RF Beam loading, LLRF feedback applications in EIC storage rings

EIC ESR Design Explored

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RF, LLRF and Longitudinal Dynamics Issues for EIC design

- High-current two ring collider- challenges in RF system implementation and dynamics
- Similar to PEP-II, (Super)KEKB, LHC and HL-LHC RF and LLRF challenges
- EIC collider designs will have very different RF and system dynamics in the two rings
- Technology choices in RF systems, and LLRF systems. Impacts of imperfections? Nonlinearity? Dynamic range?
    - Methods to optimally use RF power sources, minimize required RF station power
    - What sorts of gap transients can we expect?
    - What impact will this have on luminosity from IP shift??
    - What impacts does this have on Crab Cavity effectiveness?
    - What methods might be helpful to mitigate the impacts?
    - Methods to control low longitudinal modes within damped RF system bandwidth - longitudinal instabilities driven by cavity fundamental
    - Impact of parked cavities, operational flexibility?
- Needs research and evaluation as part of RF system design

Beam Loading in RF cavity - Pedersen Model

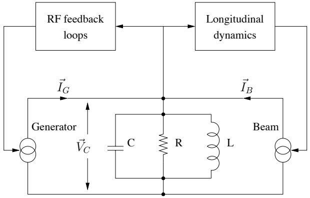


Figure 2.6: Schematic of the RF cavity model with two input currents and feedback loops

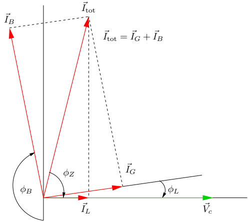


Figure 2.7: Steady-state vector diagram of accelerating cavity currents and voltages

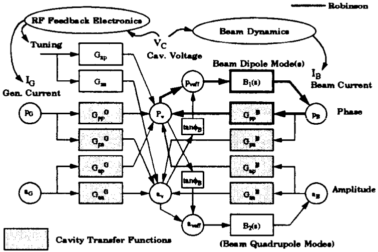


Figure 2: Generalized linear beam cavity interaction model.

- 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

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

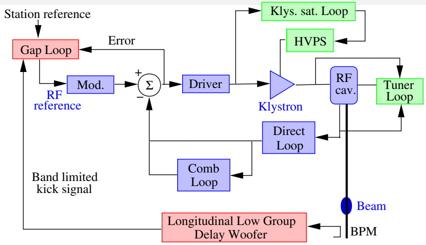


FIG. 1. (Color) System block diagram. Fast dynamics (modeled) appear in blue, slow dynamics (fixed parameters in simulation) in green, and not modeled components in red.

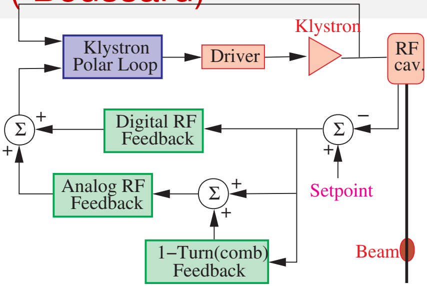


FIG. 1. (Color) Simplified LHC rf block diagram.

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

RF system and Beam Parameters - EIC Electron Ring Study

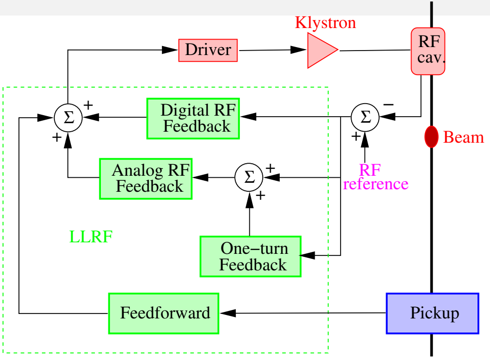
Energy	18 GeV	10 GeV	5 GeV
f_{RF} MHz	591	591	591
f_{REV} KHz	78.25	78.25	78.25
h	7560	7560	7560
Cavities	17	17	17
V_{cavity} - Nom. [MV]	3.62	1.27	0.57
$V_{RF_{TOTAL}}$ [MV]	61.5	21.6	9.6
R/Q	37	37	37
Q_o	2.3e10	2.3e10	2.3e10
Q_{ext}	71.5e4	7.91e4	5.12e4
Detuning [KHz] Optimal	-1.1	-42.4	-95.7
Avg. Beam Current [A]	0.23	2.5	2.5
Synchronous phase [deg]	143.0	170.0	173.1
Synchronous Freq. [KHz]	3.753	4.347	4.568
Number of Bunches	290	1160	1160
Particles / bunch	3.44e11	3.44e11	3.44e11

Table: Parameters for Focusing mode

- At low energy, what do we do with all the installed cavities and necessary voltage?
- Interesting idea proposed - counterphase some complement of stations
  - advantage - keeps effective RF slope for synchrotron tune
  - advantage - Keeps stored energy in cavity, minimizes gap transients
  - disadvantage - operational impact of rapid partial beam loss, KEKB experience as counterphased cavities received beam energy and INCREASE voltage

EIC LLRF, RF and Beam system simulations

- Time-Domain nonlinear simulation adapted from PEP-II and LHC tools
- The EIC simulations track the centroid motion of each bunch and include the cavity, klystron, LLRF loops, and loop delay.
- Independent simulations of the electron and ion ring are utilized.
- Longitudinal dynamics of each bunch as a rigid particle, coupled-bunch motion and interactions with the cavity impedance and LLRF loops are included. Low-mode longitudinal stability is part of the study.
- Linear and non-linear klystron models are possible, these initial results are for linear klystrons
- With models for ESR and HSR, the resulting gap transients – and time offset at the IP– can be studied.
- signal processing effects from dynamic range limitations can also be studied



- 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. The feedforward samples the longitudinal beam position, but still acts on the klystron driver.

Gap transients - Direct Loop

RF station Voltage, klystron power and bunch synchronous phase

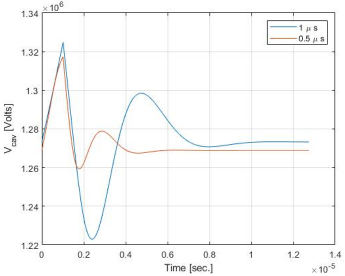


Figure: Cavity Voltage

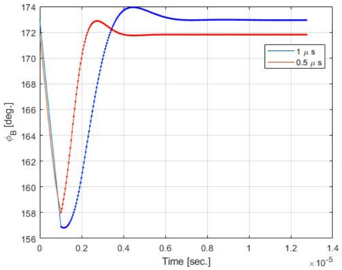


Figure: Transient bunch synchronous phase

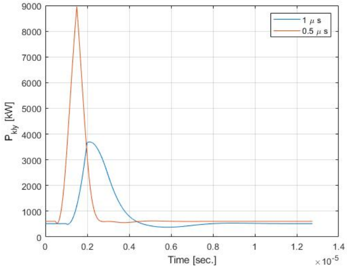


Figure: Nominal klystron/amplifier power (per cavity)

- Electron Ring operating at $E = 10$ GeV and $I_B = 2.5$A, 566 bucket gap
- LLRF direct loop designed to achieve minimum RF station impedance, evaluating two group delays in the feedback system (0.5μs and 1 μs).
- No Gap feed-forward signal - Large impact in the transient klystron power

Gap transients - Direct and Beam Feedforward loops

RF station Voltage, bunch synchronous phase

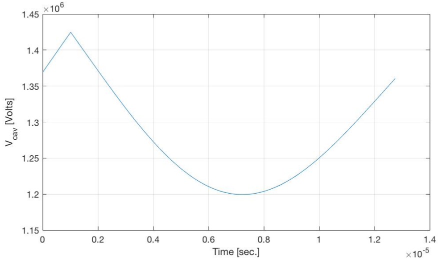


Figure: Cavity Voltage

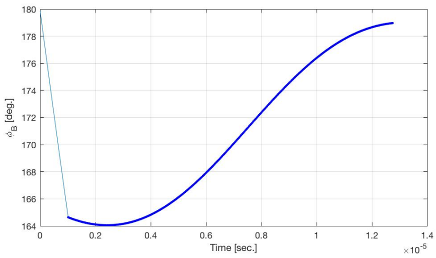
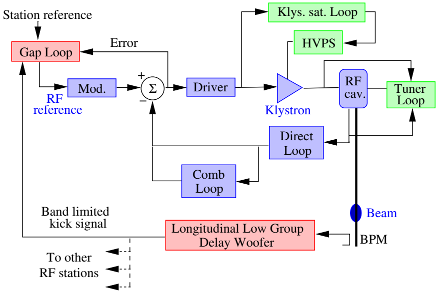


Figure: Transient bunch synchronous phase

- Electron Ring operating at $E = 10$ GeV and $I_B = 2.5$A, 566 bucket gap
- LLRF direct loop designed to achieve minimum RF station impedance. Includes 1 μs group delay in the feedback system.
- Gap feed-forward signal injected in the LLRF to keep the klystron power almost constant per revolution period
- additional options in study- reference modulation, partial detuning

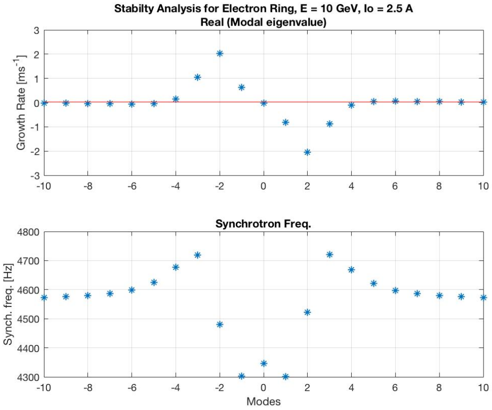
Instabilities from Fundamental-driven modes

- Estimates are based on the LLRF topology (Direct FF and Comb loops)
- Requires technical estimates of imperfections and nonlinearities
- Estimate frequency domain RF station impedance for various configurations
- Estimates growth rates for various beam currents and RF station configurations
- Complement with time domain nonlinear codes to double check the impact of nonlinearities
- PEP-II experience with double-peaked (2nd order) 1-turn delay filters

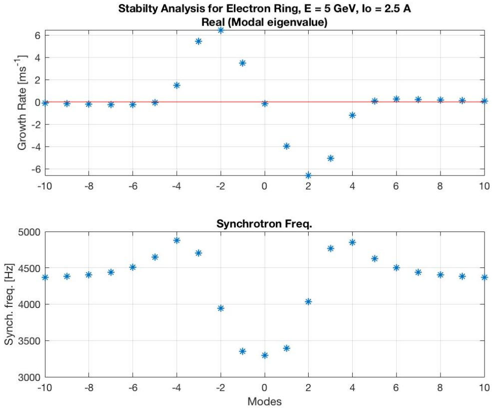


Block diagram of the PEP-II RF station showing the principal blocks controlling the beam dynamics

Instabilities from Fundamental-driven modes- only direct loop



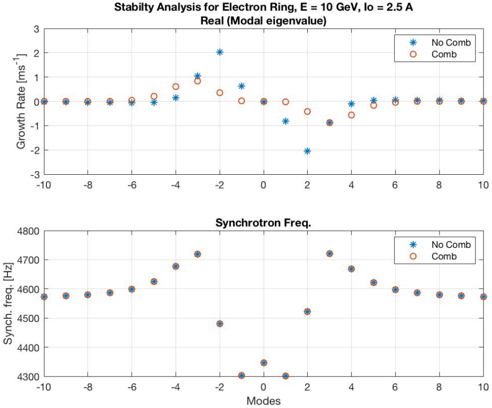
Electron ring $E = 10$ GeV



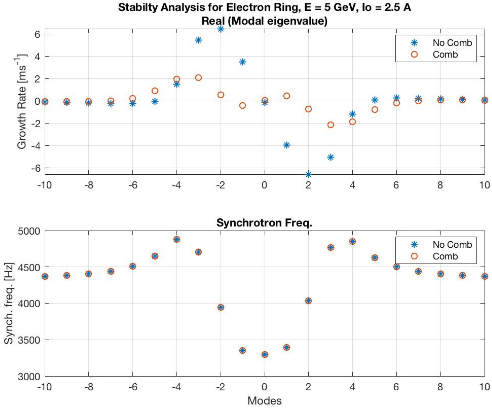
Electron ring $E = 5$ GeV

- Electron Ring operating at $E = 10$ GeV and $E = 5$ GeV and $I_B = 2.5$A
- LLRF direct loop designed to achieve minimum RF station impedance

Instabilities from Fundamental-driven modes - direct and comb loops



Electron ring $E = 10$ GeV



Electron ring $E = 5$ GeV

- Electron Ring operating at $E = 10$ GeV and $E = 5$ GeV and $I_B = 2.5$A
- LLRF direct loop and 1-turn delay (Comb) filter designed to achieve minimum RF station impedance
- For both energies, the beam is unstable for some low-order modes. For $E = 18$ GeV and $I_B = 0.23$A, the beam is stable

Crab Cavity RF systems, comments

- the gap transients, and matching in the two rings, have implications for the crab cavity systems.
- matching the gap transients between the two rings solves the IP-shift and luminosity loss vs Z issue
- There is still a synchronous phase transient in the crab cavity system (even if ring transients are matched to each other)
- Shifts in the beam synchronous phase (gap transients) generate modulation of the crab kick as a function of beam position
- The bandwidth of the high Q crab cavity RF systems limits any idea of doing some sort of Vref modulation to cancel out effects
- First studies - suggest gap magnitudes and low crab RF frequency do not have show-stopper impacts

- Studies by Themis Mastorides on impacts of RF noise in crab cavity systems suggest
  - Sensitivity of EIC is a real effect, seen in emittance growth estimations
  - "the requirements on the RF noise will probably still be significantly lower than the state of the art"
  - further studies in progress, possible mitigation with two mode feedback.
  - Opportunity to collaborate with HL-LHC on this work

Conclusions - Design Report ESR at full currents, 3 energies

- A combination of a direct loop and 1-turn delay feedback is the minimum architecture applicable to control the RF cavity voltage and reduce the beam - impedance interaction (control low mode instabilities)
- For the electron ring operating at $E = 10$ GeV and $E = 5$ GeV at maximum current $I_B = 2.5$A, the beam is unstable with LLRF optimally configured to minimize the RF station impedance presented to the beam
- To stabilize this beam dynamics, a longitudinal feedback system (so-called Woofer) needs to be included as part of the LLRF architecture
- For the electron ring operating at $E = 18$ GeV, the beam is stable for optimum design of the LLRF system
- There is work to do to optimize the required RF drive power, use of various mitigation approaches.
- Opportunities to collaborate with sister high-current projects

Summary and challenges - Value of simulation tools

- Initial estimates of required cavity power for EIC Design report configurations
- Four different schemes can be imagined to match or reduce the RF transients created by the clearing gaps. Each has a value to achieve the necessary beam performance, with different tradeoffs or challenges. These simulation methods and tools can be used to study realistic cases as the conceptual design progresses.
  - The Direct Loop LLRF solution is simple, but leads to significant klystron power for the ESR
  - A beam feedforward, or gap feedforward (e.g. PEP-II approach) has value
  - The voltage reference modulation scheme might minimize the peak klystron power, but it it might require some RF parameter adjustments (R/Q) to match the modulations for the two rings. It would also be sensitive to beam loss during the fill.
  - There are fill pattern modulation schemes, these would also be susceptible to beam loss and variations in lifetime, since the lifetimes on these high current buckets is probably different than nominal. Impact of realistic variations?
  - It is possible to combine solutions and/or use different schemes (e.g.RF gating in gap)for the two rings (OTFB for e^- and fill pattern modulation for ion?).
- Simulation tools are valuable as part of conceptual design and RF system optimization
- These methods can also help define engineering specifications for the detailed LLRF design (linearity, dynamic range, noise levels, etc.)

- J. Fox, T. Mastoridis, B. Rimmer "LLRF and Beam Dynamics estimates for a strawman EIC design with operational implications including Crab Cavity systems", B19.00001 presented at the APS April 2020 meeting
- Mastoridis, T. et al, "Beam gap transient analysis and mitigations in high-current storage rings for an electron-ion collider", PhysRevAccelBeams.23.101601
- C. Rivetta, T. Mastorides, J. D. Fox, D. Teytelman, and D. Van Winkle, Modeling and simulation of longitudinal dynamics for low energy ring–high energy ring at the positron- electron project, Phys. Rev. ST Accel. Beams 10, 022801 (2007)
- T. Mastorides, C. Rivetta, J.D. Fox, D. Van Winkle, D. Teytelman, “Analysis of Longitudinal Beam Dynamics Behavior and RF System Operative Limits at High Beam Currents in Storage Rings", Physical Review Special Topics Accelerators and Beams, Volume 11, Issue 6, June 2008.
- T. Mastorides, J.D. Fox, C.H. Rivetta, D. Van Winkle, P. Baudrenghien, “RF system models for the CERN Large Hadron Collider with application to longitudinal dynamics", Physical Review Special Topics Accelerators and Beams, Volume 13, Issue 10, October 2010.
- D. Van Winkle, J.D. Fox, T. Mastorides, C.H. Rivetta, P. Baudrenghien, A. Butterworth, J. Molendijk, “Commissioning of the LHC Low Level RF System Remote Configuration Tools",s Proceedings of International Particle Accelerator Conference 2010, Kyoto, Japan, May 2010.
- T. Mastoridis, P. Baudrenghien, J. Molendijk, “Cavity voltage phase modulation to reduce the high-luminosity Large Hadron Collider RF power requirements", Physical Review Accelerators and Beams 20, 101003 (October 2017).
- J. Byrd, S. De Santis, J. Jacob, V. Serriere, “Transient beam loading effects in harmonic RF systems for light sources", Phys. Rev. ST Accel. Beams 5, 092001 (September 2002).
- J. Fox, T. Mastorides, C. Rivetta, D. Van Winkle and D. Teytelman, “Lessons learned from positron-electron project low level rf and longitudinal feedback,” Phys. Rev. ST Accel. Beams **13**, 052802 (2010)..
- D. Teytelman, Dimtel, Inc., San Jose, CA, USA. “Transient beam loading in FCC-ee (Z)", FCC Week 2017
- D. Teytelman, Dimtel, Inc., San Jose, CA, USA. "Feedback System Specifications", JLEIC Collaboration meeting Spring 2019

Mitigation - via RF cavity stored energy

- Superconducting RF cavity has potential for higher stored energy via Q_{loaded}, smaller transients
- Alternate Idea - used at KEKB (not estimated for EIC case)
  - Shintake - NC ARES energy storage cavity system

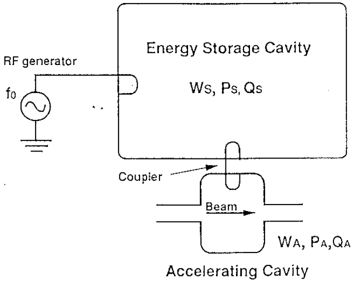
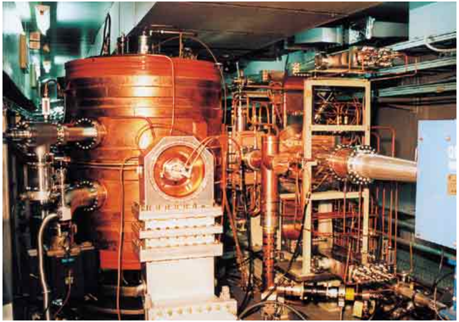


Fig. 2 Accelerating cavity coupled to an energy storage cavity.



Dynamic Range of LLRF loops, impact of linearity

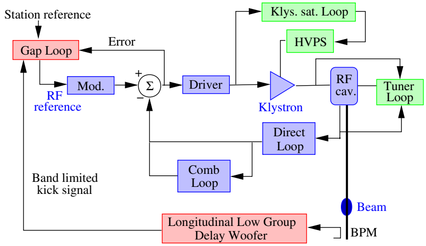


FIG. 1. (Color) System block diagram. Fast dynamics (modeled) appear in blue, slow dynamics (fixed parameters in simulation) in green, and not modeled components in red.

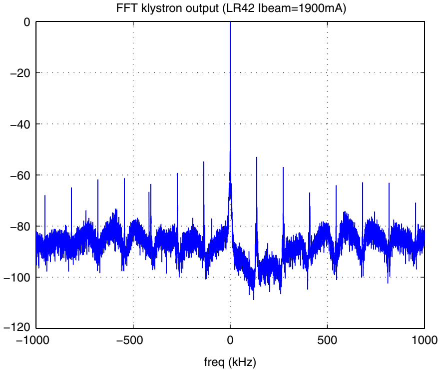


FIG. 20. (Color) Power spectrum of signals in the klystron output during closed-loop operation. ±7 revolution harmonics are visible around the 476 MHz carrier.

- 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

Interactions between cavity driven and HOM modes

- PEP-II experience with all-mode broadband feedback, using a Woofer link , or dedicated low group delay woofer - is still very sensitive to driven motion in low modes from noise in the RF systems and power supplies.
- My $0.02 the EIC broadband should do the model-based control from Ozhan's thesis
- decouple the interaction on mode 0 from HOM modes
- targets broadband power to high frequency modes, lets LLRF and power stage do mode zero.
- For EIC we want a next generation broadband longitudinal system with a modal decomposition, allows the noisy RF system and low modes to not saturate the broadband controller on the HOM modes.
- PEP-II experience - value of investment in better synchronized diagnostics

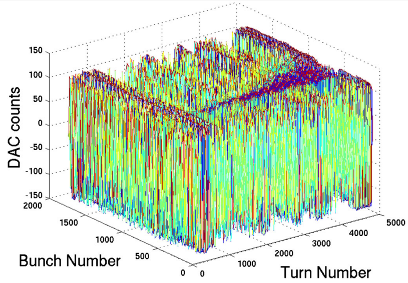
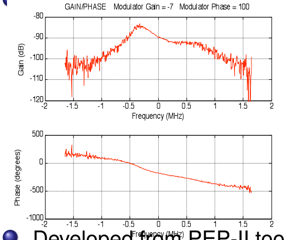


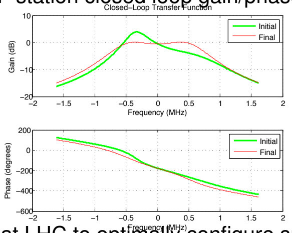
FIG. 8. (Color) Time-domain fault file from the HER showing the data at the output of the DSP filters (the output signals from the DSP baseband processing with dynamic range $+127/-128$ DAC counts) The transient content is significant enough to pass through the control filter and saturate the power stage near 1000 turns in the data set. The 5000 turns of the recording is 36 ms long and is from an 1800 mA HER fill.

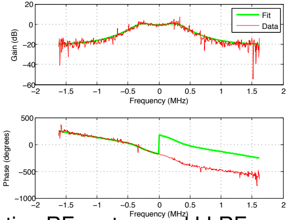
- Example PEP-II fault initiated from RF HV power supply noise

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