Gap Transient Origins and Mitigation Options for EIC
Impedance controlled LLRF systems

Ideas for discussion, guidance for path forward

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Supported in part by Jefferson Science Associates, LLC under U.S. DOE Contract No. DE-AC05-06OR23177

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Supported in part by the U.S. Department of Energy, Office of Science, Office of High Energy Physics, under Award Number DE-SC-0019287

Beam Loading in RF cavity - Pedersen Model

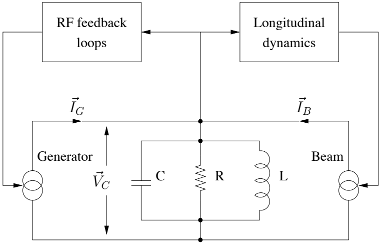


Figure 2.6: Schematic of the RF cavity model with two input currents and feedback loops

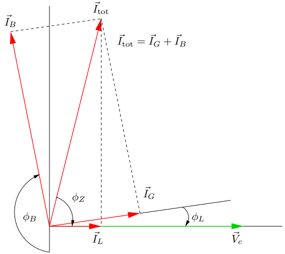


Figure 2.7: Steady-state vector diagram of accelerating cavity currents and voltages

- 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

Pedersen Cavity-Beam Interaction linear model

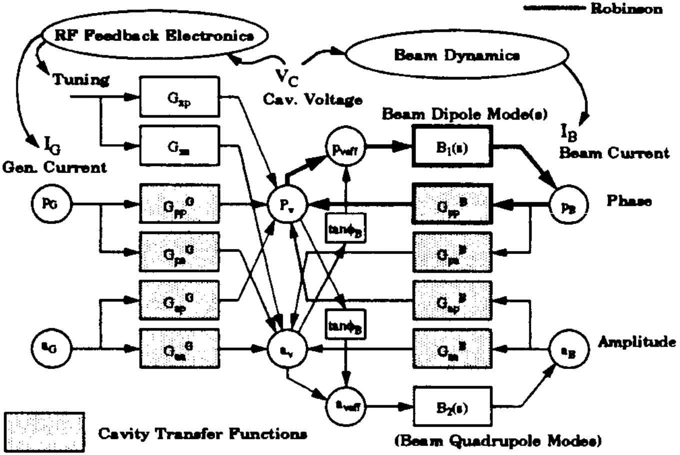


Figure 2: Generalized linear beam cavity interaction model.

Issues for EIC design

- EIC collider designs will have very different RF and system dynamics in the two rings
- Technology choices in RF systems - damped NC cavities? SC RF cavities? Choice of frequency? RF system Power stages?
  - 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 optimally use RF power sources, minimize required RF station power
  - 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

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

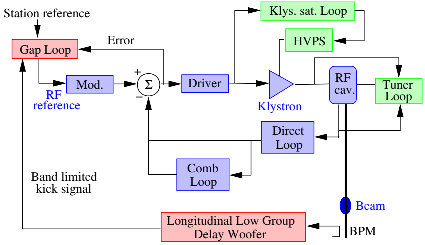


FIG. 1. (Color) System block diagram. Fast dynamics (modeled) appear in blue, slow dynamics (fixed parameters in simulation) in green, and not modeled components in red.

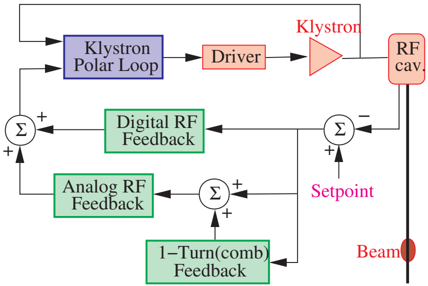


FIG. 1. (Color) Simplified LHC rf block diagram.

- 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 very non-linear system

Cavity Gap Transients - Example and Impacts

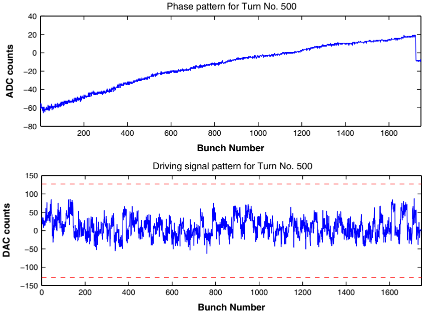


FIG. 7. (Color) HER front-end and back-end signals of the longitudinal feedback system for a single turn while the HER system is operating with nominal beam parameters at 1800 mA. The upper plot shows the phase error signal for all the bunches. The lower plot depicts the base band signal driving all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

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

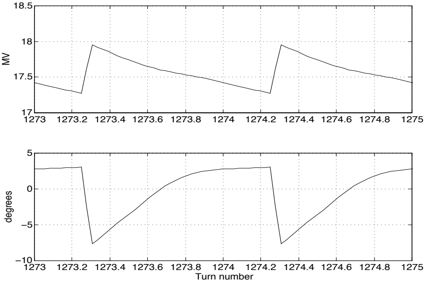


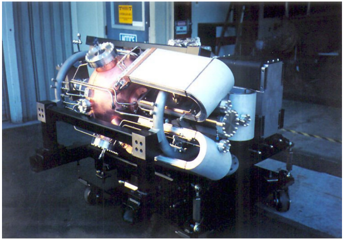
Figure 3. Cavity Voltage Transient

- Example from PEP-II simulation (Tighe)
- Mis-matched transients between collider rings causes Z shift of IP
- Z Variation on IP β function means luminosity variation with bunch
- What about interactions with Crab cavity systems?

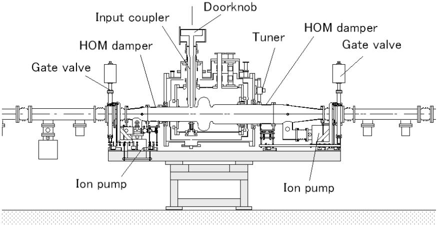
Possible EIC case - Strawman designs

Ring	E_o (GeV)	V_{tot} (MV)	$N_{cavities}$	Q_L	f_{RF} (MHz)	I_{DC} (A)	$N_{bunches}$
e -	10	19	24	5170	476.4	0.26	864
ion	200	57.6	24	28600	952.8	0.75	864

Table: Base ring and RF system parameters used in this study.



BR_040 RF Cavity 8-19-97



- Electron ring based on PEP-II damped normal conducting cavities
- Ion ring based on 2xRF superconducting cavities
- Strawman case, useful to explore gap transients
- Explore several mitigation options, matching issues

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

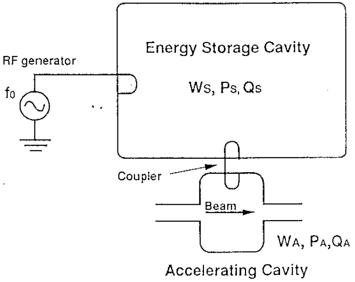
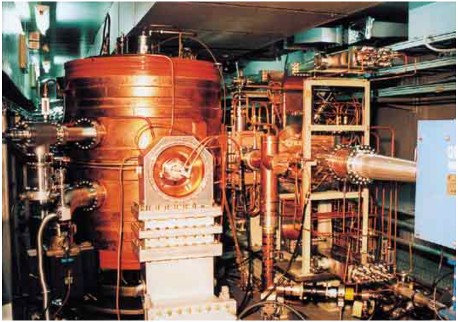
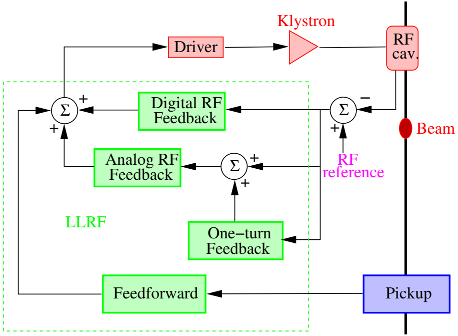


Fig. 2 Accelerating cavity coupled to an energy storage cavity.



EIC simulations for Strawman cases

- 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.
- 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.
- Time-Domain nonlinear simulation adapted from PEP-II and LHC tools



Base case - Direct loop Only

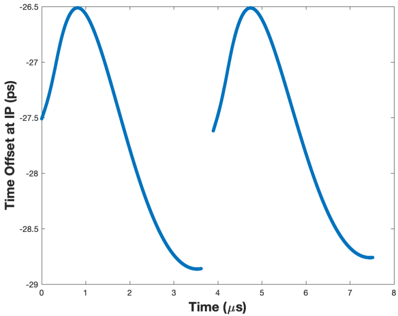


Figure: differential IP timing shift between e^- and Ion rings

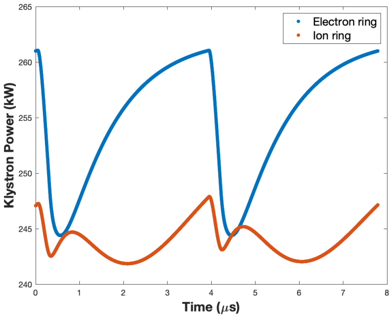


Figure: RF power demand during 1 turn (per cavity)

- Fill pattern - two bunch trains, uniform intensity 432 buckets, two 128 bucket gaps
- Unlimited klystron power, no saturation mechanisms
- LLRF configurations optimized for best loop stability each ring
- realistic loops delays (320 ns), with consistent 18 dB loop gain (group delay limit)
- p/p offset 2.4 ps (0.72 mm), σ 0.46ps

Direct loop with Comb loop (1 turn delay)

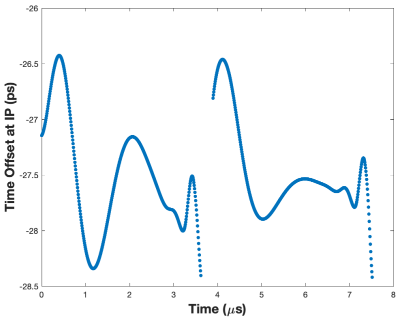


Figure: differential IP timing shift with direct plus 1 turn feedback

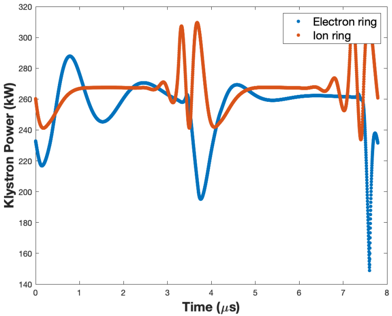


Figure: RF power demand - direct plus 1 turn feedback (per cavity)

- Fill pattern - two bunch trains, uniform intensity 432 buckets, two 128 bucket gaps
- Unlimited klystron power, no saturation mechanisms
- LLRF configurations optimized for best loop stability each ring
- realistic loops delays (320 ns), with consistent 18 dB loop gain
- p/p offset 2.0ps (0.6 mm), σ 0.46ps - tradeoff of RF transient power and Beam transient reduction

Direct loop, Comb loop, Feedforward

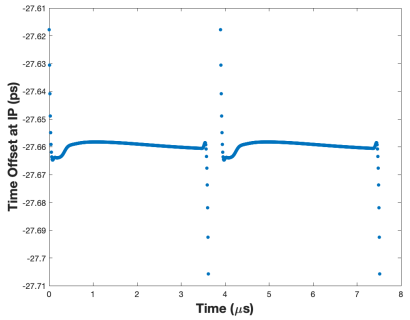


Figure: differential IP timing shift with direct, comb and feedforward

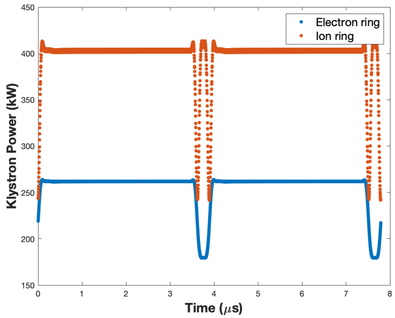


Figure: RF power demand - direct, comb and feedforward (per cavity)

- Fill pattern - two bunch trains, uniform intensity 432 buckets, two 128 bucket gaps
- Unlimited klystron power, no saturation mechanisms
- LLRF configurations optimized for best loop stability each ring
- FF with pickup noise- p/p offset 0.42ps, σ 0.1ps - but look at klystron power
- FF with no pickup noise and finite klystron bandwidth- p/p offset 0.09ps, σ 0.01ps

Mitigation - via fill pattern current modulations

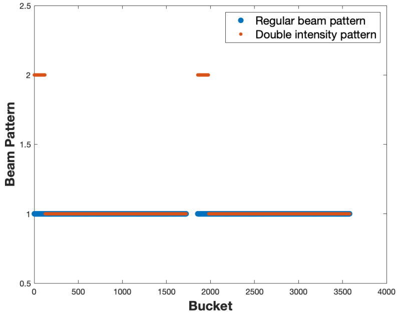


Figure: Ion ring fill patterns with double intensity for 31 bunches

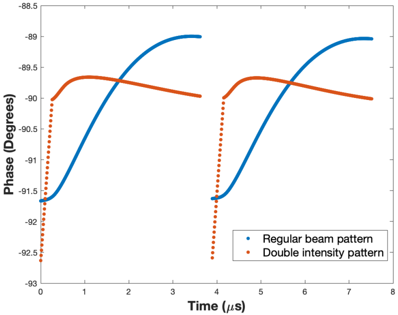


Figure: Synchronous phase variation for uniform and double intensity patterns

- origins, ideas and original studies by D.Teytelman and J. Byrd
  - put extra current at edges of gap, so "average current" is roughly the same (can also spread before and after gap)
  - Helps match transients, smaller difference
  - Lifetime or operational issues?
- Example for Ion ring - direct loop but no comb or feedforward (with comb or FF unfeasible RF transients with saturation)

Mitigation - via RF modulations of reference

- In this approach we try to match the transients rather than reduce them.
- LHC uses this approach to minimize klystron power in the LHC , V_{ref} is modulated as a function of position in the turn. Work by Mastorides and Baudrenghien
- 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.
- this example also shows the value of adding 11 extra filled buckets to the electron ring (I_{DC} adjustment)
- Degrees of freedom include cavity R/Q , Vcav adjustments to match gap transients, modulate one ring Vcav to match the other ring etc.

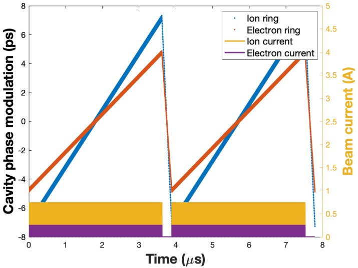


Figure: Vref modulation for minimum power

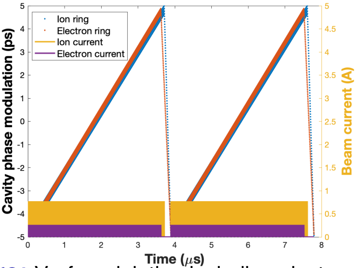


Figure: Vref modulation including electron ring fill modification

Gap transients - impact on Crab Cavity effectiveness

- 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)
- The crab cavity systems rely on phase coherent RF systems to produce symmetric differential head-tail kicks to each bunch
- 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
- Also means the collision time wrt master oscillator is modulated by bunch position, may have impacts for detector elements with timing coordinates

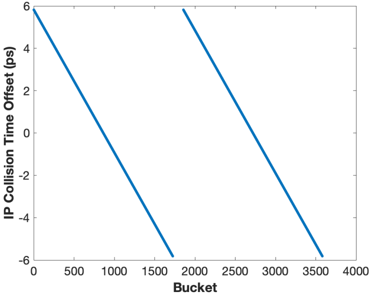


Figure: Gap Transient modulation for optimal Vref modulation. p/p modulation of 12 ps, bunch lengths of 40 ps (e-) and 107 ps (ion)

Instabilities from Fundamental-driven modes

- Estimates require some concept of the RF feedback architecture
- Requires technical estimates of imperfections and nonlinear performance
- Estimate frequency domain impedance for various configurations
- Estimate growth rates for various currents and cavity detunings.
- Still necessary to use the time domain nonlinear codes to check a couple of these cases, see if the low modes are unstable. Here the behavior of the RF feedback and nonlinear things may be important.
- PEP-II Experience with comb rotation - tradeoff of station vs beam stability

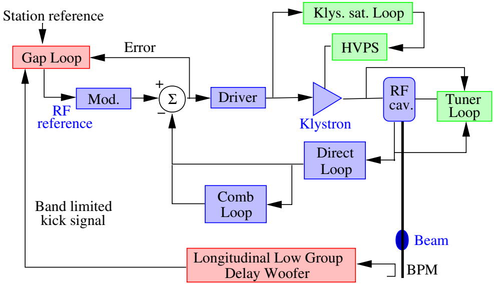


FIG. 1. (Color) System block diagram. Fast dynamics (modeled) appear in blue, slow dynamics (fixed parameters in simulation) in green, and not modeled components in red.

Estimates of Cavity-driven longitudinal motion

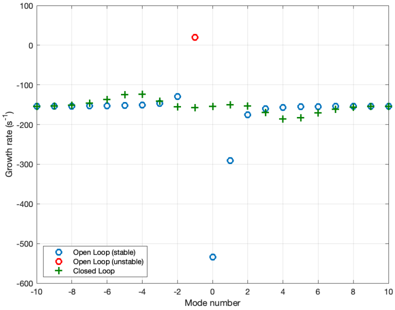


Figure: Growth rate estimates 10 GeV electron ring for low modes

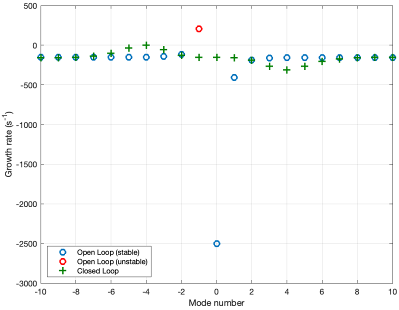
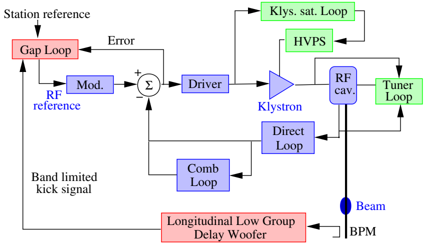


Figure: Growth rate estimates 200 GeV Ion ring for low modes

- Simulation with direct loop, no comb, linear perfect LLRF and Klystron
  - This suggests only Ion mode -4 is unstable in this configuration
  - Electron ring seems stable
  - PEP-II experience - low mode growth rates much greater than simulated due to imperfections in LLRF technical implementation, variations in station to station configurations
  - other energies and RF system configurations have not been explored

Dynamic Range of LLRF loops, impact of linearity



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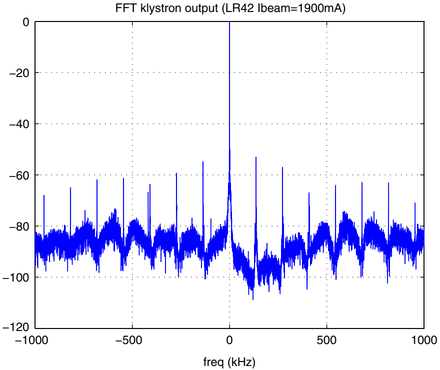

FIG. 20. (Color) Power spectrum of signals in the klystron output during closed-loop operation. ±7 revolution harmonics are visible around the 476 MHz carrier.

- 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

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.

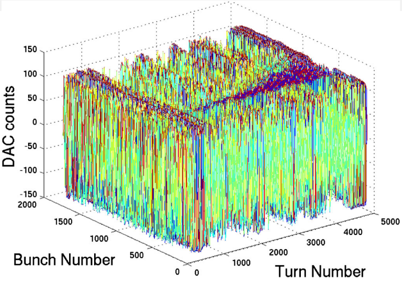

FIG. 8. (Color) Time-domain fault file from the HER showing the data at the output of the DSP filters (the output signals from the DSP baseband processing with dynamic range $+127/-128$ DAC counts) The transient content is significant enough to pass through the control filter and saturate the power stage 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
- PEP-II experience - value of investment in better synchronized diagnostics

Summary and challenges - Value of simulation tools

- Initial estimates of IP offset and required cavity power for Strawman configurations

	IP offset pk-pk (ps)	IP offset σ (ps)	Peak power electrons (kW)	Peak power ions (kW)
Realistic Delay	2.4	0.82	261	248
OTFB	2.0	0.46	288	314
FF with pickup noise	0.42	0.10	> 500	> 500
FF with klystron BW	0.09	0.01	264	414

- Three different schemes were explored to match or reduce the RF transients created by the clearing gaps. Each can achieve the necessary beam performance, with different tradeoffs or challenges. These methods and tools can be used to study realistic cases.
  - 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 (R/Q) to match the modulations for the two rings. It would also be sensitive to beam loss during the fill.
  - The fill pattern modulation schemes 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 for the two rings (OTFB for e^{-1} and fill pattern modulation for ion?).

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- D. Teytelman, Dimtel, Inc., San Jose, CA, USA. "Feedback System Specifications", JLEIC Collaboration meeting Spring 2019

HOM impedances in damped NC PEP-II cavities

Table 1. Impedance of longitudinal modes estimated from calculated and measured R/Q's and measured (fitted) Q's.

mode‡	f calc.2D (GHz)	R/Q calc.2D (Ω)	f meas. (GHz)	R/Q meas. (Ω)	Q meas. (fitted)	Rs (kΩ) (calc R/Q)	Rs (kΩ) (meas R/Q)
0-E-1	0.480	116.358	0.475	117.3	14218	1654	1668
0-M-1	0.756	39.903	0.758	44.6	18*	0.72	0.81
0-E-2	1.003	0.360	1.009	0.43	128	0.046	0.055
new			1.283	6.70	259	-	1.74
0-M-2	1.288	7.000	1.295	10.3	222	1.56	2.29
0-E-3	1.289	7.062	n.v.	n.v.	30*	0.21	n.v.
0-E-4	1.584	3.870	1.595	2.43	300	1.16	0.73
0-M-3	1.711	5.324	1.710	0.44	320	1.70	0.14
0-E-5	1.818	0.029	1.820	0.13	543*	0.016	0.070
0-M-4	1.894	0.848	1.898	0.17	2588	2.19	0.44
0-E-6	2.112	5.171	2.121	1.82	338	1.75	0.62
0-M-5	2.162	0.019	2.160	0.053	119*	0.002	0.006
0-E-7	2.255	1.009	2.265	0.064	1975*	1.99	0.13
0-E-8	2.359	0.141	2.344	n.m.	693*	0.10	n.m.

‡E = electric field, M = magnetic field boundary condition at cavity center. * Approx. fit or worst-case estimate
n.v. = mode not visible after damping. n.m. = mode not measured

- measurements from LBL studies (Rimmer, Byrd, et al)

HOM impedances in damped NC PEP-II cavities

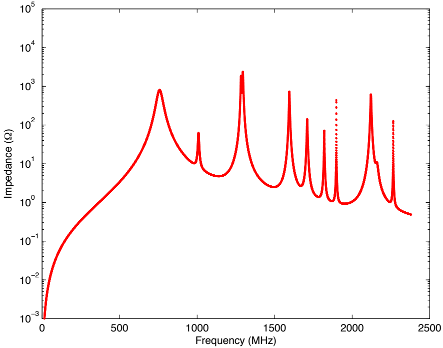


Figure 2.3: PEP-II estimated longitudinal HOM impedance per cavity, $\sum Z_i^{\|}$.

- Magnitudes in Frequency domain
- Beam samples this impedance, a function of filling pattern, and aliases impedances down into a baseband effective impedance
- Beam samples at sidebands above and below each revolution harmonic
- difference in upper and lower sidebands determine driving or damping impact

growth and damping rates

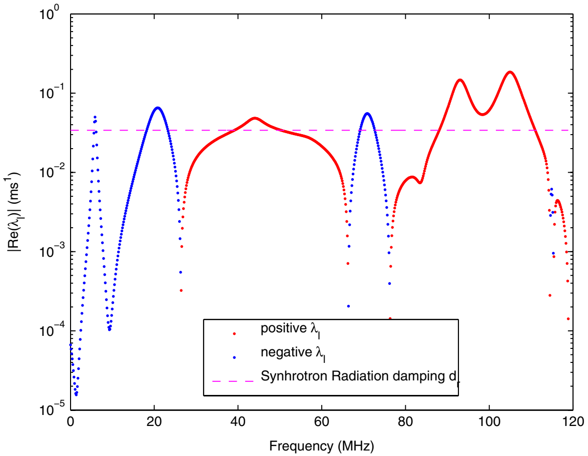
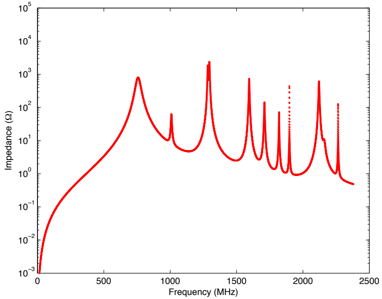


FIG. 1. (Color) Growth rate estimates from impedance measurements for 3 A LER. Impedance data from [3], growth rate estimates from [4].

Growth and Damping rates



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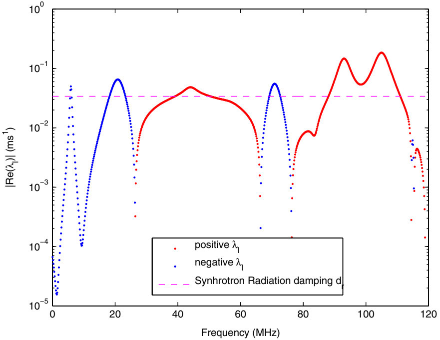


FIG. 1. (Color) Growth rate estimates from impedance measurements for 3 A LER. Impedance data from [3], growth rate estimates from [4].

- Some impedances alias to provide damping
- Some fill patterns can couple stable to unstable modes, bringing stability

growth and damping rates

General case of N equally spaced bunches, the longitudinal growth rate for mode l

$$1/\tau_l = \frac{I_0 f_{rf} \alpha}{2(E/e)Q_s} \Re(Z_{|,l}^{eff}) - 1/\tau_{rad} \quad (1)$$

$$Z_{|,l}^{eff} = \sum_{p=-\infty}^{p=\infty} \frac{\omega_{p,l}}{\omega_{rf}} \exp\left(-\omega_{p,l}^2 \sigma_\tau^2\right) Z_|(\omega_{p,l})$$

$$\omega_{p,l} = (pN + l + Q_s)\omega_{rev}$$

where the dependence on external longitudinal impedance $Z_|(\omega_{p,l})$, the scaling with beam current define the threshold current (when $1/\tau_{growth} - 1/\tau_{rad} = 0$).

What do we need to know? - HOM growth rates for both EIC rings

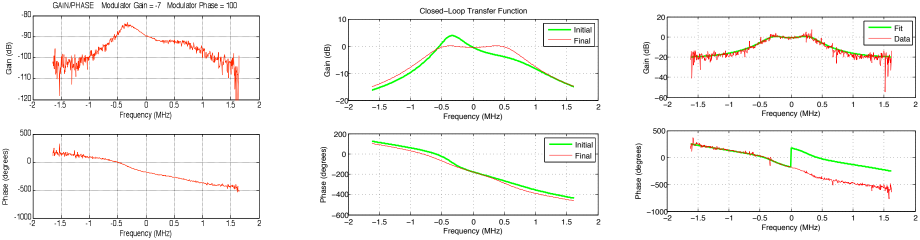
- For each ring
  - Clarify number of RF stations, Technology, number of cavities - do we have HOM data for these cavities (use SC simulations? PEP-II NC Data? what about the crab cavities?)
  - Do we understand the nominal operating station configurations?
  - Configurations with offline stations, where are the cavities parked?
  - What range of gap voltages (synchrotron tunes)
  - Nominal fill pattern? are there a family of fill patterns? (e.g. some sort of alternate fill used for a low current case where fewer bunches are filled to a nominal current?) This changes the frequency components which sample the HOM impedances.
  - Injection system and how is beam delivered? Are there situations during filling where the ring is partially filled with some unusual gap or other pattern? Impacts both for gap transients, the sampling of the HOM's and aliasing down into the baseband

Estimating HOM growth rates

- for each ring
  - Any vacuum structures or things that might have some HOM impedance to include in estimates (both transverse and longitudinal) - like the crab cavities, etc.
  - What is the synchrotron radiation loss per turn (electron ring) - is there also any sort of wiggler for damping - what is the expected damping?
  - For the Ion ring - what is the loss per turn (probably very negligible). is there a damping wiggler? what is the natural damping in the longitudinal plane?
  - broadband impedance estimate to calculate microwave instabilities(this was a talk at the April workshop)
- calculate HOM growth rates by using the fill patterns, known HOM impedances, and alias them into the baseband. We then subtract upper and lower sidebands, etc. and get growth/damping rates per mode. We compare this to damping in the machine.
- Thresholds and growth rate estimates for a range of fill patterns, and any operating RF configuration.
- Estimate the necessary damping for the range of unstable modes
- Roughly estimate required kicker voltage.
- Estimate could be made of the kicker bandwidth, choice of operating band
- Estimate the shunt impedance for a couple technical designs, the necessary kicker power, etc.

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