RF Timing Jitter in CLIC

D. Schulte

- Origin of the main linac RF phase and amplitude jitter tolerance
- Sources of main linac RF jitter
- Remarks on Mitigation strategies
- Conclusion

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RF Jitter

- An RF phase or amplitude jitter leads to
  - beam energy errors
  - multi-pulse emittance growth
- Both can lead to luminosity loss
  - the energy spread smears the luminosity spectrum
- Relevant is the RF phase with respect to the beam
- The beam loading can also lead to amplitude errors
- All drive beam bunches are generated in one place

  $\Rightarrow$ may have coherent errors
- In the following will consider jitter effects and assume that static imperfections can be tuned out

Jitter Tolerance

- For the physics an energy spread is bad
  - the intrinsic energy spread is $\sigma_{E,int} \approx 0.0035E$

  $\Rightarrow$ Previous CLIC Physics Study Group had already asked for configurations with less energy spread for some measurements

  - $\sigma_{E,jitter} \leq 0.001E$ seems acceptable
  - $\sigma_{E,jitter} \leq 0.002E$ seems significant

  $\Rightarrow$ aim for 10^{-3}
- Energy errors lead to transverse emittance growth

  $\Rightarrow$ limit luminosity loss
- The beam delivery system bandwidth is limited

  $\Rightarrow$ the resulting luminosity reduction needs to be limited

Simulation Results

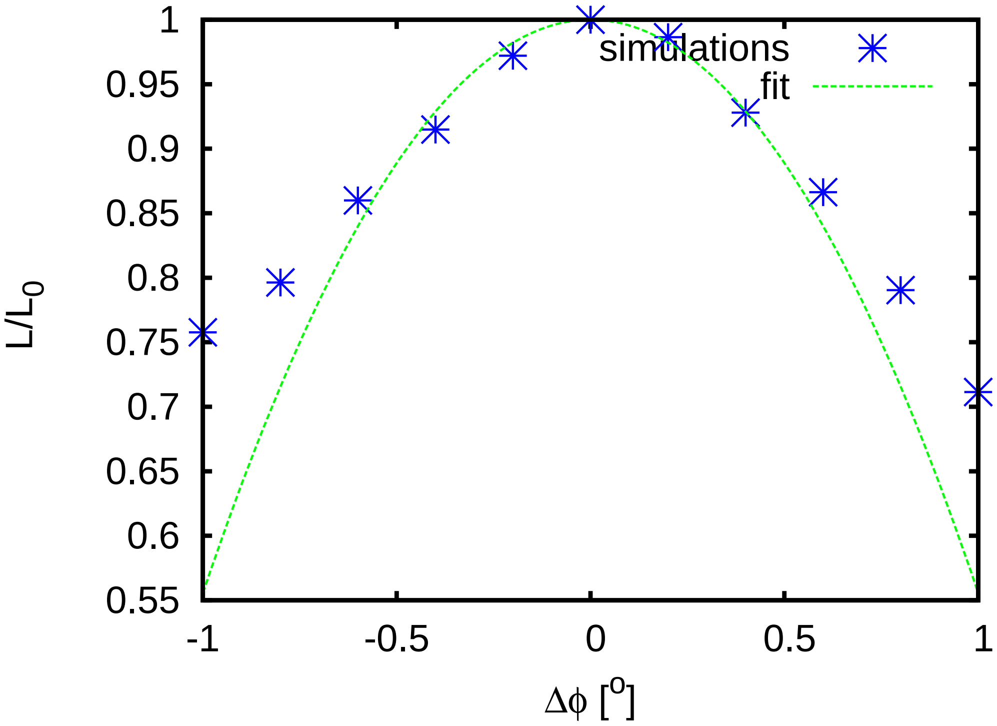
- Integrated simulations have been performed of main linac, BDS and beam-beam for perfectly aligned system (to determine BDS bandwidth)
  - for old BDS lattice and beam parameters

⇒ Limited BDS bandwidth leads to 2% luminosity loss for

  - $\sigma_\Phi \leq 0.15^\circ$
  - $\sigma_G \leq 6 \times 10^{-4} G$

- Final energy error due to uncorrelated jitter σ_{incoh} is about

$$\sigma_{coh} \approx \frac{\sigma_{incoh}}{\sqrt{10}}$$



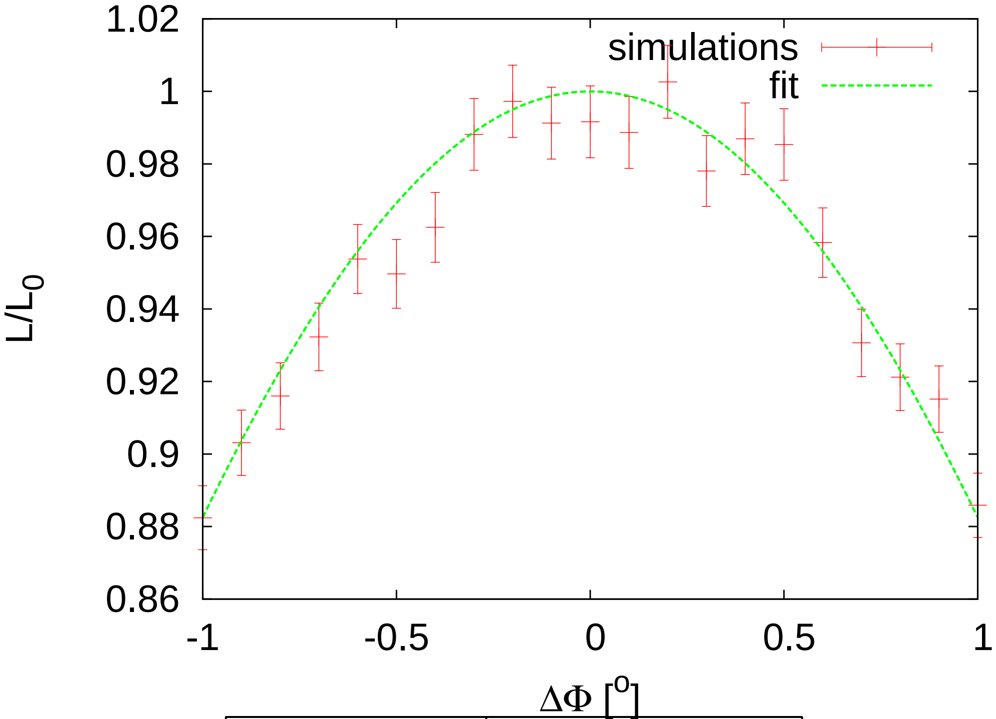
Simulation Results

- Simulation has been repeated for new parameters and BDS lattice
  - integrated simulations of main linac, BDS and beam-beam for perfectly aligned system
  - multi-pulse emittance growth in the main linac with realistic mis-alignments

⇒ Most tight is BDS bandwidth leads to 2% luminosity loss for

  - $\sigma_\Phi \leq 0.25^\circ$
  - $\sigma_G \leq 10 \times 10^{-4} G$

- Bandwidth appears significantly better
  - need to be confirmed with higher statistics



imperfection	size	$\Delta L/L\,\%$
$\sigma_{\phi,coh}$	0.5°	0.55
$\sigma_{a,coh}$	0.1%	0.4
$\sigma_{\phi,incoh}$	1.0°	0.65
$\sigma_{a,incoh}$	0.3%	0.5

Luminosity Loss

- Main beam current errors lead to different beam loading hence to energy errors
- Main beam phase errors lead to dephasing between main and drive beam and wrong timing at the collision point
  - luminosity loss from energy error is dominating
- For small perturbations one can express the luminosity loss as

$$\frac{\Delta L}{L} \approx 1.0\% \left[\left(\frac{\sigma_{\Phi,coh}}{0.1^\circ}\right)^2 + \left(\frac{\sigma_{G,coh}}{4 \cdot 10^{-4} G}\right)^2 + \left(\frac{\sigma_{\Phi,incoh}}{0.3^\circ}\right)^2 + \left(\frac{\sigma_{G,incoh}}{12 \cdot 10^{-4} G}\right)^2 + \left(\frac{\sigma_{\Phi,beam}}{0.1^\circ}\right)^2 + \left(\frac{\sigma_{I,beam}}{24 \cdot 10^{-4} I}\right)^2 \right]$$

- For new parameters and lattice

$$\frac{\Delta L}{L} \approx 1.0\% \left[\left(\frac{\sigma_{\Phi,coh}}{0.18^\circ}\right)^2 + \left(\frac{\sigma_{G,coh}}{7 \cdot 10^{-4} G}\right)^2 + \left(\frac{\sigma_{\Phi,incoh}}{0.6^\circ}\right)^2 + \left(\frac{\sigma_{G,incoh}}{22 \cdot 10^{-4} G}\right)^2 + \left(\frac{\sigma_{\Phi,beam}}{0.18^\circ}\right)^2 + \left(\frac{\sigma_{I,beam}}{42 \cdot 10^{-4} I}\right)^2 \right]$$

- Could propose following budgets

Drive beam current jitter	$7 \cdot 10^{-4}$
Drive beam phase jitter	0.2°
Main beam current jitter	10^{-3}
Main beam phase jitter	0.1°

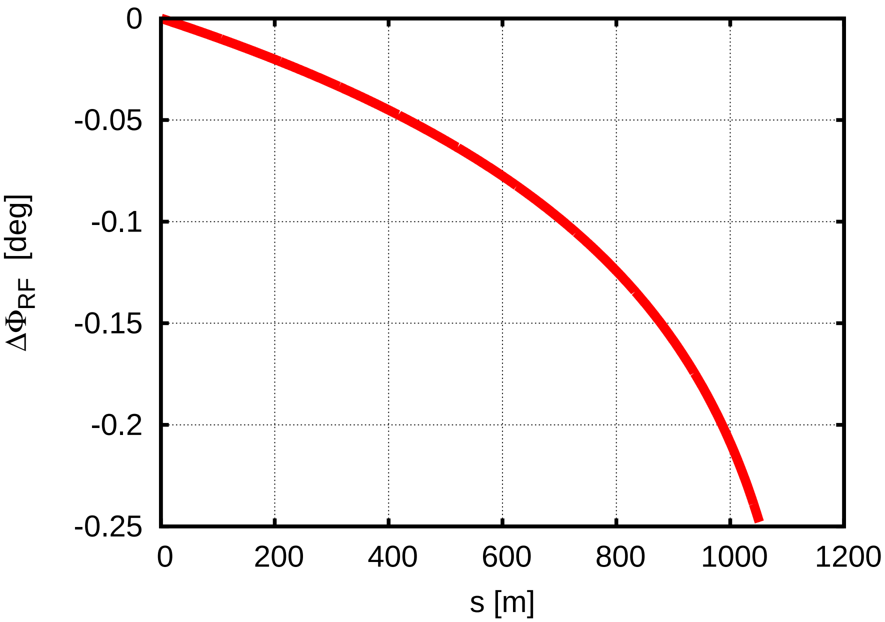
- Need to be able to measure these imperfections

Drive Beam Jitter Sources

- RF gradient error is given by drive beam current error $\Delta G/G = \Delta I/I$
- RF phase error is given by drive beam timing error $\Delta\Phi = 2\pi c\Delta t/\lambda$
- The whole drive beam is generated in one complex

  $\Rightarrow$ discuss coherent errors first
- Drive beam phase jitter sources
  - transverse jitter
  - energy errors in bunch compressors
  - timing errors in injector
  - path length changes
- Drive beam intensity errors
  - injector current variations
  - collimation
  - other losses

Transverse Drive Beam Jitter



Caluclation by E. Adli

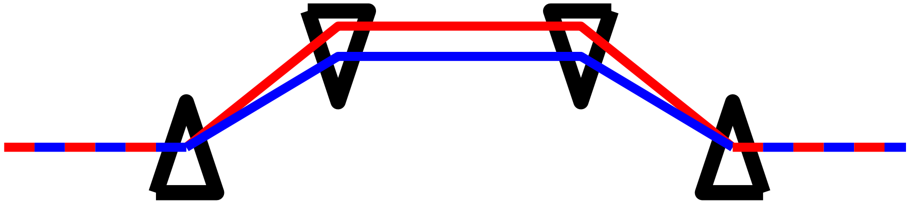
- Longitidinal motion due to transverse angles
- Assumed that systematic effect is tuned out

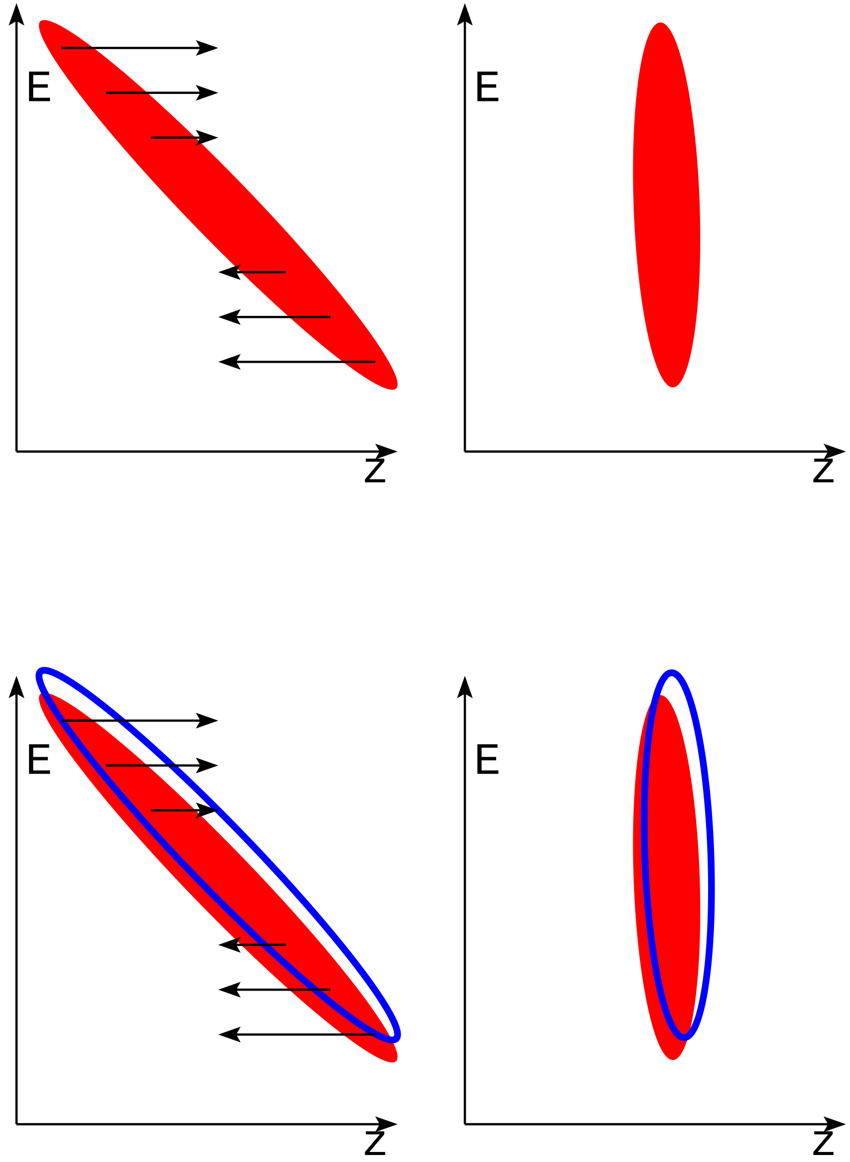
⇒ Only jitter component left

- Decelerator is most important (largest phase advance)
- Need to average over local phase error to obtain effective phase error

$$\left(\frac{\Delta x}{\sigma_x}\right)^2 + \left(\frac{\Delta x'}{\sigma_{x'}}\right)^2 + \left(\frac{\Delta y}{\sigma_y}\right)^2 + \left(\frac{\Delta y'}{\sigma_{y'}}\right)^2 \leq 1^2$$

Drive Beam Bunch Compressor





- The drive beam needs to be compressed longitudinally

  $\Rightarrow$ energy errors will translate into phase errors

$$\delta z = R_{56} \Delta E / E$$

$\Rightarrow$ Can attempt to avoid compression

Example: Tolerances for Single Stage Compressor

- Looking at compression stage just before drive beam decelerator
- Compression is $R_{56} \approx 0.36\,\mathrm{m}$

$\Rightarrow$ $\delta E/E = 3 \cdot 10^{-5}$ leads to $\delta z = 10.8\,\mu\mathrm{m}$

  - corresponds to phase tolerance

- for fully loaded operation one finds

$$\frac{\delta E}{E_0} = \frac{2\delta G}{G_0} - \frac{\delta N}{N_0}$$

$\Rightarrow$ tolerance

$|\delta G/G_0| \leq O(1.5 \cdot 10^{-5})$

$|\delta N/N_0| \leq O(3 \cdot 10^{-5})$

$|\delta \Phi| \leq O(0.01^\circ)$ for compressor RF

- Compression at an earlier stage with larger energy spread can increase tolerance for $\delta G/G_0$ and $\delta N/N_0$

$\Rightarrow$ compress in DBA, uncompress for combiner rings, recompress afterwards

- phase tolerance is not affected much

Mitigation Strategy

- Increase beam delivery system acceptance

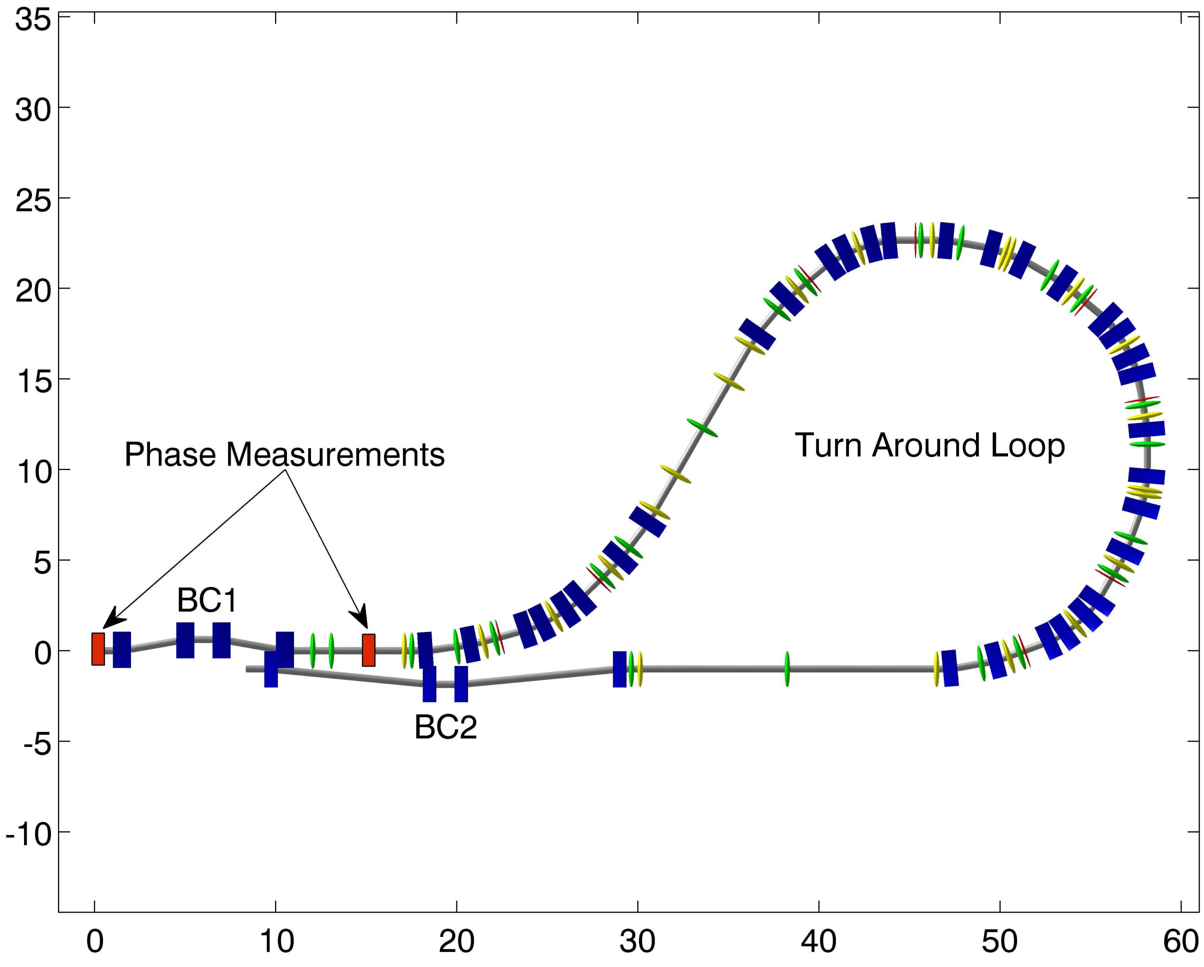
  but new limit from physics
- Stabilise drive beam
  - stable injector
  - stable RF
  - longitudinal feedback/feedforward
  - bunch compressor design
- Tie main beam to drive beam phase
  - one to the other or both to a common reference
  - via feedback/feedforward
  - via RF (e.g. bunch compressor)

Feedback/Feedforward Design

- Different locations for feedback/feedforward are possible
  - at the drive beam turn around loop
  - in the drive beam accelerator
  - in the beam transport line
- Need a timing reference
  - coupled local oscillators
  - local oscillator triggered by main beam
  - local oscillator triggered by drive beam
- Need to measure
  - beam phase
  - beam energy
  - other quantities

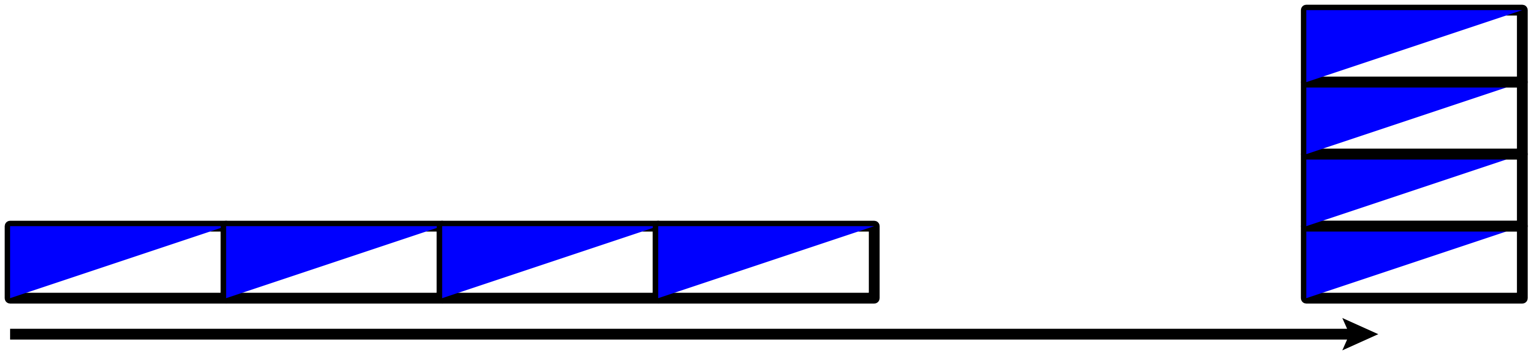
Example Feedforward at Final Turn-Around

- 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



Feedback

- Long drive beam pulse at generation $\approx 140\,\mu\mathrm{s}$
- End of pulse catches up with beginning due to combiner rings



- Also design of sequence of acceleration and bunch compression for drive beam can help to achieve required performance
  - but still need to beam able to measure final jitter

Conclusion

- A very tight tolerance on the drive beam phase jitter exists
- This leads to tight tolerances in the drive beam generation complex
- To meet these tolerances a number of methods could be used
    - using the drive beam RF to compress the main beam
    - feedforward at the final drive beam turn-around
    - beam feedback/feedforward at other locations
    - feedback on the klystron pulses
    - appropriate drive beam bunch compressor design
- Need time reference with sufficient precision
- Need to understand noise sources (e.g. klystons)