RF Cavity Simulation for SPL

Simulink Model for single RF Cavity with Lorentz Detuning and RF Feedback Loop using I/Q Components

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

SPL High Power Operation

General linac parameters

Parameter	Unit	HP-SPL	LP-SPL	Timestamp
Energy	[GeV]	5	4	15 August 2007
Beam power	[MW]	>4.0	0.192	31 March 2008
Repetition rate	[Hz]	50	2	15 August 2007
Average pulse current	[mA]	20/40	0-20	28 November 2008
Peak pulse current	[mA]	32/64	32	15 August 2007
Source current	[mA]	40/80	40	21 April 2008
Chopping ratio	[%]	62	62	21 November 2008
Beam pulse length	[ms]	0.4[2] - 1.2[3]	0.9	6 July 2009
Number of klystrons (704 MHz, 5 MW)		tbd	tbd	15 August 2007
Geometric cavity beta		0.65/1.0	0.65/1.0	24 April 2009
Number of cavities		60/184	60/144	2009-10-06
Additional cavities for debunching		0/16	0/16	2009-10-06
Cavities/klystron		tbd	tbd	22 April 2008
Cavities/cryostat		6/8	6/8	23 April 2008
Max. power/cavity	[MW]	1	0.5	21 April 2008
Length[4]	[m]	529	454	24 April 2009

Edit

(1) assuming that the full klystron power is distributed to the cavities, which means splitting ratios up to 1 klystron/16 cavities
(2) expected nominal operation
(3) ultimate operation
(4) excluding Linac4, including 16 debuncher cavities at linac end, including extraction to ISOLDE and EURISOL

Parameters from SPL twiki web page (F. Gerigk)
https://twiki.cern.ch/twiki/bin/view/SPL/SPLparameterList

$$f_{\mathrm{RF}} = 704.4\ \mathrm{MHz}$$

$$I_{\mathrm{b}} \cong 40\ \mathrm{mA}$$

$$\phi_{\mathrm{s}} = 15^{\circ}\,(LINAC)$$

$$E_{acc} = 25\ \mathrm{MV}$$

$$length_{cav} = \beta \times \frac{\lambda_{RF}}{2} \times 5\ (5\ cell,\ \pi\ \mathrm{mode})$$

$$V_{acc} = E_{acc} \times length_{cav} = 26.6\ \mathrm{MV}$$

$$P_{\mathrm{b}} = V_{\mathrm{acc}} \times I_{\mathrm{b}} \times \cos(\phi_{\mathrm{s}}) \cong 1\ \mathrm{MW}$$

$$Q_{\mathrm{L}} = \frac{V_{acc}}{\frac{R}{Q} \times I_b \times \cos(\phi_s)} \cong 1.3 \times 10^6$$

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

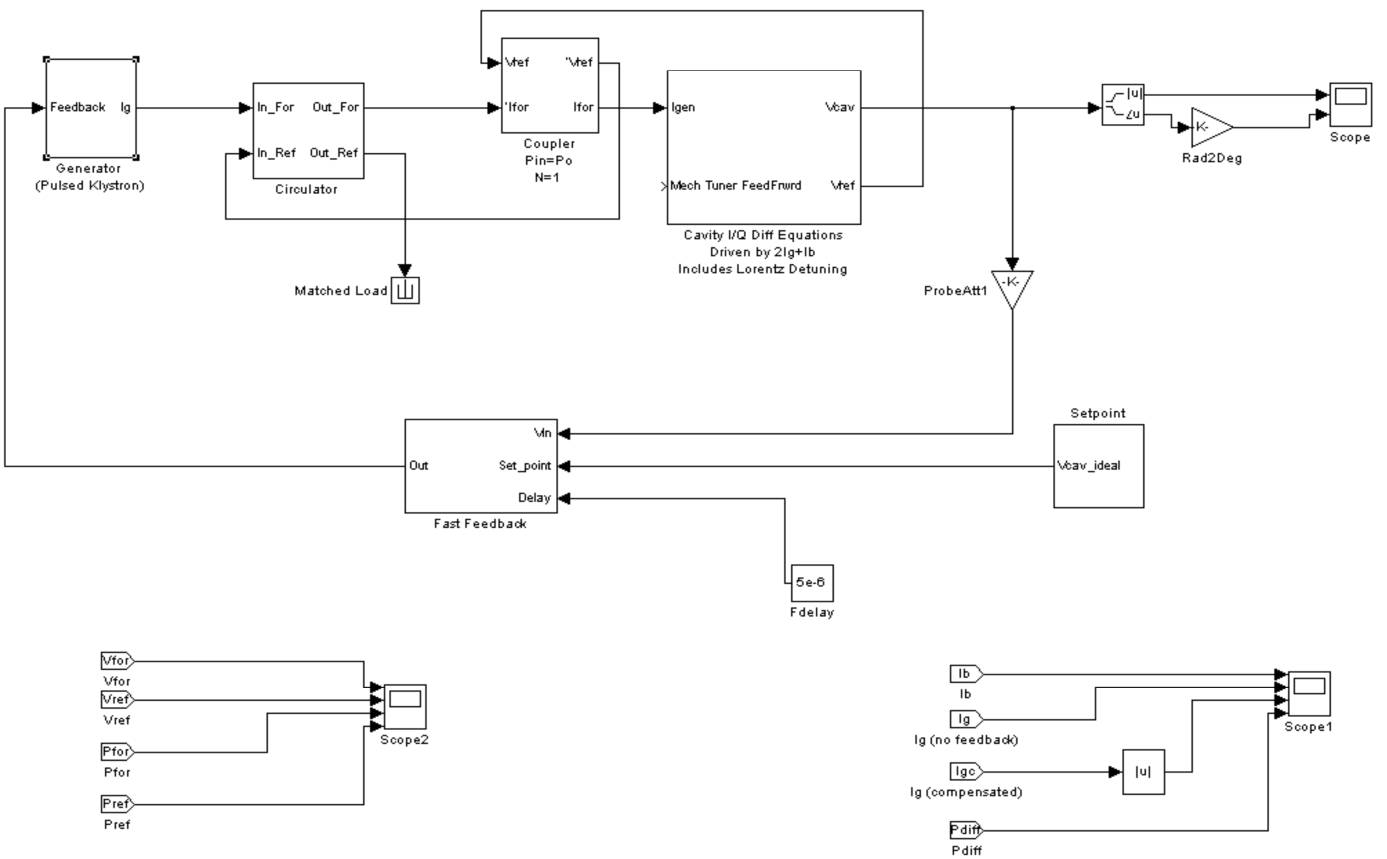
$$\tau_{\mathrm{beampulse}} = 1.2\ \mathrm{ms}$$

$$\mathrm{rep\ period} = 20\ \mathrm{ms}$$

$$I_{\mathrm{g}} \cong 40\ \mathrm{mA}$$

$$R_{\mathrm{L}} = 680\ \mathrm{M\Omega}$$

Simulink High-Level Model of Single Cavity with Feedback



$f_{RF} = 704.4$ MHz

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

$\tau_{beampulse} = 1.2$ ms

rep period $= 20$ ms

$I_g \cong 40$ mA

$R_L = 680$ MΩ

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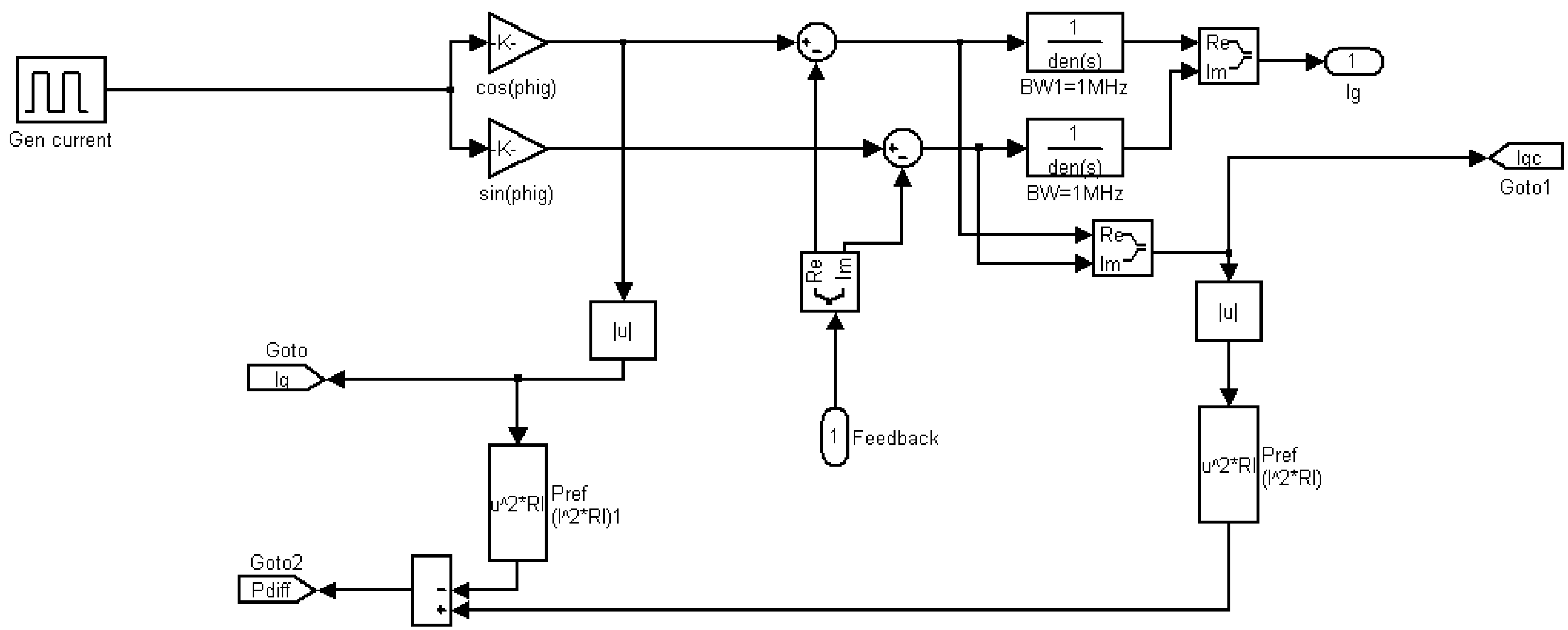
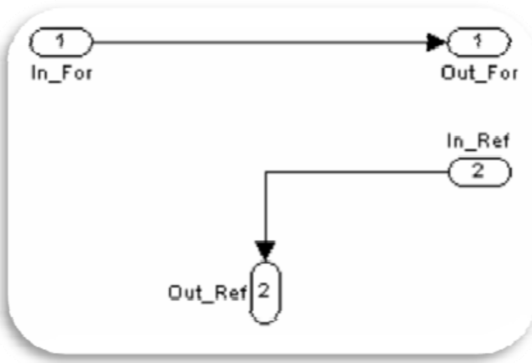
Pulsed Source

- Frequency response modeled as a high bandwidth low-pass filter for I/Q



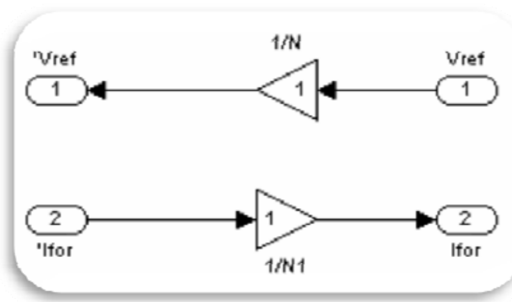
Circulator and Waveguide/Cavity Coupling

Circulator Model



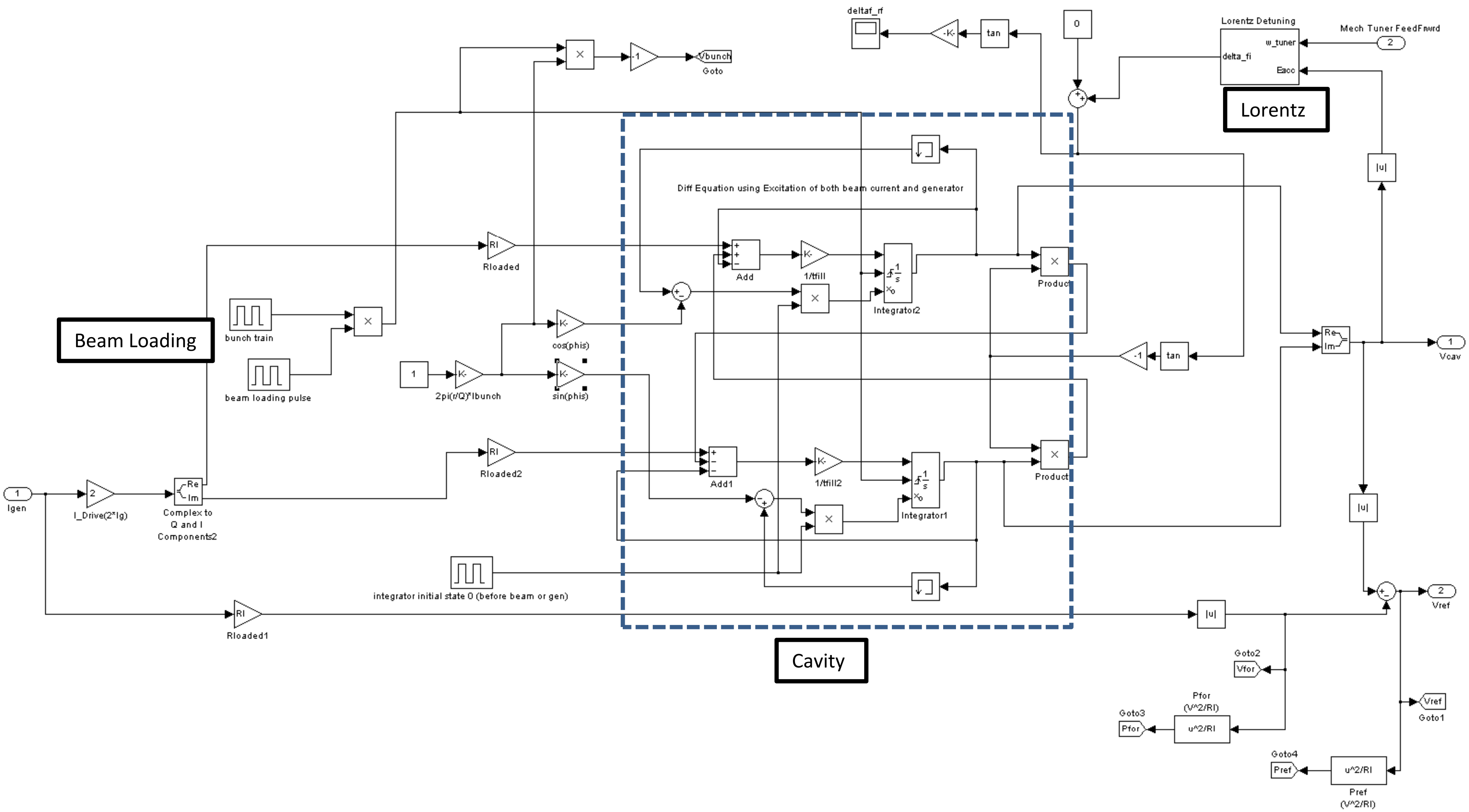
Future: refine and study how to include circulator mismatch

Coupler Model
(Turns Ratio Gain)



Cavity Model

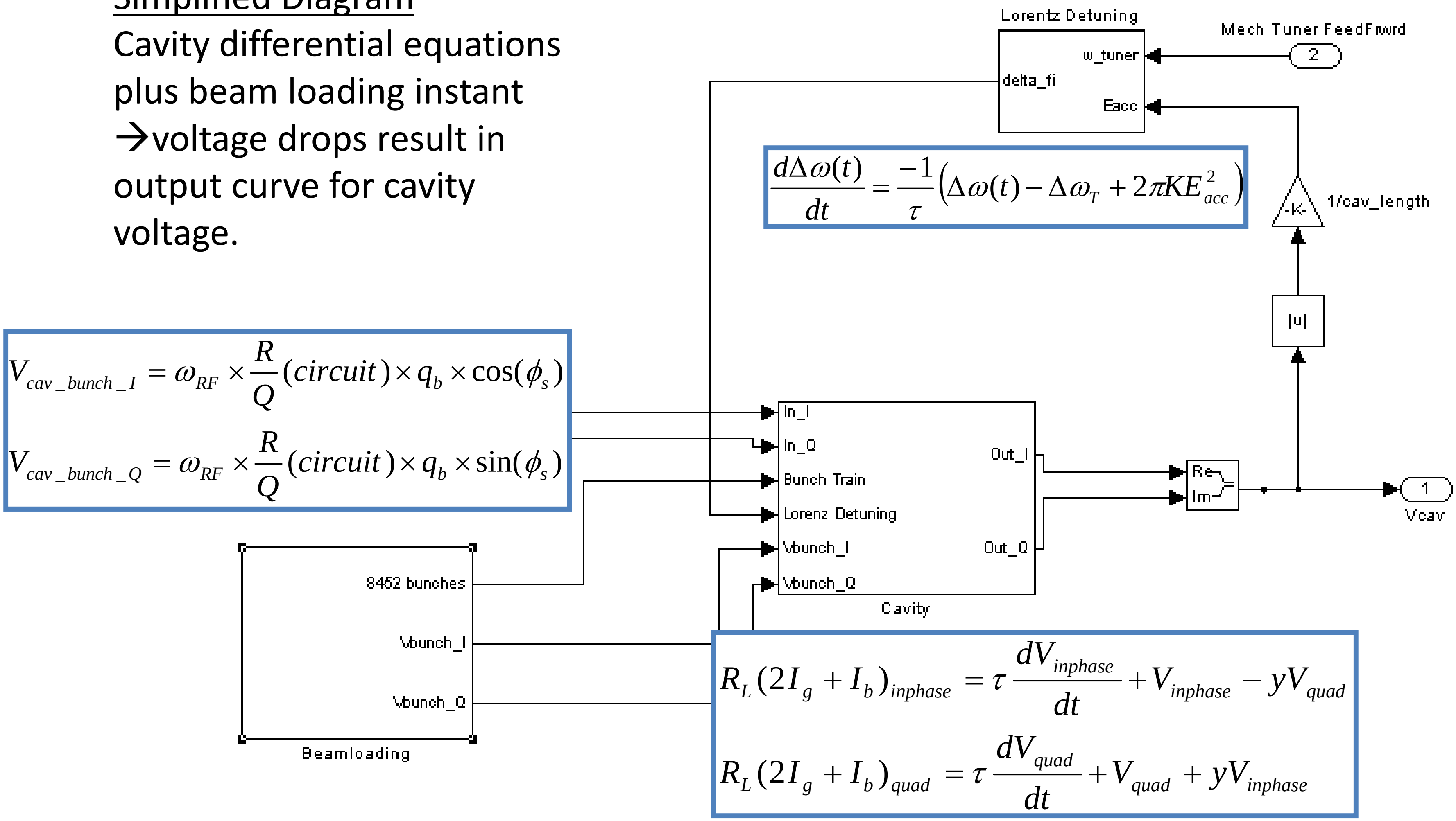
Model Created using I/Q Differential Transient Relation Driven by Generator and Beam Current



Cavity Model (cont)

<u>Simplified Diagram</u>

Cavity differential equations plus beam loading instant →voltage drops result in output curve for cavity voltage.



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

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

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

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

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

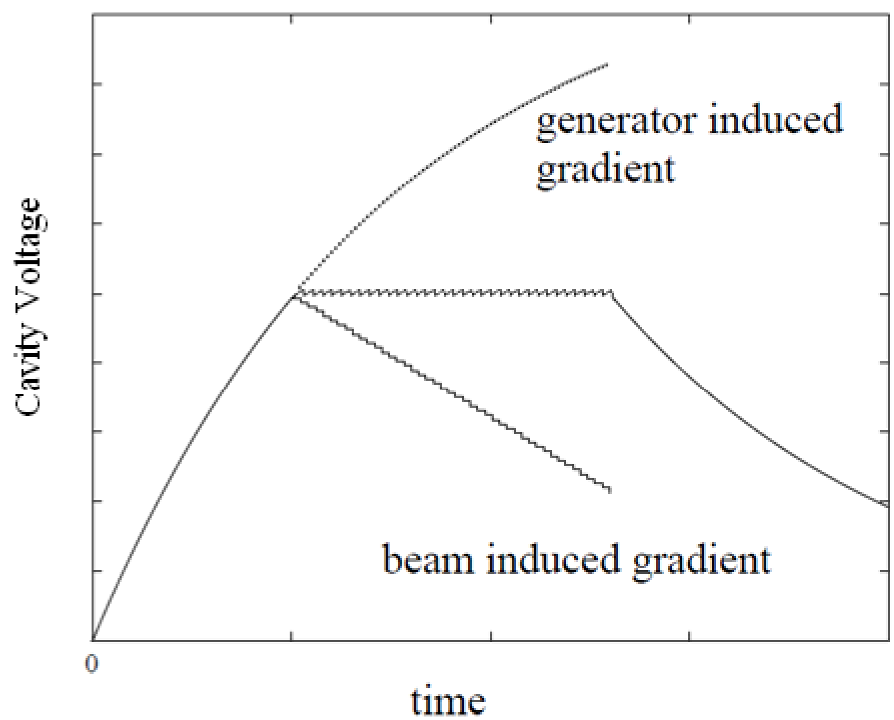
Beam Loading

- Infinitely narrow bunches induce an instant voltage drop in cavity
- Lump beam loading together in infinitesimal short “macro-bunches”, i.e. every 140 ns

- Voltage drop is equal to gene creating flattop operation

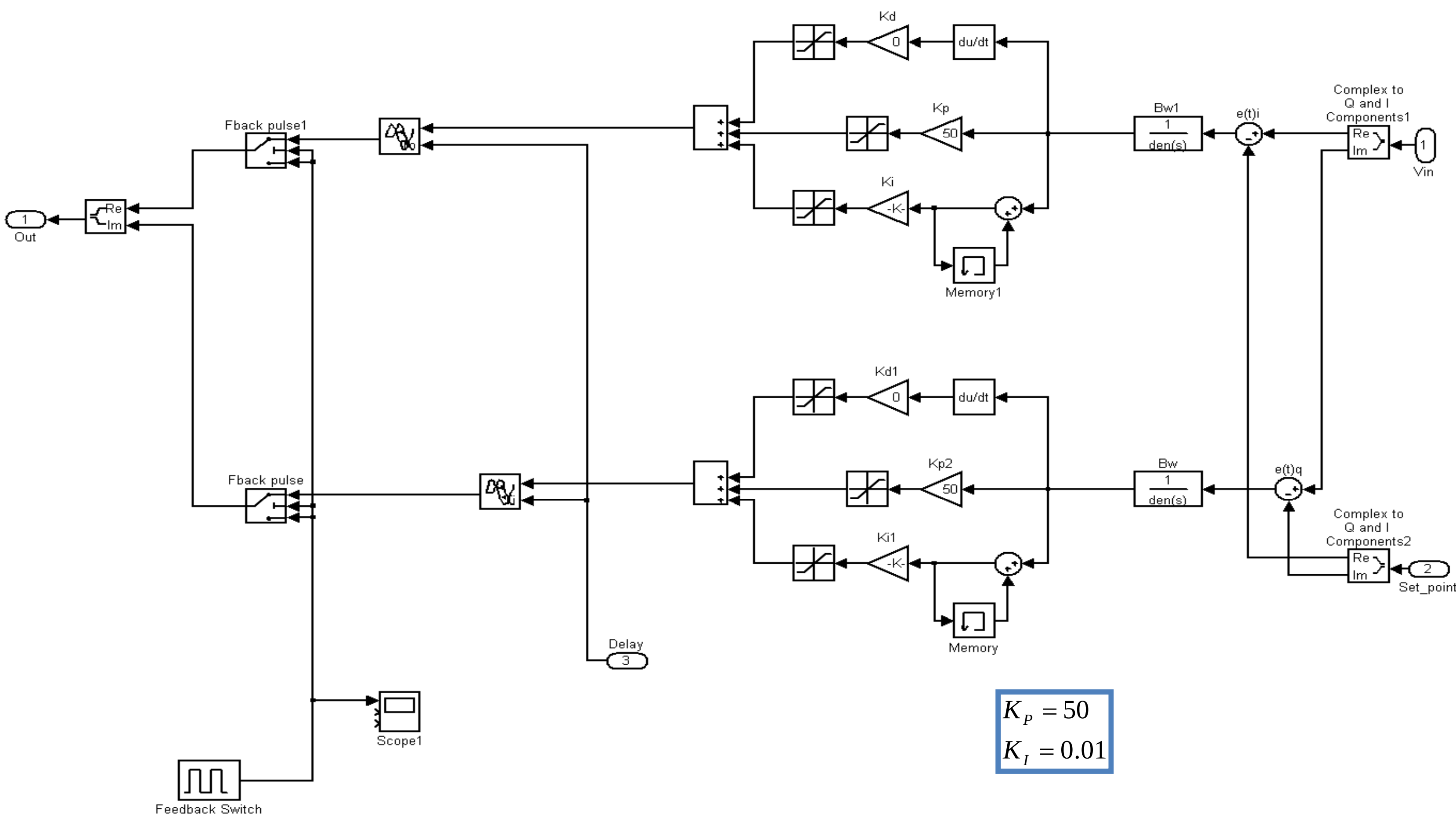
$$V_{cav\_bunch\_I} = \omega_{RF} \times \frac{R}{Q}(circuit) \times q_b \times \cos(\phi_s)$$

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



RF Feedback

- PI controller model
- Output frequency response of feedback amplifier modeled as first order low-pass filter with 100 kHz bandwidth (1 MHz Klystron BW)



$K_P = 50$

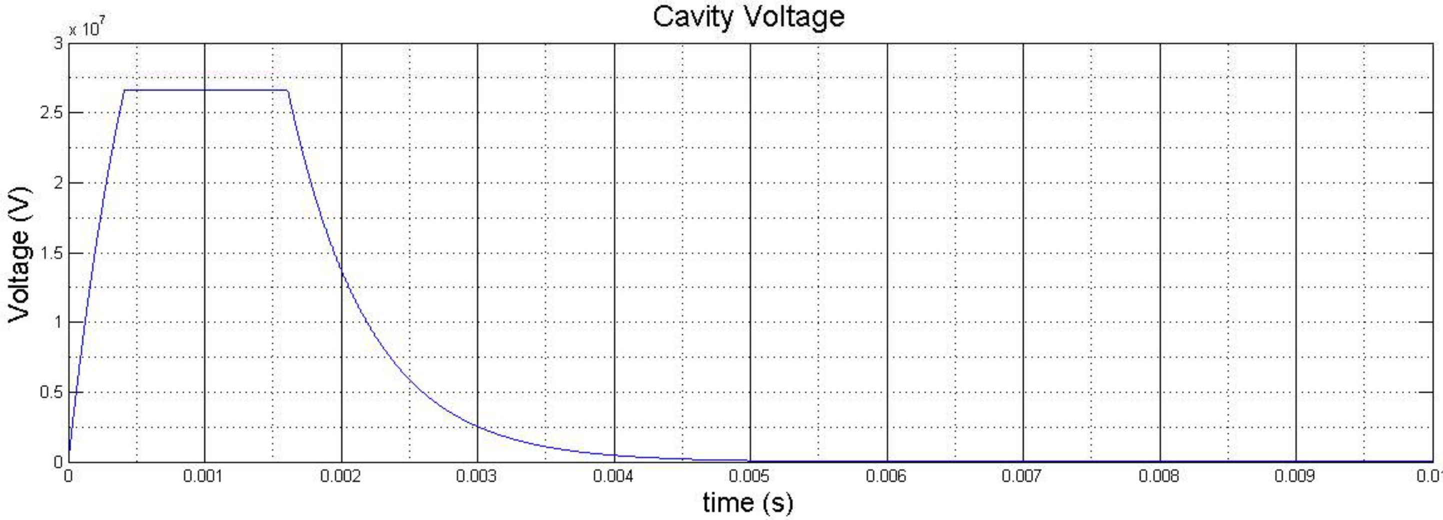
$K_I = 0.01$

Results

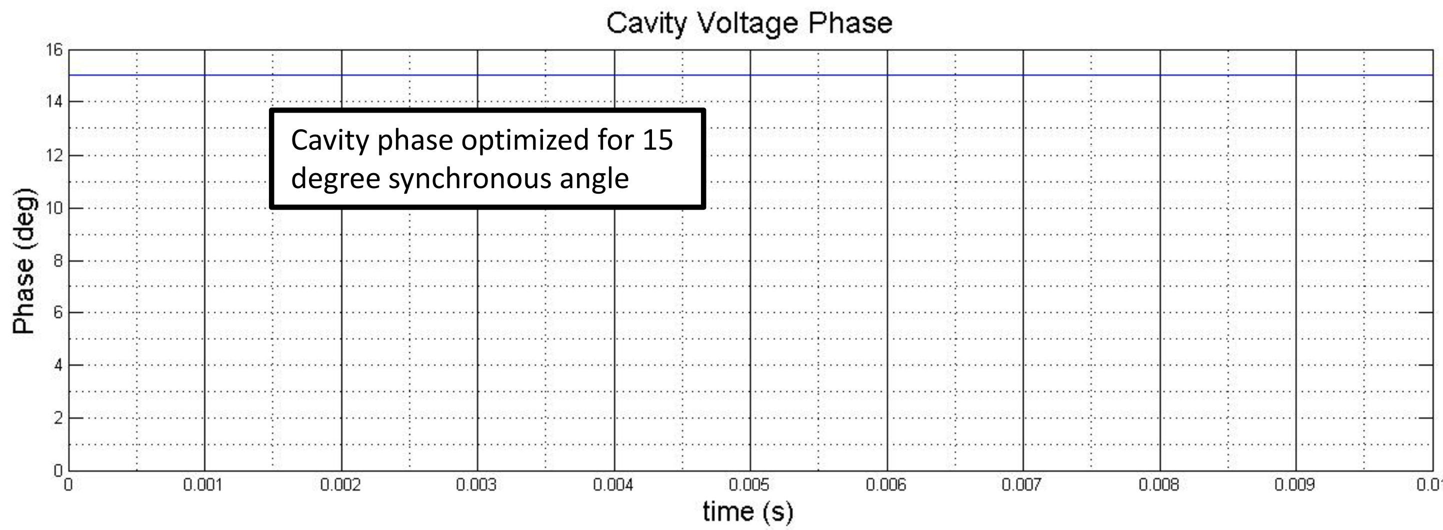
- Cavity Voltage Amplitude and Phase
- Forward and Reflected Power
- Additional Power for Feedback Transients and Control
- Effect of Lorentz Detuning on Feedback Power

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

Feedback loop is closed 0.1 ms after generator pulse and 0.1 ms after end of beam loading pulse



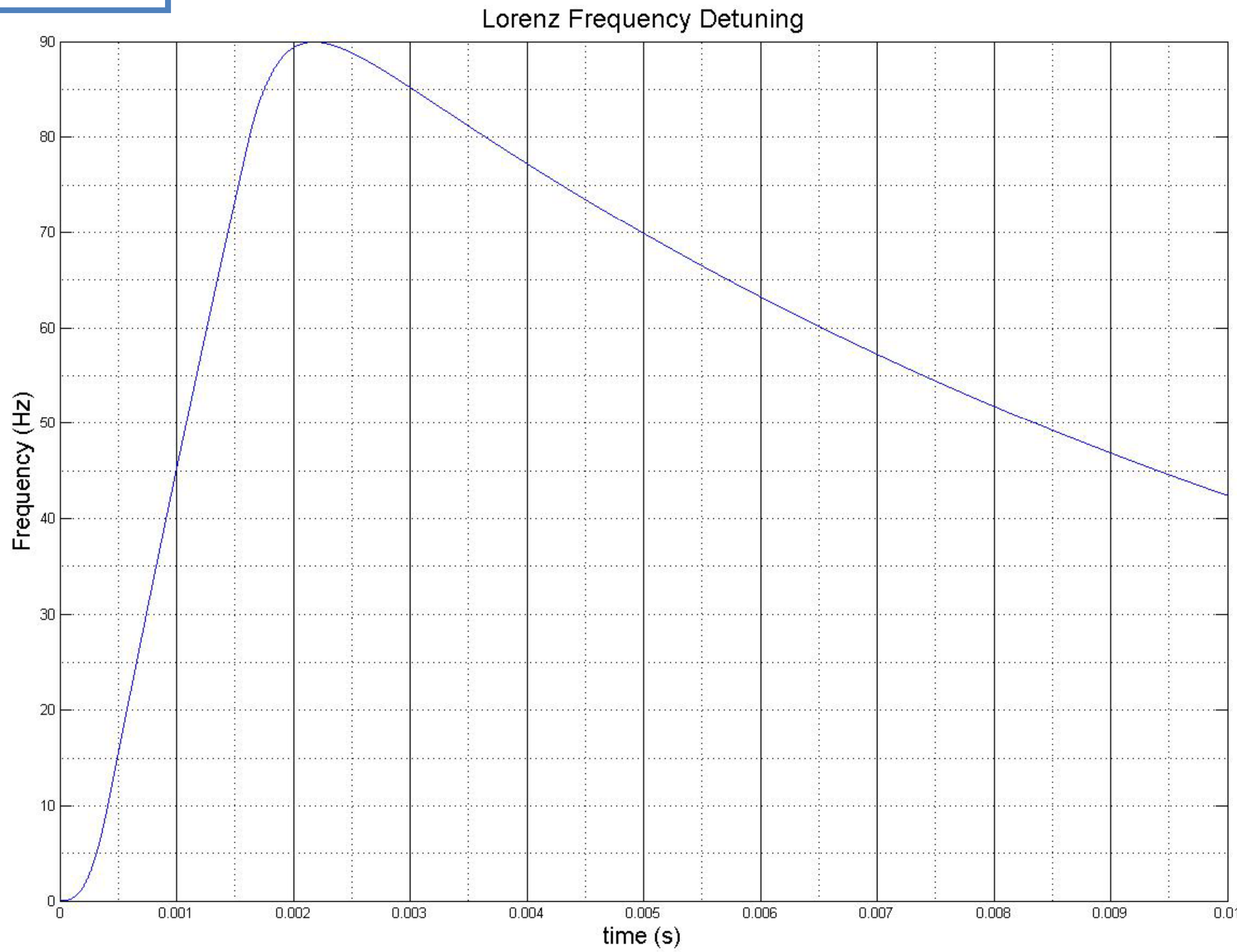
5 us delay for Feedback Loop



Cavity phase optimized for 15 degree synchronous angle

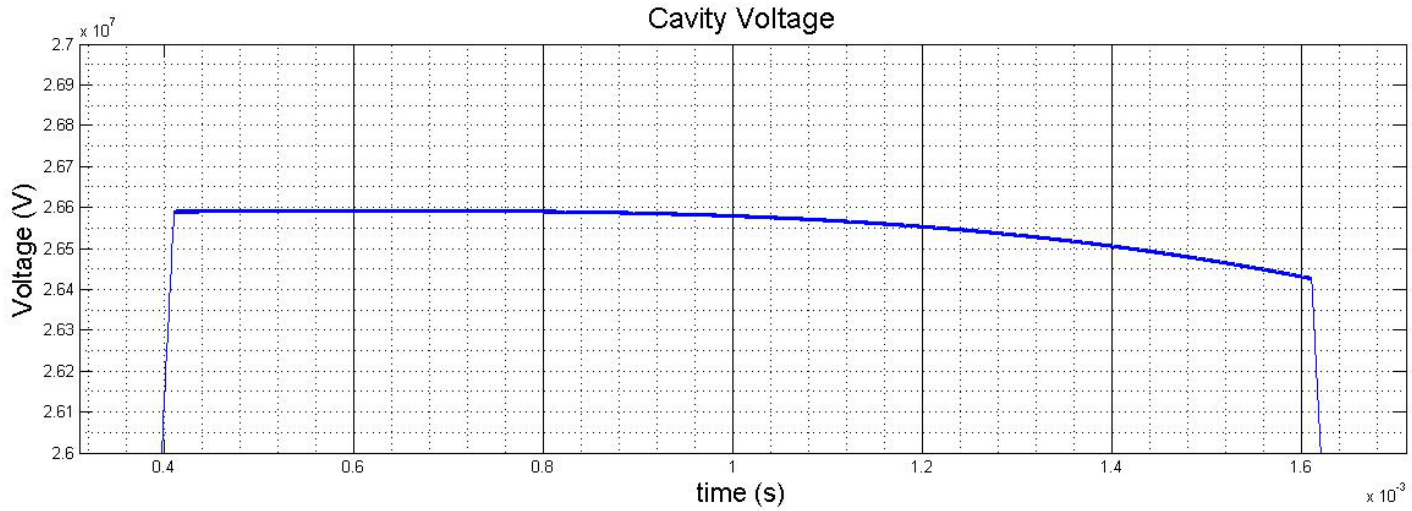
Effect of Lorentz Detuning on Cavity Voltage and Phase (Lorentz Frequency Shift)

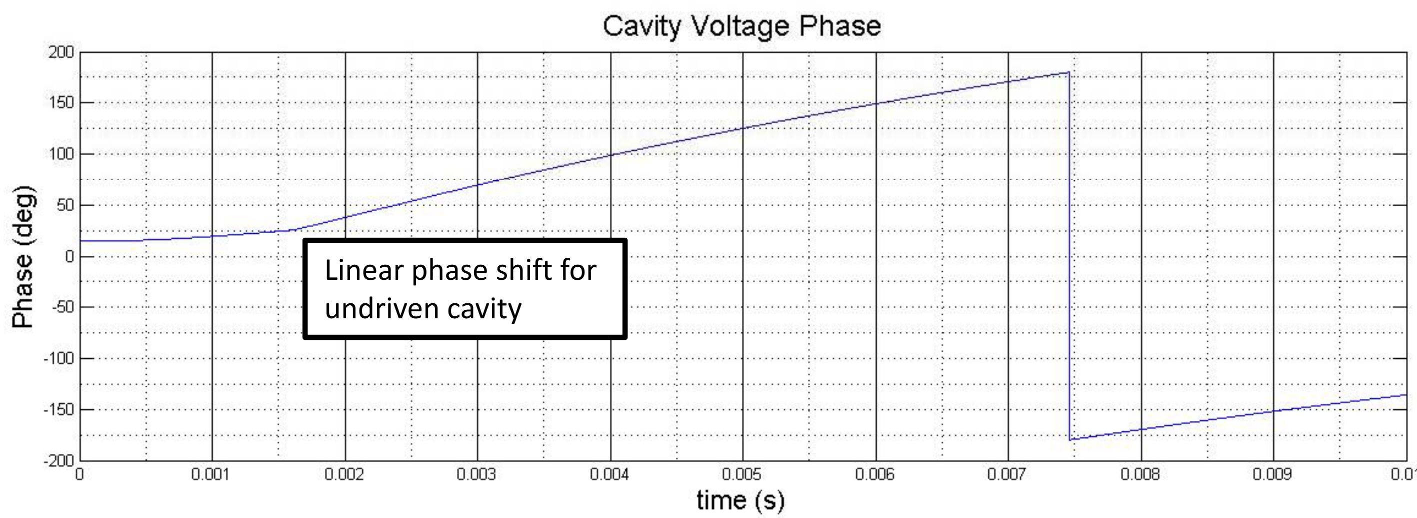
$$\frac{d\Delta\omega(t)}{dt} = \frac{-1}{\tau}\left(\Delta\omega(t) - \Delta\omega_T + 2\pi K E_{acc}^2\right)$$



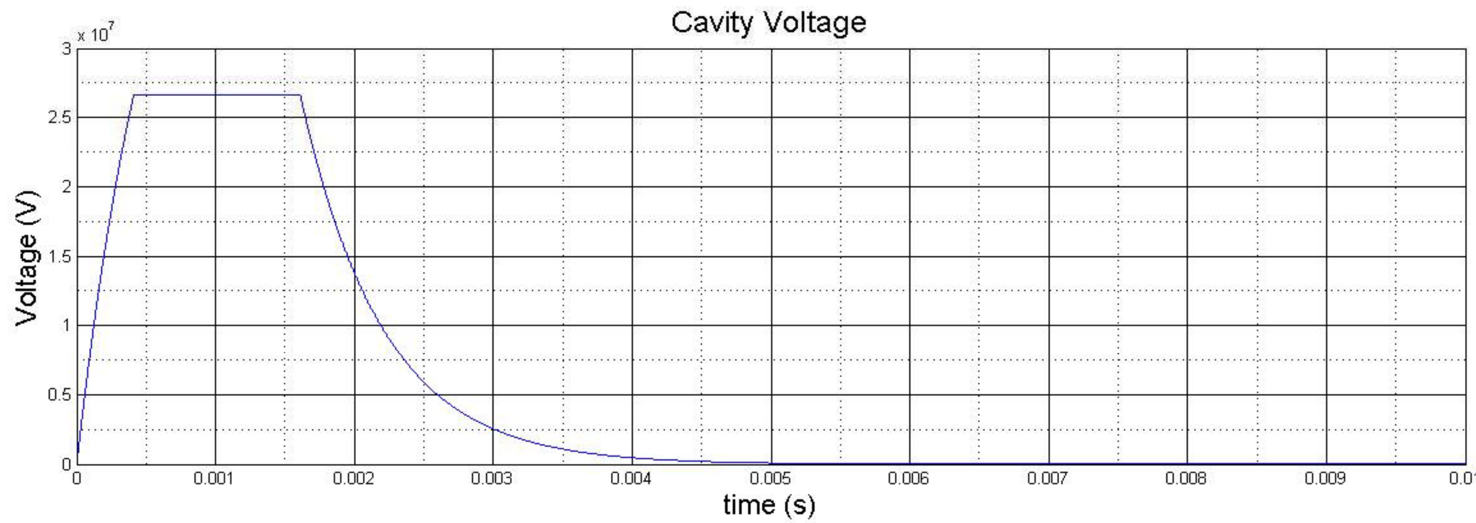
Effect of Lorentz Detuning on Cavity Voltage and Phase (Open Loop)

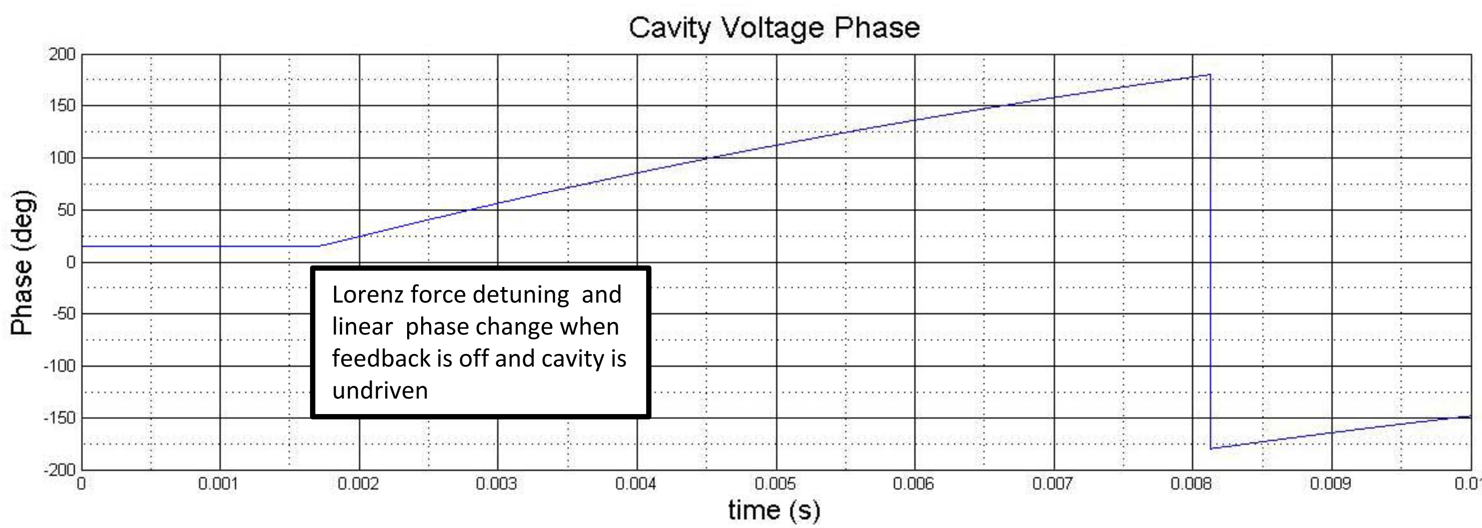
Decrease in accelerating voltage



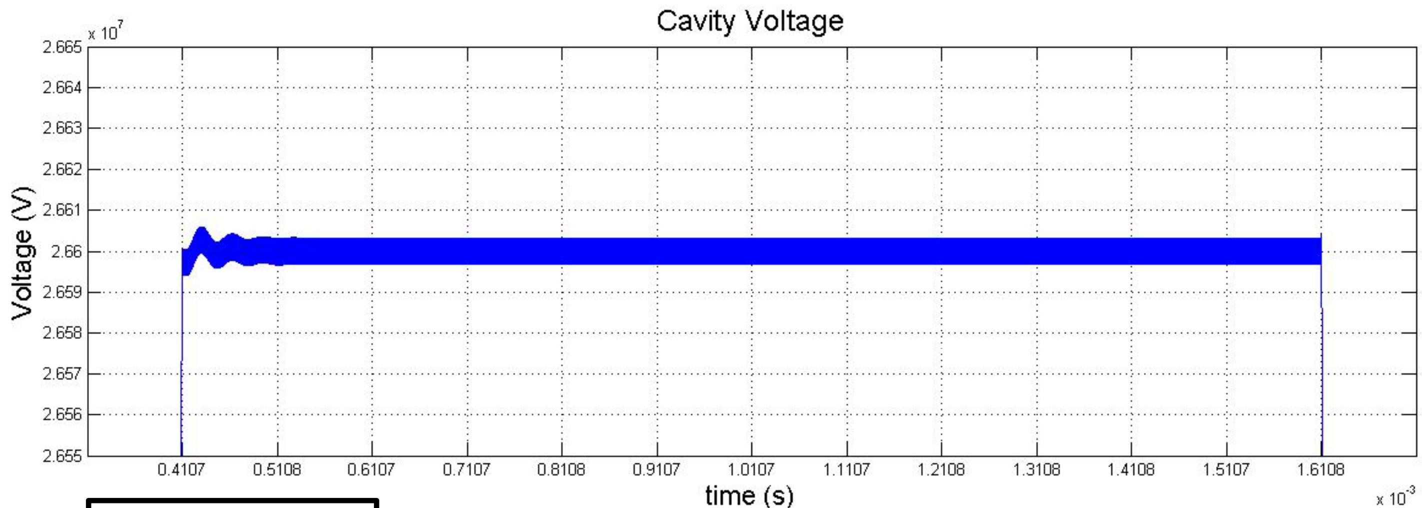


Cavity Voltage and Phase With Lorentz Detuning (Closed Loop Performance of Fast Feedback)

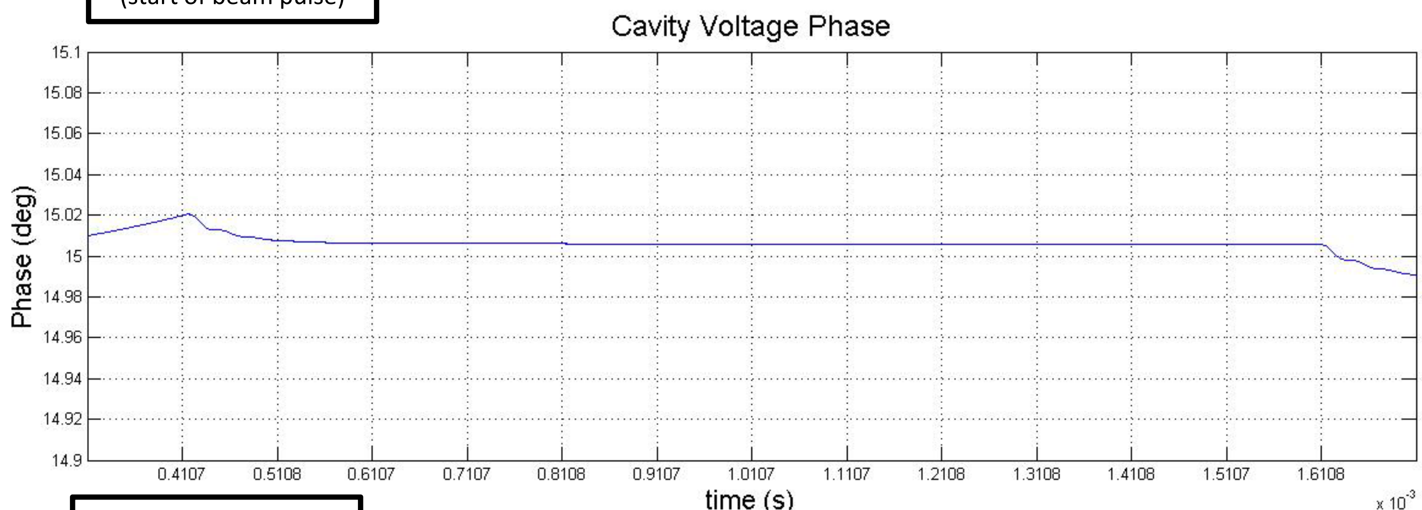




Cavity Voltage and Phase Close-up



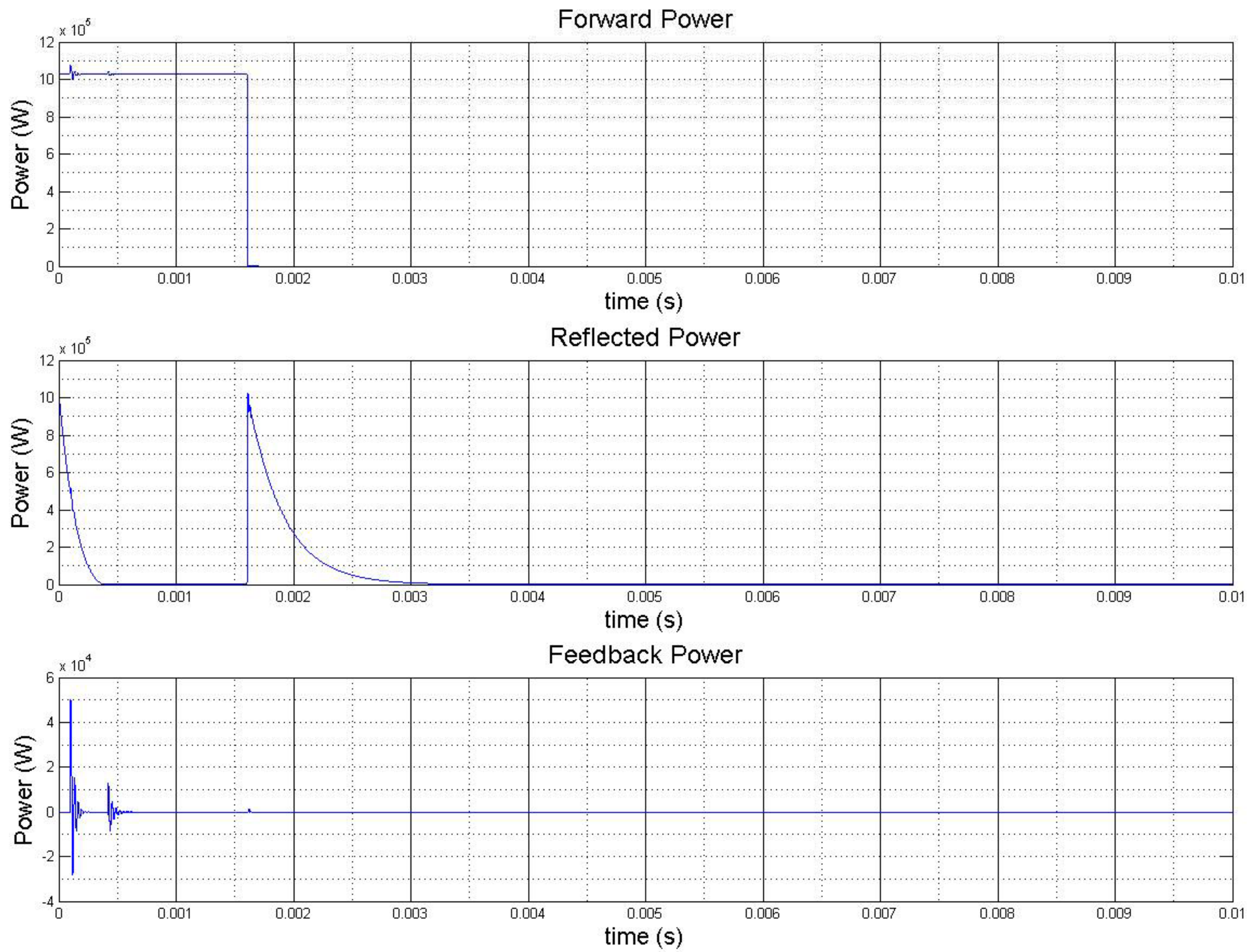
Injection Time
(start of beam pulse)



Injection Time
(start of beam pulse)

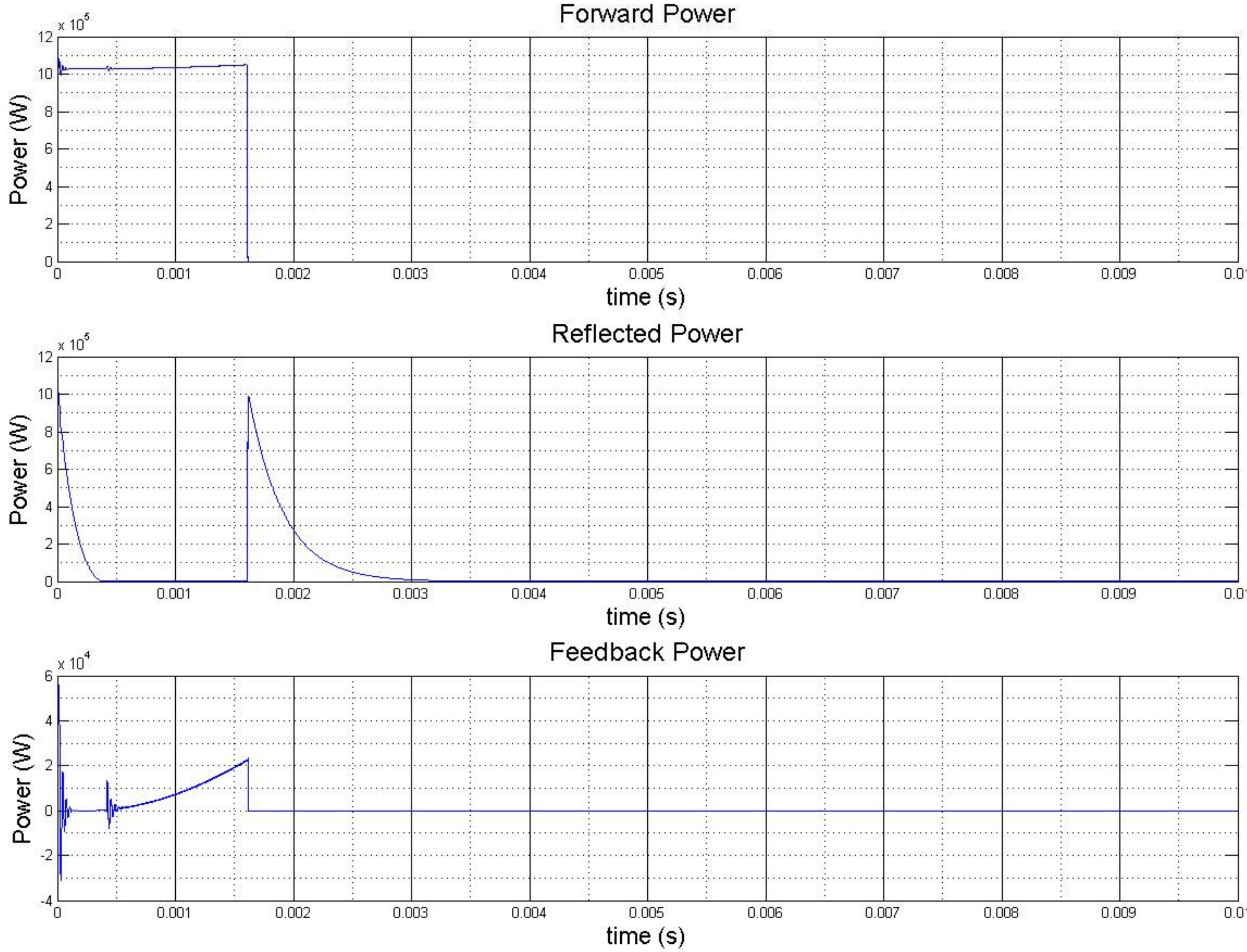
Forward and Reflected Power without Lorentz Detuning

Oscillations due to transients during closing of the feedback loop and beam loading. Feedback loop is closed 0.1 ms after generator pulse and 0.1 ms after end of beam loading pulse



Forward and Reflected Power and Feedback Power Consumption with Lorentz Force detuning

Oscillations due to transients during closing of the feedback loop and beam loading. Feedback loop is closed 0.1 ms after generator pulse and 0.1 ms after end of beam loading pulse



Frequency Considerations

- Stability Observations using Gain and Phase Margin
- Effects of Delay on Transfer Function

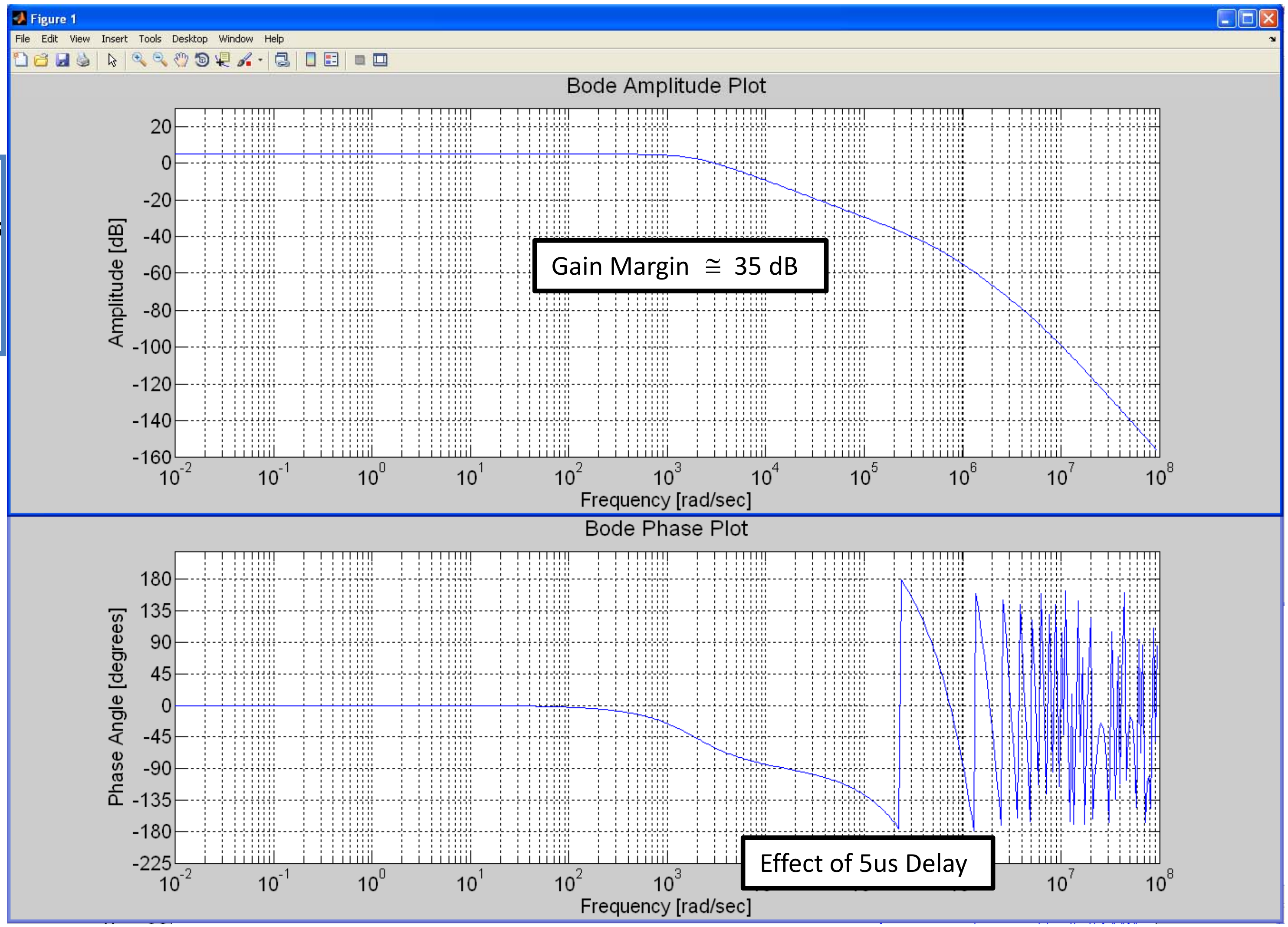
Full Open-Loop System Bode Plot (100 kHz feedback BW)

$f_{FB\_pole} = 100\,\text{kHz} = 628\,\text{krad/s}$

$f_{Kly\_pole} = 1\,\text{MHz} = 6.28\,\text{Mrad/s}$

$f_{cav\_2poles} = 318\,\text{Hz} = 2\,\text{krad/s}$

$f_{cav\_zero} = 318\,\text{Hz} = 2\,\text{krad/s}$



Next Step

- Observe stability and frequency performance using analytical methods for finding optimum integrating gain K_I
- Include and quantify effect from finite bunch length
- Observe performance for multiple non-identical cavities and use adaptive feedforward
- Observe cavity voltage response to H^- source fluctuations
- Quantify extra power required due to modulator droop and ripple