PIP-II

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LLRF System Analysis for the Fermilab PIP-II LINAC

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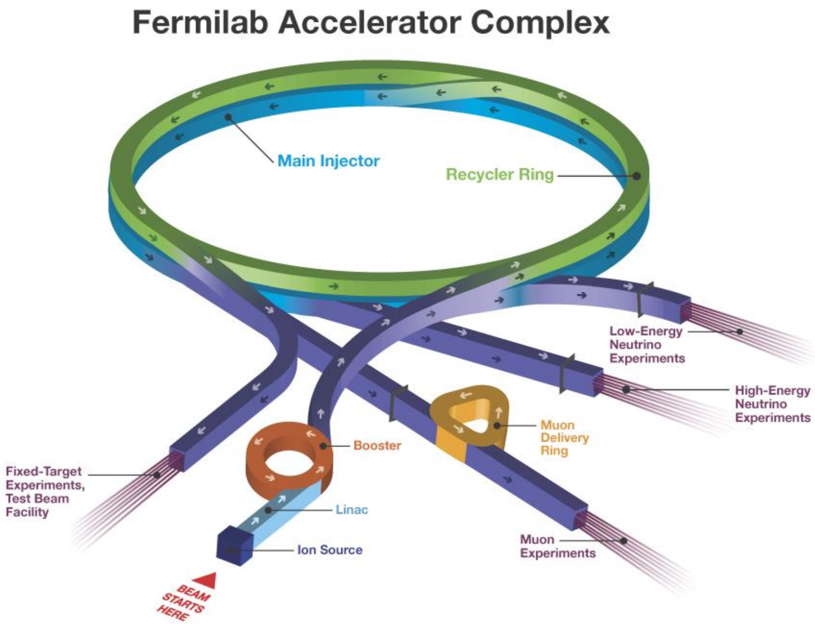
PIP-II is a partnership of:

- US-DOE
- India-DAE
- Italy-INFN
- UK-STFC-UKRI
- France-CEA, CNRS/IN2P3
- Poland-WUST, WUT, TUL

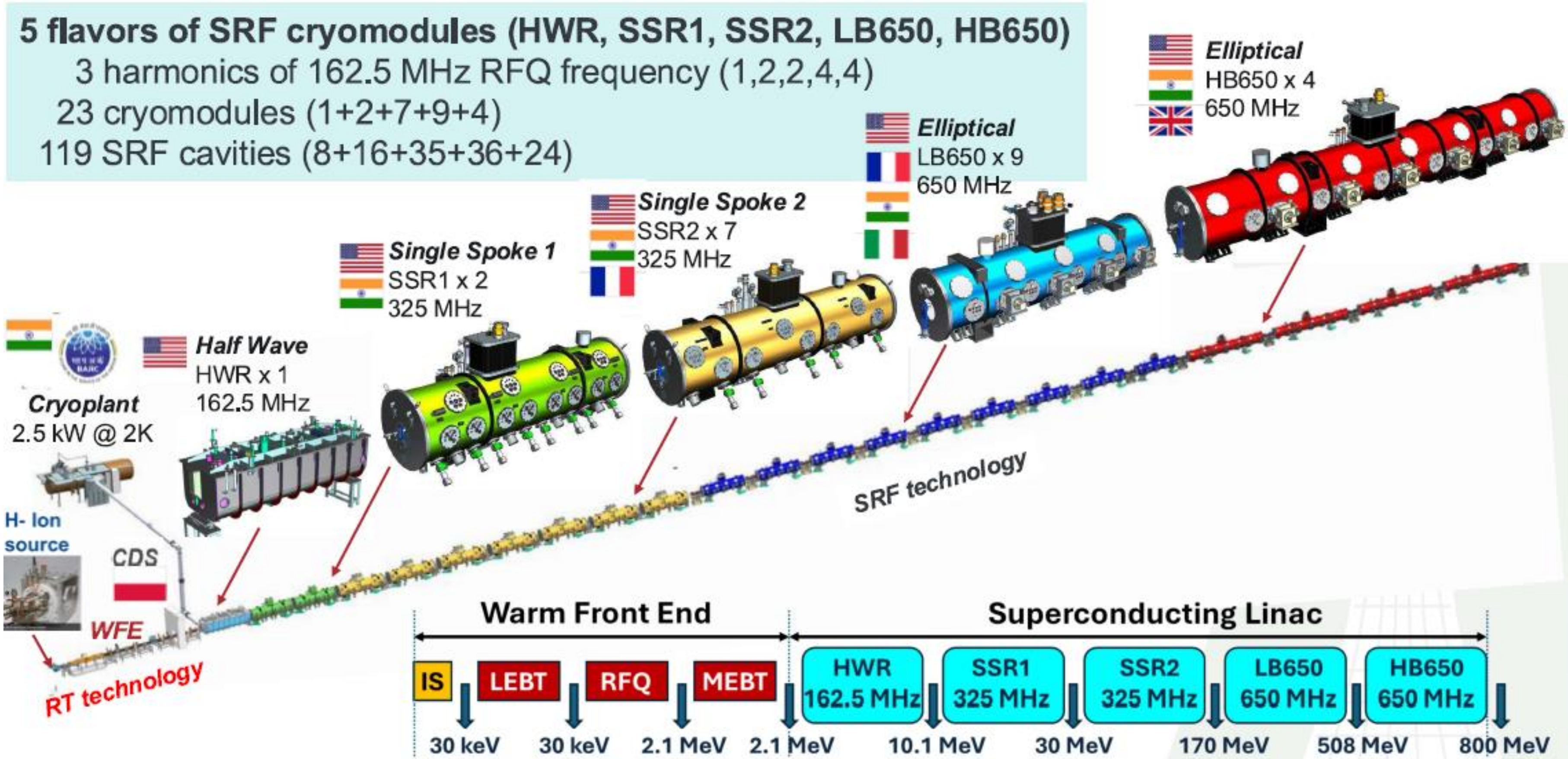
Fermilab

Outline

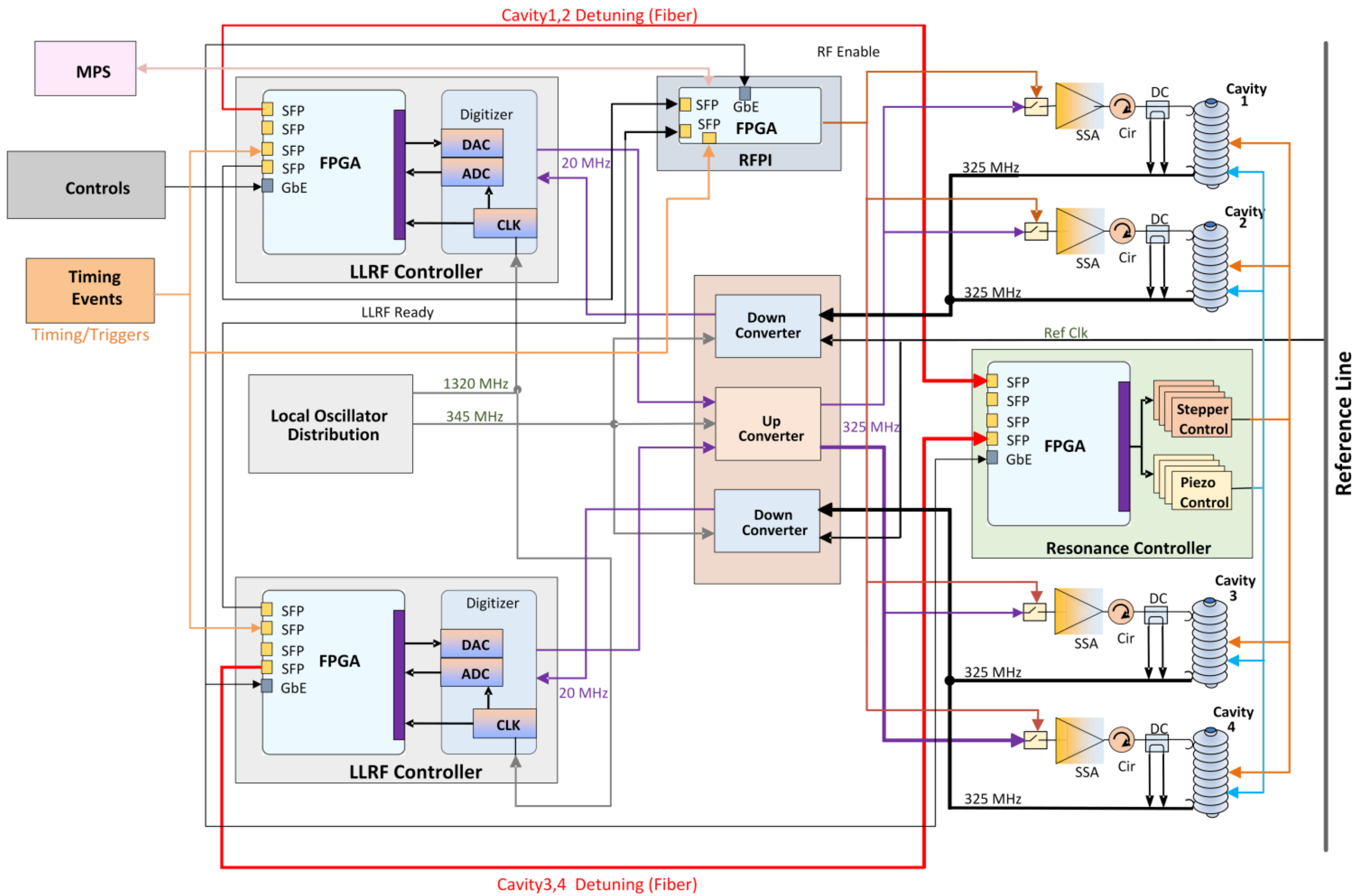
Fermilab Accelerator Complex



Fermilab Accelerator Complex



PIP2 4-Cavity RF Station

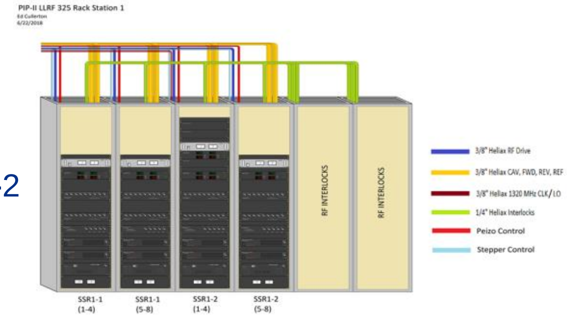


PIP2 LLRF Systems

CM type	Cavities per CM	Number of CMs	CM configuration[+]	CM length (m)	Q_0 at 2K (10^{10})	Surface resistance, (nΩ)	Loaded Q[△] (10^6)
HWR	8	1	8×(sc)	5.93	0.5	9.6 (2.75[†])	2.32
SSR1	8	2	4×(csc)	5.53	0.6	14 (10[‡])	3.02
SSR2	5	7	sccsccsc	6.3*	0.8	14.4	5.05
LB650	4	9	cccc	5.52*	2.15	9.0	10.36
HB650	6	4	cccccc	9.92*	3	8.7	9.92

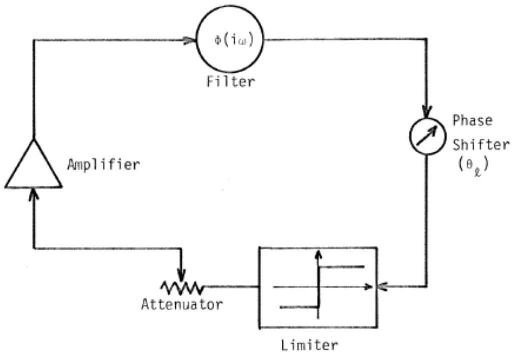
	Station 1	Station 2	Station 3	Station 4	Station 5	Station 6	Station 7	Station 8	Station 9	Station 10	Station 11	Total
	RFQ, B1-4	HWR	SSR1-1,2	SSR2-1,2,3	SSR2-4,5	SSR2-6,7	LB650-1,2,3	LB650-4,5,6	LB650-7,8,9	HB650-1,2	HB650-3,4	
Number of cavities	6	8	16	15	10	10	12	12	12	12	12	125
RF Freq (MHz)	162.5	162.5	325	325	325	325	650	650	650	650	650	

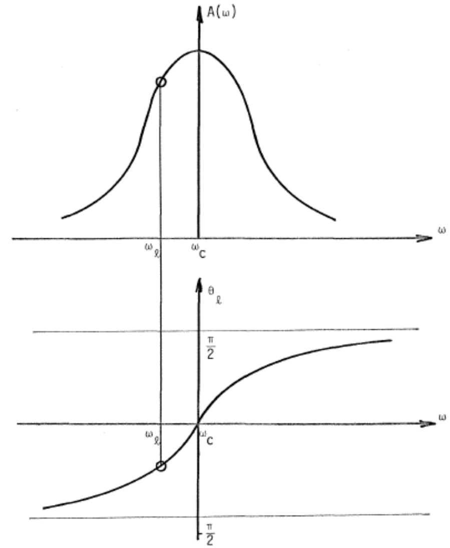
S3 – SSR1-1,SSR1-2

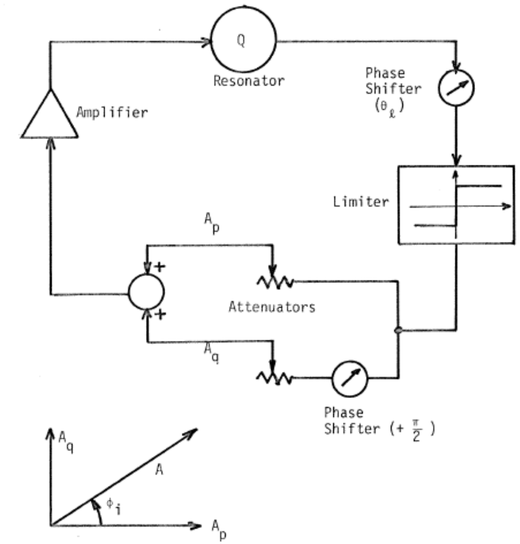


S4-S11 – SSR2 (7), LB650 (9), HB650 (4)

SEL Principle



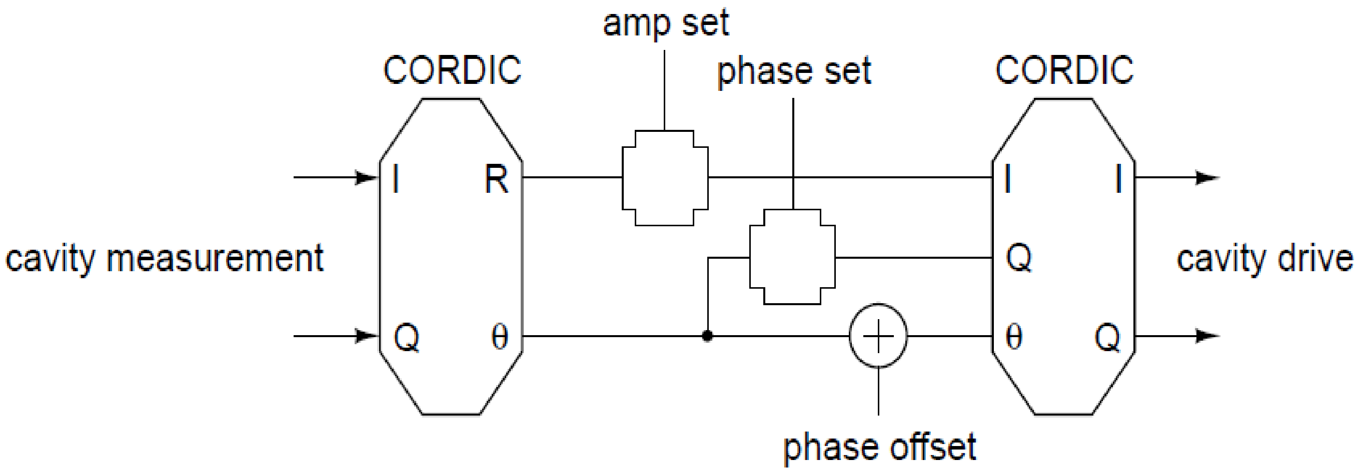


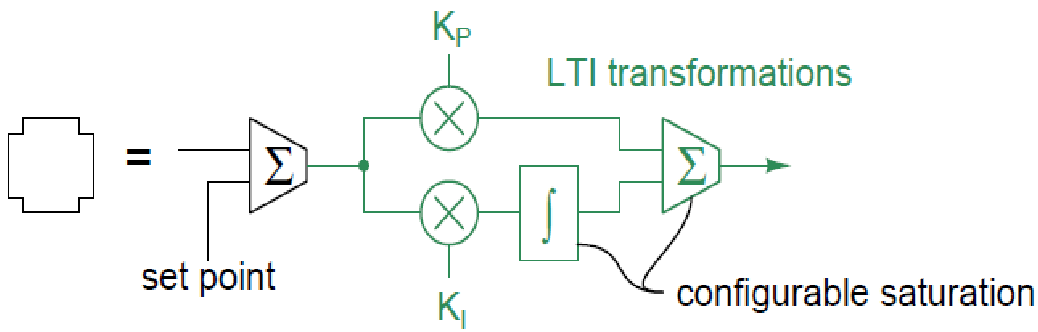


Key Features

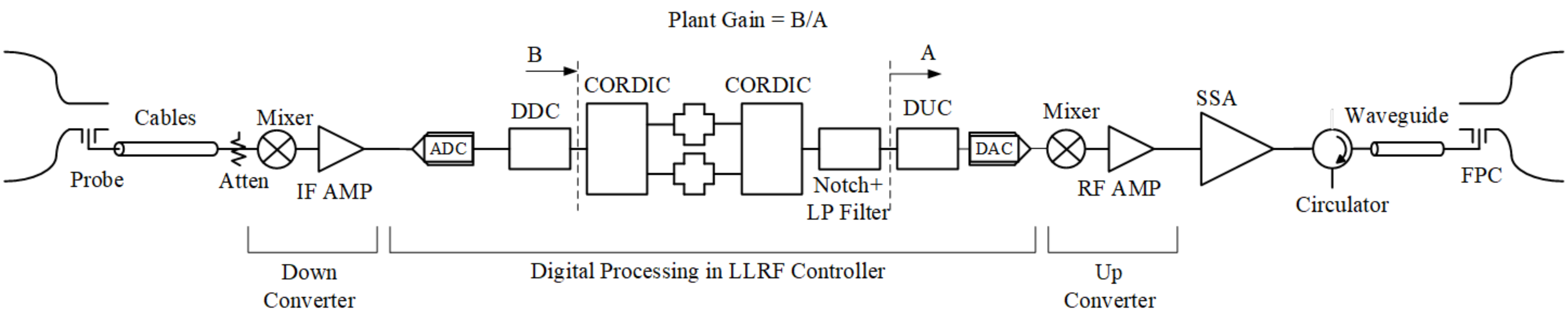
- Positive feedback configuration requires limiters
- Loop phase offset is 2nπ of oscillation frequency
- Cavity stored energy and field magnitude depends on the real or inphase(I) component of forward power
- Detuning due to microphonics and other disturbances are compensated by the quadrature(Q) component
- In GDR mode (SELAP) both positive(low gain) and negative(high gain) feedback loops are active

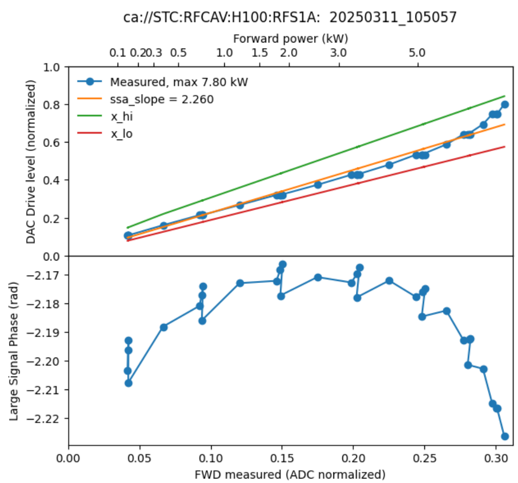
SEL System Architecture





SEL System Calibrations





SSA Calibration

$$V_0 = \left[P_t \times Q_0 \times \frac{r}{Q}\right]^{1/2}$$

Transmitted Power

$$V_0 = \left[U \times \frac{r}{Q} \times 2\pi f_0\right]^{1/2}$$

Stored Energy from Reverse Power during cavity decay

Gradient Calibration

Computing SEL Mode Limits

Real Power

$$V_{Des} = E_{Des} \times l \quad MV$$

$$\sqrt{U} = \frac{V_{Des}}{\left[\frac{r}{Q} \times 2\pi f_0\right]^{1/2}} \quad \sqrt{J}$$

$$\sqrt{P} = \sqrt{U} \times \sqrt{\frac{\pi f_0}{2Q_L}} \quad \sqrt{W}$$

$$ADC_{Fwd} = \frac{\sqrt{P}}{C_{FSfwd}}$$

$$X_{tgt} = SSASlope \times ADC_{Fwd}$$

Imag Power

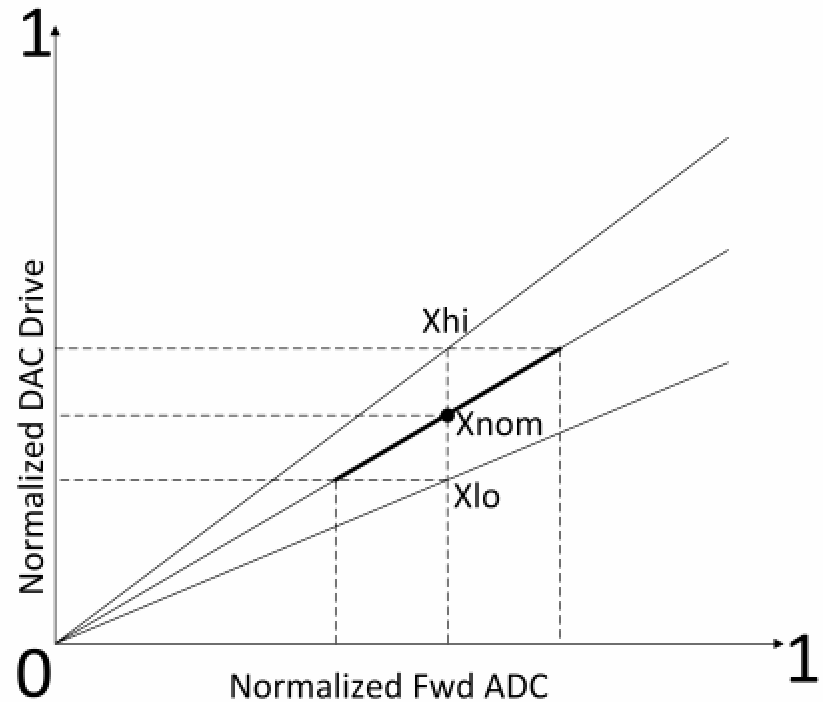
$$D_{Real} = \sqrt{1 - D_{Imag}{}^2}$$

$$Y_p = D_{Max} \times D_{Imag}$$

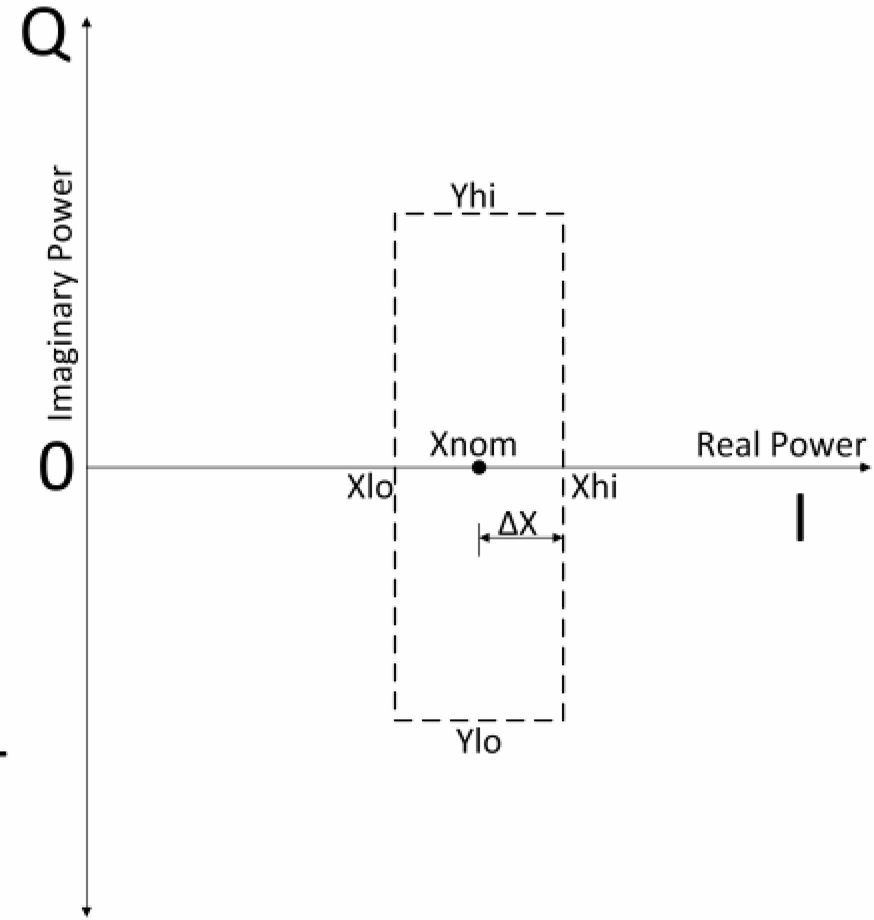
$$X_{Max} = D_{Max} \times D_{Real}$$

Mode	X_{lo}	X_{hi}	Y_{lo}	Y_{hi}
SEL Raw	-	-	-	-
SEL	X_{tgt}	X_{tgt}	0	0
SELA	$X_{tgt} \times 0.85$	$X_{tgt} \times 1.15$	0	0
SELAP	$X_{tgt} \times 0.85$	$X_{tgt} \times 1.15$	$-Y_p$	Y_p

Computing SEL Mode Limits

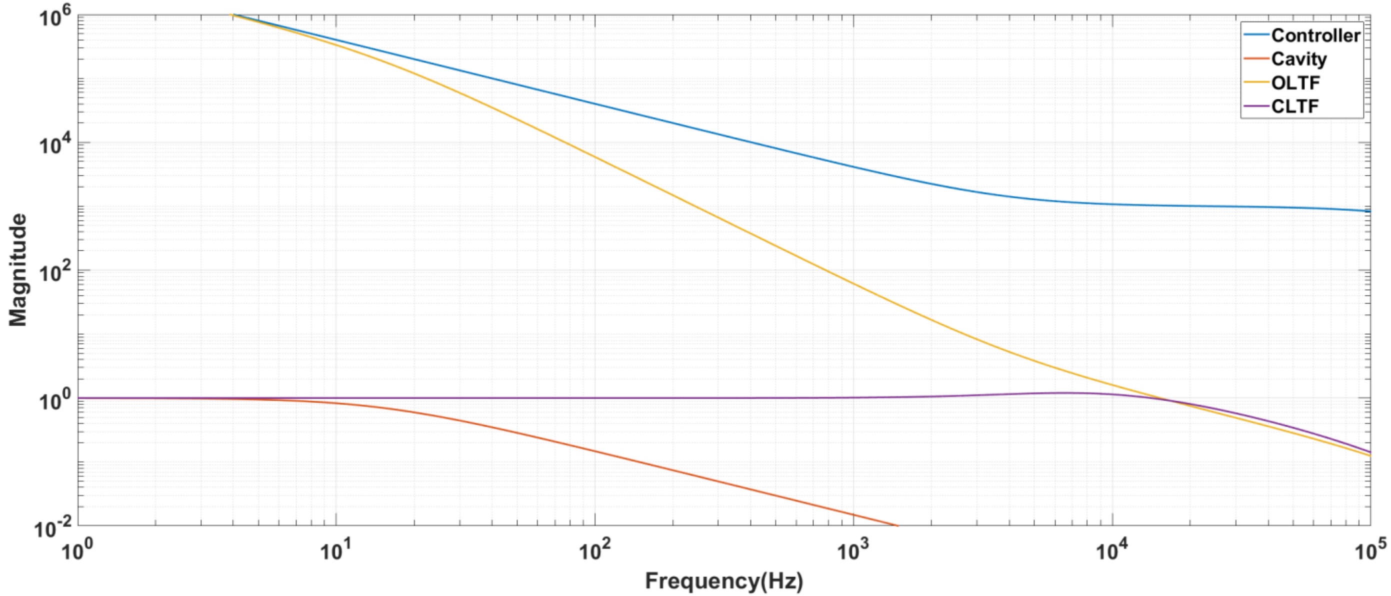


SSA Calibration



Forward Power

Gain Tuning Procedure LCLS-II

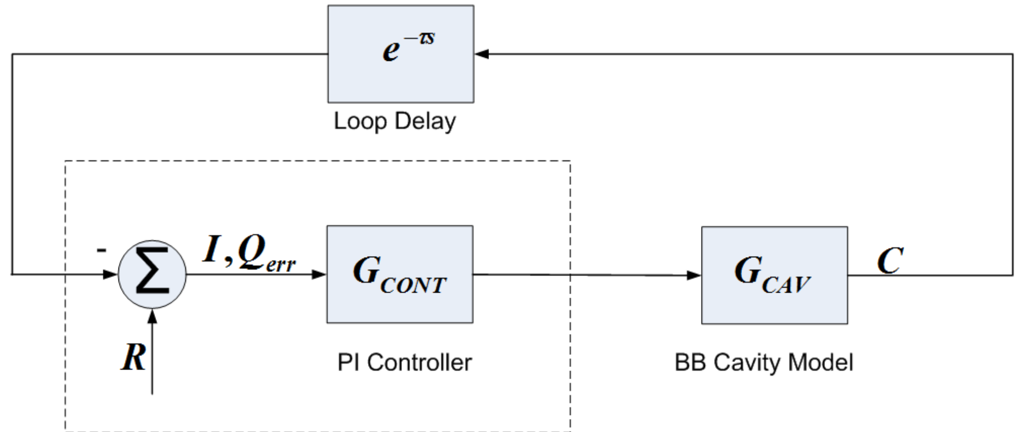


ADC Sampling Clock	94.286	MHz
System Latency	1.2	μS
Cavity Half BW	16	Hz
Plant Gain	0.73	
Field Set Point	14.6	MV
Field Full Scale	40.6	MV
Low Pass Filter BW	150	kHz
Controller Zero Place	0.25	
Target Close Loop BW	16000	Hz

Increase system gain and check if SEL limits are exceeded in the amplitude or phase feedback loops.

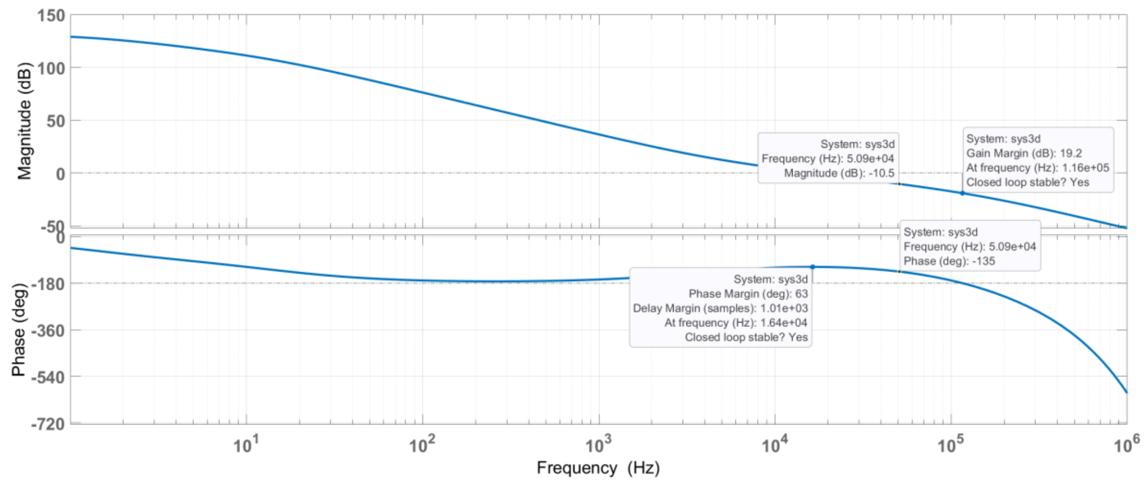
If one of the limits is crossed reduce closed loop bandwidth (system gain) Till the outputs are within the SEL limits

Stability Analysis with Bode Plot



$$G_{CONT}(s) = \frac{K_I}{s} + K_P$$

$$G_{CAV}(s) = \frac{1}{1 + s/\omega_H}$$



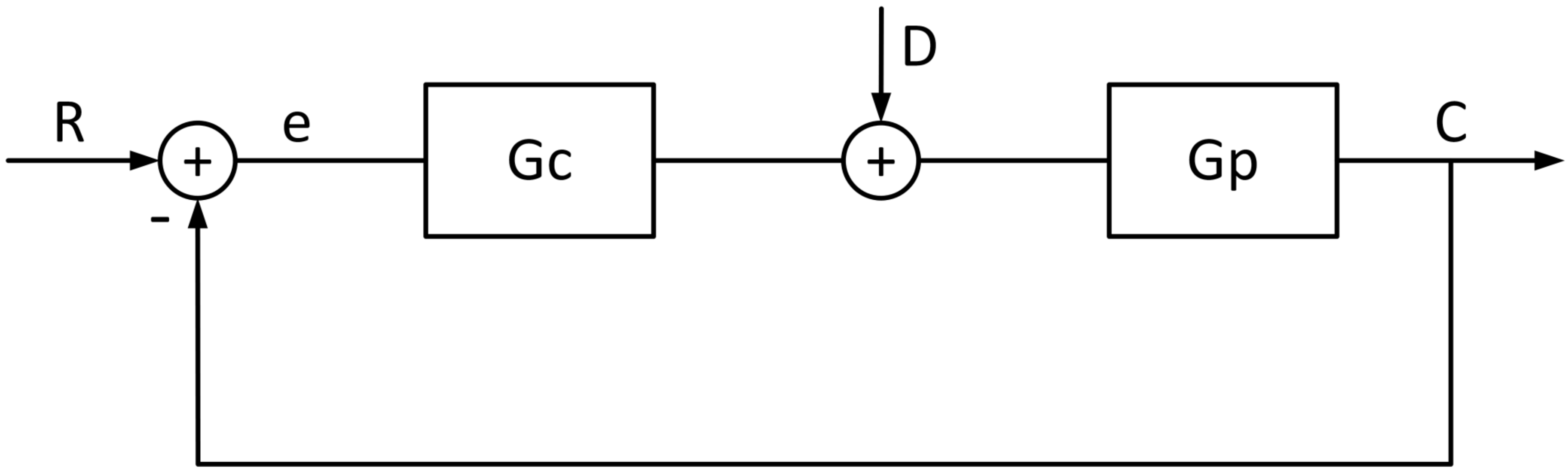
PIP-II Loop Delay Components

Delay	RFQ	Buncher	HWR	SSR1	SSR2	LB650	HB650
Total	**985**	**1200**	**920**	**2720**	**2720**	**2770**	**2720**
LLRF Controller Delay	500	500	500	2100	2100	2100	2100
LLRF-Amplifier Drive (cable)	50	150	20	70	70	70	70
Amplifier	200	100	100	200	200	200	200
HPRF Distribution	150	200	200	200	200	250	200
RF Fanback to LLRF (cable)	85	250	100	150	150	150	150
Cavity half bandwidth (Hz)	5542	8125	35	53.8	32.2	31.4	32.76
Gain (Max with 45 deg phase margin)	**23**	**16**	**3846**	**881**	**1462**	**1479**	**1430**

Cavity Type	Q_L	f_0 (MHz)	f_H (Hz)	K_P
Warm Cavity	3000	53	8.83×10^3	15
RFQ	15000	162.5	5.542×10^3	23
Buncher Cavity	10000	162.5	8.125×10^3	16
HWR Cavity	2.32×10^6	162.5	35	3548
SSR1 Cavity	3.02×10^6	325	53.8	2317
SSR2 Cavity	5.05×10^6	325	32.2	3846
LB650 Cavity	10.36×10^6	650	31.4	3935
HB650 Cavity	9.92×10^6	650	32.76	3801
LCLSII Cavity	4×10^7	1300	16.25	7600

Assumed loop delay = 1 us

Disturbance Rejection and Regulation Requirements



$$|e| = \frac{|D|}{1 + G_c}$$

PIP-II Specifications

• Energy Stability(Linac)	< 0.01%
• Amplitude Regulation(individual cavity)	< 0.06 rms %
• Phase Regulation	< 0.06 rms deg
• Maximum detuning	< 20 Hz

Disturbance Rejection and Regulation – Amplitude Loop

$$A = K_C\sqrt{P_N}, \quad A + \delta A = K_C\sqrt{P_N + \delta P}$$

$$P_N + \delta P = 1.15 \times P_N$$

$$1 + \frac{\delta A}{A} = \sqrt{1.15}, \quad \frac{\delta A}{A} = 0.0724$$

When above limits are used

$$G_{Min} = \frac{0.0724}{.0006} = 120, \quad \frac{D}{A} \leq 0.0724$$

Stability analysis gives a max gain for SSR1 cavities of 880
Provided the box limits are increased

$$G_{Max} = 880, \quad \frac{D_{Max}}{A} \leq 0.528 = 880 \times 0.0006$$

Disturbance Rejection and Regulation – Phase Loop

$$D_{Real} = \sqrt{1 - {D_{Imag}}^2}$$

$$Y_p = D_{Max} \times D_{Imag}$$

$$X_{Max} = D_{Max} \times D_{Real}$$

For example, if $D_{Imag} = 0.6, \quad Y_P = \pm 37 \quad degrees$

$$G_{Min} = \frac{37}{.06} \approx 615, \quad D_\Phi \leq 37 \quad degrees$$

Stability analysis gives a max gain for SSR1 cavities of 880
Provided the box limits are increased

$$G_{Max} = 880, \quad D_\Phi \leq 52.8 = 880 \times 0.06 \quad degrees$$

PIP-II Cavity/Amplifier Parameters

Cavity type	Aperture (diameter) (mm)	Effective length (cm)	Accelerating gradient (MV/m)	E_{peak} (MV/m)	B_{peak} (mT)	R/Q (Ω)	G (Ω)
HWR	33	20.7	9.7	44.9	48.3	272	48
SSR1	30	20.5	10	38.4	58.1	242	84
SSR2	40	43.8	11.4	40	64.5	297	115
LB650	88	70.3	16.9	40.3	74.6	341	193
HB650	118	106.1	18.8	38.9	73.1	610	260

Device or Cryomodule Type	Frequency [MHz]	Number of RF Cavities	Number of RF per Cavity	Max. RF Power per Cavity [kW]	RF Amplifier Power [kW]
RFQ	162.5	1	2	65	75
MEBT bunch cavities	162.5	4	1	1.2	3
First HWR cavity	162.5	1	1	0.4	3
Other HWR cavities	162.5	7	1	6.2	7
SSR1	325	16	1	6	7
SSR2	325	35	1	17.2	20
LB650	650	36	1	38.2	40
HB650	650	24	1	58	70

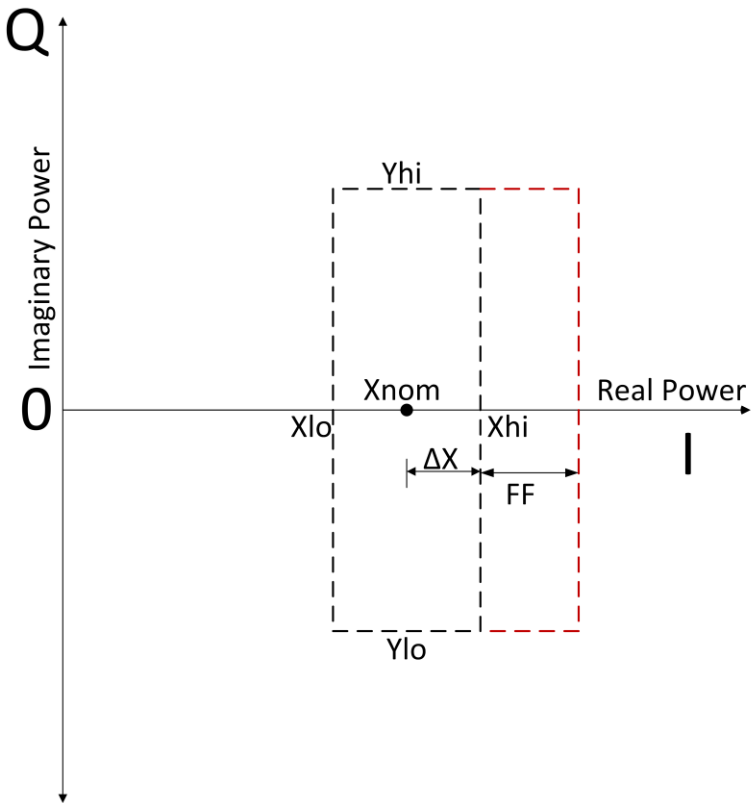
Beam Loading in PIP-II Cavities

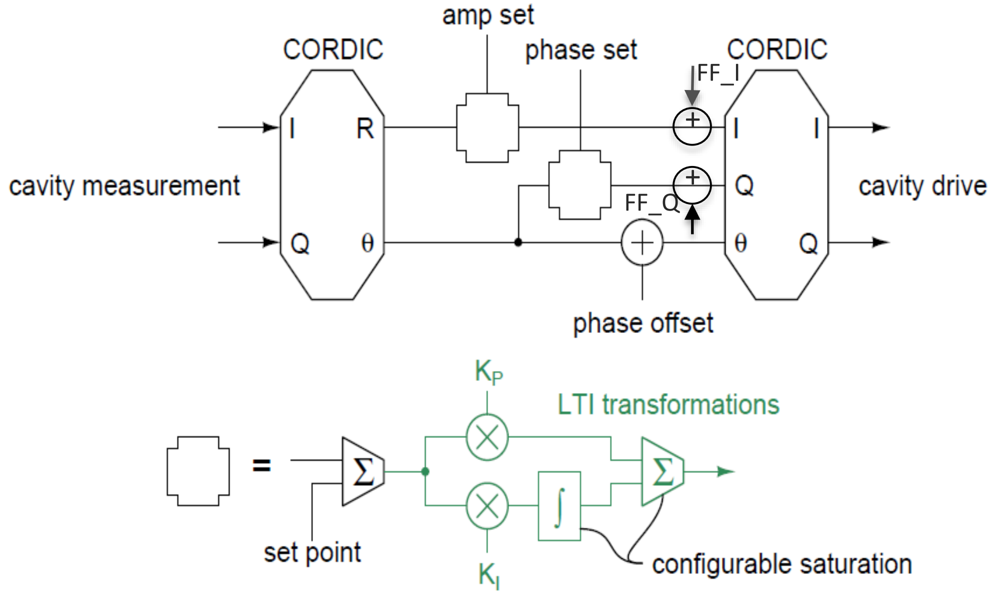
- PIP-II Beam Current = 2000 µA
- LCLS-II Beam Current = 100 µA /300 µA
- JLAB Beam Current = 400 µA

Cavity Description	Cavity Voltage (MV)	Forward Power – No beam (kW)	Forward Power – With Beam (kW)	$\sqrt{Power\ Ratio}$	Amplifier Max Power(kW)
HWR_6	2.008	2.64	4.45	**1.3**	7
SSR1_8	2.050	1.98	4.13	**1.44**	7
SSR2_5_4	4.993	6.40	11.92	**1.36**	20
LB650_5_3	11.88	15.93	28.97	**1.35**	40
HB650_4_2	19.953	24.28	40.71	**1.29**	70

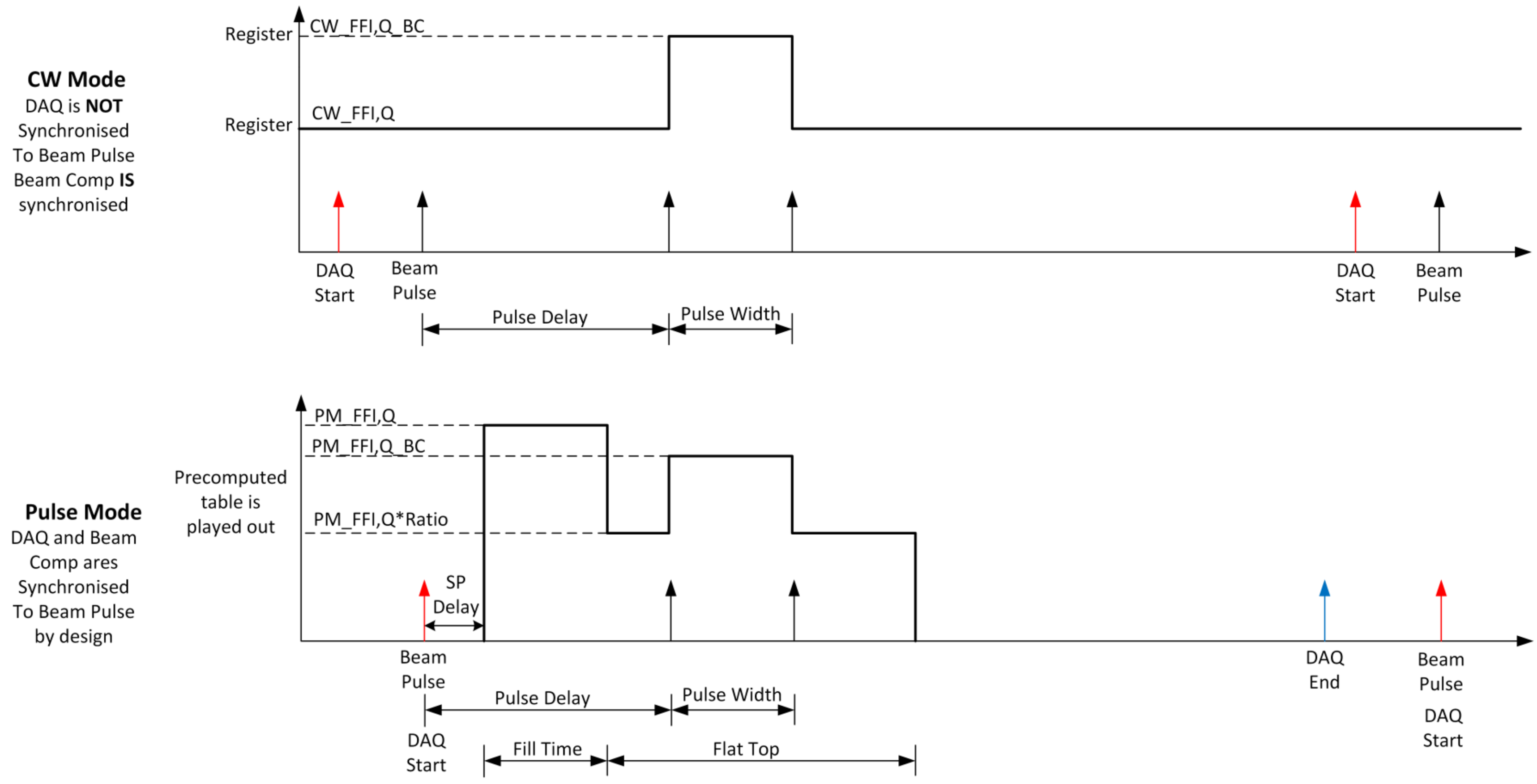
- Feedback limits currently allow for 1.15 increase in power ratio
- Feedforward beam loading compensation is needed

Adding Gated Feedforward for Beam Loading

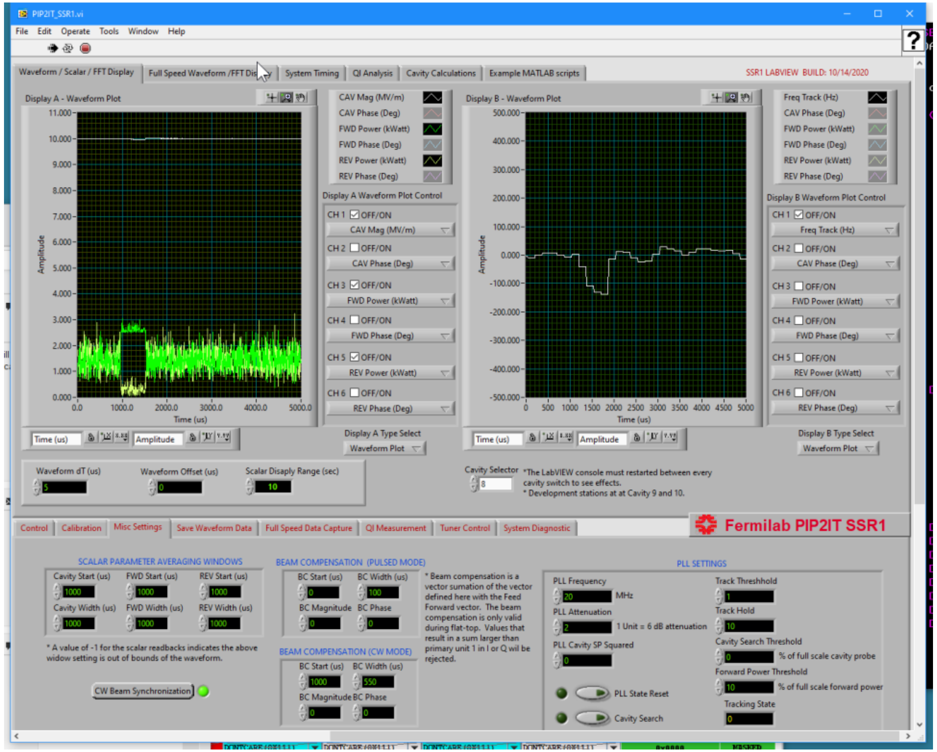


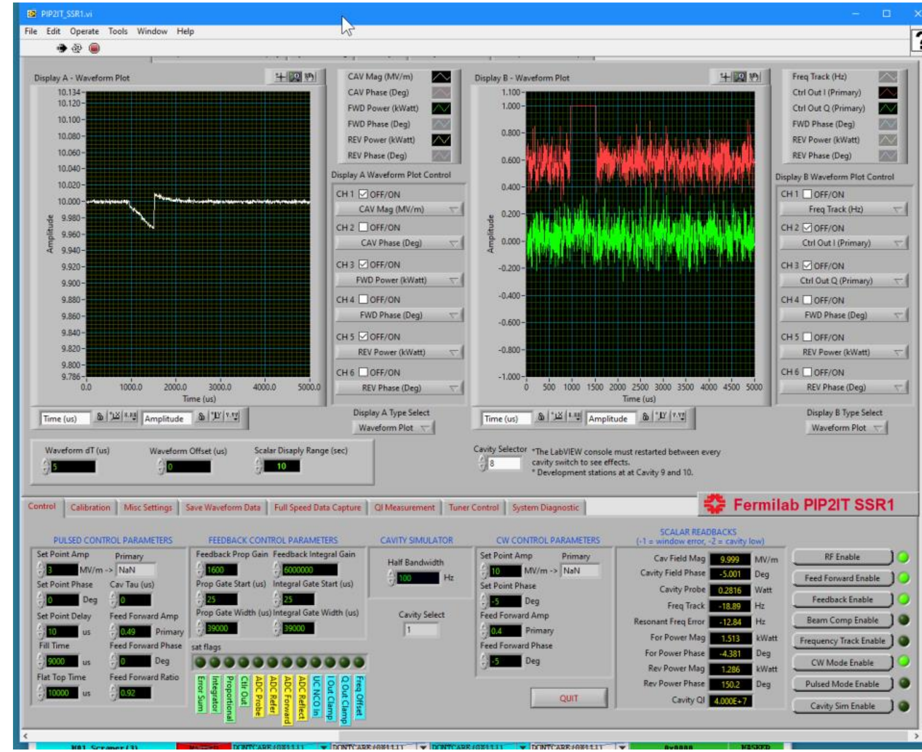


Adding Gated Feedforward for Beam Loading

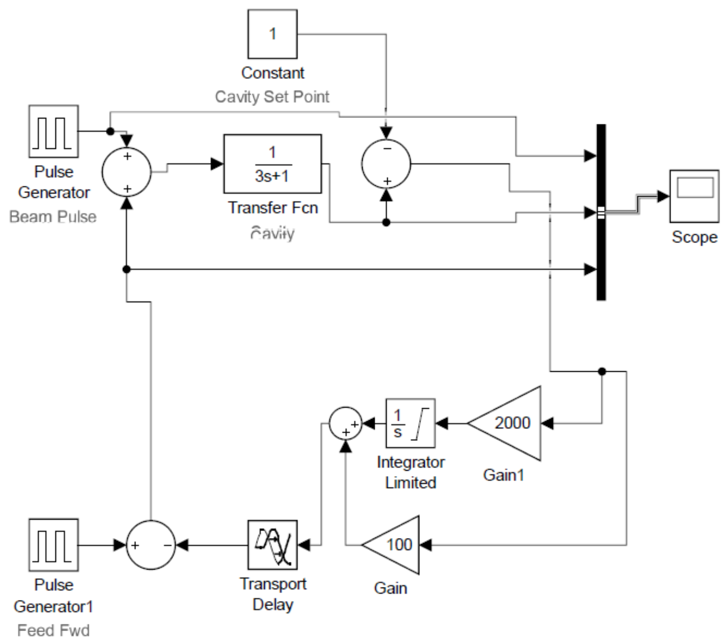


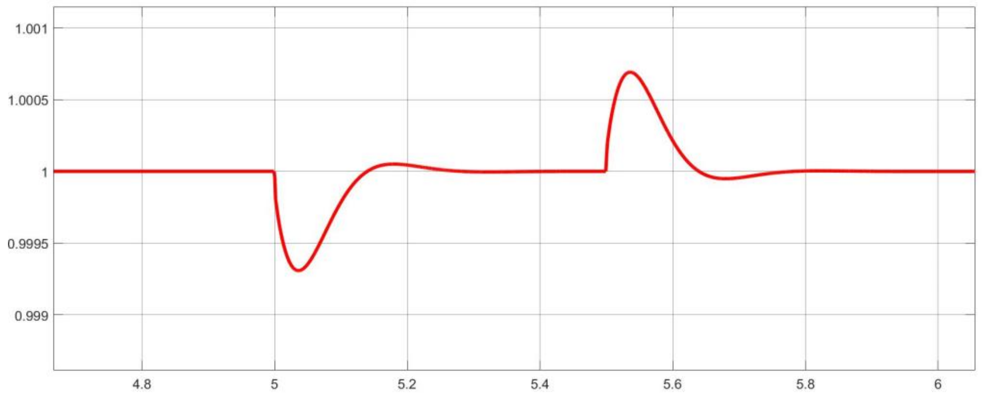
Beam Loading in SSR1 Cavity





Beam Loading in SSR1 Cavity





Steps Towards Performance Improvement

- Add feedforward(FF) beam loading compensation(BLC)
- Gating of FF BLC with beam arrival trigger is required – PIP-II beam Duty cycle is only 1%
- DAC drive limits need to be adjusted for each cavity type due to differing beam/no beam power ratios
- Loop delays of ~ 3 μs can be improved with firmware changes
- Amplifier non-linearity should be handled correctly as a variety of amplifier sizes and vendors are being used
- LCLS-II and PIP-II linacs are using the same codebase – both projects will benefit from the improvements

Summary

- The SEL Implementation for PIP-II was described
- Stabilty Analysis was used to determine theoretical feedback gain limits
- The beam loading for PIP-II cavities was compared with the output saturation limits currently being used
- The need for gated feed forward beam loading compensation was demonstrated
- Steps for improving performance were discussed

Thank You!

Backup Slides

Beam Loading Power Calculation

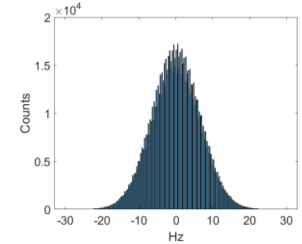
$$P_f = \frac{V_a^2(1+\beta)^2}{4\beta Q_0\left(\frac{r}{Q}\right)}\left[\left(1+\frac{I_{Re}T\left(\frac{r}{Q}\right)Q_0}{V_a(1+\beta)}\right)^2+\left(\frac{Q_0}{1+\beta}\frac{2\delta f}{f}\right)^2\right]$$

V_a	Cavity Voltage
I	Beam Current
f	Cavity Frequency
δf	Microphonics Detuning
T	Transit Time Factor
β	Cavity Coupling Factor

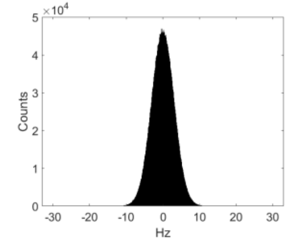
HWR Control Performance

HWR Amplitude and Phase Regulation					
	Cavity4	Cavity5	Cavity6	Cavity7	Cavity8
Cavity Field Setpoint (MV/m)	2.89	6.04	8.94	8.5	8
Amplitude Regulation (rms) %	0.0135	0.0106	0.0101	0.0081	0.0103
Phase Regulation (rms) deg	0.0228	0.0065	0.0056	0.0055	0.0062
Feedback Proportional Gain	1000	1000	1000	1000	1000
Feedback Integral Gain (rad/sec)	1,000,000	1,000,000	1,000,000	1,000,000	1,000,000

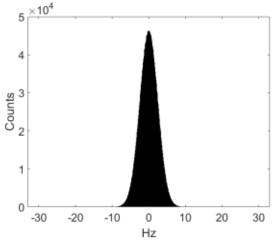
Detuning Histograms



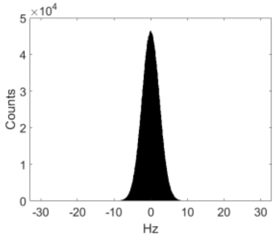
Cavity 4



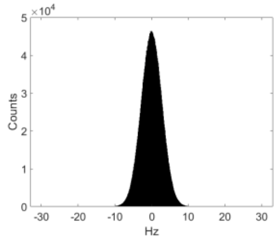
Cavity 5



Cavity 6



Cavity 7



Cavity 8

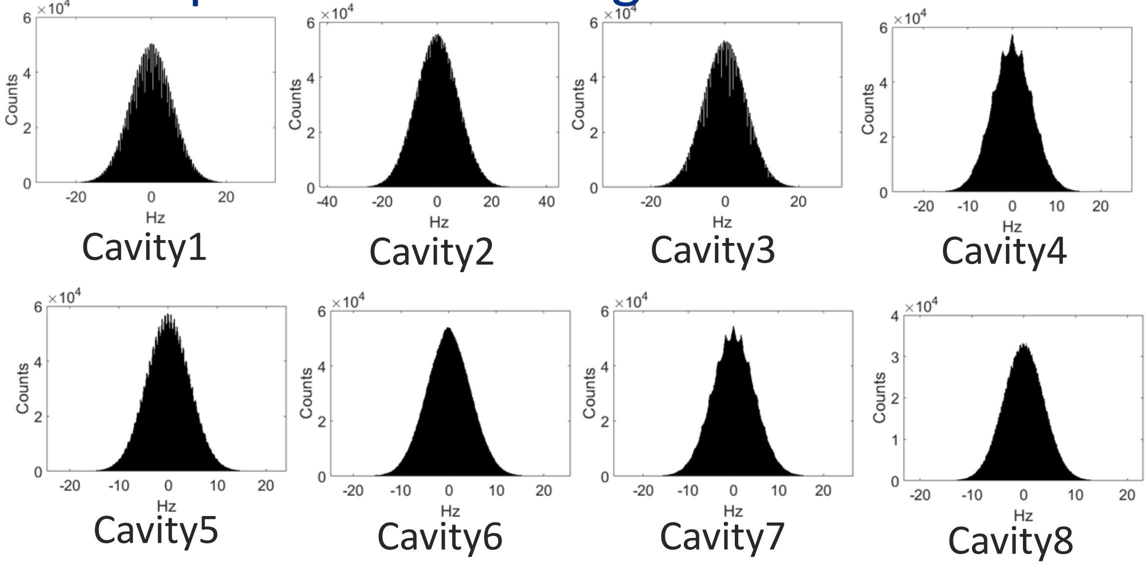
PIP-II Specifications

- Energy Stability(Linac) < 0.01%
- Amplitude Regulation(individual cavity) < 0.06 rms %
- Phase Regulation < 0.06 rms deg
- Maximum detuning < 20 Hz

SSR1 Cryomodule Testing

SSR1 Amplitude and Phase Regulation								
	Cavity1	Cavity2	Cavity3	Cavity4	Cavity5	Cavity6	Cavity7	Cavity8
Cavity Field Setpoint (MV/m)	4.88	4.63	4.78	7.32	7.8	7.56	7.32	10
Amplitude Regulation (rms) %	0.0194	0.0289	0.0219	0.0157	0.014	0.0158	0.0147	0.0124
Phase Regulation (rms) deg	0.0116	0.0164	0.0118	0.0091	0.0088	0.0093	0.0092	0.0076
Feedback Proportional Gain	1600	1600	1600	1600	1600	1600	1600	1600
Feedback Integral Gain (rad/sec)	3,000,000	3,000,000	3,000,000	3,000,000	3,000,000	3,000,000	3,000,000	3,000,000

Microphonics Detuning



Piezo Transfer Function – C1