APS-Upgrade RF System Simulations*

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Introduction

The APS-U presents new challenges for the APS RF systems

- A passive 4th harmonic 1.408 GHz superconducting bunch lengthening cavity in the Storage Ring to alleviate lifetime and emittance concerns

$\Rightarrow$ Interacts with main 352 MHz RF system

$\Rightarrow$ Reduces synchrotron tune
  - increases sensitivity to low-frequency noise
  - interaction with new Longitudinal Feedback system

- x10 amount of beam-loading in the injectors (20nC vs. 2nC)

$\Rightarrow$ 200mA in Particle Accumulator Ring h=1 (9.77MHz) and h=12 (bunch shortening)

$\Rightarrow$ 16mA in the Booster (352 MHz) with large injection transients

Needed: thorough understanding of interaction between the RF systems & beam

Birth of Beam/Cavity analysis: Robinson's stability criteria

Best copy

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AECU-3712

CAMBRIDGE ELECTRON ACCELERATOR

The R.F. system with beam loading is analyzed for stability, and a relationship determined for the range of the cavity tuning over which the system is stable.

CEA(MIT-Harvard)-11
Kenneth W. Robinson
September 10, 1956

$$
\begin{bmatrix} \Delta E / E_o \,' \\ \Delta \phi_B \,' \\ \Delta v / V_o \,' \\ \Delta \phi_V \,' \end{bmatrix}
=
\begin{bmatrix}
0 & \frac{V_o}{E_o} f_{rev} \cos\phi_S & \frac{V_o}{E_o} f_{rev} \sin\phi_S & \frac{V_o}{E_o} f_{rev} \cos\phi_S \\
2\pi h f_{rev}^2 \alpha_c & 0 & 0 & 0 \\
0 & -\sigma \frac{V_{br}}{V_o} \cos\phi_S & -\sigma & -\sigma \tan\phi_Z \\
0 & \sigma \frac{V_{br}}{V_o} \sin\phi_S & \sigma \tan\phi_Z & -\sigma
\end{bmatrix}
\begin{bmatrix} \Delta E / E_o \\ \Delta \phi_B \\ \Delta v / V_o \\ \Delta \phi_V \end{bmatrix}
$$

$$
0 < \frac{\tan\phi_Z}{\cos\phi_S} < \frac{V_o}{V_{br}} \sec^2\phi_Z
$$

The R.F. system with beam loading is analyzed for stability, and a relationship determined for the range of the cavity tuning over which the system is stable.

MASTER

CEAL- 1010

STABILITY OF BEAM IN RADIOFREQUENCY SYSTEM

by

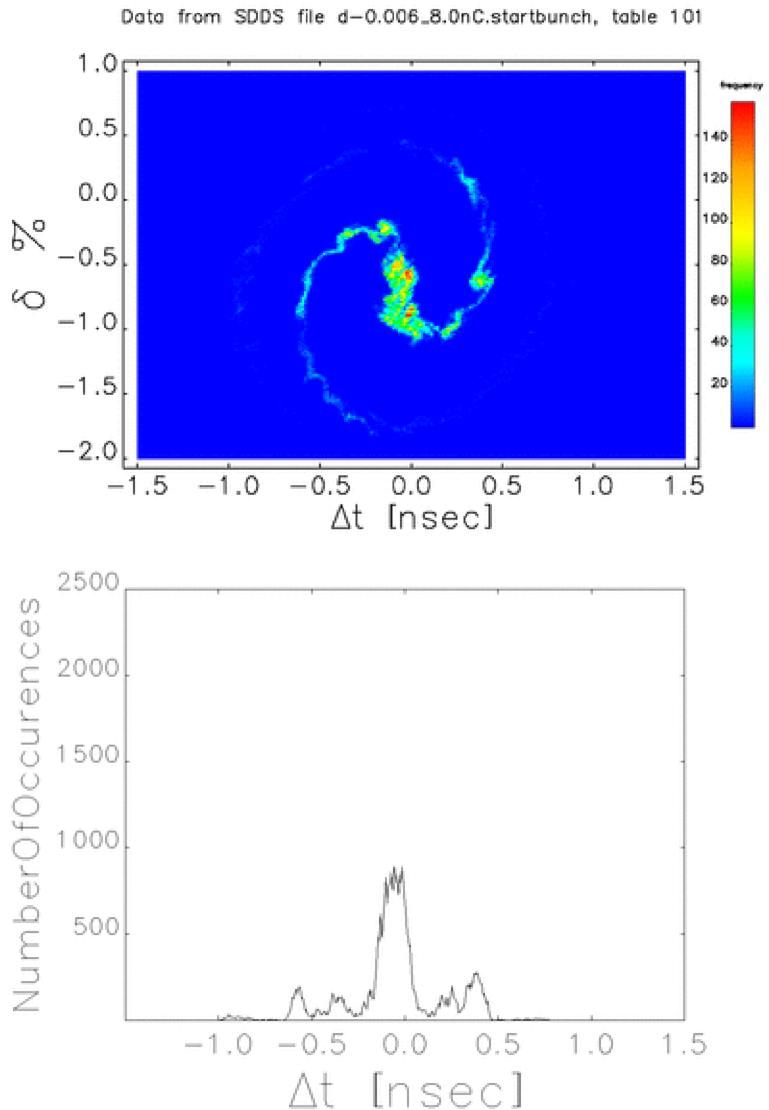
Kenneth W. Robinson

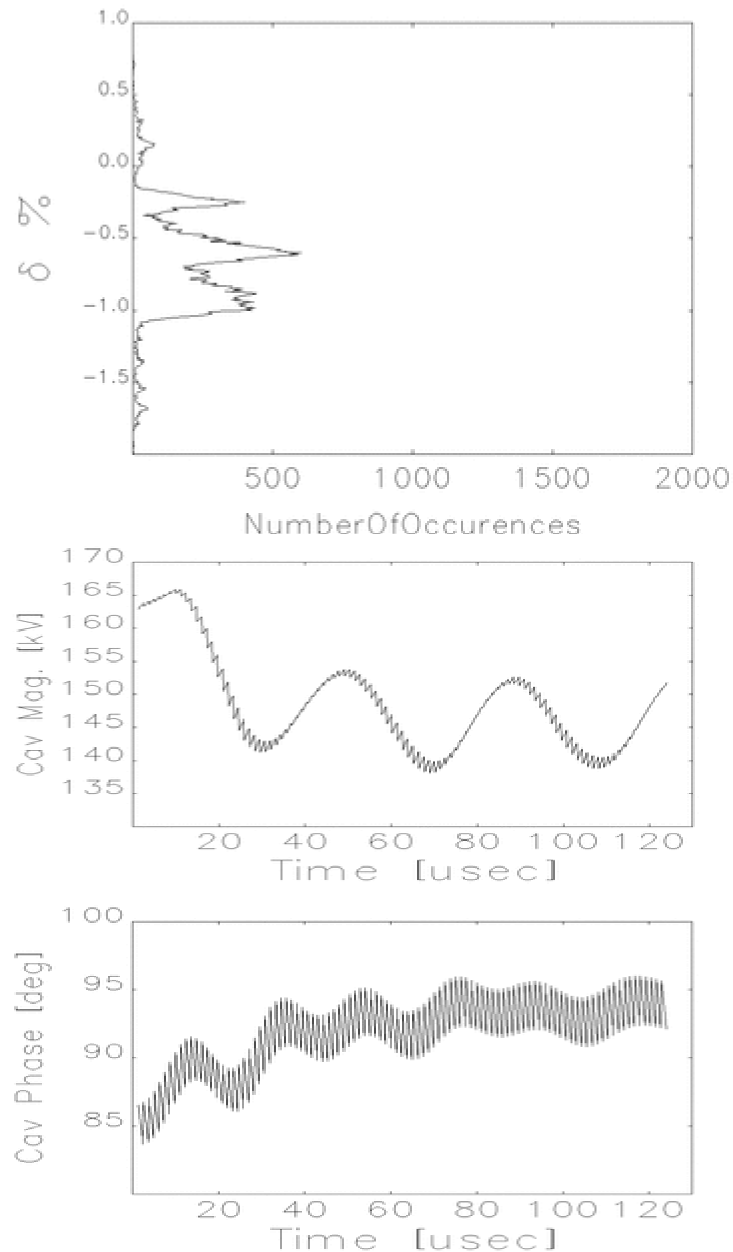
Available from the
Office of Technical Services
Department of Commerce
Washington 25, D. C.

February 27, 1964

Today: powerful tools `elegant/Pelegant` used at APS

Data Processing performed with SDDS toolkit





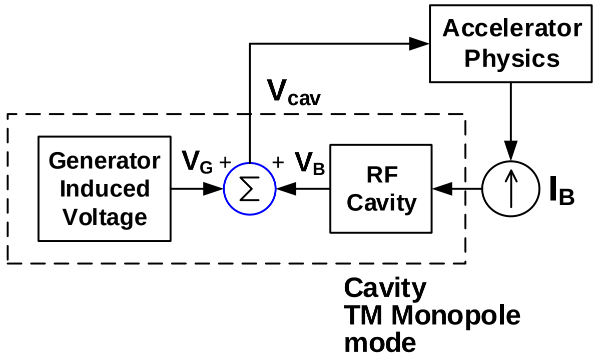
Note: Simulation of 8nC injection into Booster with RF Feed-forward

RF Control Model in `elegant`

RF control model in `elegant`

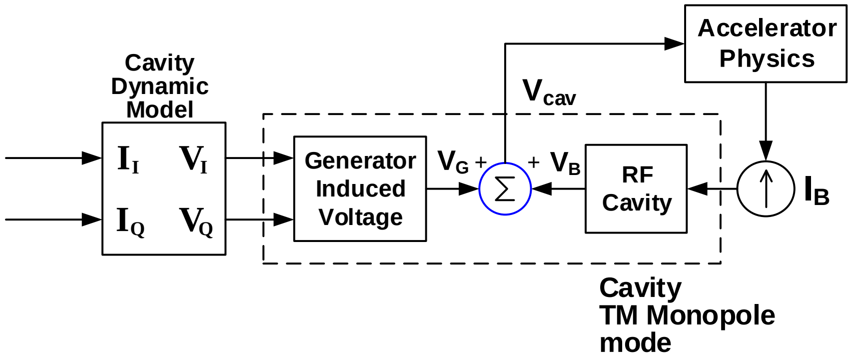
- Initial motivation was to understand double RF system for APS-U
  - Bunch lengthening cavity contributes growth of Robinson mode
  - Main RF contributes damping, but LLRF feedback reduces this
  - Main RF uses asymmetric amp/phase feedback vs. I/Q feedback, hence it’s difficult to analytically calculate stability of beam/cavity interaction
- Additionally
  - Due to the low synchrotron tune (and wide spread), how susceptible is the system to RF noise (e.g., 60 Hz line harmonics from the klystron power supplies)
  - How does that RF noise affect operation of the longitudinal feedback system (i.e., determine whether noise reduction is needed for the APS-U)
  - Study beam-loading compensation strategies for the injectors

RF control model in `elegant`



- RFMODE element simulates a generator and beam-driven TM monopole mode of a RF cavity with LLRF feedback
- electrons interact on a turn-by-turn basis with the RF cavity including beam-loading and generator induced voltage
- Beam interacts with entire machine lattice and comes back into cavity

RF control model in `elegant`

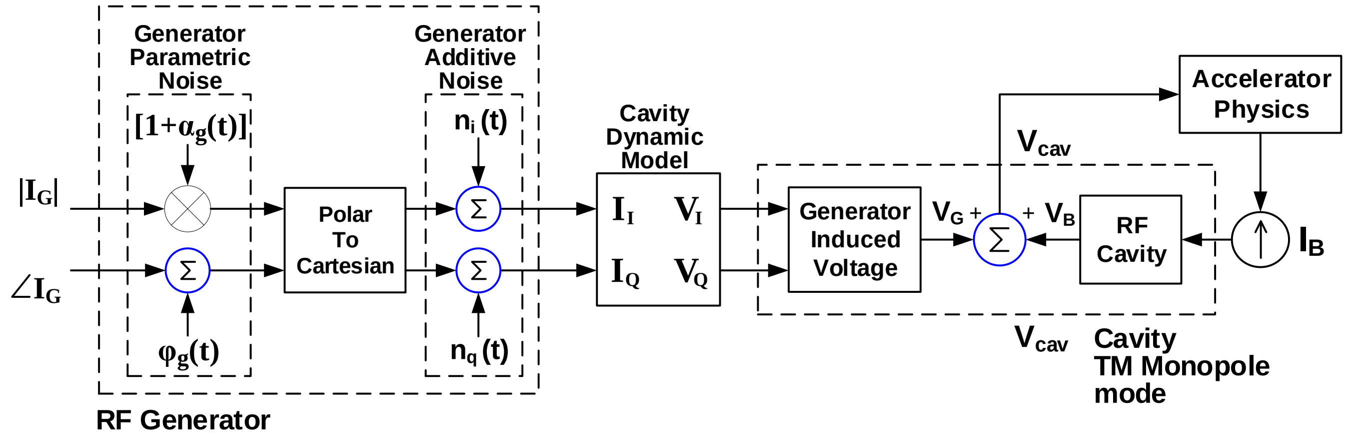


- Typical baseband model of the cavity dynamics simulates cavity response to generator current changes
- Sample rate of cavity model can be set to any number of rf buckets

Side Note:

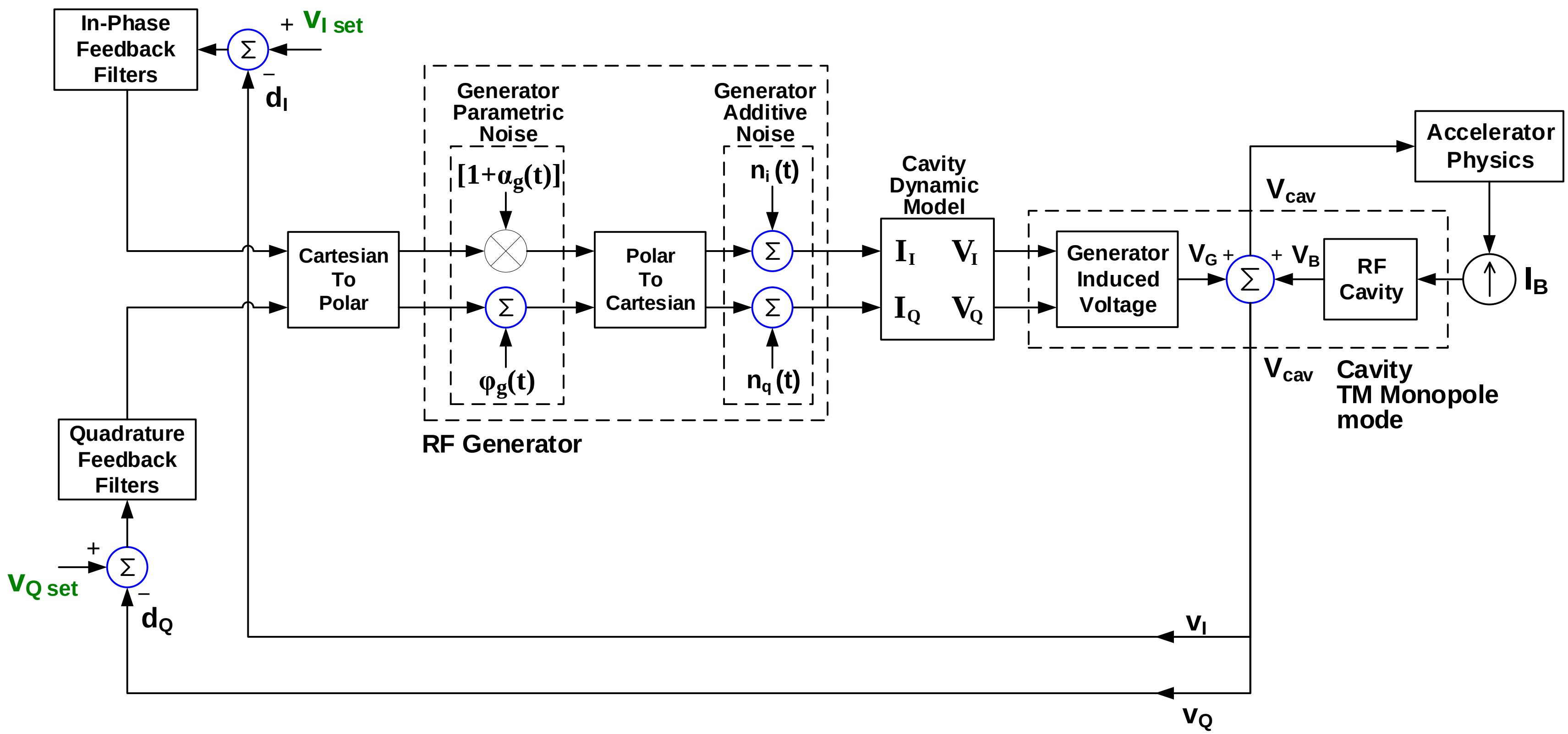
Charles Proteus Steinmetz
(1865 – 1923)
Introduced Phasor Notation

RF control model in `elegant`



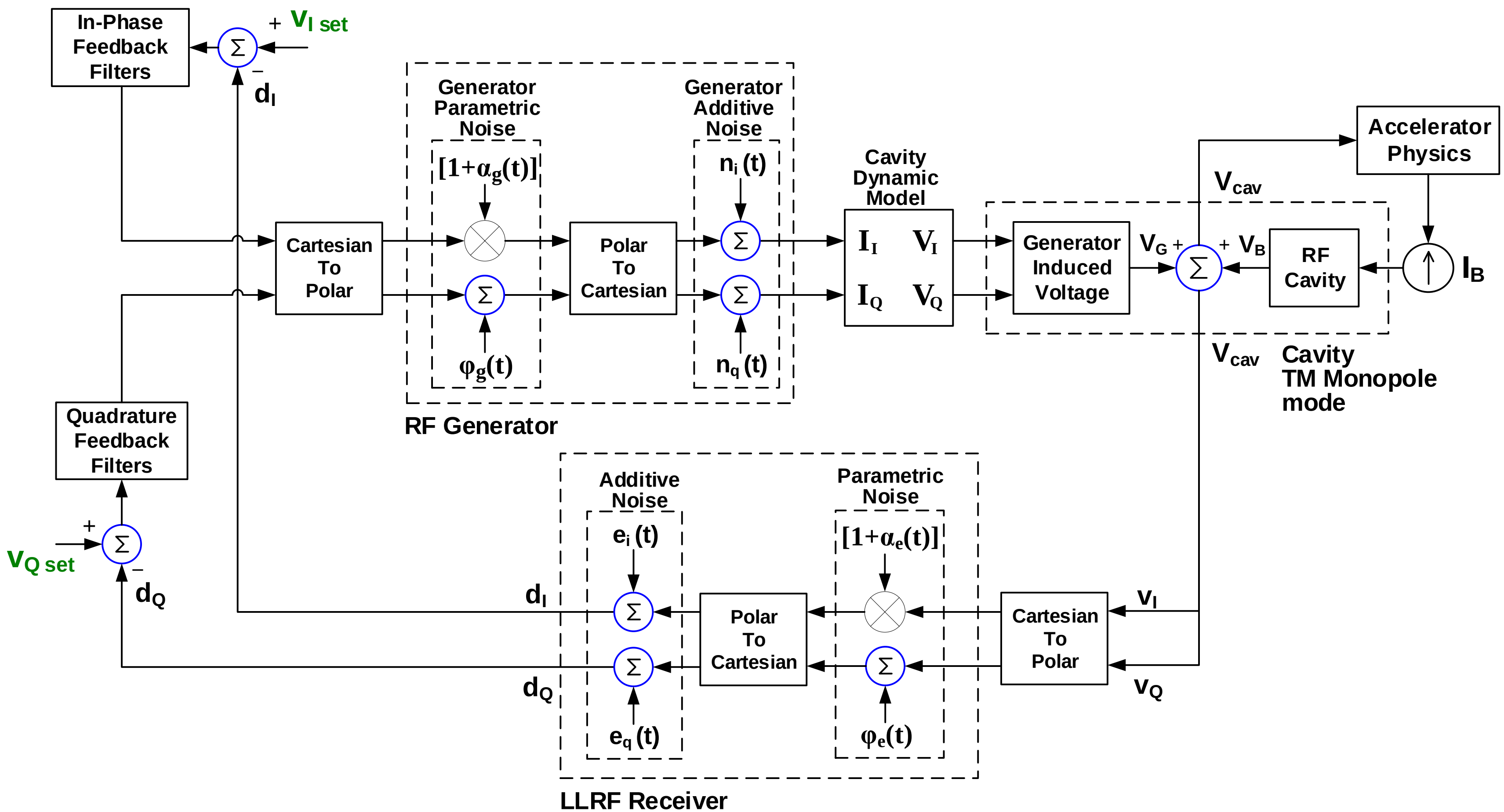
- Generator parametric and additive noise can be input as time-domain data files.
- This input is generic and can be used to inject feed-forward signals

RF control model in `elegant`



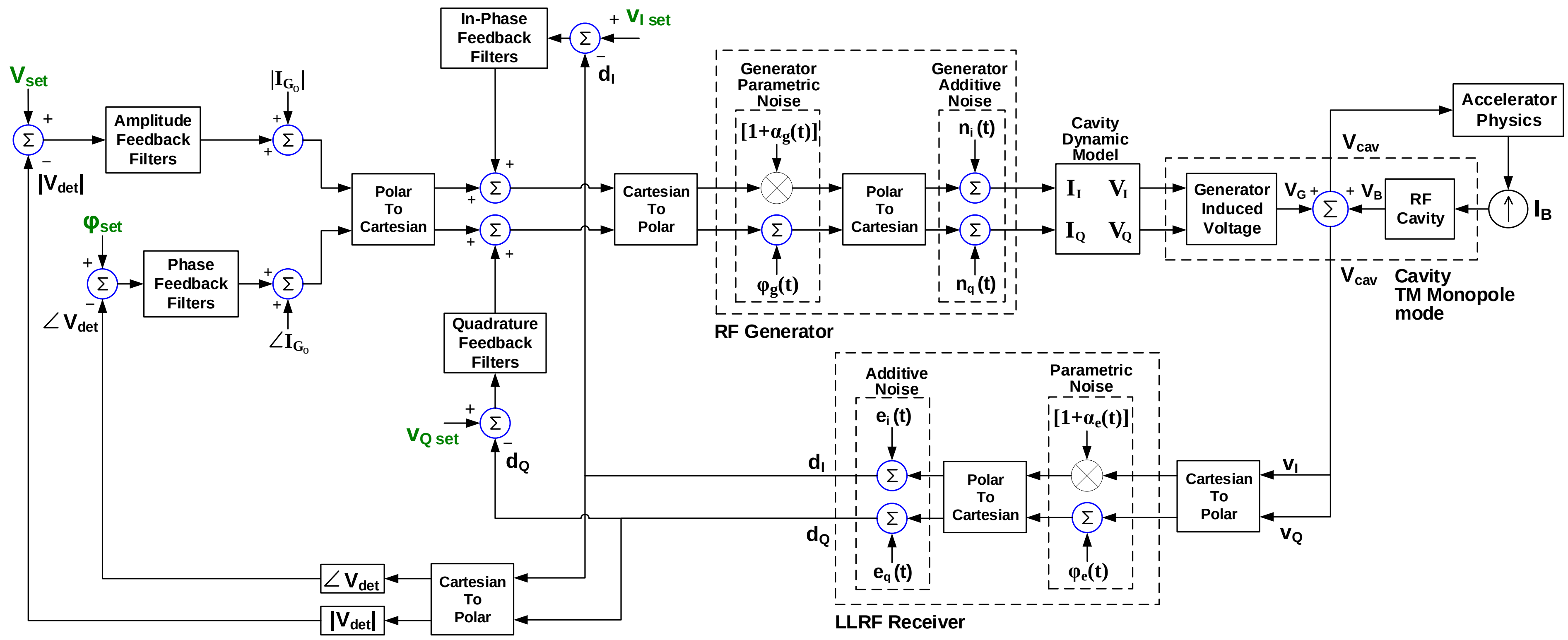
- I/Q feedback filters are input as coefficients of a digital filter

RF control model in `elegant`



- Receiver parametric and additive noise can also be input as time-domain data files.

RF control model in `elegant`

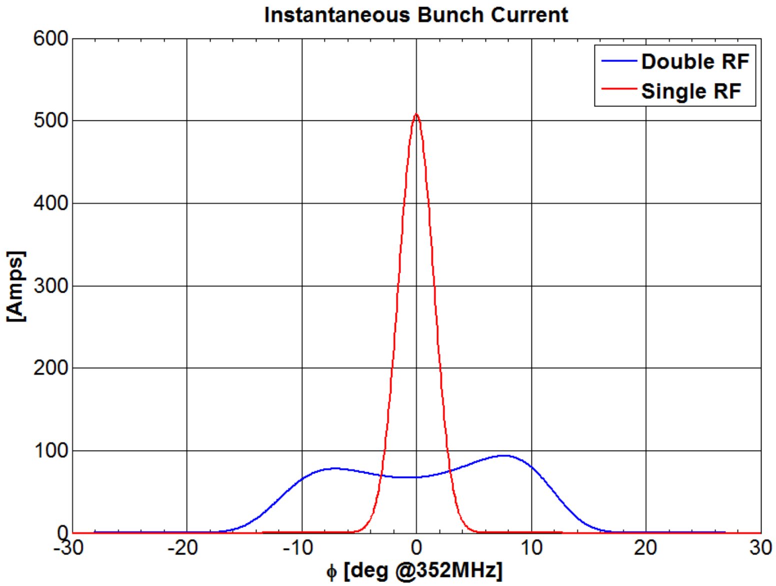


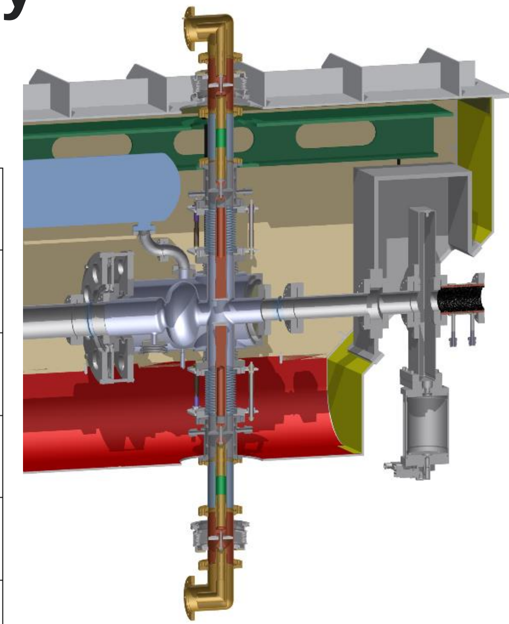
- In lieu of I/Q feedback, amplitude and phase feedback can be used.
- Amp / Phase feedback filters are also input as coefficients of digital filter

Storage Ring System

Storage Ring with Bunch-Lengthening Cavity

Workflow: Perform first order calculations of RF system parameters





Self-Consistent Solution of beam-current and beam-induced voltage

RF parameters for:

Main 352MHz system (normal conducting)

and

4th Harmonic 1.4GHz (passive superconducting)

Passive Mode Results

Harmonic RF Voltage	0.939	MV_{pk}
Harmonic RF Phase	-10.51	deg
Synchronous Phase	141.16	deg
Beam Centroid	0.5373	deg
Bunch Length	59.931	$psec_{rms}$
Bunch Length FWHM	187.23	psec
Momentum Acceptance	3.9703	%
Main RF Form Factor	0.9912	Ib / (2*Idc)
Main RF Beam I Mag.	0.3964	Amp
Main RF Beam I Phase	-0.5398	deg
Harmonic Form Factor	0.8656	Ib / (2*Idc)
Harmonic Beam I Mag.	0.3462	Amp
Harmonic Beam I Phase	-2.3163	deg

Main RF

Optimal Qext	11.39	$x\ 10^3$	
Optimal Δf	-15.35	kHz	
Actual Qext	11.25	$x\ 10^3$	
Actual Δf	-15.27	kHz	ϕ_z = -38.34 deg
P_{beam}	45.26	kW	
P_{cav}	14.09	kW	
P_{gen}	59.35	kW	
P_{rev}	0.00	kW	

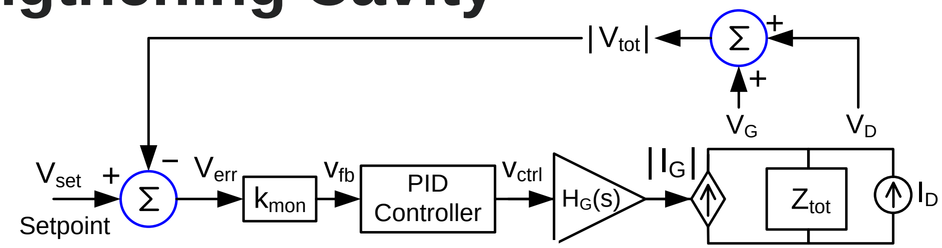
Harmonic RF

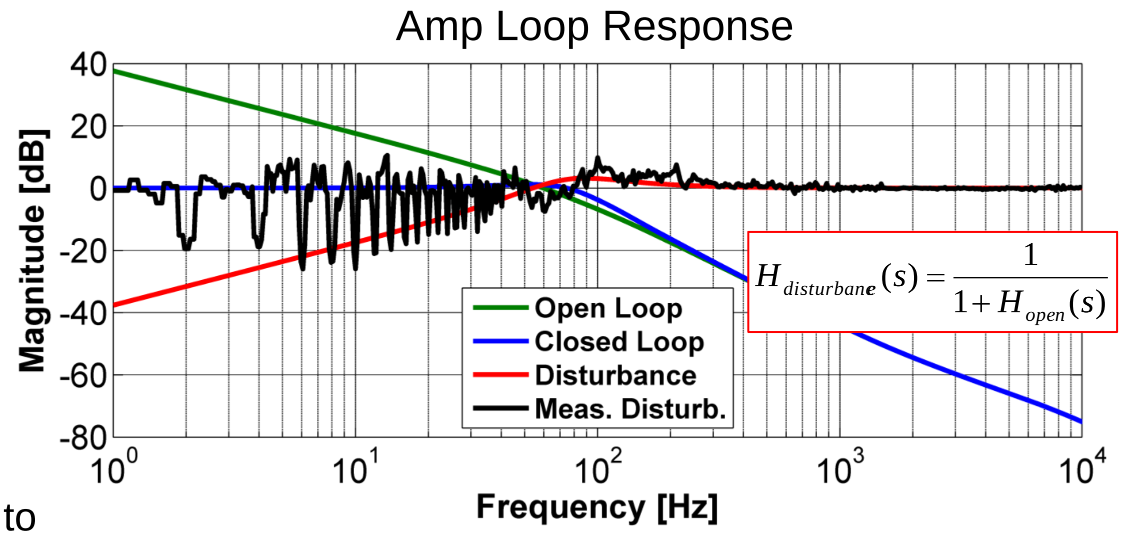
Qext	3.50	$x\ 10^5$	
Δf	14.00	kHz	ϕ_z = 81.81 deg
P_{beam}	-23.16	kW	
P_{cav}	38.55	W	
P_{gen}	0.00	kW	
P_{rev}	23.13	kW	

Storage Ring with Bunch-Lengthening Cavity

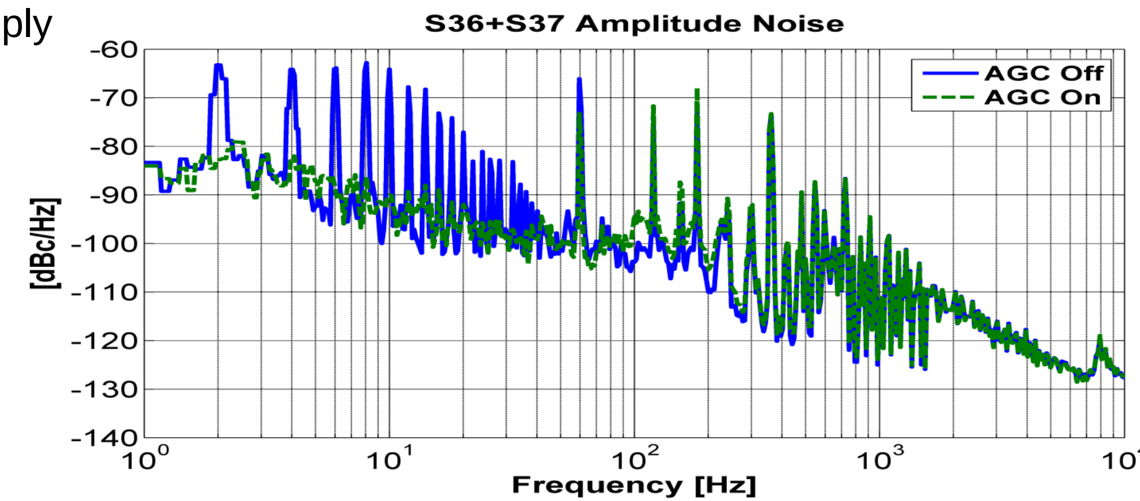
Workflow:

- **Model RF Feedback** of main system
- Test in Simulink





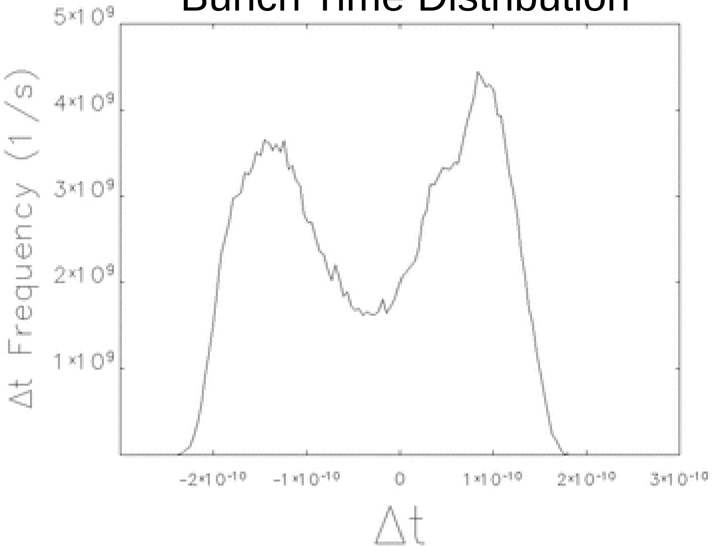
Note: low amp bandwidth is due to klystron mod-anode power supply



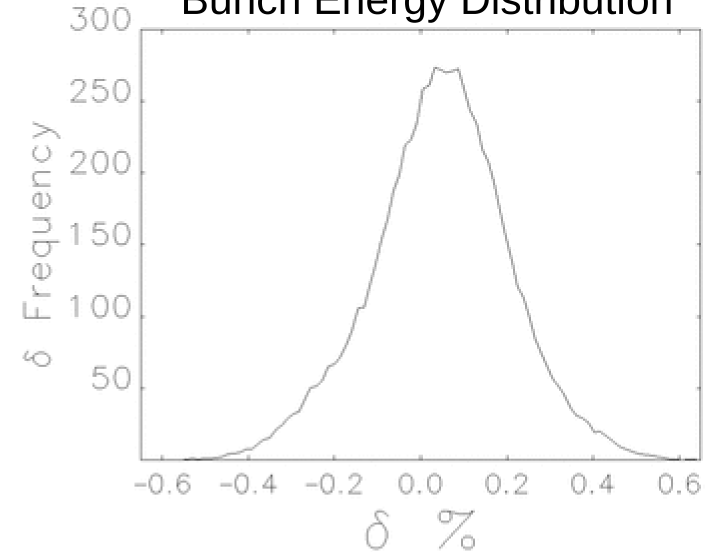
Storage Ring with Bunch-Lengthening Cavity

Workflow: Measure RF noise and inject into `elegant` to see beam response

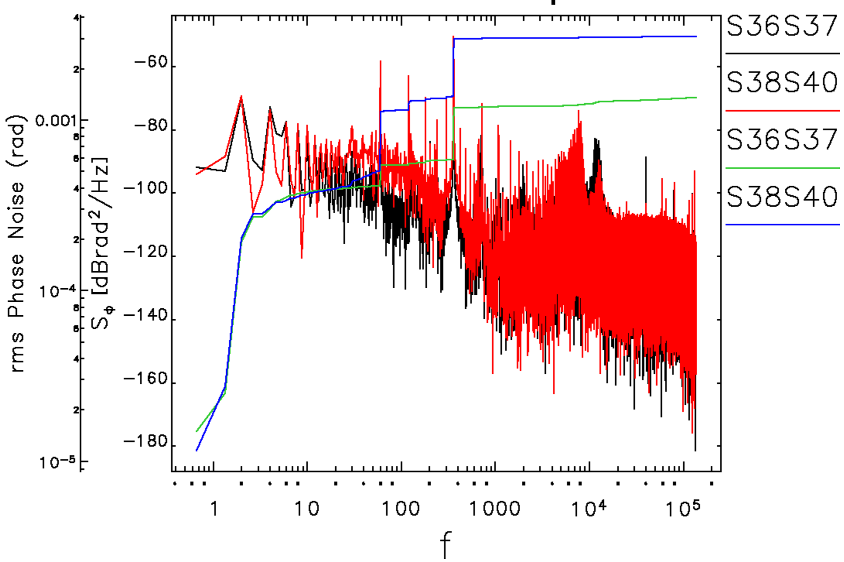
Bunch Time Distribution



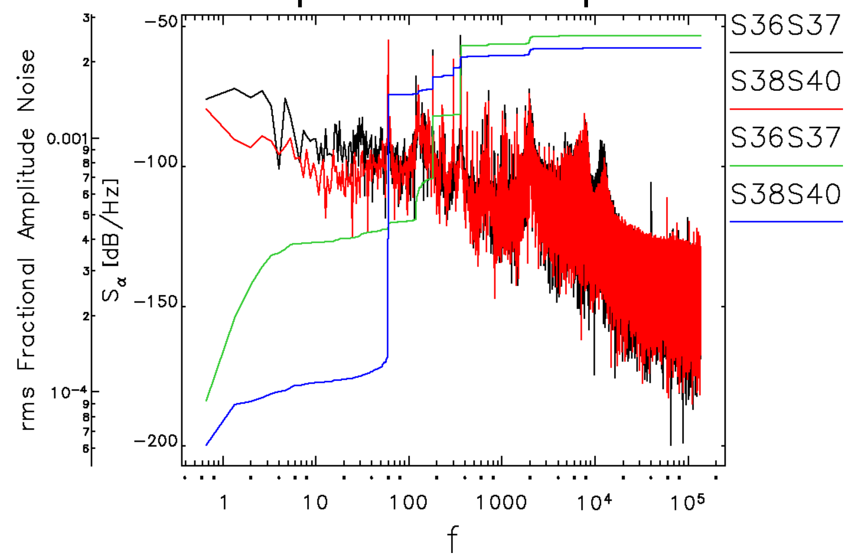
Bunch Energy Distribution



RF Phase Noise Spectrum



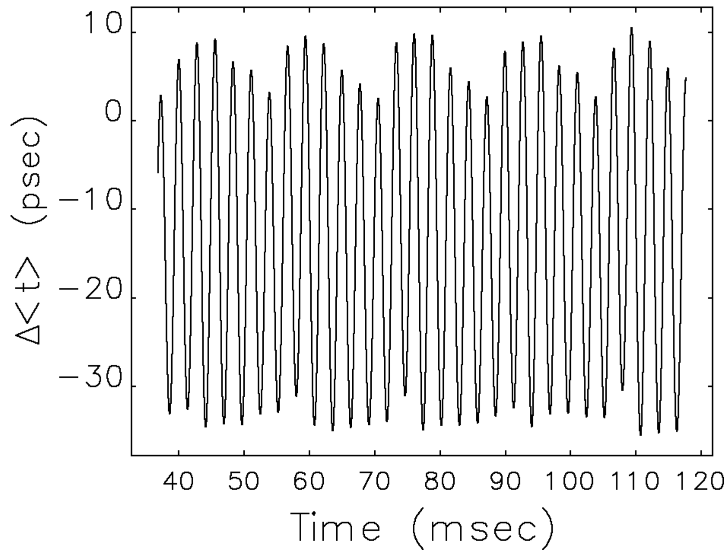
RF Amplitude Noise Spectrum



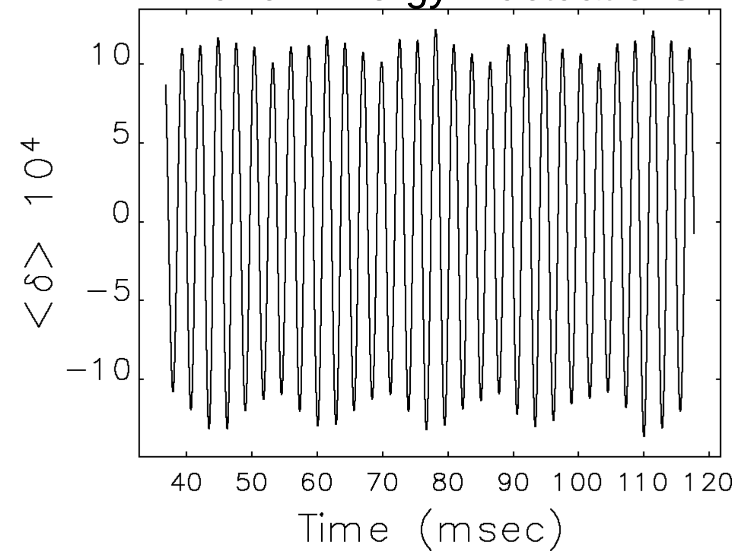
Storage Ring with Bunch-Lengthening Cavity

Workflow: Measure RF noise and inject into `elegant` to see beam response

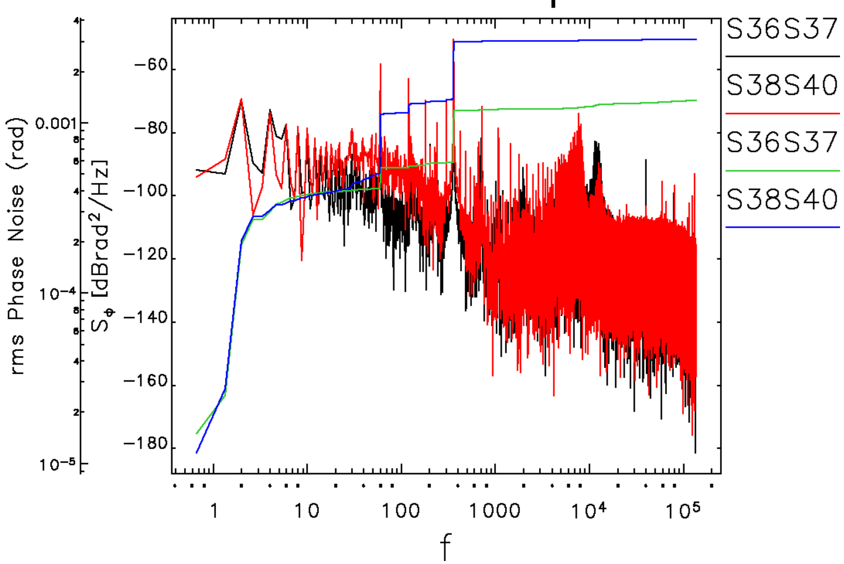
Bunch Time Fluctuations



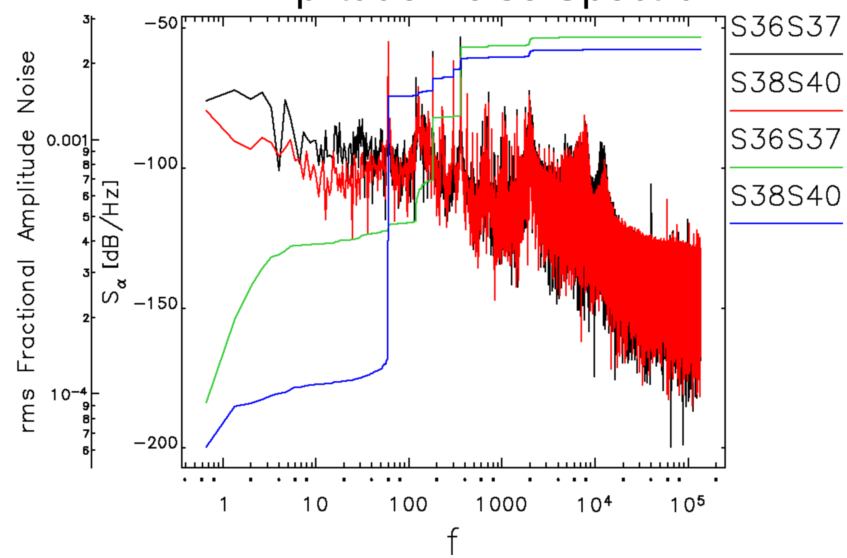
Bunch Energy Fluctuations



RF Phase Noise Spectrum



RF Amplitude Noise Spectrum

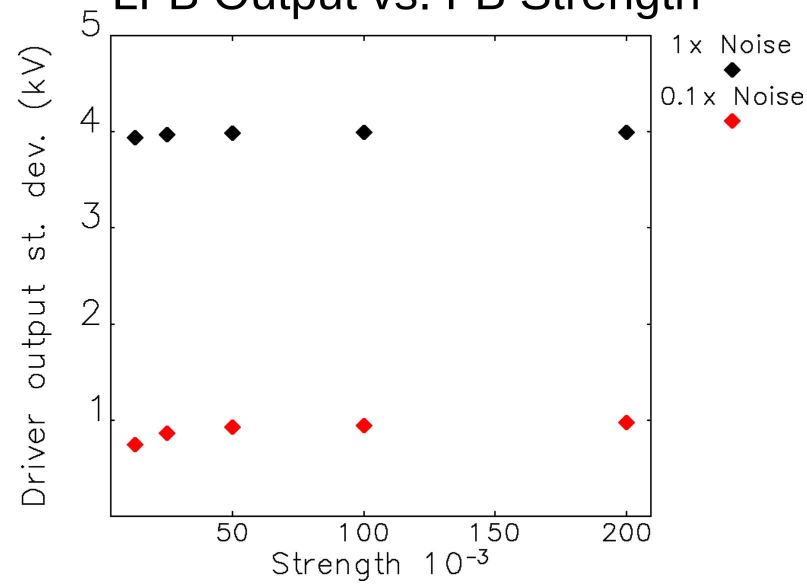


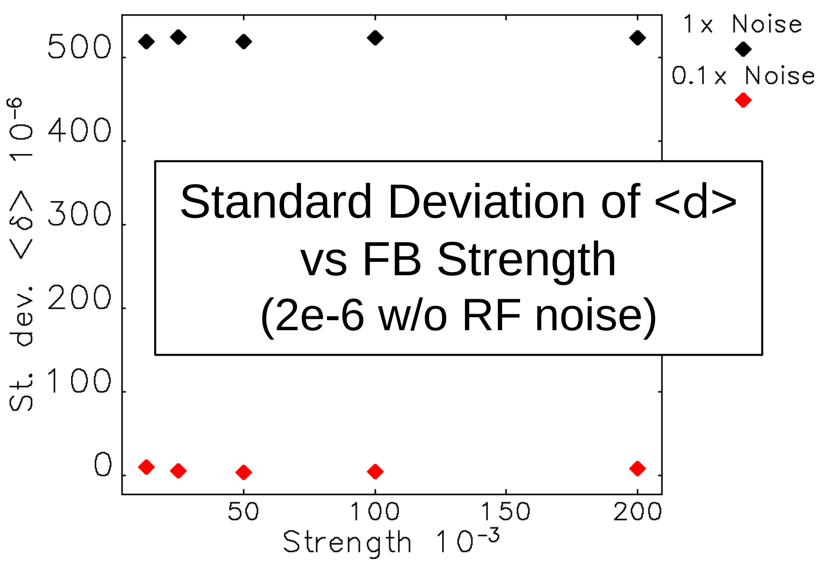
Storage Ring with Bunch-Lengthening Cavity

Workflow:

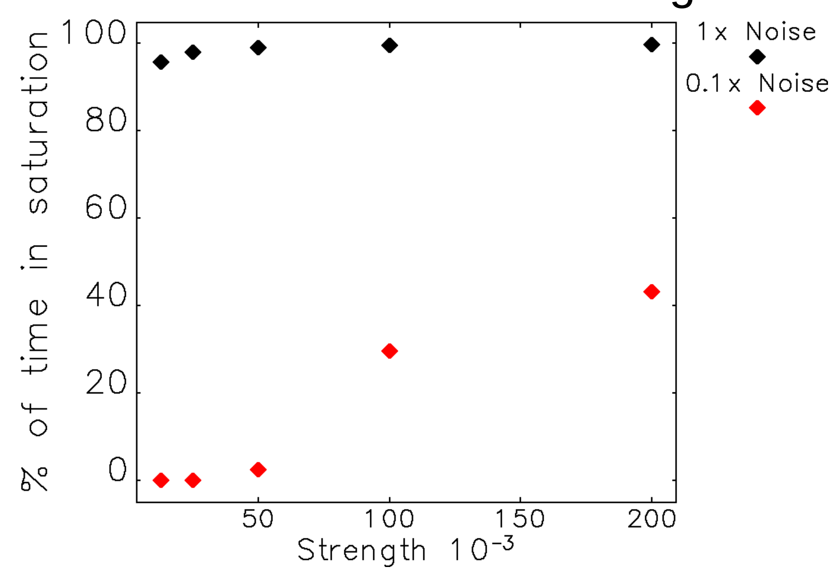
- Simulate effects of RF noise on the **longitudinal feedback system** (LFB).
- Simulated existing noise and 0.1x noise

LFB Output vs. FB Strength





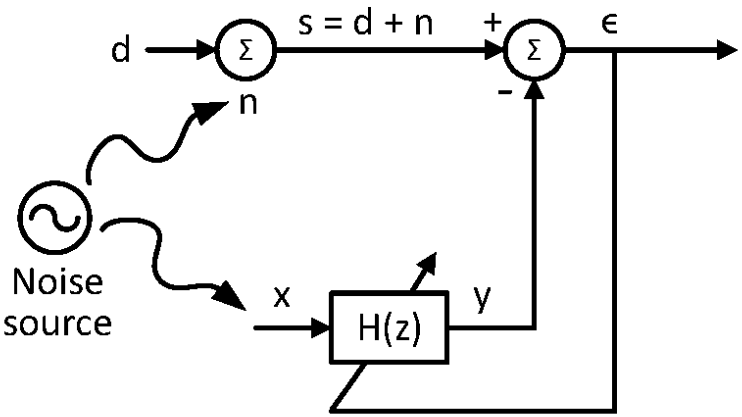
LFB Saturation vs. FB Strength

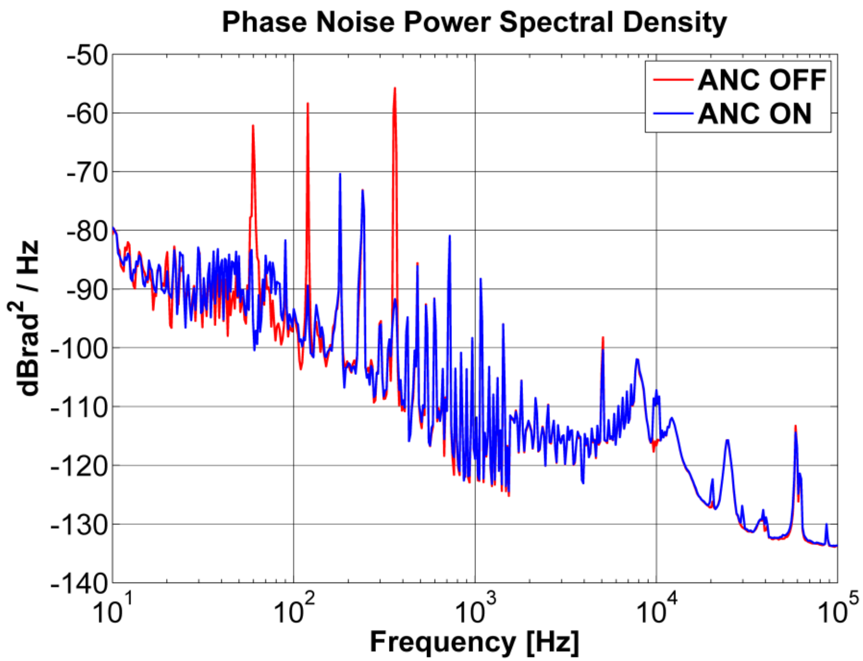


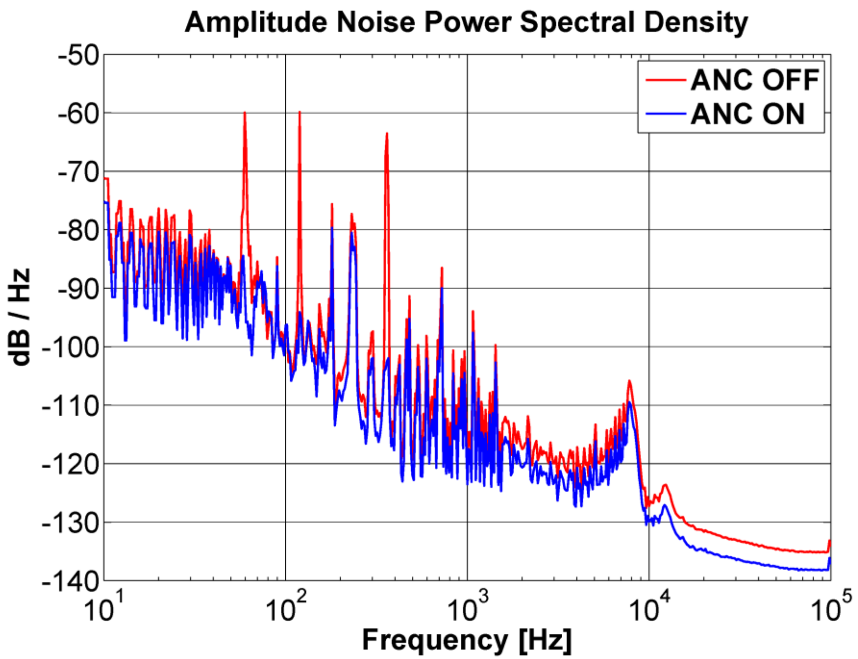
Storage Ring with Bunch-Lengthening Cavity

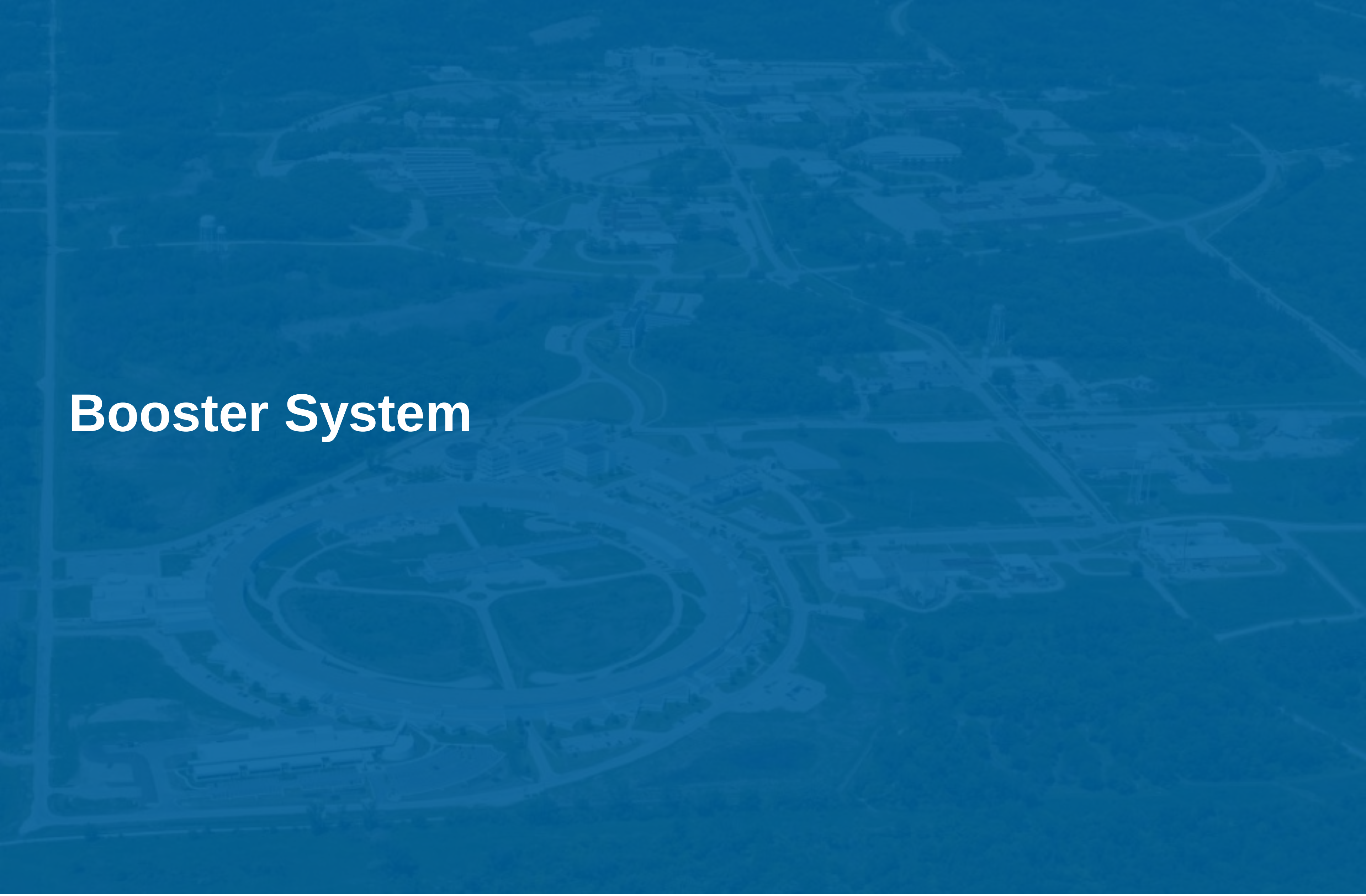
Noise reduction option: **adaptive notch filter**

- Achieved >30dB suppression at select lines
- Can expand to additional lines as needed



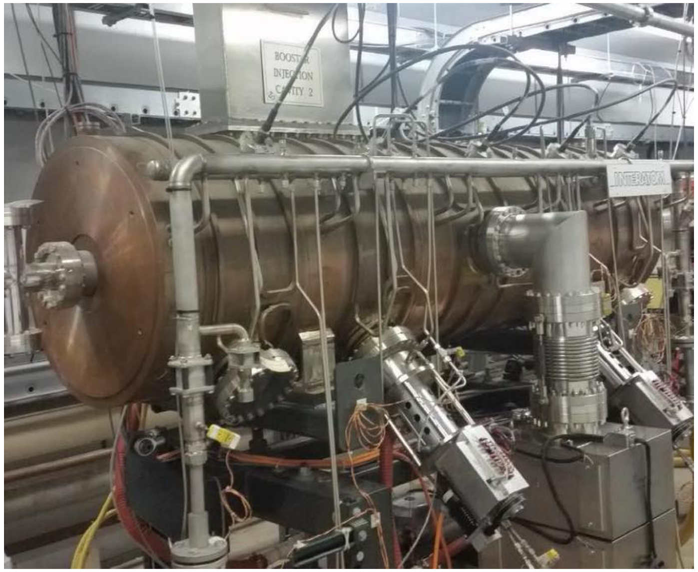






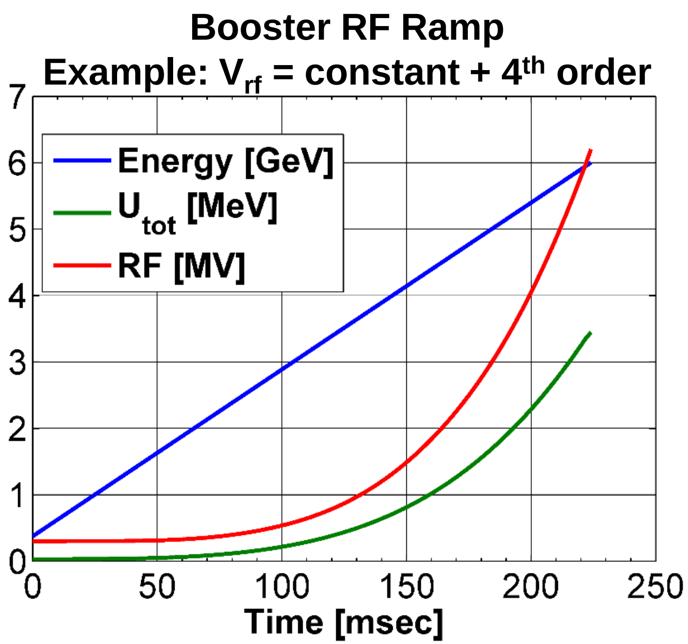
Booster System

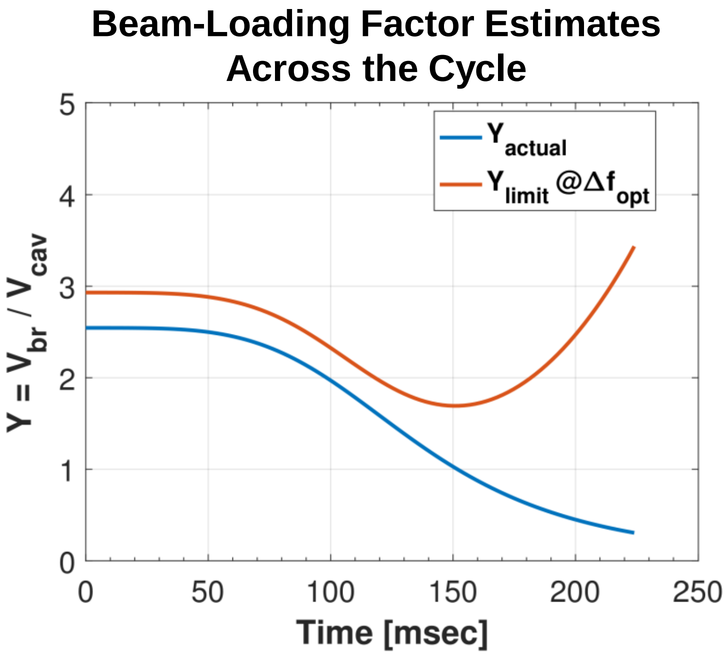
Booster: 352MHz System (4 cavities)



Large beam-loading and injection transients require exploration of beam-loading compensation strategies

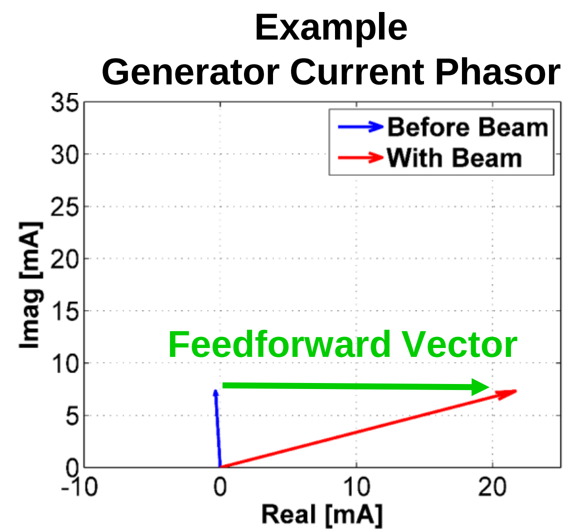
- Total $(R/Q)_a$ ~5600 W, Q_L ~20e3 => Ra = 112 MW !!
- Beam induced voltage at resonance, ~1.37 MV @20nC
- Injection voltage ~650 kV
- T_{rev} ~1.23 msec,
- Cavity time-constant: t_e ~15 to 18 msec
  - 90% fill in ~28 to 34 turns
  - 99.9% fill in ~84 to 100 turns

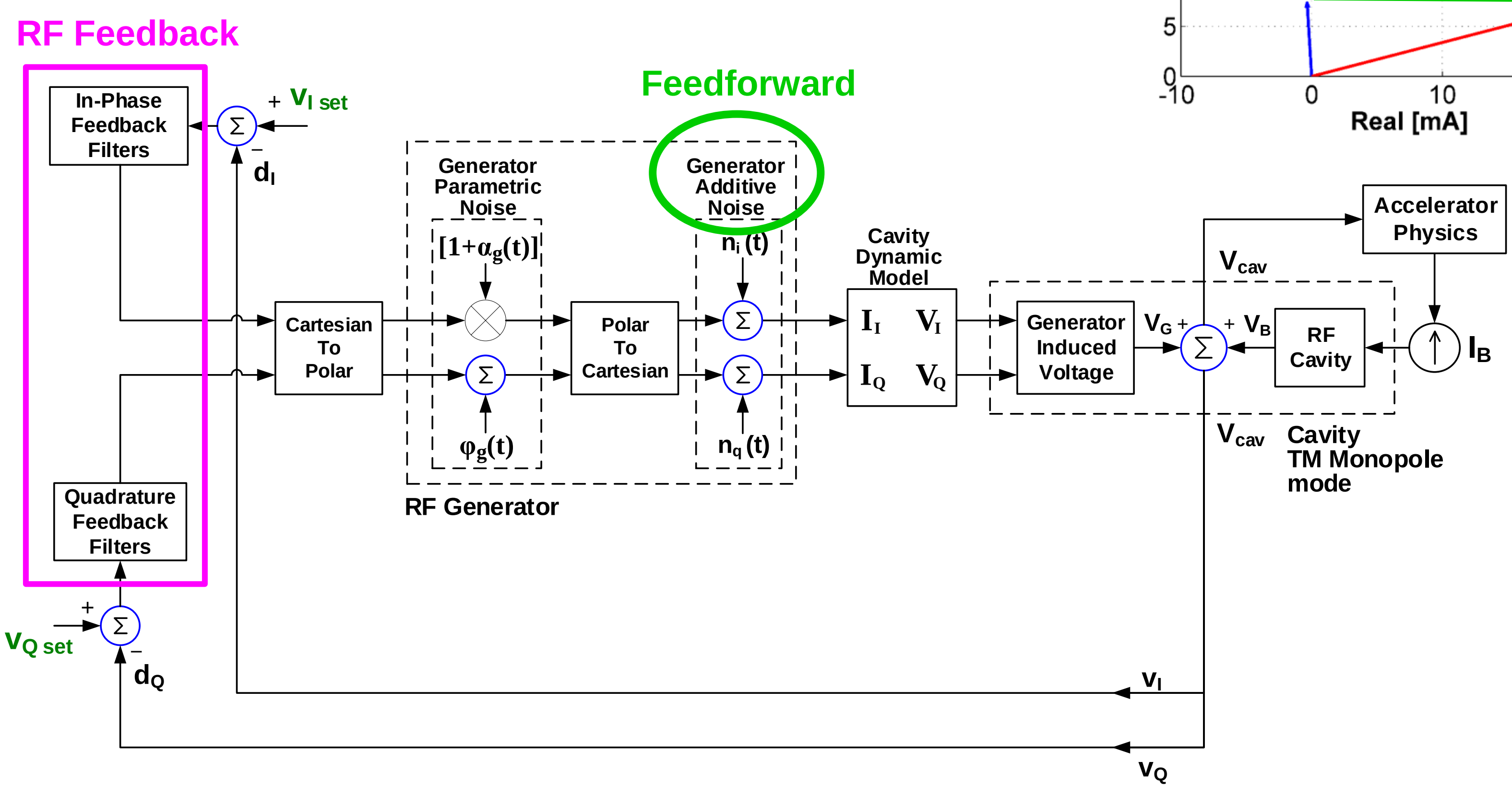




Booster: Beam-Loading Compensation Simulations

- use **Generator Additive Noise** to apply **feed-forward**
- use RF Feedback
- use cavity detuning
- explore alternative options

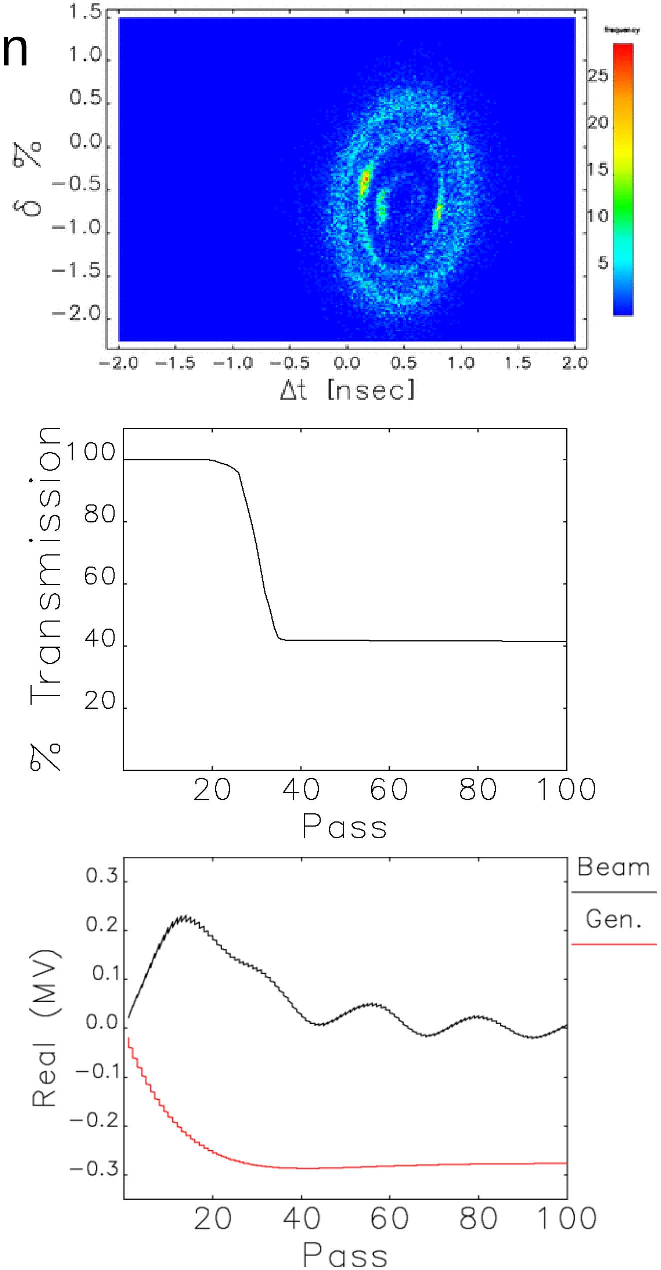




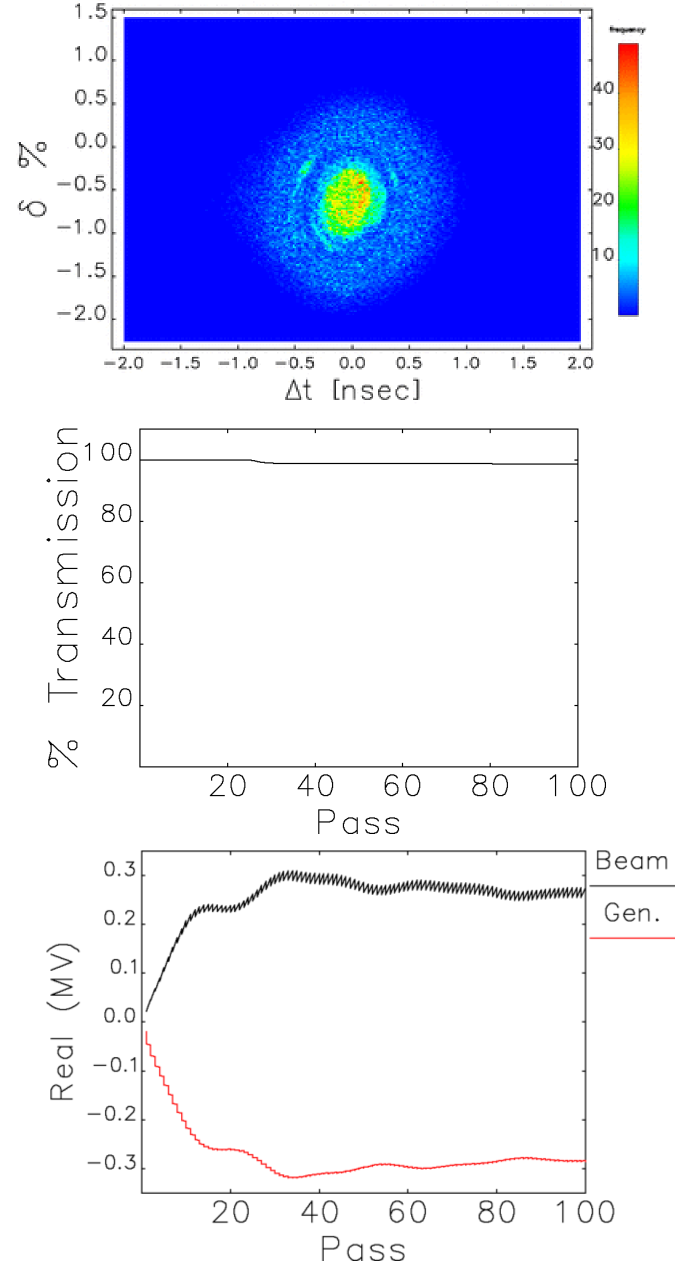
Booster

Simulation
@ 20nC

Feed-Forward ONLY

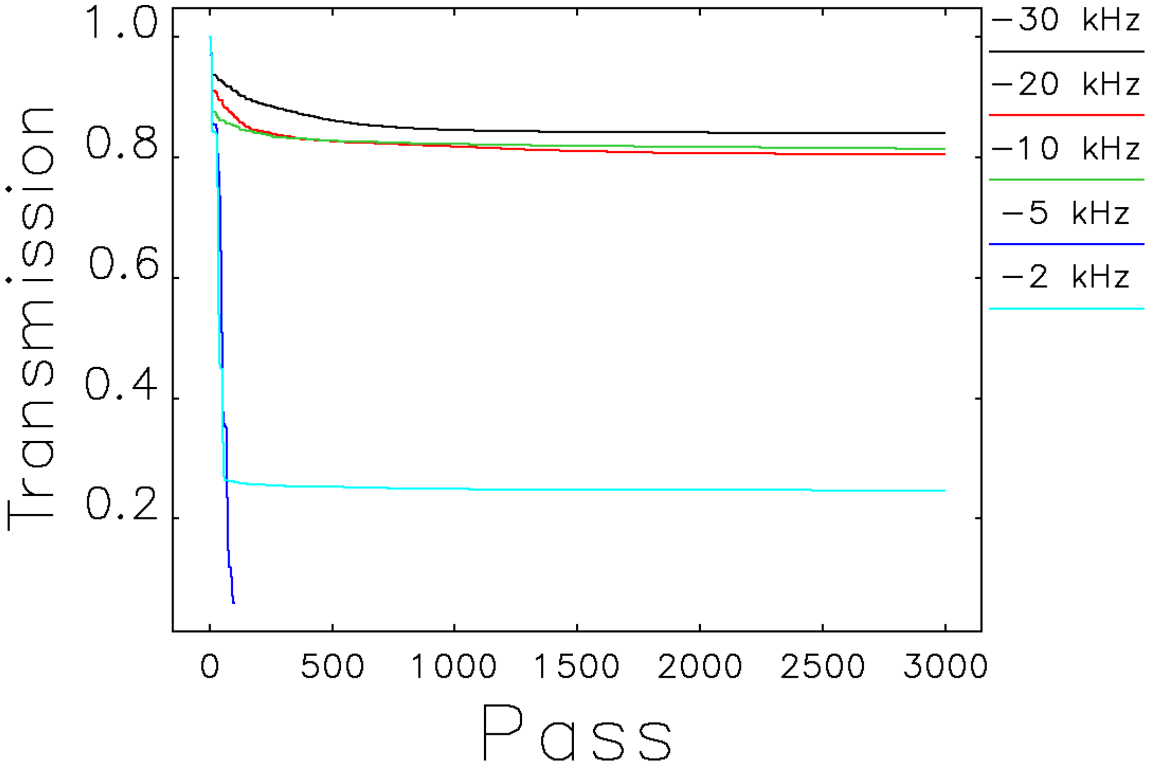


Feed-Forward + Feedback



Booster: Cavity Detuning Option

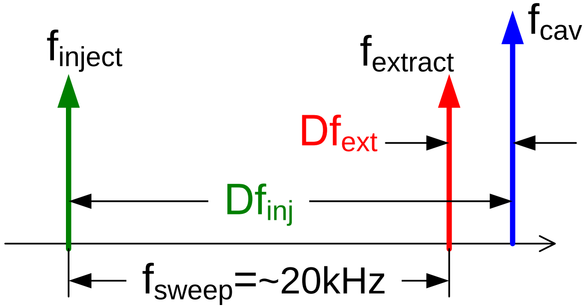
- Simply using large cavity detuning at injection time is an option to reduce the beam induced voltage.
- However, this would require adding dynamic tuners to the cavities since the detuning must be small at extraction time to reduce generator power.



Simulation @ 20nC, no Feed-Forward nor Feedback

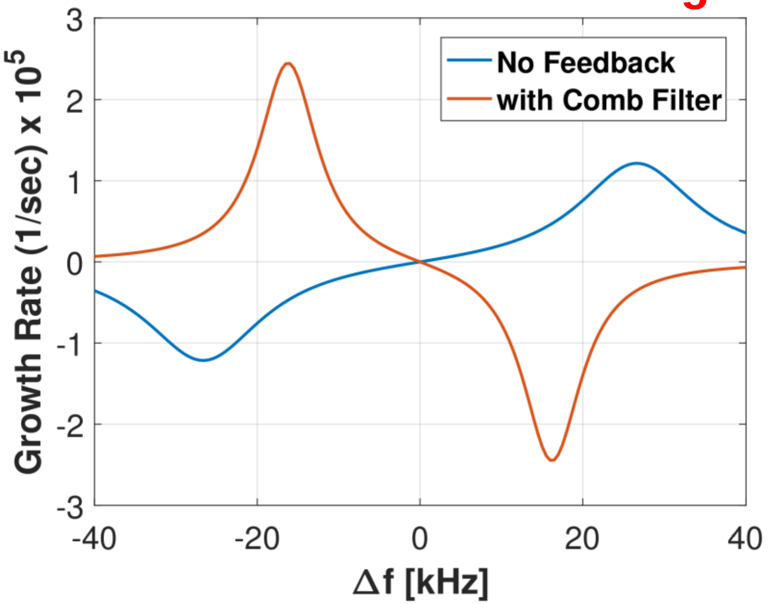
Booster: Momentum Sweep and alternative feedback

- A momentum sweep is being explored to give good Booster injection efficiency while providing low emittance to the Storage Ring
- This implies a positive drive frequency sweep

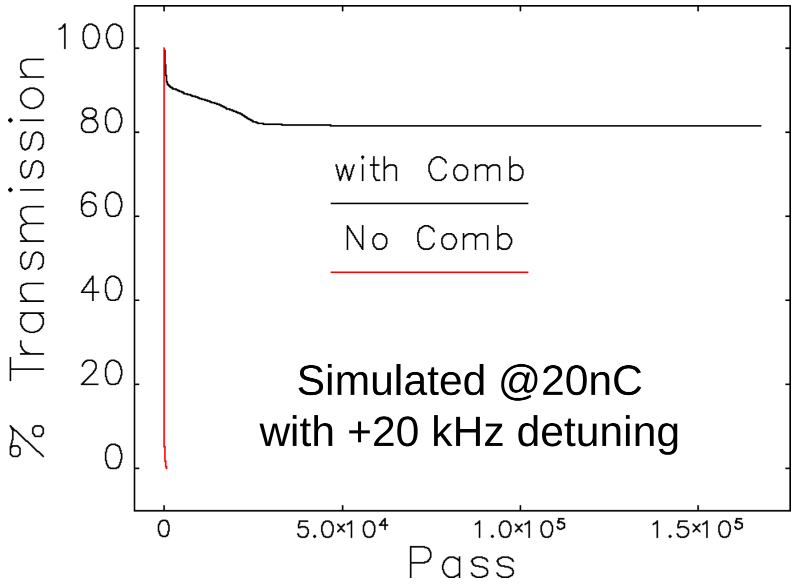


- One could take advantage of the resultant dynamic detuning, but we would be on the wrong side of the conventional Robinson Stability criterion.
- **A comb-filter can restore stability for positive detuning**.

Growth Rate vs. Detuning



Injection Efficiency



Conclusions

- Inclusion of RF Feedback/Feedforward in `elegant` has opened the door to sophisticated simulations of the RF ***system*** **/ beam** interaction
  - It is guiding the design of the APS-U RF systems
  - Can analyze interaction with other systems (e.g., longitudinal feedback)
  - Equipped to simulate RF system noise impact

- Interaction with the physicists early in the design process is strongly encouraged
  - System design decisions obviously have a huge impact on hardware (e.g., Booster momentum-sweep and dynamic tuners)

- Simulation efforts will continue to guide RF system and LLRF control design

References

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- SDDS Toolkit: M. Borland, PAC95, 2184; R. Soliday, PAC03, 3473; M. Borland et. al., PAC03, 3461
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- Radiofrequency Acceleration II: K. Robinson, CEA-11
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- Stability Analysis of an Adaptive Notch Filter for RF Noise Suppression: T. Vannoy, T. Berenc, Lee-Teng Internship 2015
- MicroTCA Hardware for AM/PM Noise Suppression: E. Wu, T. Berenc, Lee-Teng Internship 2016