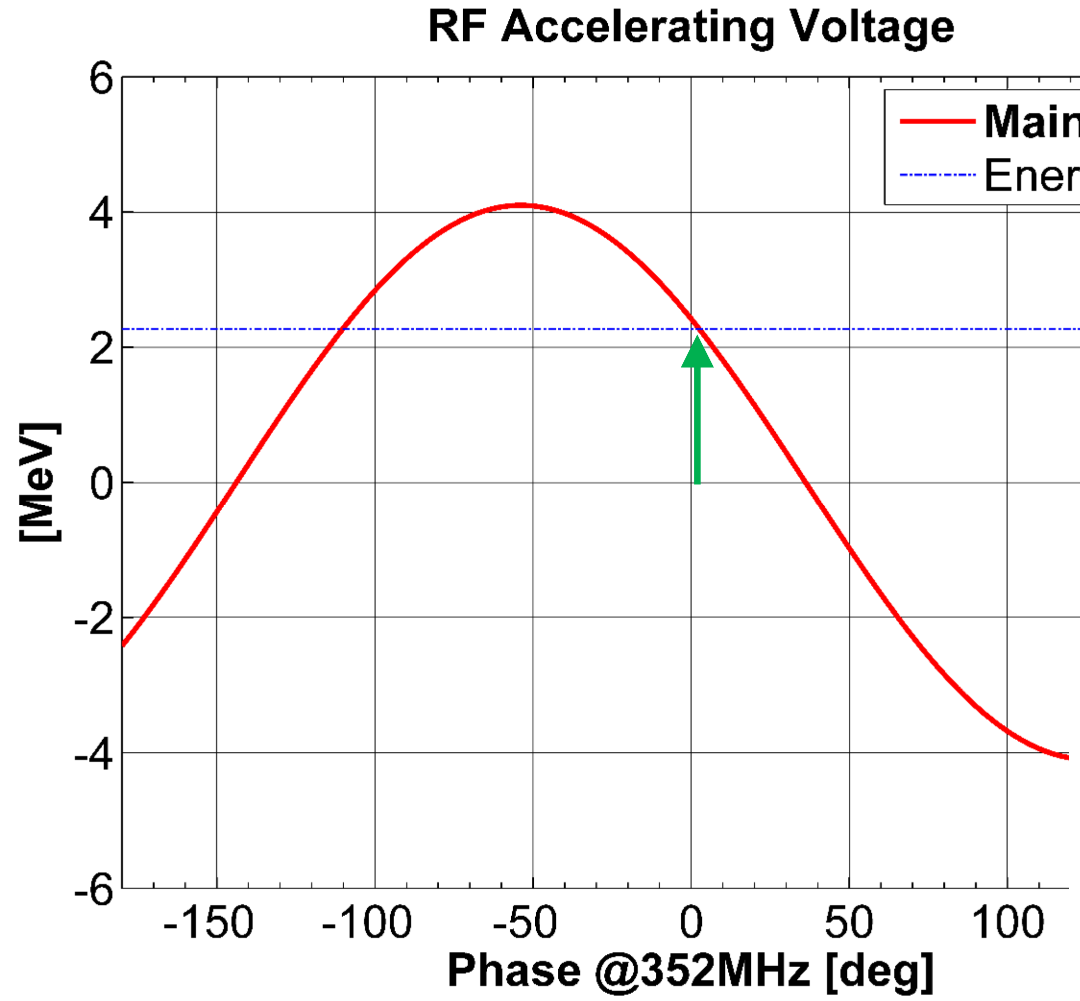
Modeling RF Feedback for APS-U Bunch-Lengthening Studies

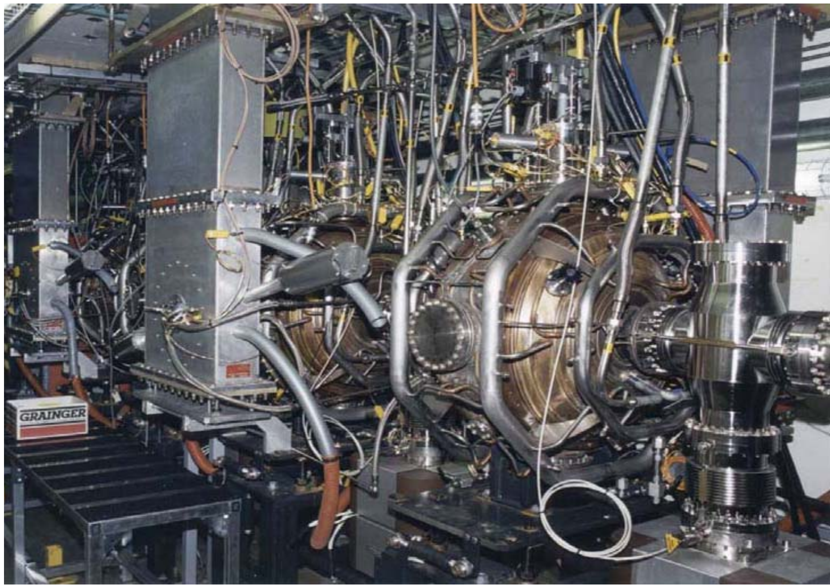
T. Berenc, M. Borland

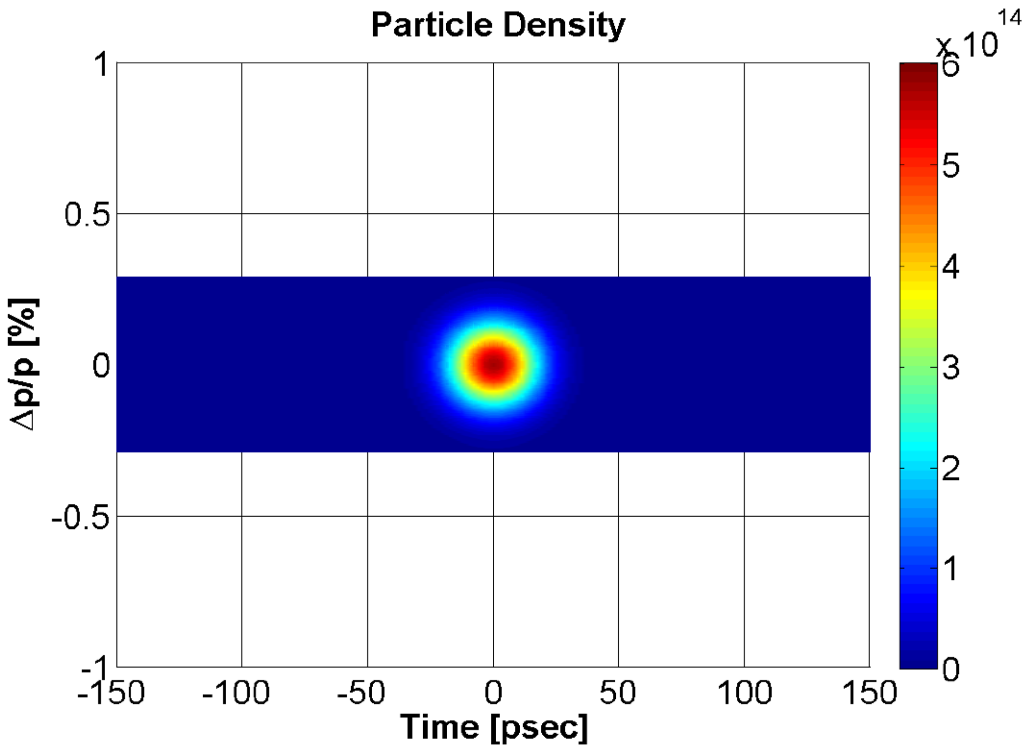
ASD Seminar 5/27/2014

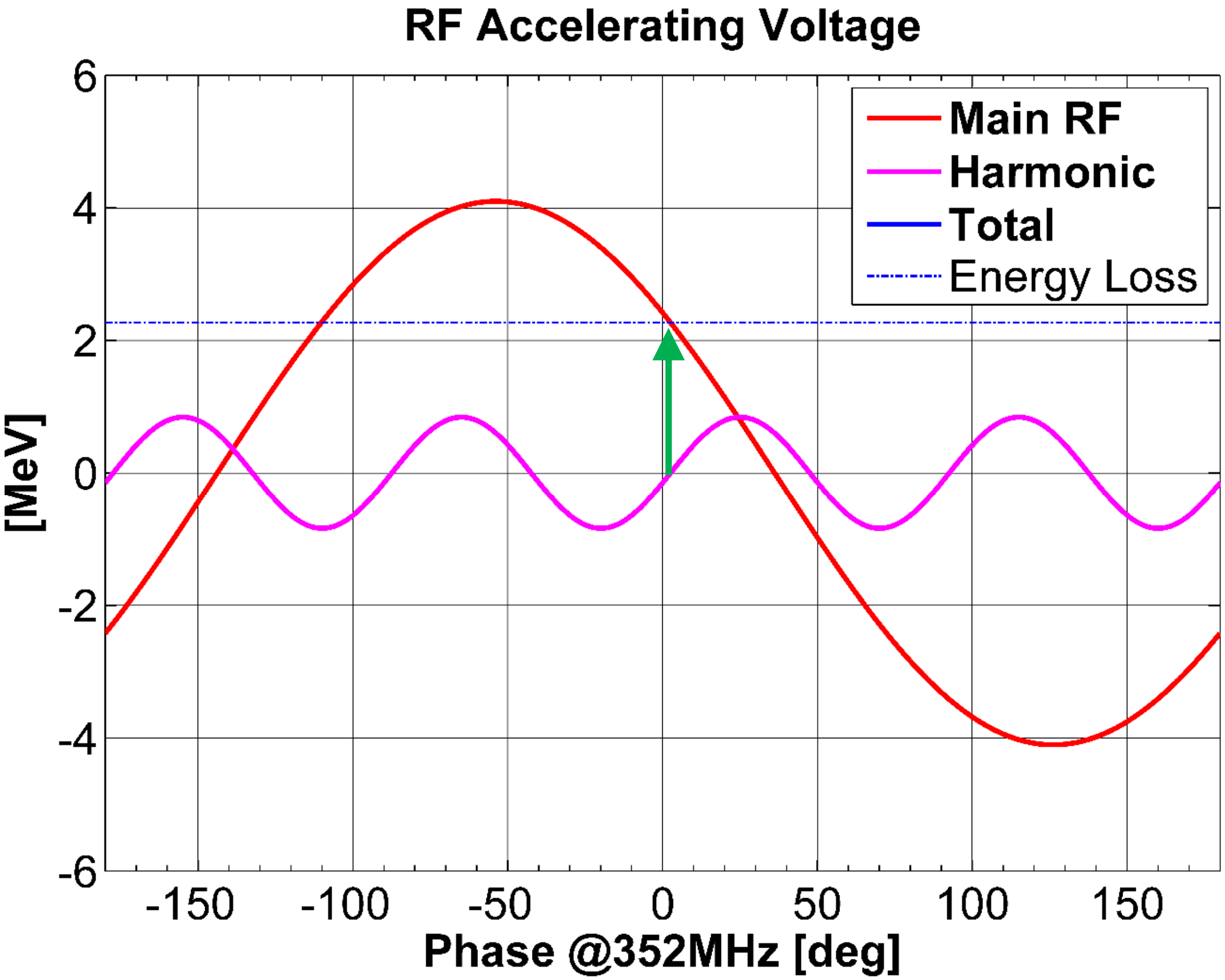
Outline

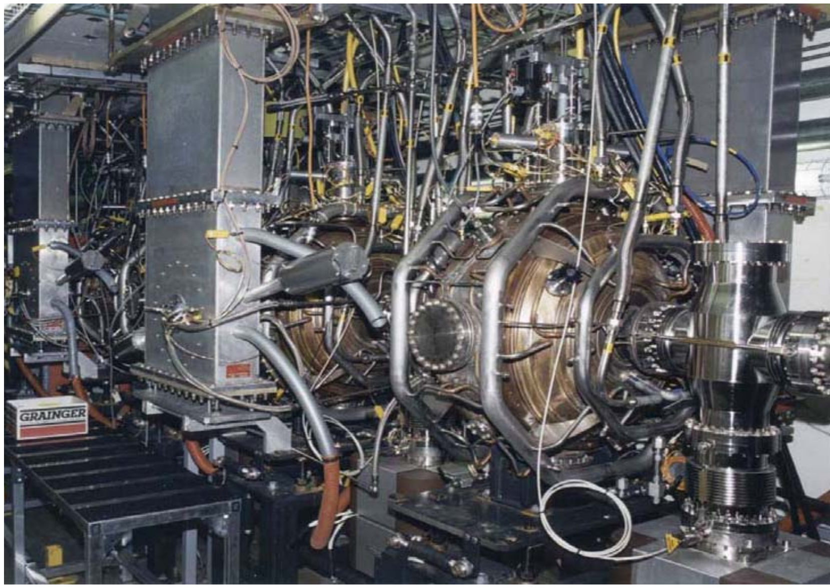
- motivation for modeling RF feedback in particle tracking studies
  - **Double RF System overview**
  - **review of Dipole Mode Instability (Robinson)**
- **RF Feedback Model**

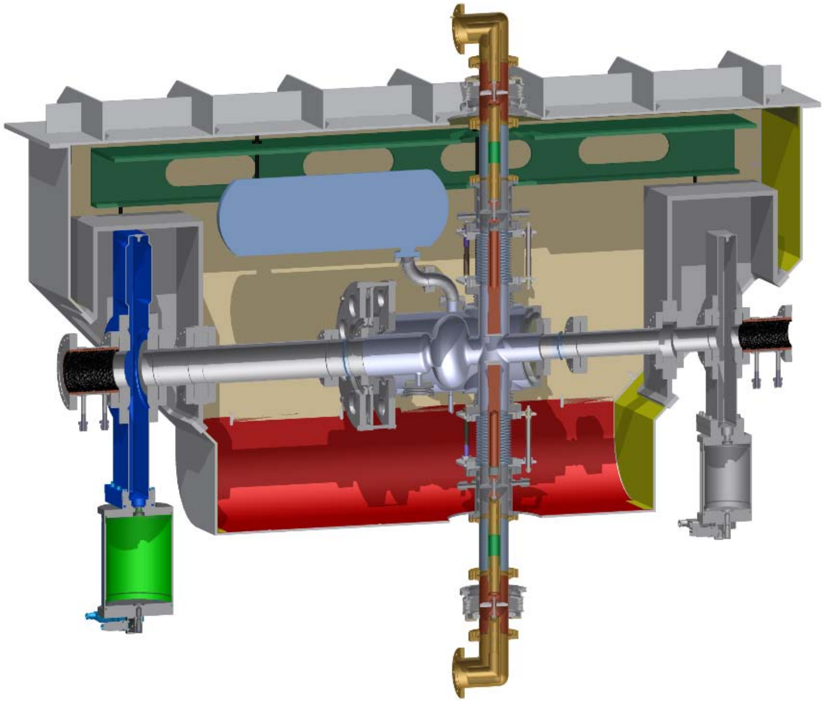

RF Accelerating Voltage
Main RF
Energy Loss
[MeV]
6
4
2
0
-2
-4
-6
-150
-100
-50
0
50
100
Phase @352MHz [deg]

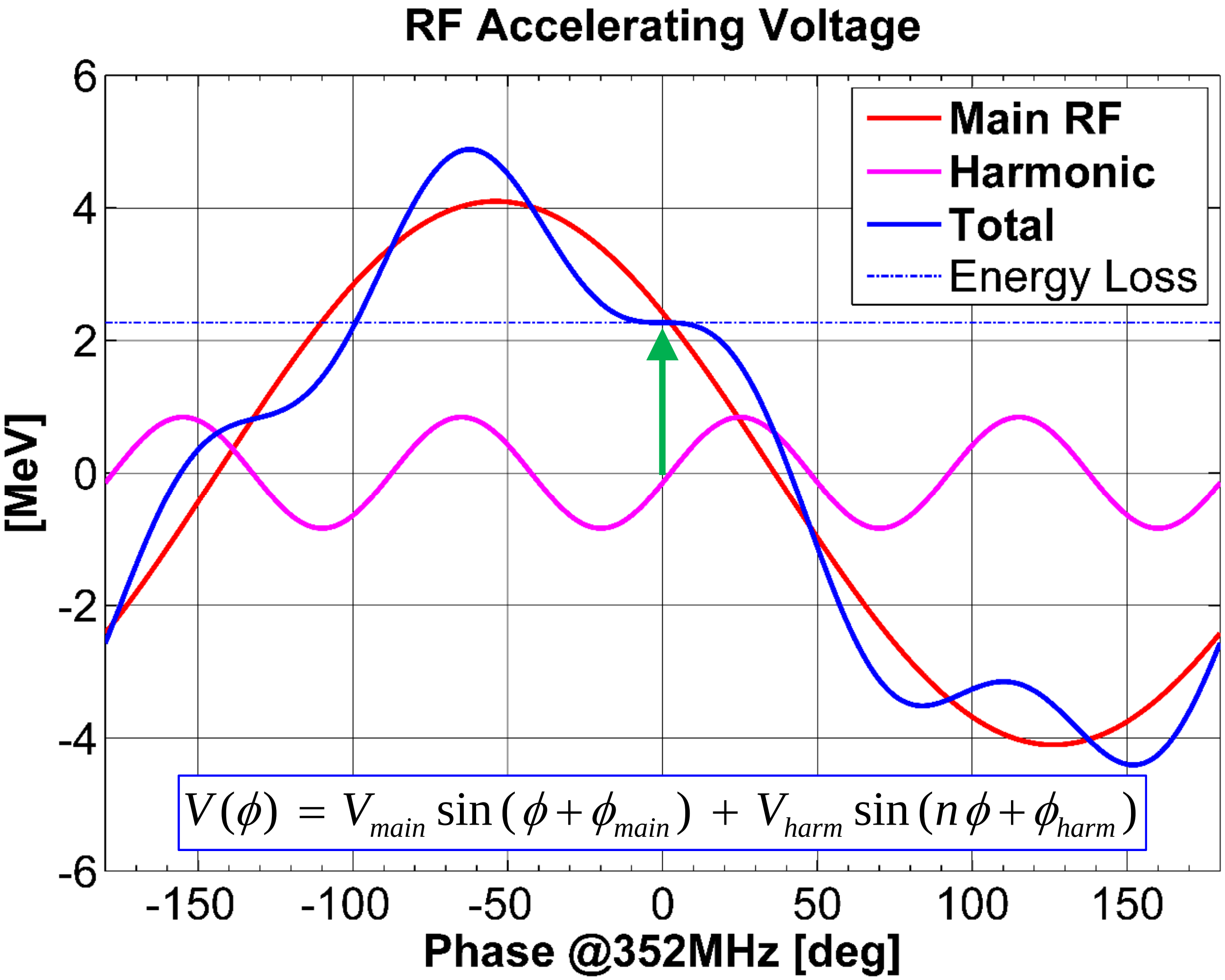

GRAINGER


Particle Density
x 10^14
Δp/p [%]
1
0.5
0
-0.5
-1
-150
-100
-50
0
50
100
150
Time [psec]
6
5
4
3
2
1
0

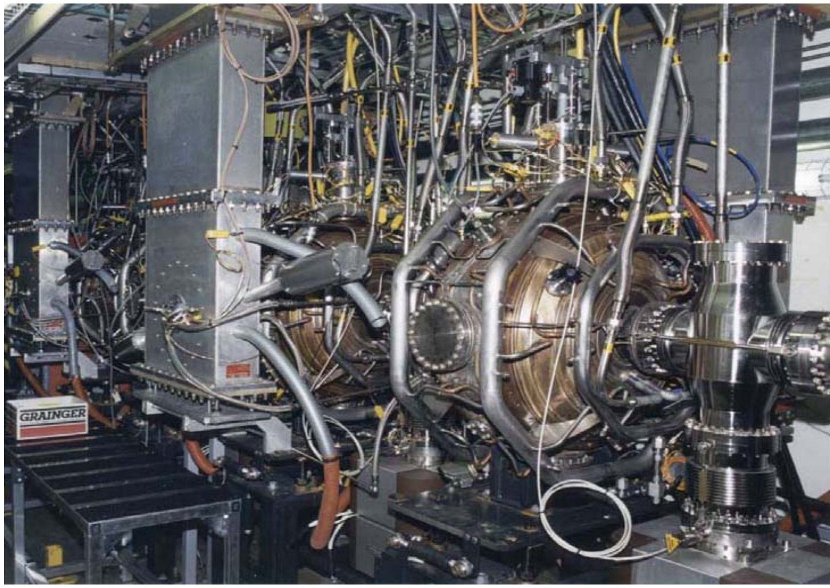

RF Accelerating Voltage
Main RF
Harmonic
Total
Energy Loss
[MeV]
6
4
2
0
-2
-4
-6
-150
-100
-50
0
50
100
150
Phase @352MHz [deg]

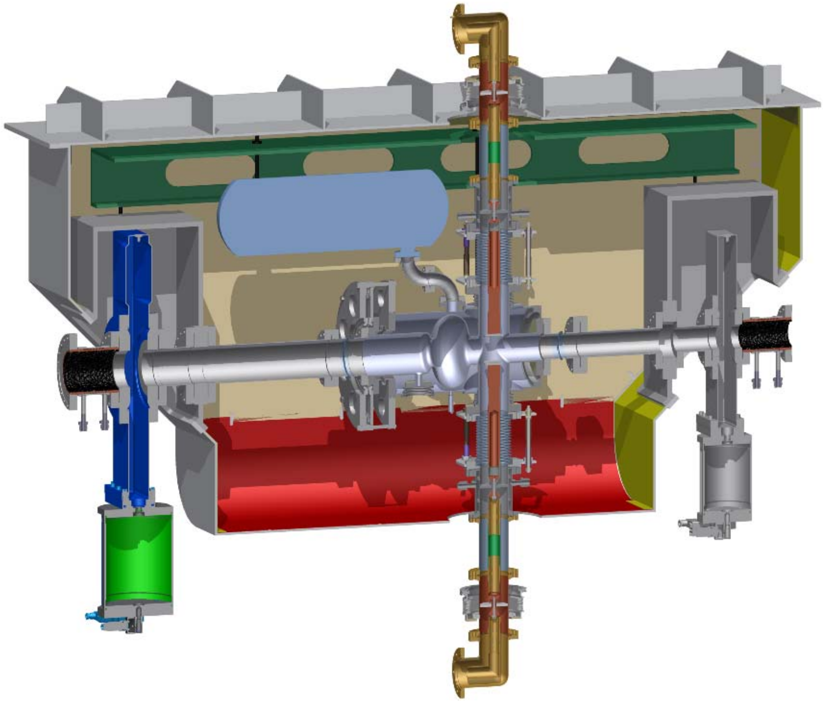

GRAINGER

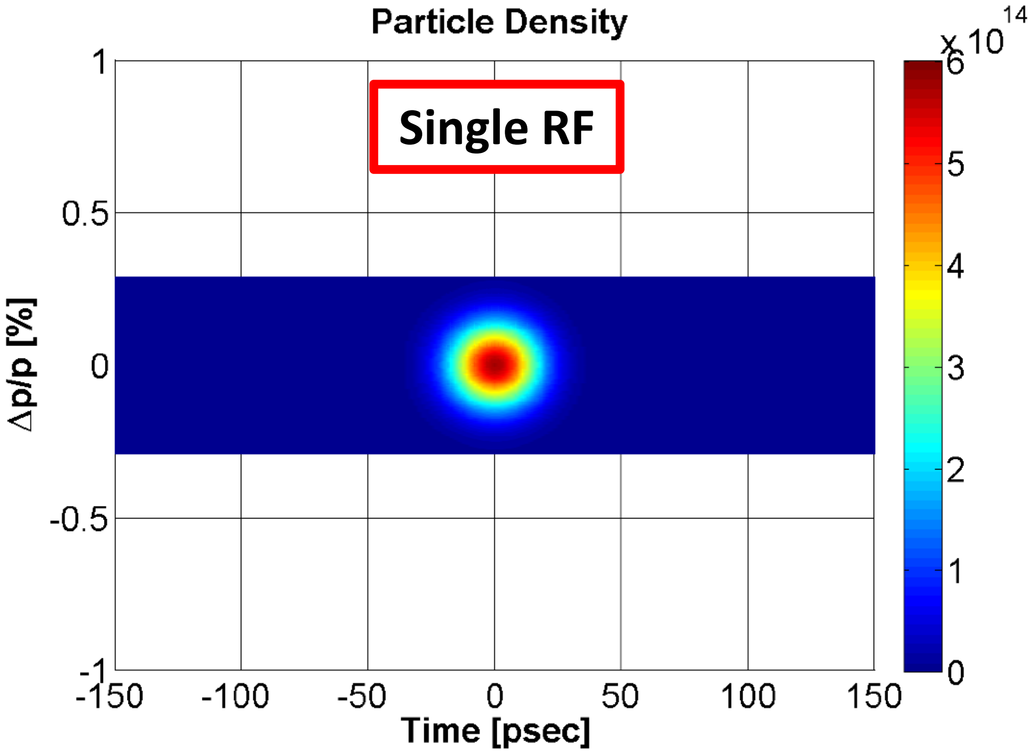


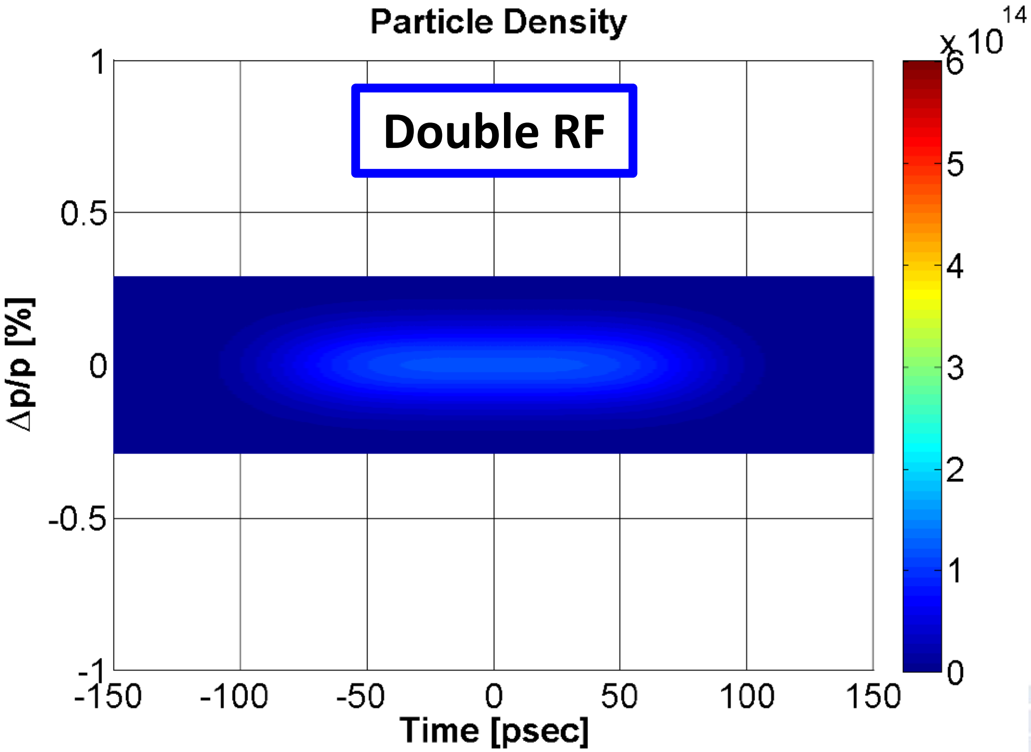


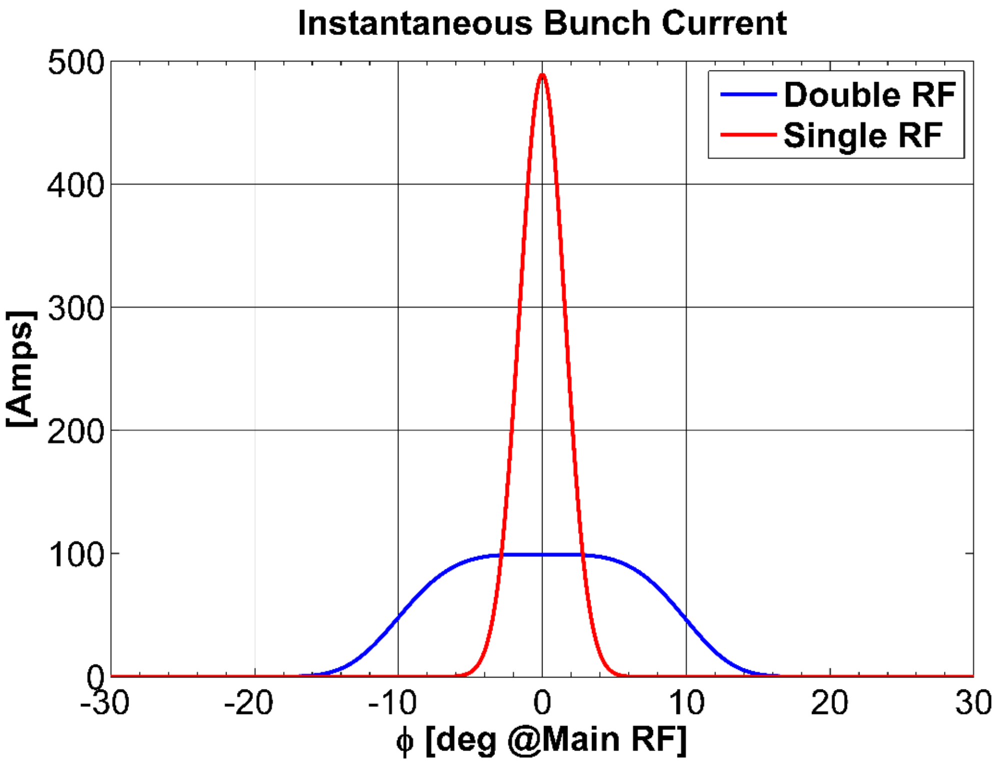
$$V(\phi) = V_{main}\sin(\phi+\phi_{main}) + V_{harm}\sin(n\phi+\phi_{harm})$$

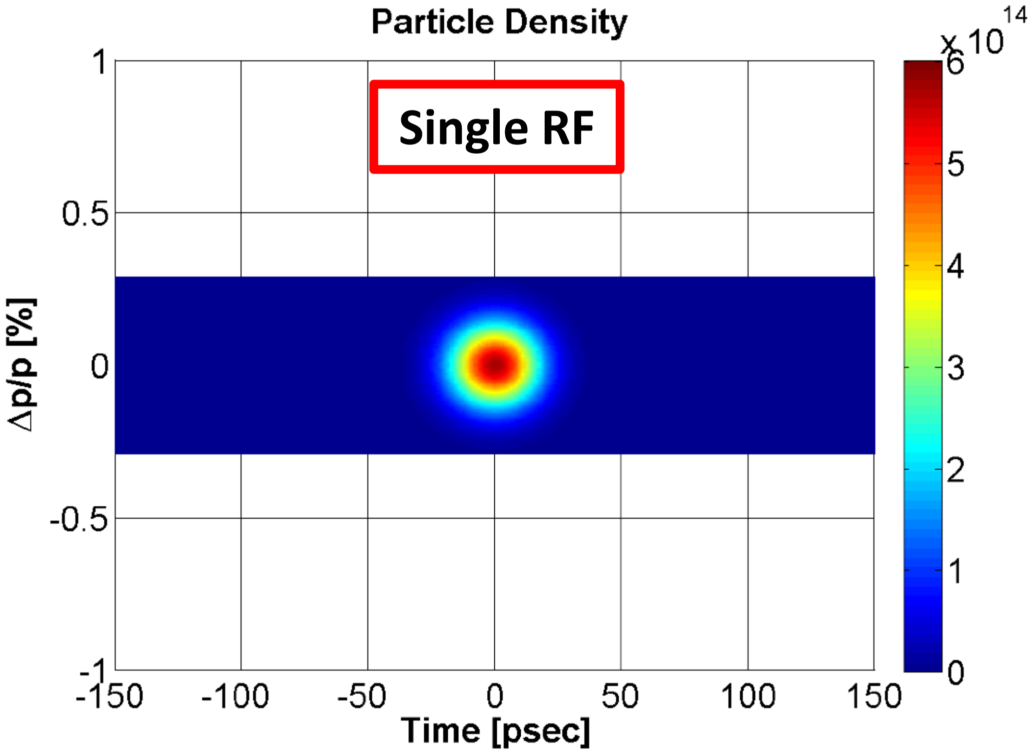




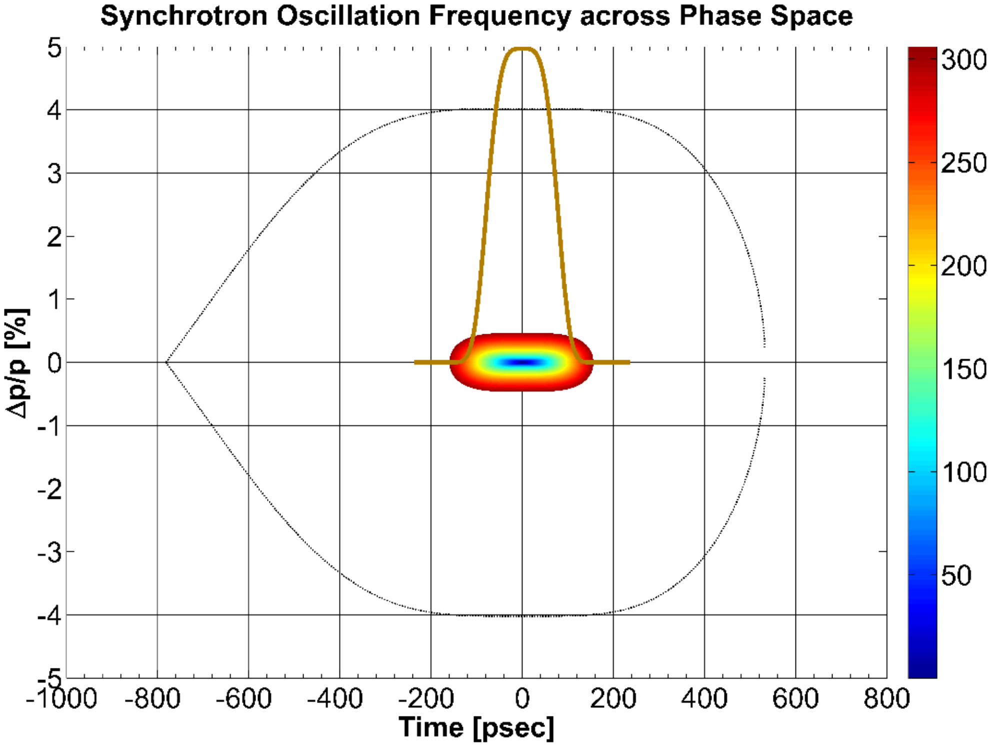

Particle Density
Single RF
x 10^14
6
5
4
3
2
1
0
1
0.5
0
-0.5
-1
Δp/p [%]
-150
-100
-50
0
50
100
150
Time [psec]

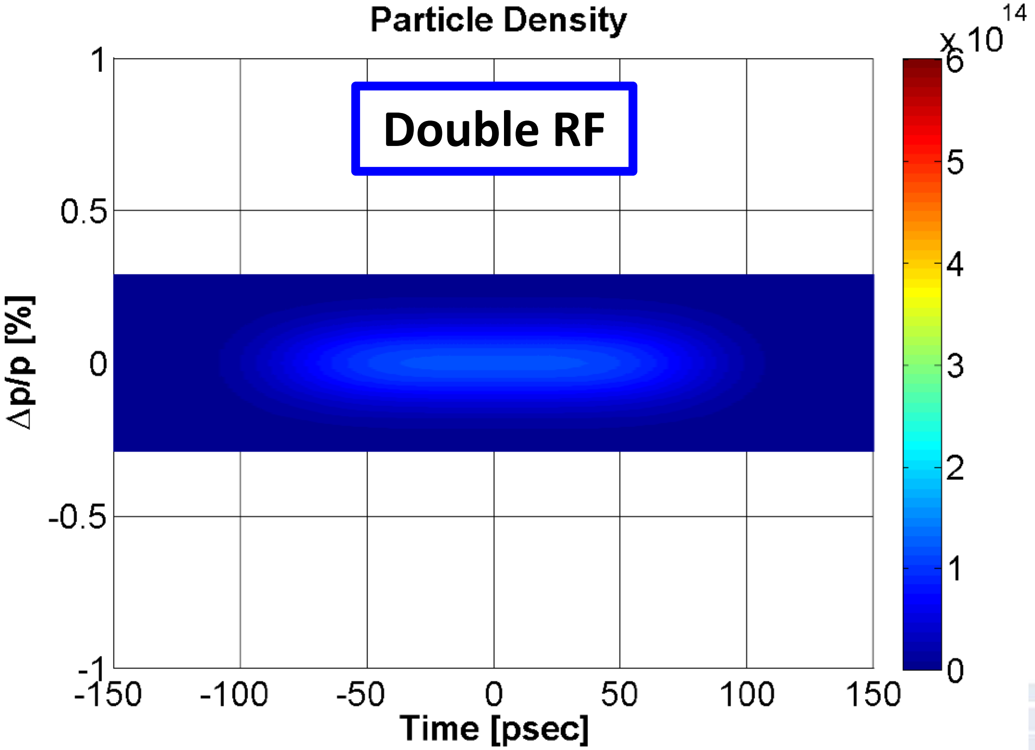

Particle Density
Double RF
x 10^14
6
5
4
3
2
1
0
1
0.5
0
-0.5
-1
Δp/p [%]
-150
-100
-50
0
50
100
150
Time [psec]


Instantaneous Bunch Current
Double RF
Single RF
500
400
300
200
100
0
[Amps]
-30
-20
-10
0
10
20
30
ϕ [deg @Main RF]

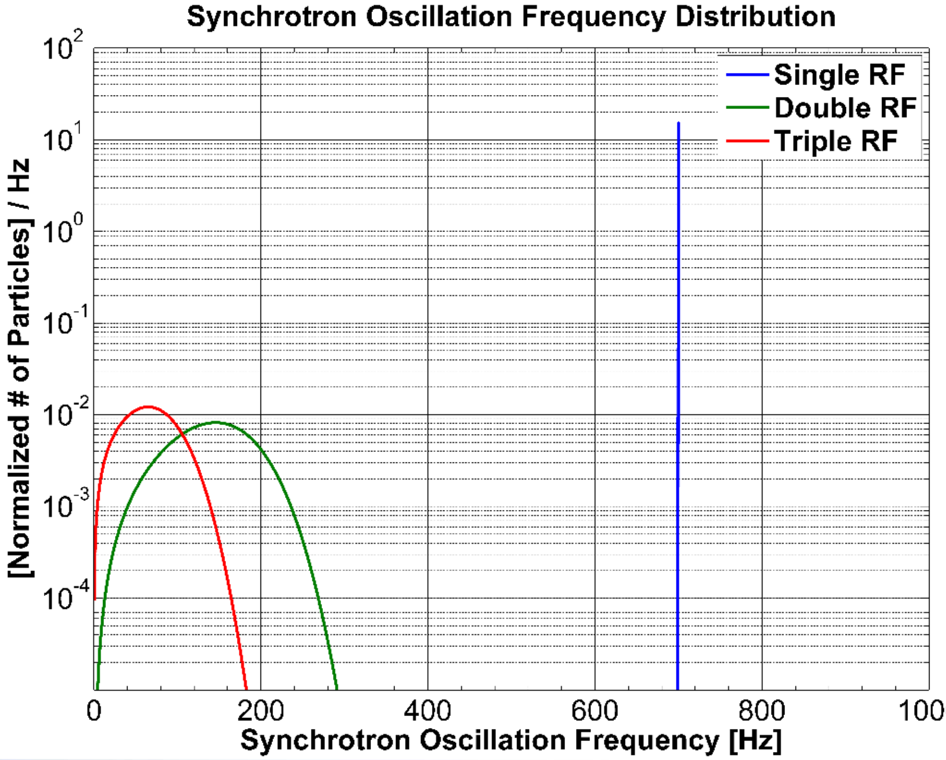

Particle Density

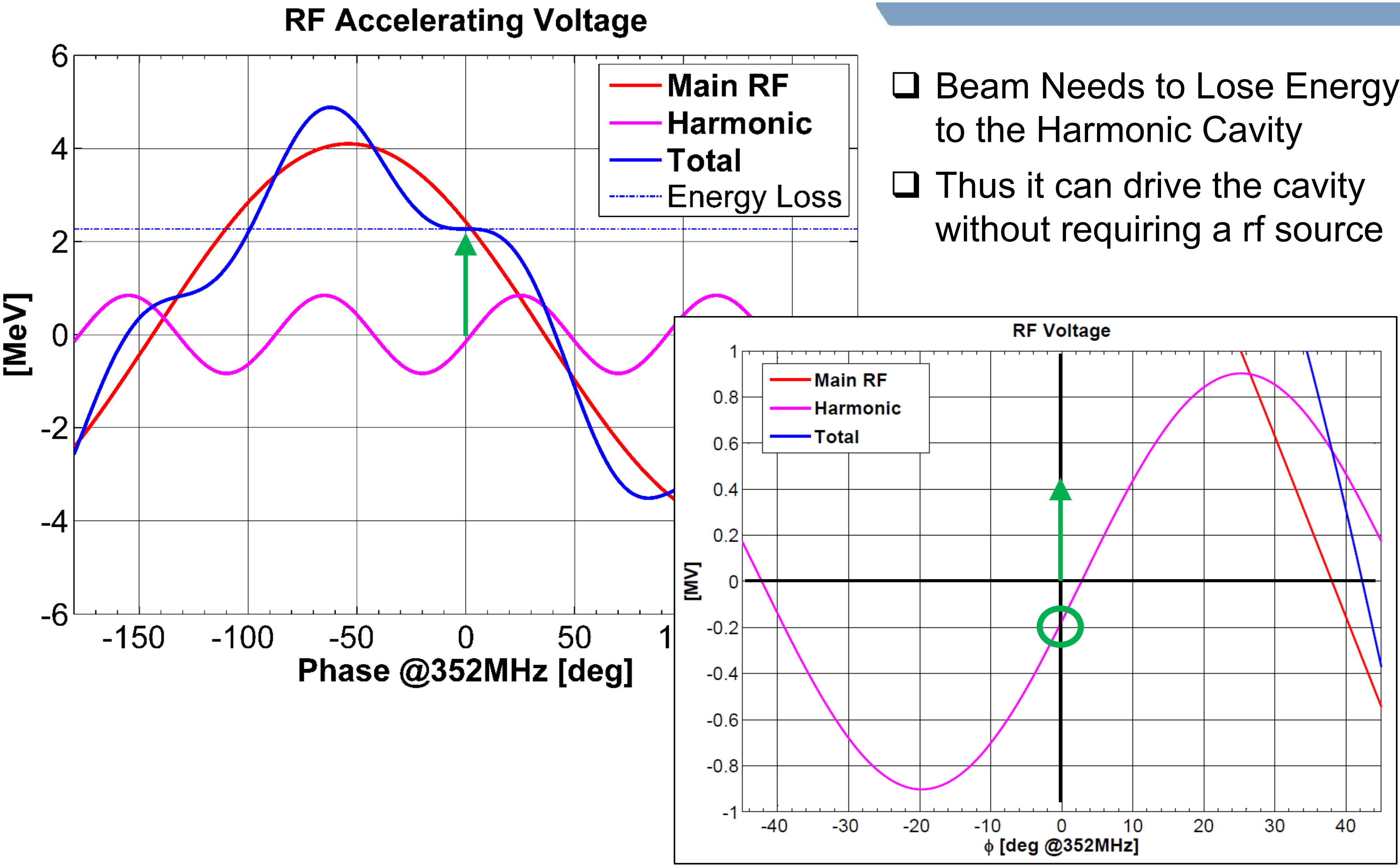
Single RF


Synchrotron Oscillation Frequency across Phase Space


Particle Density

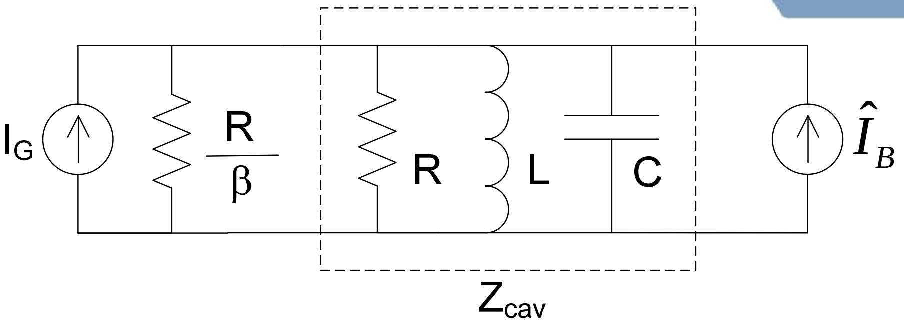
Double RF


Synchrotron Oscillation Frequency Distribution



- Beam Needs to Lose Energy to the Harmonic Cavity
- Thus it can drive the cavity without requiring a rf source

Beam Loading



$$\hat{I}_T = \left|\hat{I}_G\right| e^{j\phi_L} + \left|\hat{I}_B\right| e^{j\phi_B}$$

$$\hat{V} = \hat{I}_T \cdot \left|\hat{Z}_{eq}\right| e^{j\phi_Z}$$

Required Generator Power

$$P_G^{+} = \frac{V^2}{8\beta\left(R/Q\right)' Q_o} \cdot \left[\left(\beta + 1 + \frac{P_B}{P_{cav}}\right)^2 + \left((\beta+1)\tan\phi_Z + \frac{V\left|\hat{I}_B\right|\sin\phi_B}{2P_{cav}}\right)^2\right]$$

$$\beta_{opt} = \left|1 + \frac{P_B}{P_{cav}}\right|$$

Optimum Coupling

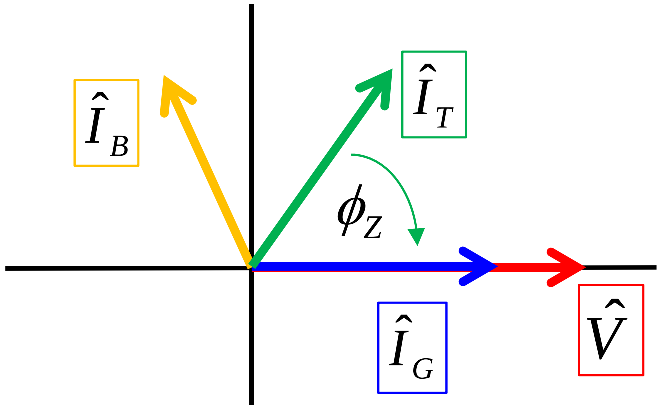
$$\tan\phi_{Z\,opt} = -\left|\hat{I}_B\right|\sin\phi_B \frac{R}{V(\beta+1)}$$

Optimum Detuning

- For a given beam current, accelerating voltage and accelerating phase, there's an optimum coupling and detuning
- If Pb = -Pcav, cavity can closed off, Pg=0
- If Pb/Pcav < -1, Pg can be made zero
- The detuning is of opposite sign for an accelerating cavity vs a passive bunch-lengthing cavity

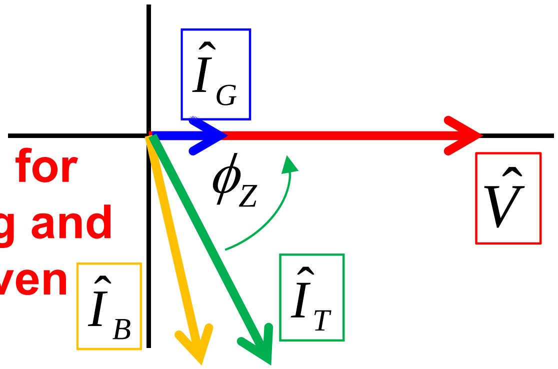
Accelerating Cavity Above Transition

=> tan < 0 => $f_{cav} < f_{rf}$



Bunch Lengthening Cavity Above Transition

=> tan > 0 => $f_{cav} > f_{rf}$

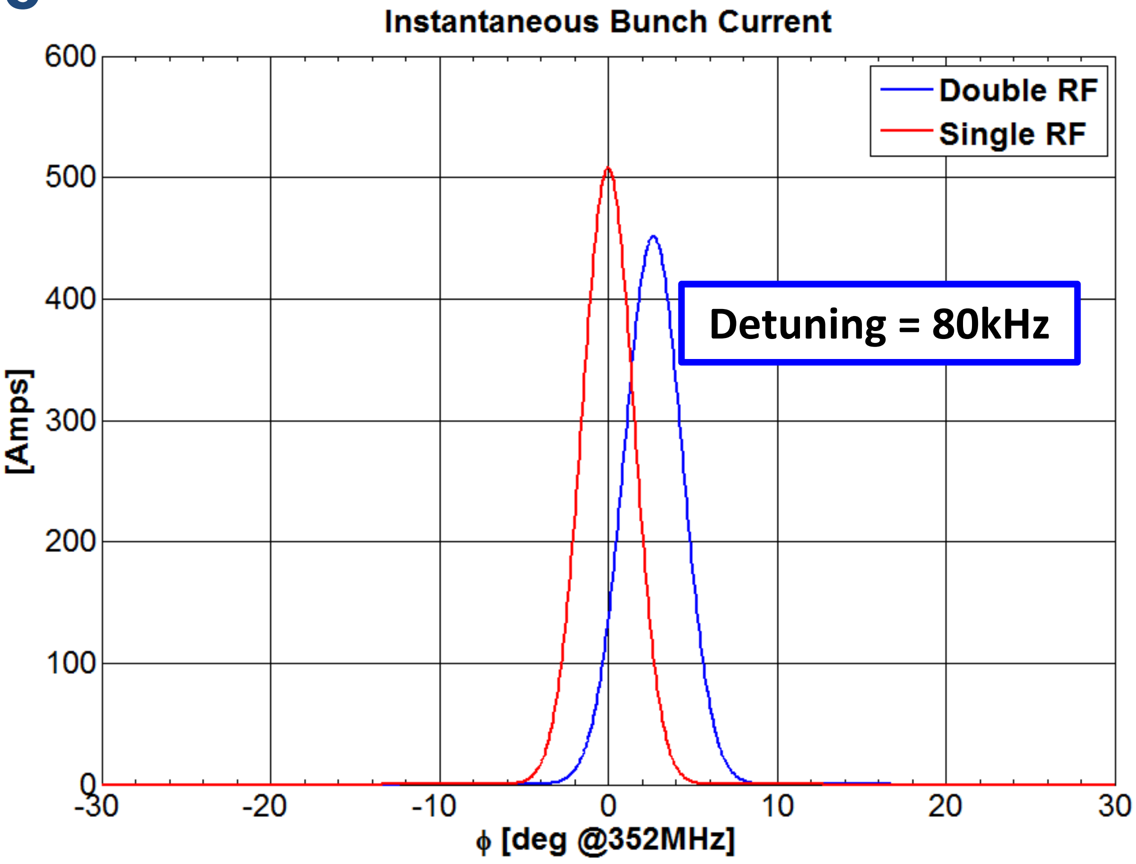


Zero P_g needed for proper coupling and detuning for given beam current

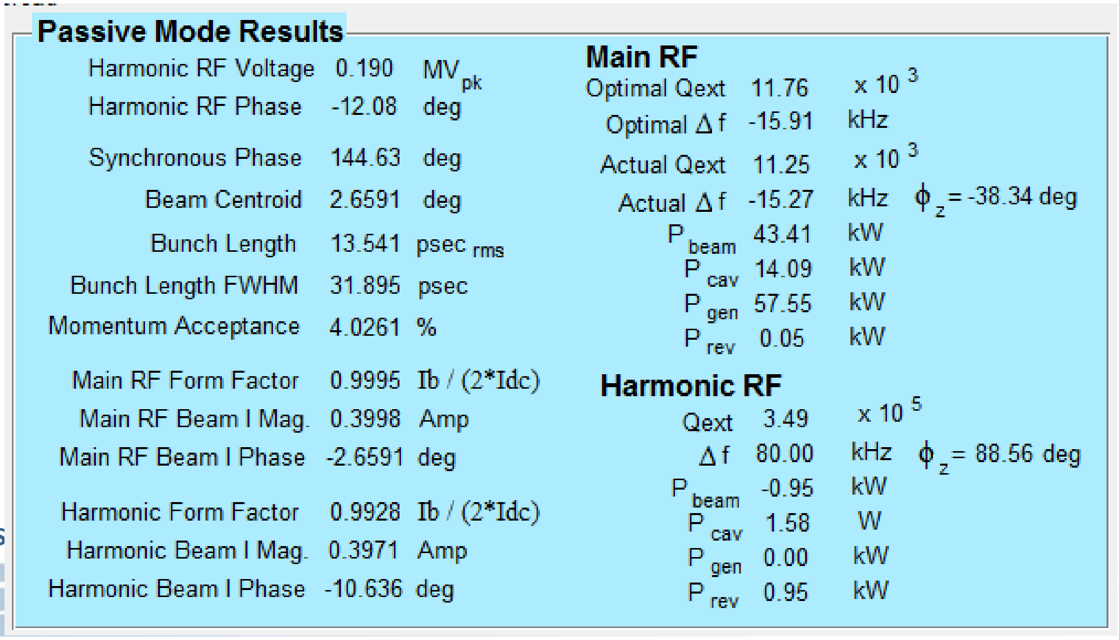
Passive Mode

self-consistent solution

200mA
Qext = 3.5e5
(optimal:
2.31e5, 15.15kHz)



Detuning = 80kHz



Passive Mode Results

Harmonic RF Voltage	0.190	MV_{pk}
Harmonic RF Phase	-12.08	deg
Synchronous Phase	144.63	deg
Beam Centroid	2.6591	deg
Bunch Length	13.541	$psec_{rms}$
Bunch Length FWHM	31.895	psec
Momentum Acceptance	4.0261	%
Main RF Form Factor	0.9995	Ib / (2*Idc)
Main RF Beam I Mag.	0.3998	Amp
Main RF Beam I Phase	-2.6591	deg
Harmonic Form Factor	0.9928	Ib / (2*Idc)
Harmonic Beam I Mag.	0.3971	Amp
Harmonic Beam I Phase	-10.636	deg

Main RF

Optimal Qext	11.76	$\times 10^3$	
Optimal Δf	-15.91	kHz	
Actual Qext	11.25	$\times 10^3$	
Actual Δf	-15.27	kHz	ϕ_z = -38.34 deg
P_{beam}	43.41	kW	
P_{cav}	14.09	kW	
P_{gen}	57.55	kW	
P_{rev}	0.05	kW	

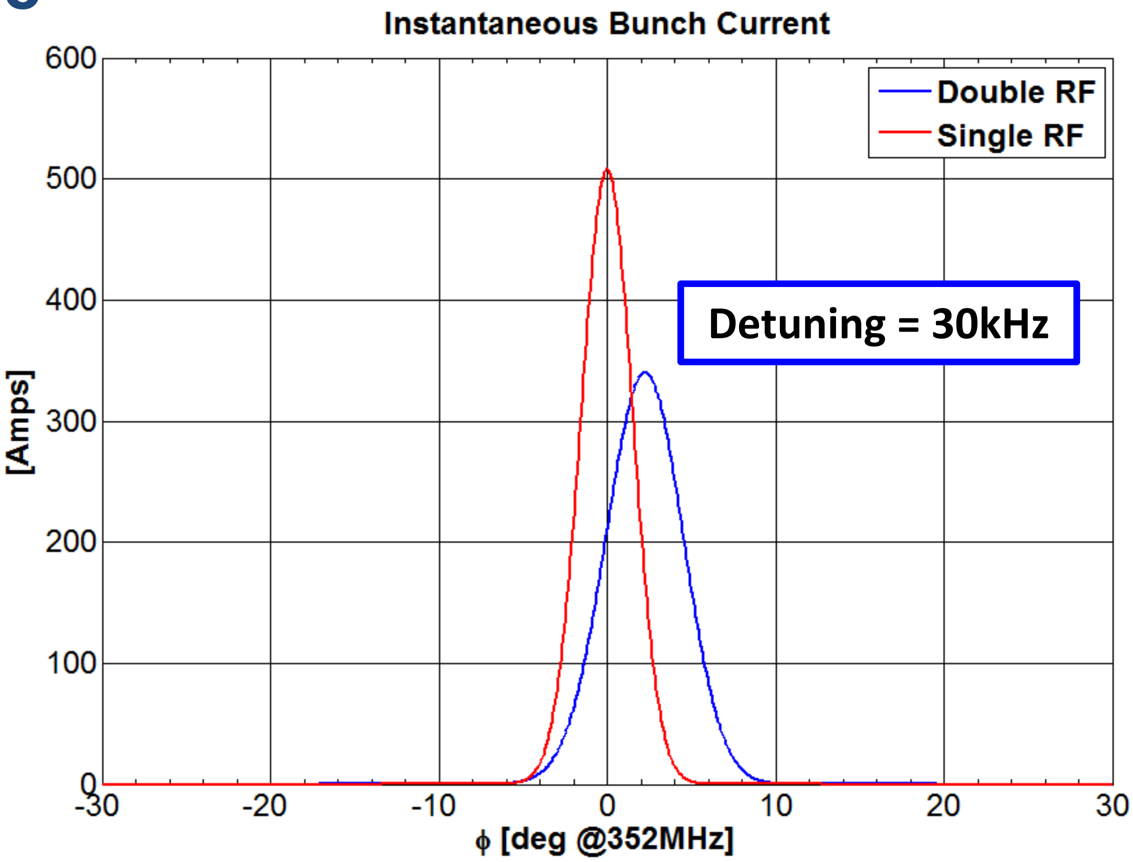
Harmonic RF

Qext	3.49	$\times 10^5$	
Δf	80.00	kHz	ϕ_z = 88.56 deg
P_{beam}	-0.95	kW	
P_{cav}	1.58	W	
P_{gen}	0.00	kW	
P_{rev}	0.95	kW	

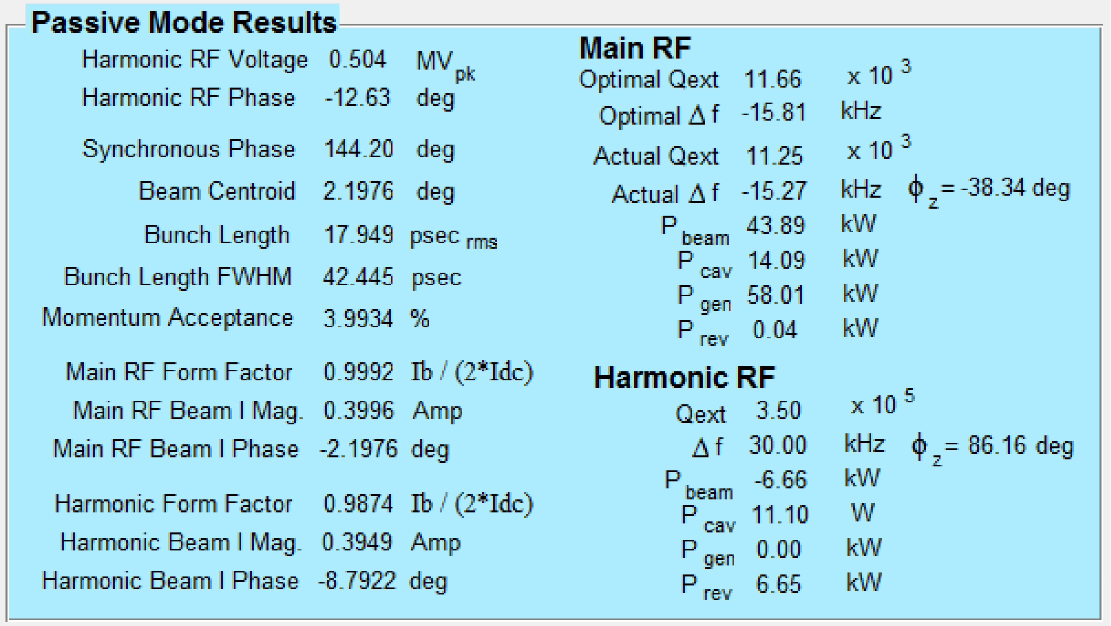
Passive Mode

self-consistent solution

200mA
Qext = 3.5e5
(optimal:
2.31e5, 15.15kHz)



Detuning = 30kHz



Passive Mode Results

Harmonic RF Voltage	0.504	MV_{pk}
Harmonic RF Phase	-12.63	deg
Synchronous Phase	144.20	deg
Beam Centroid	2.1976	deg
Bunch Length	17.949	$psec_{rms}$
Bunch Length FWHM	42.445	psec
Momentum Acceptance	3.9934	%
Main RF Form Factor	0.9992	Ib / (2*Idc)
Main RF Beam I Mag.	0.3996	Amp
Main RF Beam I Phase	-2.1976	deg
Harmonic Form Factor	0.9874	Ib / (2*Idc)
Harmonic Beam I Mag.	0.3949	Amp
Harmonic Beam I Phase	-8.7922	deg

Main RF

Optimal Qext	11.66	$x\ 10^3$	
Optimal Δ f	-15.81	kHz	
Actual Qext	11.25	$x\ 10^3$	
Actual Δ f	-15.27	kHz	ϕ_z = -38.34 deg
P_{beam}	43.89	kW	
P_{cav}	14.09	kW	
P_{gen}	58.01	kW	
P_{rev}	0.04	kW	

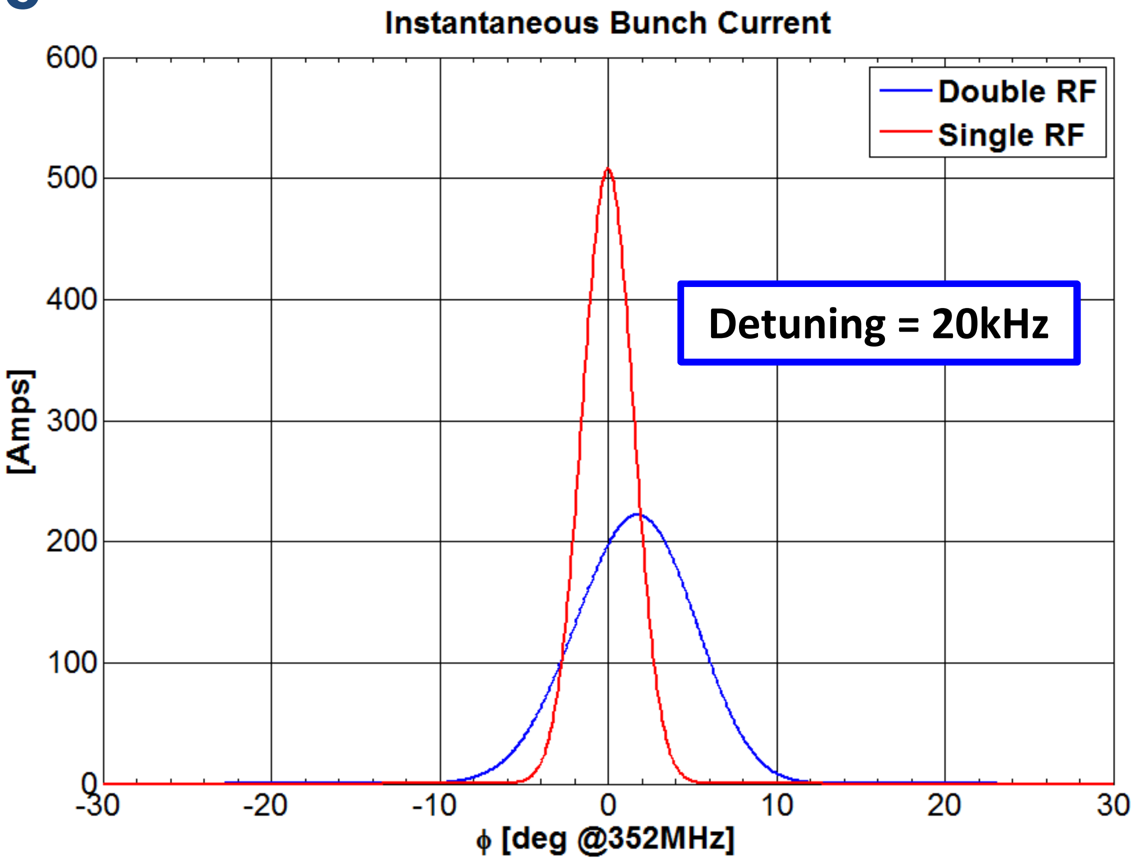
Harmonic RF

Qext	3.50	$x\ 10^5$	
Δ f	30.00	kHz	ϕ_z = 86.16 deg
P_{beam}	-6.66	kW	
P_{cav}	11.10	W	
P_{gen}	0.00	kW	
P_{rev}	6.65	kW	

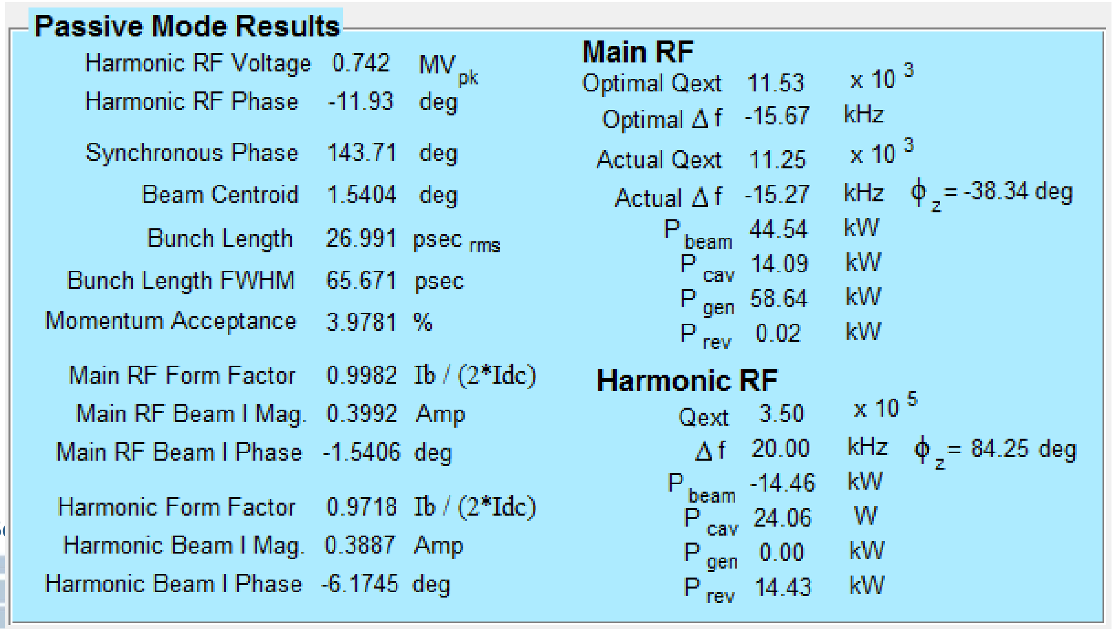
Passive Mode

self-consistent solution

200mA
Qext = 3.5e5
(optimal:
2.31e5, 15.15kHz)



Detuning = 20kHz



Passive Mode Results

Harmonic RF Voltage	0.742	MV_{pk}
Harmonic RF Phase	-11.93	deg
Synchronous Phase	143.71	deg
Beam Centroid	1.5404	deg
Bunch Length	26.991	$psec_{rms}$
Bunch Length FWHM	65.671	psec
Momentum Acceptance	3.9781	%
Main RF Form Factor	0.9982	Ib / (2*Idc)
Main RF Beam I Mag.	0.3992	Amp
Main RF Beam I Phase	-1.5406	deg
Harmonic Form Factor	0.9718	Ib / (2*Idc)
Harmonic Beam I Mag.	0.3887	Amp
Harmonic Beam I Phase	-6.1745	deg

Main RF

Optimal Qext	11.53	$\times 10^3$	
Optimal Δf	-15.67	kHz	
Actual Qext	11.25	$\times 10^3$	
Actual Δf	-15.27	kHz	ϕ_z = -38.34 deg
P_{beam}	44.54	kW	
P_{cav}	14.09	kW	
P_{gen}	58.64	kW	
P_{rev}	0.02	kW	

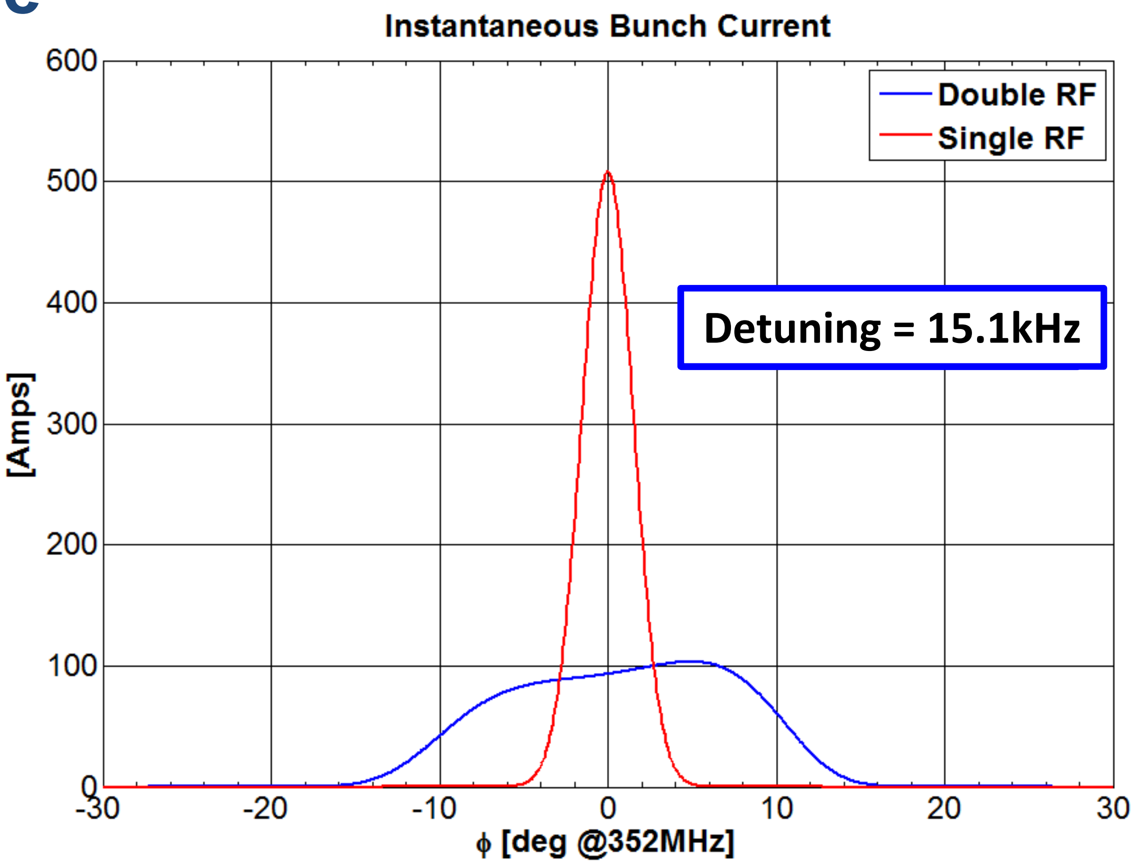
Harmonic RF

Qext	3.50	$\times 10^5$	
Δf	20.00	kHz	ϕ_z = 84.25 deg
P_{beam}	-14.46	kW	
P_{cav}	24.06	W	
P_{gen}	0.00	kW	
P_{rev}	14.43	kW	

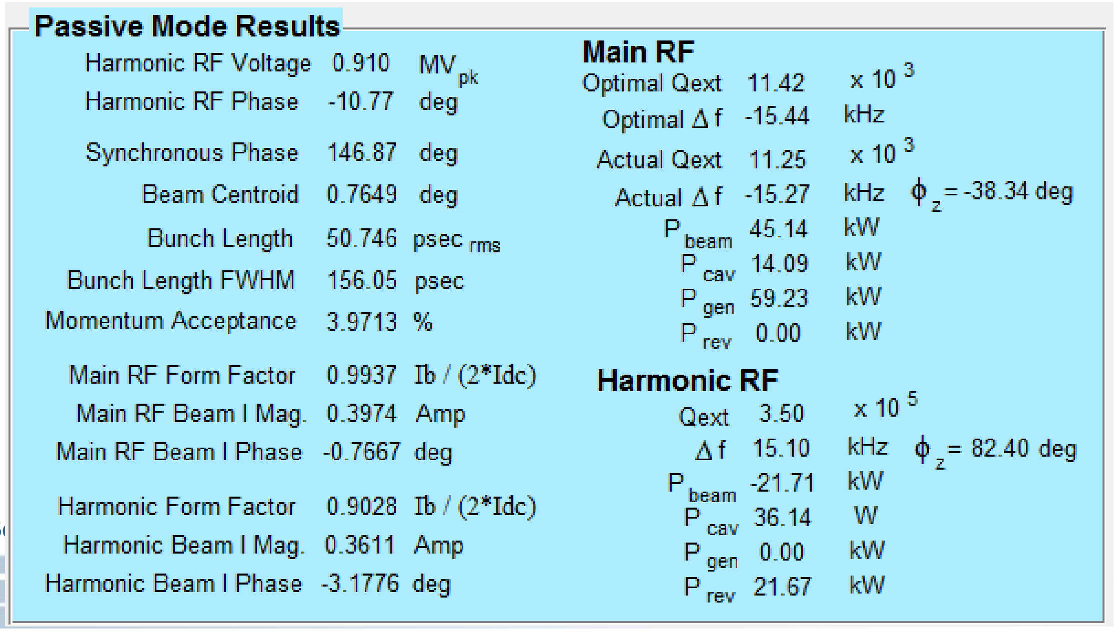
Passive Mode

self-consistent solution

200mA
Qext = 3.5e5
(optimal:
2.31e5, 15.15kHz)



Detuning = 15.1kHz



Passive Mode Results

Harmonic RF Voltage	0.910	MV_{pk}
Harmonic RF Phase	-10.77	deg
Synchronous Phase	146.87	deg
Beam Centroid	0.7649	deg
Bunch Length	50.746	$psec_{rms}$
Bunch Length FWHM	156.05	psec
Momentum Acceptance	3.9713	%
Main RF Form Factor	0.9937	Ib / (2*Idc)
Main RF Beam I Mag.	0.3974	Amp
Main RF Beam I Phase	-0.7667	deg
Harmonic Form Factor	0.9028	Ib / (2*Idc)
Harmonic Beam I Mag.	0.3611	Amp
Harmonic Beam I Phase	-3.1776	deg

Main RF

Optimal Qext	11.42	$\times 10^3$	
Optimal Δf	-15.44	kHz	
Actual Qext	11.25	$\times 10^3$	
Actual Δf	-15.27	kHz	ϕ_z = -38.34 deg
P_{beam}	45.14	kW	
P_{cav}	14.09	kW	
P_{gen}	59.23	kW	
P_{rev}	0.00	kW	

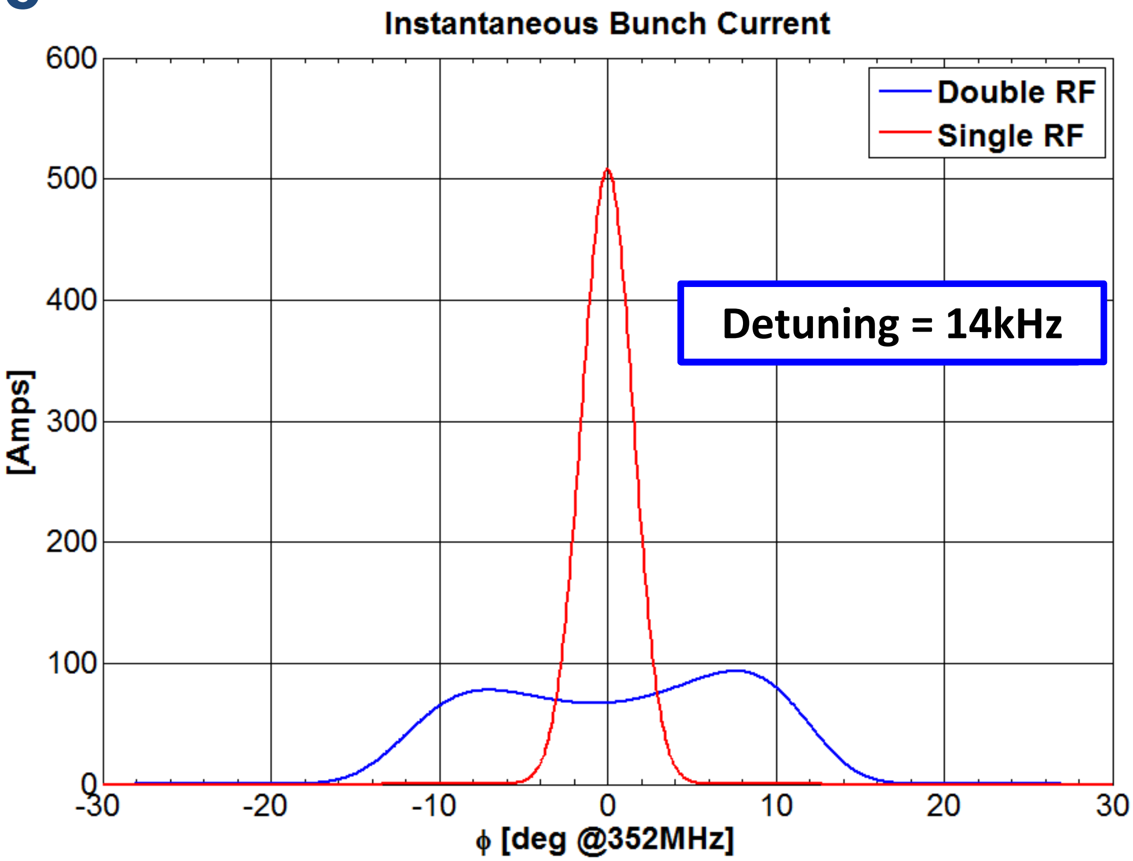
Harmonic RF

Qext	3.50	$\times 10^5$	
Δf	15.10	kHz	ϕ_z = 82.40 deg
P_{beam}	-21.71	kW	
P_{cav}	36.14	W	
P_{gen}	0.00	kW	
P_{rev}	21.67	kW	

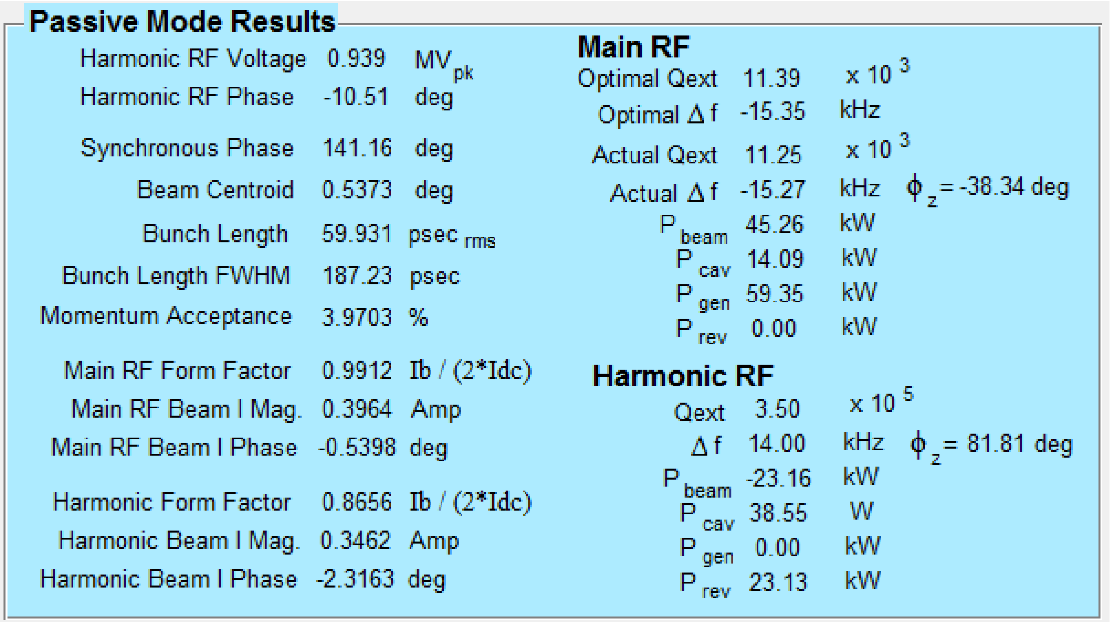
Passive Mode

self-consistent solution

200mA
Qext = 3.5e5
(optimal:
2.31e5, 15.15kHz)



Detuning = 14kHz



Passive Mode Results

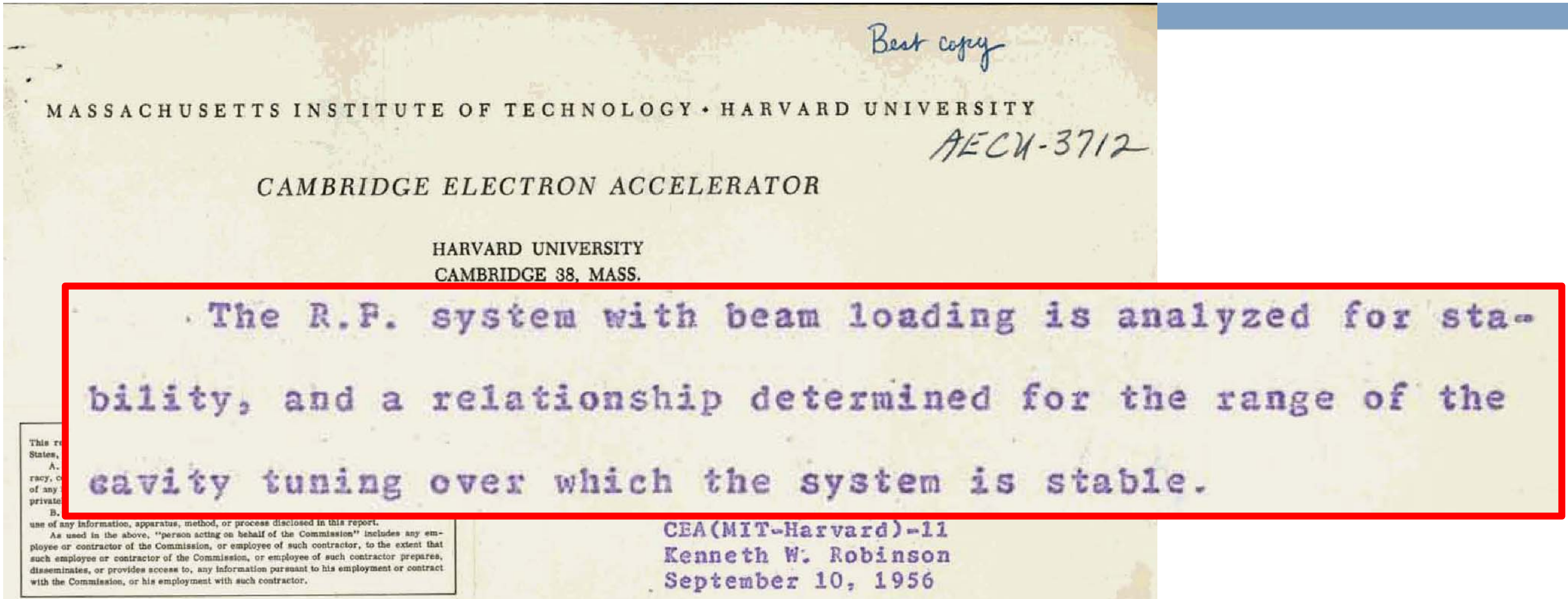
Harmonic RF Voltage	0.939	MV_{pk}
Harmonic RF Phase	-10.51	deg
Synchronous Phase	141.16	deg
Beam Centroid	0.5373	deg
Bunch Length	59.931	$psec_{rms}$
Bunch Length FWHM	187.23	psec
Momentum Acceptance	3.9703	%
Main RF Form Factor	0.9912	Ib / (2*Idc)
Main RF Beam I Mag.	0.3964	Amp
Main RF Beam I Phase	-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	$\times 10^3$	
Optimal Δf	-15.35	kHz	
Actual Qext	11.25	$\times 10^3$	
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	$\times 10^5$	
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	



Best copy

MASSACHUSETTS INSTITUTE OF TECHNOLOGY • HARVARD UNIVERSITY

AECU-3712

CAMBRIDGE ELECTRON ACCELERATOR

HARVARD UNIVERSITY
CAMBRIDGE 38, MASS.

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.

This r
States,
A.
racy, c
of any
private
B.
use of any information, apparatus, method, or process disclosed in this report.
As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

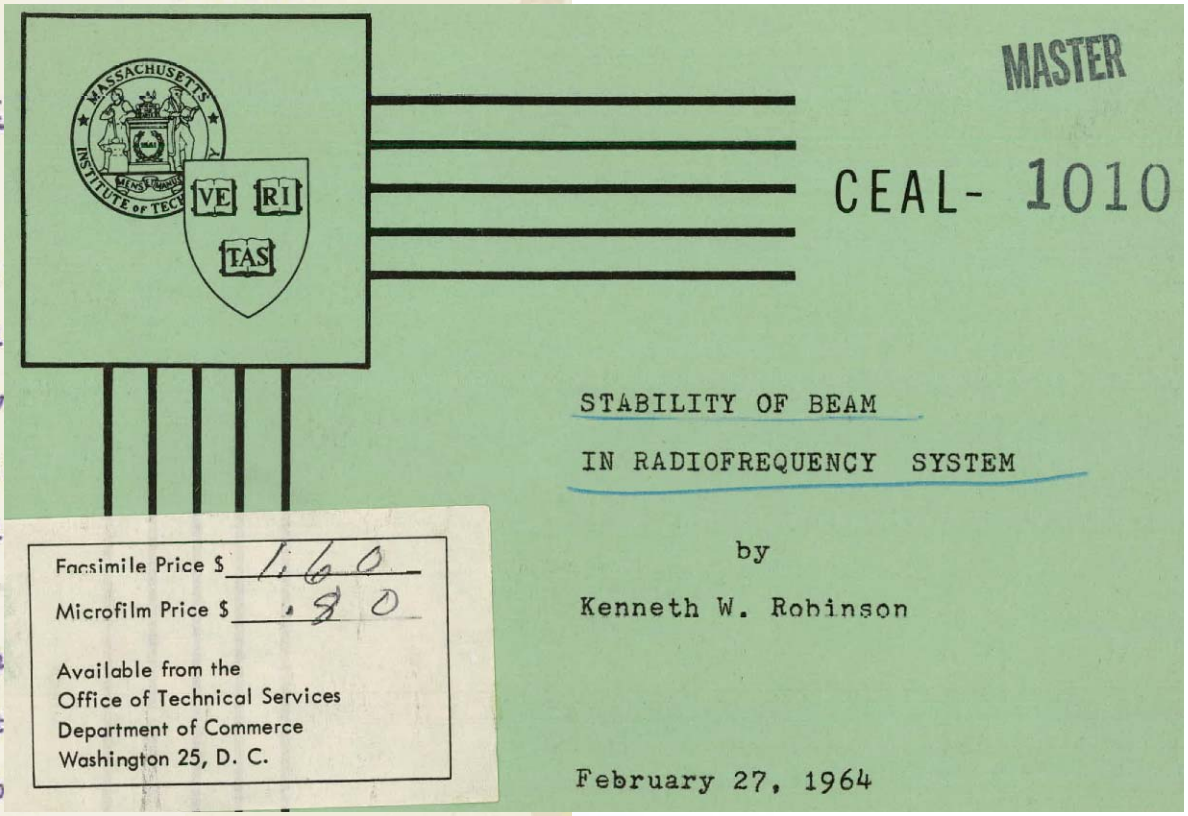
CEA(MIT-Harvard)-11
Kenneth W. Robinson
September 10, 1956

RADIOFREQUENCY ACCELERATION II

Abstract

A radiofrequency system consisting of
strongly coupled together by transmission l
This system can be regarded as a single cav
in a particular mode, and is found to be a
for the accelerator. Also methods of coupl
into the system are considered.

The R.P. system with beam loading is a
bility, and a relationship determined for t
cavity tuning over which the system is stab



MASTER

CEAL- 1010

STABILITY OF BEAM
IN RADIOFREQUENCY SYSTEM

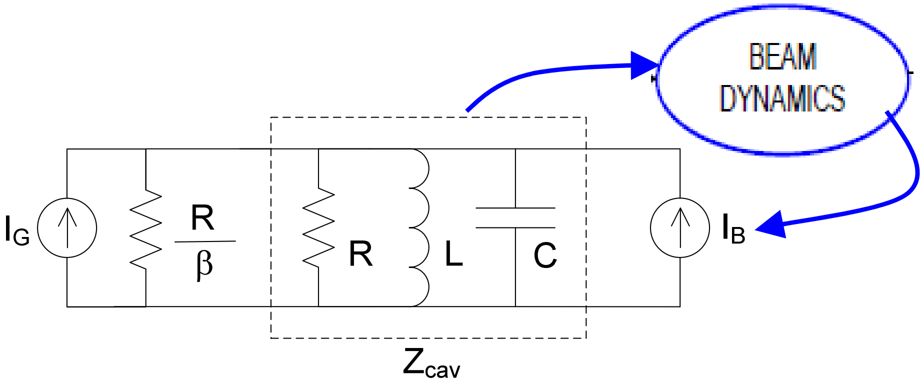
by

Kenneth W. Robinson

February 27, 1964

Facsimile Price $ 1.60
Microfilm Price $ .80

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



$$\frac{d}{dt}\frac{\Delta E}{E_o} = f_{rev}\frac{eV_o}{E_o}\sin(\phi_s + \Delta\phi) - U_{rad}(E)$$

$$\frac{d}{dt}\frac{\Delta E}{E_o} \cong f_{rev}\frac{eV_o}{E_o}\cos\phi_s\,\Delta\phi$$

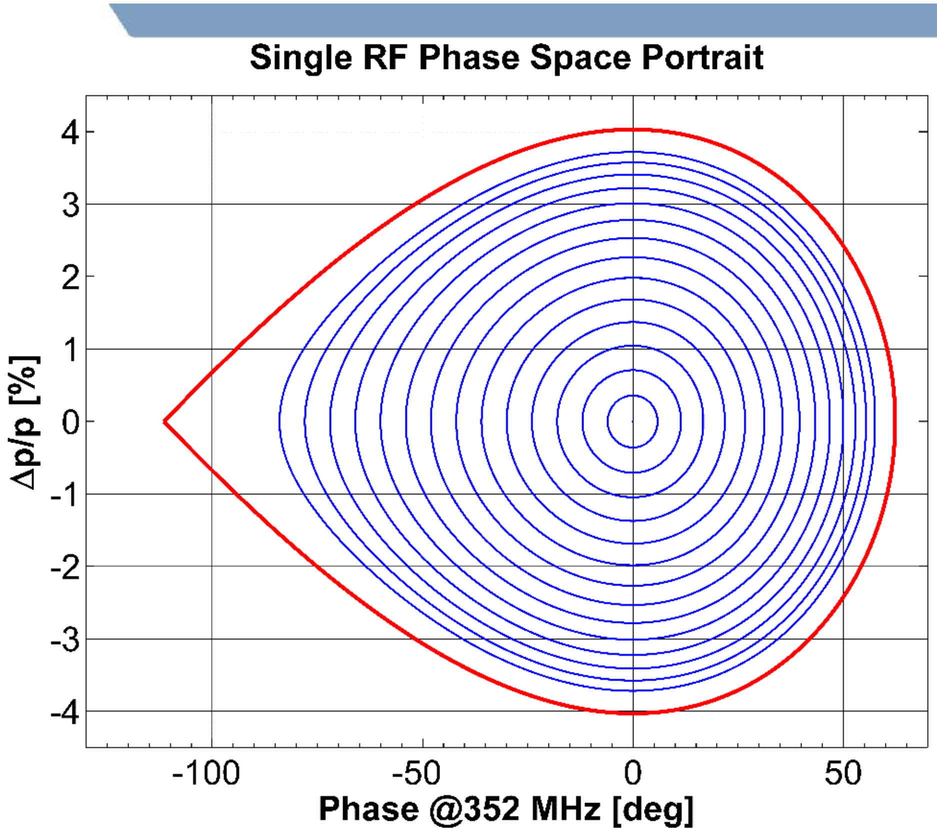
$$\frac{d}{dt}\Delta\phi = 2\pi h f_{rev}^2 \alpha_c \frac{\Delta E}{E_o}$$

Beam Dynamics

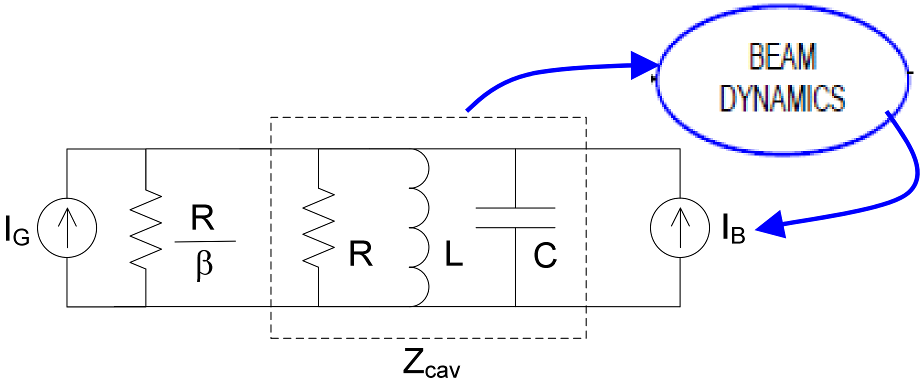
$$\begin{bmatrix}\dot{V}_I \\ \dot{V}_Q\end{bmatrix} = \begin{bmatrix}-\sigma & -\Delta\omega \\ \Delta\omega & -\sigma\end{bmatrix}\begin{bmatrix}V_I \\ V_Q\end{bmatrix} + \sigma\frac{R}{\beta+1}\begin{bmatrix}1 & 0 \\ 0 & 1\end{bmatrix}\begin{bmatrix}I_I \\ I_Q\end{bmatrix}$$

Cavity Dynamics

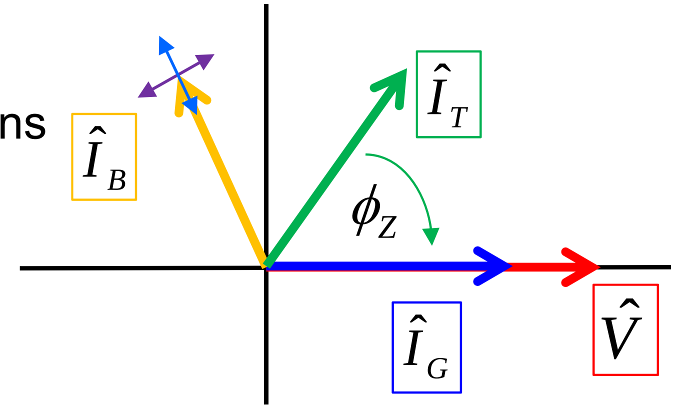
$$V_{cav}(t) = V_o\, e^{-\sigma t} e^{i\omega_o t} \qquad \Delta\omega = \omega_o - \omega_{rf}$$

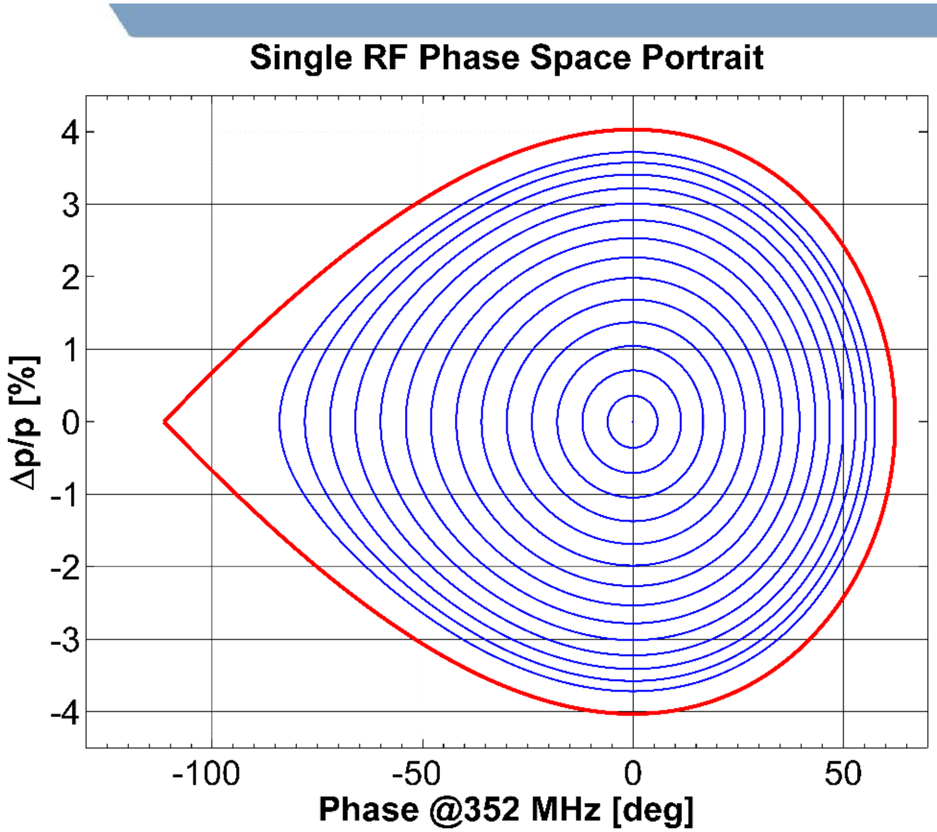


Single RF Phase Space Portrait



Account for beam current modulations driving the cavity





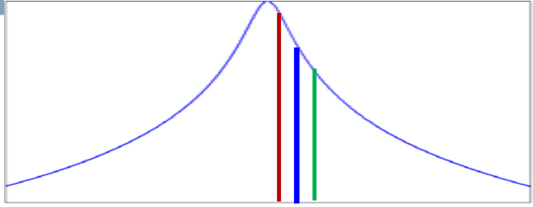
$$
\begin{bmatrix} \left(\Delta E / E_o\right)' \\ \Delta\phi_B{}' \\ \left(\Delta v / V_o\right)' \\ \Delta\phi_V{}' \end{bmatrix}
=
\begin{bmatrix}
0 & \frac{V_o}{E_o} f_{rev} \cos\phi_S & \frac{V_o}{E_o} f_{rev} \sin\phi_S & \frac{V_o}{E_o} f_{rev} \cos\phi_S \\
2\pi h f_{rev}^2 \alpha_c & 0 & 0 &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

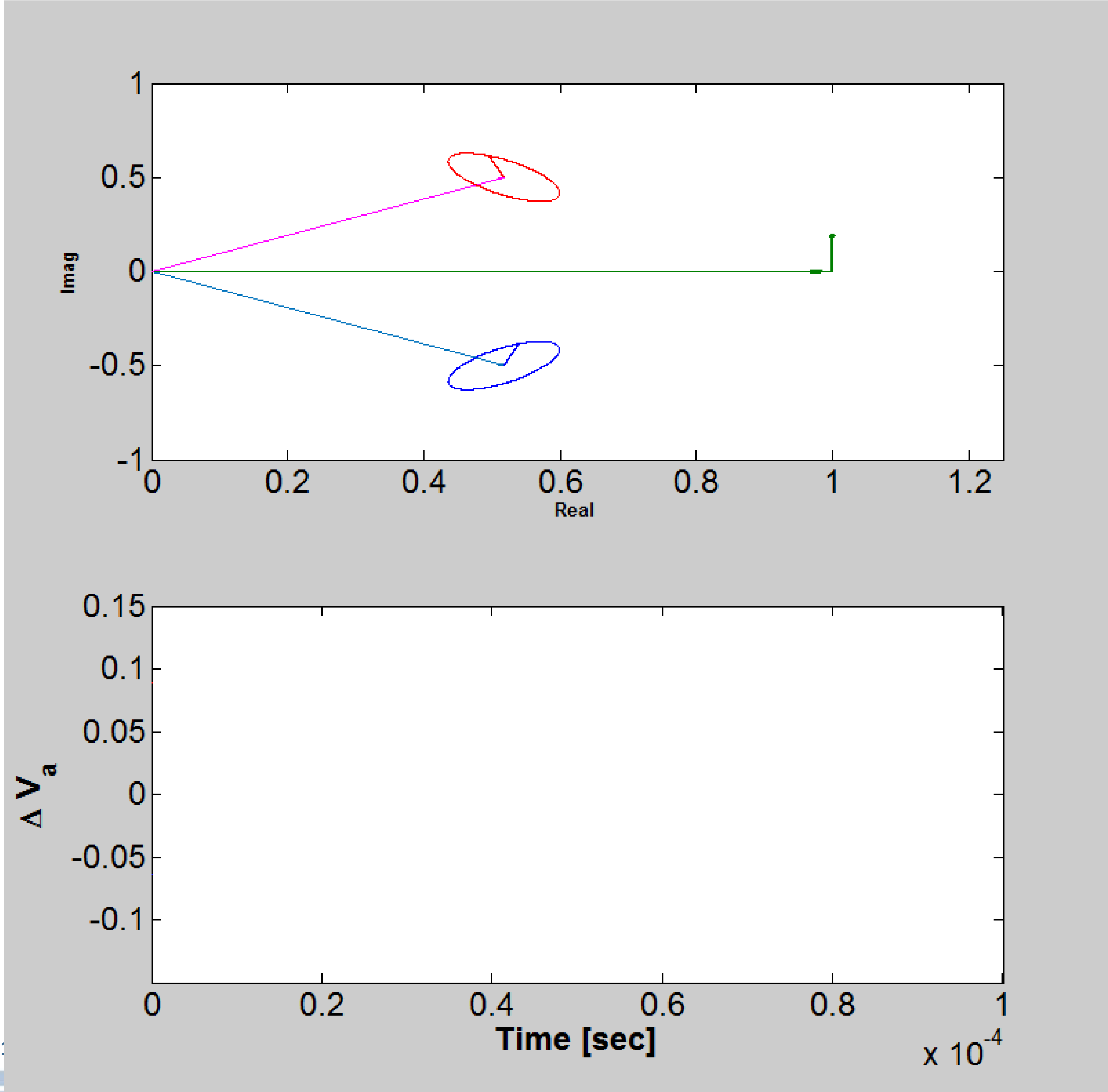
- ☐ 4th order system
  - ▪ Small signal model
  - ▪ no I_B amp variation (e.g. shape)
- ☐ Stability determined by roots of characteristic equation

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

Low-Current Limit

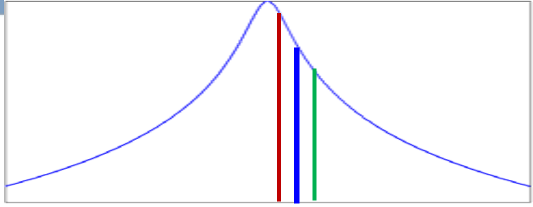
$$0 < \frac{\tan\phi_Z}{\cos\phi_S} < \frac{V_o}{V_{br}}\sec^2\phi_Z$$

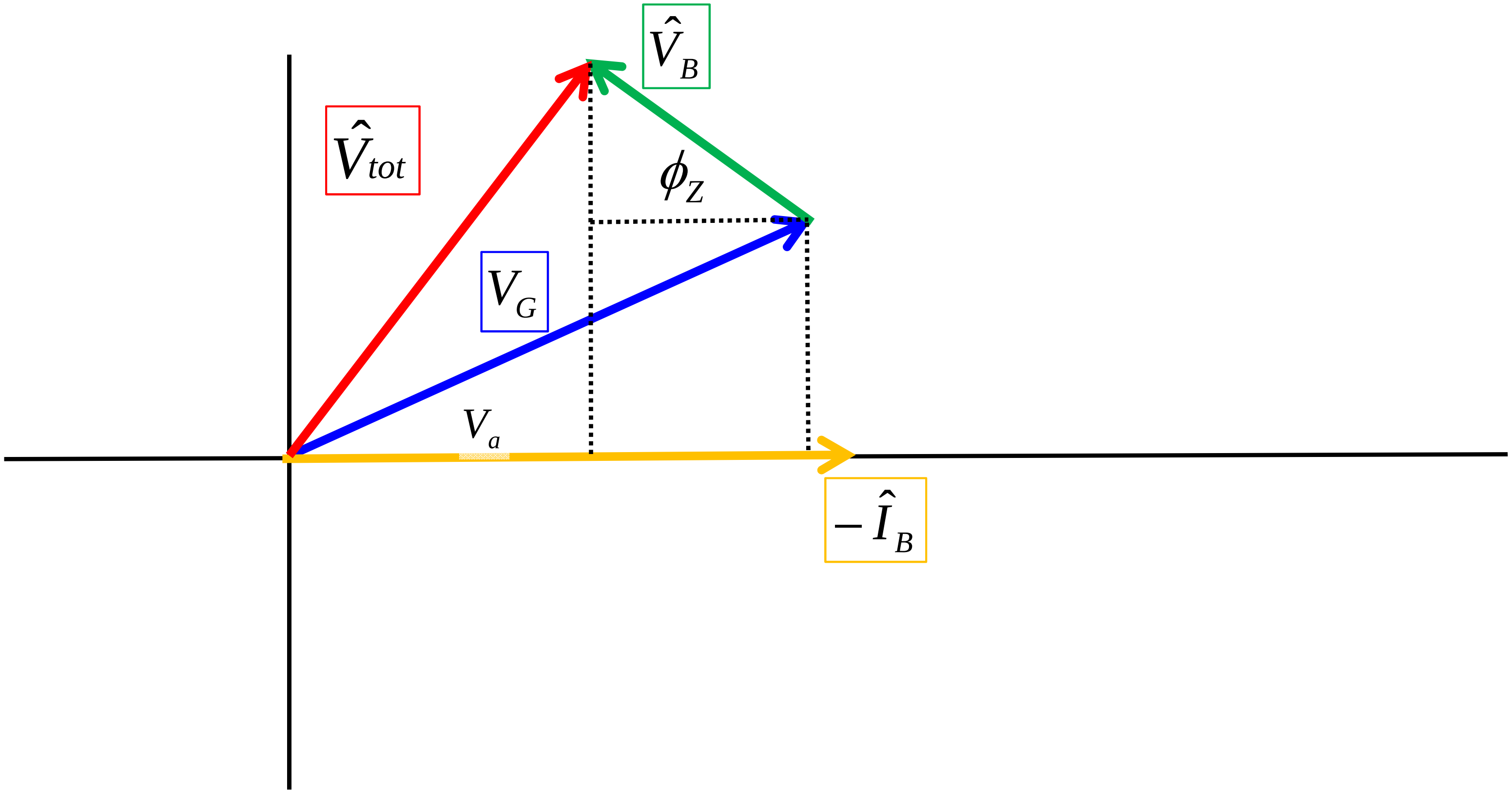




High-Current Limit

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

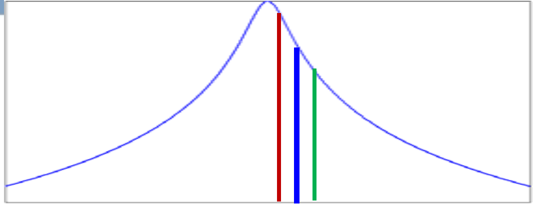


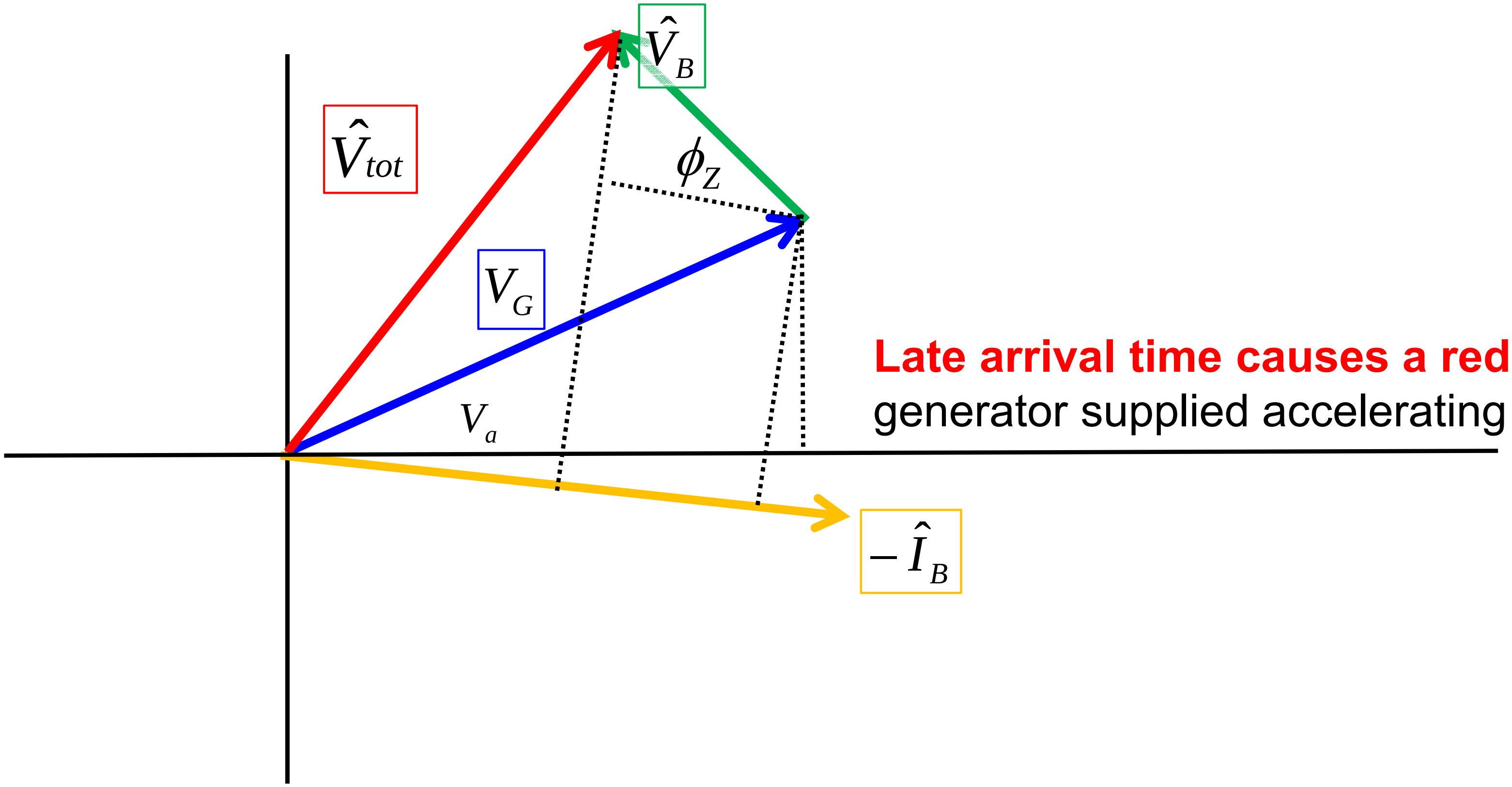


- ❑ P.B. Wilson’s physical interpretation: The high-current stability limit is reached when the beam rides on the ***crest*** of the ***generator*** voltage

High-Current Limit

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



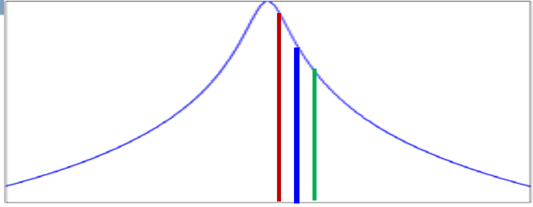


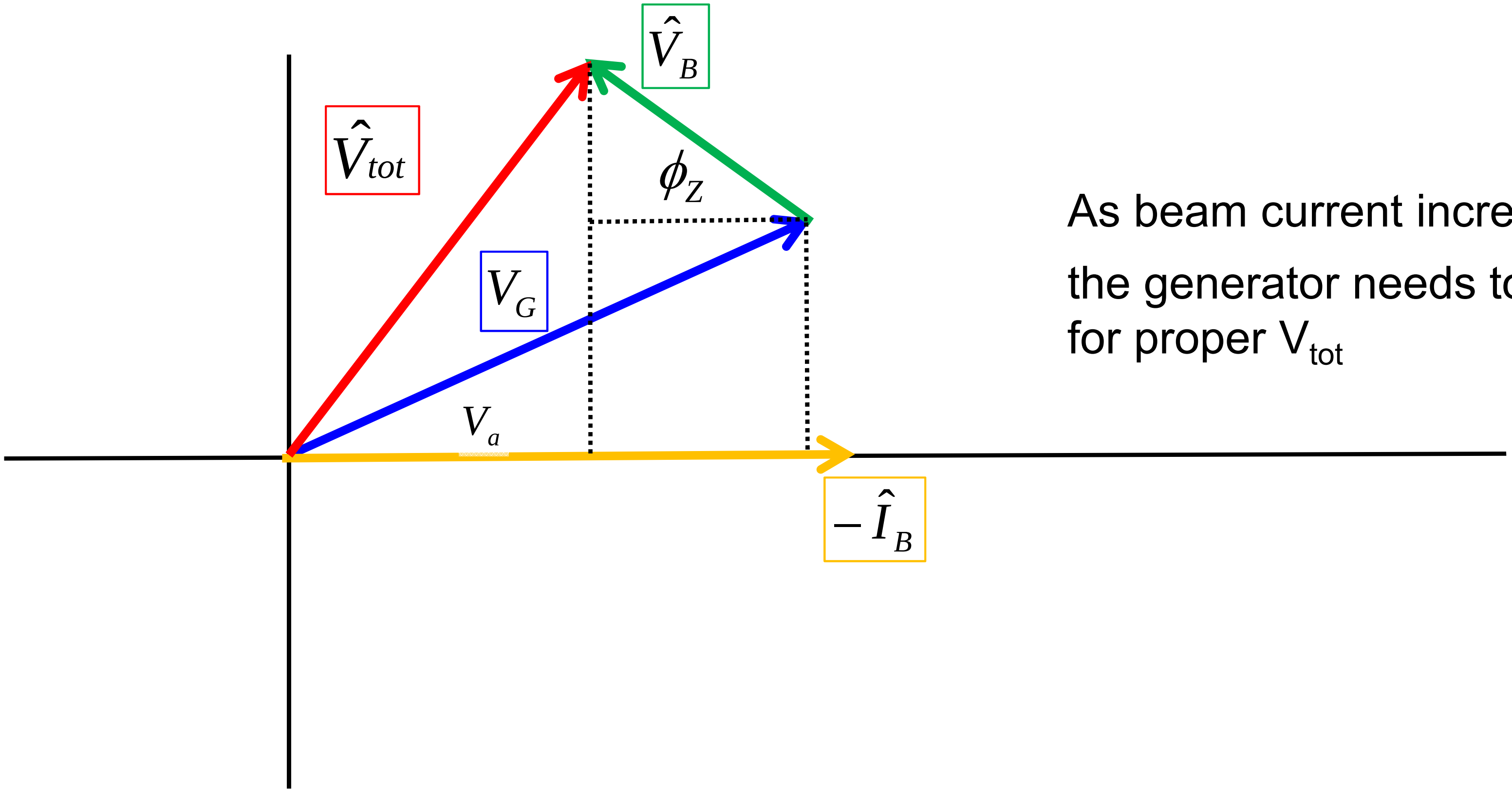
Late arrival time causes a reduction in generator supplied accelerating voltage

- ☐ P.B. Wilson's physical interpretation: The high-current stability limit is reached when the beam rides on the ***crest*** of the ***generator*** voltage

High-Current Limit

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





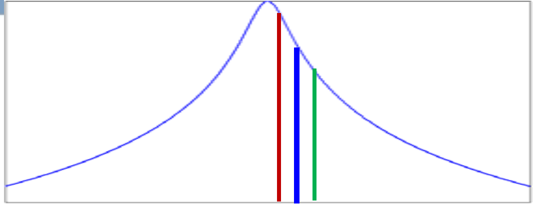
As beam current increases….

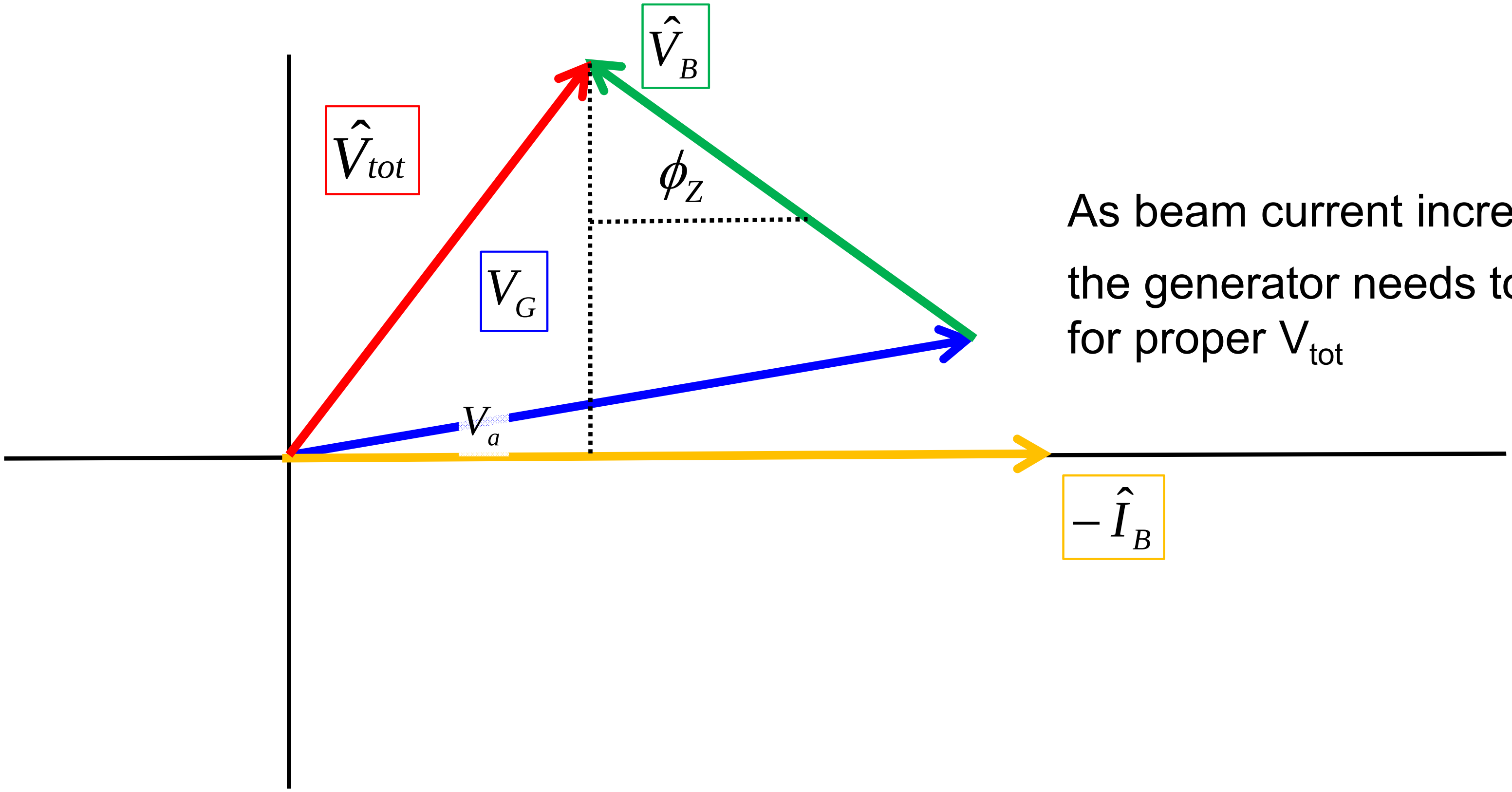
the generator needs to be adjusted for proper V_{tot}

- ☐ P.B. Wilson’s physical interpretation: The high-current stability limit is reached when the beam rides on the ***crest*** of the ***generator*** voltage

High-Current Limit

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





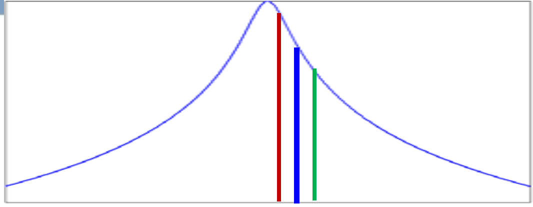
As beam current increases….

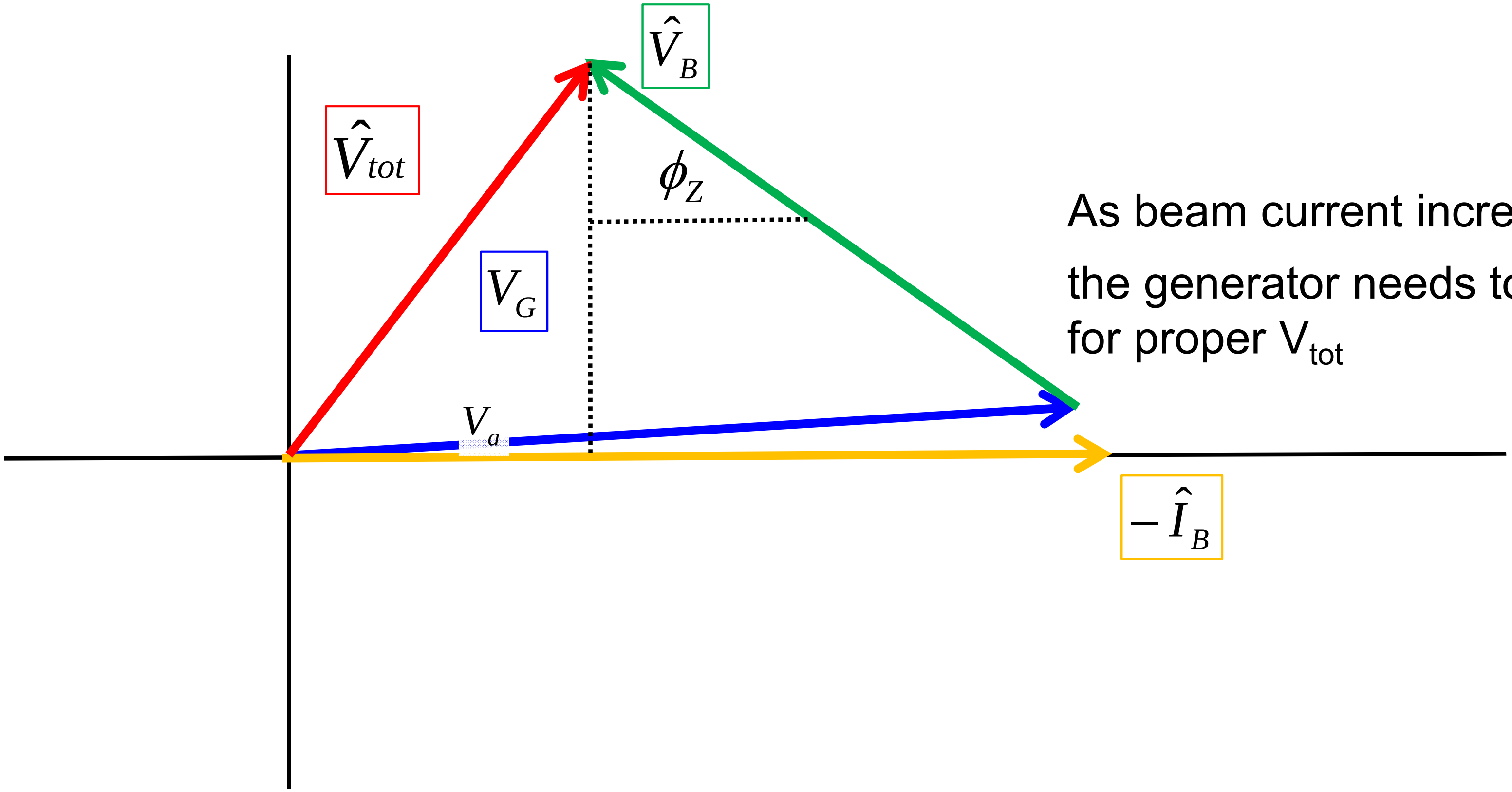
the generator needs to be adjusted for proper V_{tot}

- ☐ P.B. Wilson’s physical interpretation: The high-current stability limit is reached when the beam rides on the ***crest*** of the ***generator*** voltage

High-Current Limit

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





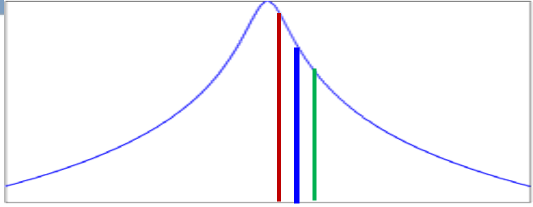
As beam current increases….

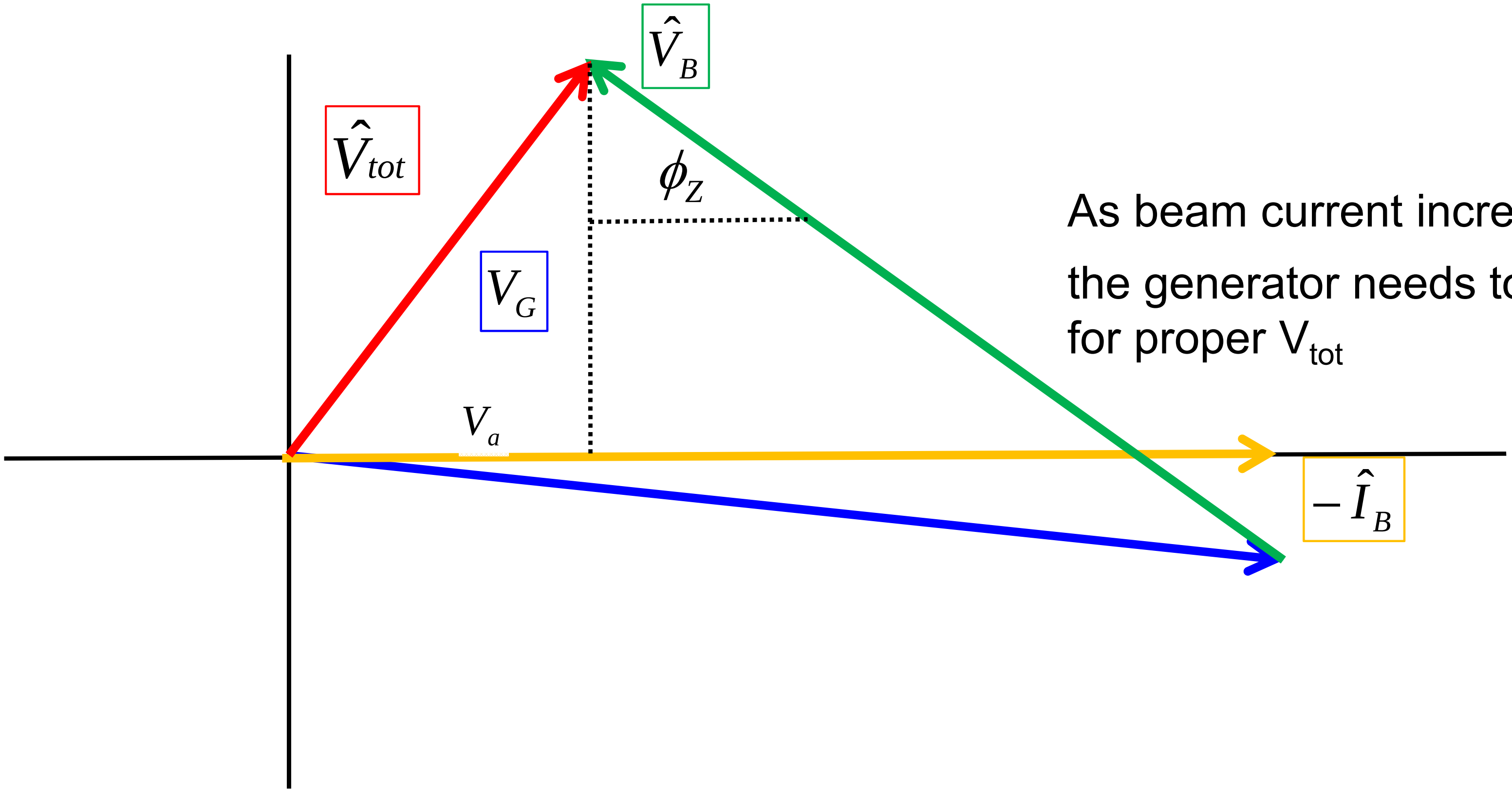
the generator needs to be adjusted for proper V_{tot}

- P.B. Wilson’s physical interpretation: The high-current stability limit is reached when the beam rides on the ***crest*** of the ***generator*** voltage

High-Current Limit

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





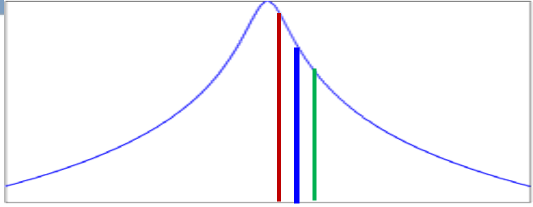
As beam current increases….

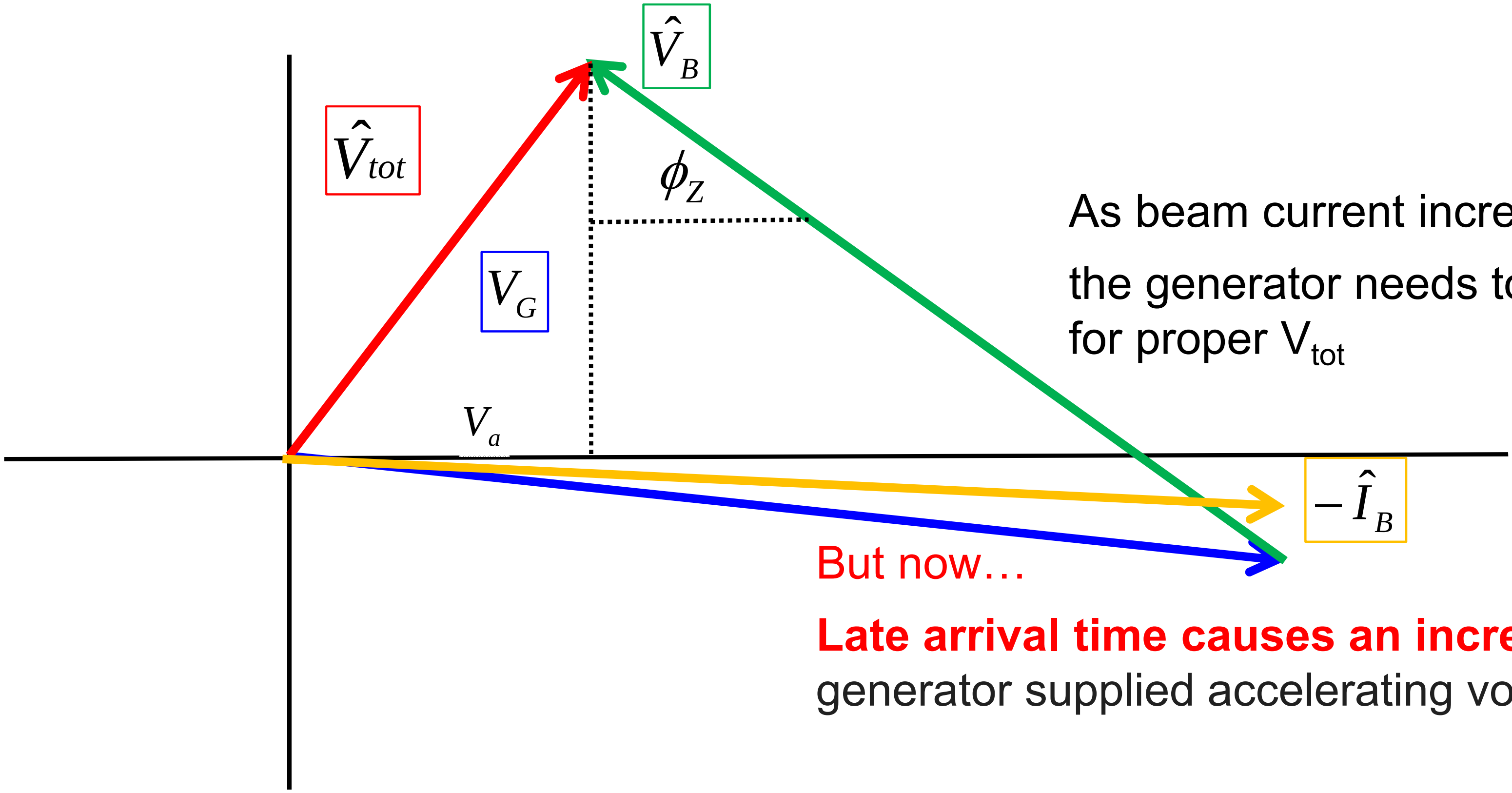
the generator needs to be adjusted for proper V_{tot}

- ☐ P.B. Wilson's physical interpretation: The high-current stability limit is reached when the beam rides on the ***crest*** of the ***generator*** voltage

High-Current Limit

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





As beam current increases….

the generator needs to be adjusted for proper V_{tot}

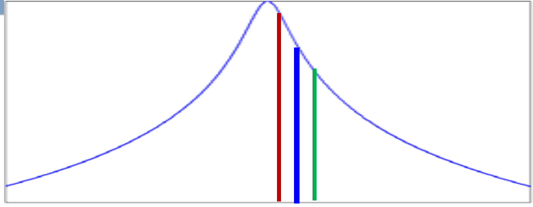
But now…

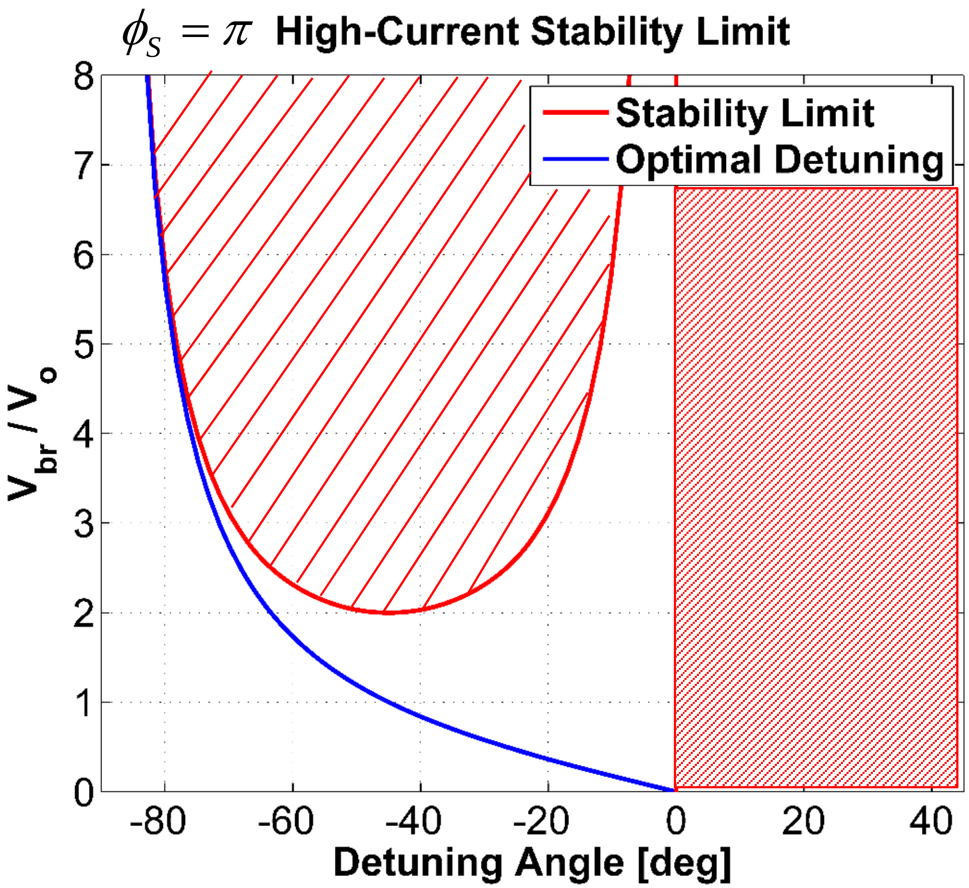
Late arrival time causes an increase in generator supplied accelerating voltage

- ❑ P.B. Wilson’s physical interpretation: The high-current stability limit is reached when the beam rides on the ***crest*** of the ***generator*** voltage
  - ❑ Only the generator voltage can provide the effective restoring force

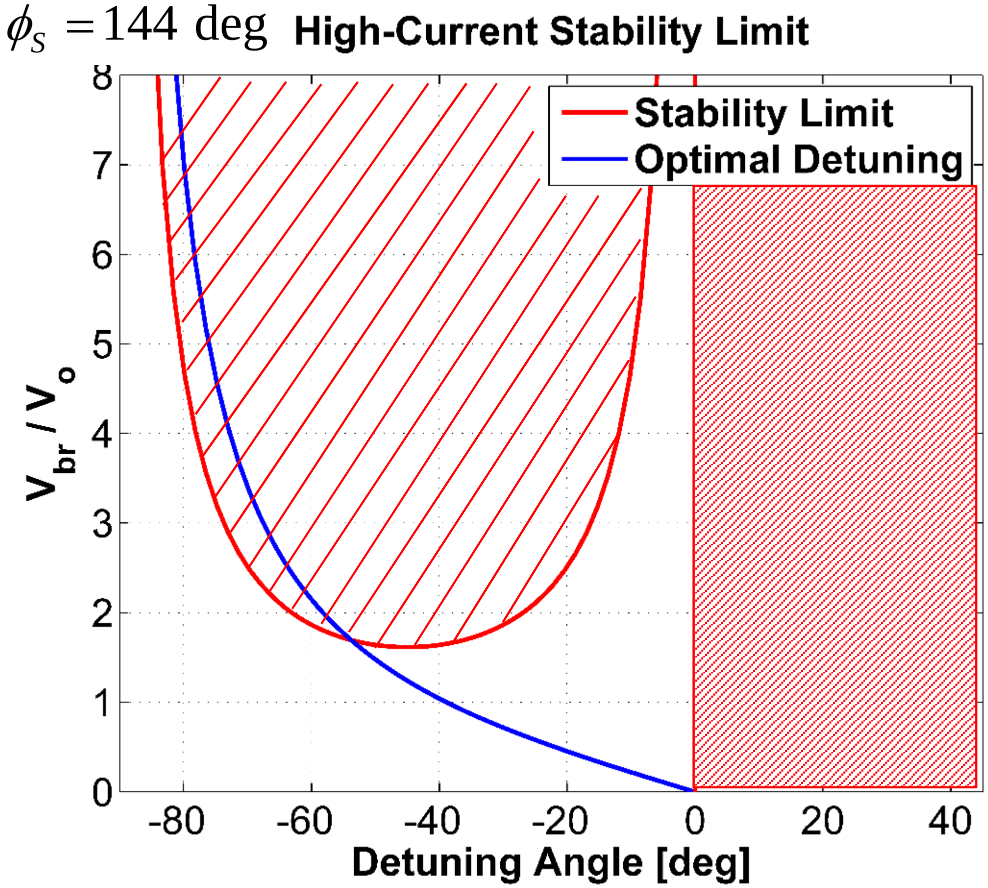
High-Current Limit

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

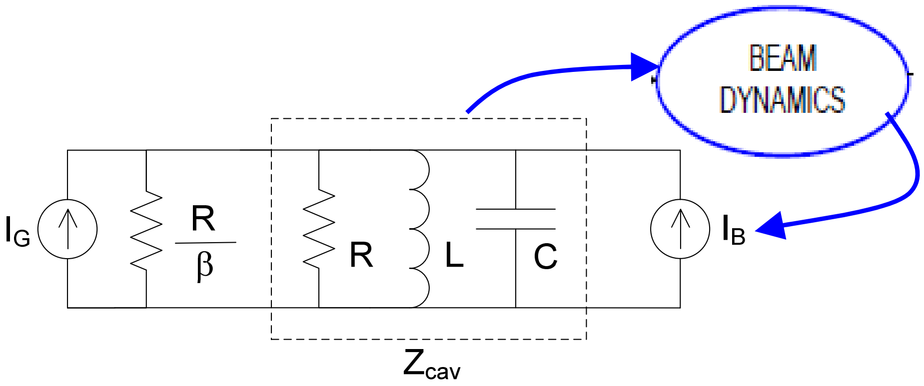




$\phi_S = \pi$ High-Current Stability Limit



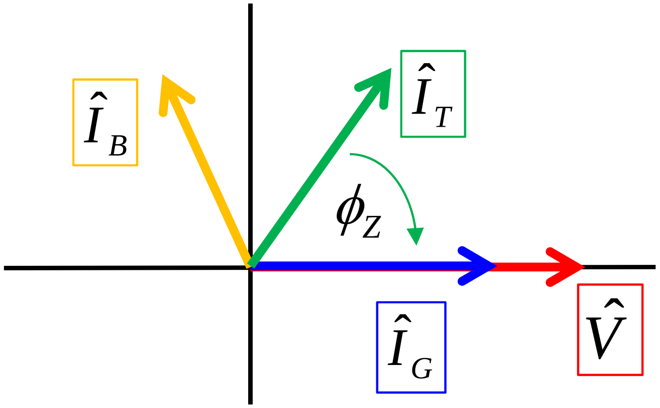
$\phi_S = 144$ deg High-Current Stability Limit



- Not only do we have **opposite detuning sign for harmonic vs. main rf**
- But….

Accelerating Cavity Above Transition

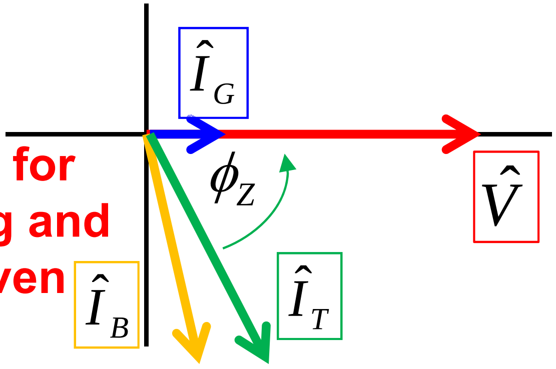
=> tan < 0 => $f_{cav} < f_{rf}$

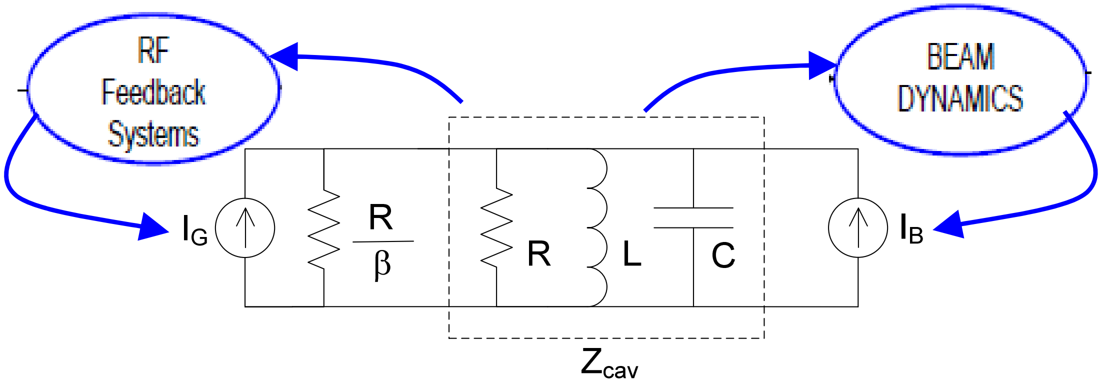


Bunch Lengthening Cavity Above Transition

=> tan > 0 => $f_{cav} > f_{rf}$

Zero P_g needed for proper coupling and detuning for given beam current

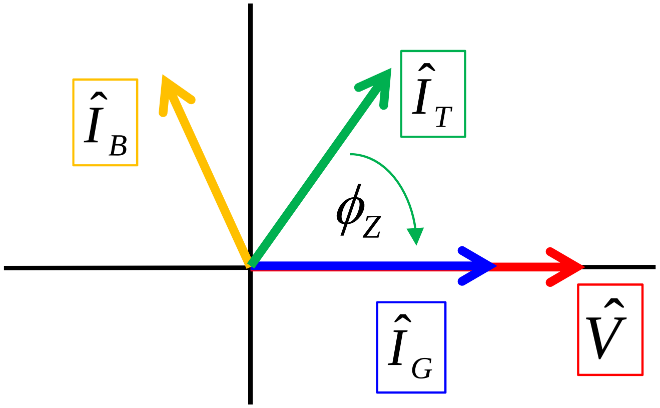




- Not only do we have **opposite detuning sign for harmonic vs. main rf**
- But….we also have **RF Feedback** in the main rf system which **effectively lowers the impedance** it presents to the beam

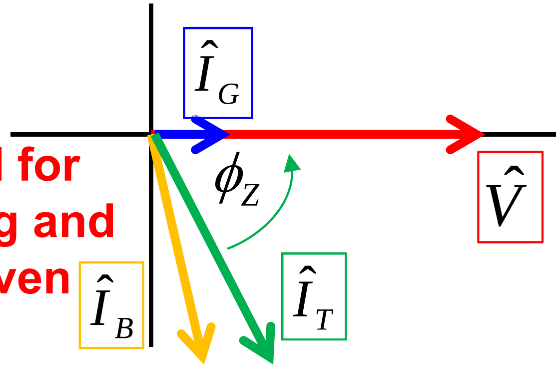
Accelerating Cavity Above Transition

=> $\tan < 0$ => $f_{cav} < f_{rf}$



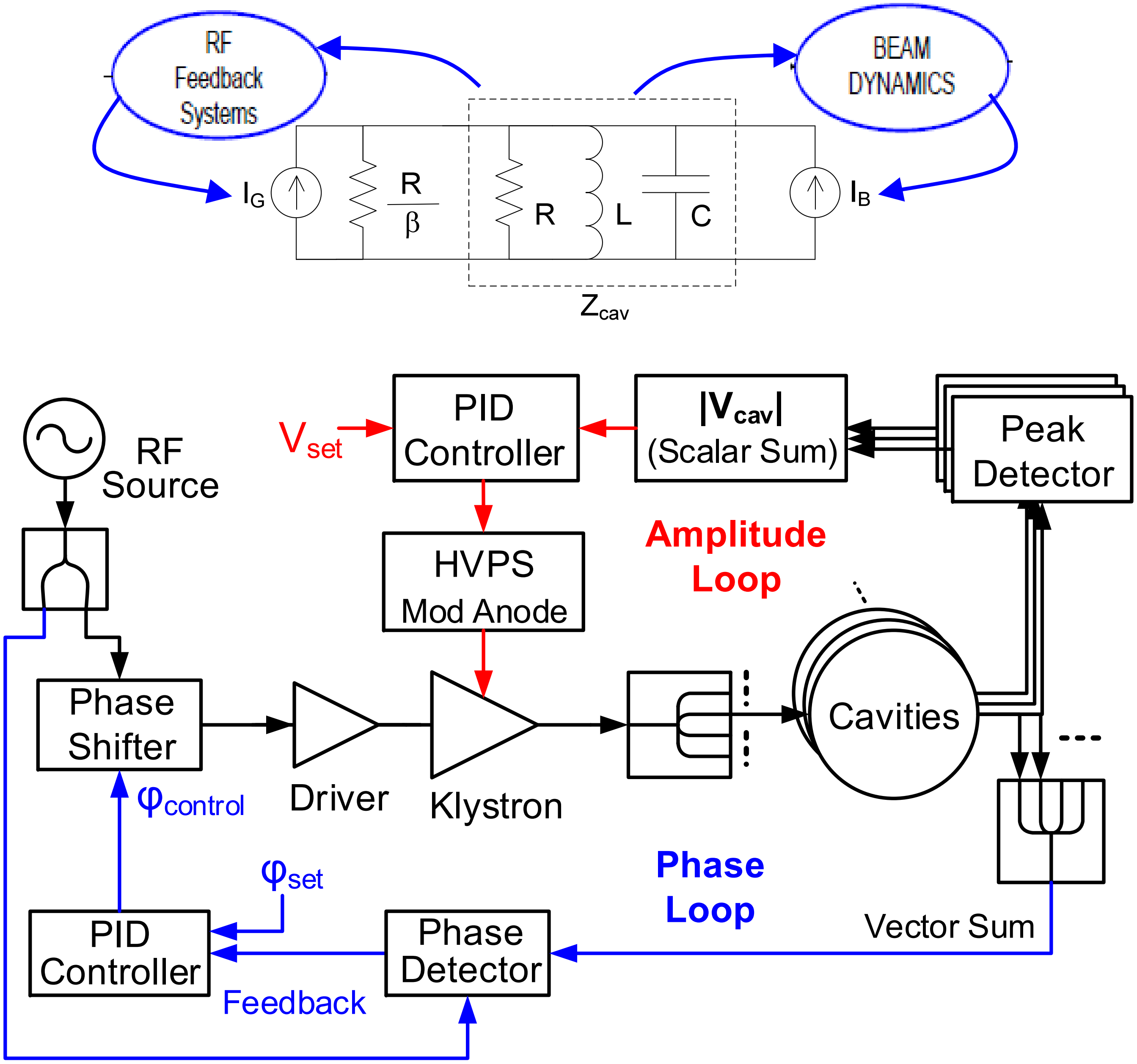
Bunch Lengthening Cavity Above Transition

=> $\tan > 0$ => $f_{cav} > f_{rf}$

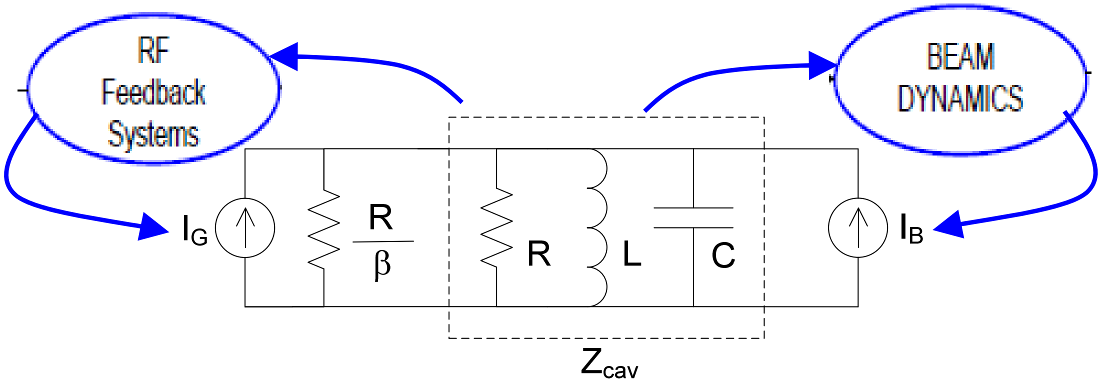


Zero P_g needed for proper coupling and detuning for given beam current


Storage Ring
RF Systems in 420



RF Feedback Systems
BEAM DYNAMICS
I_G
$\frac{R}{\beta}$
R
L
C
I_B
Z_{cav}
RF Source
V_{set}
PID Controller
$|V_{cav}|$ (Scalar Sum)
Peak Detector
HVPS Mod Anode
Amplitude Loop
Phase Shifter
Driver
Klystron
Cavities
$\varphi_{control}$
φ_{set}
Phase Loop
PID Controller
Phase Detector
Vector Sum
Feedback



RF Feedback Systems

BEAM DYNAMICS

I_G

$\frac{R}{\beta}$

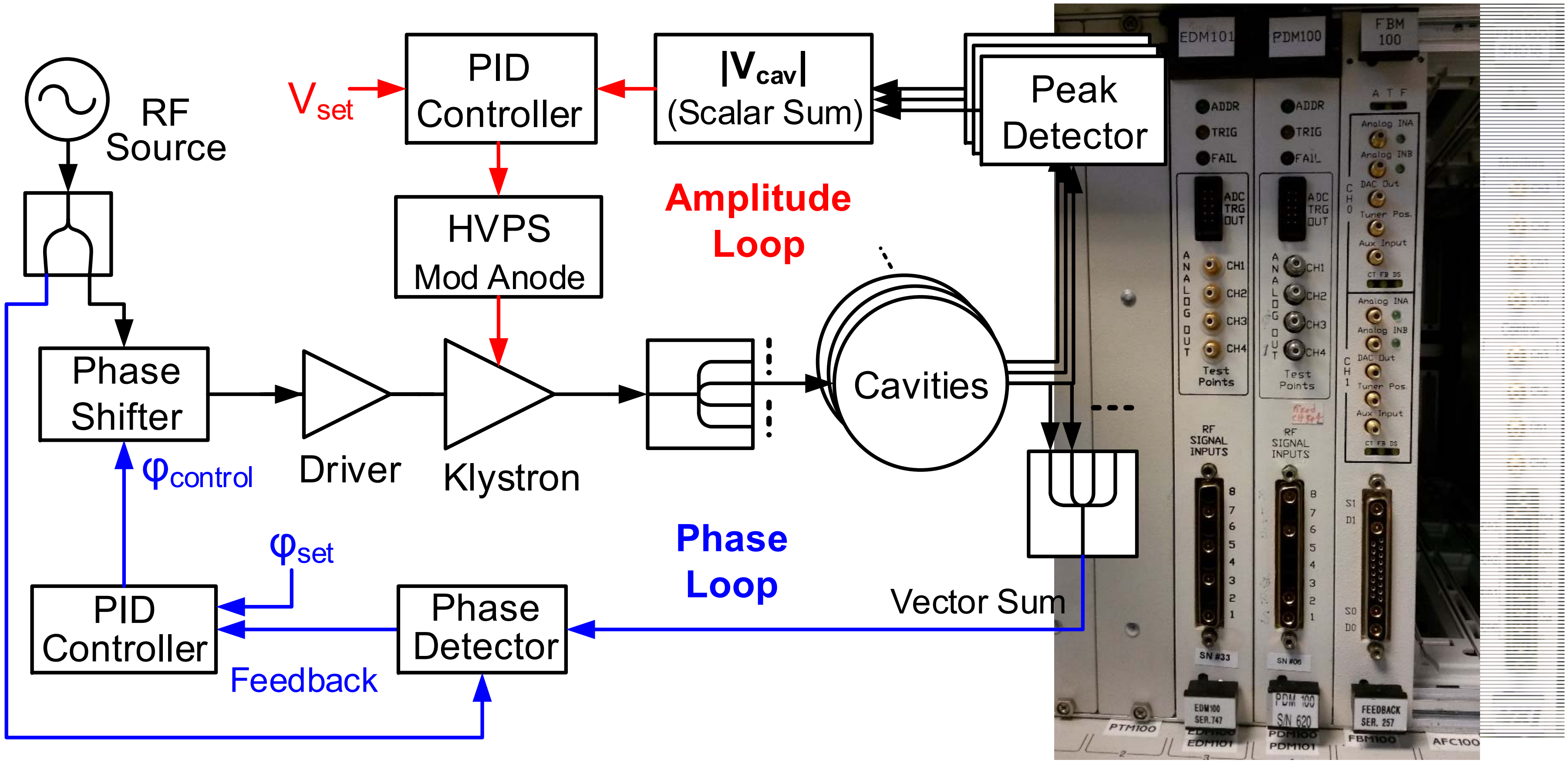
R

L

C

I_B

Z_{cav}



RF Source

V_{set}

PID Controller

$|V_{cav}|$ (Scalar Sum)

Peak Detector

HVPS Mod Anode

Amplitude Loop

Phase Shifter

Driver

Klystron

Cavities

$\varphi_{control}$

φ_{set}

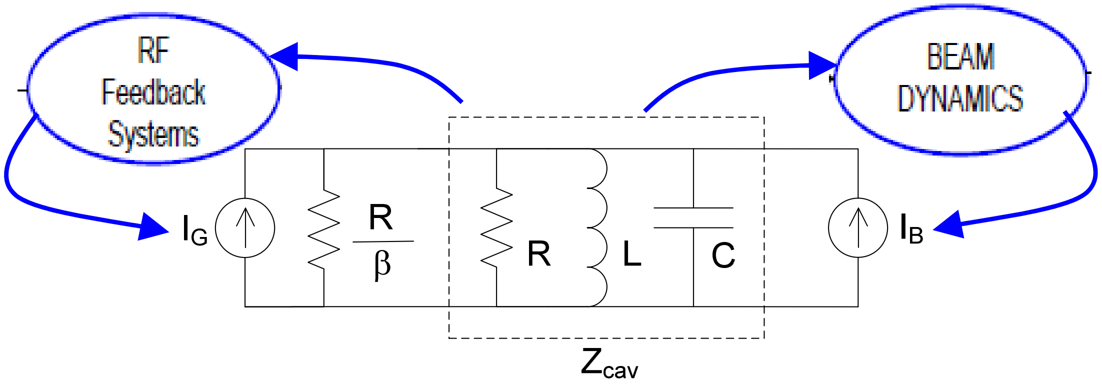
PID Controller

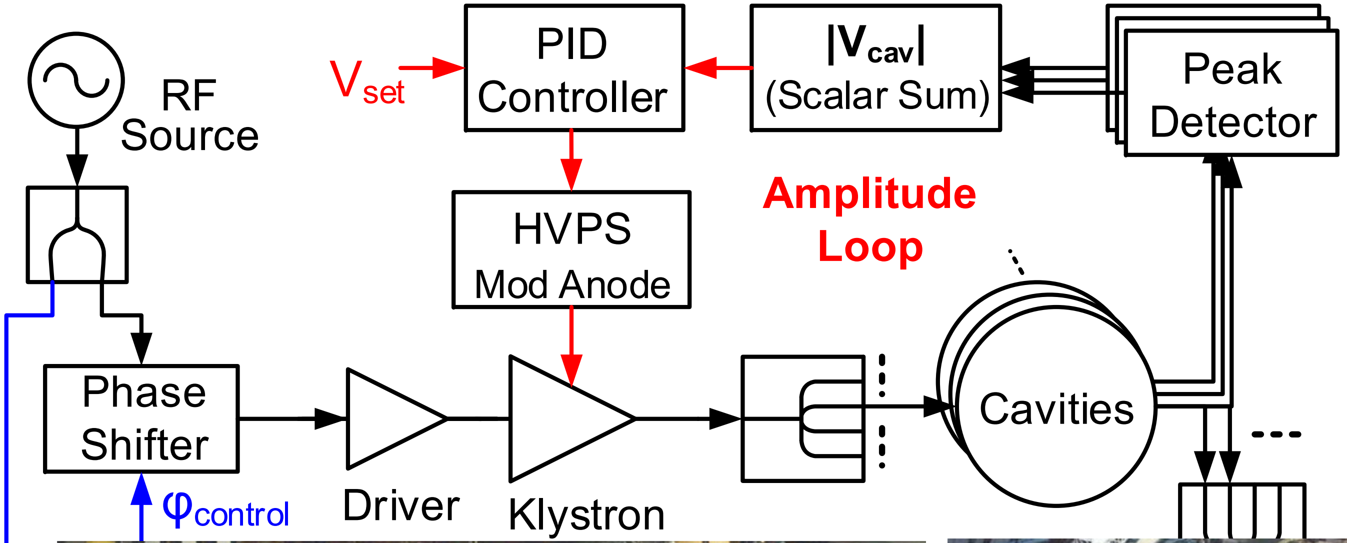
Phase Detector

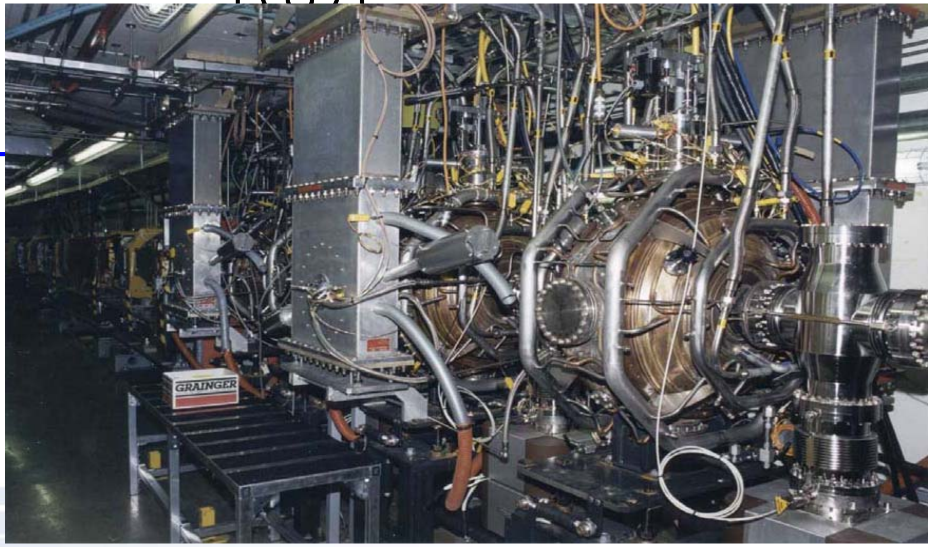
Feedback

Phase Loop

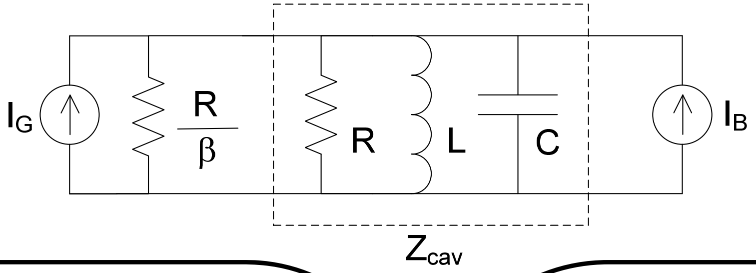
Vector Sum


RF
Feedback
Systems
BEAM
DYNAMICS
I_G
$\frac{R}{\beta}$
R
L
C
I_B
Z_{cav}


RF
Source
V_{set}
PID
Controller
$|V_{cav}|$
(Scalar Sum)
Peak
Detector
HVPS
Mod Anode
Amplitude
Loop
Phase
Shifter
Driver
Klystron
Cavities
$\varphi_{control}$

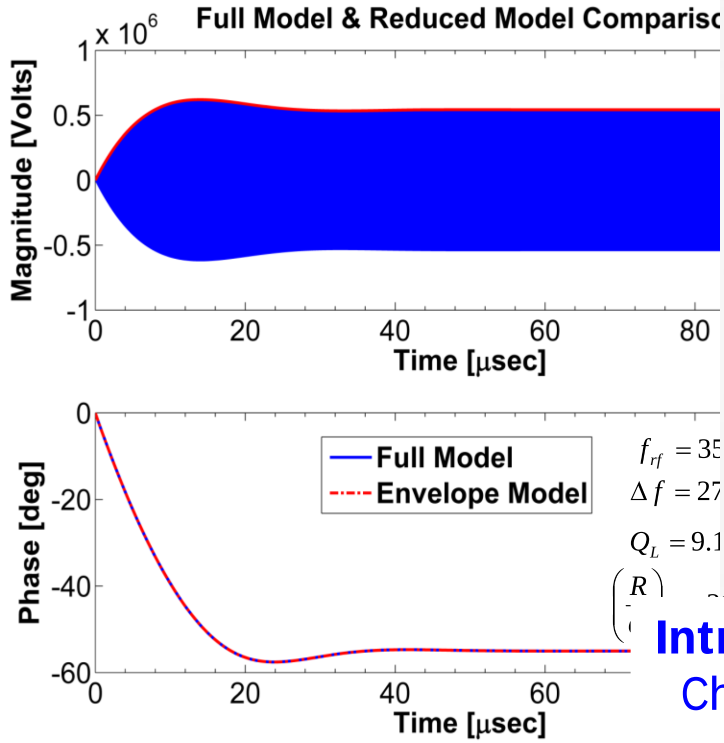

GRAINGER

Cavity Model



RF-TN-2014-002
ICMS#: aps_1660384

Envelope Equations: **Continuous-T**

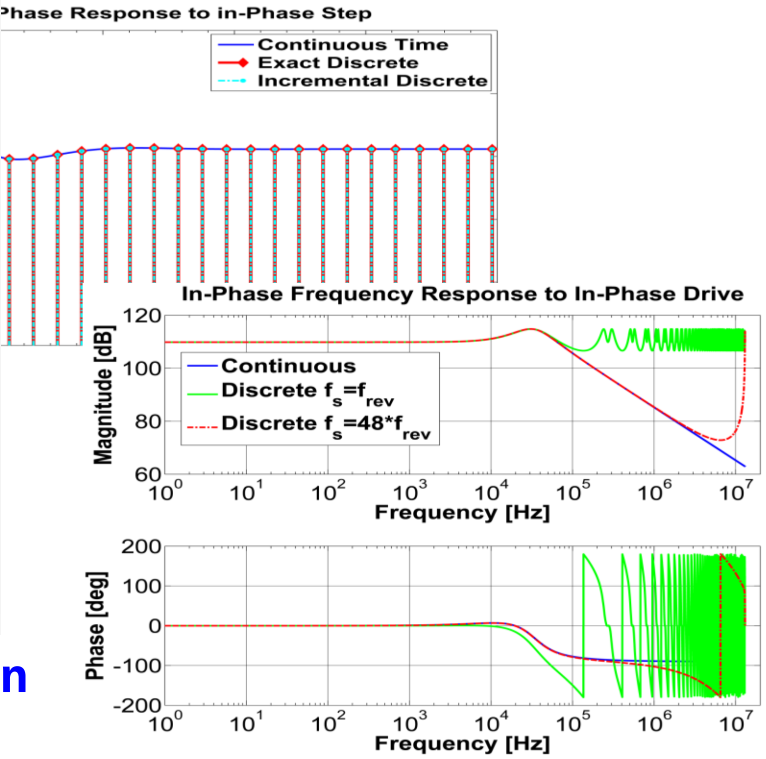


Introduced Phasor Notation

Charles Proteus Steinmetz

(1865 – 1923)

nvelope Equations: **Discrete-Time**



$$\begin{bmatrix}\dot{V}_I\\ \dot{V}_Q\end{bmatrix} = \begin{bmatrix}-\sigma & -\Delta\omega\\ \Delta\omega & -\sigma\end{bmatrix}\begin{bmatrix}V_I\\ V_Q\end{bmatrix} + \begin{bmatrix}k & 0\\ 0 & k\end{bmatrix}\begin{bmatrix}I_I\\ I_Q\end{bmatrix}$$

$$\sigma = \frac{\omega_o}{2Q_L} \qquad \Delta\omega \equiv \omega_o - \omega_{rf} \qquad k = \frac{\omega_o}{4}\left(\frac{R}{Q}\right)_a$$

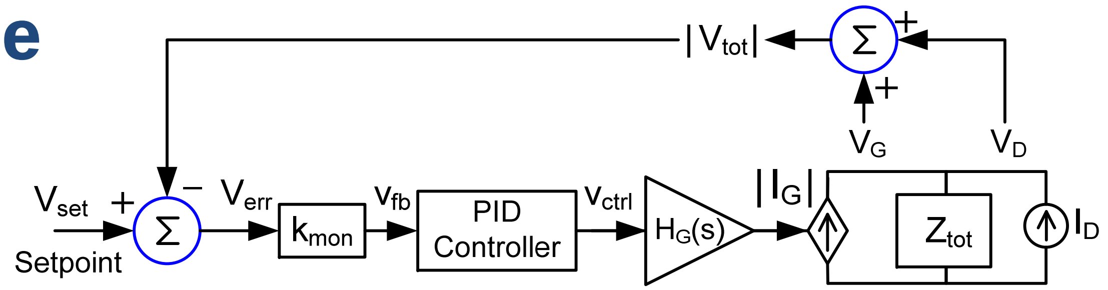
$$x(n+1) = \mathrm{A}_D\, x(n) + \mathrm{B}_D\, u(n)$$

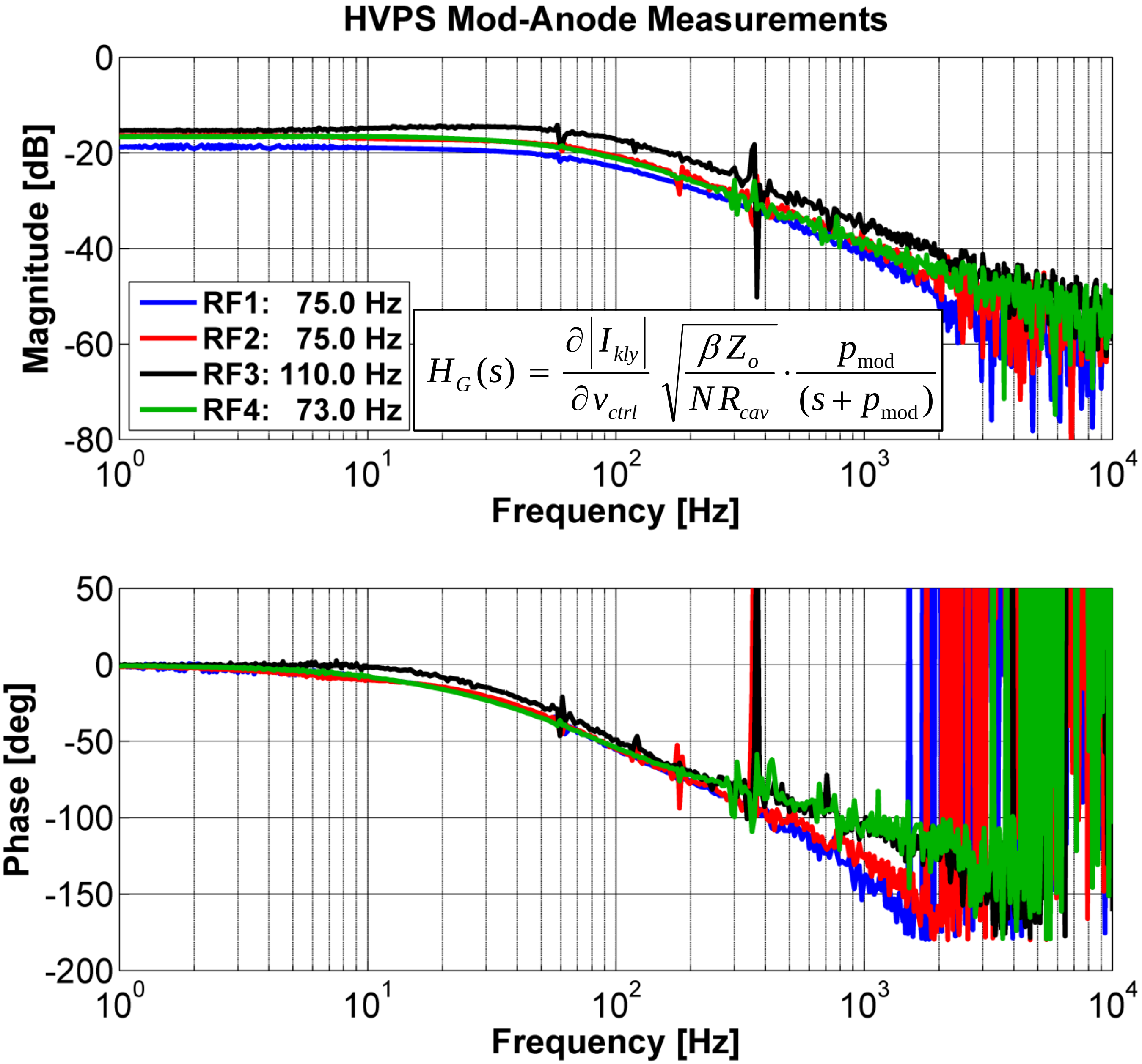
$$\mathrm{A}_D = e^{AT} = e^{-\sigma T}\begin{bmatrix}\cos\Delta\omega T & -\sin\Delta\omega T\\ \sin\Delta\omega T & \cos\Delta\omega T\end{bmatrix} \qquad \mathrm{B}_D = \frac{k}{\sigma^2 + \Delta\omega^2}\begin{bmatrix}\alpha & \beta\\ -\beta & \alpha\end{bmatrix}$$

$$\alpha = \Delta\omega\, e^{-\sigma T}\sin\Delta\omega T - \sigma e^{-\sigma T}\cos\Delta\omega T + \sigma$$

$$\beta = \sigma e^{-\sigma T}\sin\Delta\omega T + \Delta\omega\, e^{-\sigma T}\cos\Delta\omega T - \Delta\omega$$

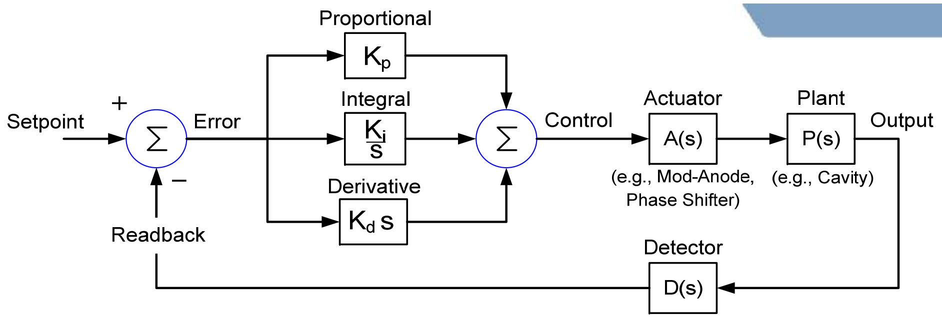
HVPS Mod-Anode (Klystron)



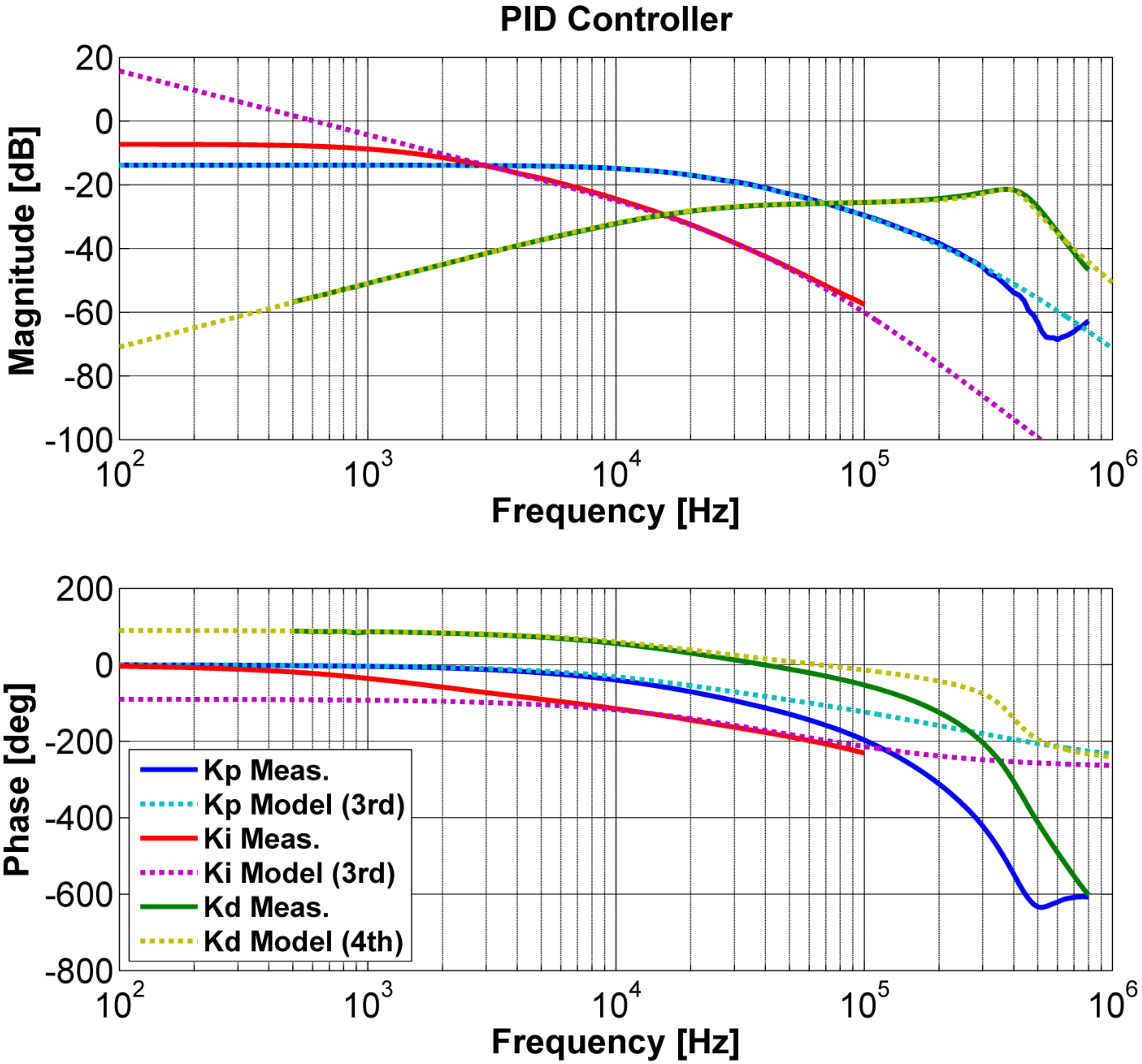

HVPS Mod-Anode Measurements

$$H_G(s) = \frac{\partial |I_{kly}|}{\partial v_{ctrl}} \sqrt{\frac{\beta Z_o}{N R_{cav}}} \cdot \frac{p_{\mathrm{mod}}}{(s+p_{\mathrm{mod}})}$$

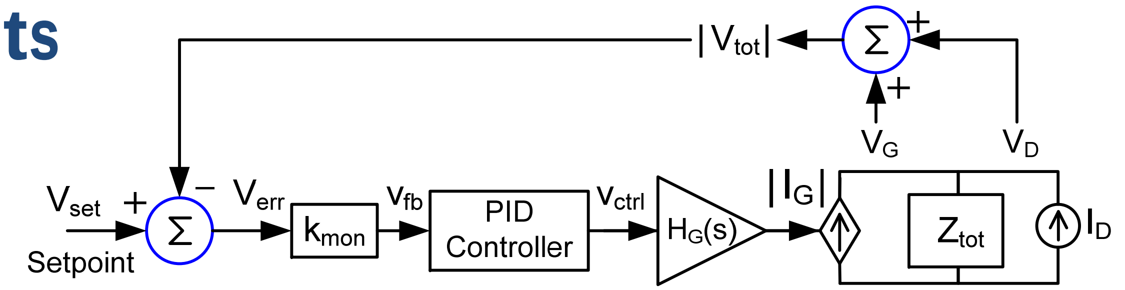
PID Controller

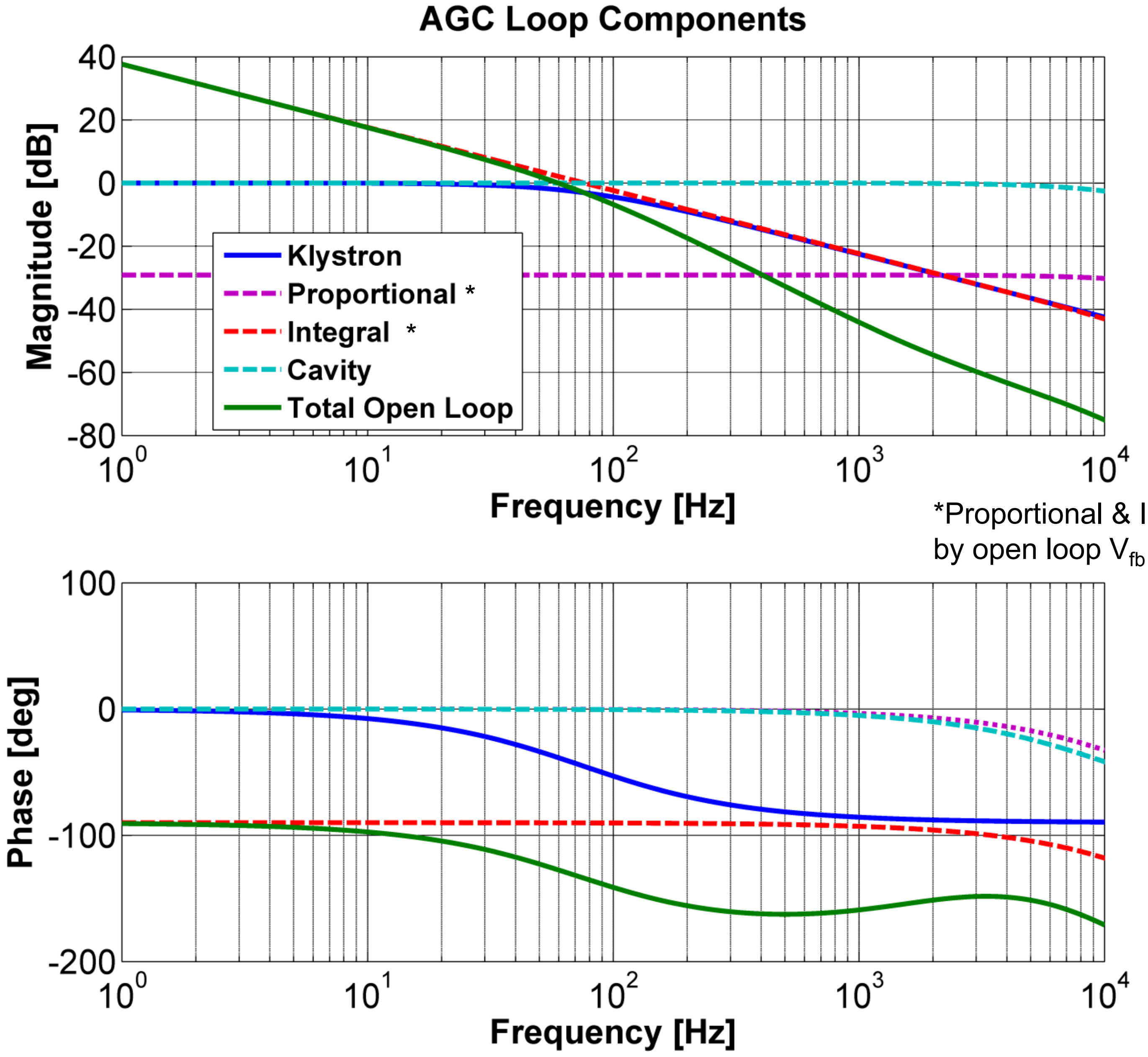


Proportional
K_p
Integral
$\frac{K_i}{s}$
Derivative
$K_d\,s$
Setpoint
+
−
Error
Readback
Control
Actuator
A(s)
(e.g., Mod-Anode, Phase Shifter)
Plant
P(s)
(e.g., Cavity)
Output
Detector
D(s)



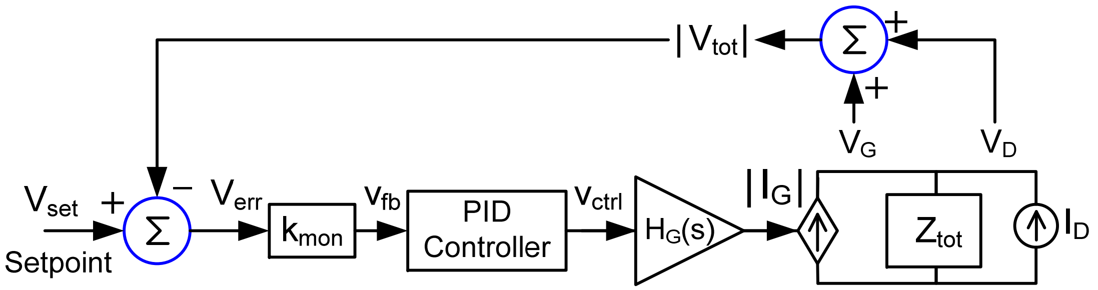
AGC Components



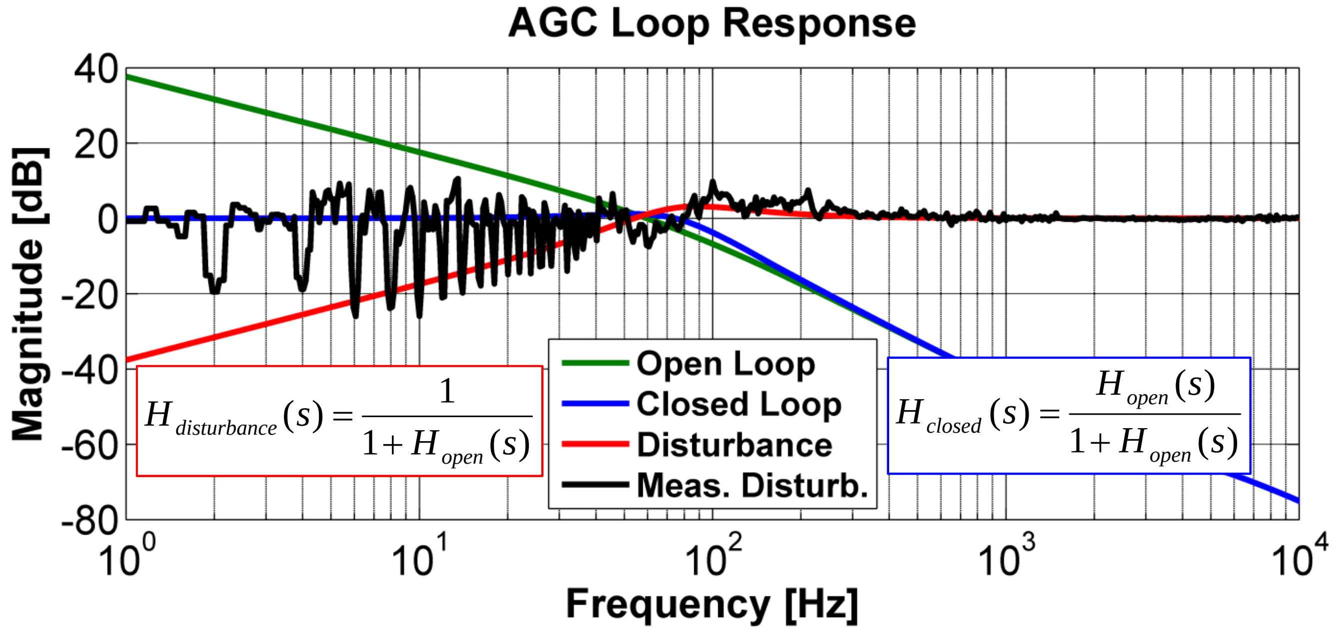


*Proportional & Integral Gain scaled by open loop V_{fb} / v_{ctrl} @resonance

AGC Loop



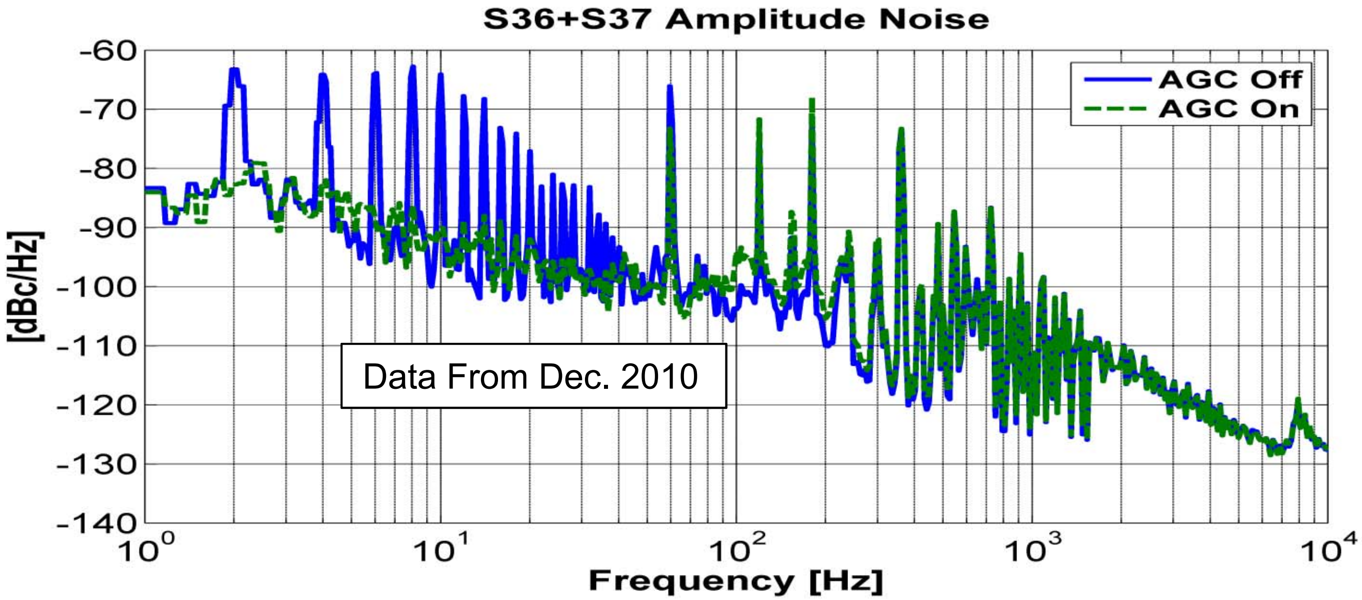
AGC Loop Response



$$H_{disturbance}(s) = \frac{1}{1 + H_{open}(s)}$$

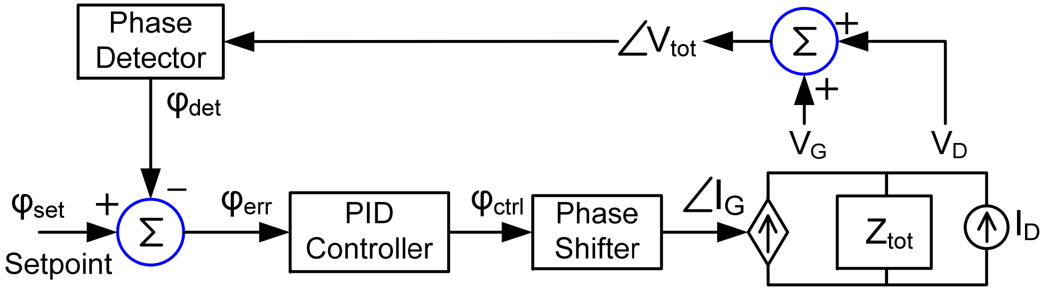
$$H_{closed}(s) = \frac{H_{open}(s)}{1 + H_{open}(s)}$$

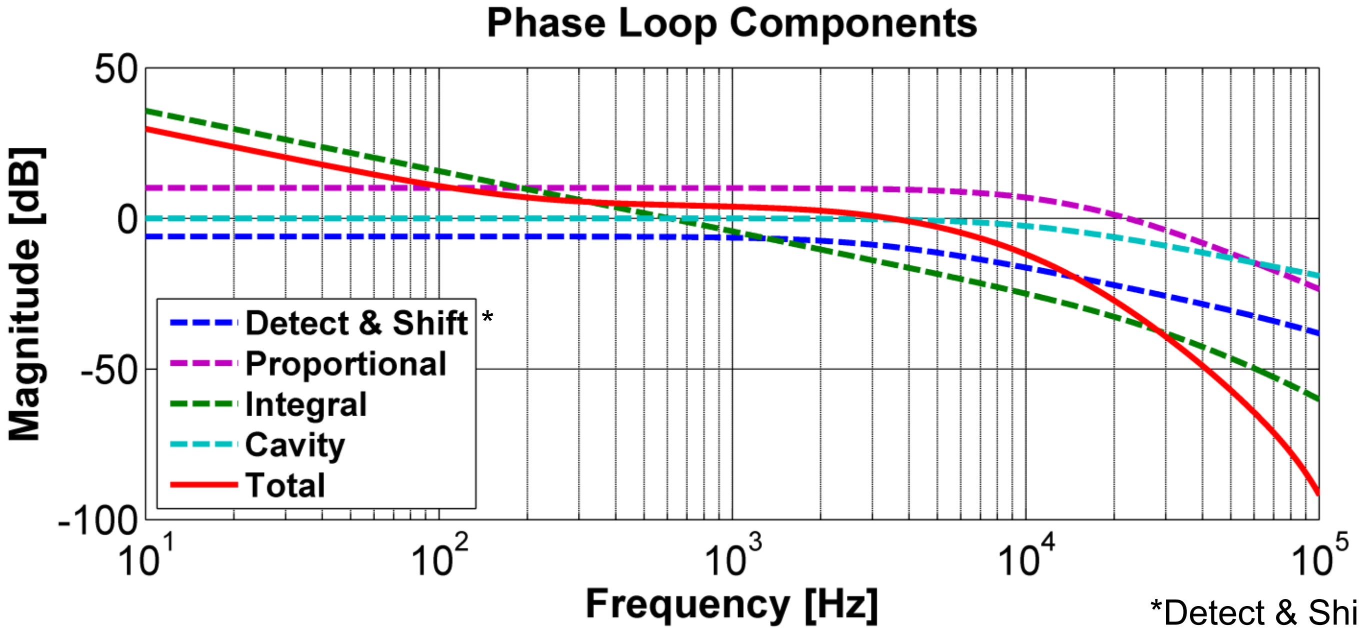
S36+S37 Amplitude Noise



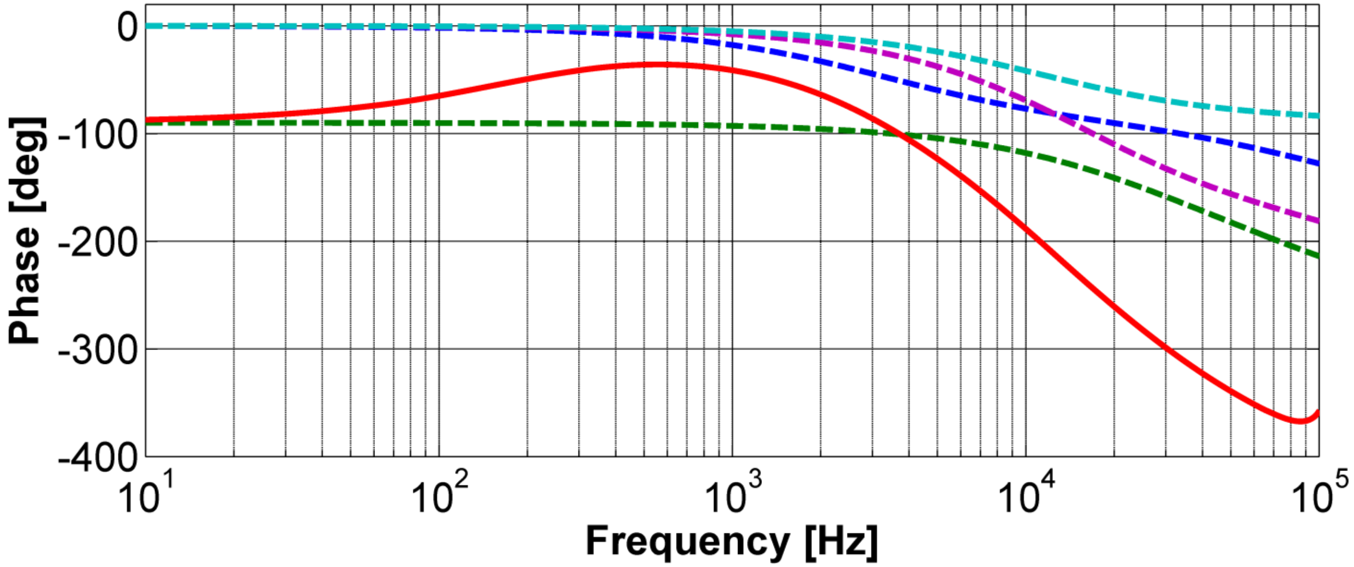
Data From Dec. 2010

Phase Loop

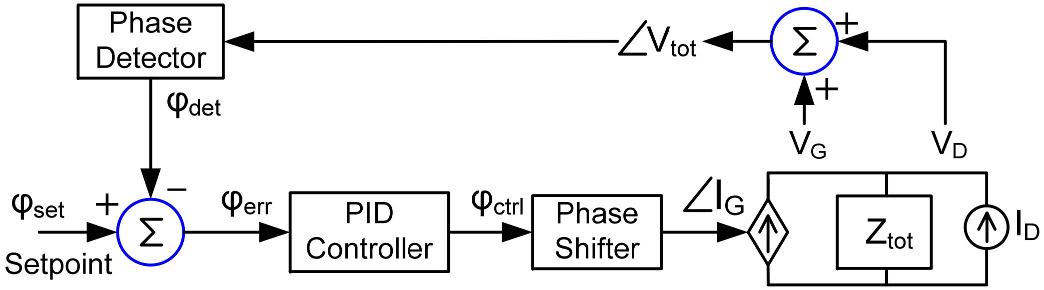


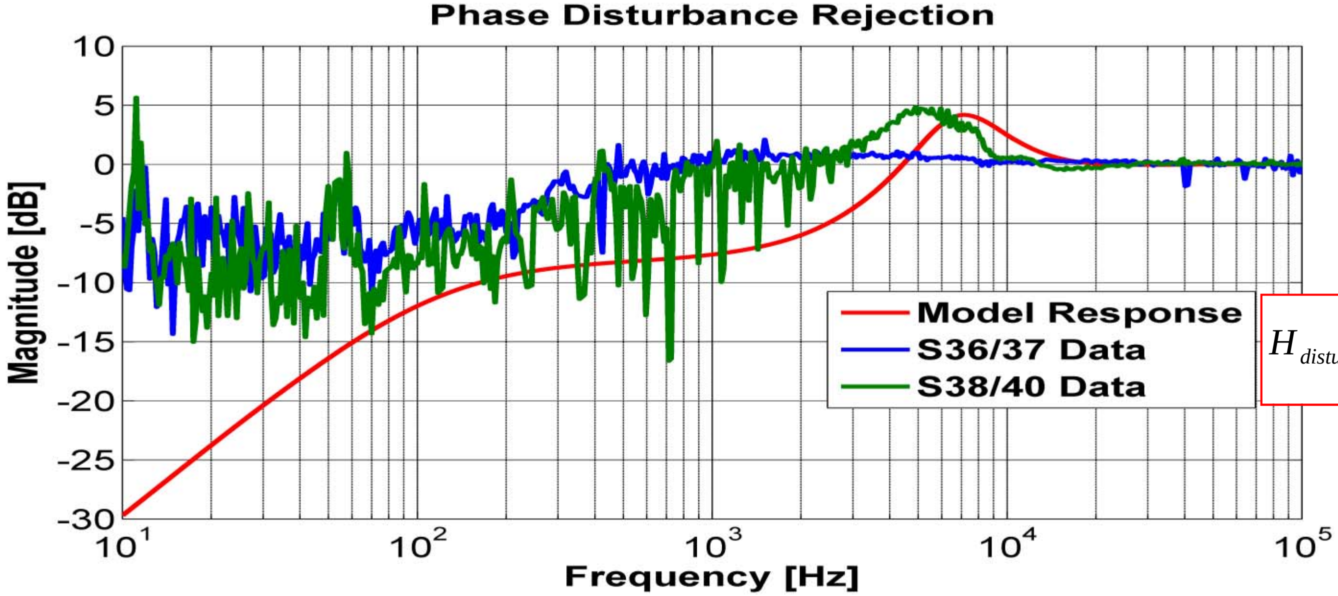


*Detect & Shift scaled by ½
due to Volts/deg gain difference

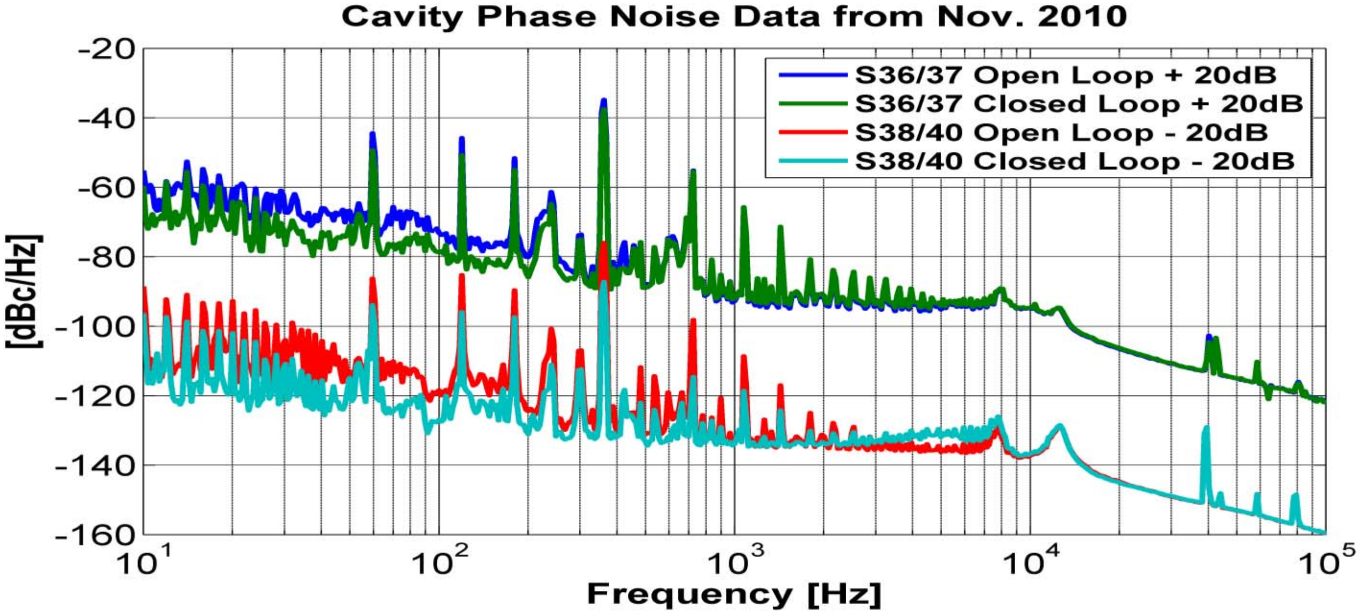


Phase Loop

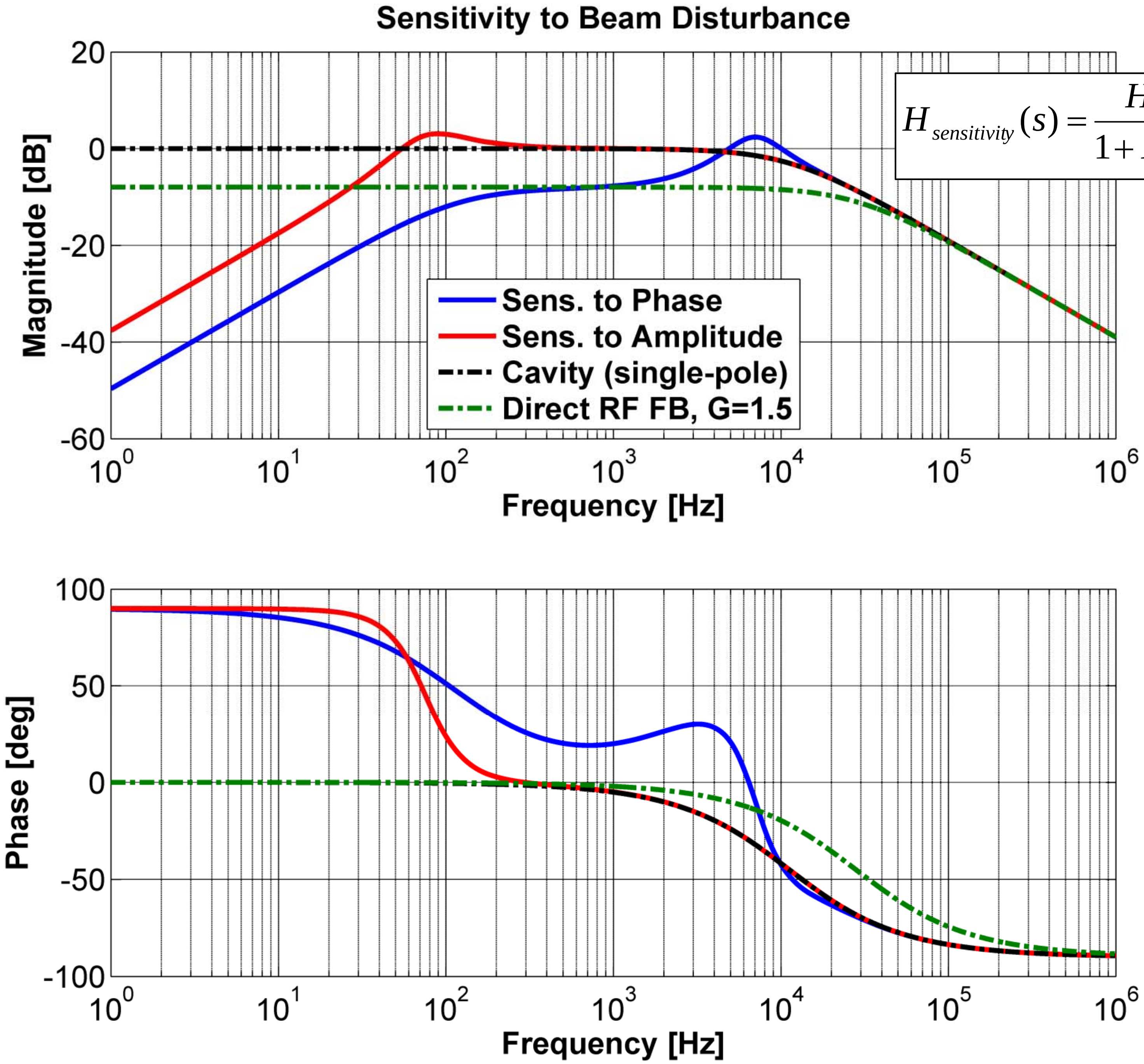




$$H_{disturbance}(s) = \frac{1}{1 + H_{open}(s)}$$

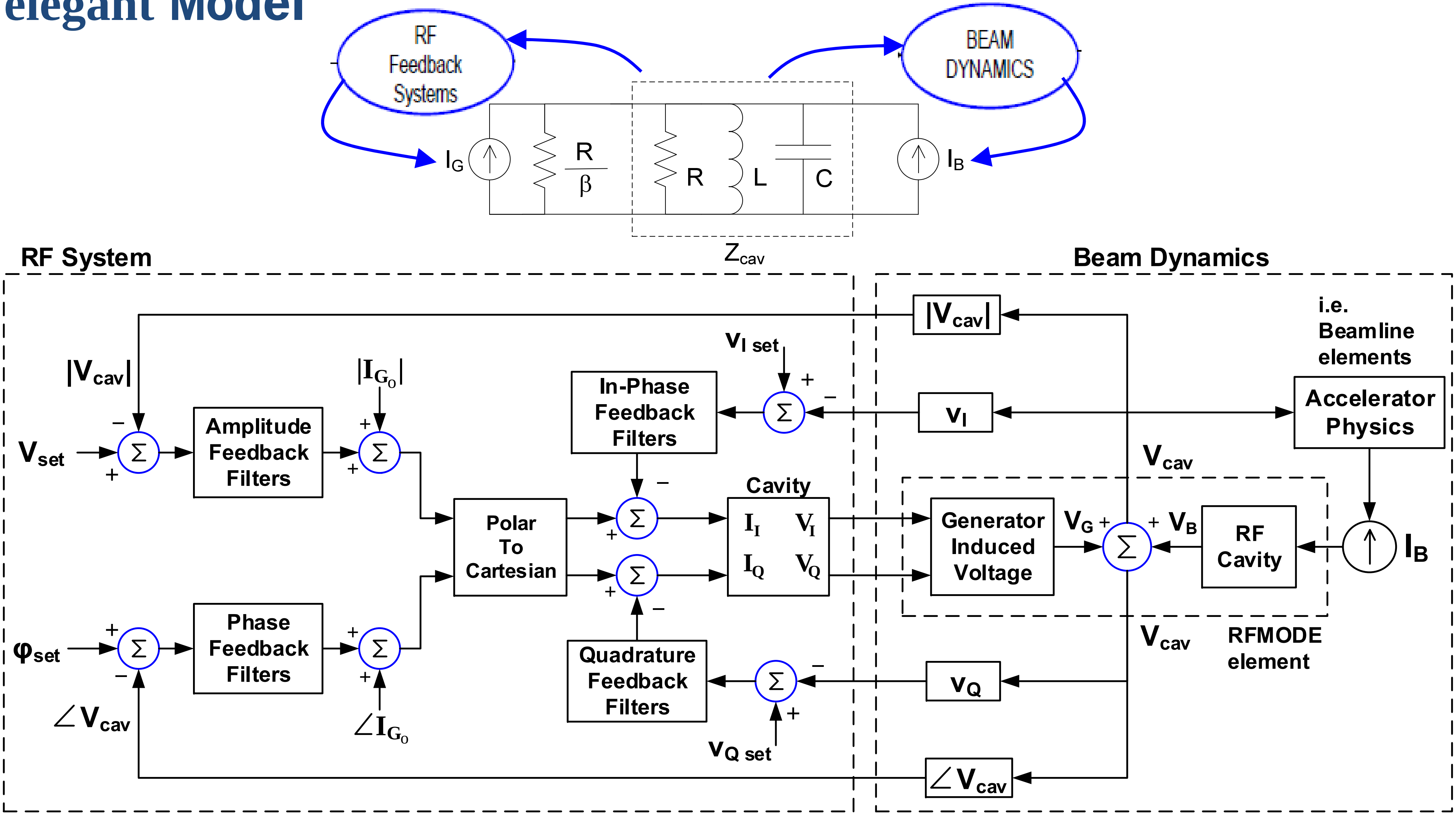


Sensitivity to Beam Disturbances



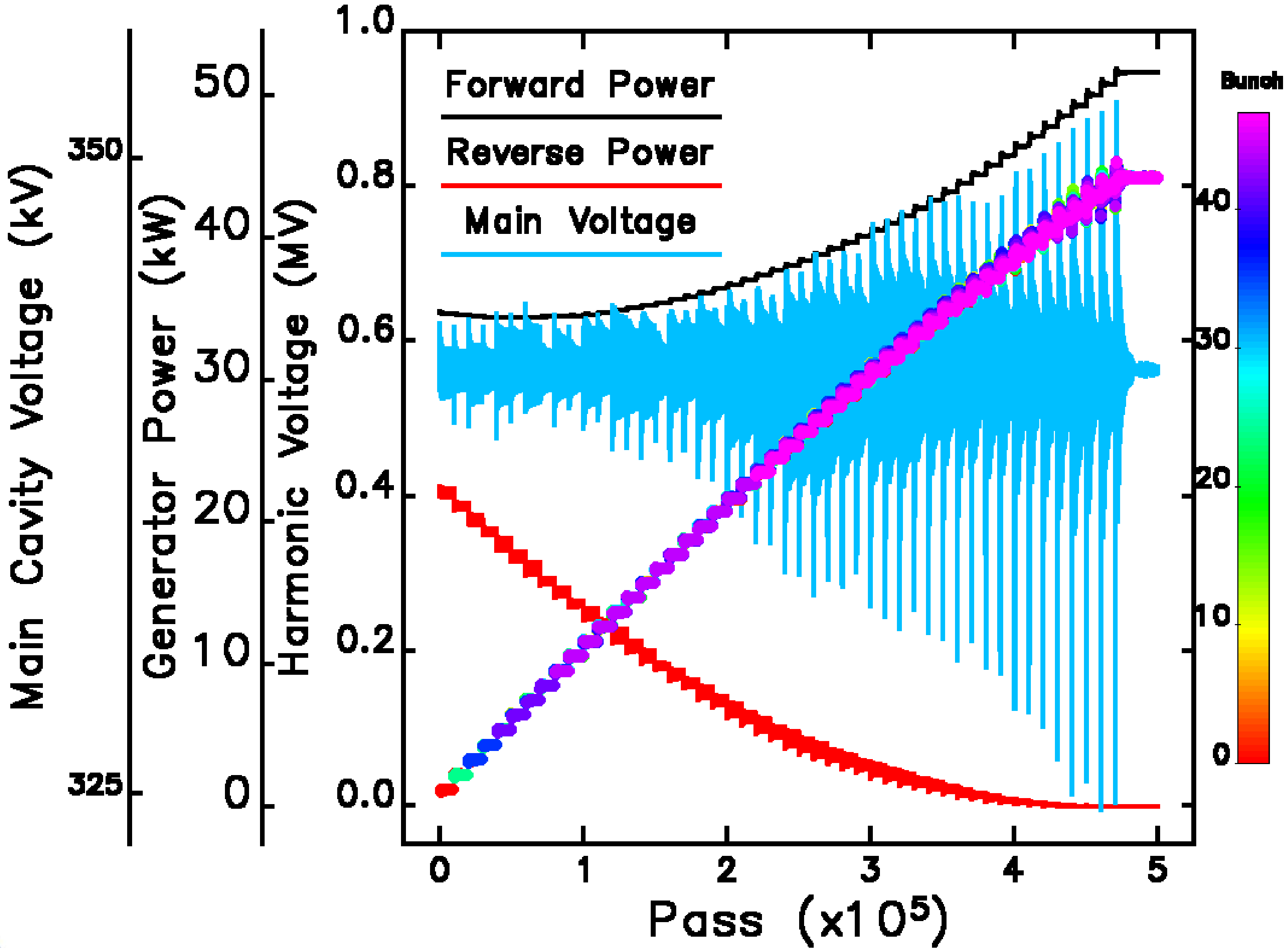
$$H_{sensitivity}(s) = \frac{H_{cav}(s)}{1 + H_{open}(s)}$$

elegant Model

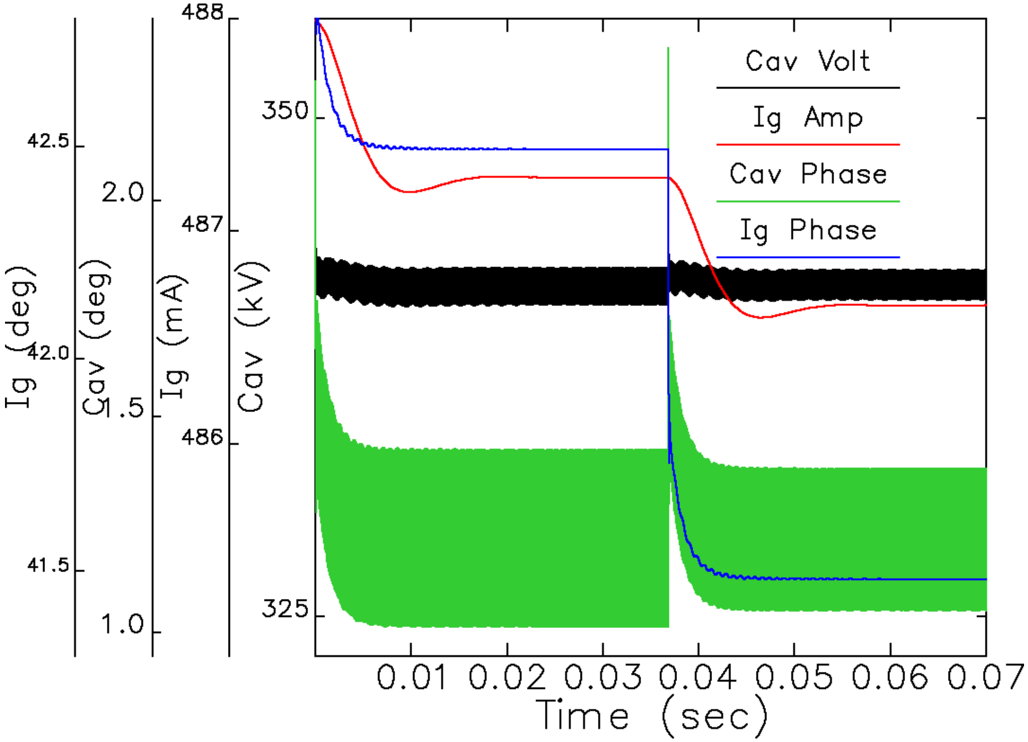


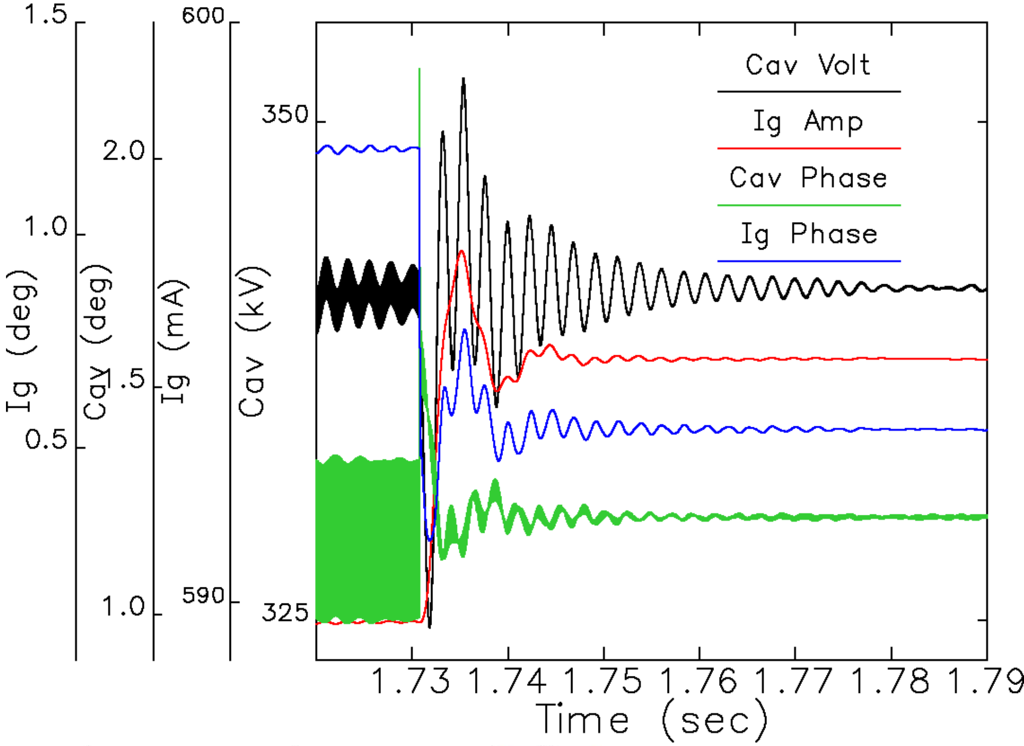
- Presently works in Amp/Phase coordinates. I/Q feedback is planned
- 4 parallel filter blocks for each amplitude and phase
  - Unlimited number of filter coefficients
  - Sample period = any integer number of rf buckets

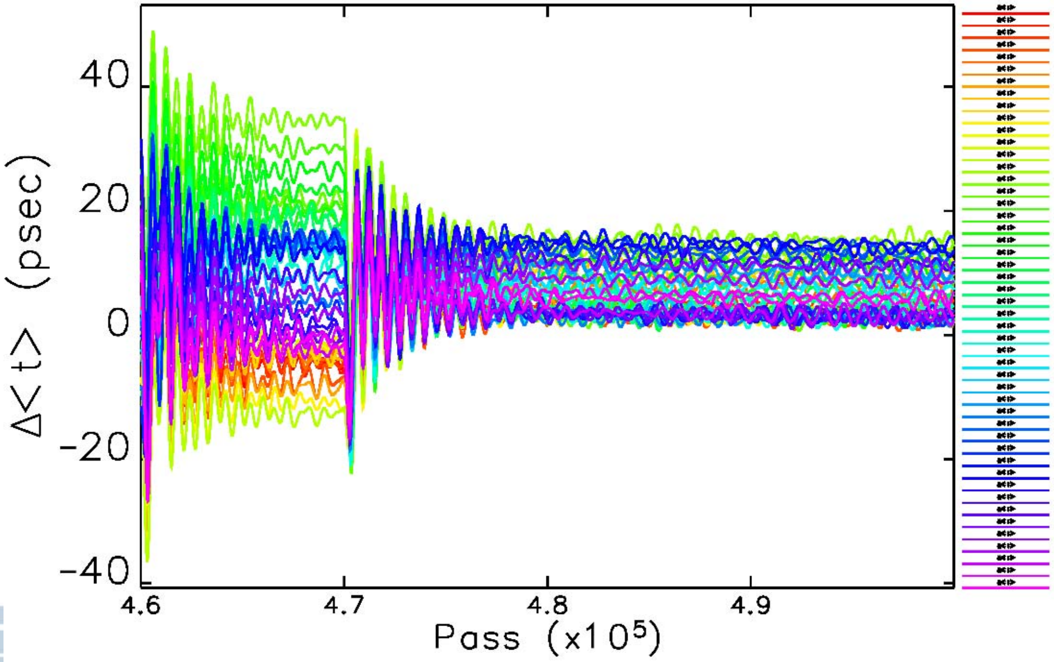
elegant Model



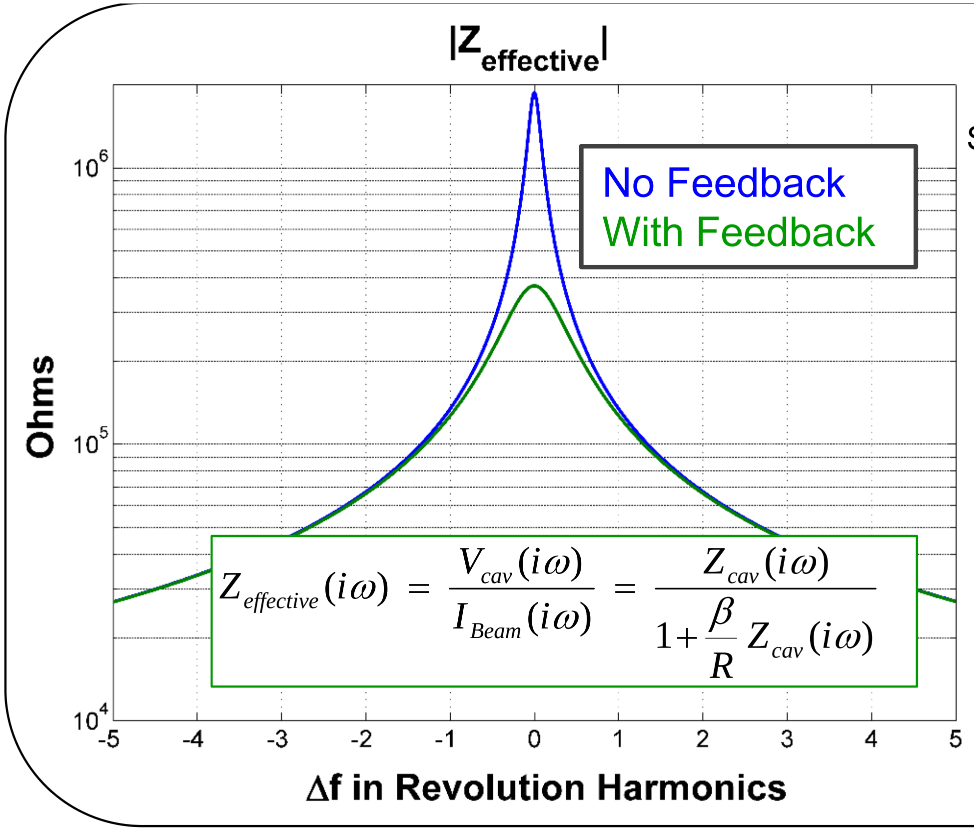
elegant Model



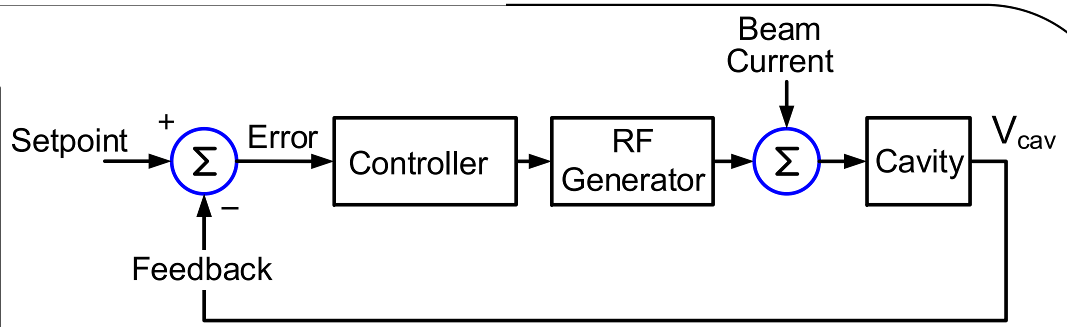




RF Feedback: Other Types of Feedback



$$Z_{effective}(i\omega) = \frac{V_{cav}(i\omega)}{I_{Beam}(i\omega)} = \frac{Z_{cav}(i\omega)}{1+\frac{\beta}{R}Z_{cav}(i\omega)}$$



Example: Direct RF Feedback

- Simple Proportional Gain

=> Controller = $\frac{\beta}{R}$, β = Loop Gain at resonance

- R and Q are reduced by (1 + Loop Gain)
- R/Q stays the same

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

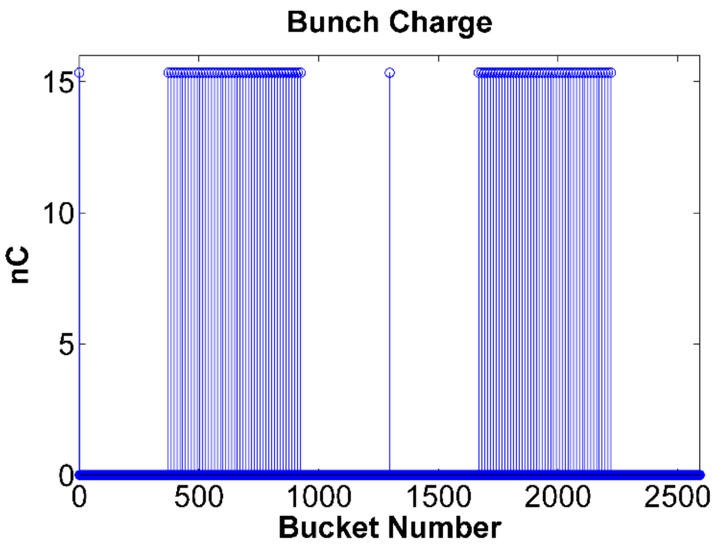
- Effectively lowers V_{br} to increase the high-current stability limit
  - Possibly useful for PAR and/or Booster ??

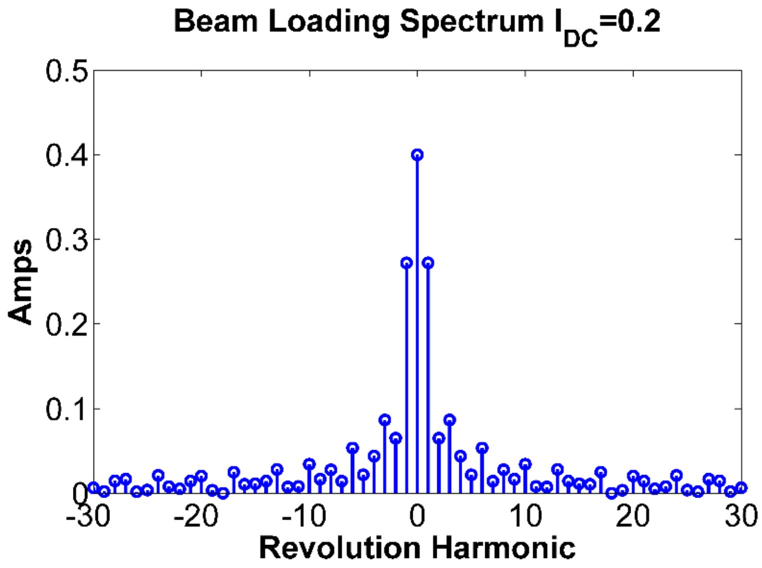
RF Feedback: Other Types of Feedback

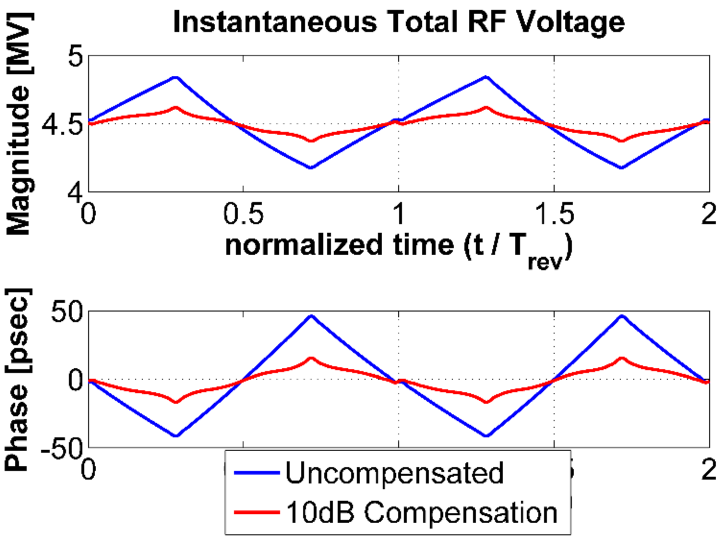
- ❑ Polar (Amplitude / Phase) or Cartesian (in-phase / quadrature): can be narrowband or wideband
- ❑ Comb Filters: reduce impedance & beam-loading at revolution harmonics & synchrotron sidebands
- ❑ Feed-Forward: feed wall-current monitor to generator to cancel the beam-current directly

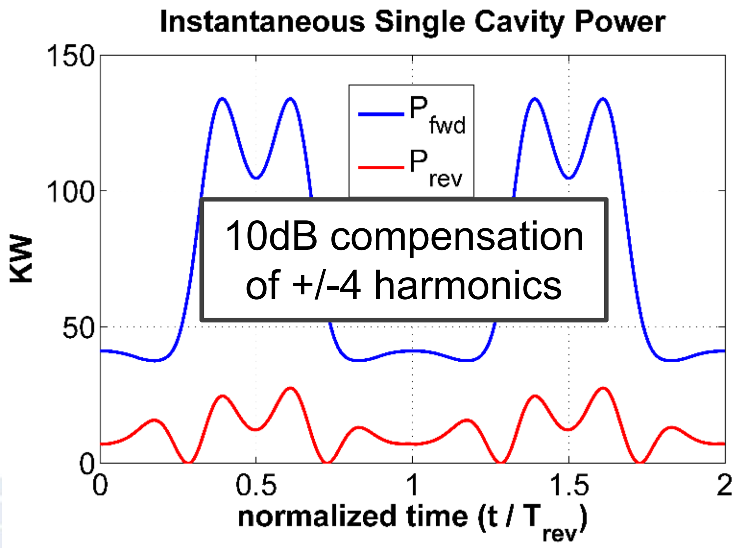
Theoretical Example of Transient Beam-Loading Compensation for Hybrid Fill

(can be achieved with combination of above)


Bunch Charge


Beam Loading Spectrum I_{DC}=0.2


Instantaneous Total RF Voltage


Instantaneous Single Cavity Power

10dB compensation of +/-4 harmonics

Summary

- ☐ Detuning of (main / harmonic) contributes (damping / growth) of Robinson stability
- ☐ But.... Robinson stability criterion is based upon extremely simplified model
  - ➢ Doesn’t capture non-linearities and mode-coupling
  - ➢ Doesn’t take into account frequency spread
  - ➢ Modification by RF Feedback explored later by Pedersen et. al., still small signal
  - ➢ Later formulation was Sacherer Integral Equation (Robinson is Dipole Mode)
- ☐ It is essential to include RF Feedback in particle tracking studies to capture the true dynamics between the beam, cavity, and rf system
  - ➢ elegant now includes capability for rf feedback
  - ➢ Model developed for Storage Ring and used for bunch-lengthening studies
    - ▪ so far no instability found using existing rf feedback model
- ☐ Other types of feedback may be useful
  - ➢ Direct Feedback or Feed-Forward for heavy beam-loading in PAR and Booster
  - ➢ Periodic beam-loading compensation for Hybrid Fills
    - ▪ Requires high bandwidth source