Gap Transient Origins and Mitigation Options Impedance controlled LLRF systems

Ideas for Collaborations

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Beam Loading in RF cavity - Pedersen Model

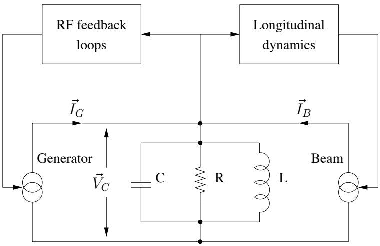

Figure 2.6: Schematic of the RF cavity model with two input currents and feedback loops

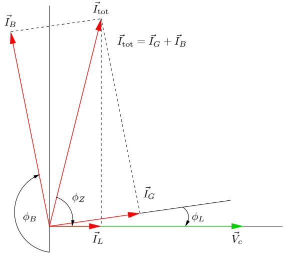

Figure 2.7: Steady-state vector diagram of accelerating cavity currents and voltages

- Coupled systems between beam dynamics, beam current, generator current, cavity phase/voltage
- Beam loading parameter $Y = I_B/I_L$
- At high beam loading, cavity is detuned for Robinson Stability
- If I_B has modulations (gaps or current variations) V_C has modulations
- V_C modulations in Magnitude and Phase, in frequency domain expressed as revolution harmonics and synchrotron sidebands

Cavity-Beam Interaction linear model

RF Cavity Feedback

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ABSTRACT

The effects of heavy beam loading due to the high circulating current in high luminosity B factories are described as well as how to cure them by means of RF cavity feedback. Fundamental limitations to maximum achievable feedback gain are discussed.

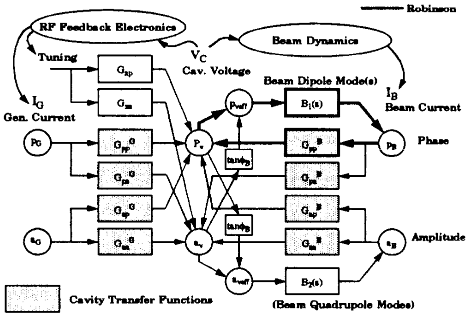


Figure 2: Generalized linear beam cavity interaction model.

PEP-II and LHC Direct and Comb loops (Boussard)

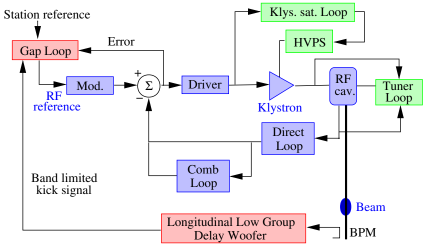


FIG. 1. (Color) System block diagram. Fast dynamics (modeled) appear in blue, slow dynamics (fixed parameters in simulation) in green, and not modeled components in red.

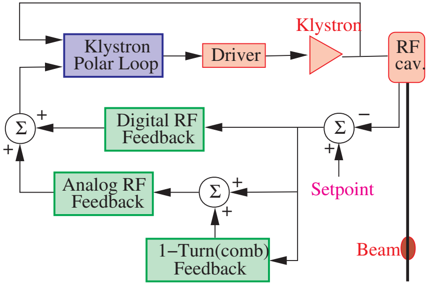
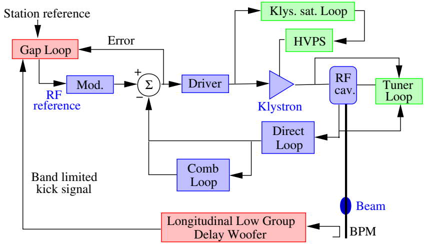


FIG. 1. (Color) Simplified LHC rf block diagram.

- LLRF systems regulate cavity voltages
- Direct and Comb loops reduce impedance seen by beam, fights longitudinal instabilities
- Modulations in beam current drive transients in cavity voltage
- Can't the klystron just compensate? what power is required?

PEP-II and Gap Feed-Forward



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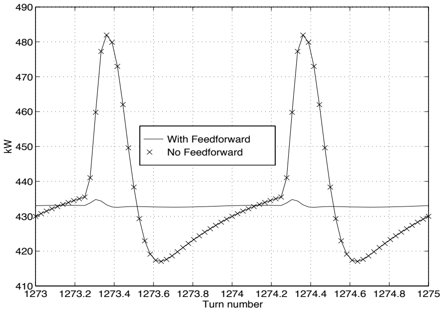


Figure 5. Forward Power Variation, with and without Feedforward.

- PEP-II used damped normal conducting cavities, 1 MW klystrons
- Klystron had insufficient power to regulate gap transients
- Unsaturated LLRF loops critical for impedance control and cavity regulation
- Strategy - learn steady state error transient, cancel this out, leaving klystron power for impedance control and cavity accelerating voltage
- adaptive system, with finite bandwidth

PEP-II Cavity Gap Transients

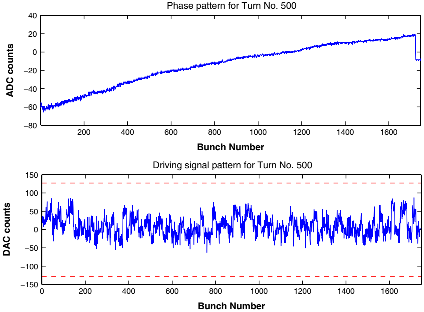


FIG. 7. (Color) HER front-end and back-end signals of the longitudinal feedback system for a single turn while the HER system is operating with nominal beam parameters at 1800 mA. The upper plot shows the phase error signal for all the bunches. The lower plot depicts the base band signal driving all the individual bunches at the same turn.

- Example from operating PEP-II HER
- The variation in synchronous phase bunch to bunch is steady state

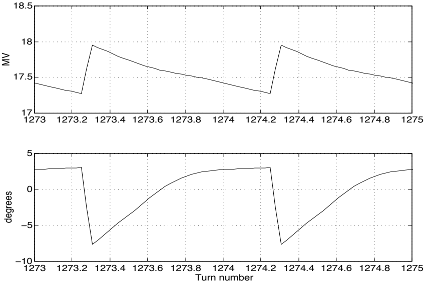
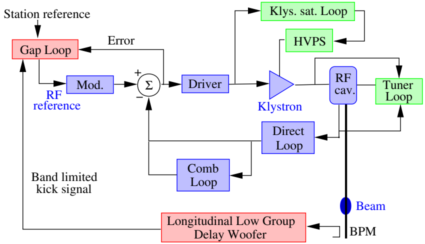


Figure 3. Cavity Voltage Transient

- Example from simulation (Tighe)
- Mis-matched transients between collider rings causes Z shift of IP
- Z Variation on IP beta function means luminosity variation with bunch

Dynamic Range of LLRF loops, impact of linearity



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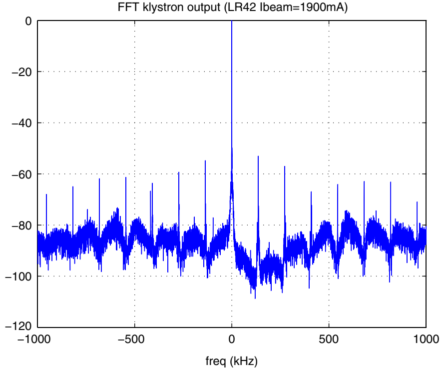


FIG. 20. (Color) Power spectrum of signals in the klystron output during closed-loop operation. ± 7 revolution harmonics are visible around the 476 MHz carrier.

- Klystron provides accelerating voltage
- Klystron provides small signal modulations for impedance control at synchrotron sidebands of revolution harmonics in cavity bandwidth
- Unsaturated LLRF loops critical for impedance control, stability of BOTH LLRF land beam

Issues for EIC design

- EIC collider design has very different RF and system dynamics in the two rings
- Plans to use PEP-II damped normal conducting cavities in electron ring
  - What sorts of gap transients can we expect?
  - What impact will this have on luminosity?
  - What methods might be helpful to mitigate the impact?
  - Methods to control low longitudinal modes within damped RF system bandwidth - longitudinal instabilities driven by cavity fundamental
  - Methods to optimally use RF power sources, minimize required RF station power
  - Impact of parked cavities, operational flexibility?
  - Develop RF system tuning tools and methods for optimal performance
  - Research new control methods for next-generation colliders
- Needs research and development
- How big a gap is really needed for Ion Clearing?

Mitigation - via RF cavity stored energy

- Superconducting RF cavity has potential for higher stored energy, smaller transients
- Alternate Idea - used at KEKB
  - Shintake - NC ARES energy storage cavity system

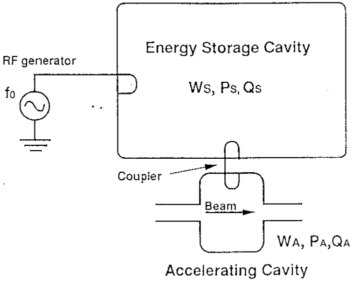
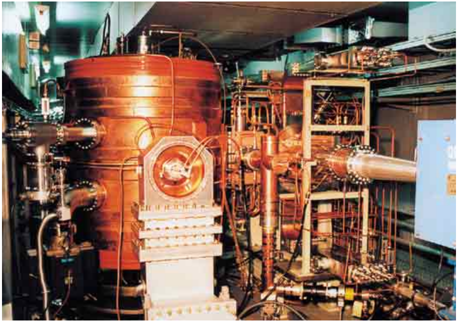
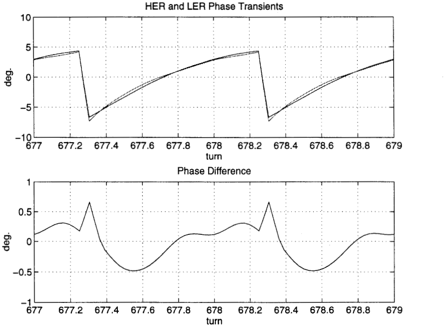


Fig. 2 Accelerating cavity coupled to an energy storage cavity.



Mitigation - via fill pattern current modulations

- PEP-II simulation adjusting LER currents near gap to minimize IP shift
  - several LER buckets near gap at 60% current
  - Helps match transients, smaller difference
- Another Idea - put extra current at edges of gap, so "average current" is roughly the same
  - Helps reduce magnitude of transient
  - Tested/evaluated by D. Teytelman at ALS study
  - Lifetime or operational issues?



The gap induced transients in the two rings must be matched to prevent excessive collision point variation. Here the transients from the two rings are matched to within 0.6° (0.1 σ_Z). Fine tuning of the simulation parameters is possible to reduce this further. Theoretically, the transients may be perfectly matched (assuming equal cavity coupling in the two rings)

Mitigation - via RF modulations of reference

- Brute-force approach- Use lots of RF power via direct loop
- Alternate Idea - used at LHC
  - modulation of reference phase to minimize RF power
  - what is possible for EIC?

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Cavity voltage phase modulation to reduce the high-luminosity Large Hadron Collider rf power requirements

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The Large Hadron Collider (LHC) radio frequency (rf) and low-level rf (LLRF) systems are currently configured for constant rf voltage to minimize transient beam loading effects. The present scheme cannot be extended beyond nominal LHC beam current (0.55 A dc) and cannot be sustained for the high-luminosity (HL-LHC) beam current (1.1 A dc), since the demanded power would exceed the peak klystron power. A new scheme has therefore been proposed: for beam currents above nominal (and possibly earlier), the voltage reference will reproduce the modulation driven by the beam (transient beam loading), but the strong rf feedback and one-turn delay feedback will still be active for loop and beam stability. To achieve this, the voltage reference will be adapted for each bunch. This paper includes a theoretical derivation of the optimal cavity modulation, introduces the implemented algorithm, summarizes simulation runs that tested the algorithm performance, and presents results from a short LHC physics fill with the proposed implementation.

LHC Mitigation - via RF modulations of reference

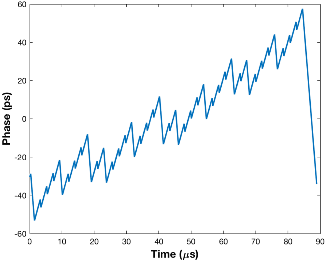


FIG. 5. Calculated cavity phase modulation for HL-LHC filling pattern and beam parameters. 2748 bunches, 2.2×10^{11} protons per bunch, 7 TeV, 16 MV rf voltage, 4.4 μs long abort gap. The phase is reported in ps with respect to the 400 MHz rf clock.

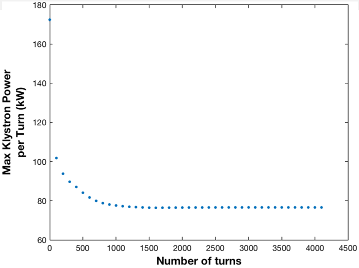


FIG. 7. Peak power reduction as the algorithm optimizes the phase modulation.

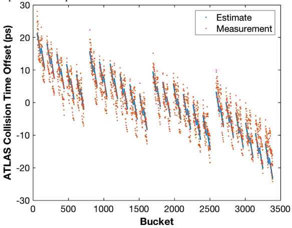


FIG. 22. Collision point time shift for the ATLAS detector.

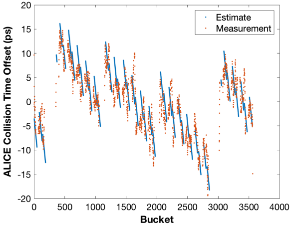
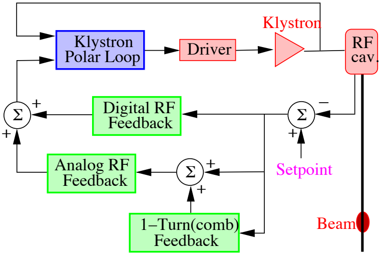


FIG. 24. Collision point time shift for the ALICE detector.

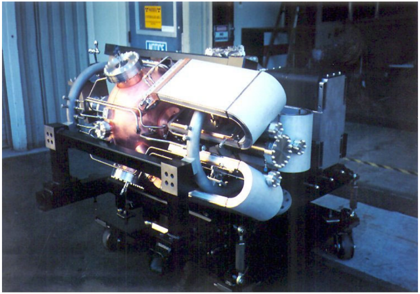
EIC study - LLRF and High Beam Loading

- EIC has challenging goals for stored current
- Two rings have totally different RF systems and longitudinal dynamics
- Interactions of filling pattern gaps, RF power systems leads to modulations of synchronous phase and IP. (shift in luminous region with Luminosity impact)
- Expand techniques required for PEP-II (world record stored current), now used at LHC and for HL-LHC studies
- Investigate the operational limits and impact on beam dynamics from the impedance-controlled RF systems. Investigate new technical LLRF implementation options.
  - Time-domain nonlinear simulation incorporates beam dynamics with technology of LLRF system
  - Based on PEP-II and LHC experience, where limits of machine were understood, and overcome, via models and simulation studies of new control techniques.
  - T. Mastorides has students, early career award to support this collaboration
  - J. Fox - collaborate via Stanford Applied Physics?



LLRF and Beam Loading - Proposed areas of study

- Expand simulation models to include technical features of possible EIC RF Systems, beam dynamics
  - builds directly on existing PEP-II and LHC models and methods
  - Goal - methods to minimize the difference in gap transients between rings
  - Methods to control low longitudinal modes within damped RF system bandwidth
  - Methods to optimally use RF power sources, minimize required RF station power
  - Develop RF system tuning tools and methods for optimal performance
  - Research new control methods for next-generation colliders



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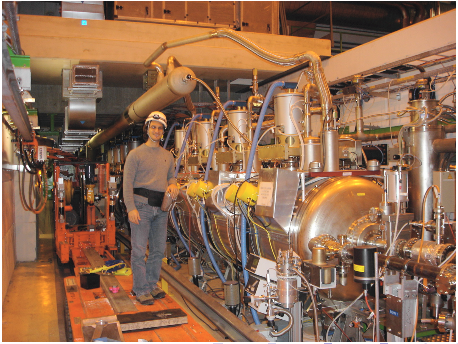
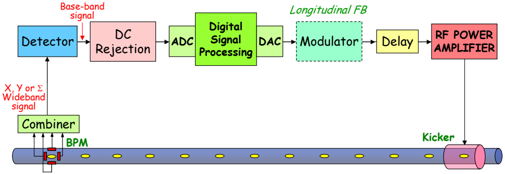


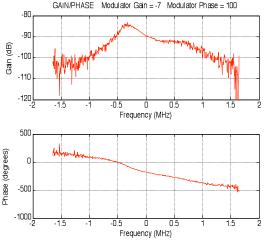
EIC Beam Instability Feedback Proposal

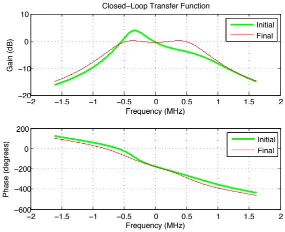
- Expand existing codes used for PEP-II, SuperKEKB
- Expands simulation models to include technical features of EIC RF Systems, beam dynamics for longitudinal, transverse modes
  - Builds directly on existing PEP-II, SuperKEKB models and methods
  - Use estimates, knowledge of cavity HOM's to study coupled bunch motion
  - Goal - estimate growth/damping rates for all modes vs. current, filling patterns
  - Estimate required system gains and bandwidths for transverse and longitudinal planes
  - Understand interaction of modes within LLRF loop bandwidth and broadband system bandwidth
  - Research new control methods for next-generation colliders
- Feedback and Dynamics group alumni developed technology and techniques required for PEP-II, ALS, DAΦNE, Bessy-II, PLS and numerous light sources worldwide. Recent intra-bunch feedback technology at SPS

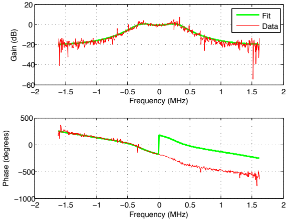


Technical examples: LHC LLRF Optimization tools

- Tool for calculation and adjustment of RF station closed loop gain/phase.







- Developed from PEP-II tools, now used at LHC to optimally configure superconducting RF system and LLRF configurations. Extension to HL-LHC