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

ILC-CLIC Beam Dynamics Workshop, June 25, 2009

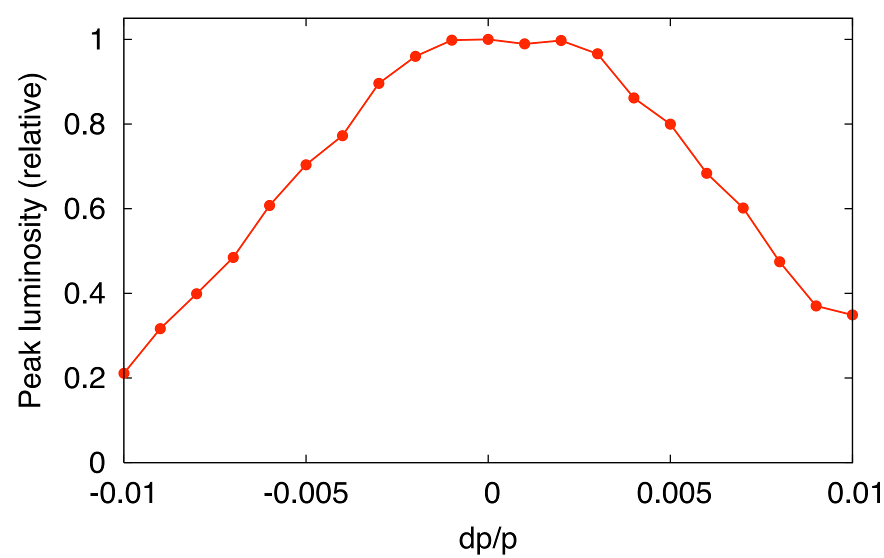
RF Jitter

- 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



Luminosity Loss

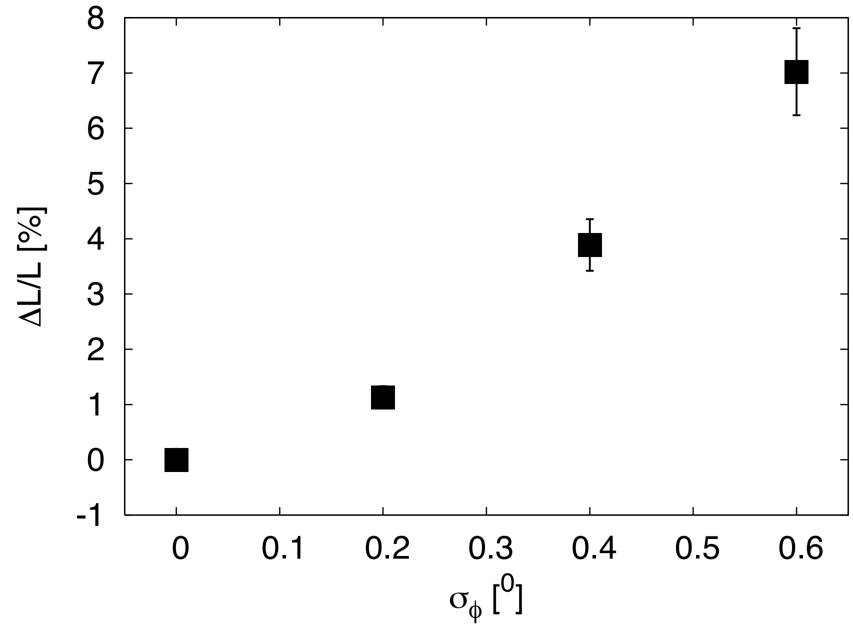
- Integrated simulations have been performed with PLACET and GUINEA-PIG of main linac, BDS and beam-beam
    - system is assumed to be perfectly aligned (to determine BDS bandwidth effect)
    - assuming target emittance at BDS
- Resulting luminosity loss is about 2% for

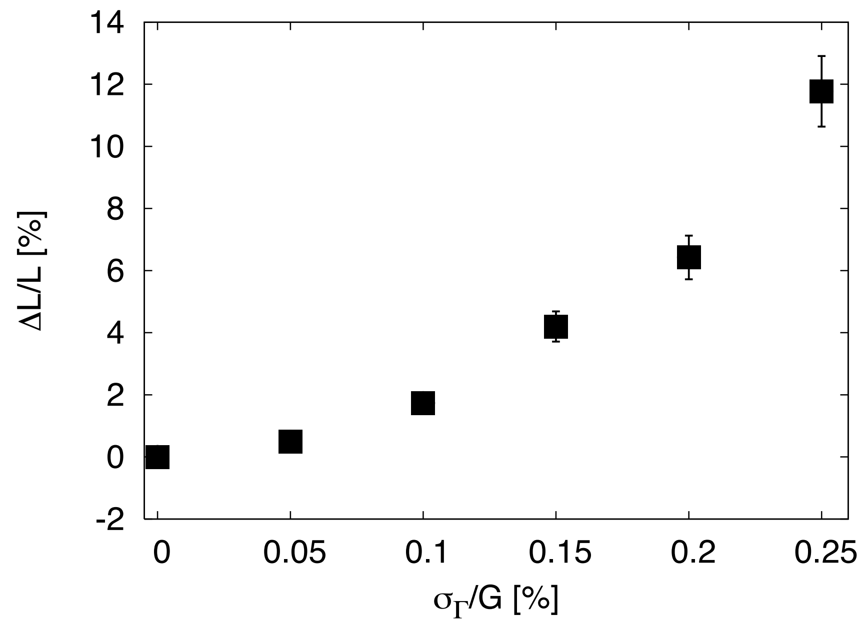
$$\frac{\sigma_G}{G} \approx 1 \times 10^{-3}$$

and

$$\sigma_\phi \approx 0.3^\circ$$

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





Emittance Growth

- To evaluate impact of RF error in misaligned machine assumed machine after ten days of ground motion and one-to-one alignment

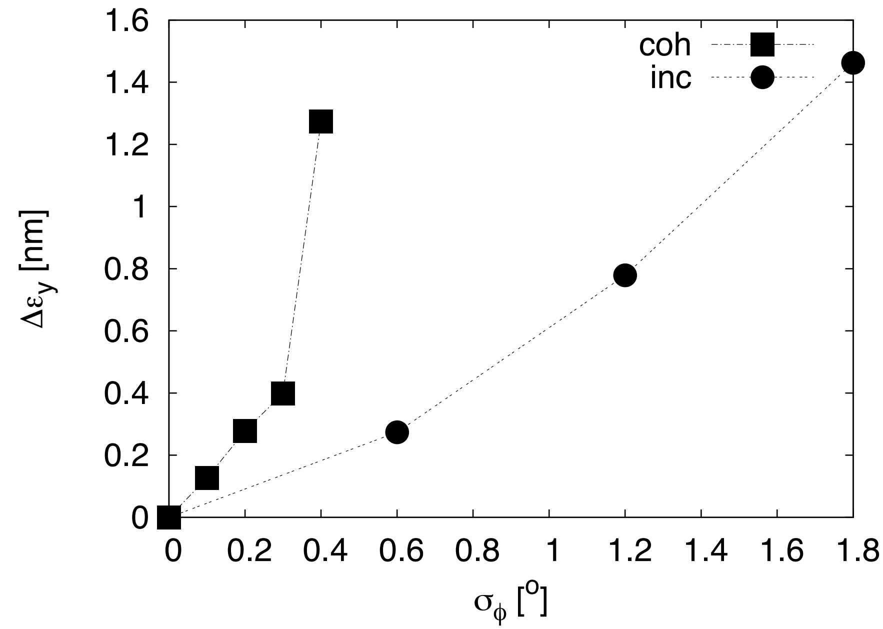
  ⇒ emittance is close to nominal

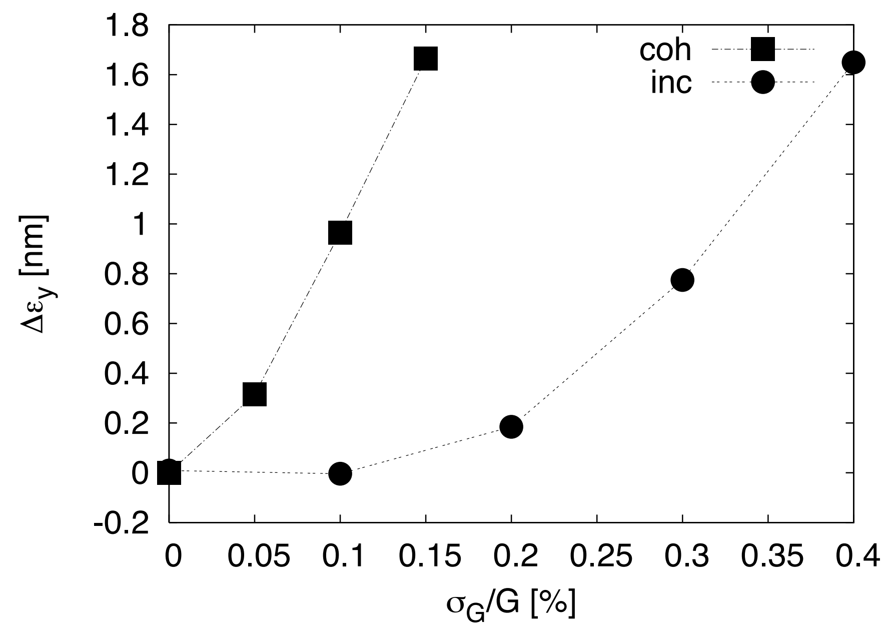
  ⇒ pessimistic, no disperison optimisation

  - only main linac emittance growth is considered

- $\Delta\epsilon_y = 0.8\,\mathrm{nm}$ corresponds to 2% luminosity loss

⇒ Resulting luminosity from emittance growth is comparable to the one caused by limited BDS bandwidth



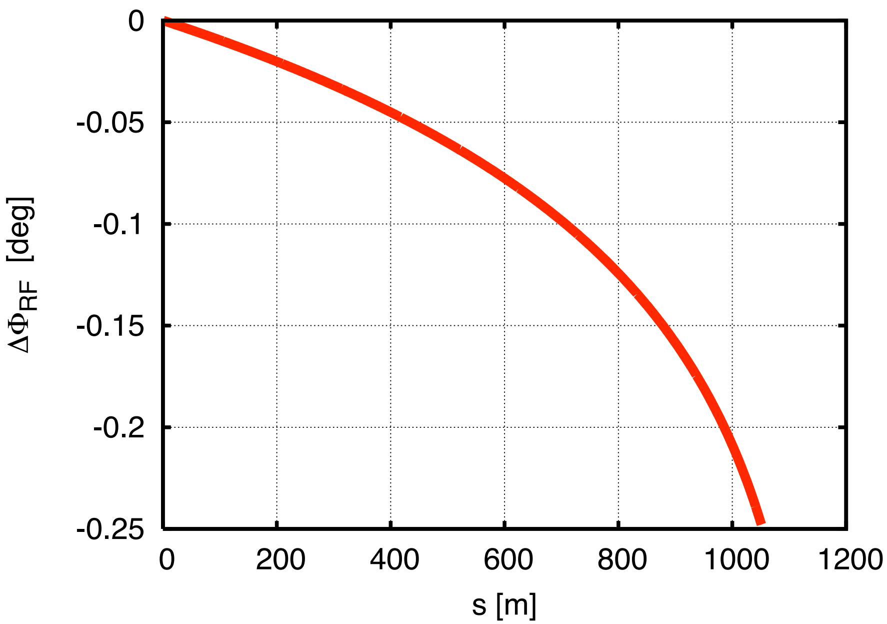


Drive Beam Jitter Sources

- 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

$\Rightarrow$ Only jitter component left

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

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

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

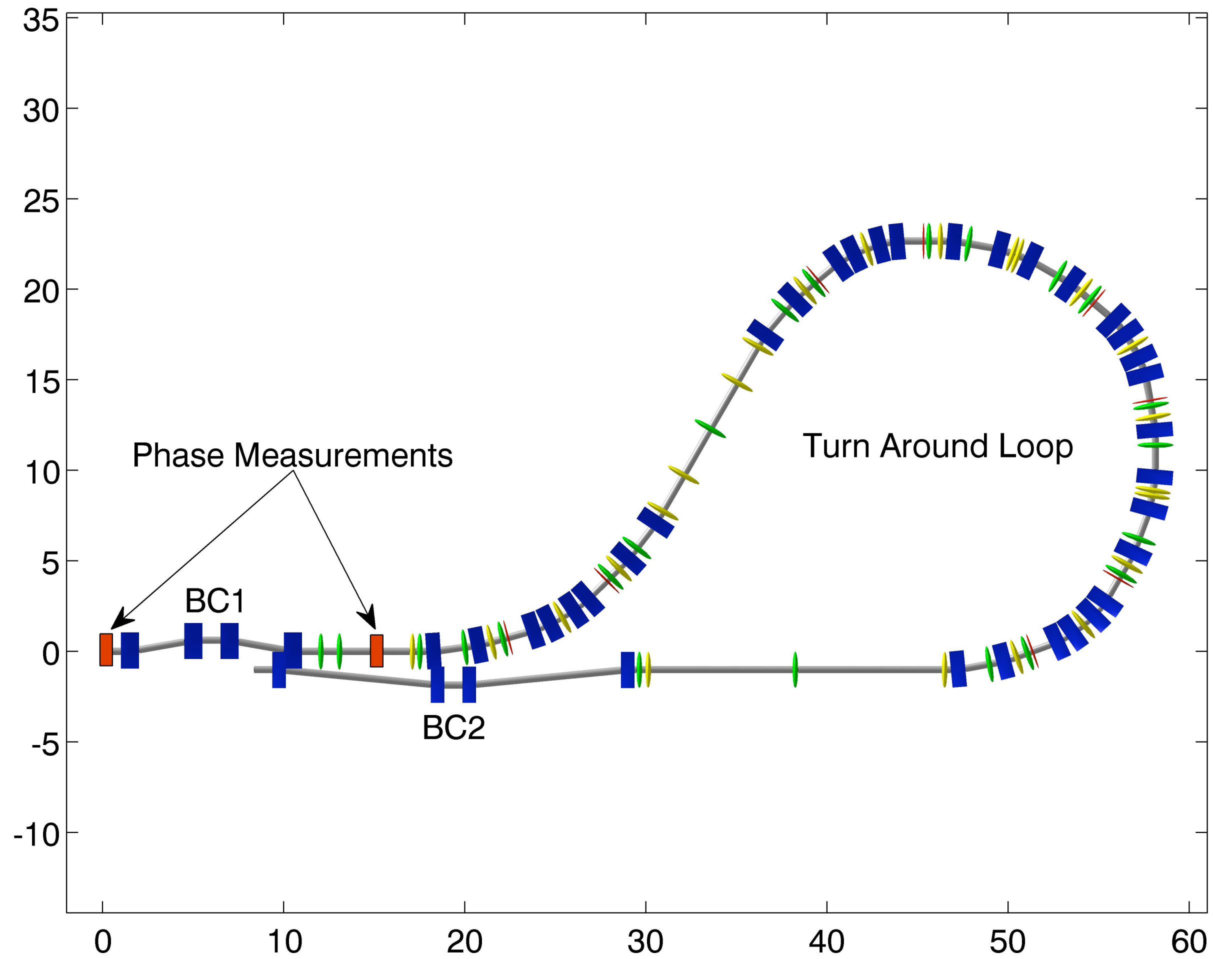
Feedforward at Final Turn-Around

- Final feedforward shown

  ultima ratio

  - requires timing reference (FP6)
  - phase measurement/prediction (FP7)
  - tuning chicane (FP7, 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
- Missing will be kicker and amplifier



Tolerances before Feedforward

- Can cure phase error
  - could also cure intensity error if we rely on off-crest running
- Want to capture 3–4 times RMS tolerance before feedforward
  - assume gain factor of 10

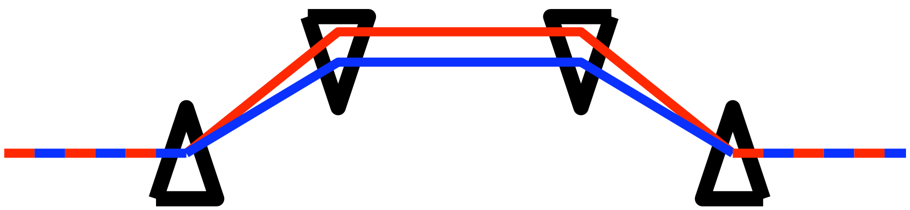
  $\Rightarrow$ would like range of $4 \times 10 \times 0.8^\circ = 32^\circ$
- Assume feedforward capture range is 10° ($\Delta z = 0.7\,\mathrm{mm}$)
  - lattice is OK but kicker needs to be evaluated

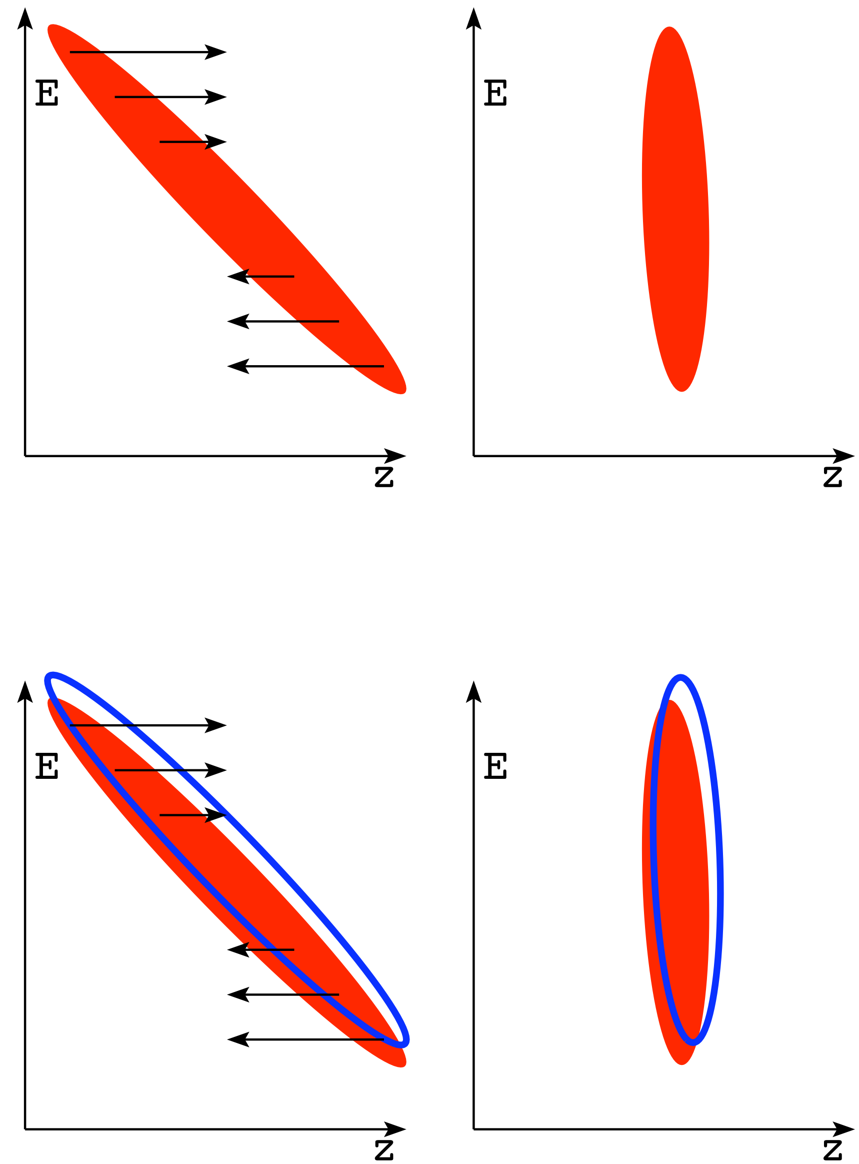
  $\Rightarrow$ can allow 2.5° RMS jitter before feedback (4σ capture)
  - assume gain factor of 10

    $\Rightarrow$ 0.25° RMS jitter after feedforward
- Beam stability in decelerator requires less than 1% overcurrent

  $\Rightarrow$ require 0.1% RMS fluctuation per 5 bunches (one PETS fill time)
  - current stability from preliminary CTF3 measurement is 0.1%
  - static variations still need to be cured

Drive Beam Bunch Compressor





- The drive beam needs to be compressed longitudinally

  ⇒ energy errors will translate into phase errors

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

- For fully loaded operation

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

⇒ Can attempt to avoid compression

Bunch Compressor Options

- Total compression after drive beam accelerator
  - energy chirp of 0.6% per $\sigma_z = 4\,\mathrm{mm}$ requires $R_{56} = 0.67\,\mathrm{m}$

  $\Rightarrow$ relative energy error tolerance is 2×10^{-4}

  $\Rightarrow$ relative gradient tolerance is 1×10^{-4}

  $\Rightarrow$ relative charge tolerance is 2×10^{-4}

  $\Rightarrow$ phase tolerance is 0.2° at $1\,\mathrm{GHz}$

- Early compression in drive beam accelerator ($4\,\mathrm{mm} \rightarrow 1\,\mathrm{mm}$), uncomression at end ($1\,\mathrm{mm} \rightarrow 2\,\mathrm{mm}$) and recomression before decelerator ($2\,\mathrm{mm} \rightarrow 1\,\mathrm{mm}$)
  - RF errors would be important at first compression
  - assume (maybe optimistic) chirp of 3% per σ_z

  $\Rightarrow$ relative energy tolerance is 10^{-3}

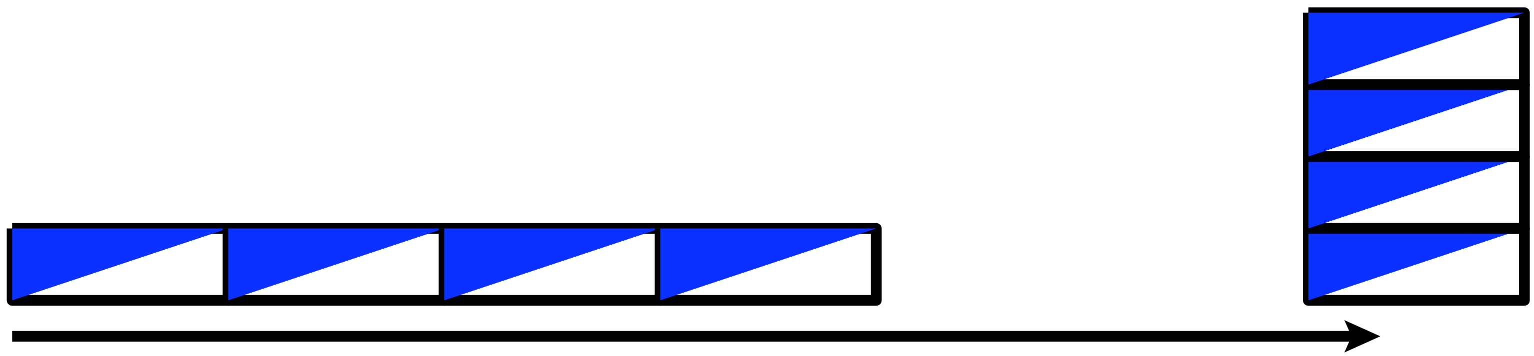
  $\Rightarrow$ relative gradient tolerance is 5×10^{-4}

  $\Rightarrow$ relative charge tolerance is 1×10^{-3}

  $\Rightarrow$ phase tolerance is 0.2° at $1\,\mathrm{GHz}$

Filtering and Feedback

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

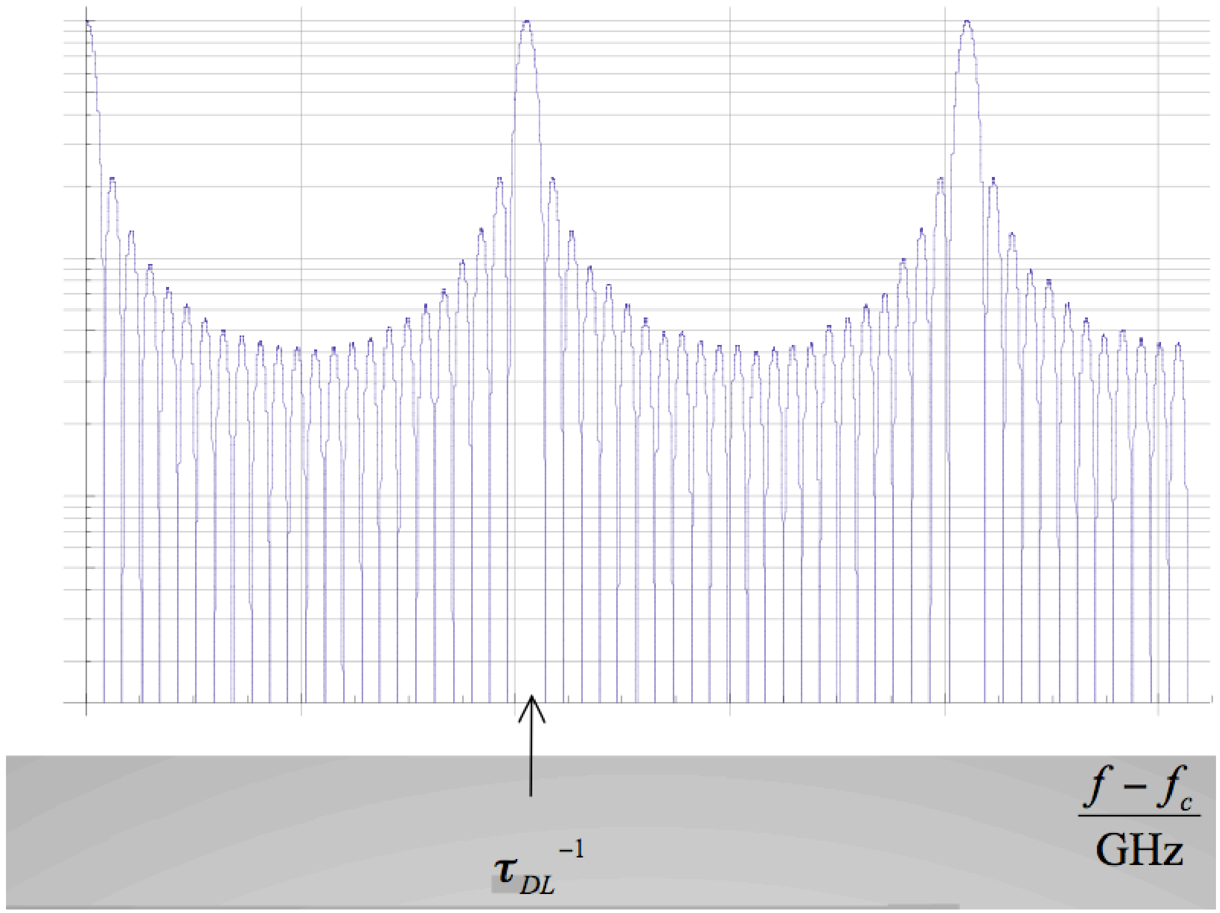


- Also design of sequence of acceleration and bunch compression for drive beam can help to achieve required performance

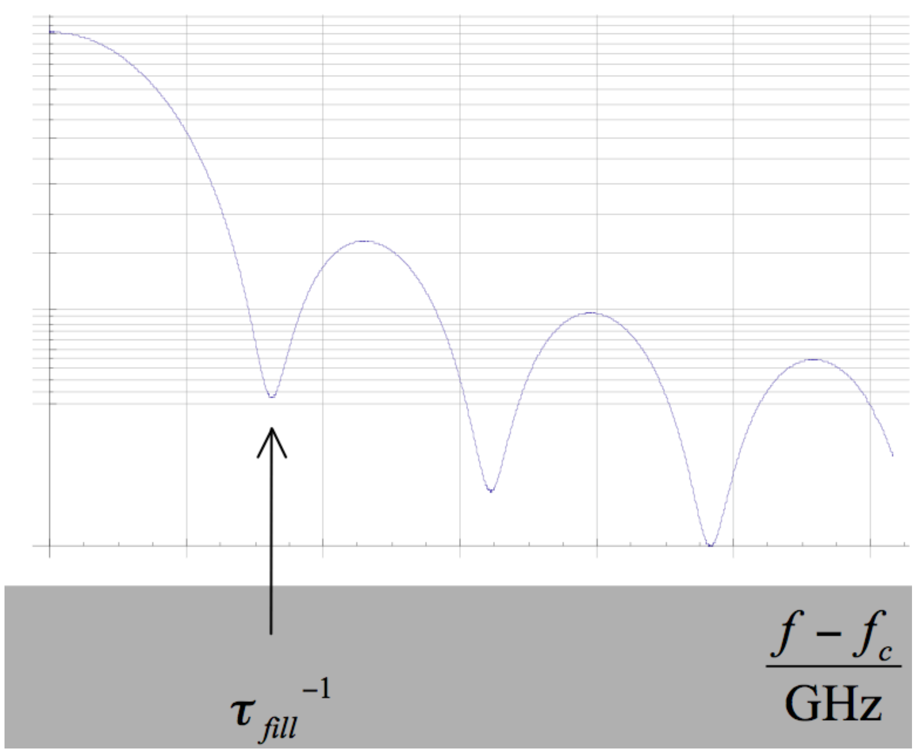
  - but still need to beam able to measure final jitter

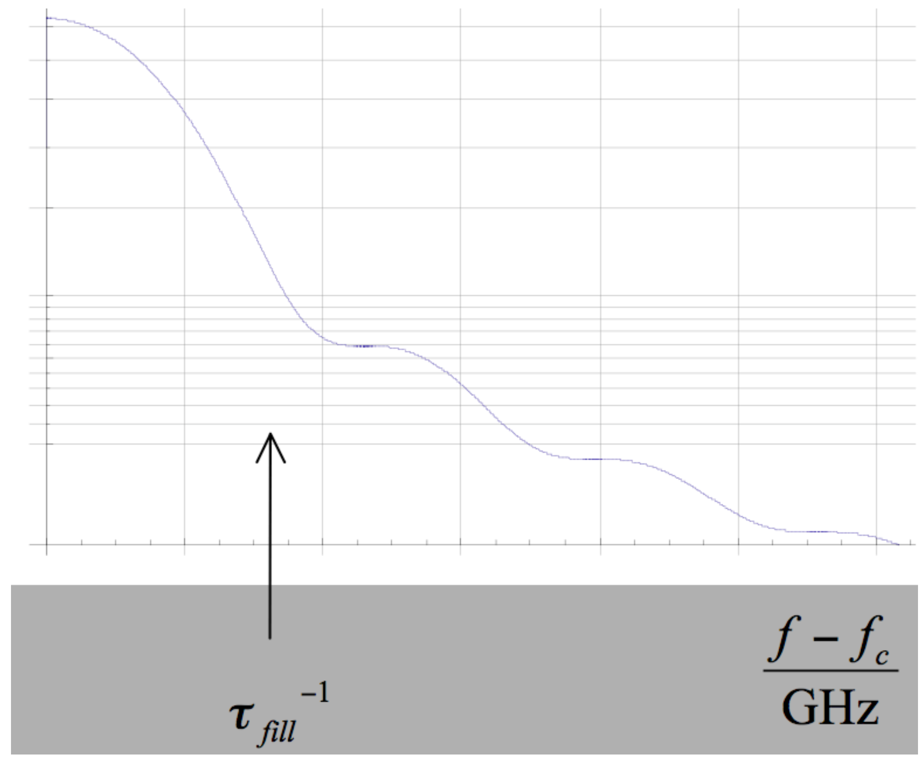
Ovelay of Pulses

- Noise is reduced by combiner rings
- No reason why klystron should have much noise at train frequency
- But good reason why beam could have noise at train frequency



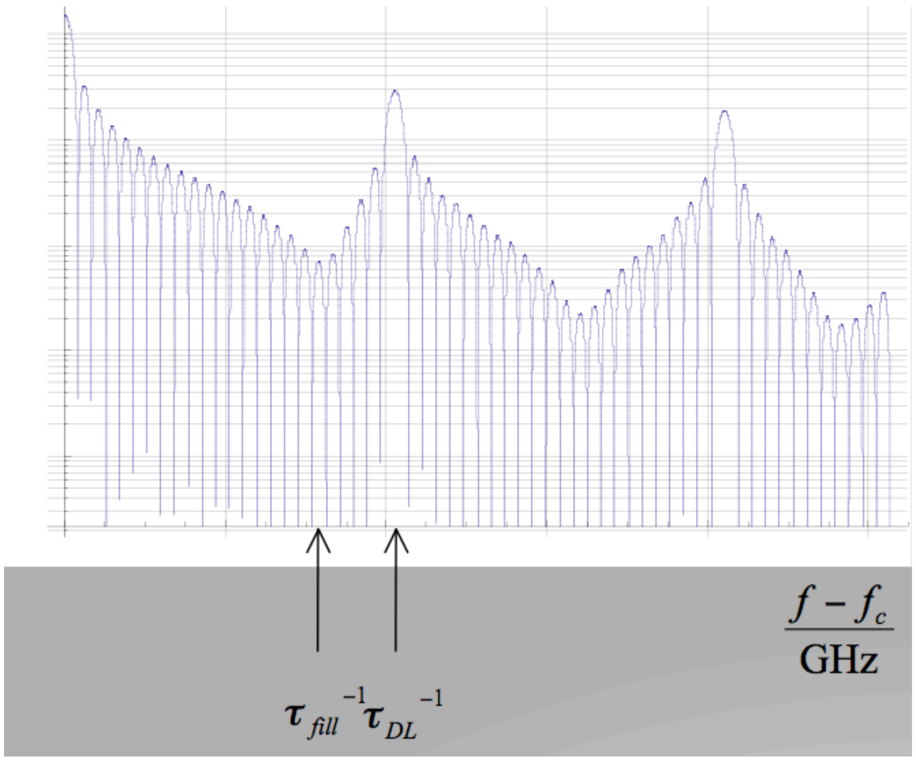
Filtering by Structures

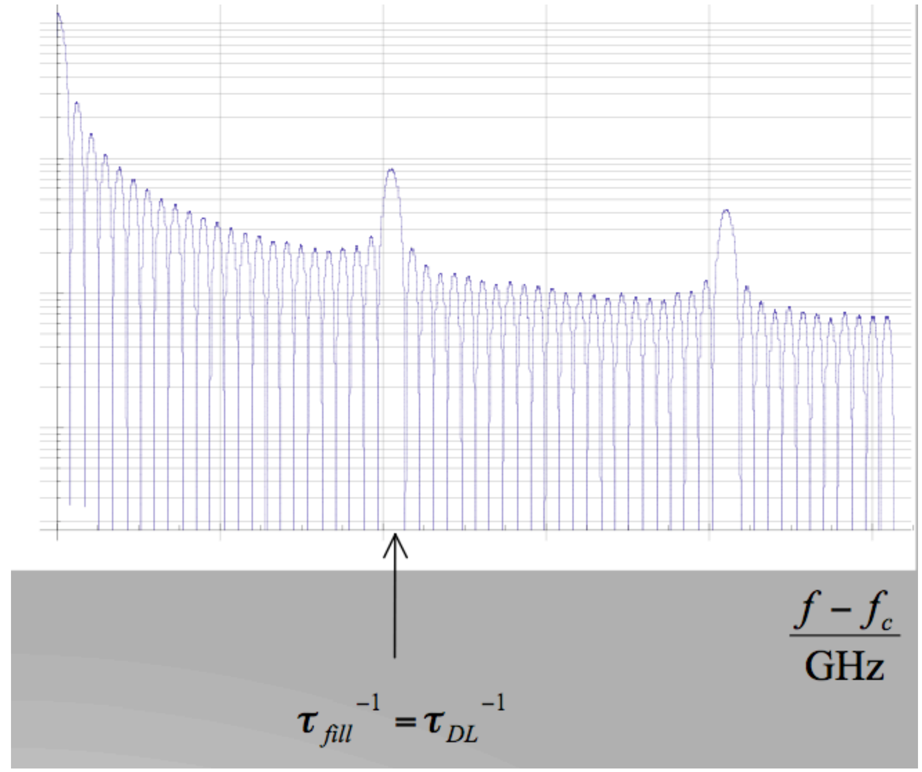




- Structures average over incoming RF noise
  - very small residual noise level at locations given by fill time
- Alse filtering of beam loading exists
- If low frequencies can be taken care of by feedback in drive beam accelerator we gain a factor in tolerances

Combination of Both Filters





- If we adjust the fill time to the half-train length we get very efficient filtering
- Need feedback up to about $4\,\mathrm{MHz}$

Conclusion

- Tolerance on the drive beam phase jitter is tight
- This leads to tight tolerances in the drive beam generation complex
- To meet these tolerances a number of methods could be used
  - 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)