Beam Instrumentation Needs for the CLIC Main Linac

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- Emittance preservation target and lattice design
- Static imperfections, BPM accuray and precision, wakemonitors
- Dynamic imperfections, BPM resolution
- RF jitter, phase and amplitude measurements
- Other

June 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. . .

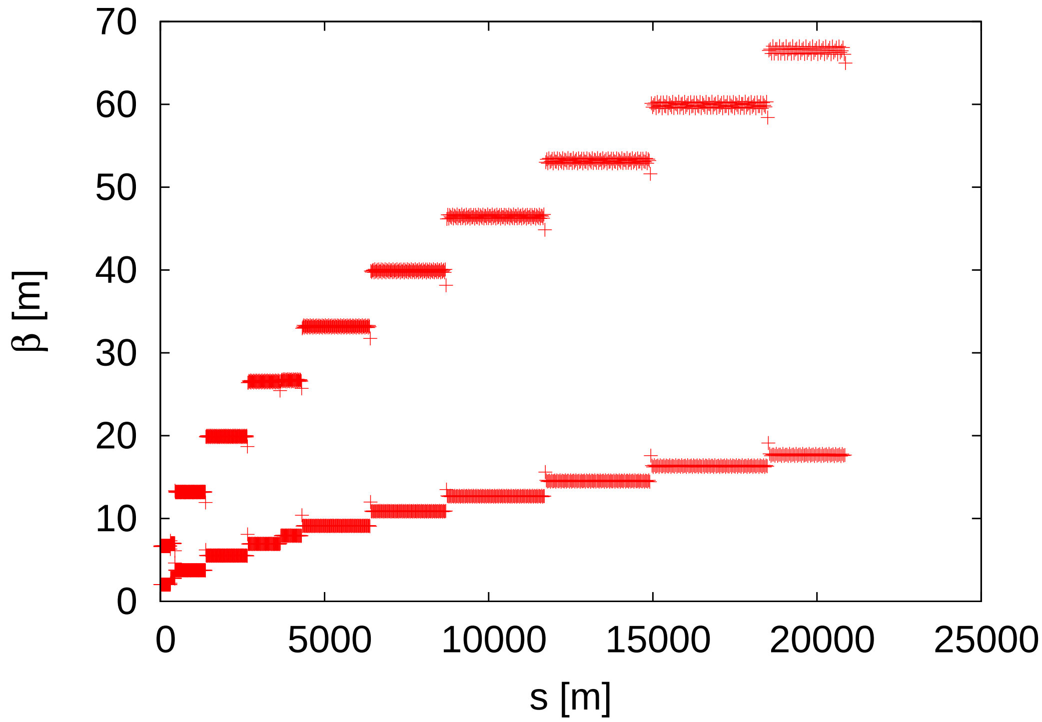
  pre-alignment, lattice design, beam-based alignment, beam-based tuning
- Dynamic imperfections

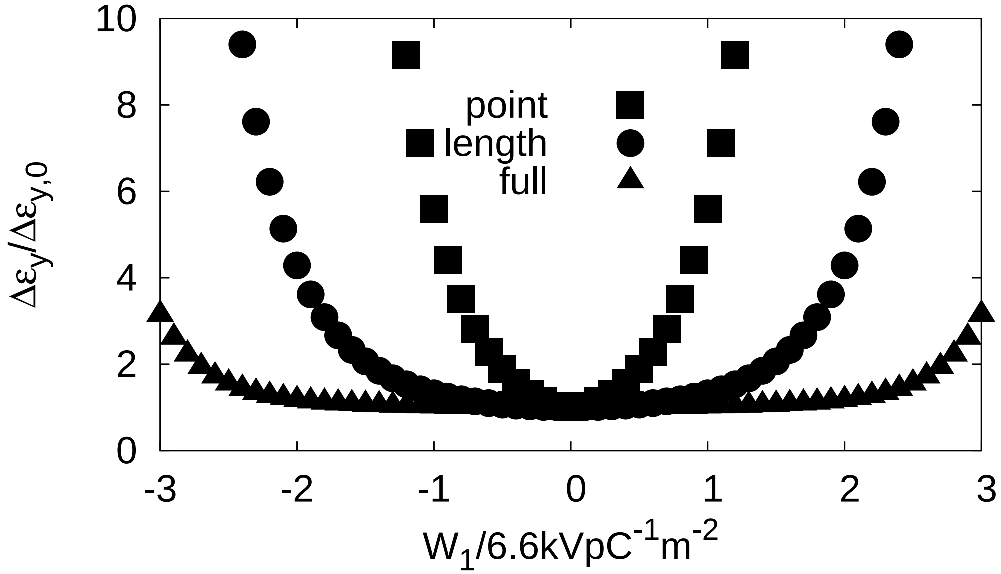
  element jitter, RF jitter, ground motion, beam jitter, electronic noise,. . .

  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

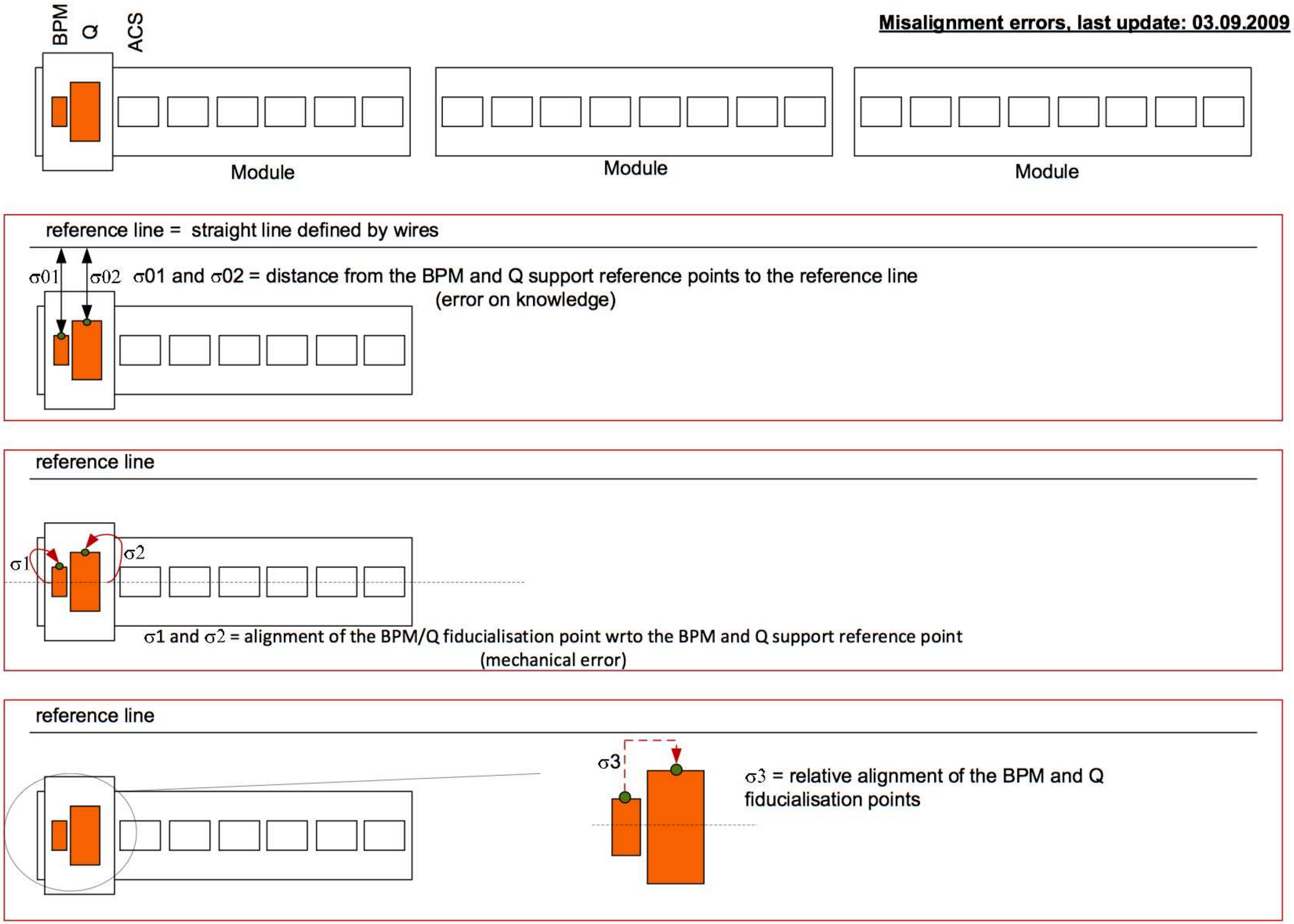
- Used $\beta \propto \sqrt{E}$, $\Delta\Phi = \mathrm{const}$
  - balances wakes and dispersion
  - roughly constant fill factor
- Total length about 21 km
  - 2010 BPMs per linac
  - fill factor about 78.6%
- 12 different sectors used
- Matching between sectors using 7 quadrupoles to allow for some energy bandwidth
- Single bunch stability ensured by BNS damping
- Multi-bunch coherent offset leads to phase shift of 90° at linac end





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)

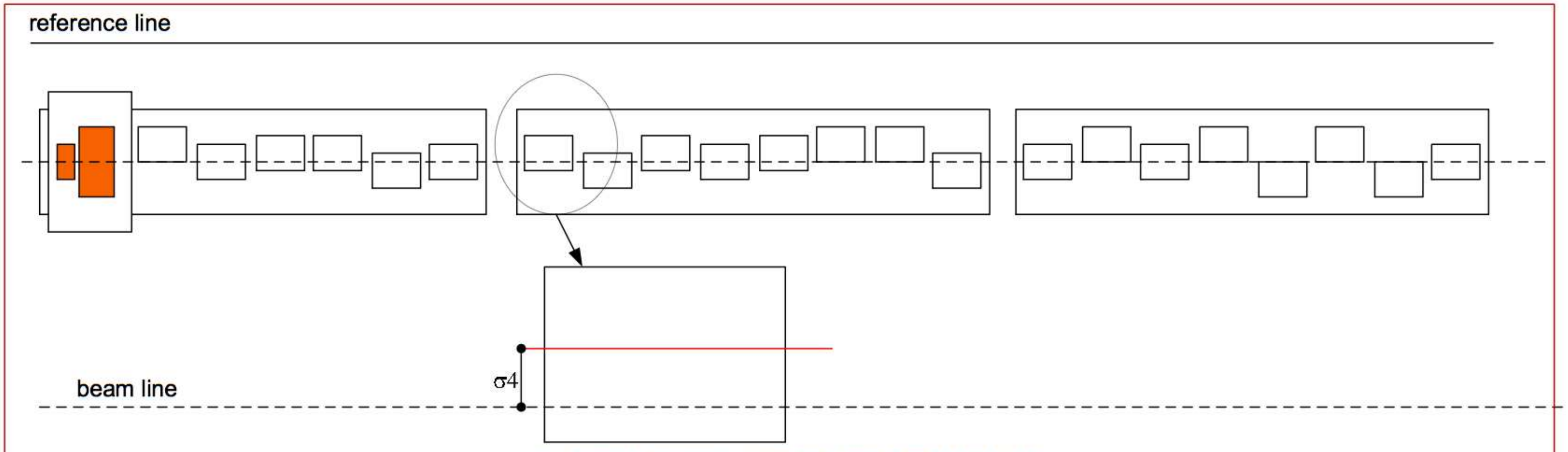
reference line

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

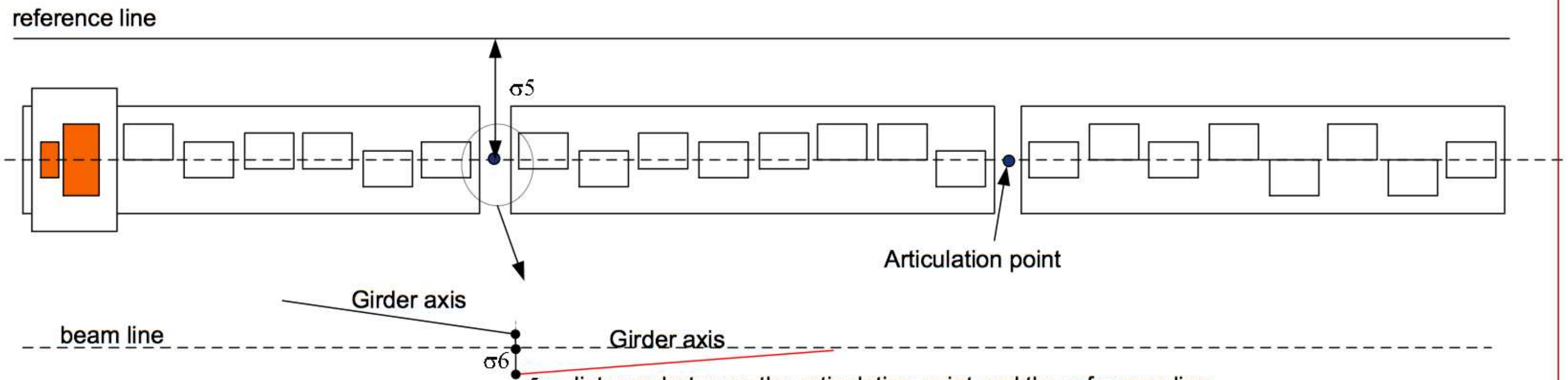
reference line

σ3 = relative alignment of the BPM and Q fiducialisation points

Alignment Model (cont)



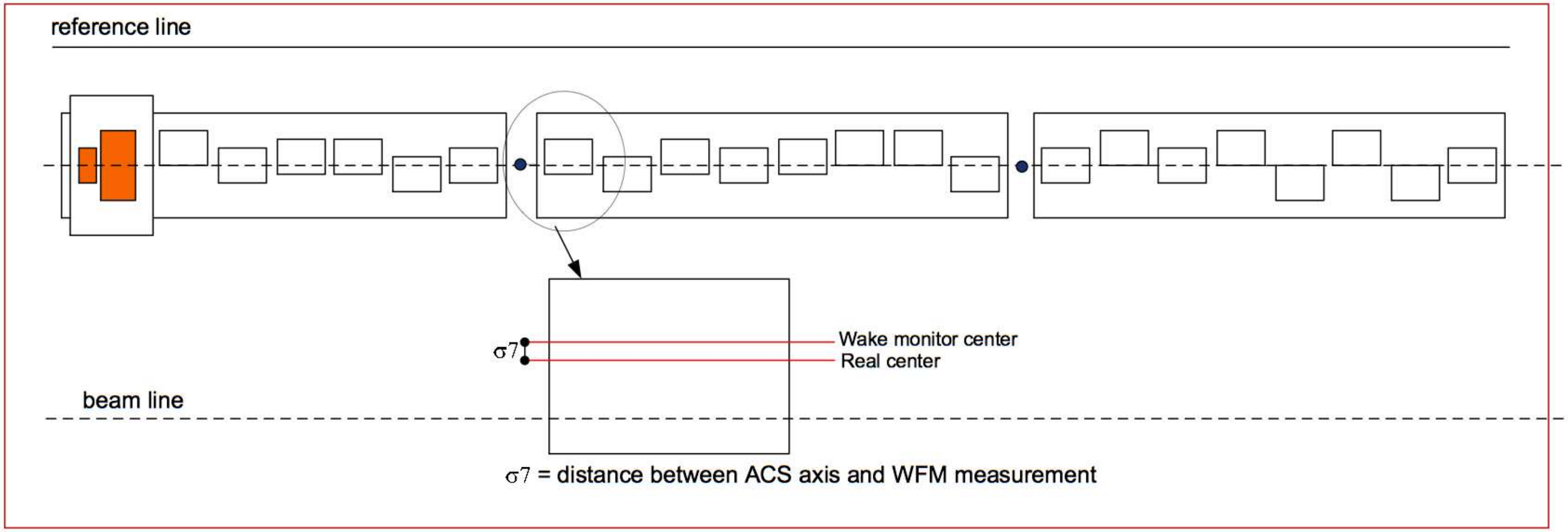
$\sigma 4$ = distance between ACS axis and girder axis line



$\sigma 5$ = distance between the articulation point and the reference line

$\sigma 6$ = 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

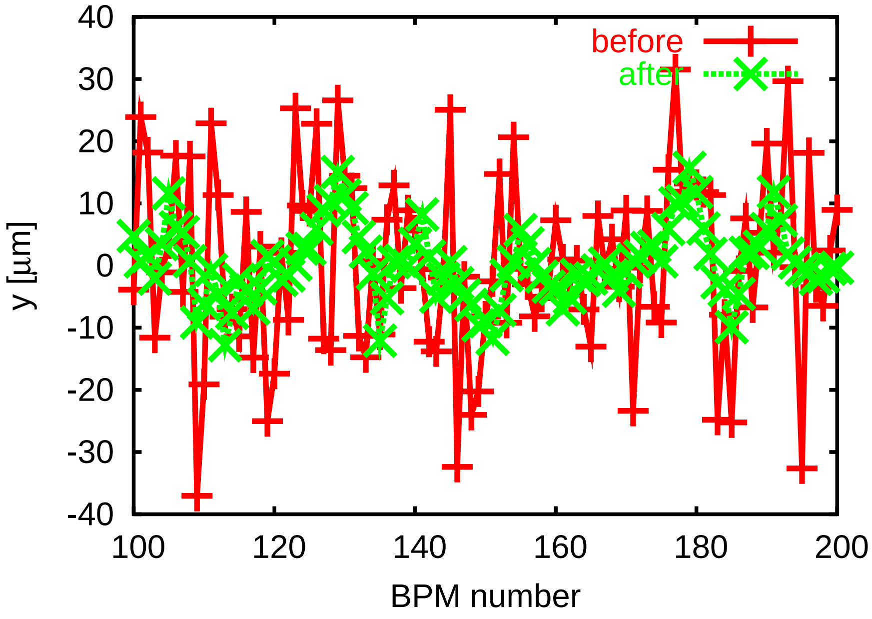
- Make beam pass linac
  - one-to-one correction
- Remove dispersion, align BPMs and quadrupoles
  - dispersion free steering
  - ballistic alignment
  - kick minimisation
- Remove wakefield effects
  - accelerating structure alignment
  - emittance tuning bumps
- Tune luminosity
  - tuning knobs

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

  ⇒ probe beam bunch length ≈ 45–$70\,\mu\mathrm{m}$

  - both beam within same pulse



- Optimise trajectories for different energies together:

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

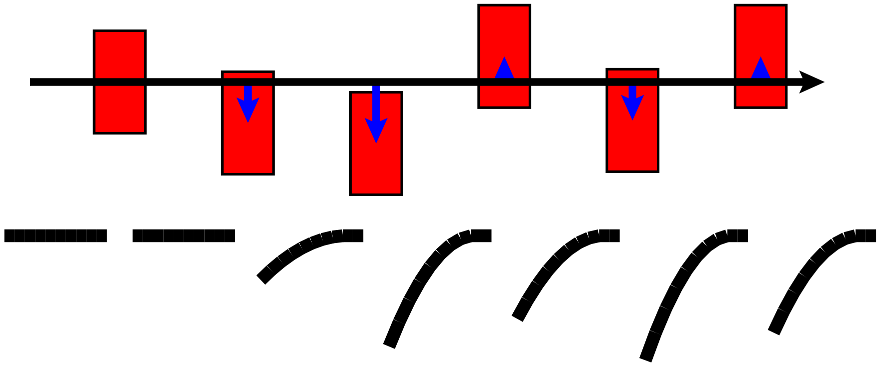
- Last term is omitted
- Idea is to mimic energy differences that exist in the bunch with different beams
- For stability want to use two parts of one pulse

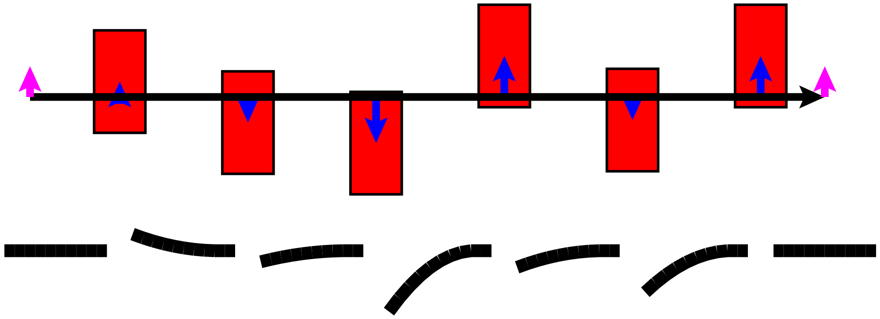
Beam-Based Structure Alignment

- Each structure is equipped with a wake-field monitor (RMS position 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

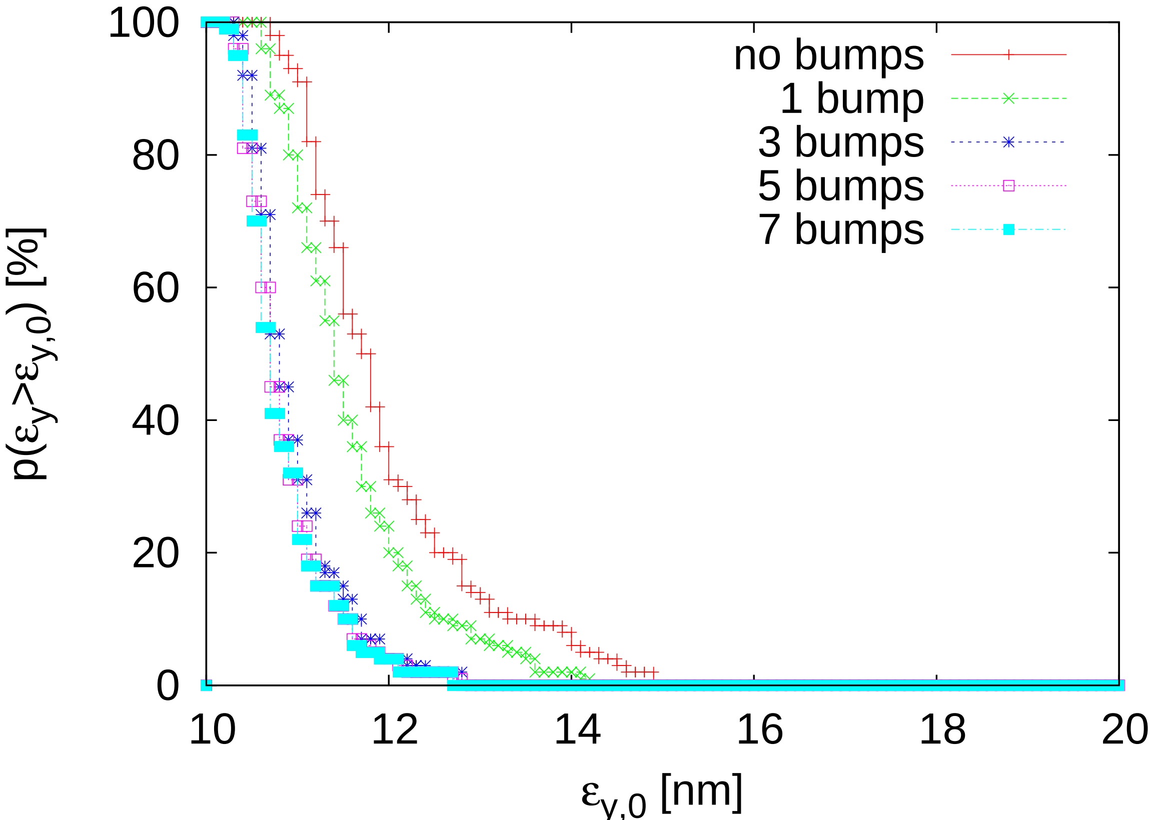
imperfection	with respect to	symbol	value	emitt. growth
BPM offset	wire reference	σ_{BPM}	14 μm	$0.367\,\mathrm{nm}$
BPM resolution		σ_{res}	0.1 μm	$0.04\,\mathrm{nm}$
accelerating structure offset	girder axis	σ_4	10 μm	$0.03\,\mathrm{nm}$
accelerating structure tilt	girder axis	σ_t	200 μradian	$0.38\,\mathrm{nm}$
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 $\Delta\epsilon_y \approx 0.13\,\mathrm{nm}$

- Note: BPM internal accuracy is assumed to be $5\,\mu\mathrm{m}$



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%	
$\cdots$	?%	

⇒ Long list of small sources adds up

⇒ Impact of feedback system is important

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)
    $\Rightarrow$ 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

Main Linac Fast Feedback Design

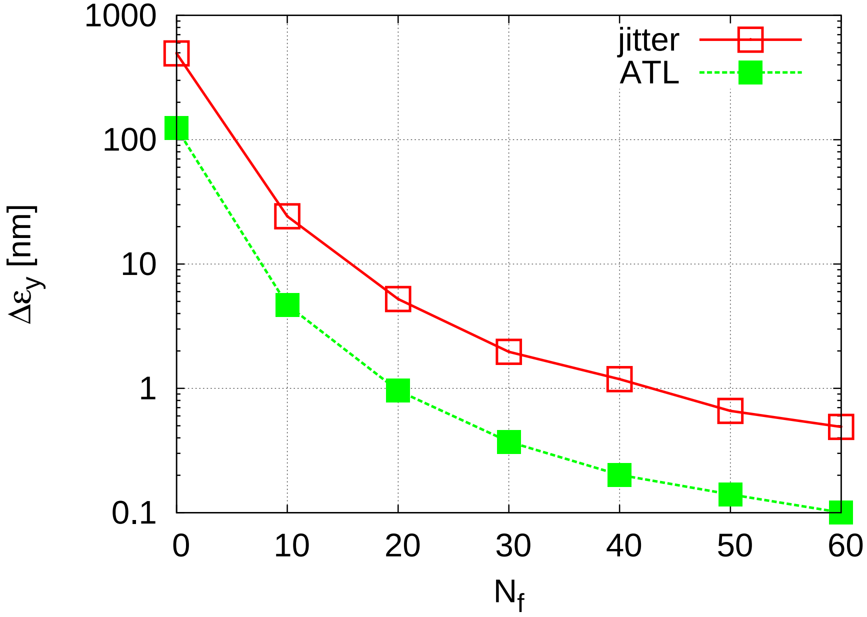
- No feedback leads to $0.5\,\mathrm{nm/s}$ with ATL (B) motion

  $\Rightarrow$ ground motion alone could be acceptable, but technical noise, supports. . .

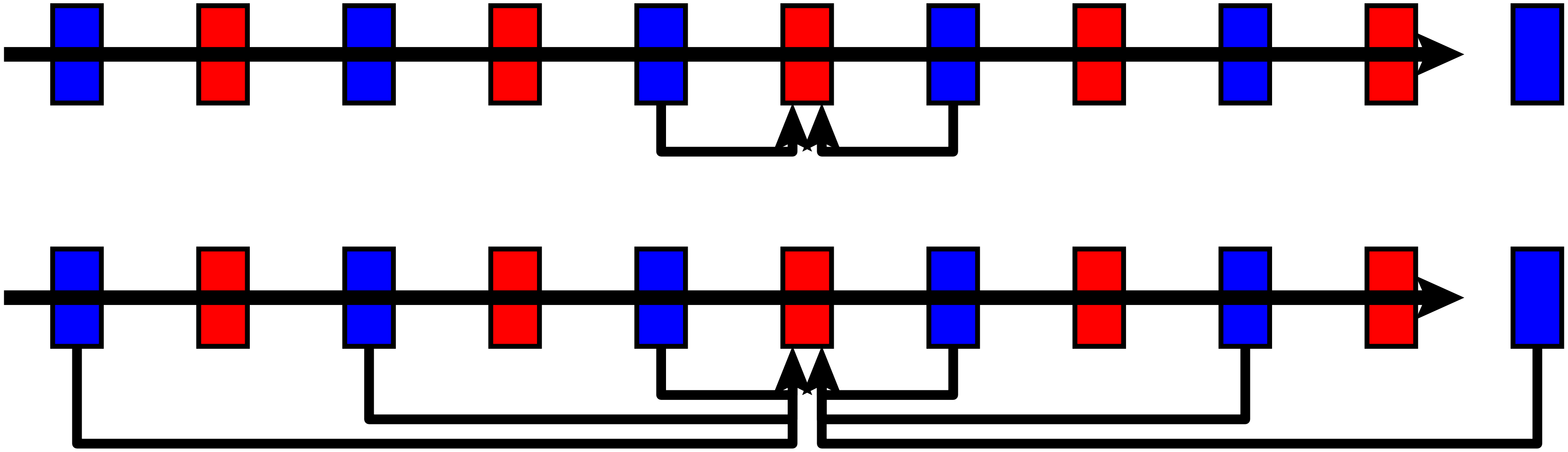
- Main basis will be a fast BPM-based orbit feedback with single MIMO

- 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)



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



BPM Resolution and Corrector Step Size

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

  $\Rightarrow$ 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 $50\,\mathrm{nm}$

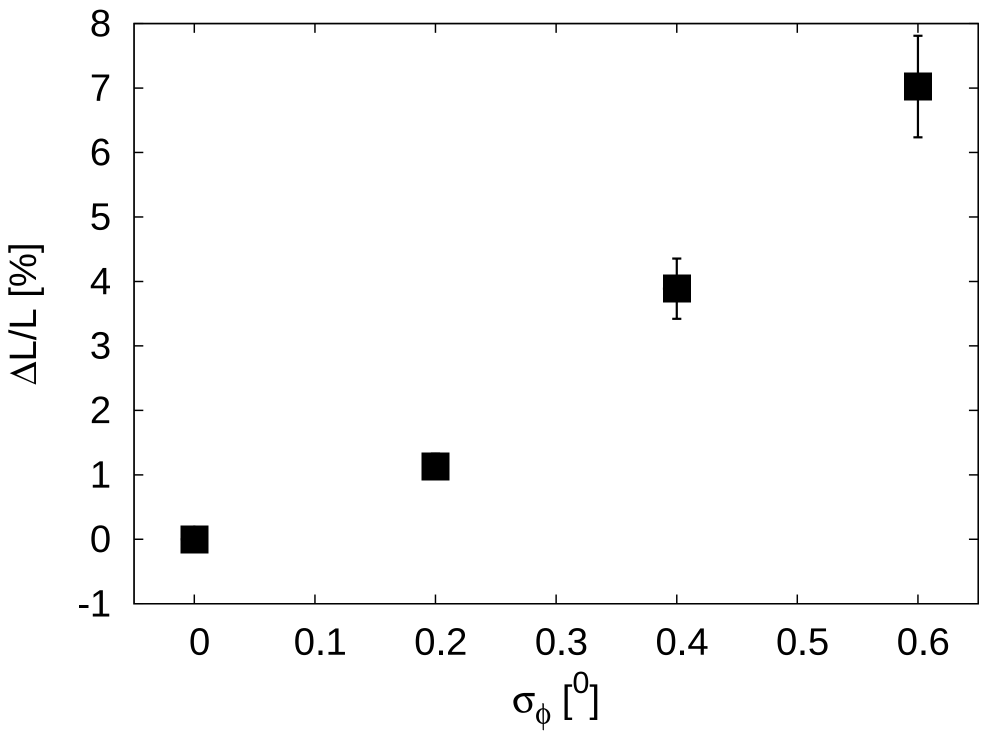
- Corrector step errors act like quadrupole jitter
  - assume use of 80 correctors simultaneously
  - $\sigma_{step} = 2\,\mathrm{nm}$ leads to $\Delta\epsilon_y = 0.04\,\mathrm{nm}$ in focusing quadrupoles
  - $\sigma_{step} = 3.6\,\mathrm{nm}$ leads to $\Delta\epsilon_y = 0.04\,\mathrm{nm}$ in defocusing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

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

Drive Beam Phase and Amplitude Jitter

- Drive beam current and phase errors lead to luminosity loss
- Most important is limited BDS energy bandwidth
  - but also emittance growth contributes

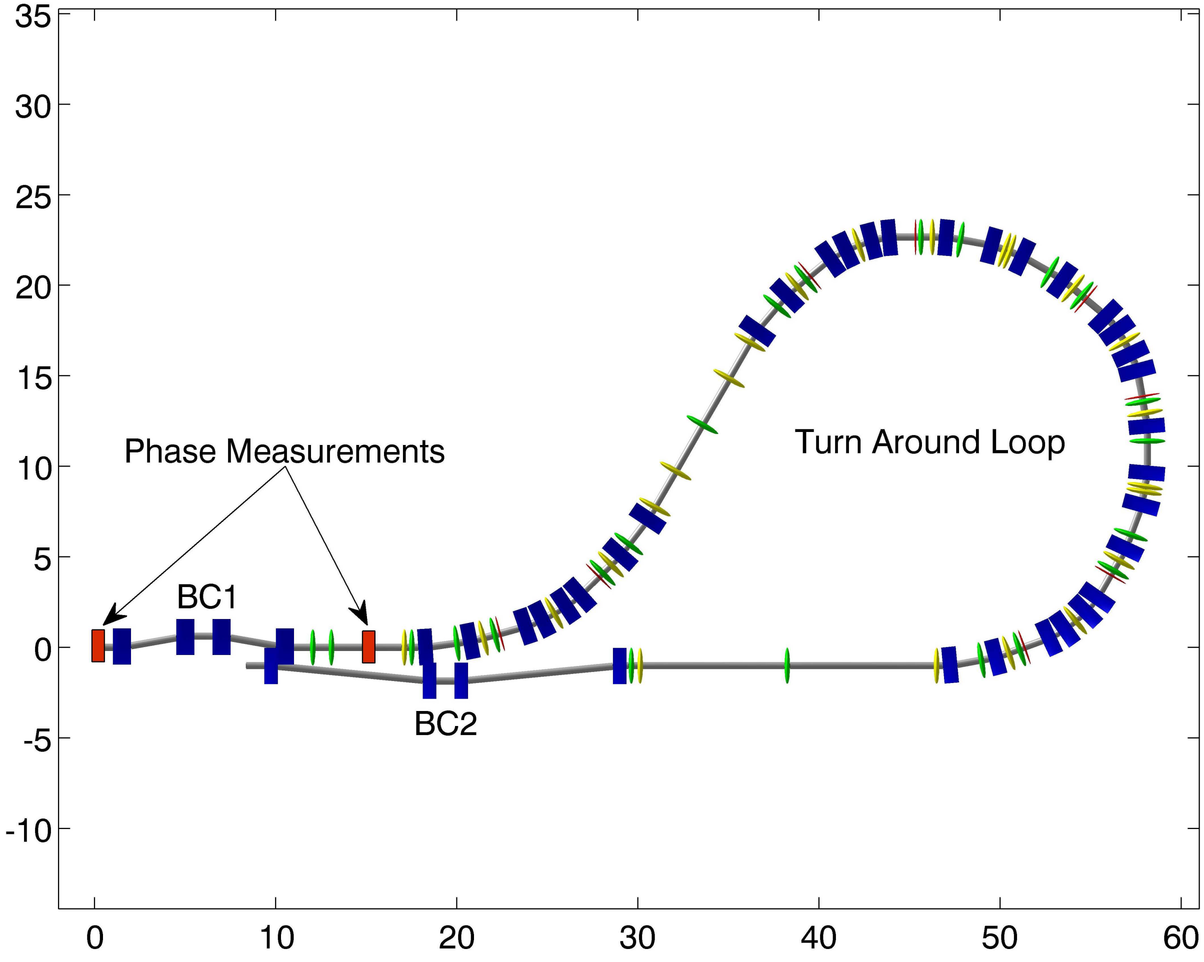
$$\frac{\Delta\mathcal{L}}{\mathcal{L}} \approx 0.01\left[\left(\frac{\sigma_{\phi,coh}}{0.2^\circ}\right)^2+\left(\frac{\sigma_{\phi,inc}}{0.8^\circ}\right)^2 + \left(\frac{\sigma_{G,coh}}{0.75\cdot 10^{-3}G}\right)^2+\left(\frac{\sigma_{G,inc}}{2.2\cdot 10^{-3}G}\right)^2\right] \quad (1)$$



Example of simulation results, a perfect machine is used with a coherent drive beam phase jitter

Feedforward at Final Turn-Around (Example Layout)

- Final feedforward shown
  - requires timing reference (FP6)
  - phase measurement/prediction (FP7)
  - tuning chicane (PSI)
- Measure phase and change of phase at BC1
- Adjust BC2 with kicker to compensate error
- One could also measure phase and energy at BC1



⇒ Need phase monitors with better than 0.1° over $\ll 60\,\mathrm{ns}$ resolution

  - two per decelerator for the main beam, at least five per decelerator for the drive beam
  - one current monitor per drive beam, energy measurement

Other Requirements for Instrumentation

- 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 vacuum requirement for the main linac is to stay below a few ntorr
  - the value is being reinvestigated
  - locally variations might be acceptable
- The radius of the aperture should be above $4\,\mathrm{mm}$
  - otherwise need an indepth discussion
- BPMs and phase monitors must be read out each pulse within 5ms

Other Instrumentation

- Beam size measurement after the main linac

  ⇒ BDS
- Luminosity emulator
  - laser wire of target beam size at the beginning of the BDS
- Breakdown detection, RF
- Beam loss detection
  - need to define a concept
- Beam energy measurement
  - need to develop a concept
- Beam size measurement in the linac
  - would be very valuable but first need to develop the concept

Conclusion

- Know requirements for BPMs, wake monitors and phase measurements
- Need to work on some other instrumentation requirements
- It is most important to close the loop
  - to include instrumentation performace in our studies
  - to identify strategies to cope with limitations or exploit high performance
  - to arrive at specifications
- We are looking forward to receive input from you