Pre-Alignment and Stabilisation Needs for CLIC

D. Schulte

- Emittance preservation target and lattice design
- Static imperfections
  modelling, beam-based alignment, tolerances
- Dynamic imperfections
  modelling, beam-based alignment, tolerances

CLIC ACE May 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. . .

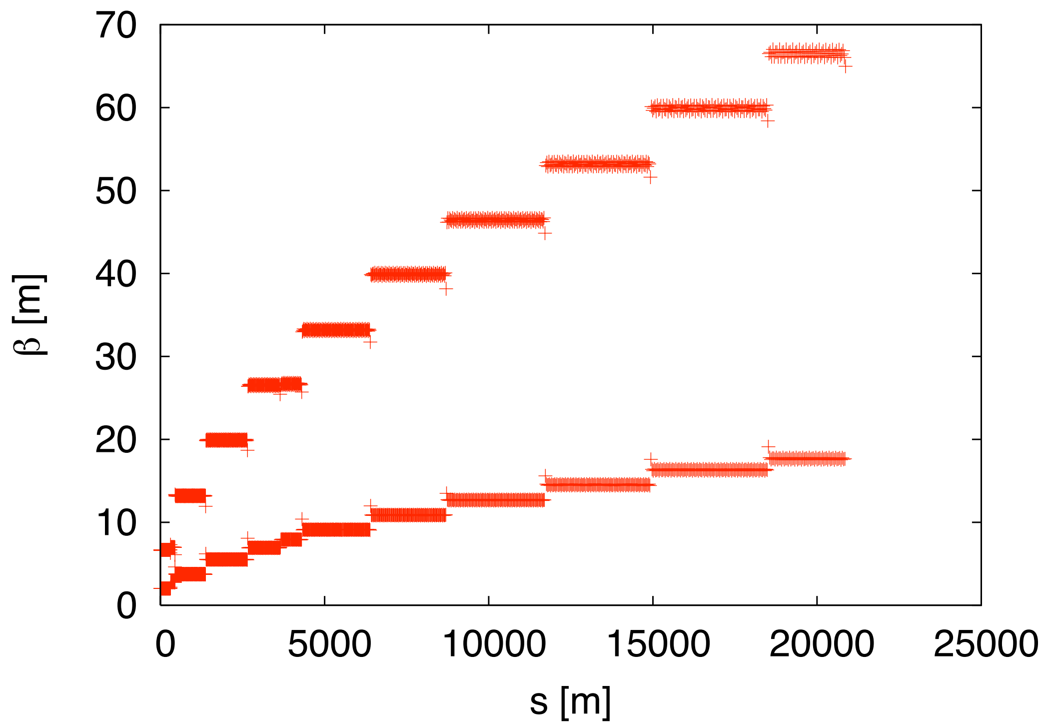
  pre-alignment, lattice design, beam-based alignment, beam-based tuning
- Dynamic imperfections

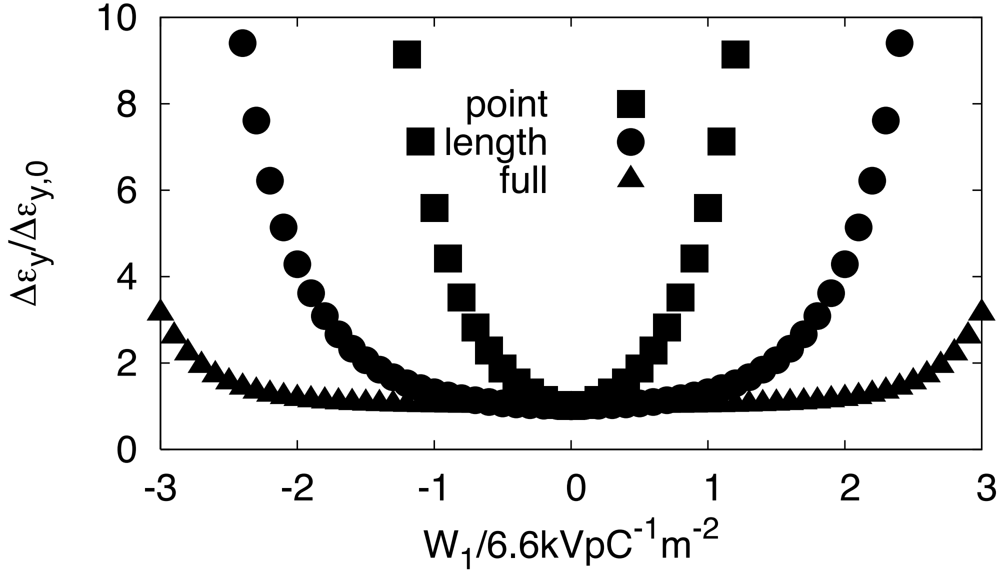
  element jitter, RF jitter, ground motion, beam jitter, electronic noise,. . .

  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 (→ tolerances 2.5 times larger)

Lattice Design

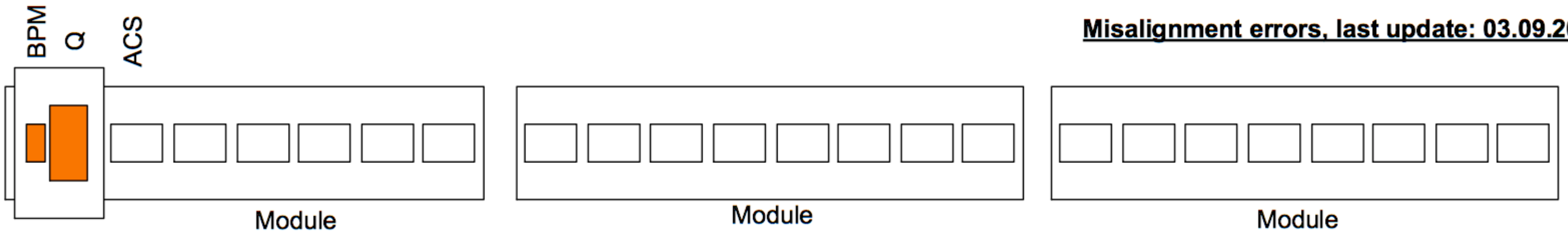
- Used $\beta \propto \sqrt{E}$, $\Delta\Phi = \mathrm{const}$
  - balances wakes and dispersion
  - roughly constant fill factor
- Total length about 21 km
  - fill factor about 78.6%
- 12 different sectors used
- Matching between sectors using 7 quadrupoles to allow for some energy bandwidth
- Single 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

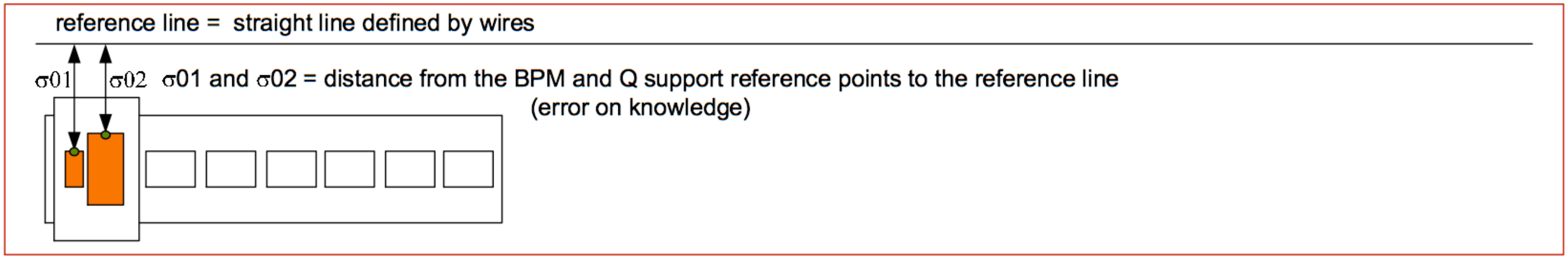




Alignment Model

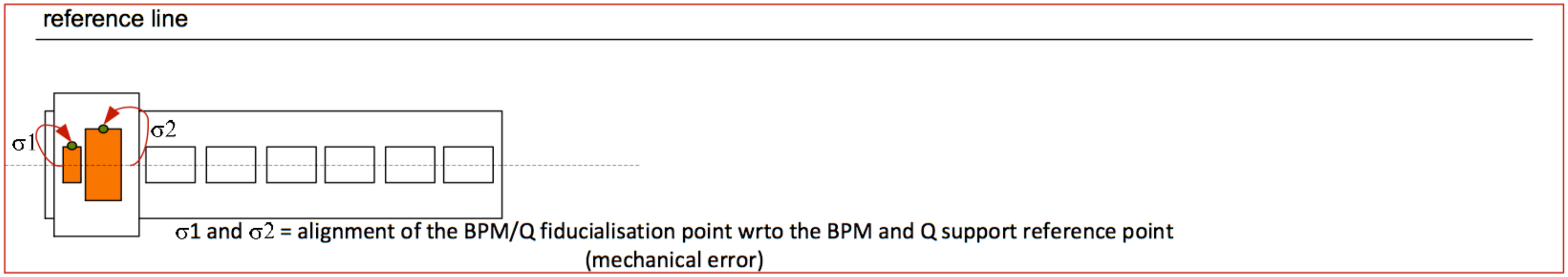
Misalignment errors, last update: 03.09.2009





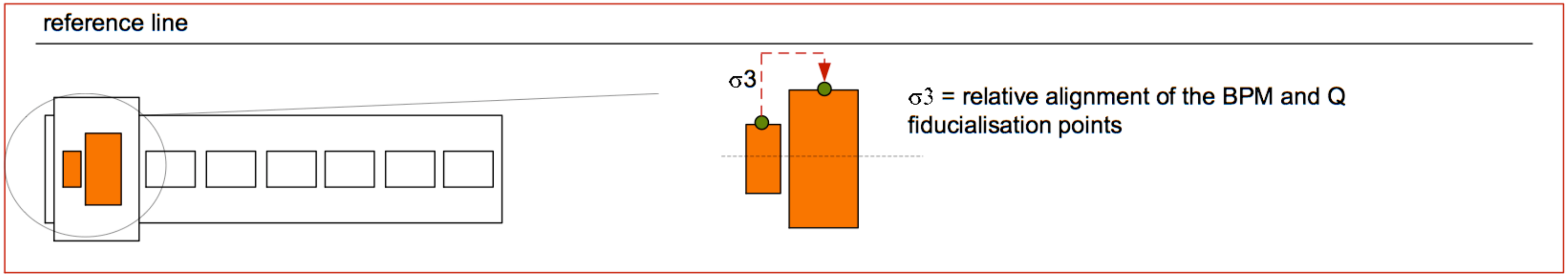
reference line = straight line defined by wires

σ01 and σ02 = distance from the BPM and Q support reference points to the reference line (error on knowledge)



reference line

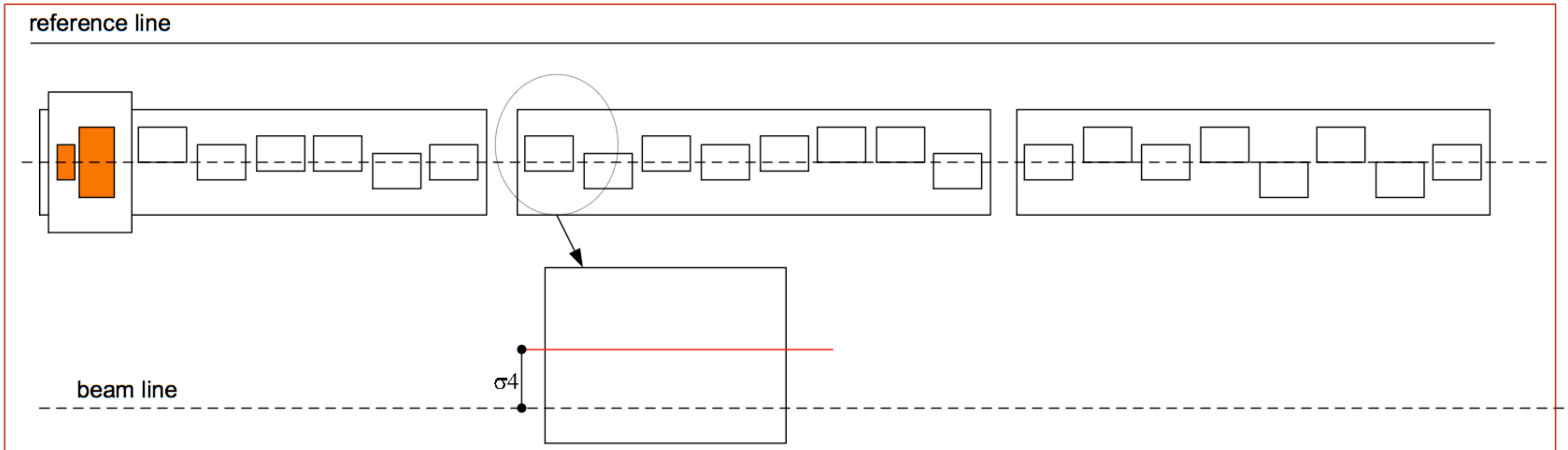
σ1 and σ2 = alignment of the BPM/Q fiducialisation point wrto the BPM and Q support reference point (mechanical error)



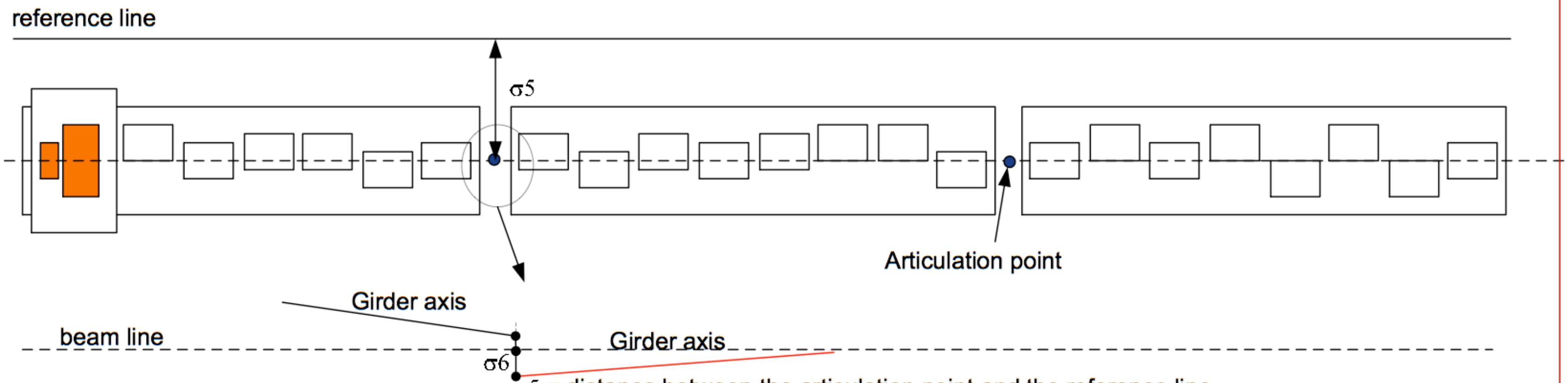
reference line

σ3 = relative alignment of the BPM and Q fiducialisation points

Alignment Model (cont)



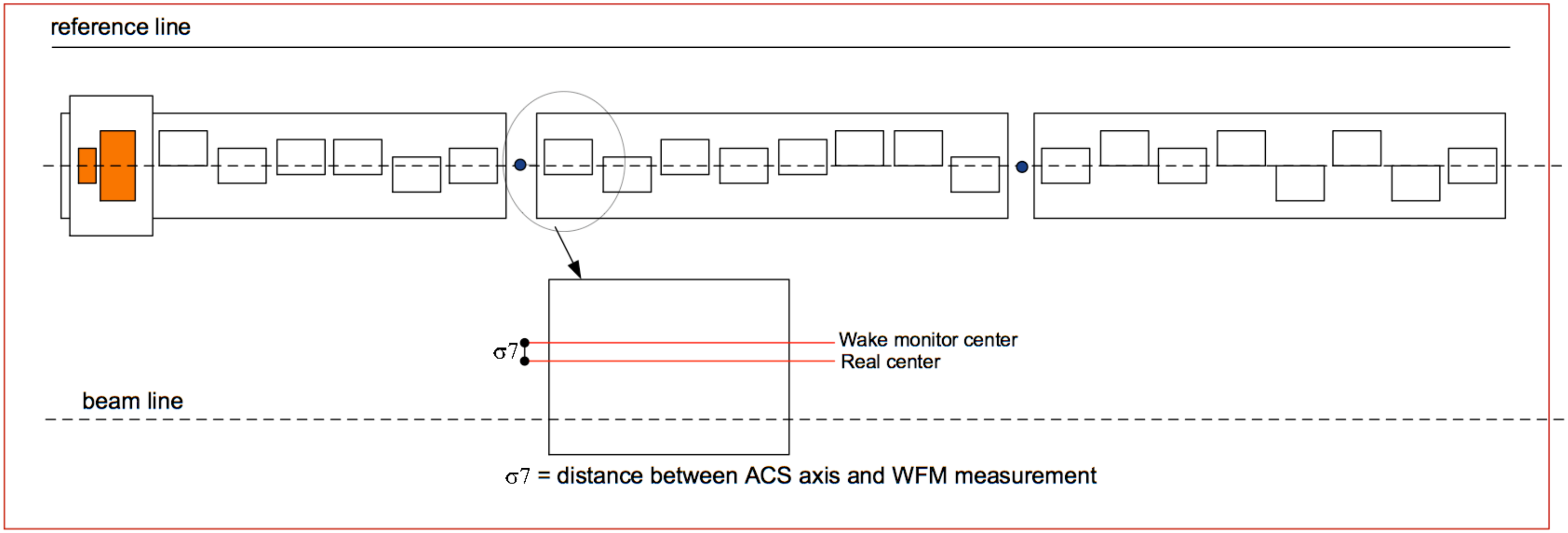
σ4 = distance between ACS axis and girder axis line



σ5 = distance between the articulation point and the reference line

σ6 = distance between the articulation point and girder axis line

Alignment Model (cont)



σ7 = distance between ACS axis and WFM measurement

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

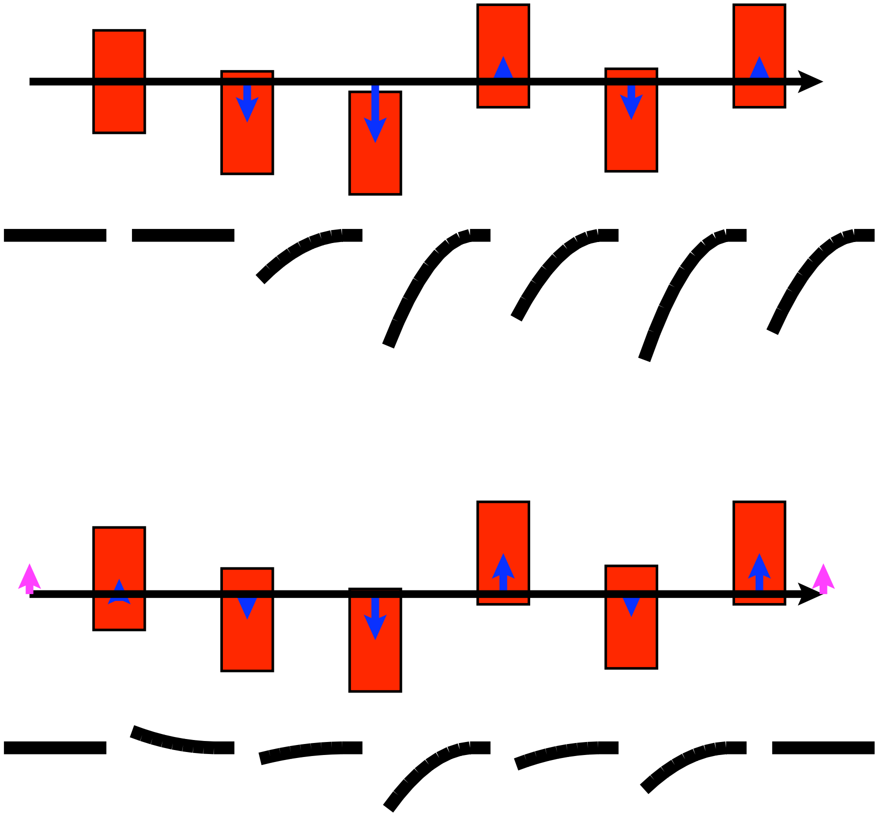
- Make beam pass linac
  - one-to-one correction
- Remove dispersion, align BPMs and quadrupoles
  - dispersion free steering
  - ballistic alignment
  - kick minimisation
- Remove wakefield effects
  - accelerating structure alignment
  - emittance tuning bumps
- Tune luminosity
  - tuning knobs

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

$\Rightarrow$ 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



- 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

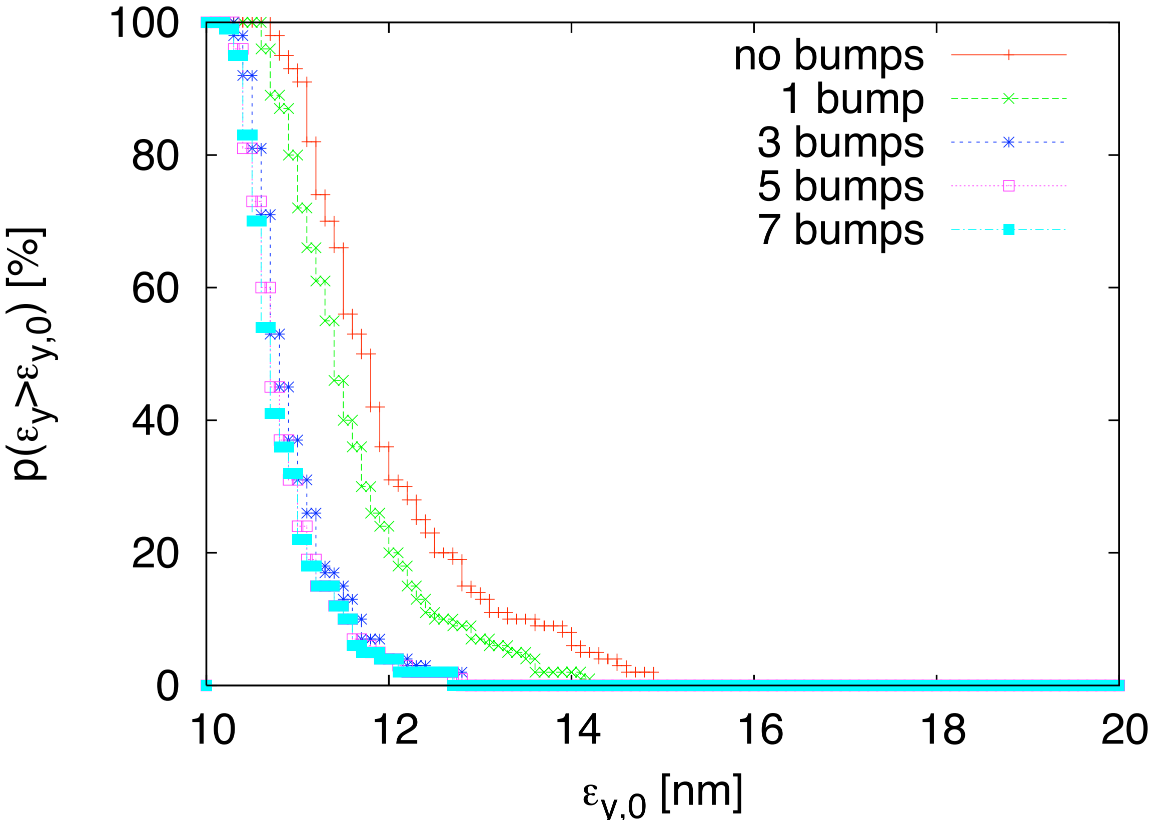
imperfection	with respect to	symbol	value	emitt. growth
BPM offset	wire reference	σ_{BPM}	14 μm	$0.367\,\mathrm{nm}$
BPM resolution		σ_{res}	0.1 μm	$0.04\,\mathrm{nm}$
accelerating structure offset	girder axis	σ_4	10 μm	$0.03\,\mathrm{nm}$
accelerating structure tilt	girder axis	σ_t	200 μradian	$0.38\,\mathrm{nm}$
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

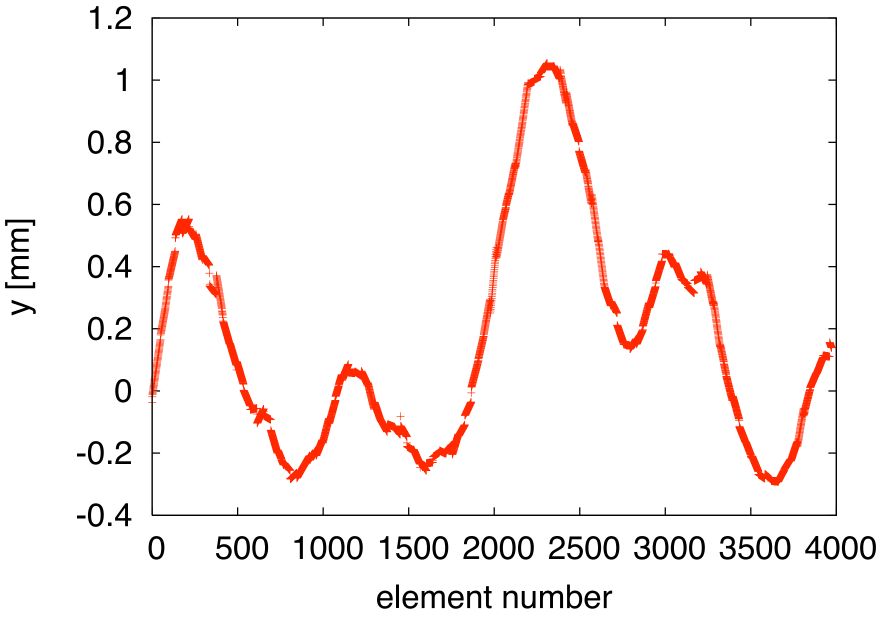
- Multi-bunch wakefield misalignments of $10\,\mu\mathrm{m}$ lead to $\Delta\epsilon_y \approx 0.13\,\mathrm{nm}$

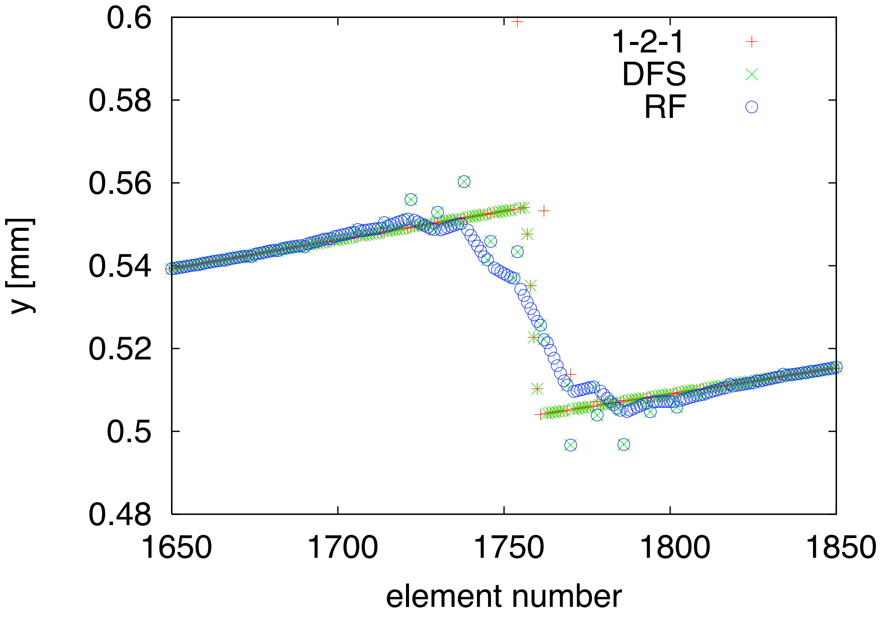
- Performance of local pre-alignment is acceptable



Wire System Misalignment Modelling

- Received a number of misalignments from Thomas Touzé
- Used 50 seeds for each error set
- Switched from one wire 1 to 2 at end point of 1 and back to 1 at end point of 2
- Used linear interpolation in between wire endpoints
  - no sag error
  - no error of geoid





Wire System Results and Further Work

- Different number of pits have been simulated

  $\Rightarrow$ seem to make little difference

- Different wire monitor accuracies have been studied

  $\Rightarrow$ makes a significant difference

case	wire length	no of pits	sensor accuracy	$\Delta\epsilon_y[\mathrm{nm}]$
1a	403.2	7	20 $\mu\mathrm{m}$	0.09
1b	403.2	7	5 $\mu\mathrm{m}$	≈ 0.01
2a	400	2	5 $\mu\mathrm{m}$	≈ 0.01
2b	400	3	5 $\mu\mathrm{m}$	≈ 0.01
2c	400	6	5 $\mu\mathrm{m}$	≈ 0.01

- Results with current model are acceptable

- More imperfections need to be included as they become available
  - systematic error of sensors
  - wire sag
  - geoid
  - . . .

Dynamic Imperfections

- Important is the multi-pulse emittance
- Counteract dynamic effects by
  - fast component stabilisation (between pulses)
  - beam-based orbit feedback
  - longitudinal feedback
  - slow component stabilisation (e.g. temperature drifts)
  - beam tuning
  - beam-based alignment when needed
  - repetition of pre-alignment
- Do not have a model of the imperfections
  - some models for ground motion
  - technical noise is not yet available
  - transfer by girder is not yet available (some model of the magnet exists)
  - impact of stabilisation feedback is not yet available

⇒ so we derive some specifications

Dynamic Imperfections

- Luminosity loss is part of the emittance budget
- But limit luminosity fluctuation to less than 10%
  - total luminosity fluctuation is not straightforwad

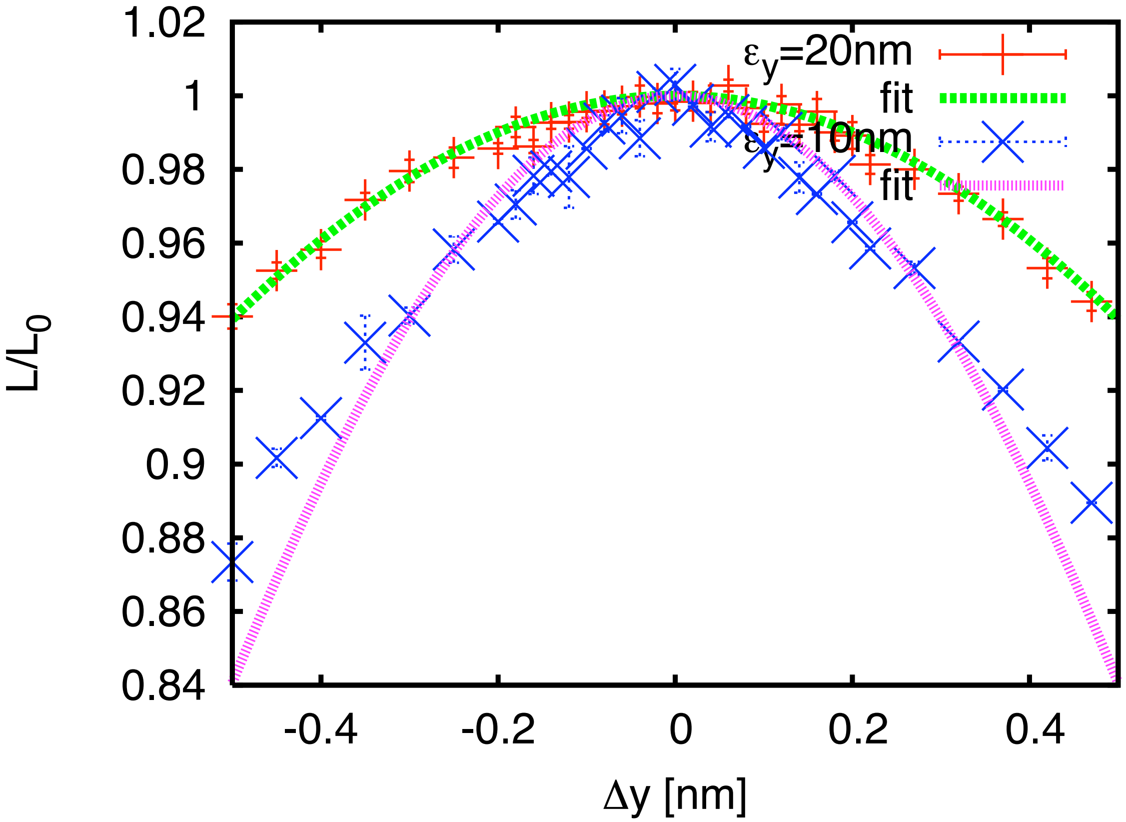
Source	budget	tolerance
Damping ring extraction jitter	0.5%	kick reproducibility $0.1\sigma_x$
Transfer line stray fields	?%	data needed
Bunch compressor jitter	1%	
Quadrupole jitter in main linac	1%	$\sigma_{jitter} \approx 1.8\,\mathrm{nm}$
RF amplitude jitter in main linac	1%	0.075% coherent, 0.22% 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%	$\sigma_{jitter} \approx 440\,\mathrm{nradian}$
Crab cavity phase jitter	2%	$\sigma_\phi \approx 0.017^\circ$
Final doublet quadrupole jitter	2%	$\sigma_{jitter} \approx 0.17(0.34)\,\mathrm{nm}$–$0.85(1.7)\,\mathrm{nm}$
Other quadrupole jitter in BDS	1%	
$\cdots$	?%	

$\Rightarrow$ Long list of small sources adds up

$\Rightarrow$ Impact of feedback system is important

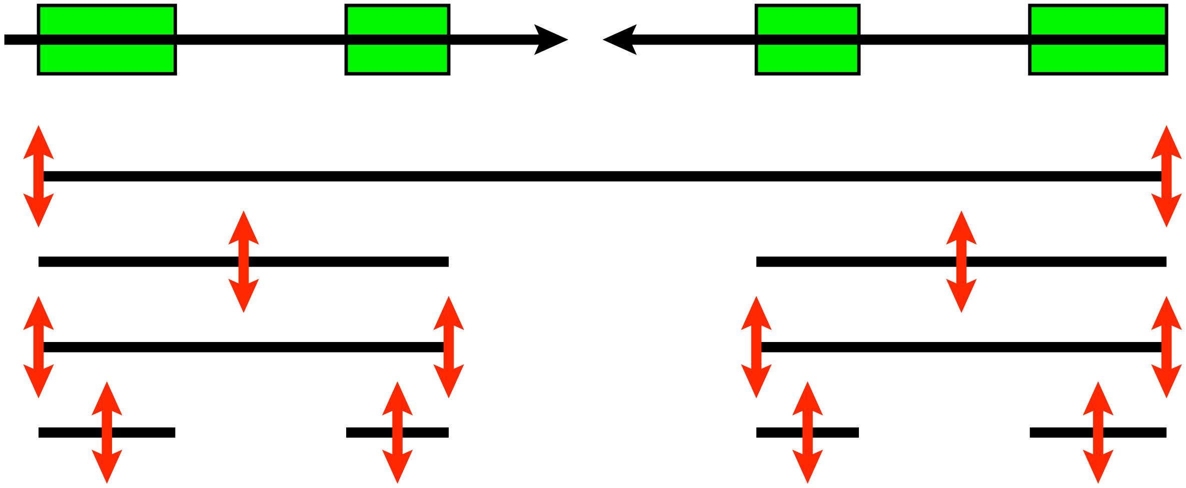
Beam-Beam Jitter Tolerance

- Beam-beam vertical jitter tolerance for 2% luminosity loss is $0.3\,\mathrm{nm}$ for rigid bunches
- Inclusion of beam-beam effects finds almost the same values
  - 0.28 nm yields 2.2%
- Tolerance does not yet include impact of beam-beam feedback
  - intra-pulse feedback
  - pulse-to-pulse feedback
- Parasitic kicks will decrease tolerance in multi-bunch case by about 10%



Final Doublet Jitter

- Support points are assumed to be independent
- Main effect is beam-beam offset at interaction point
- One support structure
  - \- relative tolerance on end points $\approx 3.6\sigma_{beam-beam}$
- 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 $\approx 0.5\sigma_{beam-beam}$
  - \- end points $\approx 0.7\sigma_{beam-beam}$



$\Rightarrow$ Single support seems excluded

$\Rightarrow$ Chose two or four

- need to consider motion on support

$\Rightarrow$ Raw tolerance for quadrupole supports is 0.17–$0.85\,\mathrm{nm}$ depending on configuration

- assuming independent support point jitter

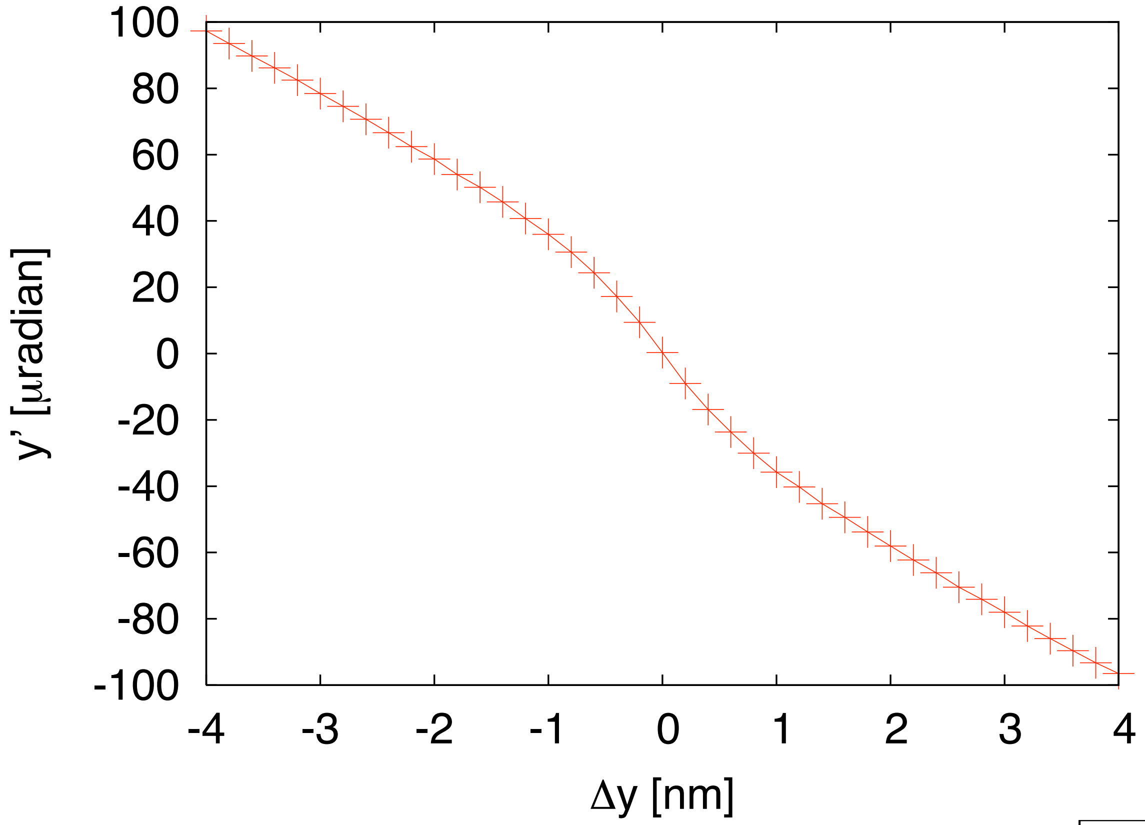
- Integration of support and stabilisation system in detector is important to study

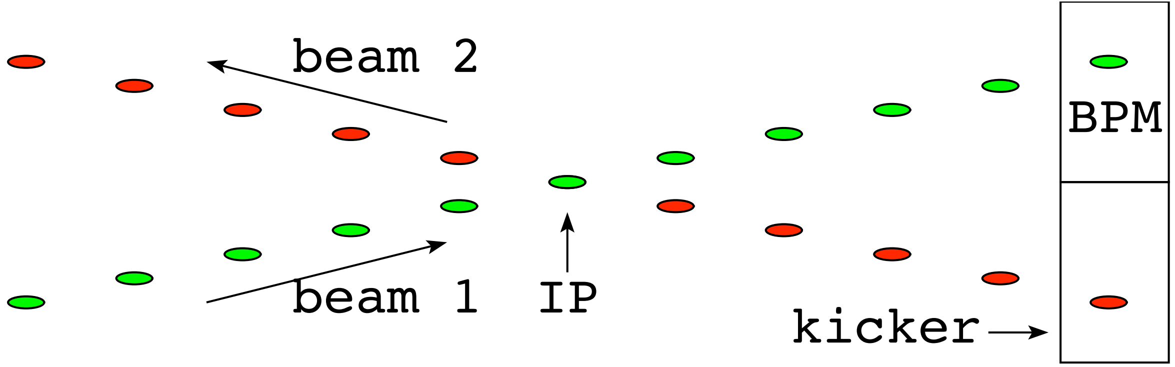
Feedback Studies

- No design for RTML feedback sofar
- Conceptual feedback exists for main linac
- Some studies for BDS exist but no full feedback concept
  - has to come for CDR
- Integrated feedback study is needed
  - most feedback acts on same beam property (orbit)
    ⇒ have to share bandwidth or integrate into one controller
  - speed of feedback is critical
- Knowledge of the system response is critical for feedback speed
- Have foreseen studies of
  - modelling of ground motion
  - modelling of stabilisation feedback in main linac (BDS not clear)
  - BDS beam-based feedback design
  - beam-beased feedback controller design
  - main linac and BDS feedback performance with some inclusion of RTML

Intra-Pulse Interaction Point Feedback

- Simple beam-beam feedback based on deflection angle at IP
  - but want to include more information
- Beam-based feedback will demagnify beam-beam offset at certain frequencies but will amplify at others
- Intra-pulse feedback is dominated by latency
- Assuming 40 ns one can hope for about a factor 2
- Only cures offsets
- Currently not yet in the baseline
- Collaboration with JAI





Pulse-to-Pulse Tolerance with Feedback

- The frequency response of the feedback is controller dependent
- One can trade-off different properties

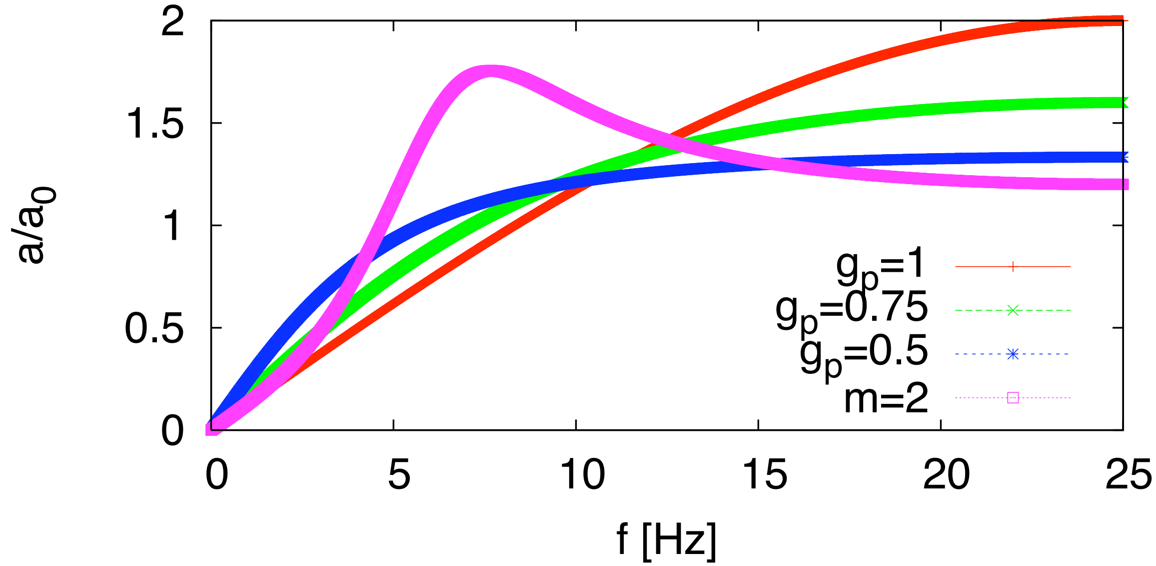
  - but within limits
- Simple feedback is shown

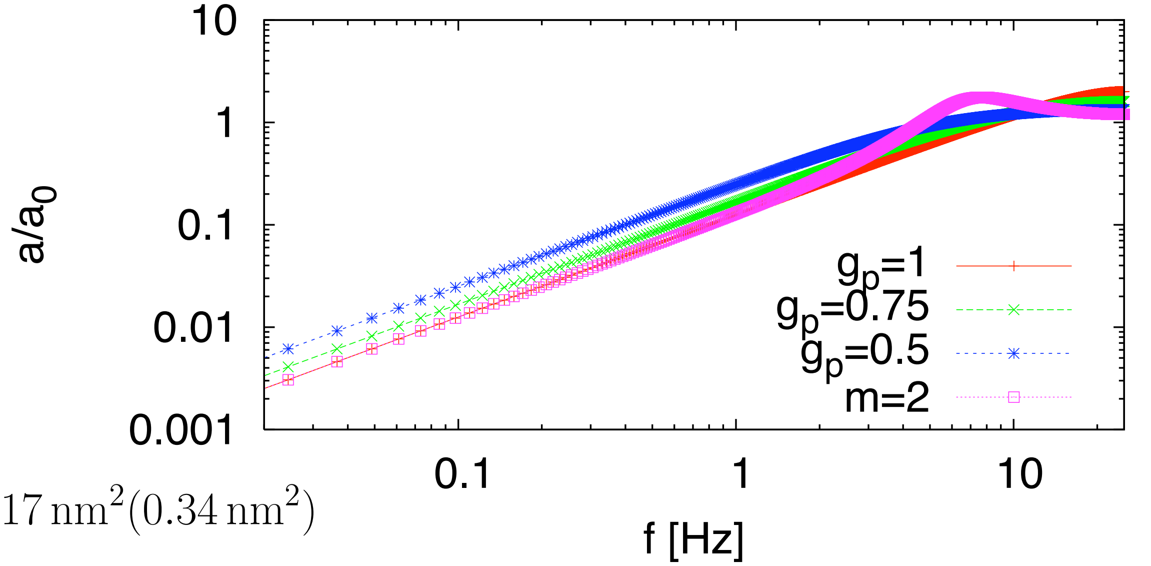
$$c_{n+1} = c_n + g_p R y_n$$

- One case of use of recursive filter als shown
- BPM resolution of $1\,\mu\mathrm{m}$ will add luminosity loss of $\approx 0.1\%$

$\Rightarrow$ Frequencies above $\approx 5\,\mathrm{Hz}$ are not demagnified

$$\int_0^\infty db^2(f)\{d^2(f)pg(f)+pn(f)\}df \leq 0.17\,\mathrm{nm}^2(0.34\,\mathrm{nm}^2)$$





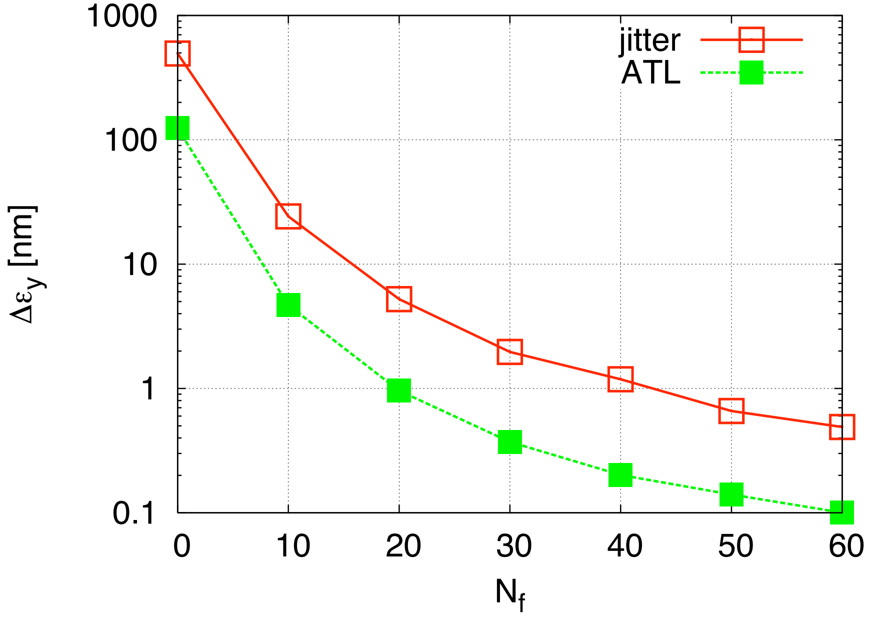
Main Linac Fast Feedback Design

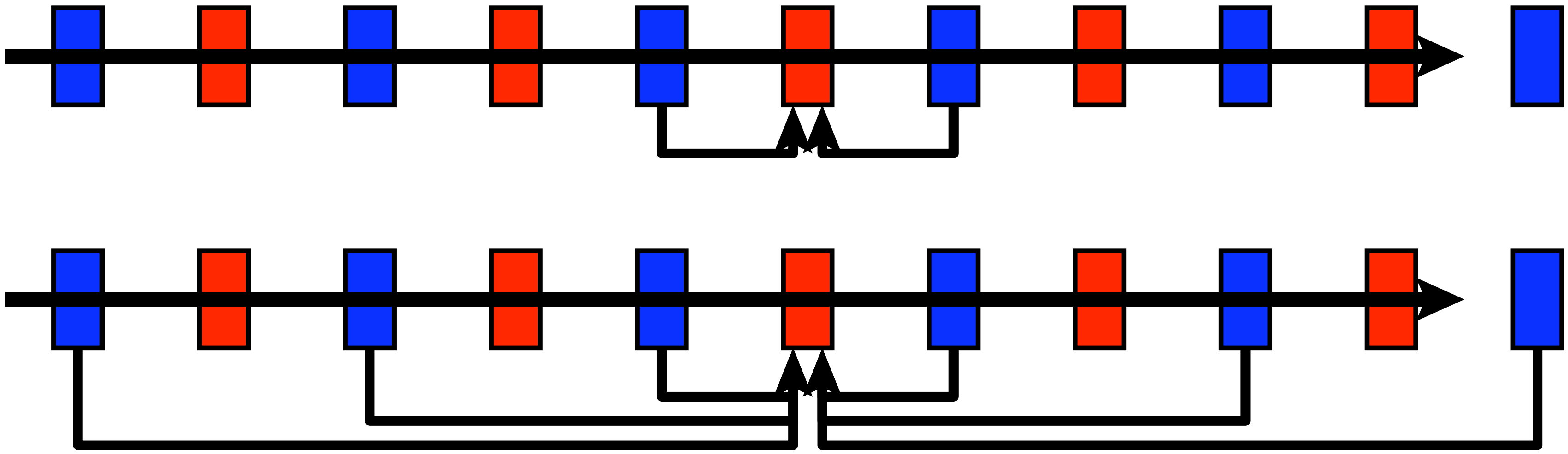
- No feedback leads to $0.5\,\mathrm{nm/s}$ with ATL (B) motion

  ⇒ ground motion alone could be acceptable, but technical noise, supports. . .

- Main basis will be a fast BPM-based orbit feedback with single MIMO
- 1000 s ATL motion and 100 nm quadrupole jitter are shown
- Chose 41 BPM stations (8 BPMs each) and 40 corrector stations (2 correctors each)

⇒ can run for O(1000 s)



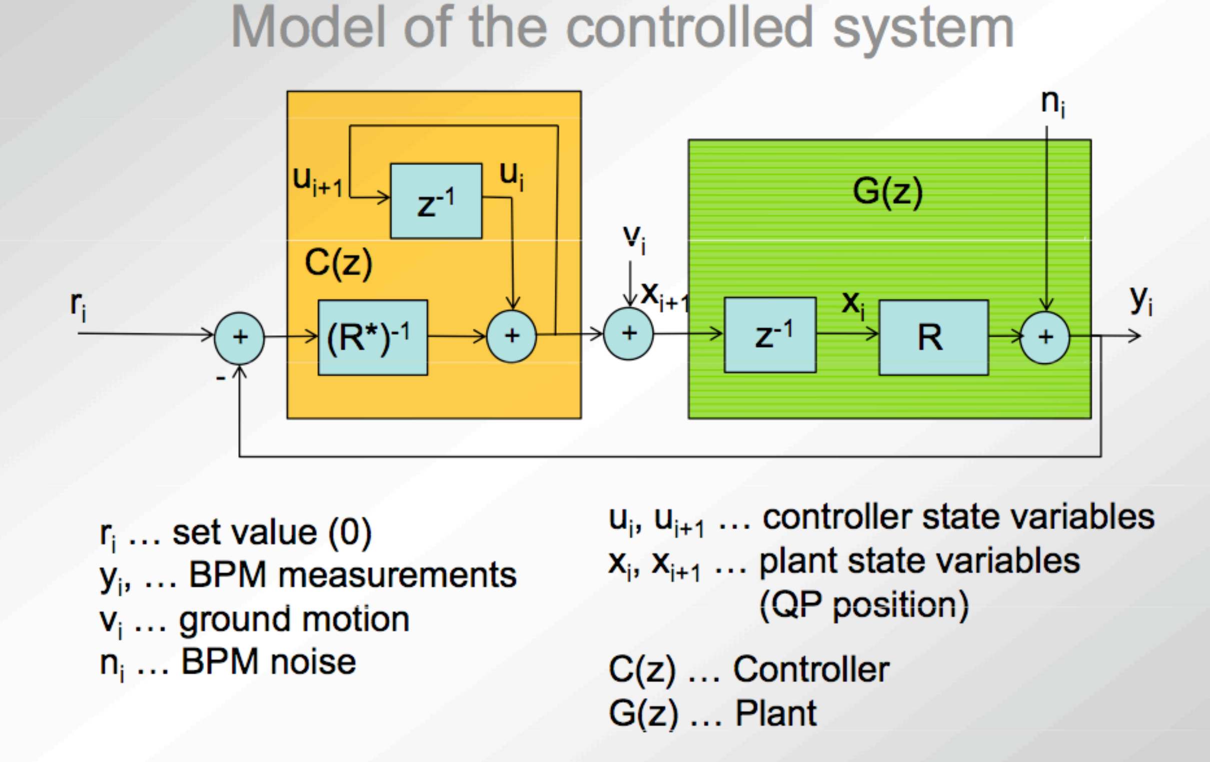


Feedback Critical Issues

- Speed of convergence
  - stabilisation feedback fails at low frequencies
  - BPM resolution will be limiting
  - imperfect system knowledge
- Cross talk of imperfections
  - e.g. energy jitter via dispersion

⇒ Full study
  - different effects
  - different areas
  - different timescales

- One integrated feedback
  - clever feedback design
  - robust controller
  - adaptive controller



Model of the controlled system

r_i … set value (0)
y_i, … BPM measurements
v_i … ground motion
n_i … BPM noise

u_i, u_{i+1} … controller state variables
x_i, x_{i+1} … plant state variables (QP position)

C(z) … Controller
G(z) … Plant

thanks to Juergen

BPM Resolution and Corrector Step Size

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

  $\Rightarrow$ little effect left for smaller gain g or better resolution
  - would like to resolve $0.1\sigma_y$ at end of main linac with

    $\Rightarrow$ ask to explore BPM resolution of about $50\,\mathrm{nm}$
- 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

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

Main Linac Mover Requirements

- Coarse mechanical motion
  - structure girders, quadrupoles and BPM support
  - range: $\approx 1\,\mathrm{mm}$
  - resolution: $\Delta \approx 1\,\mu\mathrm{m}$
  - precision: $\approx 0.5\,\mu\mathrm{m}$
  - speed: may take a few pulses, but controlled
- Fine quadrupole motion
  - resolution: $\Delta \approx 5\,\mathrm{nm}$
  - 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

Conclusion

- Typical local alignment tolerances are of the order of $10\,\mu\mathrm{m}$
  - in particular BPM position and wake monitors
- The first results of wire reference system look very promising
  - more complete studies to follow
- Dynamic tolerances have been studied
  - but need a better model
  - produced some simple specifications sofar
- Feedback conceptual design is an important ingredient
  - main linac baseline feedback layout exists
  - BDS will follow soon
- Controler design
  - optimisation depends on noise model and feedback layout
  - knowledge of the system response is vital and is being studied
- Some resources are available for the beam dynamics work (J. Resta Lopez at JAI, J. Pfingstner (PhD student), J. Snuverink (fellow), fraction of DS)