LLRF Cavity Simulation for SPL

Simulink Model for HP-SPL Extension to LINAC4 at CERN from RF Point of View

Acknowledgement:
CEA team, in particular O. Piquet (simulink model)
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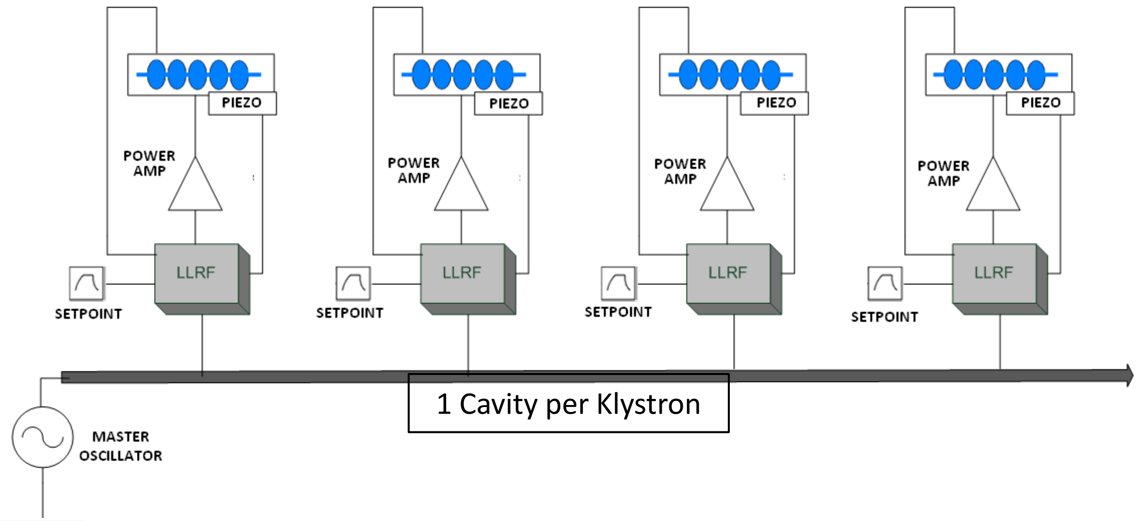
Presentation Overview

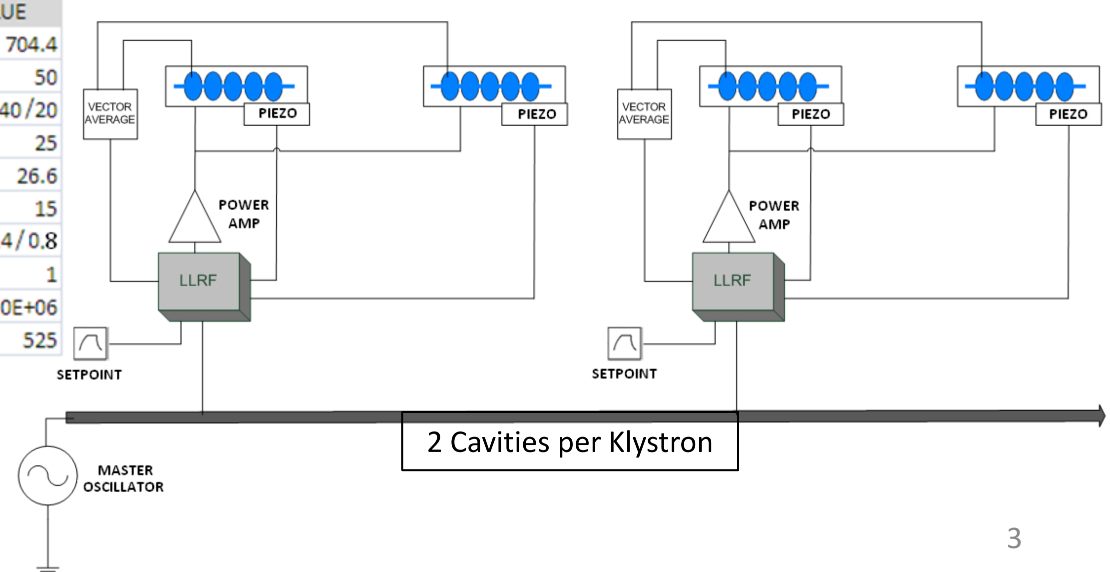
- SPL Characteristics
- Single Cavity Model and Simulation Results
- Dual Cavity Model and Simulation Results
- Error Analysis

SPL High Current Operation

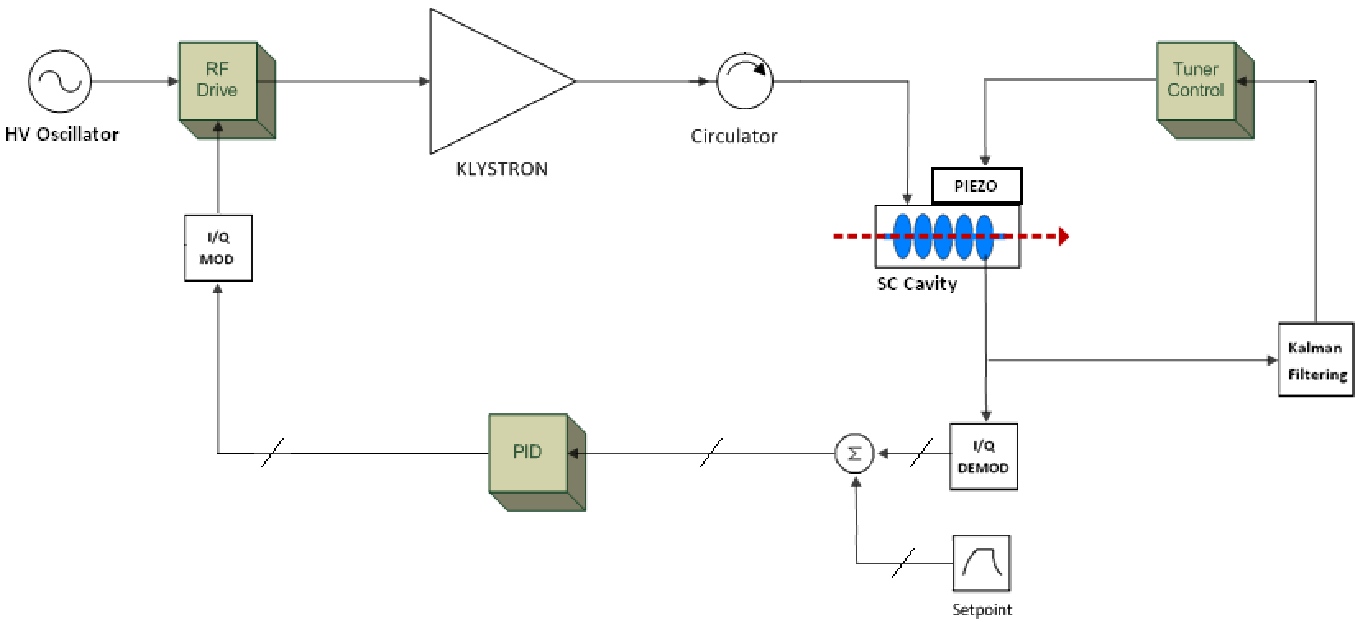
- Possible operation using 1, 2 and 4 cavities fed by a single power amplifier.



GENERAL PARAMETERS FOR HIGH POWER SPL		
PARAMETER	UNIT	VALUE
Resonant Frequency	MHz	704.4
Repetition Rate	Hz	50
Average Pulse Current	mA	40 / 20
Accelerating Field	MV/m	25
Accelerating Voltage	MV	26.6
Beam Synchronous Angle	Degrees (LINAC)	15
Length of Beampulse	ms	0.4 / 0.8
Power Delivered to Beam per Cavity	MW	1
Cavity/Generator Coupling Loaded Quality Factor		1.30E+06
Geometry Factor (R/Q)	Ohm (LINAC)	525



High-Level Diagram of Single Cavity + Control System



$f_{RF} = 704.4$ MHz

$I_{b,DC} = 40$ mA

$\phi_s = 15^\circ$ (LINAC)

$P_b = V_{acc} \times I_{b,DC} \times \cos(\phi_s) = 1.0285$ MW

$Q_L = 1.3113 \times 10^6$

$\frac{R}{Q} = 525\ \Omega$ (LINAC)

$\tau_{beampulse} = 0.4$ ms

rep period $= 20$ ms

$R_L = 680\ \mathrm{M\Omega}$

$$I_g = \frac{V_{acc}}{R_L} + I_{b,DC}\cos(\phi_s) = 77.3 \text{ mA}$$

$$\tau_{fill} = \frac{2Q_L}{\omega_{RF}} = 0.5926 \text{ ms}$$

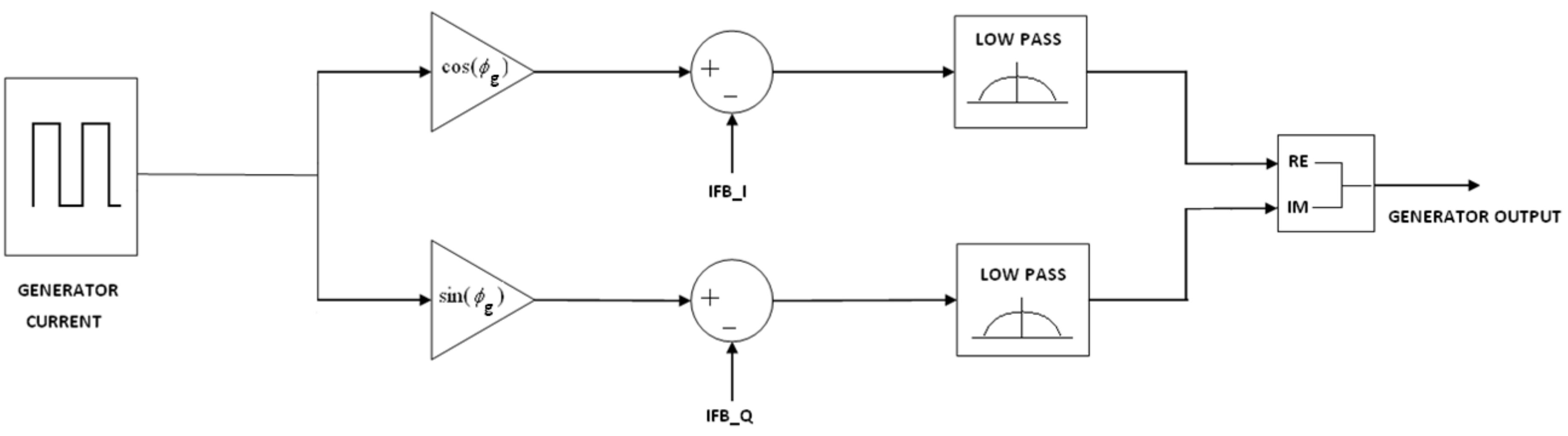
$$\alpha = \frac{I_g}{I_{b,DC}\cos(\phi_s)} = 2$$

$$t_{inj} = \tau_{fill}\ln(\alpha) = 0.4108 \text{ ms}$$

RF Drive and Generator Model

- Generator current modeled as square pulse for the duration of injection + beam pulse time

- High bandwidth compared to feedback loop and cavity (1 MHz)

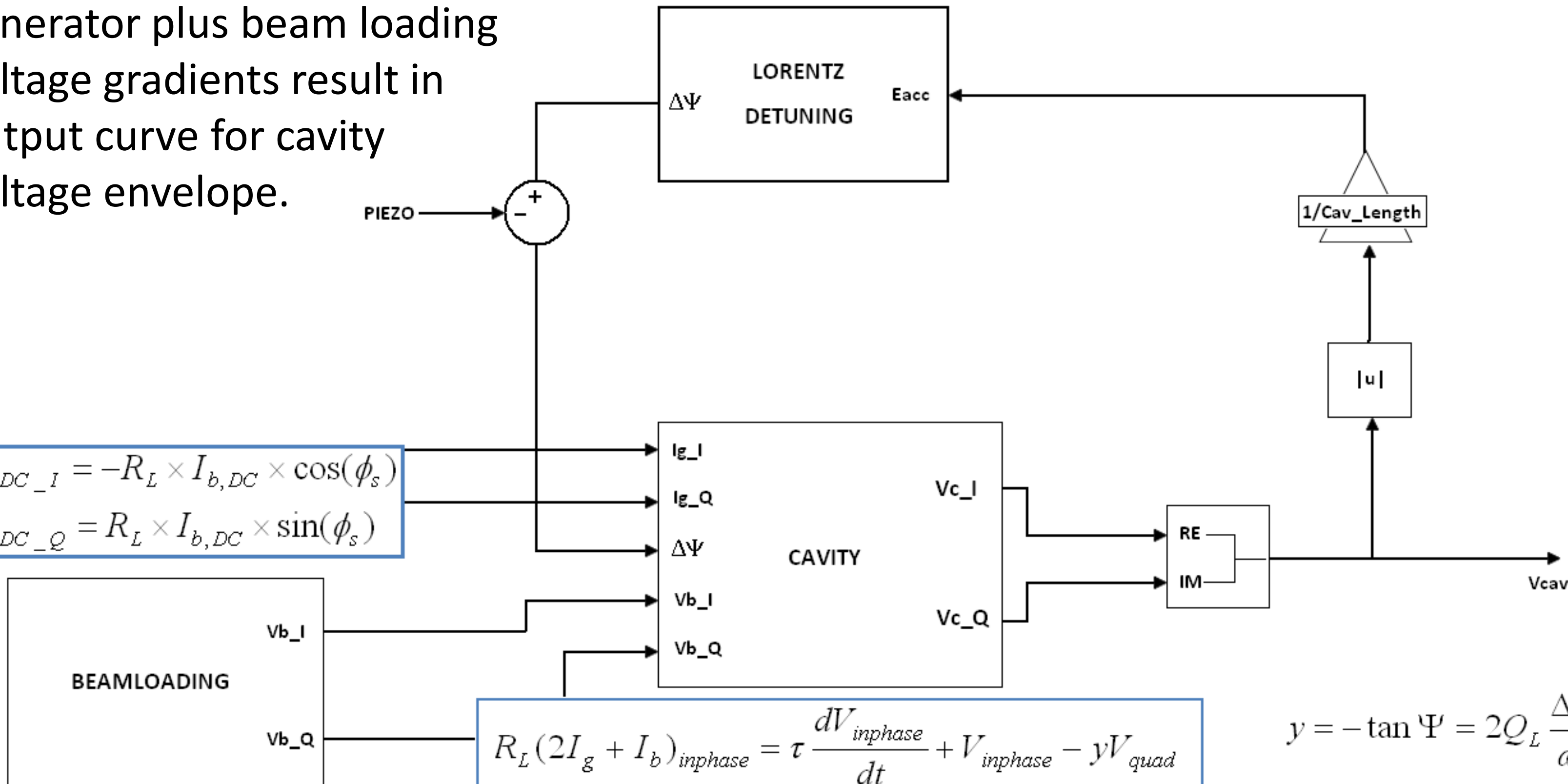


Cavity Model (cont)

<u>Simplified Diagram</u>

Cavity differential equations, generator plus beam loading voltage gradients result in output curve for cavity voltage envelope.

$$\frac{d\Delta\omega(t)}{dt} = \frac{-1}{\tau}\left(\Delta\omega(t) - \Delta\omega_T - 2\pi K E_{acc}^2\right)$$



$$V_{beam\_DC\_I} = -R_L \times I_{b,DC} \times \cos(\phi_s)$$

$$V_{beam\_DC\_Q} = R_L \times I_{b,DC} \times \sin(\phi_s)$$

$$R_L(2I_g + I_b)_{inphase} = \tau \frac{dV_{inphase}}{dt} + V_{inphase} - yV_{quad}$$

$$R_L(2I_g + I_b)_{quad} = \tau \frac{dV_{quad}}{dt} + V_{quad} + yV_{inphase}$$

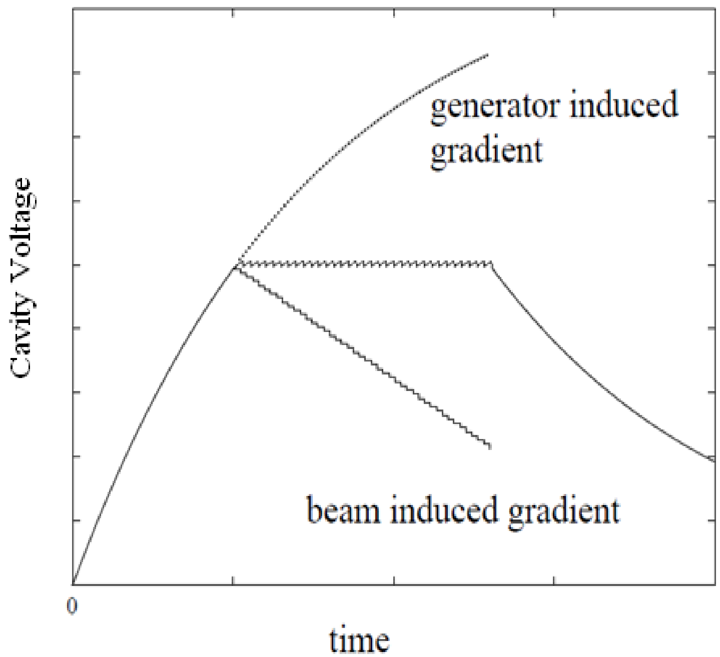
$$y = -\tan\Psi = 2Q_L \frac{\Delta\omega}{\omega_0}$$

$$\tau = \frac{2Q_L}{\omega_0}$$

Beam Loading

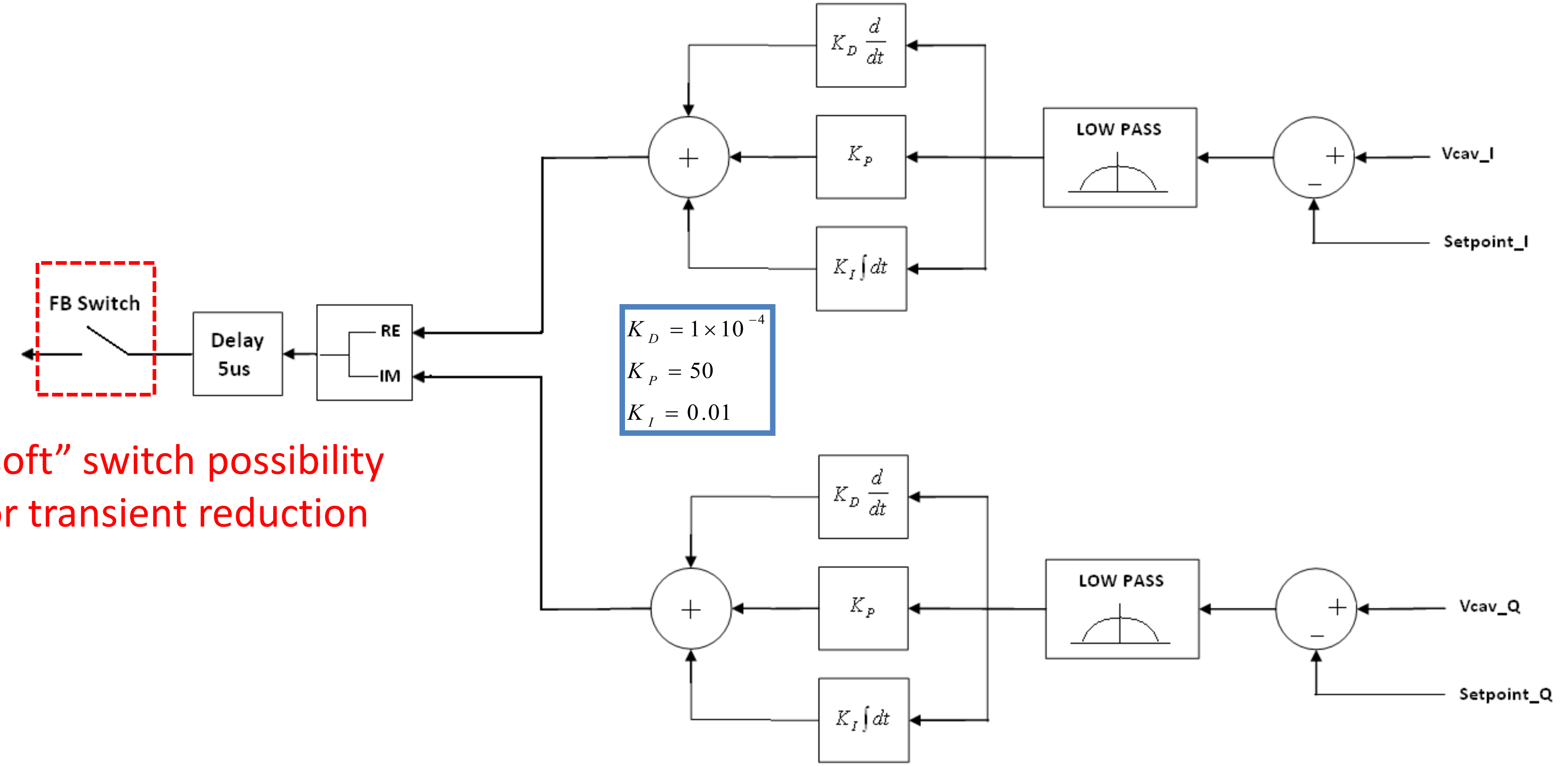
- Infinitely narrow bunches induce instant voltage drops in cavity
- Voltage drop is equal to generator induced voltage increase between bunches creating flattop operation
- Envelope of RF signal in I/Q

$$V_{cav\_bunch} = \omega_{RF} \times \frac{R}{Q}(circuit) \times q_b$$



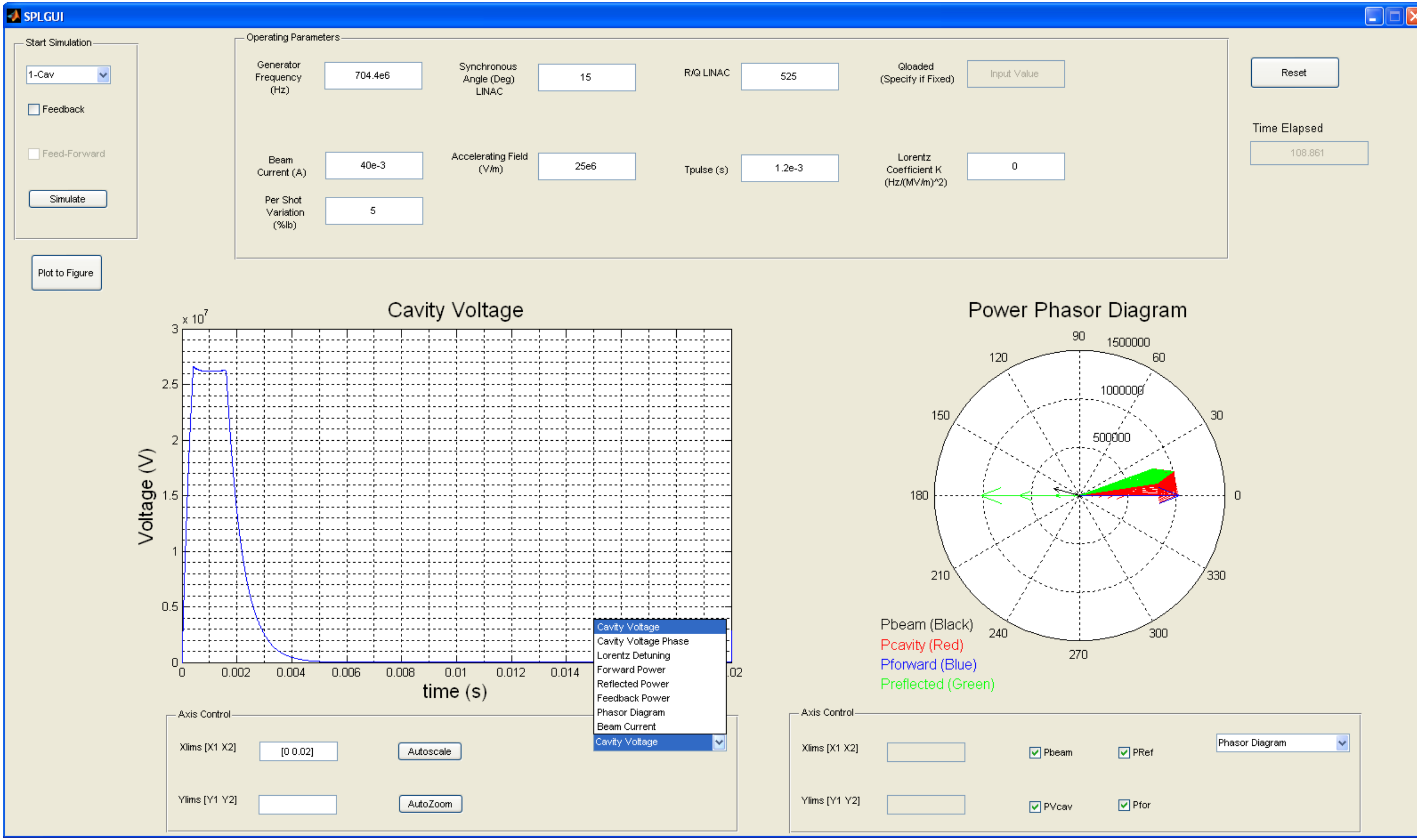
RF Feedback

- PID controller
- Limit bandwidth in feedback loop to 100 kHz
- (Klystron bandwidth is 1 MHz)



“soft” switch possibility
for transient reduction

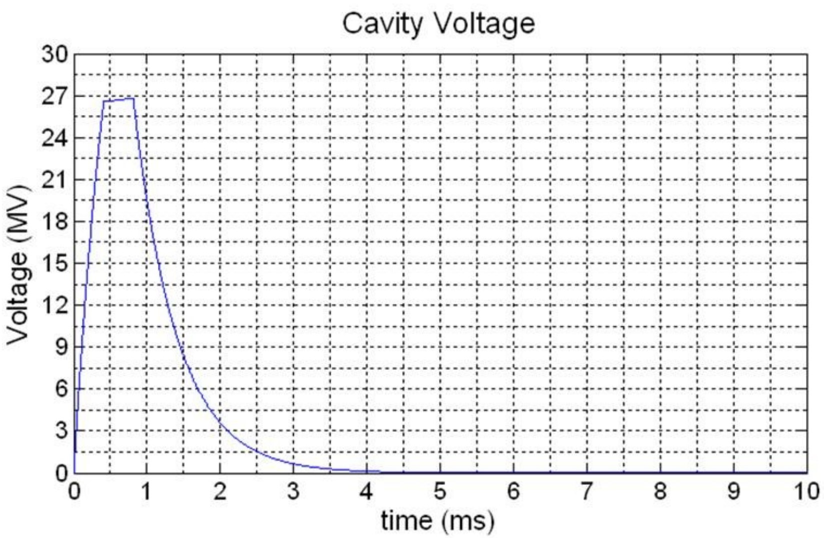
Graphical User Interface



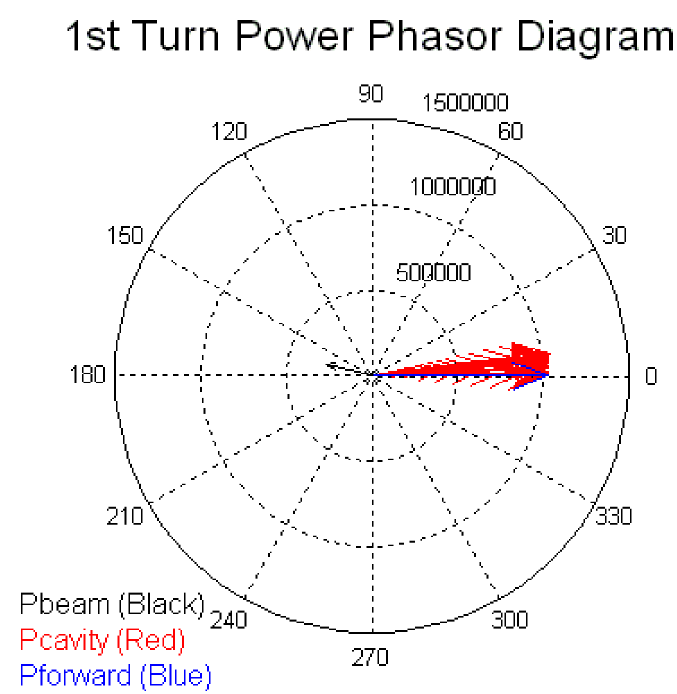
Results

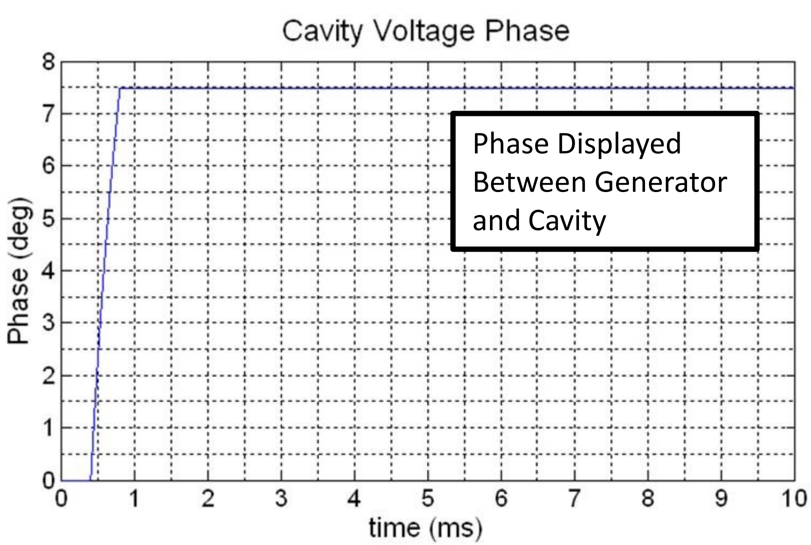
- Cavity Voltage Amplitude and Phase
- Forward and Reflected Power
- Additional Power for Feedback Transients and Control
- Effect of Lorentz Detuning on Feedback Power
- Effect of Source Current Fluctuations
- Mismatched Low-Power Case
- Effects of Beam Relativistic Beta Factor on Cavity Voltage During Beamloading

Cavity Voltage Magnitude and Phase in the Absence of Lorentz Detuning (Open Loop)



Reactive Beamloading Results in Vacc Deviation

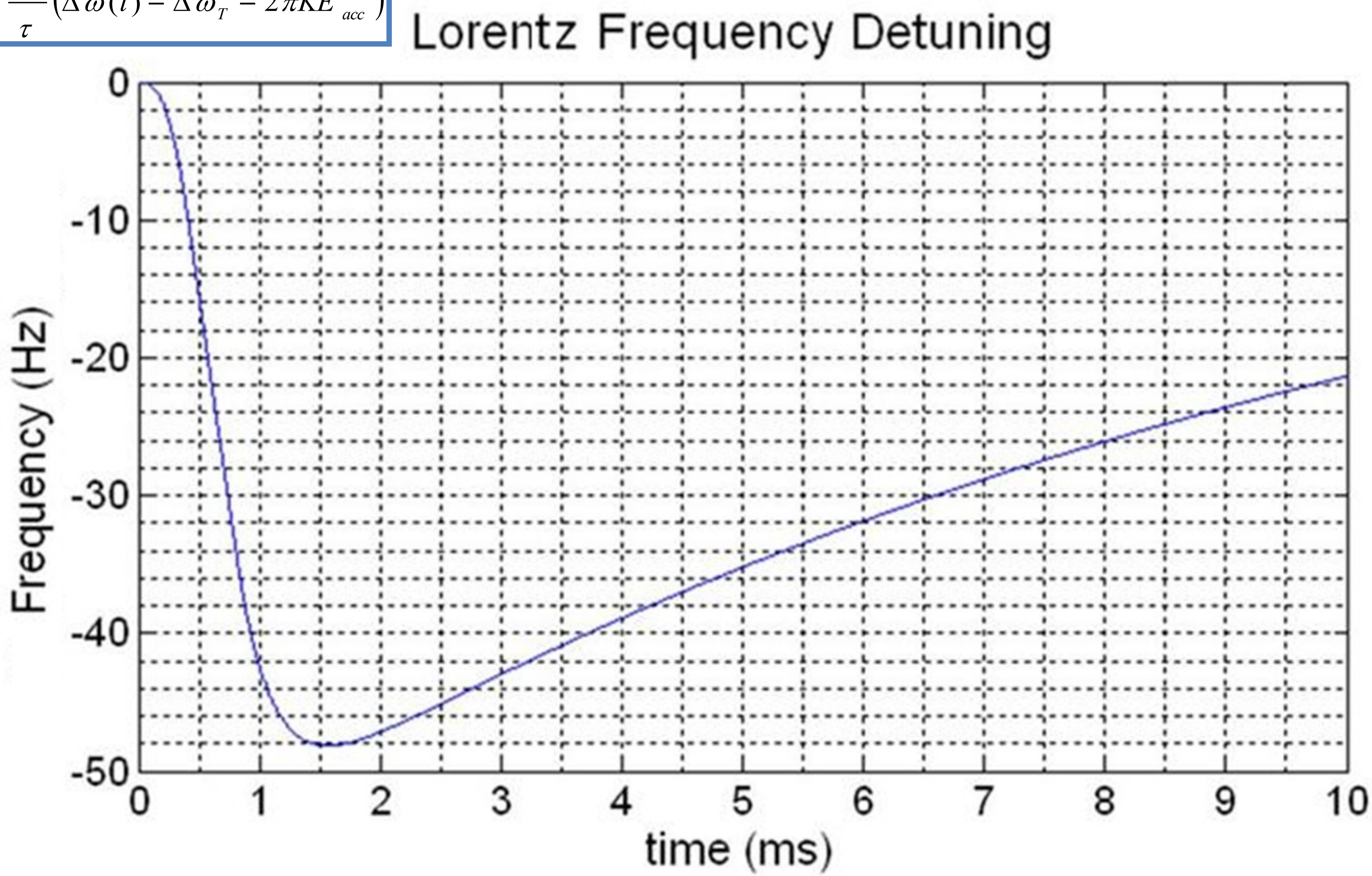




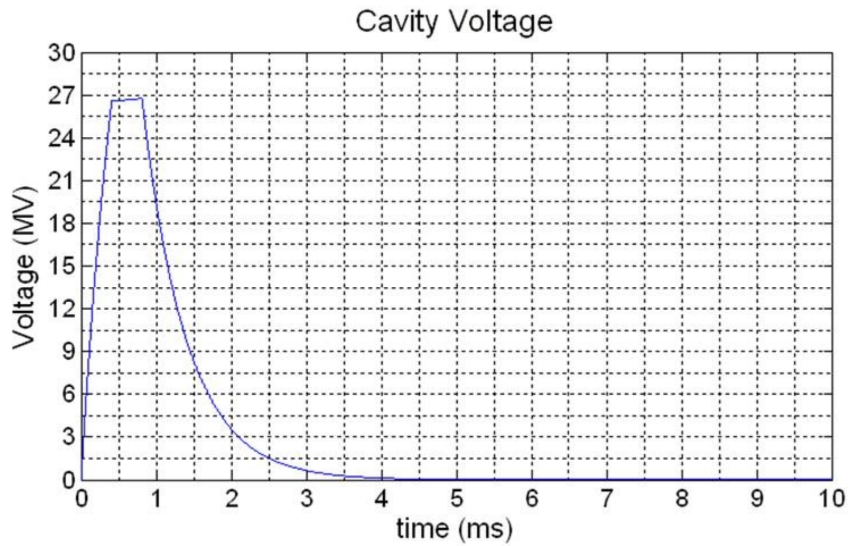
Phase Displayed Between Generator and Cavity

Effect of Lorentz Detuning on Cavity Voltage and Phase (Lorentz Frequency Shift)

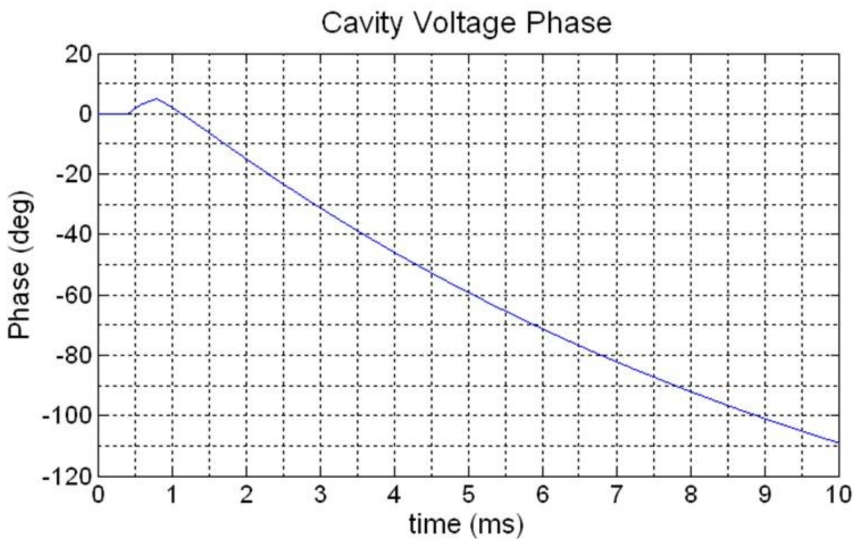
$$\frac{d\Delta\omega(t)}{dt} = \frac{-1}{\tau}\left(\Delta\omega(t) - \Delta\omega_T - 2\pi K E_{acc}^2\right)$$



Effect of Lorentz Detuning on Cavity Voltage and Phase (Open Loop)

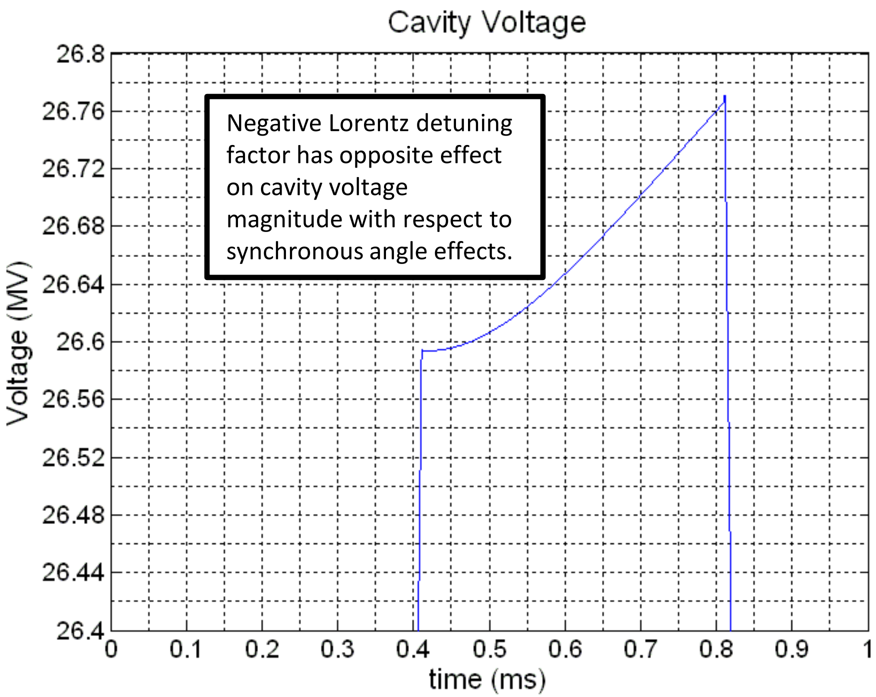


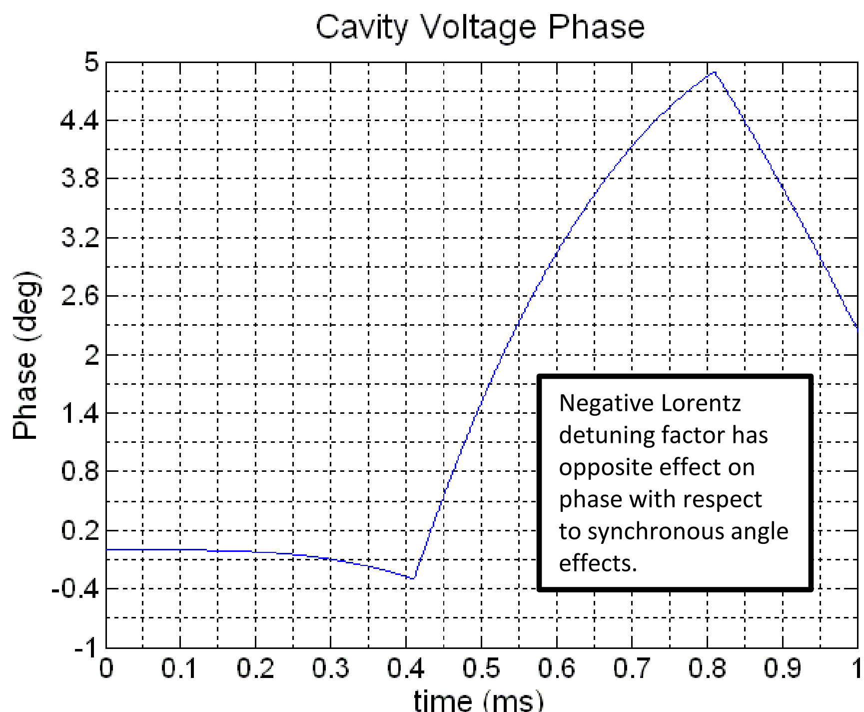
Lorentz effects oppose those of the synchronous angle



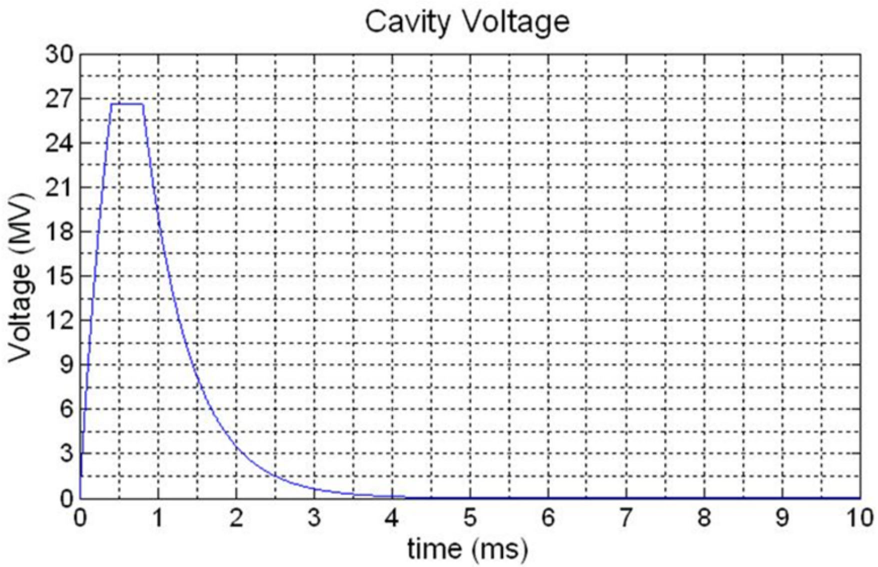
Approximately linear phase shift for undriven cavity during field decay

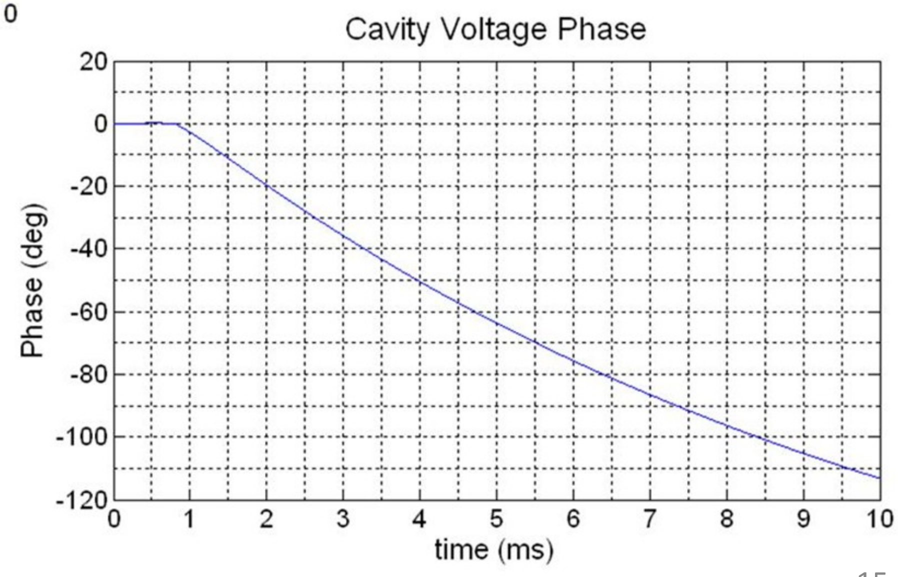
Effect of Lorentz Detuning on Cavity Voltage and Phase (Open Loop Close-Up)



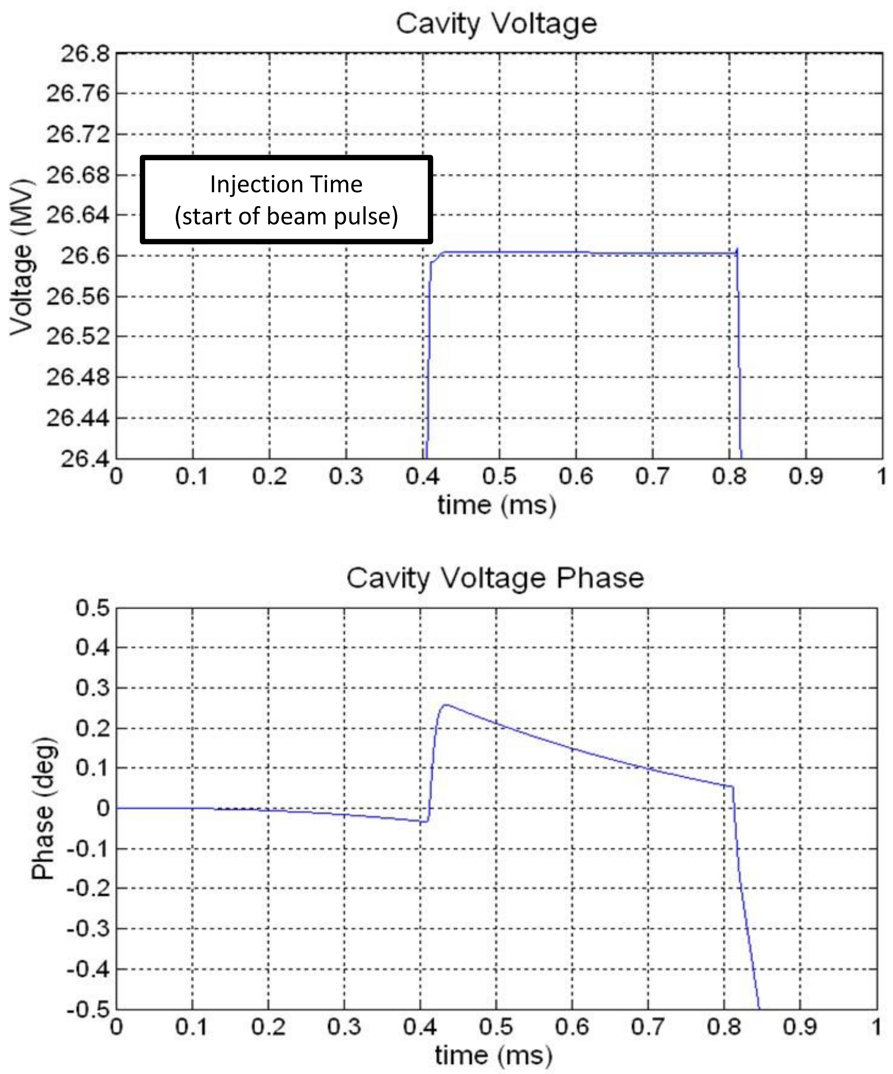


Cavity Voltage and Phase With Lorentz Detuning (Closed Loop Performance of Fast Feedback)

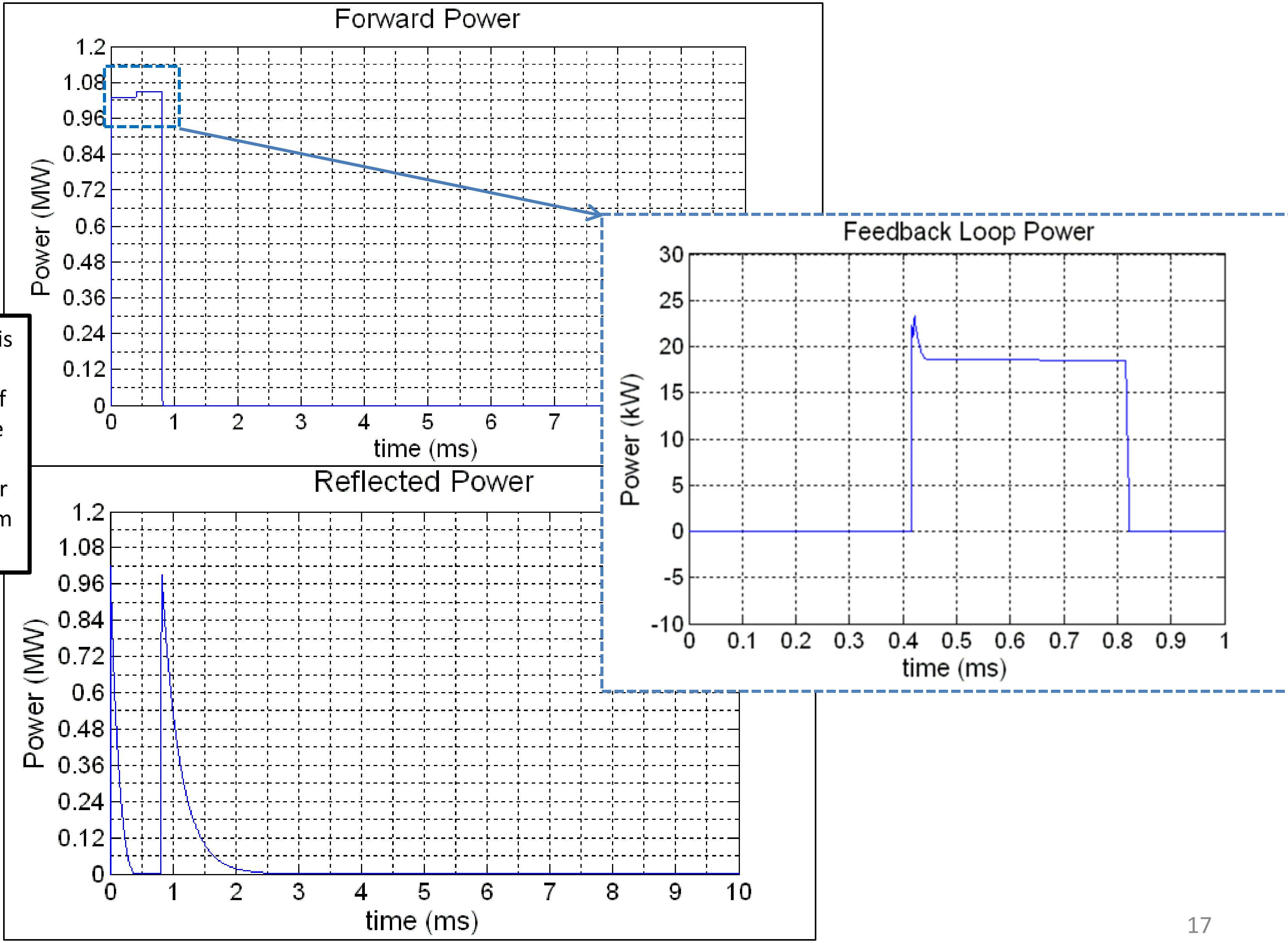




Cavity Voltage and Phase Close-up

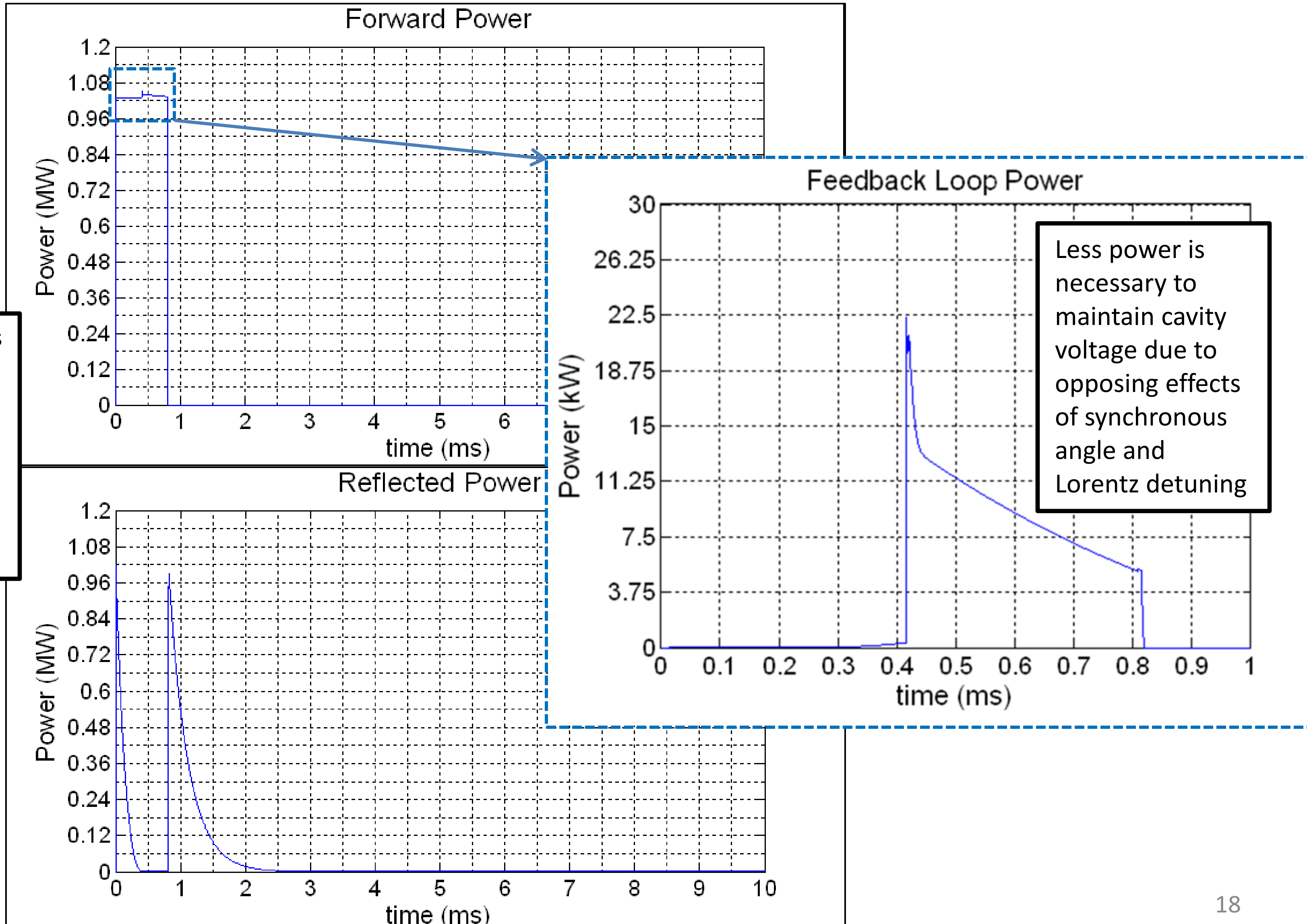


Forward and Reflected Power without Lorentz Detuning



Feedback loop is closed (ON) 10 us after start of generator pulse and opened (OFF)10 us after end of the beam pulse.

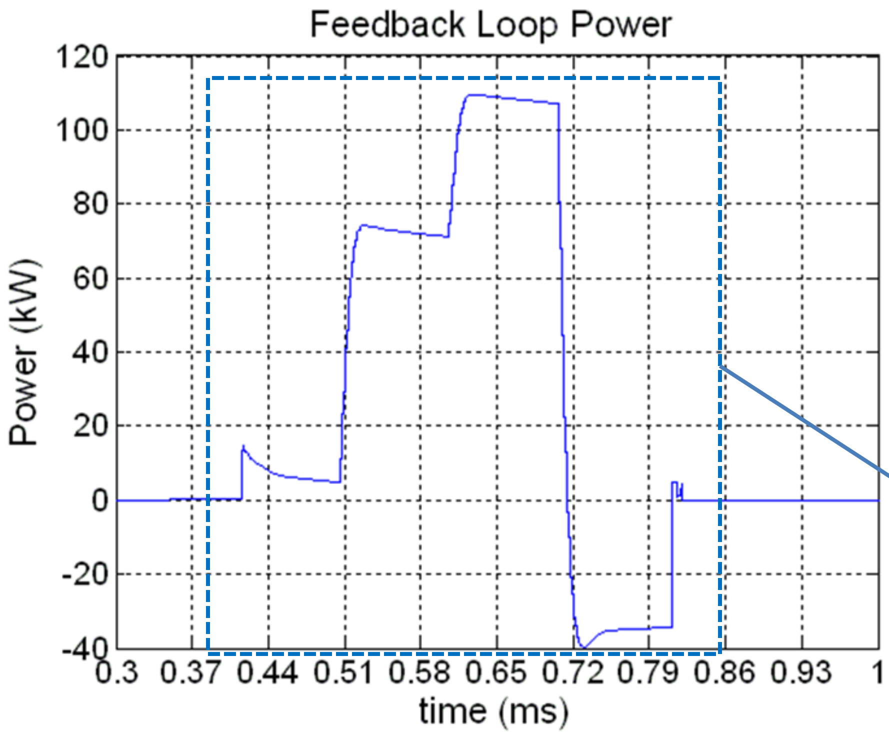
Forward and Reflected Power with Lorentz Force detuning



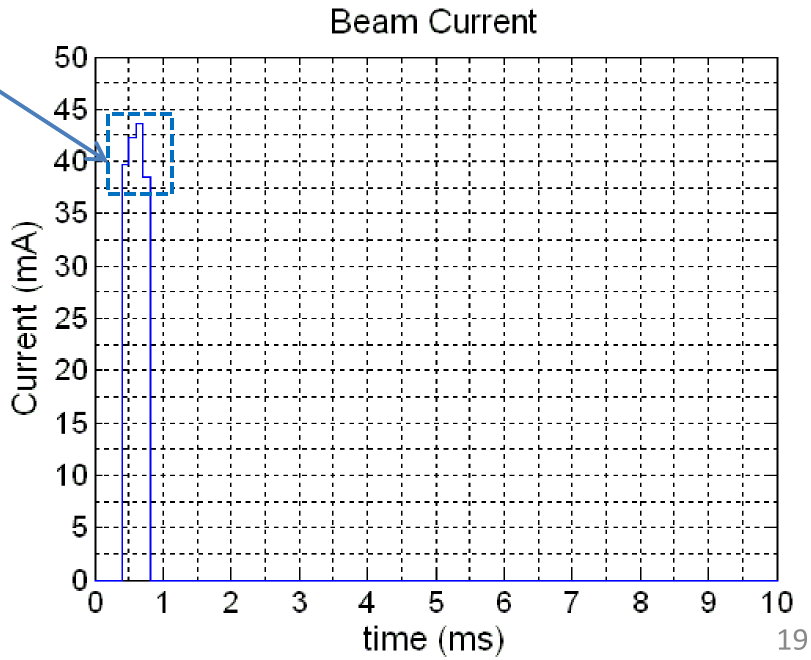
Feedback loop is closed 10 us after start of generator pulse and opened 10 us after the end of the beam pulse.

Less power is necessary to maintain cavity voltage due to opposing effects of synchronous angle and Lorentz detuning

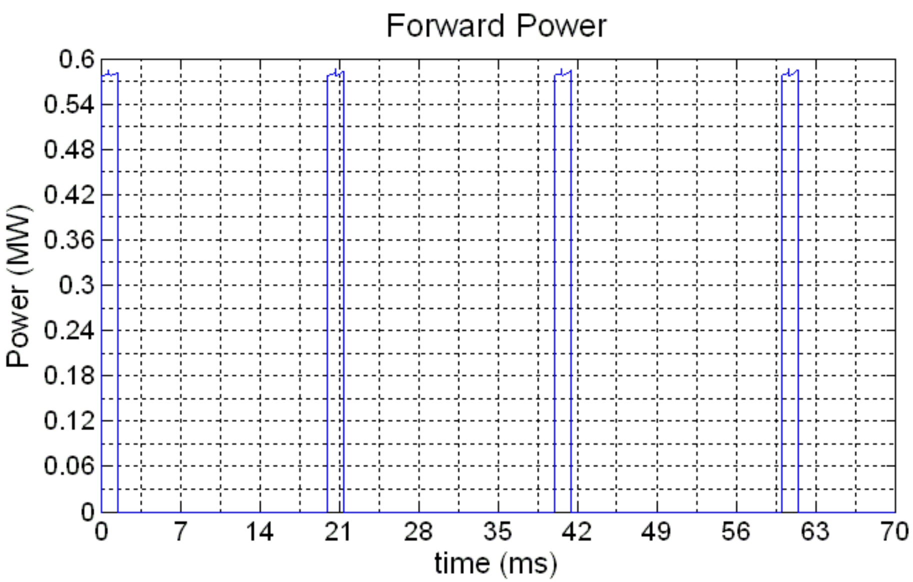
Effects of Source Beam Current Variation

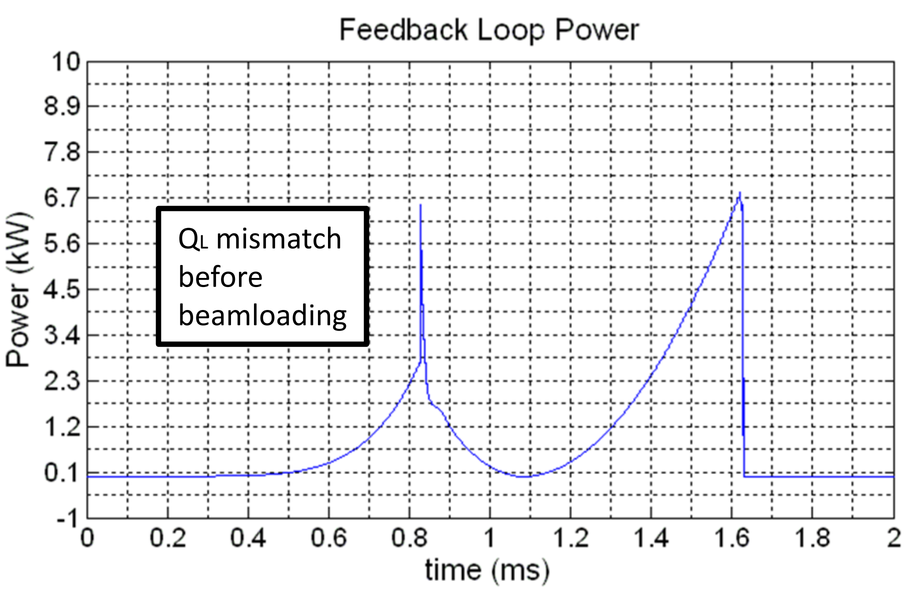


5% variation in Ib for 40mA case requires approximately 60kW of additional power.



SPL Low Current Operation (Power Analysis)





$$I_{b,DC} \cong 20 \ \text{mA}$$

$$P_b = V_{acc} \times I_{b,DC} \times \cos(\phi_s) \cong 514 \ \text{kW}$$

$$Q_{L,\text{fixed}} = \frac{V_{acc}}{\frac{R}{Q} \times I_{b,40\,\text{mA}} \times \cos(\phi_s)} \cong 1.3113 \times 10^{6}$$

$$I_g = \frac{V_{acc}}{R_L} + I_{b,DC}\cos(\phi_s) = 58 \ \text{mA}$$

$$\alpha = \frac{I_g}{I_{b,DC}\cos(\phi_s)} = 3$$

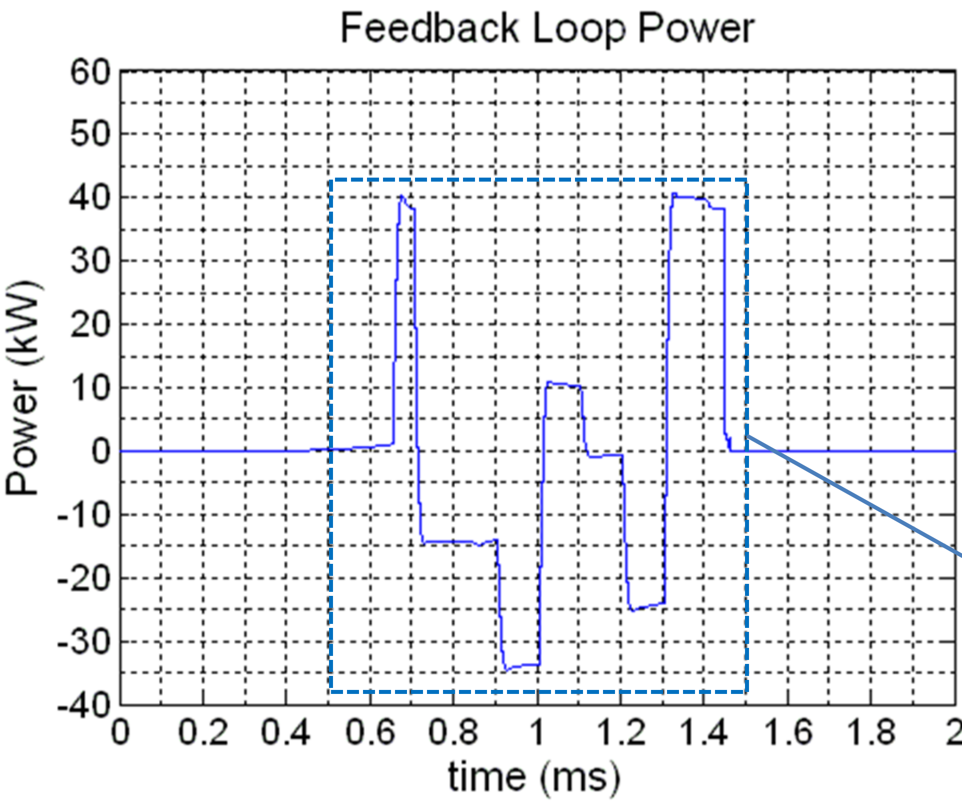
$$\tau_{fill} = \frac{2Q_L}{\omega_{RF}} = 0.5926 \ \text{ms}$$

$$t_{inj} = \tau_{fill}\ln(\alpha) = 0.6510 \ \text{ms}$$

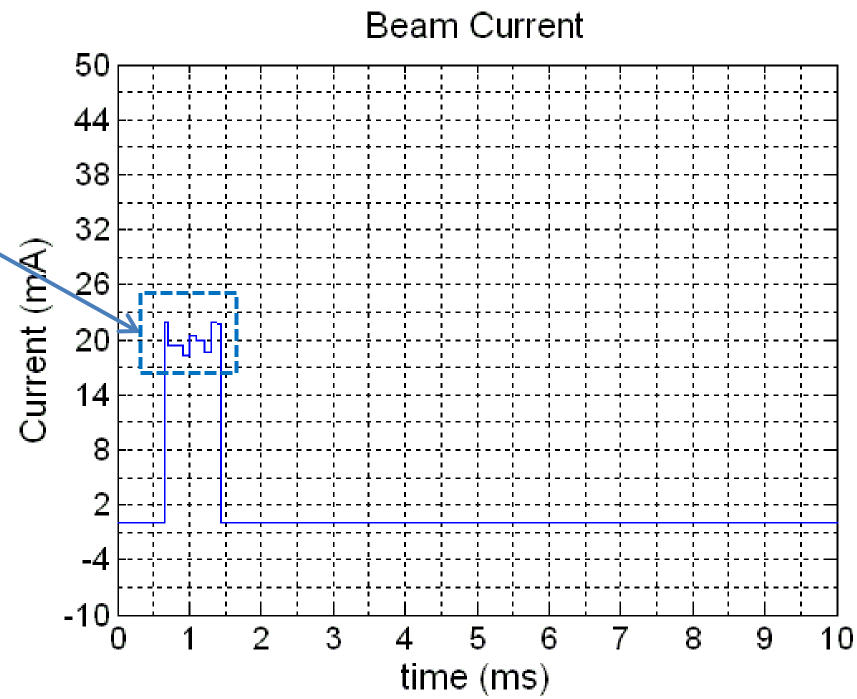
$$P_{fwd} = \frac{1}{4} R_L \left| I_g \right|^2 = 578 \ \text{kW}$$

$$t_{pulse} = 0.8 \ \text{ms}$$

Effects of Source Beam Current Variation



5% (1mA) results in approx. 20kW FB power increase



Transit Time Factor Variation with Relativistic Beta (SPL β=1 cavities)

• The shunt impedance relates the voltage in the cavity gap to the power dissipated in the cavity walls.

$$R_{sh} = \frac{V^2}{P_d}$$

•The corrected shunt impedance (effective shunt impedance) relates the accelerating voltage in the cavity to the power dissipated. This quantity describes the voltage that a particle travelling at a certain speed will "see" when traversing the cavity.

$$V_{cav} = \int_{gap} E(t=0,z)\,dz$$

$$V_{acc}(\beta) = \int_{gap} E(t=0,z)\cos\left(\frac{2\pi}{\beta\lambda_{RF}} z\right)dz$$

•The correction applied is known as the "Transit Time Factor". For even symmetric field distributions:

$$T(\beta) = \frac{\int_{gap} E(t=0,z)\cos\left(\frac{2\pi}{\beta\lambda_{RF}} z\right)dz}{\int_{gap} E(t=0,z)\,dz}$$

Transit Time Factor Variation with Relativistic Beta (SPL β=1 cavities)

- Until now, the cavity dynamics have been modeled from the point of view of a beam travelling at the speed of light (β =1).

- We now investigate how the cavity voltage is affected during beam loading with a "slower" beam.

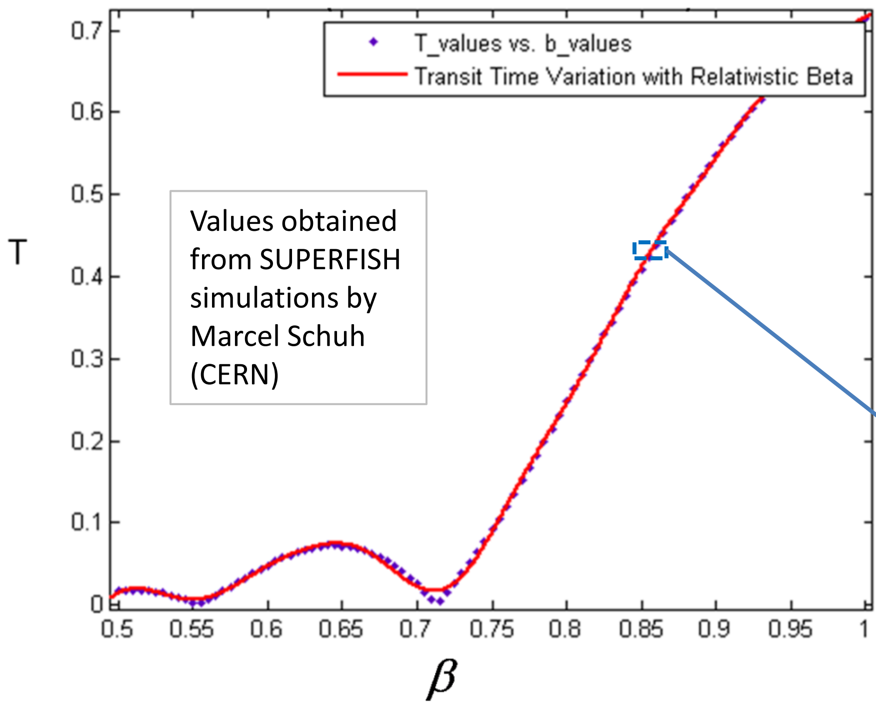
$$R_{sh,eff} = R_{sh} T_{\beta<1}{}^{2} = R_{sh,\beta=1}\left(\frac{T_{\beta<1}}{T_{\beta=1}}\right)^{2}$$

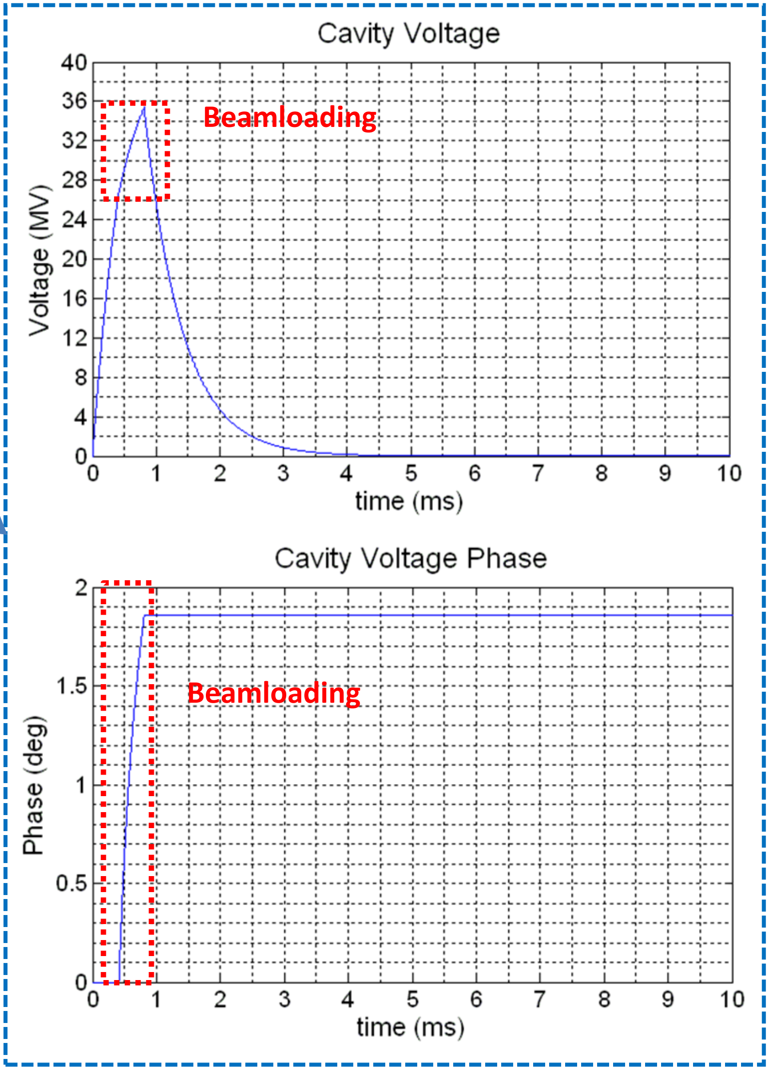
$$V(t)_{gen} = R_{sh,\beta=1} I_g \left(1 - e^{\frac{-t}{\tau}}\right) \qquad t_{ON} < t < t_{OFF}$$

$$V(t)_{beam} = -R_{sh,eff} I_{b,DC}\left(1 - e^{\frac{-(t-t_{inj})}{\tau}}\right) \qquad t_{inj} < t < t_{inj+pulse}$$

$$V_{cav,\beta=1}(t) = V(t)_{gen} + V(t)_{beam} = R_{sh,\beta=1} I_g \left(1 - e^{\frac{-t}{\tau}}\right) - R_{sh,eff} I_{b,DC}\left(1 - e^{\frac{-(t-t_{inj})}{\tau}}\right) \qquad t_{inj} < t < t_{inj+pulse}$$

Transit Time Factor Variation with Relativistic Beta (SPL β=1 cavities, open loop simulation)

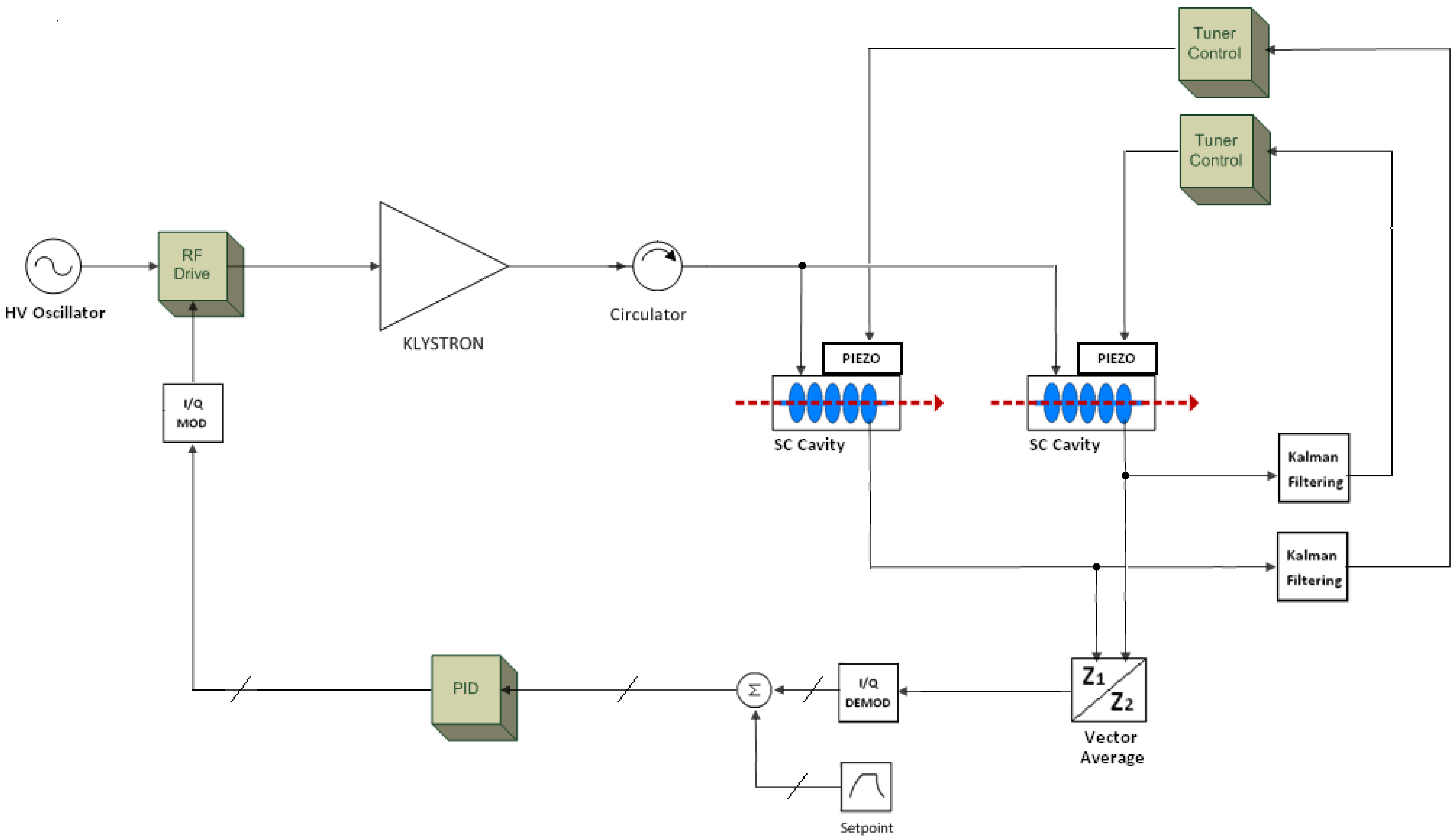




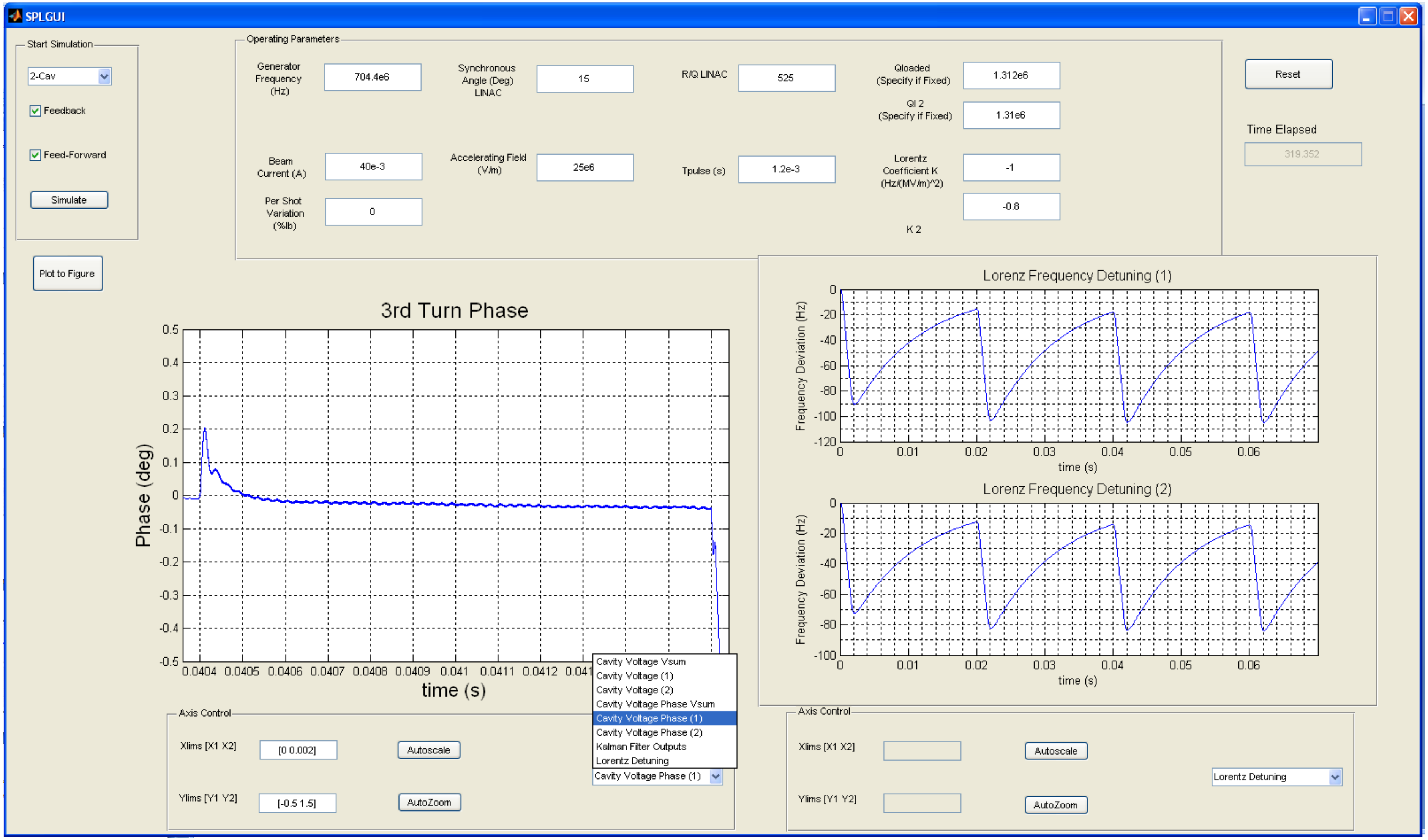
- Weaker beamloading will result in a higher flattop equilibrium and less phase detuning of the cavity for the same generator power.

- Beta value taken from beam energy at beginning of SPL β=1 section.

High Level Diagram for Dual Cavity + Control System



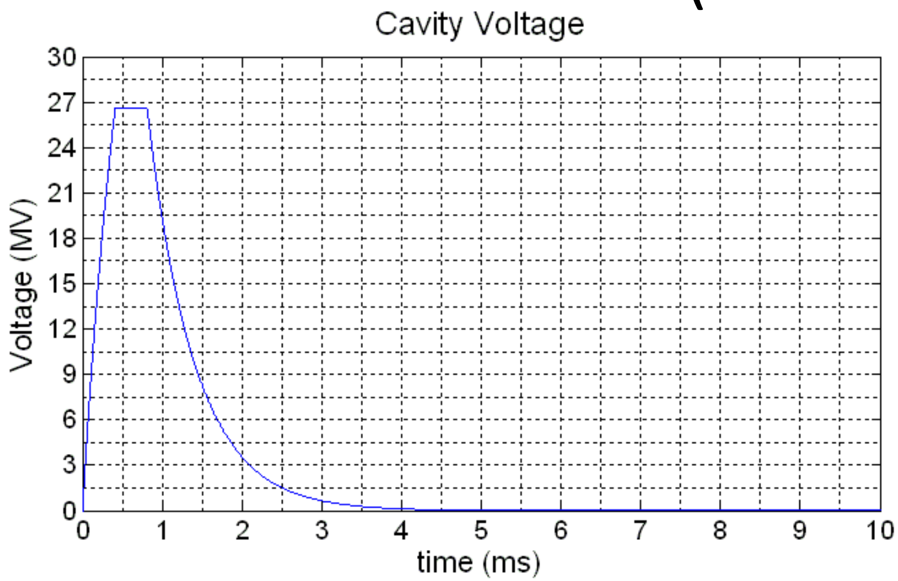
2-Cavity GUI


SPLGUI
Start Simulation
2-Cav
Feedback
Feed-Forward
Simulate
Plot to Figure
Operating Parameters
Generator Frequency (Hz)
704.4e6
Synchronous Angle (Deg) LINAC
15
R/Q LINAC
525
Qloaded (Specify if Fixed)
1.312e6
Ql 2 (Specify if Fixed)
1.31e6
Beam Current (A)
40e-3
Accelerating Field (V/m)
25e6
Tpulse (s)
1.2e-3
Lorentz Coefficient K (Hz/(MV/m)^2)
-1
-0.8
K 2
Per Shot Variation (%Ib)
0
Reset
Time Elapsed
319.352
3rd Turn Phase
Phase (deg)
time (s)
Lorenz Frequency Detuning (1)
Lorenz Frequency Detuning (2)
Frequency Deviation (Hz)
time (s)
Cavity Voltage Vsum
Cavity Voltage (1)
Cavity Voltage (2)
Cavity Voltage Phase Vsum
Cavity Voltage Phase (1)
Cavity Voltage Phase (2)
Kalman Filter Outputs
Lorentz Detuning
Cavity Voltage Phase (1)
Axis Control
Xlims [X1 X2]
[0 0.002]
Autoscale
Ylims [Y1 Y2]
[-0.5 1.5]
AutoZoom
Axis Control
Xlims [X1 X2]
Autoscale
Ylims [Y1 Y2]
AutoZoom
Lorentz Detuning

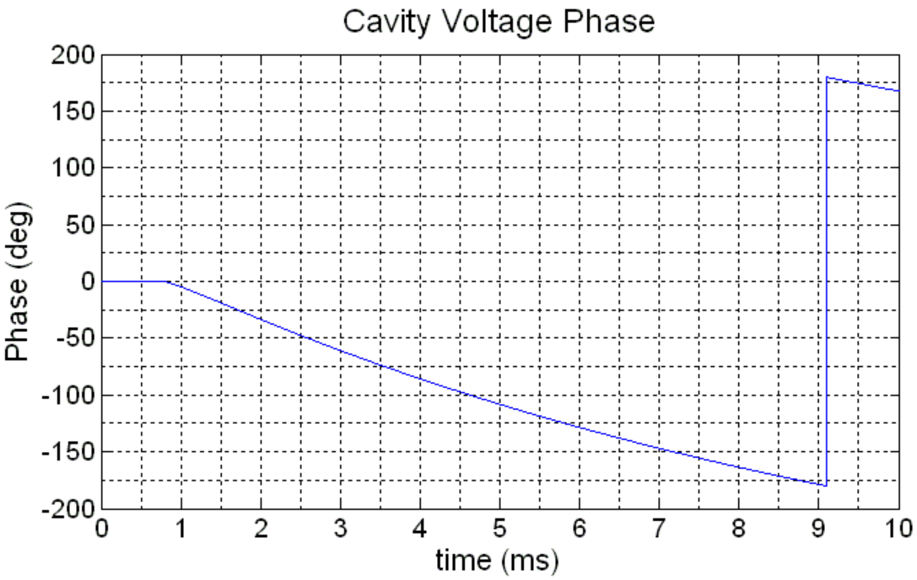
Results

- Cavity Phase Variation Without Feed-Forward
- Effects of Adaptive Feed-Forward
- Effects of Loaded Quality Factor Variation

Vcav Magnitude and Phase for Dual Cavity Case (K=-1 and -0.5)

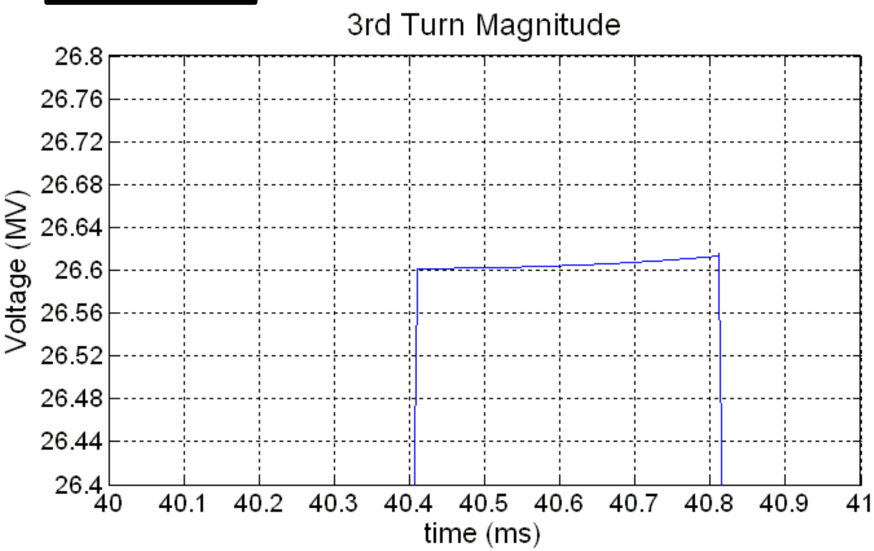


Voltage magnitude and phase of vector average

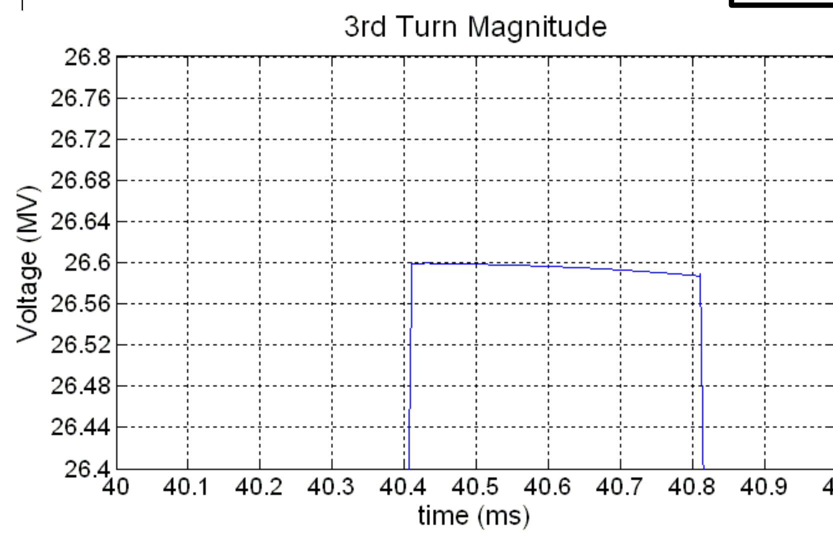


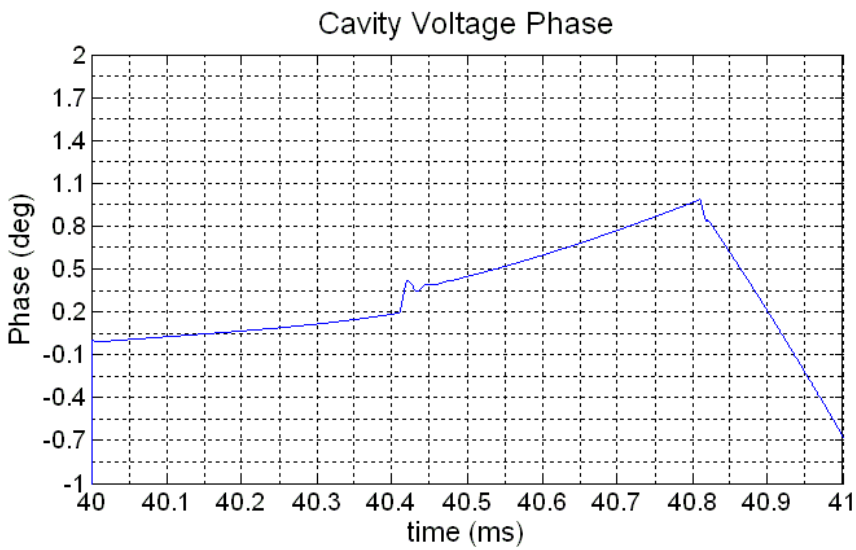
Vcav Magnitude and Phase for Dual Cavity Case (Without Feed-Forward)

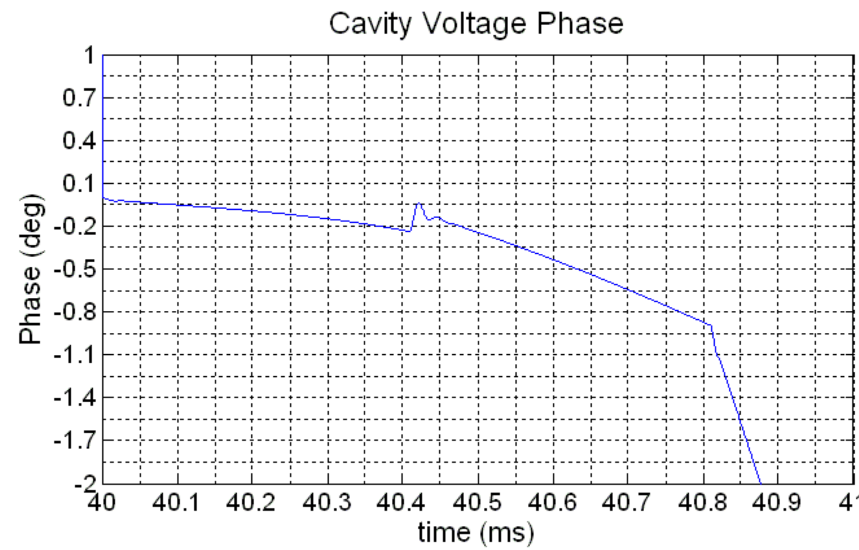
K=-0.5 $Hz/\left(\frac{MV}{m}\right)^2$



K=-1 $Hz/\left(\frac{MV}{m}\right)^2$

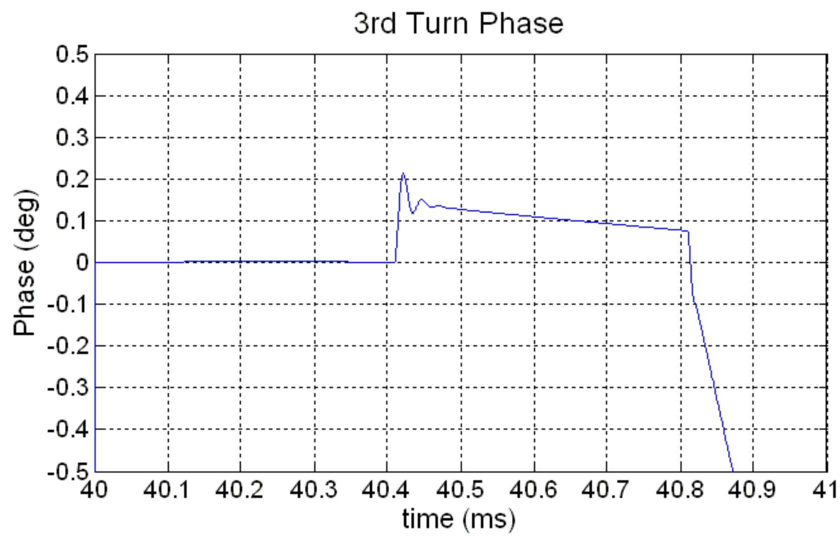




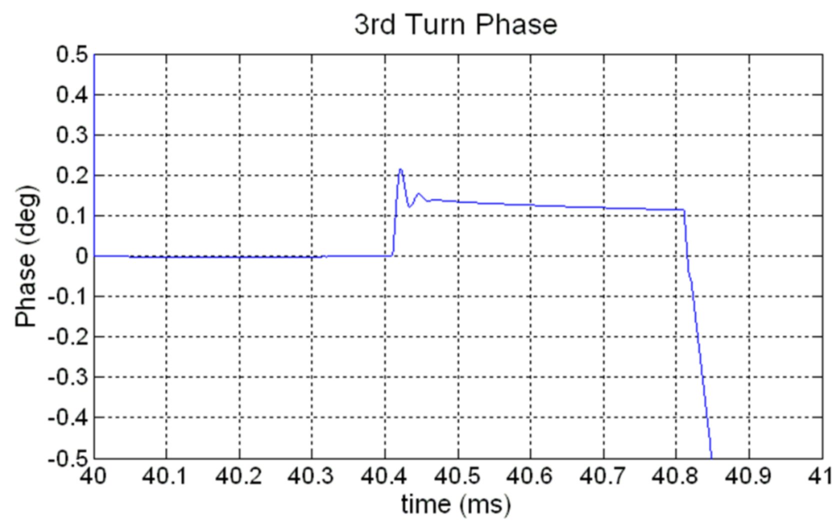


Vcav Magnitude and Phase for Dual Cavity Case (With Feed-Forward)

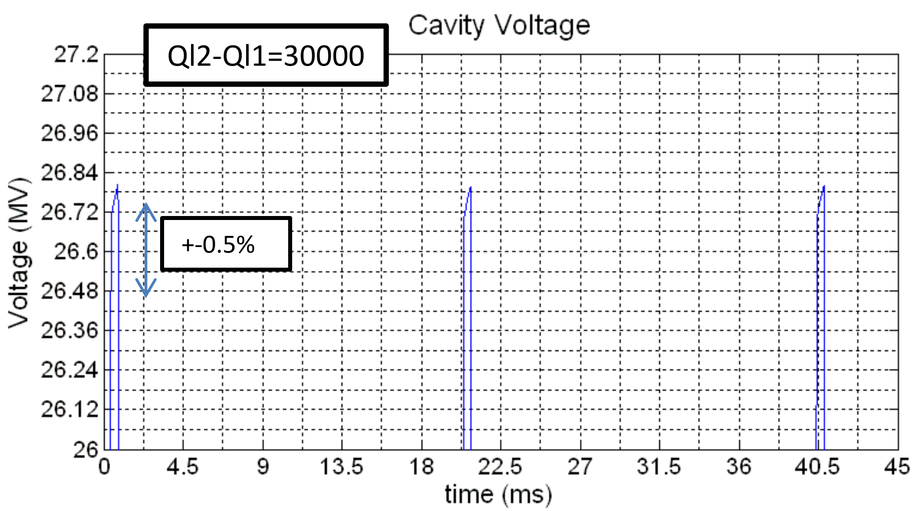
Cavity 1 (K=-1 $Hz/\left(\frac{MV}{m}\right)^2$)

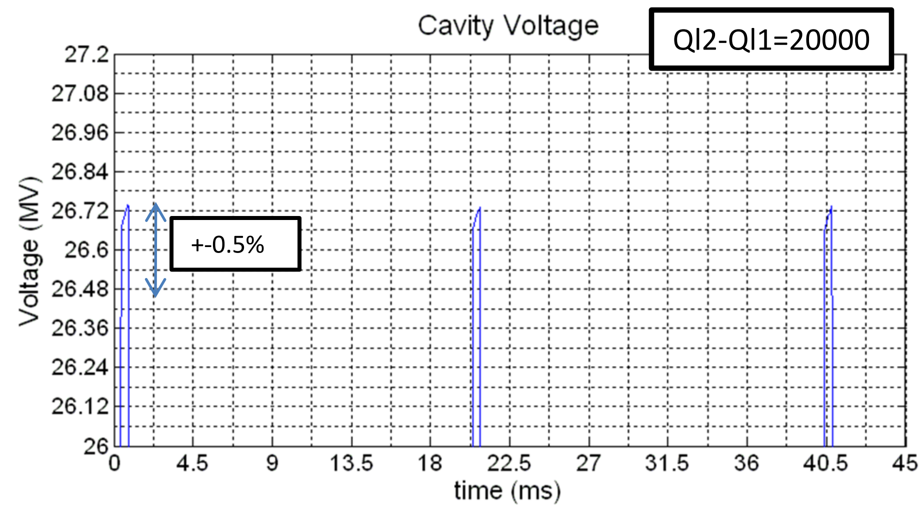


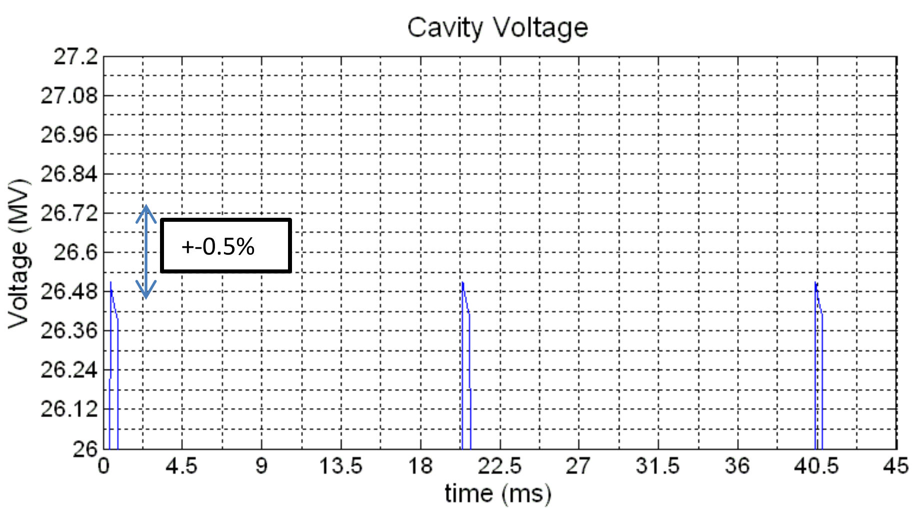
Cavity 2 (K=-0.5 $Hz/\left(\frac{MV}{m}\right)^2$)

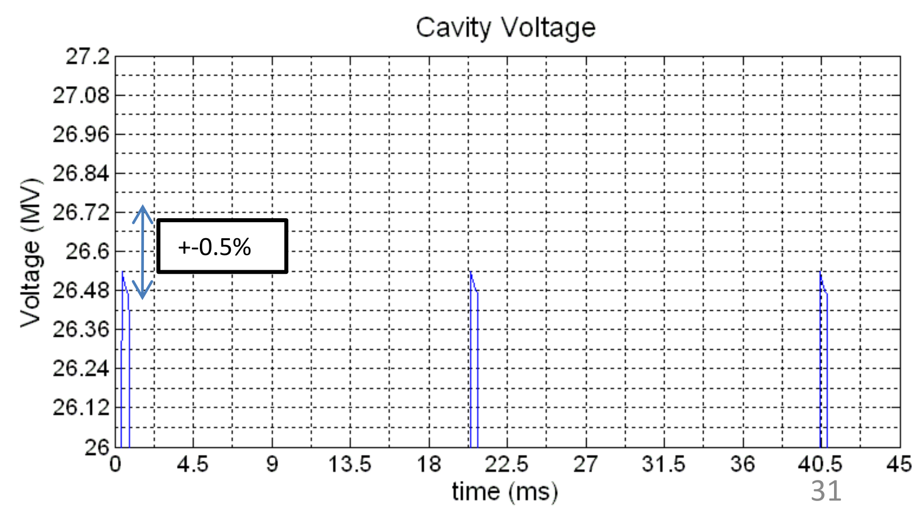


Loaded Quality Factor Fluctuation Effects on Cavity Voltage Magnitude









Error Analysis

- Vector average is maintained within specifications with RF feedback loop, but individual cavities deviate depending on their parameters.

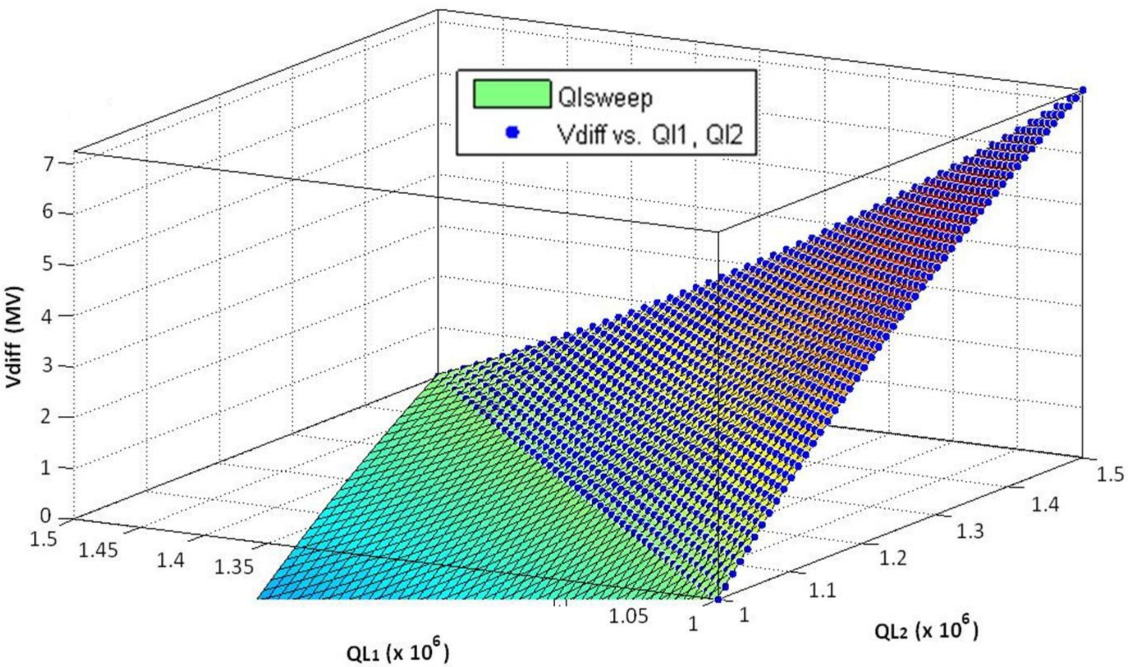
- Characterize deviation of cavity voltage with variations in loaded quality factor and Lorentz detuning coefficients

- Curves fitted for difference in cavity voltage magnitude and phase between 2 cavities controlled by a single RF feedback loop, with a setpoint at nominal accelerating voltage magnitude and phase.

- With this information, the overall effects of the cavity voltage deviation due to Lorentz detuning and loaded quality factor mismatches can be investigated with a model for the whole length of the SPL (investigated at CERN by Piero Antonio Posocco).

Effects of Varying Loaded Quality Factor on Cavity Voltage Magnitude

p00=1.725e+006
p10=34.88
p01=-37.66
p20=-8.311e-006
p11=1.527e-007
p02=9.27e-006



$$V_{Diff} = f(Q_{L1}, Q_{L2}) = f(x, y) = V_{c2} - V_{c1}$$

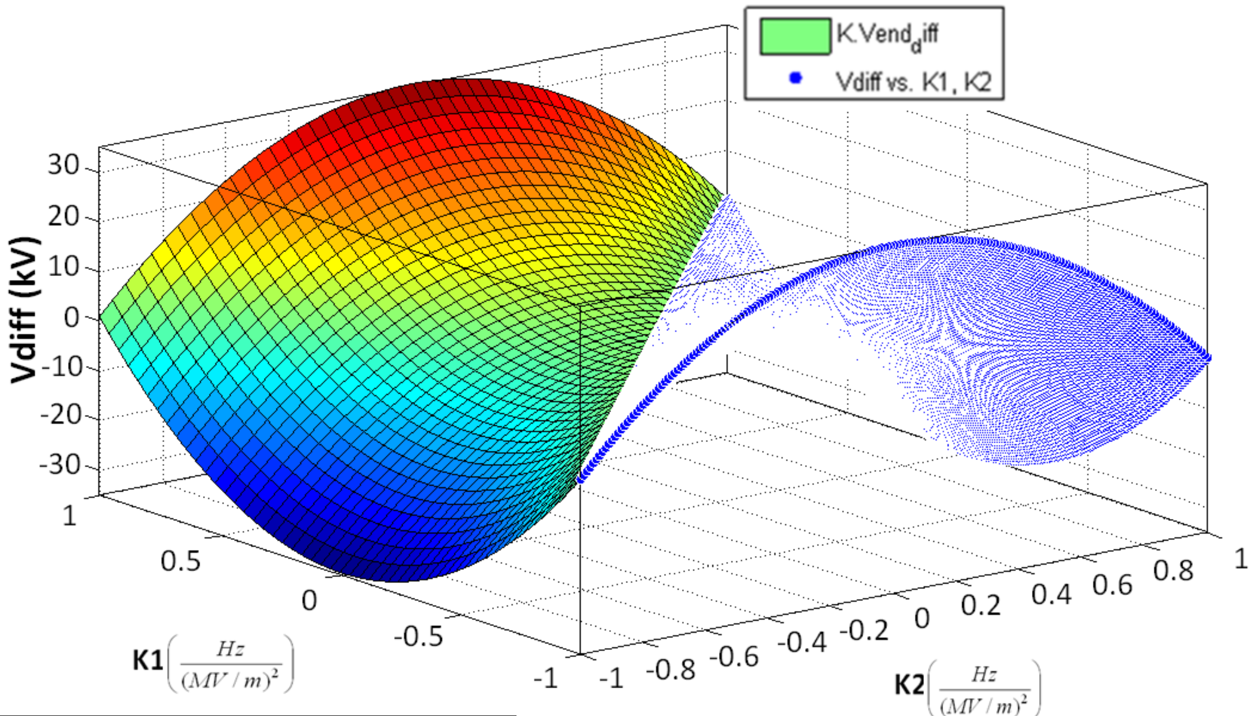
$$V_{c1} = V_{acc} + \frac{V_{Diff}}{2}$$

$$V_{c2} = V_{acc} - \frac{V_{Diff}}{2}$$

$$V_{Diff}(x,y) = p00 + p10\,x + p01\,y + p20\,x^2 + p11\,xy + p02\,y^2$$

Effects of Varying Lorentz Detuning Coefficient on Cavity Voltage Magnitude

p00= 25.8
p10= -2.05e+014
p01= 2.014e+014
p20= -3.496e+028
p11= -1.565e+026
p02= 3.505e+028



$$V_{Diff} = V_{c2} - V_{c1} = f(K_1, K_2) = f(x, y)$$

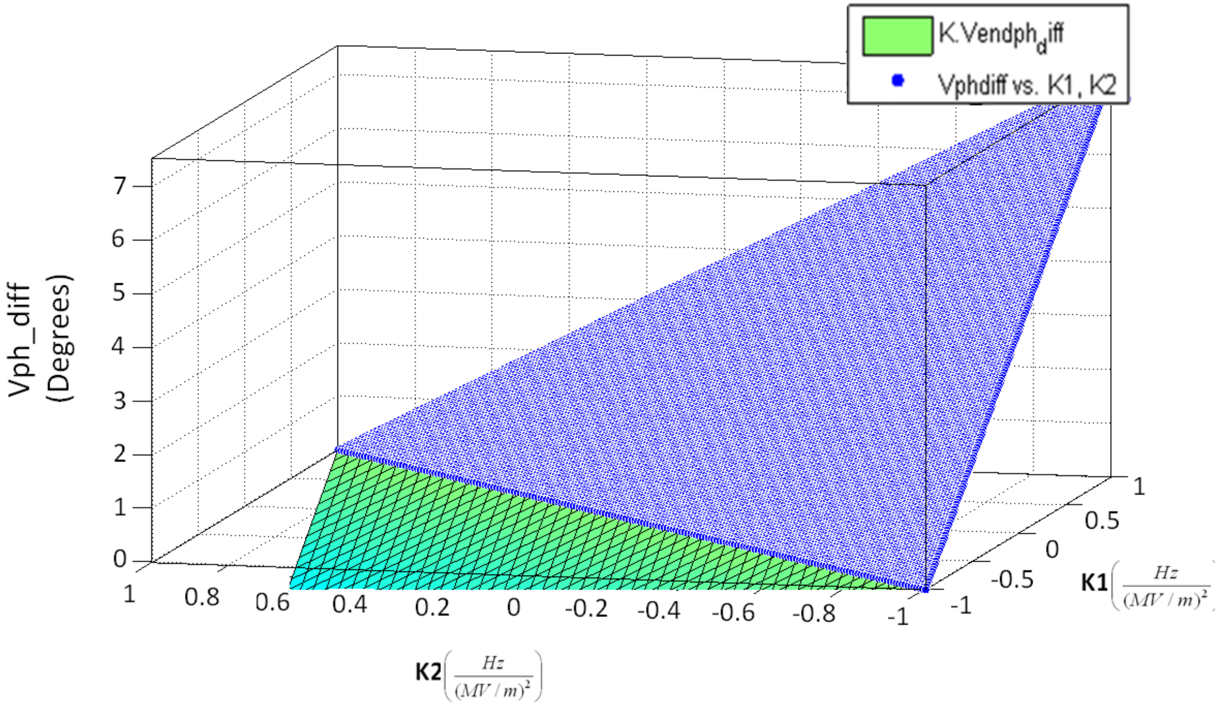
$$V_{c1} = V_{acc} + \frac{V_{Diff}}{2}$$

$$V_{c2} = V_{acc} - \frac{V_{Diff}}{2}$$

$$V_{Diff}(x,y) = p00 + p10\,x + p01\,y + p20\,x^2 + p11\,xy + p02\,y^2$$

Effects of Varying Lorentz Detuning Coefficient on Cavity Voltage Phase

p00= -0.0004408
p10= 3.768e+012
p01= -3.768e+012



$$V_{Diff} = V_{c2} - V_{c1} = f(K_1, K_2) = f(x, y)$$

$$V_{c1} = V_{acc} + \frac{V_{Diff}}{2}$$

$$V_{c2} = V_{acc} - \frac{V_{Diff}}{2}$$

$$V_{Diff}(x,y) = p00 + p10x + p01y + p20x^2 + p11xy + p02y^2$$

In Summary…

- In order to cater for the needs of project specifications, a high flexibility simulation model was developed.
- Flexible graphical user interface allows for efficient handling of simulation data.
- 1, 2 and 4 cavities can be observed from RF point of view for a wide set of parameters.
- Can estimate practical issues that can arise during development of the real LLRF system in terms of power, stability of accelerating field and technology necessary for operation.

Next Step

- Investigate different possible optimisations to transit time factor effects in terms of forward power, loaded quality factor and injection time along the LINAC.
- Characterize power amplifier and other components from real measurements in terms of their transfer functions.
- Characterize the behavior of the piezo-electronic tuner within the control loop.
- Develop a full digital/analogue control system using hardware and test in a cold cavity.