

System Identification and MIMO Controller exploiting Symmetries of the RF-System

Sven Pfeiffer
FLASH Seminar
31.1.2012

FLASH - Overview

Field Requirements

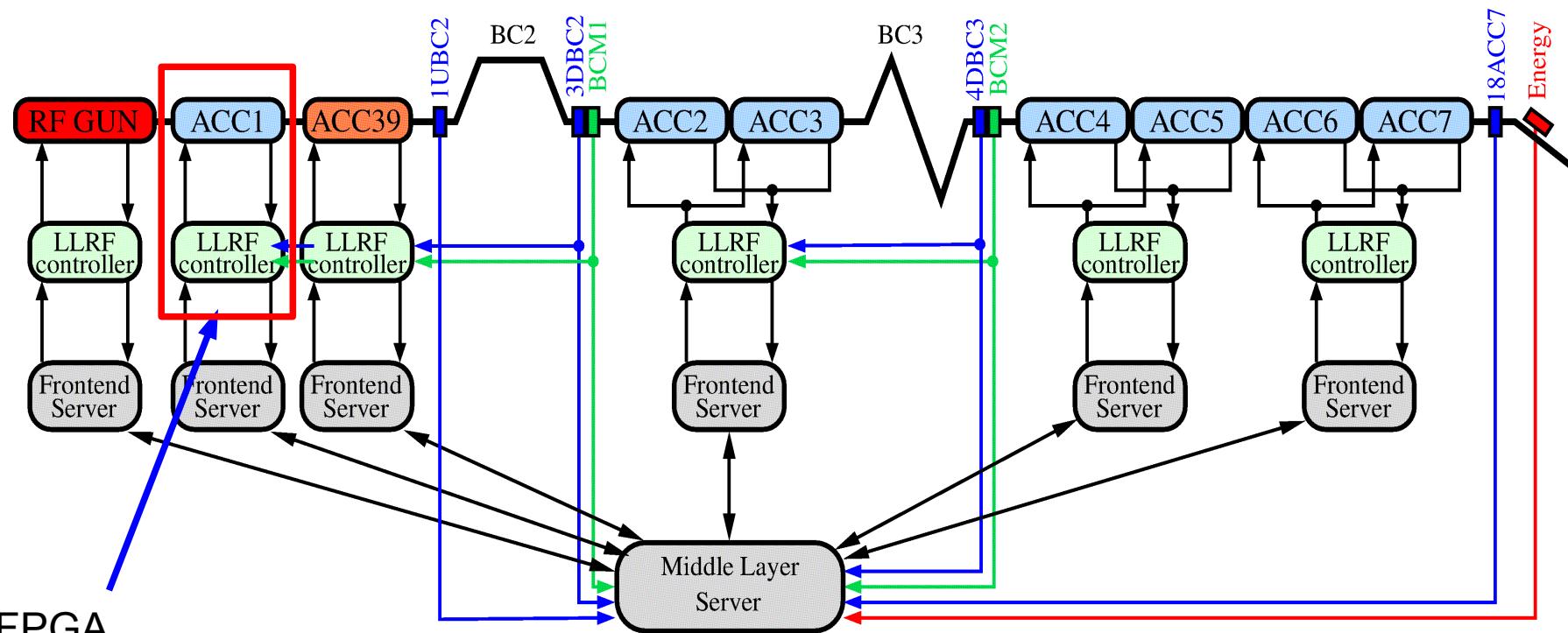
$\Delta A/A < 0.01\%$
 $\Delta \text{phase} < 0.01$

Beam Performance (BAM, BCM)

$\Delta A/A \sim \Delta t_A$
 $\Delta \text{phase} \sim \Delta C \sim \Delta \sigma_z$

Example: $\Delta A/A = 0.01\%$

$\Delta t_A \sim 70\text{fs}$ (Goal: $< 20\text{fs}$)



FPGA
Acts within a pulse

From pulse to pulse

Perfect Field controller is the first
step to an optimal beam controller!

Outline

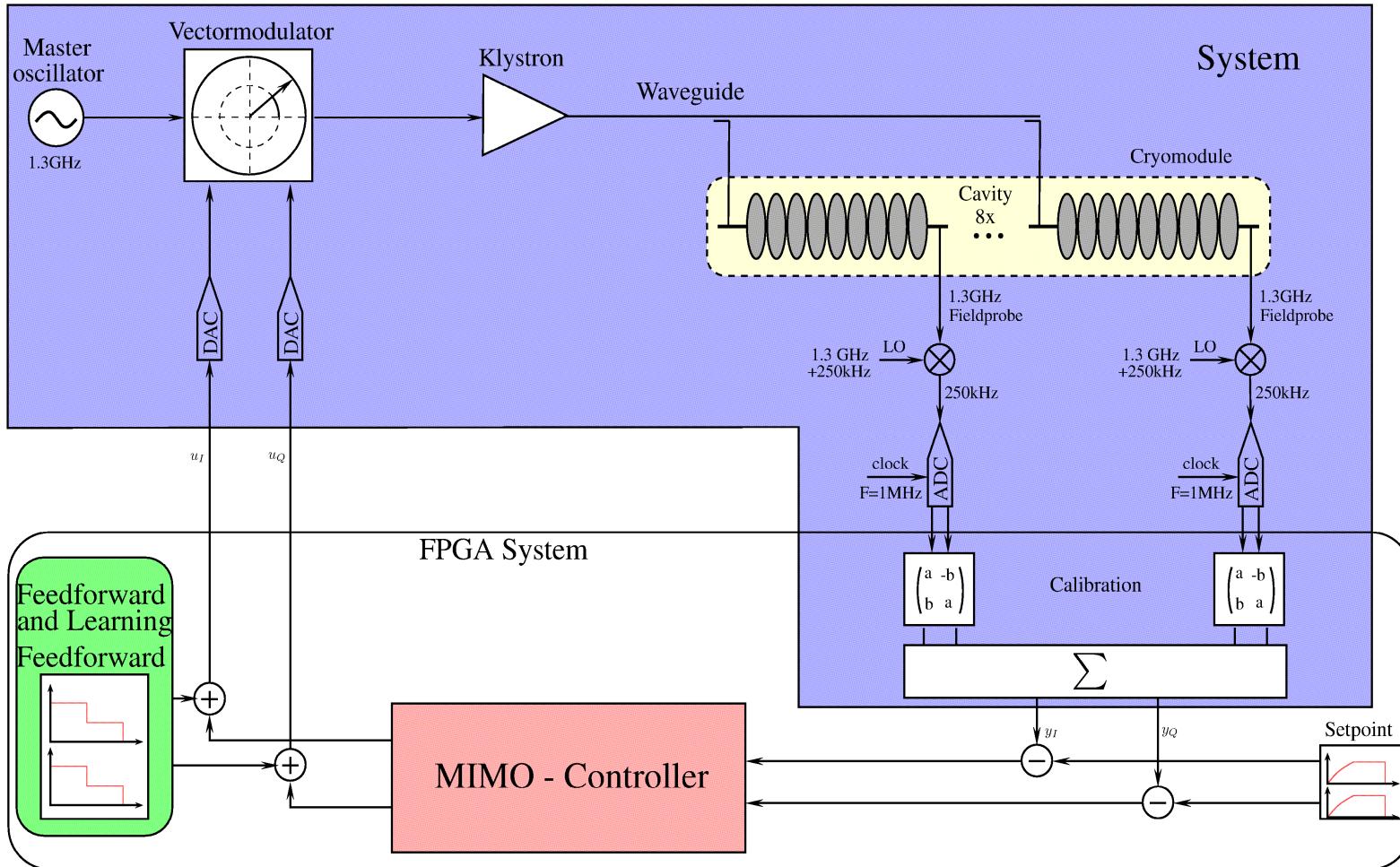
1. System Identification

Black Box Model, Bode Plot,
Identification methods

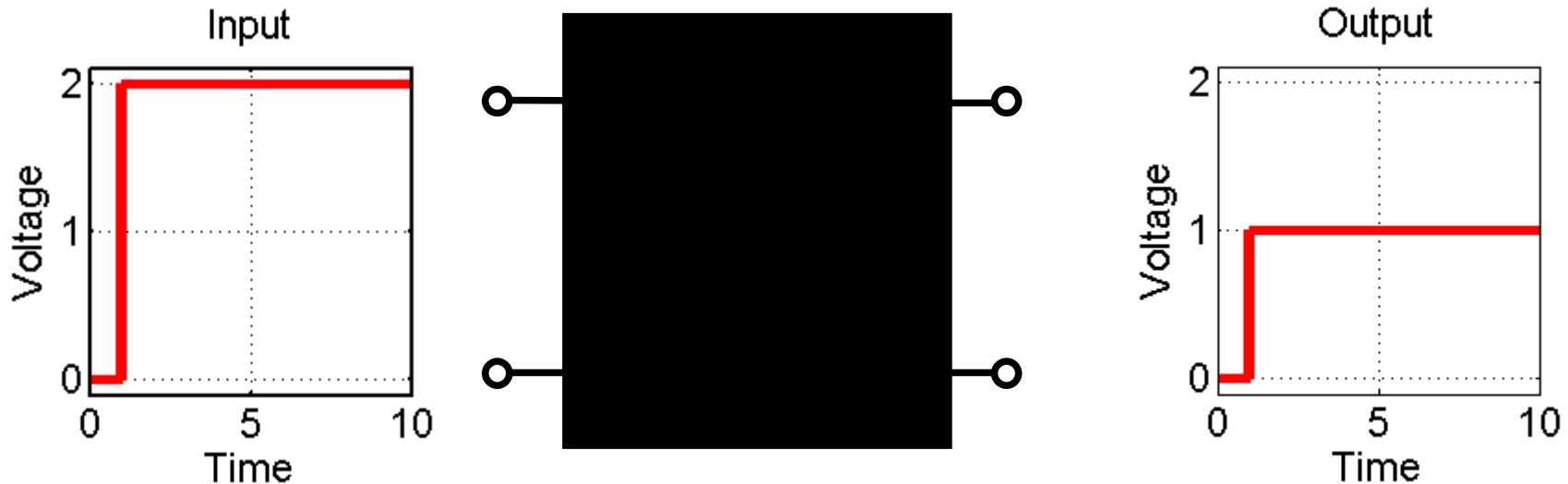
Tutorial

2. MIMO Controller

Based on Model,
Develop Controller as SISO system

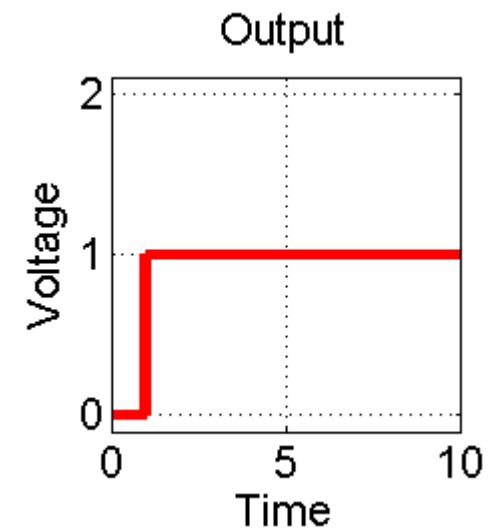
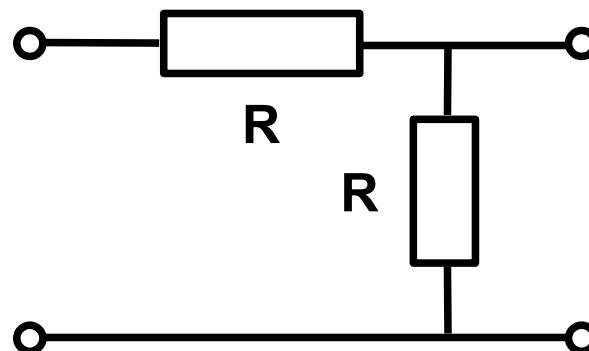
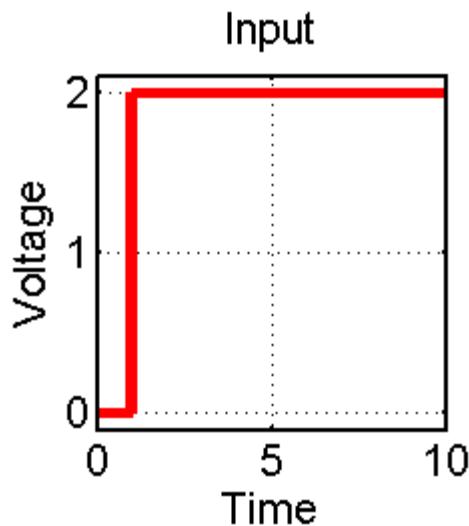


System Identification – Black Box



What is inside the black box?

System Identification – Black Box



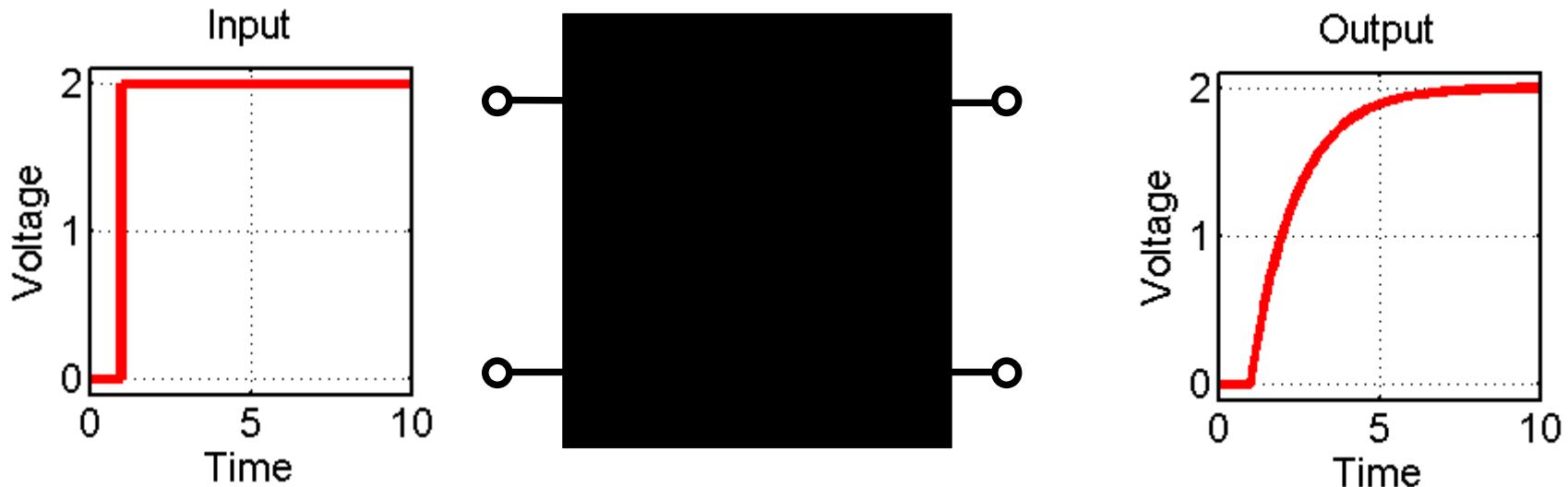
Voltage Divider

$$\text{Output} = \frac{R}{R+R} * \text{Input}$$

$$\text{Gain} = 1/2$$

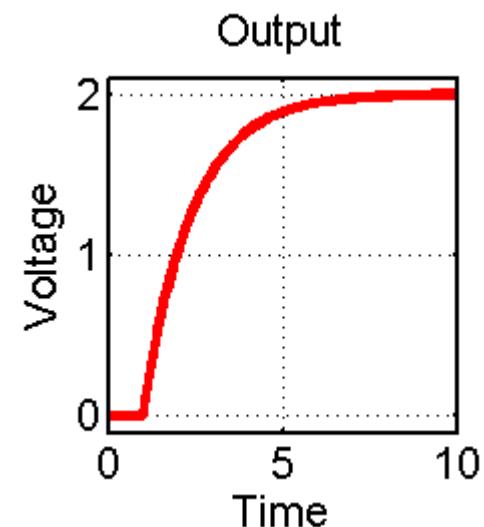
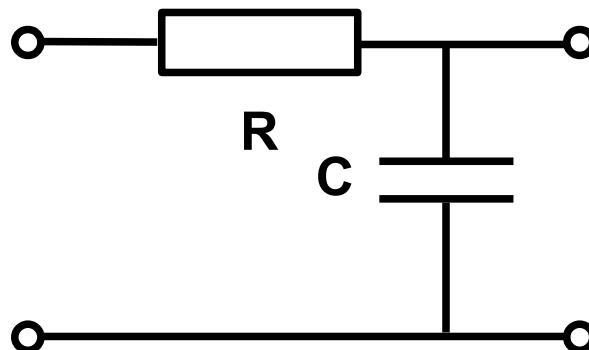
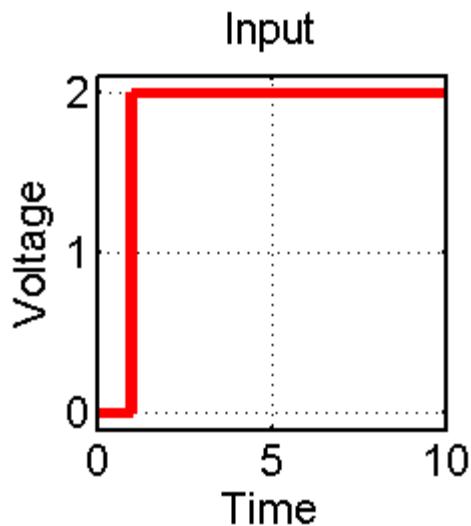
Static System

System Identification – Black Box



What is inside the black box?

System Identification – Black Box



Low Pass Filter

$$U_{OUT}(t) = U_{IN}(t) \cdot (1 - e^{-t/\tau})$$

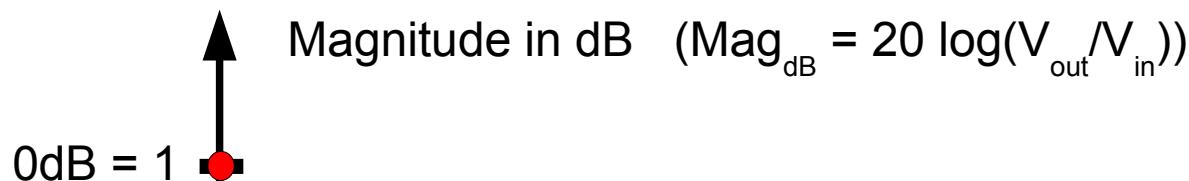
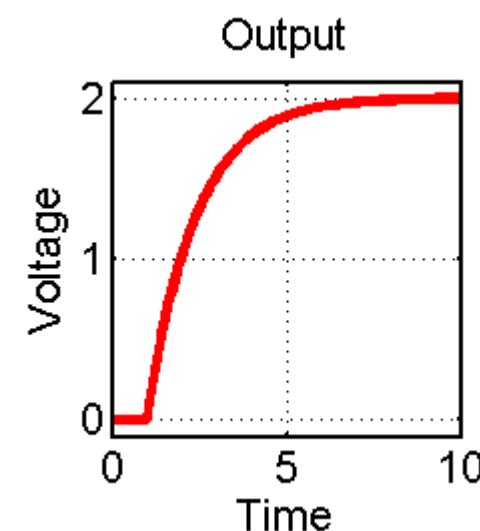
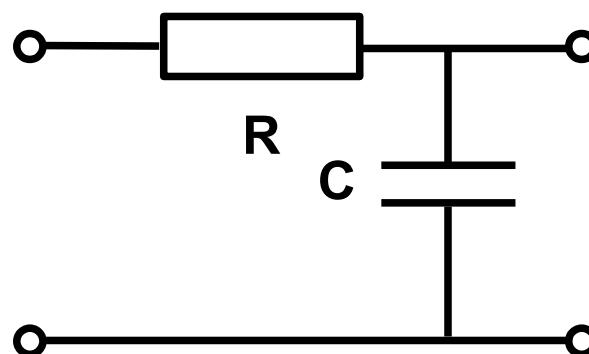
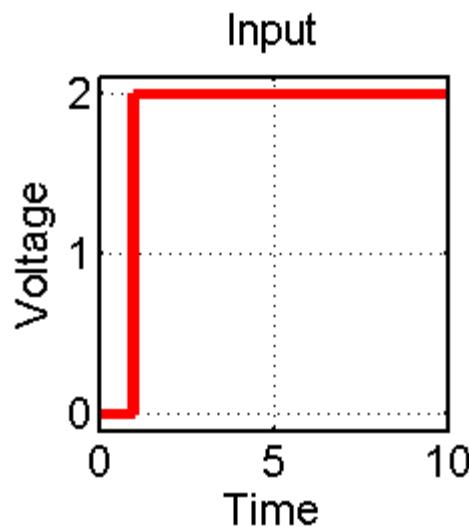
Time constant

$$\tau = R \cdot C$$

Dynamic System

What is the static gain?

Low Pass Filter

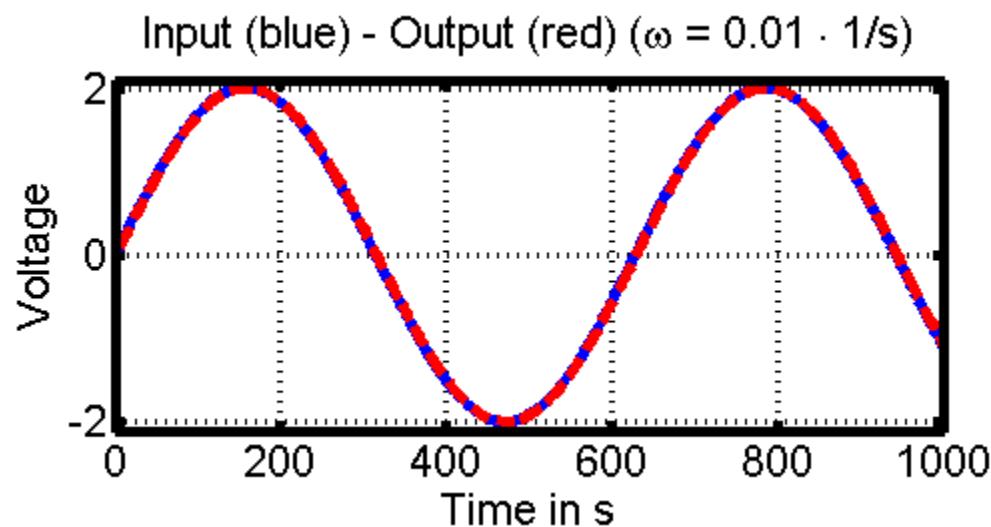
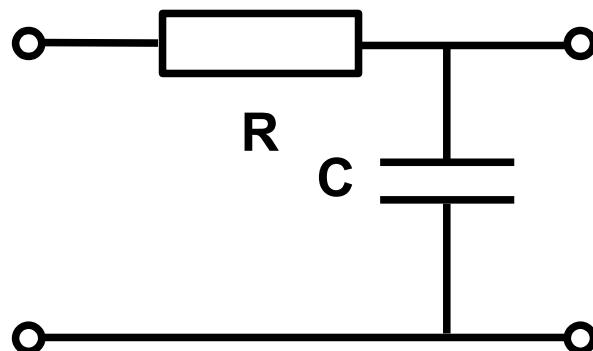


$$\omega = 2\pi f$$

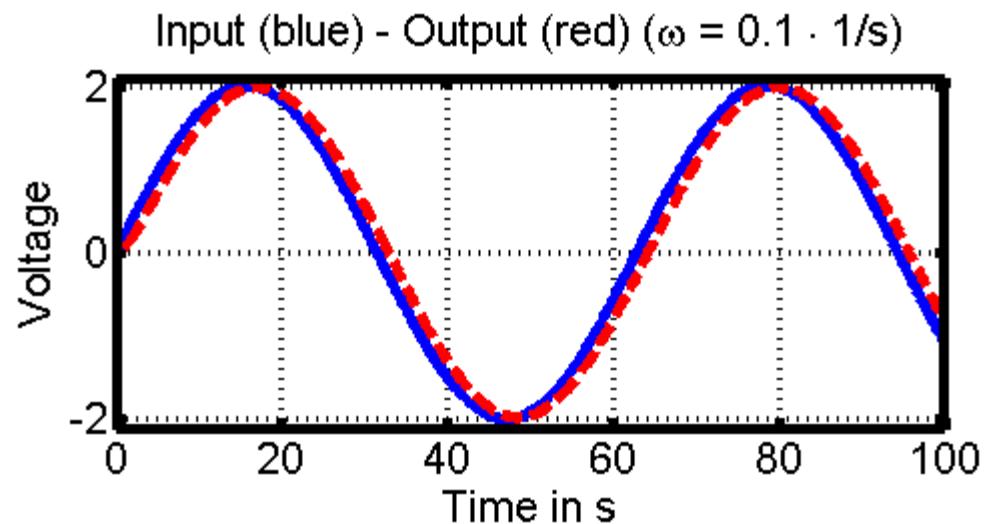
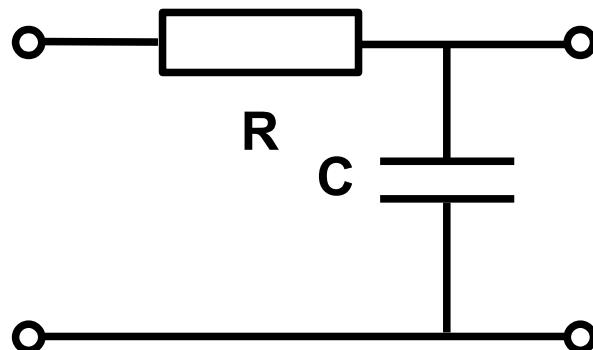
System Identification – Black Box

Dynamic System

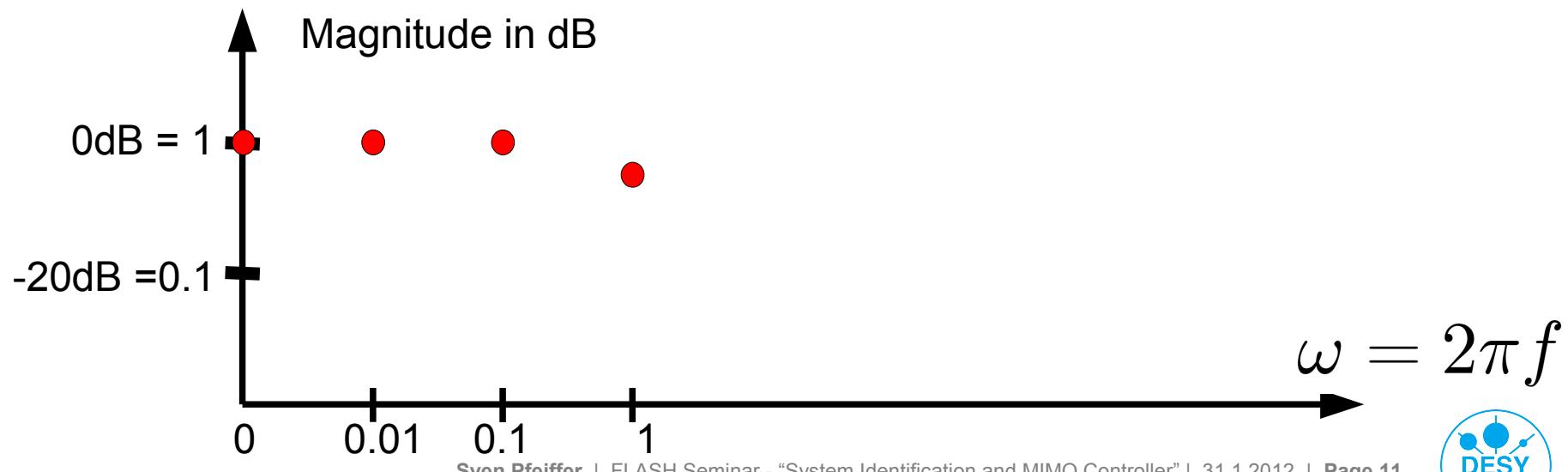
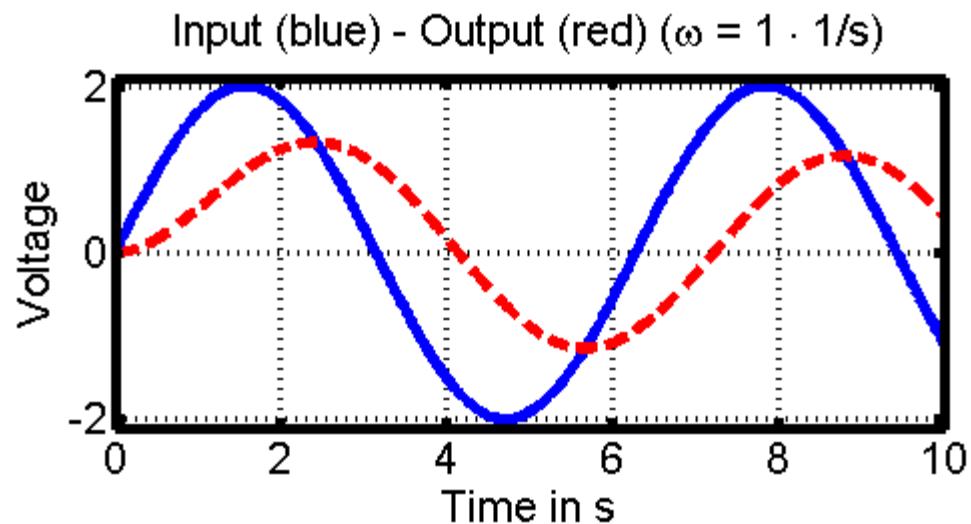
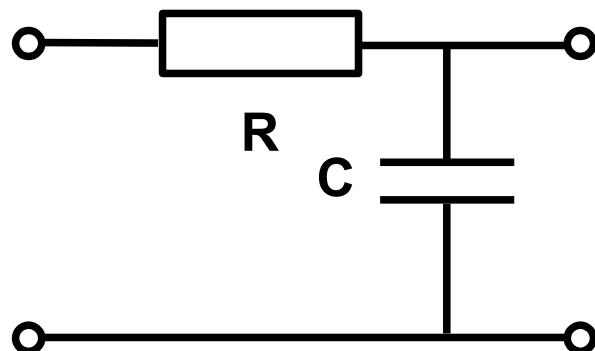
Low Pass Filter



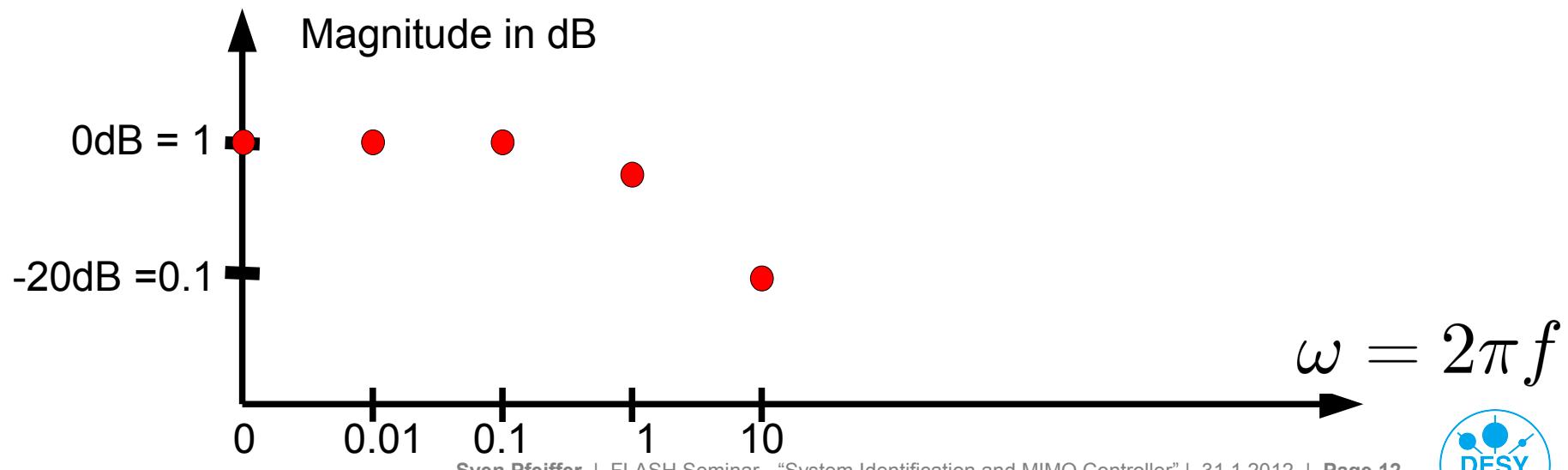
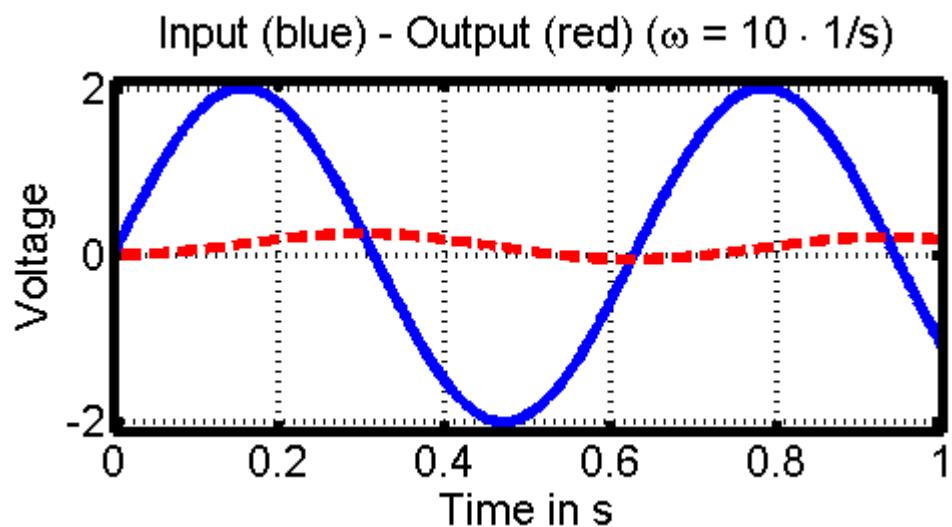
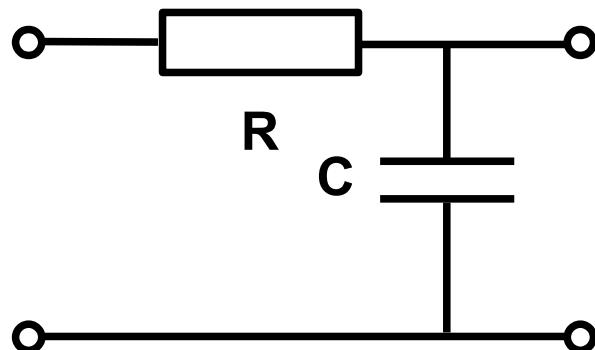
Low Pass Filter



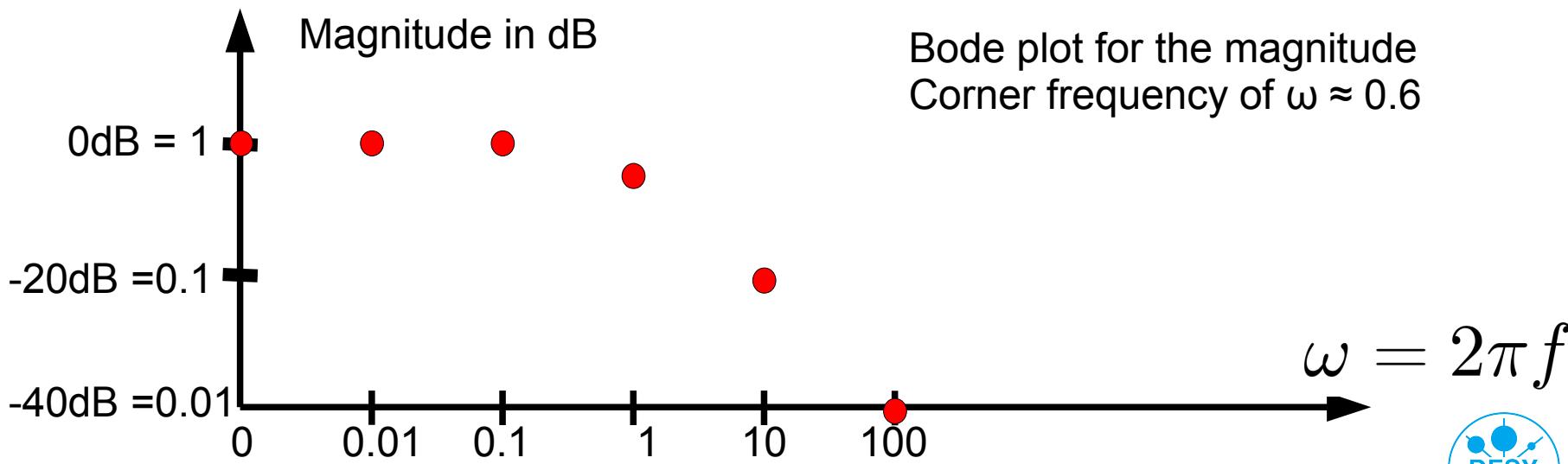
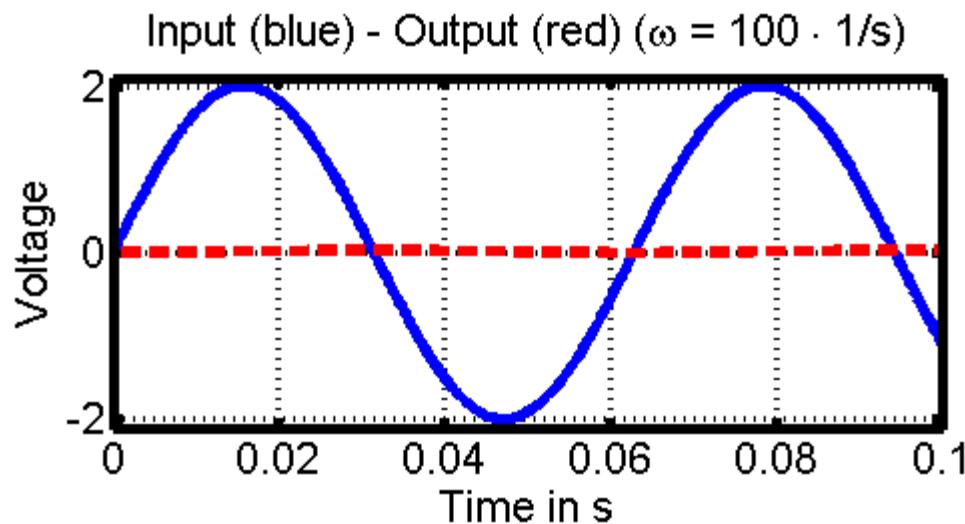
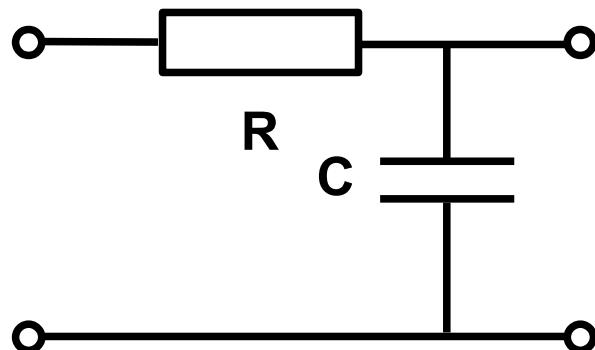
Low Pass Filter



Low Pass Filter



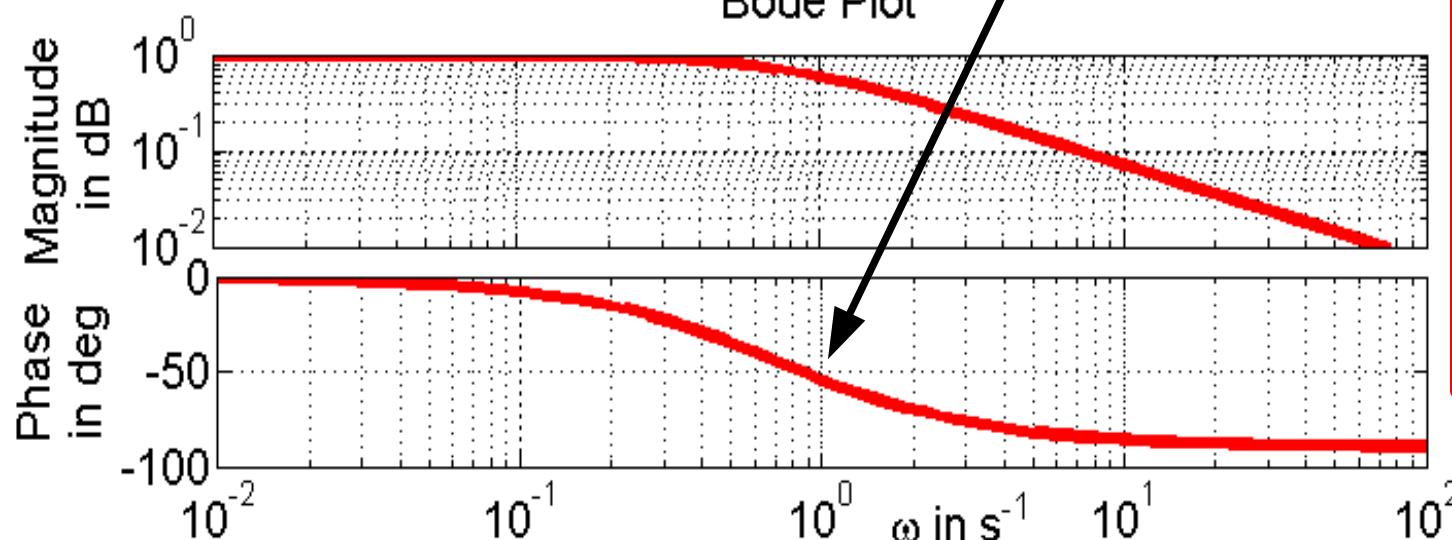
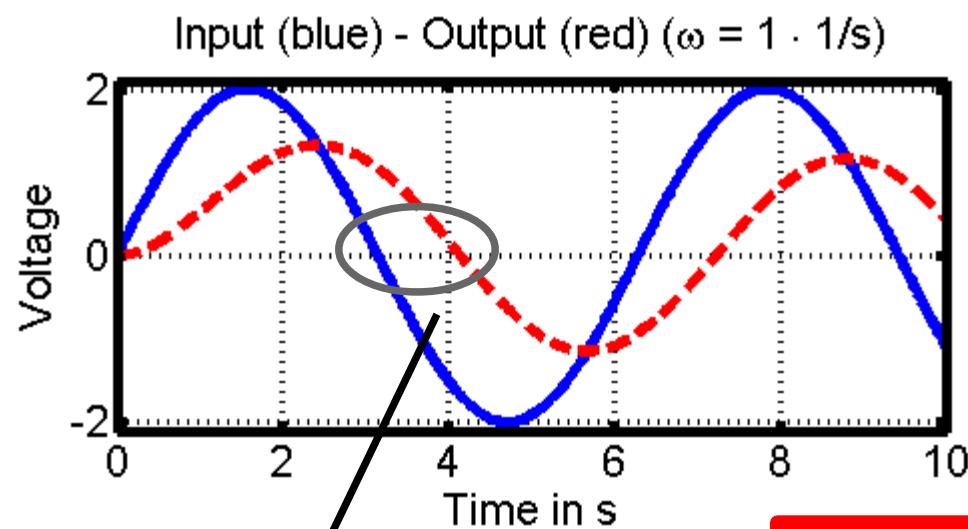
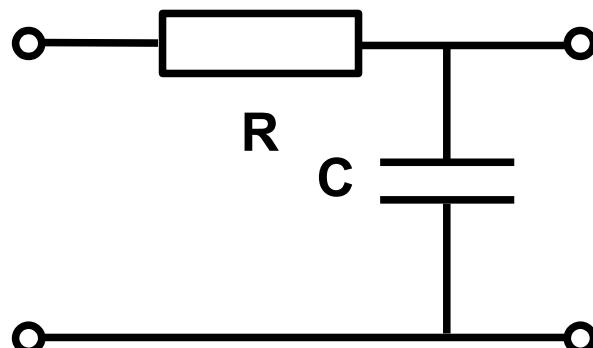
Low Pass Filter



System Identification – Black Box

Dynamic System

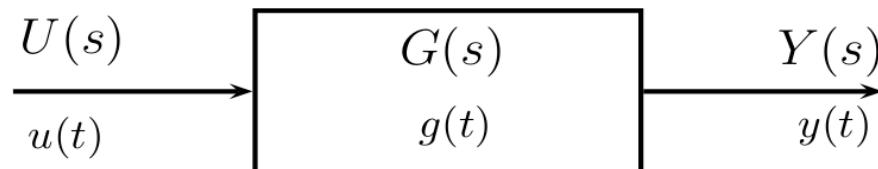
Low Pass Filter



Time Domain

Frequency
Domain

Time to Frequency Domain



Time Domain

2 Signals are given

- System impulse response ($g(t)$)
- Input signal ($u(t)$)

Looking for output signal $y(t)$

$y(t)$ by solving the convolution integral

Frequency Domain

2 Signals are given

- System impulse response ($G(s)$)
- Input signal ($U(s)$)

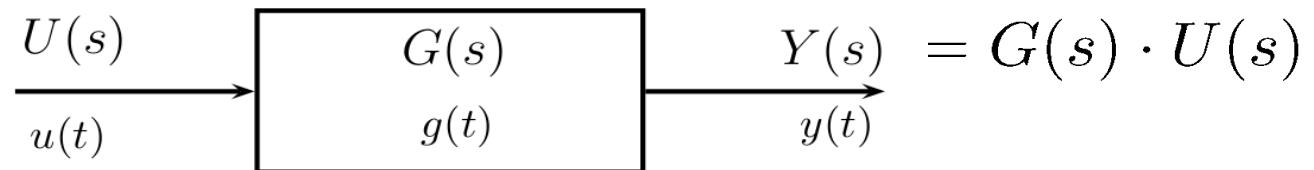
Looking for output signal $Y(s)$

$Y(s)$ by multiplying $G(s)$ and $U(s)$

$$\underbrace{(u * g)(t)}_{y(t)} = \int_{-\infty}^{\infty} u(\tau)g(t - \tau)d\tau \quad \bullet \longrightarrow Y(s) = G(s) \cdot U(s)$$

Laplace Transformation

System Identification - Basics



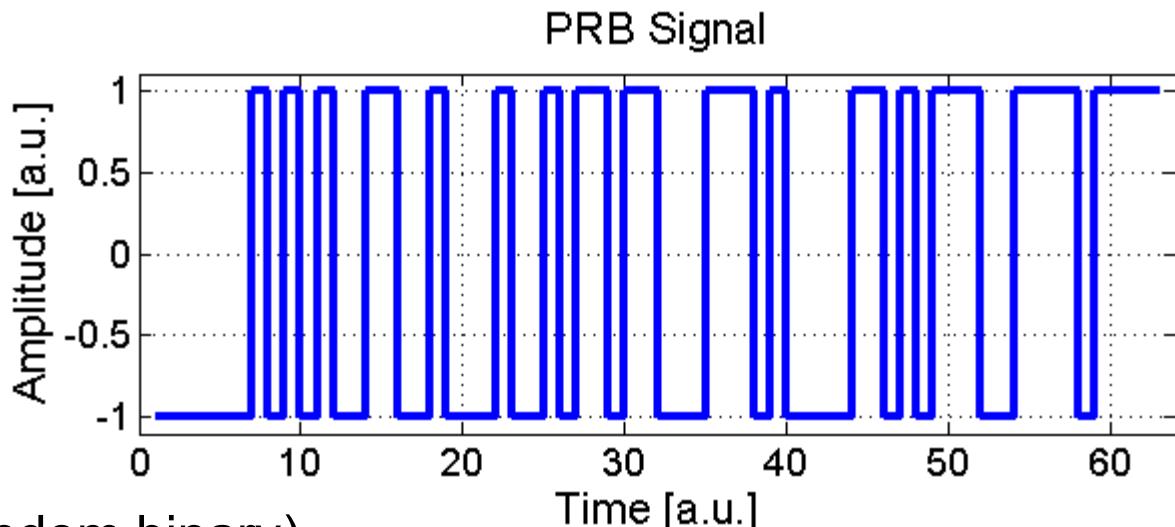
Goal: Get the transfer function $G(s)$

$$G(s) = \frac{Y(s)}{U(s)}$$

Excite the system by different signals

Theory:

- step
- sine
- ramp
- impulse

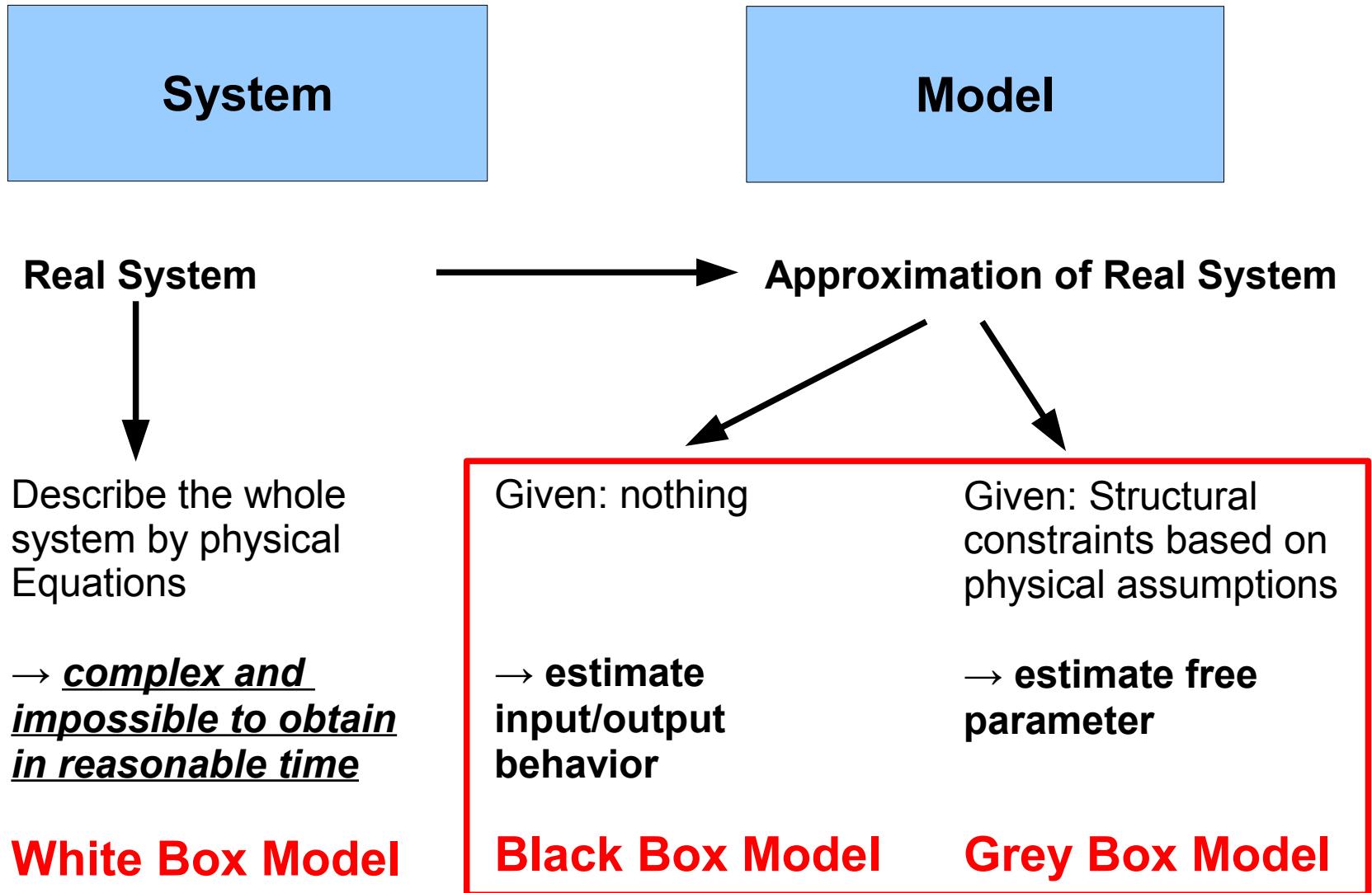


Practice:

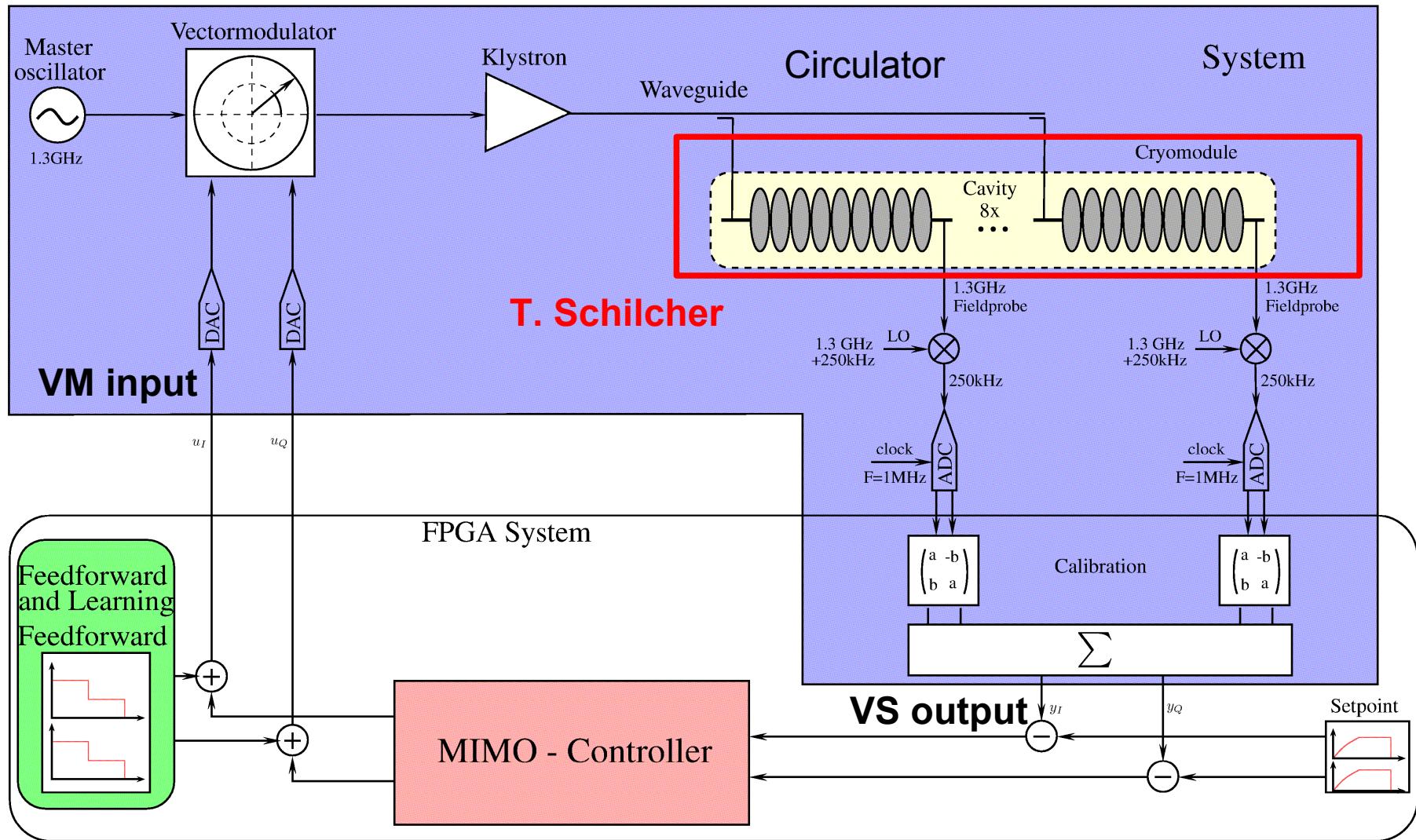
- prb signals (pseudo random binary)

Different possibilities to get a model of $G(s)$

System Identification - Types



System Identification – SC Module



System Identification – SC Module

$$G_\pi(s) = \frac{2(\omega_{1/2})_\pi}{\Delta\omega_\pi^2 + (s + (\omega_{1/2})_\pi)^2} \begin{pmatrix} s + (\omega_{1/2})_\pi & -\Delta\omega_\pi \\ \Delta\omega_\pi & s + (\omega_{1/2})_\pi \end{pmatrix}$$

[Dissertation T. Schilcher]

$$\begin{pmatrix} Y_I(s) \\ Y_Q(s) \end{pmatrix} = \begin{bmatrix} G_1(s) & -G_2(s) \\ G_2(s) & G_1(s) \end{bmatrix} \begin{pmatrix} U_I(s) \\ U_Q(s) \end{pmatrix}$$

A block diagram showing a rectangular block labeled $G_{cav}(s)$. Two input arrows enter from the left, labeled $U_I(s)$ and $U_Q(s)$. Two output arrows exit to the right, labeled $Y_I(s)$ and $Y_Q(s)$.

System Identification and MIMO Controller exploiting Symmetries of the RF-System

Symmetry Groups
SO(2) - Structure
Simplest form: Rotation Matrix

$$R = \begin{bmatrix} \cos(\delta) & -\sin(\delta) \\ \sin(\delta) & \cos(\delta) \end{bmatrix}$$



Detuning, Klystron
Chain, ...

System Identification – SC Module

$$G_\pi(s) = \frac{2(\omega_{1/2})_\pi}{\Delta\omega_\pi^2 + (s + (\omega_{1/2})_\pi)^2} \begin{pmatrix} s + (\omega_{1/2})_\pi & -\Delta\omega_\pi \\ \Delta\omega_\pi & s + (\omega_{1/2})_\pi \end{pmatrix}$$

[Dissertation T. Schilcher]

$$\begin{pmatrix} Y_I(s) \\ Y_Q(s) \end{pmatrix} = \begin{bmatrix} G_1(s) & -G_2(s) \\ G_2(s) & G_1(s) \end{bmatrix} \begin{pmatrix} U_I(s) \\ U_Q(s) \end{pmatrix}$$

Assume:
Main behavior is known
Grey Box Model

**System Identification and MIMO Controller
exploiting Symmetries of the RF-System**

Symmetry Groups
SO(2) - Structure
Simplest form: Rotation Matrix

$$R = \begin{bmatrix} \cos(\delta) & -\sin(\delta) \\ \sin(\delta) & \cos(\delta) \end{bmatrix}$$



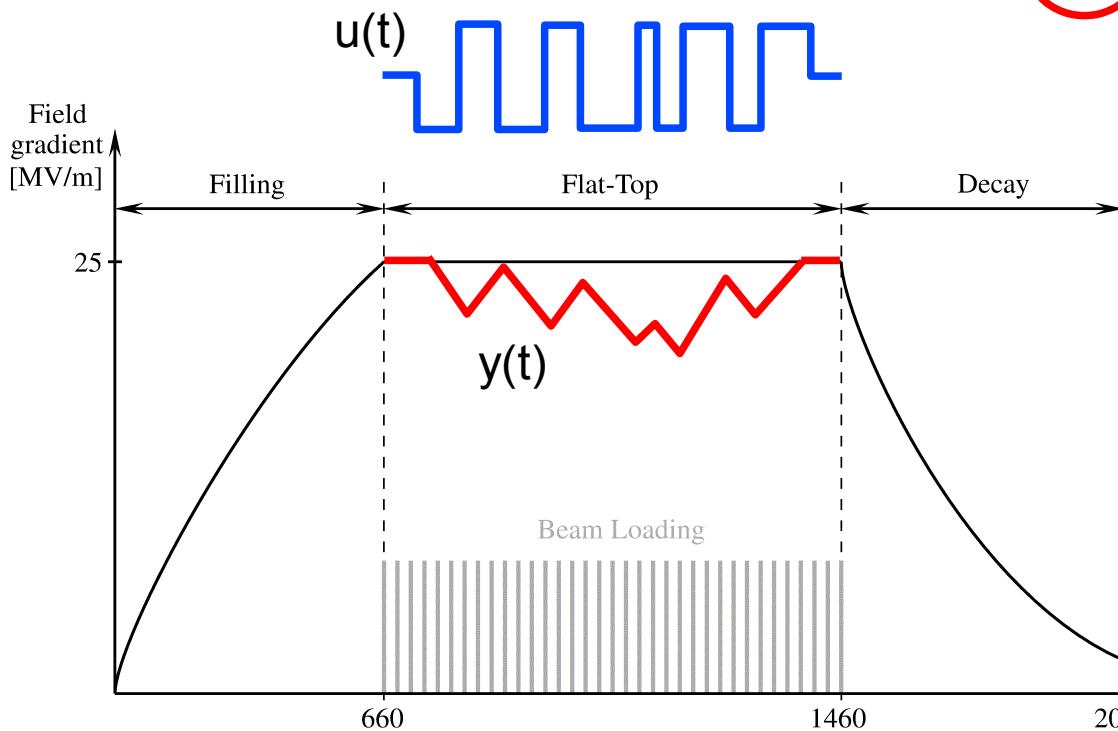
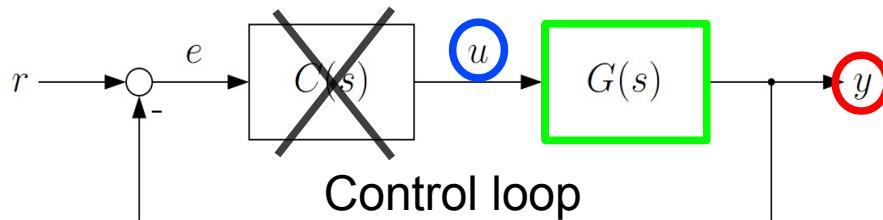
Detuning, Klystron
Chain, ...

System Identification – Grey Box Model

Restrictions at FLASH for SI:

Pulsed mode

Limited excitation time – Flattop



Known:

- Bandwidth (1 real pole)
- Resonant modes (8/9 pi mode,...)
- (2 poles – complex conjugate pole pair)

$$\begin{aligned} x(k+1) &= \begin{bmatrix} \Phi_r & 0 \\ 0 & \Phi_c \end{bmatrix} x(k) + \begin{bmatrix} \Gamma_r \\ \Gamma_c \end{bmatrix} u(k) \\ y(k) &= [C_r \quad C_c] x(k) \end{aligned}$$

Grey box model:

- Fixed model structure
- Get physical insight
- Specific excitation signals
- 2 step identification for different frequency ranges
- 200Hz vs. 200kHz (800kHz)



System Identification – SC Module

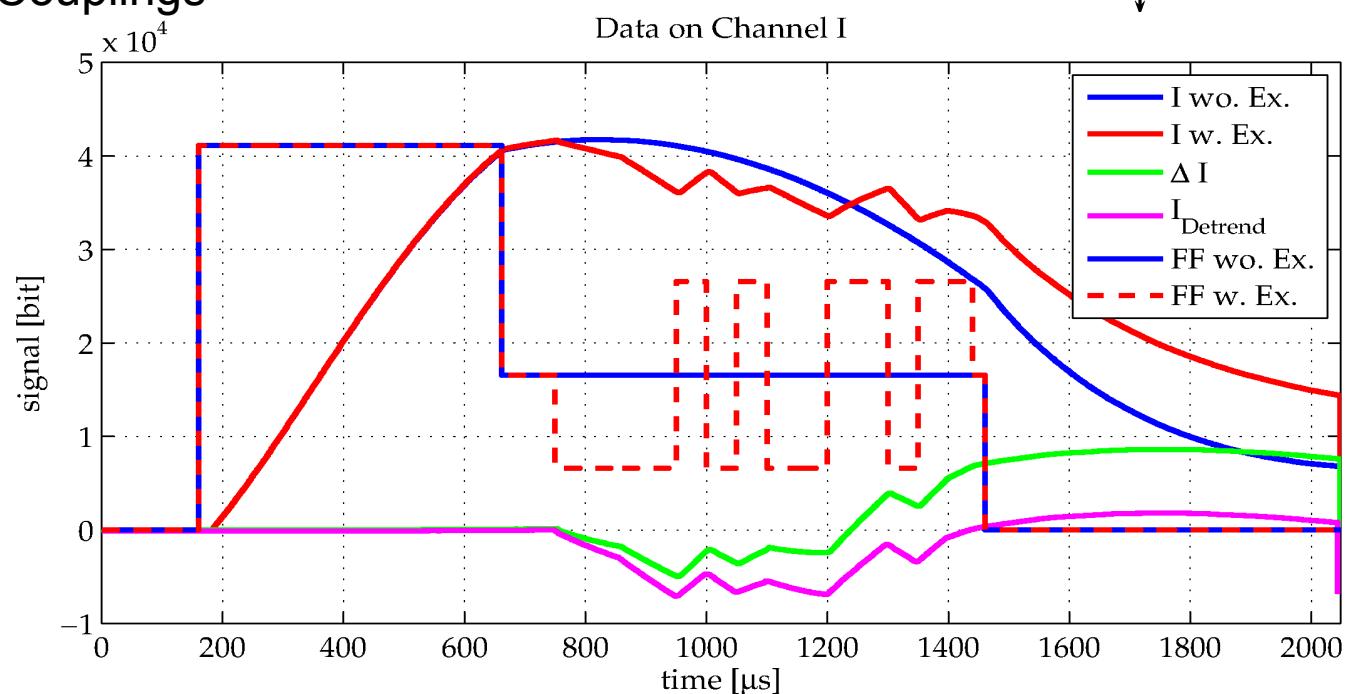
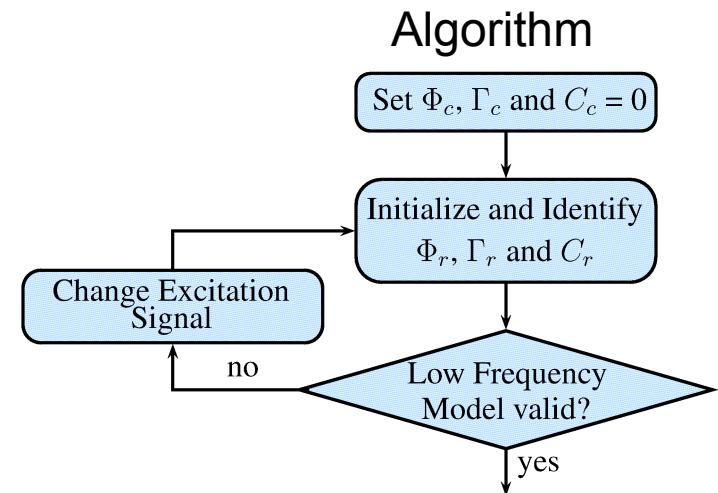
2 step identification

Grey box model:

First focus only on low frequency behavior

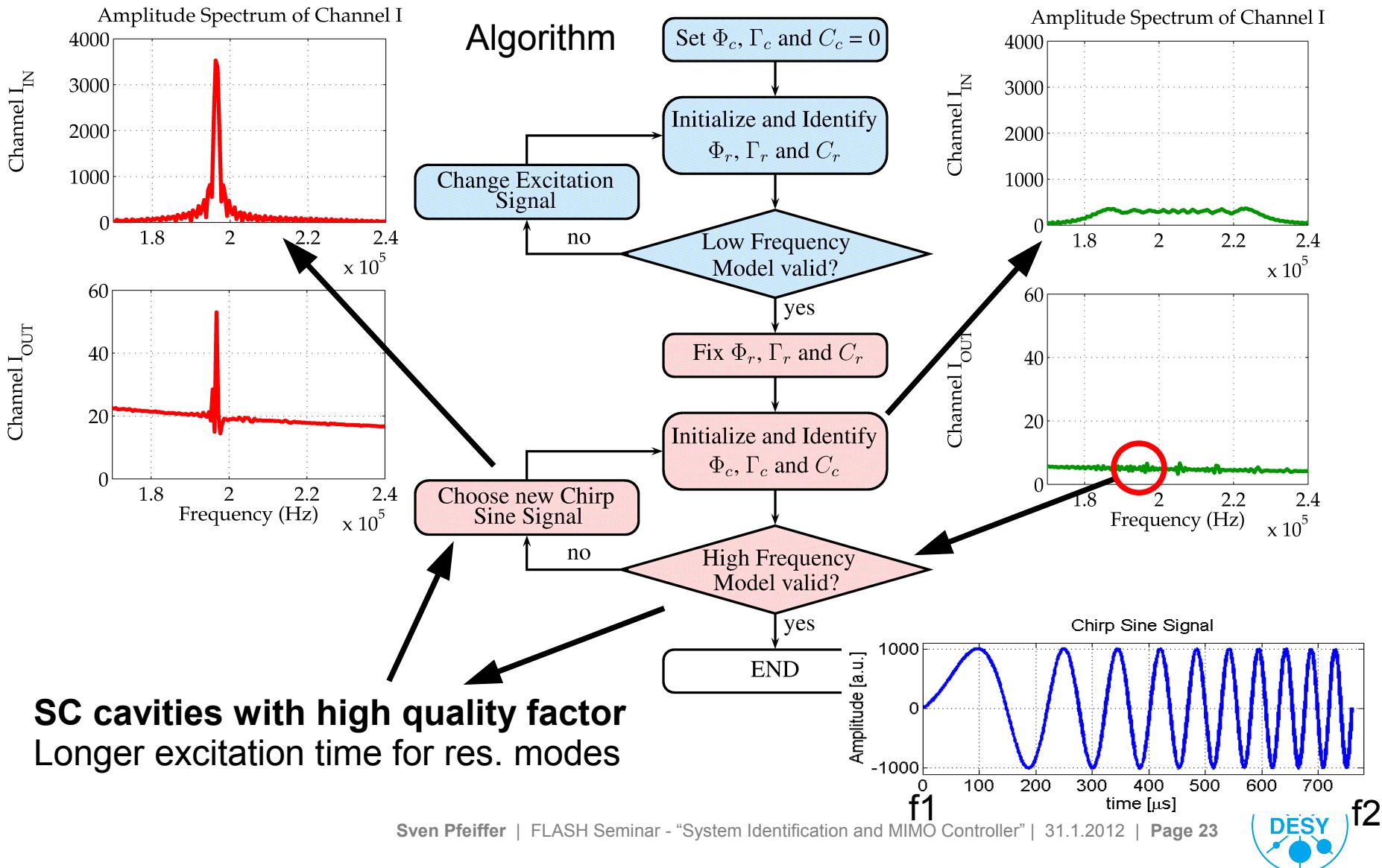
Low frequency PRB excitation signal

- Bandwidth
- Static Gain - Cross Couplings

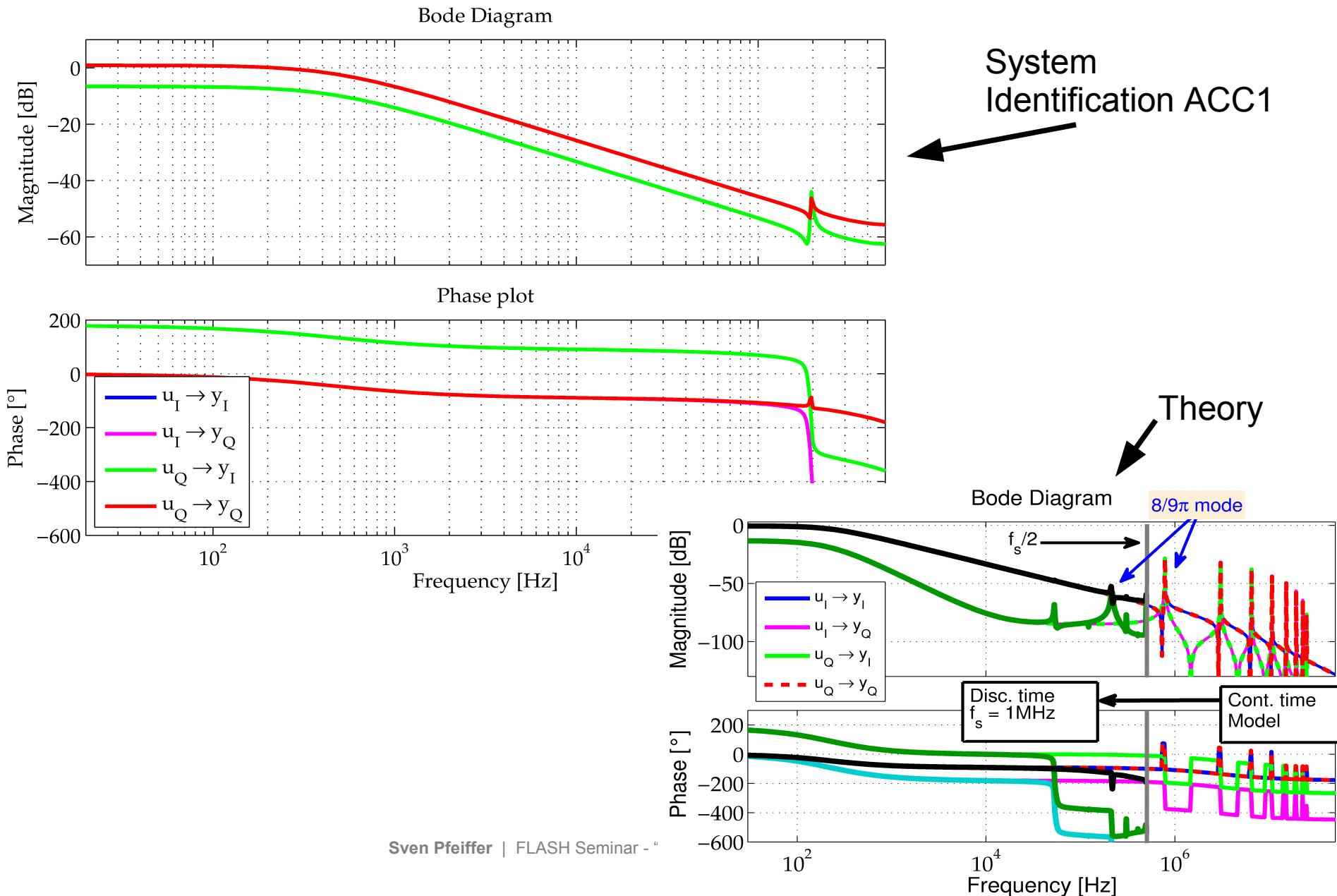


System Identification – SC Module

2 step identification



System Identification – Bode Plot

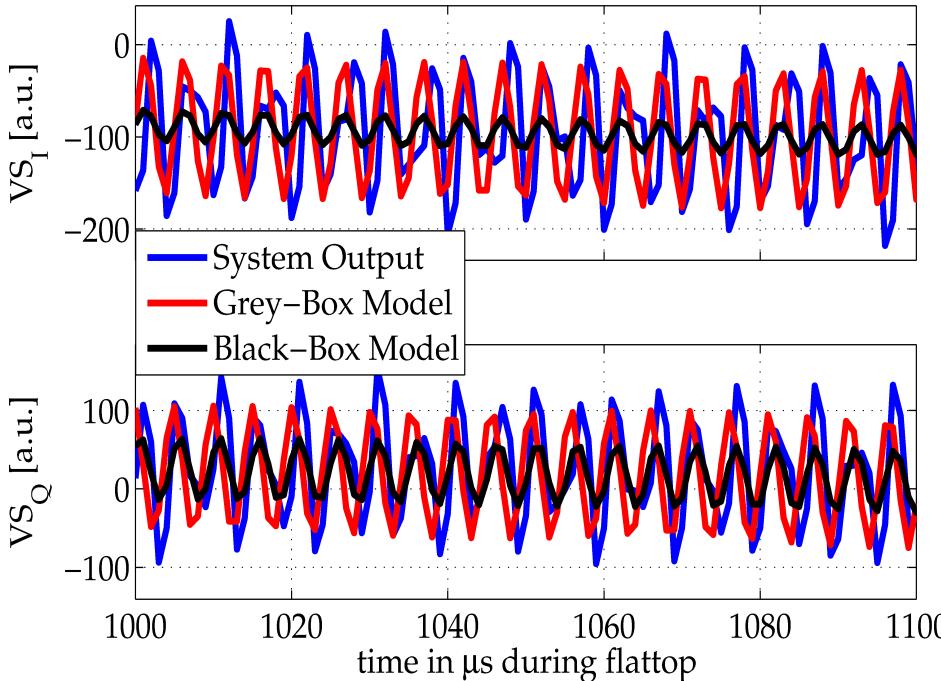
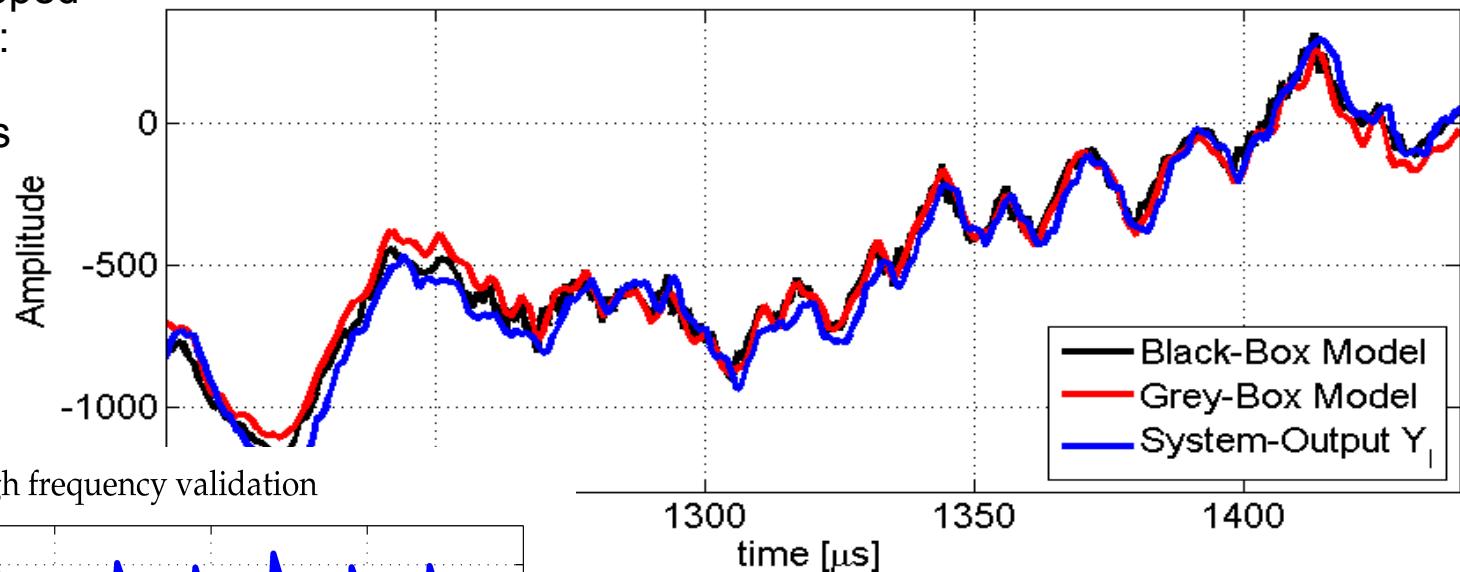


System Identification – Cross Validation (VME)

All tools are developed
on **VME – System**:

Sampling time: 1us

Data Validation Y_1 - System vs. Model



Low frequency behavior

Black – Box Model

Grey – Box Model

High frequency behavior

Black – Box Model

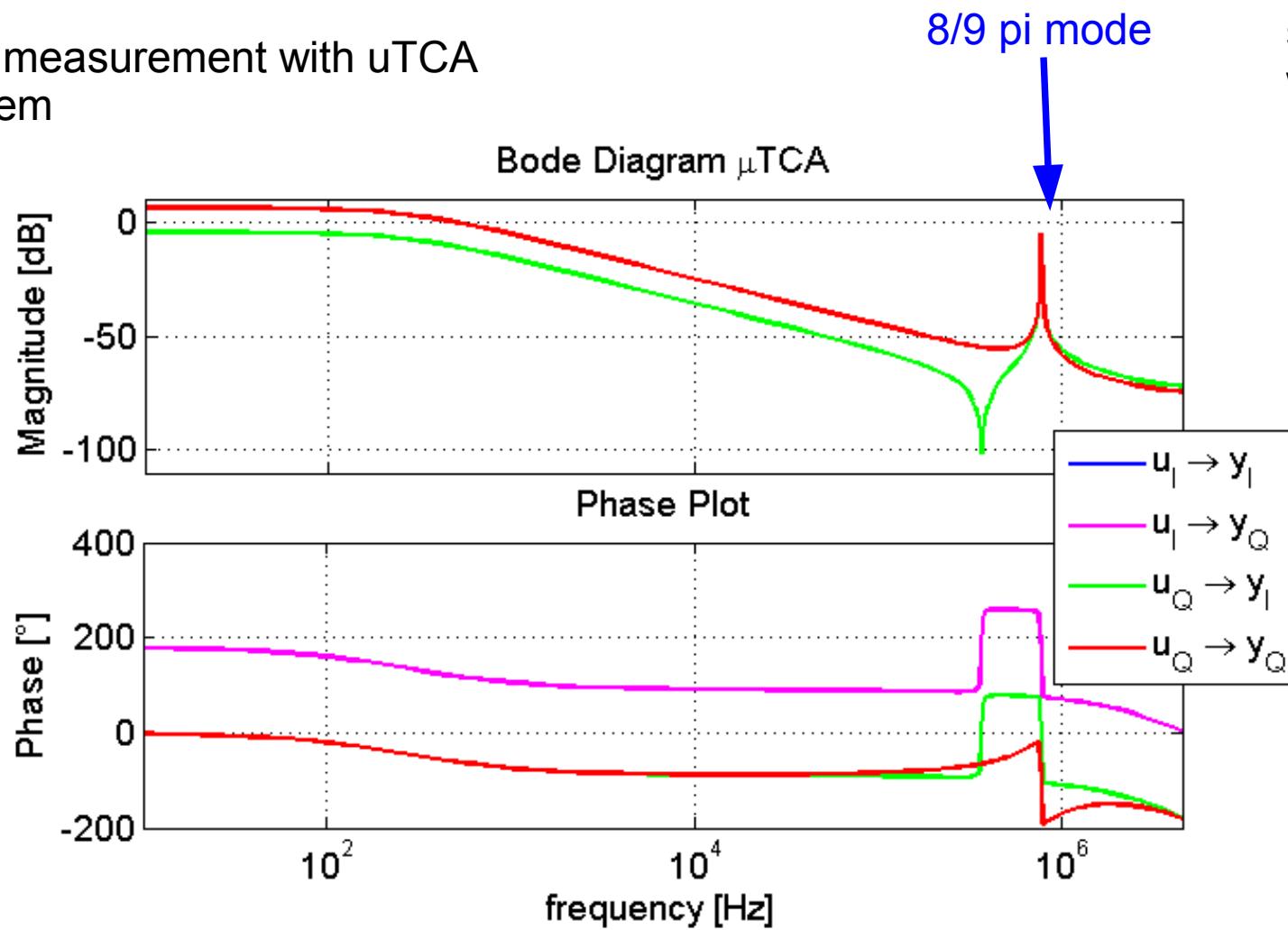
Grey- Box Model

System Identification - uTCA

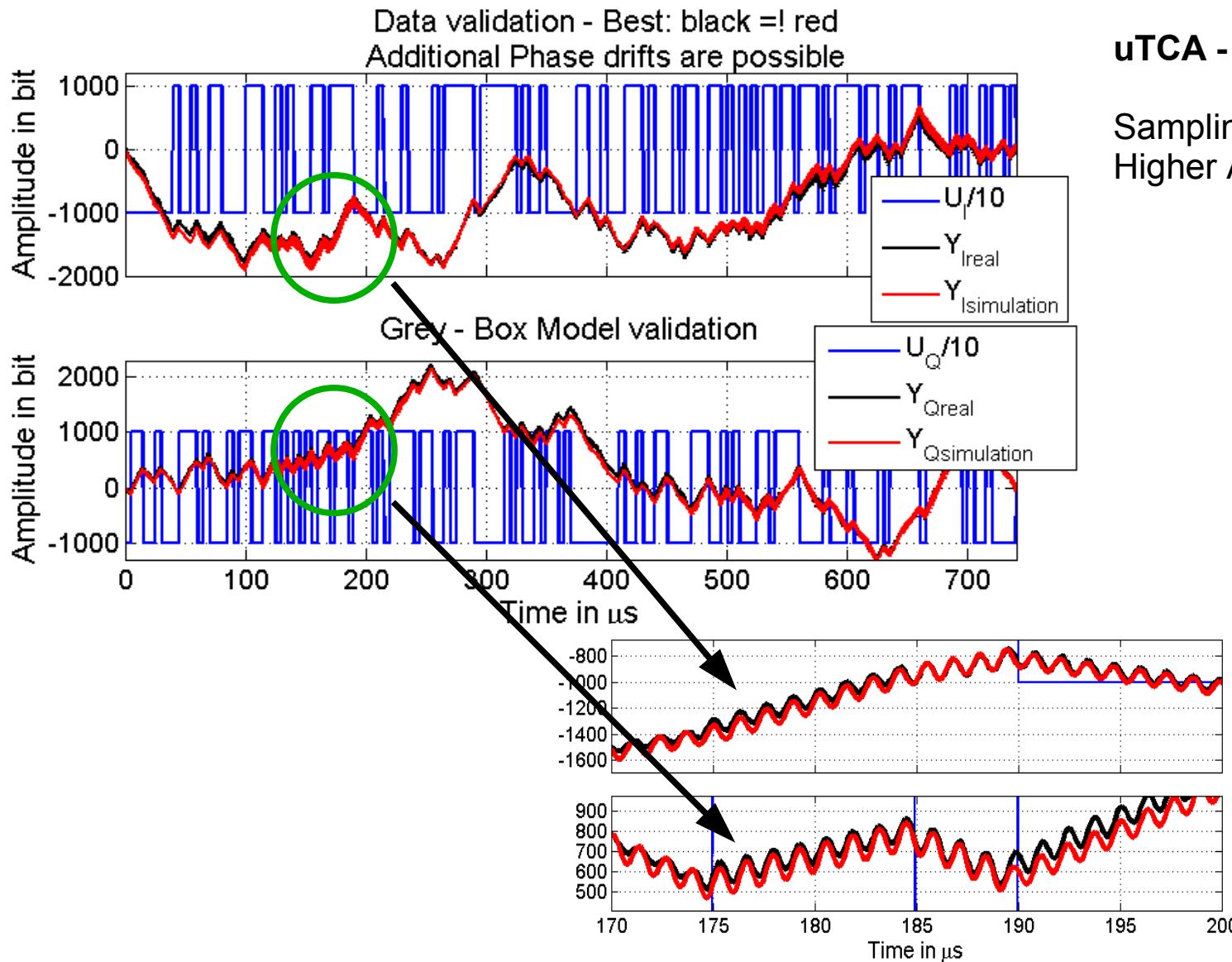
All tools for System Identification
are developed for VME System

One measurement with uTCA
System

7/9 pi mode
During next
study period
with uTCA



System Identification – Cross Validation (uTCA)



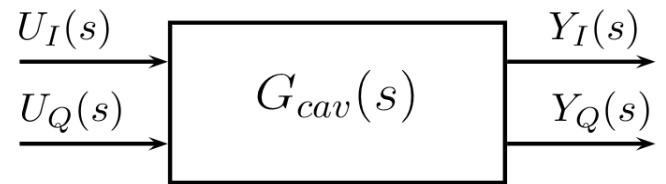
Controller Design

$$\begin{pmatrix} Y_I(s) \\ Y_Q(s) \end{pmatrix} = \begin{bmatrix} G_1(s) & -G_2(s) \\ G_2(s) & G_1(s) \end{bmatrix} \begin{pmatrix} U_I(s) \\ U_Q(s) \end{pmatrix}$$



Scaling and Rotation Part

$$G(s) = \text{Scaling} * \text{Rotation} = K * G_1(s) * R$$

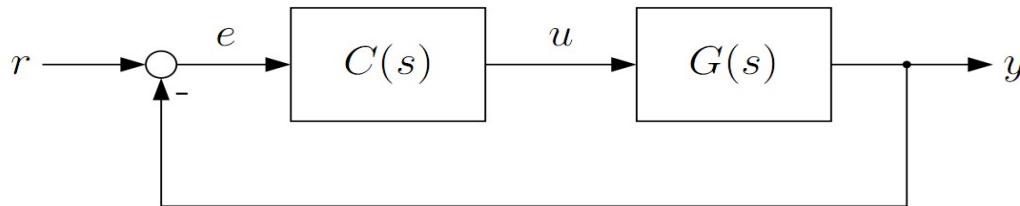


$$R = \begin{bmatrix} \cos(\delta) & -\sin(\delta) \\ \sin(\delta) & \cos(\delta) \end{bmatrix}$$

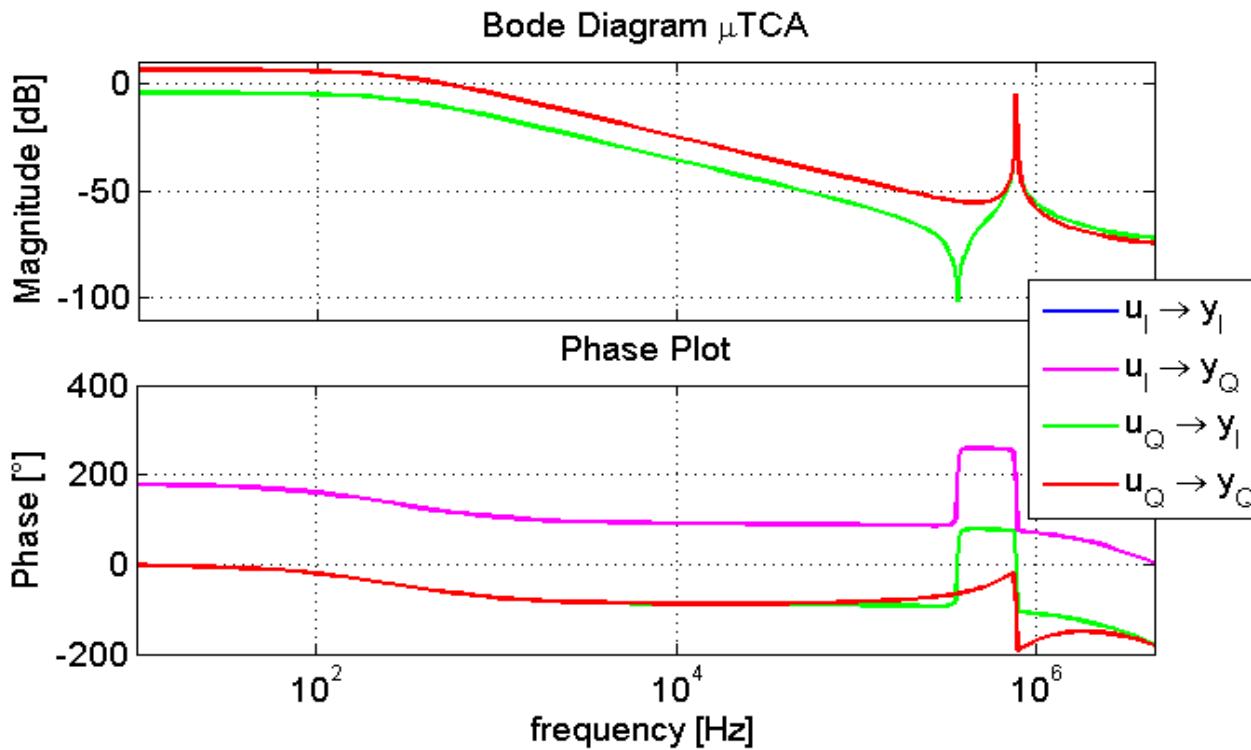
Benefit: $K * G_1(s)$ is SISO \rightarrow Controller Design \rightarrow SISO Controller $C(s)$ is very easy

$$C_{new}(s) = R^{-1} \cdot C(s) = \begin{bmatrix} C_1(s) & C_2(s) \\ -C_2(s) & C_1(s) \end{bmatrix}$$

Controller Design

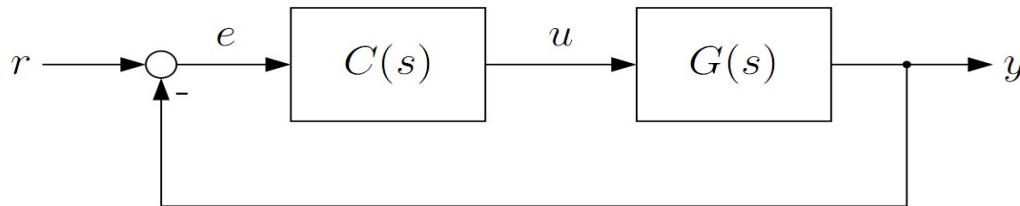


$$C(s) = \begin{bmatrix} C_1(s) & C_2(s) \\ -C_2(s) & C_1(s) \end{bmatrix} \quad \begin{pmatrix} Y_I(s) \\ Y_Q(s) \end{pmatrix} = \begin{bmatrix} G_1(s) & -G_2(s) \\ G_2(s) & G_1(s) \end{bmatrix} \begin{pmatrix} U_I(s) \\ U_Q(s) \end{pmatrix}$$



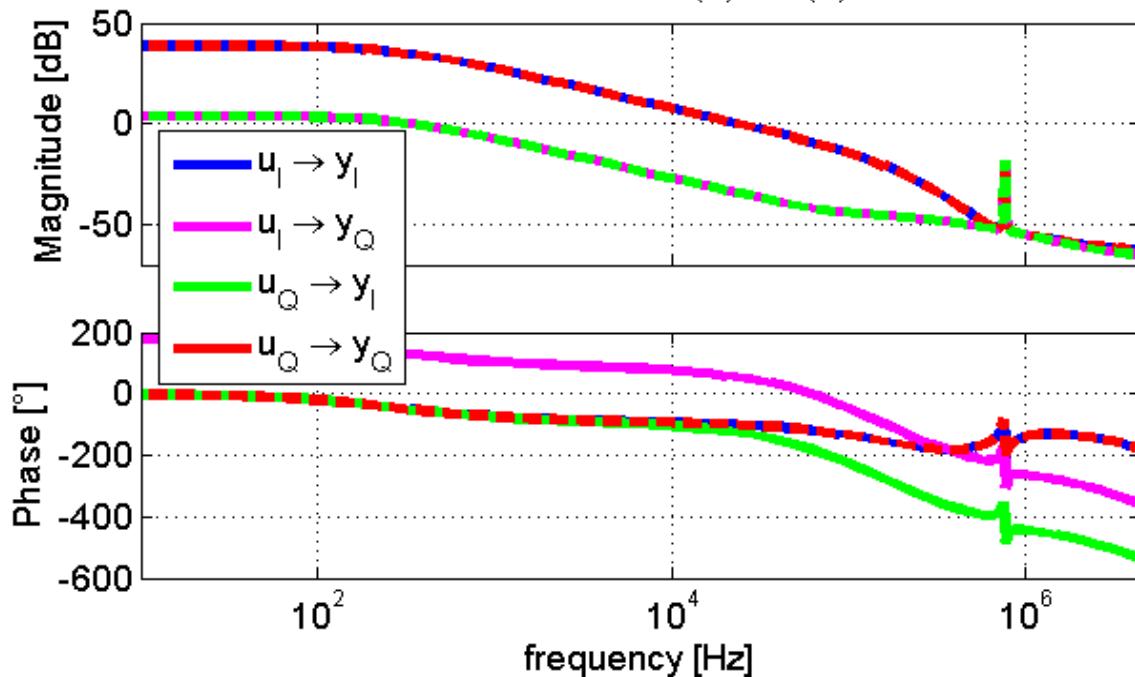
- $G(s)$ for μ TCA
- from $u(t)$ to $y(t)$
- Static coupling of -20dB (0.1)
- **Controller should decouple the system and reduce the 8/9 pi mode**

Controller Design



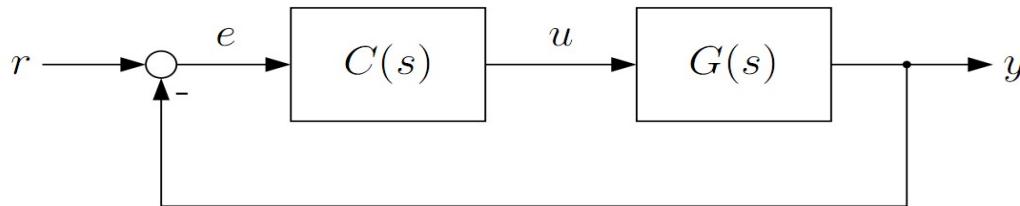
$$C(s) = \begin{bmatrix} C_1(s) & C_2(s) \\ -C_2(s) & C_1(s) \end{bmatrix} \quad \begin{pmatrix} Y_I(s) \\ Y_Q(s) \end{pmatrix} = \begin{bmatrix} G_1(s) & -G_2(s) \\ G_2(s) & G_1(s) \end{bmatrix} \begin{pmatrix} U_I(s) \\ U_Q(s) \end{pmatrix}$$

Bode Plot of $C(s) \cdot G(s)$



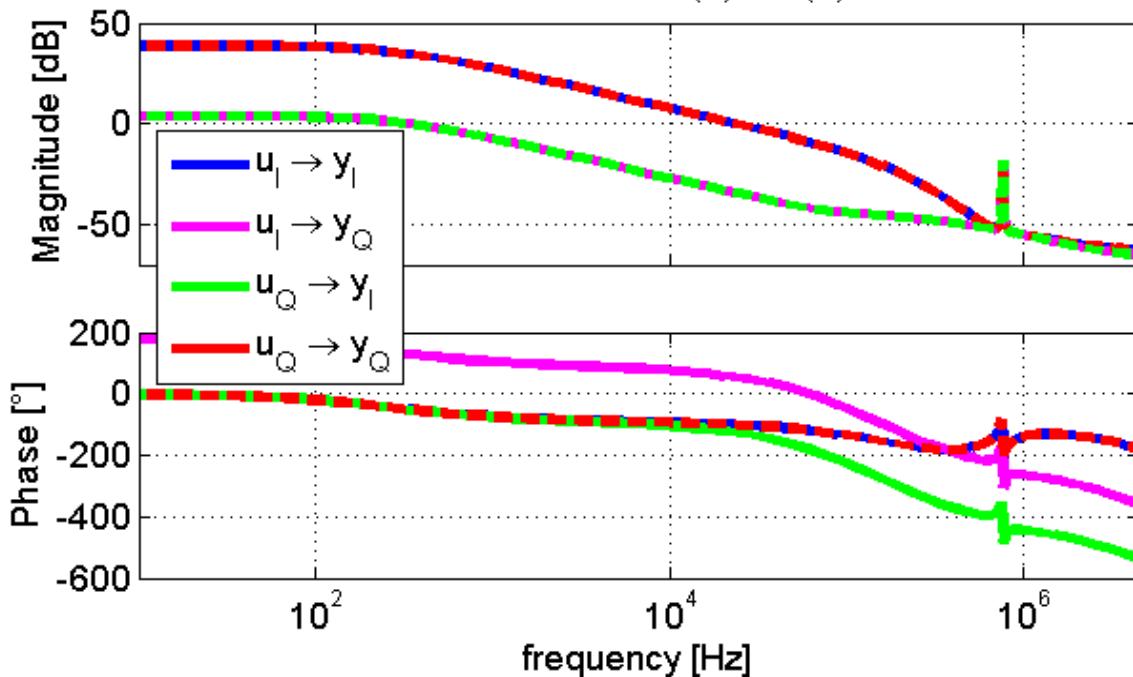
- $C(s) * G(s)$
- from $e(t)$ to $y(t)$
- Static coupling of -40dB (0.01)
- Current developments on dynamic decoupling
→ necessary for BBF

Controller Design



$$C(s) = \begin{bmatrix} C_1(s) & C_2(s) \\ -C_2(s) & C_1(s) \end{bmatrix} \quad \begin{pmatrix} Y_I(s) \\ Y_Q(s) \end{pmatrix} = \begin{bmatrix} G_1(s) & -G_2(s) \\ G_2(s) & G_1(s) \end{bmatrix} \begin{pmatrix} U_I(s) \\ U_Q(s) \end{pmatrix}$$

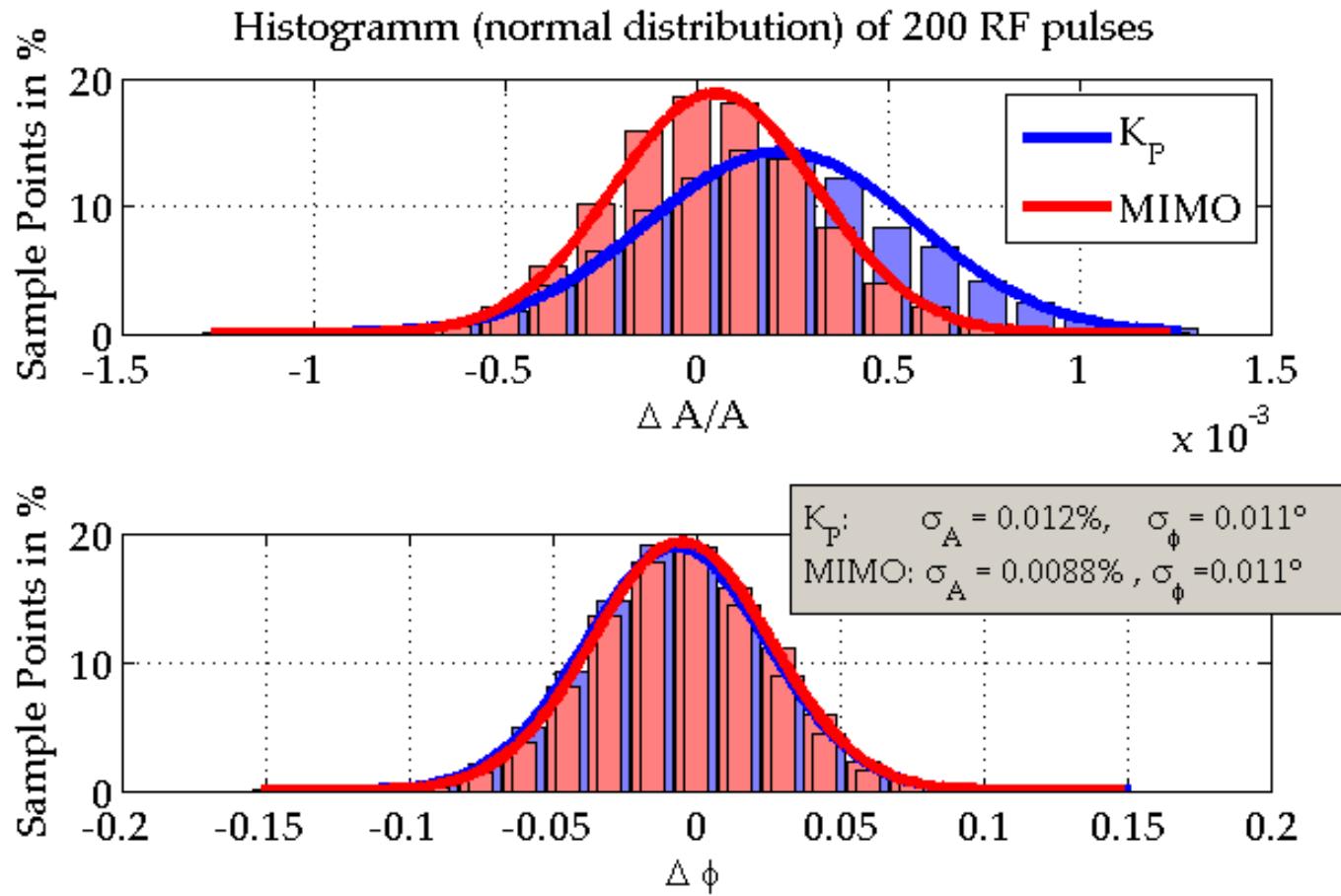
Bode Plot of $C(s) \cdot G(s)$



- $C(s) * G(s)$
- from $e(t)$ to $y(t)$
- Static coupling of -40dB (0.01)
- Current developments on dynamic decoupling
→ necessary for BBF

Part of my next
FLASH-Seminar

Field Controller - Results



Thank you for your attention!