RF transients and mitigations

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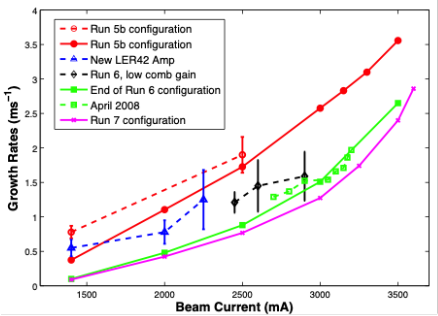
1. Introduction
2. LLRF
3. Voltage reference modulation
4. Fill pattern modulation
5. Summary and Conclusions

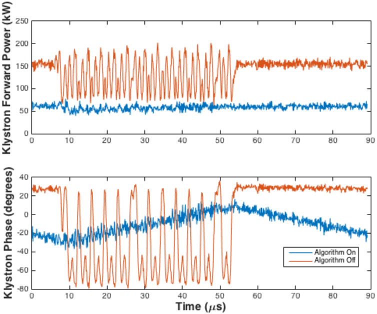
Introduction

- The RF transients created by the clearing gaps will be very different in the two dissimilar rings.
- As a result, the electron and ion bunches will have slightly different arrival times at the IP, with significant luminosity effects.
- Three possible schemes to reduce or match the gap transients have been explored. Their performance has been evaluated through simulations:
  - “Traditional" LLRF feedback systems, including one-turn feedback (OTFB) and feedforward systems.
  - Modulating the voltage reference.
  - Introducing double intensity bunches.

Simulations

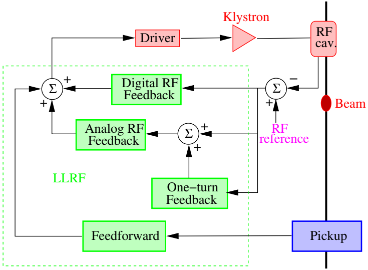
- The simulations were created in Simulink, using past experience from similar tools on PEP-II, LHC, SPS, and CLIC.
- The PEP-II, LHC, and SPS simulations were verified with measurements.
  - The PEP-II studies focused on the sensitivity of beam instabilities to individual LLRF parameters [1].
  - For the LHC they were used to develop optimization and setting up tools at startup. Since then they have been used to study various effects and develop algorithms, such as the voltage reference modulation algorithm for power minimization [2], [3].





EIC simulations

- The EIC LLRF model includes a digital loop (low bandwidth), an analog loop (high bandwidth), and OTFB. These loops sample the cavity voltage and act on the klystron driver.
- A feedforward system is included too. The feedforward samples the beam position instead, but still acts on the klystron driver.
- The EIC simulations track the centroid motion of each bunch.
- Independent simulations of the electron and ion ring were created. The LLRF was optimized for each ring. The resulting gap transients – and thus time offset at the IP – were calculated from the simulations.



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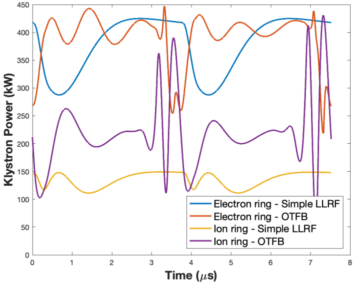
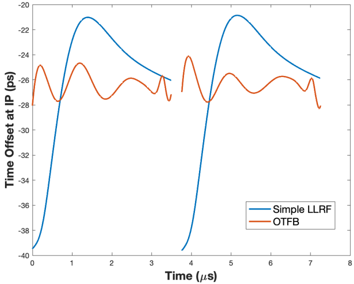
Gap transient reduction through the LLRF

- This is a “brute force" approach: the LLRF samples the beam perturbation of the accelerating field and tries to compensate by modulating the klystron current.
- The LLRF performance is limited by the loop delay (estimated to ≈300 ns) and the closed loop bandwidth: the system cannot respond instantaneously.
- This solution significantly increases the required peak klystron power due to the high transients in the klystron current. This is especially true for the ion ring. The OTFB and/or feedforward systems further increase the required power.



LLRF performance

- The time offset at the IP is high (5.1 ps rms) when only the digital and analog loops are employed (*). For comparison, the bunch length is about 40 ps.
- The time offset is reduced to 0.85 ps rms with the OTFB, but the klystron power increase for the ion ring is too high (from ≈150 kW to ≈420 kW).



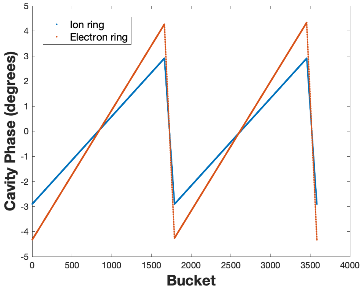
(*) There is currently no quantified specification on the transient matching.

Non-idealities

- A realistic klystron bandwidth was introduced in the simulations. For most of the LLRF configurations there is no significant effect since the closed loop bandwidth is much narrower than the klystron.
- The klystron bandwidth does increase the transients with the feedforward though. As a result, the first few bunches in the beginning of the train experience a higher time offset (still much lower than the OTFB case).
- The effect of pickup noise on the feedforward performance was also evaluated. There is a measurable, but not significant effect on performance and peak klystron power.

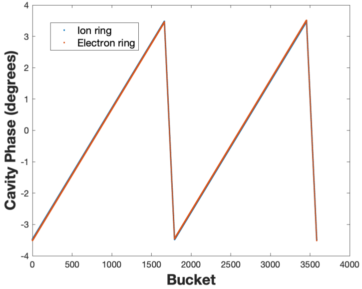
Voltage reference modulation

- In this approach we try to match the transients rather than reduce them.
- With P. Baudrenghien, we showed how V_{ref} could be modulated to minimize klystron power in the LHC (V_{cav} and I_g have the same phase) [4].
- Effectively, the LLRF is allowing the periodic modulation of the cavity phase due to the beam current, while at the same time maintaining the high gain feedback for impedance reduction and voltage control.
- Klystron transients are minimized. The power is the same on the beam-on and beam-off segments for the ion ring.



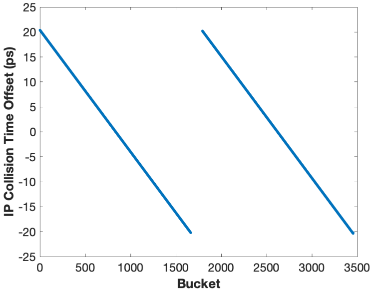
Matching the modulation

- A consequence is that V_{cav} – and thus the beam phase – is now modulated significantly.
- It is possible though to adjust RF station parameters (R/Q, I_{DC}, V_{cav}) to achieve the same modulation on both rings so that the bunches collide at the IP.



IP time shift

- With the matching modulations, all bunches will collide at the IP as desired (no longitudinal shift).
- The collision *time* will be slightly shifted with respect to the absolute RF reference though (40 ps peak-to-peak variation, comparable to the bunch length). This small time shift is not an issue for the detector. Additionally, since it is known, it can be used to modulate the detector trigger.



Challenges

Beam loss effects

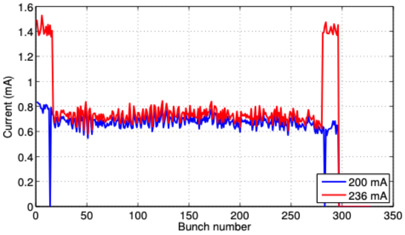
- The reference phase modulation algorithm will automatically adapt to beam loss. The klystron peak power will remain minimized as a result.
- If the beam loss is significant and asymmetric between the two rings, RF parameters will have to be adjusted during the fill as well to keep the transients matched.

Crab cavities

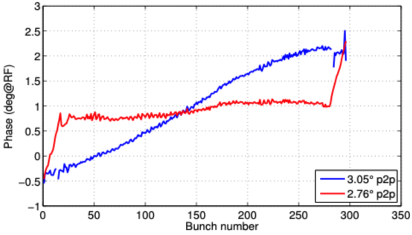
- The crab cavities will *not* be modulated, and as a result most bunches will not experience full crabbing.
- The HL-LHC will employ the same scheme. Emi Yamakawa presented estimates of luminosity effects due to the phase modulation.
- The luminosity reduction is estimated to about 2%.
- The EIC situation is much better though due to the much smaller bunch length. In addition, the EIC will employ full crabbing, whereas the HL-LHC will use partial crabbing to reduce collision pileup at the detectors.
- We anticipate *very* small effects on luminosity, but need to quantify them.

Fill pattern modulation

- A “Fill Pattern Modulation" scheme was suggested for the ALS by John Byrd *et al.* in 2002 [5].
- The fill pattern is adjusted “to partially compensate for the beam loading transient".
- D. Teytelman measured the phase transients in the ALS with such a modulated fill pattern [6]



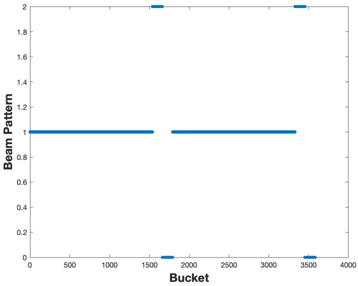
D. Teytelman [6]



D. Teytelman [6]

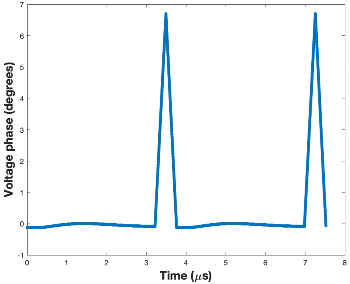
EIC Fill pattern modulation

- The beam intensity is doubled over a segment comparable in length to the gap. This segment could precede or follow the gap.
- As a result, the average current over the double intensity segment and gap is equal to the average current during the normal beam segment.



Double intensity bunches

- The net transient of the double intensity segment and the gap on the cavity voltage is almost zero. As a result, the gap transients on the normal intensity bunches are now negligible.
- The transient cancellation is not exact because the cavity energy loss is higher during the double intensity segment. We will develop a mathematical description to determine the optimal beam pattern.



Peak klystron power (kW)

	Simple LLRF	OTFB	FF	V_{ref} modulation	Pattern modulation
e^-	436	500	458	433	
ions	150	430	680	115	125

- There are only small variations for the electron ring, so all schemes are possible.
- The peak power is too high for the ion ring with the OTFB or feedforward. On the other hand, both the voltage reference and fill pattern modulation schemes lead to a *reduction* in peak klystron power.

Summary and challenges

- Three different schemes were presented to match or reduce the RF transients created by the clearing gaps. Each can achieve the necessary beam performance, but they present different tradeoffs or challenges.
- The LLRF solution is simple, but leads to significant klystron power for the ion ring.
- The voltage reference modulation scheme would minimize the peak klystron power, but it would require some RF parameter adjustments to match the modulations for the two rings. It would also be sensitive to beam loss during the fill.
- The fill pattern modulation scheme would require injection manipulations to achieve the required pattern. It would also be susceptible to beam loss, since the lifetimes on these high current buckets is probably different than nominal.
- It is possible to combine solutions and/or use different schemes for the two rings (OTFB for e^{-1} and fill pattern modulation for ion?).

Future steps

- We will continue studying, refining these schemes, and fully evaluating the effect of the outlined challenges.
- It is important to determine any coupling to the crab cavity system, especially for the voltage reference modulation idea.
- We need a specification on the transient matching. We can compare the relative performance of each scheme, but a hard limit is required for the final decision.
- The optimal fill pattern with double intensity bunches will be determined theoretically.
- We need to estimate the possible beam current variations from fill to fill (total current, bunch variation) both for the fill pattern and voltage reference modulation schemes.

Acknowledgments

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