Introduction to LLRF

OHO 高エネルギー加速器セミナー OHO'21

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Mathieu Omet

Disclaimer

- This lecture will give only a rough overview, it is incomplete by its nature

Contents

- Introduction
- Cavity theory
- LLRF system overview
- Signal sampling
- Digital signal processing and implementation
- Controller theory
- Example features of an LLRF system
- Summary

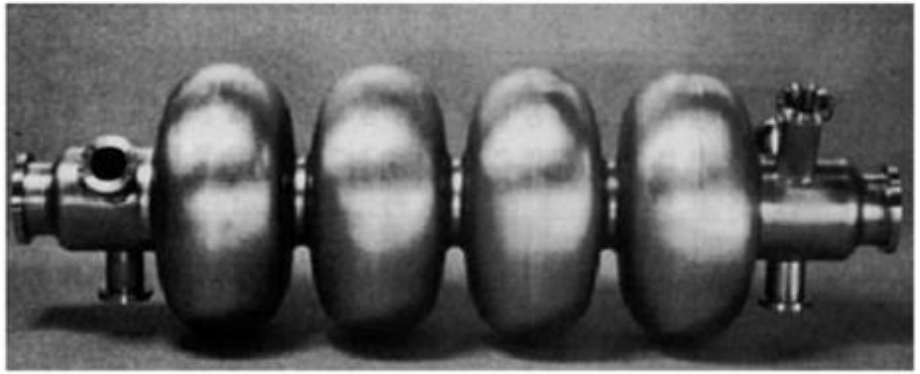
Introduction

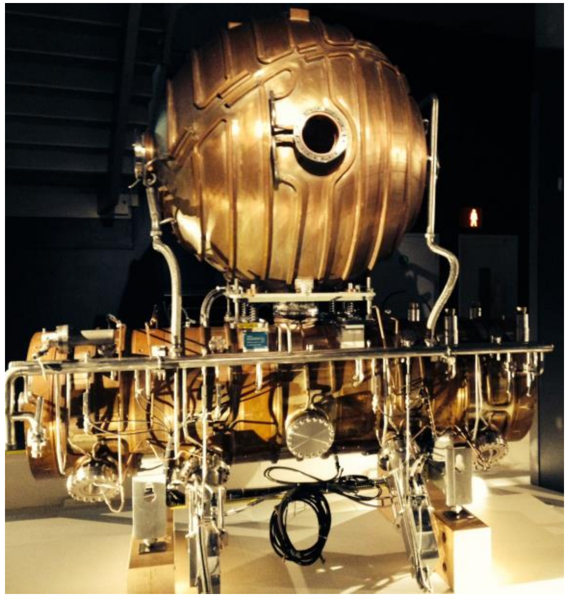
What does LLRF stand for?
What is it about?

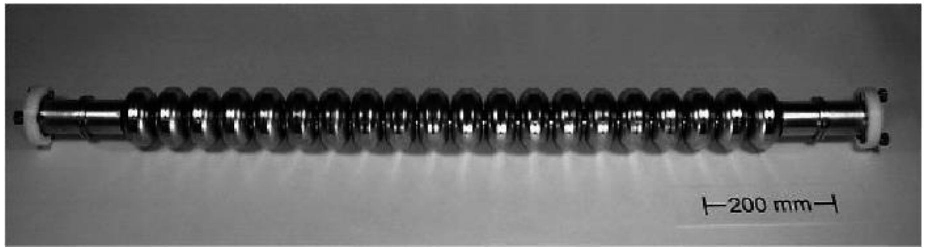
- Low Level Radio Frequency
- The goal: control the amplitude and phase of electro-magnetic fields within cavities
  - Required at a wide range of facilities, from small test facilities to large scale accelerators
- These fields can have high amplitudes and high frequencies
- Thus down-conversion to small amplitudes for detection is applied
  - (and in some cases also a down-conversion to low frequencies, while preserving amplitude and phase information, is applied)

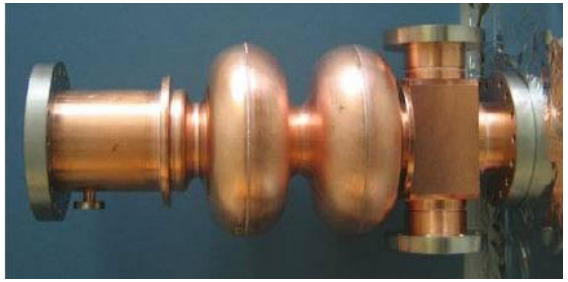
Superconducting and Normal Conducting Cavities

- Frequency ranges from MHz to tens of GHz



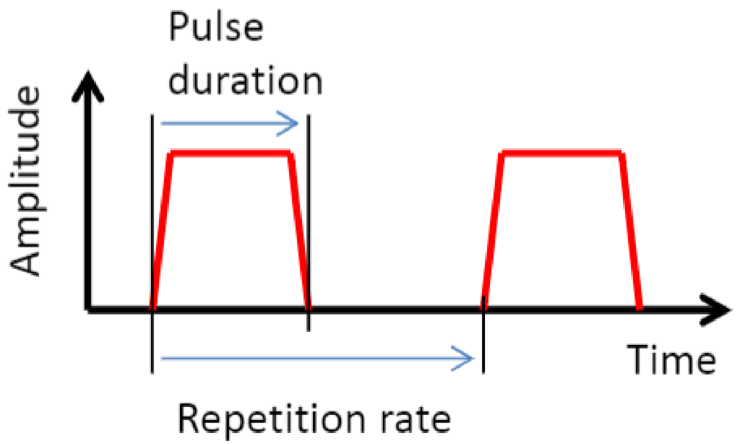




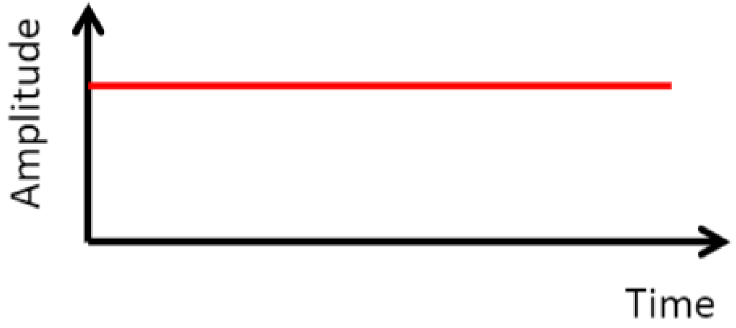


Modes of Operation

- Pulsed mode
  - Short Pulse mode (SP)
    - Duty factor of e.g. 1%
  - Long Pulse mode (LP)
    - Duty factor of 10% to 50%
  - Only a certain portion of time is useable for beam acceleration

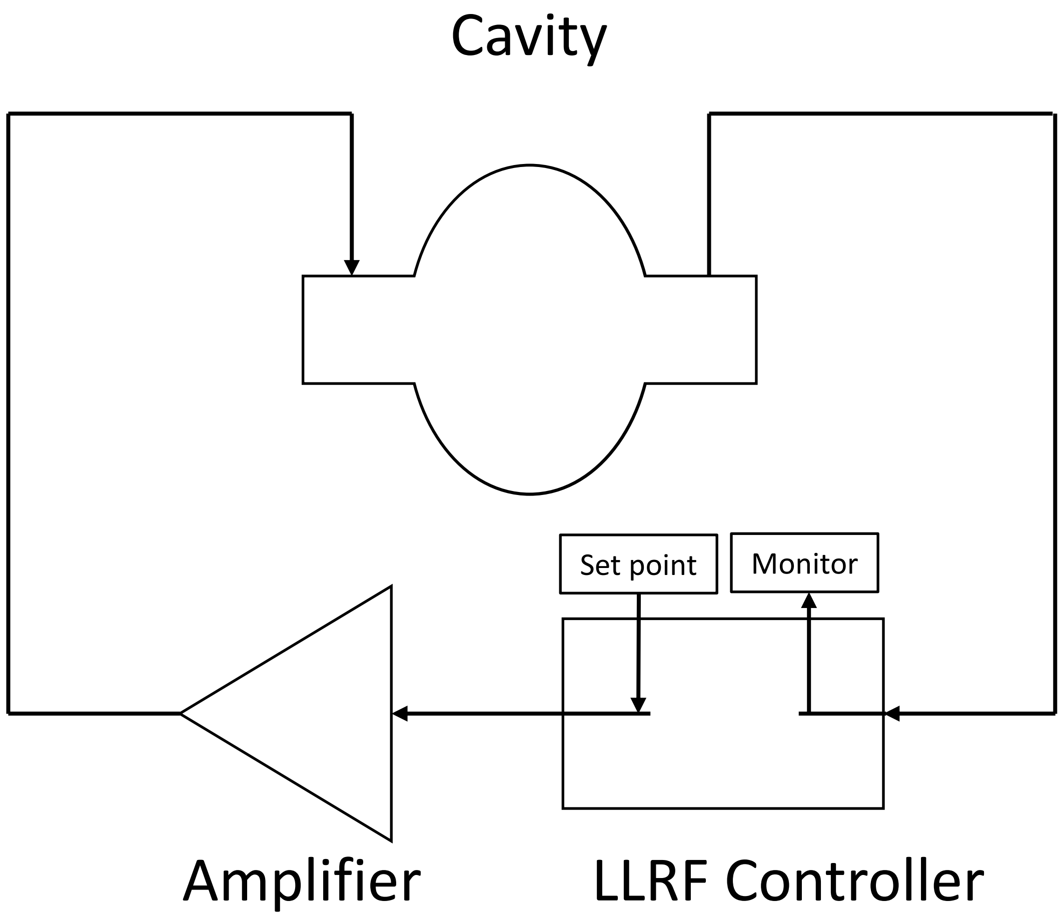


- Continuous Wave (CW)
  - Continuous RF field
  - Duty factor of 100%
  - Beam can be accelerated all the time



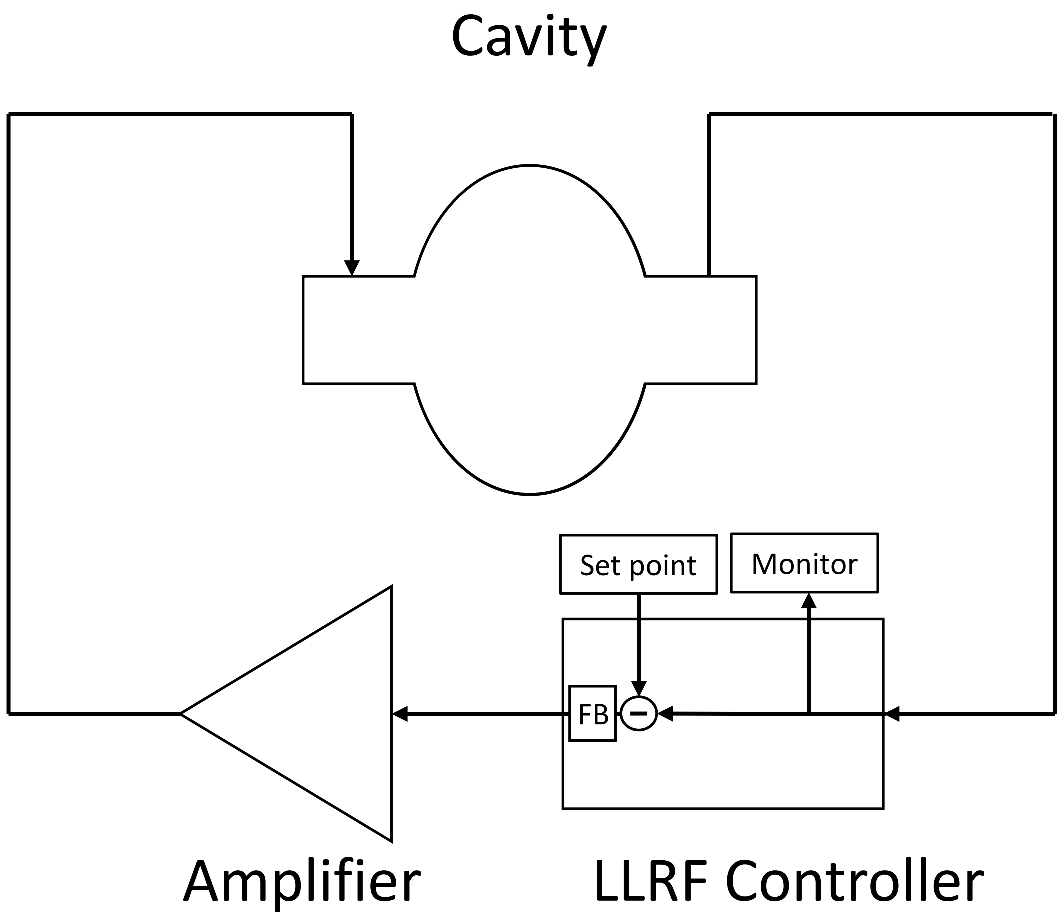
Most basic layout of an RF system

- Open loop operation
  - Controller creates drive signal corresponding to a set point
  - Signal is amplified
  - Signal is coupled into the cavity
  - Signal is coupled out of the cavity
  - Signal is detected by the controller



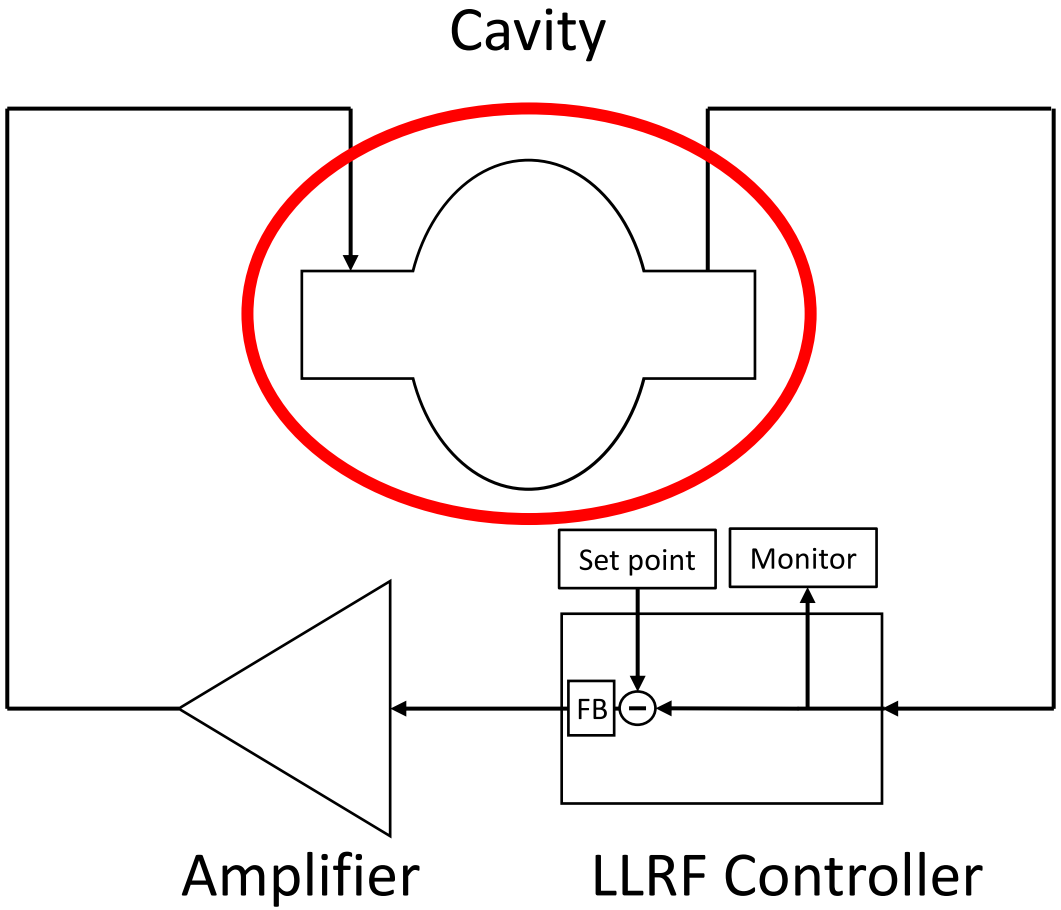
Most basic layout of an RF system

- Closed loop operation
  - Controller creates drive signal corresponding to a set point
  - Signal is amplified
  - Signal is coupled into the cavity
  - Signal is coupled out of the cavity
  - Signal is detected by the controller
  - Controller compares signal to the set point and adjusts the drive signal accordingly



Most basic layout of an RF system

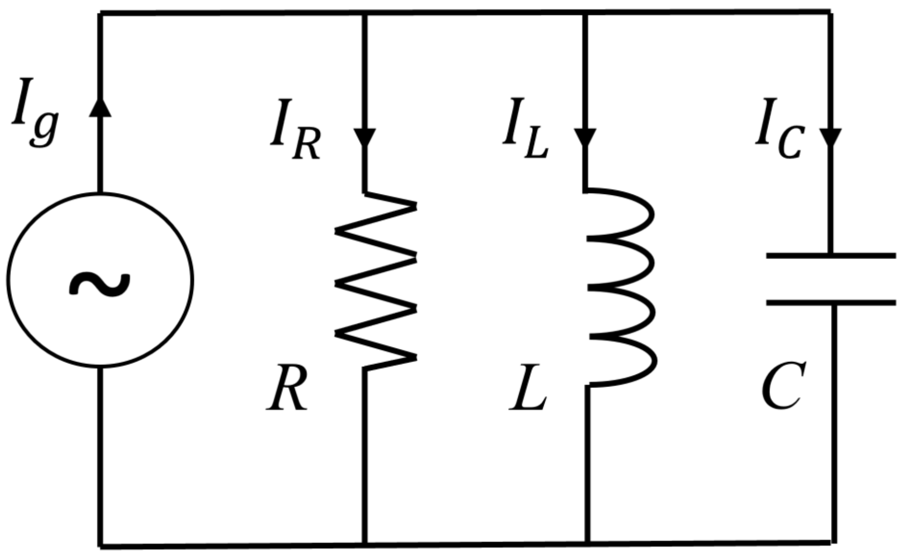
- Let's take a look at the cavity first



Cavity Theory

Cavity modeling: RCL model

- Electric circuit
  - Resistor R
  - Inductor L
  - Capacitor C
- Forms a harmonic oscillator



Cavity modeling: Quality factor in general

Resonance frequency

Stored energy

$$Q = 2\pi \frac{\text{stored energy in cavity}}{\text{dissipated energy per cycle}} = \frac{2\pi f_0 W}{P_{diss}}$$

Dissipated power

Cavity modeling: Unloaded quality factor

- Assumes losses only due to surface resistance

Capacitance — Square of amplitude of oscillating voltage

$$Q_0 = \frac{2\pi}{T} \cdot \frac{\frac{1}{2} C V_0^2}{\frac{1}{2} \frac{V_0^2}{R}}$$

Time period of an RF cycle — Resistance

$$Q_0 = \omega_0 R C = \frac{R}{L\omega_0} = \frac{\omega_0 W}{P_{diss}}$$

$$W = \frac{1}{2} C V_0^2$$

$$P_{diss} = \frac{V_0^2}{2R}$$

$$\omega_0 = \frac{1}{\sqrt{LC}}$$

$$\omega_0 = 2\pi f_0$$

Cavity modeling: External quality factor

- Accounts for external losses (e.g. via the power coupler)

$$Q_{ext} = 2\pi \frac{\text{stored energy in cavity}}{\text{dissipated energy in external devices per cycle}} = \frac{\omega_0 W}{P_{ext}}$$

Dissipated power in all external devices

Cavity modeling: Loaded quality factor

- Accounts for all losses

$$Q_L = 2\pi \frac{\text{stored energy in cavity}}{\text{total energy loss per cycle}} = \frac{\omega_0 W}{P_{tot}}$$

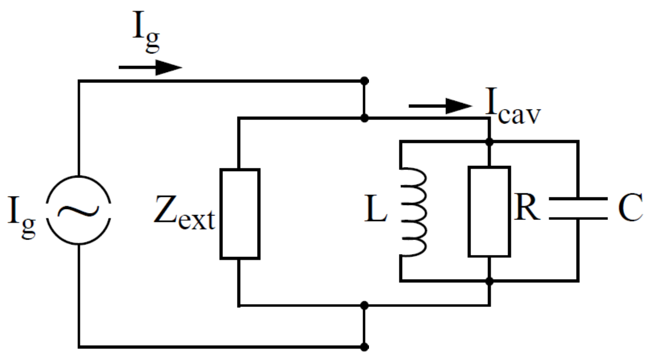
$$P_{tot} = P_{diss} + P_{ext}$$

$$\frac{1}{Q_L} = \frac{1}{Q_0} + \frac{1}{Q_{ext}}$$

In case of SC cavities Q_0 is several orders of magnitude larger than Q_{ext}. Thus, Q_L is in the same order as Q_{ext}.

Cavity modeling:
Definition of the Loaded Quality Factor

- Add transition line
- Impedance Z_{ext} is like a parallel resistor to R (characteristic impedance of a coaxial cable: 50 Ω)
- Both can be replaced by the loaded shunt impedance R_L



$$\frac{1}{R_L} = \frac{1}{R} + \frac{1}{Z_{ext}}$$

$$Q_0 = \omega_0 RC = \frac{R}{L\omega_0} = \frac{\omega_0 W}{P_{diss}}$$

$$\frac{R}{Q_0} = \omega_0 = \frac{1}{\omega_0 C} = \sqrt{\frac{L}{C}}$$

R/Q_0 depends only on ω_0, C, and L, which means it depends only on the cavity geometry and not the surface resistance.

Cavity modeling: Definition of the Loaded Quality Factor

- The shunt impedance R_{sh} depends on the dissipated power
- Includes factor ½ of the time average

$$P_{diss} = \frac{1}{2} \cdot \frac{V_{cav}^2}{R} = \frac{V_{cav}^2}{R_{sh}}$$

$$R = \frac{1}{2} R_{sh} = \frac{1}{2} \frac{r}{Q} Q_0$$

- Definition of normalized shunt impedance

$$\frac{r}{Q} := \frac{R_{sh}}{Q_0} = \frac{2R}{Q_0}$$

Cavity modeling: Definition of the Loaded Quality Factor

- Coupling between cavity and transmission line

$$\beta = \frac{R}{Z_{ext}}$$

$$\frac{1}{R_L} = \frac{1}{R} + \frac{1}{Z_{ext}}$$

$$R_L = \frac{R}{1+\beta}$$

$$\frac{r}{Q} := \frac{R_{sh}}{Q_0} = \frac{2R}{Q_0}$$

$$Q_L = \frac{Q_0}{1+\beta}$$

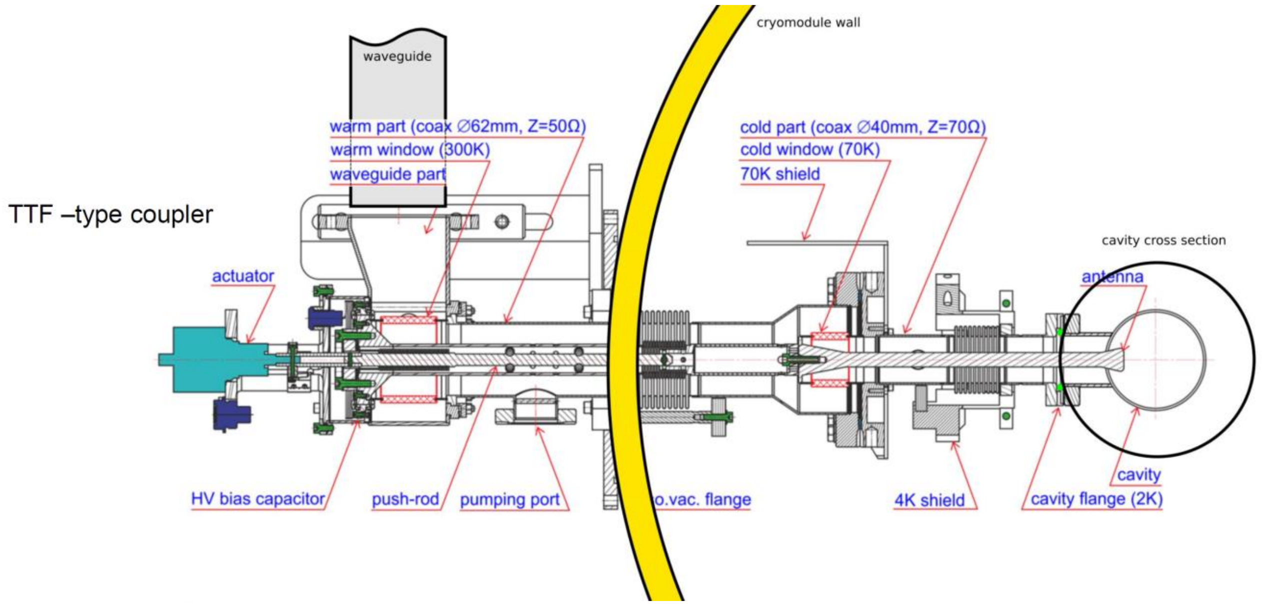
$$\omega_{1/2} = \frac{\omega_0}{2Q_L}$$

Q_L can be manipulated by changing the coupling β

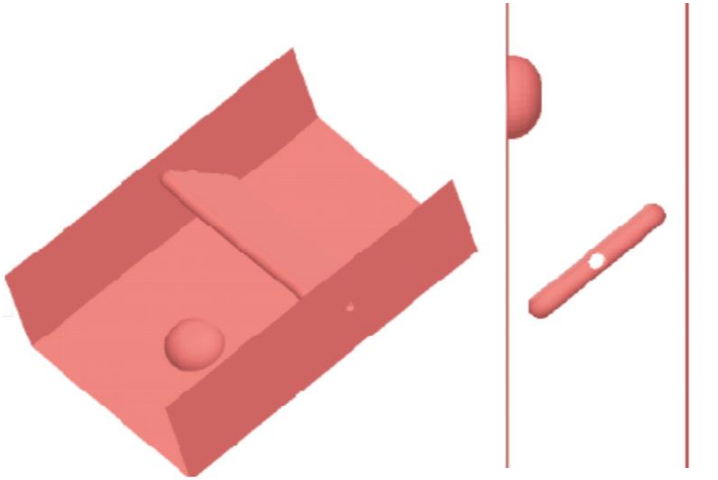
And with this the cavity bandwidth

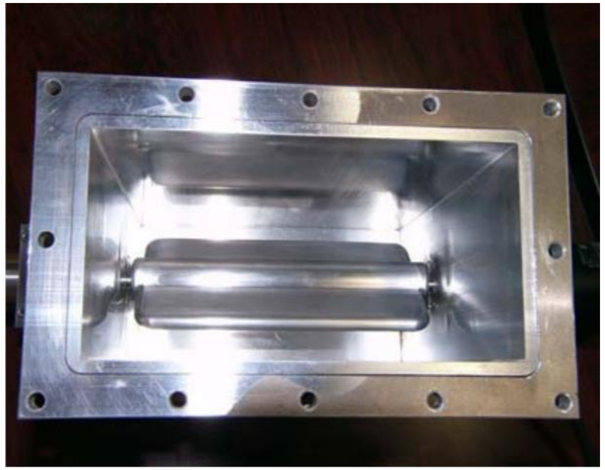
Solutions for Changing the Coupling

- Change input depth via movable input coupler antenna



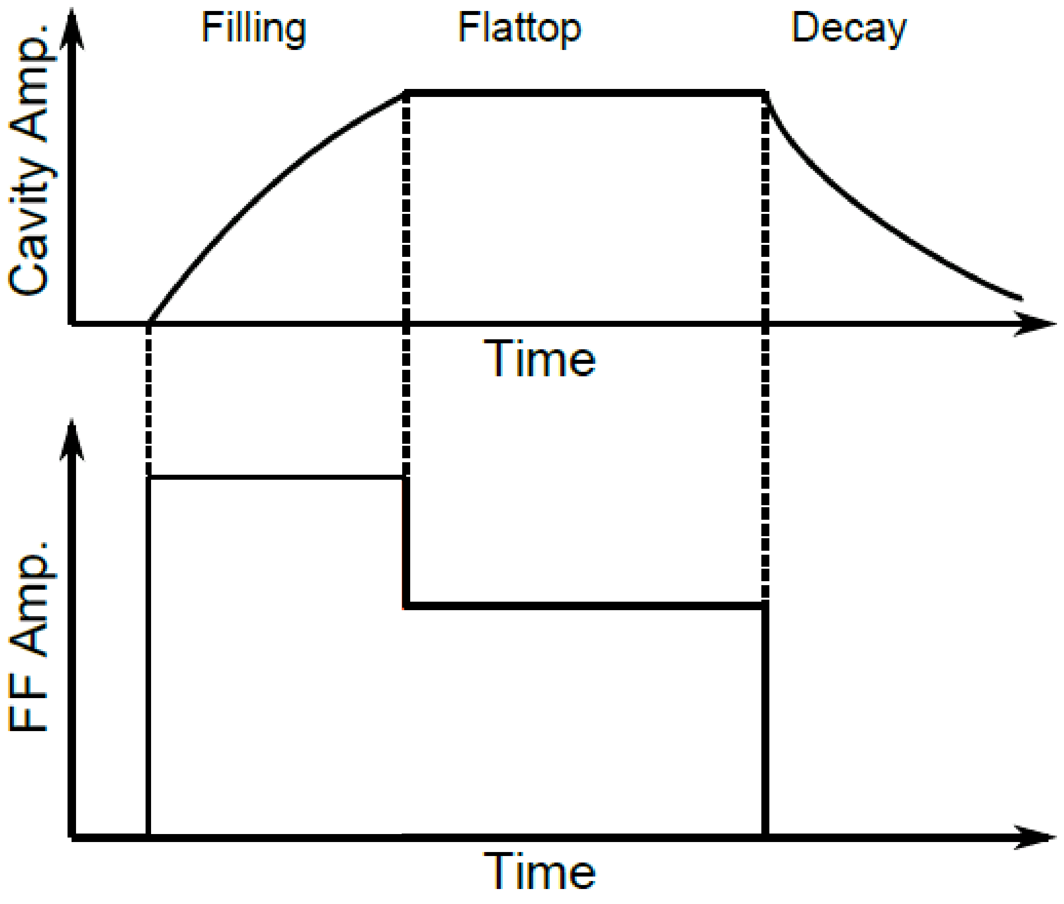
- Change angle of plate of waveguide reflector



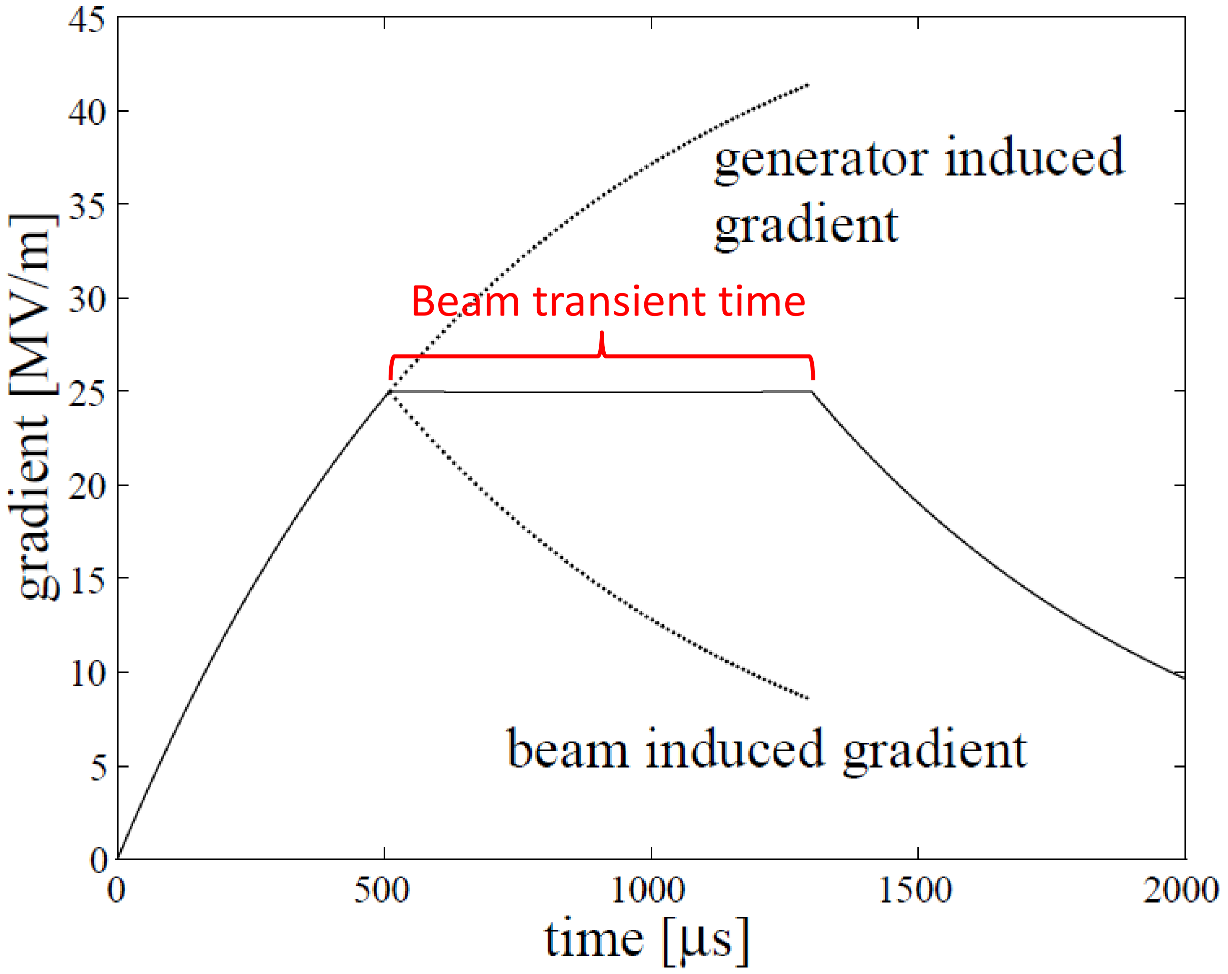


Pulsed Operation with Beam Loading

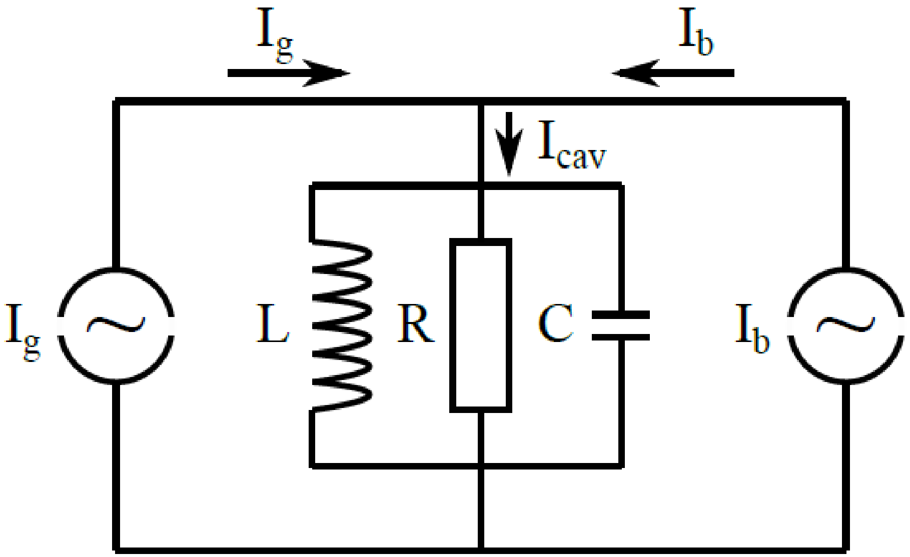
- Without beam



- With beam



Derivation of Filling and Flattop Powers



$$I_C + I_R + I_L = I_{cav}$$

$$\dot{I}_C + \dot{I}_R + \dot{I}_L = \dot{I}_{cav}$$

$$\begin{aligned} \dot{I}_C &= C\ddot{V}_{cav} \\ \dot{I}_R &= \frac{1}{R_L}\dot{V}_{cav} \\ \dot{I}_L &= \frac{1}{L}V_{cav} \end{aligned}$$

$$C\ddot{V}_{cav} + \frac{1}{R_L}\dot{V}_{cav} + \frac{1}{L}V_{cav} = \dot{I}_{cav}$$

Derivation of Filling and Flattop Powers

$$\ddot{V}_{cav} + \frac{1}{R_L C}\dot{V}_{cav} + \frac{1}{LC}V_{cav} = \frac{1}{C}\dot{I}_{cav}$$

$$\frac{1}{R_L C} = \frac{\omega_0}{Q_L}$$

$$\frac{1}{LC} = \omega_0^2$$

$$\ddot{V}_{cav} + \frac{\omega_0}{Q_L}\dot{V}_{cav} + \omega_0^2 V_{cav} = \frac{1}{C}I_{cav}$$

$$V_{\text{hom}} = e^{-\frac{\omega_0 t}{2Q_L}}\left(C_1 e^{i\alpha t} + C_2 e^{-i\alpha t}\right)$$

$$\alpha = \omega_0\sqrt{1 - \frac{1}{4Q_L^2}}$$

One particular solution can be found with

$$I_{cav} = \hat{I}e^{i\omega t}$$

$$V_{cav} = \hat{V}e^{i(\omega t+\phi)}$$

Φ is the angle between the generator current and the resonator voltage

Derivation of Filling and Flattop Powers

$$V_{\text{par}} = \frac{R_L \hat{I} e^{i(\omega t + \phi)}}{\sqrt{1 + \tan^2 \phi}}$$

with $\tan \phi = R\left(\frac{1}{\omega L} - \omega C\right) = Q\left(\frac{\omega}{\omega_0} - \frac{\omega_0}{\omega}\right)$

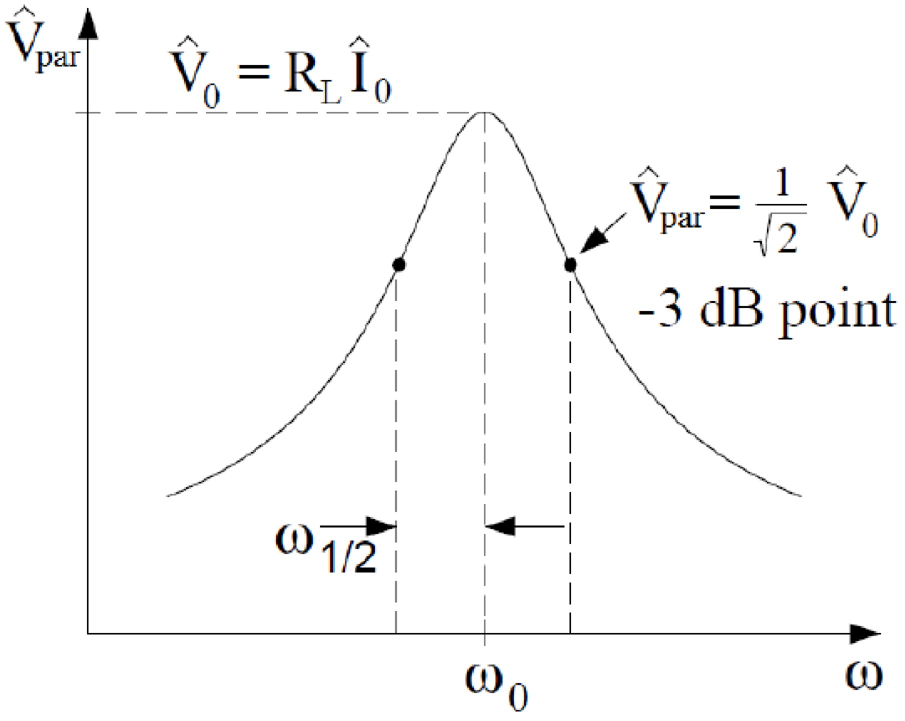
The particular solution is also called a stationary solution. If the generator frequency ω is very close to the resonance frequency ω_0, the following approximation can be done:

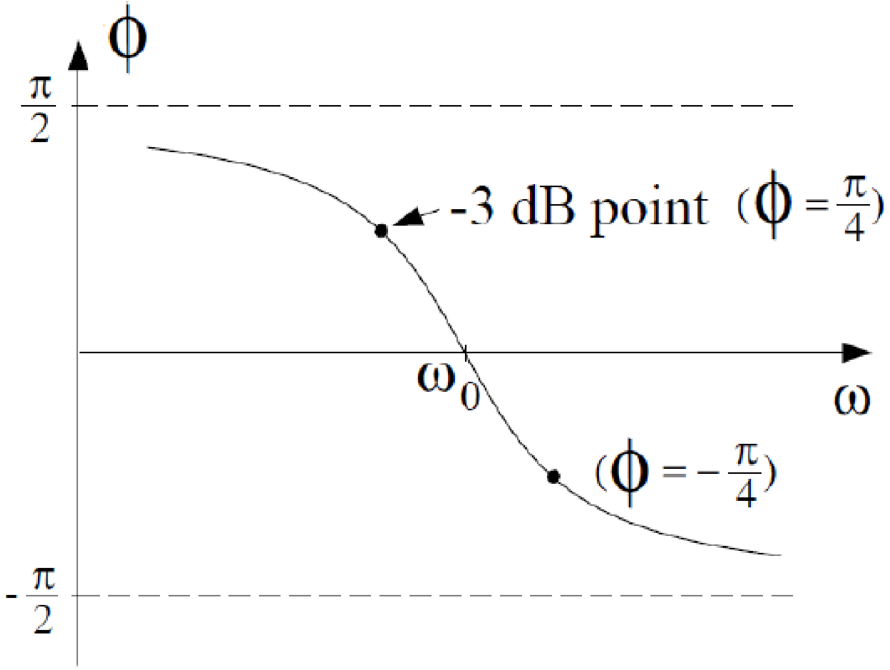
$$\hat{V}_{\text{par}}(\Delta\omega) \approx \frac{R_L \hat{I}}{\sqrt{1 + \left(2 Q_L \frac{\Delta\omega}{\omega}\right)}}$$

where $\Delta\omega = \omega_0 - \omega$

Derivation of Filling and Flattop Powers

The frequency dependency of the amplitude is known as the Lorentz curve





Bandwidth of the cavity is defined by the -3 dB point

Derivation of Filling and Flattop Powers

The general solution is:

$$V_{cav} = V_{\text{hom}} + V_{\text{par}} = e^{-\frac{\omega_0 t}{2Q_L}} \left(C_1 e^{i\alpha t} + C_2 e^{-i\alpha t}\right) + \frac{R_L \hat{I} e^{i(\omega t - \phi)}}{\sqrt{1 + \tan^2 \phi}}$$

since $Q_L >> 1$ One can approximate: $\alpha \approx \omega_0$

for $C_1 = C_2 = -\frac{R_L \hat{I}}{2}$

$$V_{\text{fill}} = V_0 \left(1 - e^{-\frac{t}{\tau}}\right)$$

with $V_0 = R_L \hat{I} \approx 2 R_L I_g = \frac{r}{Q} Q_L I_g$ $\tau = \frac{2Q_L}{\omega_0}$

$\hat{I}$ represents an AC current

I_g represents a DC current

$$\hat{I} \approx 2I_g$$

$$\hat{I}_b \approx 2I_{b0}$$

$$I_{cav} = 2I_g - 2I_{b0}$$

$$V_{\text{flat}} = \frac{r}{Q} Q_L \left(I_g \left(1 - e^{-\frac{t}{\tau}}\right) - I_{b0} \cos(\phi_b) \left(1 - e^{-\frac{t - T_{\text{inj}}}{\tau}}\right)\right)$$

Derivation of Filling and Flattop Powers

$$\frac{\mathrm{d}V_{\mathrm{flat}}}{\mathrm{d}t} = 0$$

We would like to have a constant voltage over the flattop

$$\frac{d}{dt}\frac{r}{Q}Q_L\left(I_g\left(1-e^{-\frac{t}{\tau}}\right)-I_{b0}\left(1-e^{-\frac{t-T_{inj}}{\tau}}\right)\right)=0$$

$$\frac{d}{dt}\frac{r}{Q}Q_L\left(I_g-I_g e^{-\frac{t}{\tau}}-I_{b0}+I_{b0}e^{-\frac{t-T_{inj}}{\tau}}\right)=0$$

$$\frac{r}{Q}Q_L\left(I_g\frac{1}{\tau}e^{-\frac{t}{\tau}}-I_{b0}\frac{1}{\tau}e^{-\frac{t-T_{inj}}{\tau}}\right)=0$$

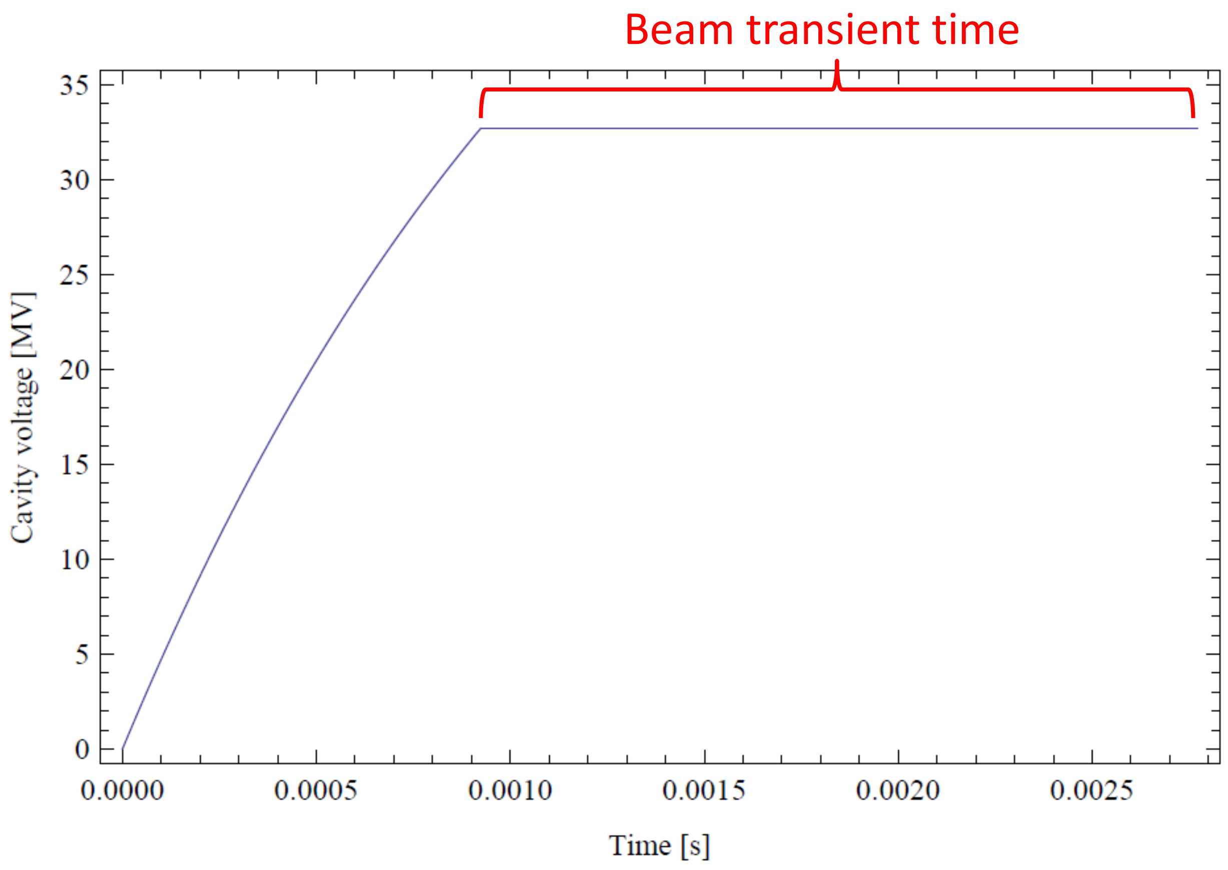
$$I_g e^{-\frac{t}{\tau}} = I_{b0}e^{-\frac{t-T_{inj}}{\tau}}$$

$$I_g = I_{b0}e^{\frac{T_{inj}}{\tau}}$$

Derivation of Filling and Flattop Powers

$$V_{\text{fill}} = V_0 \left(1 - e^{-\frac{t}{\tau}}\right)$$

$$V_{\text{flat}} = \frac{r}{Q} Q_L I_{b0} \left(e^{\frac{T_{\text{inj}}\omega_0}{2Q_L}} - 1\right)$$



Parameter	Value
Filling time	923 µs
Beam current	5.8 mA
Q_L	5.44E6

Derivation of Filling and Flattop Powers

$$P = \frac{1}{4}\frac{r}{Q}Q_L I_g^2$$

$$P_{\text{fill}} = \frac{V_{cav}^2}{4\frac{r}{Q}Q_L\left(1 - e^{-\frac{T_{\text{inj}}\omega_0}{2Q_L}}\right)^2}$$

$$V_{cav} = 31.5\ \text{MV/m} \cdot 1.038\ \text{m} = 32.7\ \text{MV}$$
$$Q_L = 5.44 \cdot 10^6$$
$$T_{inj} = 923\ \mu\text{s}$$

P_{fill} is 190 kW

$$P_{flat} = \frac{V_{cav}^2}{4\frac{r}{Q}Q_L}\left(1 + \frac{\frac{r}{Q}Q_L I_{b0}}{V_{cav}}\right)^2$$

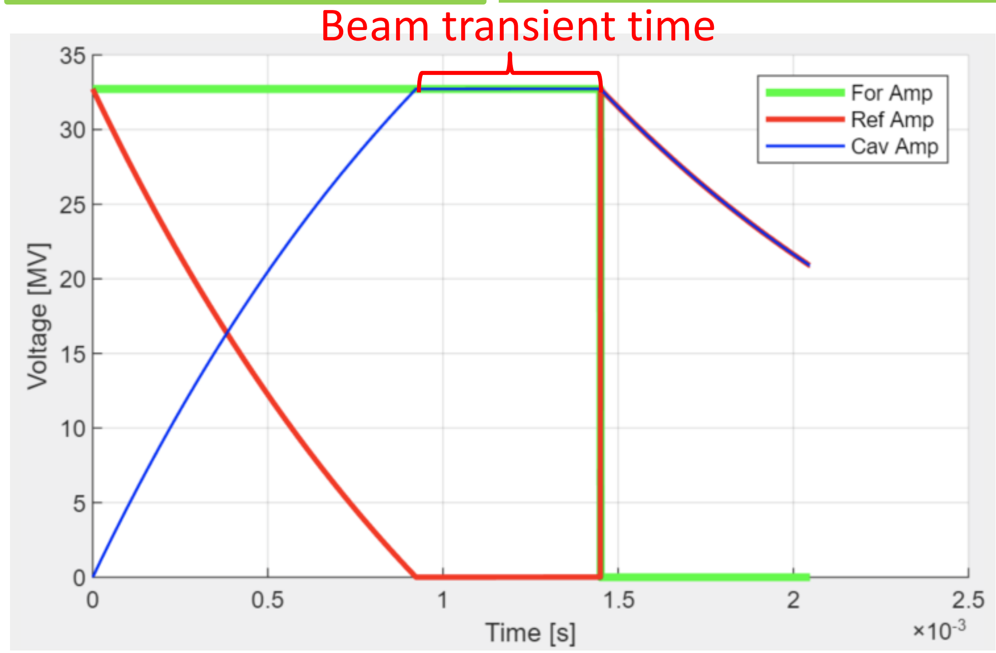
$I_{b0} = 5.8$ mA $\qquad \phi_b = 180°$

P_{flat} is 190 kW

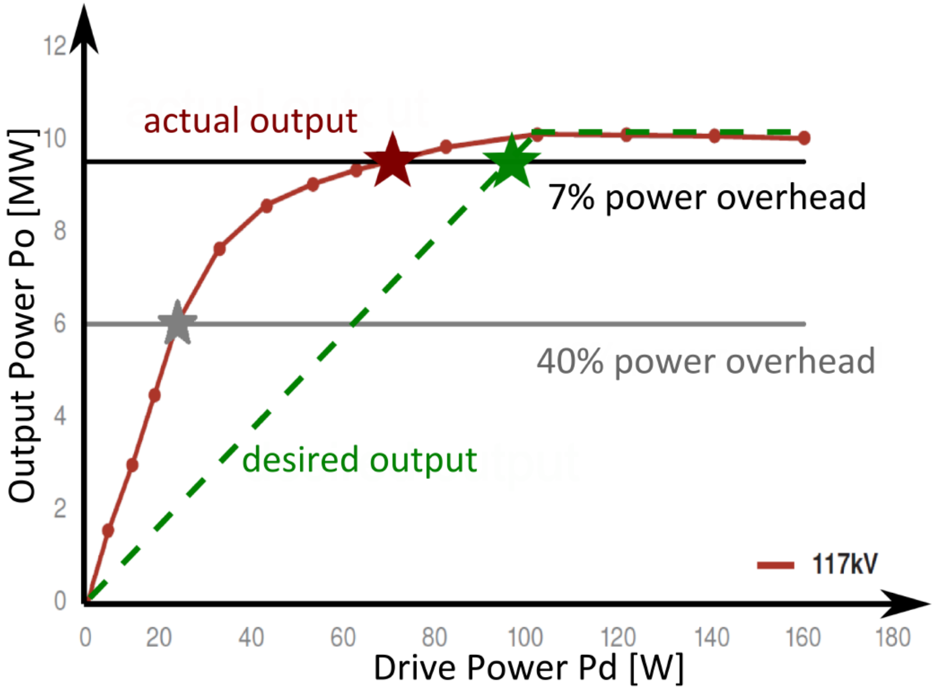
Derivation of Filling and Flattop Powers

- One can stay at a single working point of the power amplifier throughout the whole RF pulse

P_{fill} is 190 kW P_{flat} is 190 kW



Non-linear behavior of a klystron (red curve)



Derivation of Filling and Flattop Powers

- Set of equations for finding optimal parameters

The optimal coupling β_{opt}

$$\beta_{opt} = 1 + \frac{\frac{r}{Q} Q_0 I_{b0}}{V_{cav}} \cos(\phi_b)$$

Minimum power for maintaining the cavity voltage

$$P_{min} = \beta_{opt} \frac{V_{cav}^2}{\frac{r}{Q} Q_0}$$

Optimum tuning angle

$$\tan(\phi_{opt}) = -\frac{\frac{r}{Q} Q_{L,opt} I_{b0}}{V_{cav}} \sin(\phi_b)$$

For superconducting cavities one can simplify

$$Q_{L,opt} = \frac{V_{cav}}{\frac{r}{Q} I_{b0} \cos(\phi_b)}$$

$$\phi_{opt} = -\phi_b$$

$$P_{flat,min} = \frac{V_{cav}^2}{\frac{r}{Q} Q_{L,opt}} = V_{cav} I_{b0} \cos(\phi_b)$$

Example set of parameter

$$V_{cav} = 31.5 \text{ MV/m} \cdot 1.038 \text{ m} = 32.7 \text{ MV}$$

$$I_{b0} = 5.8 \text{ mA}$$

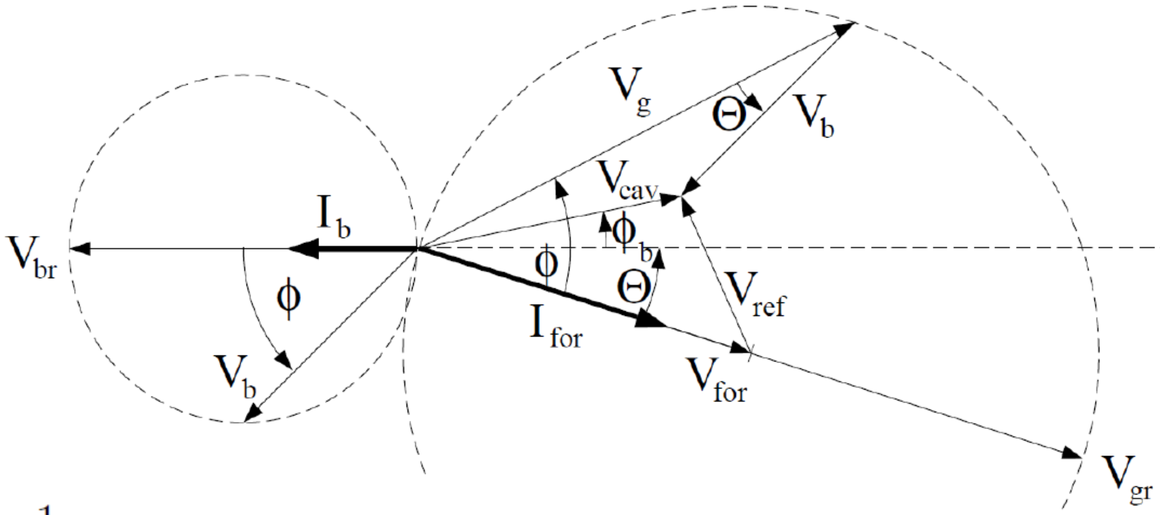
$$\cos(\phi_b) = 1$$

$$Q_{L,opt} = 5.44 \cdot 10^6$$

$$P_{flat,min} = 190 \text{ kW}$$

Detuned Cavity with Beam Loading

In reality cavities are detuned by the tuning angle Φ. The sources are Lorentz force detuning and microphonics.



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

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

$$V_{cav} = \frac{1}{2}\frac{1}{1+\tan^2(\phi)}(1+i\tan(\phi))\frac{r}{Q}Q_L(2I_g + 2I_{b0})$$

$$V_g = \frac{1}{\sqrt{1+\tan^2(\phi)}}(1+i\tan(\phi))\frac{r}{Q}Q_L I_g = \cos(\phi)e^{i\phi}\frac{r}{Q}Q_L I_g$$

$$V_b = \frac{1}{2}\frac{1}{1+\tan^2(\phi)}(1+i\tan(\phi))\frac{r}{Q}Q_L I_{b0} = \frac{1}{2}\cos(\phi)e^{i\phi}\frac{r}{Q}Q_L I_{b0}$$

Cavity Differential Equation Continues in Time

Differential equation for a driven LCR circuit

$$\ddot{\mathbf{V}}(t) + \frac{\omega_0}{Q_L}\dot{\mathbf{V}}(t) + \omega_0^2\mathbf{V}(t) = \frac{\omega_0 R_L}{Q_L}\dot{\mathbf{I}}(t)$$

$\frac{\omega_0}{Q_L} \ll \omega_0$ The cavity is a weakly damped system

$\omega_{res} = \omega_0$ good approximation, since $\omega_{res} = \omega_0 \sqrt{1 - \frac{1}{4Q_L^2}} \approx \omega_0$

Driving current I_g and Fourier component I_b of pulsed beam are harmonic with time dependence $e^{i\omega t}$.
Therefore, we separate the fast RF oscillation from the real and imaginary parts of the field vector.

$$\mathbf{V}(t) = (V_r(t) + iV_i(t)) \cdot e^{i\omega t}$$
$$\mathbf{I}(t) = (I_r(t) + iI_i(t)) \cdot e^{i\omega t}$$

Insertion in equation above and omission of the second-order time derivatives of V yields…

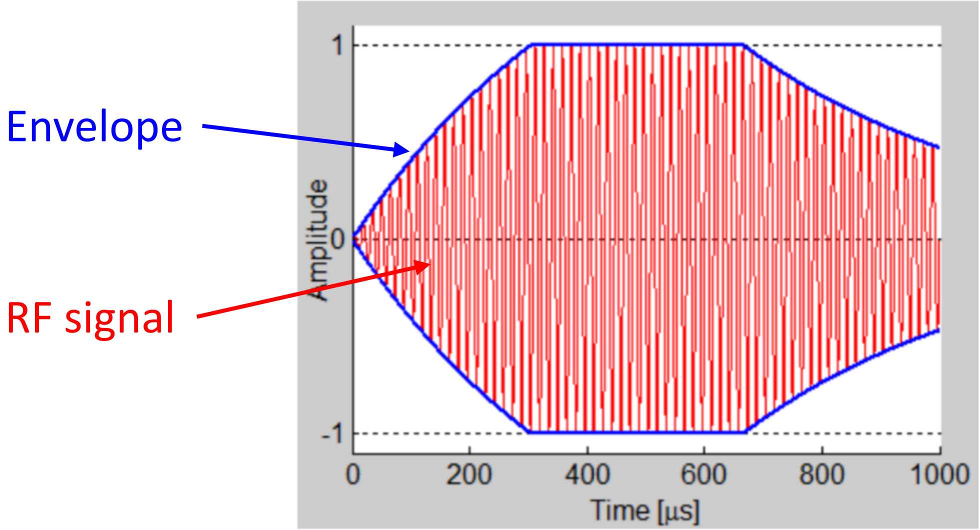
Cavity Differential Equation Continues in Time

… the first-order differential equation for the envelope:

$$\dot{V}_r + \omega_{1/2} V_r + \Delta\omega\, V_i = R_L\, \omega_{1/2}\, I_r$$
$$\dot{V}_i + \omega_{1/2} V_i - \Delta\omega\, V_r = R_L\, \omega_{1/2}\, I_i$$

with $\omega_{1/2} = \frac{\omega_0}{2Q_L}$ cavity bandwidth

$\Delta\omega = \omega_0 - \omega$ cavity detuning



In state space formalism

$$\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix} V_r \\ V_i \end{pmatrix} = \begin{pmatrix} -\omega_{1/2} & -\Delta\omega \\ \Delta\omega & -\omega_{1/2} \end{pmatrix} \cdot \begin{pmatrix} V_r \\ V_i \end{pmatrix} + \begin{pmatrix} R_L\omega_{1/2} & 0 \\ 0 & R_L\omega_{1/2} \end{pmatrix} \cdot \begin{pmatrix} I_r \\ I_i \end{pmatrix}$$

$$\dot{x}(t) = \mathbf{A} \cdot x(t) + \mathbf{B} \cdot u(t)$$

$$\mathbf{A} = \begin{pmatrix} -\omega_{1/2} & -\Delta\omega \\ \Delta\omega & -\omega_{1/2} \end{pmatrix}$$
$$\mathbf{B} = \begin{pmatrix} R_L\omega_{1/2} & 0 \\ 0 & R_L\omega_{1/2} \end{pmatrix}$$
$$x = \begin{pmatrix} V_r \\ V_i \end{pmatrix}$$
$$u = \begin{pmatrix} I_r \\ I_i \end{pmatrix}$$

Cavity Differential Equation Continuous and Discreate in Time

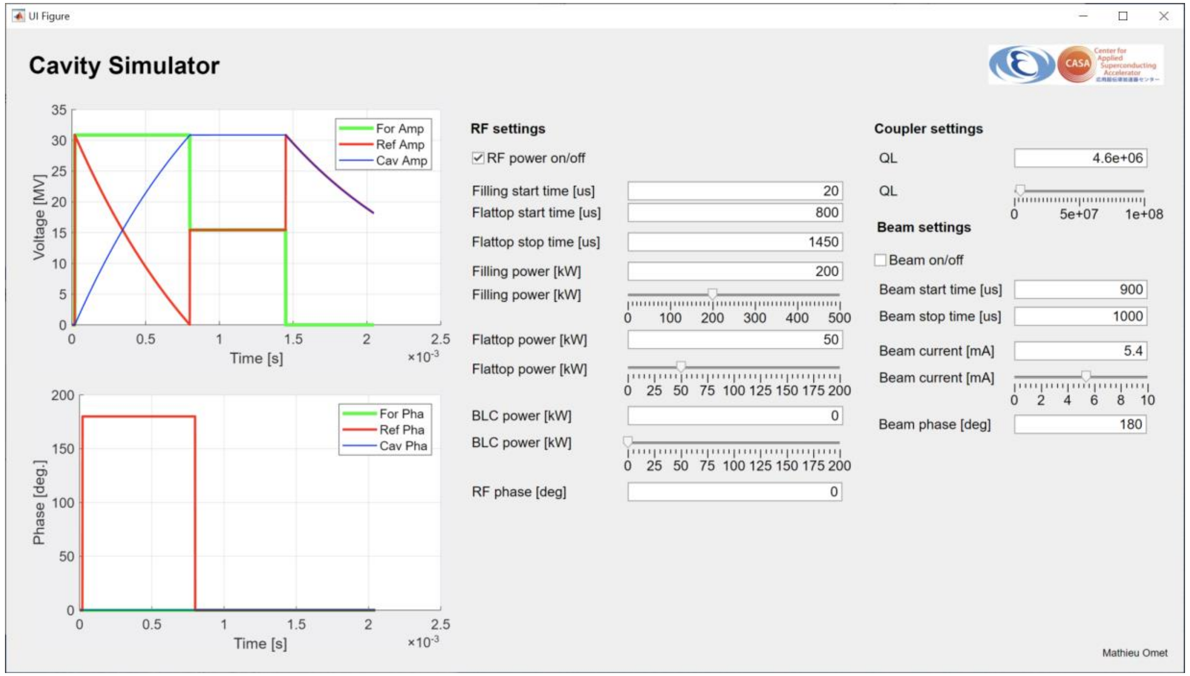
$$\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix} V_r \\ V_i \end{pmatrix} = \begin{pmatrix} -\omega_{1/2} & -\Delta\omega \\ \Delta\omega & -\omega_{1/2} \end{pmatrix} \cdot \begin{pmatrix} V_r \\ V_i \end{pmatrix} + \begin{pmatrix} R_L\omega_{1/2} & 0 \\ 0 & R_L\omega_{1/2} \end{pmatrix} \cdot \begin{pmatrix} I_r \\ I_i \end{pmatrix}$$

$$\begin{bmatrix} V_{i,n} \\ V_{q,n} \end{bmatrix} = \begin{bmatrix} 1 - T\omega_{1/2} & -T\Delta\omega \\ T\Delta\omega & 1 - T\omega_{1/2} \end{bmatrix} \begin{bmatrix} V_{i,n-1} \\ V_{q,n-1} \end{bmatrix} + T\omega_{1/2}R_L \begin{bmatrix} I_{i,n-1} \\ I_{q,n-1} \end{bmatrix}$$

Cavity Simulator Live Demo

- Demo of single cavity in pulsed operation
  - E.g., let's check the parameter set we have derived earlier

$$V_{cav} = 31.5\ \mathrm{MV/m} \cdot 1.038\ \mathrm{m} = 32.7\ \mathrm{MV}$$
$$I_{b0} = 5.8\ \mathrm{mA}$$
$$\cos(\phi_b) = 1$$
$$Q_{L,opt} = 5.44 \cdot 10^6$$
$$P_{flat,min} = 190\ \mathrm{kW}$$
$$T_{inj} = 923\ \mu\mathrm{s}$$



  - Let's see for what kind of operation low and high Q_L values are interesting

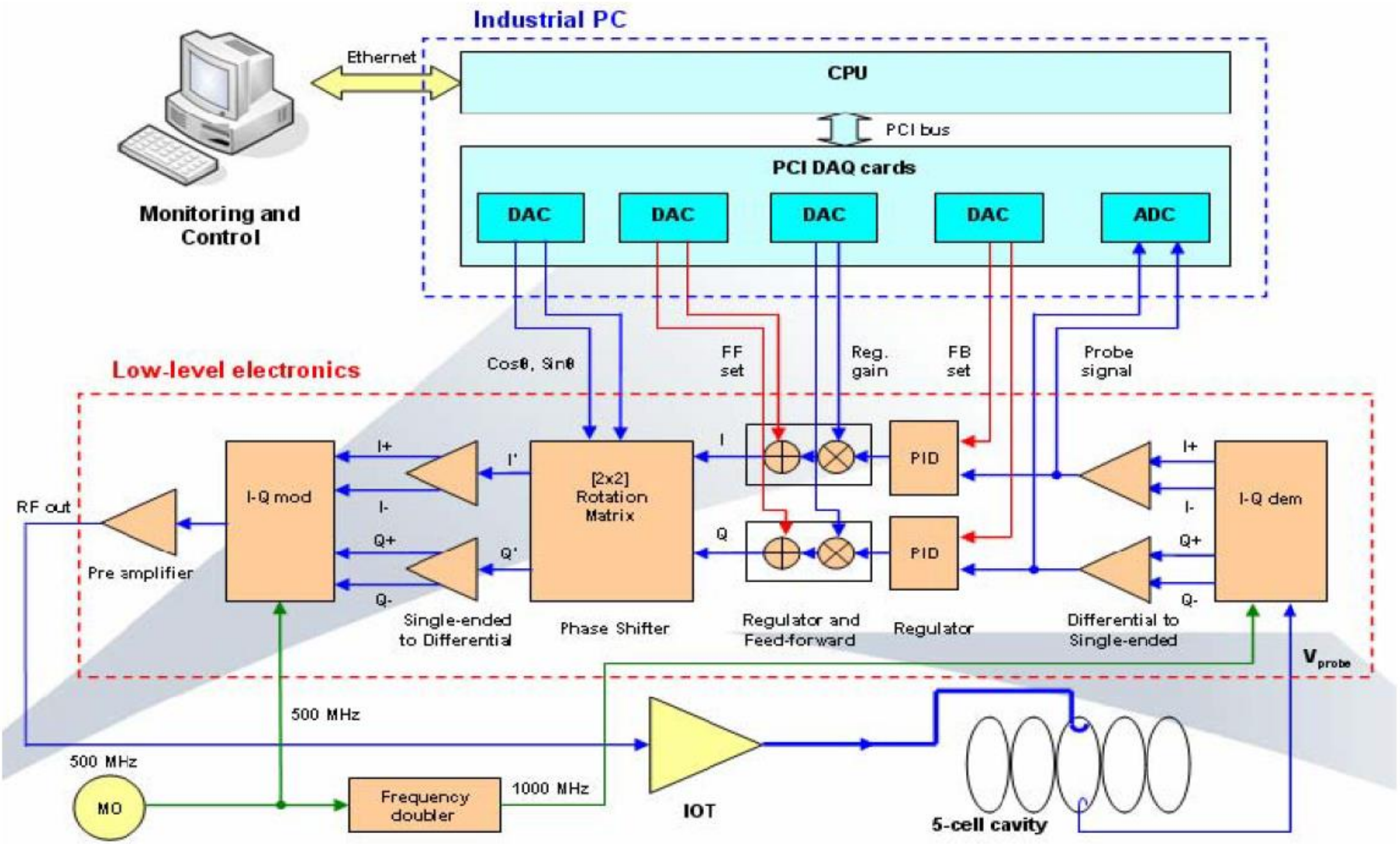
LLRF Systems

Types of LLRF Systems

- Analog
  - Designed, optimized and built for a specific purpose
  - Hard to modify
  - Need extra hardware for e.g. data recording

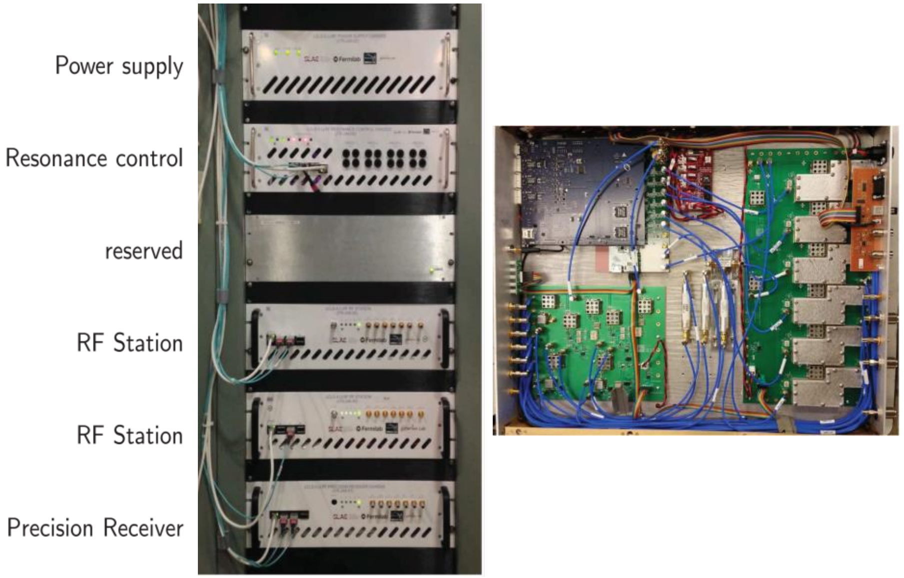
- Digital
  - More flexibility
    - On how to design the system
    - Always possible to add, change, tweak digital algorithms
  - Modern algorithms can be realized
  - Remotely maintainable to a large degree

Example of an Analog LLRF System

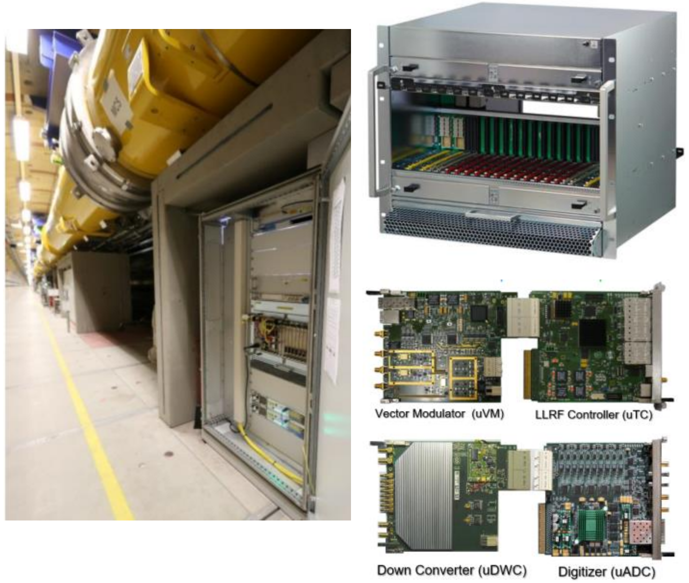


Types of Digital LLRF Systems

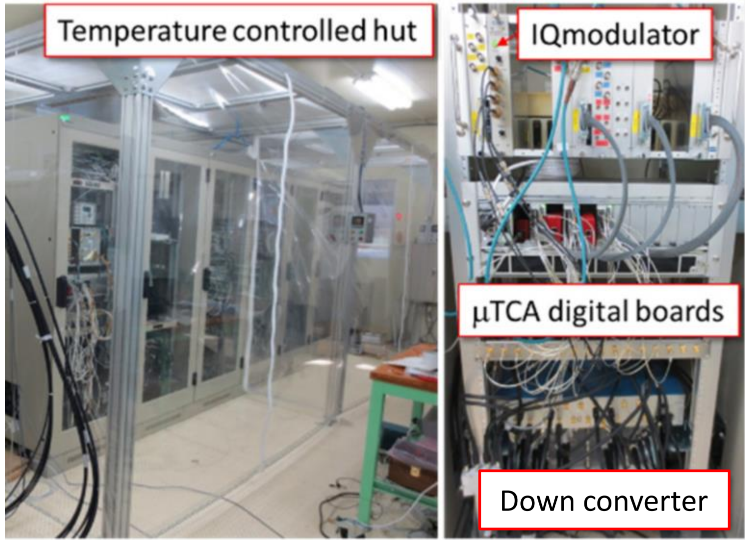
- 19-inch modules (“Pizza box”)
  - Individually developed and built hardware
  - Well optimized
- Crate-based systems
  - Of-the-shelf components
  - Well optimized cards available
  - Highly modular
- Mixed systems
  - Best of both worlds



LCLS-II prototype LLRF system at FNAL CMTS



µTCA.4-based LLRF systems at European XFEL at DESY



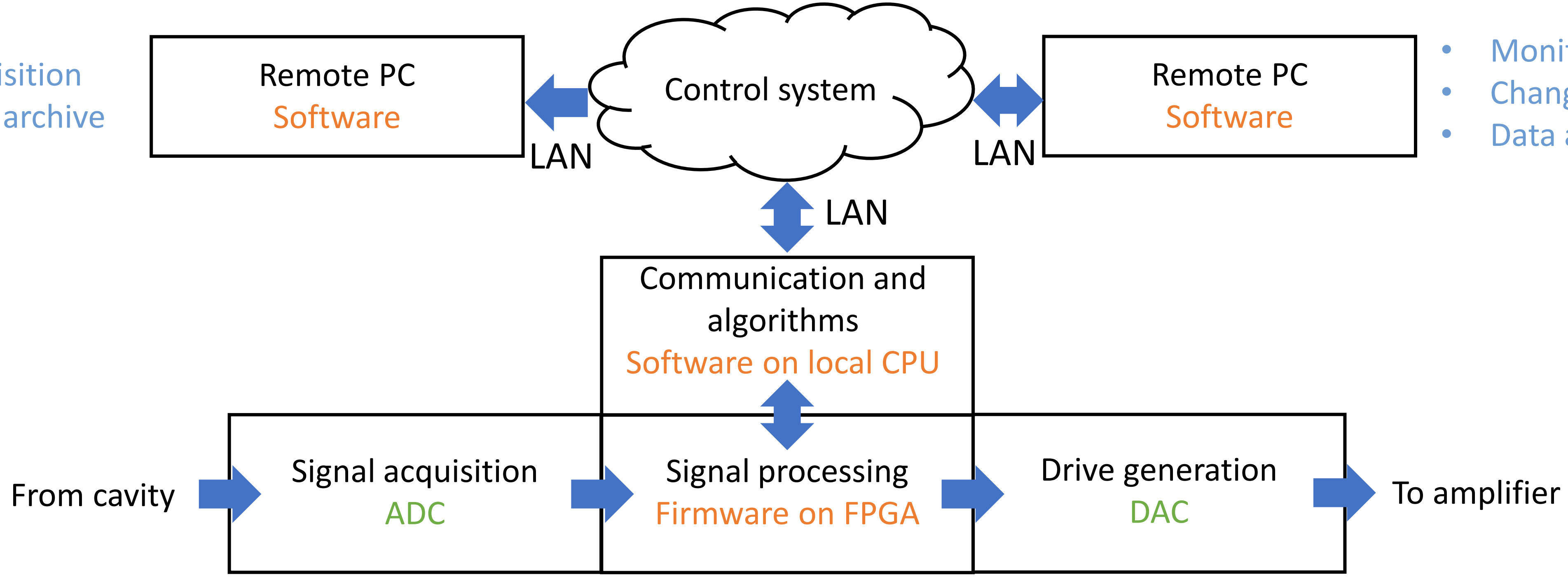
µTCA.0-based LLRF system at cERL at KEK

System Architecture Example

- Distribution of data

- Data acquisition
- Long time archive

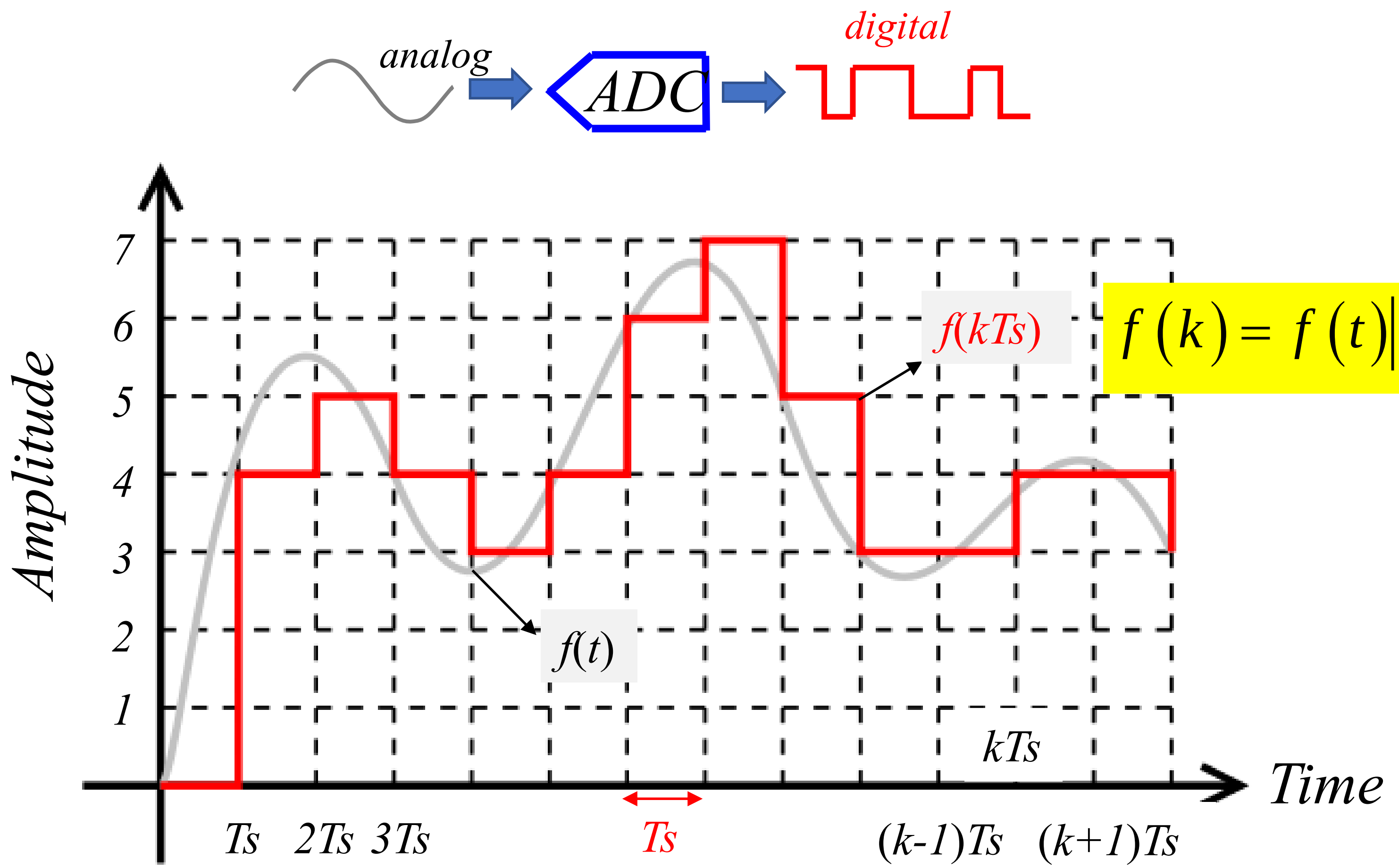
- Monitoring
- Change settings
- Data acquisition



- Digital filter
- Feedback
- Generation of digital drive signal
- Possibly other algorithms, calculations and functionalities

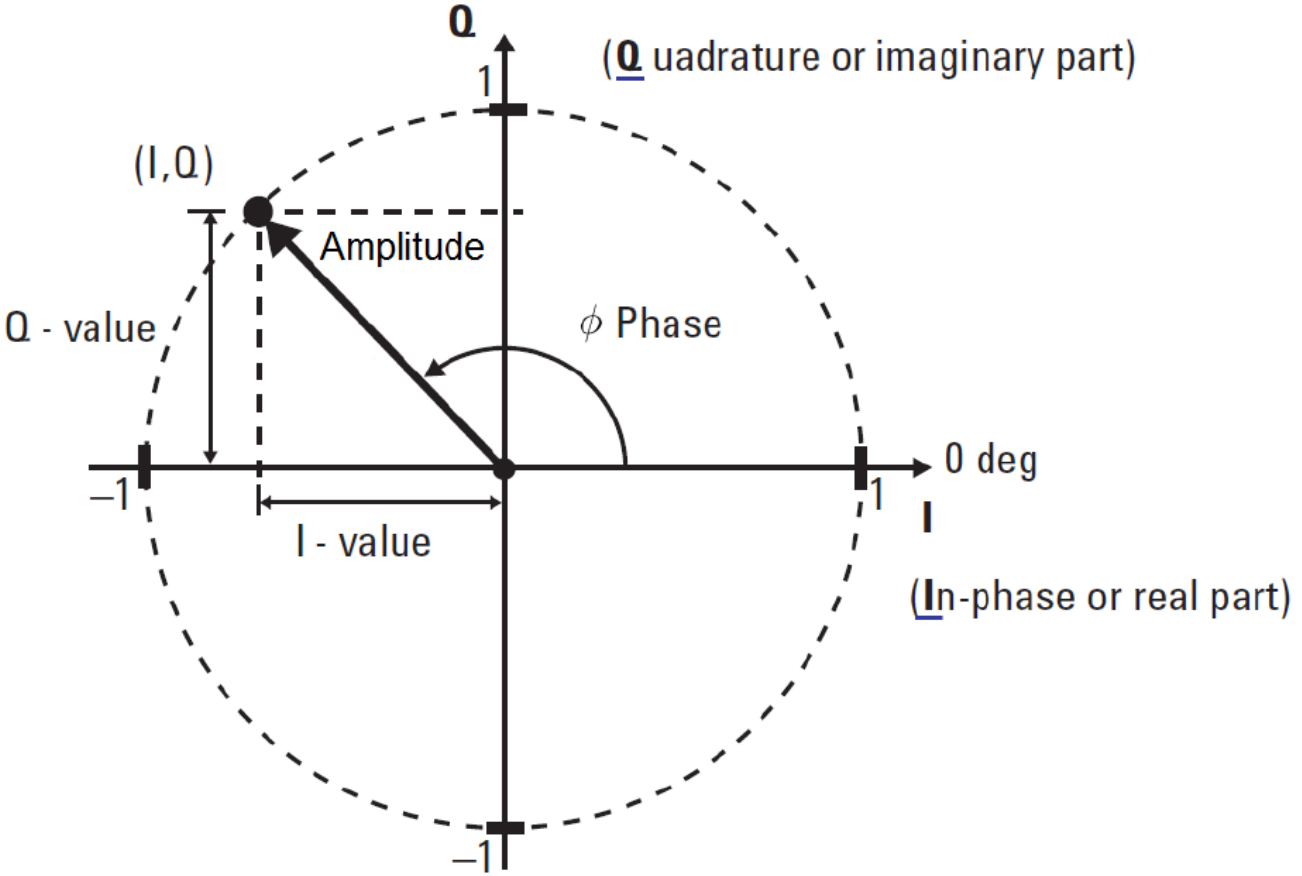
Signal Sampling

Goal: Convert an Analog Signal into a Digital Signal



$$f(k) = f(t)\big|_{t=k\cdot T_s}$$

Representation in Quadrature and In-phase



$$I = A\cos(\phi)$$

$$Q = A\sin(\phi)$$

$$A = \sqrt{I^2 + Q^2}$$

$$\phi = \operatorname{atan}\left(\frac{Q}{I}\right)$$

Down Conversion in Frequency

- Nyquist-Shannon theorem: $f_s > 2f_{RF}$
  - If this is fulfilled, a perfect reconstruction of f_{RF} is guarantied.

$$S_{RF}(t) = A_{RF} \cdot \sin(2\pi \cdot f_{RF} \cdot t + \phi_{RF})$$

$$\phi_{RF} = 0$$

$$S_{LO}(t) = A_{LO} \cdot \sin(2\pi \cdot f_{LO} \cdot t + \phi_{LO})$$

$$A_{LO} = 1 \qquad \phi_{LO} = 0$$

$$S_{LO \cdot RF}(t) = \sin(2\pi \cdot f_{LO} \cdot t) \cdot \sin(2\pi \cdot f_{RF} \cdot t)$$

$$= \frac{1}{2}(\cos(2\pi \cdot (f_{LO} - f_{RF}) \cdot t) - \cos(2\pi \cdot (f_{LO} + f_{RF}) \cdot t))$$

$$S_{IF}(t) = \frac{1}{2}\cos(2\pi \cdot f_{IF} \cdot t)$$

- Preserves amplitude and phase information

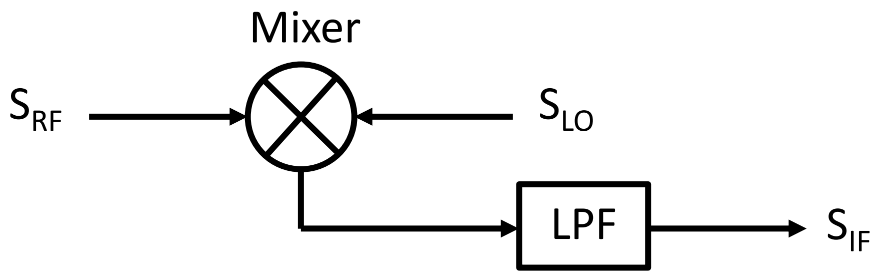
Example frequencies

$f_{RF} = 1.3$ GHz

$f_{LO} = 1.31$ GHz

RF: Radio frequency
LO: Local oscillator
IF: Intermediate frequency

$f_{IF} = 10$ MHz



Sampling methods

- IQ Sampling
- Under sampling & Over sampling

IQ Sampling

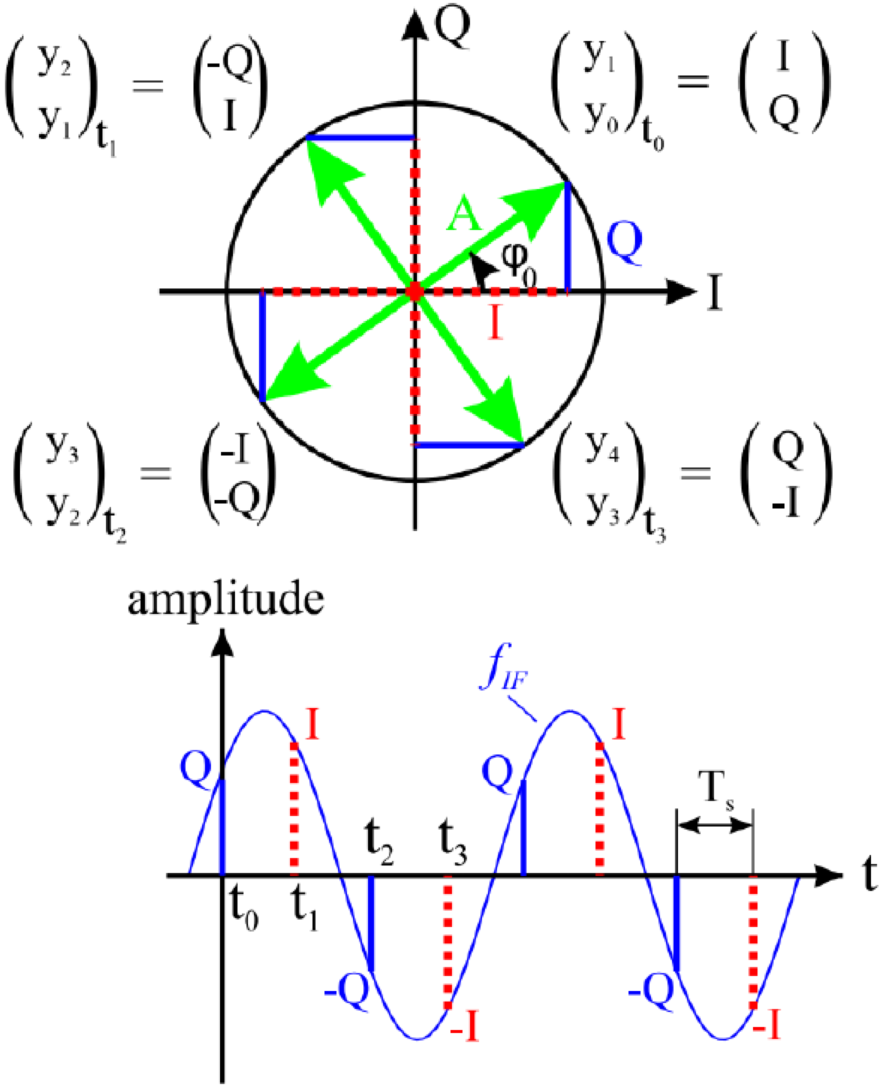
$$f_s = 4 \cdot f_{IF}$$

$$f_{IF}(0) = Q$$

$$f_{IF}(\frac{\pi}{2}) = I$$

$$f_{IF}(\pi) = -Q$$

$$f_{IF}(\frac{3\pi}{2}) = -I$$



$$\begin{pmatrix} I \\ Q \end{pmatrix}_n = \begin{pmatrix} \cos(\Delta\phi_n) & -\sin(\Delta\phi_n) \\ \sin(\Delta\phi_n) & \cos(\Delta\phi_n) \end{pmatrix} \cdot \begin{pmatrix} f_{IF,n+1} \\ f_{IF,n} \end{pmatrix}$$

Undersampling and Oversampling

$$\frac{f_s}{f_{IF}} = \frac{M}{L} = m$$

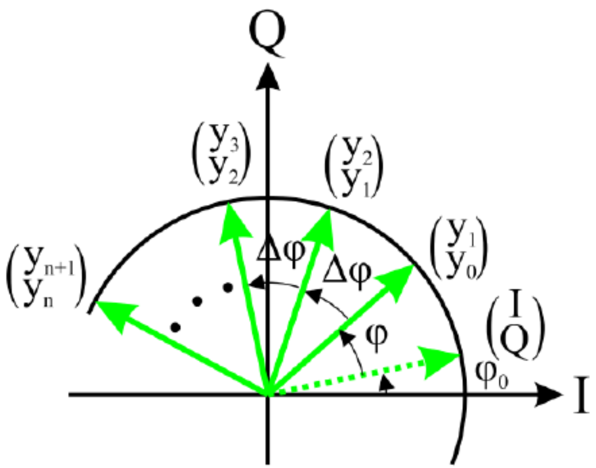
$m = 4$ corresponds to the IQ sampling

$m < 2$ corresponds to undersampling

$m > 2$ to oversampling

$$\Delta\phi = \frac{2\pi}{m}$$

$$\begin{pmatrix} I \\ Q \end{pmatrix}_n = \frac{1}{\sin(\Delta\phi + \phi)} \begin{pmatrix} \cos(n\Delta\phi + \phi) & -\cos((n+1)\Delta\phi + \phi) \\ -\sin(n\Delta\phi + \phi) & \sin((n+1)\Delta\phi + \phi) \end{pmatrix} \cdot \begin{pmatrix} y_{IF,n+1} \\ y_{IF,n} \end{pmatrix}$$



$$I = \frac{2}{m} \sum_{n=0}^{m-1} y_n \cos\left(\frac{2\pi n}{m}\right)$$

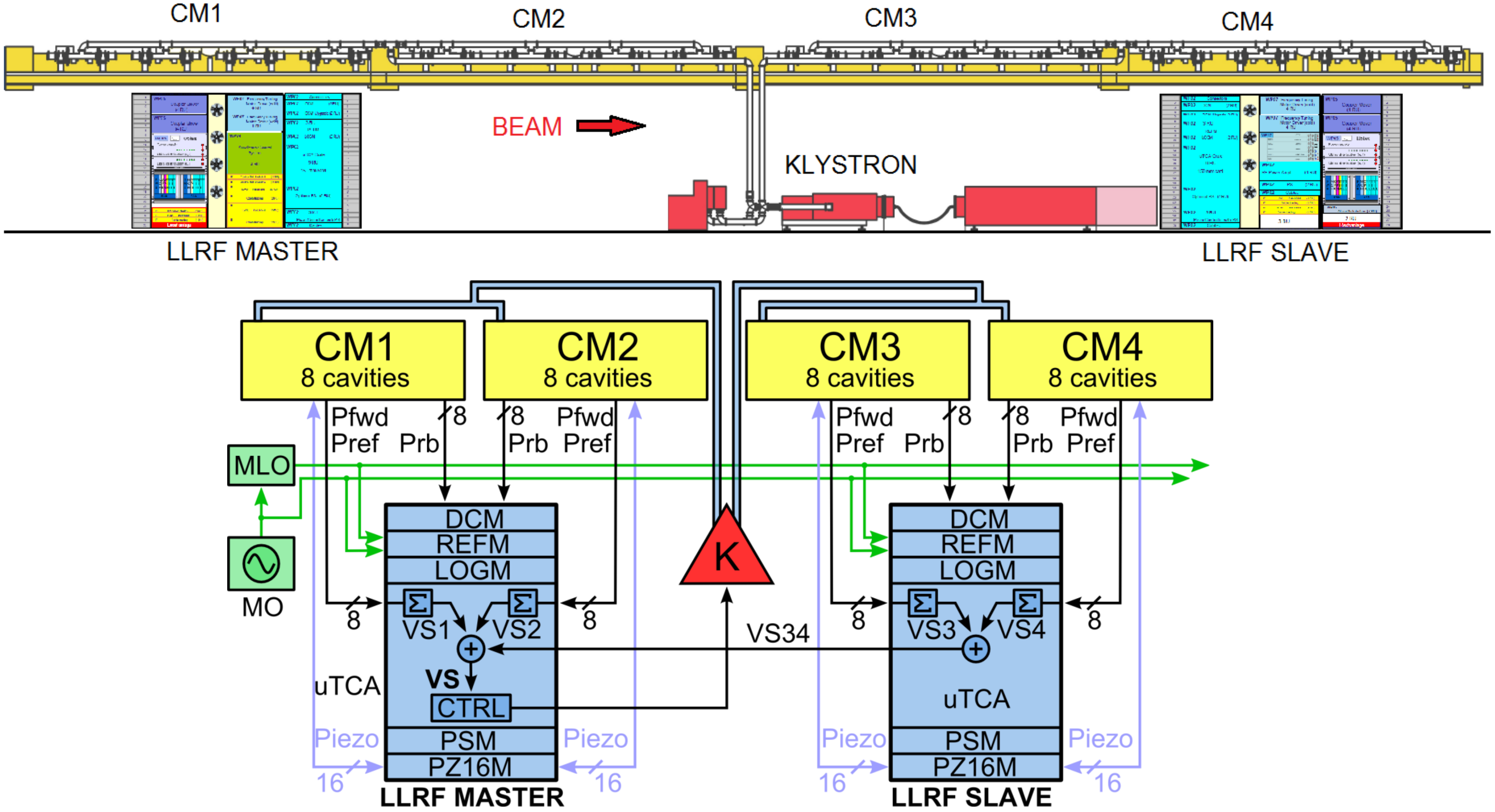
$$Q = \frac{2}{m} \sum_{n=0}^{m-1} y_n \sin\left(\frac{2\pi n}{m}\right)$$

Undersampling and Oversampling

- Advantages of undersampling
  - Relaxed requirements for ADC due to lower sampling rate (possible cost reduction)
  - Relaxed requirements for FPGA due to lower data rate (possible cost reduction)
  - Possible to detect IF signals with higher frequency than the ADC sampling rate
- Advantages of oversampling
  - More sample points per period
  - Noise reduction due to averaging in the calculation of I and Q values
  - Choice of IF location in the first Nyquist zone is more flexible (corresponding to e.g. an available analog anti-aliasing low pass filter or to the ADC circuit optimization)

Digital Signal Processing and Implementation

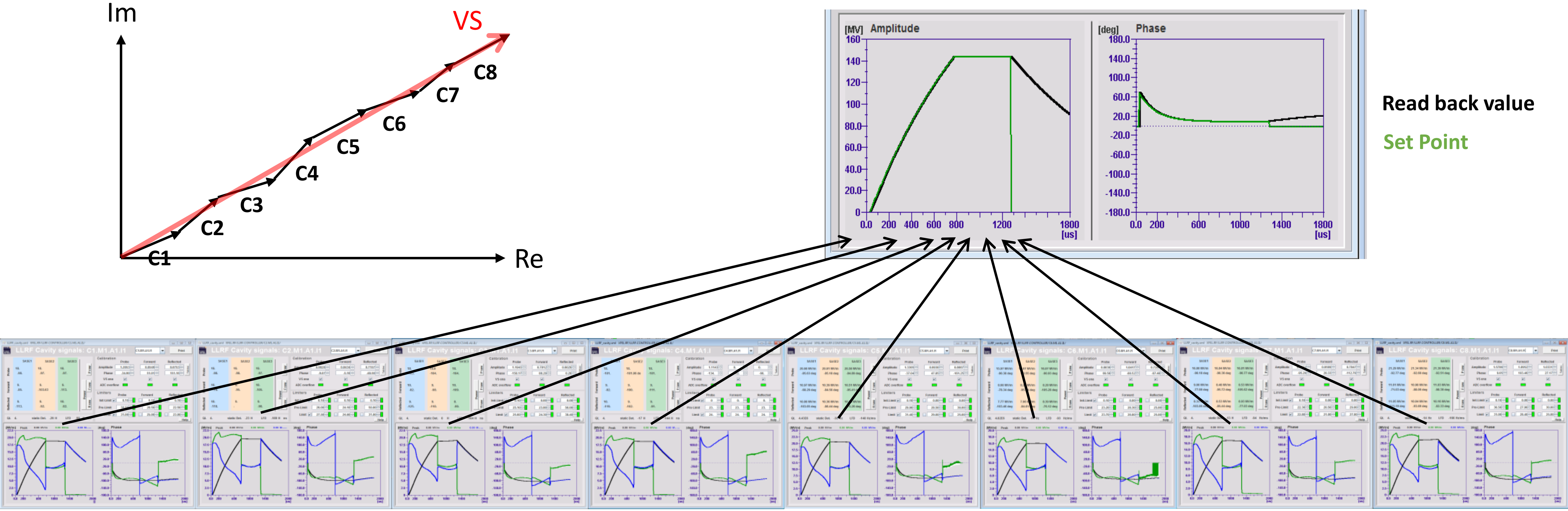
Vector Sum Control of 32 Cavities at the European XFEL



Vector Sum Control

- Drive multiple cavities with one power source

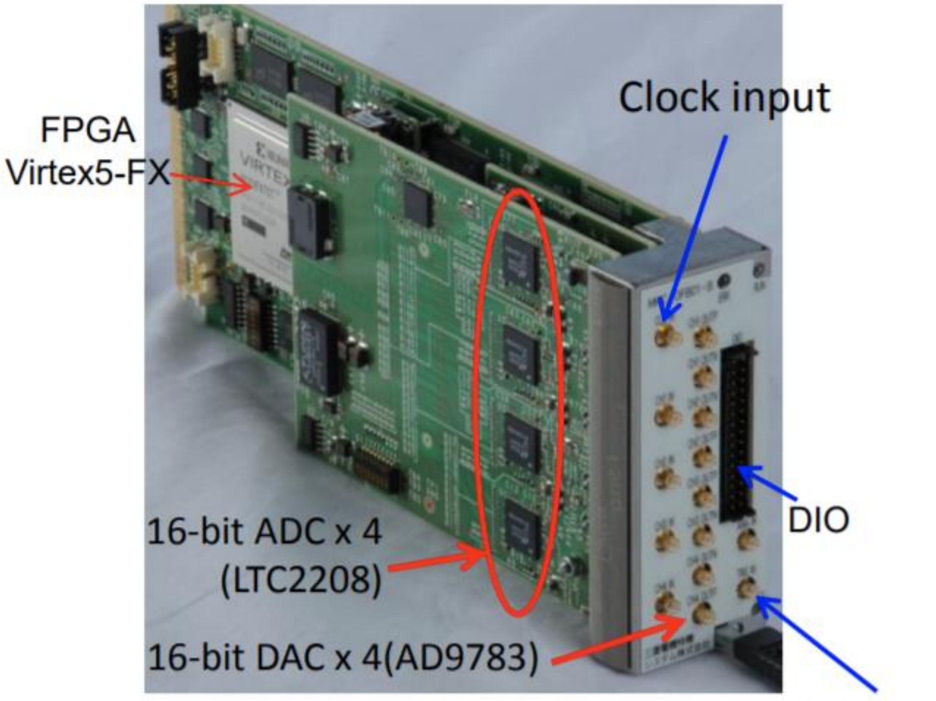
Vector Sum



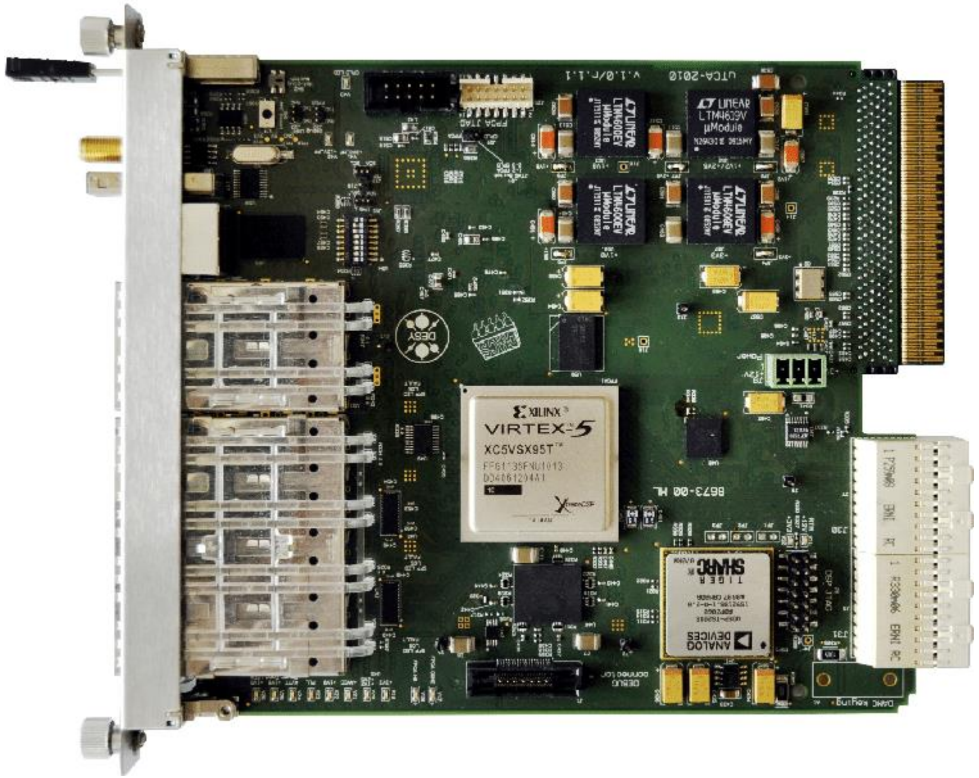
C1 C2 C3 C4 C5 C6 C7 C8

Field-Programmable Gate Array (FPGA)

- Typically all time-critical digital signal processing is implemented on a FGPA



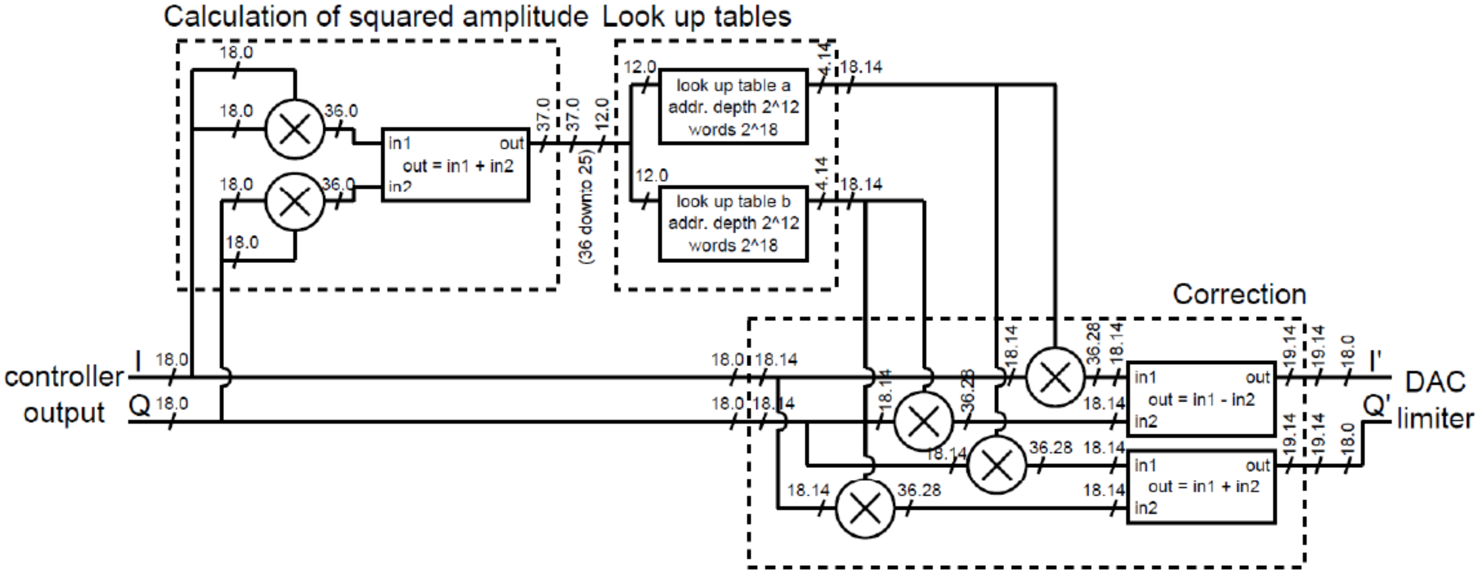
AMC(Advanced Mezzanine Card)



How to implement algorithms on a FPGA

- Write down the requirements for the firmware
- Make a flow chart and check signal widths
- Create your code
- Create a test bench for your code
- Test and debug your code within the test bench
- Test and debug your code on the target hardware (typically a test setup identical to the production system)
- Deploy the firmware on the production hardware
- If the requirements have changed, revise them and go through all previous steps

Example of Flowchart for a VHDL Algorithm for the FPGA

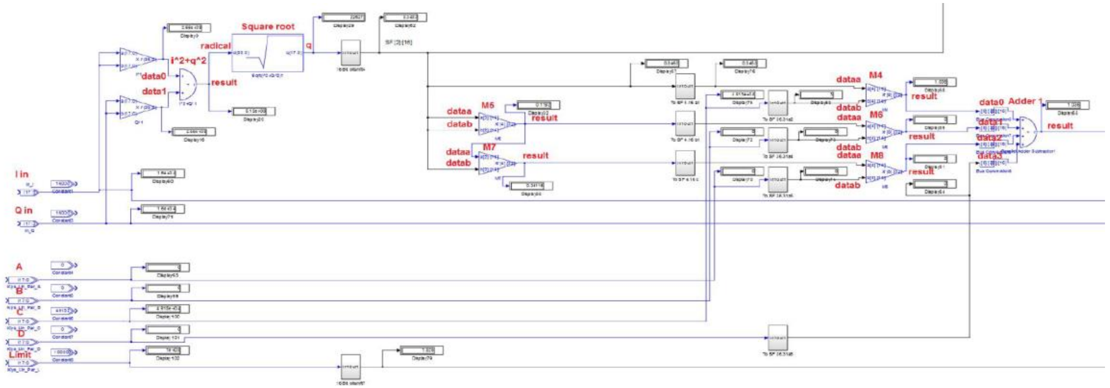


Ways to Create VHDL Code

- Write directly VHDL source code
  - Absolute control over functionality
  - Allows optimization for different goals (e.g. clock cycles, resources, etc.)
  - Needs good understanding
  - Can take longer to get to the result

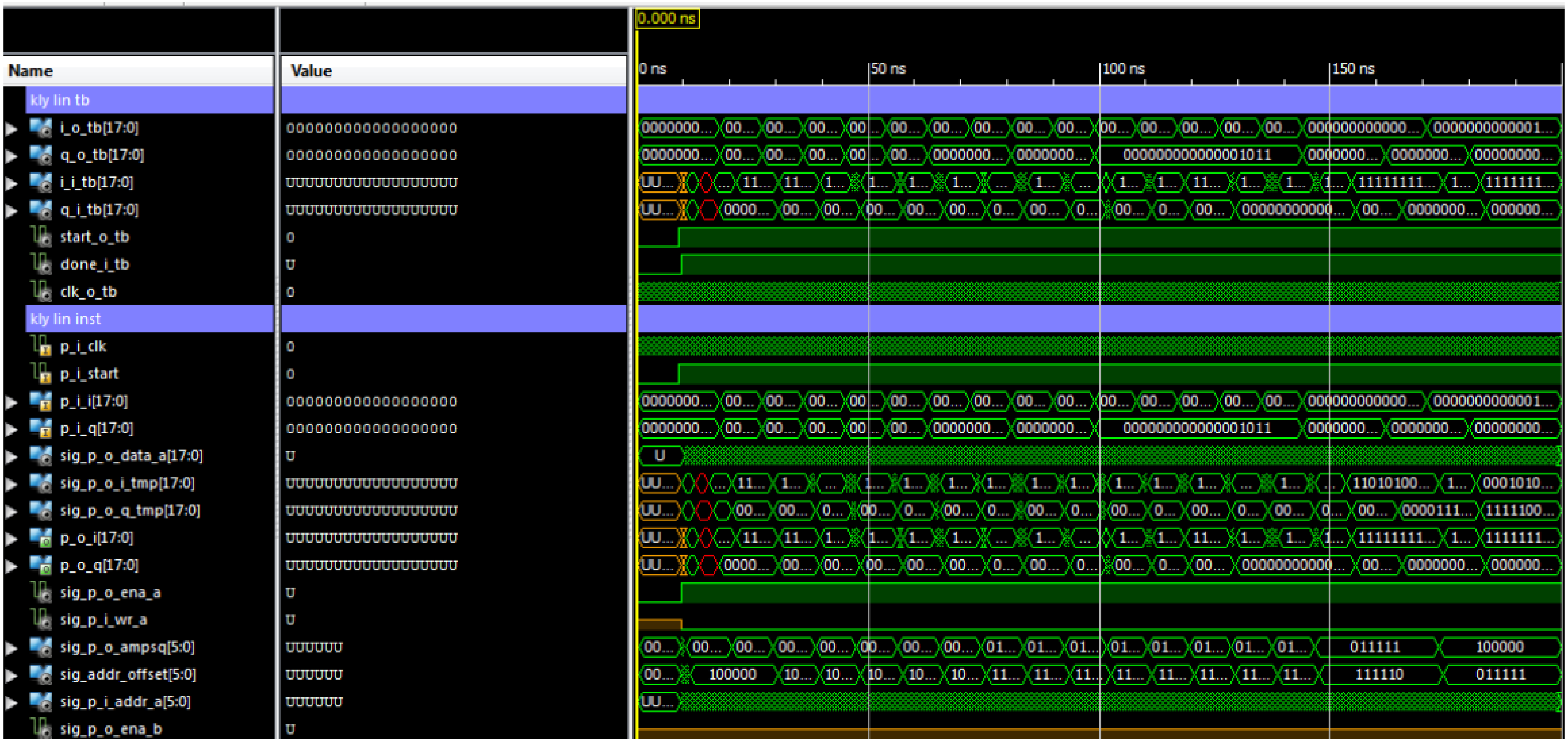
```
-- (this is a VHDL comment)

-- import std_logic from the IEEE library
library IEEE;
use IEEE.std_logic_1164.all;

-- this is the entity
entity name_of_entity is
   port (
          IN1  : in std_logic;
          IN2  : in std_logic;
          OUT1: out std_logic);
end entity name_of_entity;

-- here comes the architecture
architecture name_of_architecture of name_of_entity is

-- Internal signals and components would be defined here

begin

  OUT1 <= IN1 and IN2;

end architecture name_of_architecture;
```

- Use e.g. MathWorks Simulink to create VHDL code
  - Allows quick prototyping
  - Good graphical representation of signal flow
  - Less control
  - Creates VHDL code, which most times cannot be easily debugged by a human



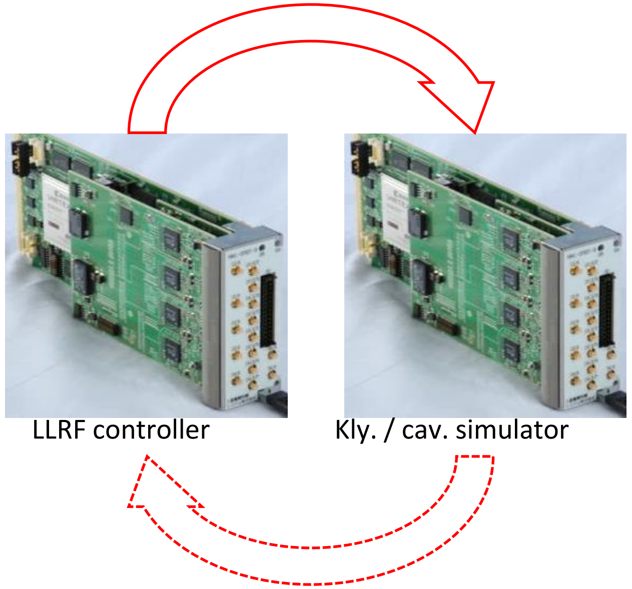
VHDL = VHSIC Hardware Description Language
VHSIC = Very High Speed Integrated Circuit

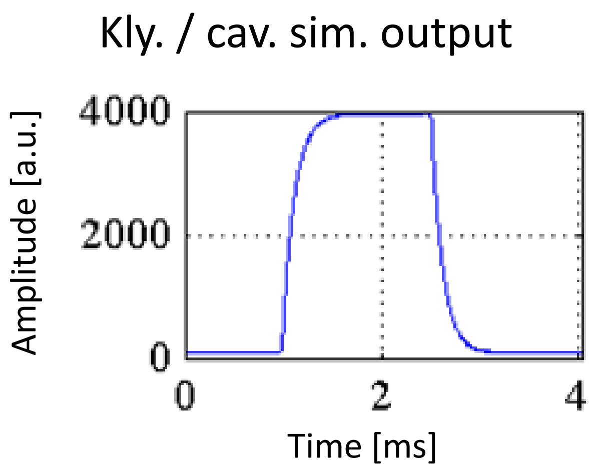
Test the Code on a Test Bench



FPGA-based Simulator

- Operating cavities is expensive (e.g, cryo in case of SRF cavities, high power amplifiers, etc.)
- Development and test also possibly with simulators
- Example implemented at KEK
  - Klystron simulator based on two direct lookup tables
  - Cavity simulator based on the time discrete cavity differential equation
  - Test setup realized in a development rack
  - Two µTCA cards (Xilinx Virtex 5 FX)
    - LLRF controller
    - klystron / cavity simulator
  - Feedforward (open loop) and feedback (closed loop) operation modes worked

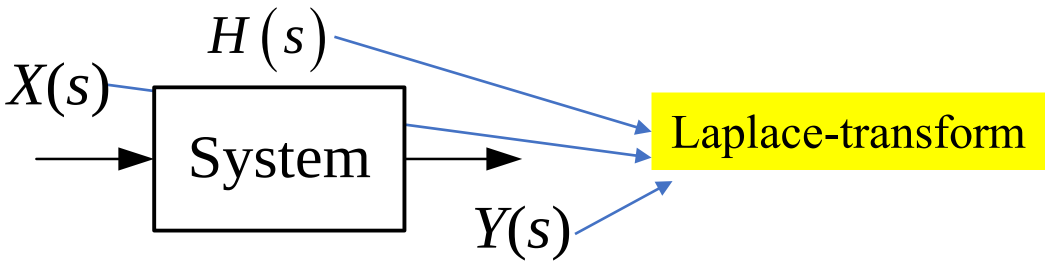




Controller Theory

Transfer Function

- A **Transfer Function** is the ratio of the output of a system to the input of a LTI system.
- The X(s) and Y(s) are the Laplace-transform of the input/output signal, respectively.
- Key point: The transfer function H(s) includes information of a system (usually can be seen **as a representation of a given system**). i.e. if we know the transfer function H(s) of a specified system (assume initial states = 0), we can calculate the output Y(s) by input X(s).



$$H(s) = \frac{Y(s)}{X(s)}, \quad Y(s) = H(s) \cdot X(s).$$

Laplace-Transform

- Formula of the Laplace-Transform

Time domain — $h(t)$ → Impulse response, (time domain representation of a system)

Laplace-transform $H(s) = \int_{t=0}^{+\infty} h(t) e^{-st} dt$

Complex freq. domain — $H(s)$ → Transfer function

Inverse Laplace transformation $f(t) = L^{-1}\{F(s)\} = \frac{1}{2\pi j} \int_{s=\alpha - j\omega}^{\alpha + j\omega} F(s) \cdot e^{st} ds$

Laplace-Transform

TABLE 15.1

Properties of the Laplace transform.

Property	$f(t)$	$F(s)$
Linearity	$a_1 f_1(t) + a_2 f_2(t)$	$a_1 F_1(s) + a_2 F_2(s)$
Scaling	$f(at)$	$\frac{1}{a}F\left(\frac{s}{a}\right)$
Time shift	$f(t-a)u(t-a)$	$e^{-as}F(s)$
Frequency shift	$e^{-at}f(t)$	$F(s+a)$
Time differentiation	$\frac{df}{dt}$	$sF(s) - f(0^-)$
	$\frac{d^2f}{dt^2}$	$s^2F(s) - sf(0^-) - f'(0^-)$
	$\frac{d^3f}{dt^3}$	$s^3F(s) - s^2f(0^-) - sf'(0^-) - f''(0^-)$
	$\frac{d^nf}{dt^n}$	$s^nF(s) - s^{n-1}f(0^-) - s^{n-2}f'(0^-) - \cdots - f^{(n-1)}(0^-)$
Time integration	$\int_0^t f(x)dx$	$\frac{1}{s}F(s)$
Frequency differentiation	$tf(t)$	$-\frac{d}{ds}F(s)$
Frequency integration	$\frac{f(t)}{t}$	$\int_s^\infty F(s)ds$
Time periodicity	$f(t) = f(t+nT)$	$\frac{F_1(s)}{1-e^{-sT}}$
Initial value	$f(0)$	$\lim_{s\to\infty} sF(s)$
Final value	$f(\infty)$	$\lim_{s\to 0} sF(s)$
Convolution	$f_1(t) * f_2(t)$	$F_1(s)F_2(s)$

TABLE 15.2

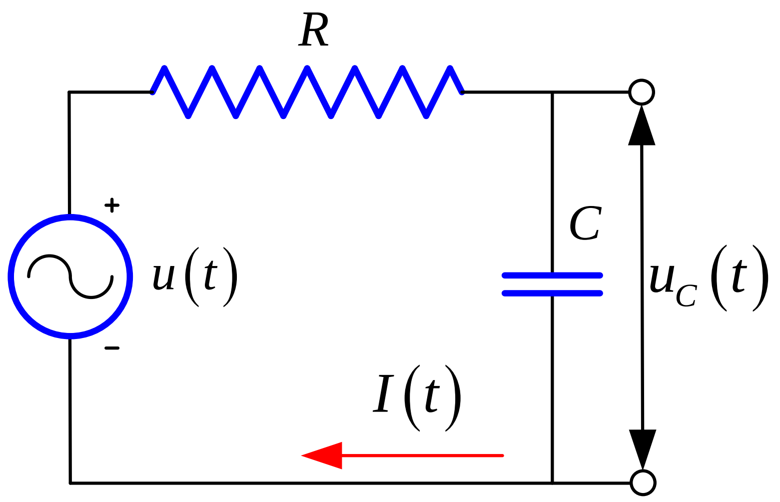
Laplace transform pairs.*

$f(t)$	$F(s)$
$\delta(t)$	1
$u(t)$	$\frac{1}{s}$
e^{-at}	$\frac{1}{s+a}$
t	$\frac{1}{s^2}$
t^n	$\frac{n!}{s^{n+1}}$
te^{-at}	$\frac{1}{(s+a)^2}$
t^ne^{-at}	$\frac{n!}{(s+a)^{n+1}}$
$\sin \omega t$	$\frac{\omega}{s^2+\omega^2}$
$\cos \omega t$	$\frac{s}{s^2+\omega^2}$
$\sin(\omega t + \theta)$	$\frac{s\sin\theta + \omega\cos\theta}{s^2+\omega^2}$
$\cos(\omega t + \theta)$	$\frac{s\cos\theta - \omega\sin\theta}{s^2+\omega^2}$
$e^{-at}\sin \omega t$	$\frac{\omega}{(s+a)^2+\omega^2}$
$e^{-at}\cos \omega t$	$\frac{s+a}{(s+a)^2+\omega^2}$

*Defined for $t \geq 0$; $f(t) = 0$, for $t < 0$.

Hot to obtain a Transfer Function (Example: RC circuit)

- TF is related to the differential equation
- The differential equation reads:



$$I(t) = C \cdot \frac{du_C(t)}{dt} = \frac{u(t) - u_C(t)}{R}$$

Current on C — Current on R

$$\text{then,} \quad \frac{du_C(t)}{dt} + \frac{u_C(t)}{RC} = \frac{u(t)}{RC}, \; u_c(0^-) = 0$$

Laplace Transform

$$f'(t) \Leftrightarrow sF(s)$$

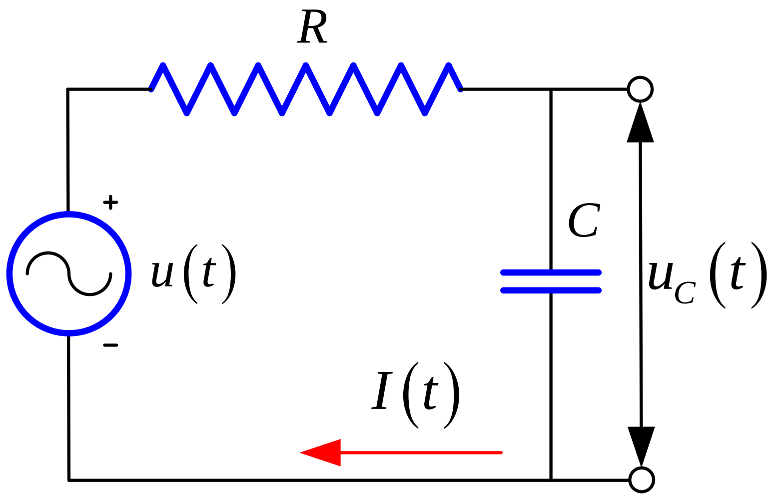
$$\text{then,} \quad sU_C(s) + \frac{U_C(s)}{RC} = \frac{U(s)}{RC} \quad \text{and} \quad \frac{U_C(s)}{U(s)} = \frac{\frac{1}{RC}}{s + \frac{1}{RC}}$$

Transfer function

Transfer function of RC circuit

Example: RC circuit

- If we know the TF (assume initial state = 0), in principle, we know the system output $u_c(t)$ according to the given input $u(t)$ (unit step).



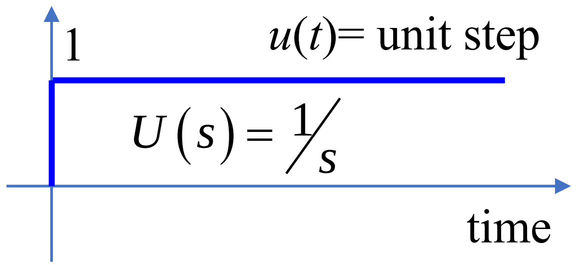
$$H(s)=\frac{U_C(s)}{U(s)}=\frac{\frac{1}{RC}}{s+\frac{1}{RC}}$$

$$U_C(s)=\frac{\frac{1}{RC}}{s+\frac{1}{RC}}\cdot\frac{1}{s}$$

$U(s)$: $\frac{1}{s}$; τ: RC

$$H(s)=\frac{\frac{1}{RC}}{s+\frac{1}{RC}}\overset{L^{-1}}{\Rightarrow}L^{-1}\{H(s)\}=\frac{1}{\tau}e^{\frac{-t}{\tau}}\ (\tau=RC)$$

$$\frac{U_C(s)}{s}\overset{L^{-1}}{\Rightarrow}\int_0^t L^{-1}\{H(s)\}dx$$



$$u_C(t)=\int_0^t\frac{1}{\tau}e^{\frac{-x}{\tau}}dx=\left(-e^{\frac{-x}{\tau}}\right)\Bigg|_{x=0}^{x=t}=1-e^{\frac{-t}{\tau}}\ (t>=0)$$

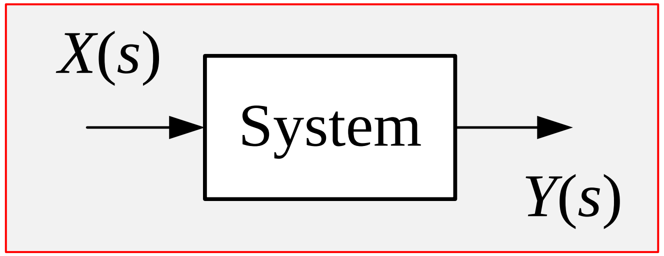
Example: RC circuits

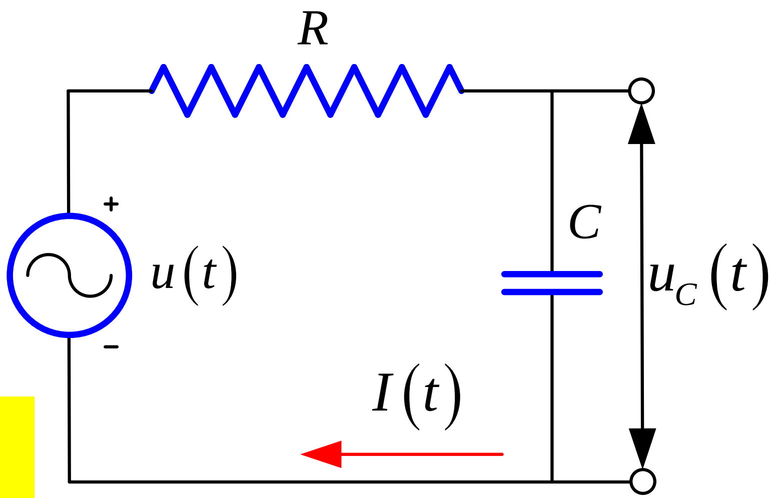
- Go back to the differential equation:

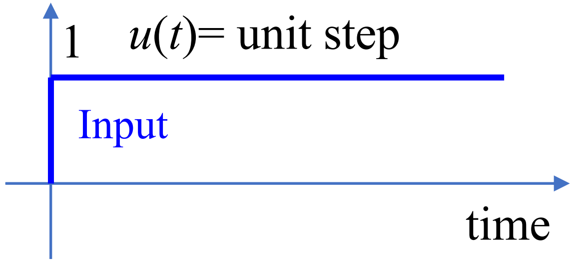
$$\frac{du_C(t)}{dt}+\frac{u_C(t)}{RC}=\frac{u(t)}{RC}$$

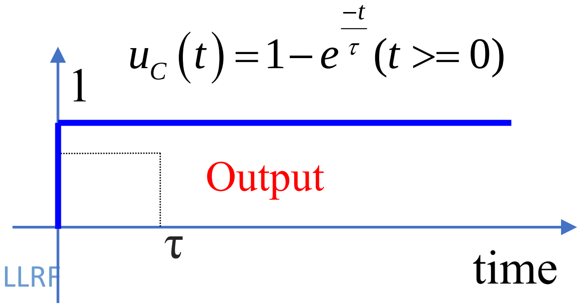
Solution of the differential equation

$$u_C(t)=1-e^{\frac{-t}{\tau}}\;(t>=0)$$





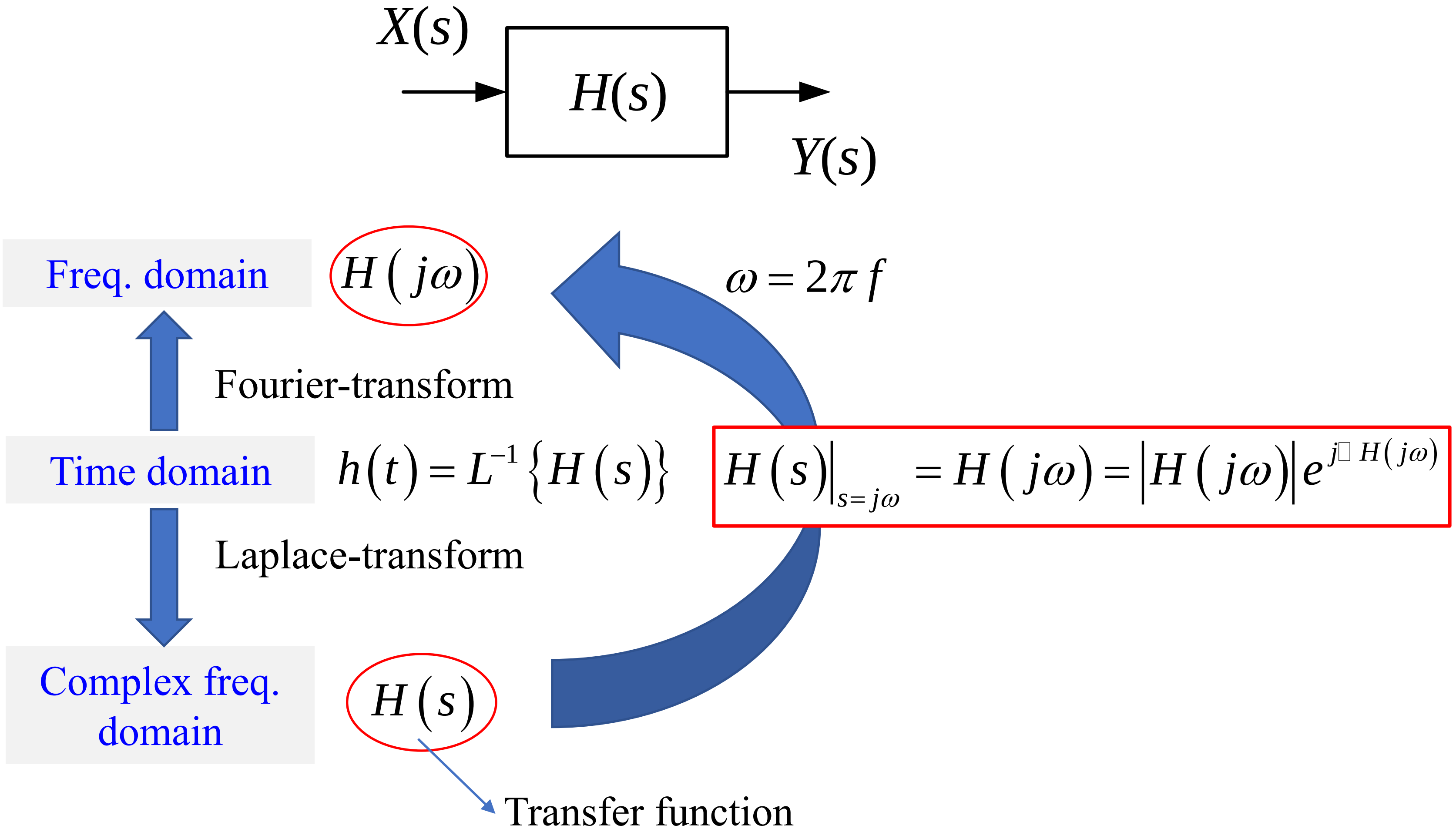




Usually, we also call the parameter τ time constant.

Frequency response

- It is a measure of magnitude and phase of the output as a function of frequency.
- From TF to transfer function: H(s)→H(jω).



Frequency response

- If we know H(jω), we also know H(j2π·f)
- And then A(f) & P(f)

$$H(s)\big|_{s=j\omega} = H(j\omega) = \left|H(j\omega)\right| e^{j\angle H(j\omega)} = \left|H(j2\pi f)\right| e^{j\angle H(j2\pi f)}$$

Amplitude vs. frequency

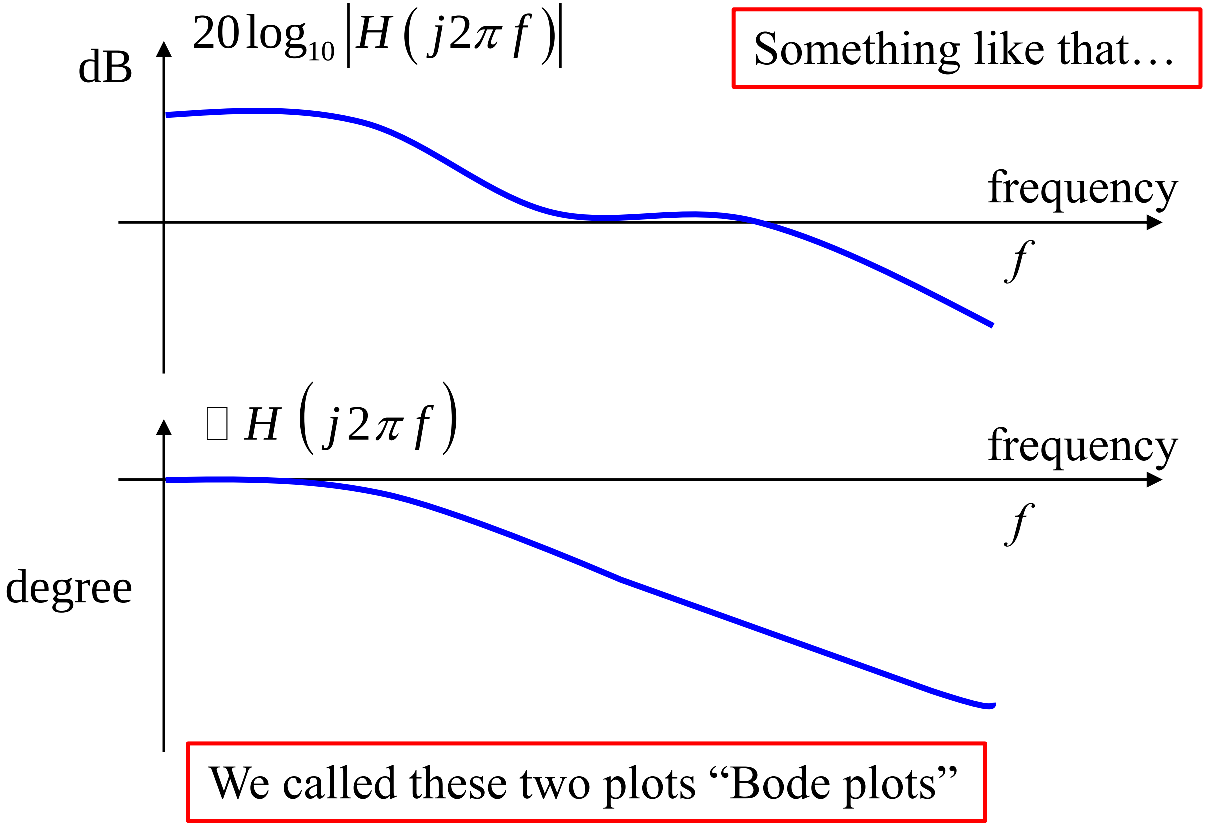
Phase vs. frequency

- We can also plot A(f) & P(f), if we know their expressions

Frequency response (Bode plot)

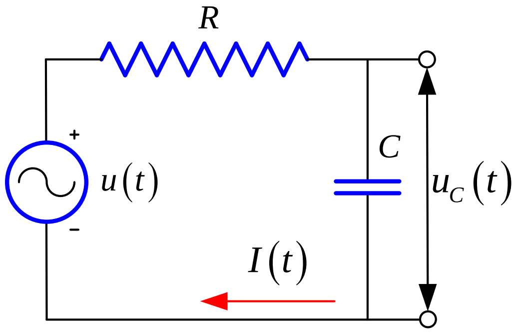
- Bode diagram: plots of the amplitude-frequency and phase-frequency response of the system H(s).

$$H(s)\big|_{s=j\omega} = H(j\omega) = \left|H(j\omega)\right| e^{j\angle H(j\omega)} = \left|H(j2\pi f)\right| e^{j\angle H(j2\pi f)}$$



Bode diagram

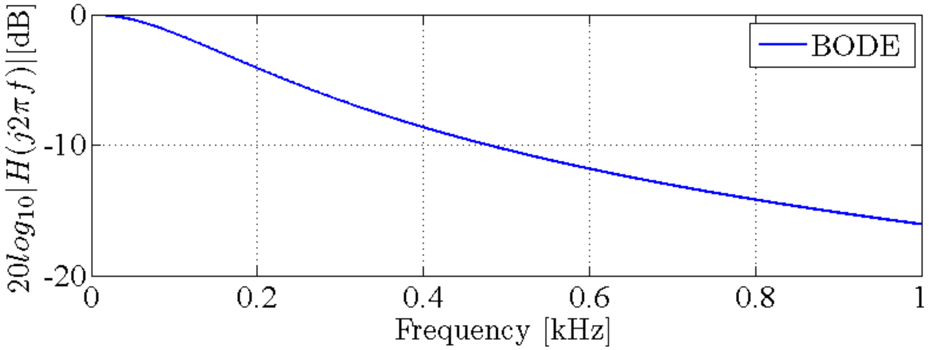
- Bode diagram: plots of the amplitude-frequency and phase-frequency response of the system H(s).



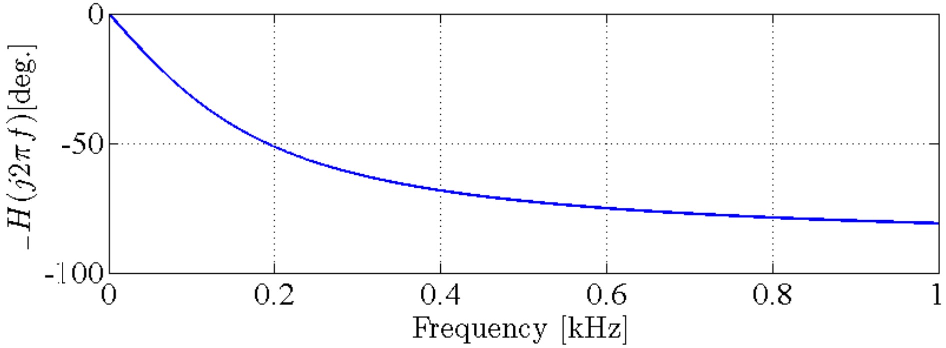
$$|H(j2\pi f)| = \frac{\frac{1}{\tau}}{\sqrt{(2\pi f)^2 + \left(\frac{1}{\tau}\right)^2}}, \quad and \ \angle H(j2\pi f) = -\arctan(2\pi f \tau)$$

Here τ =1 ms

Amplitude vs. frequency



Phase vs. frequency

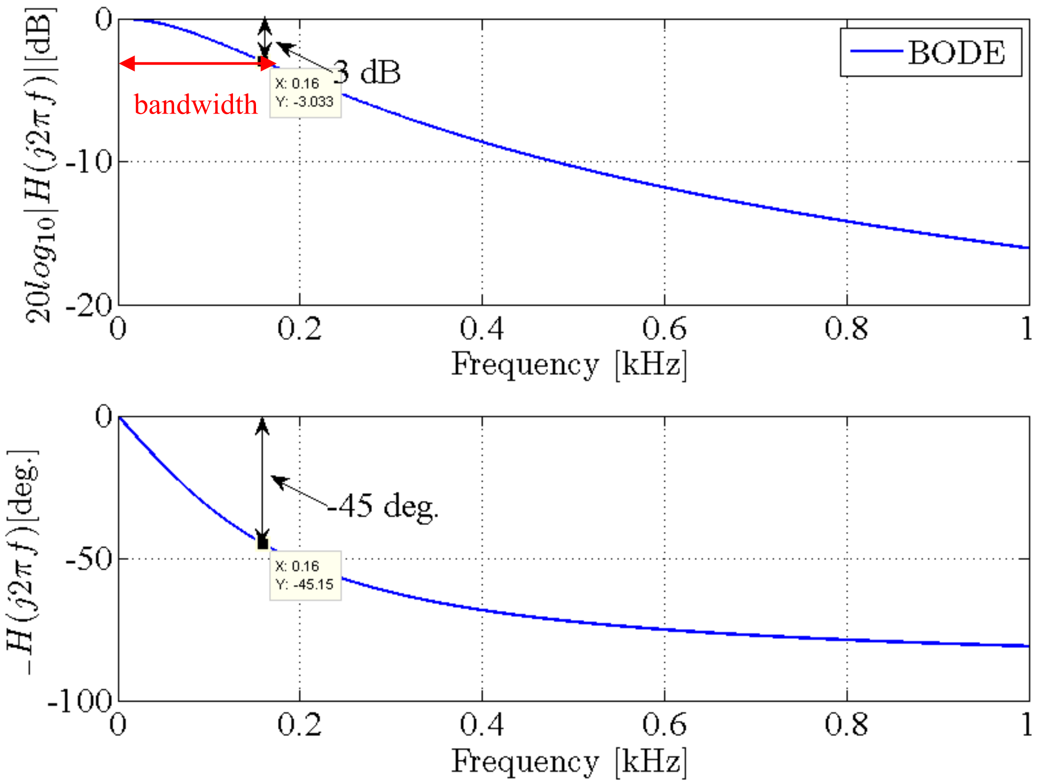


Bode diagram

How about some special case,
$\omega = 1/\tau = 1000$ [rad/s]. f=160 Hz

$$\left|H\left(j\frac{1}{\tau}\right)\right| = \frac{\frac{1}{\tau}}{\sqrt{\left(\frac{1}{\tau}\right)^2 + \left(\frac{1}{\tau}\right)^2}} = \frac{1}{\sqrt{2}}$$

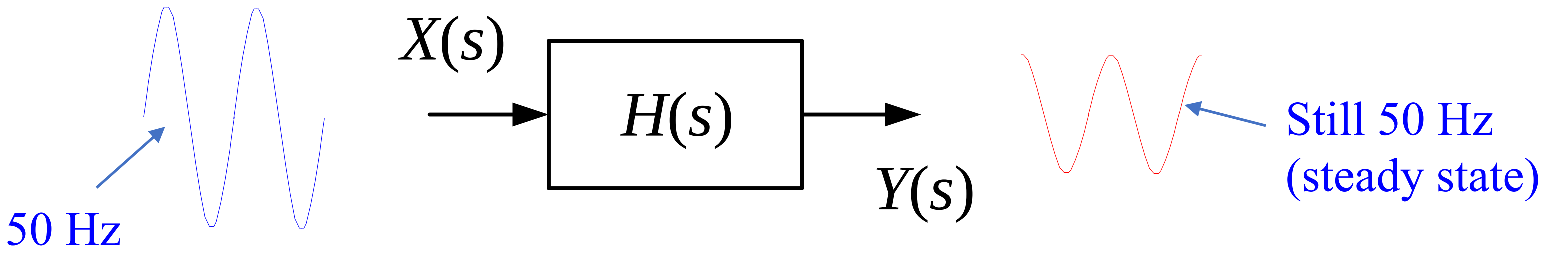
$$\angle H\left(j\frac{1}{\tau}\tau\right) = -\arctan\left(\frac{1}{\tau}\tau\right) = -45^\circ$$



The **half power point** is that frequency at which the output power **(not voltage)** has dropped to half of its mid-band value.

Frequency response

- If we know the frequency response of a system or its bode diagram, then let's consider a sinusoidal signal



$$H(s)\big|_{s=j\omega} = H(j\omega) = |H(j\omega)|\, e^{j\angle H(j\omega)}$$

E.g. a 50 Hz sinewave

$$\text{If input}: \cos(2\pi \cdot 50t),$$

$$\text{Then output}: |H(j\omega)| \cos(2\pi \cdot 50t + \angle H(j\omega))$$

Steady state output

Still 50 Hz, but…

Magnitude gain

Phase shift

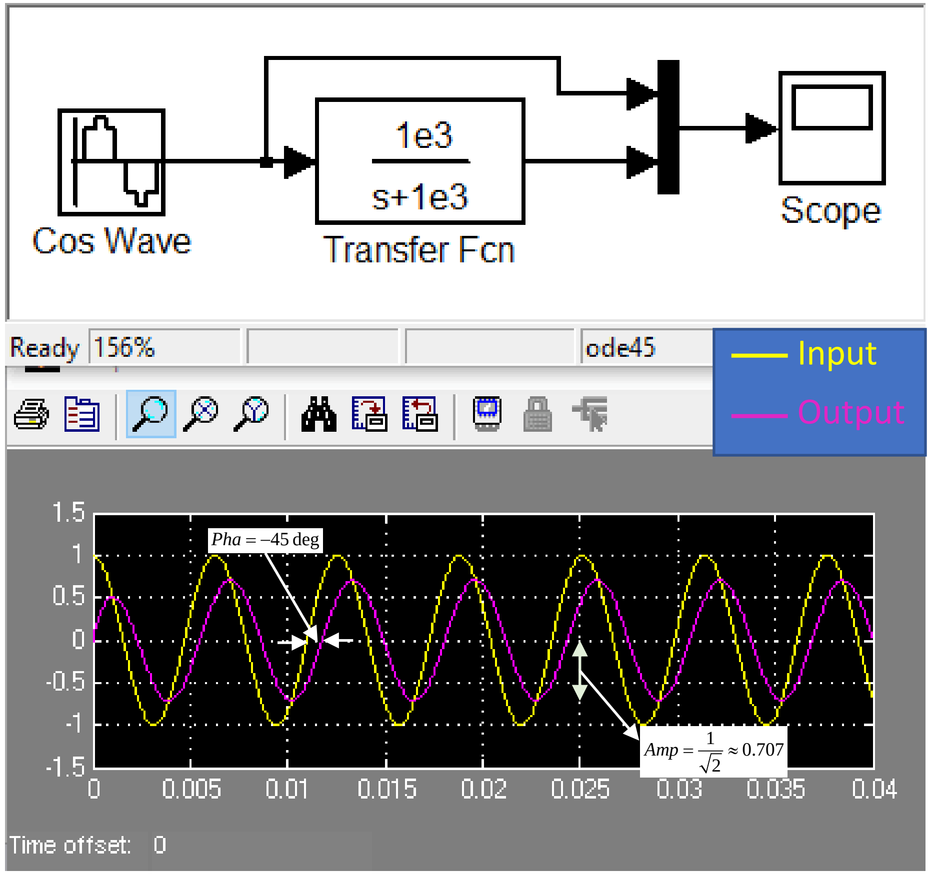
Frequency response

- We can simulate this with using Matlab/Simulink
- The input is a 160 Hz sinusoidal signal

Special case,
$\omega = 1/\tau = 1000$ [rad/s].
$f = \omega/2\pi = 160$ Hz

$$\left|H\left(j\frac{1}{\tau}\right)\right| = \frac{\frac{1}{\tau}}{\sqrt{\left(\frac{1}{\tau}\right)^2 + \left(\frac{1}{\tau}\right)^2}} = \frac{1}{\sqrt{2}}$$

$$\angle H\left(j\frac{1}{\tau}\tau\right) = -\arctan(1) = -45^\circ$$



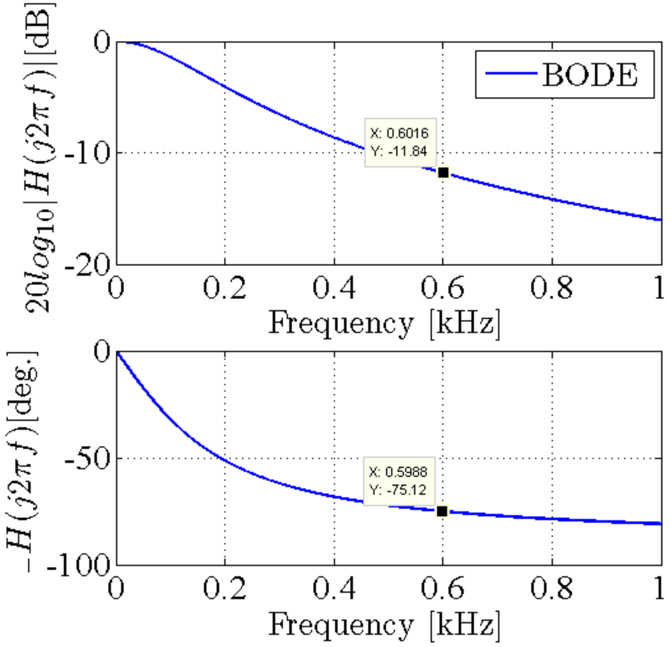
$$If\ input: \cos(2\pi \cdot 160t),$$

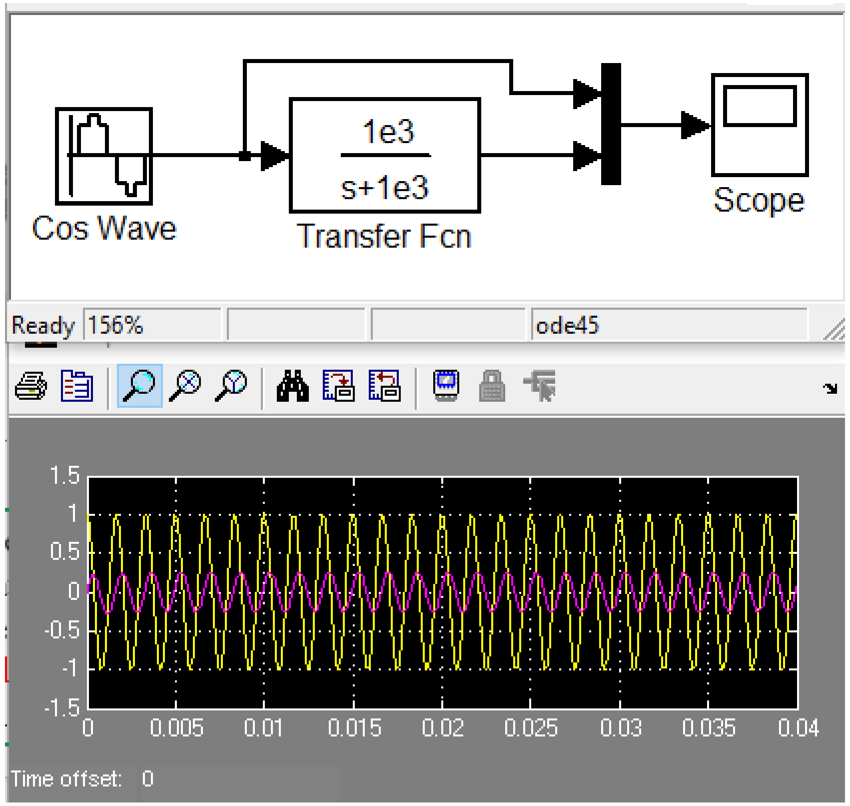
$$Then\ output: |H(j\omega)|\cos(2\pi \cdot 160t + \angle H(j\omega)) = \frac{1}{\sqrt{2}}\cos\left(2\pi \cdot 160t - \frac{\pi}{4}\right)$$

$|H(j\omega)|$ $\angle H(j\omega)$

Frequency response

- How about f = 600 Hz ?





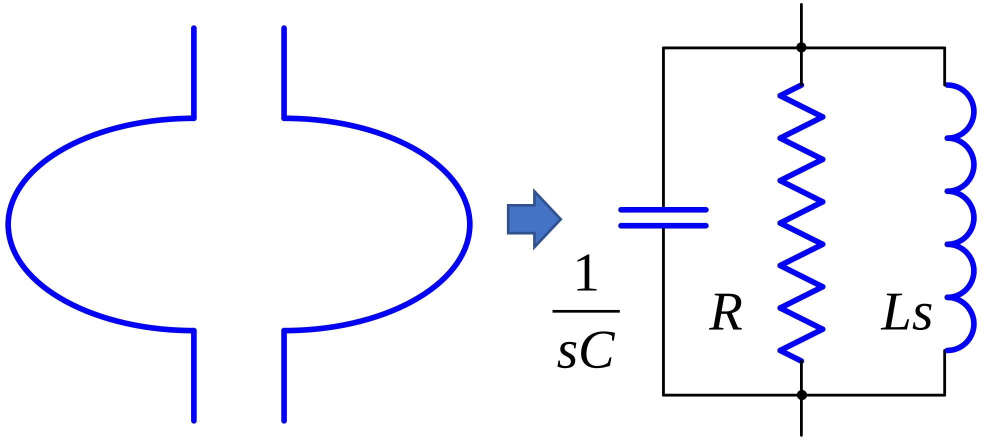
$|H(j\omega)|$ $\quad$ $\measuredangle H(j\omega)$

$$If\ \ input:\ \cos(2\pi \cdot 600t)\,,$$

$$Then\ output:\ |H(j\omega)|\cos\left(2\pi \cdot 600t + \measuredangle H(j\omega)\right) \approx \frac{1}{4}\cos\left(2\pi \cdot 600t - \frac{5\pi}{12}\right)$$

Example of cavity

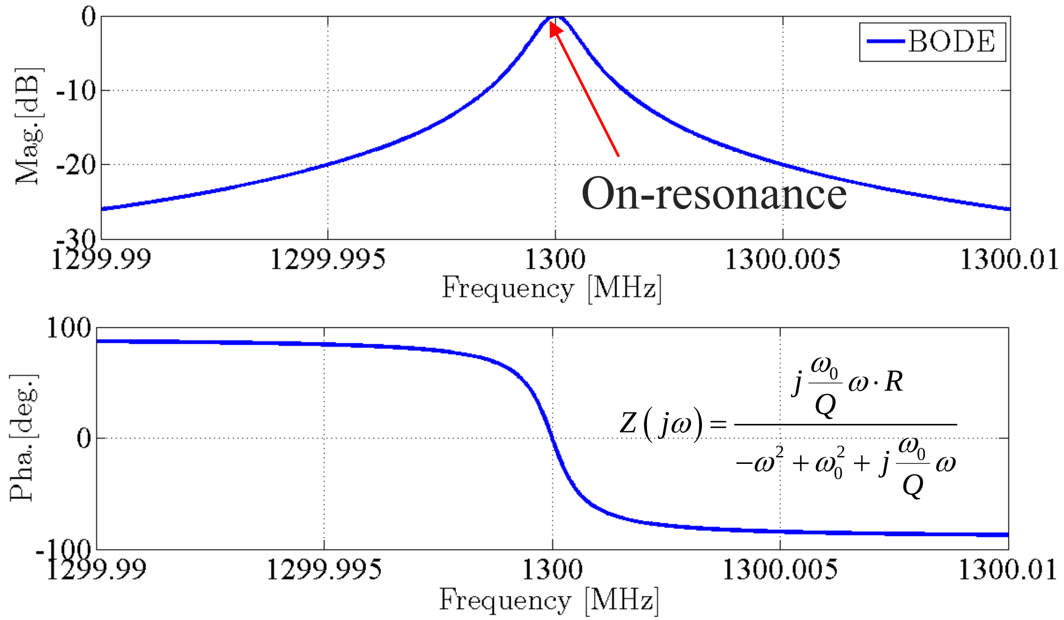
- Bode diagram (Plots of the amplitude-frequency and phase-frequency response of the system)



$$Z(s) = \frac{\frac{s}{C}}{s^2 + \frac{1}{RC}s + \omega_0^2} = \frac{\frac{R\omega_0}{Q}s}{s^2 + \frac{\omega_0}{Q}s + \omega_0^2}$$

$$E.g.\ \omega_0 = 2\pi f_0 = 2\pi\left(1.3\times10^9\right)[rad/s]$$

$$Q = 1.3\times10^6$$



Bode Plot

- Magnitude vs. frequency
- Phase vs. frequency

Bode plot (SC vs. NC)

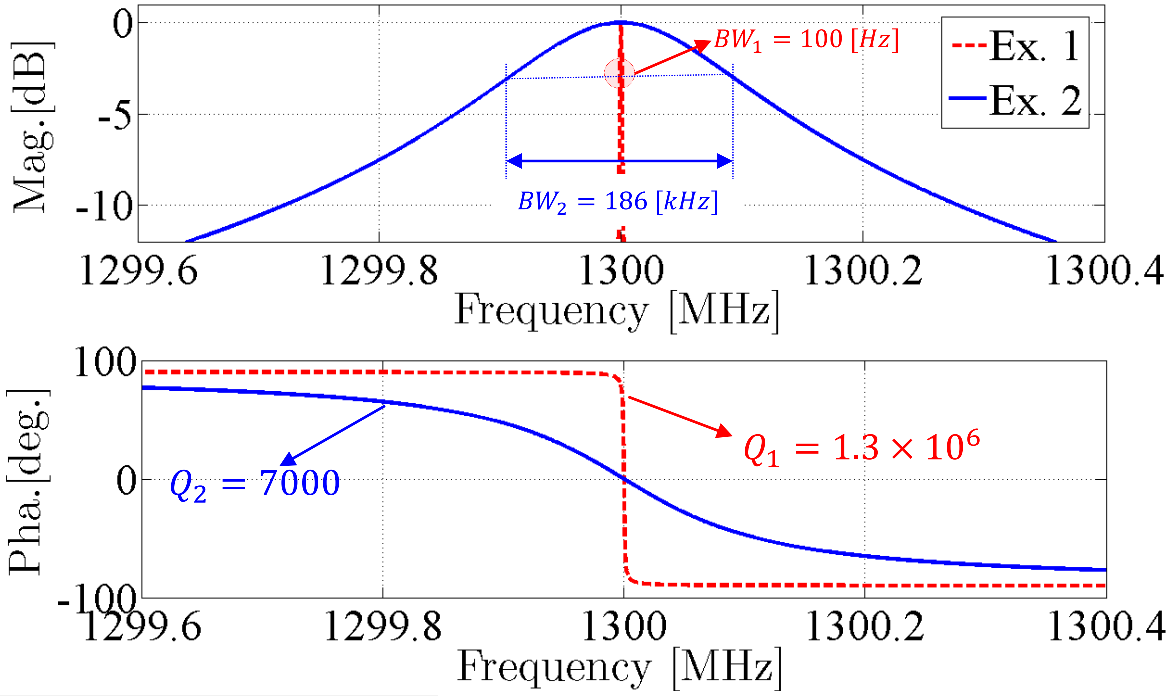
Ex. 1 Bode Plot (SC)

- $\omega_0 = 1.3 \cdot 2\pi\ [rad/s]$
- $Q_1 = 1.3 \times 10^6$
- $BW_1 = 100\ [Hz]$

We can clearly see that the bandwidth is related to the Q value.

Ex. 2 Bode Plot (NC)

- $\omega_0 = 1.3 \cdot 2\pi\ [rad/s]$
- $Q_2 = 7000$
- $BW_2 = 186\ [kHz]$

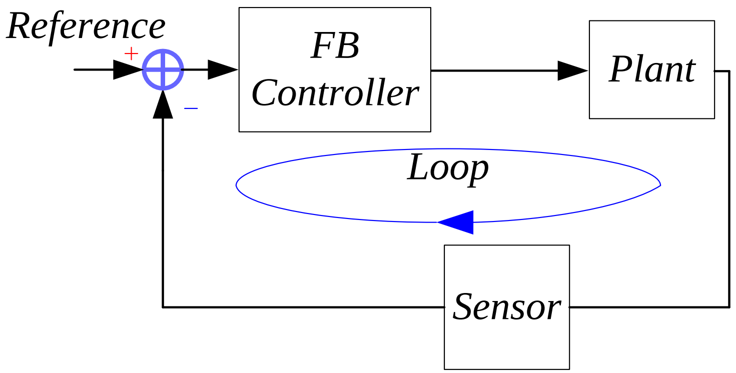


Resonance frequency of a cavity (1.3 GHz)

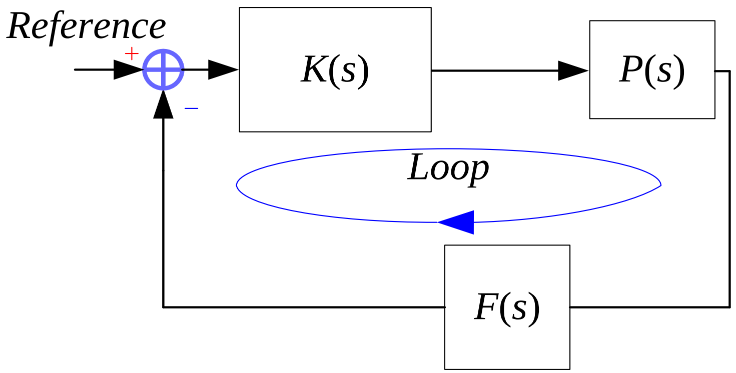
$$BW_{3dB} = \frac{f_0}{Q},\ f_0 = \frac{\omega_0}{2\pi},\ Half\ \ BW\left(\omega_{0.5}\right) = \frac{f_0}{2Q}$$

Transfer function of a FB system

- Let us go back to the basic control system, now let's review it in the viewpoint of the transfer functions.



Basic control system



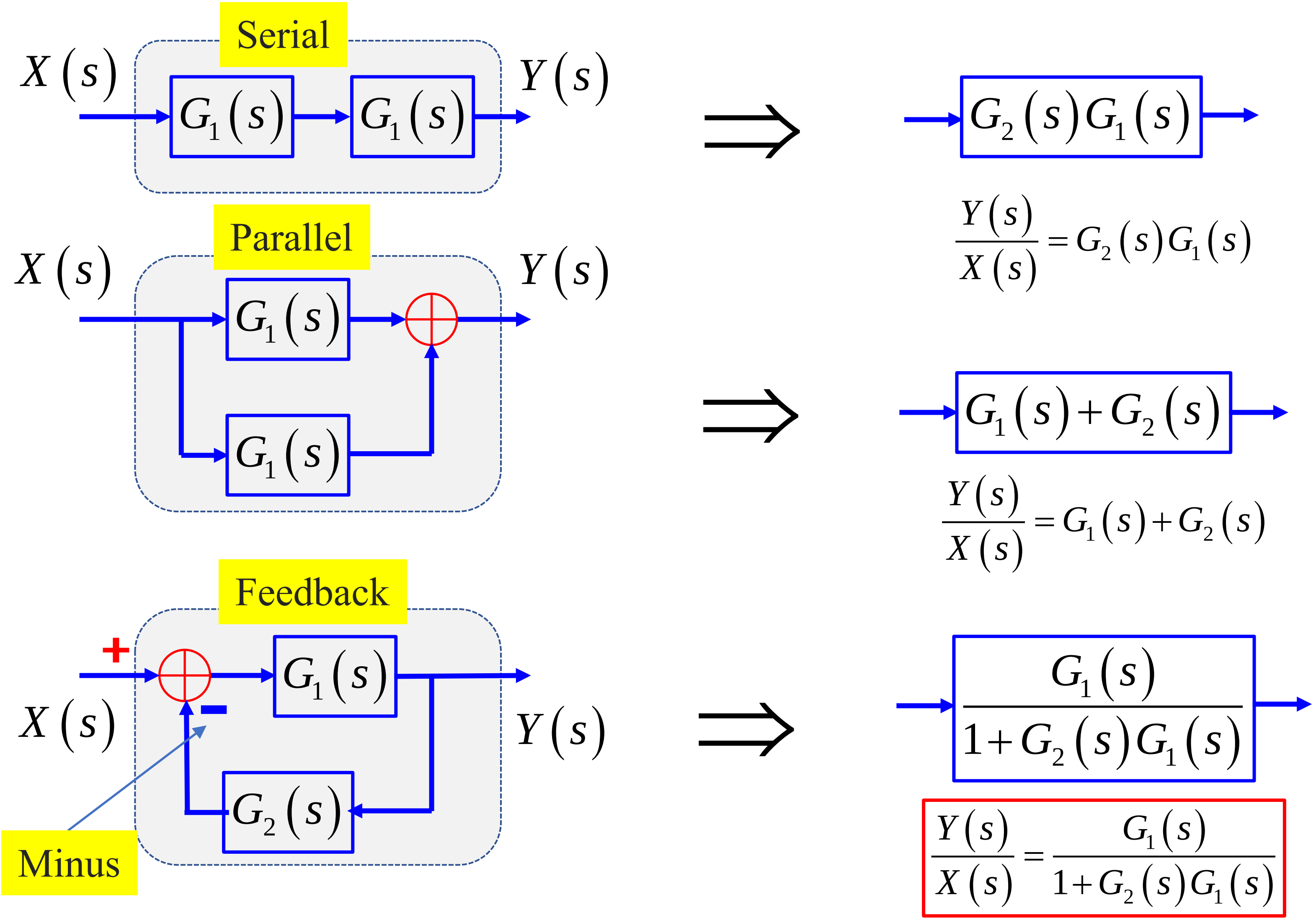
TF representation

LLRF system

- $K(s)$: Controller. generally, a proportional & integral (PI) controller
- $P(s)$: Plant you want to control
- F(s): Detector (sensor), to measured the response of the plant

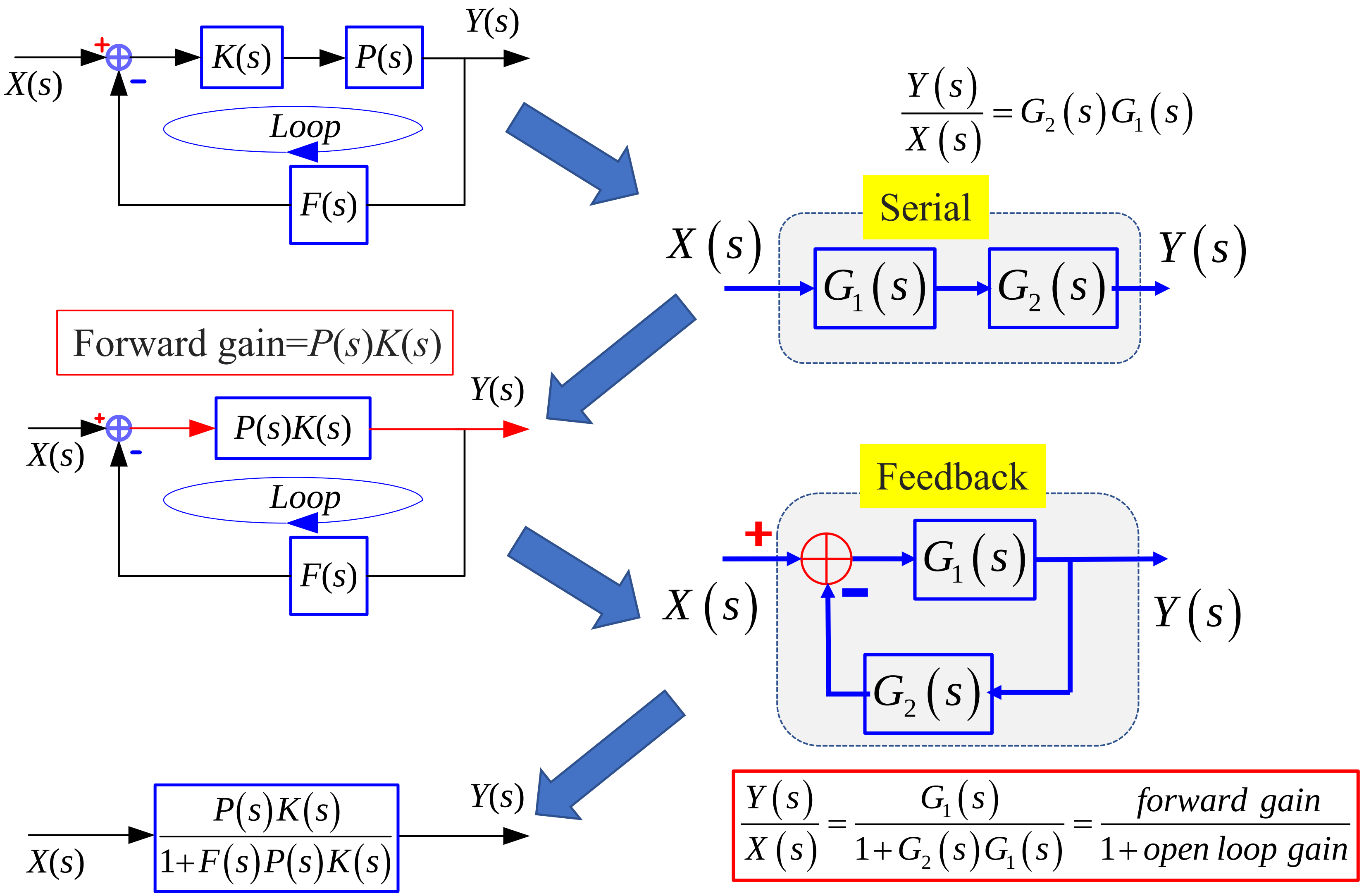
Block diagram transformations

- How to calculate the transfer function of the whole system, if we know the transfer function of each subsystem?



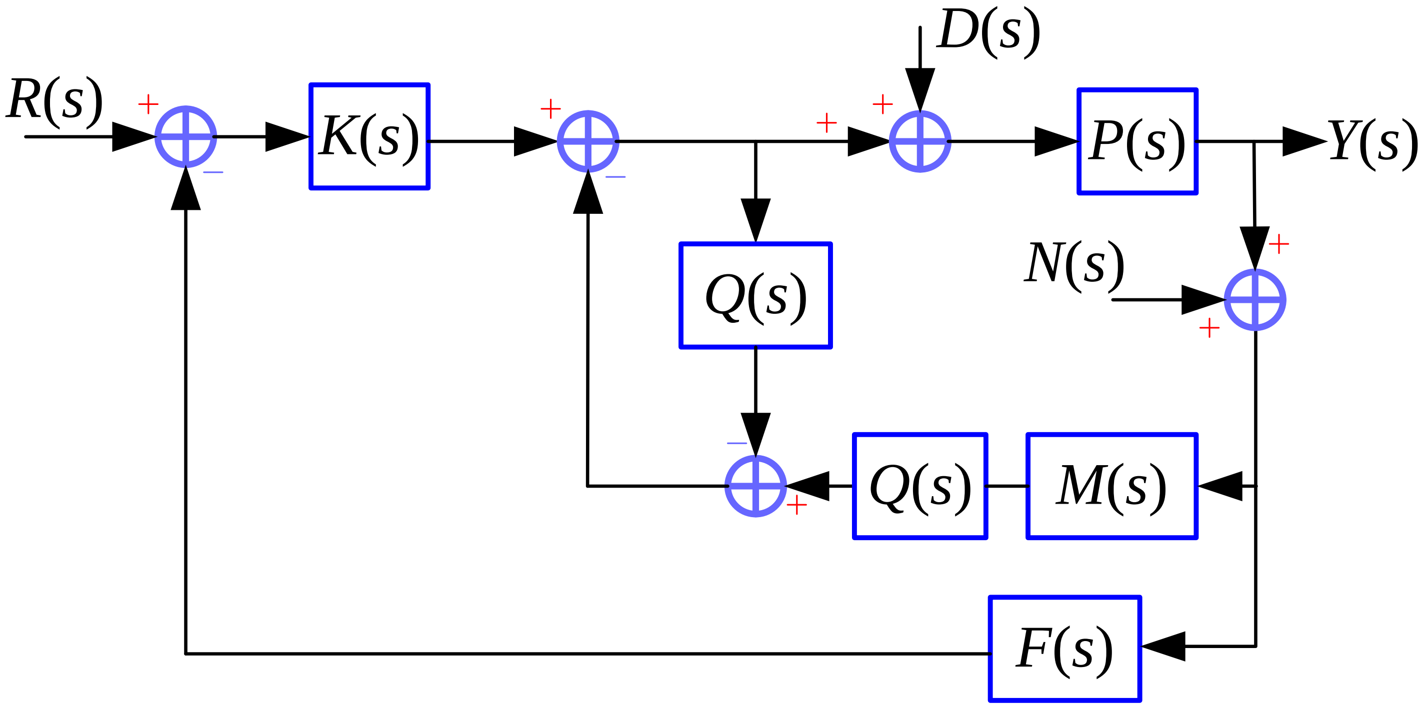
Example

- How to calibrate the transfer function from X(s) to Y(s)?



Mason’s rule

- To go a little bit further. In some cases, to calculate the transfer function is not so easy, for example (too many loops):

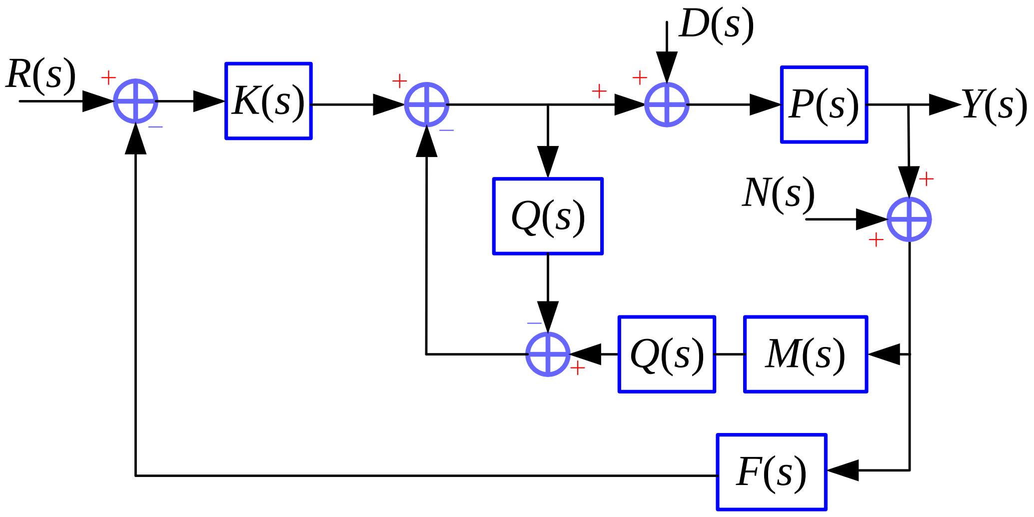


$$H_{d\to y} = \frac{Y(s)}{D(s)} = ?$$

$$H_{n\to y} = \frac{N(s)}{D(s)} = ?$$

$$H_{r\to y} = \frac{R(s)}{D(s)} = ?$$

Mason's rule



Mason's Gain Rule:

$$M = \frac{\sum_j M_j \Delta_j}{\Delta}$$

M = transfer function or gain of the system

M_j = gain of one forward path

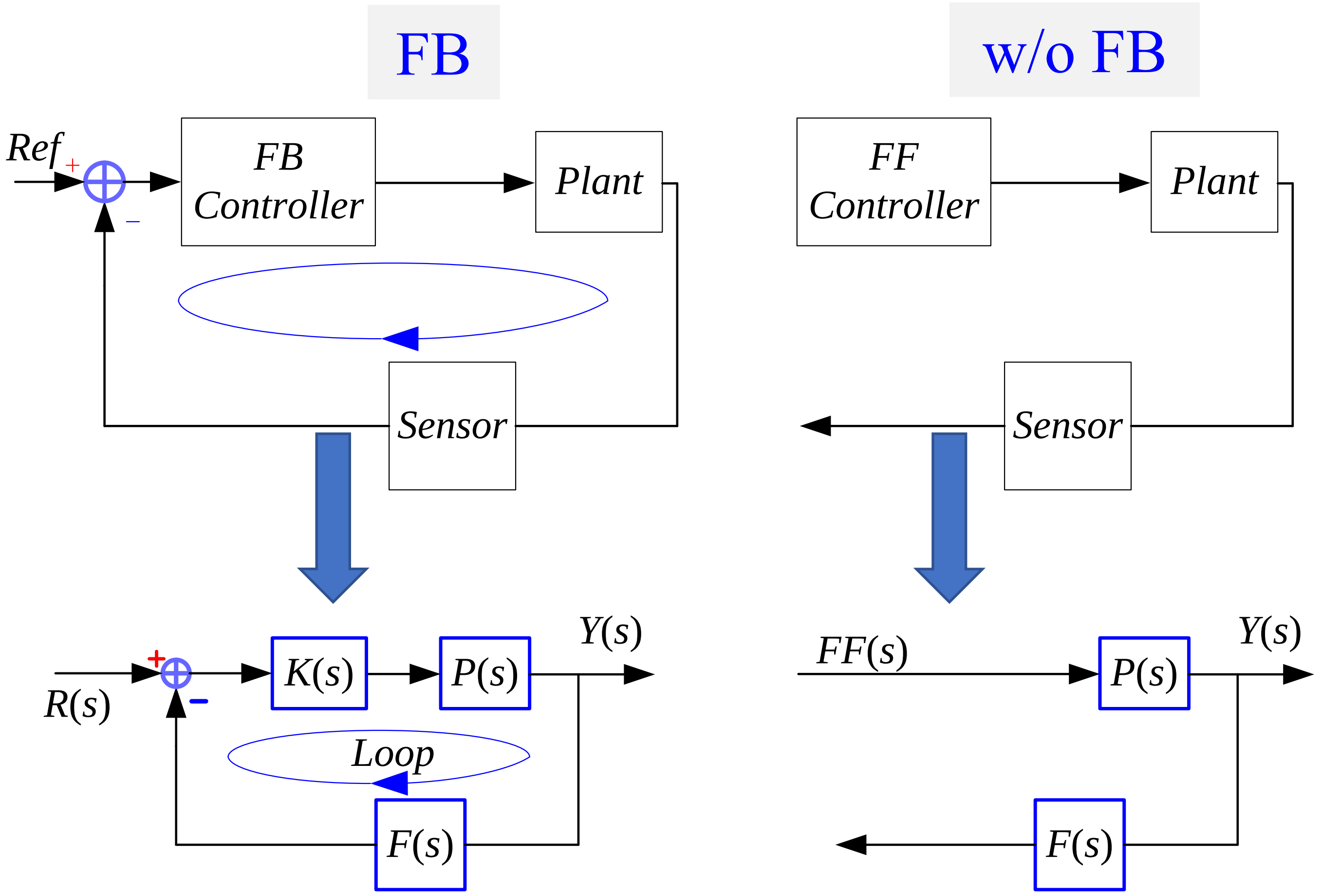
j = an integer representing the forward paths in the system

Δ_j = 1 – the loops remaining after removing path j. If none remain, then Δ_j = 1.

Δ = 1 - Σ loop gains + Σ nontouching loop gains taken two at a time - Σ nontouching loop gains taken three at a time + Σ nontouching loop gains taken four at a time - · · ·

With FB vs. w/o FB

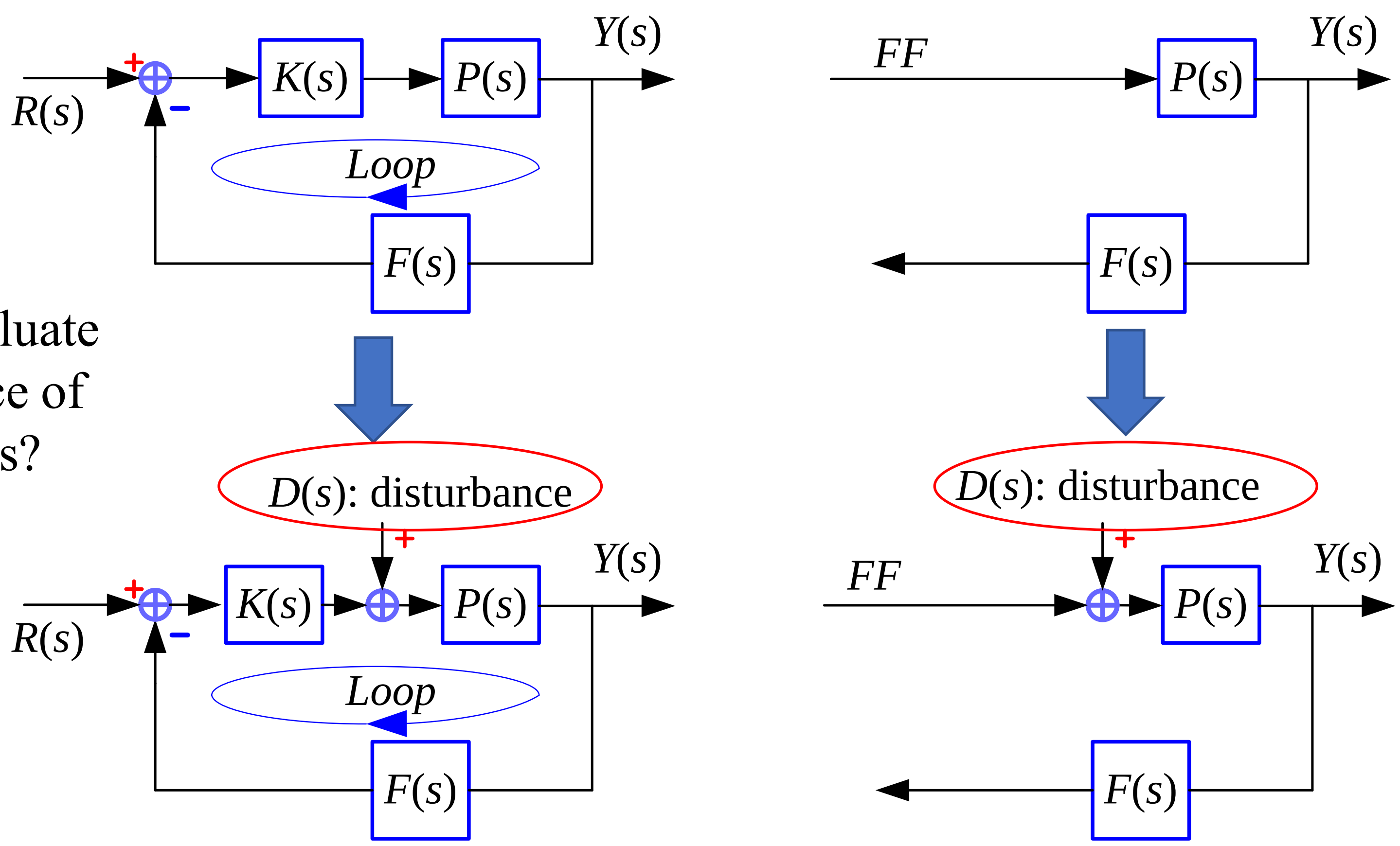
- In the following let's find an answer to the question: "Why de we need feedback?"
- We will do so by evaluating the transfer functions



Disturbance Rejection

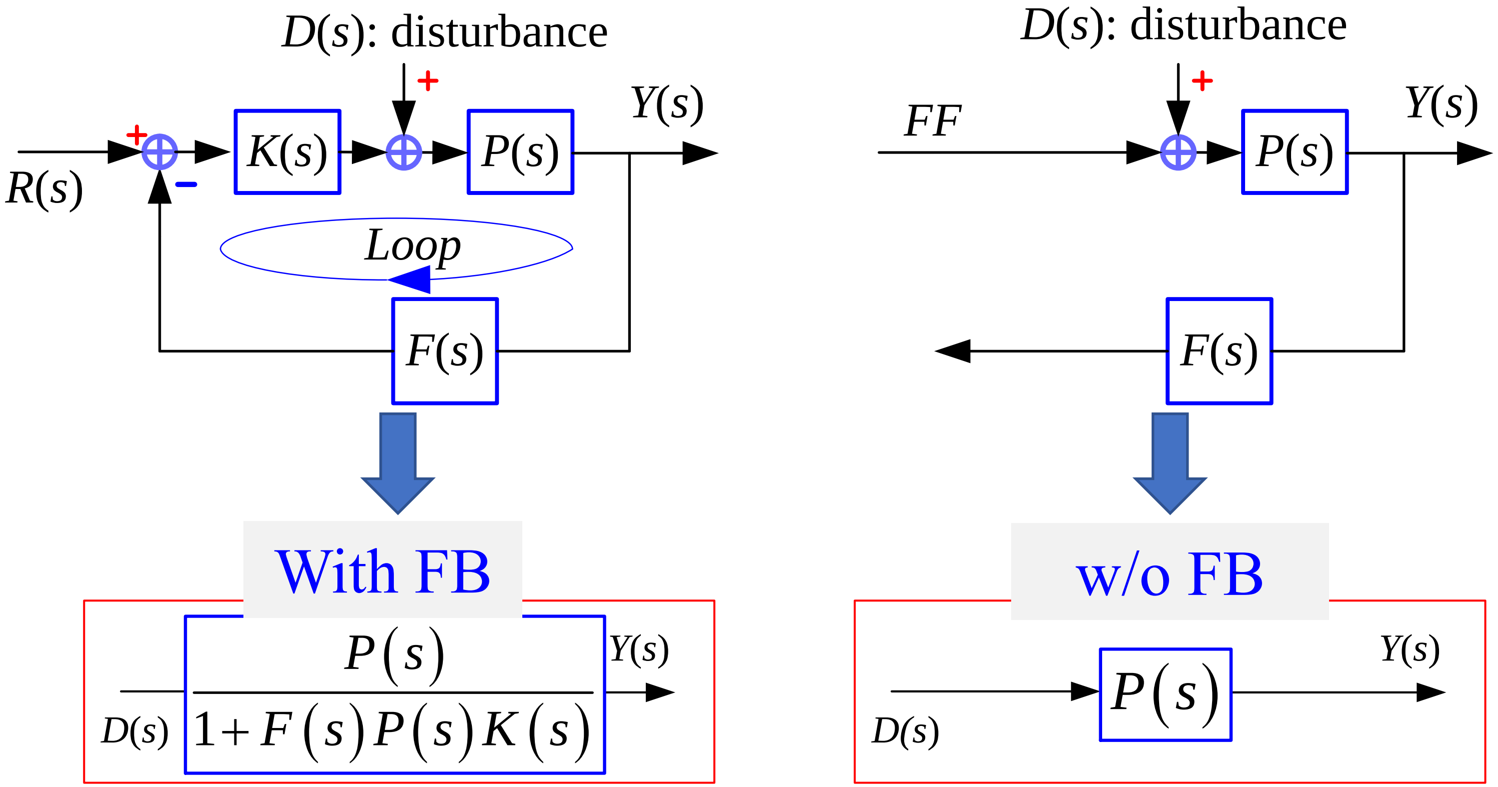
- In the real case, disturbances exists in the system (not only LLRF system, but almost al of the control system), so the actual system is something like:

How to evaluate the influence of disturbances?



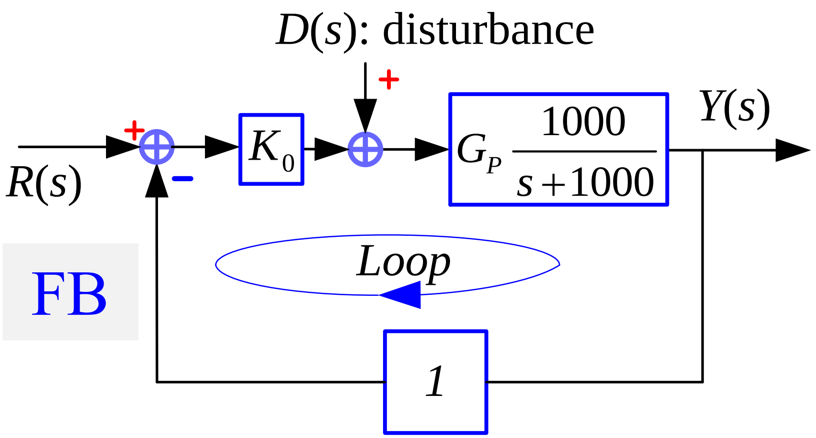
Disturbance Rejection

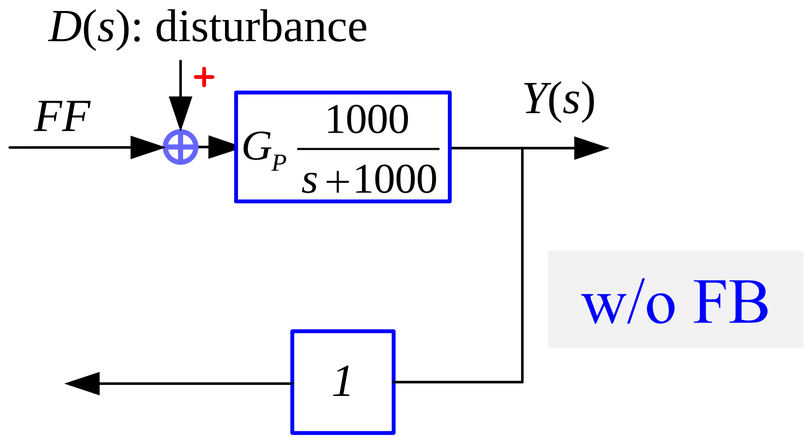
- Obviously, the existence of the disturbance (or perturbation) will influence the system, but is it same for FB and FF?

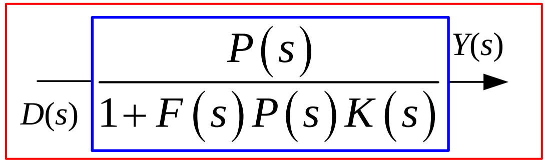


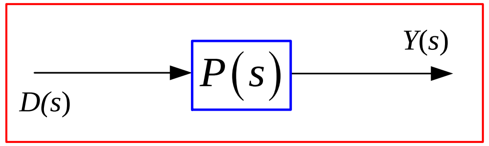
Disturbance Rejection

- Let's give each component (H(s)) some meaning







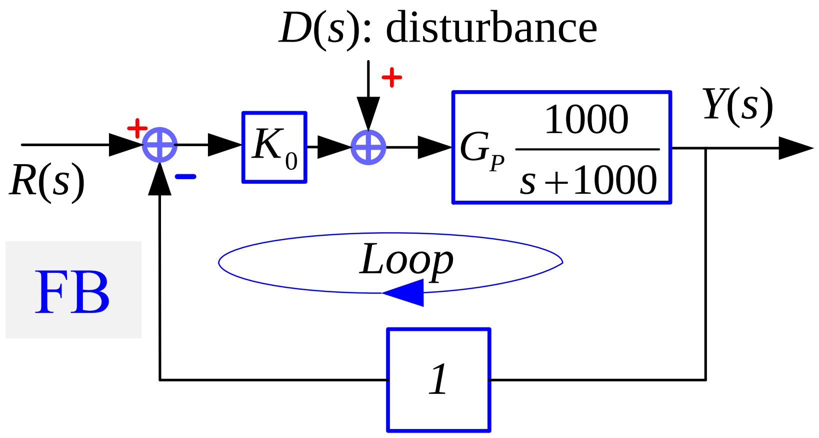


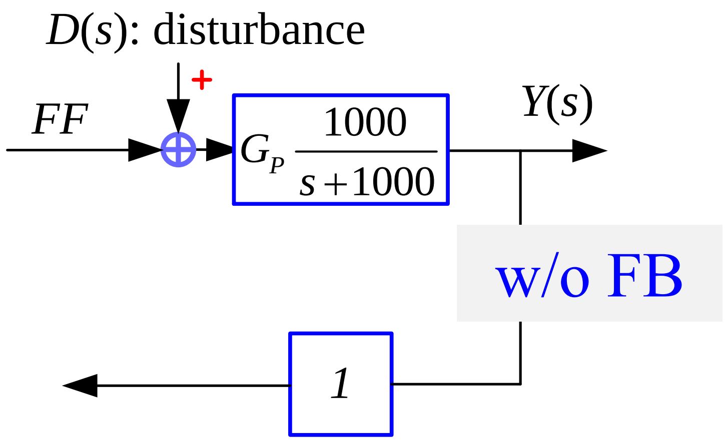
$$H_{d\to y} = \frac{Y(s)}{D(s)} = \frac{\dfrac{1000G_P}{s+1000}}{1+\dfrac{1000K_0G_P}{s+1000}} = \frac{1000G_P}{s+\left(1000+1000K_0G_P\right)}$$

$$H_{d\to y} = \frac{Y(s)}{D(s)} = \frac{1000G_P}{s+1000}$$

Disturbance Rejection

- Furthermore, if GP =1, then





$$H_{d\to y}(s)=\frac{1000}{s+(1000+1000K_0)}$$

$$H_{d\to y}(s)=\frac{Y(s)}{D(s)}=\frac{1000}{s+1000}$$

Considering the $H(j\omega)$

$$H_{d\to y}(j\omega)=\frac{1000}{j\omega+(1000+1000K_0)}$$

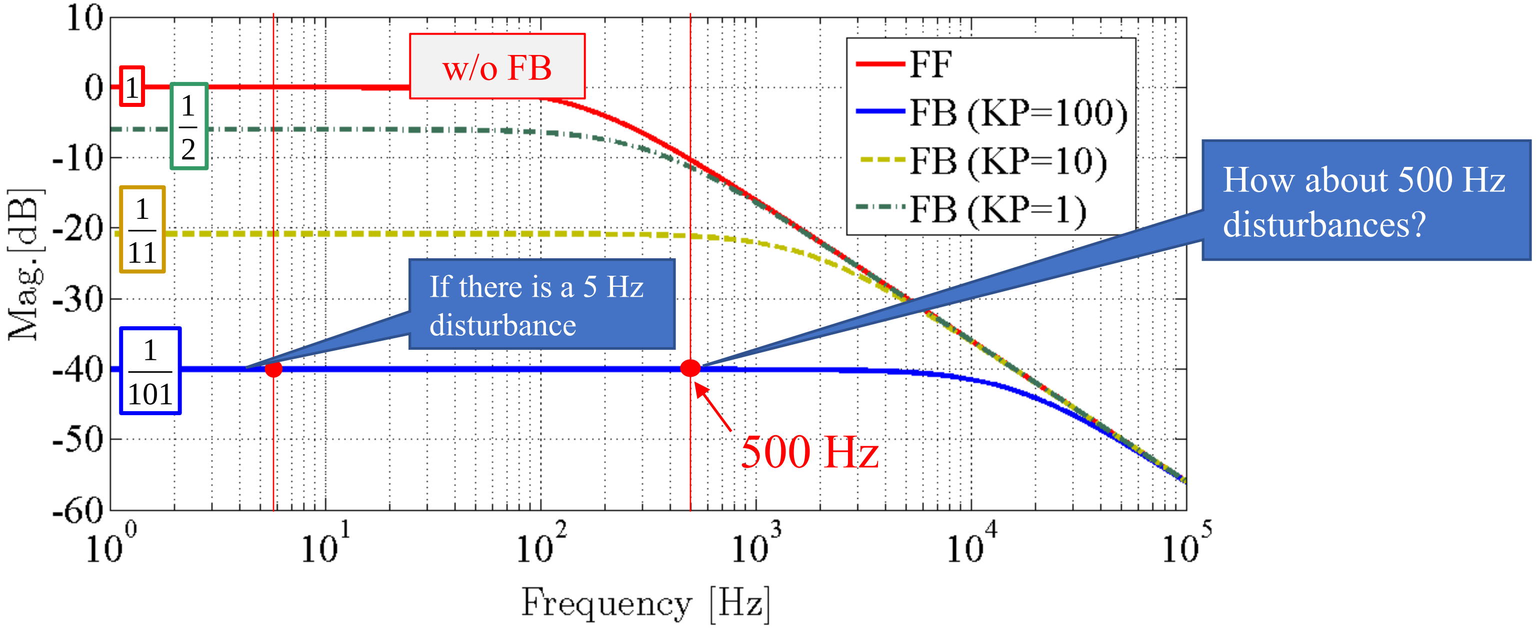
$$H_{d\to y}(j\omega)=\frac{1000}{j\omega+1000}$$

Disturbance Rejection

- The best way is to compare their frequency response or bode plot?
- Bode diagram: plots of the amplitude-frequency and phase-frequency response of the system H(s).

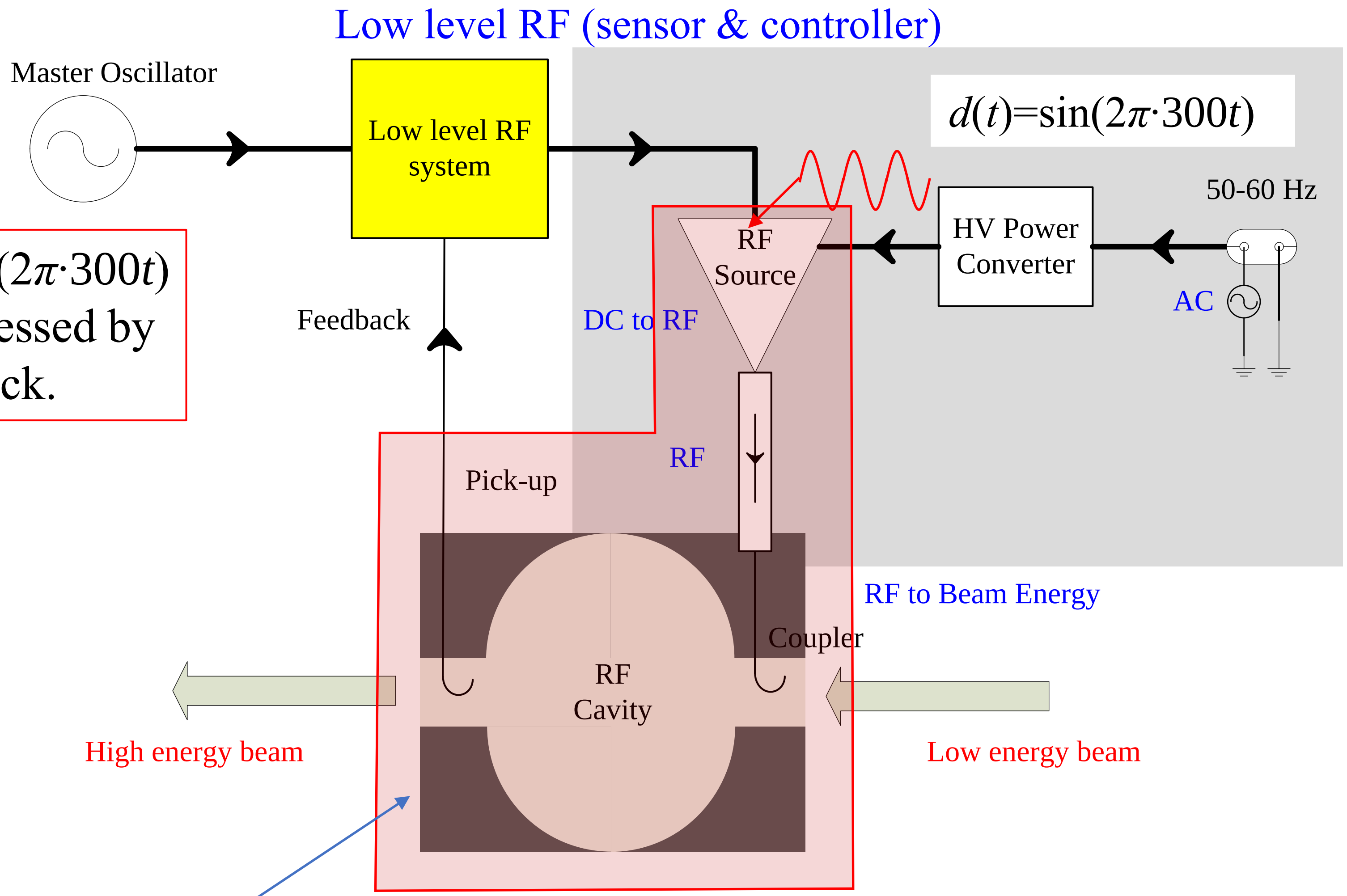
FB	w/o FB
$H_{d\to y}(j\omega)=\dfrac{1000}{j\omega+(1000+1000K_0)}$	$H_{d\to y}(j\omega)=\dfrac{1000}{j\omega+1000}$
$H_{d\to y}(j\cdot 0)=\dfrac{1}{1+K_0}\approx\dfrac{1}{K_0}(K_0 \gg 1)$	$H_{d\to y}(j\cdot 0)=1$

Let's find out the 0 Hz in the plot



Power convertor ripples in RF system

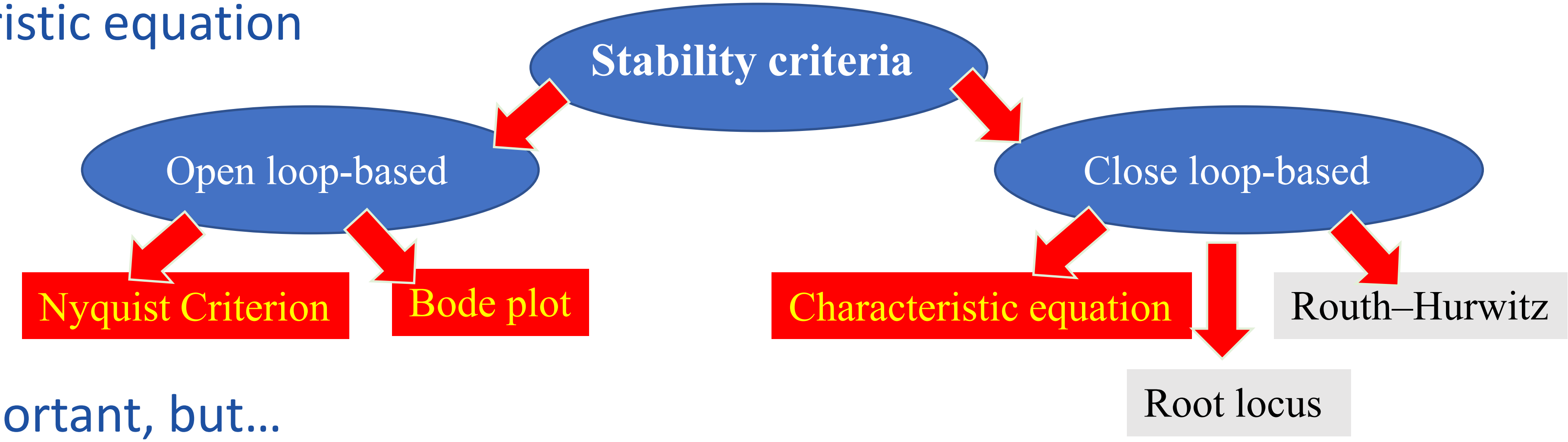
That $d(t)=\sin(2\pi\cdot 300t)$ will be suppressed by LLRF feedback.



Plant: P(s)

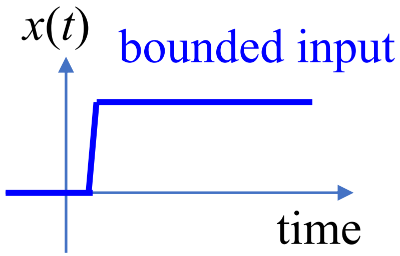
Stability Criteria

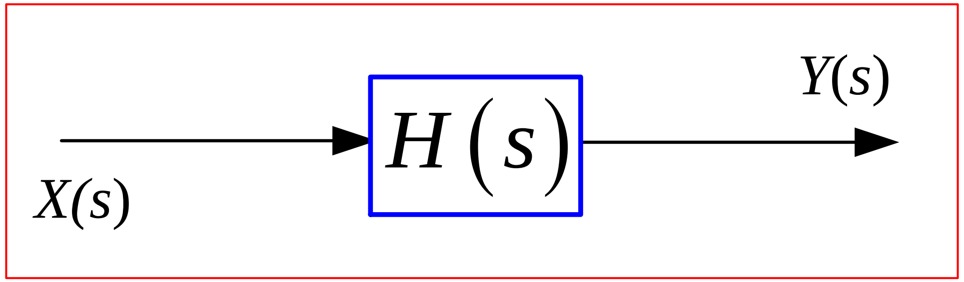
- Stability is most important for a feedback system. If the system is not stable, there is no meaning for any efforts.
- The Stability Criteria for a feedback system includes
  - Root locus
  - Solve the characteristic equation
  - Open loop bode plot & Nyquist Criterion
  - Routh–Hurwitz stability criterion
  - All of them are important, but…

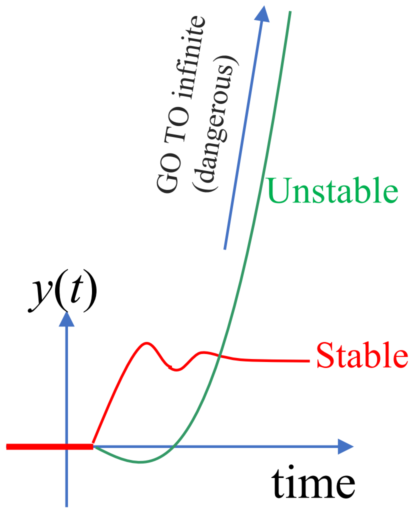


Stability Criteria (poles position)

- Definition: A stable system is a dynamic system with a bounded response to a bounded input.





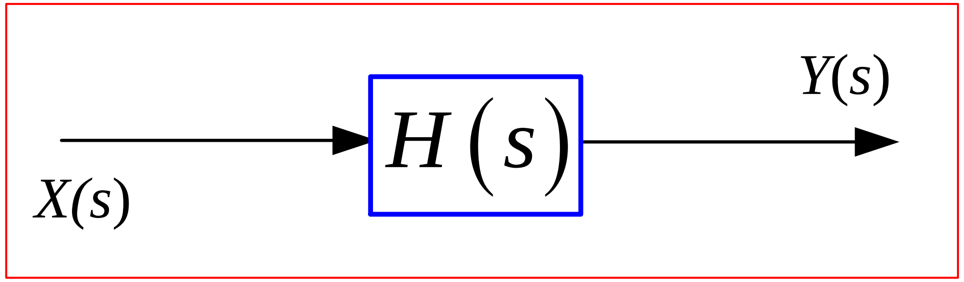


We can not try all of the bounded input signal

$$H(s) = \frac{numerator}{denominator} = \frac{b_m s^m + b_{m-1} s^{m-1} + b_{m-2} s^{m-2} + \cdots b_1 s + b_0}{s^n + a_{n-1} s^{n-1} + a_{n-2} s^{n-2} + \cdots a_1 s + a_0}$$

Characteristic equation

Stability Criteria (poles position)



$$H(s) = \frac{numerator}{denominator} = \frac{b_m s^m + b_{m-1}s^{m-1} + b_{m-2}s^{m-2} + \cdots b_1 s + b_0}{s^n + a_{n-1}s^{n-1} + a_{n-2}s^{n-2} + \cdots a_1 s + a_0}$$

$$= \frac{K(s - z_1)(s - z_2)\cdots(s - z_{n-1})(s - z_n)}{(s - p_1)(s - p_2)\cdots(s - p_{n-1})(s - p_n)}$$

$H(s)\big|_{s=p} = \infty$ Poles

$H(s)\big|_{s=z} = 0$ zeros

Complex number

A necessary and sufficient condition for a feedback system to be stable is that all the **poles** of the system transfer function have negative real parts.

Example

- The system H (s) should be stable because all of the poles is in the have negative real part.
- The system G(s) should be unstable because some poles have positive real part.

$$H(s) = \frac{s+1.5}{s^3+4s^2+6s+4} = \frac{s-(-1.5)}{\left[s-(-1+i)\right]\cdot\left[s-(-1-i)\right]\left[s-(-2)\right]}$$

$Three\ poles: -1 \pm i, -2$

$One\ zeros: -1.5$

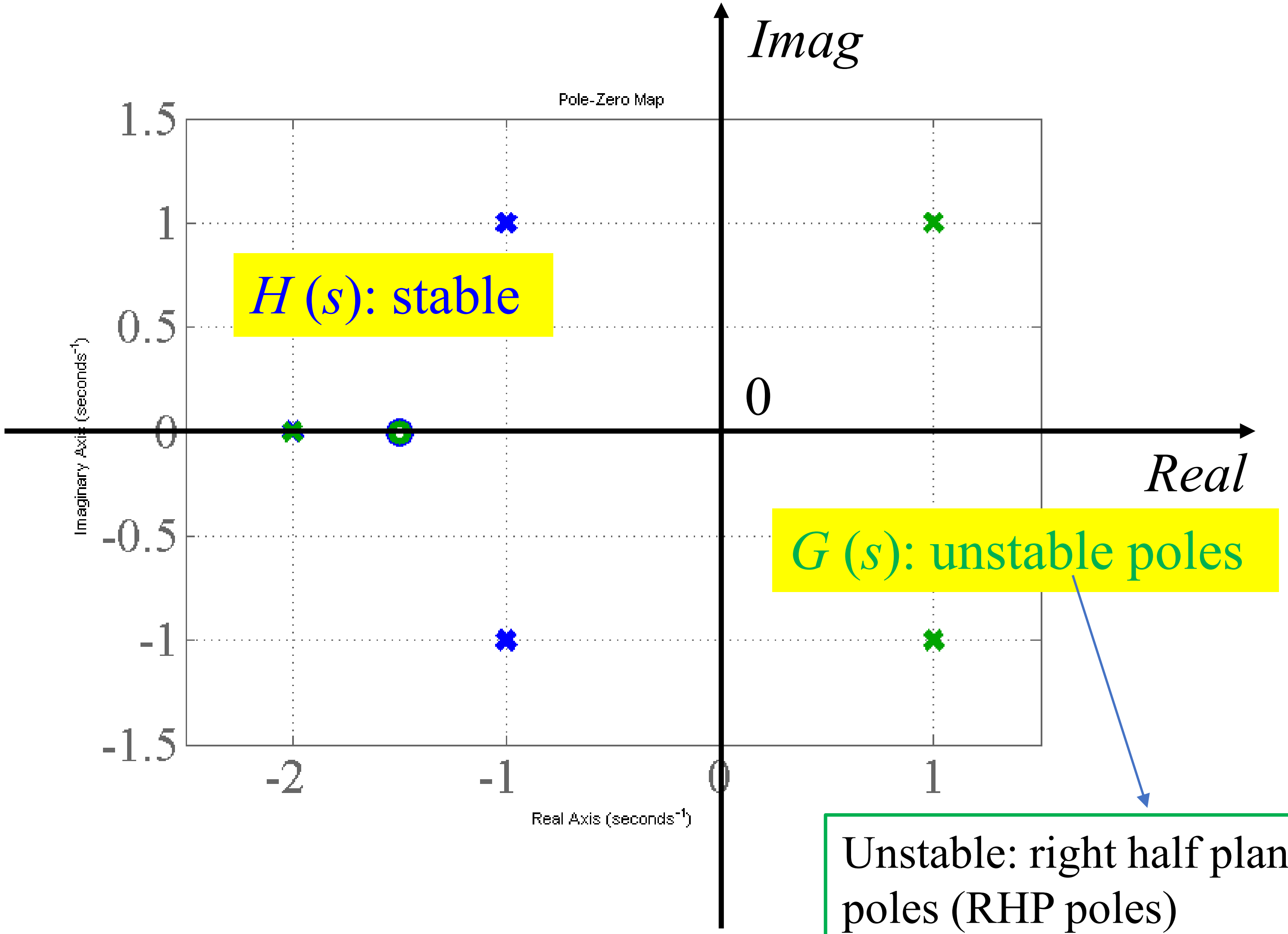
$$G(s) = \frac{s+1.5}{s^3-2s+4} = \frac{s-(-1.5)}{\left[s-(1+i)\right]\cdot\left[s-(1-i)\right]\left[s-(-2)\right]}$$

positive real part

$Three\ poles: 1 \pm i, -2$

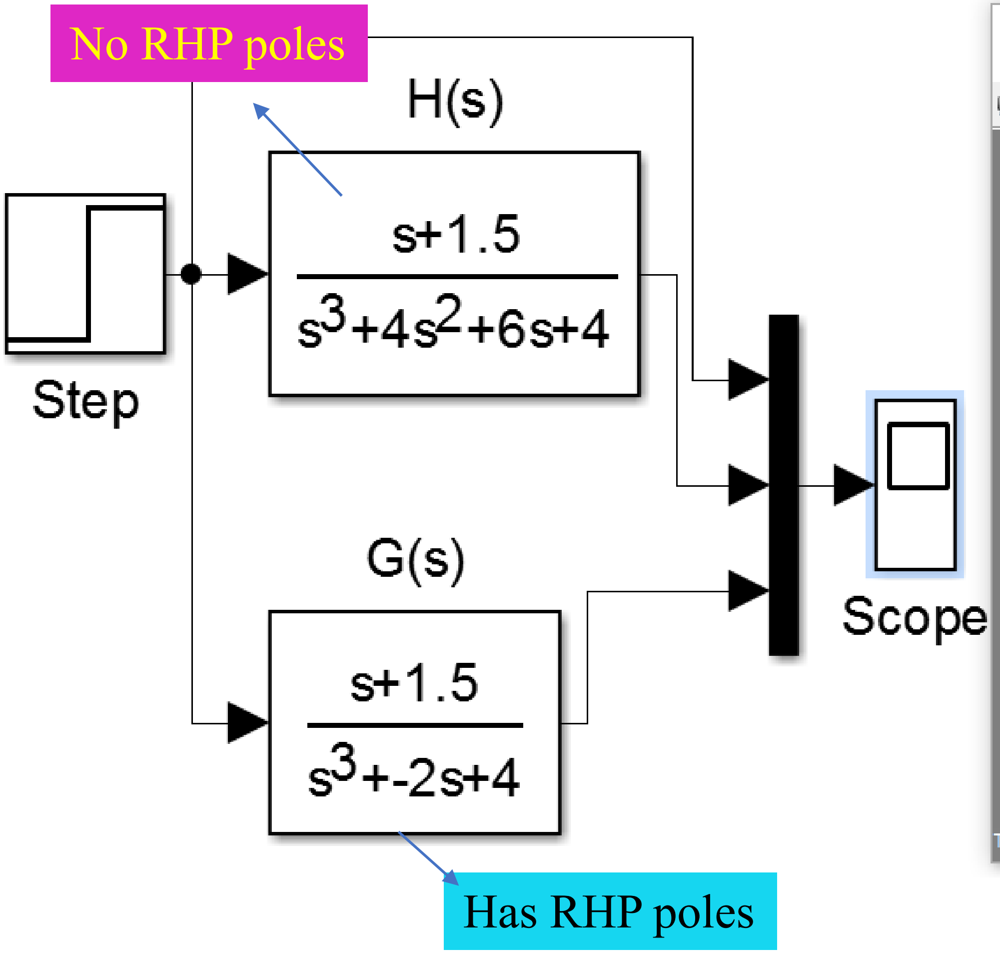
$One\ zeros: -1.5$

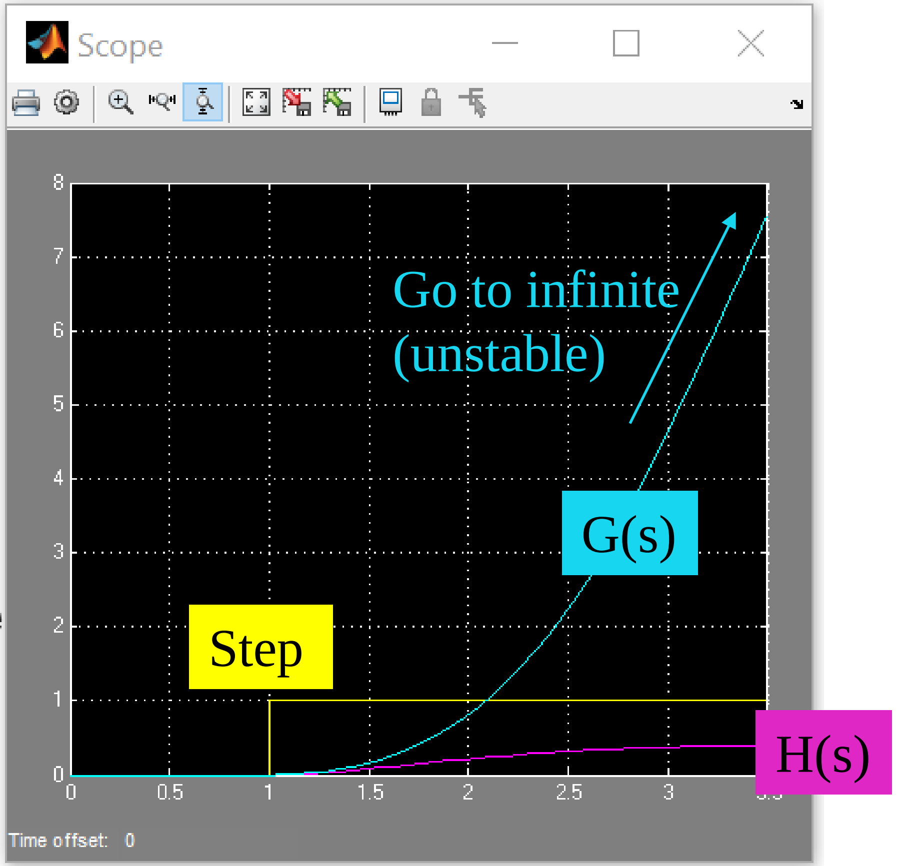
Example (pole-zero map)



Unstable: right half plane poles (RHP poles)

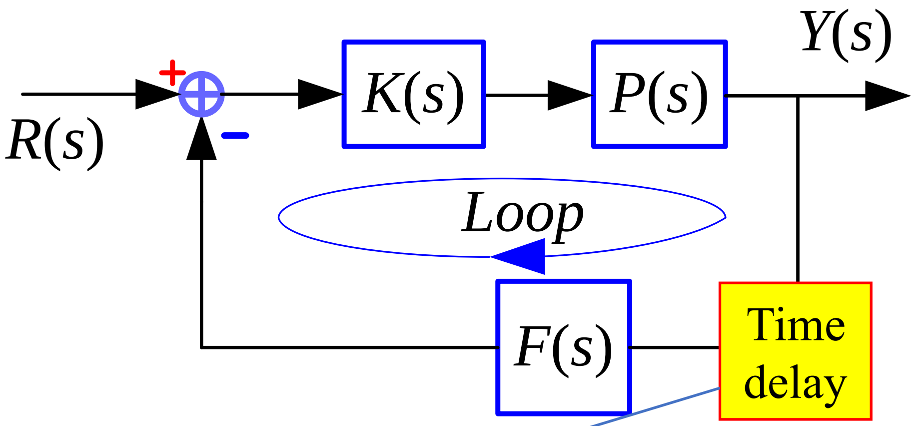
Example (pole-zero map)





Stability Criteria (bode plot)

- It is easy to solve the linear equation, but can not answer questions like “if I increase the gain in K(s), what would happen? The FB system is still stable or not? If not, why it becomes unstable? ”.
- Furthermore, in some system, the characteristic equation is not like a polynomial, thus it is difficult find out the poles directly (such as system with time delay).

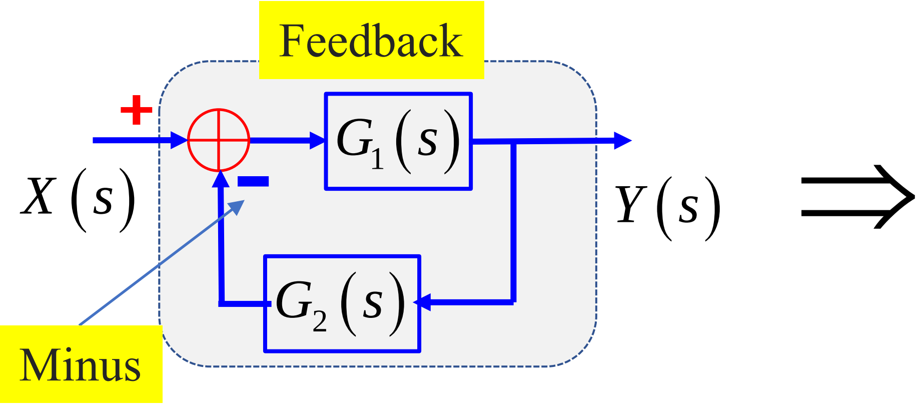


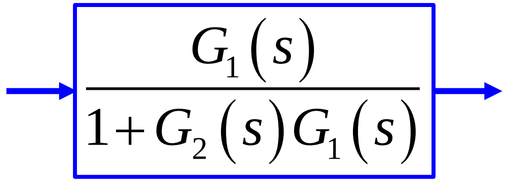
$$NOT\ like\ H_{delay}(s) = \frac{b_m s^m + b_{m-1} s^{m-1} + b_{m-2} s^{m-2} + \cdots b_1 s + b_0}{s^n + a_{n-1} s^{n-1} + a_{n-2} s^{n-2} + \cdots a_1 s + a_0}$$

Stability Criteria (bode plot)

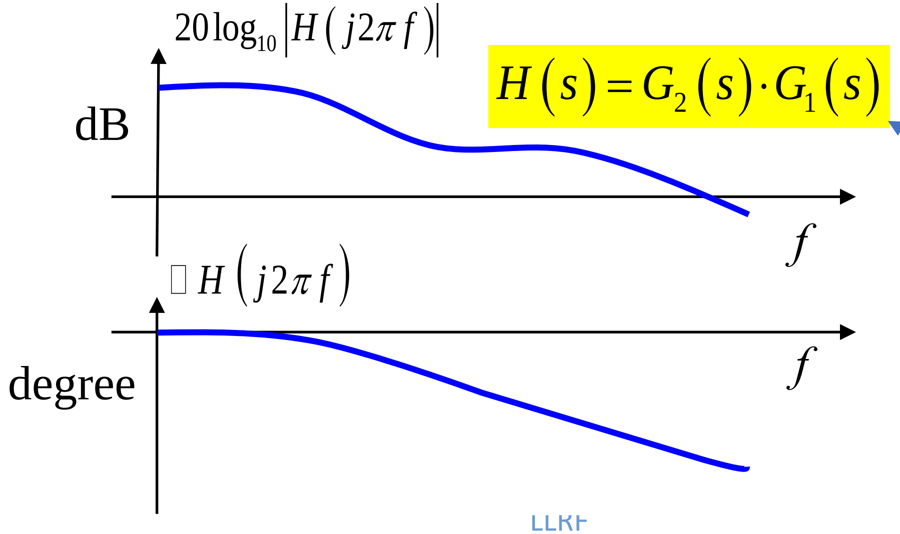
$$H(s)\big|_{s=j\omega} = H(j\omega) = |H(j\omega)|e^{j\angle H(j\omega)} = |H(j2\pi f)|e^{j\angle H(j2\pi f)}$$

- Still remember the bode plot? It is a very popular method to judge the system stability and also analyze the system performance by its open loop TF.





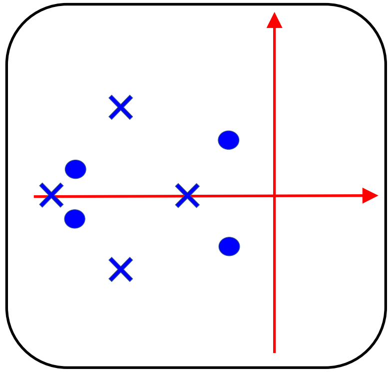
$$\frac{Y(s)}{X(s)} = \frac{G_1(s)}{1+G_2(s)G_1(s)} = \frac{forward\ gain}{1+open\ loop\ gain}$$



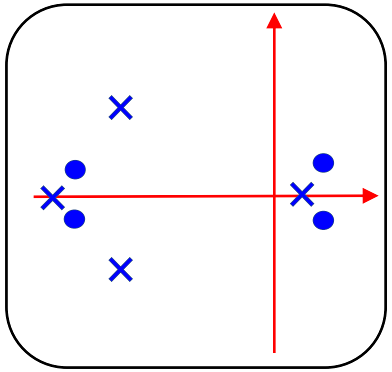
IMPORTANT:
open loop TF

Stability Criteria (bode plot)

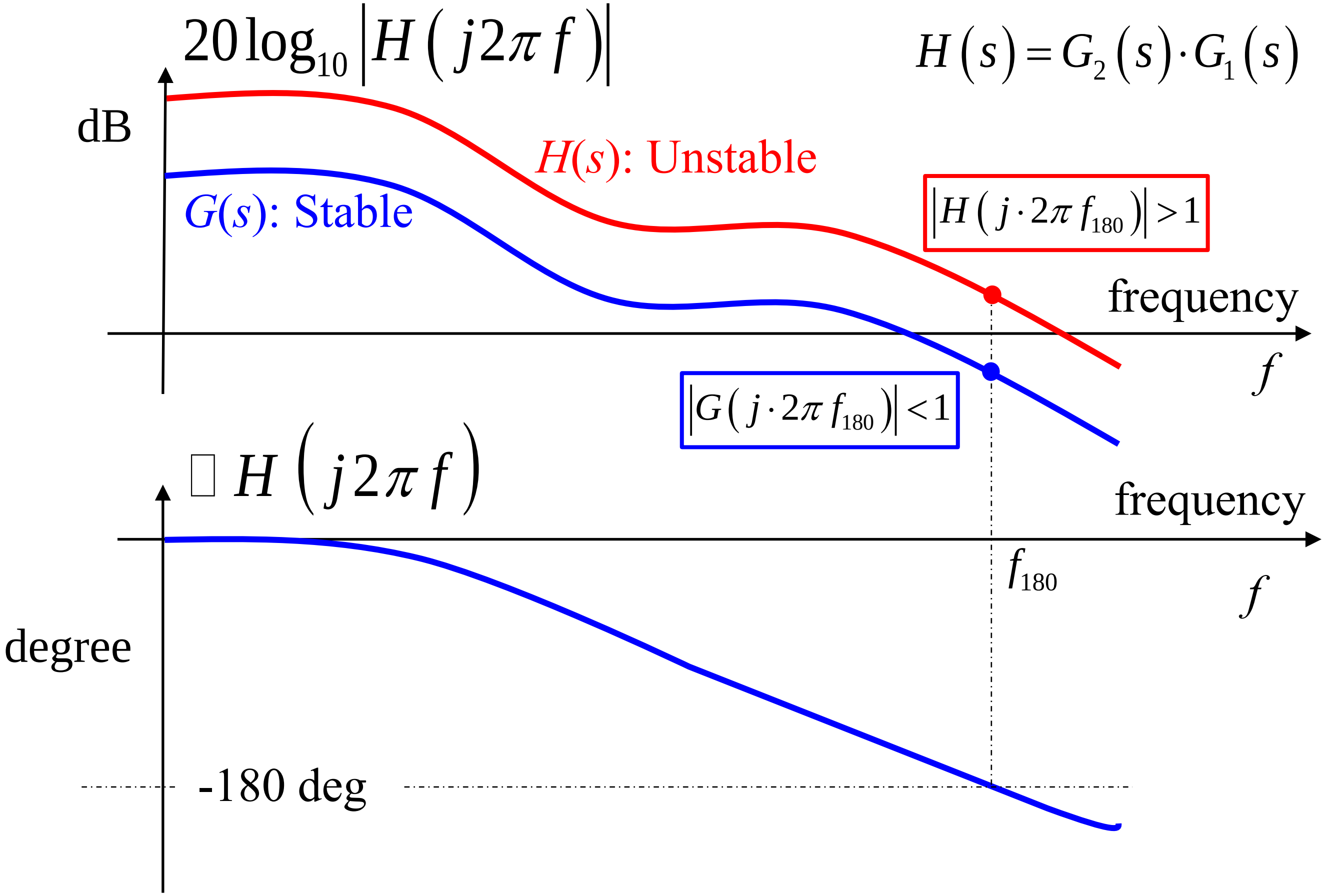
- Suitable for bode plot:
  1) Minimum phase,
  2) SISO system.



minimum phase

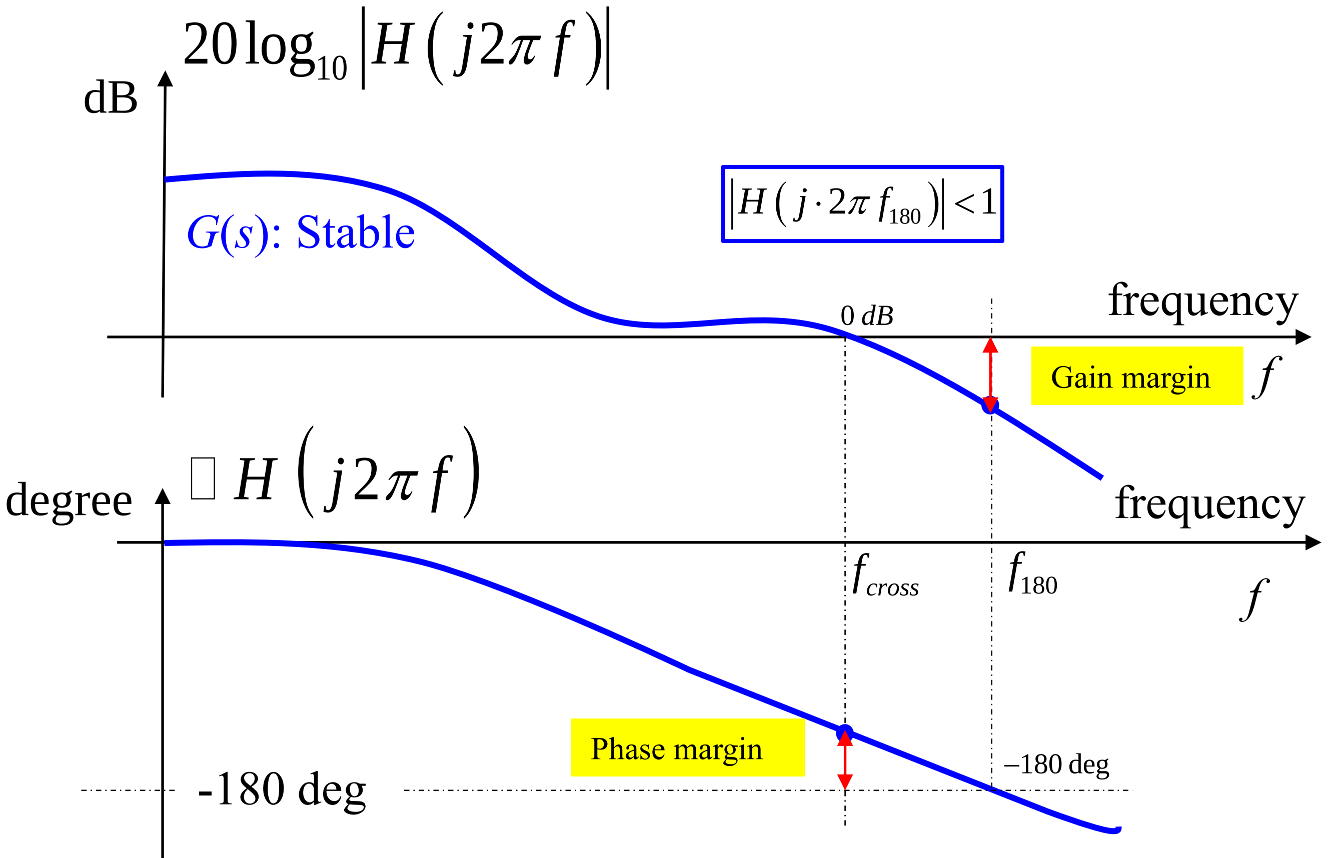


Non-minimum phase



The closed loop is stable, if the open loop gain is less than 1 (0 dB) at a phase of the open loop of -180 degree (or +180, -540, etc.).

Gain Margin and Phase Margin



Gain Margin: $0-20\log_{10}|G(j\cdot 2\pi f_{180})|$

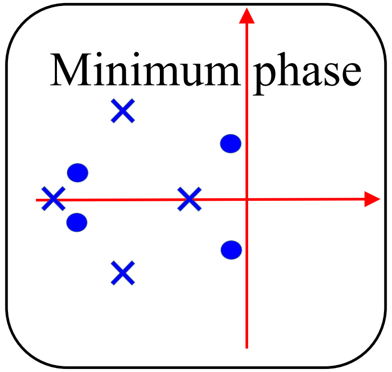
Phase Margin $180+\angle G(j\cdot 2\pi f_{cross})$

Larger margin→ Better robustness

Stability Criteria (Nyquist diagram)

$$H_{OL}(s) = \frac{0.9(1+0.4s)(1+2.5s)}{(s^2+s+1)(1+1.3s)(1.2s-1)}$$

- Benefits of Nyquist diagram
  - More information
  - Non-minimum phase okay
  - MIMO also okay



Bode $H_{OL}(j\omega) = |H_{OL}(j\omega)| e^{j\angle H_{OL}(j\omega)}$

Nyquist $H_{OL}(j\omega) = \mathrm{Re}(H_{OL}(j\omega)) + j \cdot \mathrm{Im}(H_{OL}(j\omega))$

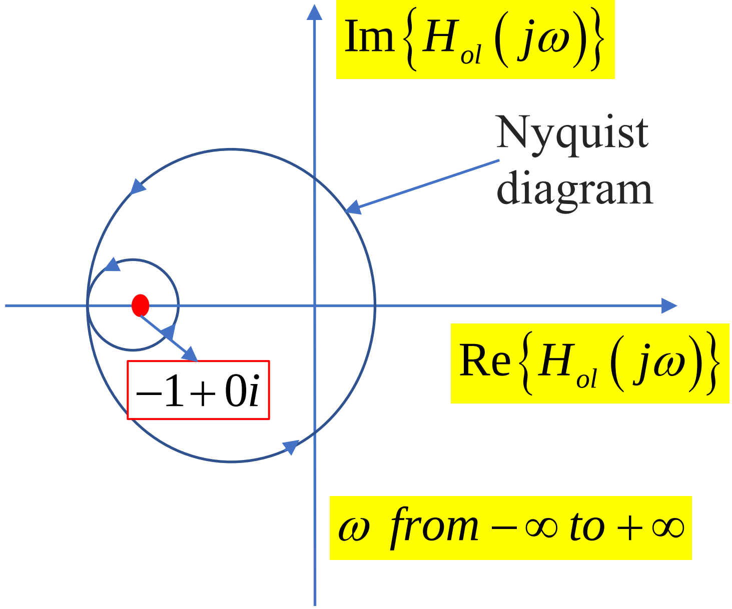
$P_{cl} = P_{ol} - N,$

$P_{cl} = \textit{number of the close loop RHP poles}$

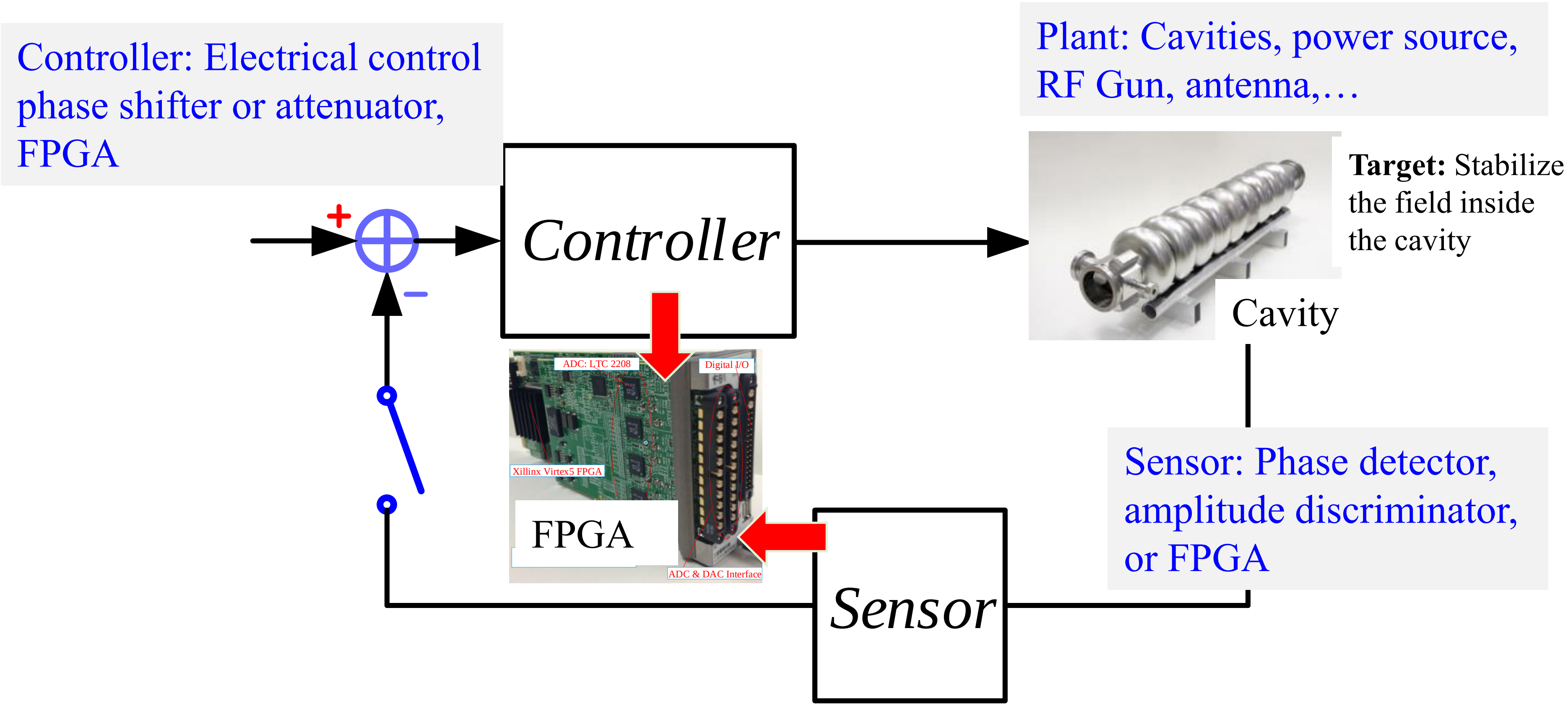
$P_{ol} = \textit{number of the open loop RHP poles}$

$N = \textit{times to encircle the } (-1+0i)$

Clockwise:-1
Anti-clockwise:+1

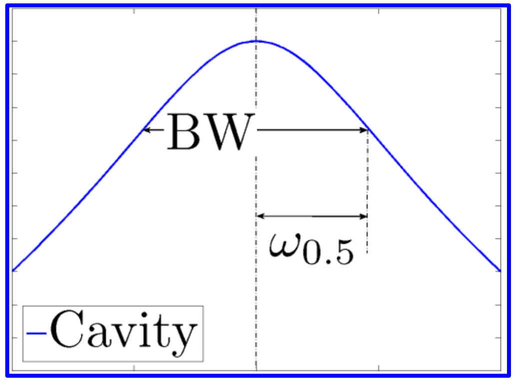


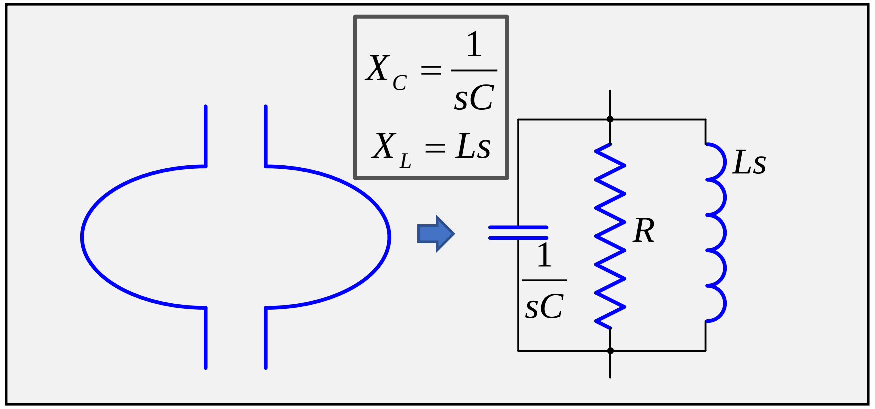
LLRF system

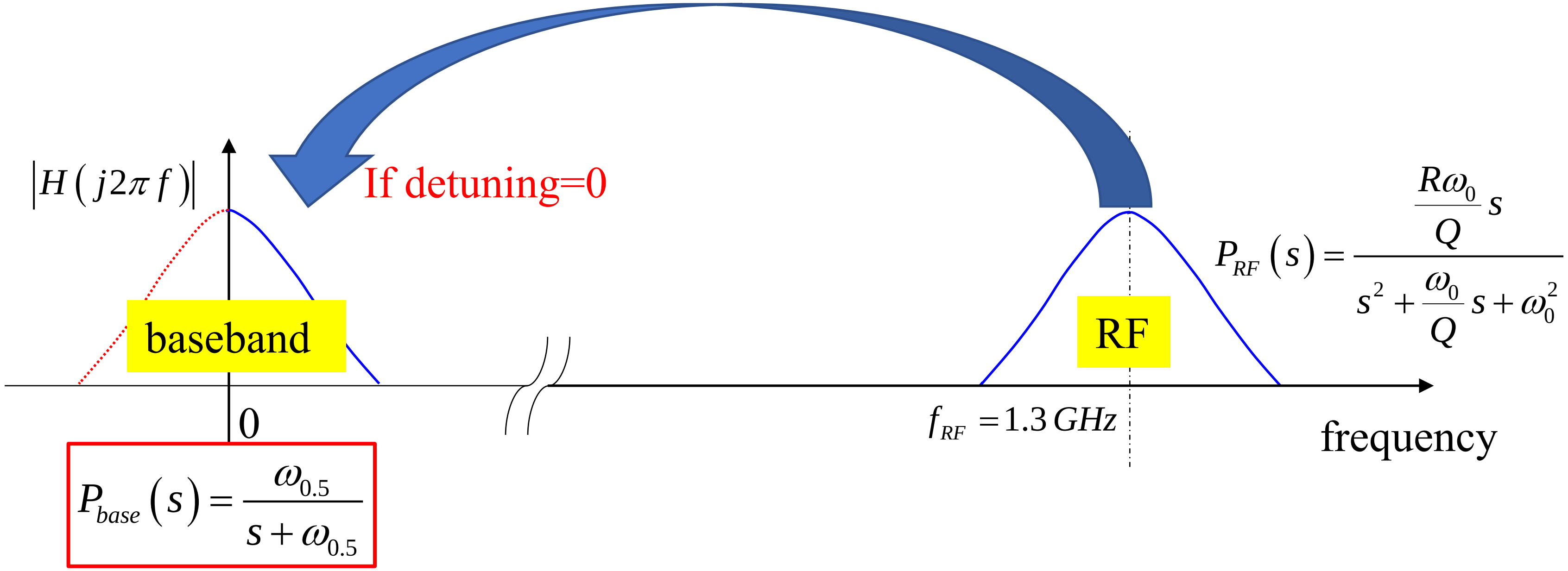

Controller: Electrical control phase shifter or attenuator, FPGA
Plant: Cavities, power source, RF Gun, antenna,…
+
−
Controller
ADC: LTC 2208
Digital I/O
Xilinx Virtex5 FPGA
FPGA
ADC & DAC Interface
Target: Stabilize the field inside the cavity
Cavity
Sensor: Phase detector, amplitude discriminator, or FPGA
Sensor

Cavity (detuning=0)

- Cavity is like a parallel resonance circuit.
- First of all, we consider the simplest case: no cross component (detuning=0)

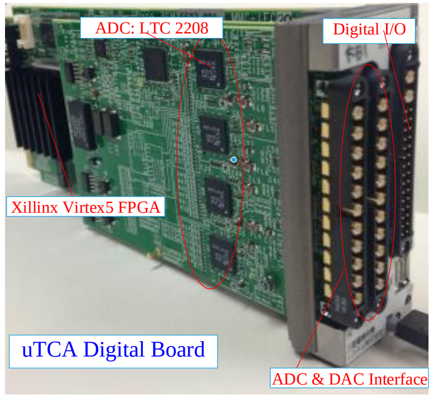






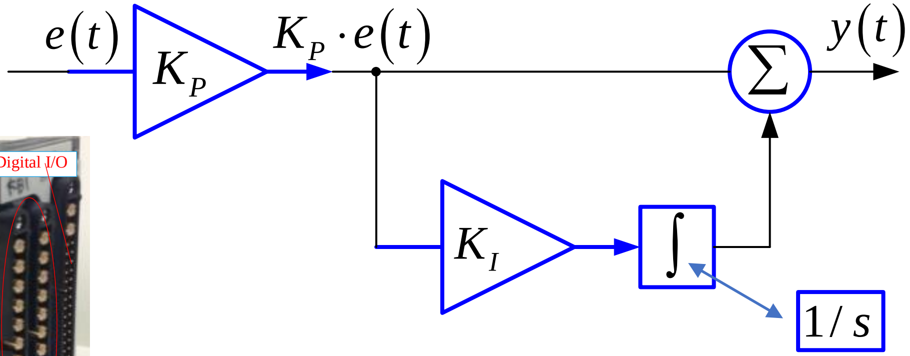
PI controller

- PI control is very popular in the FB control system (& LLRF FB control system)



Usually performed in the FPGA (or DSP)

PI Controller



$$y(t) = K_P \cdot e(t) + K_P \cdot K_I \cdot \int e(t)\,dt$$

$$Y(s) = K_P \cdot E(s) + K_P \cdot K_I \cdot \frac{E(s)}{s}$$

$$K(s) = \frac{Y(s)}{E(s)} = K_P\left(1 + \frac{K_I}{s}\right)$$

Transfer function

Lapalce Transform

$$\int f(t)\,dt \Leftrightarrow \frac{F(s)}{s}$$

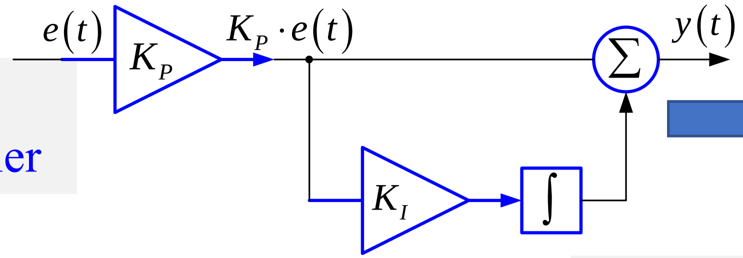
Analytical Study (components)

- PI control is very popular in the FB control system (& LLRF FB control system)
- Cavity and detector are a low-pass filters with different bandwidth.

Sys. Components

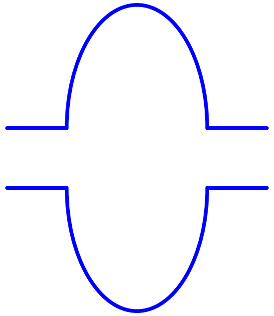
Transfer function

PI Controller

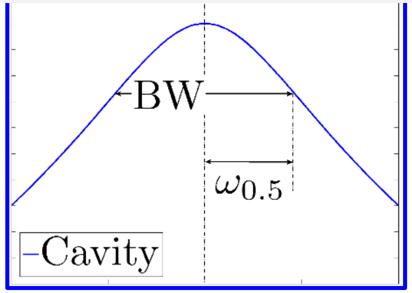


$$K(s) = K_P\left(1 + \frac{K_I}{s}\right)$$

Cavity



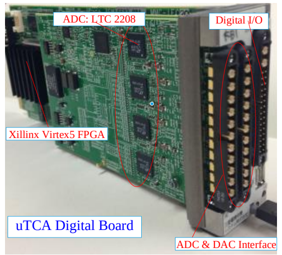
Frequency response

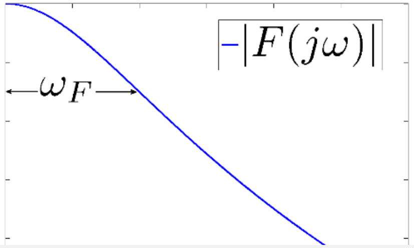


$$P(s) = \frac{\omega_{0.5}}{s + \omega_{0.5}}$$

Half bandwidth

Detector



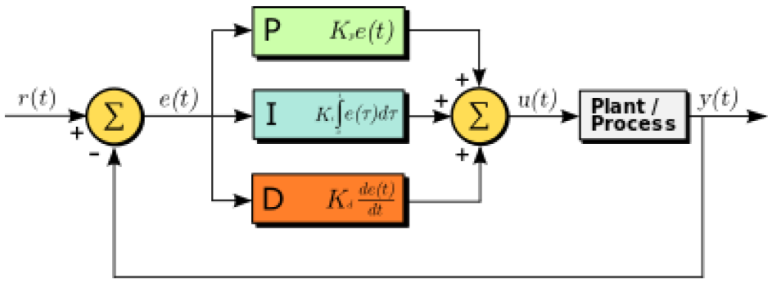


Frequency response

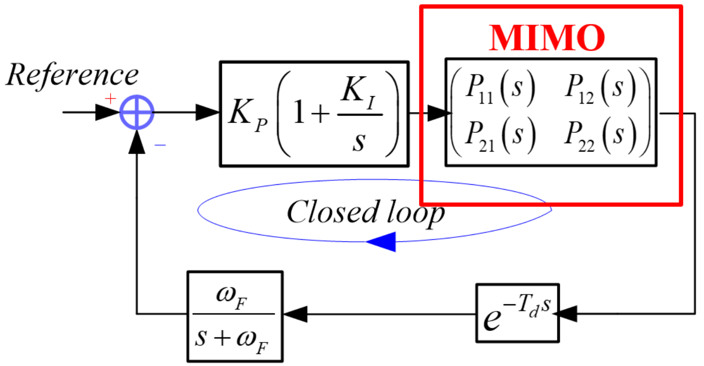
$$F(s) = \frac{\omega_F}{s + \omega_F}$$

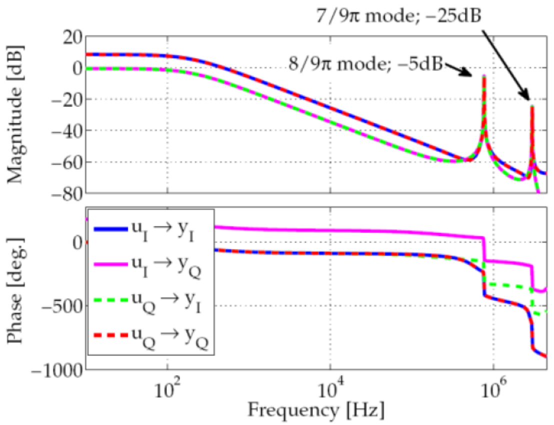
Further Types of Feedback Controller

- Classic feedback controller
  - P: proportional controller output scales with the input error
  - I: integral controller minimizes the steady state error left from the proportional controller correction
  - D: differential controller tries to minimize rapid error changes



- Modern feedback controller
  - E.g. 2x2 MIMO (multiple input multiple output) controller (can do PID and more)
    - Cancellation of a passband mode
    - Cancellation of cross coupling between inputs

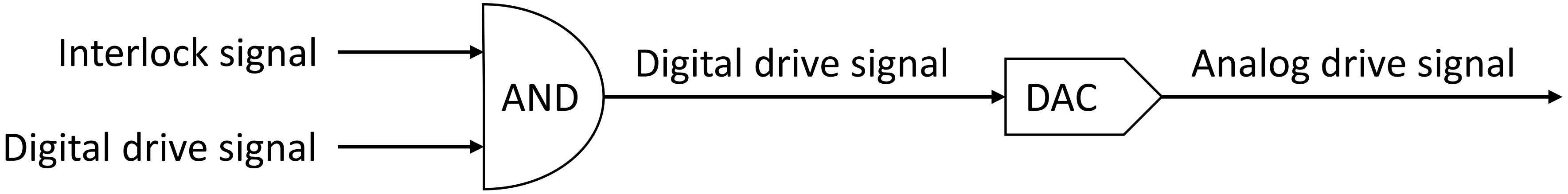




Example Features of an LLRF System

Interlock

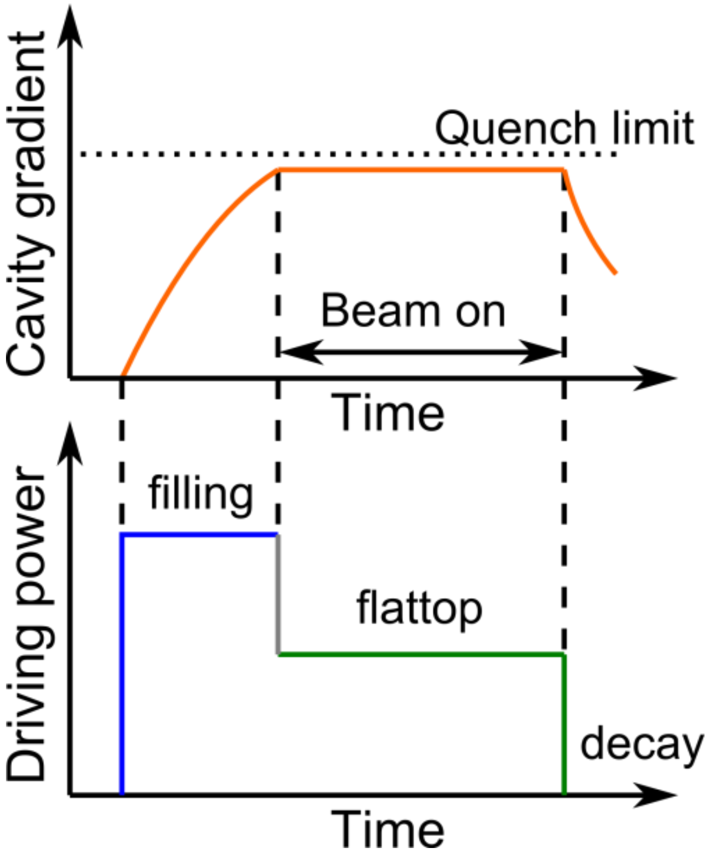
- Every facility typically has a Personal Protection System (PPS) and most facilities have a Machine Protection System (MPS)
- Since the LLRF system is a sub-system of a facility, it must have interlock capabilities
- Typically hardwired in hardware or firmware
  - E.g., logical 'and' just before the DAC

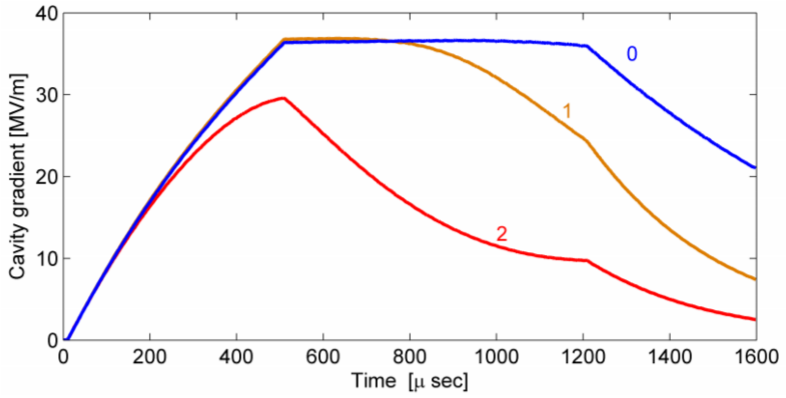


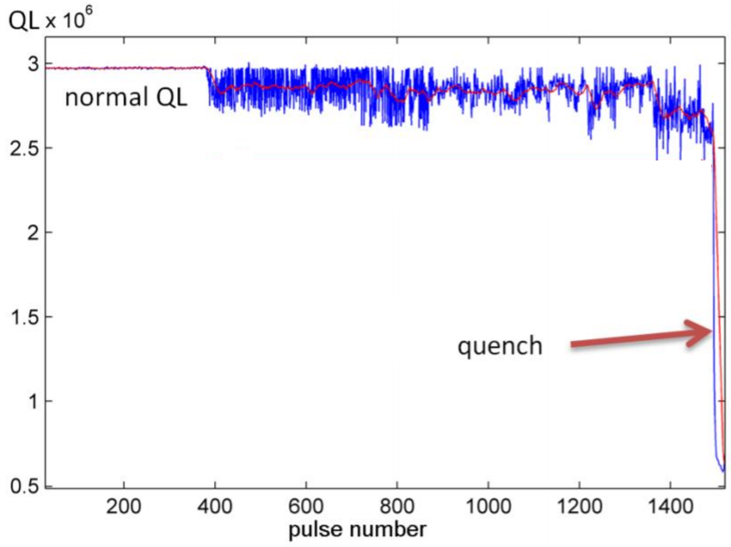
Exception Prevention and Handling

- The LLRF system should prevent certain exceptions
  - Limiters
    - Maximal setpoint voltage
    - Maximal drive signal amplitude
    - Etc.
- The LLRF system should also include a certain degree of exception handling
  - Algorithms for monitoring or computing parameters and for reacting accordingly
    - Turn off RF drive in case of klystron trip
    - Quench detection
    - Etc.

Operation Close to the Quench Limit

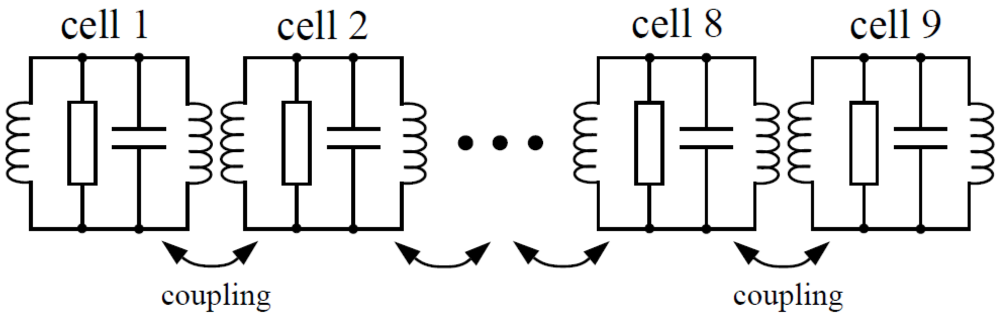




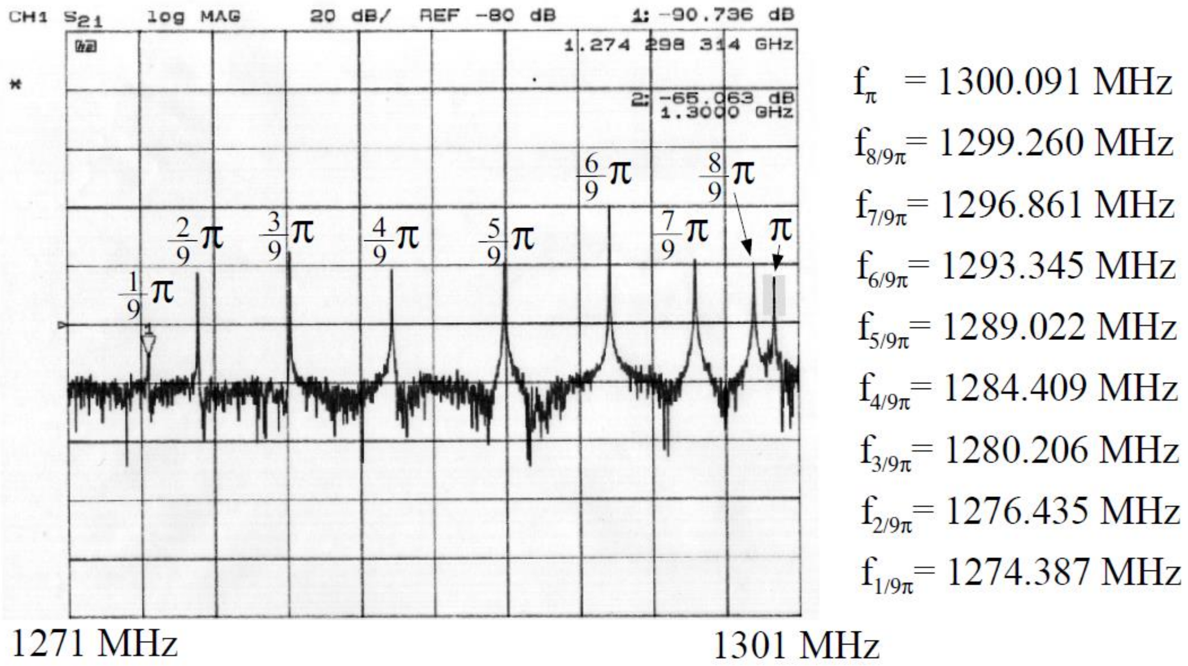


- Quench detection is a common feature of LLRF systems
- If Q_L drops below a predefined limit, the drive is turned off
- Should create interlock for the beam
- RF is turned back on manually or by an automation algorithm

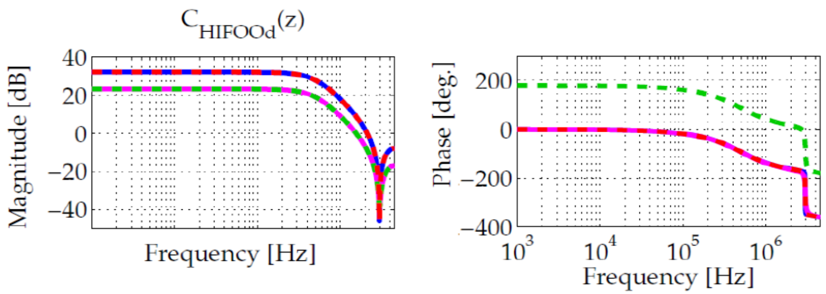
Suppression of Unwanted Passband Modes



Passband Modes of 9-cell Cavities

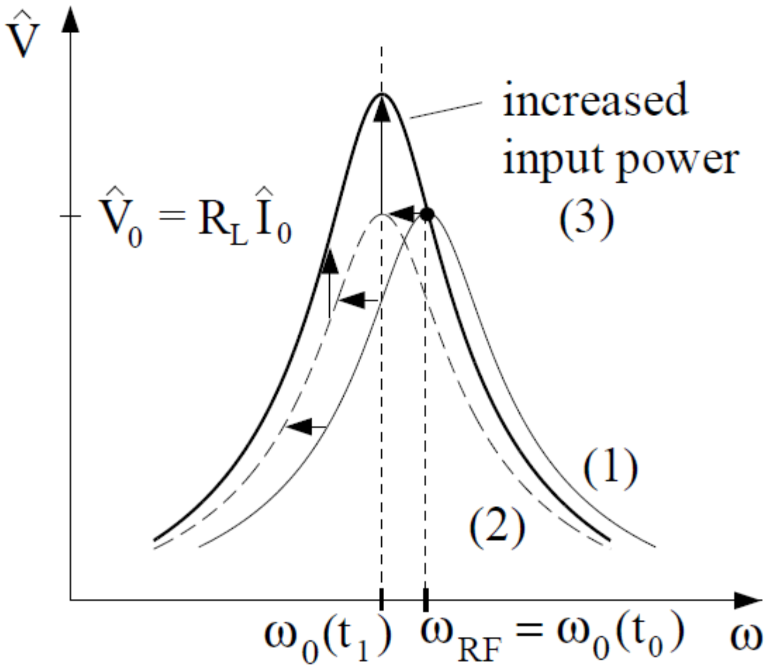


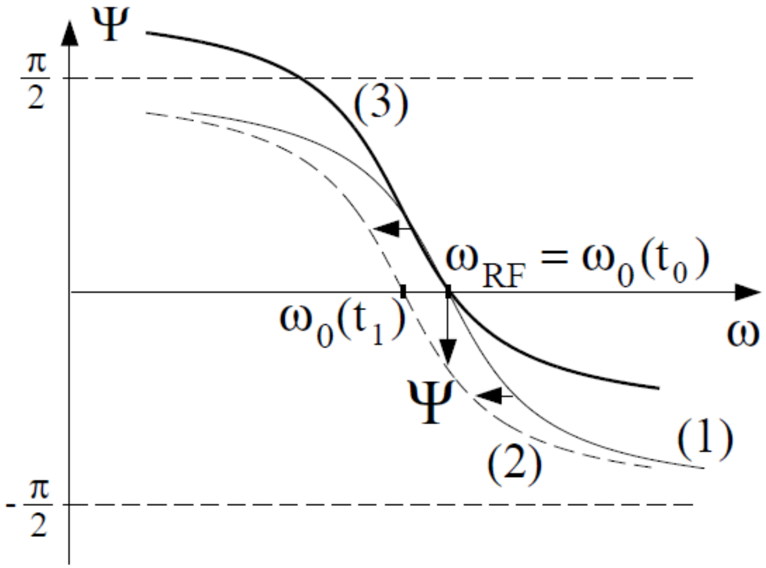
- Implement filter (e.g. Notch filter at ADC) in order to suppress frequency of the 8π/9-mode

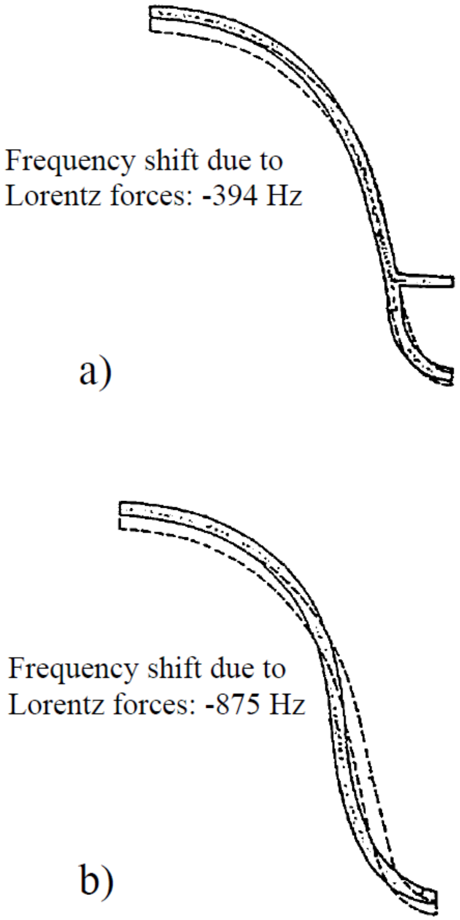


Detuning

- Detuning lowers the amplitude / requires more power to reach the same amplitude
- Detuning induces change of phase
- The sources are Lorentz force detuning and microphonics

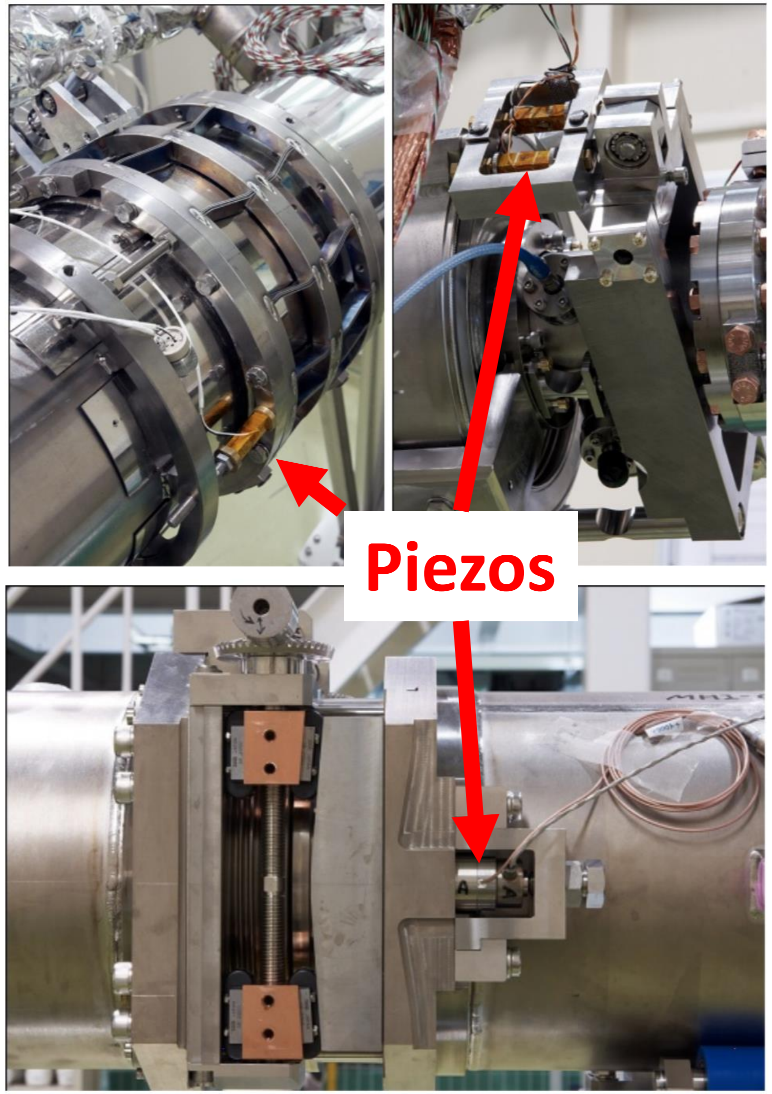


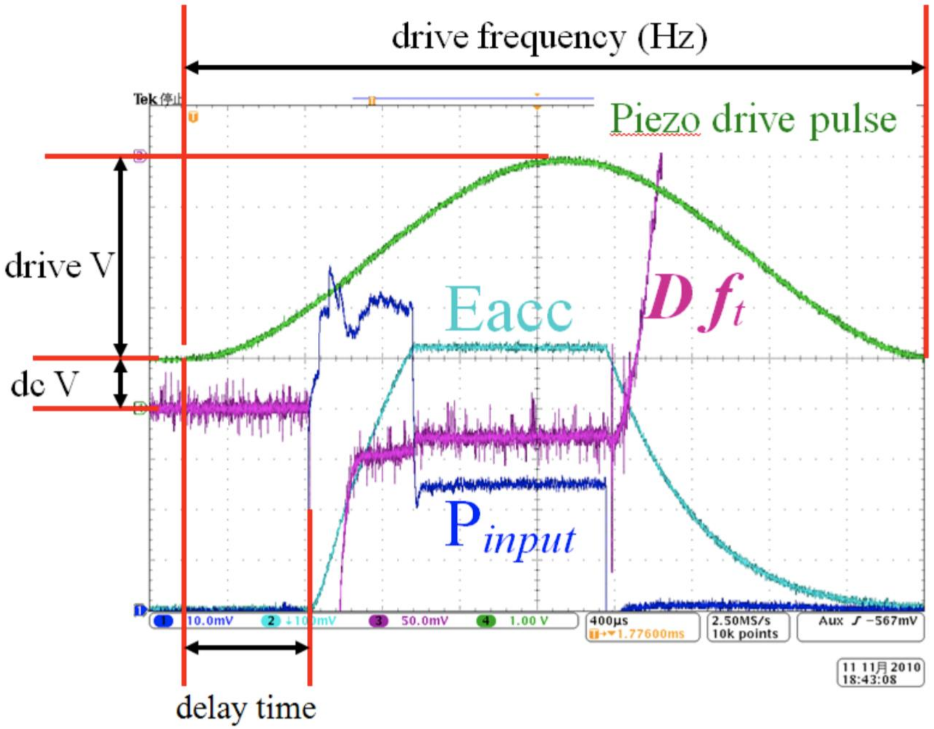




Detuning Compensation

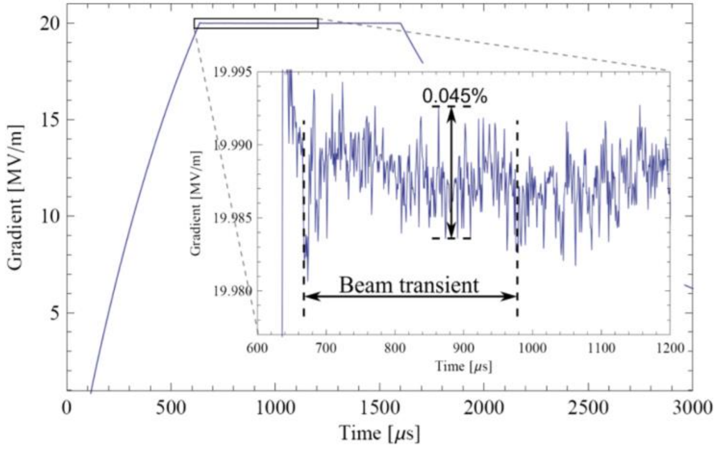
- Motor tuner
  - Slow
  - Pre-tune cavity
  - Compensation of static detuning
- Piezo tuner
  - Fast
  - Compensation of dynamic detuning (E.g. Lorentz force detuning, etc.)
  - Piezo control is typically part of the LLRF system



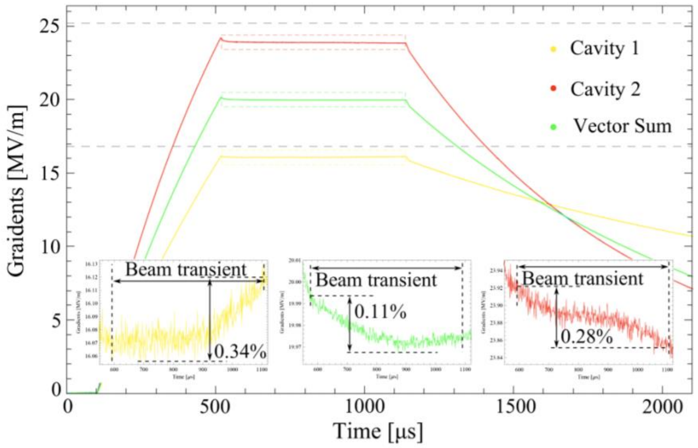


Benchmarking the System Performance

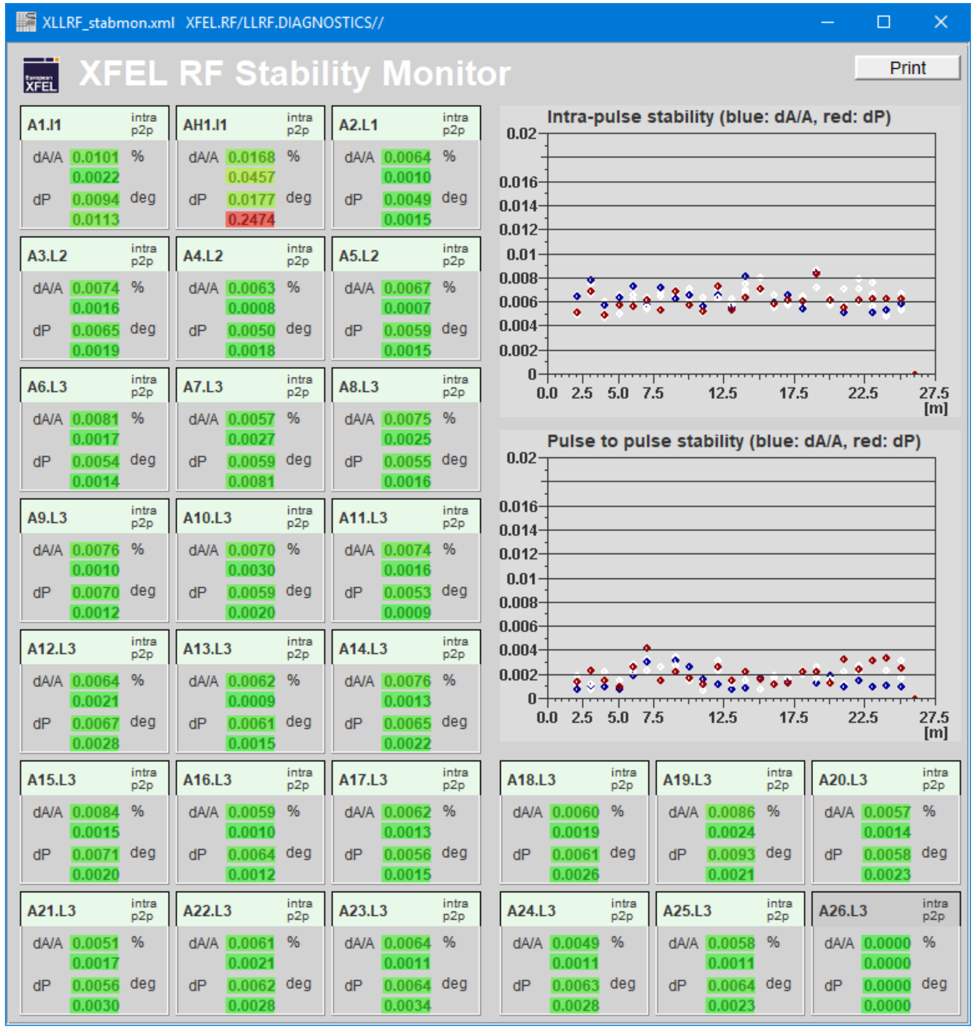
- RF stability (VS)
  - Intra train
  - Inter train
- Long term drifts
- Must be better than requirements for (beam) operation



KEK STF: Q_L = 2E7



KEK STF: $Q_{L,cav1}$ = 9E6, $Q_{L,cav2}$ = 3E6



European XFEL: overview of VS stabilities, requirements: $\Delta A/A \leq 0.01\%$, $\Delta\Phi \leq 0.01$ deg.

Summary and Bibliography

Summary

- What you should learn about, when are planning to get involved with LLRF
  - Your facility
    - What are the requirements? (e.g. for short time and long-time stability, etc.)
    - How to integrate the LLRF system (e.g. interlock, communication, etc.)
  - Theory
    - Cavity
    - RF
    - Signal processing
    - Controller
  - Analog hardware
  - Digital hardware
  - Firmware
  - Software
    - E.g. communication, computations, automation, data analysis, data storage, data visualization, user interface, etc.

Thank you very much for your attention! Questions?

- Bibliography

  - S. Pfeiffer, *LLRF Controls and Feedback*, The CERN Accelerator School, 2016
  - S. Sievers et al., *Second-sound measurements on a 3 GHz SRF cavity at low acceleration fields*, SRF'13, 2013
  - T. Schilcher, *Vector Sum Control of Pulsed Accelerating Fields in Lorentz Force Detuned Superconducting Cavities*, PhD Thesis, 1998
  - S. Simrock et al., *Cavity Field Control*, LLRF Lecture, 5th LC School, 2010
  - M. Omet, *Digital Low Level RF Control Techniques and Procedures Towards the International Linear Collider*, PhD Thesis, 2014
  - J. Branlard, *LLRF controls and RF operations*, SRF 2019 Tutorial, SRF2019, 2019
  - J. Branlard, *Superconducting cavity quench detection and prevention for the European XFEL*, ICAEPCS'13, 2013
  - L. Doolittle et al., *High Precision RF Control for SRF Cavities in LCLS-II*, SRF2021, 2017
  - J. Branlard et al., *Installation and First Commissioning of the LLRF System for the European XFEL*, IPAC17, 2017
  - T. Miura et al., *Digital LLRF Control System for cERL*, 13th Annual Meeting of Particle Accelerator Society of Japan, 2016
  - T. Hellert et al., *Detuning related coupler kick variation of a superconducting nine-cell 1.3 GHz cavity*, Phys. Rev. Accel. Beams 21, 042001, 2018
  - D. Kostin, *Experience with the Eu-XFEL RF Couplers*, AWLC'20, 2020
  - S. Michizono, *STF-LLRF system and its study plan*, LCWS'12, 2012
  - A. Mielczarek et al., *uTCA-based Controller*, MIXDES 2011, 2011
  - S. Fukuda, *KEK HLRF Status and S1- global*, LCWS'08, 2008
  - C. Pagani et al., *Test results of the international S1-global cryomodule*, Proceedings of the 8th Annual Meeting of Particle Accelerator Society of Japan, 2011
  - F. Qiu, *Tutorial on control theory*, 10th International Accelerator School for Linear Colliders, Japan, 2016
  - M. Omet, *Status Update of the European XFEL*, Seminar at KEK, 2019
  - M. Omet et al., *High-gradient near-quench-limit operation of superconducting Tesla-type cavities in scope of the International Linear Collider*, Phys. Rev. ST Accel. Beams 17, 072003, 2014