The ESS LLRF Control System

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2012-05-04

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Outline

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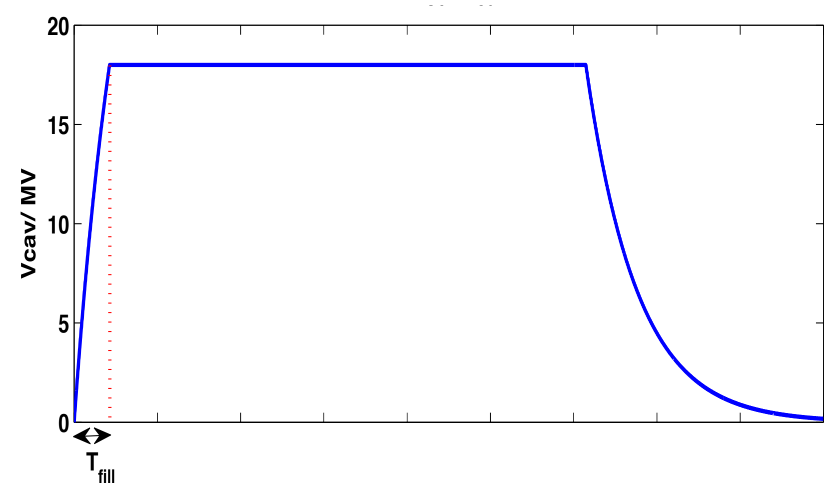
- ✓ LLRF Introduction and Requirements
- ✓ Issues in LLRF Control
- ✓ Control Methods Consideration
- ✓ Summary

Cavity Field Stability Requirement

- ✓ Control and maintain the specified phase and amplitude stability of accelerating field in RF cavity during beam traveling
- ✓ Also maintain the filling stage of the RF pulse



The stability requirement is from the beam dynamic:

$$V_{acc,n} = V_c\left(1+\delta_V\right)\cos(\varphi_b+\delta_\varphi)$$

$$V_{tot} = \sum_{n=1}^{N} V_{acc,n}$$

$$\frac{\sigma_E}{E} = \frac{\left\langle V_{tot}^2\right\rangle - \left\langle V_{tot}\right\rangle^2}{\left\langle V_{tot}\right\rangle^2}$$

In the case of fixed sync. phase:

$$\left(\frac{\sigma_E}{E}\right)_{corr.} \approx \frac{1}{\cos(\varphi_b)}\sqrt{\frac{1}{2}\left(1+\cos\left(2\varphi_b\right)\right)\sigma_V^2+\frac{1}{2}\left(1-\cos\left(2\varphi_b\right)\right)\sigma_\varphi^2+\frac{1}{4}\left(3\cos\left(2\varphi_b\right)-1\right)\sigma_\varphi^2}$$

$$\left(\frac{\sigma_E}{E}\right)_{uncorr.} \approx \frac{1}{\sqrt{N}}\frac{1}{\cos(\varphi_b)}\sqrt{\frac{1}{2}\left(1+\cos\left(2\varphi_b\right)\right)\sigma_V^2+\frac{1}{2}\left(1-\cos\left(2\varphi_b\right)\right)\sigma_\varphi^2+\frac{1}{4}\left(3\cos\left(2\varphi_b\right)-1\right)\sigma_\varphi^2}$$

$$\left(\frac{\sigma_E}{E}\right)^2 = \left(\frac{\sigma_E}{E}\right)_{corr.}^2 + \left(\frac{\sigma_E}{E}\right)_{uncorr.}^2$$

Further reading: A. Mosnier ; J. M. Tessier, Field Stabilization for Tesla. Tesla reports 1994-16
Krafft, G ; Merminga, L, Energy Spread from RF Amplitude and Phase Errors, EPAC 96.

Stability Requirements in different accelerators

- ✓ The stability requirement varies in different accelerators, determined by specific application.

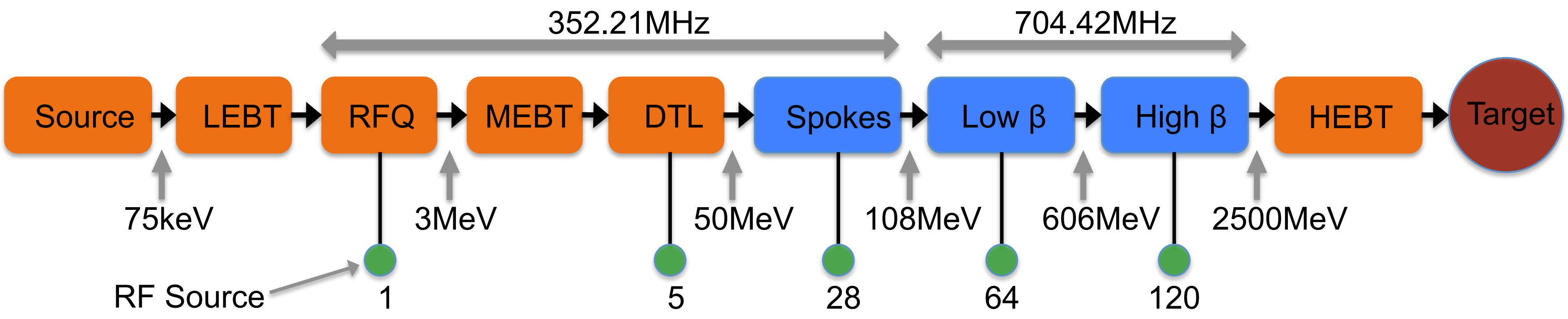
	XFEL	ILC	SNS	JPARC
Amp./Phase Stability	0.01%, 0.01° (rms)	0.1%, 0.1° (rms)	±0.5%, ±0.5°	±1%, ±1°

- ✓ The stability is specified in peak to peak rather than in rms in proton machine due to beam velocity is dependent on energy gain.

- ✓ In some case, the requirement on phase stability differs by time scale, short term(during the pulse), medium term (pulse to pulse), long term (minutes to hours). At XFEL, the requirement is: 0.01° (short term), 0.03° (medium term) , 0.1-0.5° (Long term).

- ✓ The stability at ESS?

Requirments at ESS



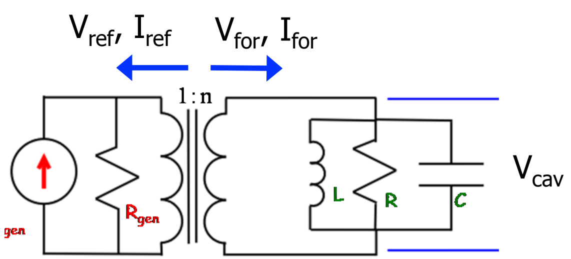
- ✓ Cavity phase and amplitude stability, frequency control
- ✓ Minimize the required overhead power for control
- ✓ Automated operation, remote control
- ✓ Availability, maintenance, upgradability
- ✓ Support Linac commissioning

- ✦ **High intensity, 50mA**
- ✦ **Long pulse, 2.9ms**
- ✦ **High gradient**
- ✦ **Spoke cavity**

- ✦ **High Efficiency**
- ✦ **High availability; 95%**

The ideal cases

- ✓ Consider an ideal beam current inject into an ideal superconducting cavity at ideal time
- ✓ Ideal beam current: no synchronous phase, continuous current during pulse
- ✓ Ideal superconducting cavity: optimized Q_L for beam current, no reflection power at beam duration
- ✓ Ideal injection time



$$V_{cav} = V_{ref} + V_{for} = V_g + V_b$$

V_g, *generator current* I_g *induced voltage;*

V_g, *beam current* I_b *induced voltage;*

$I_b = 2I_{b0}, I_{b0}$ *is average DC current*

QL optimizing:

At steady state:

$$P_g = P_c + P_b + P_r, (P_r = 0)$$

$$\beta = \frac{P_g}{P_c} = 1 + \frac{P_b}{P_c} \approx \frac{P_b}{P_c},$$

$(P_b >> P_c$, *for superconducting cavity*$)$

$$Q_L = \frac{Q_0}{1+\beta} \approx \frac{Q_0 P_c}{P_b} = \frac{V_{cav}^2}{P_b (R/Q)}$$

$$P_b = V_{cav} I_{b0}$$

for beam induced voltage,

$$V_b = \frac{1}{2}(R/Q)Q_L \cdot 2I_{b0} = I_{b0}(R/Q)Q_L$$

$$\Rightarrow V_b = V_{cav}$$

Ideal injection time:

Steady state for V_g, *(don't consider beam):*

$$\Gamma = \frac{V_{ref}}{V_{for}} = \frac{\beta - 1}{\beta + 1}, \quad V_g = V_{ref} + V_{for} = \frac{2\beta}{\beta+1} V_{for}$$

At filling stage: (const. V_{for} *input)*

$$V_g(t) = V_{ref}(t) + V_{for}$$

$$V_{ref}(t) = V_g(1 - e^{-t/\tau}) - V_{for}$$

$$V_{ref}(t) = 0 \quad \Rightarrow t_{inj} = \tau \ln\left(\frac{2\beta}{\beta - 1}\right)$$

for superconducting cavity, $\beta >> 1$,

$$t_{inj} \approx \tau \ln 2 = \frac{2Q_L}{\omega} \ln 2$$

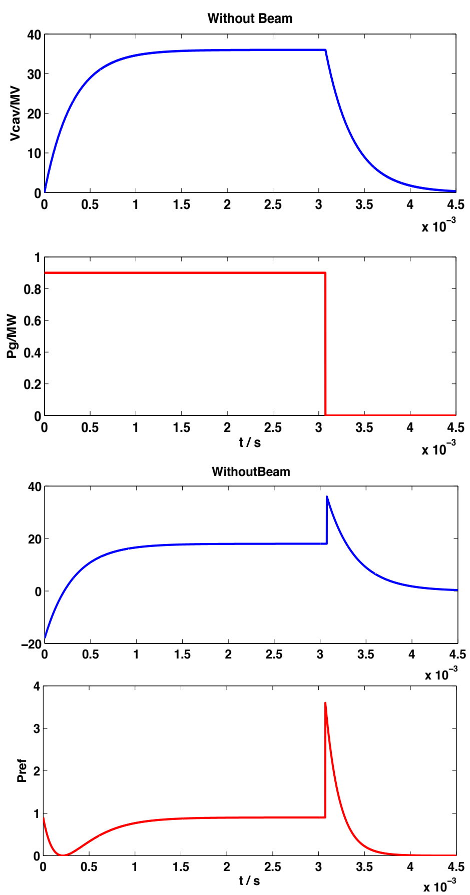
$$V_{cav} = V_g(t_{inj}) = \frac{1+\beta}{2\beta} V_g = V_{for} \approx 0.5 V_g$$

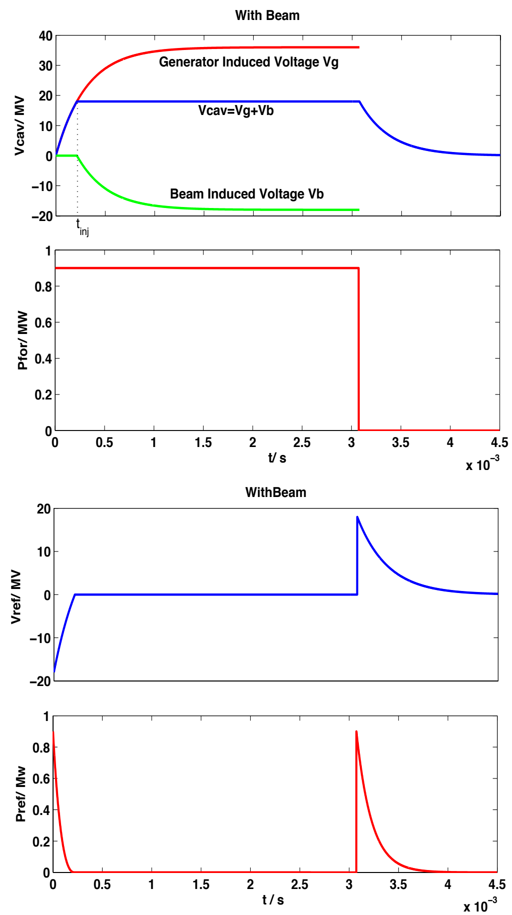
Further reading:

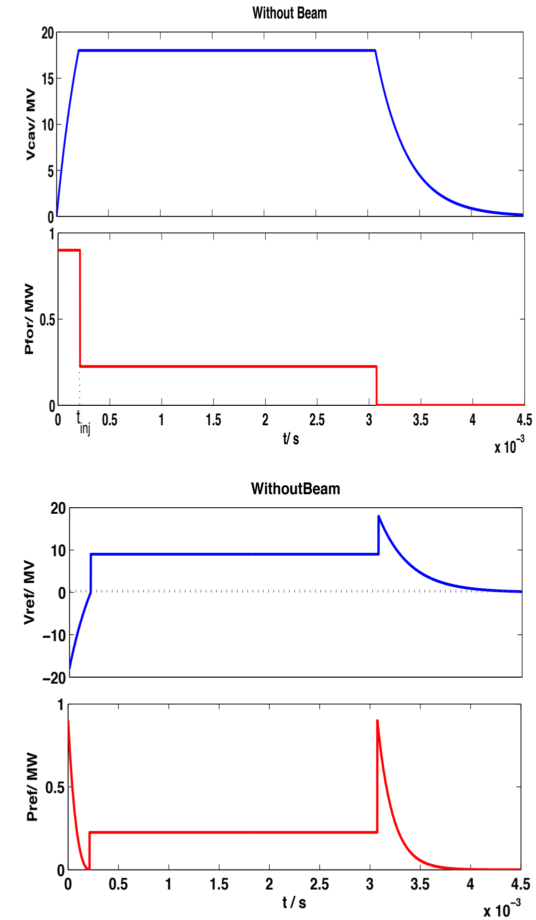
D. McGinnis, A Simple Model for a Superconducting RF cavity with a Vector Phase Modulator, 2007.

T. Schilcher, Vector Sum Control of Pulsed Accelerating Fields in Lorentz Force Detuned Superconducting Cavities. Ph. D. Thesis of DESY, 1998

The ideal cases







Perturbations in real world

Beam Loading

- Synchronous phase
- Beam chopping
- Pulse beam transient
- Charge fluctuations
- Non-relativistic beam
- Pass band modes
- HOMs, wake-field

Cavity

- Lorentz force detuning
- Microphonics
- Thermal effects (Quench…)

Power Supply

- Modulator drop and ripple
- Klystron nonlinearity

Phase reference distribution

- Reference thermal drift
- Master oscillator phase noise

Electronics crates

- Crates power supply noise
- Cross talk, thermal drift
- Clock jitter, nonlinearity

Further reading: LLRF Experience at TTF and Development for XFEL and ILC, S. Simrock, DESY, ILC WS 2005

Lorentz Force Detuning

- ✓ The radiation pressure on cavity walls
  - ➔ cavity shape changes by a volume ΔV
    - ➔ cavity resonance frequency is shifted
- ✓ Lorentz force detune is repetitive from pulse to pulse
- ✓ Lorentz force detuning coefficient K typically a few $Hz/(MV/m)^2$

Radiation pressure :

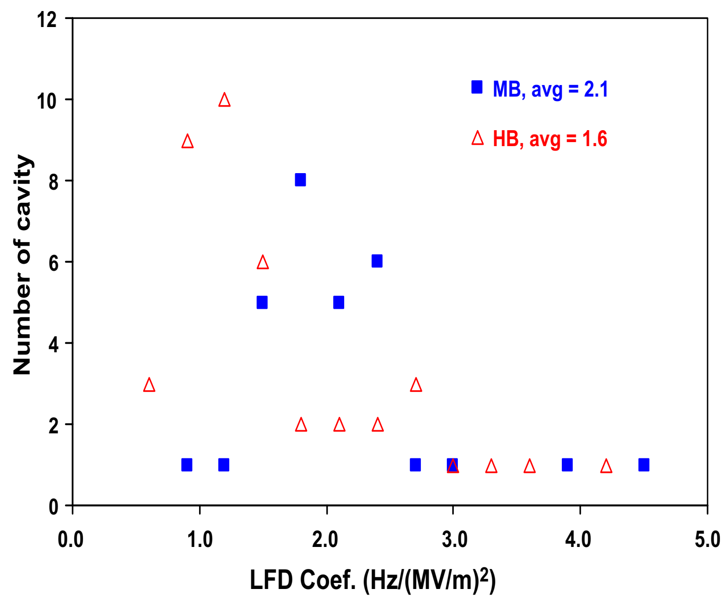
$$P_s = \frac{1}{4}\left(\mu_0 \left|\vec{H}\right|^2 - \varepsilon_0 \left|\vec{E}\right|^2\right)$$

Cavity perturbation theory:

$$\frac{\omega_0 - \omega}{\omega_0} = \frac{\int_{\Delta V} \left(\varepsilon_0 \left|\vec{E}\right|^2 - \mu_0 \left|\vec{H}\right|^2\right) dV}{\int_{V} \left(\varepsilon_0 \left|\vec{E}\right|^2 - \mu_0 \left|\vec{H}\right|^2\right) dV}$$

TM_{010} induced static detuning:

$$\Delta f = -K \cdot E_{acc}^2$$



Further reading: T. Schilcher. Vector Sum Control of Pulsed Accelerating Fields in Lorentz Force Detuned Superconducting Cavities. Ph. D. Thesis of DESY, 1998

Dynamic effects of cavity detuning

✓ Any cavity has an infinite number of mechanical eigenmodes of vibration. A 2nd-order differential equation can be used to describe the dynamics.

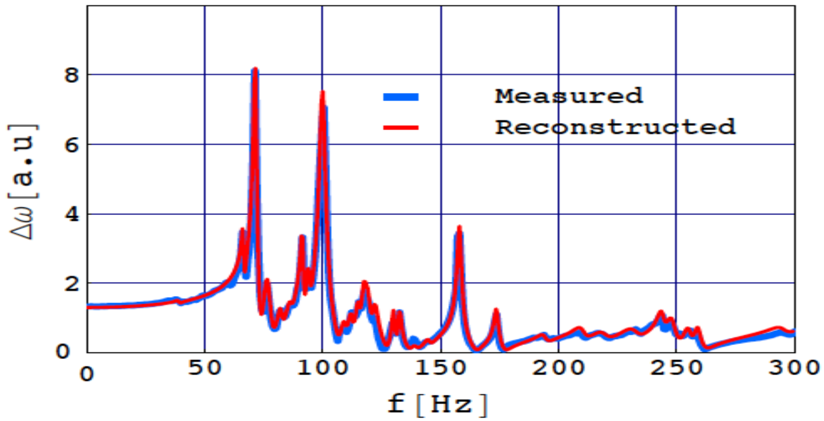
2nd-order differential equation of dynamic detuning,

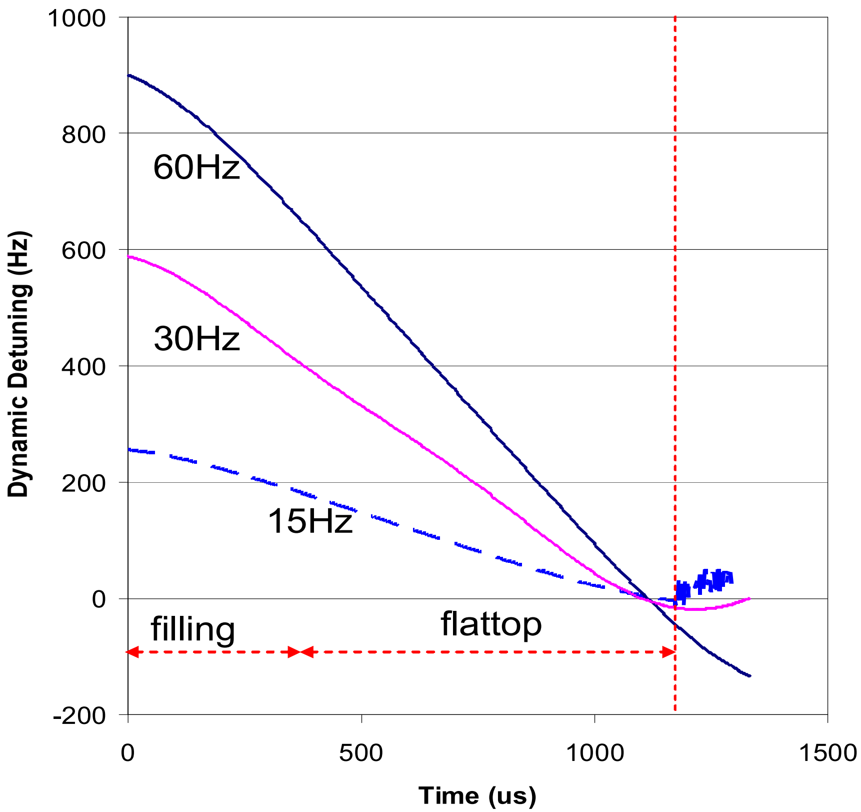
$$\Delta\ddot{\omega}_n + \frac{2}{\tau_{m,n}}\Delta\dot{\omega}_n + \Omega_n^2\Delta\omega_n = -2\pi K_n\Omega_n^2 \cdot E_{acc}^2(t) + n(t)$$

$$\Delta\omega(t) = \sum_n \Delta\omega_n(t), \quad K = \sum_n K_n$$

In steady state:

$$\Delta\omega_\infty = \sum_n \Delta\omega_{n\infty} = -2\pi\sum_n K_n \cdot E_{acc}^2$$

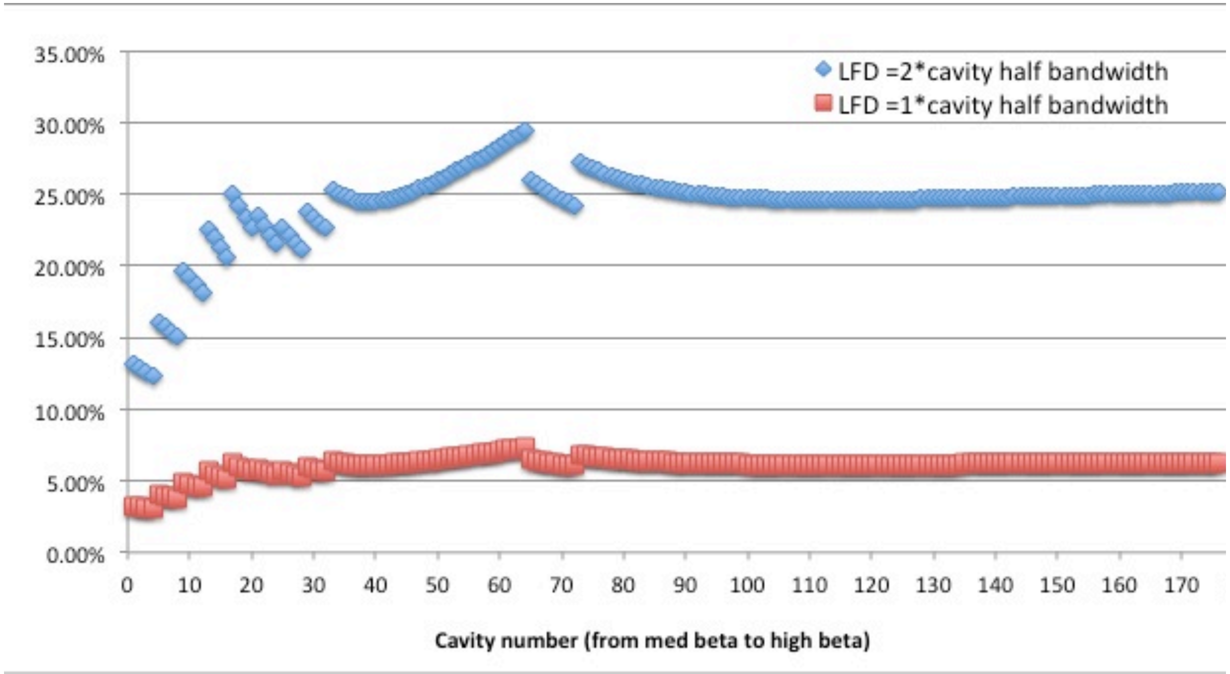




S. Kim, I. E. Campisi, F. Casagrande et al, Status of the SNS Cryomodule Test, PAC07.
M.Doleans, Studies of Elliptical Superconducting Cavities at Reduced Beta, PhD thesis, 2003.

Overhead calculation for LFD in elliptical cavity

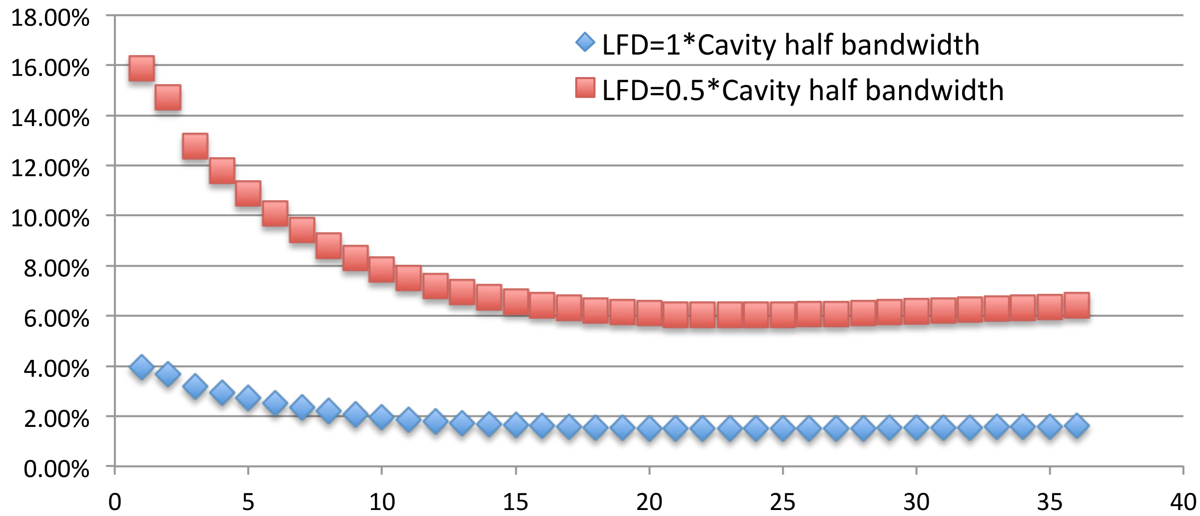
- It makes calculation easier to discuss detuning according to the rate $\Delta f/f_{1/2}$
- Below $f_{1/2}$, (K~1.5 for high beta, K~2 for med beta), most cavity overhead is <7%.
- 25% or more are required for detuning > 2 $f_{1/2}$ (K~3 for high beta, K~4 for med beta)
- Appropriate pre-detuning for both sync. phase and LFD is assumed



Overhead for LFD in Spoke cavity

Table 3: Overhead estimation under different K for spoke cavity ($E_{acc} = 8.5MV/m$)

K ($Hz/(MV/m)^2$)	Δf (Hz)	$f_{1/2}$ (Hz)	$\Delta f / f_{1/2}$	φ_D (°)	Overhead w.o. predetuning	Overhead with predetuning
1	72.25	1174	0.06	3.5	0.09%	0.02%
5	361.25	1174	0.31	17.1	2.37%	0.59%
9	650.25	1174	0.55	29.0	7.67%	1.92%
13	939.25	1174	0.80	38.7	16.00%	4.00%
17	1228.25	1174	1.05	46.3	27.36%	6.84%



R. Zeng, Power Overhead Calculation for Lorentz Force Detuning, ESS-tech notes, 2012

Klystron droop and ripple

- ✓ Perturbations in the cathode voltage results in the change of the beam velocities, and then led to the variations of the RF output phase
- ✓ 1% error in cathode voltage leads to more than 10 deg. variation in RF output phase
- ✓ High frequency ripple with larger amplitude is hard to be eliminated by feedback, especially in normal conducting cavity

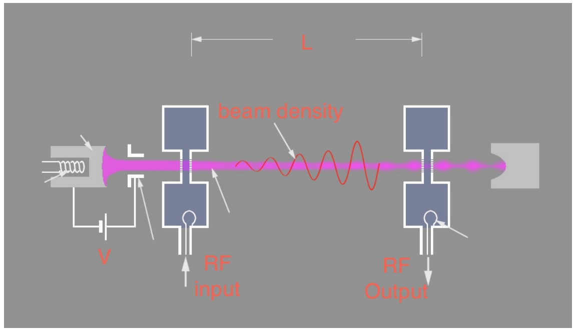


Table 1: Measurement for the phase and amplitude variations in other labs

	RF freqency /MHz	Cathode voltage change	Phase variation /deg.	Amplitude variation
JPARC[1]	312	3.40%	25	~8%(power)
SNS [2,3]	805	3%	~50(max)	~8%(power)
PEPII[4]	476		~14° /kV	
SACLAY[5]	704.4	200V@95kV	10° /kV@92kV	

$$t = \frac{L}{v} = \frac{L}{\sqrt{\frac{eV}{m}}}, \quad \theta = \omega t$$

$$d\theta = -\frac{\omega L}{\sqrt{\frac{2eV}{m}}} \cdot \frac{dV}{V}$$

relativistic case:

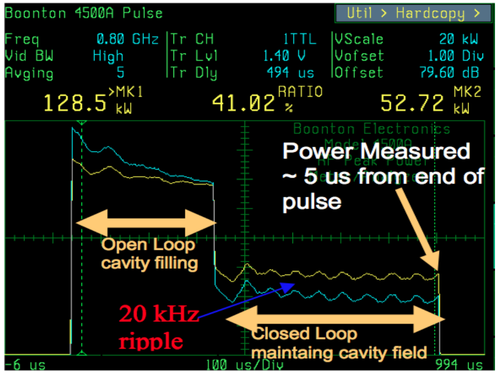
$$d\theta = -\frac{e\omega L V}{mc^3\beta^3\gamma^3} \cdot \frac{dV}{V}$$

$$P_{out} \propto V^{5/2}$$

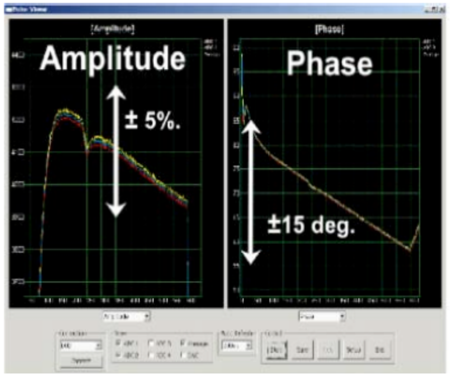
$$V_{out} \propto P_{out}^{1/2}$$

$$V_{out} \propto V^{5/4}$$

$$\frac{dV_{out}}{V_{out}} \propto \frac{5}{4}\frac{dV}{V}$$



SNS



JPARC

Further reading: R. Zeng et, al. The Droop and Ripple's Influence on Klystron Output, ESS tech-note.

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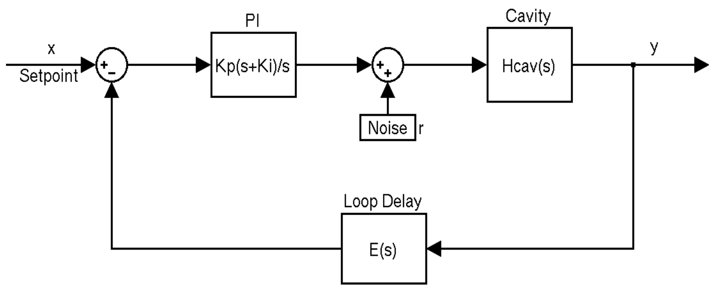
Droop and ripple control by feedback

- The errors can be suppressed in feedback loop a factor of loop gain G. The loop gain is limited by loop delay and also by pass-band mode
- Integral gain of $Ki=2\pi f_{HBW}$ is intorduced to eliminate the steady errors and reduce low frequency noises

- Assuming that 15 degree phase error is induced by per 1% error from modulator, to control the error to 0.5°, we should restrict the droop and ripple number from modulators:



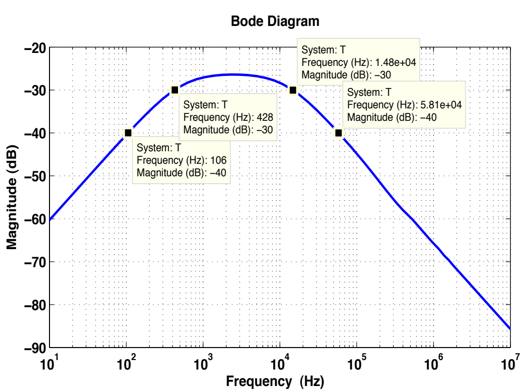


Table 5: Noise tolerances of PI feedback closed loop at different frequencies (Superconducting cavity, $K_p = 20, K_i = 2\pi \times 518$)

Frequency range /kHz	Gain available	Tolerance in output phase/°	Tolerance in cathode voltage
<0.1, or >58	>100	>50	>3.3%
0.1 ~ 0.4, 15 ~ 58	30 ~ 100	15 ~ 50	1% ~ 3.3%
0.4 ~ 15	20 ~ 30	10 ~ 15	0.7% ~ 1%

Table 6: Noise tolerances of PI feedback closed loop at different frequencies (Normal conducting cavity, $K_p = 1, K_i = 2\pi \times 10^4$)

Frequency range /kHz	Gain available	Tolerance in output phase/°	Tolerance in cathode voltage
<0.1, or > 1000	>100	>50	>3.3%
0.1˜0.3, 300˜1000	30 ~ 100	15 ~ 50	1% ~ 3.3%
0.3 ~ 1, 100 ~ 300	10 ~ 30	5 ~ 15	0.33% ~ 1%
1 ~ 100	2 ~ 10	1 ~ 5	0.07% ~ 0.33%

Synchronous phase

- ✓ The purpose of beam off-crest acceleration by a sync. phase is to minimize the energy spread resulted from wake fields.
- ✓ By pre-detuning the cavity with motor tuner, the effect of the sync. phase acceleration is compensated.
- ✓ It can be also compensated by extra power overhead, which was the case in LEP at CERN to avoid ponderomotive oscillation (CW, 8 cavity/klystron)

$$\text{in cavity RLC circuit, in steady state, } \frac{dV_{cav}}{dt}=0,$$

$$V_{cav}=\frac{R_L\cdot I_{total}}{1-iR_L\left(\frac{1}{\omega L}-\omega C\right)},\quad R_L=\frac{1}{2}(R/Q)Q_L$$

$$\tan\varphi_D=R_L\left(\frac{1}{\omega L}-\omega C\right)=Q_L\left(\frac{\omega_0}{\omega}-\frac{\omega}{\omega_0}\right)\approx 2Q_L\frac{\Delta\omega}{\omega},$$

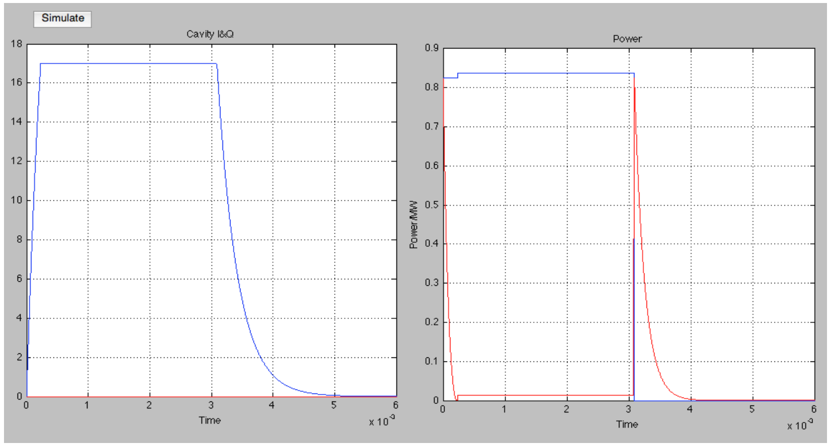
$$I_{total}=I_g-I_b=\left(I_{gr}-iI_{gi}\right)+\left(I_{br}-iI_{bi}\right)$$

$$\Rightarrow\left(I_{gr}-I_{br}\right)+i\left(I_{gi}-I_{bi}\right)=\frac{V_{cav}}{R_L}\left(1-i\tan\varphi_D\right)$$

$$\Rightarrow\begin{cases}I_{gr}=\frac{V_{cav}}{R_L}+I_{br}=\frac{V_{cav}}{R_L}+I_b\cos\varphi_b\\ I_{gi}=-\frac{V_{cav}}{R_L}\tan\varphi_D+I_{bi}=-\frac{V_{cav}}{R_L}\tan\varphi_D-I_b\sin\varphi_b(\text{note defination }\varphi_b)\end{cases}$$

$$\text{To minimize RF power, have } Q_L=\frac{2V_{cav}}{(R/Q)I_b\cos\varphi_b}\text{ and } I_{gi}=0,$$

$$\Rightarrow\tan\varphi_D=-\frac{I_b\sin\varphi_b}{I_b\cos\varphi_b}=-\tan\varphi_b$$



Further reading: Electroacoustic instabilities in the LEP-2 superconducting cavities, D. Boussard, et, al. 7th RF superconducting workshop, 1995

Beam loading

- ✓ One bunch of the beam travelled through an RF cavity will experience the RF voltage, the induced field from previous bunches, and half of the self-induced field (Fundamental Theory of Beam Loading)
- ✓ Beam loading effects is not so significant, but get worst when there are charge fluctuation and beam chopping

$$I_{DC} = \frac{q}{T_b} = \frac{q\omega}{2\pi}$$

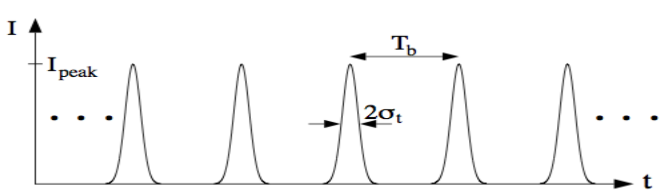
$$\omega C \approx \omega_0 C = \frac{Q_L}{R_L} = \frac{2}{(R/Q)},$$

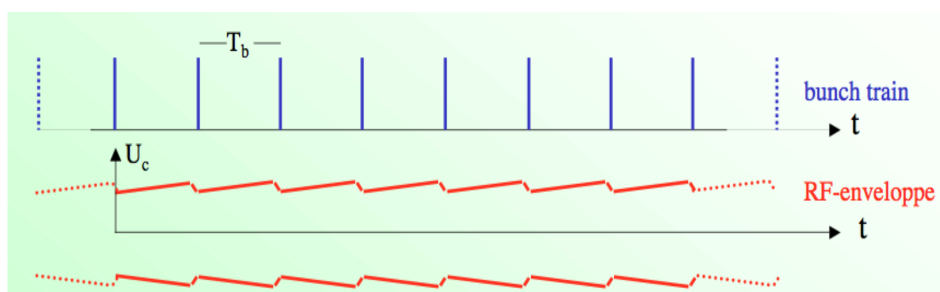
$$V_{b0} = \frac{q}{C} = \frac{1}{2}\frac{\omega(R/Q)}{4} q = \pi(R/Q)\cdot I_{DC}$$

assume no detune and other perturbation,

$$V_b(t) = -\left(\frac{1}{2}V_{b0}e^{-(t-nT_b)/\tau} + V_{b0}e^{-(t-(n-1)T_b)/\tau} + V_{b0}e^{-(t-(n-2)T_b)/\tau} + \cdots + V_{b0}e^{-(t-T_b)/\tau} + V_{b0}e^{-t/\tau}\right)$$

$$V_{cav}(t) = V_g(t) + V_b(t) = V_{g\infty}\left(1-e^{-t/\tau}\right) + V_b(t), \qquad \tau = \frac{2Q_L}{\omega}$$





Further reading: Interaction between RF-System, RF-Cavity and Beam, Thomas Weis, 2005

An beam chopping example in JPARC

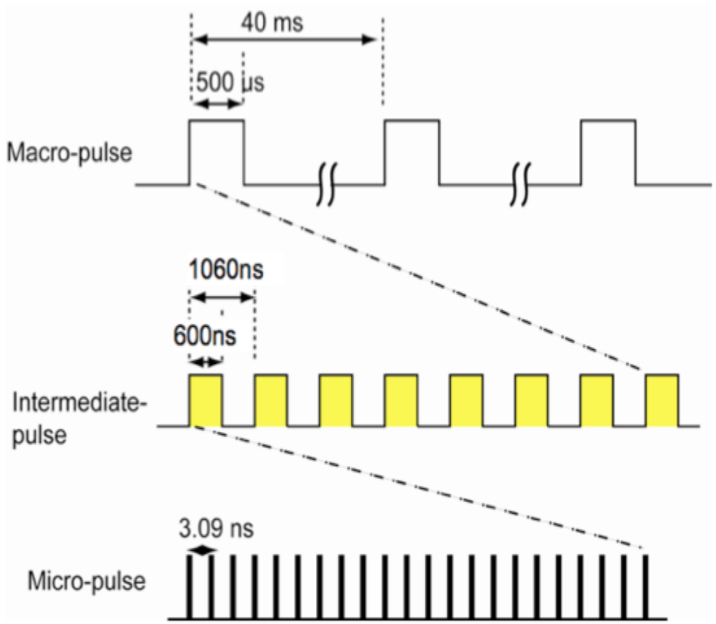


Figure 1: Linac beam structure.

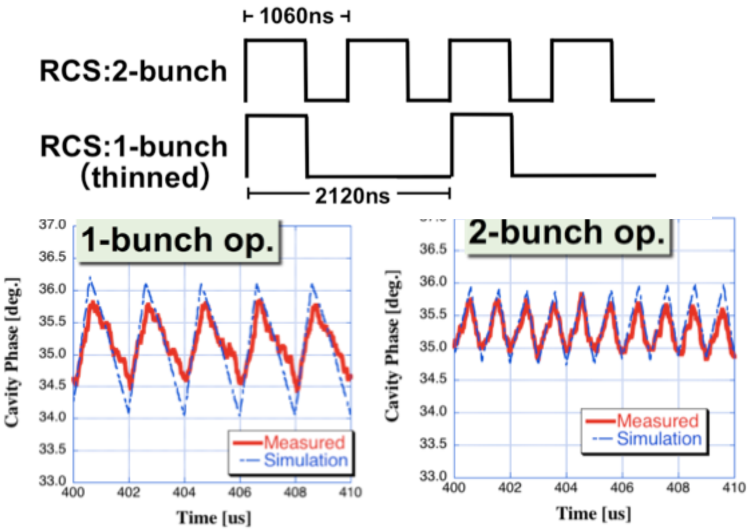
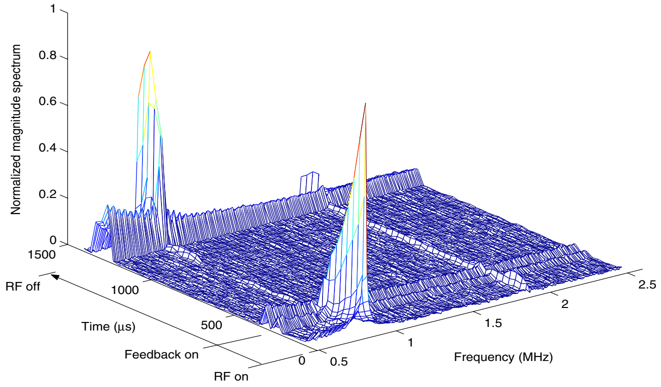


Figure 8: The phase variations in the Debuncher2 caused by the chopped beam of the one-bunch and two-bunch operation, respectively.

Further reading: T. Kobayashi, M. Ikegami, BEAM TEST OF CHOPPED BEAM LOADING COMPENSATION FOR THE J-PARC LINAC 400-MEV UPGRADE, Linac 10.

Non-relativistic beam, HOMs, Passband mode

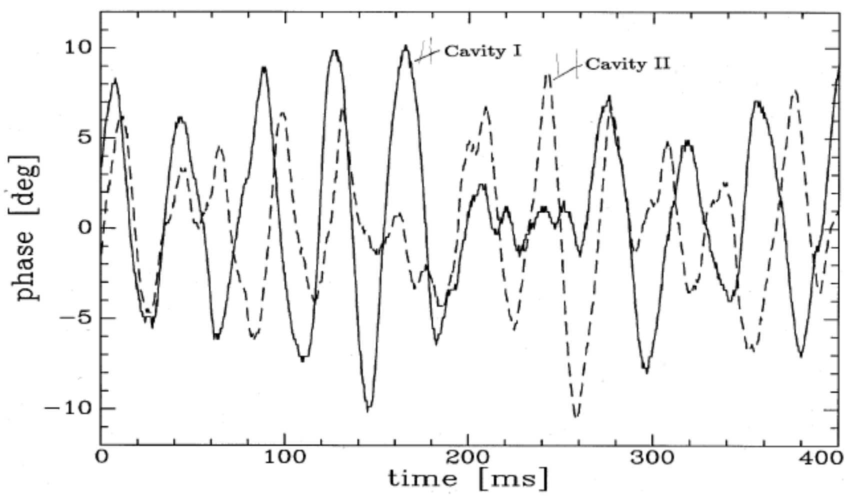
- ✓ Non-relativistic beam
- ✓ HOMs and pass band modes are excited in the cavity during beam loading.
- ✓ The pass band mode closest to the fundamental mode is to be concerned. It is one of the reasons causes instabilities and limit the loop gain
- ✓ This mode can be excited by the chopped beam pulses and the switching edges of the rf pulses.
- ✓ A special filter can be applied to suppress this mode in digital domain



Further reading: Hengjie Ma et al., "Low-level rf control of Spallation Neutron Source: System and characterization," Physical Review Special Topics - Accelerators and Beams 9, no. 3, 2006

Microphonics

- ✓ Caused by the mechanical vibrations in the accelerator environment, such as vacuum pumps, helium pressure fluctuations, traffic, ground motion, ocean waves…
- ✓ It is a slow perturbation, not predictable, and usually of the order of several Hz to several 10Hz
- ✓ Avoid the domain frequencies in the microphonics spectrum close to the cavity mechanical modes



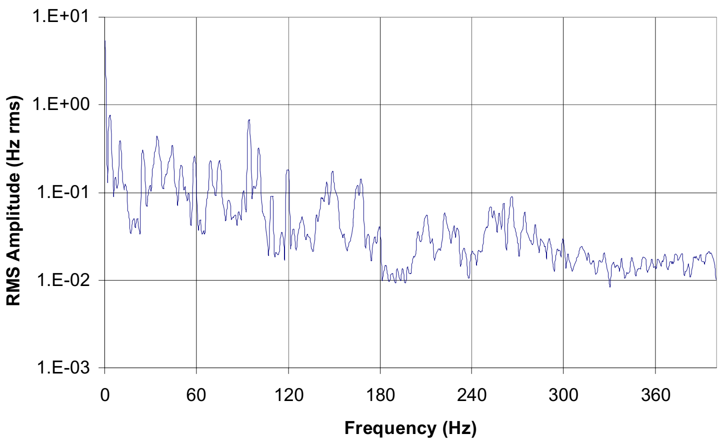


Figure 3: Typical background microphonics spectrum

Further reading: S. Simrock, M. Grecki, 5th LC School, Switzerland, 2010, LLRF & HPRF.
J.R. Delayen, G. Davis, Microphonics and Lorentz Transfer Function Measurements on the SNS Cryomodules, 2003.

Thermal drift and crates noise

- ✓ Thermal drift in phase reference line and down converter, master oscillator and crate noise are out of the feed back control loop.

- ✓ Special cautions should be taken:

  Temperature-stabilized phase reference line;

  Low phase noise master oscillator;

  Down convert board temperature and channels cross talk control;

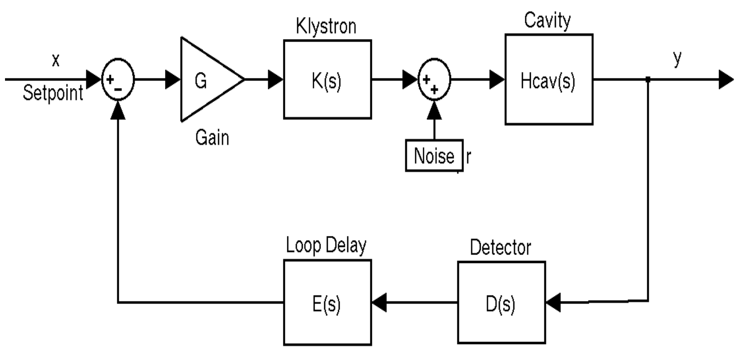
  Crate power noise;

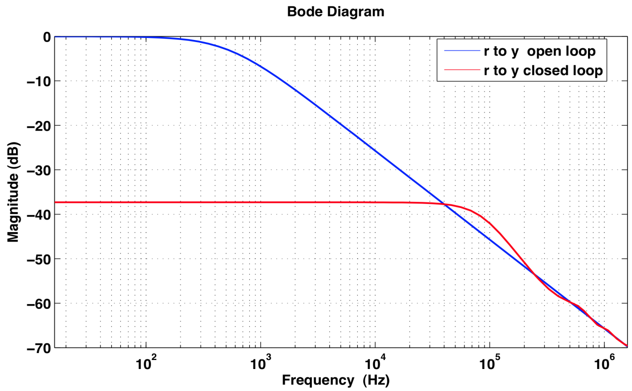
  ADC non-linearization (non-IQ sampling);

  Drift calibration in digital control;

Feedback

- The errors could be suppressed in feedback loop a factor of loop gain G. The loop gain is limited by loop delay and also by pass-band mode
- Large loop gain will result in more overshoot.
- Average loop gain at SNS is about 50 for superconducting cavity, less than 10 for normal cavity





$$H_o(f) = G H_{cav} e^{-j\tau f},$$

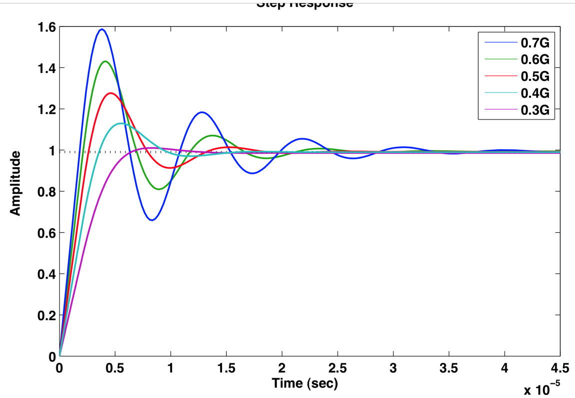
$$|H_o(f)| = \frac{G}{\sqrt{\left(\frac{f}{f_{hbw}}\right)^2 + 1}},$$

$$\varphi = \angle H_o(f) = -\arctan\left(\frac{f}{f_{hbw}}\right) - \tau f.$$

The instability is happening when:

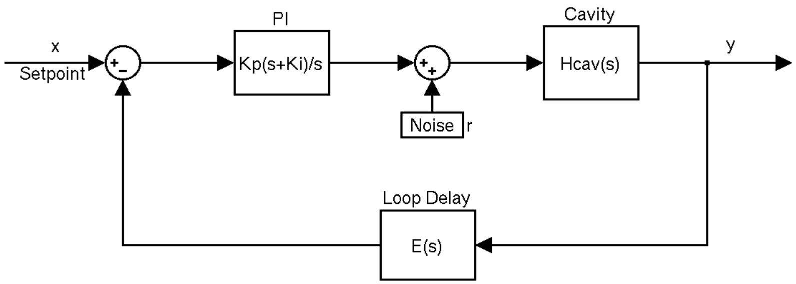
$$|H_o(f)| \geq 1,$$

$$\varphi = -180^\circ + n \cdot 360^\circ, \quad n = \pm 1, \pm 2, \ldots$$



Integral-proportional controller

- ✓ Integral gain of $Ki=2\pi f_{HBW}$ is then introduced to eliminate the steady errors and reduce low frequency noises
- ✓ The PI feedback loop can suppresses effectively low frequency noise but the performance degrades as frequency increases, while the far higher frequency noise is filtered by cavity itself



$$H_o(f) = K_p\left(1+\frac{K_i}{j2\pi f}\right)H_{cav}(f)\,e^{-j2\pi\tau f}$$
$$= K_p\left(\frac{j2\pi f + K_i}{j2\pi f}\right)\left(\frac{f_{hbw}}{jf + f_{hbw}}\right)e^{-j\pi\tau f},$$
$$|H_o(f)| = K_p\sqrt{1+\left(\frac{K_i}{2\pi f}\right)^2}\Big/\sqrt{1+\left(\frac{f}{f_{hbw}}\right)^2},$$
$$\varphi = \angle H_o(f) = \arctan\left(\frac{2\pi f}{K_i}\right) - \arctan\left(\frac{f}{f_{hbw}}\right) - \frac{\pi}{2} - 2\pi\tau f.$$

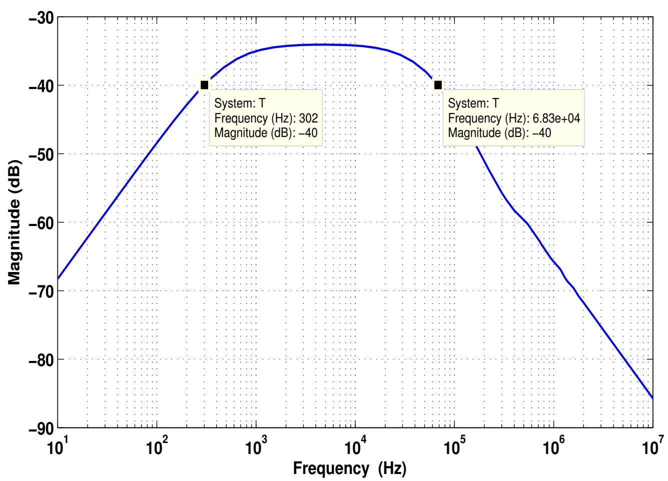


Figure 13: Noise suppression performance of PI feedback closed loop as a function of frequency for superconducting cavity($K_p = 50, K_i = 2\pi \times 518$)

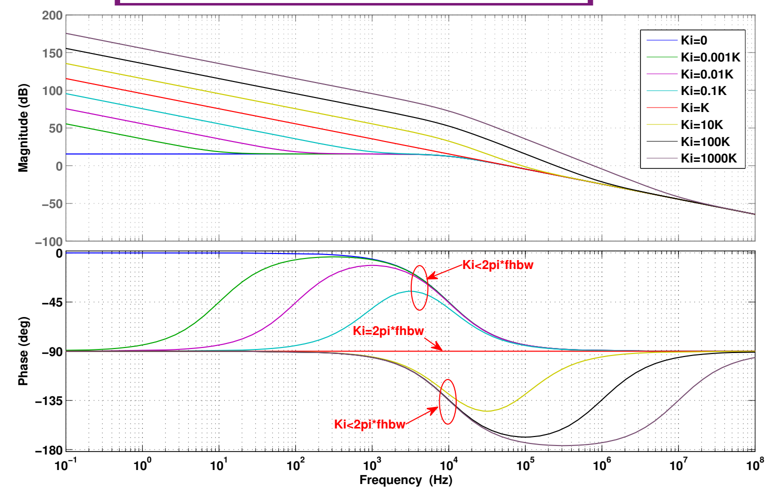


Figure 11: Phase margin reduced in open loop under different integral gains (without delay, $K = 2\pi f_{hbw}$)

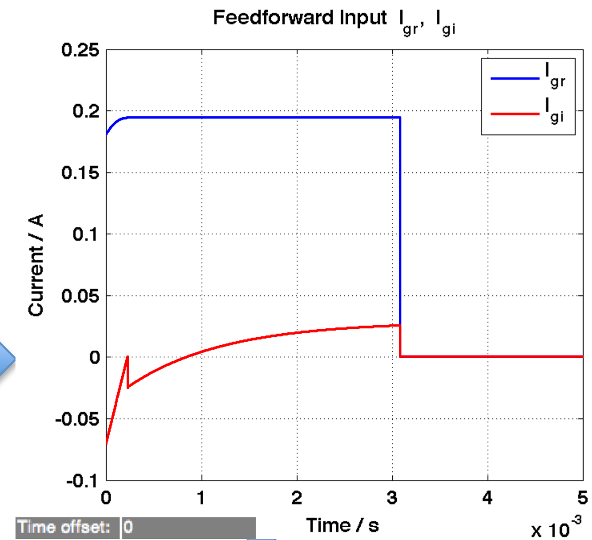
Further reading: R. Zeng et, al. The Droop and Ripple's Influence on Klystron Output, ESS tech-note.

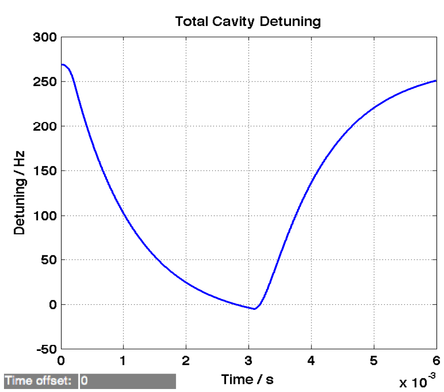
Feedforward

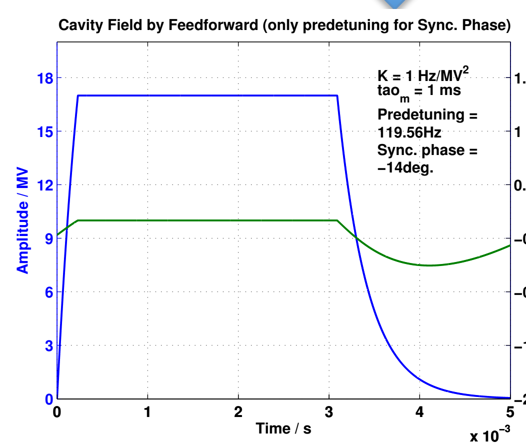
- ✓ Feed forward is to deal with the repetitive errors from pulse to pulse.
- ✓ In simplicity, It adds the errors learned to every pulse by feed forward table

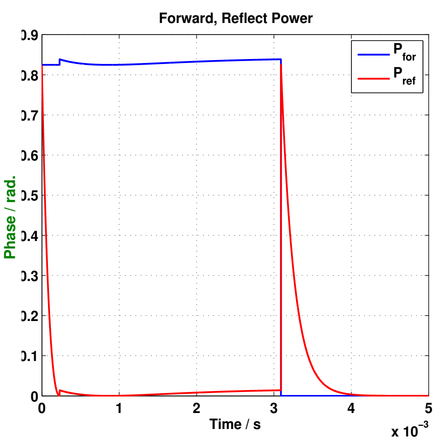
$$\begin{cases} I_{gr} = \dfrac{V_{cav}}{R_L} + I_{br} = \dfrac{V_{cav}}{R_L} + I_b \cos\varphi_b \\ I_{gi} = -\dfrac{V_{cav}}{R_L}\tan\varphi_D + I_{bi} = -\dfrac{V_{cav}}{R_L}\tan\varphi_D - I_b \sin\varphi_b \end{cases}$$

note here we take V_{cav} as the reference $V_{cav} = V_{cav} + i \cdot 0$



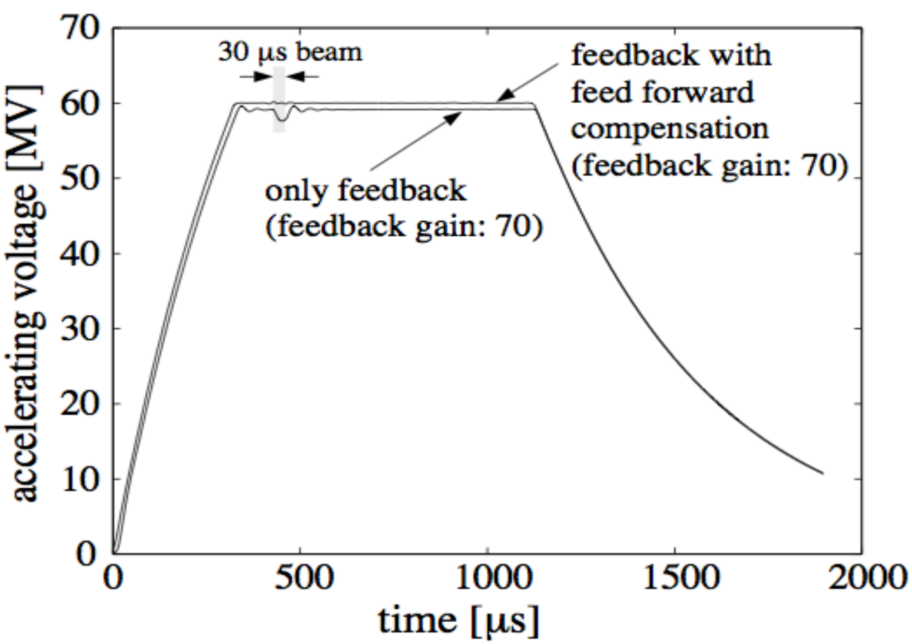




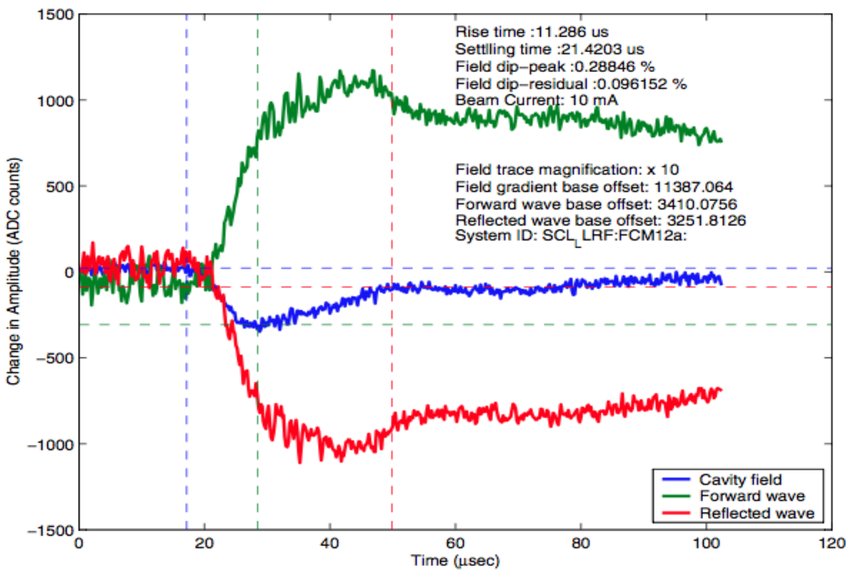


Feedforward

- ✓ The oscillation is happening when feedback is applied during beam loading due to loop delay and high loop gain.
- ✓ Feedforward compensation



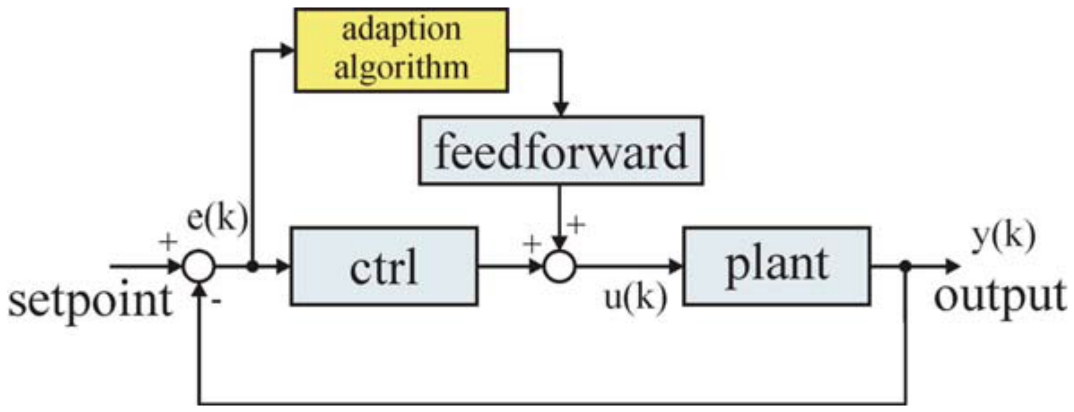
DESY



SNS

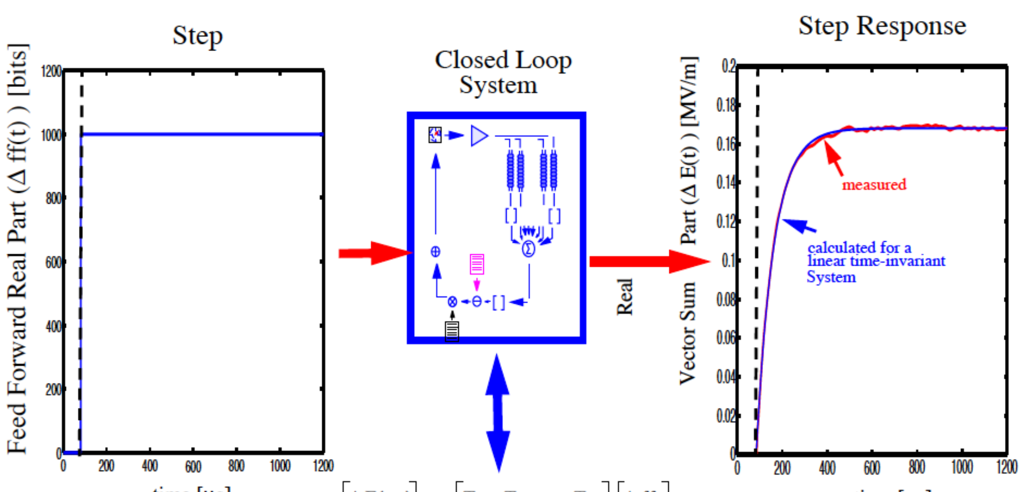
Adaptive Feed forward

- ✓ The Repetitive perturbations and the system performance may vary slowly with the time(thermal drift, microphonics, cathode voltage variations, component aging).
- ✓ Adaptive algorithm is crucial here in order to compensate the possible changes of the environmental and operating conditions



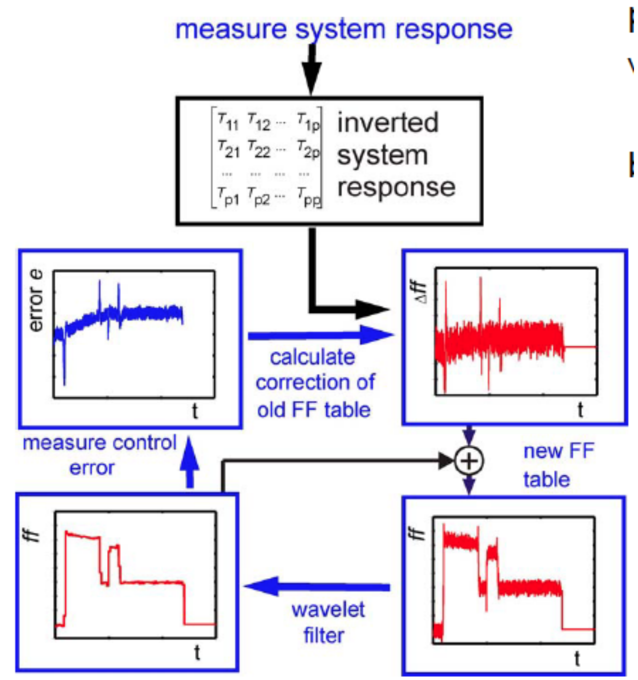
Adaptive feedforward at DESY TTF

- ✓ measure the step responses continually to maintain a current system model.
- ✓ The step size should be select carefully
- ✓ It is direct, straightforward, but need large computation capacity, measurement response not fast



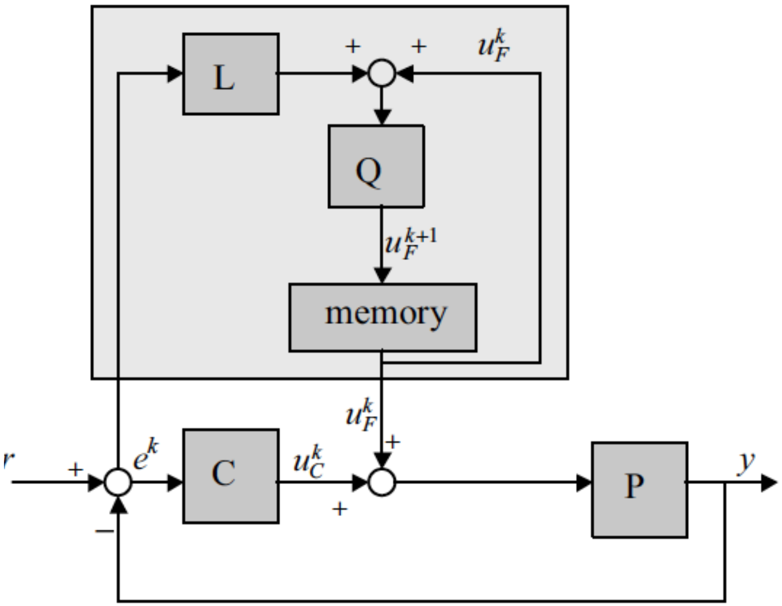
$$\begin{bmatrix} \Delta E(\tau_1) \\ \Delta E(\tau_2) \\ \cdots \\ \Delta E(\tau_n) \end{bmatrix} = \begin{bmatrix} T_{11} & T_{12} & \cdots & T_{1n} \\ T_{21} & T_{22} & \cdots & T_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ T_{n1} & T_{n2} & \cdots & T_{nn} \end{bmatrix} \begin{bmatrix} \Delta ff_1 \\ \Delta ff_n \\ \cdots \\ \Delta ff_n \end{bmatrix}$$

$$\Delta ff(t) = \sum_j \Delta ff_j \Theta(t - t_j).$$



LLRF Development for TTF II and Applicability to X-FEL & ILC, S. Simrock, ILC WS 2004

Adaptive feedforward at SNS



$$\|U_{\mathrm{F}}^{k+2}(\mathrm{j}\omega) - U_{\mathrm{F}}^{k+1}(\mathrm{j}\omega)\|_\infty \quad < \|U_{\mathrm{F}}^{k+1}(\mathrm{j}\omega) - U_{\mathrm{F}}^{k}(\mathrm{j}\omega)\|_\infty$$

$$U_{\mathrm{F}}^{k+1} = Q(U_{\mathrm{F}}^{k} + LE^k)$$

$$\left\| 1 - \frac{LP}{1+CP} \right\|_\infty < 1$$

$$L(s) = \alpha\left(sB_z^{-1} - (B_z^{-1}A_z(\Delta\omega_{\mathrm{L}}) - K_{\mathrm{P}}) + \frac{1}{s}K_I\right).$$

in time domain, the learning controller is

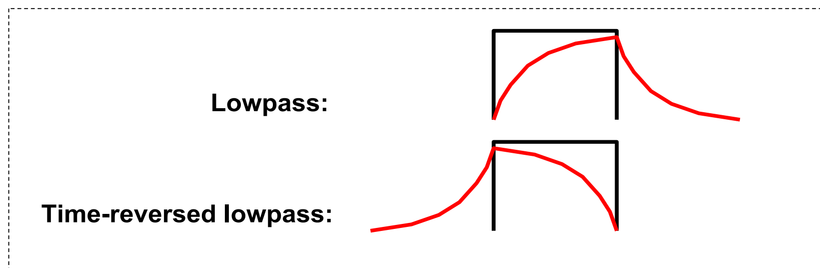
$$v_{\mathrm{F}}^{k+1}(t) = f \cdot u_{\mathrm{F}}^{k}(t) + \alpha B_z^{-1}\dot{e}^k - \alpha\left(B_z^{-1}A_z(\Delta\omega_{\mathrm{L}}) - K_{\mathrm{P}}\right)e^k(t) + \alpha K_I \int_0^t e^k(\tau)\,\mathrm{d}\tau$$

- ✓ Q-filter is added to suppress the high frequency component due to that modeling of high-frequency dynamics are difficult and may lead to an inadequate model and unstable behavior
- ✓ L-filter (self learning filter) that compensates well for low frequencies, and it has the characteristics of PID
- ✓ a forgetting factor is introduced to put different weights to the past feedforward controller outputs

S.I. Kwon, A.H. Regan, “SNS Superconducting RF. Cavity Modeling - Iterative Learning Control,”. Nuclear Instruments and Methods in Physics Research A 482 (2002) 12–31

New Adaptive Feedforward at FLASH

- ✓ A possible scheme: take the current drive signal of the pulse as the feedforward input for the next pulse…Unfortunately, it is unstable
- ✓ Instead, add a time-reversed low-pass filter: record feedback error signal e(t), time reverse e(t)→e(-t), low pass filter e(-t), reverse filtered signal in time again, shift signal in time to compensate loop delay



FF_{new} = TRLP(FB_{last})+FF_{last} ***…is surprisingly stable :)***

time-reversed low-pass

Further reading: Alexander Brandt, LLRF Automation and Adaptive Feedforward, FLASH Seminar, 2006

Alexander Brandt, Development of a Finite State Machine for the Automated Operation of the LLRF Control at FLASH, PhD thesis, DESY, 2007.

Summary

- ✓ LLRF has to maintain the stability of the RF field, and minimize the required overhead power. Automated operation and easy maintenance should be taken into account, especially in large-scale facilities.
- ✓ A variety of perturbations can be seen everywhere in the accelerator environment
- ✓ PI Feedback is an effective and classical way to deal with the perturbations but at the cost of the more overhead consumption and rising instability.
- ✓ Feedforward is essential for the repetitive perturbations and need automatically update. We should look into more advanced control methods to be able to achieve better performance

Thank you for the attention!