Beam specifications impact on RF and LLRF design

The CLIC Damping Rings LLRF

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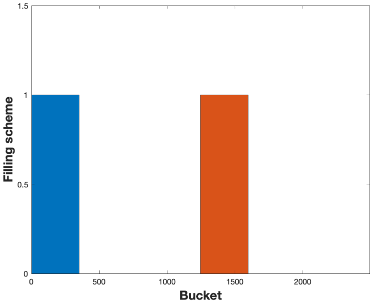
Introduction and Motivation

- The Compact Linear Collider (CLIC) Damping Rings need to generate ultra-low emittance bunches to achieve high luminosity in CLIC.
- Strong wiggler magnets are required to significantly increase the energy loss per turn at the CLIC damping rings.
- A high total voltage Radio Frequency (RF) system is needed to compensate these losses.
    - The resulting strong beam loading transients affect the bunch position and length.
- On the other hand, in order to maintain the luminosity loss below 1%, the bunch position has to be regulated within $\pm 1^\circ$ at 2 GHz ($\pm 400\mu$m) at the DR extraction.
- These conflicting specifications lead to a challenging design for the Low-Level RF (LLRF) system.
- The motivation of this work is to explore the various possible topologies for the LLRF system, estimate their effectiveness and performance potential, determine the feasibility of the above specifications, and identify the design challenges.

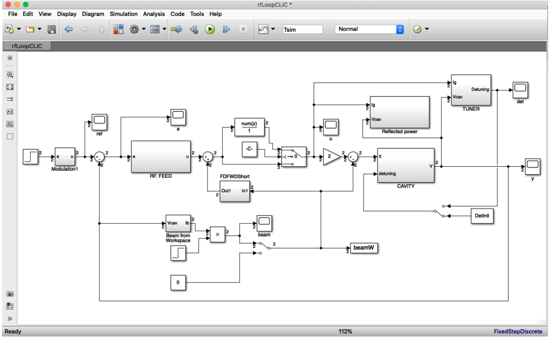
CLIC DR parameters

Bunch population	5.7e9
Energy loss/turn	5.8 MeV
RF Voltage	6.5 MV
Bunches per train	352
Revolution frequency	802 kHz
Number of cavities	32
Bunch spacing	0.5 ns
RF frequency	2 GHz
Harmonic number	2493



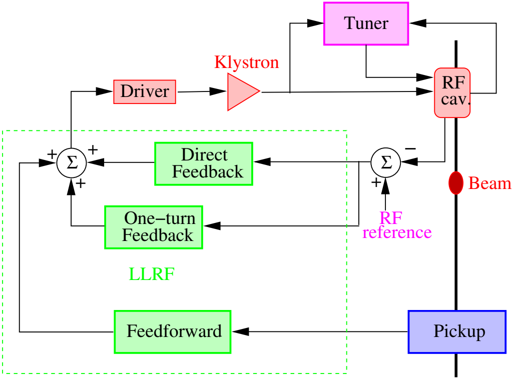
Simulation Description

- A time-domain simulation is used to evaluate the transient beam loading effects and the impact of LLRF and RF system design choices and technical characteristics.
- Parameters, filter coefficients, and more are set in MATLAB. Simulink block models represent the RF cavities (ARES-type, $R/Q = 7.5$, $Q_0 = 55,000$), klystrons, the LLRF loops, and the beam.
- The longitudinal dynamics (synchrotron oscillation) are not included. The results therefore apply to static conditions (stable circulating beams) but cannot be extrapolated to injection transients.



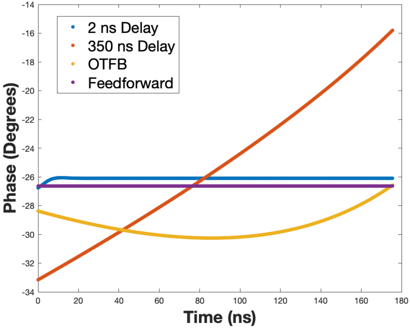
Proposed LLRF

- The proposed LLRF will include a feedback system – including a one-turn feedback (OTFB) – and a feedforward system.
- Both systems act on the klystron drive, but the feedback system samples the cavity voltage, whereas the feedforward measures the beam current and phase with respect to the RF clock via a pickup.



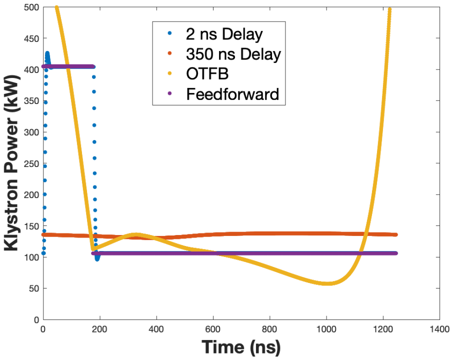
Beam-Loading transient reduction with LLRF

- The performance metrics are the peak klystron power and the beam phase modulation over the bunch train. Four configurations are evaluated.
  - The simple feedback with 350 ns delay leads to unacceptable beam performance, almost equal to uncompensated beam loading.
  - The OTFB solution has a much lower variation along the bunch train, but there are significant transients.
  - The unrealistic system with a 2 ns delay and the feedforward system achieve almost perfect beam loading compensation.



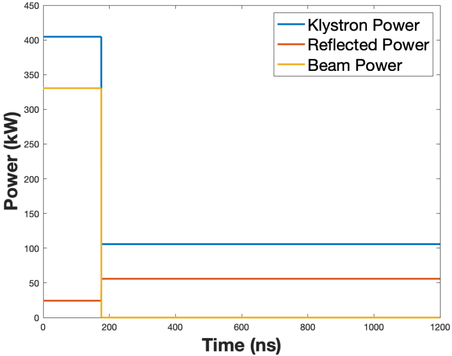
Instantaneous klystron power

- As expected, there is a tradeoff between performance and klystron power.
- The simple feedback with 350 ns delay barely responds to the beam, so the klystron power is almost constant.
- All other solutions have really big power transients when the beam is present (0 to 176 ns). The beam power is 331 kW.



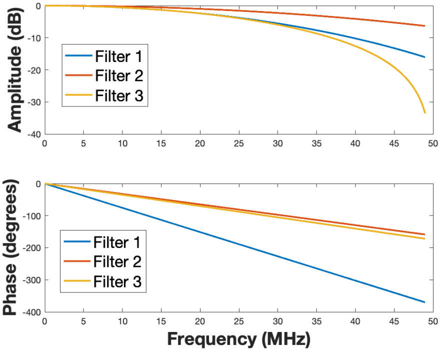
Proposed LLRF

- It is possible to reach the beam specifications with a careful LLRF design.
- The use of a feedforward system will be necessary though.
  - The cost is of course peak klystron power which must fully compensate the instantaneous beam loading power.
  - In addition, the reflected power will be significant, so the high-power RF design (cavity windows, circulator, waveguides, and more) should be compatible.



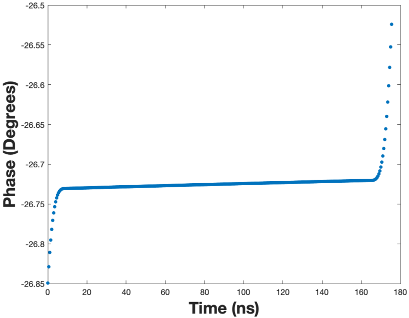
Feedforward Non-idealities

- Feedforward performance will be limited by the beam measurement precision.
- Since the feedforward system is trying to fully cancel the beam current through the klystron, its performance is very sensitive to its gain setting.
- *The klystron bandwidth will limit the LLRF responsiveness*
  - The performance reduction is very sensitive to its (unknown) frequency response.
  - Three models were used (20 MHz bandwidth) for the klystron response.



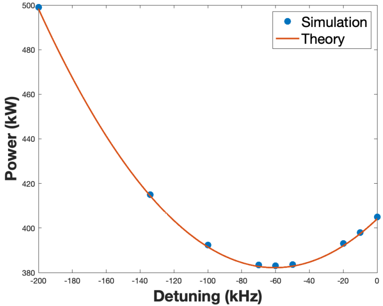
Klystron Bandwidth

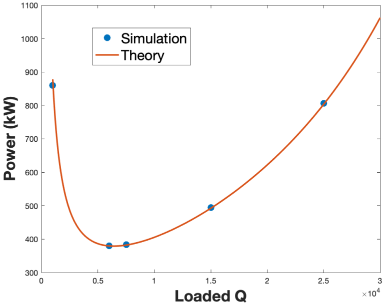
- No effect on transient beam loading compensation (RF loop bandwidth $\ll$ klystron bandwidth).
- It does affect the beam current cancellation through the feedforward though (cannot fully cancel beam current).
  - The peak-to-peak phase is 1.2°, 0.33°, and 0.52° for the three models respectively.
  - The modulation over the central 90% of the bunch train is much smaller ($\approx 0.01°$).
  - The klystron response can potentially be partially compensated by an equalizer filter.



Optimal RF Parameters

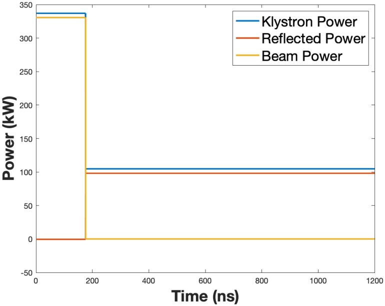
- The RF parameters were then optimized to minimize peak klystron power, assuming a LLRF system with a feedforward and for the same ARES-type cavity ($R/Q = 7.5$, $Q_0 = 55,000$).
- The optimal Q_L is 6,400 and the minimum peak klystron power is 379 kW.

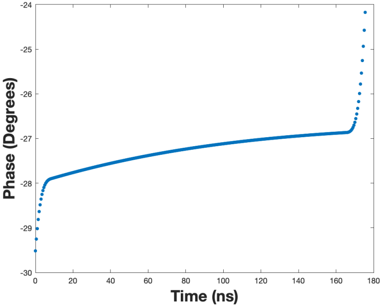




Alternative Schemes

- Various alternative schemes were investigated and are summarized at the end of this talk: Lower loop delay, cavity reference modulation, partial feedforward compensation, number of cavities, very low R/Q.
- A higher $R/Q = 100$ cavity design ($Q_0 = 30{,}000$) is simpler and slightly reduces the wall power losses. The beam performance is still well within specifications.
- On the other hand, it significantly increases the sensitivity to the klystron bandwidth and feedforward non-idealities. Simplistically, the beam and cavity phases deviate more from the ideal value by the time the feedforward is able to act through the klystron (shorter filling time).





Conclusions and Future work

- The CLIC damping rings generate ultra-low emittance bunches and have very tight specifications for longitudinal beam position. This work shows that it is possible to achieve these specifications with the appropriate LLRF.
- The system performance will greatly depend on the klystron frequency response and to a lesser extent on the measurement noise from the beam pickup and on the accurate and precise feedforward gain setting.
- The peak power requirements are strongly related to the instantaneous beam power, which is rather demanding and dominates the size and cost of the Damping Rings RF system.
- There is still a lot of work to be done, but we now have powerful simulation tools to help explore new ideas.
  - Investigate other solutions: “focusing/defocusing" cavities, double frequency RF system, RF pulse compressor.
  - As the CLIC design matures, the simulations and models developed for this work will be used to study the nonlinear behavior of the power stage, to implement limiters or saturating elements in the LLRF systems, and to study the effect of noise.
  - The effectiveness of an equalizing filter to compensate the klystron response will be investigated once the klystron specifications are defined.
  - A study of longitudinal coupled-bunch instabilities is also essential once the CLIC design matures.

Acknowledgments

- I would like to thank Philippe Baudrenghien for many useful conversations, ideas, and suggestions.
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This work is presented in more detail in our paper, *Low level Radio Frequency studies for the Compact Linear Collider Damping Rings*

Thank you for your attention!

Alternative Schemes

- High R/Q cavity
  - The higher R/Q cavity design is simpler and slightly reduces the wall power losses.
  - On the other hand, it significantly increases the sensitivity to the klystron bandwidth and feedforward non-idealities.
- Lower loop delay (150 ns)
  - This lower loop delay is still comparable to the length of the bunch train.
  - The use of the feedforward is necessary even in the case of a lower loop delay.
- Cavity Reference Modulation
  - Modulate the cavity feedback reference using an adaptive algorithm to achieve a constant beam phase for all bunches.
  - This solution achieves similar results to the feedforward solution, since they both aim to cancel the beam effect in the cavity.
  - The feedforward and cavity reference modulation algorithms will eventually ask the same current from the klystron to achieve this.
  - We think the feedforward scheme will be much easier to implement.

Alternative Schemes

- Partial compensation
  - Since the feedforward performance could significantly exceed the beam specifications, it might be possible to slightly reduce the peak klystron power by *deliberately* reducing the feedforward gain.
  - Unfortunately, the CLIC DR beam specifications are so tight and the beam loading so significant, that lowering the feedforward gain by 5%, only reduces the peak power by $\approx$ 23 kW, while bringing the beam performance close to the specification limit.
- Increase number of cavities
  - Same voltage per cavity → same beam performance
  - Small peak power reduction, but for a significant production cost (cavities, klystrons). Higher impedance.
- Very Low R/Q
  - By lowering the R/Q significantly, the beam loading effect is reduced and thus the beam phase remains almost constant along the bunch train. This approach could potentially work, but it would require an unrealistic R/Q of 0.4.