Main Linac Beam Dynamics and Specifications

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- Parameters and Design
- Static Imperfections and Beam-Based Alignment
- Dynamic Effects and Feedback

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Luminosity

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

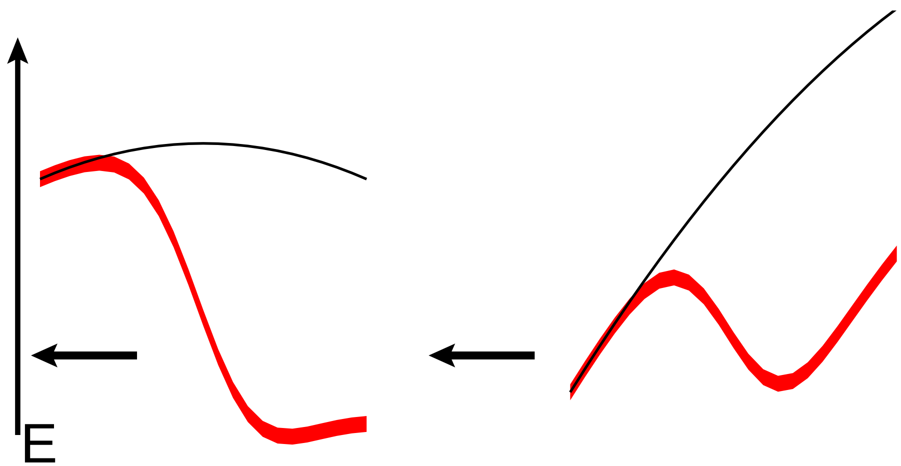
$$\mathcal{L} \propto H_D \frac{N}{\sqrt{\beta_x\epsilon_x}\sqrt{\beta_y\epsilon_y}}\eta P$$

- 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 wakefields in main linac, other effects

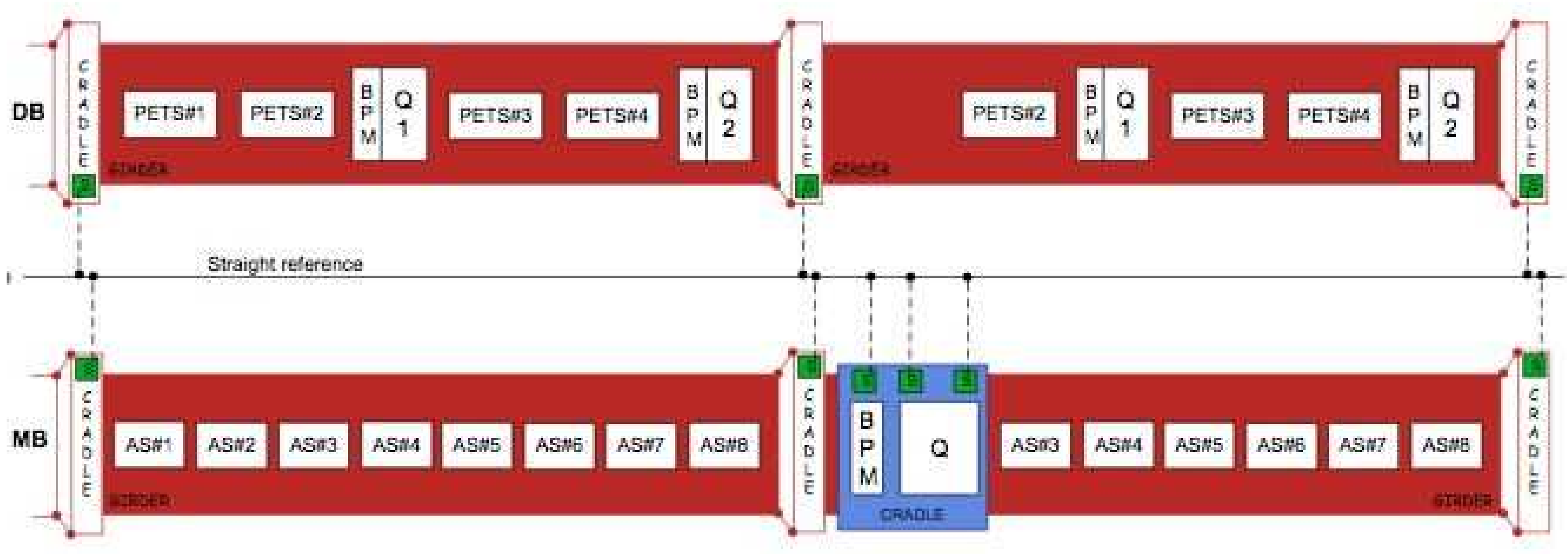
- For scaling we keep the wakefield effect constant
  - transverse single bunch kick ($NW_\perp(2\sigma_z) \approx 2.8 \cdot 10^{14}\,\mathrm{V/pCm^2}$)
  - transverse multi bunch kick
- For each structure
  - determine $\sigma_z(N)$ that yields $\sigma_E/E = 0.35\%$ (average RF phase 15°)
  - determine N that yields target transverse kick



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
  - $\epsilon_x = 660\,\mathrm{nm}$ 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

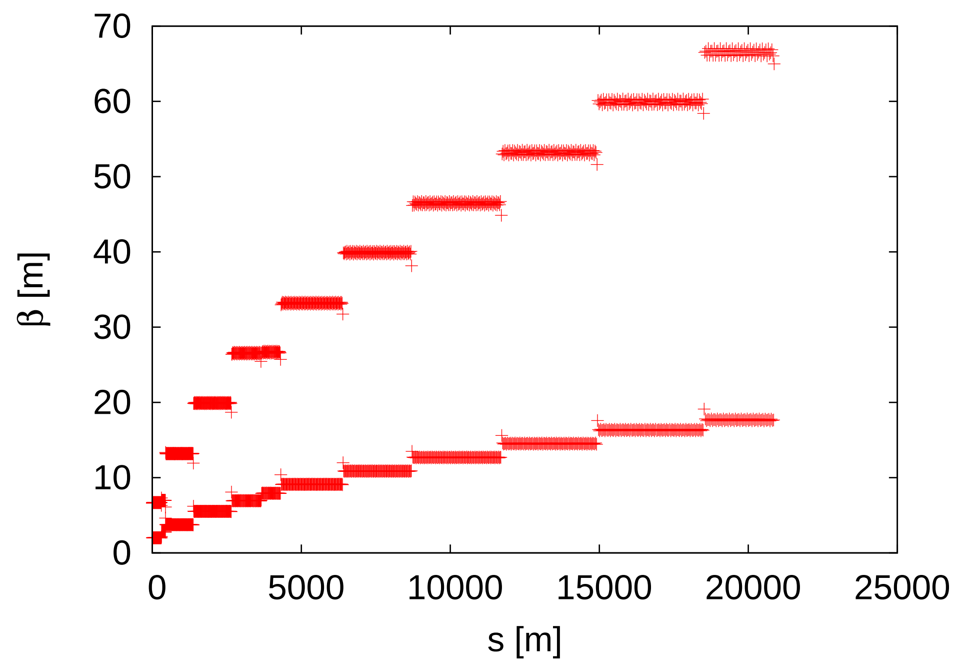
Module Layout



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

Lattice Design

- 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
- Preliminary lattice
  - made for $N = 3.7 \times 10^9$
  - quadrupole dimensions need to be confirmed
  - some optimisations remain to be done
- Total length 20867.6m
  - fill factor 78.6%

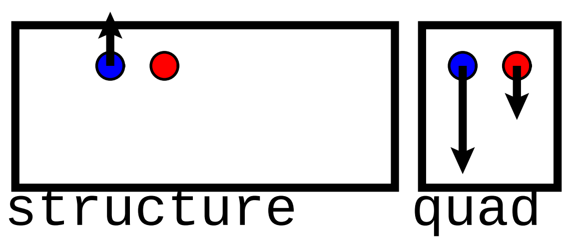


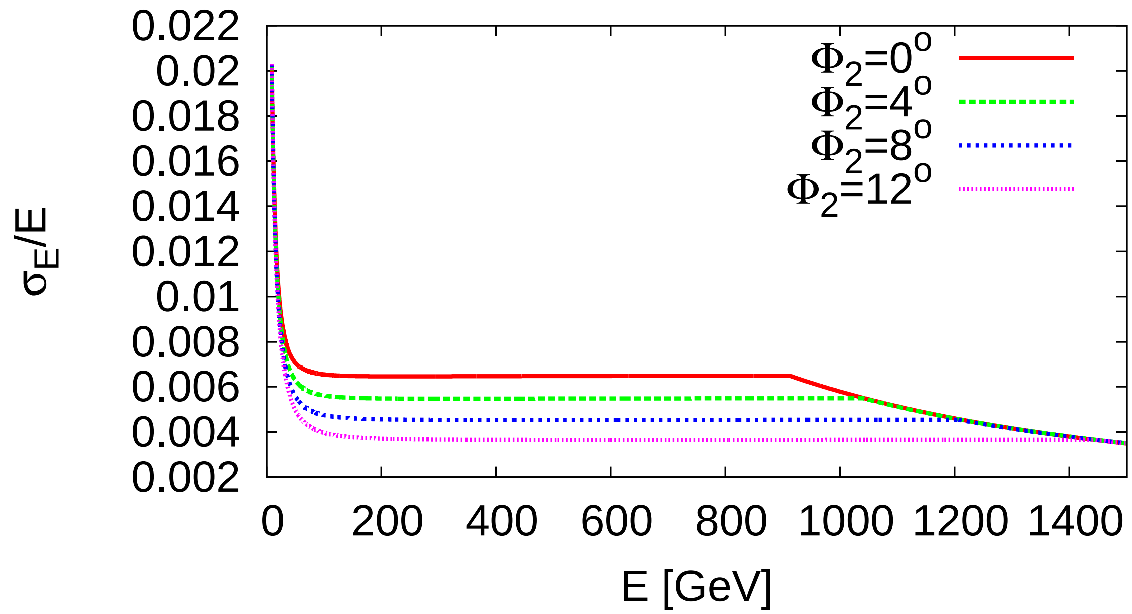
- 12 different sectors used
- Matching between sectors using 7 quadrupoles to allow for some energy bandwidth

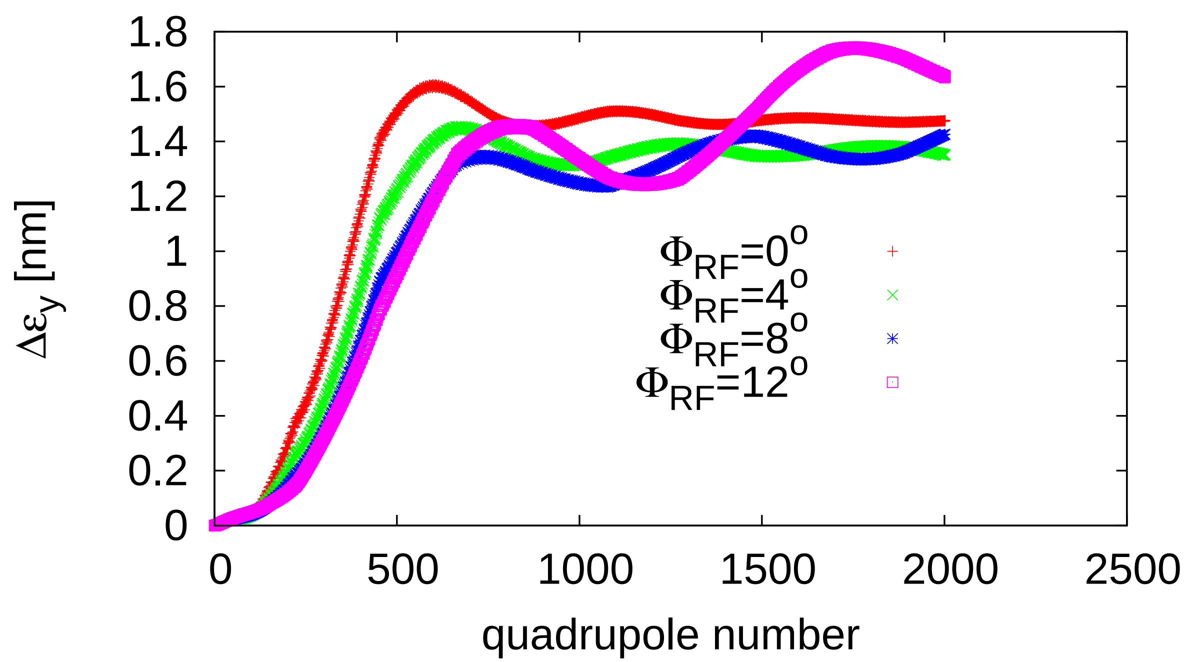
Energy Spread and Beam Stability

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

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







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

  $\Rightarrow$ 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

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 Tolerance	14 µm 40 µm	1σ 3σ

BEAM-BASED ALIGNMENT

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

5

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

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

Structure Tilt

- Two main contributions to effective structure tilt exist
  - from the survey
  - from the structure fabrication
- Longitudinal shift of one structure side with respect to other mimics structure tilt
  - non-expert calcuation yields effective tilt is given by shift as $\theta \approx \Delta z/(2a)$
  - in our case $\Delta z = 1\,\mu\mathrm{m}$ corresponds to $\theta \approx 180\,\mu\mathrm{radian}$
  - model is confirmed by RF experts
- Structure tilt can impact beam-based alignment
  - old alignment gave $\Delta\epsilon_y = 2.6\,\mathrm{nm}$, improved one yields $\Delta\epsilon_y = 0.4\,\mathrm{nm}$
- Structure tilt can impact RF tolerances and breakdown requirements

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

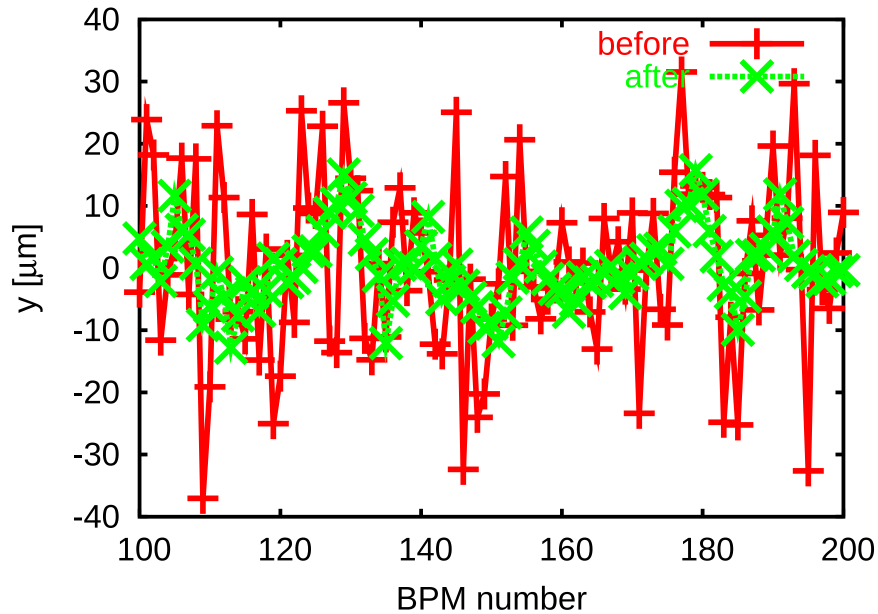
\- Tune luminosity
  - tuning knobs

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:

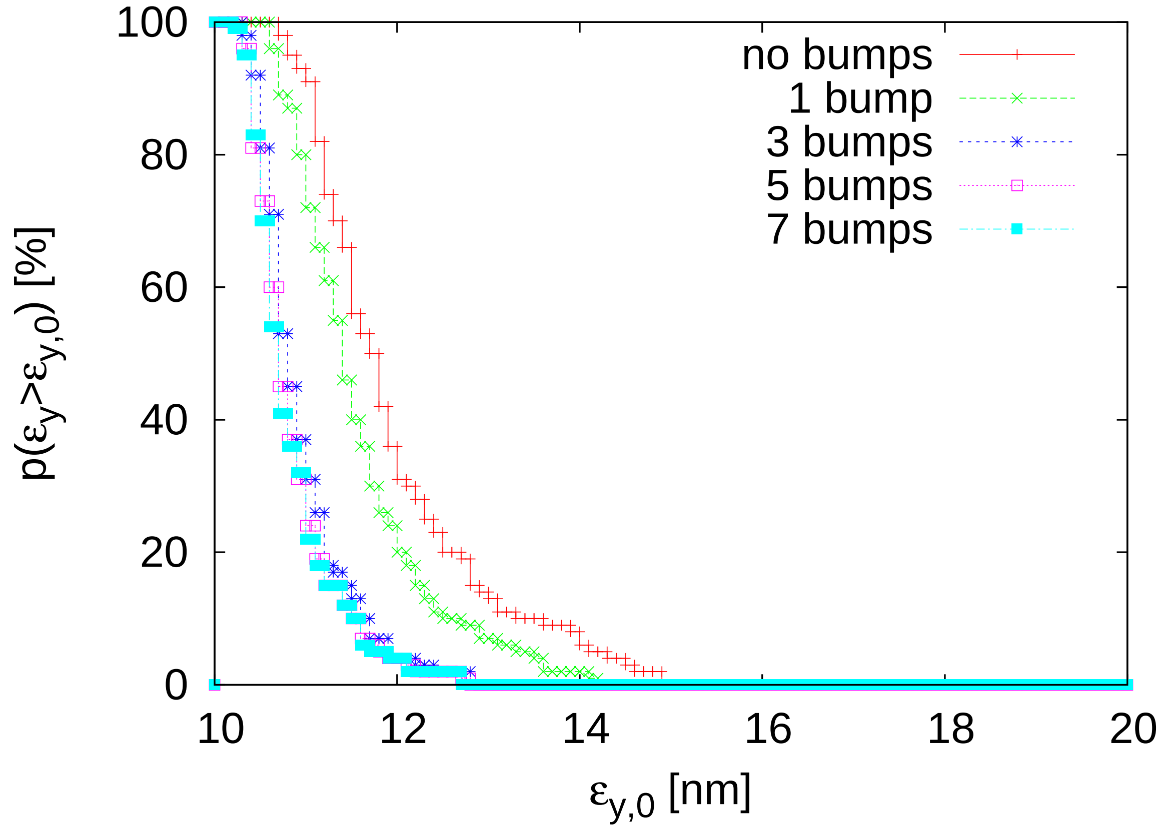
$$S = \sum_{i=1}^{n} \left(w_i (x_{i,1})^2 + \sum_{j=2}^{m} w_{i,j} (x_{i,1} - x_{i,j})^2 \right) + \sum_{k=1}^{l} w'_k (c_k)^2$$

- 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

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

	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



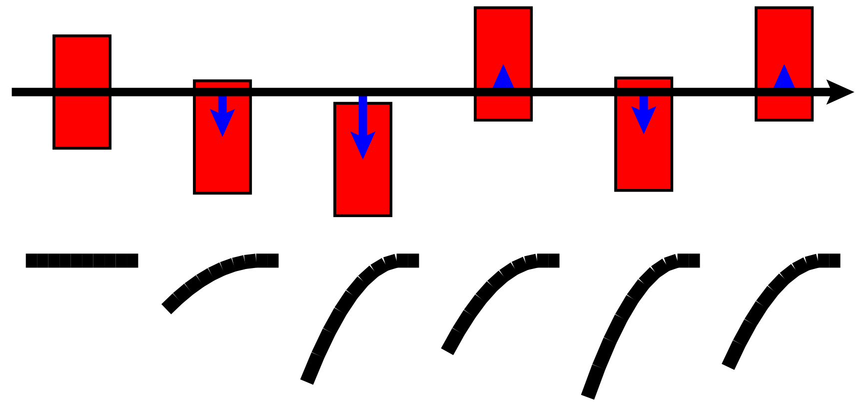
Beam-Based Structure Alignment

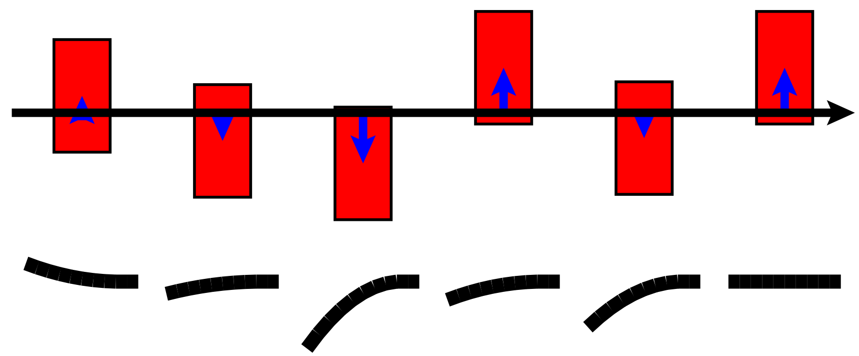
- Each structure is equipped with a wakefield monitor (RMS position error $5\,\mu\mathrm{m}$)
- Up to eight structures on one movable girders

⇒ 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

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

Long-Range Wakefields Effects

- We allow $W_\perp = 10\,\mathrm{kV/pCm^2}\;G/150\,\mathrm{MV/m}\;4\times 10^9/N$
  - assume kick only a next bunch
- Assume point-like bunches

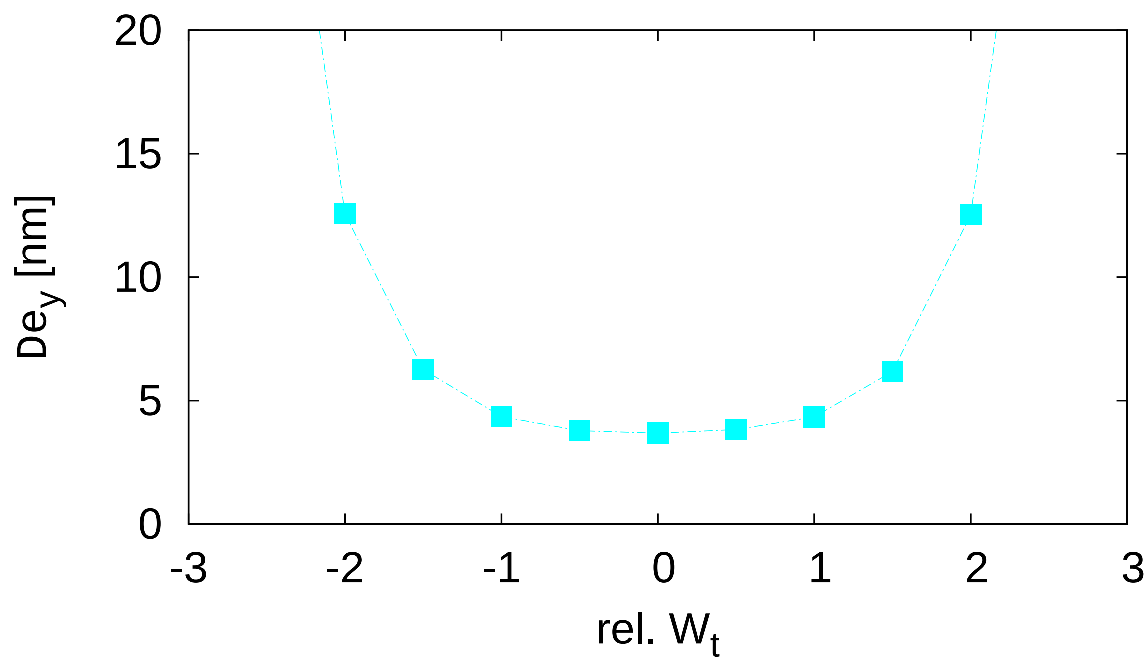
⇒ Coherent offset of the train leads to little emittance growth

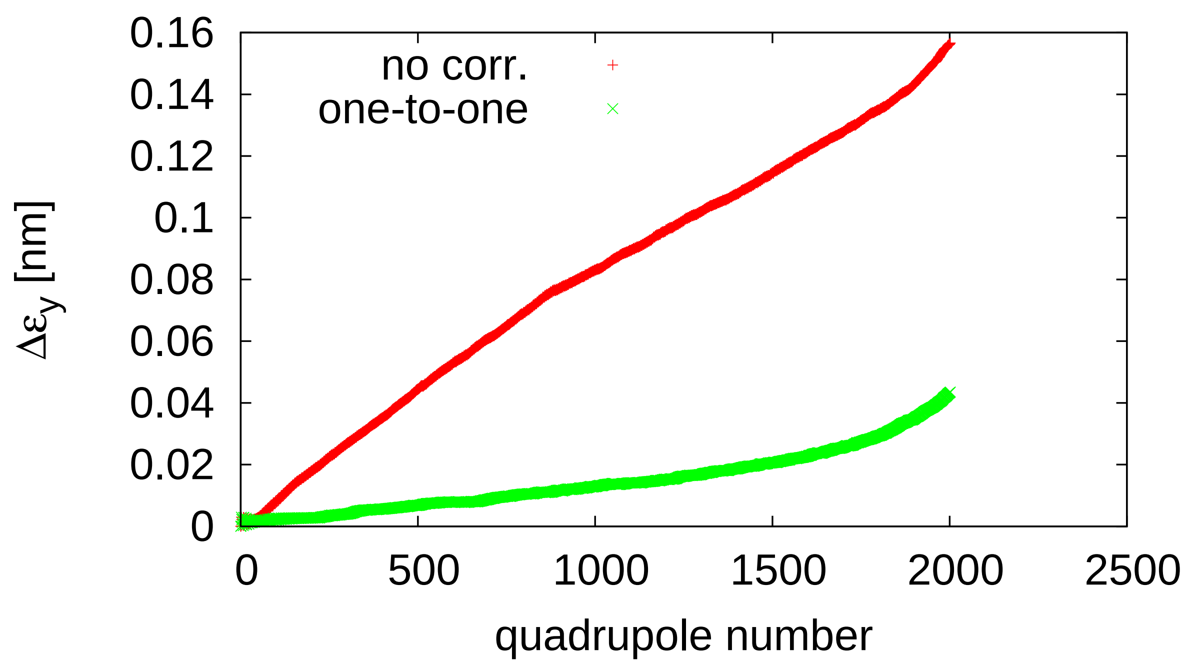
  bunch energy spread stabilises

- Use full bunches
- Study a perfect linac with 10 $\mu\mathrm{m}$ RMS misaligned longrange wakes
  - emittance growth only due to long-range wake

  ⇒ $\Delta\epsilon_y \approx 0.04\,\mathrm{nm}$ after one-to-one steering

  ⇒ acceptable





Breakdown Rate

- Direct limit to breakdown rate
  - 1% luminosity loss budget
  - assuming that a pulse with breakdown leads to no luminosity
  - have 7×10^4 structures per linac

  $\Rightarrow$ breakdown rate $0.01/14 \times 10^4 \approx 0.7 \times 10^{-7}$
- Assumed strategy is to switch off corresponding PETS and slowly go up to power again
- Indirect luminosity loss exists due to switching off of PETS
  - if structures are tilted this deflect the beam

$$\frac{\Delta y'}{\sigma_{y'}} = \frac{\theta G L e}{2E}\sqrt{\frac{\gamma\beta_y}{\epsilon}}$$

- Due to the tilt, switching off a pair of structures leads to a transverse deflection of

$$\left\langle \frac{\Delta y'^2}{\sigma_{y'}^2} \right\rangle \approx 0.16$$

$\Rightarrow \Delta\epsilon_y \approx 0.8\,\mathrm{nm}$, time to recover from switching off structure is important

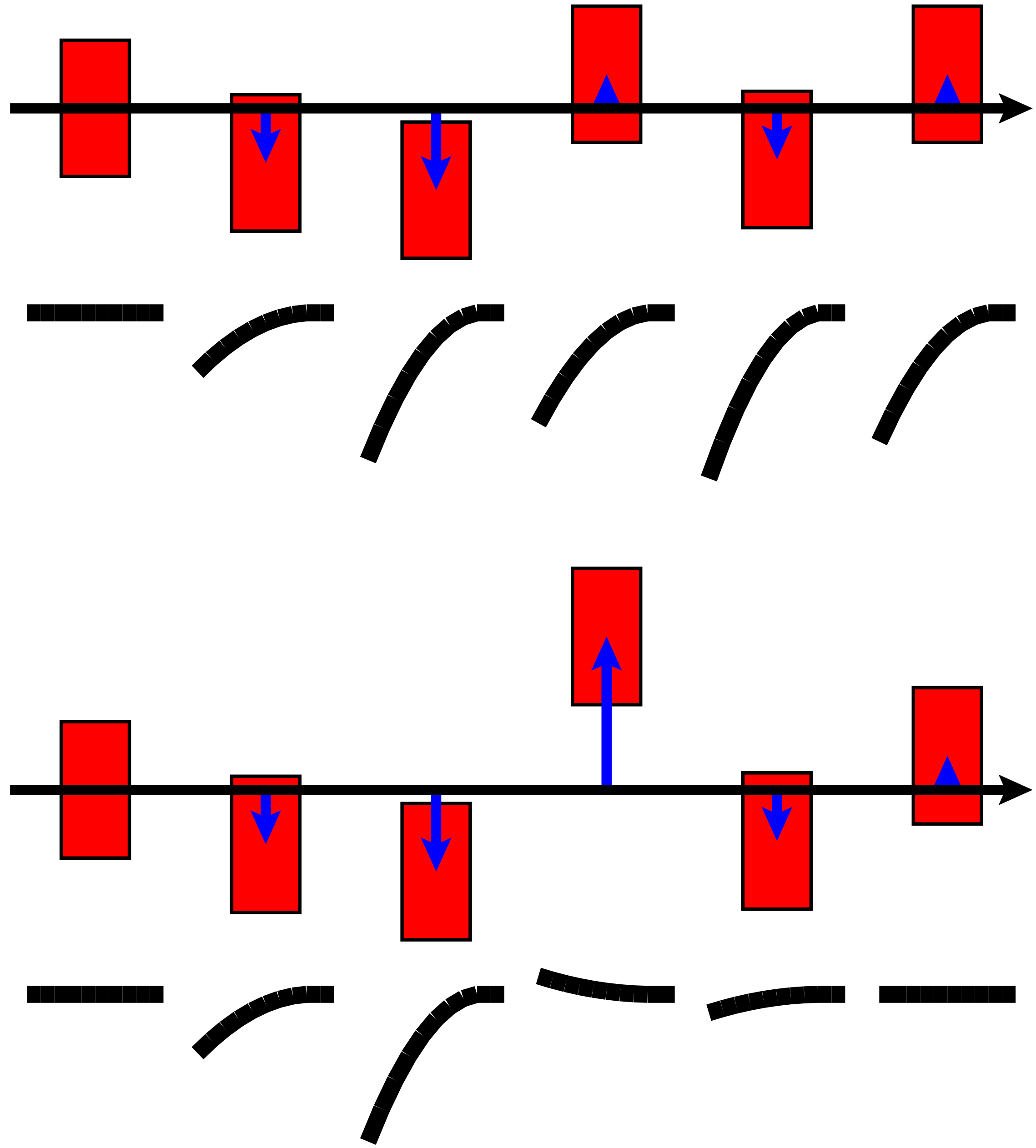
- Need to study full effects

Summary of Accelerating Structure Tolerances

- Structure tilts
  - structure precision
  - for quadrants $\sigma_{ang} \leq 200\,\mu\mathrm{radian}$ corresponds to $\sigma_{\Delta z} \leq 1\,\mu\mathrm{m}$
- Mean transverse misalignment of relevant groups of structure to the beam
  - wake monitors
  - $\sigma_{wm} \leq 5\,\mu\mathrm{m}$
- RMS transverse misalignment of the individual structures to the beam
  - structure mechanical alignment on girder
  - $\sigma_{cav,rms} \leq 10\,\mu\mathrm{m}$
- misalignment of the structure pieces to the beam
  - depends on details of long-range wake, but likely $\sigma_{cav,part} \leq 5\,\mu\mathrm{m}$ is sufficient

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

Single Bunch Dynamic Tolerances

- For jitters 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

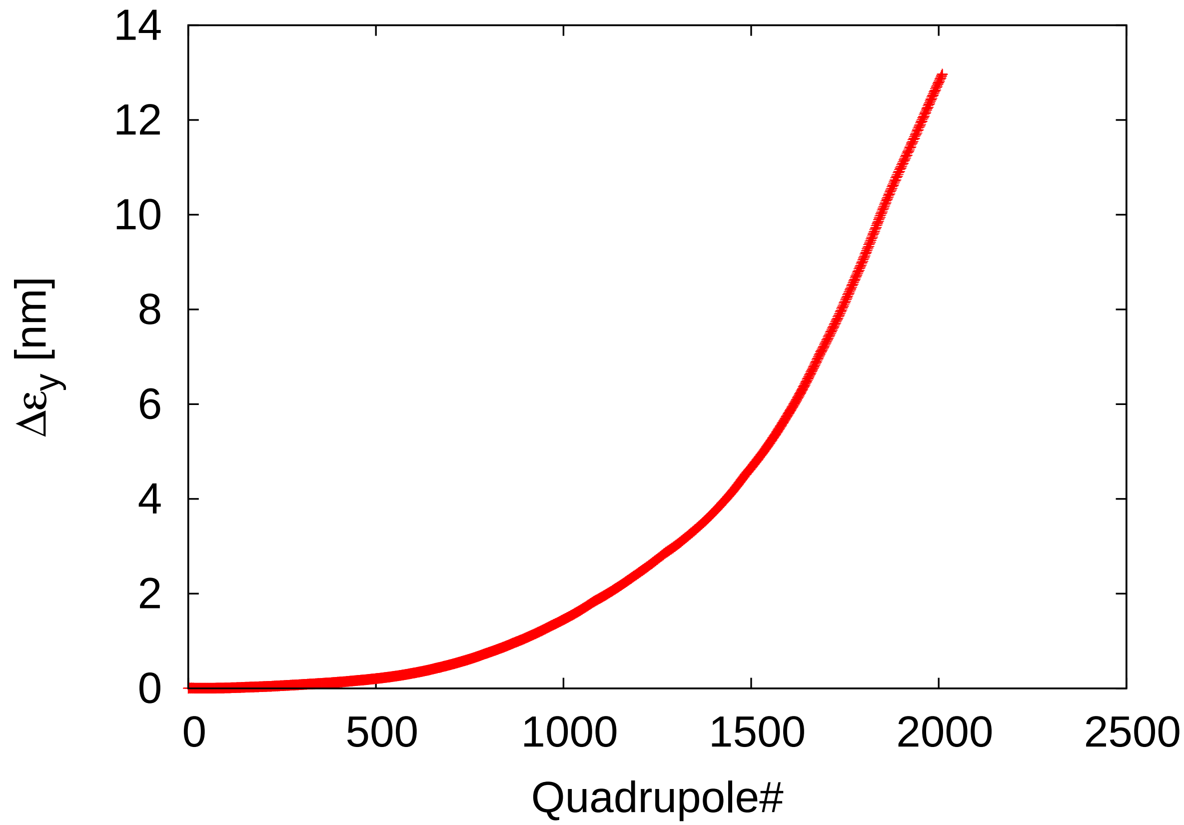
Current Conceptual Feedback Strategy

- Stabilisation of elements using local mechanical feedback
- Information from survey system is only recorded, not used directly
- Intra-pulse beam feedback
  - possible only at IP, BPM based
- Pulse-to-pulse feedback
  - main linac, BPM based orbit feedback
- Retuning
  - slow process in the main linac
- Complex beam-based alignment and tuning
  - not in normal running conditions
- Other feedback systems (e.g. tunnel temperatur)
- Will focus on mechanical feedback and the next layer
  - strong interaction between these two layers

Emittance Degradation with Time (1)

- All quadrupoles are stabilised against high frequency noise
  - but low frequency noise remains
- Can describe ground motion by ATL law

  $\langle [y_i(t) - y_j(t)]^2 \rangle = At\|z_i - z_j\|$
  - random walk in space and in time
  - expectation value for emittance growth is linear in time
  - we use $A = 0.5 \cdot 10^{-12}\,\mathrm{m/s}$



- Emittance growth in CLIC main linac depends on operational parameters, e.g. RF phases
  - typical result from simulation is given for $t = 100\,\mathrm{s}$ and no beam-based correction

⇒ Emittance growth is $0.13\,\mathrm{nm/s}$, total dynamic budget is used after $40\,\mathrm{s}$

⇒ Need fast feedback

- On shorter time scale element jitter will be also important

Overall Fast Feedback Design

- Main basis will be a fast BPM-based orbit feedback

  ⇒ feedback on same beam property at different locations

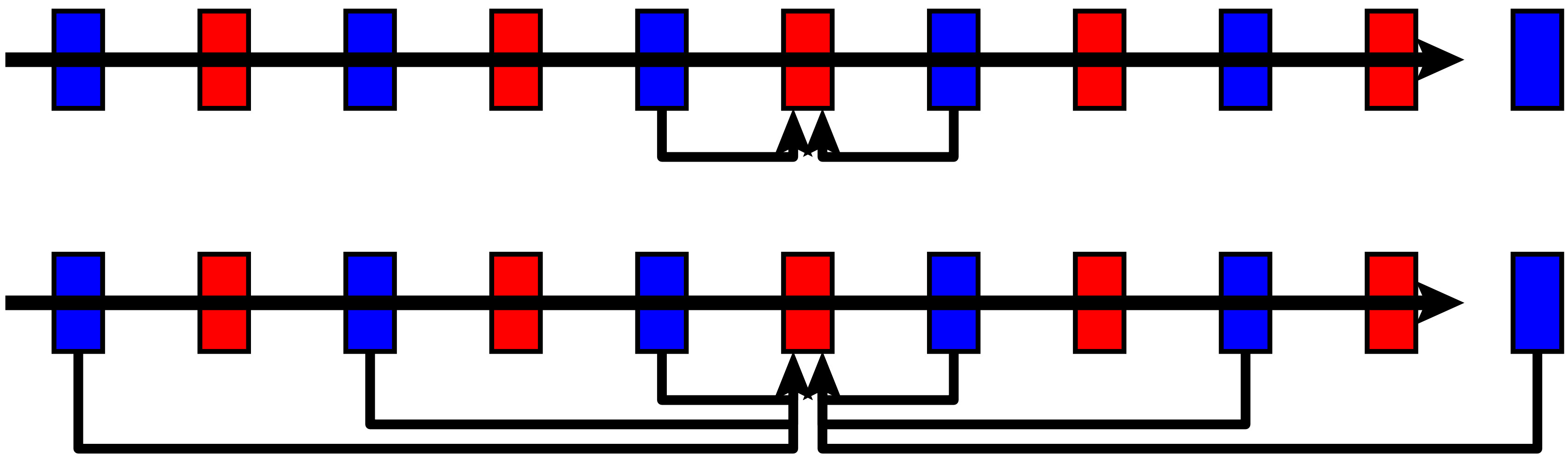
- Three alternatives considered

  - chain of independent MIMOs, have to share bandwidth, slow

  - chain of decoupled MIMOs, but no perfect decoupling

  - single MIMO, model error needs to be studied

- Except for collision point beam position and angle will be corrected by each feedback



Emittance Degradation with Time (2)

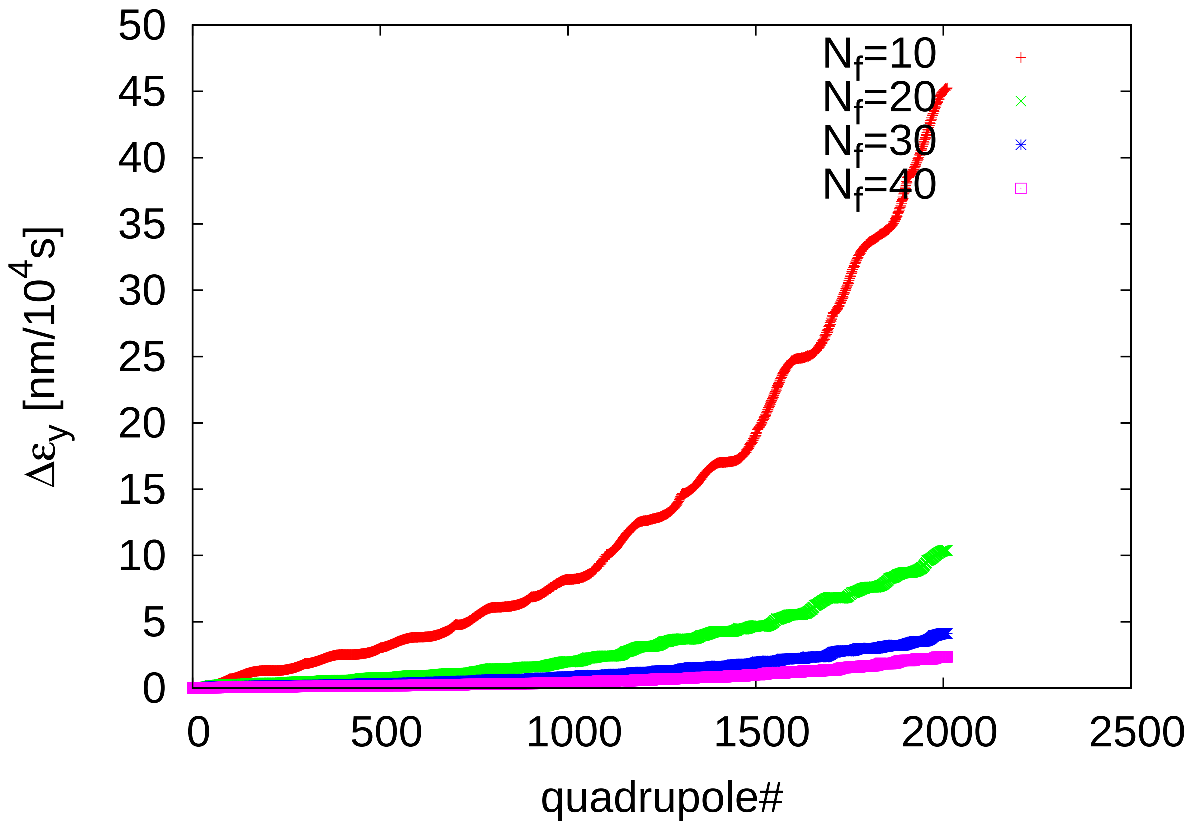
- Example with fixed feedback stations in main linac is shown
  - different number N_f of feedback stations
  - ATL-like ground motion with $A = 0.5 \cdot 10^{-12}\,\mathrm{m/s}$
- Growth is about

$$\Delta\epsilon_y \approx 0.45 \frac{\mathrm{nm}}{\mathrm{s}} \frac{1}{N_f^2} t$$

- For 40 feedback stations, $\Delta\epsilon_y \approx 1\,\mathrm{nm}$ after $1\,\mathrm{h}$

  $\Rightarrow$ need next layer of feedback

  $\Rightarrow$ be careful with tuning



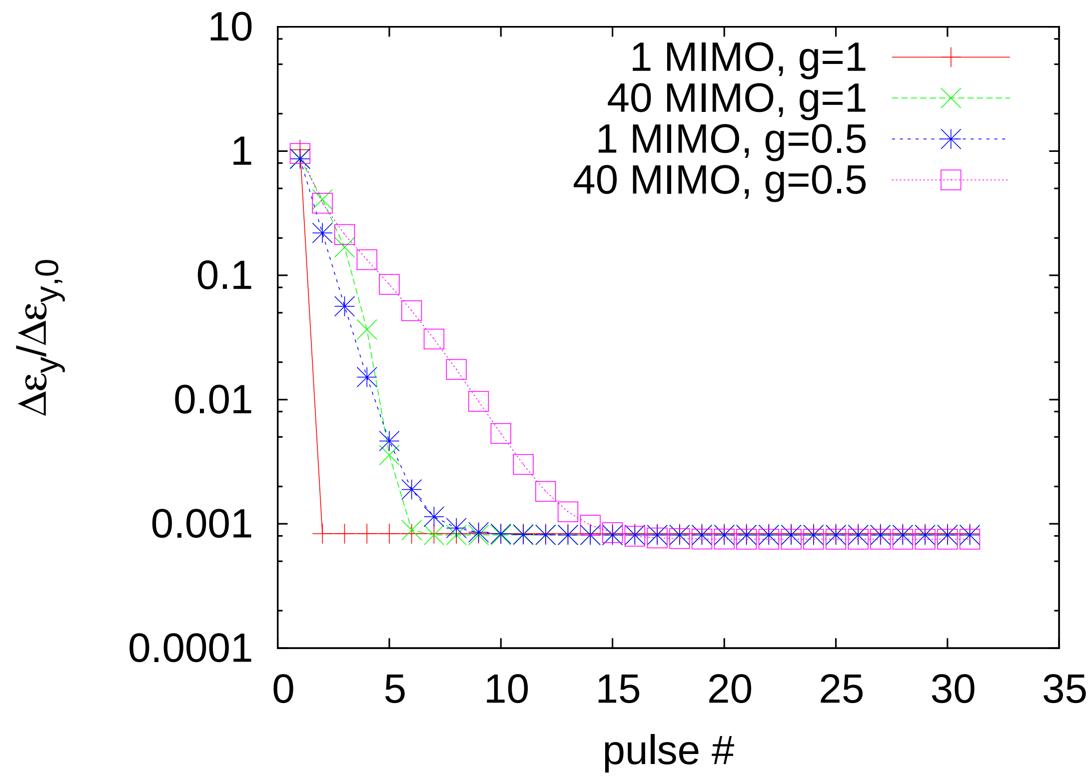
Main Linac Feedback

- Comparison of decoupled feedback and MIMO
- Simulation contained
  - random misalignment of quadrupoles over some time
  - then machine is assumed to be sufficently stable pulse to pulse to be static
  - 40 feedback stations have been sued

⇒ One single MIMO gives much better performance

⇒ Residual emittance growth after convergence reduced by factor of about 1000

  - consistent with ATL motion results



Main Linac BPM Resolution

- The BPM resolution will limit the feedback bandwidth
- Assume pulse-to-pulse uncorrelated BPM readout jitter
- BPM resolution is determined by need to see beam jitter
  - beam jitter is measured in vertically focusing quadrupoles
  - beam is smallest at the end of the linac
  - with $\beta_y \approx 65\,\mathrm{m}$ and $\epsilon_y \approx 10\,\mathrm{nm}$ we find $\sigma_y \approx 465\,\mathrm{nm}$

  $\Rightarrow$ require BPM resolution of about $50\,\mathrm{nm}$
- For 50 nm resolution, the multi-pulse emittance growth is $\Delta\epsilon_y \approx 0.04\,\mathrm{nm}$, the corresponding luminosity loss is $\Delta\mathcal{L}/\mathcal{L} \approx 0.1\,\%$, if we attempt full correction from one pulse to the next
- Open for dispute if significant cost savings possible

Further Feedback Studies

- Alternative feedback configurations
  - MICADO
  - variable bandwidth
- Integration with RTML and BDS
  - some simplification may be possible/needed
- Integration of more noise sources
  - e.g. RF phase and amplitude jitter
- Stabilisation feedback
  - performance, including uniformity
- Development of improved controller
- Automatic determination of response matrix
  - to follow slow variation of the machine

Conclusion

- Dispersion free steering can achieve the emittance preservation
  - provided specifications can be met
  - specifications will be reviewed for optimisation
    - e.g. more detailed pre-alignment model
  - dynamic effects during correction need to be included in more detail
- The effective structure may dominated by the structure production precision
  - an important effect for the beam dynamics
  - even for break downs
- A concept for orbit feedback exists
  - integration with other transport systems required
  - integration of other noise sources ongoing
  - system knowledge is a concern

Reserve Slides

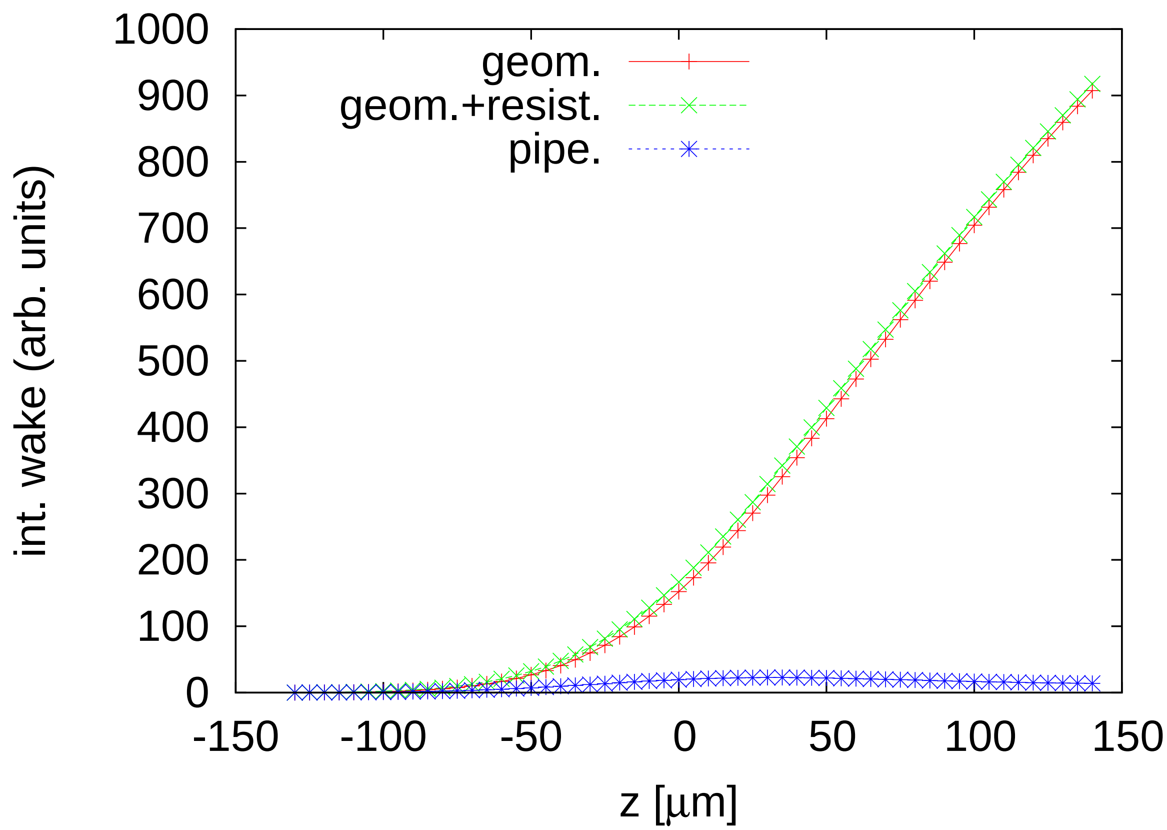
Resistive Wall Wakefield

- Comparing wakefield
  - for a beam pipe of $r = 3\,\mathrm{mm}$
  - averaging over structure irises
  - taking into account average fill factors

⇒ Impact of resistive wall on beam jitter amplification is small

  - but not a lot of margin

⇒ alignment of the beam pipe is also important



- Long-range wakefield has $1/\sqrt{z}$ shape

  ⇒ worst is last bunch

$$\frac{\sum_{j=0}^{n-1} N_j e^2 W_\perp(j\delta z)}{2} \int_0^L \frac{\beta(s)}{E(s)} ds \approx 0.1$$

⇒ multi-bunch jitter amplification is small

Corrector Step Error

- The steps performed by the correctors may not be predictable
  - will lead to additional emittance growth
- A random error in the corrector step can be regarded as quadrupole jitter
- A simple estimate of allowed error is given by

$$\sigma_{step} \approx \sigma_{jitter}\sqrt{\frac{N_{quad}}{N_{corrector}}}$$

$N_{corrector}$ is the number of correctors used

- To be negligible for $N_{corrector} = 80$ we require $\sigma_{step} < 5\,\mathrm{nm}$

$\Rightarrow$ Should use minimum step size of $\Delta = 5\,\mathrm{nm}$ to reduce impact of step size to much less than quadrupole jitter

- Typical movements are some $100\,\mathrm{nm}$ (but site dependent)
  - we require convergence between pulses
- Residual emittance for simple algorithm

$$\Delta\epsilon_y \approx 2\,\mathrm{nm}\left(\frac{\Delta y}{100\,\mathrm{nm}}\right)^2$$