LLRF Controls and Feedback

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<u>Outline:</u>

1. Introduction/Motivation
2. System Description
3. System Modelling
4. Feedback Controller Design
5. Examples

1. Introduction/Motivation

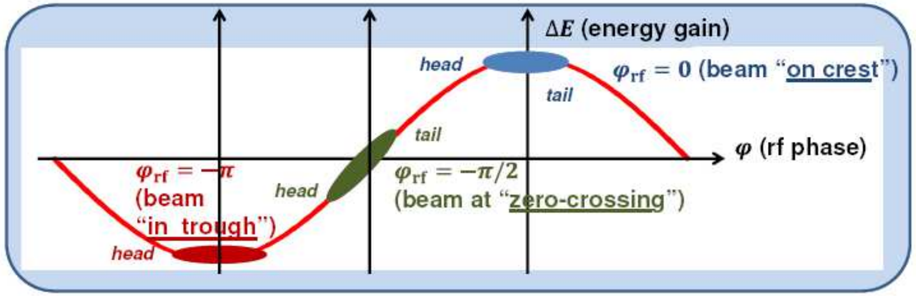
- LLRF and Feedback
  - Examples: ERL vs. FEL
  - Differences
- Basic LLRF components
- Disturbances and Noise - Fast and Slow Distortions

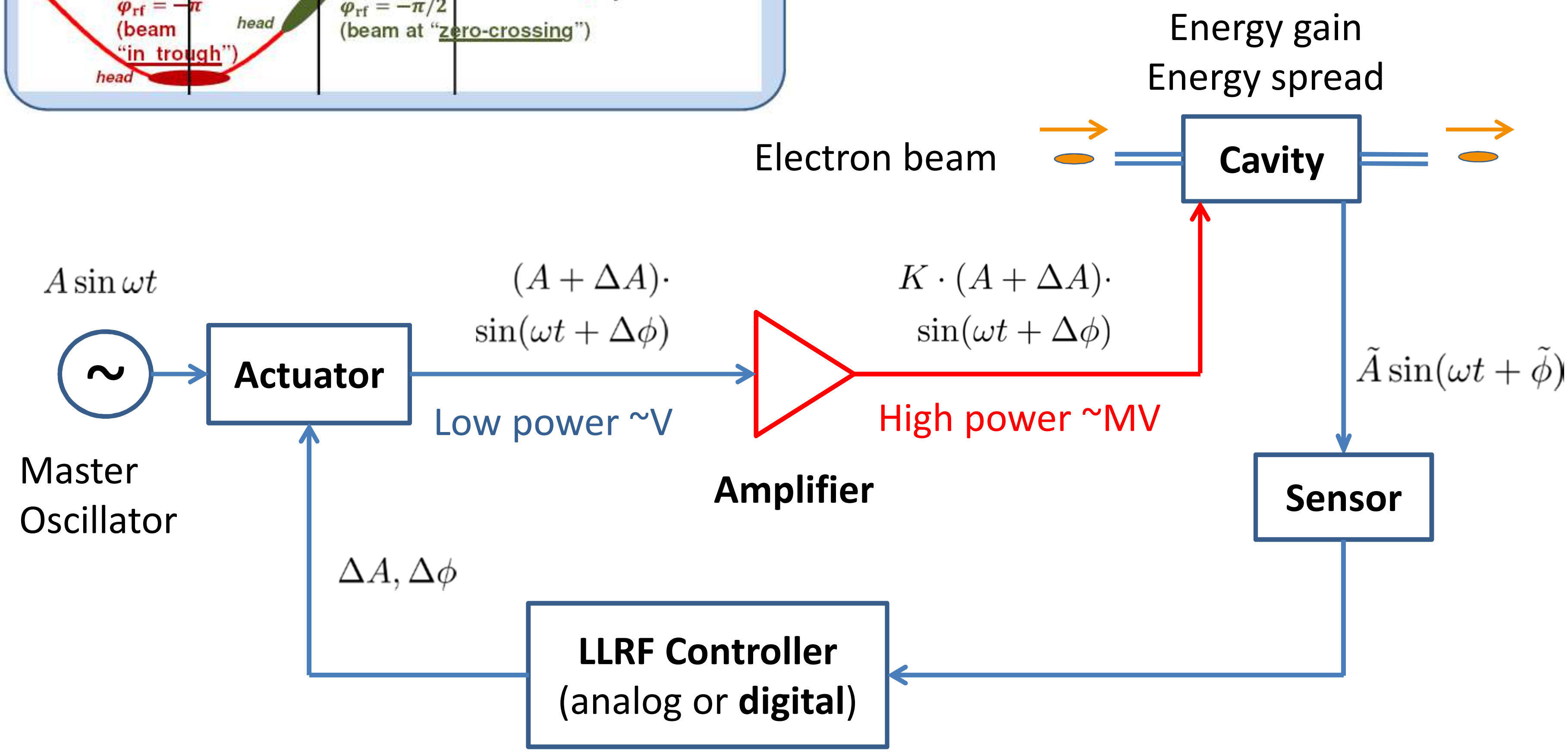
LLRF Controls and Feedbacks

See talk S. Di Mitri: "Bunch Length Compressors"

Typical RF stability values: $\Delta A/A = 0.1\% \ldots 0.01\%$

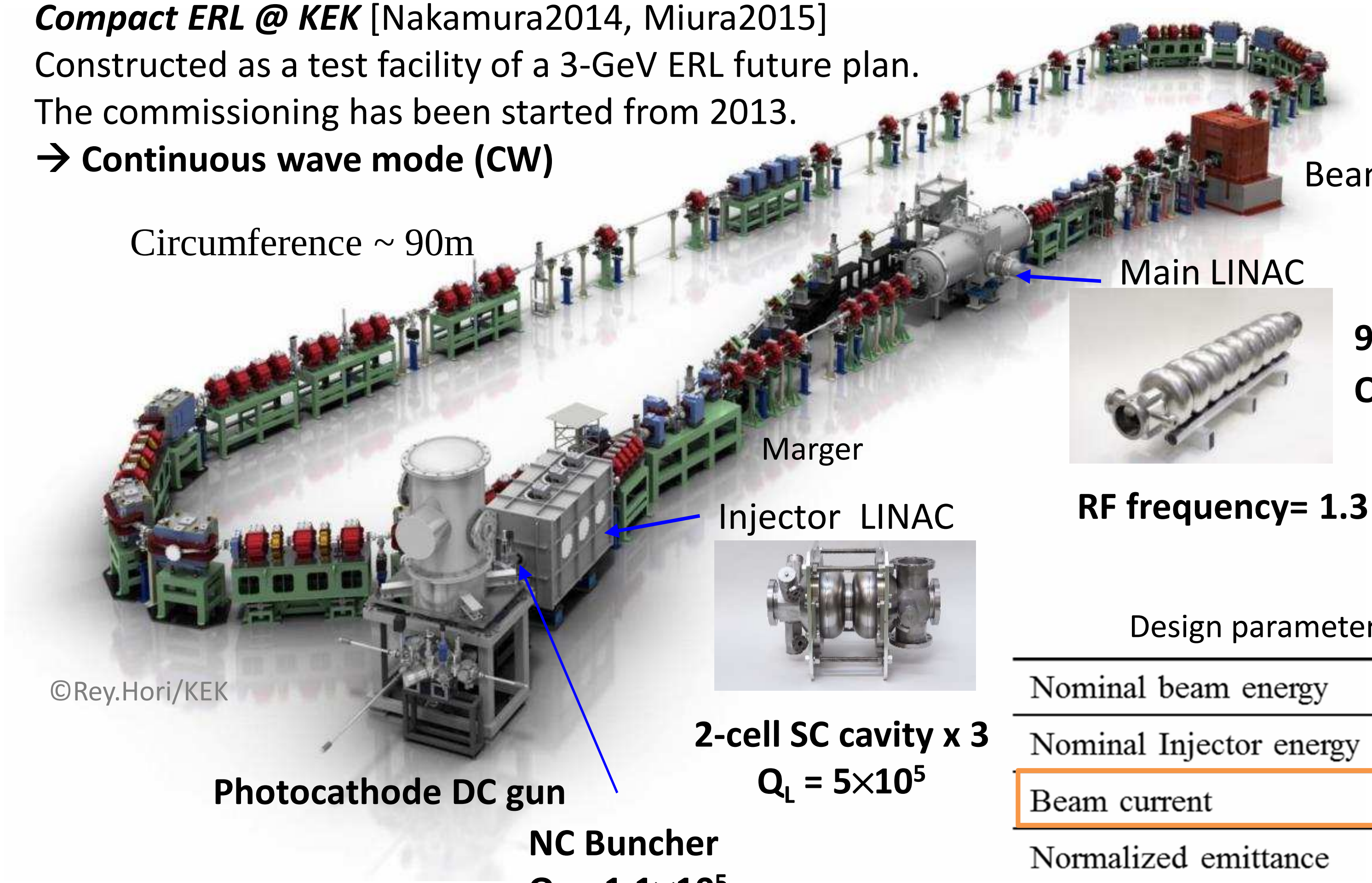
$$\Delta\phi = 0.1^o \ldots 0.01^o$$





Example 1: Energy Recovery Linac (ERL)

Compact ERL @ KEK [Nakamura2014, Miura2015]
Constructed as a test facility of a 3-GeV ERL future plan.
The commissioning has been started from 2013.
→ **Continuous wave mode (CW)**



$Q_L = 1.1\times10^5$

9-cell SC cavity x 2
$Q_L = 1\times 10^7$

RF frequency= 1.3 GHz

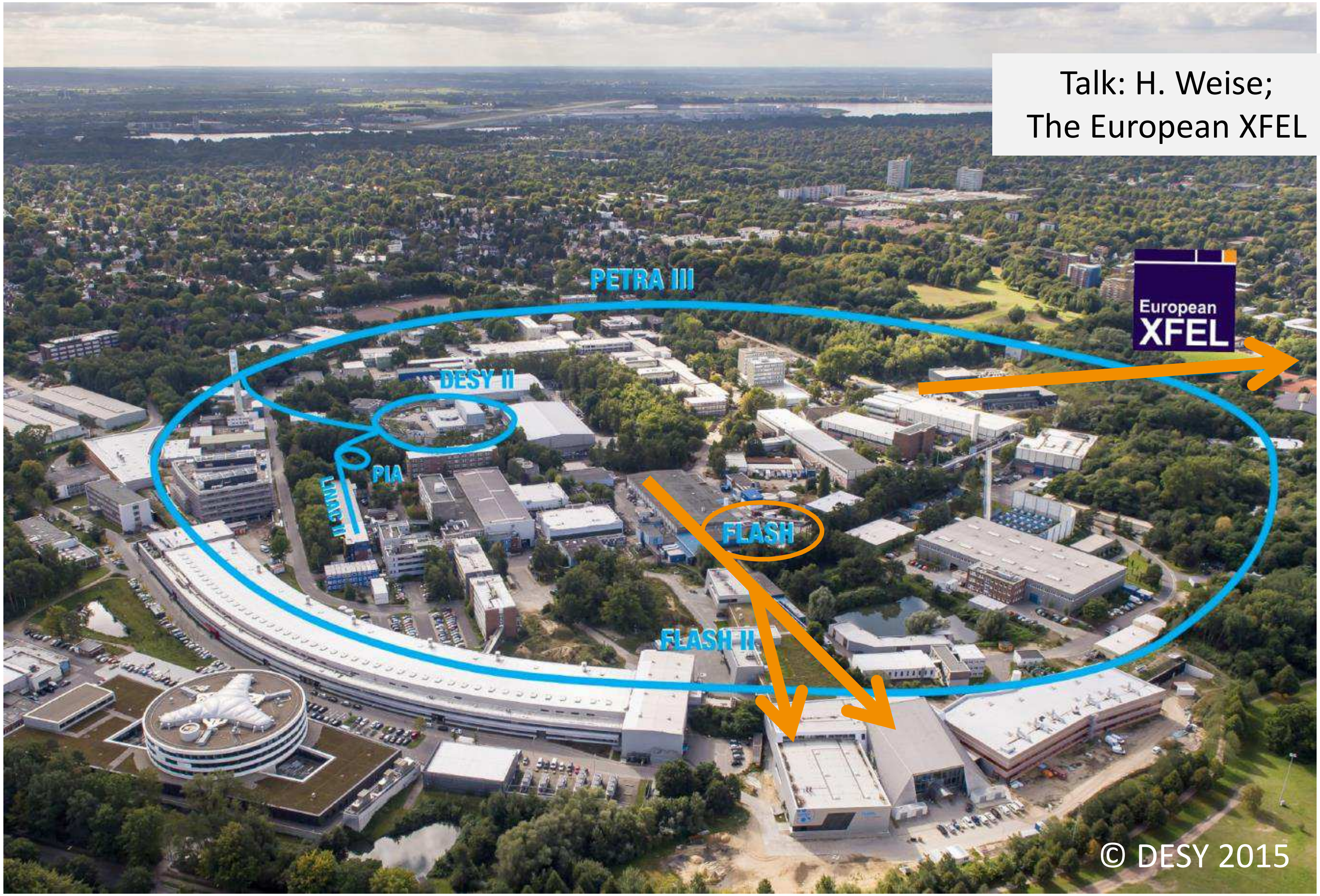
2-cell SC cavity x 3
$Q_L = 5\times10^5$

Design parameters of the cERL

Nominal beam energy	35 MeV
Nominal Injector energy	5 MeV
Beam current	10 mA (initial goal)
Normalized emittance	0.1 – 1 mm·mrad
Bunch length	1-3ps (usual) 100fs (short bunch)

Talk: *Concept of ERL;* 4th of June

Example 2: Free-Electron Laser (FEL)



Talk: H. Weise;
The European XFEL

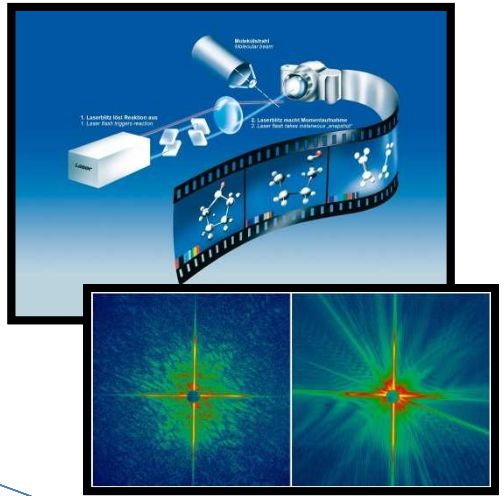
Free-Electron-LASer in Hamburg (FLASH)

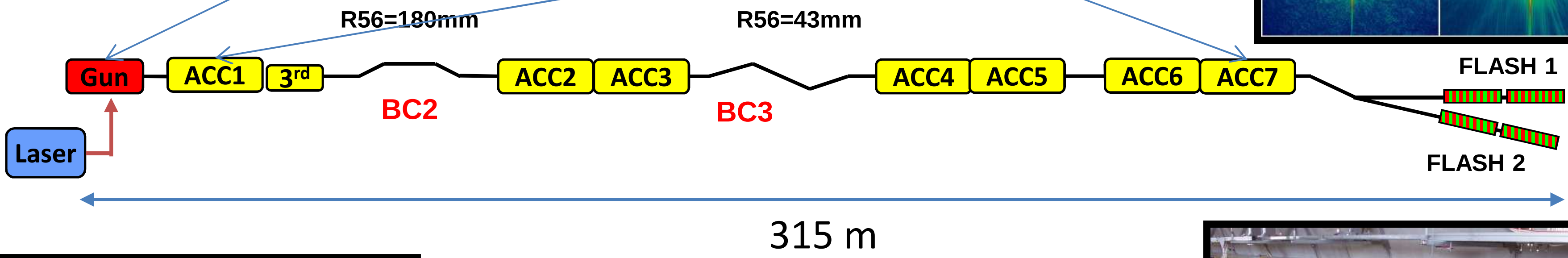
Operated at 10 Hz (100 ms)
Pulse length ~ 1ms
→ 1% duty cycle

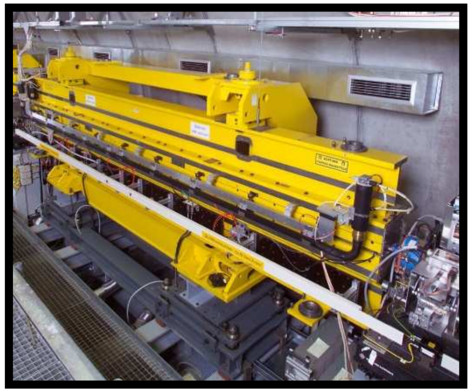
Max. 1.2 GeV beam energy
Wavelength > 4.1 nm

NRF gun ($Q_L = 1.2 \cdot 10^5$)
Klystron with 5 MW input power

SRF cavities ($Q_L = 3 \cdot 10^6$)
Klystron with 5/10 MW input power







Example ERL and FEL Parameters

Compact ERL @ KEK

- Photocathode DC gun
- NRF Buncher
  - **Q_L = 1.1·10^5**
- SRF cavities
  - **Q_L = 4.8·10^5 ... 1.3·10^7**
- Driven by **SSA, Klystron, (IOT)**
  - 1 Amplifier per cavity
    → **single cavity regulation**

- Operated in **Continuous Wave (CW)**
- **High beam loading (10's of mA)**

FLASH @ DESY

- NRF gun
  - **Q_L = 1.2·10^5**
- SRF cavities
  - **Q_L = 3.0·10^6**
- Driven by **Klystron**
  - 1 amplifier for RF gun
    → **single cavity regulation**
  - 1 amplifier per 8/16 cavities
    → **multi-cavity regulation**

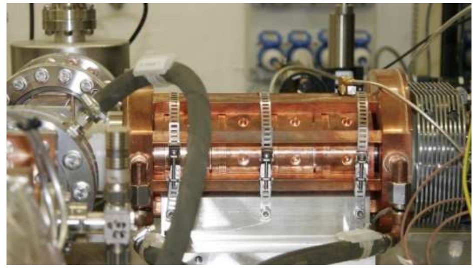
- Operated in **Short Pulse (SP)**
- **Moderate beam loading (mA)**

Goal of LLRF Controls and Feedback:

- Stabilize certain properties/values to high performance
- Being able to measure the quantities

Basic LLRF Components in an RF field Feedback Loop

newsline.linearcollider.org



LLRF'15, Shanghai, Nov 3-6, 2015 (T. Miura)

Plant: Series connection of components

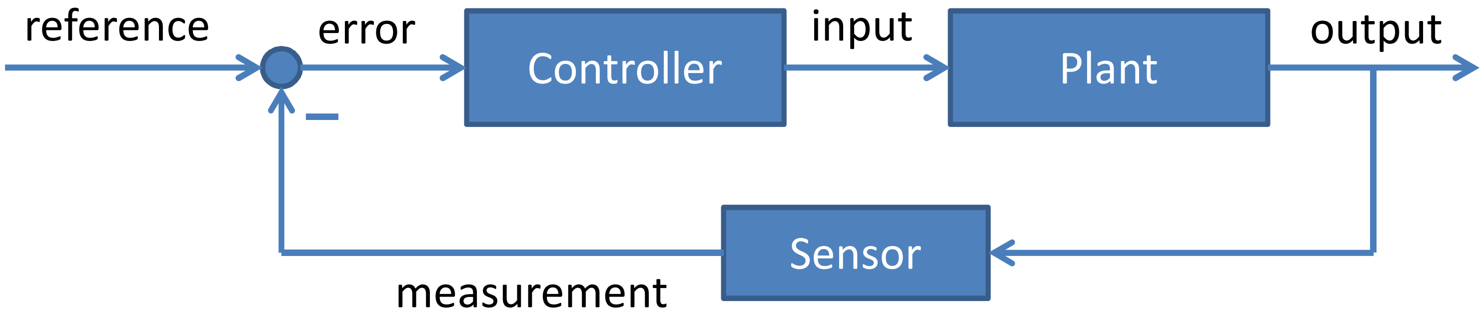
- Amplifier (Klystron, Solid State Amplifier (SSA), …)
- Cavities (normal- or superconducting – NRF or SRF)
- Pre-amplifier etc…

Sensor: Ability to measure signal to be controlled

- Pick-ups, antenna, magnetic loop, …

Controller: Processing unit

- Analog (resistor, capacitance, operational amplifier, logic blocks, …)
- Digital (Microcontroller, DSP, FPGA,…)



(LL)RF Applications

Linear or circular machines

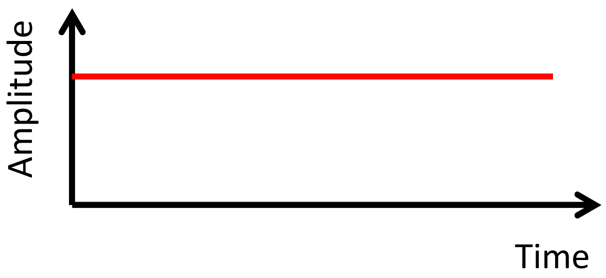
Normal-/superconducting RF systems

- RF field frequency
  - Typical in accelerators: MHz … tens of GHz

CW – Continuous Wave

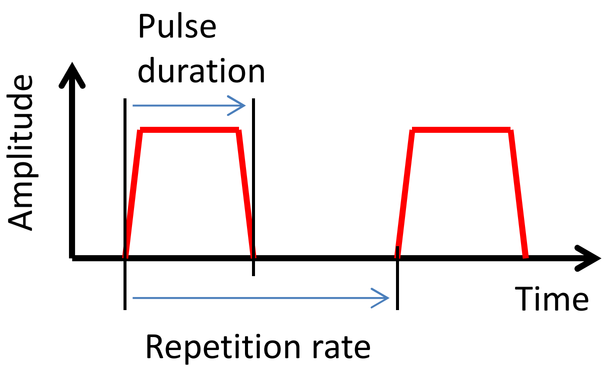
- Continuous RF field
  - Duty factor 100%

$$\mathrm{DF} = t_{pulse} \cdot f_{rep}$$



Pulsed Mode

- Certain amount of time is useable for beam acceleration
  - LP – Long Pulse Mode
    - DF 10% - 50%
  - SP – Short Pulse Mode
    - DF 1 %, e.g. 1ms on, 99ms off



Disturbances and Noise - Fast and Slow Distortions

Disturbance to plant input - $d_u(t)$

- DAC, vector modulator, temperature & humidity (PCB)

Disturbance to plant - $d_P(t)$

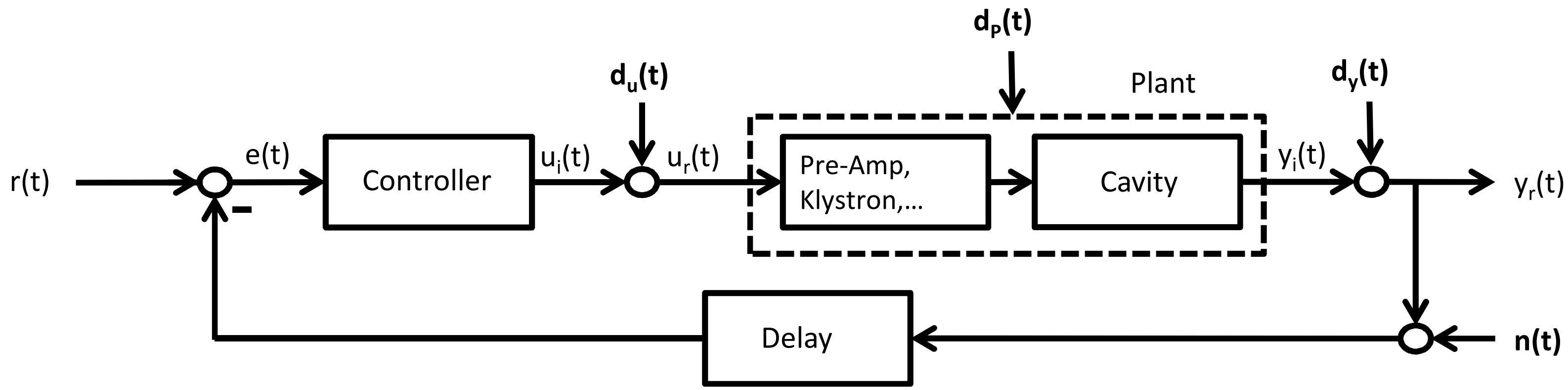
- Pre-amplifier, Klystron, HV modulator, cavity length (motor tuner or water regulation), Beam (beam loading and multi bunch effects)

Noise – n(t)

- ADC distortions, noise, quantization noise, temperature & humidity (PCB)

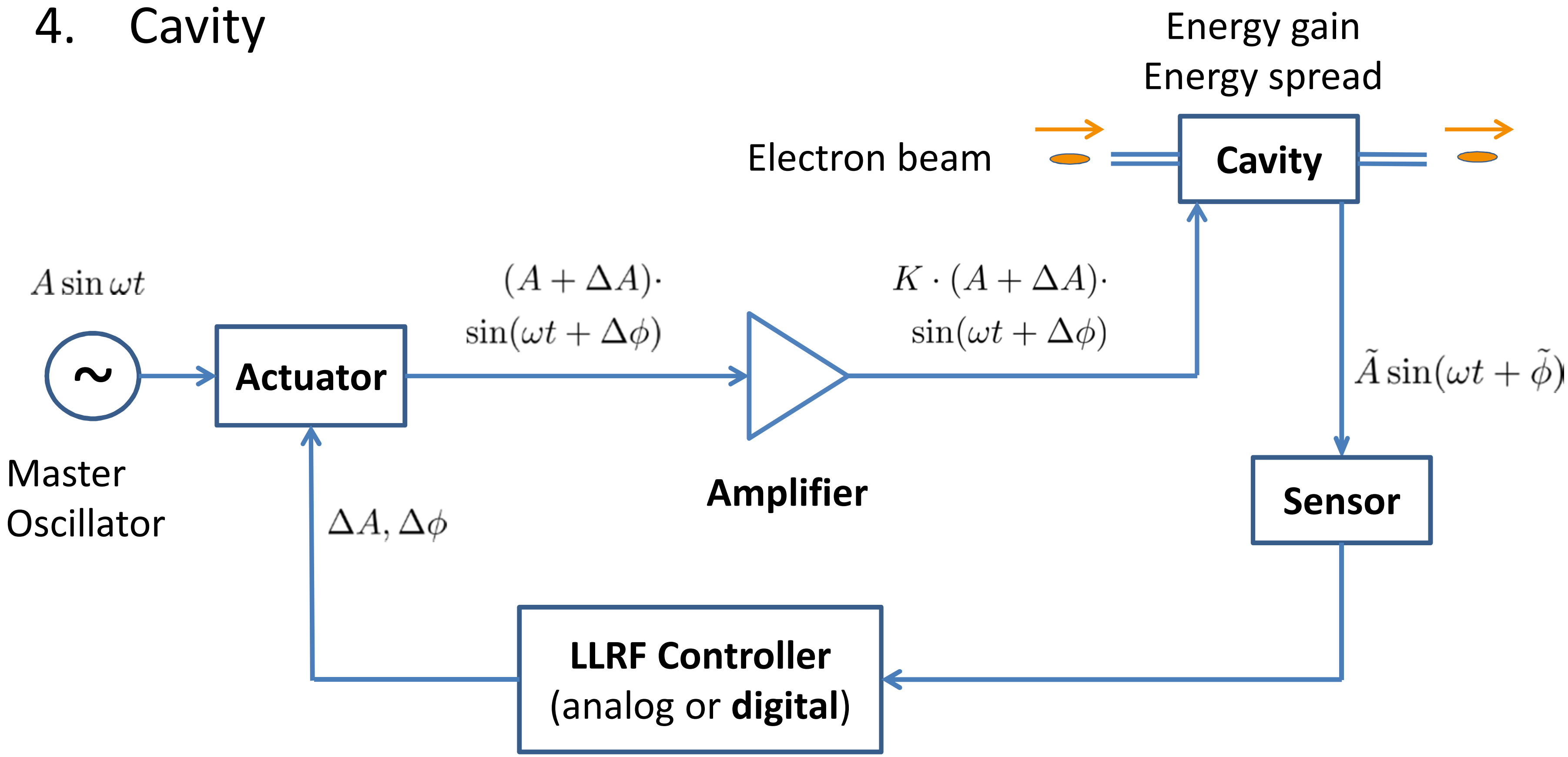
Other:

- Aging, switching in electronics (e.g. fans), ground motion and vibrations, faults in devices and components, thermal heating within macro-pulse, …
- Electromagnetic interference (EMI)
- Drifts
  - Electronics
  - Synchronization system
  - Timing distribution



2. System Description for RF Field Control Loop

1. **Sensor (RF detection)**
2. Actuator (RF manipulation)
3. Amplifier
4. Cavity

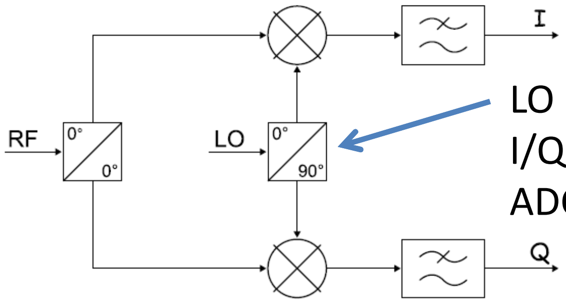


RF detection

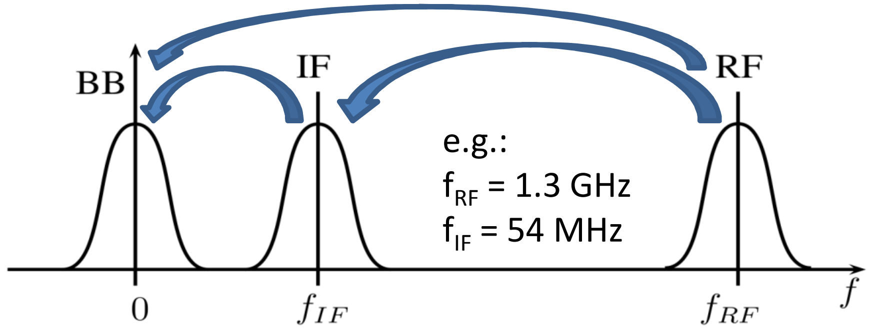
Details → see backup slides

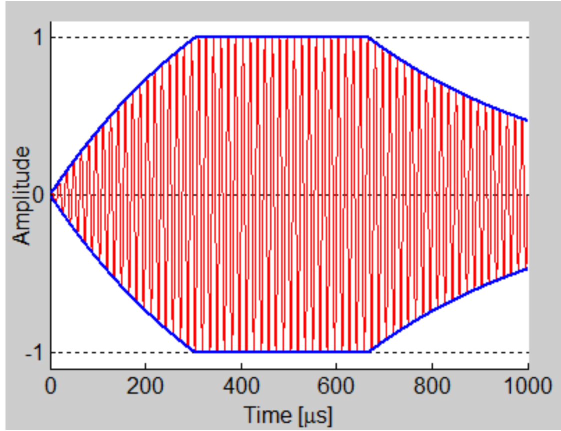
[Hoffmann.2008]

1. Baseband sampling (RF → BB)

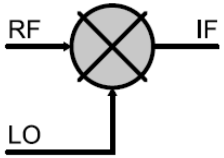


LO split by hybrid
I/Q sampled by 2 ADCs

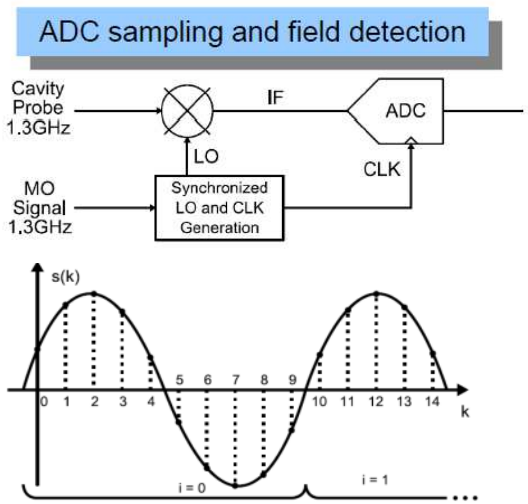




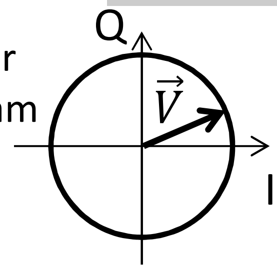
2. Down-conversion from RF → IF → BB



$$|f_{IF}| = |f_{RF} - f_{LO}|$$



Phasor diagram



$$I = A \cdot \cos\phi$$
$$Q = A \cdot \sin\phi$$
$$A = \sqrt{I^2 + Q^2}$$
$$\phi = \mathrm{atan2}(Q, I)$$

RF signal

$$\tilde{A}\sin(\omega t + \tilde{\phi})$$

Sensor

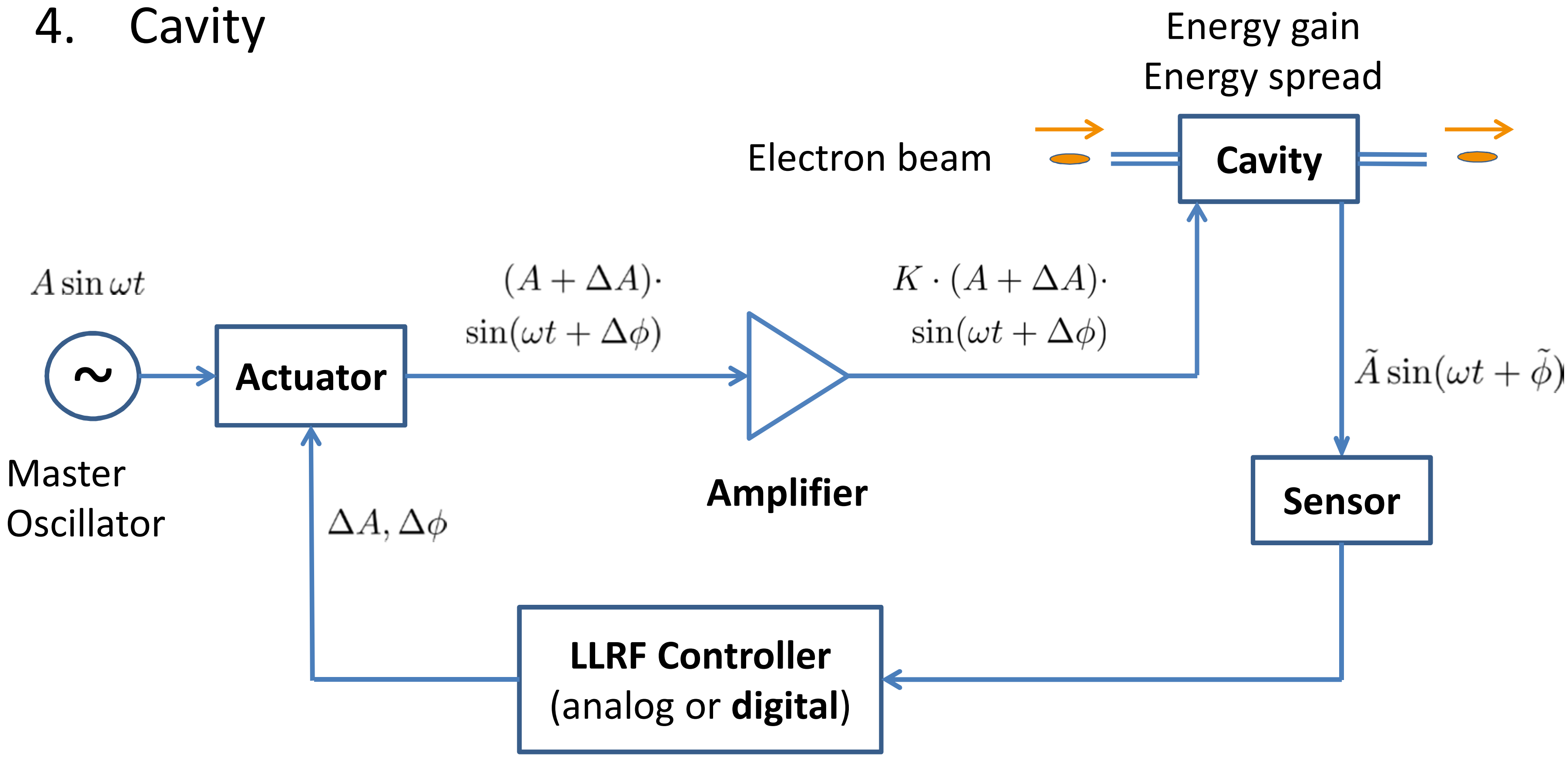
Envelope of RF signal

data processing
e.g. LLRF Controller

I/Q pair as amplitude and phase information w.r.t. MO signal

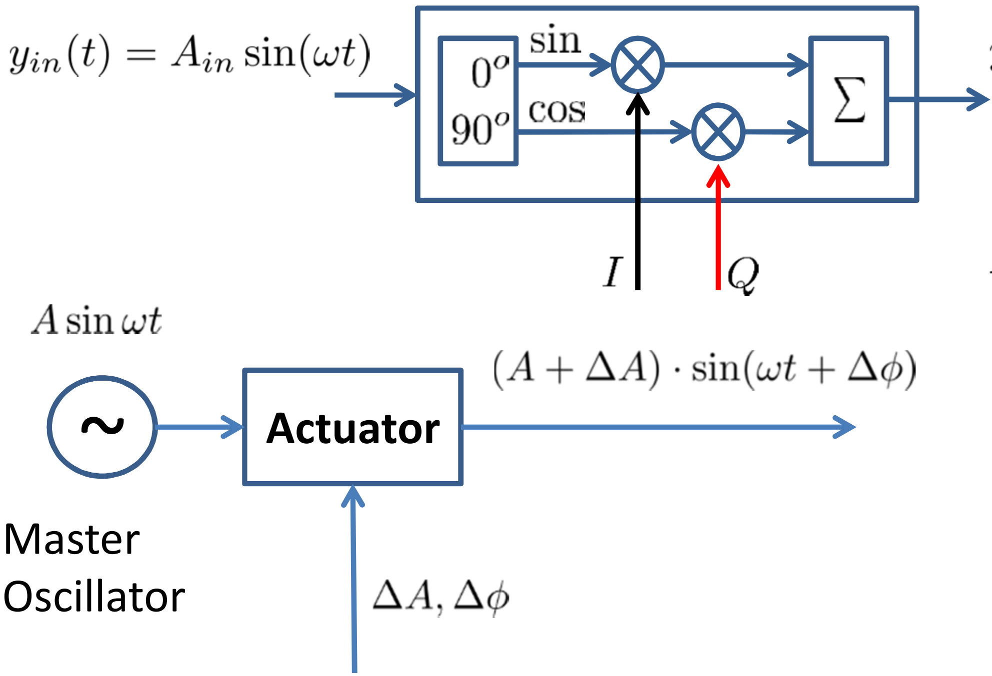
RF Field Control Loop

1. Sensor (RF detection)
2. **Actuator (RF manipulation)**
3. Amplifier
4. Cavity



RF field manipulation

- Up conversion using vector modulator
  - MO signal split to 0° and 90°
- VM with bandwidth usually tens of MHz (>> cavity BW)

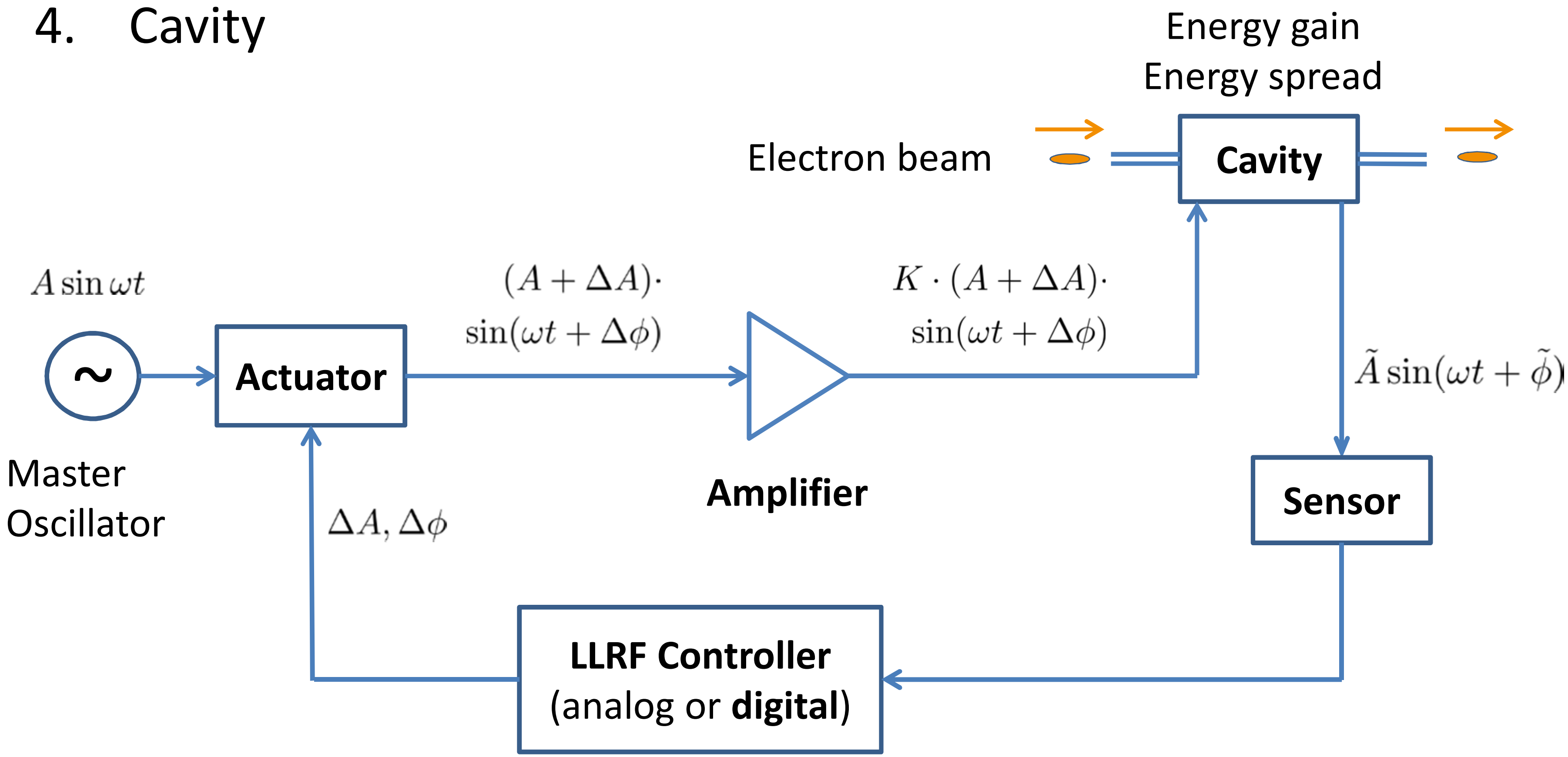


$$y_{out}(t) = I \cdot A_{in}\sin(\omega t) + Q \cdot A_{in}\cos(\omega t)$$
$$= A_{out}\sin(\omega t + \Delta\phi)$$

$$A_{out} = A_{in} \cdot \sqrt{I^2 + Q^2}$$
$$\Delta A = A_{in} \cdot (\sqrt{I^2 + Q^2} - 1)$$
$$\Delta\phi = \mathrm{atan2}(Q, I)$$

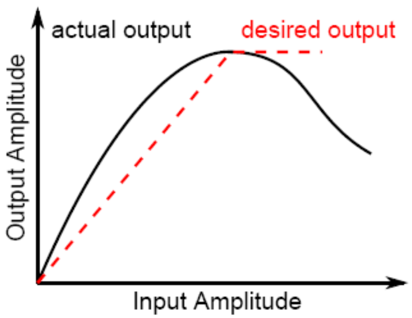
RF Field Control Loop

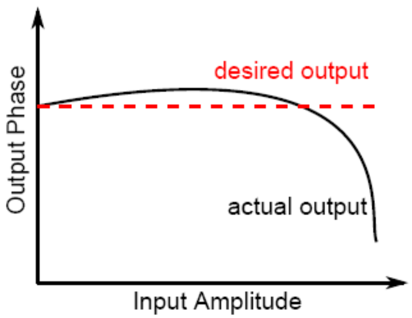
1. Sensor (RF detection)
2. Actuator (RF manipulation)
3. **Amplifier**
4. Cavity



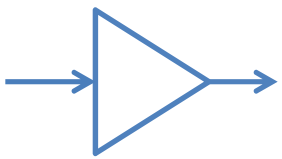
Amplifier Example: Klystron

- Non-linear behavior in amplitude (e.g. saturation at max. output) and phase
- Linearization of static characteristic curve
- Bandwidth usually tens of MHz (>> cavity BW)





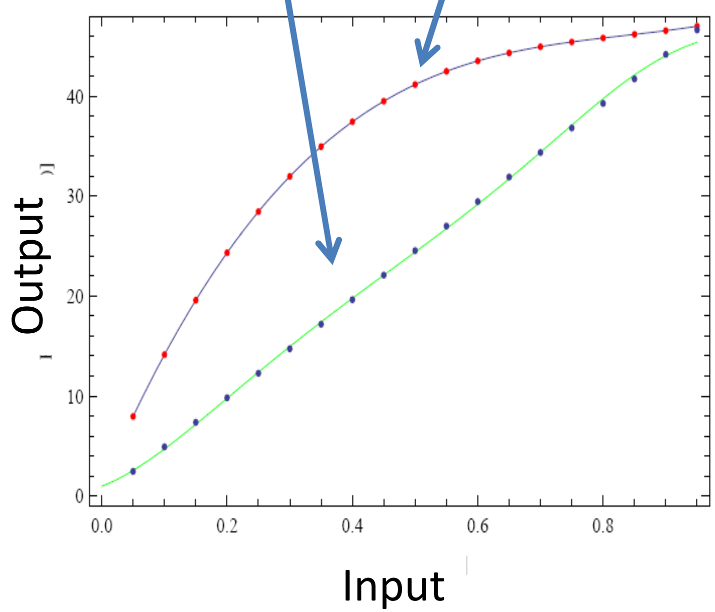
Output amplitude and phase is function of input amplitude

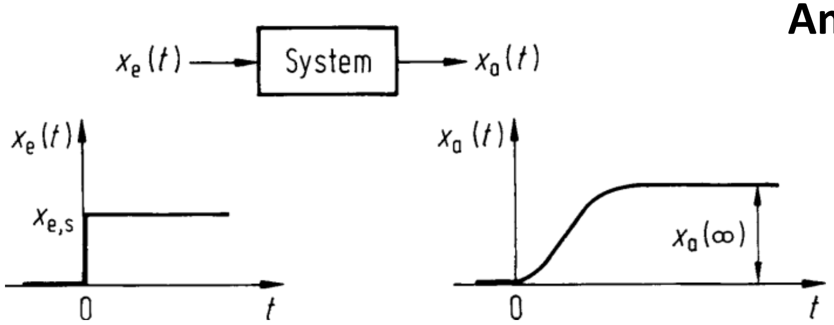


Amplifier

Characterization

Linearization

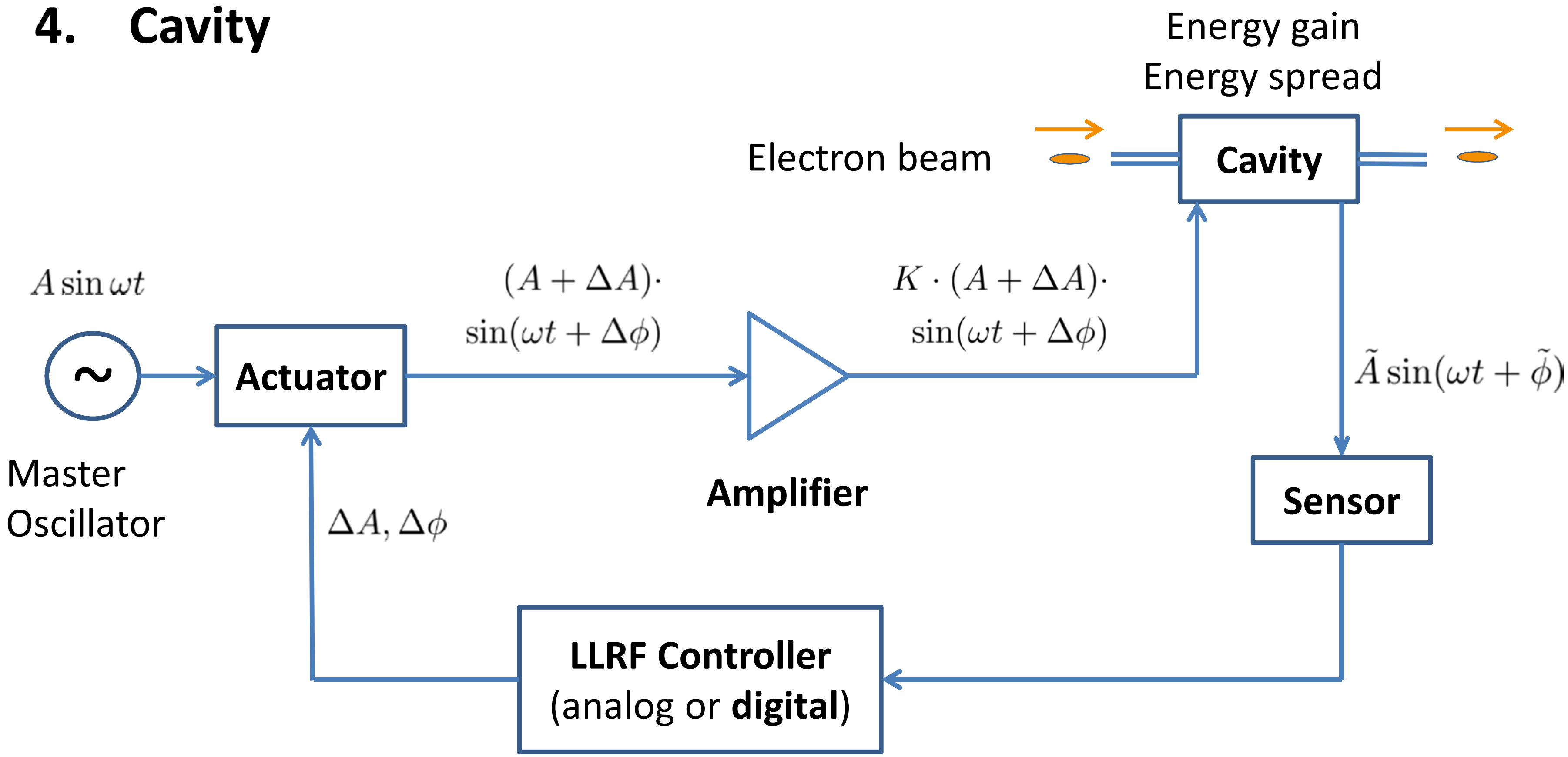




Examples: See PhD Thesis M. Omet, KEK, 2014
http://www-lib.kek.jp/cgi-bin/kiss_prepri.v8?KN=201424001&OF=8.

RF Field Control Loop

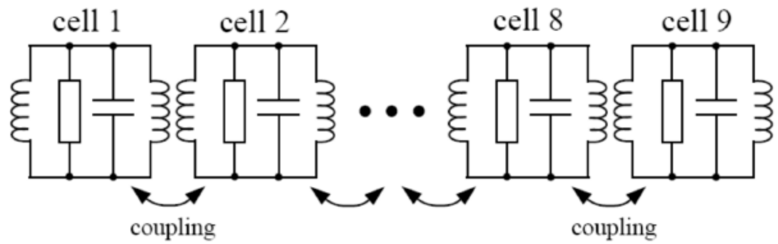
1. Sensor (RF detection)
2. Actuator (RF manipulation)
3. Amplifier
4. **Cavity**



Example: 9 Cell SRF Cavity

[Schilcher.1998]

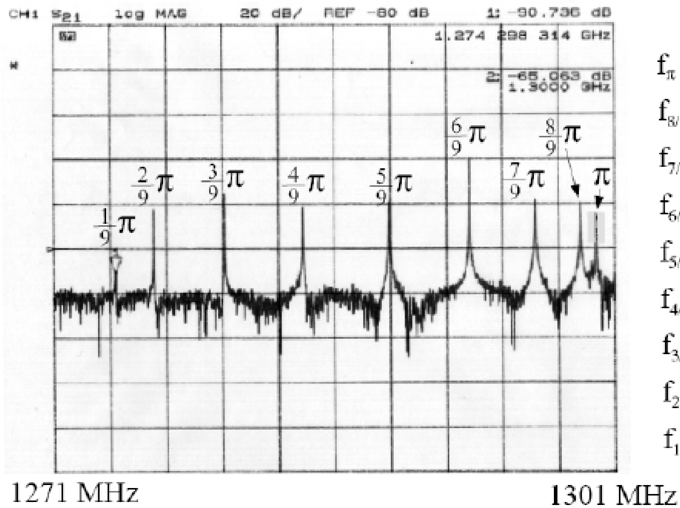
http://tt.desy.de/desy_technologies/accelerators_magnets_und_cryogenic_technologies/weld_free_cavity/index_eng.html



Modelled with 9 magnetically coupled resonators (RCL circuits)

Parameters for SRF cavity

Operating frequency:	1.3 GHz
Length:	1.036 m
Aperture diameter:	70 mm
Cell to cell coupling:	$\approx 2\%$
Quality factor Q_0:	$\approx 10^{10}$
$\mathrm{r/Q} := r_{sh}/Q_0$:	1036Ω



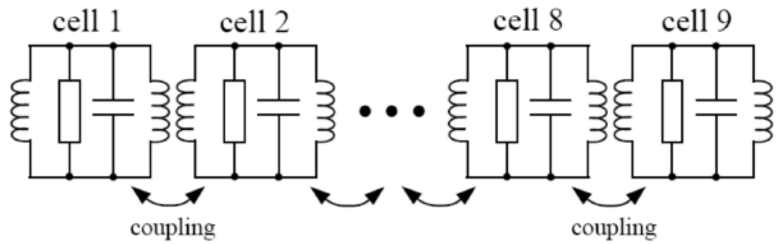
f_π = 1300.091 MHz
$f_{8/9\pi}$ = 1299.260 MHz
$f_{7/9\pi}$ = 1296.861 MHz
$f_{6/9\pi}$ = 1293.345 MHz
$f_{5/9\pi}$ = 1289.022 MHz
$f_{4/9\pi}$ = 1284.409 MHz
$f_{3/9\pi}$ = 1280.206 MHz
$f_{2/9\pi}$ = 1276.435 MHz
$f_{1/9\pi}$ = 1274.387 MHz

- Pi mode is used for acceleration (TM010 mode)
- 8pi/9 mode only 800kHz separated from operating frequency → may influence accelerating field stability

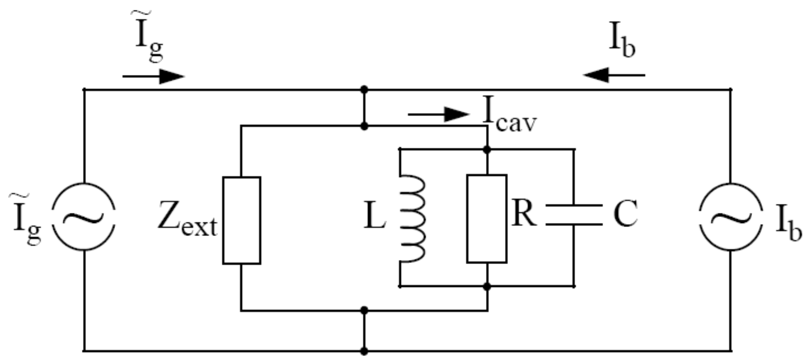
Mechanical model is neglected at this point, see example at the end

From RCL circuit to cavity characteristics

http://tt.desy.de/desy_technologies/accelerators_magnets_und_cryogenic_technologies/weld_free_cavity/index_eng.html



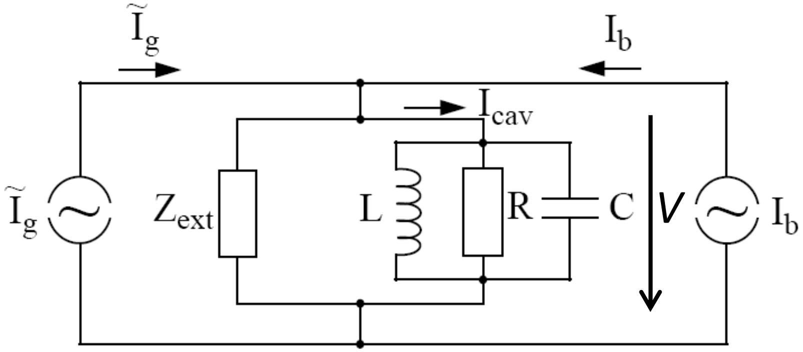
- RCL circuit equations need to be mapped to measurable cavity parameters (bandwidth, shunt impedance, quality factor etc.)
- Start with high frequency modelling
- End with baseband model required in LLRF control scheme with down-conversion



Consider only 1 RCL circuit (as simplification)

From RCL to differential cavity equation

RCL circuit



$$\ddot{V}(t) + \frac{1}{R_L C}\dot{V}(t) + \frac{1}{LC}V(t) = \frac{1}{C}\dot{I}(t)$$

$$I_C + I_{R_L} + I_L = I = \tilde{I}_g + I_b$$

$$\frac{1}{R_L C} = \frac{\omega_0}{Q_L} \text{ and } \frac{1}{LC} = \omega_0^2$$

$$\dot{I}_L = \frac{V}{L}, \dot{I}_R = \frac{\dot{V}}{R_L}, \dot{I}_C = C\ddot{V}$$

Cavity characteristics

Coupling factor:

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

Loaded shunt impedance:

$$R_L = \left(\frac{1}{R} + \frac{1}{Z_{ext}}\right)^{-1} = \frac{R}{1+\beta}$$

Loaded quality factor:

$$Q_L = \left(\frac{1}{Q_0} + \frac{1}{Q_{ext}}\right)^{-1} = \frac{Q_0}{1+\beta}$$

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

Differential cavity equation with harmonic RF driving term $I(t) = \hat{I}_0 \sin(\omega t)$

Differential cavity equation

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

$$\ddot{V}(t) + 2\omega_{1/2}\dot{V}(t) + \omega_0^2 V(t) = \omega_{1/2} R_L \dot{I}(t)$$

Solution for input signal $I(t) = \hat{I}_0 \sin(\omega t)$ **(RF source) is given as cavity properties with approximation for high Q cavities :**

$\omega_0 \ldots$ Cavity resonance frequency
$\omega \ldots$ Driving frequency (RF source)

$$V(t) = \hat{V}\sin(\omega t + \psi(t))$$

$$\hat{V} \approx \frac{R_L \hat{I}_0}{\sqrt{1 + (2Q_L \frac{\Delta\omega}{\omega})^2}} \quad ; \quad \tan\psi \approx 2Q_L \frac{\Delta\omega}{\omega}$$

Cavity detuning

$$\Delta\omega = \omega_0 - \omega \ll \omega$$

Tuning angle

$$\psi(t) = \angle(I(t), V(t))$$

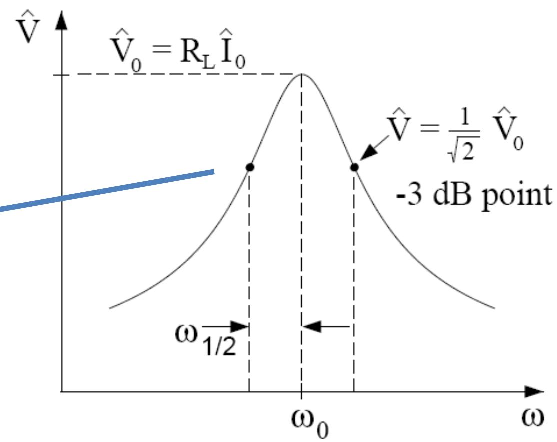
Angle between driving current and cavity voltage

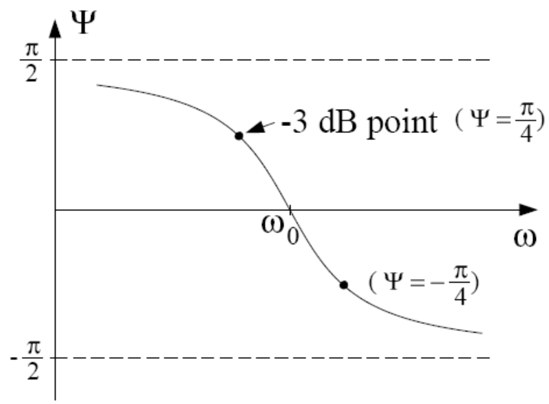
Steady state amplitude and phase of cavity signal with respect to the RF source

Half cavity bandwidth

$$\omega_{1/2} = \frac{\omega_0}{2Q_L} = \frac{1}{\tau}(\ll \omega)$$

with time constant τ

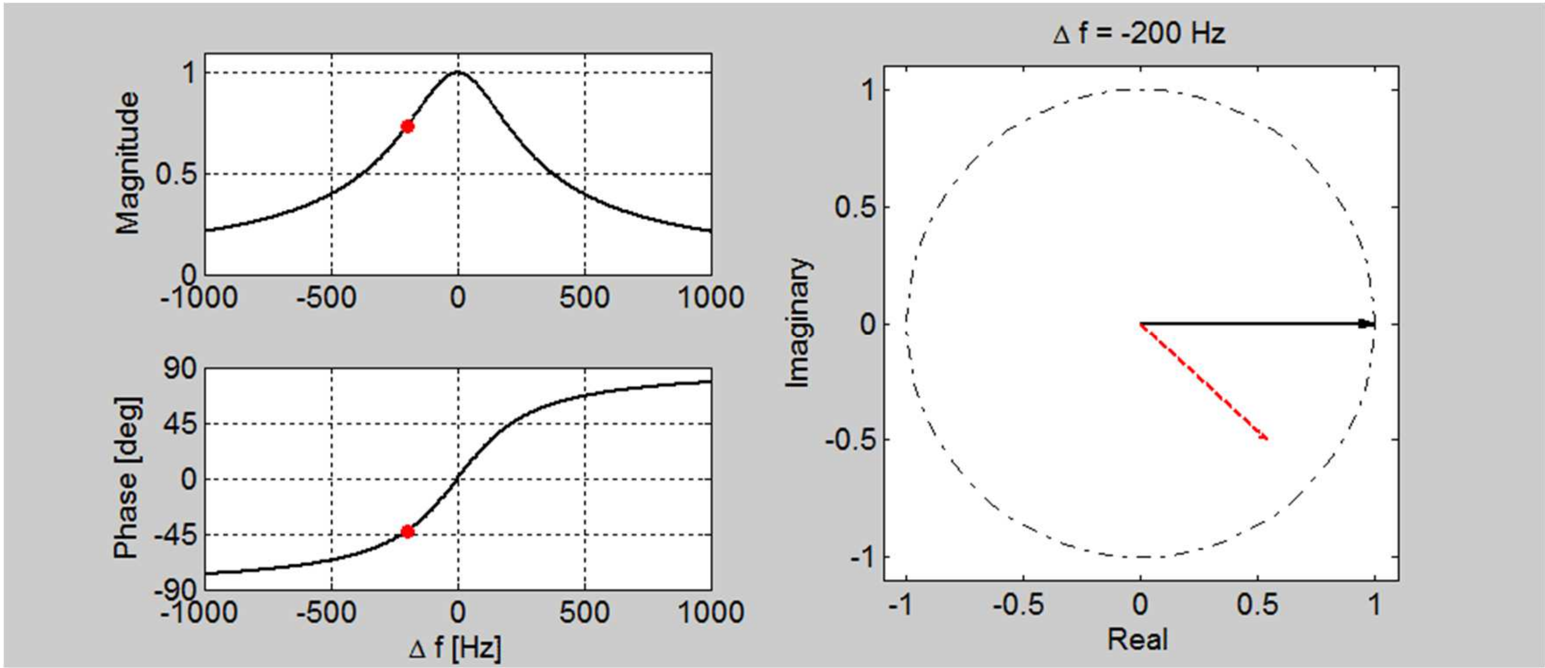




Differential cavity equation

Steady state solution of cavity model (field) for sinusoidal input signal (RF source) with amplitude of one

Black: RF source $I(t) = \hat{I}_0 \sin(\omega t)$
Red: Cavity field $V(t) = \hat{V} \sin(\omega t + \psi(t))$



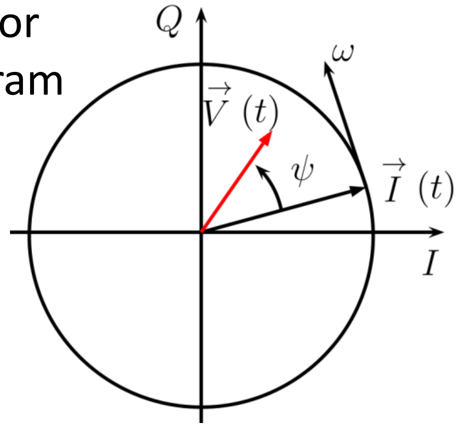
Variation of cavity detuning

$$\Delta\omega = \omega_0 - \omega \ll \omega$$

$$\hat{V} \approx \frac{R_L \hat{I}_0}{\sqrt{1 + \left(2Q_L \frac{\Delta\omega}{\omega}\right)^2}} \quad ; \quad \tan\psi \approx 2Q_L \frac{\Delta\omega}{\omega}$$

$$\ddot{V}(t) + 2\omega_{1/2}\dot{V}(t) + \omega_0^2 V(t) = \omega_{1/2} R_L \dot{I}(t)$$

Phasor diagram



Cavity baseband model

The high (carrier) frequency cavity model is not of our interest for studying the cavity response under feedback operation; we are interested at the baseband model (envelope of RF signal)!

Separation of fast RF oscillations from the slowly changing amplitude and phases of the field vector

$$V = \vec{V}(t)e^{j\omega t} \text{ and } I = \vec{I}(t)e^{j\omega t} \quad ; \vec{V}(t) = V_I + jV_Q$$

I… in-phase (real)
Q… quadrature (imaginary)

First order cavity differential equation for envelope, i.e. the cavity baseband equation:

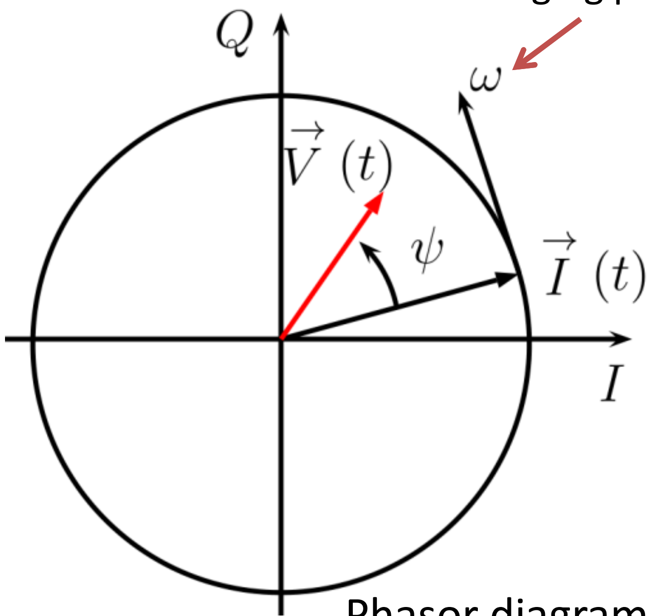
$$\dot{V}_I + \omega_{1/2} V_I + \Delta\omega V_Q = R_L \omega_{1/2} I_I$$
$$\dot{V}_Q + \omega_{1/2} V_Q - \Delta\omega V_I = R_L \omega_{1/2} I_Q$$

As short hand notation with complex vector field:

$$\dot{\vec{V}} + (\omega_{1/2} - j\Delta\omega)\vec{V} = \omega_{1/2} R_L \vec{I}$$

Remember: $\Delta\omega \ll \omega$ and $\omega_{1/2} \ll \omega$

Remove fast changing part!



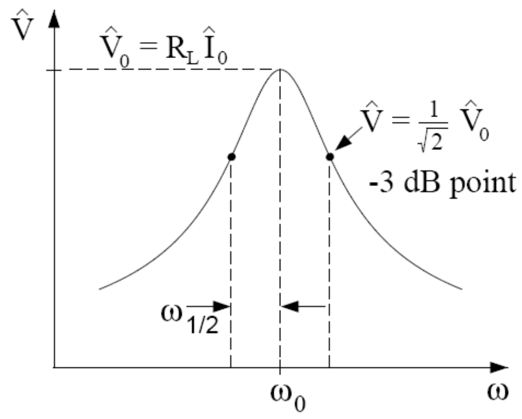
Phasor diagram

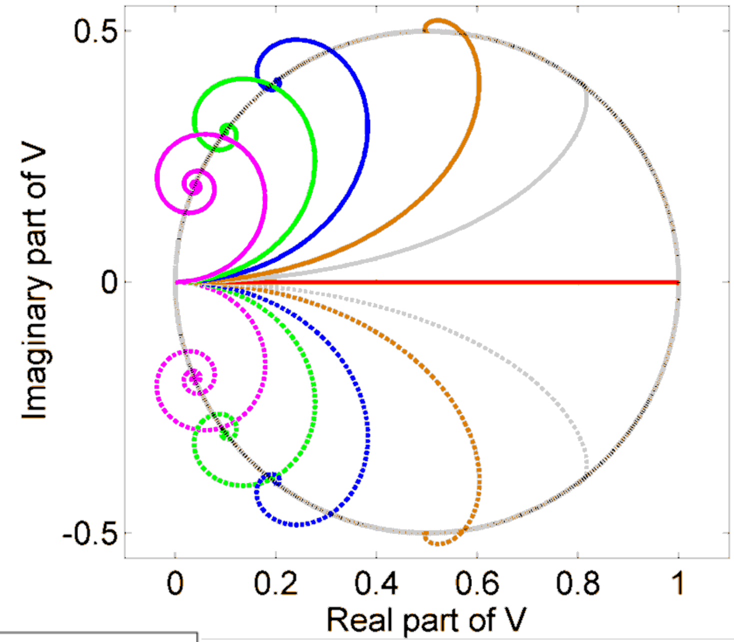
Step response

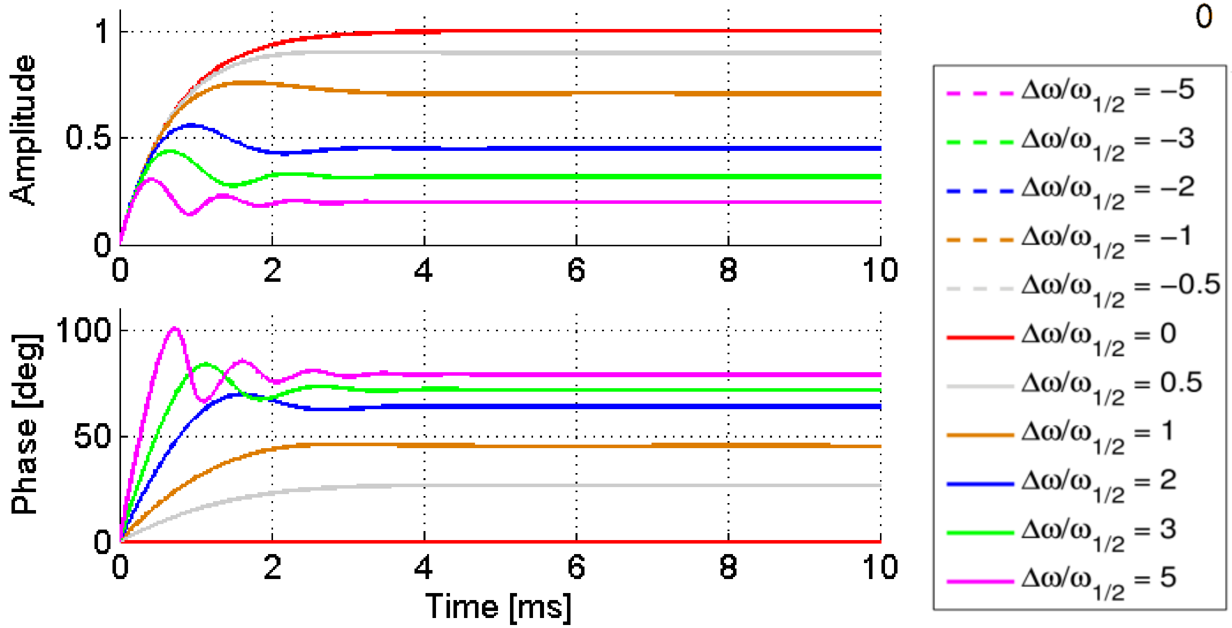
Cavity BB: $\dot{\vec{V}} + (\omega_{1/2} - j\Delta\omega)\,\vec{V} = \omega_{1/2} R_L\,\vec{I}$

$$R_L\,\vec{I} = \begin{cases} 1 & : t \geq 0 \\ 0 & : t < 0 \end{cases}$$

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







Additional Passband Modes

- Short outline, for details, see [Schilcher.1998] and [Vogel.2007]
- n-th mode:

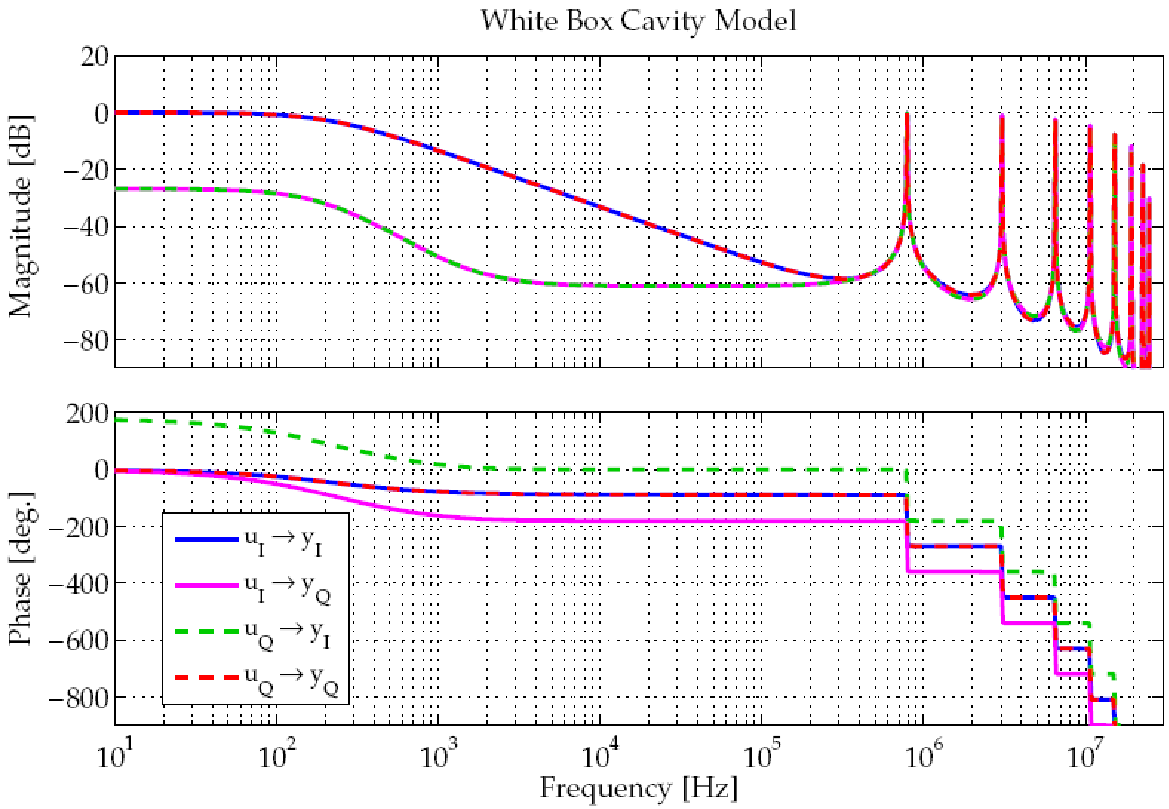
$$\dot{\vec{V}} + \left((\omega_{1/2})_{\frac{n}{9}\pi} - j(\Delta\omega)_{\frac{n}{9}\pi}\right)\vec{V} = (-1)^{n+1} K_{\frac{n}{9}\pi} (\omega_{1/2})_{\frac{n}{9}\pi} R_L \vec{I}\ ,\ n = 1 \ldots 9$$

- Cavity field is the sum of all passband contributions

$$\Delta\omega = -2\pi \cdot 10\ Hz$$

$$Q_L = 3 \cdot 10^6$$

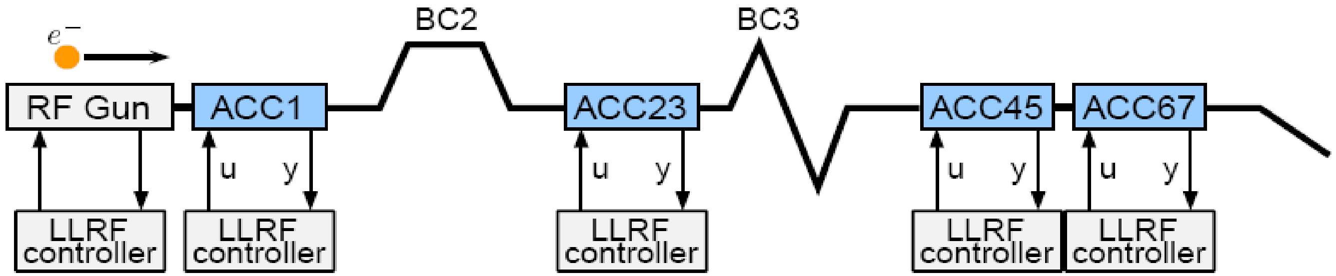
For variation in the coupling $K_{\frac{n}{9}\pi}$ and loaded quality factor $(\omega_{1/2})_{\frac{n}{9}\pi}$ see e.g. [Vogel.2007]



Summary System Description

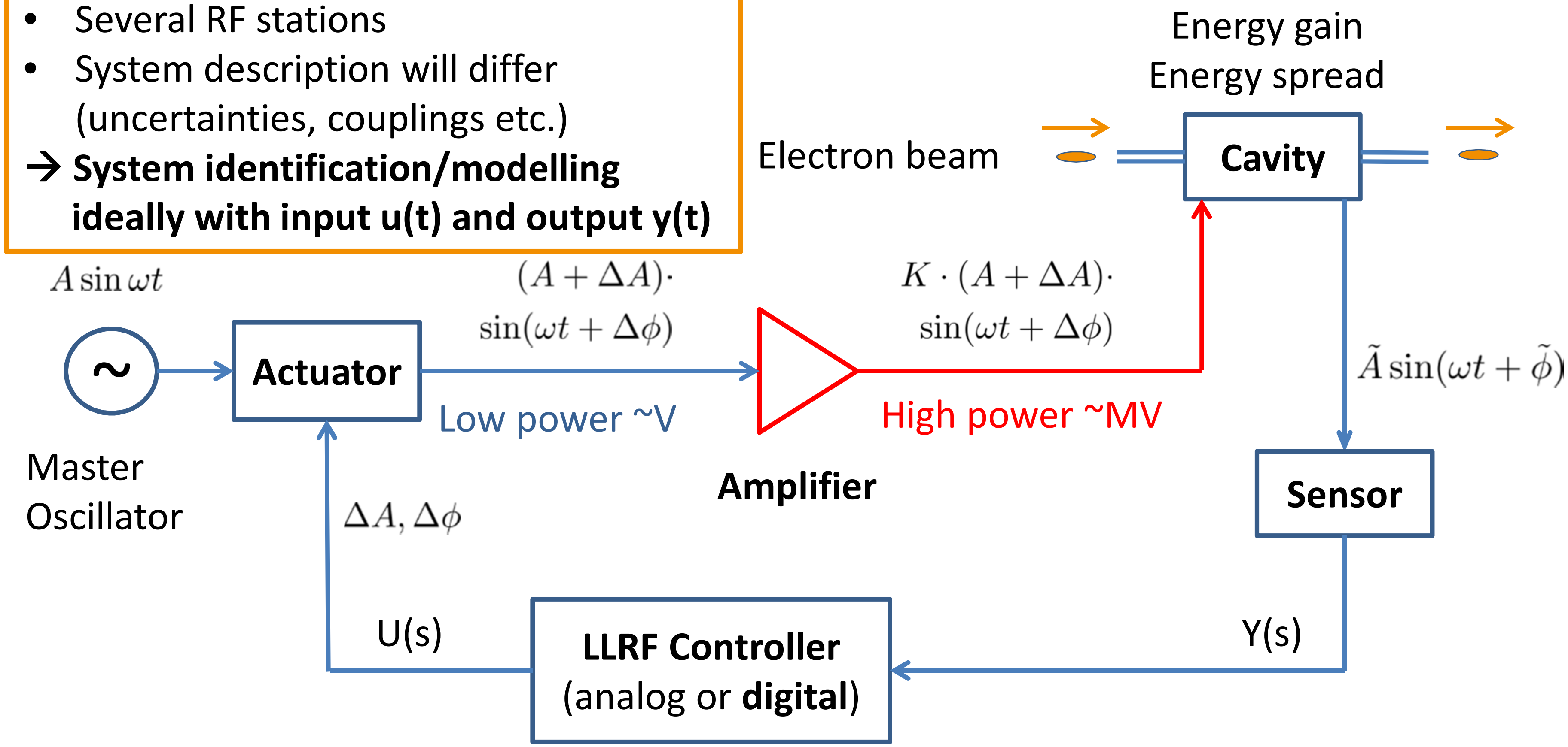
- RF field detection
  - Down-conversion to baseband (envelop of HF signal)
  - Direct A/P sampling nowadays possible (high speed ADCs)
    → May worsen SNR of ADC
  - Preferred method depends on your application
- RF field manipulation
  - Up-conversion from baseband to HF
  - Bandwidth in tens of MHz range
- Amplifier (Klystron)
  - Mostly non-linear input/output behavior
    → Linearization desired
  - Bandwidth in tens of MHz range
- Cavity (9-cell SRF cavity)
  - Differential equation as baseband model
  - Bandwidth (Hz … kHz), detuning and higher order modes

System Overview – Example at FLASH



- Several RF stations
- System description will differ (uncertainties, couplings etc.)

→ **System identification/modelling ideally with input u(t) and output y(t)**



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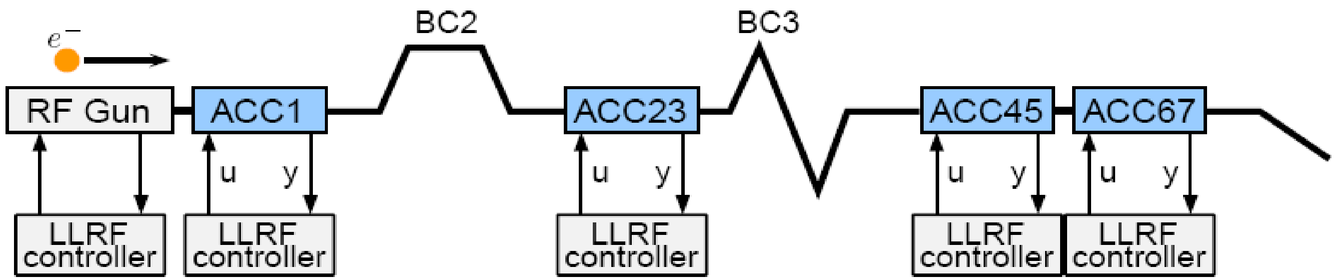
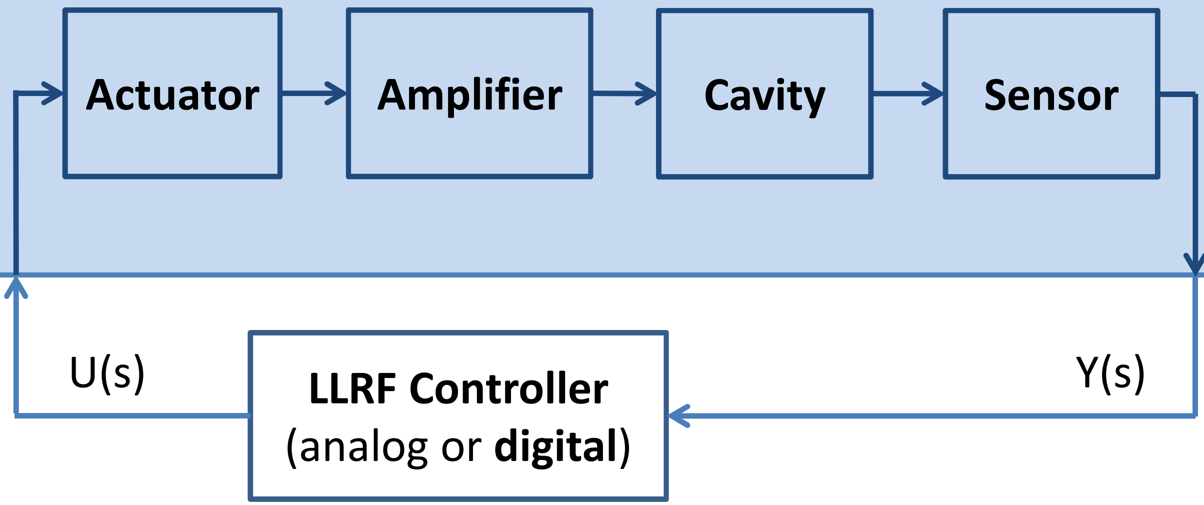


- Several RF stations
- System description will differ (uncertainties, couplings etc.)

→ **System identification/modelling ideally with input u(t) and output y(t)**

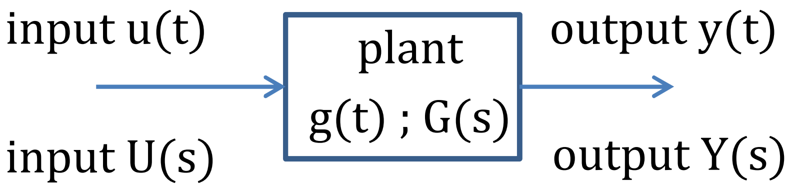
System model by identification for model based controller design (LLRF controller)



3. System Modeling - General

1. System Input-Output Modeling
2. Laplace Transformation
3. Bode Diagram
4. Example: System Modeling using Matlab

System I/O Representation



Time domain

- Convolution of impulse response g(t) and input u(t)

$$y(t) = g(t) * u(t)$$

- Makes analysis very complicated

Frequency domain

- Laplace transformation used in system analysis

$$s := \sigma + j\omega$$

- Multiplication of impulse response G(s) and input U(s)

$$Y(s) = G(s) \cdot U(s)$$

- Makes system analysis easier

Transformation into Frequency Domain

- Fourier transformation
  - Defined for all t

$$F(f) = \int_{t=-\infty}^{\infty} f(t) \cdot e^{-i2\pi f t} dt$$

- Laplace transformation
  - $s := \sigma + j\omega$
  - Defined for all t ≥ 0 (causal system)
  - $f(t) = 0, \forall t < 0$

$$F(s) = \int_{t=0}^{\infty} e^{-st} f(t)\, dt$$

- Inverse Laplace transformation

$$f(t) = \mathcal{L}^{-1}\{F(s)\} = \frac{1}{2\pi j} \int_{s=\alpha-j\infty}^{\alpha+j\infty} F(s) \cdot e^{st}\, ds$$

Example: Cavity Equation

Find transformation as table in www

Sl. No.	Time Domain f(t)	S Domain F(s)
	t	
1	Unit impulse $\delta(t)$	1
2	Unit step	$\frac{1}{s}$
3	t	$\frac{1}{s^2}$
4	t^n	$\frac{n!}{s^{n+1}}$
5	$f'(t)$	$sF(s) - f(0)$
6	$f''(t)$	$s^2F(s) - sf(0) - f'(0)$
7	e^{at}	$\frac{1}{s-a}$; s > a
8	$t^n e^{at}$	$\frac{n!}{(s-a)^{n+1}}$
9	$\sin at$	$\frac{a}{s^2+a^2}$; $s > 0$
10	$\cos at$	$\frac{s}{s^2+a^2}$; $s > 0$

http://electricalstudy.sarutech.com/images/laplace-transform-table1.gif

From time domain

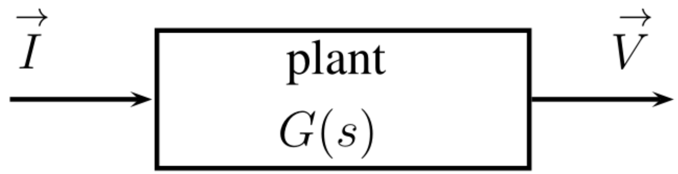
$$\dot{\vec{V}} + (\omega_{1/2} - j\Delta\omega)\,\vec{V} = \omega_{1/2} R_L\,\vec{I}$$

To frequency domain

$$s\vec{V} + (\omega_{1/2} - j\Delta\omega)\,\vec{V} = \omega_{1/2} R_L\,\vec{I}$$

$$(s + (\omega_{1/2} - j\Delta\omega))\,\vec{V} = \omega_{1/2} R_L\,\vec{I}$$

$$G(s) = \frac{\vec{V}}{\vec{I}} = \frac{\omega_{1/2} R_L}{s + (\omega_{1/2} - j\Delta\omega)}$$



Example: Cavity Equation

Complex I/Q representation:

$$G(s) = \frac{\vec{V}(s)}{\vec{I}(s)} = \frac{\omega_{1/2} R_L}{s + (\omega_{1/2} - j\Delta\omega)}$$

$$\vec{V}(s) = \frac{\omega_{1/2} R_L}{s + (\omega_{1/2} - j\Delta\omega)} \cdot \vec{I}(s)$$

I/Q representation (MIMO):

$$\dot{V}_I + \omega_{1/2} V_I + \Delta\omega V_Q = R_L \omega_{1/2} I_I$$
$$\dot{V}_Q + \omega_{1/2} V_Q - \Delta\omega V_I = R_L \omega_{1/2} I_Q$$

Assume $\boldsymbol{\Delta}\omega = \mathbf{0}$:

$$\dot{V}_I + \omega_{1/2} V_I = R_L \omega_{1/2} I_I$$
$$\dot{V}_Q + \omega_{1/2} V_Q = R_L \omega_{1/2} I_Q$$

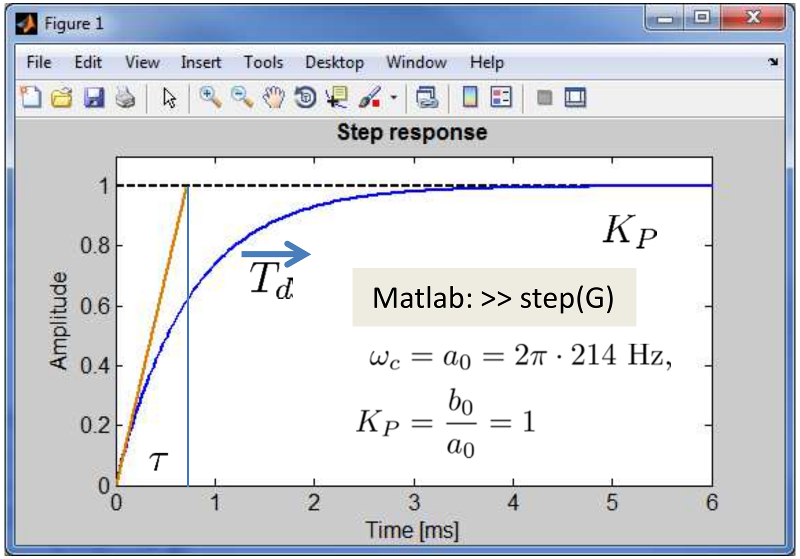
$\rightarrow$ 2 decoupled 1^{st} order SISO systems

$$G_{II}(s) = G_{QQ}(s) = \frac{V_x}{I_x} = \frac{R_L \omega_{1/2}}{s + \omega_{1/2}}$$

First order system:

$G(s) = \frac{b_0}{s + a_0}$

Static gain: $K_P = b_0/a_0$ for s $\rightarrow 0$
Time constant: $\tau = 1/a_0$
Step response: $y(t) = K_p(1 - e^{-t/\tau})$



System with time delay T_d:

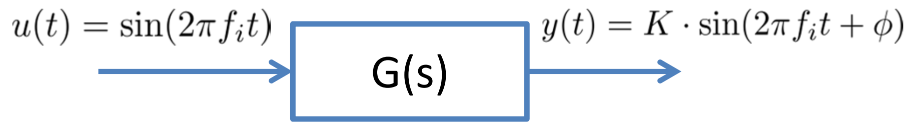
$$G_d(s) = G(s) \cdot e^{-T_d \cdot s}$$

$G(s)$ ... time delay-free system
$G_d(s)$ ... time delayed system

Bode diagram

Bode magnitude and phase plot

- Magnitude: $20\log_{10}(|G(s=j\omega)|)$
- Phase: $\arg(G(s=j\omega))$



First order system:

$G(s) = \frac{b_0}{s+a_0}$

Static gain (s → 0): $K_P = b_0/a_0$
Corner frequency: $f_c = a_0$

System with time delay T_d:

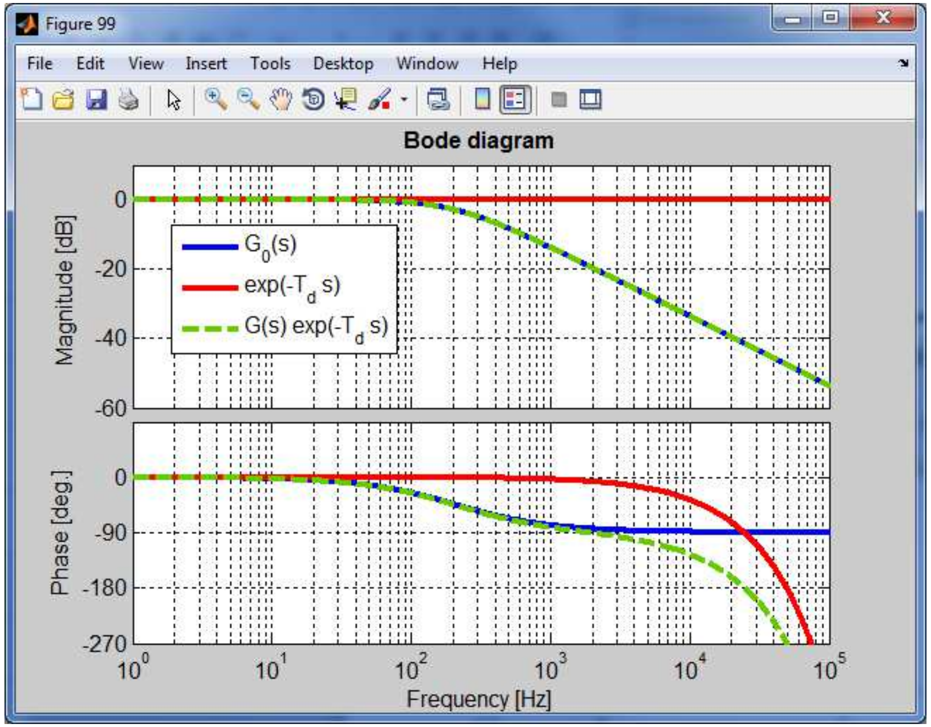
$$G(s) = G_0(s) \cdot e^{-T_d \cdot s}$$

- $G_0(s)\ldots$ time delay-free system
- Time delay with gain of 1 and phase roll-off of:

$$|e^{-T_d \cdot s}| = 1$$

$$\angle(e^{-T_d \cdot s}) = \phi(\omega) = -T_d\omega \qquad [rad]$$

$$= -T_d\omega\frac{180}{pi} \; [deg]$$



Example:

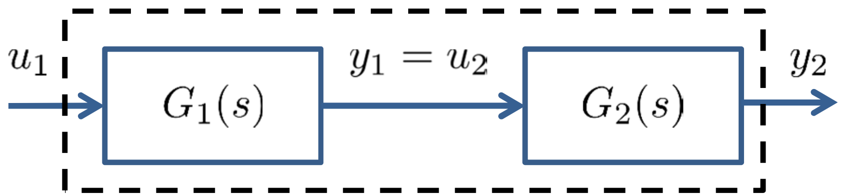
$\omega_c = a_0 = 2\pi \cdot 214$ Hz,

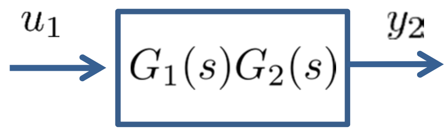
$K_P = \frac{b_0}{a_0} = 1$ and

$T_d = 10\mu s$

Serial, parallel and feedback connection of blocks

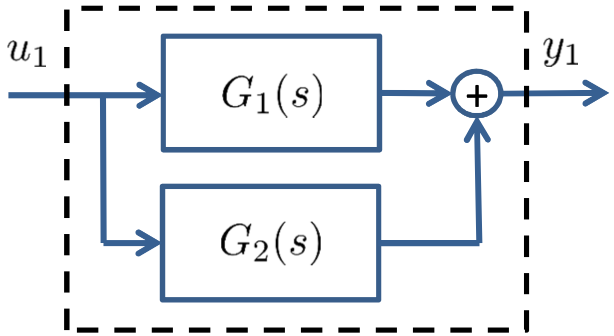
- **Serial connection**

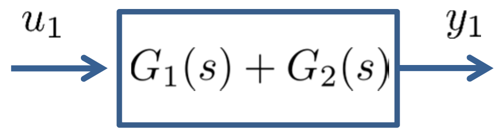




$$Y_2(s) = G_1(s) \cdot G_2(s) \cdot U_1(s)$$

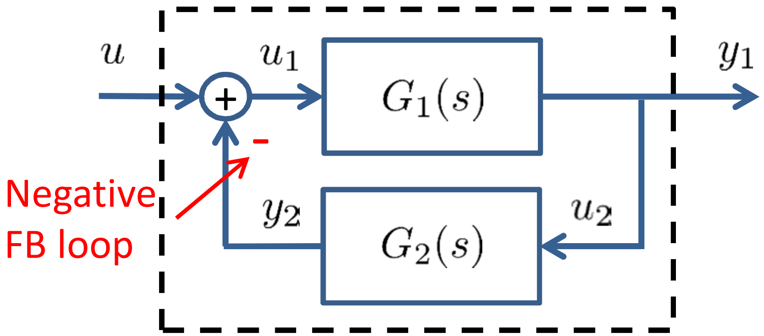
- **Parallel connection**

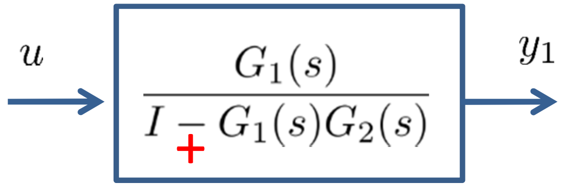




$$Y_1(s) = (G_1(s) + G_2(s)) \cdot U_1(s)$$

- **Feedback**



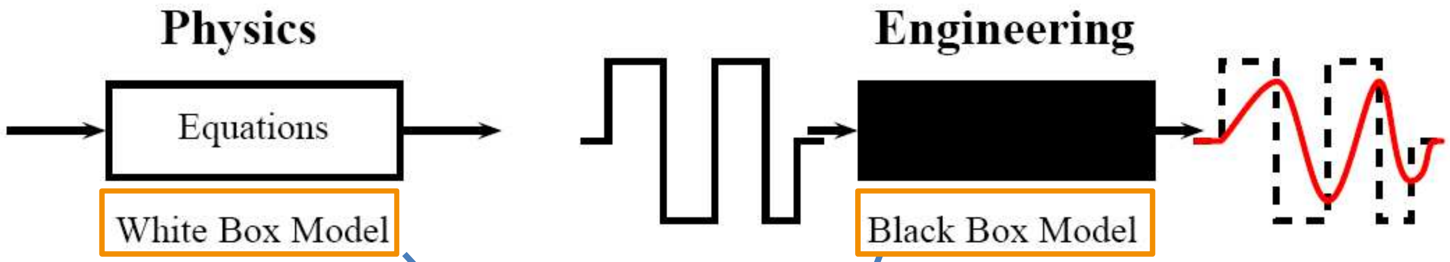


$$Y_1(s) = \frac{G_1(s)}{I \mp G_1(s)G_2(s)} \cdot U(s)$$

$$G_{cl} = \frac{Y_1(s)}{U(s)} = \frac{\text{forward gain}}{I \mp \text{loop gain}}$$

System Modelling

A system model is a simplified representation or abstraction of the reality.
Reality is generally too complex to copy exactly.
Much of the complexity is actually irrelevant in problem solving, e.g. controller design.

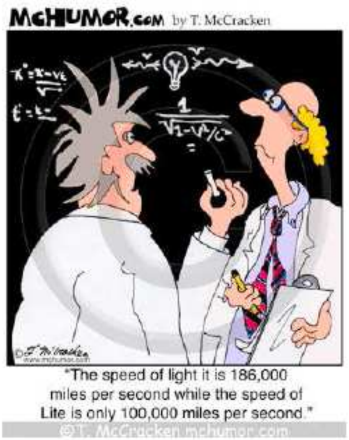


Fully based on physical description e.g. cavity equation

Identification Methods

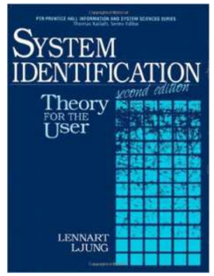
Usage of defined input signal u(t)
→ observation of output signal y(t)
→ $G(s) = Y(s)/U(s)$

[Pfeiffer.2014]



Grey Box Model

Parameter estimation based on physical equation
→ Find some free parameters

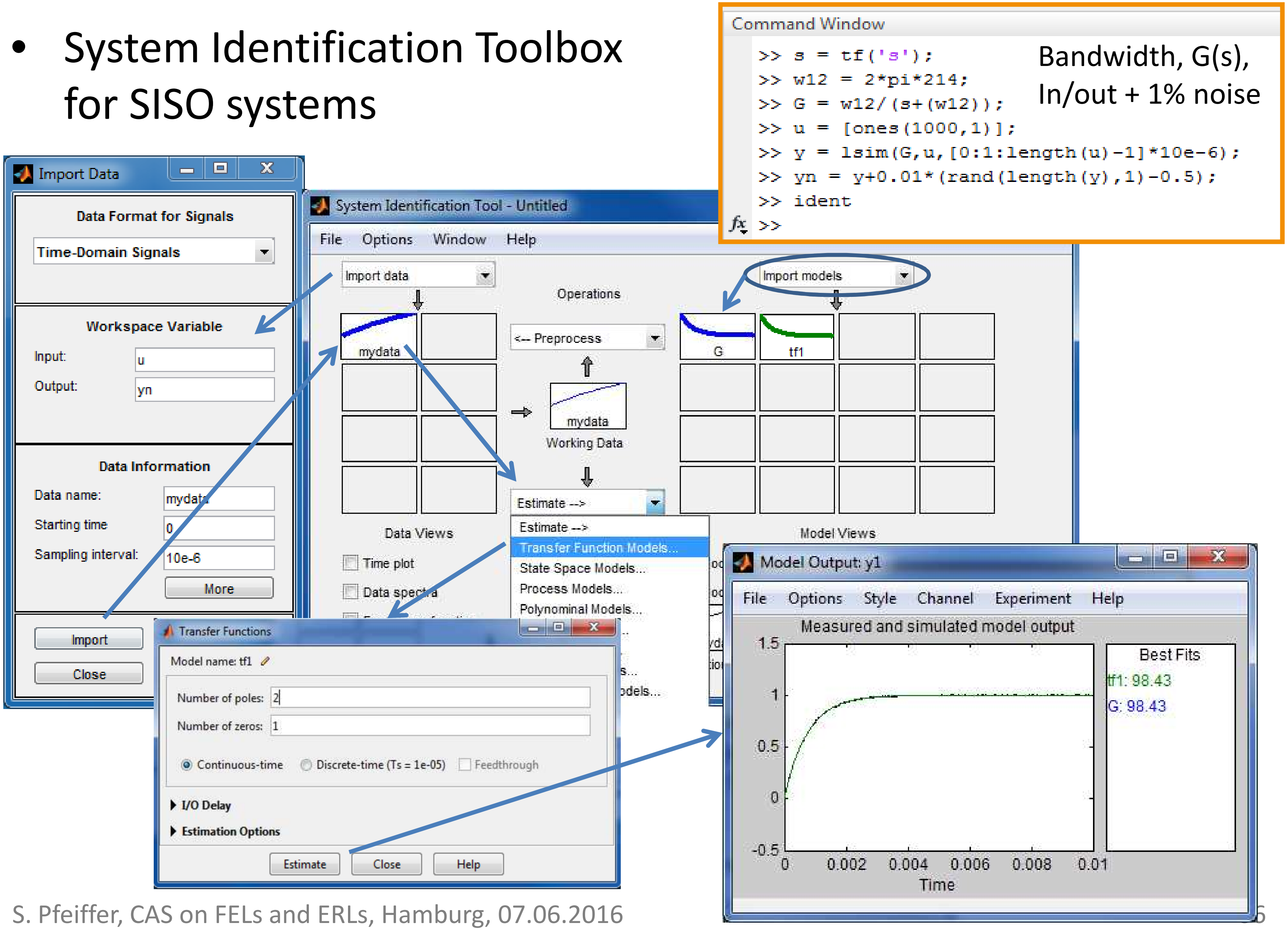


[Ljung.1999]

→ System identification using special input signals

System Identification using Matlab

- System Identification Toolbox for SISO systems

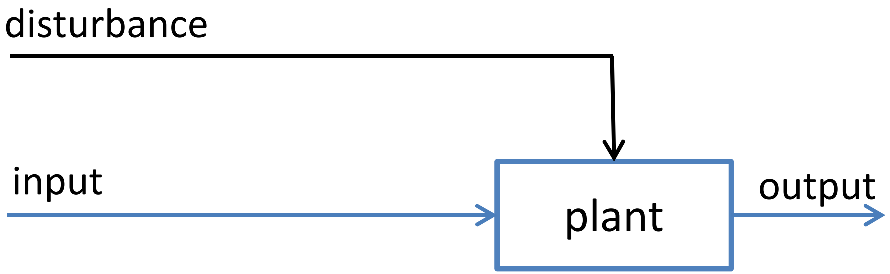


4. Feedback Controller Design

1. Ways to control
2. Control Objective
3. Stability
4. Gang of four
5. Types of control

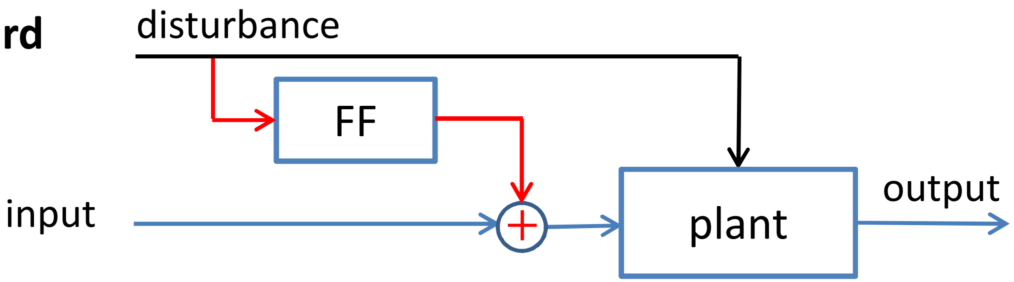
Ways to Control

Open loop (simple)



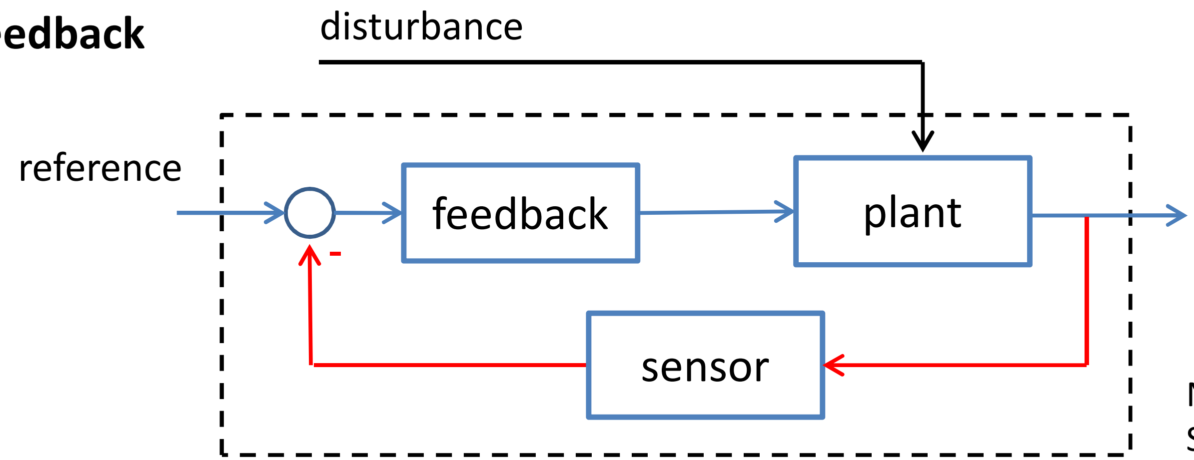
Precise knowledge on I/O behavior;
No action on disturbances

Feed forward



Precise knowledge on I/O behavior;
Act by feedforward e.g. on disturbances
→ *No action on signal to be controlled*

Feedback



Feedback and regulate the signal to be controlled by acting on the input

New system with new properties !
See: connection of systems

Objective of a feedback control problem

Make the output y(t) behave in a desired way by manipulating the plant input u(t)

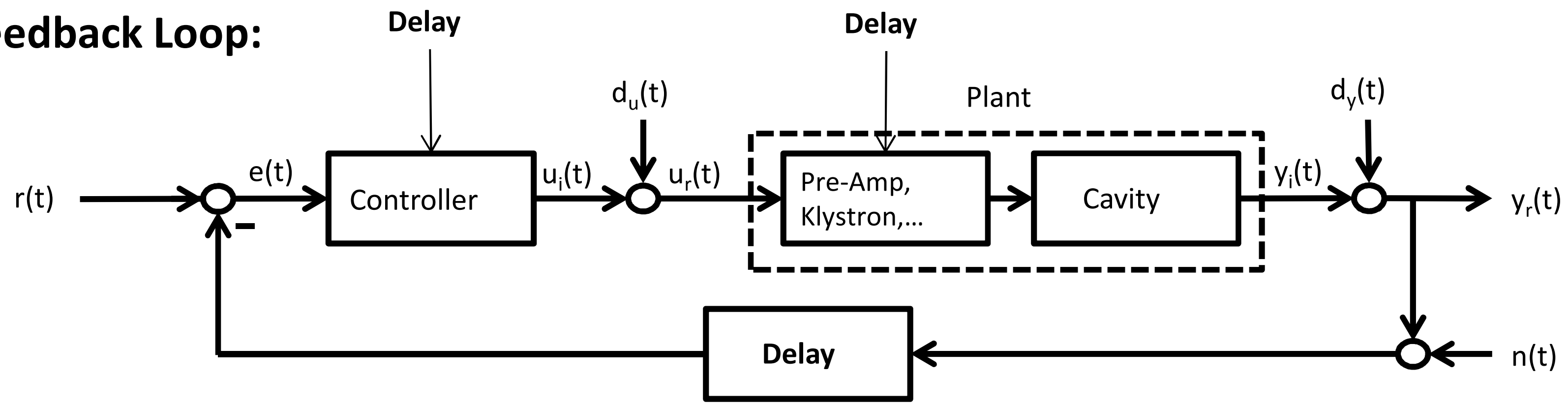
- ***Regulator problem*** (output disturbance rejection with constant reference)
  - Counteract the effect of a disturbance $d_Y(t)$
- *Servo problem* (reference tracking without disturbance)
  - Manipulate u(t) to keep the output y(t) close to the reference r(t)

Goal: in both cases the control error e(t) = r(t) - y(t) should be minimal

Additional: High robustness to plant/process variations $\tilde{G}(s) = G(s) + \Delta G(s)$

→ e.g. certain phase margin ~60 deg (see next slide)

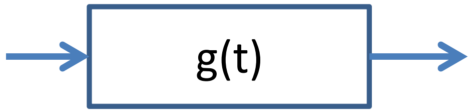
Feedback Loop:



Stability Criteria's (incomplete!)

A system is stable if for a given bounded input signal the output signal is bounded and finite (BIBO stable); if not, the system is called unstable

Stable if impulse response absolutely integrable and bounded



$$\int_{t=-\infty}^{\infty} |g(t)|dt < \infty$$

Stable or unstable linear systems

- Open loop or closed loop
- Unstable open loop: Stabilize closed loop system behavior using feedback controller

Stability check in s-domain by e.g.:

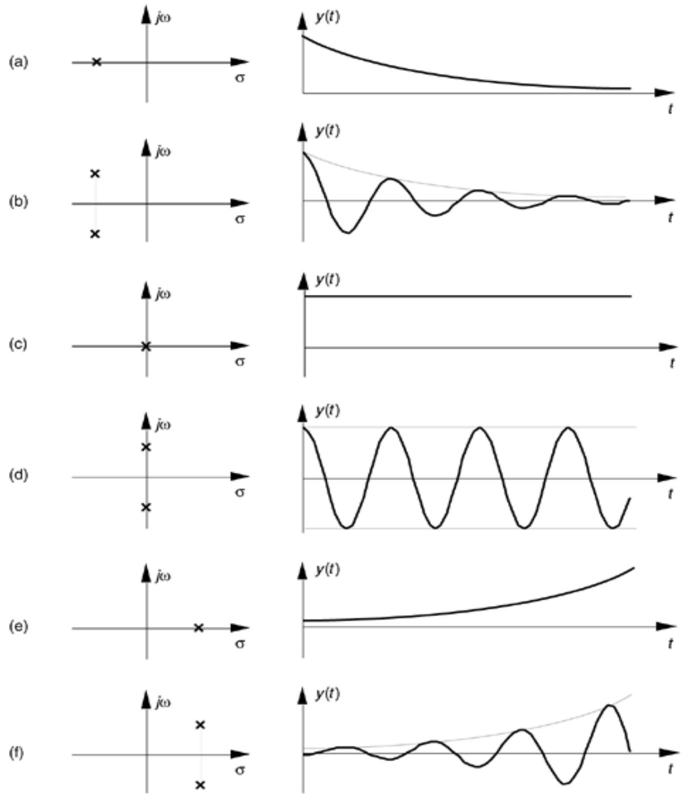
- **Pole location (all poles in left half plane)**
- Bode diagram
- Nyquist plot
- H-infinity norm for MIMO systems

Non-linear systems → harmonic balance

→ **Check stability for *"Gang of four (six)"***

$$G(s) = \frac{b_m s^m + b_{m-1}s^{m-1} + \ldots + b_1 s + b_0}{s^n + a_{n-1}s^{n-1} + \ldots + a_1 s + a_0}$$

This system has *n* poles and *m* zeros, and if it is physically realizable we have *n* ≥ *m*.



Understanding Digital Signal Processing (2nd Edition)
Mar 25, 2004by Richard G. Lyons

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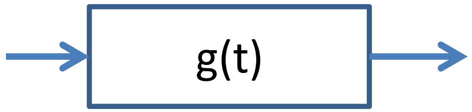

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- **Nyquist plot**
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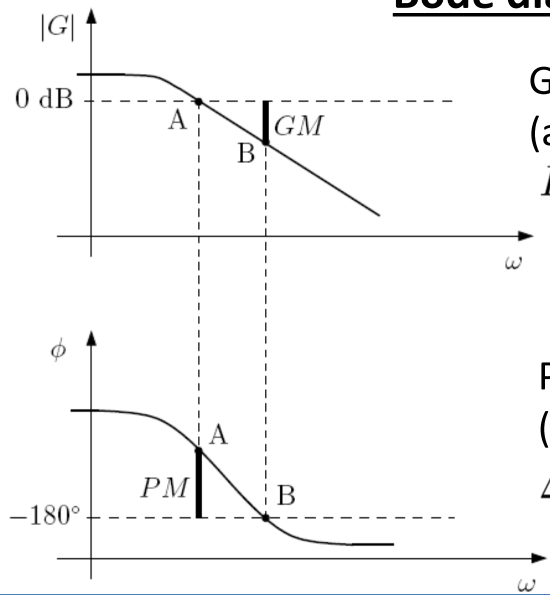
Non-linear systems → harmonic balance

→ **Check stability for *"Gang of four (six)"***

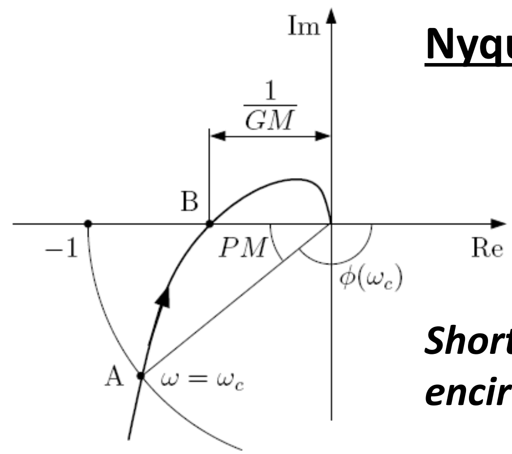
Bode diagram



Gain margin (at -180 deg.)
$K_P < \mathrm{GM}$

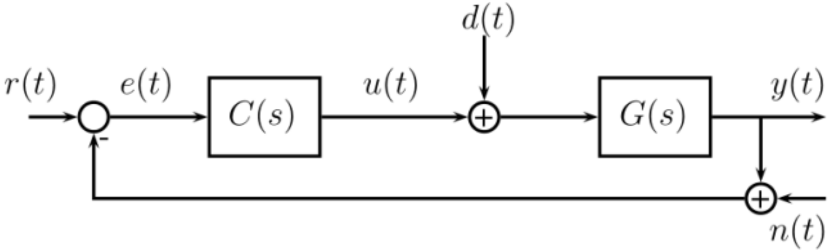
Phase margin (at 0 dB)
$\Delta\phi < \mathrm{PM}$

Nyquist plot



Short: Do not encircle -1!

Gang of Four



Response of y(t) to disturbance d(t) and response of u(t) to measurement noise n(t):

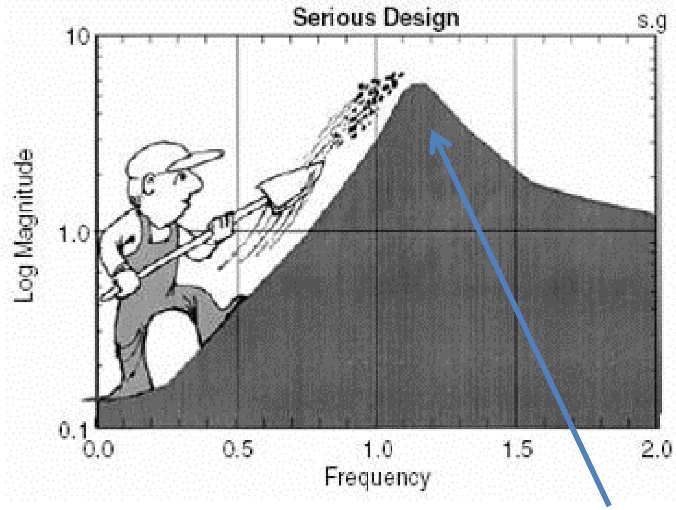
$$G_{yd} = \frac{G}{1+GC} \qquad G_{un} = -\frac{C}{1+GC}$$

Robustness to process variations:

$$S = \frac{1}{1+GC} \quad \text{and} \quad T = \frac{GC}{1+GC}$$

S is called sentitivity function
T is called complementary sentitivity function
Both depends on the loop transfer function L = GC
Coupling: S + T = 1
Typical: S(0) small, S(∞) = 1; T(0) = 1, T(∞) small

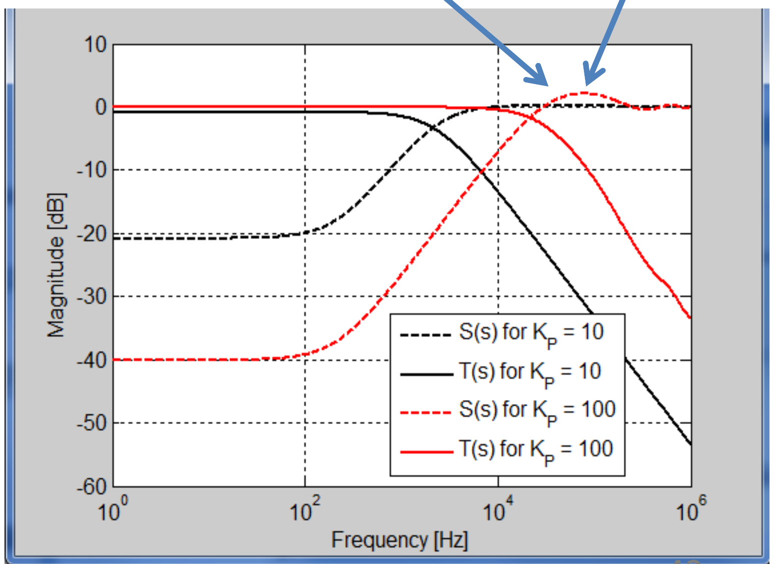
(Gang of six (6 TF to be checked) using reference filter)



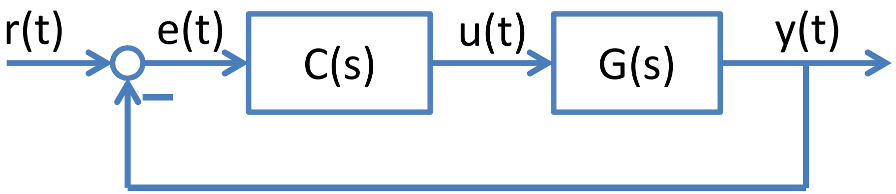
2005 - "Respect the Unstable," IEEE Control Systems Magazine, Vol. 23, No. 4, pp. 12-25, August 2003.

Waterbed effect

Oscillations at high frequencies



Types of Feedback Control



Classical FB Control

- Frequency domain analysis

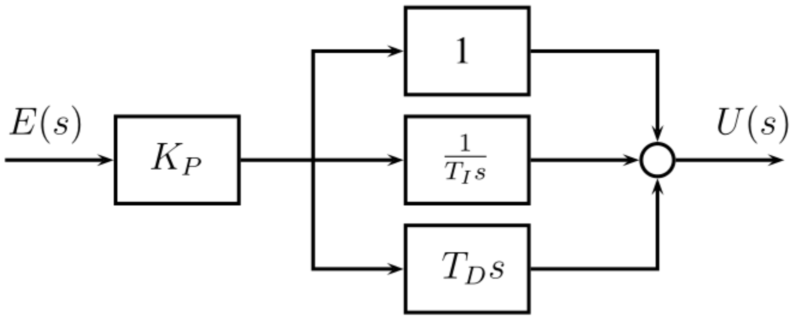
→ Bode Diagram, Nyquist Plot

PID-Control

$\frac{U(s)}{E(s)} = C(s) = K_P$

$$u(t) = K_P \left(e(t) + \frac{1}{T_I} \int_{t_0}^{t} e(\tau) d\tau + T_D \dot{e}(t) \right)$$

$$U(s) = K_P \left[1 + \frac{1}{T_I s} + T_D s \right] E(s)$$



Modern FB Control

- Time domain analysis

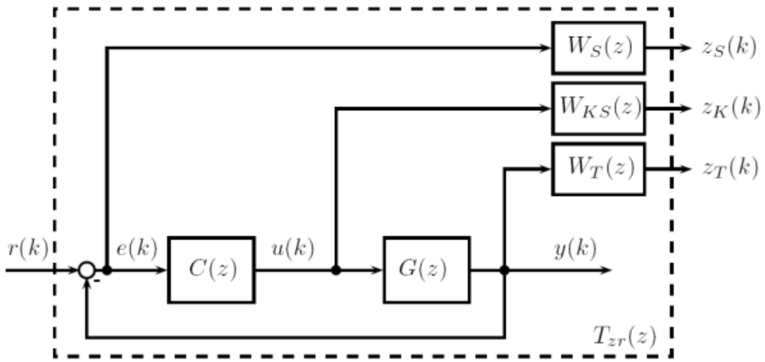
→ State space representation

$$\dot{x}(t) = Ax(t) + Bu(t)$$
$$y(t) = Cx(t) + Du(t)$$

→ Linear-quadratic regulator (LQR) etc.

$$u(t) = -K \cdot x(t)$$

→ H-infinity optimization by shaping the sensitivity and complementary sensitivity function



$$\|T_{zr}(z)\|_\infty = \left\| \begin{bmatrix} W_S(z) \cdot S(z) \\ W_{CS}(z) \cdot C(z)S(z) \\ W_T(z) \cdot T(z) \end{bmatrix} \right\|_\infty < 1$$

5. Examples

- RF field feedback loop
- Microphonics suppression
- Disturbance rejection

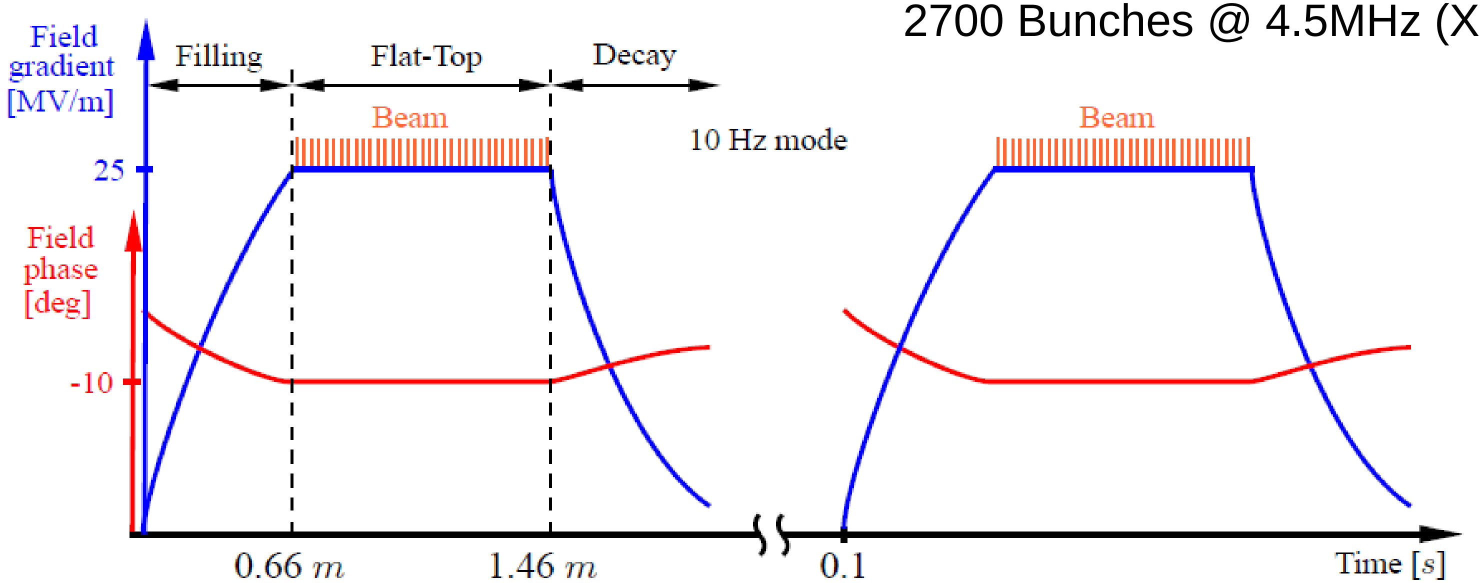
Example: RF field Control @ FLASH

Radio Frequency Field → ***Control Strategies***

Pulsed operation - 10 Hz
2ms pulse length
(Filling, Flattop and Decay)

1) **Adaptation by Learning**
2) **Fast Controller (FPGA)**
3) **Beam Loading Compensation**

2400 Bunches @ 3MHz (FLASH),
2700 Bunches @ 4.5MHz (XFEL)

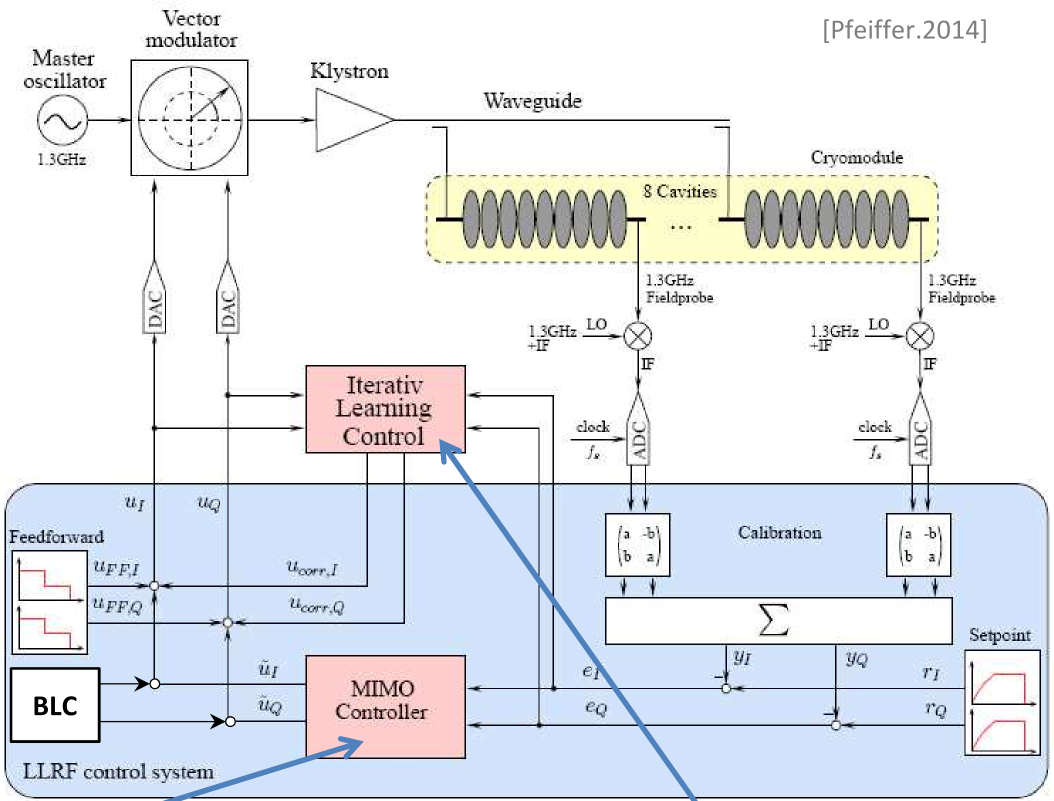


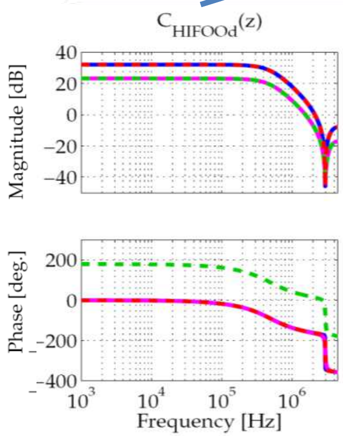
Model-Based Controller Design to reach:

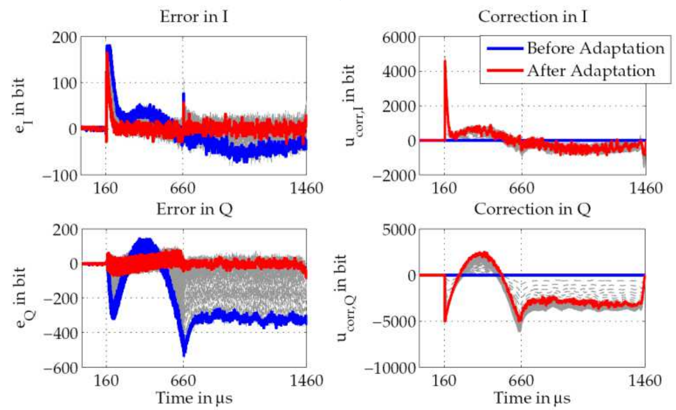
$$\mathbf{\Delta A/A < 0.01\%} \text{ and } \mathbf{\Delta\phi < 0.01deg}$$

Example: RF field Control @ FLASH

[Pfeiffer.2014]







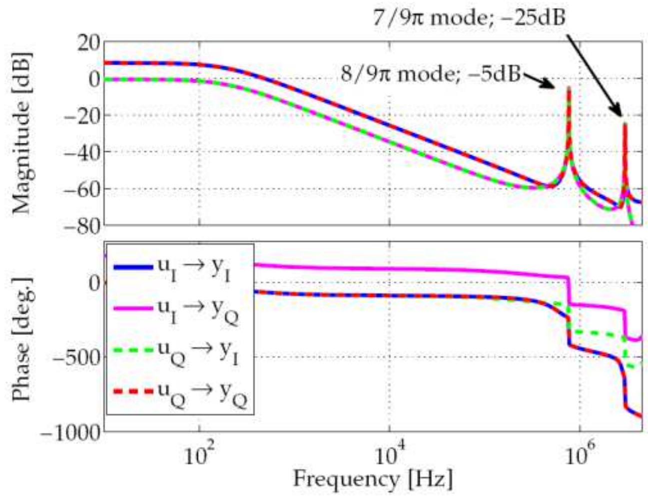
Pulsed mode (10 Hz) @ 1% duty cycle

LLRF Controls:

- Iterative Learning Control for pulse to pulse FF adaptation
- MIMO FB for intra-pulse FB

System Identification

- Low frequency
- High frequency



Iterative Learning Control

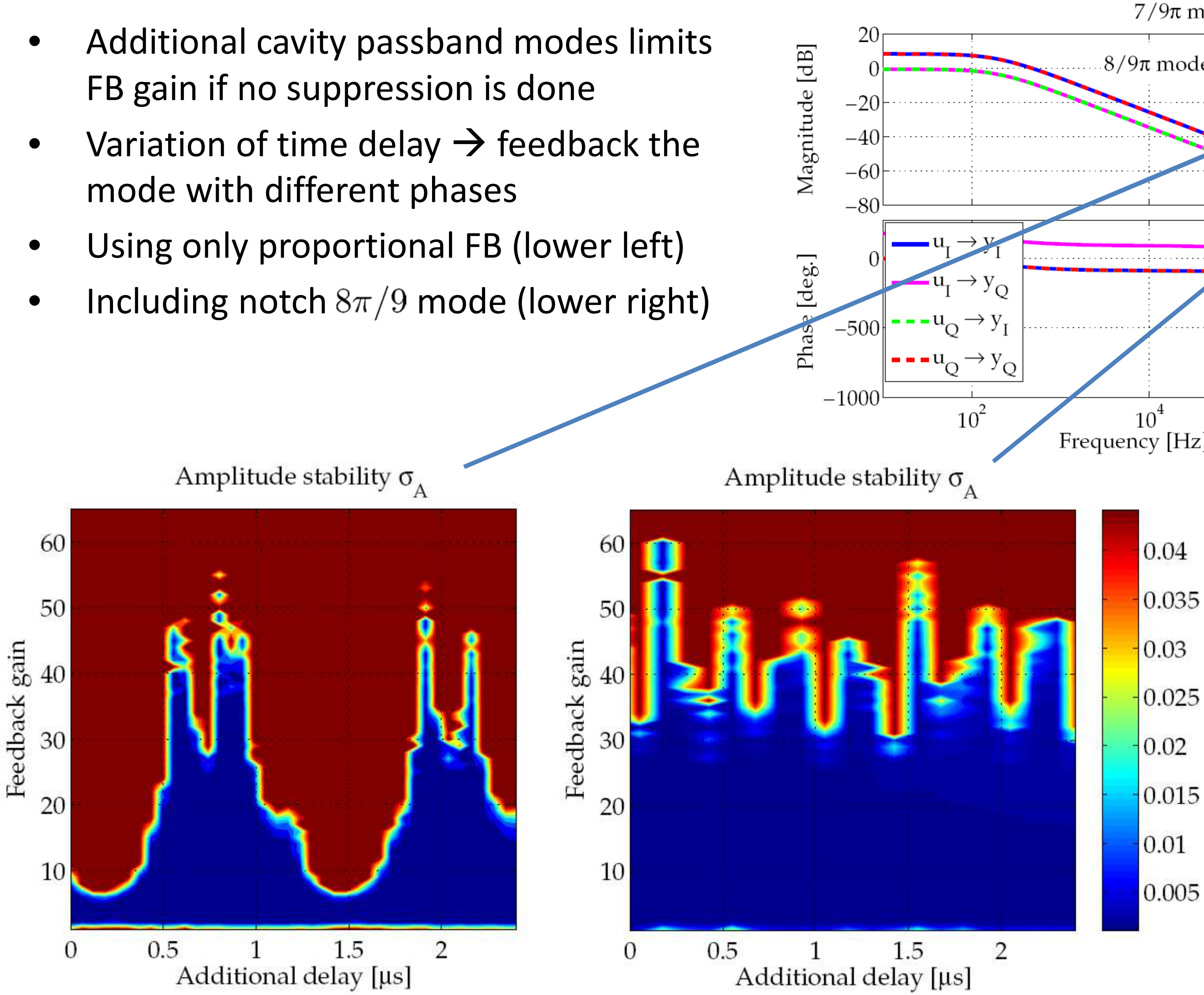
- Minimizing repetitive P2P errors

MIMO Controller (IIR filter)

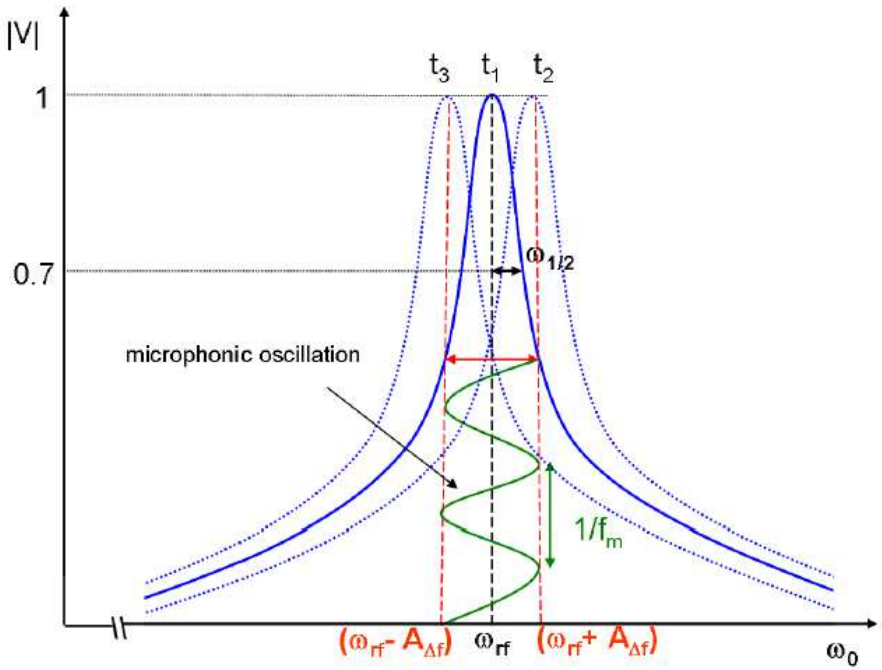
- Notch for $8\pi/9$ mode at ADC
- MIMO suppresses $7\pi/9$ mode

Example: RF field Control @ FLASH

- Additional cavity passband modes limits FB gain if no suppression is done
- Variation of time delay → feedback the mode with different phases
- Using only proportional FB (lower left)
- Including notch $8\pi/9$ mode (lower right)



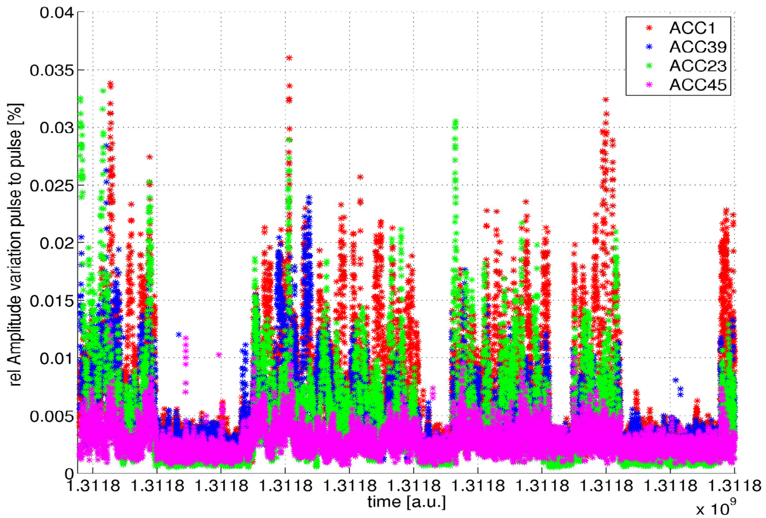
Microphonics and its Suppression



Measurement @ FLASH (Q_L… $3\cdot10^6$)

→ RF field control is active

→ Large variations in amplitude stability

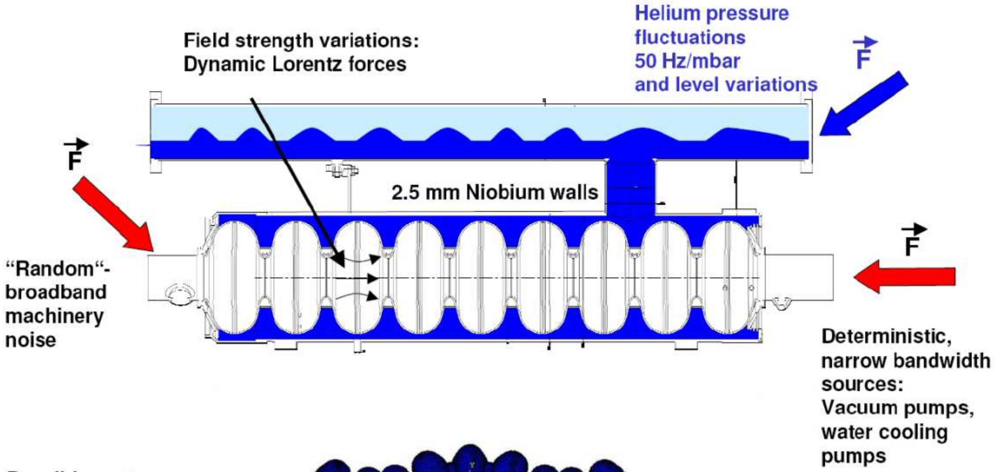


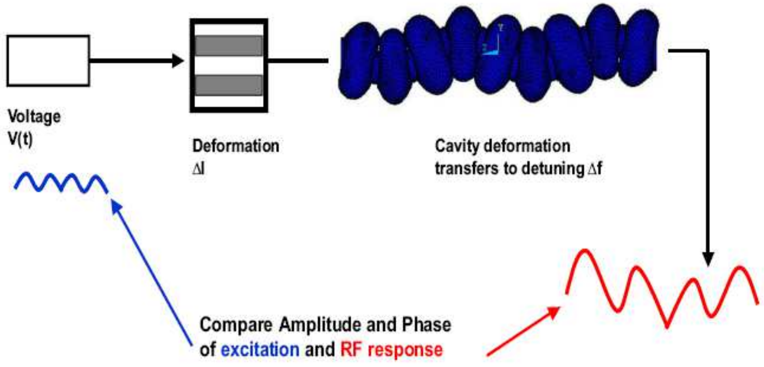
- From pulsed mode to CW: smaller cavity bandwidth (Q_L… 10^7)
- Microphonics dominate system performance
- Harmonic and stochastic microphonics
  - Distribution along cavities or modules (phase advance)
  - Mechanical response on the individual cavities

… due to compacting machine @ XFEL injector (distance ~ 400m)

Example: Microphonics Suppression

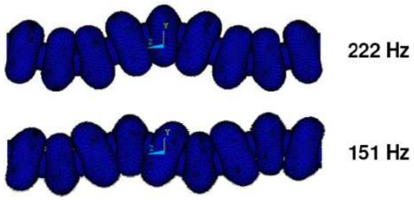
A. Neumann, *Compensating Microphonics in SRF Cavities to Ensure Beam Stability for Future Free-Electron-Lasers, PhD thesis, 2008*

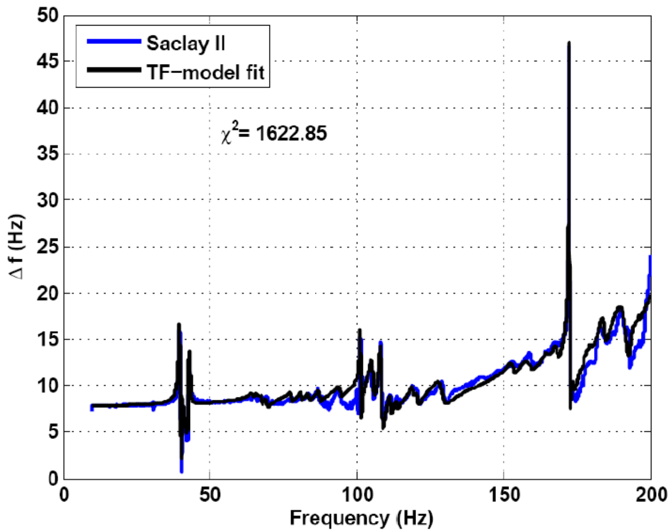




$$\tilde{H}_{PZT}(f_m) = \frac{\tilde{\Delta f}(f_m)}{\tilde{\Delta V}(f_m)} = A\, e^{j\varphi}$$

Possible system response of cavity-tank-tuner system predicted by FEM simulations





Individual modes:

$$\Delta\ddot{\omega}_{cav,k}(t) + 2\xi\omega_{m,k} \cdot \Delta\dot{\omega}_{cav,k}(t) + \omega_{m,k}^2 \cdot \Delta\omega_{cav,k} = \pm k_{p,k} 2\pi\omega_{m,k}^2 V_{Piezo}(t)$$

$$\Delta\omega_{cav}(t) = \sum_k \Delta\omega_{cav,k}(t)$$

$$H_k(s) = \frac{\omega_k^2 M_k}{s^2 + 2\xi_k\omega_k s + \omega_k^2}$$

Low pass:

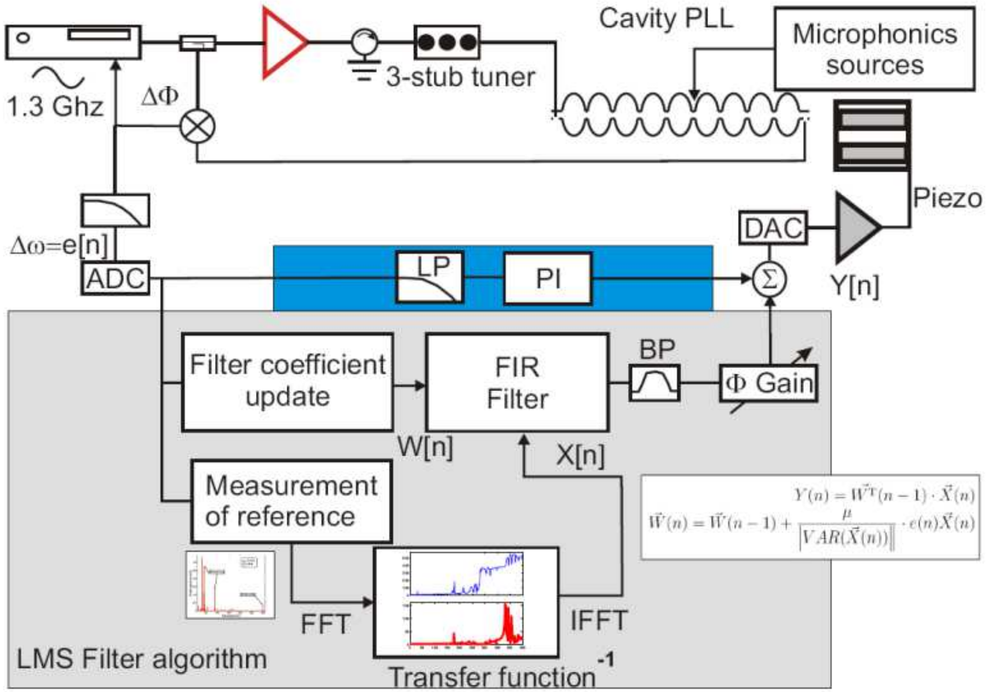
$$H_0(s) = \frac{M_0}{\tau s + 1}$$

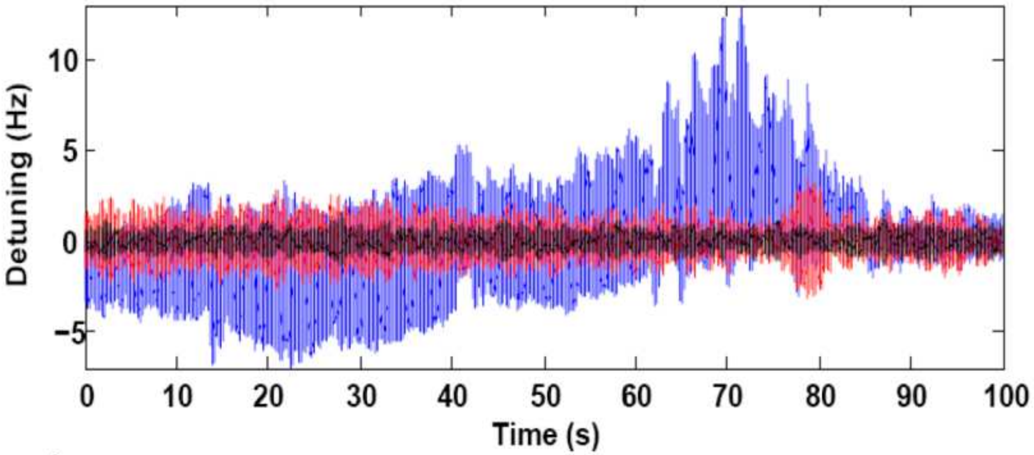
Total model:

$$H(s) = \left(H_0(s) + \sum_{k=1}^{N} H_k(s)\right) \cdot H_{delay}(s)$$

Example: Microphonics Suppression

- Feedback (LP + PI)
- Adaptive Feedforward



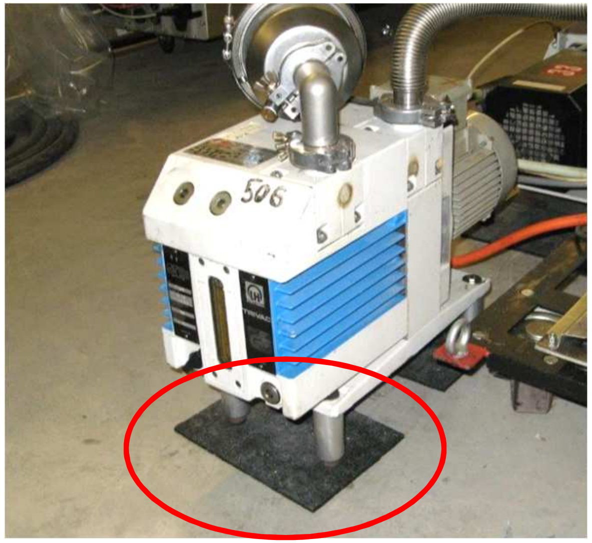


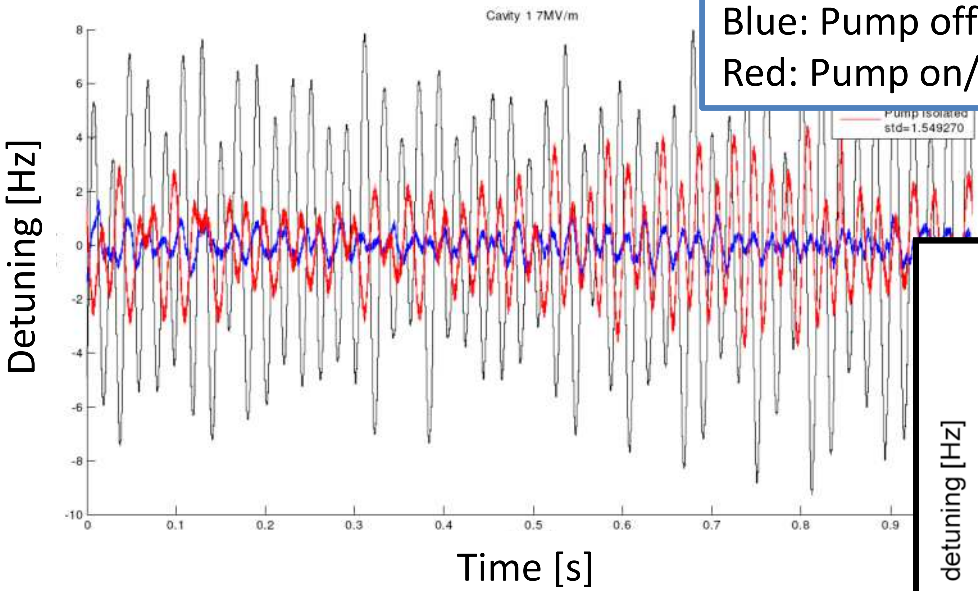
Blue: open loop
Red: PI control
Black: FF+PI control

Passive Microphonics Reduction

- Measurement at CMTB - DESY
- Try to decouple cavities from external noise sources
- Microphonics reduced using anti vibration mat for vacuum pump

Courtesy of: Jürgen Eschke

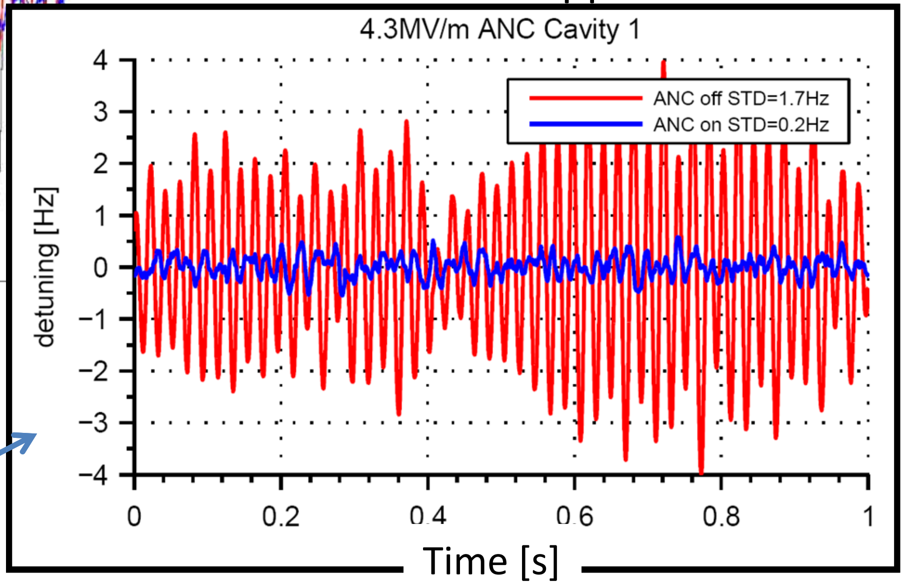




Black: Pump on
Blue: Pump off
Red: Pump on/isolated

Courtesy of: Radoslaw Rybaniec

Applied feedback



Blue: active noise cancellation (ANC) off
Red: ANC on

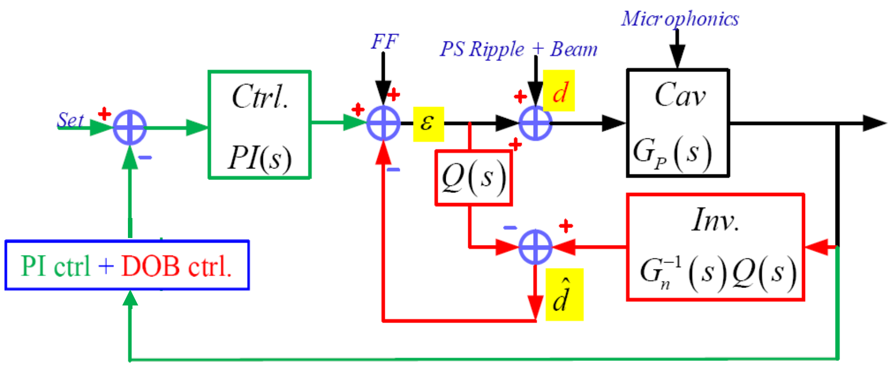
[Rybaniec.2016]

Example: Disturbance rejection @ cERL (KEK)

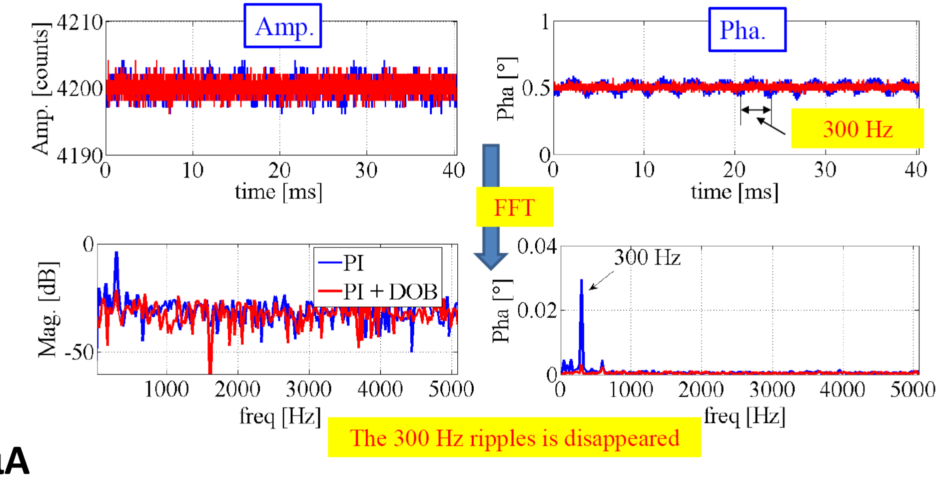
Reference:
F. Qiu et al., Phys. Rev. ST Accel. Beams 18, 092801, 2015.

- PI feedback loop (CW mode) and disturbance rejection loop
- Estimate the disturbance d using plant inverse and filter Q(s)

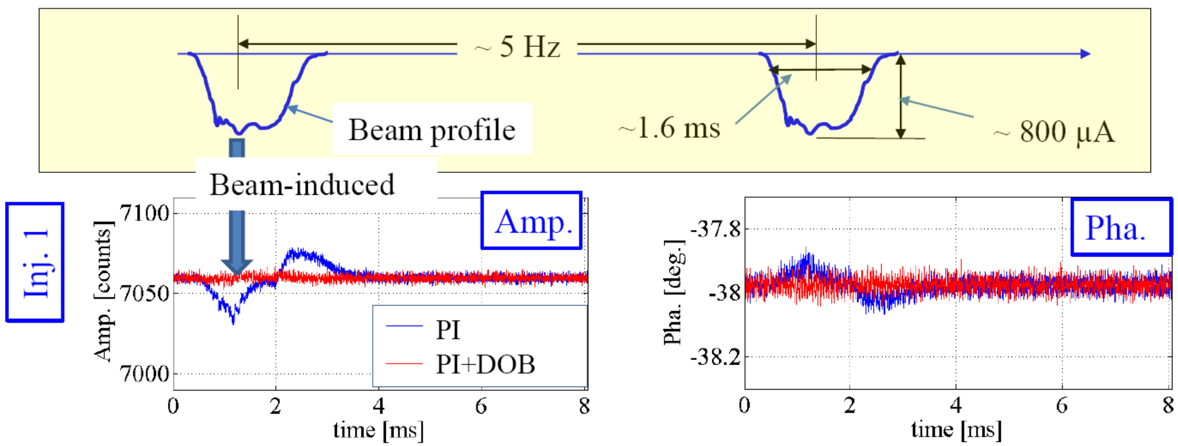
  → Disturbance Observer Based control (DOB)



Power-supply ripples rejection



Beam loading as disturbance 1.6ms and 800 µA



This approach may also be helpful for microphonics reduction

Outlook: Timing and Synchronization

Basic assumption for digital control: Clock is working exactly!

Reality: Clock is working up to some accuracy & precision ...

Talk tomorrow: Timing and Synchronization, Marco BELLAVEGLIA (INFN-LNF)

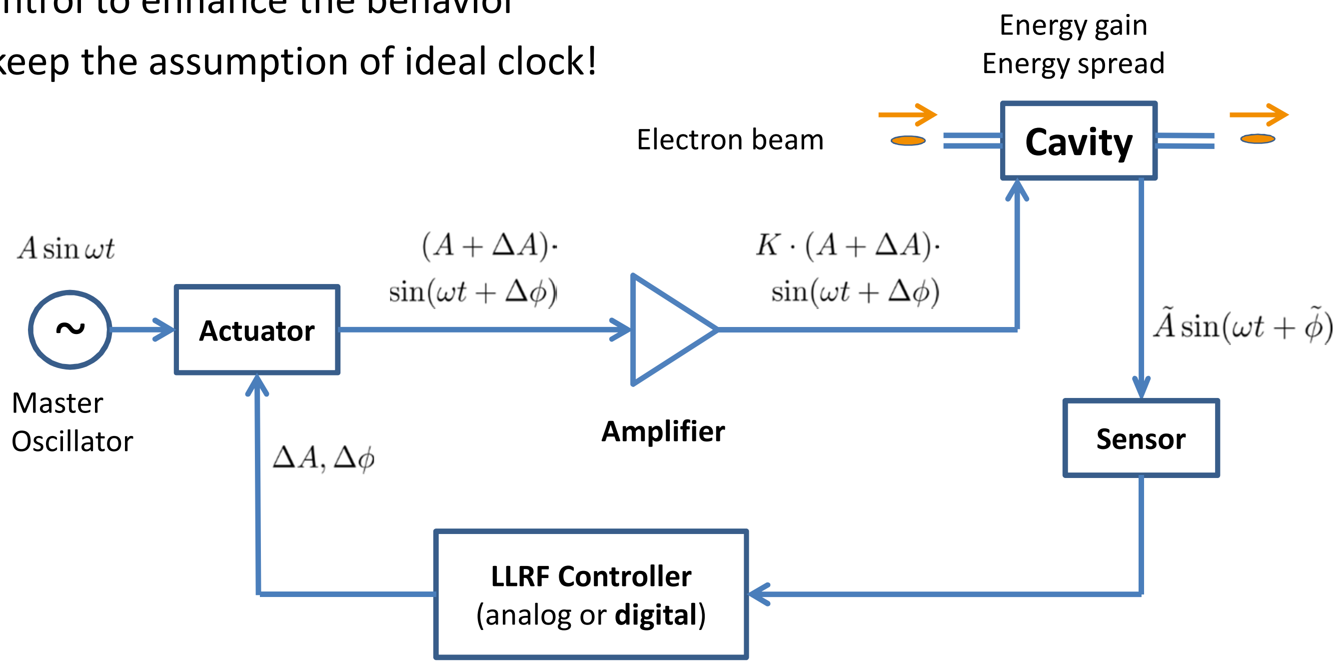
The clock is synchronized to the MO. The clock is connected to all digital LLRF components!

- FPGA, ADC, DAC, etc.

Goal: Improve the clock (timing and synchronization system)

→ Use feedback control to enhance the behavior

→ By this you can keep the assumption of ideal clock!



Question???

Thank you for your attention!

Contact: sven.pfeiffer@desy.de

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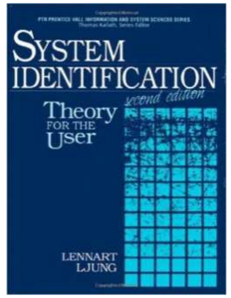
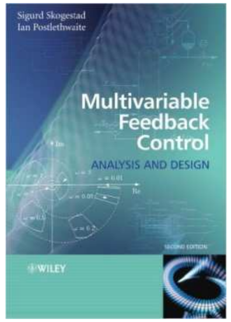
- Pictures from DESY website; *https://media.desy.de/DESYmediabank/?l=de&c=3976* and other sources in www

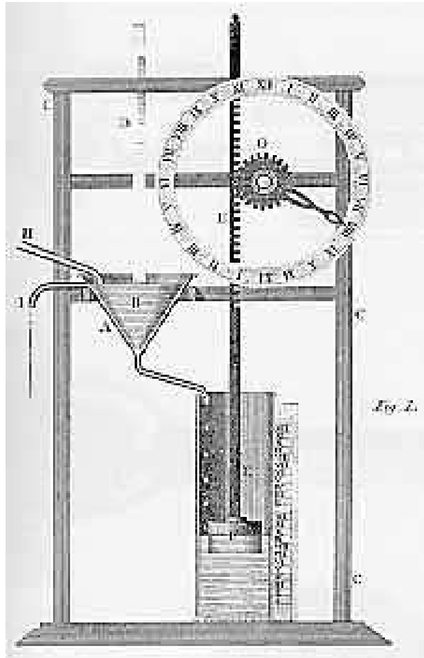




1. Introduction/Motivation

Brief history of feedback control (human designed)

- Automatic feedback control systems have been known and used for more than 2000 years (300 B.C. by a Greek mechanican)
  - Water clock – slow tickle of water into measuring container
  - Ensure at constant flowing rate → Float regulator similar to todays flush toilet
  - If water level in the supply tank not at correct level the float opens or closes the water supply → 1st feedback to keep supply tank at constant level



- Around 1681 Denis Papin's invention of a safety valve for regulation of steam pressure
- In the 17th century Cornelis Drebbel invented a purely mechanical temperature control system
- 1745 speed control was applied to a windmill by Edmund Lee
- Nowadays control systems theory began in the latter half of the 19th century
  - Started with stability criteria for a third order system based on the coefficients of the differential equation

[Nise, Norman S. 2004, Control Systems Engineering, 4th Edition, Wiley, USA.]

Digital vs. Analog Control

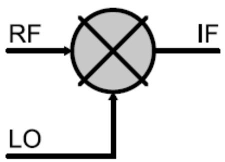
	Digital	Analogue
Implementation	Learning curve + s/w effort	Easier/known ☺
Latency	Longer	Short ☺
DAQ/control	I/Q sampling (also direct) or DDC	Ampli/phase , IF downconversion
Algorithms	Sophisticated. ☺ State machines, exception handling…	Simple. Linear, time-invariant (ex: PID)
Multi-user	Full ☺	Limited
Remote control & diagnostics	Easy, often no additional h/w ☺	Difficult, extra h/w
Flexibility / reconfigurability	High (easier upgrades) ☺	Limited
Drift/tolerance	No drifts, repeatability ☺	Drift (temperature..), components tolerance
Transport distance without distortion	Longer ☺	Short
Radiation sensitivity	High	Small ☺

M. E. Angoletta "Digital LLRF" *EPAC'06*

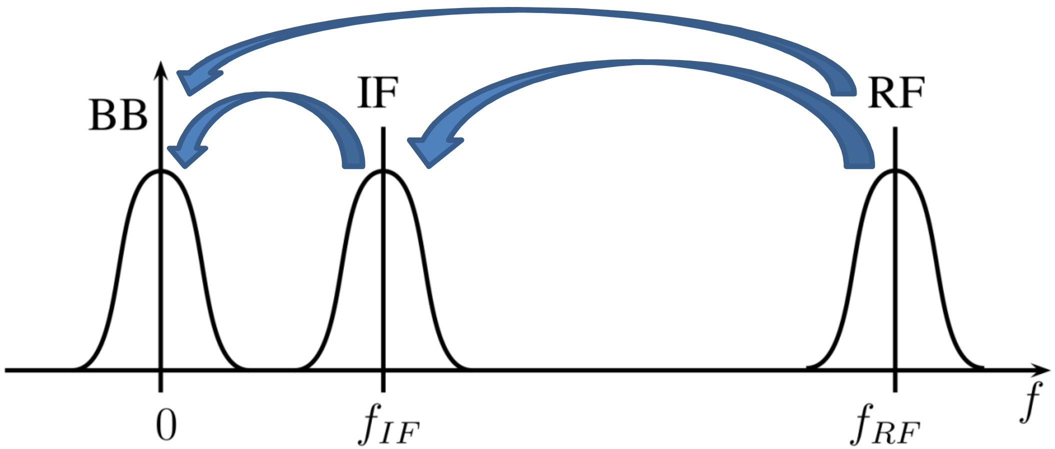
RF detection

1. Direct Amplitude and Phase Detection
   → No down-conversion
   → Analog or digital (up to 800MHz ADCs)
2. **Baseband sampling (analog I/Q detector)**
3. **Digital I/Q sampling**
4. **IF Sampling (non-I/Q sampling)**

$$I = A \cdot \cos\phi$$
$$Q = A \cdot \sin\phi$$
$$A = \sqrt{I^2 + Q^2}$$
$$\phi = \mathrm{atan2}(Q, I)$$



- 2.-4. is based on mixing a reference signal (LO) with the RF signal → RF signal down-converted to an intermediate frequency and into base-band

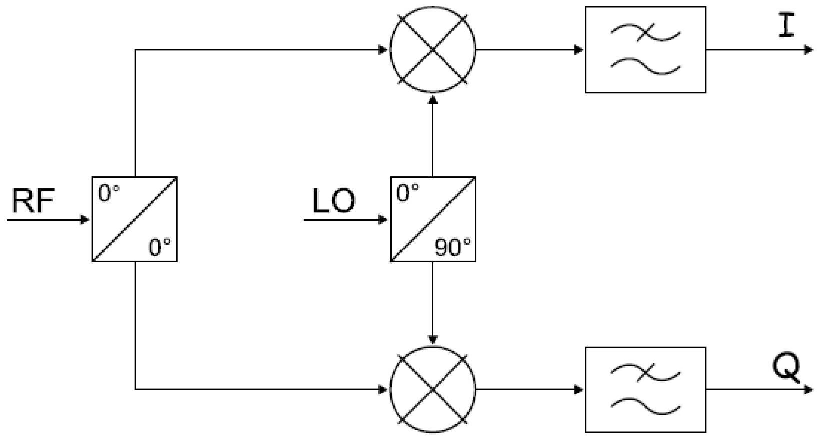


e.g.:
f_{RF} = 1.3 GHz
f_{IF} = 54 MHz

Baseband sampling

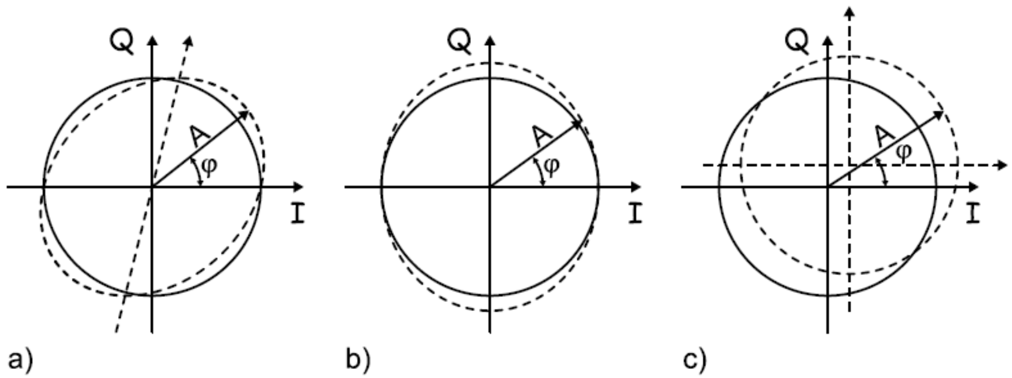
- Analog I/Q detector (direct conversion from RF to BB)
- Multiplication with LO
- LO split by hybrid → phase difference of 90 deg

$$A = \sqrt{I^2 + Q^2}$$
$$\tan\varphi = \frac{Q}{I}.$$



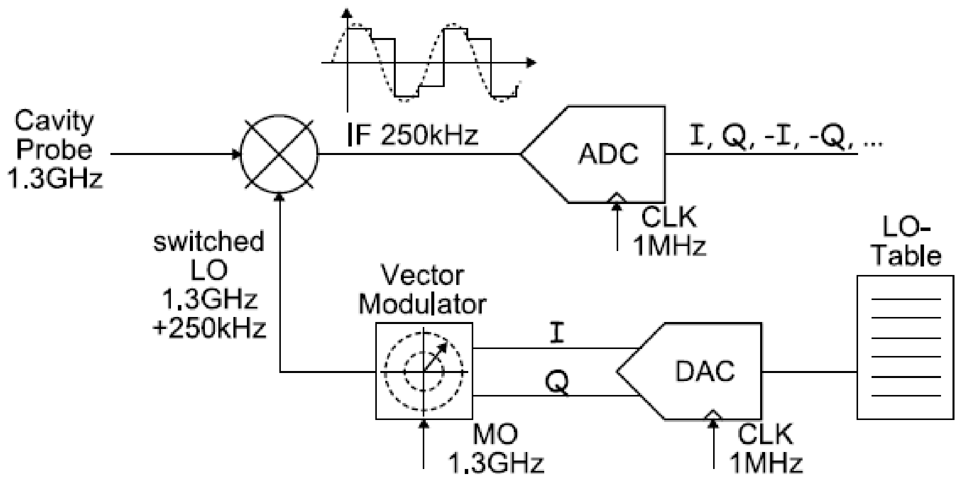
2 ADCs necessary for digitalization
→ Higher costs, more space, reduced reliability

Problem:
I/Q imbalance and offsets
→ Phase dependent amplitude measurement

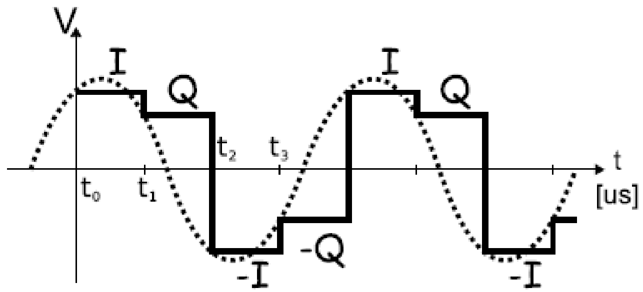


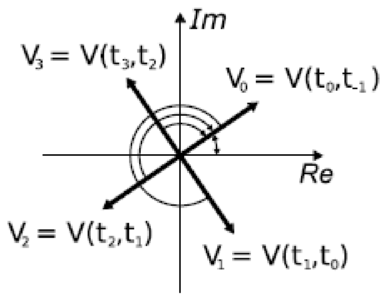
Digital I/Q sampling

- Alternative to baseband sampling: only 1 ADC and switched LO (by 90 deg)
- Output signal represents I, Q, -I, -Q
- Field vector computed by 2 samples (I/Q value) and shifted by n · 90 deg (n…0,1,2,3)



Problems:
Nyquist frequency is $f_s/4$
Rectangular output signal
→ high bandwidth needed (amplifier etc.)



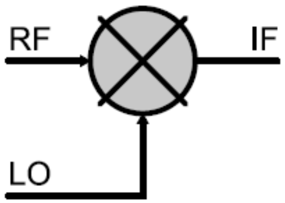


IF Sampling (non-I/Q sampling)

RF signal mixed down to an intermediate frequency (IF)

$$y_{RF}(t) = A_{RF} \cdot \sin(\omega_{RF} t + \phi_{RF})$$

$$y_{LO}(t) = A_{LO} \cdot \cos(\omega_{LO} t + \phi_{LO})$$



$$y_{IF}(t) = y_{RF}(t) \cdot y_{LO}(t)$$

$$|f_{IF}| = |f_{RF} - f_{LO}|$$

$$y_{IF}(t) = \frac{1}{2} A_{RF} A_{LO} \cdot (\sin[(\omega_{RF} - \omega_{LO})t + (\phi_{RF} - \phi_{LO})]$$ **Lower sideband**

$$+ \sin[(\omega_{RF} + \omega_{LO})t + (\phi_{RF} + \phi_{LO})])$$ **Upper sideband**

If LO and RF frequency equal $\Rightarrow$ lower sideband at DC, upper sideband at 2 f_{RF}

If phase is 0 deg between LO and RF $\Rightarrow$ amplitude detector (in phase) I

If phase is 90 deg between LO and RF $\Rightarrow$ phase detector (in quadrature) Q

IF Sampling (non-I/Q sampling)

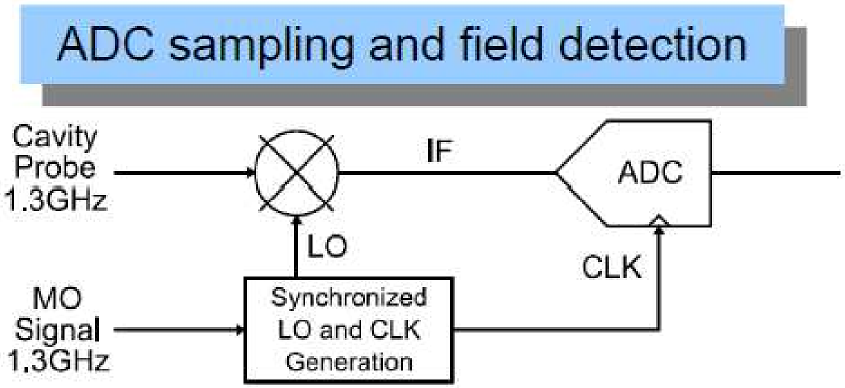
RF signal mixed down to an intermediate frequency (IF)

→ sampled and mapped into base-band

$$y_{IF}(t) = \frac{1}{2} A_{RF} A_{LO} \cdot \left(\sin[(\omega_{RF} - \omega_{LO})t + (\phi_{RF} - \phi_{LO})] \right.$$ **Lower sideband**

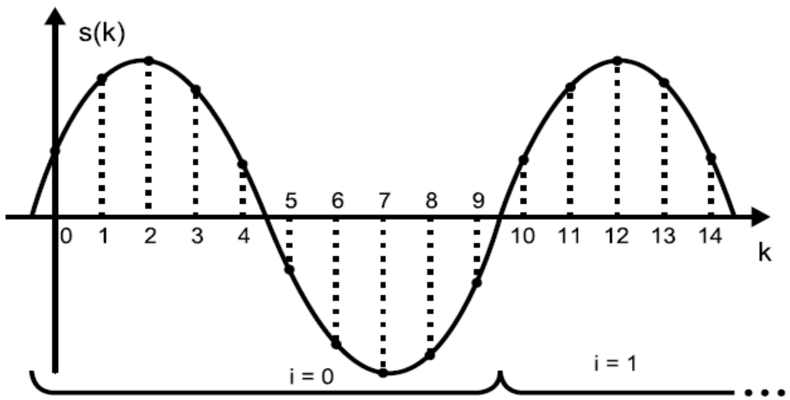
~~$$\left. + \sin[(\omega_{RF} + \omega_{LO})t + (\phi_{RF} + \phi_{LO})] \right)$$ Upper sideband~~

Low pass filtered



$$I[i] = \frac{2}{M} \sum_{k=0}^{M-1} s[k+iM] \cos((k+iM)\Delta\varphi)$$

$$Q[i] = \frac{2}{M} \sum_{k=0}^{M-1} s[k+iM] \sin((k+iM)\Delta\varphi).$$



Step-window for I/Q detection

I/Q pair as amplitude and phase information w.r.t. MO signal

Differential cavity equation

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

ω_0 … Cavity resonance frequency
ω … Driving frequency

Solution for input signal $I(t) = \hat{I}_0 \sin(\omega t)$ **(RF source) is given as cavity properties with approximation for high Q cavities :**

$$V(t) = \hat{V}\sin(\omega t + \psi(t))$$

$$\hat{V} \approx \frac{R_L \hat{I}_0}{\sqrt{1 + \left(2Q_L \frac{\Delta\omega}{\omega}\right)^2}} \quad ; \quad \tan\psi \approx 2Q_L \frac{\Delta\omega}{\omega}$$

Tuning angle

$\psi(t) = \angle(I(t), V(t))$

Angle between driving current and cavity voltage

As cavity properties with approximation for high Q cavities:

$$\tan\psi = Q_L\left(\frac{\omega_0}{\omega} - \frac{\omega}{\omega_0}\right)$$
$$\approx 2Q_L\frac{\Delta\omega}{\omega} \quad \text{for } \omega_0 \approx \omega$$

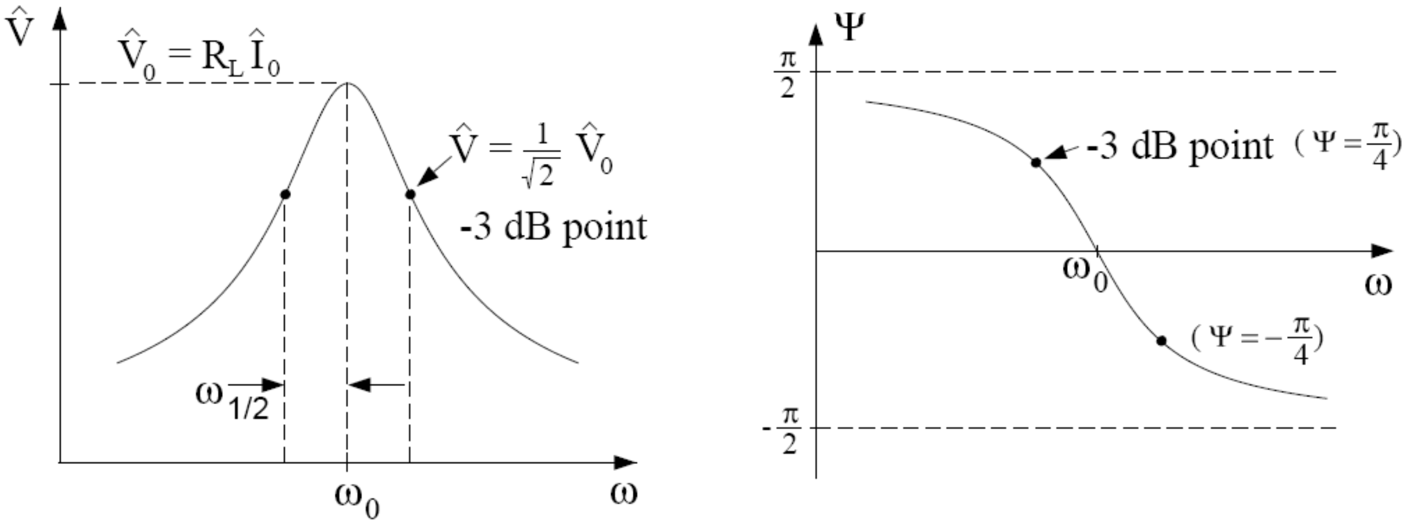
$$\hat{V}(\Delta\omega) \approx \frac{R_L \hat{I}_0}{\sqrt{1 + \left(2Q_L \frac{\Delta\omega}{\omega}\right)^2}}$$

Cavity detuning

$\Delta\omega = \omega_0 - \omega \ll \omega$

Phase and Amplitude of cavity signal with respect to the RF source

Resonance curve for amplitude and phase in steady state (no transients)



Half cavity bandwidth

$$\omega_{1/2} = \frac{\omega_0}{2Q_L} = \frac{1}{\tau} (\ll \omega)$$

With time constant τ

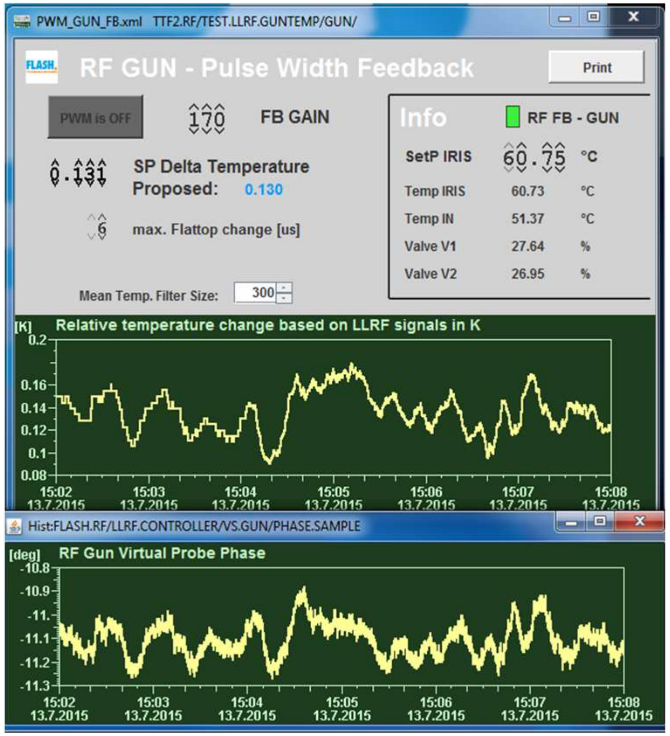
$$\ddot{V}(t) + 2\omega_{1/2}\dot{V}(t) + \omega_0^2\, V(t) = 2\omega_{1/2}\, R_L\, \dot{I}(t)$$

The high (carrier) frequency cavity model is not of our interest for studying the cavity response under feedback operation; we are interested at the baseband model (envelope of HF signal)!

Example: RF GUN Frequency Control @ FLASH

- RF gun temperature disturbance rejection
- Normal conducting RF (NRF) cavity as heater @ FLASH

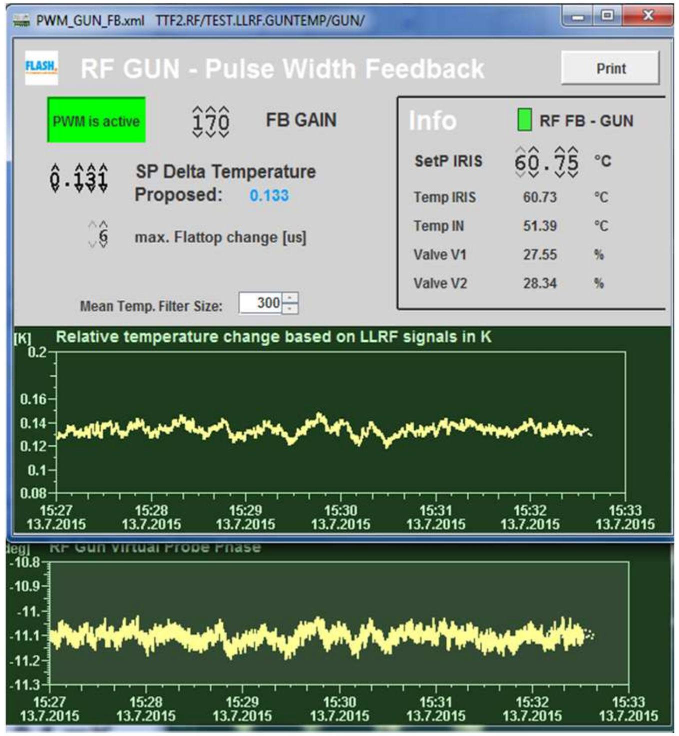
Same y-scaling for both panels



Operated in pulsed mode
→ Pulse Width Modulation
to keep cavity on resonance

Factor > 3 improvement

PWM off	PWM on
ΔT [K]	ΔT [K]
Pk2pk ~ 0.1K	**Pk2pk ~ 0.03K**
$\Delta\phi$ [deg.]	$\Delta\phi$ [deg.]
Pk2pk ~ 0.4°	**Pk2pk ~ 0.17°**



Detuning: $\psi = \phi_P - \phi_F$; $\Delta T = \dfrac{\tan\psi \cdot f_0}{2Q_L K_{f/T}}$

$K_{f/T}$ = 21 kHz/K
Q_L = 10.000
f_0 = 1.3 GHz

Resolution ~ 0.1 mK
(Sub-mK)

Extremely precise frequency control is essential for all NRF cavities due to limited FB gain caused by high bandwidth (e.g. QL = 10000 → $f_{1/2}$= 65kHz) and relatively large system delay (~2 µs)!