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An Introduction to LLRF Control

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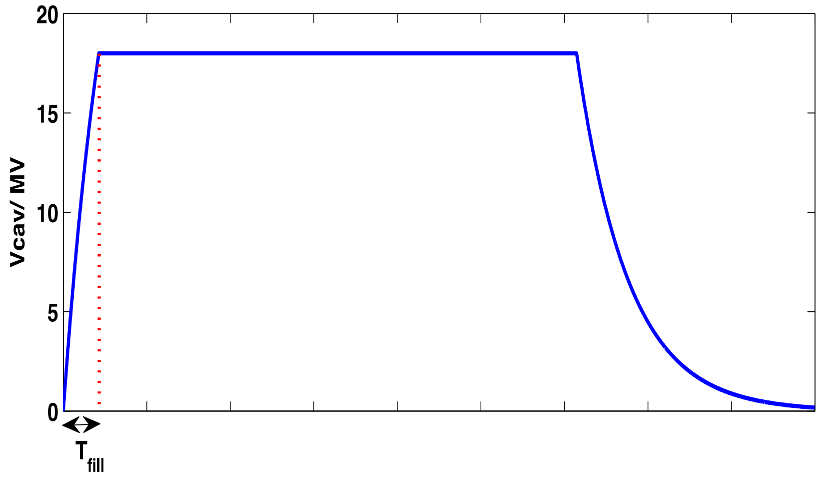
Outline

- ✓ What is LLRF doing?
- ✓ Why need LLRF? Perturbations in RF field.
- ✓ How does LLRF control? Feedback+Feedforward
- ✓ Challenges of LLRF control at ESS
- ✓ Summary

What is LLRF doing?

Phase and amplitude stability

- ✓ 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:

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

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

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

In the case of fixed sync. phase:

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

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

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

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 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?

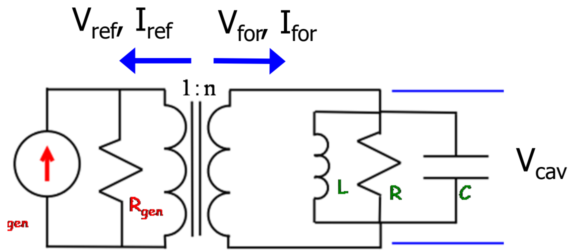
Other issues

- ✓ Minimize the required overhead power for control
- ✓ Automated operation, remote control
- ✓ Availability, maintenance, upgradability
- ✓ Support Linac commissioning
- ✓ …

Why need LLRF?

The ideal case

- ✓ 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 :

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

$$b = \frac{P_g}{P_c} = 1 + \frac{P_b}{P_c} » \frac{P_b}{P_c},$$

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

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

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

for beam induced voltage,

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

$$Þ \ V_b = V_{cav}$$

Ideal injection time:

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

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

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

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

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

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

for superconducting cavity, $b >> 1$,

$$t_{inj} » t \ln 2 = \frac{2Q_L}{w} \ln 2$$

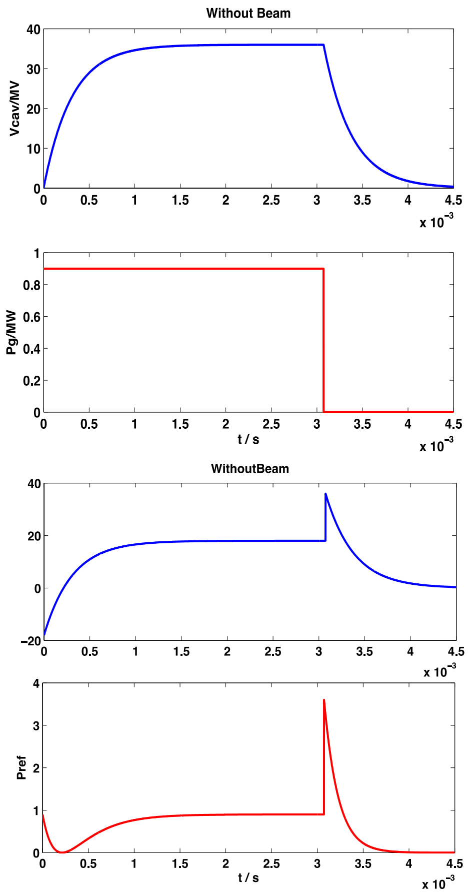
$$V_{cav} = V_g(t_{inj}) = \frac{1+b}{2b} V_g = V_{for} » 0.5 V_g$$

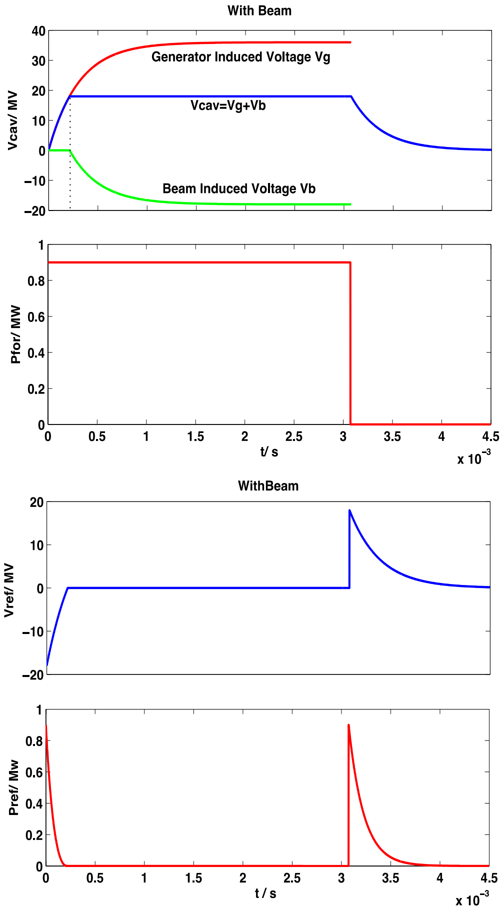
Further reading:

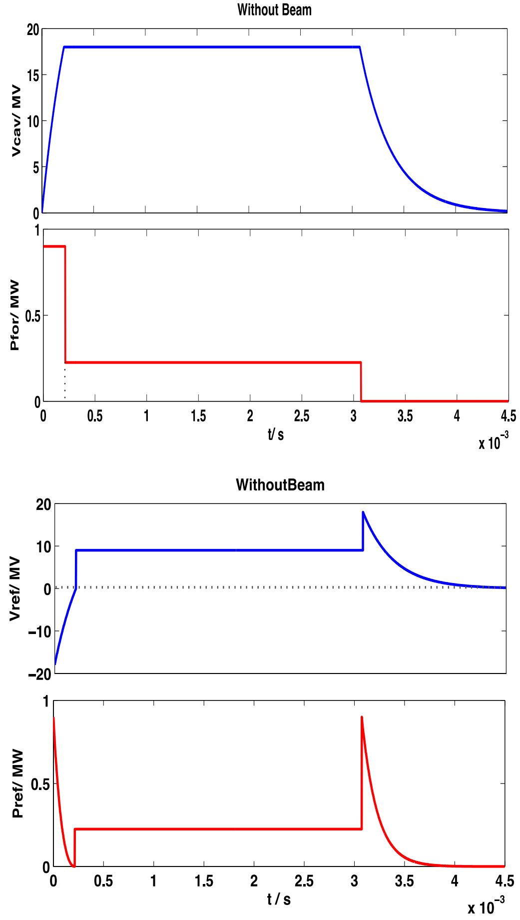
D. McGinnis, A Simple Model for a Superconducting RF cavity with a Vector Phase Modulator, 2007.

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

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)

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

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

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

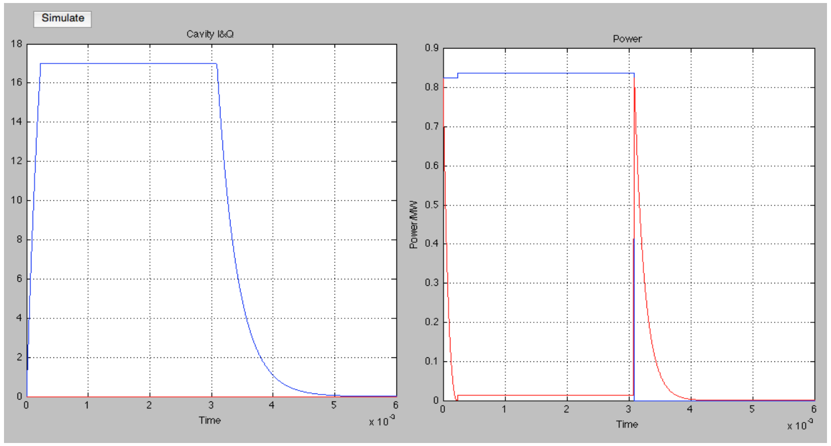
$$I_{total}=I_g-I_b=(I_{gr}-iI_{gi})+(I_{br}-iI_{bi})$$

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

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

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

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



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

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

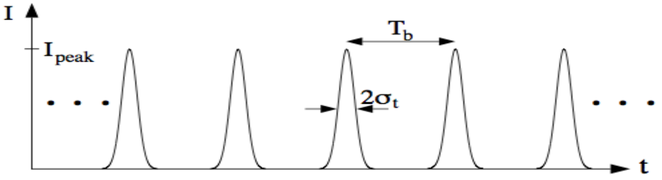
$$\omega C\approx\omega_0 C=\frac{Q_L}{R_L}=\frac{2}{(R/Q)},$$

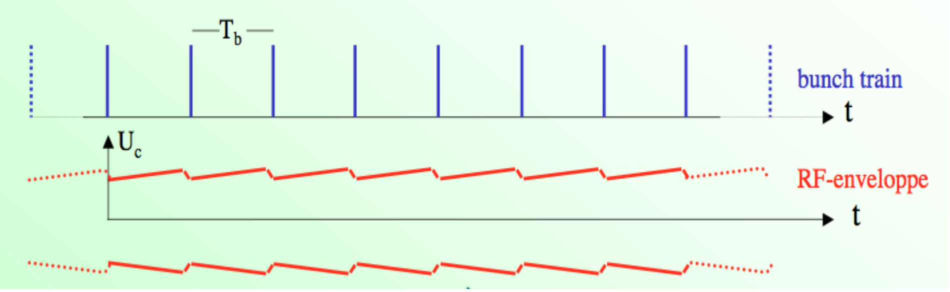
$$V_{b0}=\frac{q}{C}=\frac{1}{2}\frac{\omega(R/Q)}{4}q=\pi(R/Q)\cdot I_{DC}$$

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

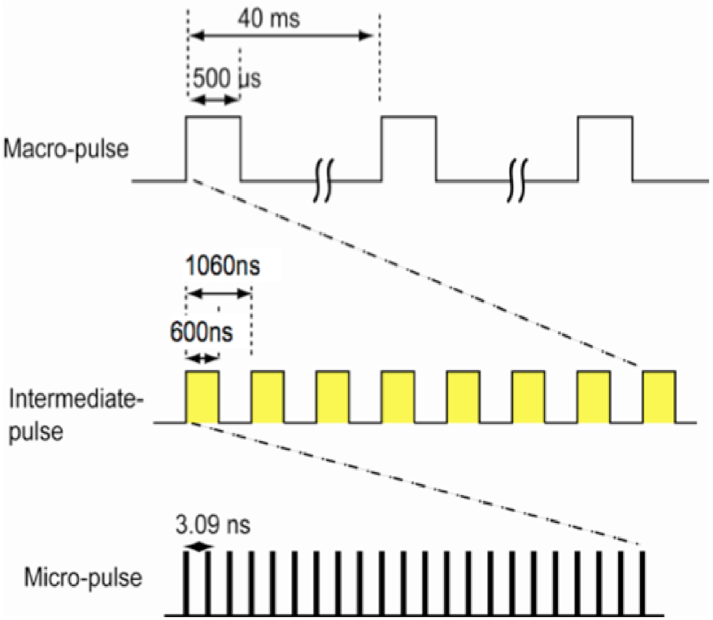


Figure 1: Linac beam structure.

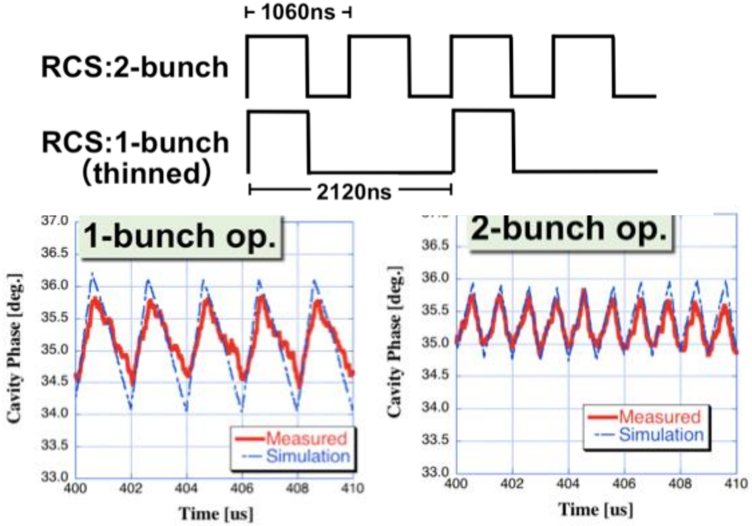
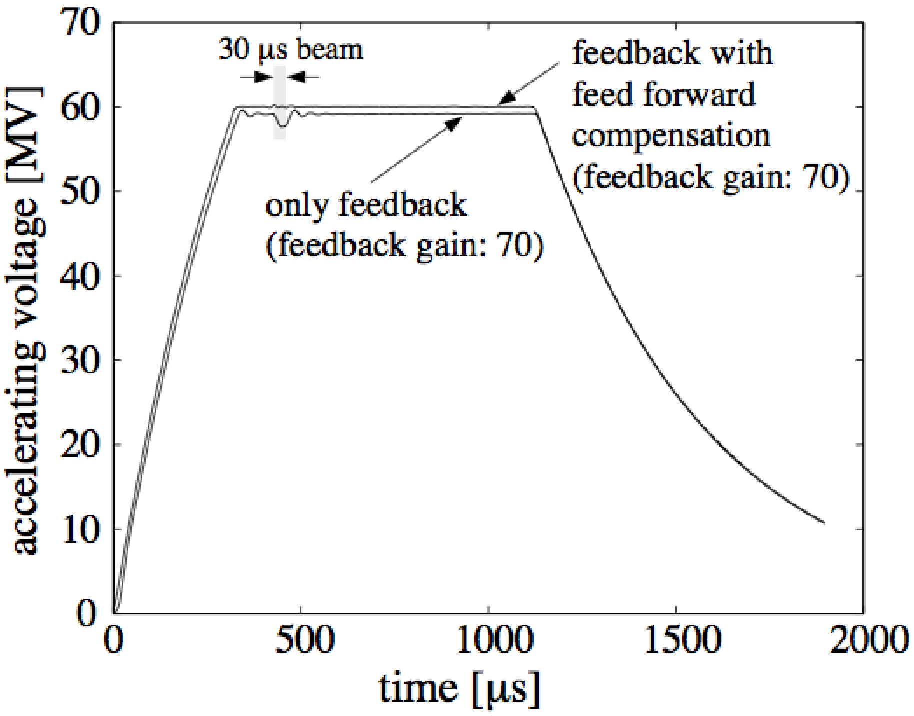


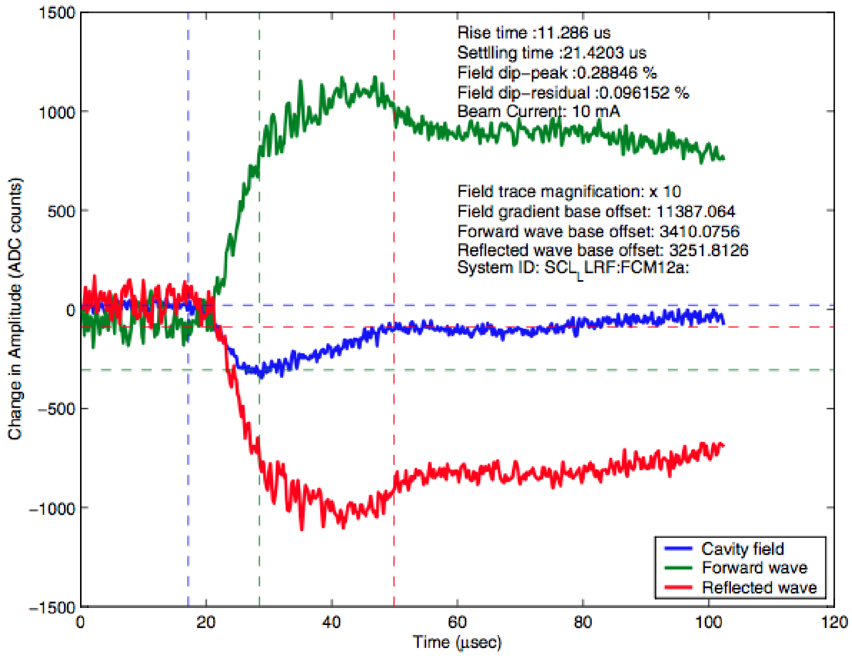
Figure 8: The phase variations in the Debuncher2 causec by the chopped beam of the one-bunch and two-buncl operation, respectively.

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

Beam loading under feedback

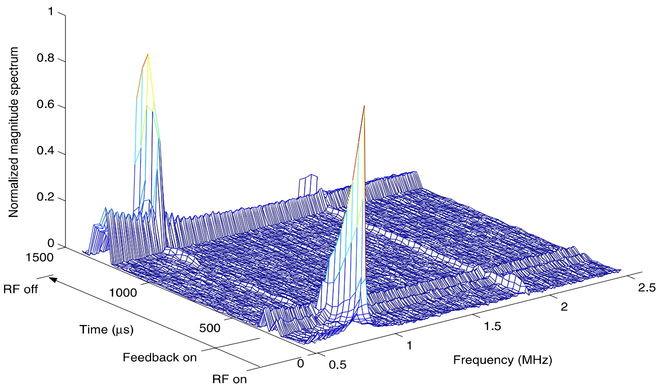
- ✓ The oscillation is happening when feedback is applied during beam loading due to loop delay and high loop gain.





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

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
- ✓ A stiffening ring to is usually applied in high gradient cavities

Radiation pressure :

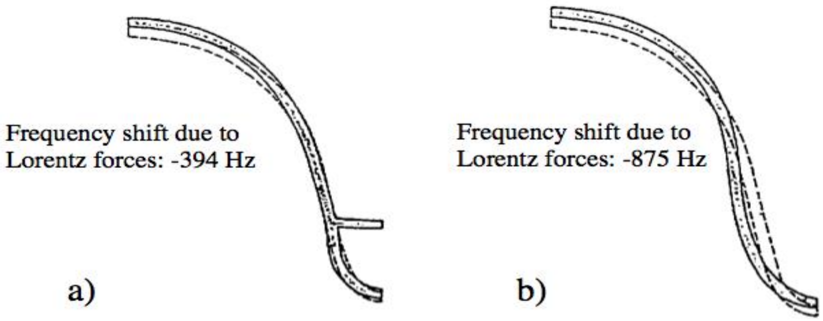
$$P_s = \frac{1}{4}\left(\mu_0\left|\vec{H}\right|^2 - \epsilon_0\left|\vec{E}\right|^2\right)$$

Cavity perturbation theory:

$$\frac{\omega_0 - \omega}{\omega_0} = \frac{\int_{\Delta V}\left(\epsilon_0\left|\vec{E}\right|^2 - \mu_0\left|\vec{H}\right|^2\right)dV}{\int_{V}\left(\epsilon_0\left|\vec{E}\right|^2 - \mu_0\left|\vec{H}\right|^2\right)dV}$$

TM_{010} induced static detuning:

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



: 3.13: Cavity Cell Deformation of a TESLA cavity due to Lorentz force at a gradient of 25 MV/m. The wall thickness of niobium is 2.5 mm.
a) Cavity cell with stiffening ring
b) Cavity cell without stiffening ring

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.
- ✓ The dynamic detuning can be well describe also by 1st order differential equation when mechanical modes frequency unknown.

2nd-order differential equation of dynamic detuning,

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

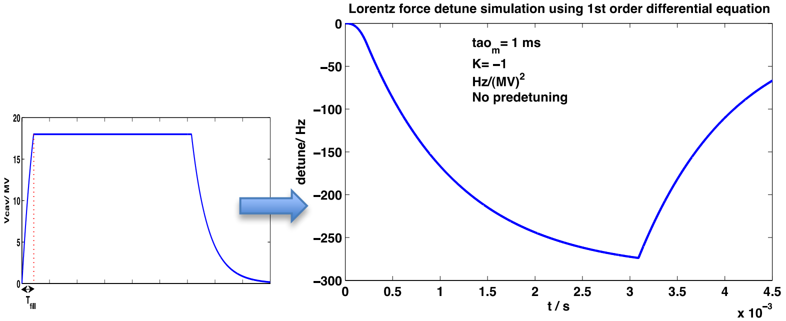
$$\Delta\omega(t) = \sum_n \Delta\omega_n(t), \quad K = \sum_n K_n$$

In steady state:

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

1st-order differential equation of dynamic detuning,

$$\tau_m\Delta\dot{\omega}_n + \Delta\omega = -2\pi K_n \cdot E_{acc}^2(t) + n(t)$$



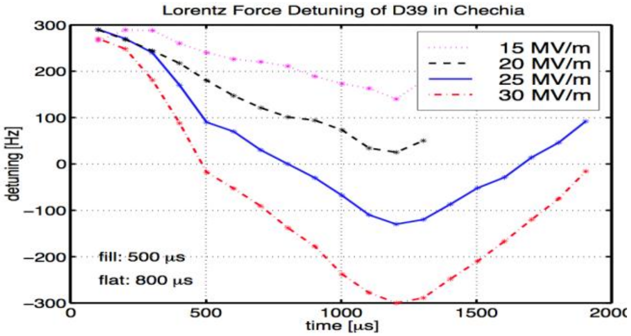
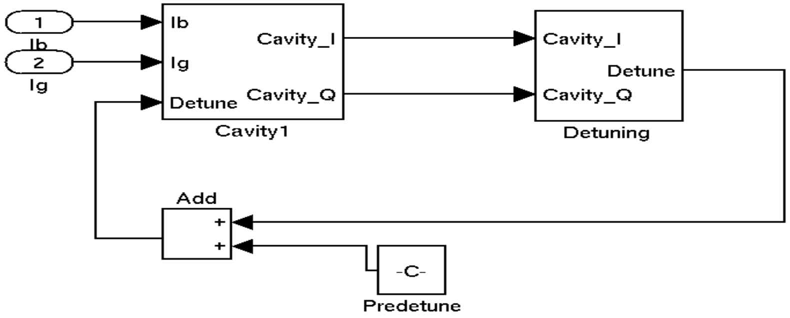


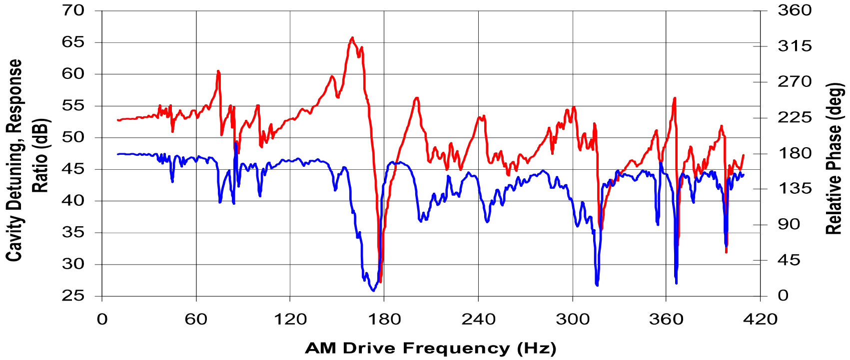
Fig. 2: Lorentz force detuning measured for a TESLA cavity at different gradients.

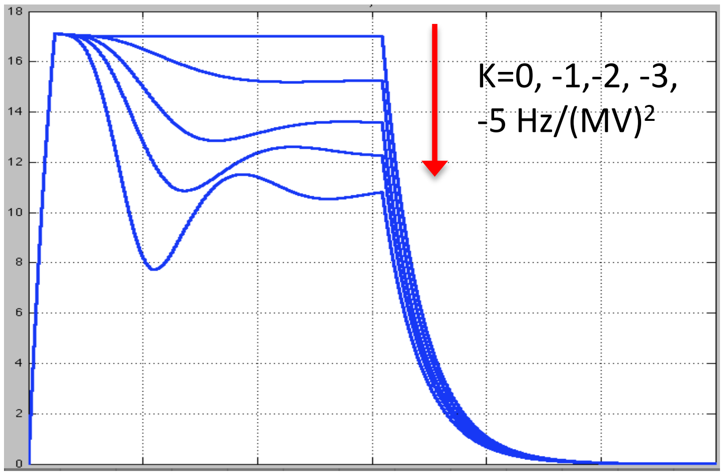
Further reading: J.R. Delayen, Ponderomotive instabilities and microphonics—a tutorial, 12th SRF workshop, 2006.
S.N.Simrock, Achieving Phase and Amplitude Stability in Pulsed Superconducting Cavities, PAC2001

Closed loop between RF field and detuning

- ✓ If no control on RF cavity, the cavity detuning will cause the RF field to change, which then will in turn impact further on the cavity detuning.
- ✓ Such a closed feedback system between the electromagnetic mode and the mechanical modes can lead to instabilities.







Further reading: J.R. Delayen, Ponderomotive instabilities and microphonics—a tutorial, 12th SRF workshop, 2006.

Detune by the piezo tuner

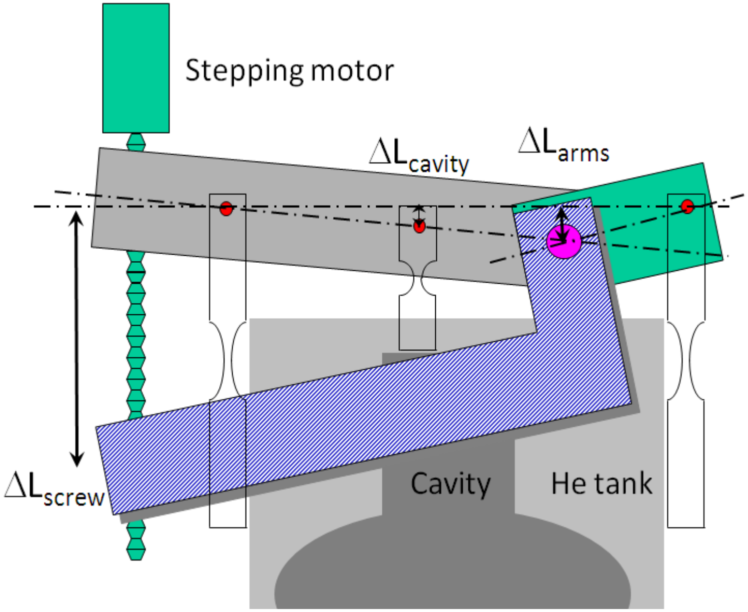
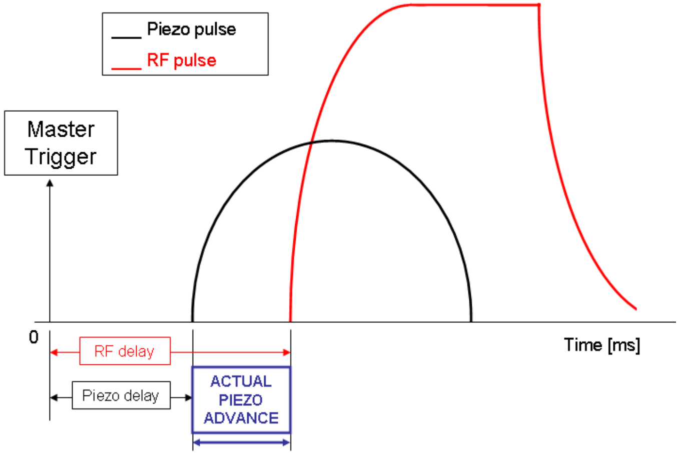


Fig. 3.2 – schematic representation of the TTF tuner working principles



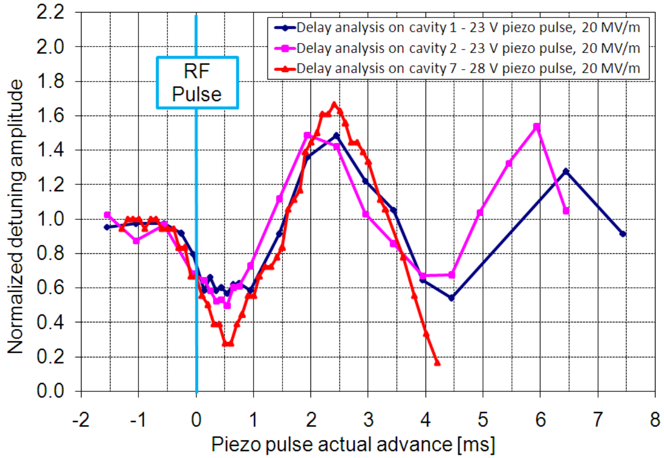
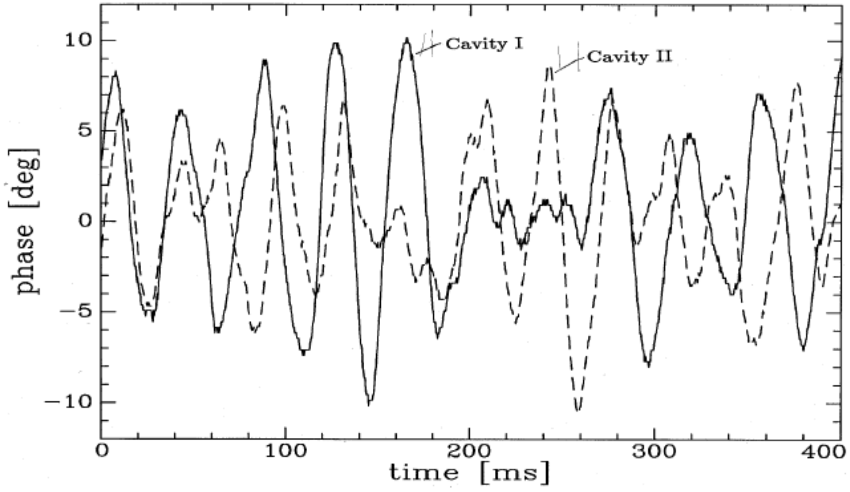


Fig. 5.2 - normalized absolute value of the detuning over the flat-top vs. piezo pulse actual advance

Further reading: Rocco Paparella, PhD thesis. Fast frequency tuner for high gradient SC cavities for ILC and XFE

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



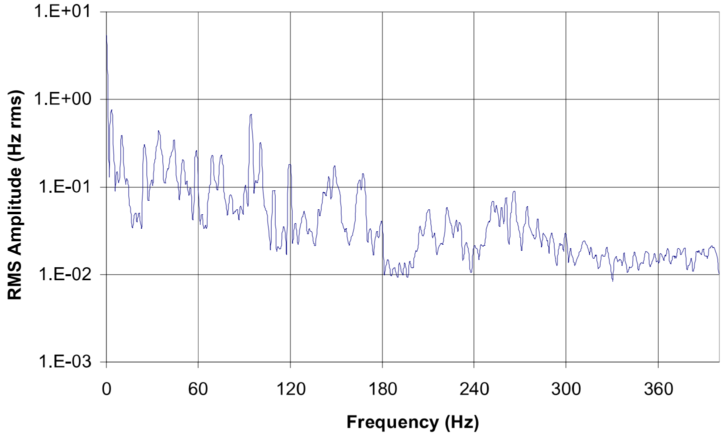


Figure 3: Typical background microphonics spectrum

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.

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

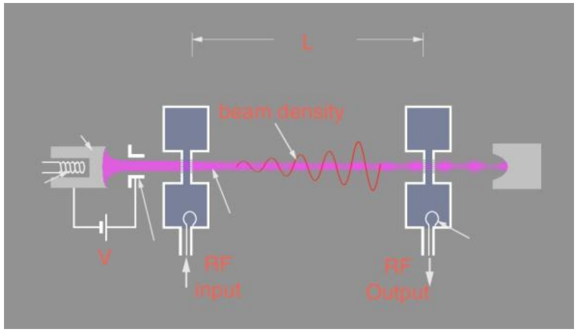


Table 1: Measurement for the phase and amplitude variations in other labs

	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	

$$t = \frac{L}{u} = \frac{L}{\sqrt{\frac{eV}{m}}}, \quad q = wt$$

$$dq = -\frac{wL}{\sqrt{\frac{2eV}{m}}} \times \frac{dV}{V}$$

relativistic case:

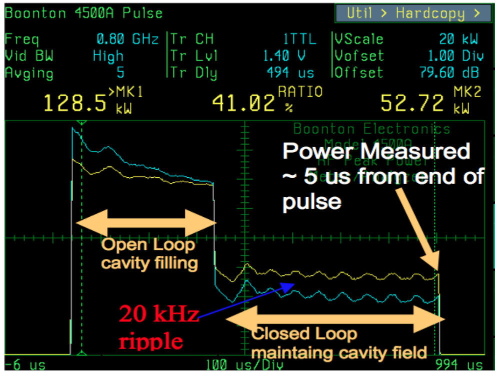
$$dq = -\frac{eWLV}{mc^3 b^3 g^3} \times \frac{dV}{V}$$

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

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

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

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



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Boonton 4500A Pulse                         Util > Hardcopy >
Freq        0.80 GHz |Tr CH        1TTL |VScale      20 kW
Vid BW      High     |Tr Lvl     1.40 V |Vofset    1.00 Div
Avging         5     |Tr Dly     494 us |Offset   79.60 dB
   128.5 >MK1          41.02 RATIO          52.72 MK2
         kW                  %                    kW
-6 us                   100 us/Div                 994 us
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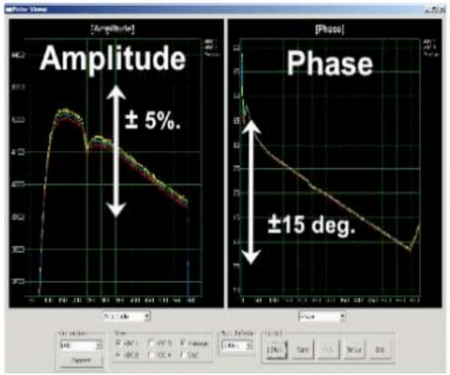
SNS



JPARC

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

Thermal drift and crates noise

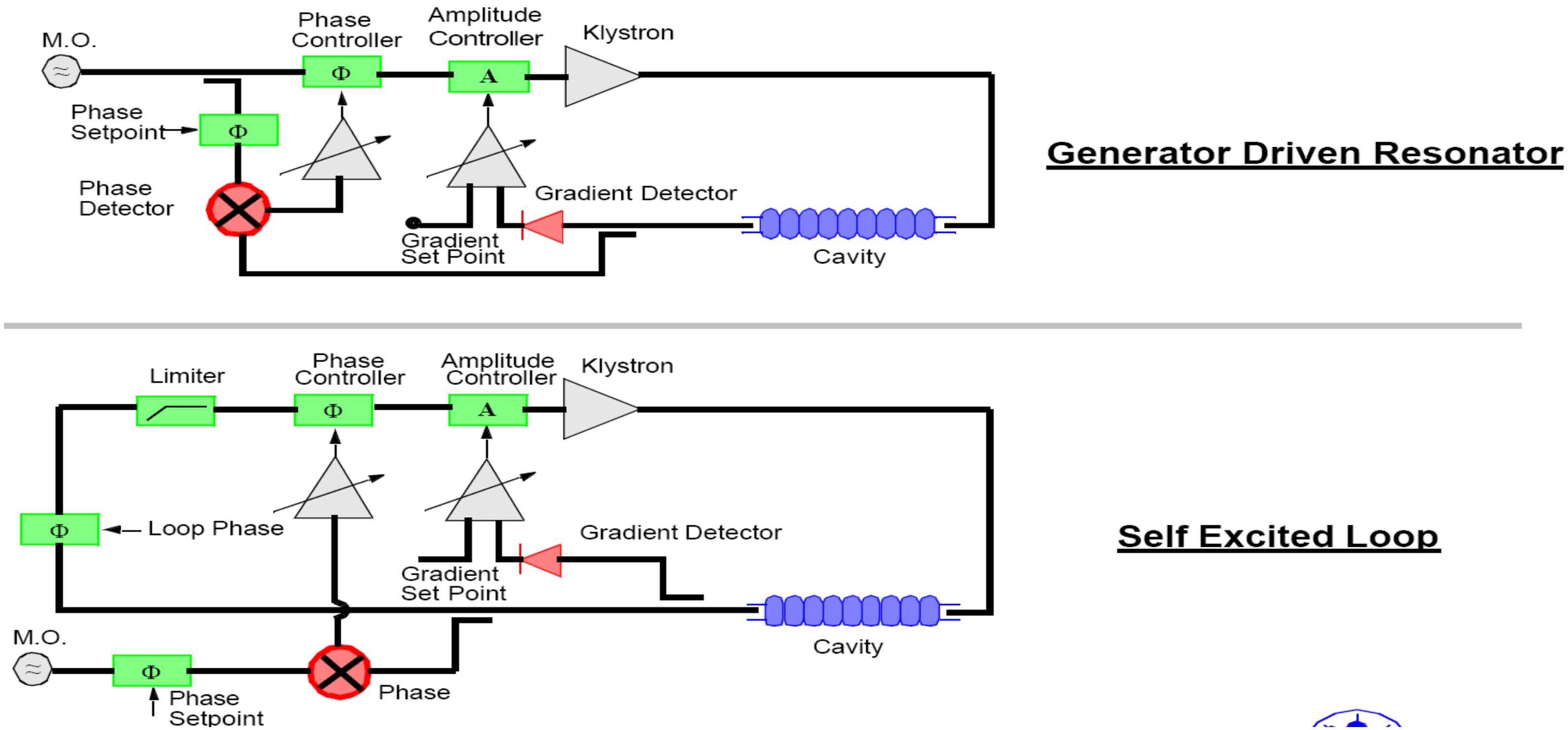
✓ Thermal drift in phase reference line and down converter, master oscillator and crate noise are out of the feed back control loop.

✓ 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;

How does LLRF control?

GDR and SEL

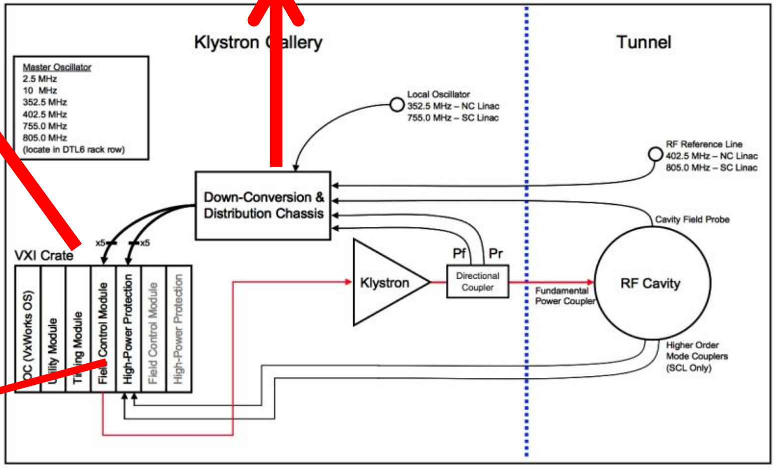


- ✓ SEL is running exactly on resonance, not affected by cavity detune, and hence the amplitude is inherently stable
- ✓ Start up may be slow, may be not good for pulse operation

Further reading: S. Simrock, M. Grecki, 5th LC School, Switzerland, 2010, LLRF & HPRF.

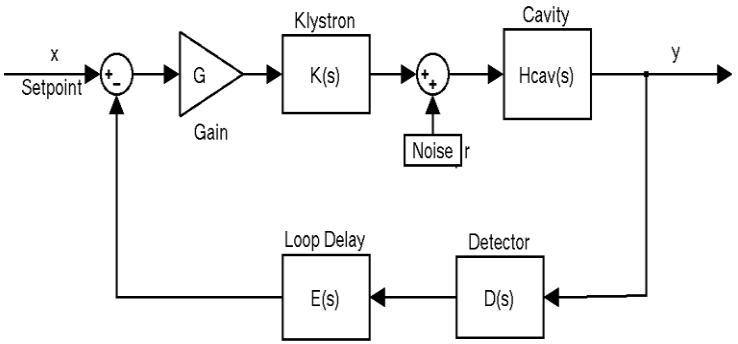
A typical LLRF System at SNS

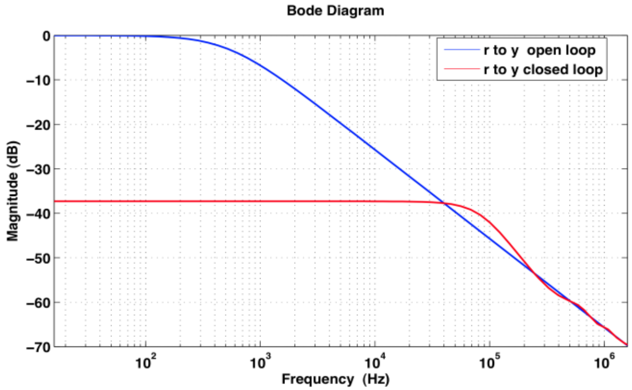
- ✓ Modern LLRF system makes full use of the advantages from new technologies of the Electronic and Communication.
- ✓ Key controllers (feedback and feed forward) and other signal processing are implemented in digital domain (FPGA, DSP).

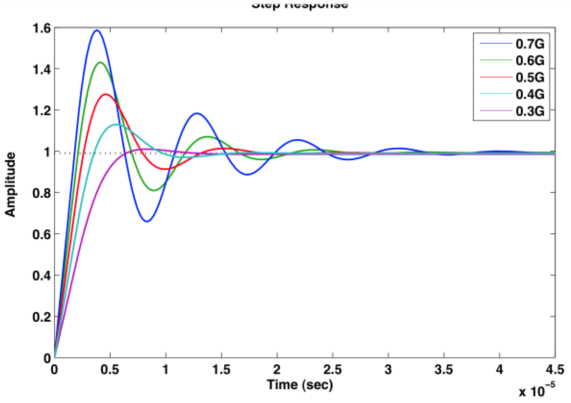


Feedback

- 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







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

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

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

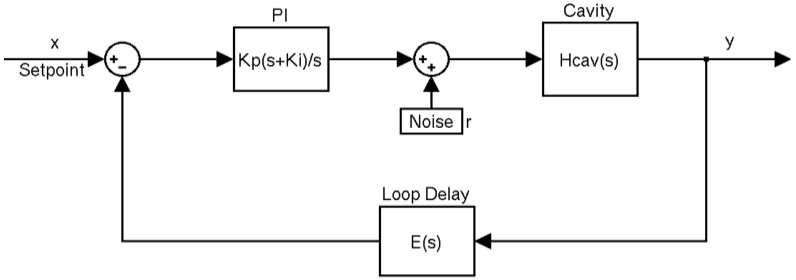
The instability is happening when:

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

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

Integral-proportional controller

- ✓ Integral gain of Ki=2πf$_{HBW}$ 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



$$H_o(f) = K_p\left(1 + \frac{K_i}{j2\pi f}\right) H_{cav}(f)\, e^{-j2\pi\tau f}$$

$$= K_p\left(\frac{j2\pi f + K_i}{j2\pi f}\right)\left(\frac{f_{hbw}}{jf + f_{hbw}}\right) e^{-j\pi\tau f},$$

$$|H_o(f)| = K_p\sqrt{1 + \left(\frac{K_i}{2\pi f}\right)^2} \Big/ \sqrt{1 + \left(\frac{f}{f_{hbw}}\right)^2},$$

$$\varphi = \angle H_o(f) = \arctan\left(\frac{2\pi f}{K_i}\right) - \arctan\left(\frac{f}{f_{hbw}}\right) - \frac{\pi}{2} - 2\pi\tau f.$$

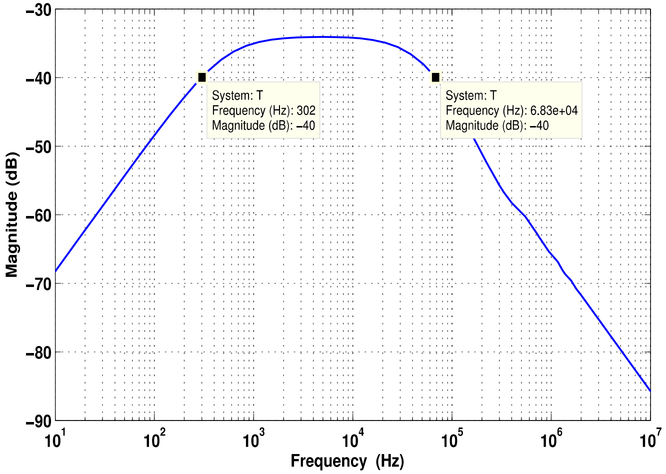


Figure 13: Noise suppression performance of PI feedback closed loop as a function of frequency for superconducting cavity($K_p = 50, K_i = 2\pi \times 518$)

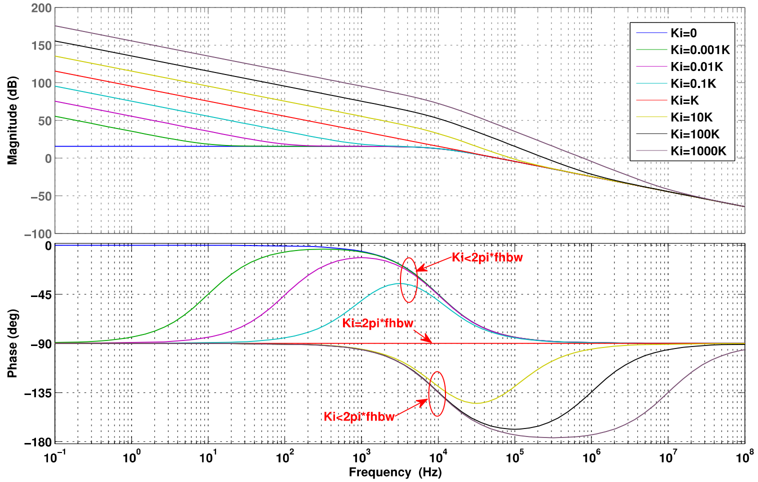


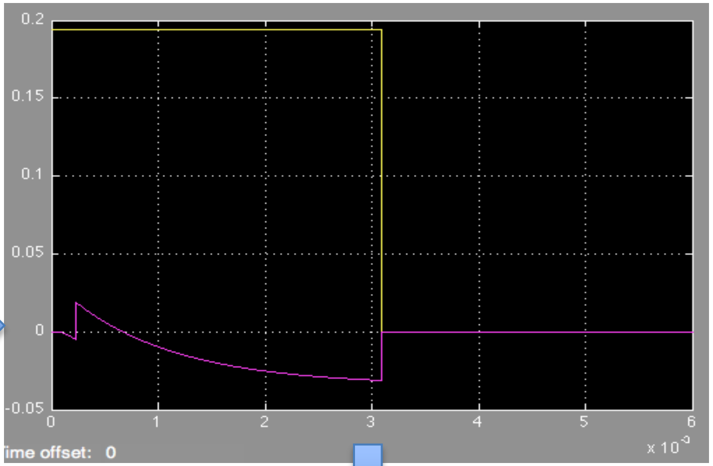
Figure 11: Phase margin reduced in open loop under different integral gains (without delay, $K = 2\pi f_{hbw}$)

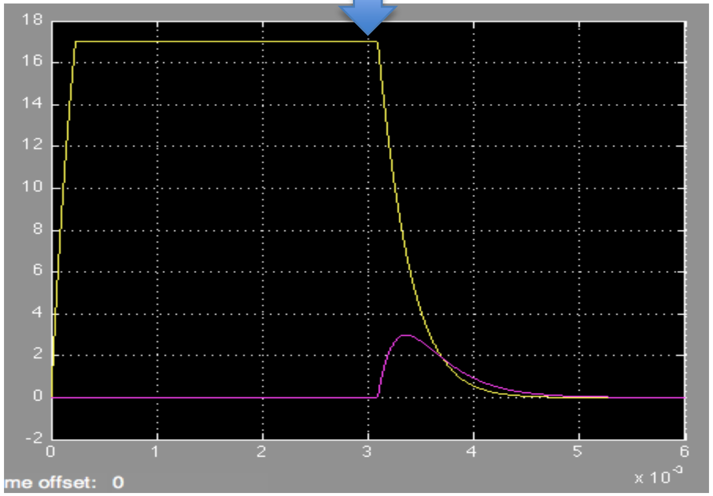
Further reading: R. Zeng et, al. The Droop and Ripple's Influence on Klystron Output, ESS tech-note.

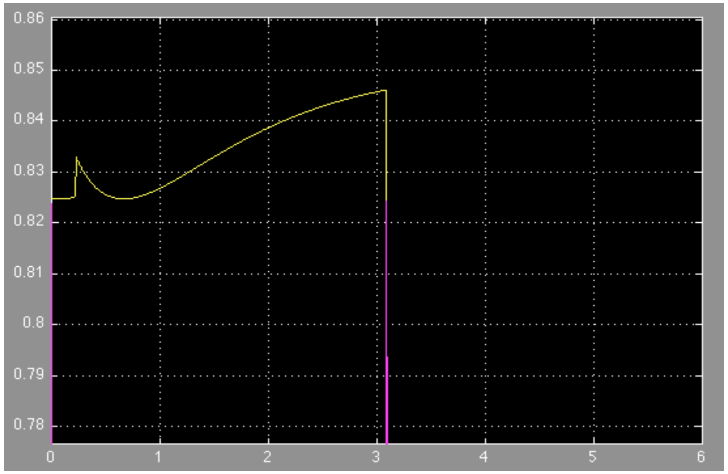
Feedforward

- ✓ 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
- ✓ Take an example for only-Lorentz detuning case in simulation

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







Adaptive Feedforward

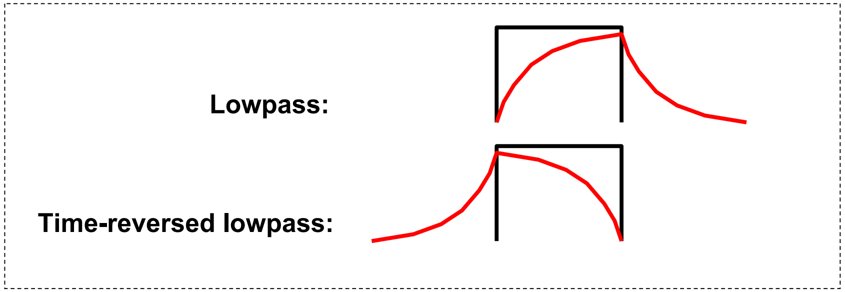
- However, there are some perturbation always going on, like temperature drift, operation condition changing…

- It is desirable to automatically update the feedforward table corresponding to the changes

- A possible scheme: take the current drive signal of the pulse as the feedforward input for the next pulse…

- Unfortunately, it is unstable (don't forget the overshoot from feedback)…

- Add a time-reversed low-pass filter



$FF_{new} = TRLP(FB_{last}) + FF_{last}$ *…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.

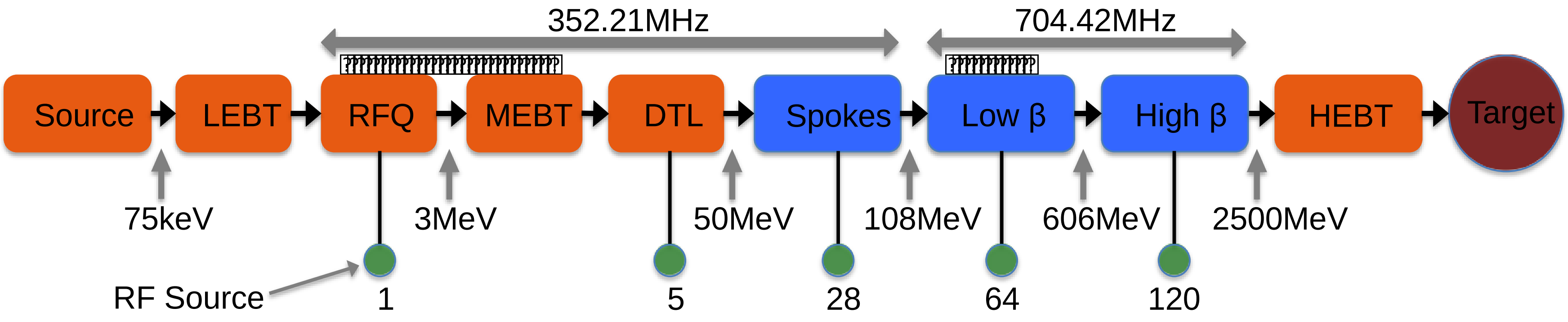
MPC and system identification

- ✓ The real world is still not good enough when there are some high frequency perturbations…
- ✓ Some advanced control methods: Model Predictive Control, System identification…
- ✓ Build mathematical models of the RF system based on measured data from the system(it might be a higher-order models, requiring large memory and calculations)
- ✓ Predict the future input of the system based on the mathematical model built and the output required.
- ✓ Develop costumed algorithm for particular perturbations
- ✓ …..

Further reading: S. Simrock, M. Grecki, 5th LC School, Switzerland, 2010, LLRF & HPRF.
J. Richalet, et, al. Model Predictive Heuristic Control: Applications to Industrial Processes, Automatica,Vol.14, 1978

Challenges of LLRF control at ESS

Challenges at ESS



- **More than 200 LLRF stations to be built by 2019 for RFQ, DTL, spoke and elliptical cavities . (One klystron for one cavity.)**
- **Multi-cavity control is also being considered.**
- **Many issues to be addressed**
- **Stringent demands from ESS leads to tough challenges**

Pulse length:
2.86 ms
Rep rate:
14 Hz
Current:
50mA

Issues to be addressed

Frequency Generation
1. Generation of required frequencies (RF, LO, IF, Clks)
2. Low phase noise

Phase Reference Distribution
1. Phase stable and low temperature coefficient cable or fiber
2. Phase drift control
3. Distribution of the frequencies at each LLRF station

Frequency Conversion
1. Down/up conversion
1. Selection of the IF and sampling rate
3. High isolation between channels
4. Low noise and phase drift!"#$%&#'!!

Diagnostics
1. Parameters calculation and monitoring (Q value, cavity detuning etc.)
2. Signals monitoring (power, vacuum, temperature etc.)
3. Faults fast detection, locating and analysis
4. Timing, logic, algorithm communication checking
5. Cavity simulator
6. Interlock

Cavity Field Control
1. Amplitude and phase setting
2. IQ detection
3. Feedback
4. Feed forward
5. Beam loading compensation
6. Klystron linearization
7. Fault avoidance, detection, recovery and tolerance
8. Beam based feedback

Cavity Resonance Control
1. Pre-detuning to compensate synchronous phase operation
2. Normal conducting cavity frequency control
3. Dynamic Lorentz force compensation
4. Microphonics control
!

Control System Sever
1. High degree of automation to enable easy operation, fast fault detection and recovery
2. Fast communication and high-speed data exchange
3. Powerful database to support fast detection and recovery and adaptive control
4. Interface to control system
5. Remote access/control

RF Control Hardware
1. Selection of FPGA/DSP, FLASH/SDRAM, fast and high resolution ADC, DAC
2. Boards with which interface to communication (VME, VXI, ATCA, PCI or Ethernet…?)
3. Hardware debug points
4. Hardware concerns: SNR (ADC nonlinearity, DC/DC convert noise, clock jitter, crosstalk) and temperature independency
'

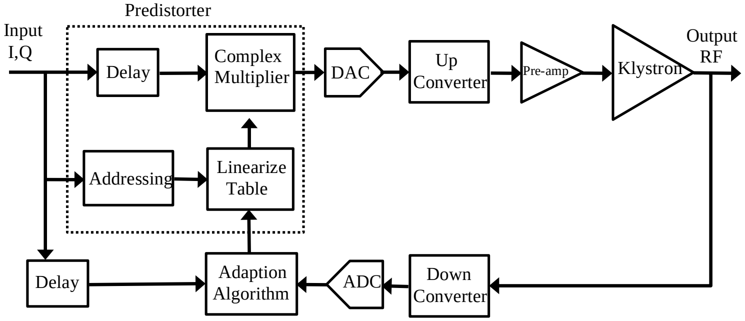
⇔

Host CPU

General purpose CPU or system on chip to implement the control server

Challenges at ESS

- ✓ High Efficiency
  - ✦ Klystron Linearization
  - ✦ Minimize power overhead.



- ✓ High availability 95%
  - ✦Avoid failures that cause the whole system to fail
  - ✦Redundancy
  - ✦Automatically detect
  - ✦Fast recovery

- ✓ Others
  - ✦ **High intensity**
  - ✦ **Long pulse**
  - ✦ **High gradient**
  - ✦ **Spoke cavity**

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, from outer the cavity (power supply, drive signal, the control crates) to inner the cavity (beam loading, Lorentz force detuning, microphonics)

- ✓ PI Feedback is an effective and classical way to deal with the perturbations but at the cost of the more overhead consumption for overshoot and at risk of rising instability.

- ✓ Feedforward is essential for the repetitive perturbations and need automatically update, meantime avoiding the instability caused by feedback…

- ✓ There are many issues to be addressed at ESS and also big challenges, we have to figure out the requirements for LLRF and find suitable solutions for ESS. We should look into more advanced control methods to be able to better complete the tasks

- ✓ At last, “A LLRF without feedback?”

Thank you for the attention!