Modelling of LLRF Limitations on LHC Performance

Digital RF Controllers and Impedance Control Architectures for the next-generation colliders, damping rings, and light sources.

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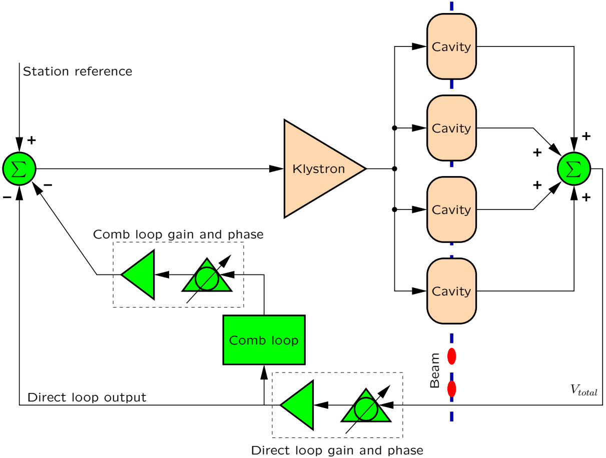
Background

- The stable operation of high beam loaded colliders and light sources requires the control of higher-order mode impedances as well as the precise control of the accelerating fundamental impedance.
- Impedance controlled LLRF architectures modify the impedance seen by the beam with feedback techniques. A particular issue with high-current (highly-beam loaded) machines.
- This system has multiple dynamic loops. Stability of BOTH the LLRF loops and stability of the beam, are necessary conditions. A trade-off in stability between the two systems is necessary.

Background


Station reference
Klystron
Cavity
Cavity
Cavity
Cavity
Comb loop gain and phase
Comb loop
Direct loop output
Direct loop gain and phase
Beam
V_{total}
+
−
−
+
+
+
+

LARP Proposal Overview

- Develop/expand existing LLRF/Beam Dynamics models to understand LHC limits on machine performance due to LLRF system implementation.
- Study growth rates, station stability and longitudinal emittance effects due to LLRF implementation. Propose optimal configuration algorithms.
- Understand necessary system specifications, study critical architecture and technical issues for next generation digital LLRF system implementations.
- This proposal aims to understand LLRF limits in LHC and evaluate new, more stable implementations of these techniques.

Similarities between PEP-II and LHC RF systems

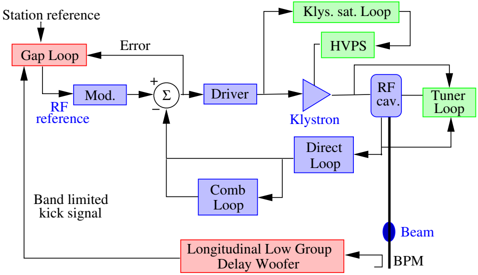
The PEP-II and LHC systems are related

- The PEP-II and LHC systems define the state of the art for direct and comb loop feedback techniques to implement impedance control.
- The LLRF is implemented with a mix of Analog, RF and Digital technologies.
- The LHC LLRF systems are very similar in topology and in the basic technology of implementation to the PEP-II systems. Common primogeniture.
- PEP-II operations experience, analysis techniques and simulation tools may be helpful in LHC operation. Study future operational issues before they are reached in the machine.
- Next-generation implementations can be designed based on LHC requirements.

PEP-II RF Feedback Configuration

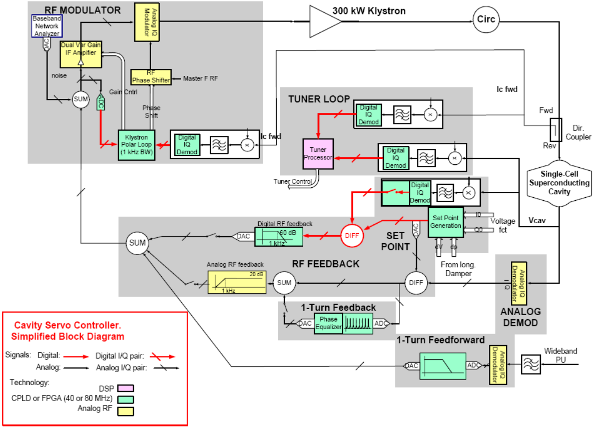
- Mix of baseband analog, hybrid analog/digital and digital control loops.
- Complex calibration and configuration. Subject to numerous drifts, offsets and imperfections from the analog circuit implementation and high power klystron behavior.

- RF cavities, Direct and Comb Loops
- Longitudinal Beam Dynamics
- HVPS, Klystron bias, Tuner Loops
- Longitudinal Low Group Delay Woofer



RF Systems (LHC)

Technology of implementation uses wideband analog, digital IIR (comb loop) and slow digital software loops.



LLRF/Beam Dynamics simulation

- The overall low order longitudinal dynamics is comprised by the intrinsic beam dynamics interacting with the RF station dynamics.
  - The interaction between the beam and the RF stations is defined by the effective longitudinal impedance $Z_{eff}^{||}(\omega)$ presented by the RF stations to the beam.
  - The effective impedance is defined by the cavity impedance and the LLRF feedback loops performing the impedance control.
- RF station control loops are designed to be stable and to present the minimum impedance $Z_{eff}^{||}(\omega)$ to the beam.
  - There is a trade-off between those criteria. Consequently, between RF station and beam stability.
- To assess system stability and performance for the low-order mode beam dynamics, a combined design of the RF stations and the Longitudinal Damper is necessary.

PEP-II System Simulation

The simulation

- A nonlinear time domain model which captures the low-mode dynamics of the system, including implementation imperfections [1].
- The same tools optimally configure the RF stations and measure the growth/damping rates of the beam as are used in the real machine.
- Sensitivity analysis of configuration parameters and technology imperfections. Predicts limits of control for various operating points. [4]
- Conducts studies without requiring machine time and predicts the ultimate limits of the configurations so that new approaches or new hardware implementations can be developed before these limits are reached.

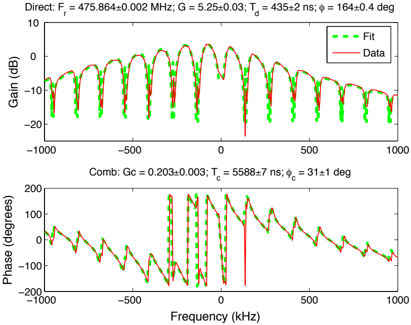
Experience from PEP-II to LHC

RF Station Configuration

Machine is unstable without feedback - control loops cannot be opened to measure gain, phase margins in operation.

Example of configuration

- Transfer Function estimated using a linear station model.
- Setting of RF station parameters based on the optimization of open loop model.
- Tuning is necessary over range of station operating points.

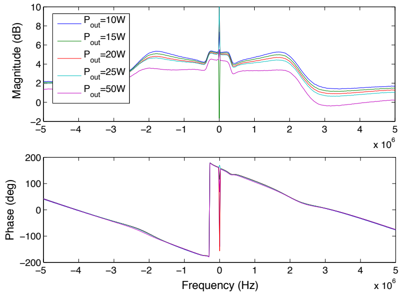


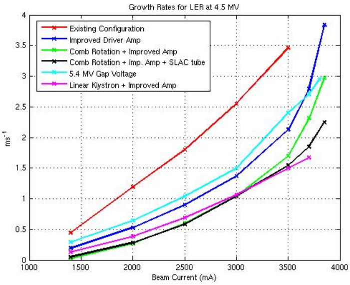
PEP-II performance limitations due to LLRF imperfections.

- The simulation and the physical machine had similar, but not identical dynamics. Consistent difference - actual machine had faster low-mode instability growth rates.
  - Subtle differences between simulation RF station transfer functions, machine functions led to understandings of LLRF imperfections.
- The interaction between the effective longitudinal impedance of the RF station and the beam is quantified by the growth rate.
- Both model and machine growth rates highly sensitive to LLRF system parameters.
  - Simulation led to understanding of new control strategies.
  - Implement phase rotation in the comb filter to reduce the growth rate
  - Proposed asymmetric comb filters to reduce the growth rate
  - Simulation predicts limits of existing implementation before limits in operation.

Limitations in LLRF understood via simulation model

- Non-linear implementations on Klystron, Driver amplifiers.
- Imperfect up, down conversion with I,Q mismatch.
- Drifts, necessity to reconfigure RF stations over time, operating points.
- PEP-II experience suggests improved LLRF implementation.

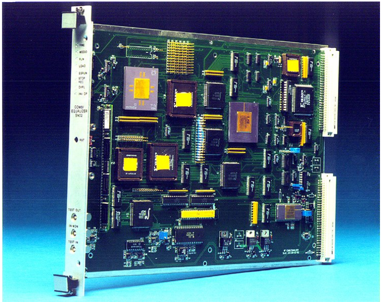


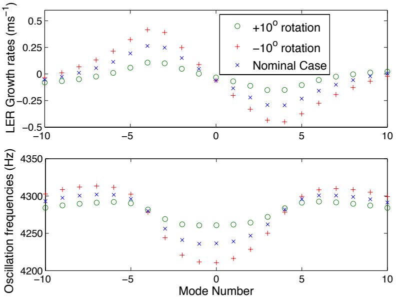


Experience from PEP-II to LHC

Comb Phase Rotation

The comb rotation is an example of the new optimal configurations that have been developed. It was determined that a small reduction on the phase margin for the direct and comb loops can lead to a substantial reduction in Growth Rates and the a rotation of the comb phase by 10° has been implemented.





Existing LHC Simulations

- PEP-II Simulation does not evaluate the Longitudinal Emittance Dilution and other intrinsic behaviors in hadron beams due to noise and other imperfections.
- CERN is developing simulation programs to study the interaction between the beam dynamics and the RF stations (J. Tuchmantel [2], J. Holma [3]).

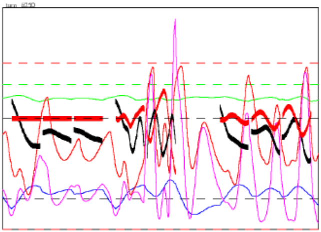


Figure: Injection Instability.

- There is collaborative interest from F. Pedersen and J. Tuchmantel. This collaboration can be educational for both groups.

Our LARP Proposal and Contribution to LHC

- Expand the existing LLRF-Beam Dynamics simulation model to look at effects in the LHC system.
- Update our beam model to trace not only centroid, but also first/second moments.
- Look for the impact of additive noise and other technical imperfections on the longitudinal phase space, other impacts besides strictly impedance-driven growth rates and operational limits.
- Study configurations before/during commissioning and suggest optimal conditions and improvements.
- Study options for new form of all-digital RF impedance control architecture, replacing analog based techniques.

Proposal

Phase I

- Collaborate with CERN in model development, expand with best features of both models.
- Add longitudinal distribution to PEP-II model.
- Participate in LHC commissioning, take data, compare model results to actual machine performance.
- Validate simulation predictions against LHC measurements, use tool to predict performance and robustness. Suggest optimal configurations, predict limits of implementation.

Proposal

Phase II

- Continue LHC RF commissioning involvement, compare model results with machine performance.
- Develop specifications for next generation architecture, highlight critical technical choices.
- Investigation of a new all-digital RF impedance control architectures (replacing the analog circuit techniques)
  - Requires very low-group delay processing architectures.
- Evaluate key technical functions (direct digital down conversion? Hybrid down/up conversion? Noise performance? Dynamic range requirements? Intermodulation performance?, etc.)

CERN Collaborators and Interest

- Technical discussions with F. Pedersen, P. Baudrenghein, and J. Tuckmantel about similarities of LLRF implementations, experience from PEP-II.
- Interest in estimation of LLRR limits to longitudinal emittance growth. CERN LLRF workshop, discussions on PEP-II simulation results, nonlinear effects in PEP-II.
- Meetings at EPAC on measurement techniques to characterize non-linear LLRF implementations. PEP Experience discussion.

Resources request

Phase I (duration 6 months)

- Travel: 2 visits x 2 weeks/visit to CERN. Establish contacts, Collaboration on dynamics model expansion, Collect Parameters.
- 0.5 FTE Junior, 0.15 FTE Senior Salaries to be covered by LARP.
- 0.5 FTE Senior Salary, covered by SLAC.

Phase II (duration 6 months post Phase I)

- M&S: 15K in addition to SLAC R&D contribution for evaluation modules and critical sampler components.
- Travel: 2 visits x 2 weeks/visit to CERN.
- 0.5 FTE Junior, 0.15 FTE Senior Salaries to be covered by LARP.
- 0.5 FTE Senior Salary, covered by SLAC.

Summary

- LLRF Limitations on LHC Performance.
- Build on experience and tools developed from PEP-II LLRF modeling.
- Expand models, understand limits of existing implementation.
- Participate in LHC LLRF studies and commissioning.
- Specify necessary performance for next-generation LLRF systems.
- LHC is a very realistic potential facility to study these limits and possibly use these new techniques.
- CERN is interested in a collaboration investigating the noise, imperfections and limits in these architectures.

References

- [1] “Modeling and Simulation of Longitudinal dynamics for Low Energy Ring-High Energy Ring at the Positron-Electron Project”, PRST Acc. Beams 10,022801 (2007) Issue 2 - Feb 2007. (summary presented at EPAC 2006).
- [2] “Simulation of LHC with Realistic RF System”, J. Tückmantel, (CERN), Chamonix XI Workshop 2001 pp. 306-311.
- [3] J. Holma, CERN-AB-2007-012, CERN, Geneva, Switzerland
- [4] “Simulation and Results of the Longitudinal Dynamics for PEP-II Rings”, presented to the MAC review 2006 (www.slac.stanford.edu/∼ rivetta/MAC_rivetta.pdf).