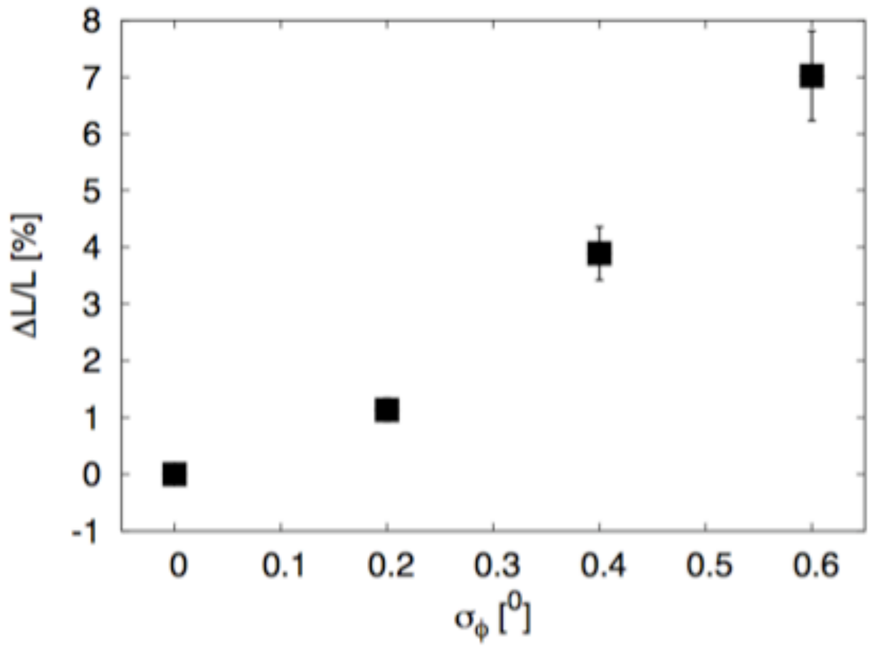
Phase Stability

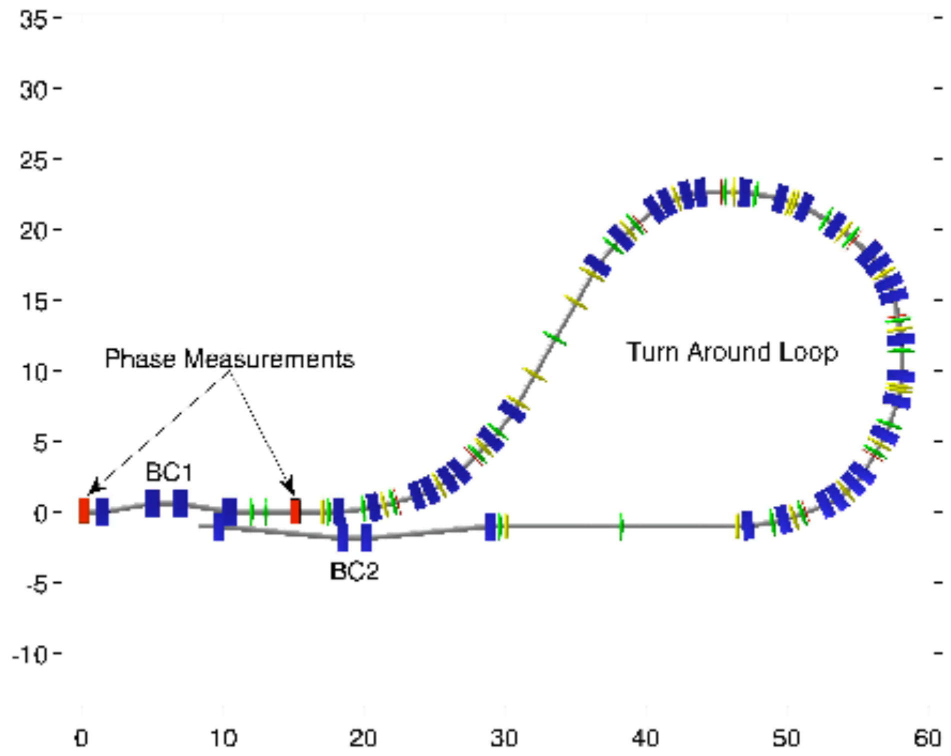
- In each decelerator, the same drive beam bunches produce the RF power for a main beam bunch
- The BDS bandwidth is limited
- Tight tolerances exist on the main beam energy error
- Hence tight tolerances on the drive beam phase and amplitude
- Errors can be coherent from decelerator to decelerator or not
- Emittance growth due to RF jitter can become relevant but remains at the same level



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

Example Feedforward at Final Turn-Around

- Final feedforward shown
  - 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



Try to have kicker evaluated, bandwidth is a problem (30MHz) due to main linac structure fill time

Can feedforward on phase

- in principle could also cure intensity is we run off-crest, but do not want to rely on this

Wish for corrections range 3-4 RMS jitter tolerance before feedforward

- ideally 24°-32° (up to 2.5mm in z) would allow tolerance of 8°RMS assuming factor 10 demagnification by feedforward (remaing is 0.8°RMS independent form decelerator to decelerator)

Assume range of the feedforward is about 10° at 12GHZ

- lattice is OK
- limited by kicker/amplifier
- corresponds to about 0.7mm in z
- corresponds to 0.5mradian kick
- assume that we can reduce jitter by about a factor 10
- yield initial tolerance of about 2.5-3° RMS, assume 2° RMS as new tolerance

More work needed to evaluate the feedforward range

Bandwidth needs to be O(30MHz), from main linac accelerating structure fill time

For the beam current additonal limit for decelerator beam stability (to be reviewed)

- less than 1% over current
- need current stability in ~5 bunches of 0.1-0.2% (5-10 sigma)
- consistent with current jitter for power production
- in CTF3 first, preliminary measurements show ~0.1% from pulse to pulse with little fluctuation within pulse (static intensity variations neglected)

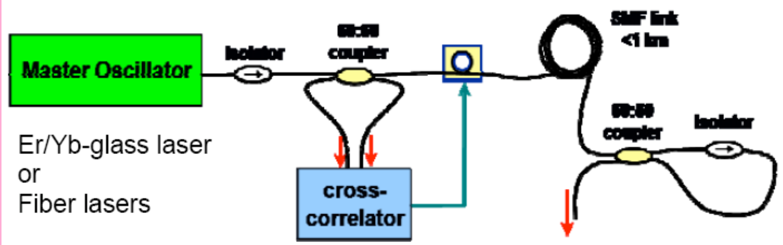
Global timing distribution: ongoing R&D efforts

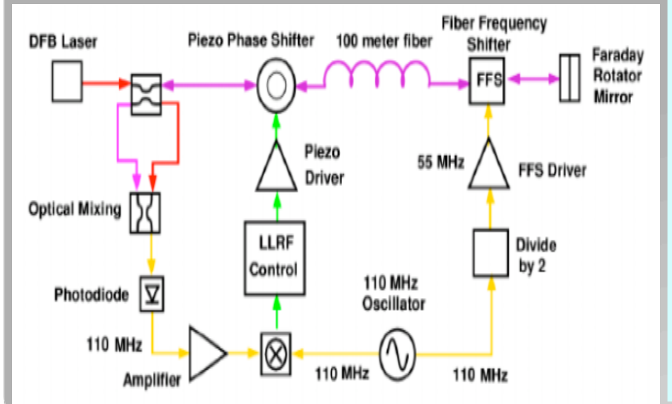
Two major R&D efforts are ongoing on the development of optical clock systems:

...

Both systems are fully consistent: each of them fulfils the requirements for a complete fs timing system.

[M. Ferianis, "Timing and Synchronization in Large Scale Linear Accelerators", LINAC 2006, Knoxville, Tennessee USA]

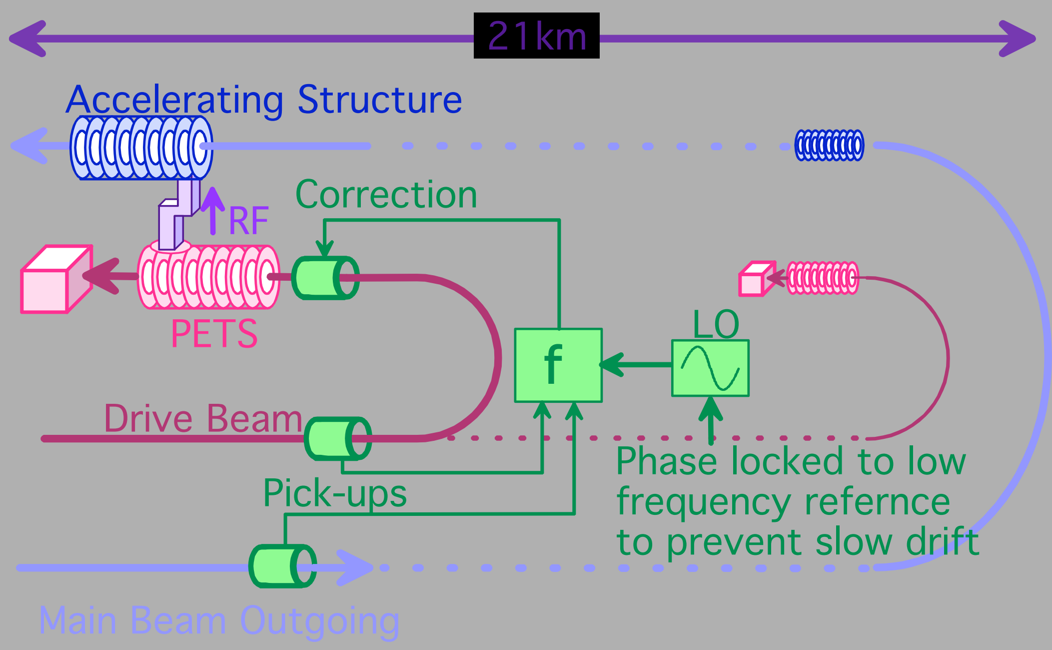




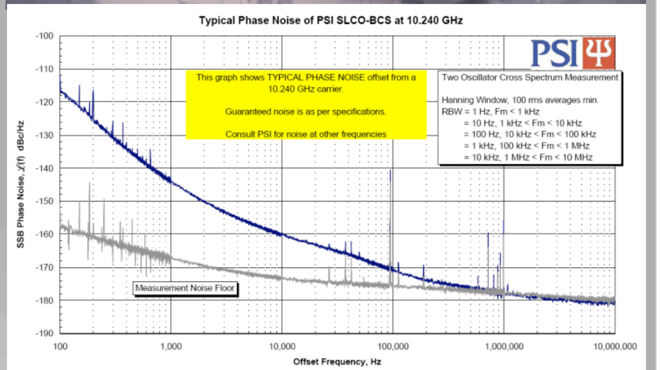
The distribution of ultrafast optical pulse trains across **300 meters** of fiber with **sub-femtosecond timing jitter** and 83 fs of drift over 25 hours, as measured between the outputs from two independent links, is demonstrated.

[J. A. Cox et. al, "Sub-femtosecond Timing Distribution of an Ultrafast Optical Pulse Train over Multiple Fiber Links", OSA / CLEO/QELS 2008]

Alternate CLIC timing schemeHigh precision phase detectorOther parameters influencing the RF phase noise



Commercially available **Sapphire Loaded Cavity Oscillator** with 3…5 fs integrated phase noise.



Use low frequency global timing signal to compensate for slow frequency drifts. Use outgoing main beam for precision synchronization of phase. I.e. measure average phase between RF extracted from the outgoing main beam, and subtract from the later measurement for the drive beam phase.

See also: A. Andersson, J.P.H. Sladen: "Precision beam timing measurement system for CLIC synchronization", EPAC 2006;
A. Andersson, J.P.H. Sladen: "First tests of a precision beam phase measurement system in CTF3", PAC2007

Drive Beam Phase Error Sources

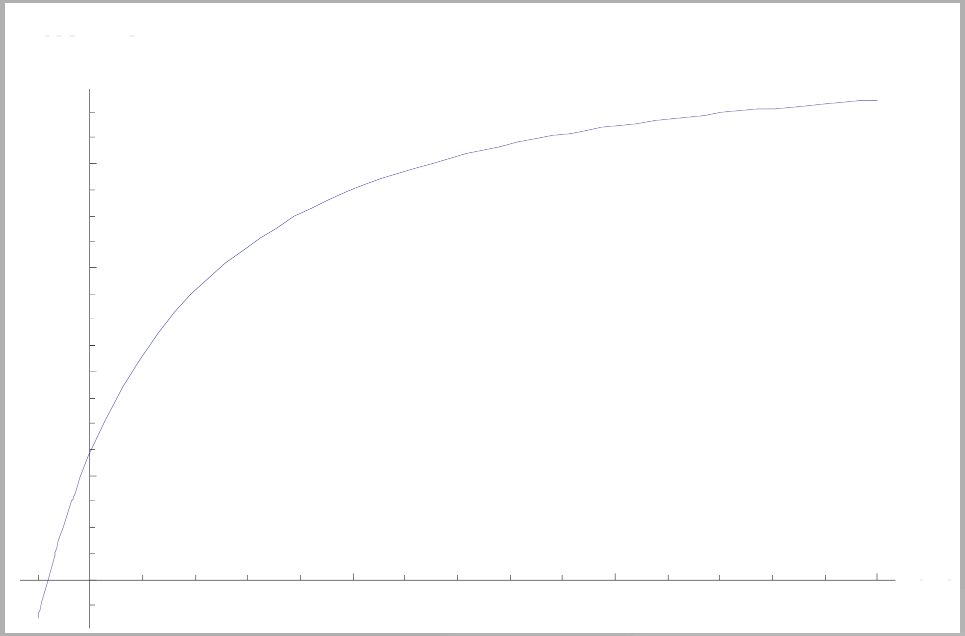
- We do not yet have a baseline design for the overall concept of compression stages for the drive beam accelerator
  - This will come in the next few months
  - Need to stay somewhat generic
- Four main error sources
  - Drive beam phase and energy errors from injector
  - RF phase errors for RF producing energy chirp for compression
  - RF gradient variations
  - Drive beam current variations

Drive Beam Phase Error Sources

- Simplest concept is
  - Total compression after drive beam accelerator
  - For energy chirp 0.6%/sigma_z, requires R56=4mm/0.6%=67cm
  - Energy tolerance for 2° (12GHz)=140um shift is 2e-4
    - Gradient tolerance 1e-4, current tolerance=2e-4
  - Phase tolerance is about 0.2° (12GHz)
- Likely concept is
  - Early compression drive beam accelerator (4->1mm)
  - Uncompression at end of drive beam accelerator (1->2mm)
  - Recompression at final turn around (2->1mm)
  - RF/current errors would be important at early compression, could use large energy chirp
  - For energy chirp 3%/sigma_z (maybe optimistic), requires R56=4mm/3%=22cm
  - Energy tolerance for 2° (12GHz)=140um shift is 1e-3
    - Gradient tolerance 5e-4, current tolerance=1e-3
  - Phase tolerance is about 0.2° (12GHz)

Klystron phase pushing

- Phase pushing denotes the phase variation resulting from voltage variation. It transforms modulator noise to phase noise
- Phase pushing of a klystron: $\delta\varphi = -2\pi \frac{L}{\lambda}\left(V\left(2+V\right)\right)^{-3/2}\delta V$



(where *V* is in units of 511 kV)

L: Length of klystron

E.g.: at 120 kV, one gets a phase pushing of -0.018°/V *L/λ,* i.e. to stabilize the output phase to 0.2° for a klystron of L = 10 λ, the voltage must vary for less than 1 V or 10^{-5}!

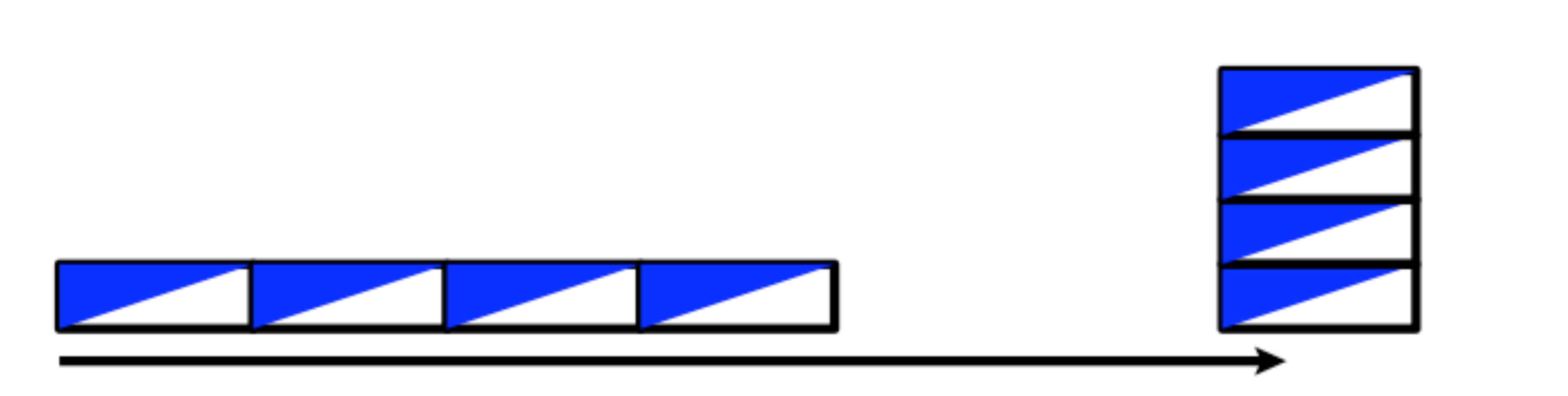
➔ For small phase pushing: stable modulator, short klystron, high voltage!

Filtering and Feedback

Three filtering processes

- drive beam accelerator structure (RF errors and current errors)
- combination scheme (all errors)
- main linac accelerating structures (all errors)

Can use feedback for very slow variations

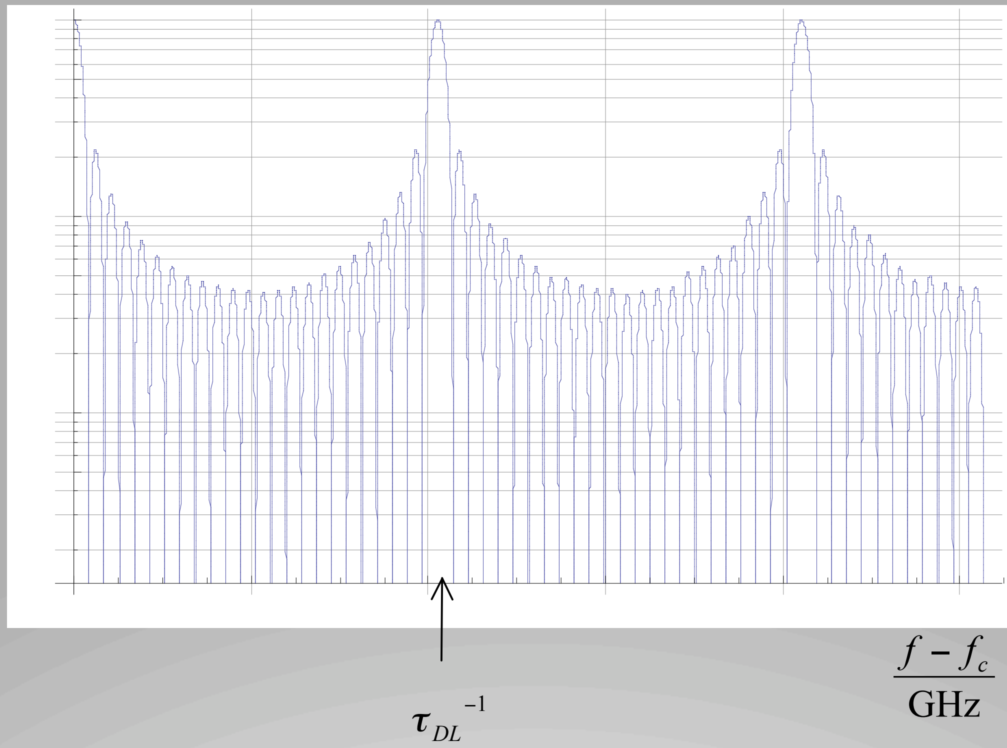


Delay loop and combiner rings as filter

- Laplace transform of recombination scheme:

DL (243.5 ns) CR1 (x3, 487.5 ns) CR2 (x4, 1461.8 ns)

- Transfer function



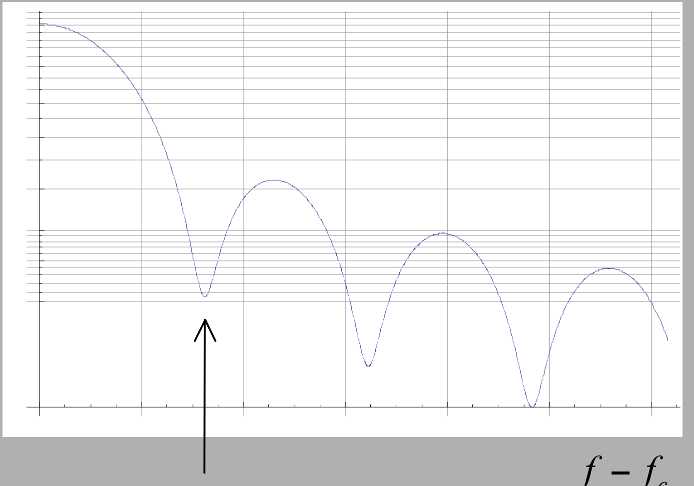
No reason to have very strong 4MHz component in klystron

But this is the switching frequency of the drive beam injector, so good reason for noise

The accelerating structure as filter

- filtering the klystron signal:

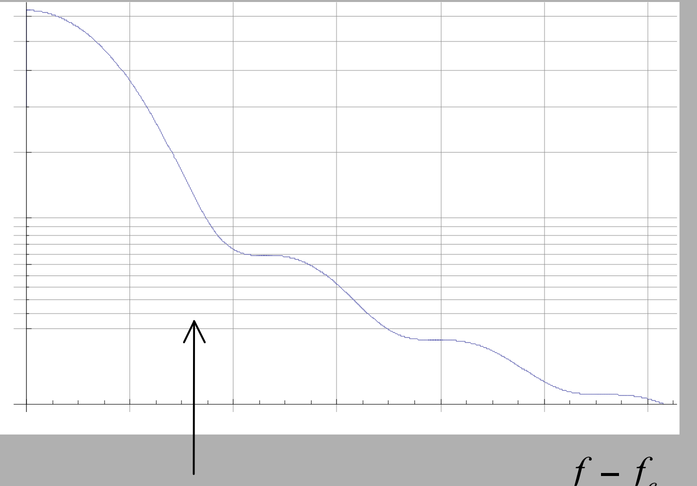
$$\left|\frac{V_{acc}}{\sqrt{P_{klystron}/(33\,\mathrm{MW})}}\right|$$



τ_{fill}^{-1} $\quad \frac{f-f_c}{\mathrm{GHz}}$

- filtering the beam signal:

$$\left|\frac{V_{acc}}{I_{beam}/(4.21\,\mathrm{A})}\right|$$



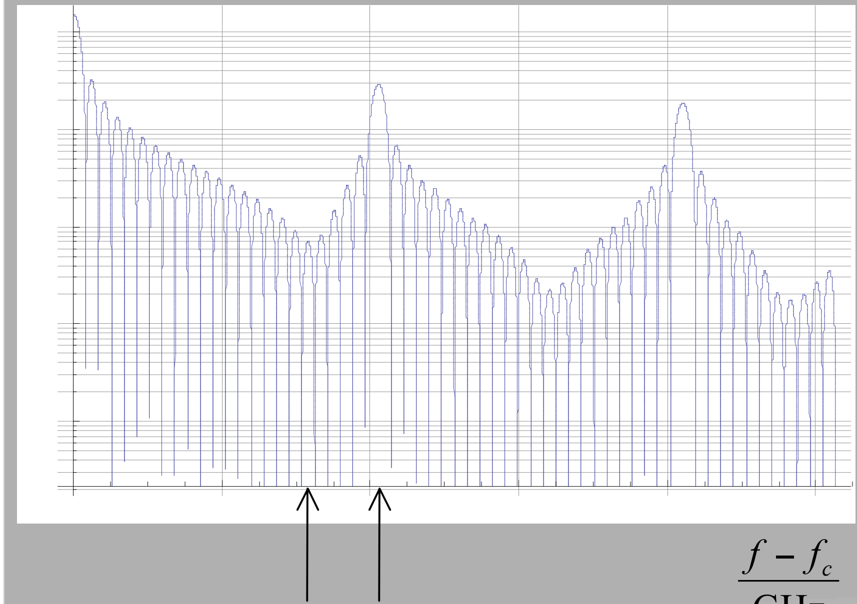
τ_{fill}^{-1} $\quad \frac{f-f_c}{\mathrm{GHz}}$

Yields roughly a factor of a few to an order of magnitude at MHz (unoptimised case)

Approximation used: linearized dispersion $\beta(\omega) = \frac{\omega_0}{c} + \frac{\omega-\omega_0}{v_g}$

Applying those filters together

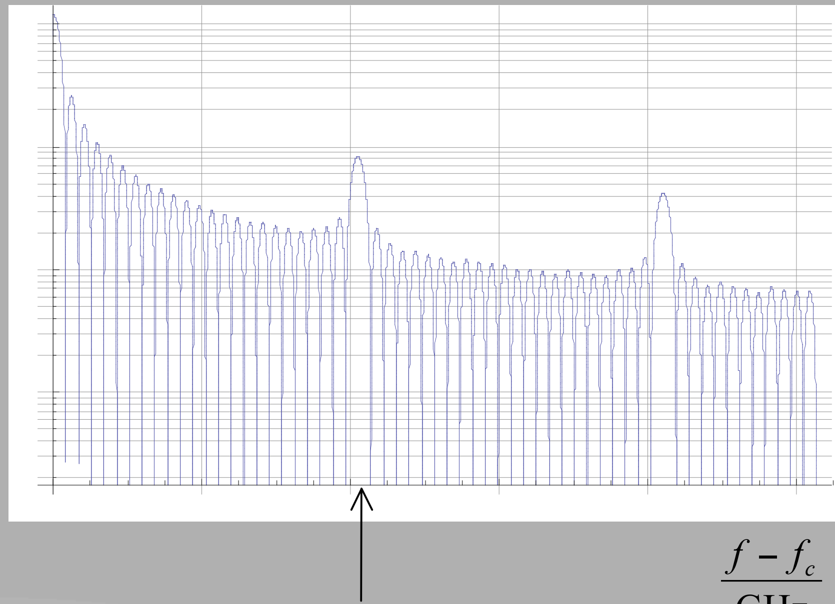
- With the accelerating structure unchanged:



$\tau_{fill}^{-1} \tau_{DL}^{-1}$

$\frac{f - f_c}{\text{GHz}}$

- Acc. structure adjusted to $\tau_{fill} = \tau_{DL}$:



$\tau_{fill}^{-1} = \tau_{DL}^{-1}$

$\frac{f - f_c}{\text{GHz}}$

Feedback below 4MHz can be effective
- local drive beam current, initial phase and energy, RF phase and amplitude
- global enrgy feedback

Compare also: D. Schulte, E.J.N. Wilson, F. Zimmermann: "The Impact of Longitudinal Drive Beam Jitter on the CLIC Luminosity", LINAC 04