Beam Dynamic and the CLIC Module

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- Emittance preservation target and lattice design
- Static imperfections
- Dynamic imperfections
- Operational considerations

CLIC Module Review September 15 2009

Low Emittance Transport Challenges

- Main linac is a most important source of emittance growth, is closely linked to the technology and imperfections have been studied in some detail
  - it is anticipated that we will not allow for tighter specifications elsewhere
  - but remains to be confirmed
- Static imperfections

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

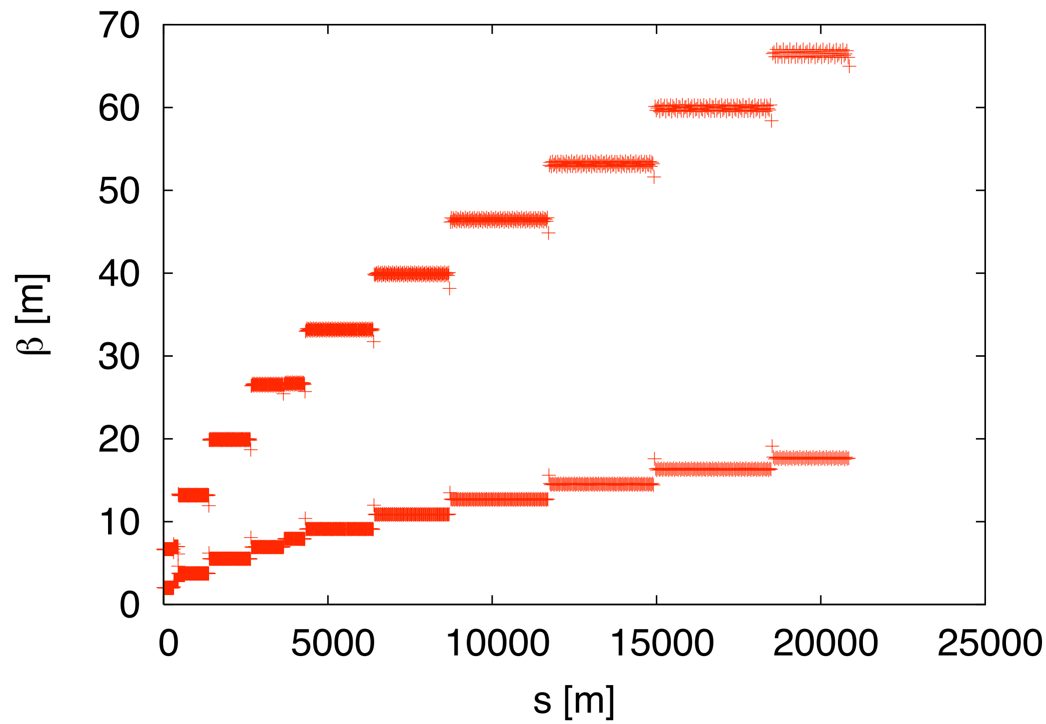
  pre-alignment, lattice design, beam-based alignment, beam-based tuning
- Dynamic imperfections

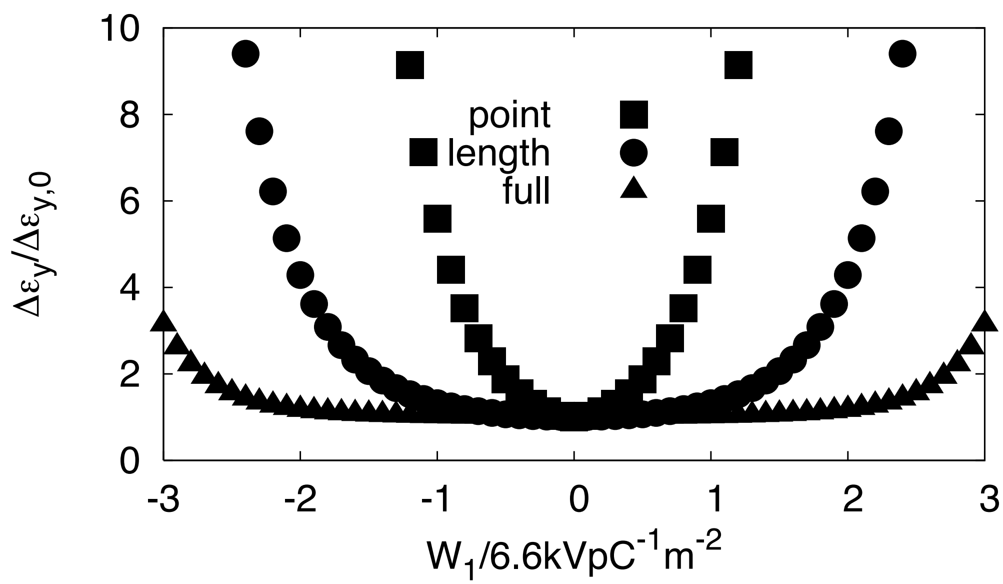
  element jitter, RF jitter, ground motion, beam jitter, electronic noise,...

  lattice design, BNS damping, component stabilisation, feedback, re-tuning, re-alignment
- 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 ($\rightarrow$ tolerances 2.5 times larger)

Lattice Design

- Used $\beta \propto \sqrt{E}$, $\Delta\Phi = \mathrm{const}$
  - balances wakes and dispersion
  - roughly constant fill factor
- Total length about 21 km
  - fill factor about 78.6%
- 12 different sectors used
- Matching between sectors using 7 quadrupoles to allow for some energy bandwidth
- Single bunch stability ensured by BNS damping
- Multi-bunch coherent offset leads to phase shift of 90° at linac end
- Bunch-to-bunch offset amplification shown





Magnet Specifications

Parameter	value
Field gradient	$\geq 200\,\mathrm{T/m}$
Minimum inner radius of beam pipe	$\geq 4\,\mathrm{mm}$
Accuracy of magnetic centre	$10\,\mu\mathrm{m}$
Alignment beam pipe to magnetic centre	$30\,\mu\mathrm{m}$
Accuracy of field gradient	0.1%
Horizontal stability of field centre	$2\,\mathrm{nm}$
Vertical stability of field centre	$1\,\mathrm{nm}$
Stability of field gradient	0.5×10^{-4}
Corrector resolution	$5\,\mathrm{nm}$
Corrector speed	$\leq 5\,\mathrm{ms}$
Corrector range	$\pm 10\,\mu\mathrm{m}$
Corrector time requ.	$\leq 5\,\mathrm{ms}$
Corrector field stability	0.5×10^{-4}
Residual field gradient	$0.2\,\mathrm{T/m}$
Residual field at centre	$2\,\mu\mathrm{T}$

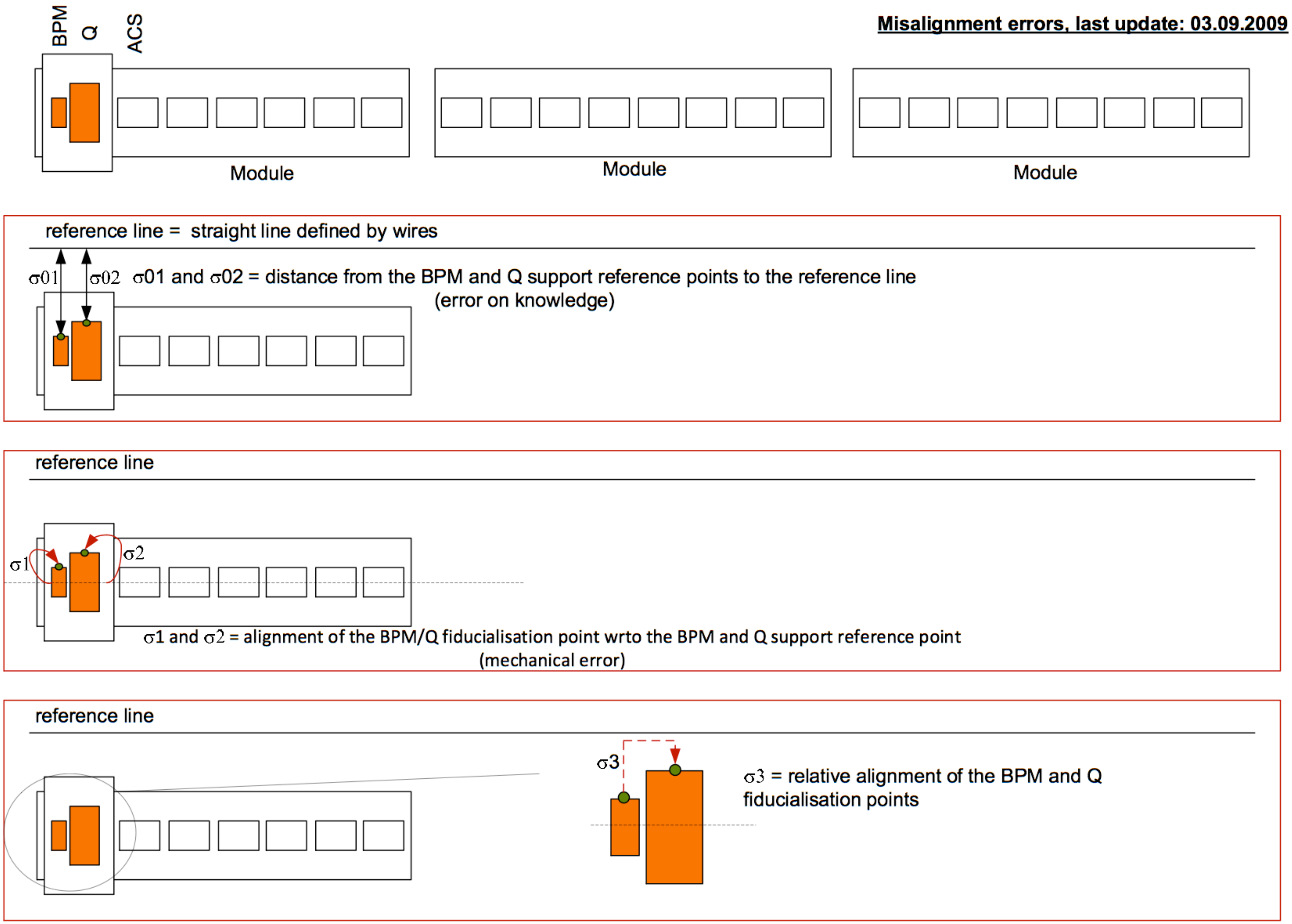
- Magnets come in four lengths $0.35\,\mathrm{m}$ to $1.85\,\mathrm{m}$

Alignment Tolerances

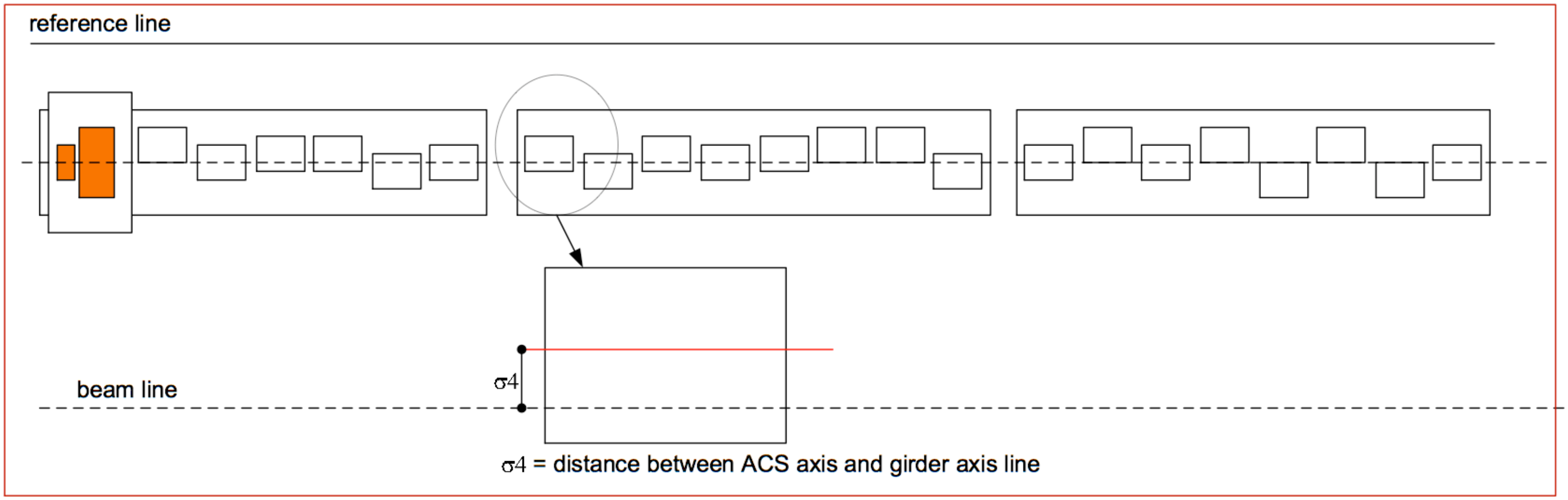
- Long- and short-distance imperfections exist
  - they can be treated largely independently
- Short-range alignment performance predictions have been made by the alignment experts
  - they have been endorsed by the beam dynamics

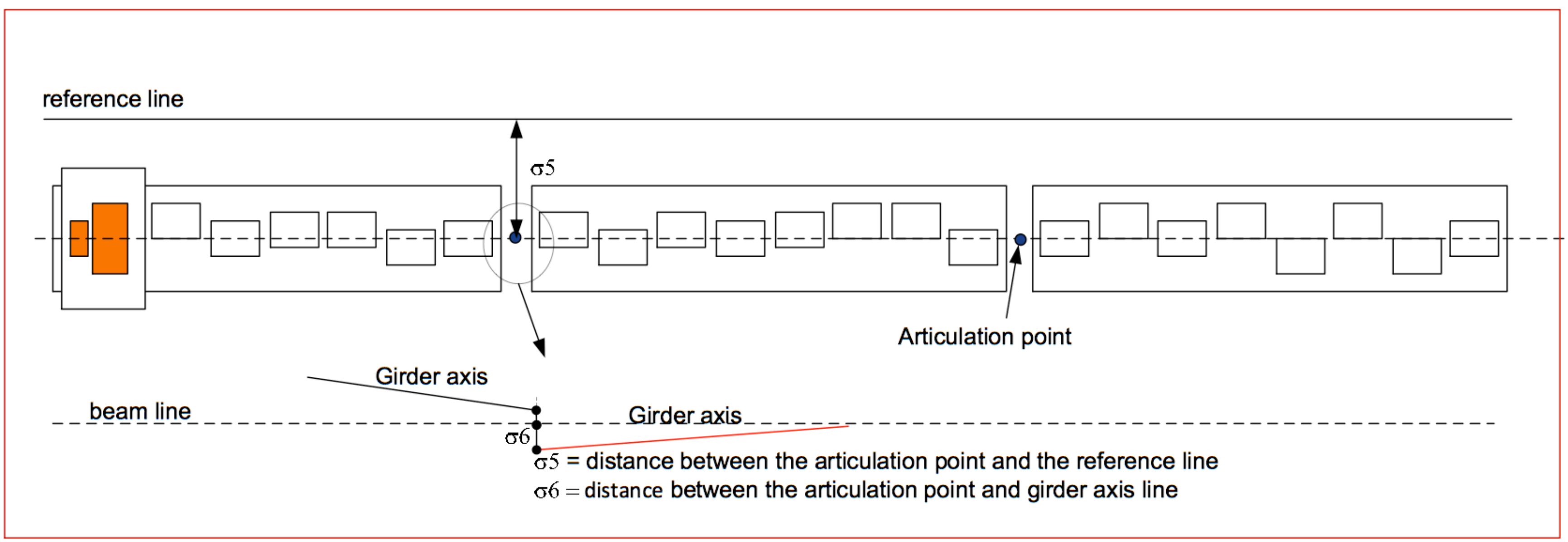
  ⇒ they appear acceptable
- Long-range alignment performance predictions have been made
  - model needs to be completed
  - sofar the performance is acceptable
- Trade-off for cost would need to be studied
  - can only be done for specific scenarios
  - beam-based alignment performance depends on all imperfections with trade-offs
- Note: in the following plots articulation point after the quadrupoles is missing

Alignment Model

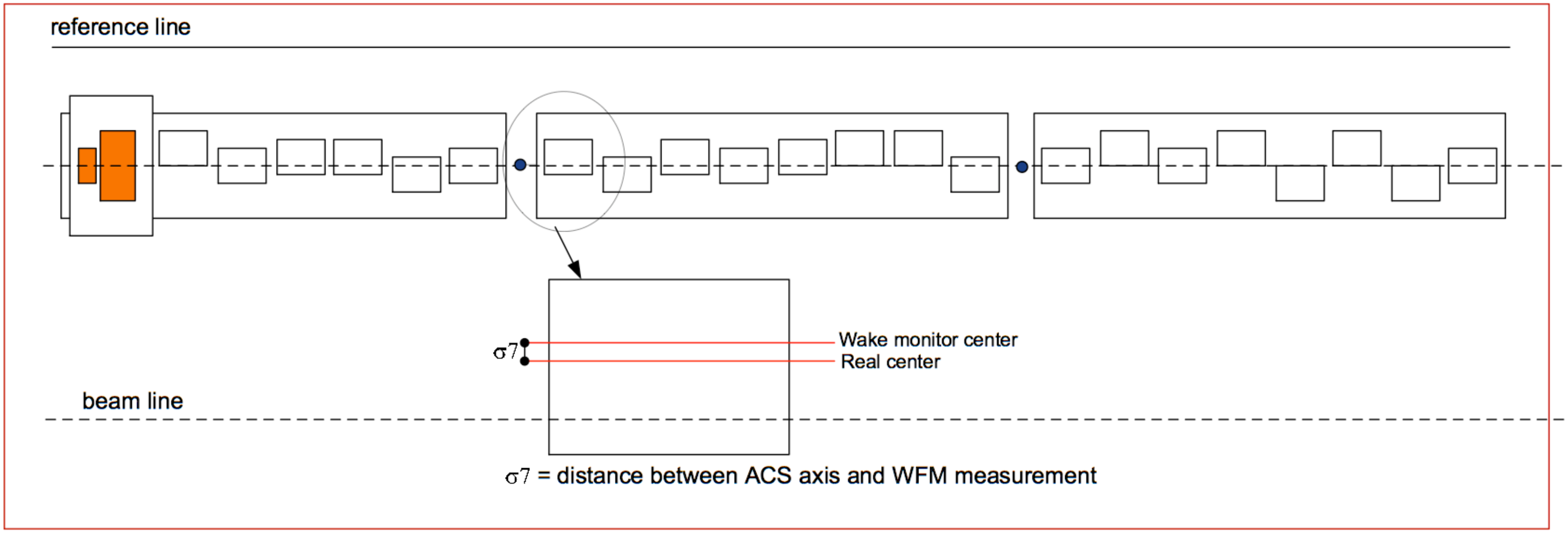


Alignment Model (cont)





Alignment Model (cont)



imperfection	with respect to	symbol	target 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

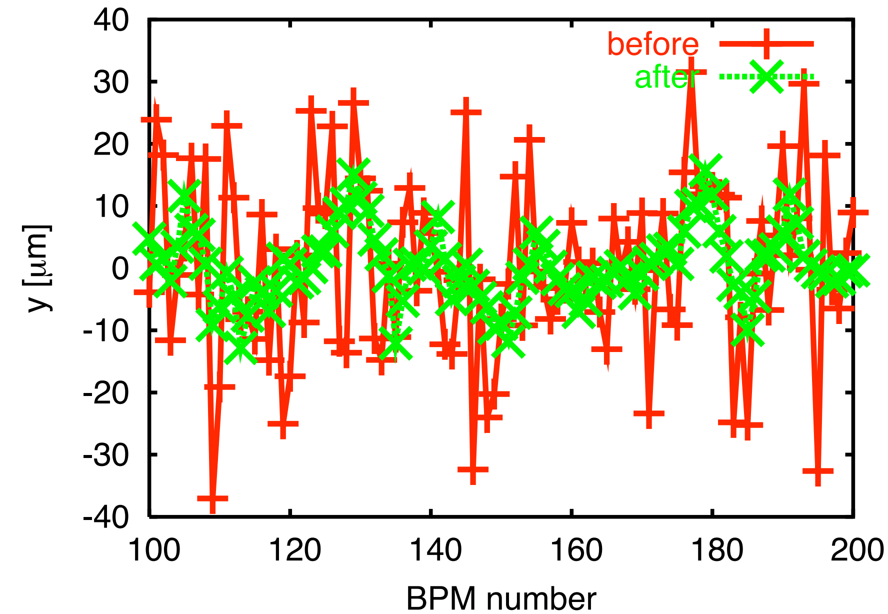
- Make beam pass linac
  - one-to-one correction
- Remove dispersion, align BPMs and quadrupoles
  - dispersion free steering
  - ballistic alignment
  - kick minimisation
- Remove wakefield effects
  - accelerating structure alignment
  - emittance tuning bumps

- Tune luminosity
  - tuning knobs

Dispersion Free Correction

- Basic idea: use different beam energies
- Our scheme: accelerate beam with different gradient and initial energy along the pulse
  - dream: 10ns transition, 20ns nominal, 100ns transition, 20 ns probe beam

  $\Rightarrow$ probe beam bunch length ≈ 45–$70\,\mu\text{m}$
  - both beam within same pulse



- 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

Beam-Based Structure Alignment

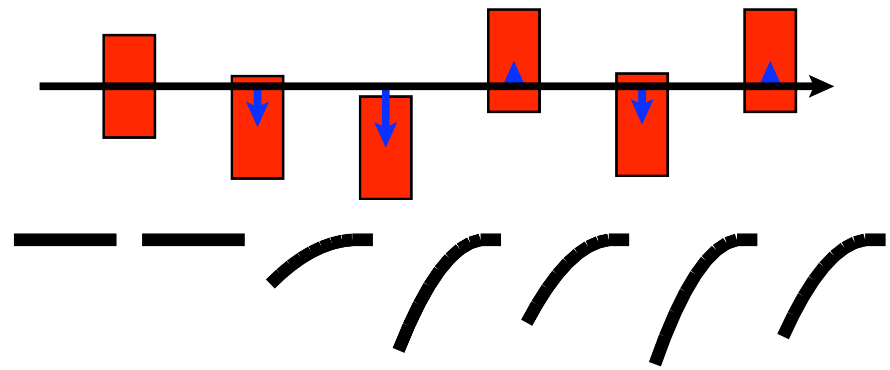
- Each structure is equipped with a wake-field monitor (RMS position accuracy $5\,\mu\mathrm{m}$)
- Up to eight structures on one movable girders

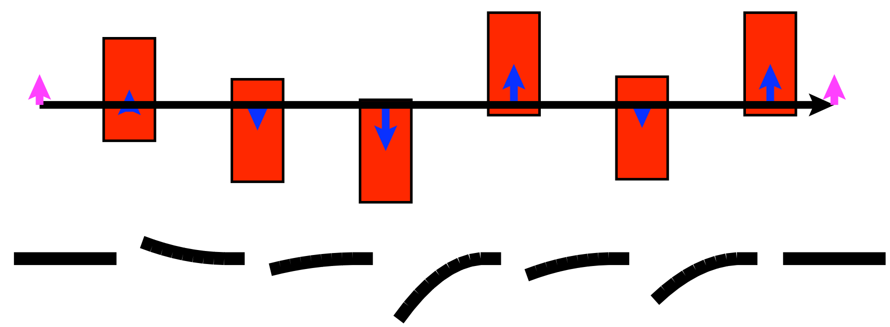
⇒ Align structures to the beam minimising the mean offset

  ⇒ need two signals per girder in each plane, offset and slope

  ⇒ but only for a limited number of girders at any given moment

- Girder step size $\leq 1\,\mu\mathrm{m}$
- Easiest is to move girders independent of others
  - if girders are linked at least one independent point before and after BPM/quadrupole unit



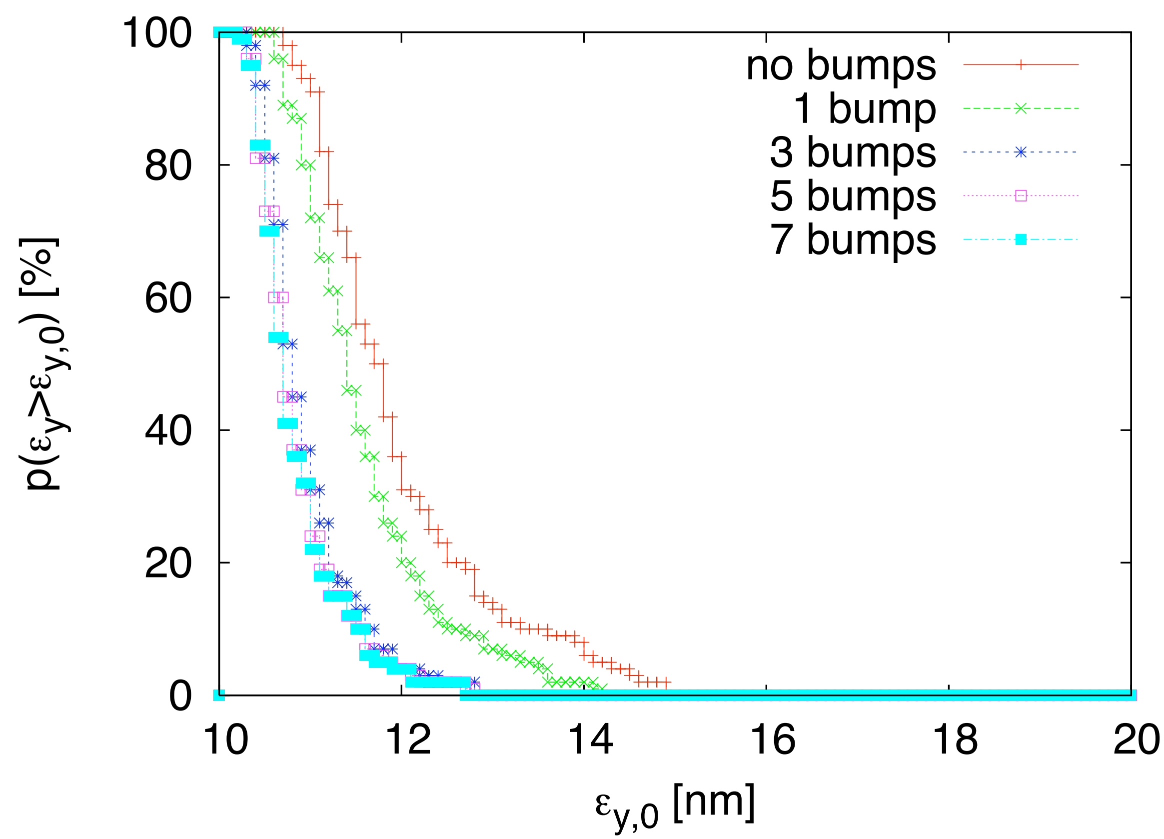


- For our tolerance $\sigma_{wm} = 5\,\mu\mathrm{m}$ we find $\Delta\epsilon_y \approx 0.5\,\mathrm{nm}$
  - some dependence on alignment method

Final Emittance Growth

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	$0.04\,\mathrm{nm}$
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	$\approx 0.12\,\mathrm{nm}$

- Selected a good DFS implementation
  - trade-offs are possible
- Multi-bunch wakefield misalignments of $10\,\mu\mathrm{m}$ lead to $\Delta\epsilon_y \approx 0.13\,\mathrm{nm}$
- Performance of local prealignment is acceptable



Dynamic Imperfections

- Luminosity loss is part of the emittance budget
- But limit luminosity fluctuation to less than 10%
  - total luminosity fluctuation is not straightforwad
- For the main linac the following tolerances apply

Source	budget	tolerance
Transfer line stray fields	?%	data needed
Quadrupole jitter in main linac	1%	$\sigma_{jitter} \approx 1.5\,\mathrm{nm}$
RF amplitude jitter in main linac	1%	0.075% coherent, 0.22% incoherent
RF phase jitter in main linac	1%	0.2° coherent, 0.8° incoherent
RF break down in main linac	1%	rate$< 3 \cdot 10^{-7}\,\mathrm{m}^{-1}\mathrm{pulse}^{-1}$
Structure pos. jitter in main linac	0.1%	$\sigma_{jitter} \approx 880\,\mathrm{nm}$
Structure angle jitter in main linac	0.1%	$\sigma_{jitter} \approx 440\,\mathrm{nradian}$

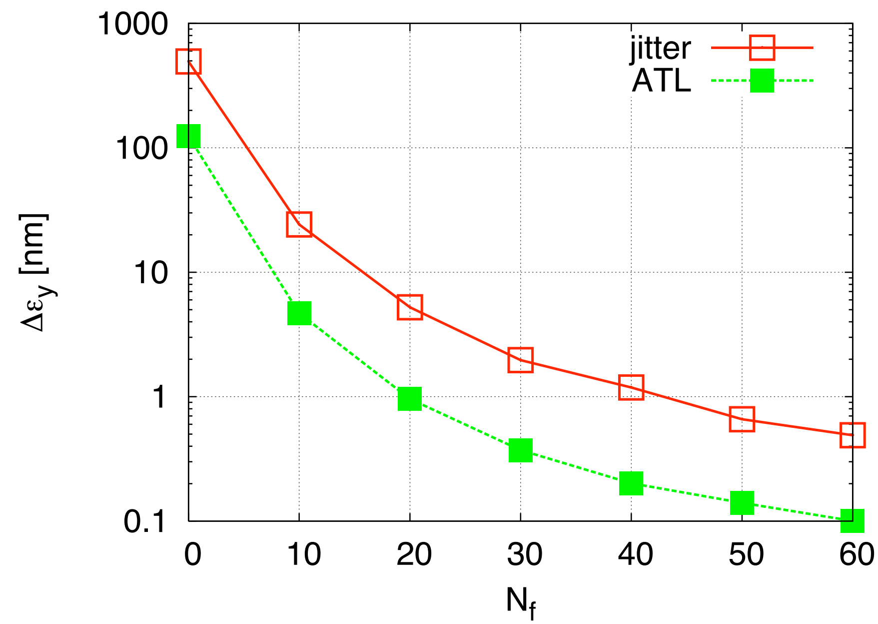
$\Rightarrow$ Long list of small sources adds up

$\Rightarrow$ Impact of feedback system is important

Main Linac Fast Feedback Design

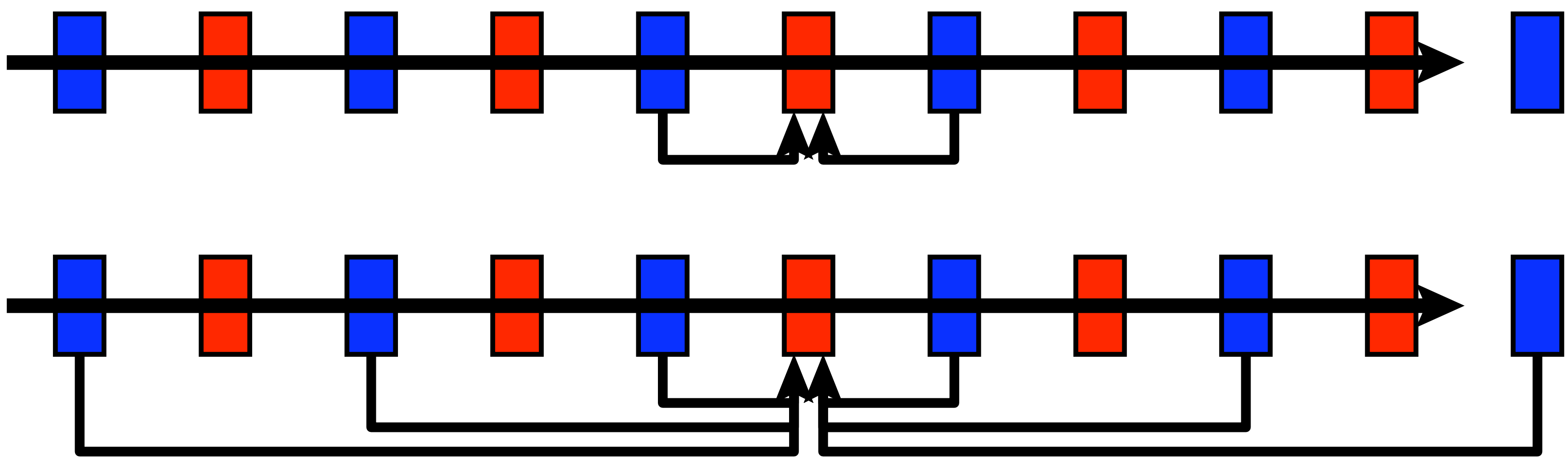
- Pulse-to-pulse feedback with $5\,\mathrm{ms}$ data aquisition, $10\,\mathrm{ms}$ data treatment and $5\,\mathrm{ms}$ corrector use
- No feedback leads to $0.5\,\mathrm{nm/s}$ with ATL (B) motion

  $\Rightarrow$ ground motion alone could be acceptable, but technical noise, supports...
- Main basis will be a fast BPM-based orbit feedback with single MIMO
- Chose 41 BPM stations (8 BPMs each) and 40 corrector stations (2 correctors each)



- 1000 s ATL motion and 100 nm quad jitter

  $\Rightarrow$ can run for O(1000 s)



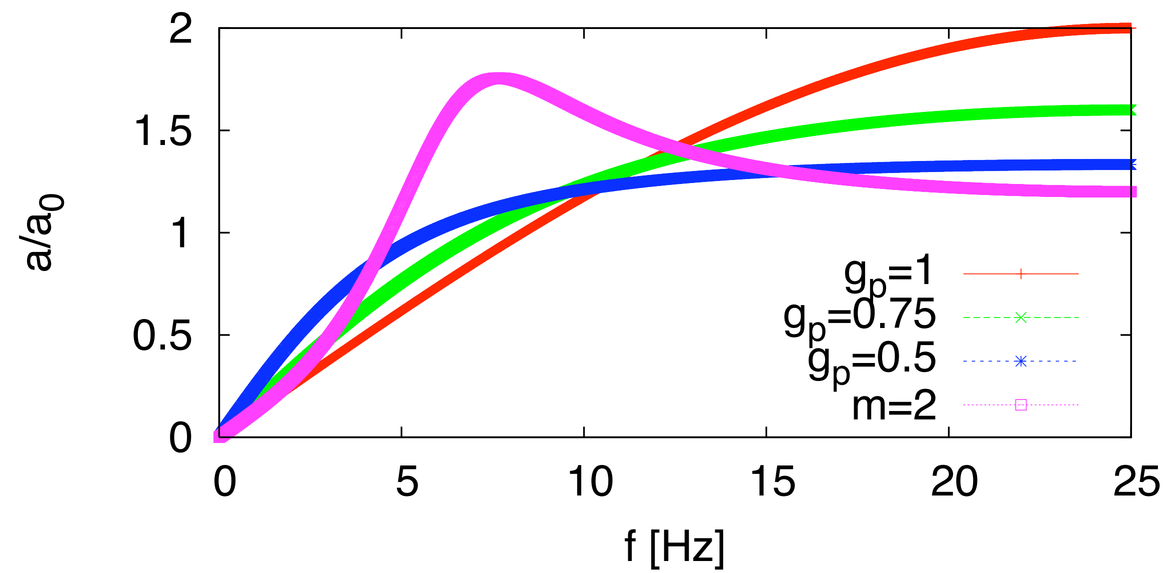
Pulse-to-Pulse Tolerance with Feedback

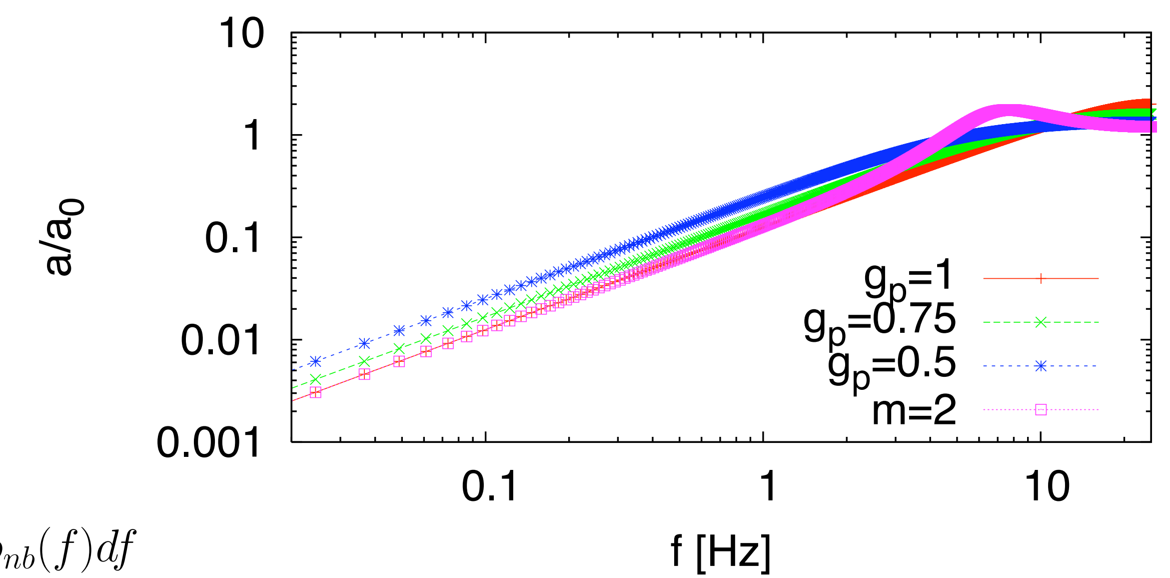
- The frequency response of the feedback is controller dependent
  - working on a design but need to take into account next layer (Juergen)
- One can trade-off different properties
  - but within limits
- Simple feedback is shown

$$c_{n+1} = c_n + g_p R y_n$$

- One case of use of recursive filter als shown
- Figure of merit

$\int_0^\infty R_b^2(f)\{R_s^2(f)p_g(f)+p_n(f)\}+p_{nb}(f)df$





BPM Resolution and Corrector Step Size

- Assume pulse-to-pulse uncorrelated BPM readout jitter
  - For 100 nm resolution, the emittance growth is for $g = 1$ $\Delta\epsilon_0 \approx 0.1\,\mathrm{nm}$

  ⇒ little effect left for smaller gain g or better resolution

  - would like to resolve $0.1\sigma_y$ at end of main linac with

    ⇒ ask to explore BPM resolution of about $50\,\mathrm{nm}$ but could accept somewhat worse

- Corrector step errors act like quadrupole jitter
  - assume use of 80 correctors simultaneously
  - $\sigma_{step} = 2\,\mathrm{nm}$ leads to $\Delta\epsilon_y = 0.04\,\mathrm{nm}$ in focusing quadrupoles
  - $\sigma_{step} = 3.6\,\mathrm{nm}$ leads to $\Delta\epsilon_y = 0.04\,\mathrm{nm}$ in defocusing quadrupoles

  ⇒ require step size of $\Delta y = 5\,\mathrm{nm}$ with precision $\sigma_{step} = 2\,\mathrm{nm}$

- Note these requirements are chosen such that the impact of the imperfections is negligible

  ⇒ if they are too tight the topic needs to be reviewed

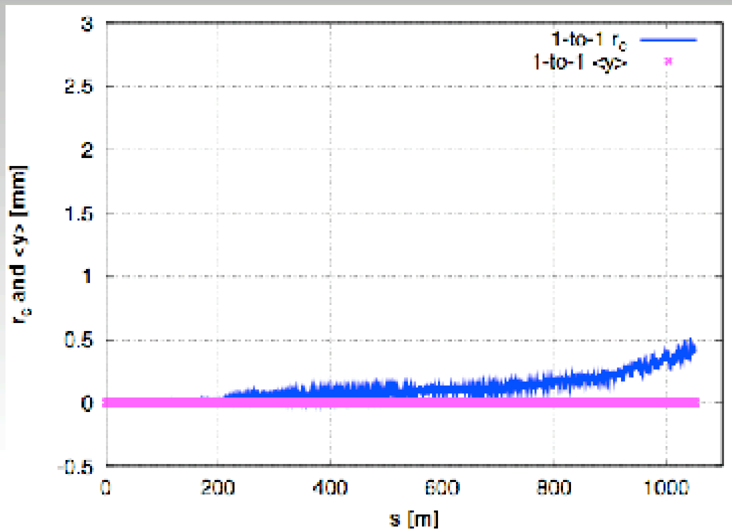
Main Linac Mover Requirements

- Coarse mechanical motion
  - structure girders, quadrupoles and BPM support
  - range: $\approx 1\,\mathrm{mm}$
  - step size: $\Delta \approx 1\,\mu\mathrm{m}$
  - precision: $\approx 0.5\,\mu\mathrm{m}$
  - speed: may take a few pulses, but controlled
- Fine effective quadrupole motion
  - step size: $\Delta \approx 5\,\mathrm{nm}$
  - range: $\approx 20\,\mu\mathrm{m}$
  - precision: $\approx 2\,\mathrm{nm}$
  - speed: from pulse to pulse
- Very fine quadrupole motion
  - resolution: $\Delta \approx 0.1\,\mathrm{nm}$?
  - range and precision: tbd
  - speed: works in intervall between pulses
- Precision could be defined as function of step size

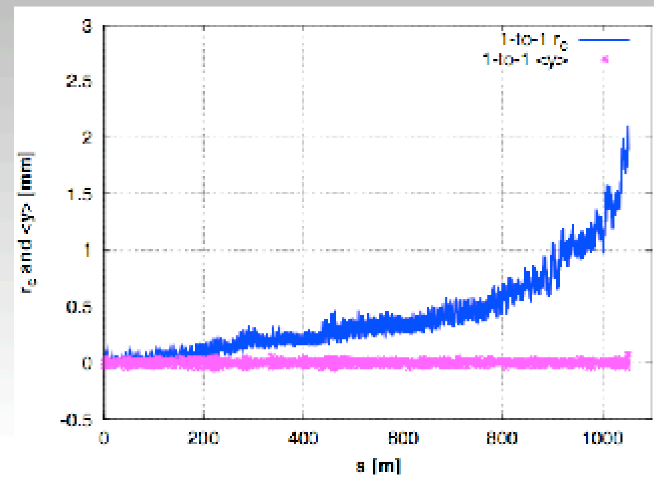
Drive Beam Specifications

- Criterium: beam centrois not moved by more than $1\,\mathrm{mm}$
- PETS offset: $100\,\mu\mathrm{m}$
  - the PETS give relatively small transverse kicks
- PETS tilts: $1\,\mathrm{mradian}$
  - the PETS give relatively small longitudinal kicks
- Quadrupole offsets: $20\,\mu\mathrm{m}$
  - only for $1\,\mu\mathrm{m}$ the criterion would be fulfilled
- BPM accuracy (internal and alignment together): $20\,\mu\mathrm{m}$
  - the better the accuracy the more machines work already after one-to-one steering
- BPM resolution: $2\,\mu\mathrm{m}$ with time resolution $50\,\mathrm{ns}$
  - we would like to be able to perform dispersion free steering in a single pulse
  - better would be same as for main beam BPM ($20\,\mathrm{ns}$)
- BPM stability: $2\,\mu\mathrm{m}$

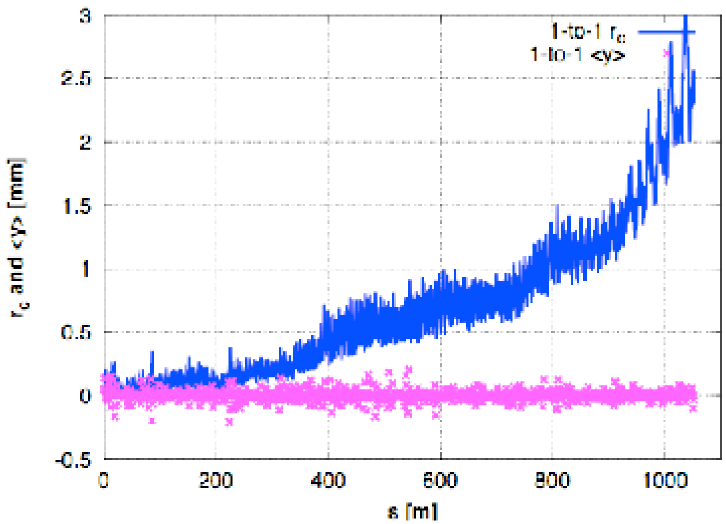
Effect on reducing number of BPMs



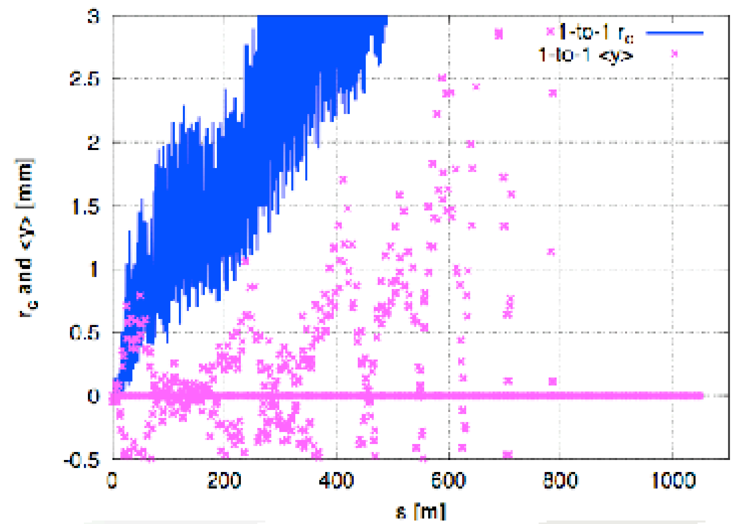
N=1



N=2



N=3



N=4

(perfect BPMs and single machine simulated, for illustration purposes)

Vacuum Specifications

- Main driver for the vacuum specifications is the fast beam-ion instability
- In case of CLIC two main ionisation processes exist
  - collision ionisation
  - field ionisation
- Results need to be confirmed
  - uncertainties on field ionisation
- Preliminary result is that the main linac vacuum has to stay below $10\,\mathrm{ntorr}$ H_2O, CO or N_2

Structure Breakdowns

- It is assumed that a breakdown in any structure will render the beqam pulse useless for luminosity
- It is required that each breakdown can be detected
- It is required that each accelerating structure can be switched off
- The average RMS transverse kick that switching off a PETS causes is $0.4\sigma_y$

  - the capability of slow switching on seems necessary

Other Constraints

- It is very advisable to be able to move the main linac girders without moving the drive beam girders
  - otherwise aligning the accelerating structure will move the PETS
- Instrumentation must fully perform at half the bunch charge and half the number of bunches
  - Graceful degradation at lower intensities
  - More work needed in this field
- The beam physics keeps an impedance model of the machine

  $\Rightarrow$ give us your impedance estimates
  - we will tell you if it is OK
- At a later stage we may define impedance budgets
- The radius of the aperture should be above $4\,\mathrm{mm}$
  - otherwise need an indepth discussion