RF Timing Jitter in CLIC

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

RF Jitter

- An RF phase or amplitude jitter leads to
  - beam energy errors
  - 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 $\sigma_{E,int} \approx 0.003E$

  $\Rightarrow$ 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

Transverse Emittance Growth

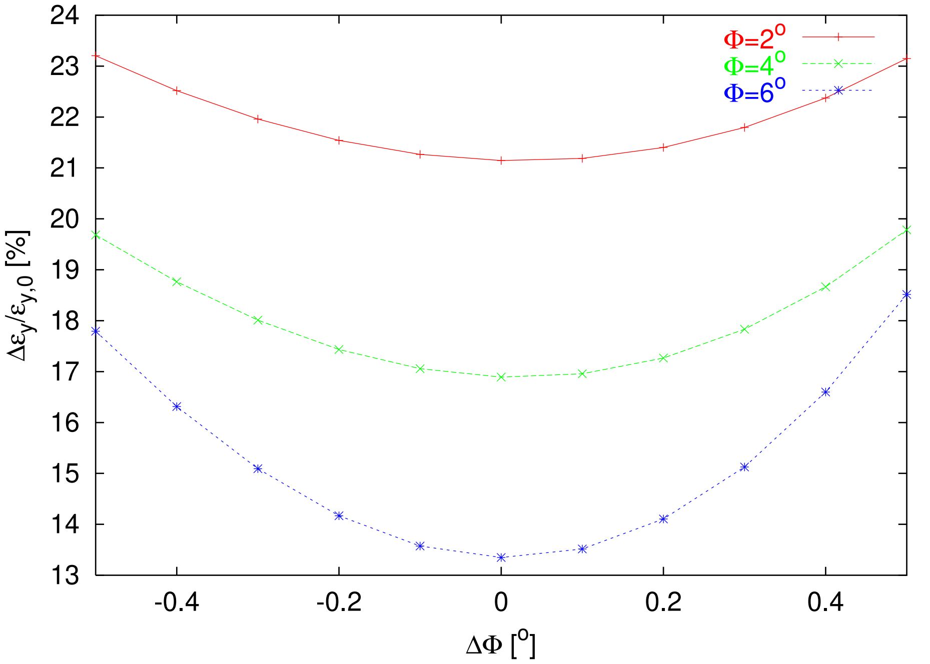
- Had been simulated with PLACET a while ago

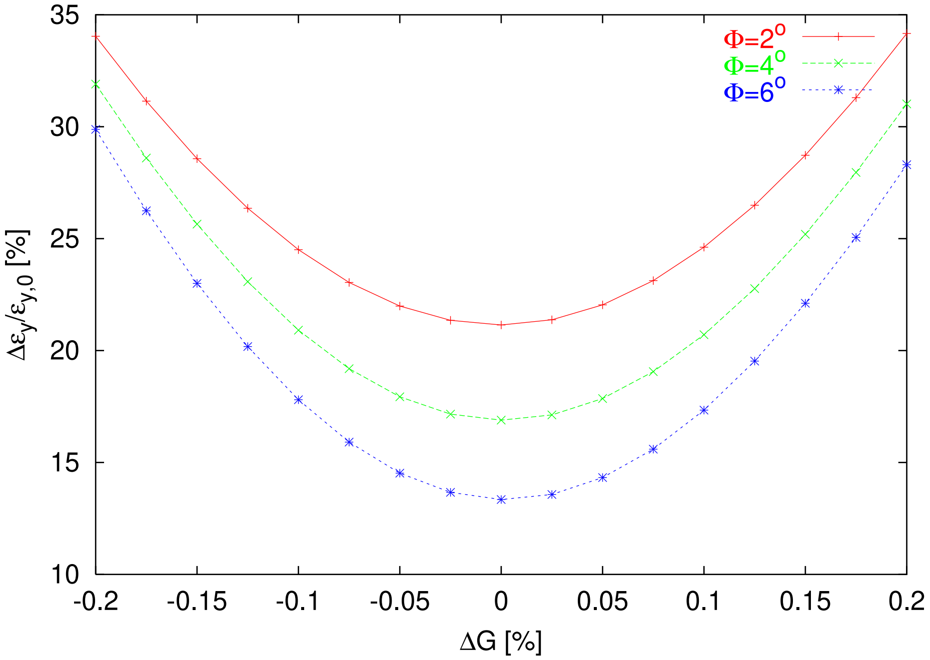
⇒ Limits from the emittance growth but tigther tolerance from energy spread

- Dispersion free steering can be carried out
  - use beams accelerated at different gradients or RF phases
  - minimise absolute offset in BPMs
  - simultaneously minimise difference of trajectories

  ⇒ should be able to improve compensation of gradient related effects along the linac, if necessary

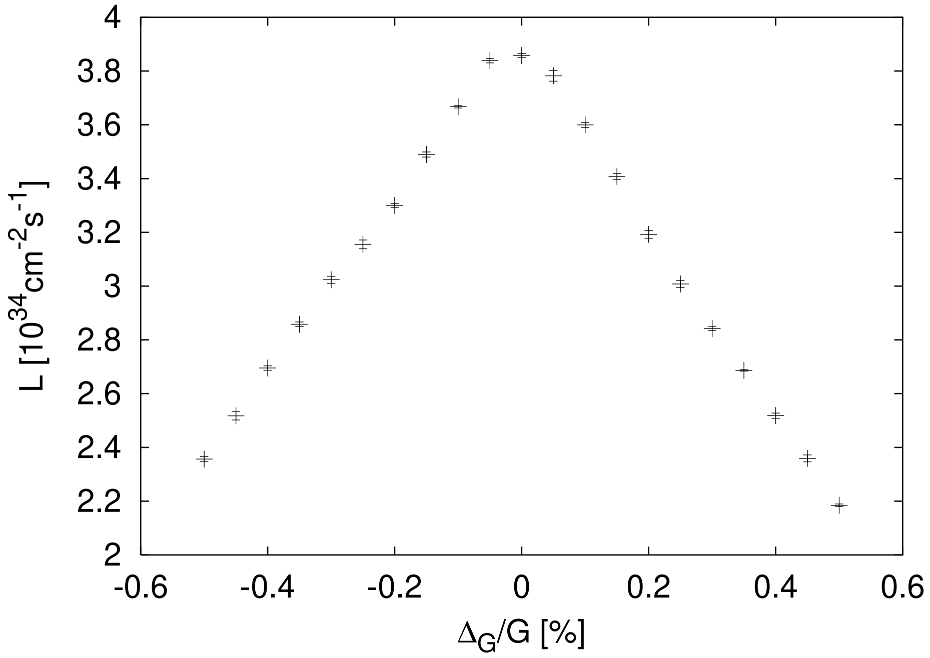
Results for Emittance Growth





$\Rightarrow$ From energy error $\Delta G \leq 0.001G$ and $\Delta\Phi \leq 0.25°$

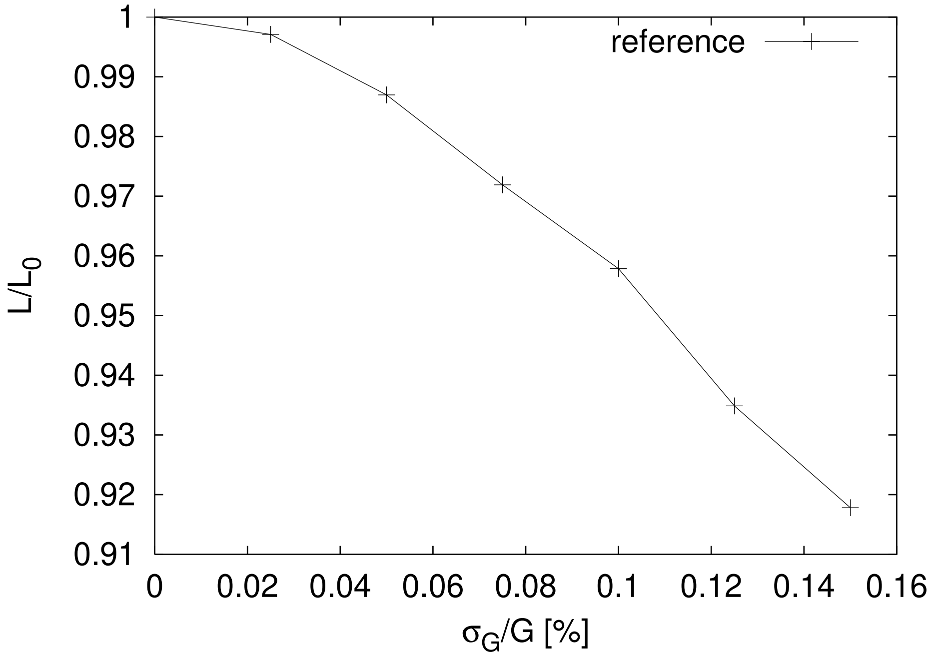
Full Simulation of Perfect Machine

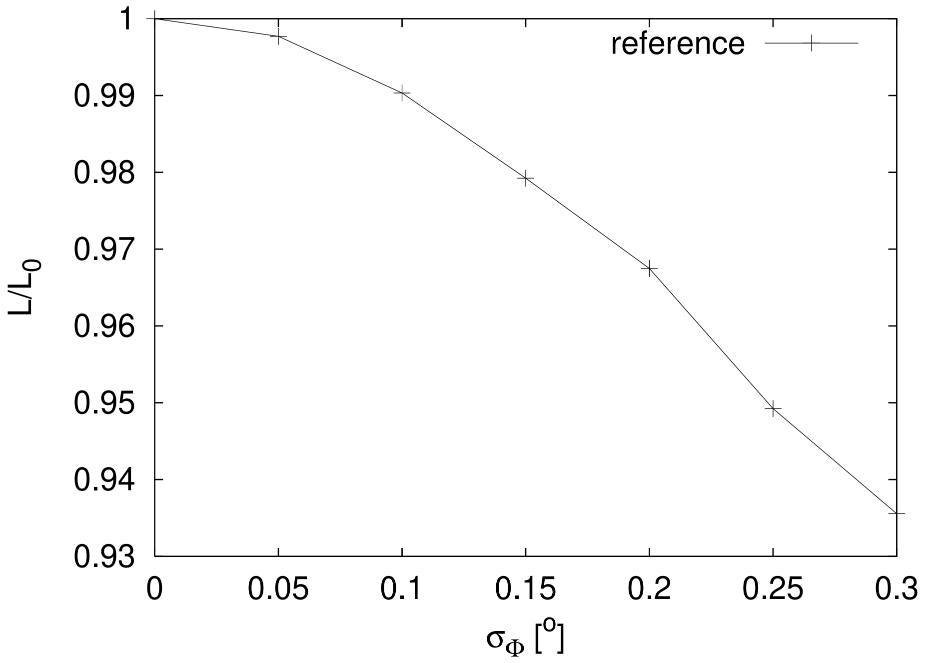


- Study of luminosity including transport through the main linac and the beam delivery system as well as beam-beam effects
- Limit assumed to be a luminosity loss of $\Delta L/L \leq 0.02$ per beam
- Simulation have been performed with PLACET and GUINEA-PIG using a perfect machine with 10nm initial vertical emittance

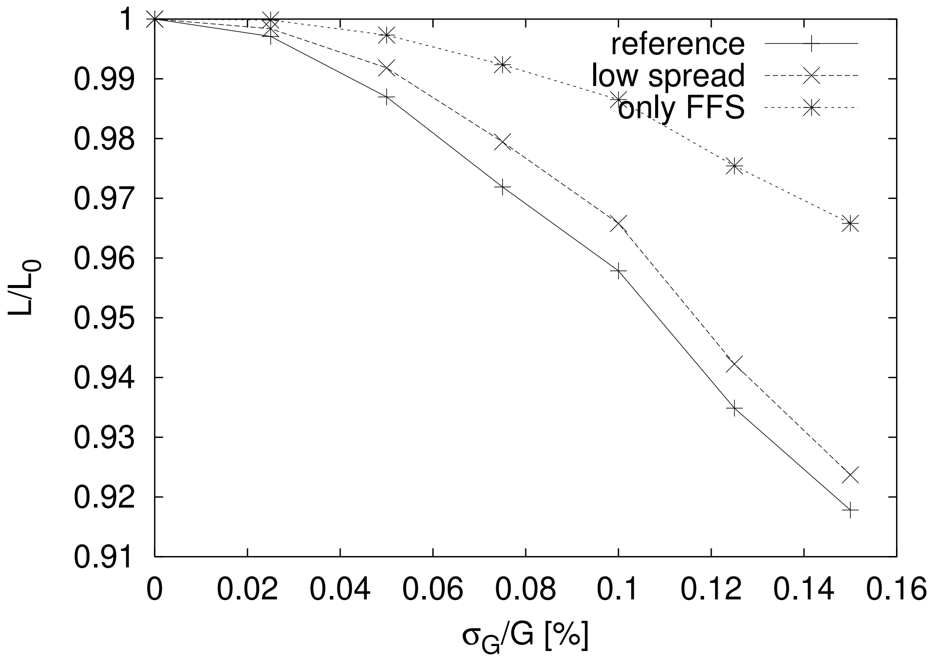
  $\Rightarrow$ turns out to give tighter tolerance than energy spread

Simulation Results





Resulting Tolerances



- With full BDS, one finds for 2% luminosity loss:
  - $\sigma_\Phi \leq 0.15^\circ$ corresponds to $\approx 4\,\mu\mathrm{m}$
  - $\sigma_G \leq 6 \times 10^{-4} G$
- For lower energy spread:
  - $\sigma_G \leq 7 \times 10^{-4} G$
- With full FFS only:
  - $\sigma_G \leq 12 \times 10^{-4} G$

RF Jitter Sources

- The RF is produced by the drive beam
- Small timing errors of the drive beam lead to RF phase jitter

  $\Delta\Phi = 2\pi c \Delta t/\lambda$

- Drive beam amplitude errors lead to gradient errors

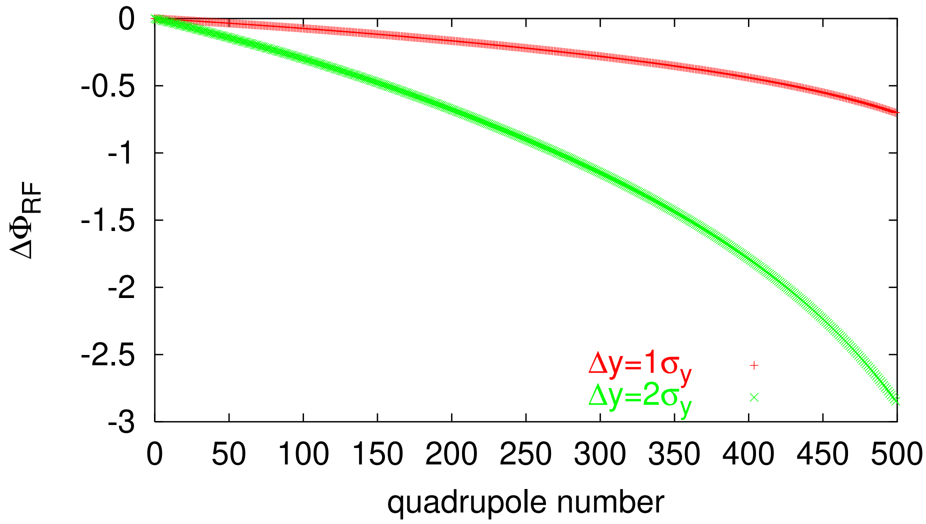
  $\Delta G/G = \Delta I/I$

- The whole drive beam is generated in one complex

  $\Rightarrow$ worry about coherent errors first

- Variations within the drive beam pulse will be considered at the end
- 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



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

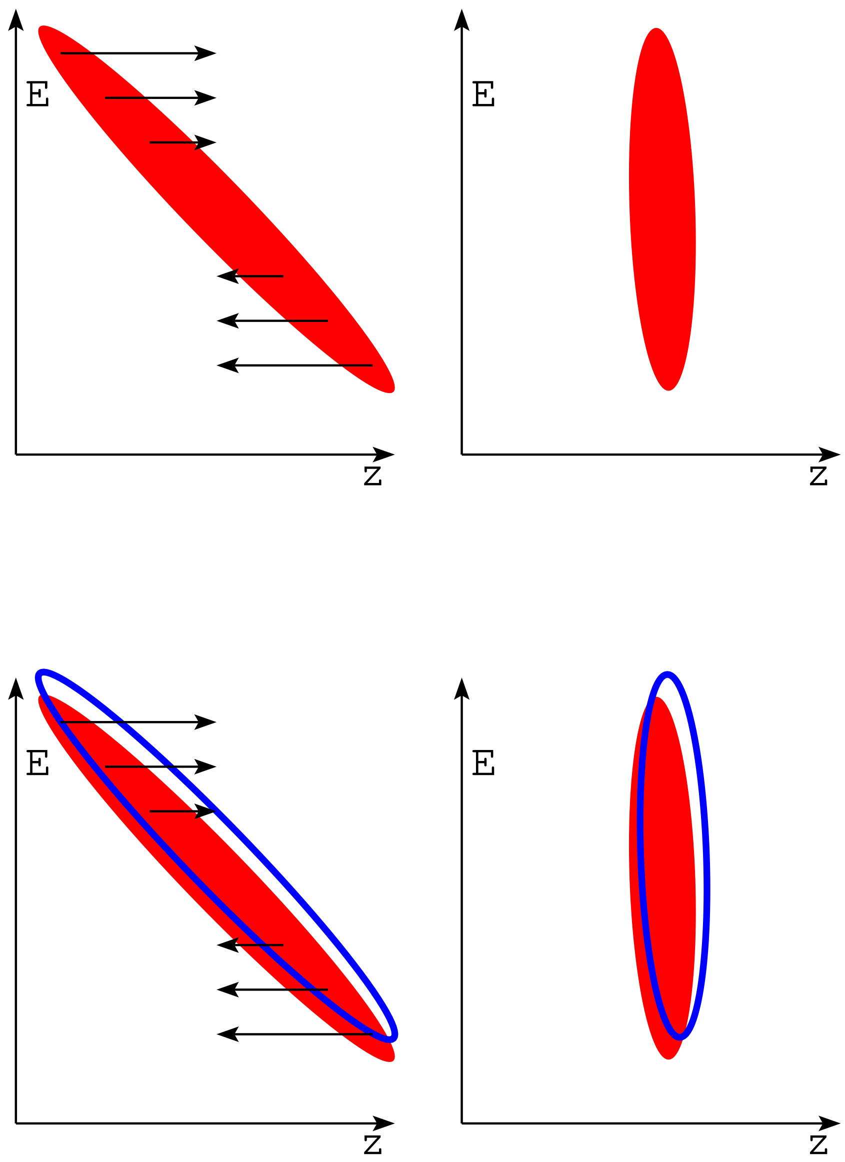
$\Rightarrow$ Only jitter component left

- Simulations done with PLACET
- Need to average over local phase error to obtain effective phase error

$\Rightarrow$ Tighter tolerance from phase error than from transverse beam break-up

$$\left(\frac{\Delta x}{\sigma_x}\right)^2 + \left(\frac{\Delta x'}{\sigma_{x'}}\right)^2 + \left(\frac{\Delta y}{\sigma_y}\right)^2 + \left(\frac{\Delta y'}{\sigma_{y'}}\right)^2 \leq 0.9^2$$

Drive Beam Bunch Compressor



- The drive beam needs to be compressed longitudinally

  $\Rightarrow$ energy errors will translate into phase errors

Example: Tolerances for Single Stage Compressor

- Assuming one compression stage at the end of the drive beam accelerator or before decelerator
- $\sigma_z \approx 4\,\mathrm{mm}$ and $\sigma_E \approx 0.01E$

$\Rightarrow$ required compression $R_{56} \approx 0.4\,\mathrm{m}$

$\Rightarrow$ $\delta E/E = 10^{-5}$ leads to $\delta z \approx 4\,\mu\mathrm{m}$

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

$\Rightarrow$ tolerance

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

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

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

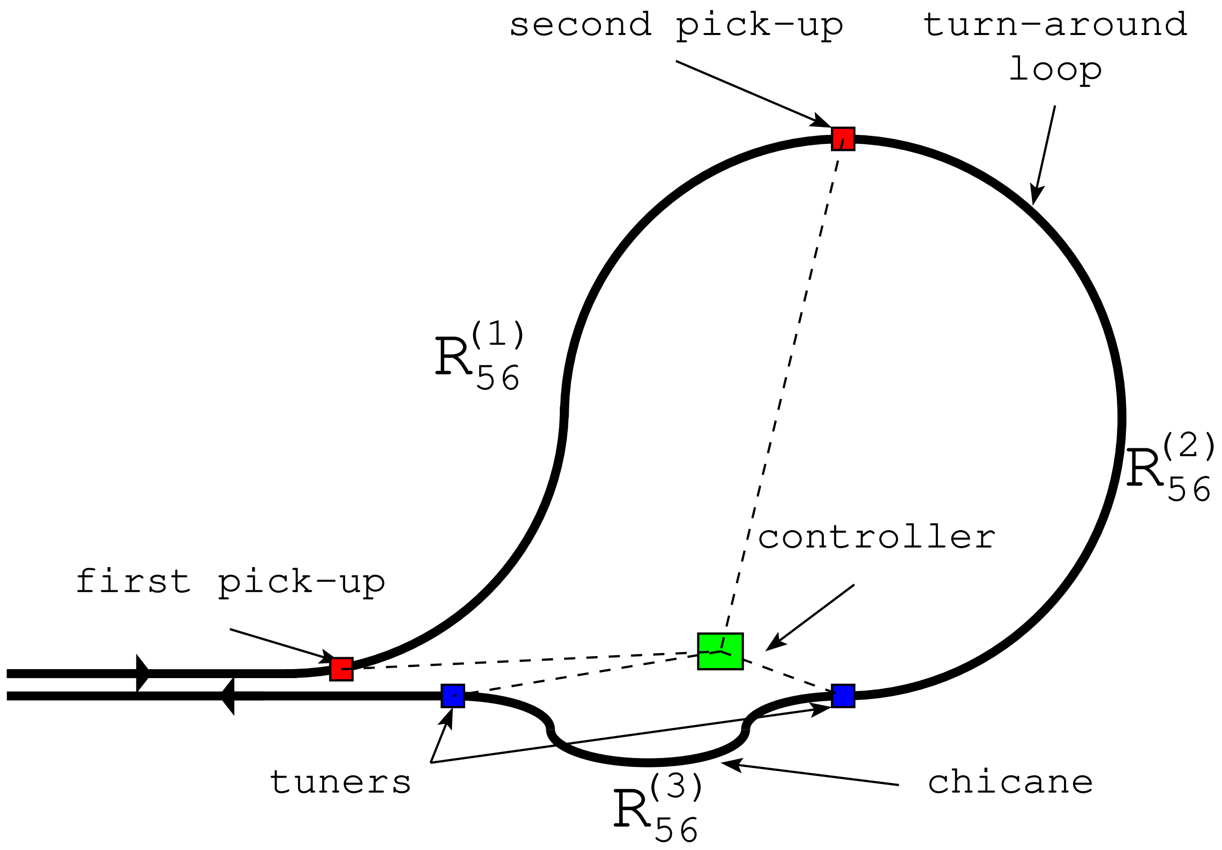
- Tie main beam to drive beam phase

  - 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



- Measure
  - phase+energy
  - phase with compression

Drive Beam Bunch Compressor Simulations

- Parameters at drive beam accelerator (DBA)

parameter	symbol	unit	value
particles per bunch	N	$[10^{10}]$	6
energy before DBA	E_0	[MeV]	50
energy after BDA	E_f	[MeV]	2000
bunch length before DBA	$\sigma_{z,0}$	[mm]	4
bunch length after DBA	$\sigma_{z,f}$	[mm]	0.4

- Simulation taking RF, single-bunch wakefield, multi-bunch beam loading and compression with linear R_{56} into account

- $\sigma_z = 400\,\mu\mathrm{m}$ can be transported and does not create large energy spread

variable	unit	
L_1	[m]	4.3
G_1	[MV/m]	13
ϕ_1	[°]	60
$R_{56}^{(1)}$	[m/MV]	0.00105
$\delta N/N$	$[10^{-3}]$	0.2
δz	[$\mu\mathrm{m}$]	600
$\delta E_0/E_0$	$[10^{-3}]$	0.1
$\delta G/G$	$[10^{-4}]$	2
$\delta\phi$	[°]	0.008

Stabilising Bunch Compressor

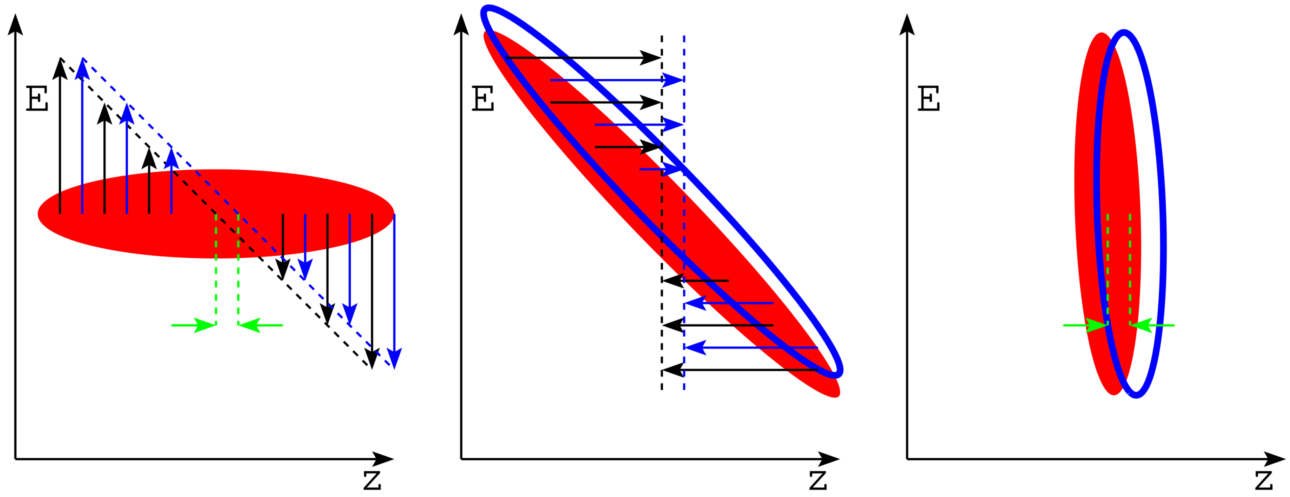
- Basic idea: to get rid of dependence on initial beam energy use two-stage compression
- ansatz:

$$\begin{pmatrix} \delta z_f \\ \delta E_f \\ \delta N_f \end{pmatrix} = M \begin{pmatrix} \delta z_i \\ \delta E_i \\ \delta N_i \end{pmatrix}$$

variable	unit	first	second
L_1	[m]	2	16
G_1	[MV/m]	13	13
ϕ_1	[$^\circ$]	60	-60
$R_{56}^{(1)}$	[m/MV]	0.0022	-0.00025
$\delta N/N$	[10^{-3}]	0.3	
δz	[μm]	70	
$\delta E_0/E_0$	[10^{-3}]	6	
$\delta G/G$	[10^{-4}]	200	2.8
$\delta\phi$	[$^\circ$]	0.8	0.01

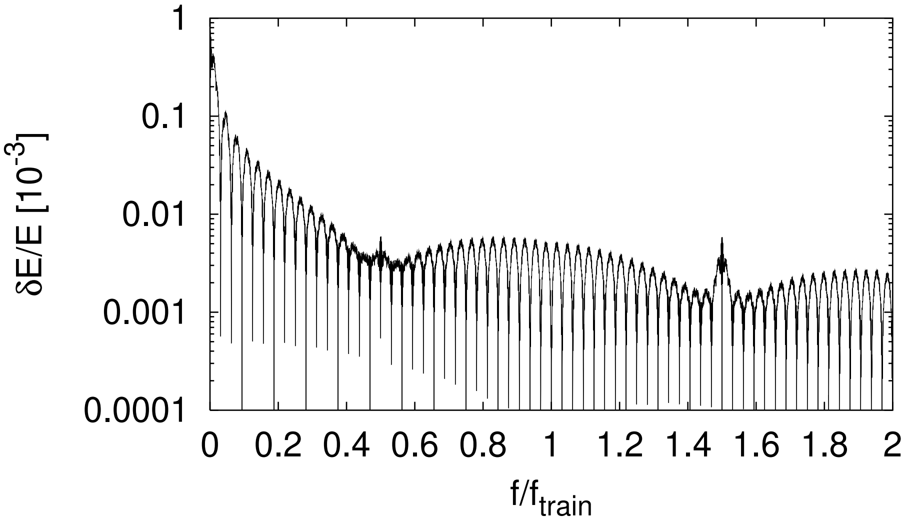
- Can tune to compensate δN and δE_0 if they are correlated

Coupling Main Beam and Drive Beam Phase with the Main Beam Bunch Compressor



- The energy spread to compress the main beam is produced by RF
- If one uses the drive beam to generate the RF, it will automatically set the main beam to it's own phase

Phase Mixing



- Perturbation of drive beam can have different fequencies
- Can lead to variation of errors within a pulse
- Requires inclusion of the delay loop and combiner rings
- Example: jitter of klystron phase in second stage of bunch compressor
- Simplified model for drive beam and main beam accelerating structure (constant impedance, no losses)

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 turnaround
  - 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)