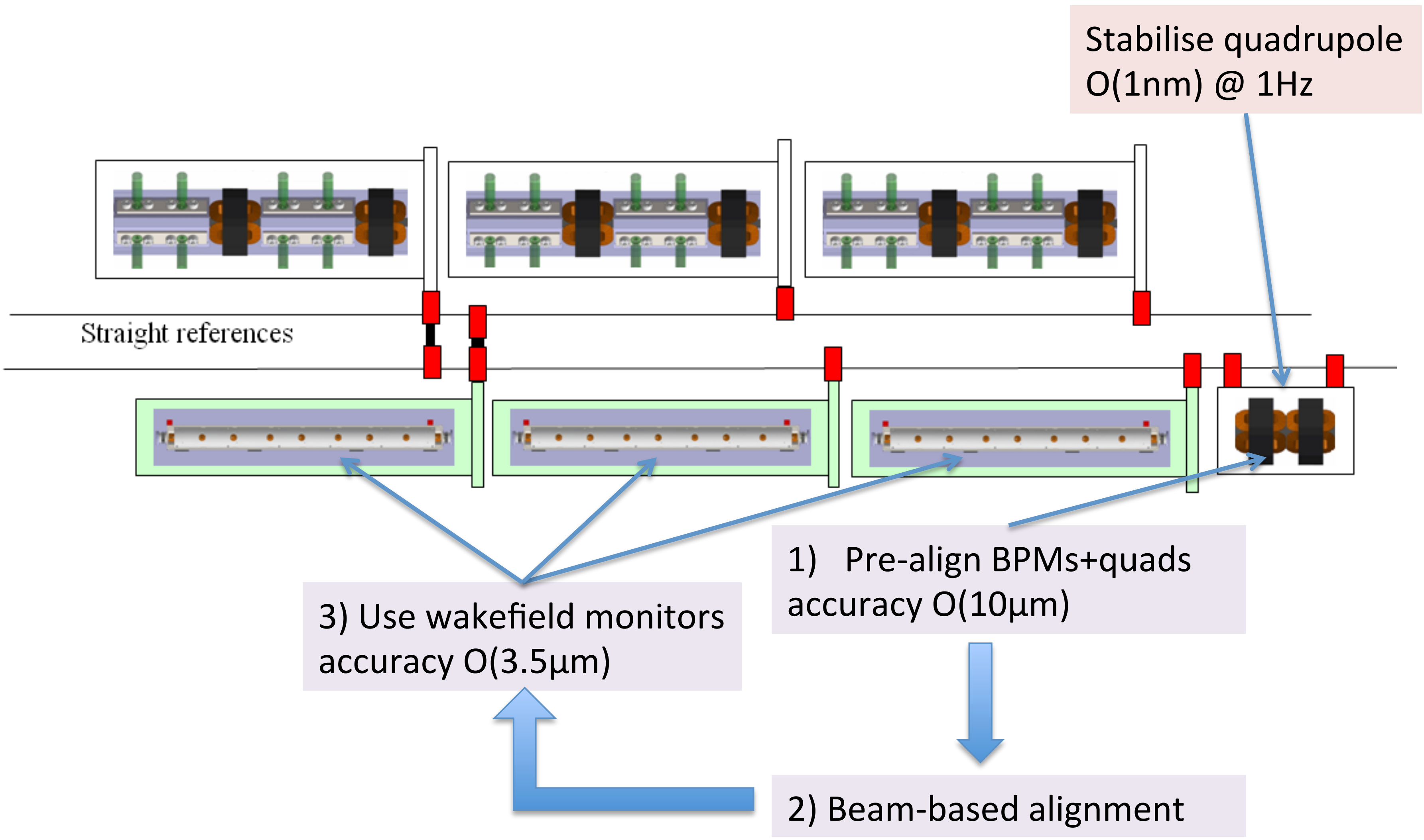


Schematic of the CLIC Type-0 module



The total emittance growth in a linac without imperfections is about zero.

Main Linac Tolerances



Stabilise quadrupole
O(1nm) @ 1Hz

1) Pre-align BPMs+quads
accuracy O(10µm)

2) Beam-based alignment

3) Use wakefield monitors
accuracy O(3.5µm)

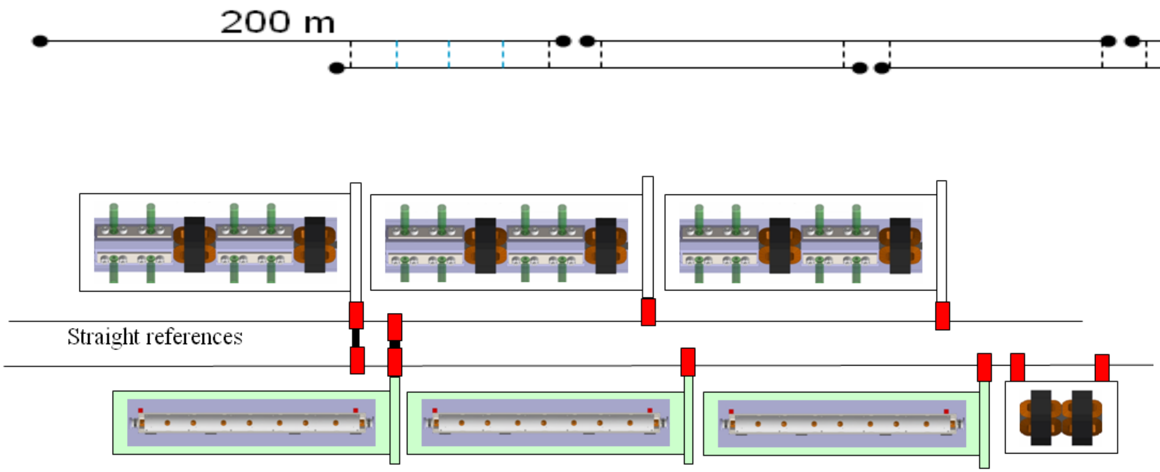
Tolerance for static imperfections in CLIC

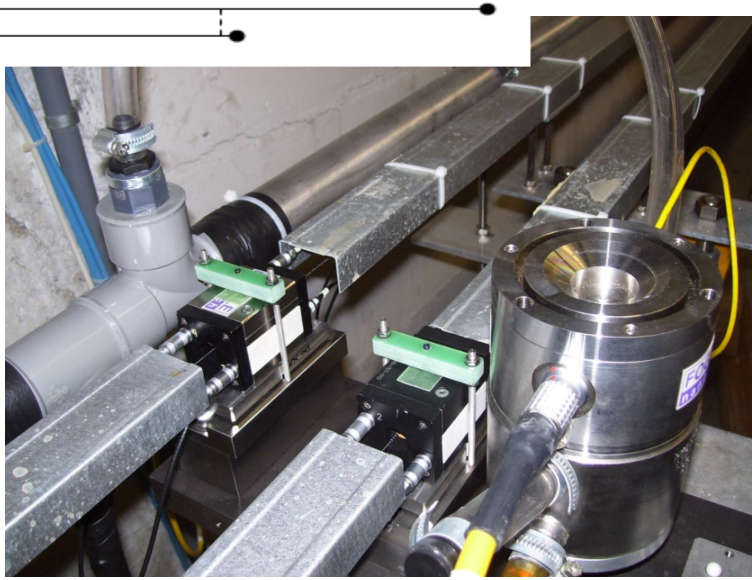
Error	CLIC	with respect to
Quad Offset	17 µm	girder/survey line
Quad roll	≤100 µrad	survey line
Girder Offset	9.4 µm	survey line
Girder tilt	9.4 µrad	survey line
Acc Structures Offset	5 µm	girder
Acc Structures tilt	200 µrad	girder
BPM Offset	14 µm	girder/survey line
BPM resolution	0.1 µm	BPM center
Wakefield monitor	3.5 µm	wake center

- In ILC the specifications have much larger values than in CLIC
  - More difficult alignment in super-conductive environment
  - Dedicated effort for CLIC is needed

- Wakefield monitors are currently foreseen only in CLIC

Pre-alignment System

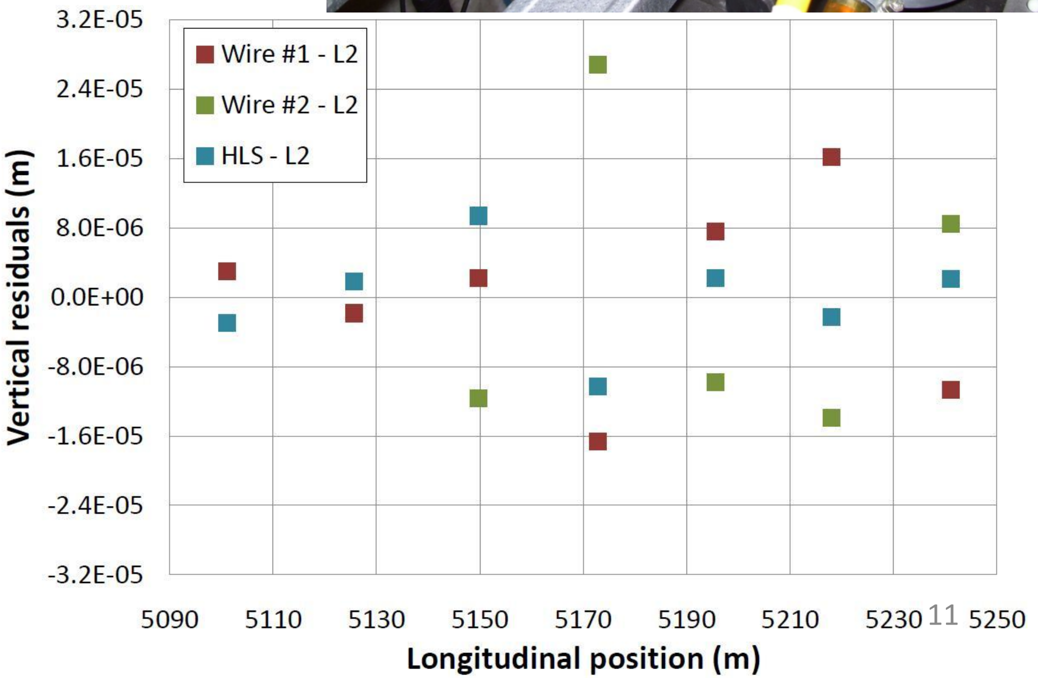




- Required accuracy of reference point is 10µm

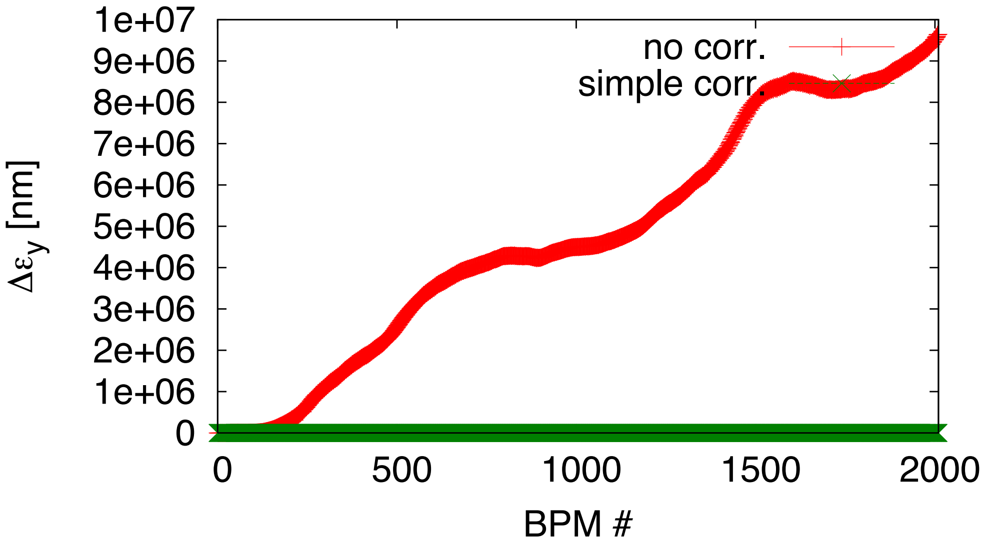
- Test of prototype shows
  - vertical RMS error of 11µm
  - i.e. accuracy is approx. 13.5µm

- Improvement path identified

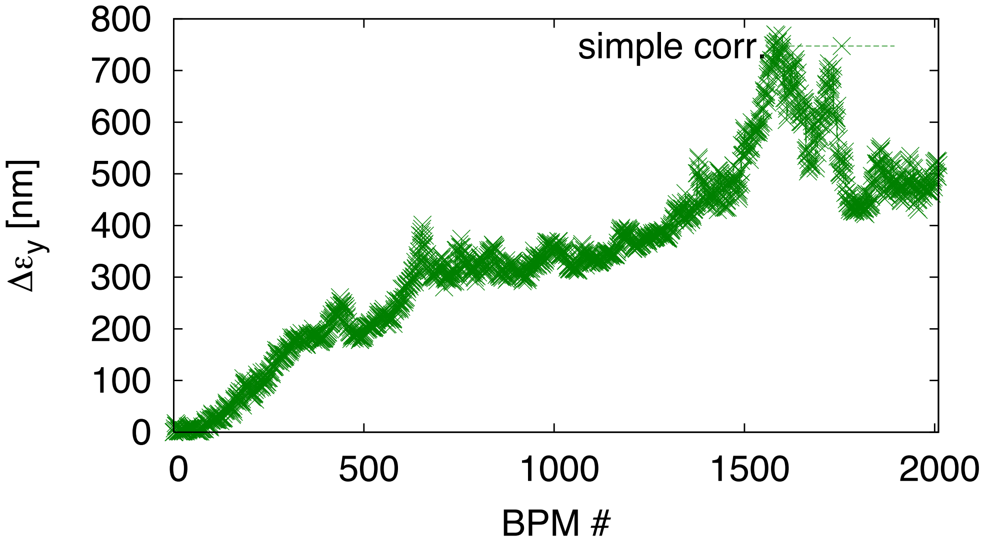


Emittance growth in CLIC

Simple orbit correction



- Initial emittance growth is enormous
- After one-to-one correction growth is still large



Dispersion-Free Steering in CLIC

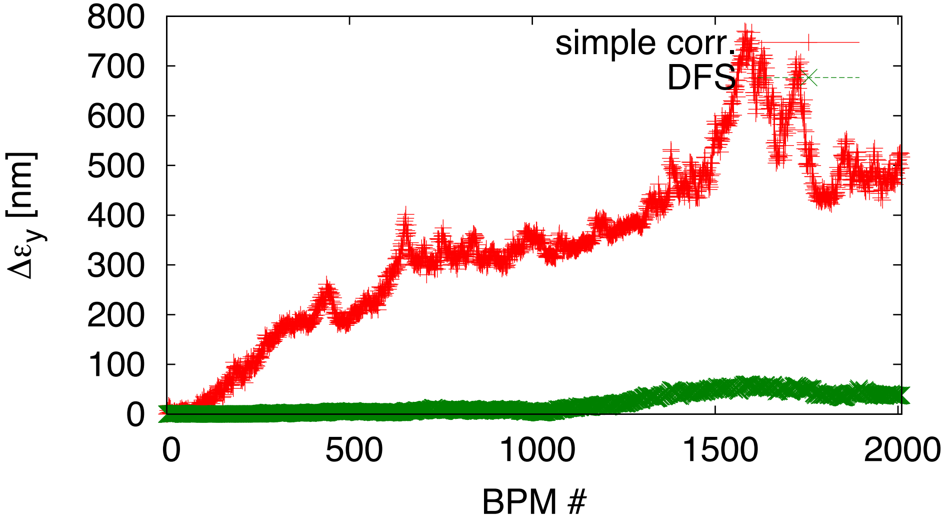
Dispersion-free correction (DFS)

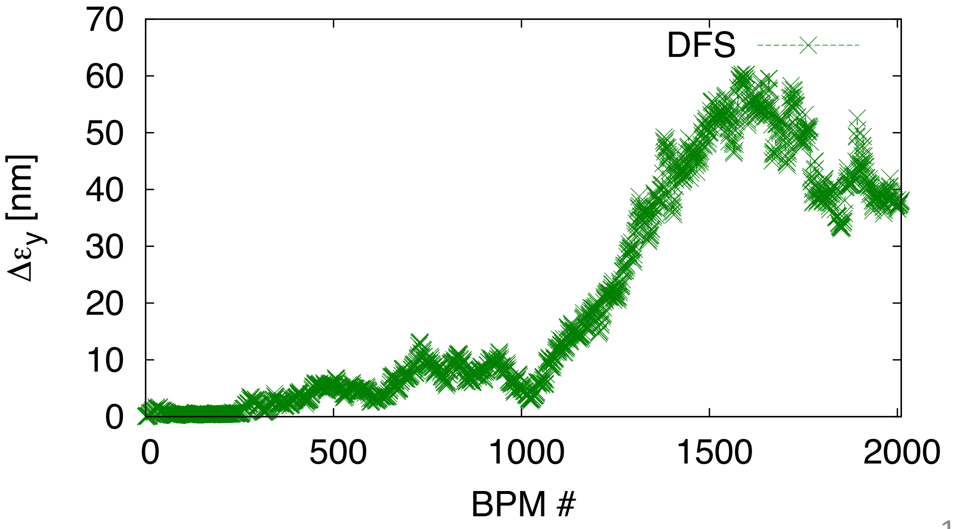
$$\chi^2 = \sum_{\text{BPMs}} \frac{y^2_{\text{BPMreading}}}{\sigma^2_{y,\text{BPM}} + \sigma^2_{\text{res}}} + \sum_{\text{BPMs}} \frac{\left[\Delta y_{\text{meas}} - \Delta y_{\text{model}}\left(\vec{\theta}\right)\right]^2}{2\sigma^2_{\text{res}}}$$

The emittance growth is largely reduced by DFS, but it is still too large

Main cause of emittance growth are:

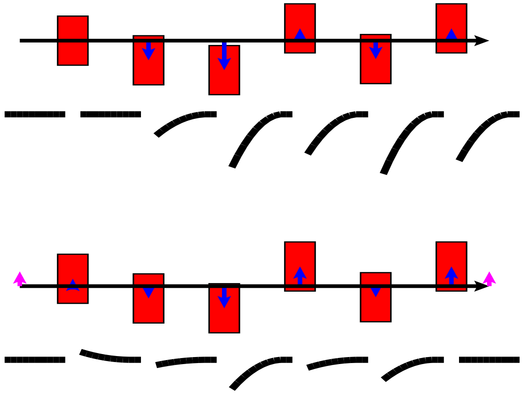
- Trajectory is smooth but not centered in the structures
- Effective coherent structure offsets
- Structures initial scatter remains uncorrected

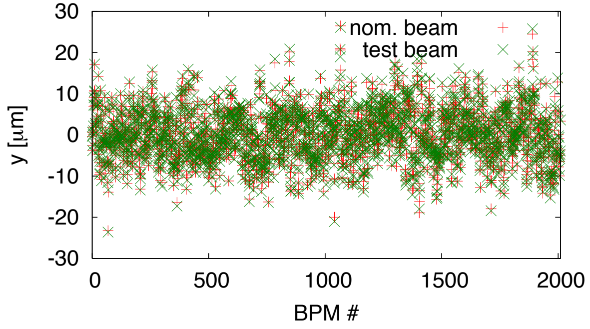




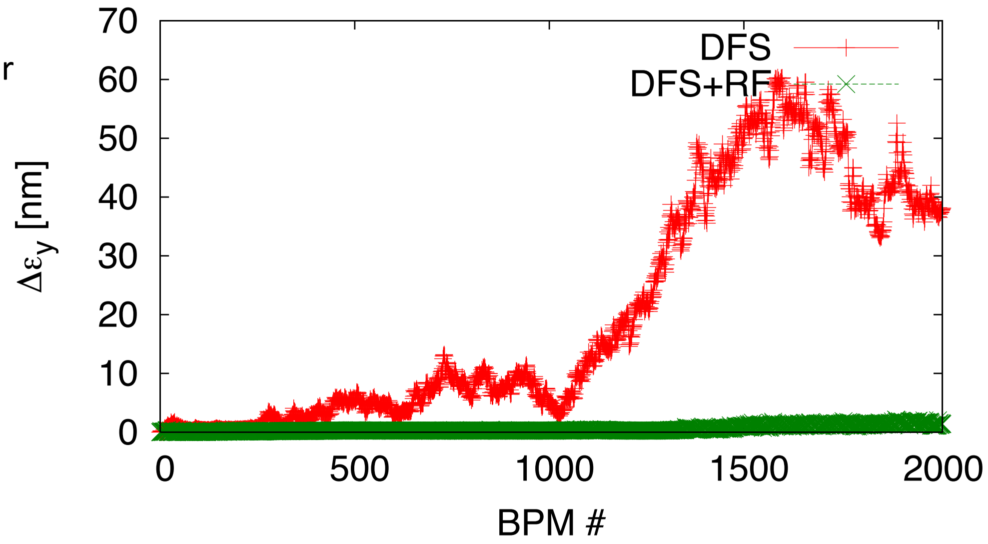
RF-structure alignment in CLIC

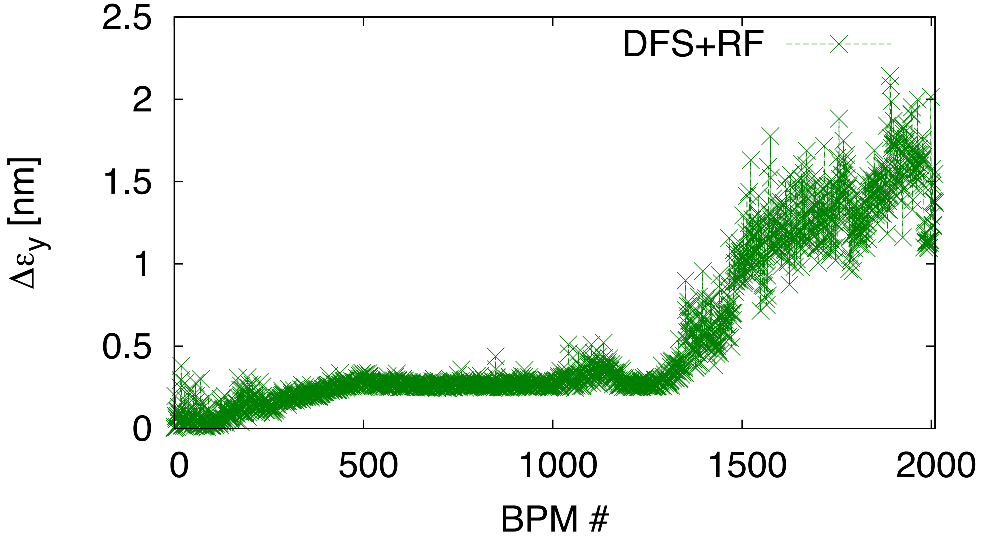
RF structures are equipped with wakefield position monitors: girders are moved to zero the average center of the beam w.r.t. the structures





Beam trajectory is hardly changed by structure alignment but emittance growth is strongly reduced

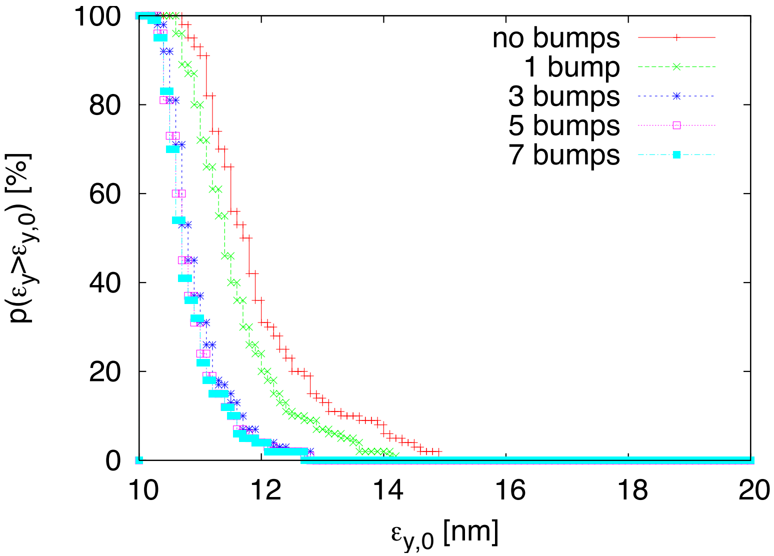




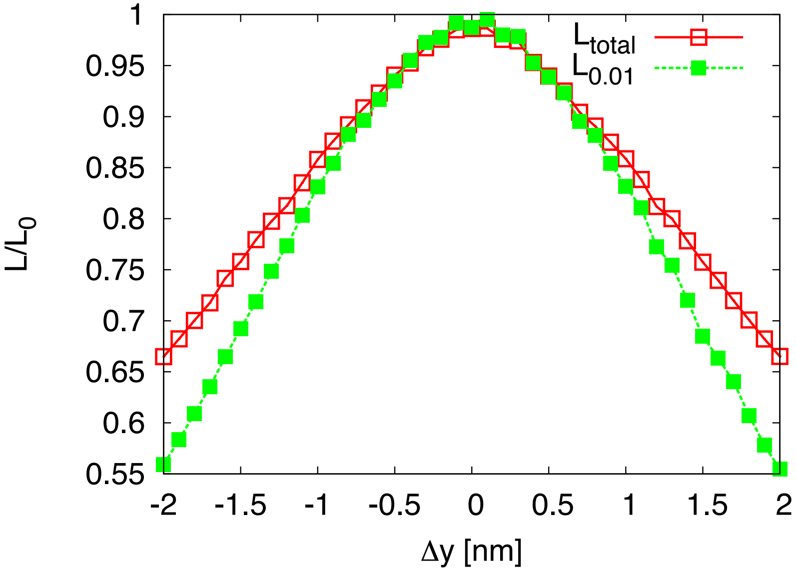
Final emittance growth in CLIC

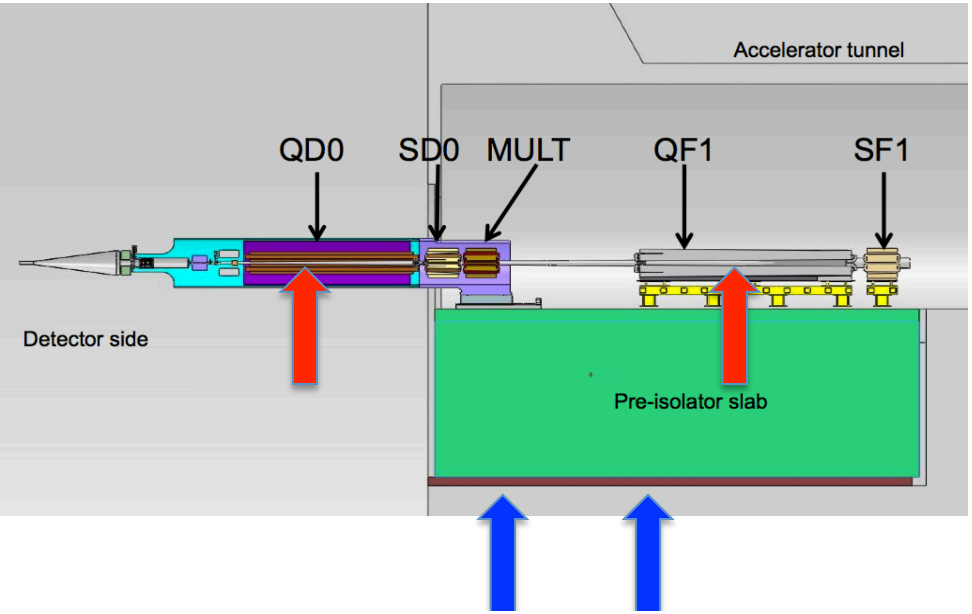
Imperfection	With respect to	Value	Emittance growth
Wakefield monitor	wake center	3.5 µm	0.54 nm
Acc Structures tilt	girder	200 µrad	0.38 nm
BPM Offset	girder/survey line	14 µm	0.37 nm
Quad roll	longitudinal axis	100 µrad	0.12 nm
Articulation point offset	wire reference	12 µm	0.10 nm
BPM resolution	BPM center	0.1 µm	0.04 nm
Acc Structures Offset	girder	10 µm	0.03 nm
Girder end point	articulation point	5 µm	0.02 nm
		TOTAL	1.60 nm

- Selected a good DFS implementation
  - Trade-offs are possible
- Multi-bunch wakefield misalignments of 10 µm lead to 0.13 nm emittance growth
- Performance of local pre-alignment is acceptable



Ground Motion and Its Mitigation

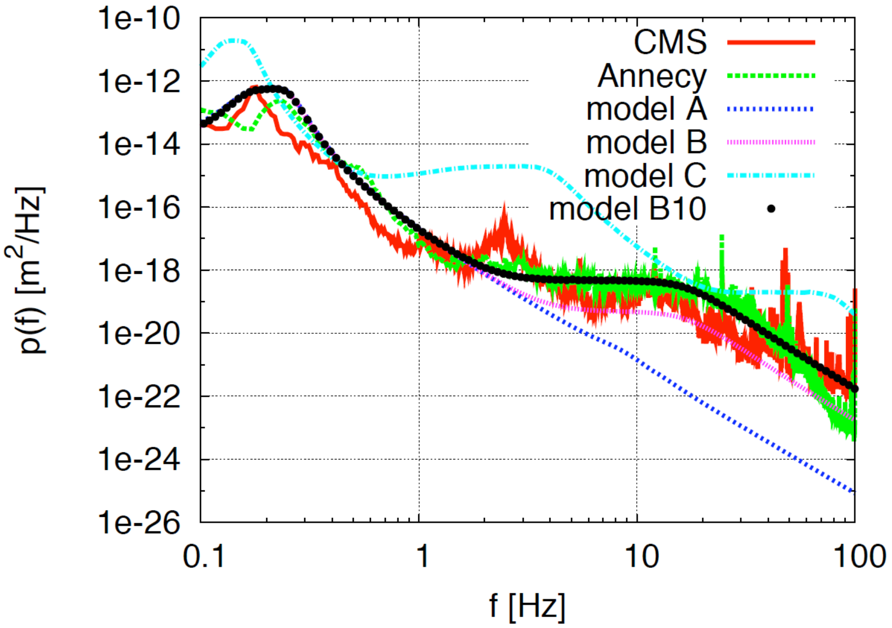




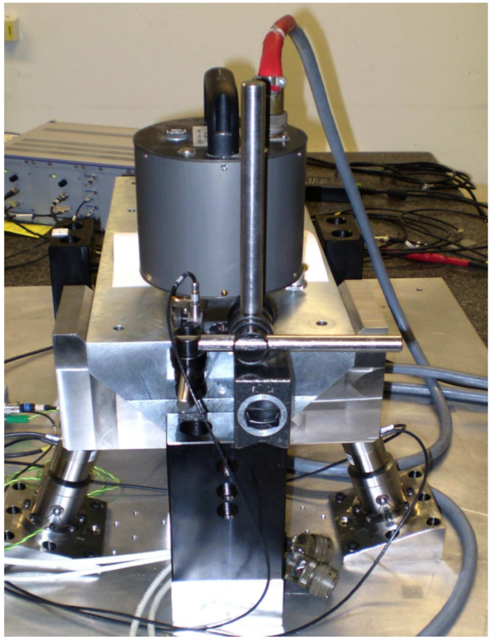
Natural ground motion can impact the luminosity

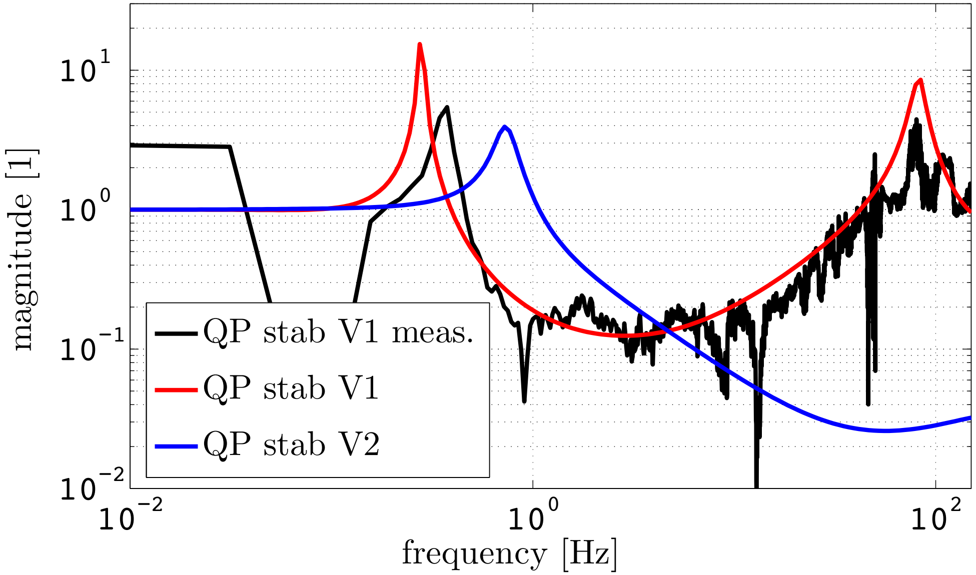
- typical quadrupole jitter tolerance O(1nm) in main linac and O(0.1nm) in final doublet

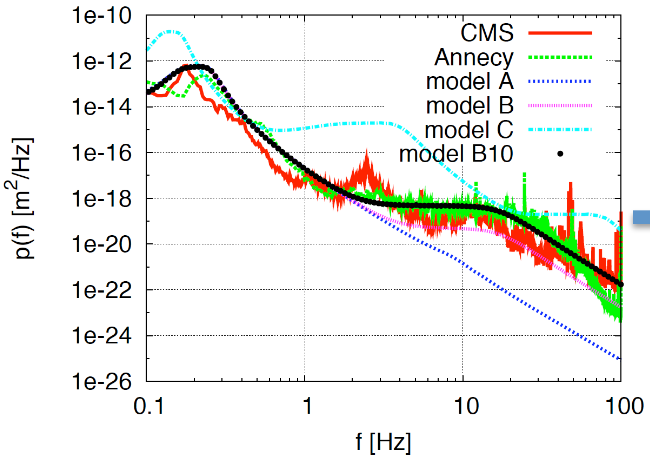
-> develop stabilisation for beam guiding magnets



Active Stabilisation Results







Code

Machine model
Beam-based feedback

Luminosity achieved/lost [%]	
	B10
No stab.	53%/68%
Current stab.	108%/13%
Future stab.	118%/3%

Close to/better than target

ILC static errors and cures

- Agreed “standard” errors: Next slide
  - Random Gaussian distributions are used for most studies

- DMS (Dispersion Matching Steering) correction as standard correction method
  - For dispersion measurement, change beam energy 10% ~ 20%
  - Simulation studies using many different codes and by different persons.
  - BPM scale error is important ← non-zero design dispersion (see 3rd next slide)

- Other methods (Kick minimum, Balistic, wake bumps, etc.) as additional or alternative corrections.

- Studies for upgrade to 1TeV ECM

- No serious problem expected.
  - An example shown: next-next slide

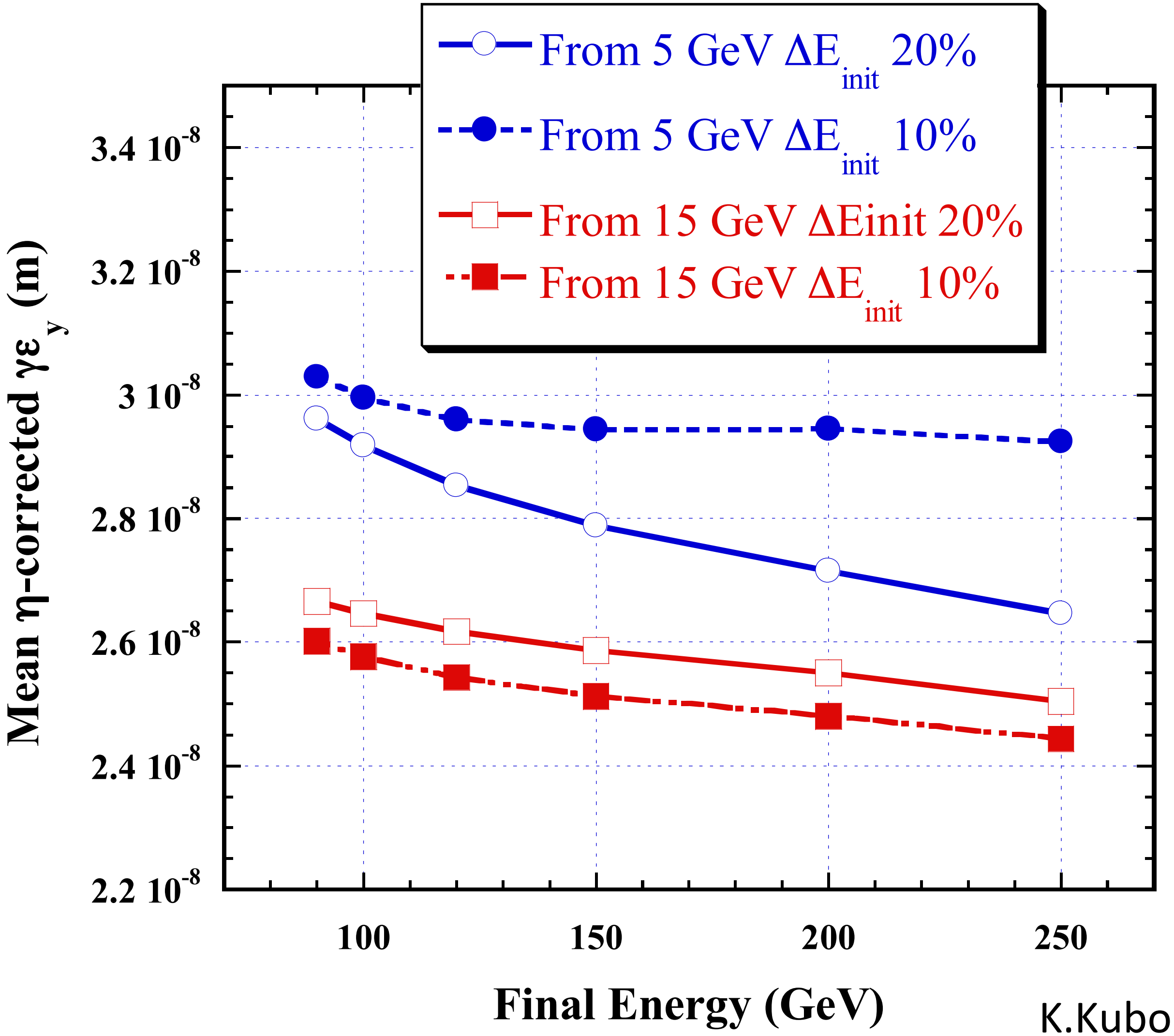
ILC static imperfections

"standard" errors

Error	ML Cold	with respect to
Quad Offset	300 μm	cryo-module
Quad roll	300 μrad	design
RF Cavity Offset	300 μm	cryo-module
RF Cavity tilt	300 μrad	cryo-module
BPM Offset (initial)	300 μm	cryo-module
Cryomoduloe Offset	200 μm	design
Cryomodule Pitch	20 μrad	design

Dependence on Initial and Final energy

“Standard” static errors + BPM resolution 1um + DMS



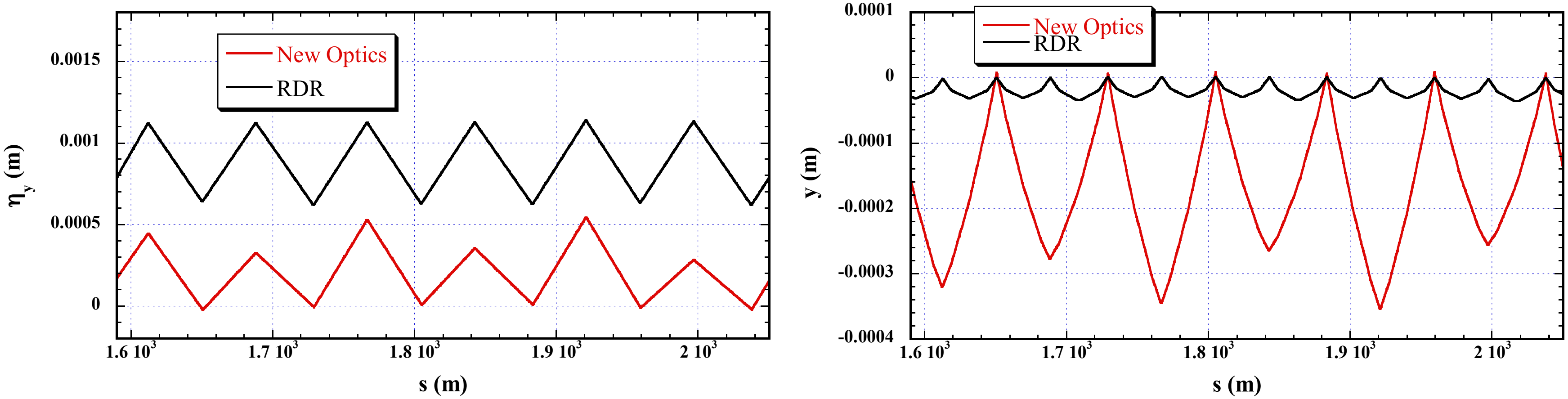
ΔE_{init}:
Change of initial energy for dispersion measurement

K.Kubo LCWS 2011 Oregon

BPM Scale error affects DMS

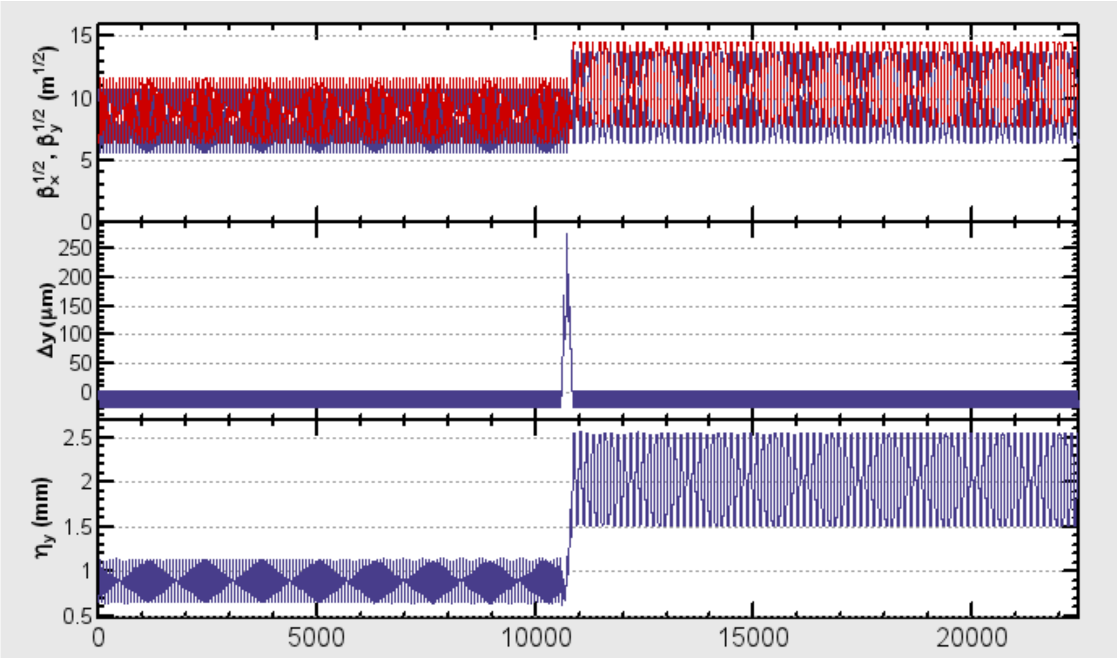
In DMS, dispersion is measured at each BPM and adjusted as design.
For non-zero design dispersion, BPM scale error affects the accuracy.
We will need good BPM scale calibration (< 5%) for baseline optics.
Alternative optics may mitigate the effect. (Zero dispersion at every other BPM)

Vertical Orbit and Dispersion
Base line optics (same as RDR) and new possible optics



K.Kubo, ILC-CLIC-LET-Workshop, 2009 CERN

Lattice of upgraded linac (1 TeV ECM)

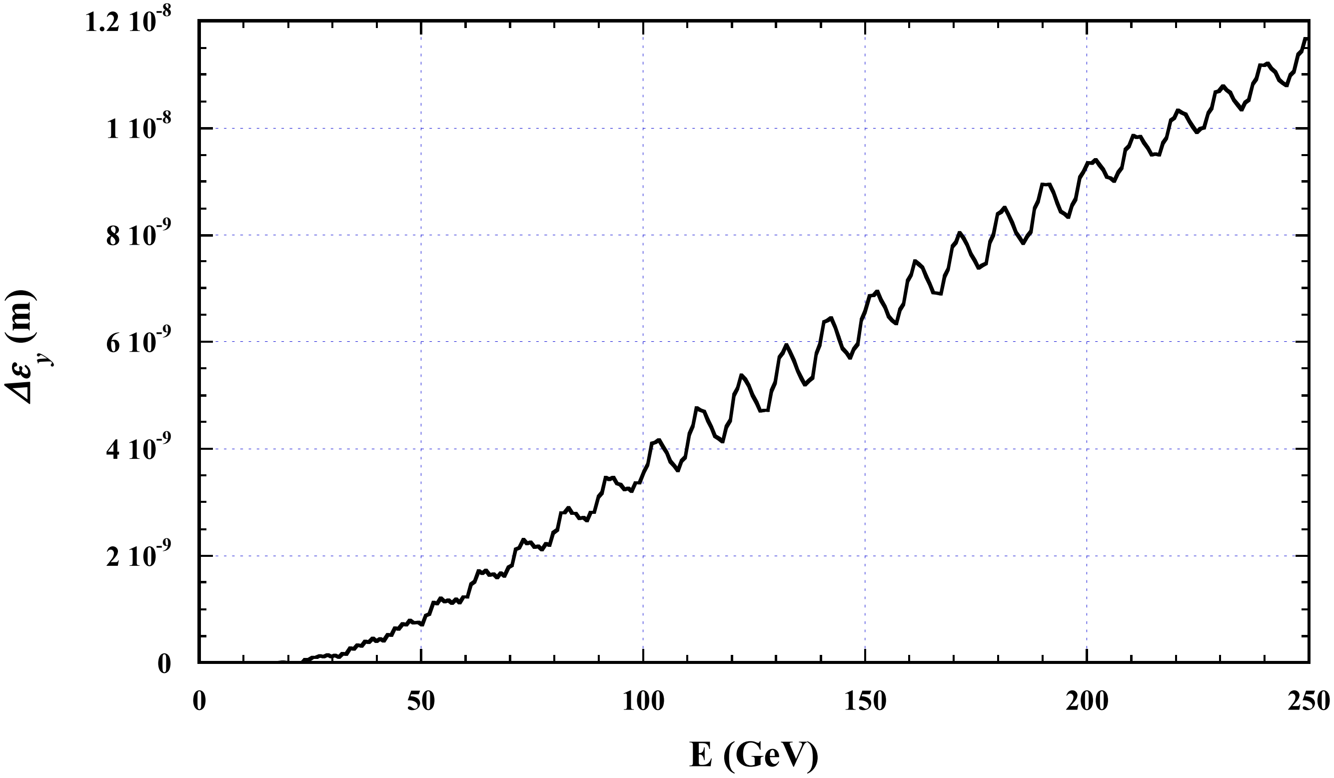


Part of E_beam 25~250 GeV of old linac will be used for 275~500 GeV of new linac.

For using the same quad magnet (week for higher energy), FOFODODO lattice will be used instead of FODO.

Emittance growth by Cavity tilt

Emittance growth along ML
Cavity tilt random change 15 urad,
    equivalent to Fixed 300 urad + 5% gradient change
Emittance growth proportional to square of the change



Final emittance growth in ILC

Initial vertical normalized emittance at the exit of the DR is 20 nm.
Vertical emittance at the exit of the ML must be 31 nm or below.

Error	with respect to	value	$\Delta\gamma\epsilon_y$ [nm]	$\Delta\gamma\epsilon_{y,121}$ [nm]	$\Delta\gamma\epsilon_{y,dfs}$ [nm]
Cavity offset	module	$300\ \mu$m	3.5	0.2	$0.2(0.2)$
Cavity tilt	module	$300\ \mu$radian	2600	< 0.1	$1.8(8)$
BPM offset	module	$300\ \mu$m	0	360	$4(2)$
Quadrupole offset	module	$300\ \mu$m	700000	0	$0(0)$
Quadrupole roll	module	$300\ \mu$radian	2.2	2.2	$2.2(2.2)$
Module offset	perfect line	$200\ \mu$m	250000	155	$2(1.2)$
Module tilt	perfect line	$20\ \mu$radian	880	1.7	—

- The results of the reference DFS method is quoted, results of a different implementation in brackets

- Note in the simulations the correction the quadrupoles had been shifted, other wise some residual effect of the quadrupole misalignment would exist

ILC ML major dynamic errors

ML 15 GeV to 250 GeV

Source	Assumption (Tolerance)	Induced orbit jitter	Induced emittance growth
Quad vibration (offset change)	100 nm	1.5 sigma	0.2 nm
Quad+steering strength jitter	1E-4	1 sigma	0.1 nm
Cavity tilt change	3 urad	0.8 sigma	0.5 nm
Cavity to cavity strength change, assuming 300 urad fixed tilt	1%	0.8 sigma	0.5 nm

Pulse to pulse and in each pulse (flatness)

ILC Other considered issues, examples

- Coupler wake and RF transverse kicks
  - No problem because of short bunch length (compare with in RTML)

- Emittance dilution in undulator for e+ production
  - Dispersive effect will be small.
  - Wakefield in the narrow beam pipe can be significant.
    - May need movers.

- Specification of magnet change speed
  - For BBA, or startup after shutdown, etc.
  - Required speed will be achievable without serious R&D.

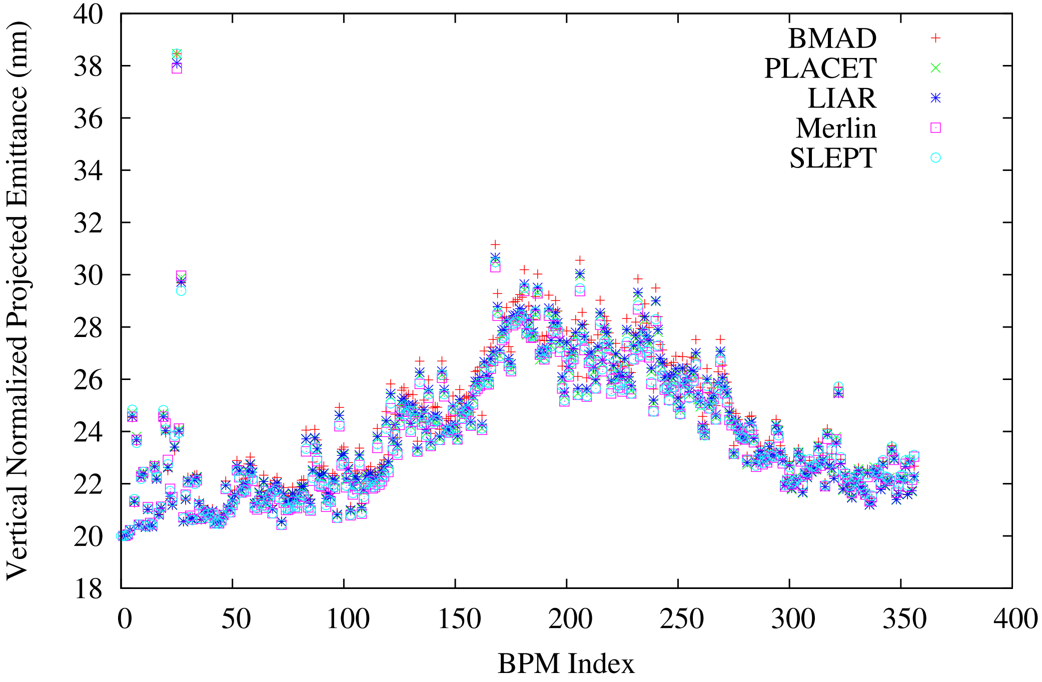
Code benchmarking

We rely on simulations: code validation is essential.

Emittance dilution after performing DFS in LIAR and reading misalignments and corrector settings into the other codes.

Parameter	unit	value
Energy	GeV	5.0
σ_δ	%	3.0
σ_z	mm	300
Charge	10^{10} e	2.0
$\gamma\epsilon_x$	nm	8000
$\gamma\epsilon_y$	nm	20
dP_z/d_z	m^{-1}	0.0

Error	RMS	With respect to...
Quad Offset	300 μm	Cryostat
Quad Tilt	300 μrad	Cryostat
BPM Offset	300 μm	Cryostat
RF Cavity Offset	300 μm	Cryostat
RF Cavity Pitch	200 μrad	Cryostat
Cryostat Offset	200 μm	Survey Line



SLAC-TN-06-035

Experimental Activities

Simulations are not sufficient.

- Measure of transverse wakefields in the CLIC accelerating structures (CLASSE, ex-ASSET)
  - So far we rely on simulations, experimental verification needed
  - Short- and long- wakefields at FACET/SLAC

- Beam-based Alignment algorithms and System Identification Procedures at SLC (T-501 at SLAC)
  - Dispersion-Free steering in a linac has never been proven

- Collimator wakefields measurement at ESTB (SLAC)
  - Critical for beam delivery system performance (next talks)

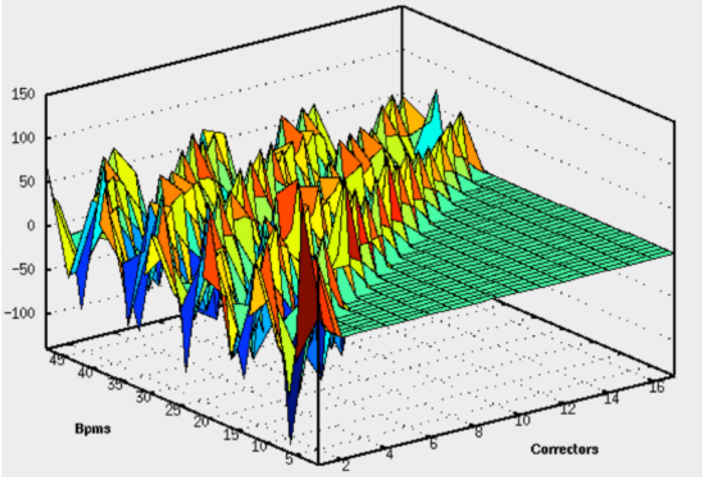
T501: CERN BBA at SLAC

T501: FACET test-beam proposal to study advanced global correction schemes for future linear colliders.

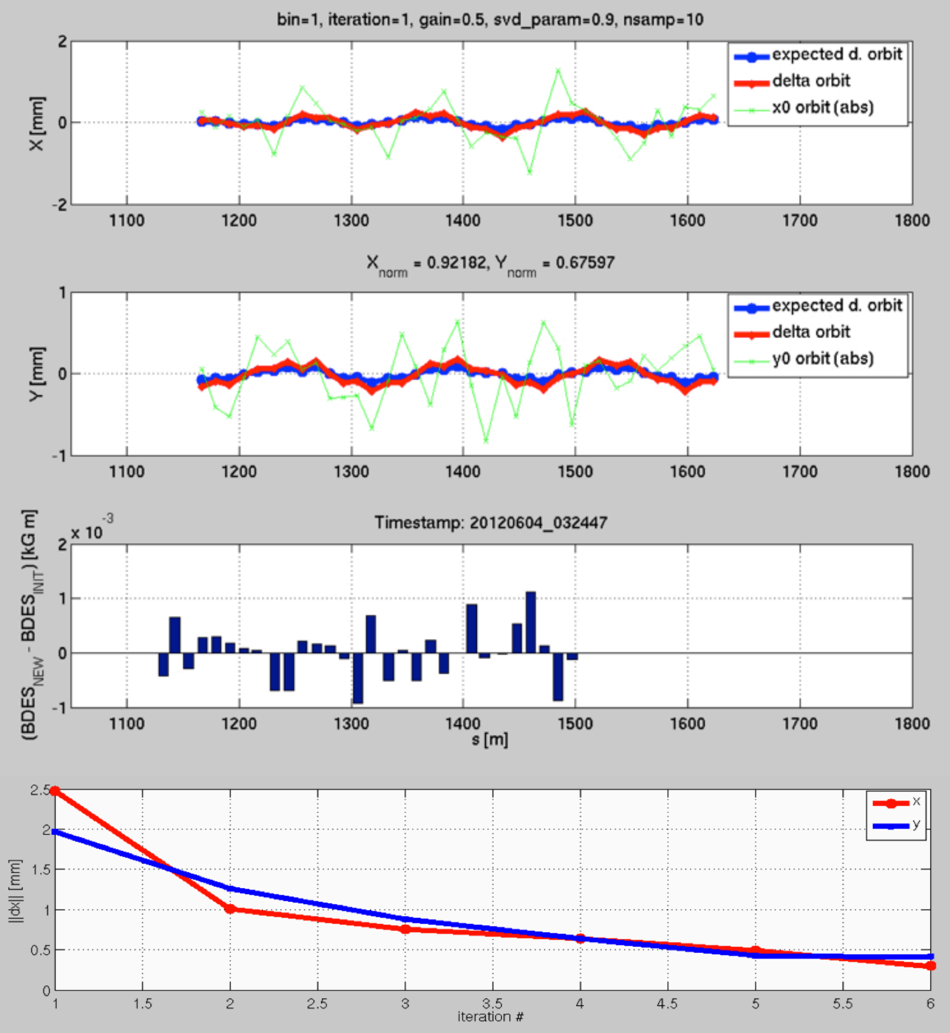
CERN-SLAC collaboration where algorithms developed at CERN are tested on the SLAC linac.

The study includes linac system identification, global orbit correction and global dispersion correction.

Successful system identification and global orbit correction has been demonstrated on a test-section of 500 m of the linac.



(Above) Identified Rx response matrix for the test-section of the linac (17 correctors, 48 BPMs)



Horizontal and Vertical Obrits

Convegence

(Above) Global orbit correction of test-section, with feed-forward to prevent the correction to affect FACET S20 experimental area.

A. Latina, J.Pfingstner, D. Schulte (CERN), E. Adli (SLAC)

Conclusions

- Extensive studies exist both for CLIC and ILC
- CLIC requirements are tighter but beam-based alignment procedures seem to fully recover the performance
- CLIC showed an excellent synergy with the pre-alignment / stabilization groups
- Simulation code are growing and becoming more trustworthy
- Experimental programs are on-going with promising results

Possible Further studies

(some studies already exist but not completed)

- Studies with realistic alignment model
    - Alignment engineers and beam dynamics physicists should agree.
- More realistic DMS procedure
    - E.g. Simulations combined with upstream (RTML)
- Optics choice, for making less sensitive to BPM scale error (ILC)
- Simulations with failed components (BPM, Cavities, Magnets)
- …

None of these are expected to be critical.

Acknowledgements

These results have been obtained by the efforts of many people

Alignment and stabilization team:

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CLIC Beam Physics Group:

- D. Schulte, P. Eliasson, G. Rumolo, R. Tomas, Y. Papaphilippou, B. Dalena, B. Jeanneret et al.

ILC International Collaborators:

- N. Solyak, K. Ranjan, K. Kubo, J. Smith, P. Tenenbaum, N. Walker, F. Poirier et al.