CONTROL SYSTEM DESIGN FOR SRF CAVITIES BASED ON A KALMAN FILTER OBSERVER

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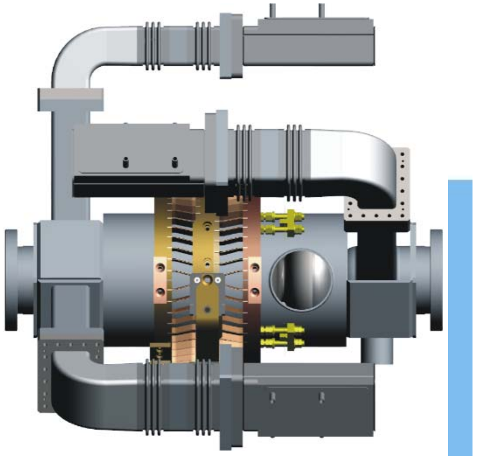
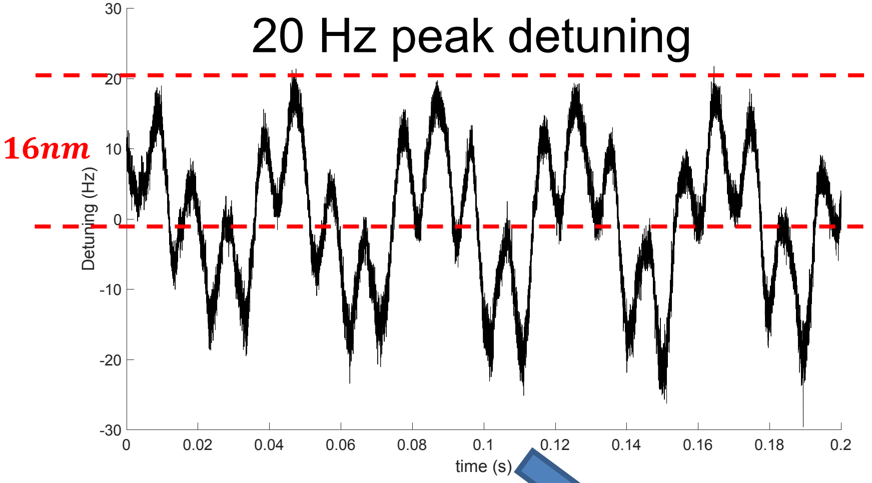


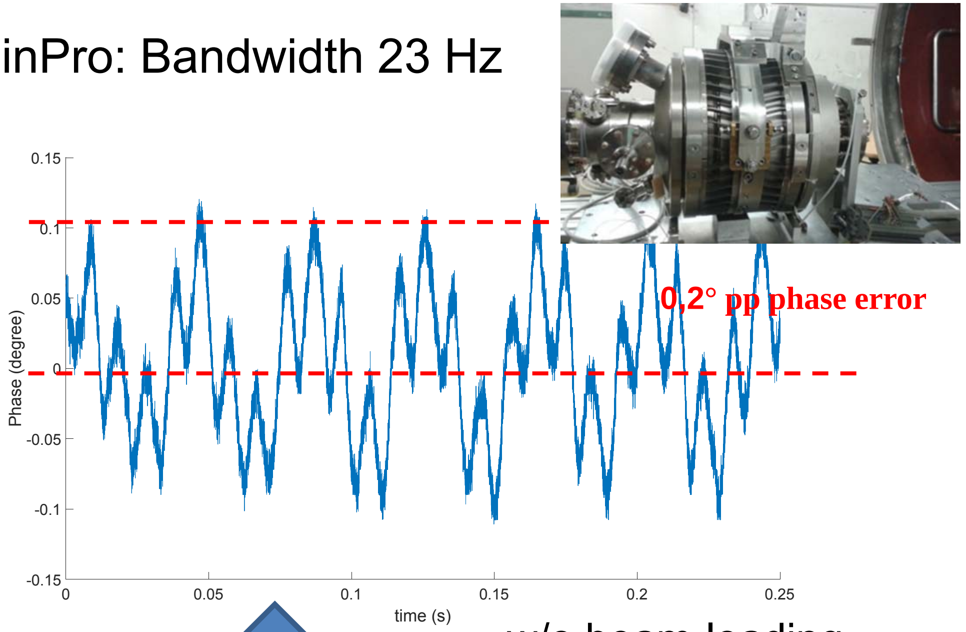
AGENDA

1. Why do we need advanced SRF cavity control?
2. Control concept using the Kalman Filter
3. Kalman Filter simulation and hardware implementation
4. Future plans

Detuning influence to the cavity stability

Example: Gun 1.0 cavity of bERLinPro: Bandwidth 23 Hz

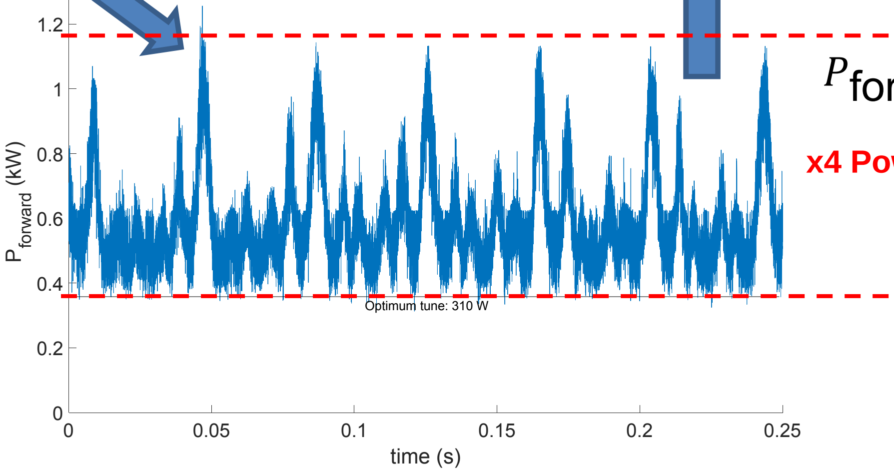




Bessy VSR frequency sweep by the deformation is 700KHz/mm

- $f_{1/2} = \frac{f_0}{2 \cdot Q_L} = 15Hz$
- $20nm \rightarrow 45°$

Precise field control is required, e.g. below 0.01 deg. in phase, 1e-4 relative amplitude



w/o beam-loading

$$P_{\text{forward}} = \frac{V_{\text{cav}}^2}{4\frac{R}{Q}Q_{\text{L}}}\left(1 + \frac{\Delta f}{f_{1/2}}\right)^2$$

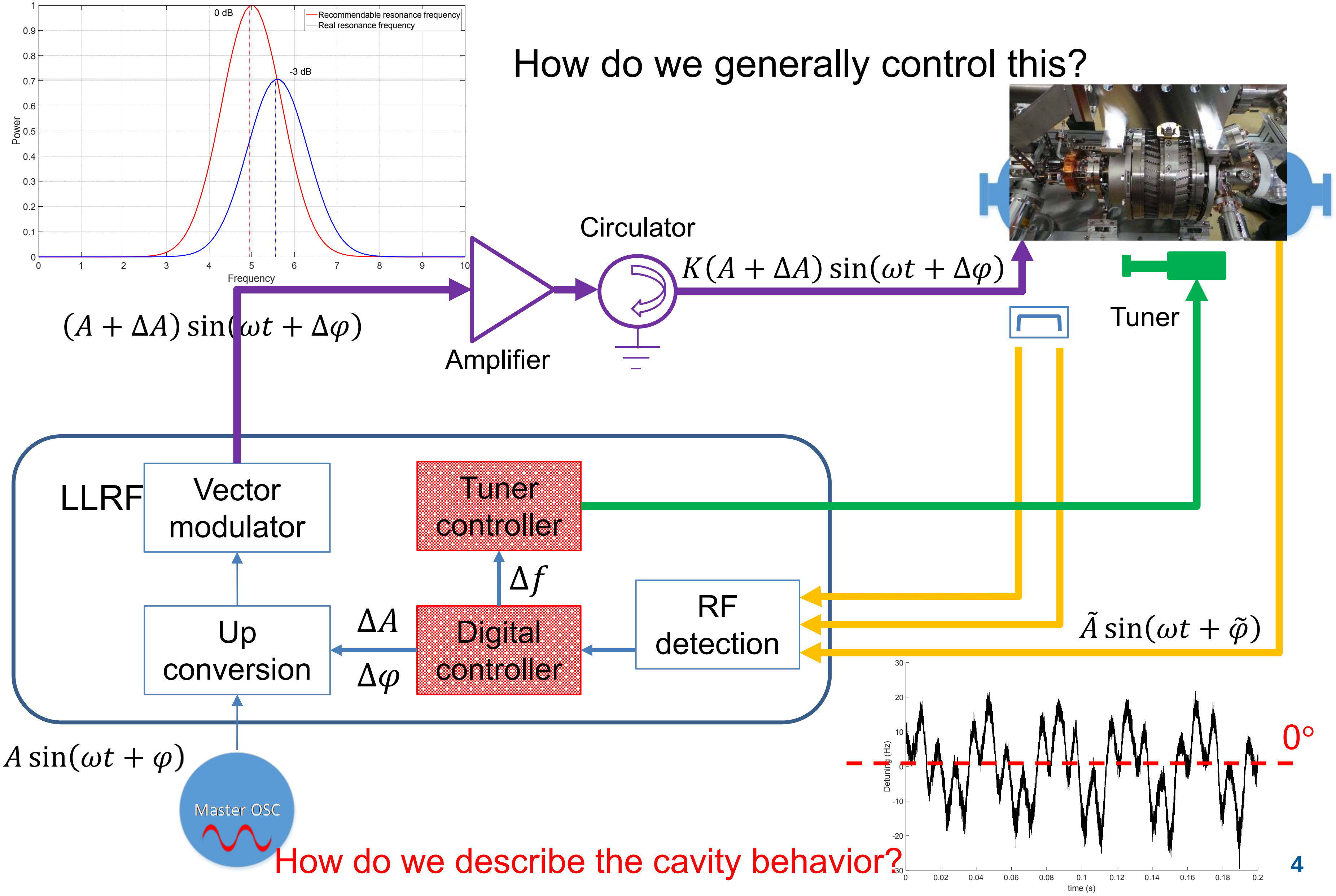
x4 Power

Stability paid by RF power, is limited and eventually not good enough!

How do we usually handle this?

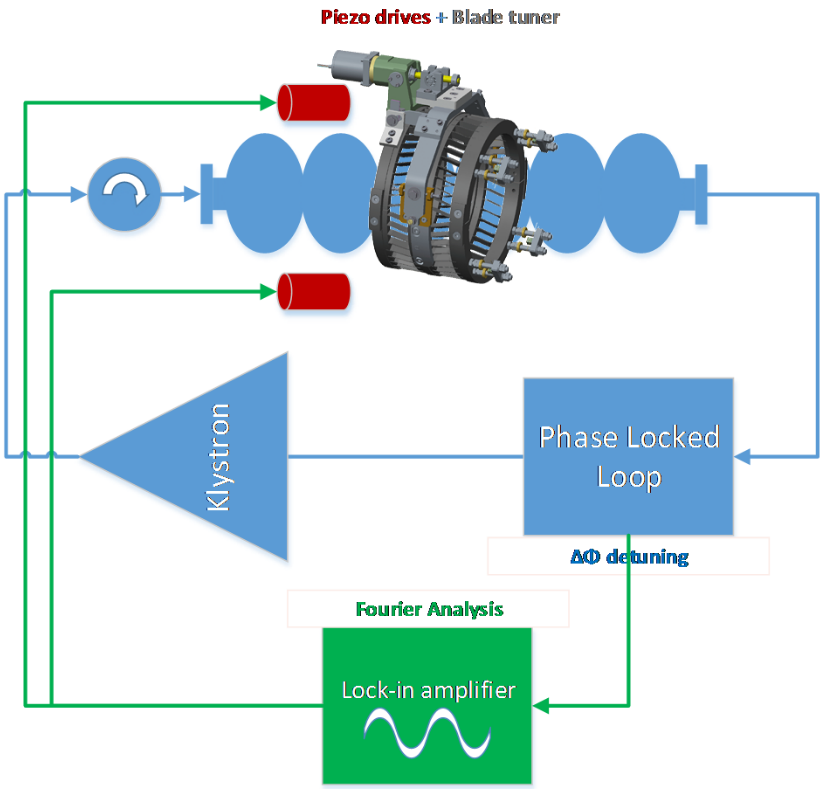
LLRF scheme

How do we generally control this?



How do we describe the cavity behavior?

Mechanical properties of the cavity


Piezo drives + Blade tuner

Klystron

Phase Locked Loop

ΔΦ detuning

Fourier Analysis

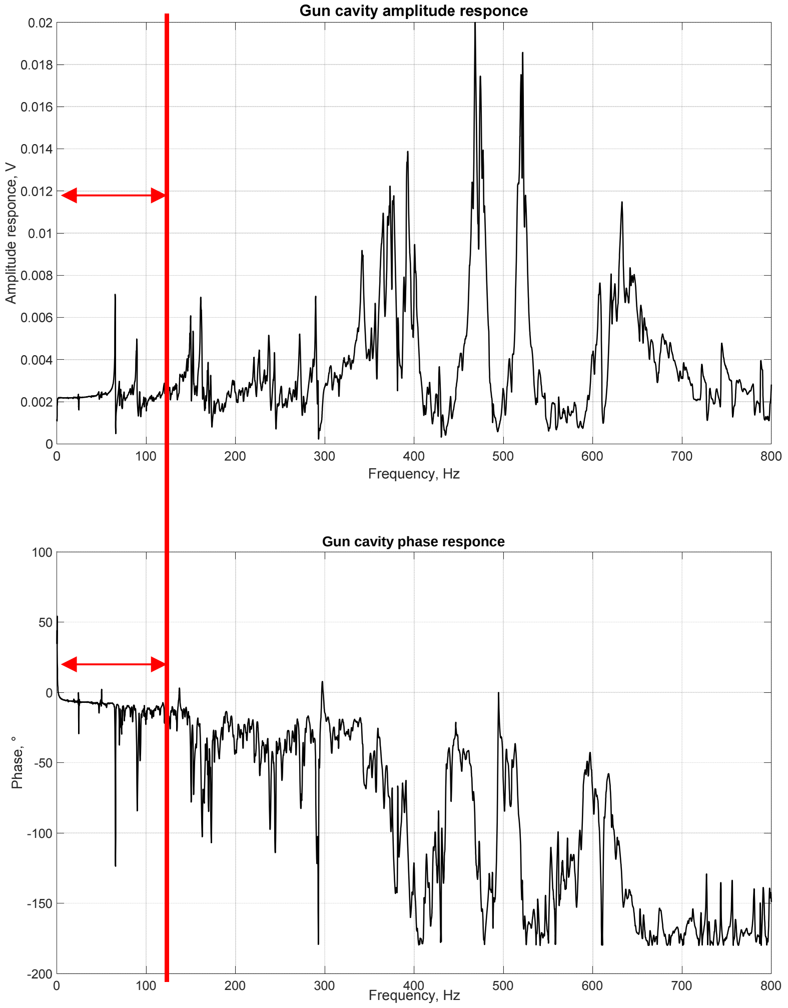
Lock-in amplifier

$$\Delta\ddot{\omega}_k(t) + 2\varepsilon\omega_{m,k}\Delta\dot{\omega}_k(t) + \omega_{m,k}^2\Delta\omega_k(t) = \pm k_k 2\pi\omega_{m,k}^2 E_{acc}^2(t)$$

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

B. Gustavsen and A. Semlyen, "Rational approximation of frequency domain responses by vector fitting", IEEE Trans. Power Delivery, vol. 14, no. 3

Lorentz force and mechanical vibrations region of interest



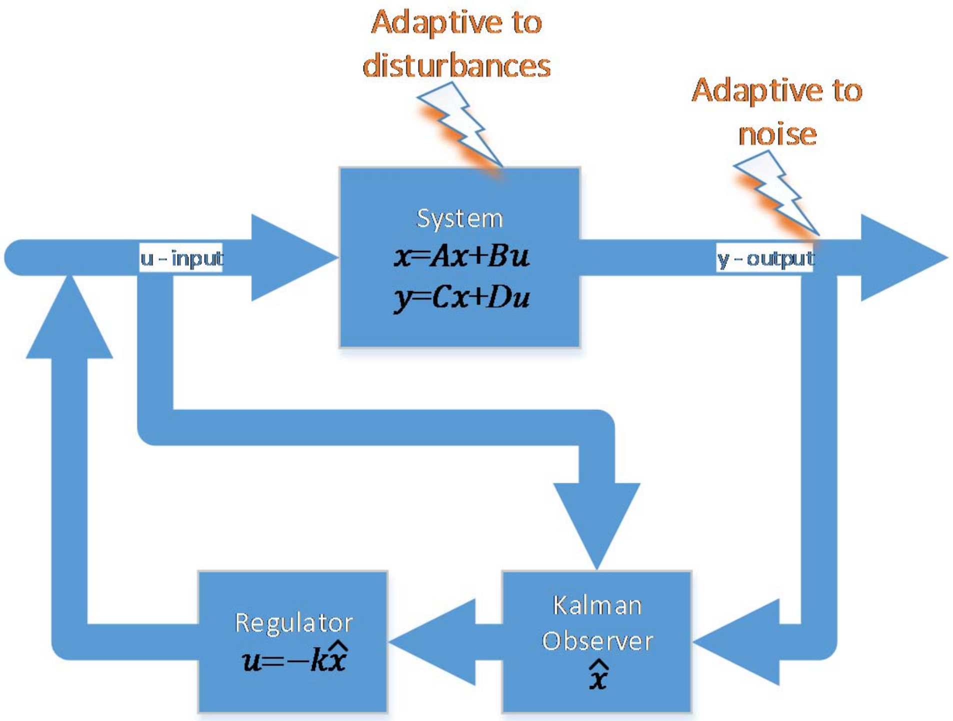
How control theory helps us to control cavity?

Control approaches used in accelerators

Modern control approaches

- Passive control: all kinds of mass damper, harmonic absorbers, shock absorbers
    - Isn’t robust to any change of system parameters
    - Doesn’t have any energy expenses
- Classical PID regulator
    - Amplifiers all outer disturbances and system intrinsic noises
    - Requires additional energy pump
    - Requires parameters adjustment if conditions are varying
- Main tone cancellation
    - Sort of adaptive technique
    - Can adopt in the real-time
    - Requires additional feedback regulator
    - Not a feedforward approach
- Feedforward control: LQR + Kalman observer
    - Allows optimal control: reaction speed vs energy expenses
    - Based on the physical model of the system
    - Doesn’t require full set of parameters and thus less sensors
    - Feedforward approach allowing adjusting on the fly

Essence of control approaches



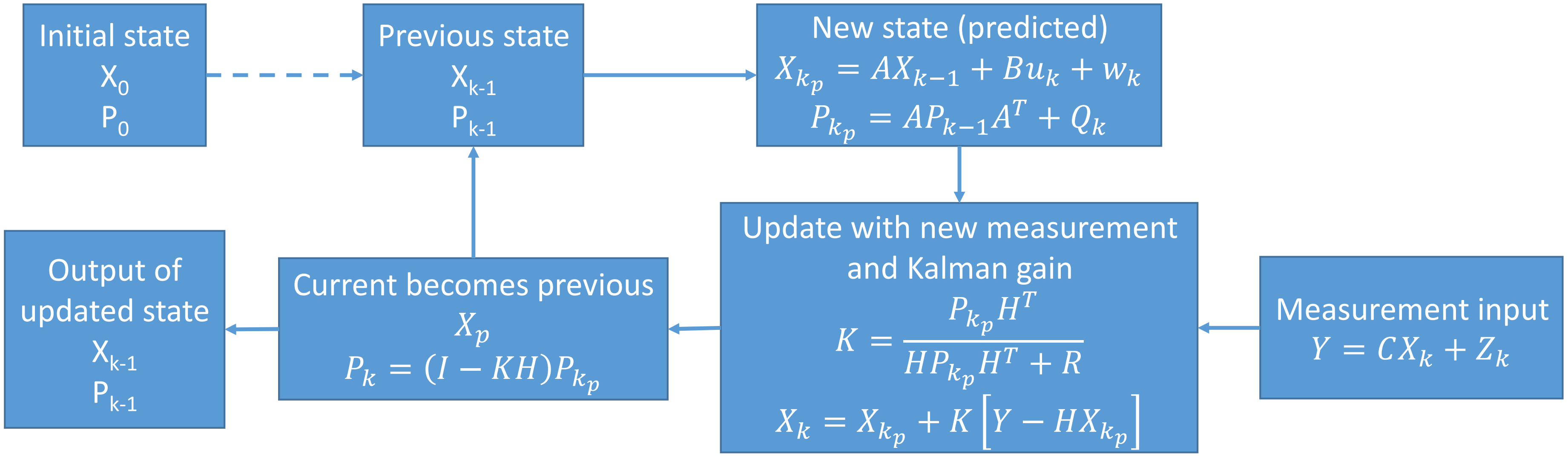
Robust to limited data about system!

How does Kalman Observer work?

The multi-dimension matrix model

Michael van Biezen. http://www.ilectureonline.com/

Predicted state based on physical model and previous state



Initial state
X_0
P_0

Previous state
X_{k-1}
P_{k-1}

New state (predicted)
$X_{k_p} = AX_{k-1} + Bu_k + w_k$
$P_{k_p} = AP_{k-1}A^T + Q_k$

Update with new measurement and Kalman gain
$$K = \frac{P_{k_p}H^T}{HP_{k_p}H^T + R}$$
$$X_k = X_{k_p} + K\left[Y - HX_{k_p}\right]$$

Measurement input
$Y = CX_k + Z_k$

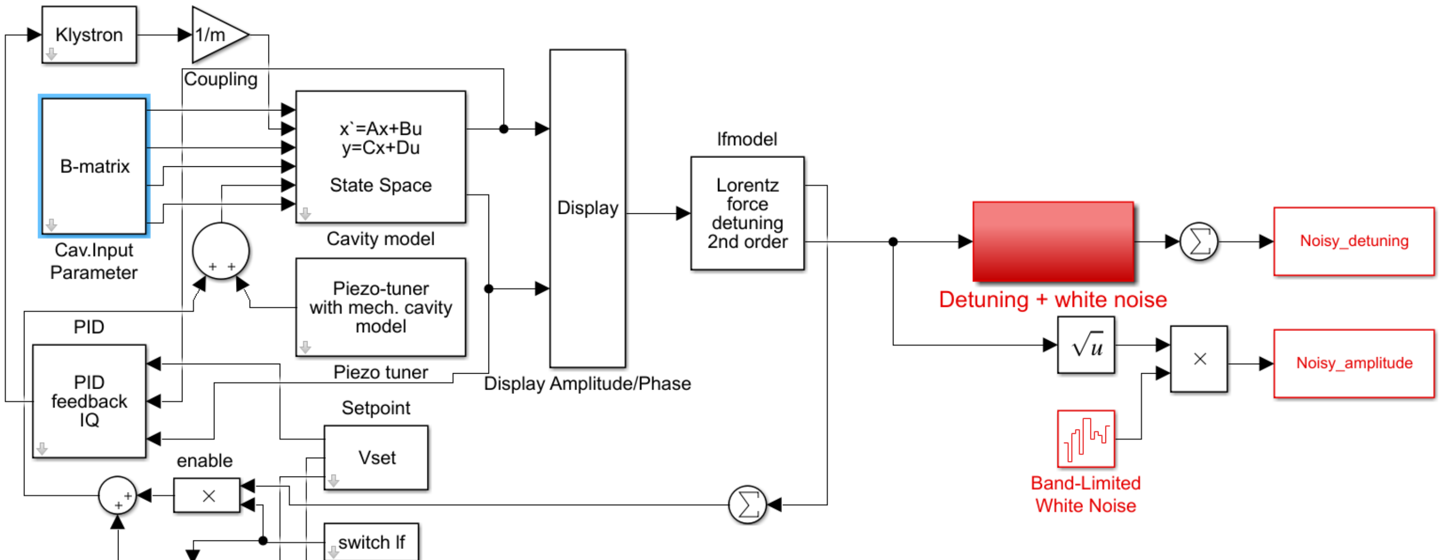
Current becomes previous
X_p
$P_k = (I - KH)P_{k_p}$

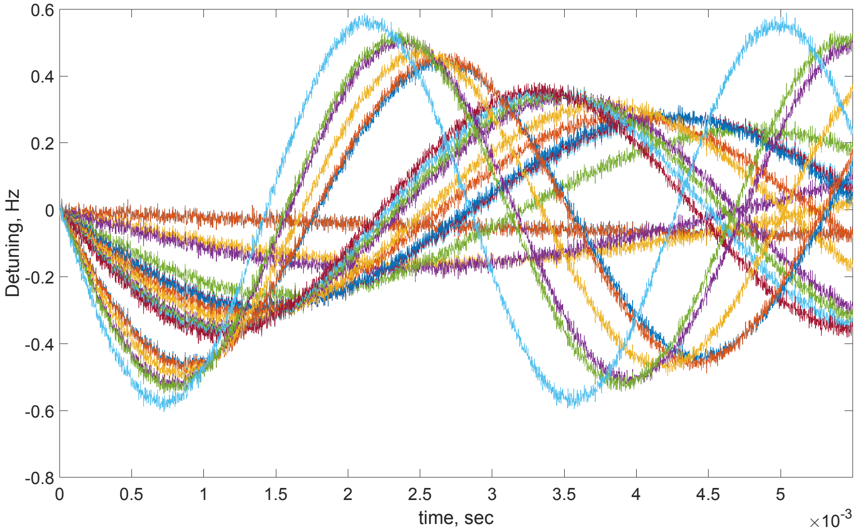
Output of updated state
X_{k-1}
P_{k-1}

- $K = \frac{E_{EST}}{E_{EST}+E_{MEA}}$
- $0 < K \leq 1$
- If $K \to 0,\ EST_t = EST_{t-1}$
- If $K \to 1,\ EST_t = K \cdot MEA$

Measurements	KG	Estimates
Measurements are accurate	**1**	Estimates are unstable
↕	0.8	↕
	0.6	
	0.4	
	0.2	
Measurements are inaccurate	**0**	Estimates are stable (small error)

Cavity behavior model as the KF input





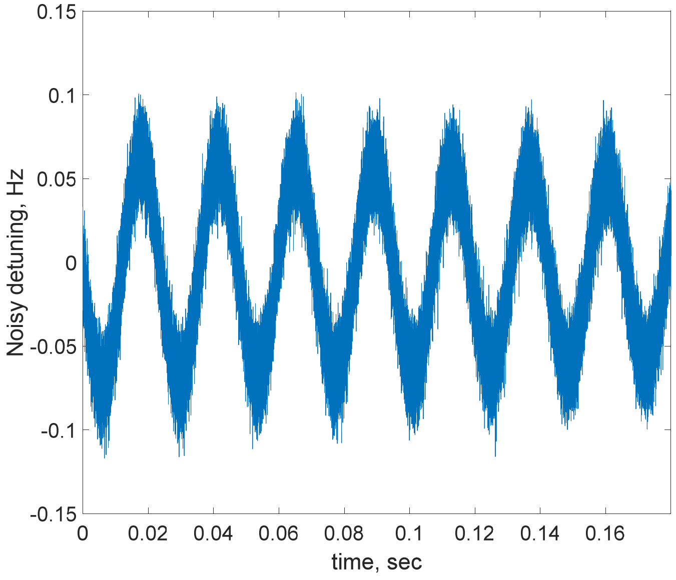
- 2^nd order Lorentz Force detuning block describes up to 20 modes
- Individual noisy detuning of each mode generated
- Cavity field amplitude is generated

Lets test Kalman filter response under different input noises!

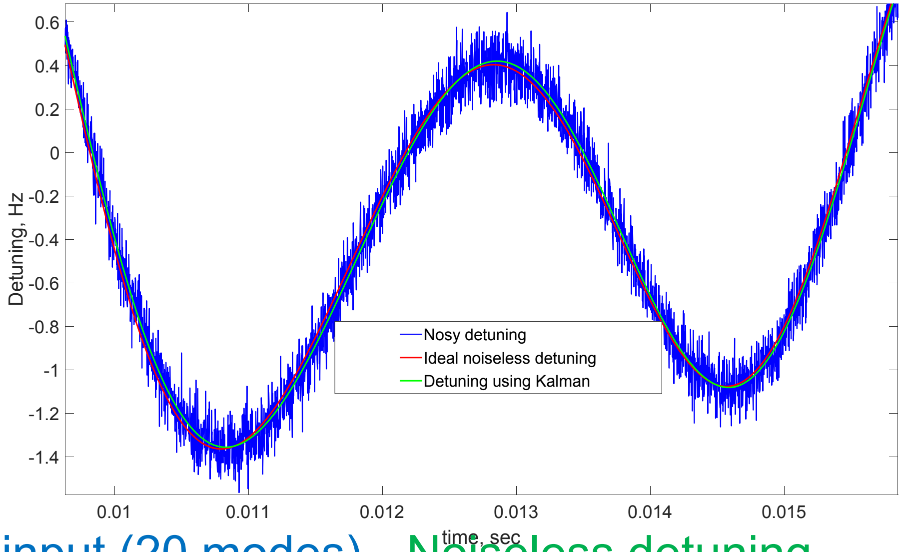
KF response to 20 noisy eigenmodes

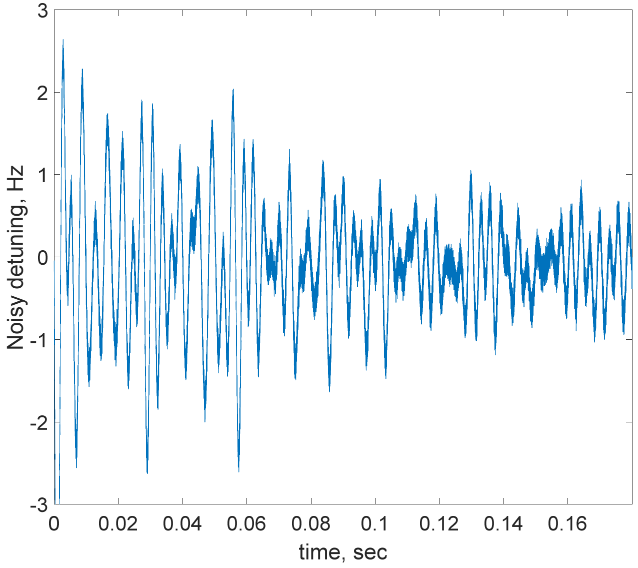
20 eigenmodes are detuned

SNR=4,2dB



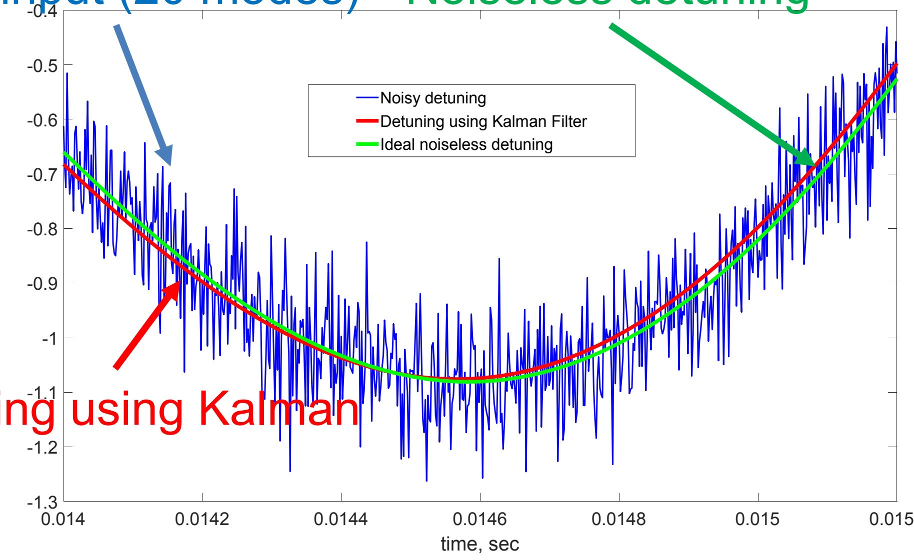
Peak 10mHz difference → 0,04°





Noisy input (20 modes)

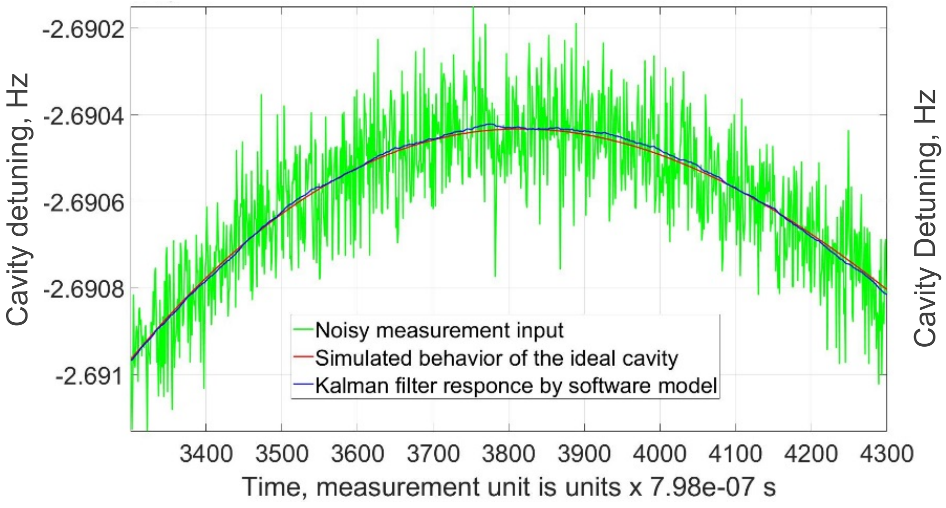
Noiseless detuning



Detuning using Kalman

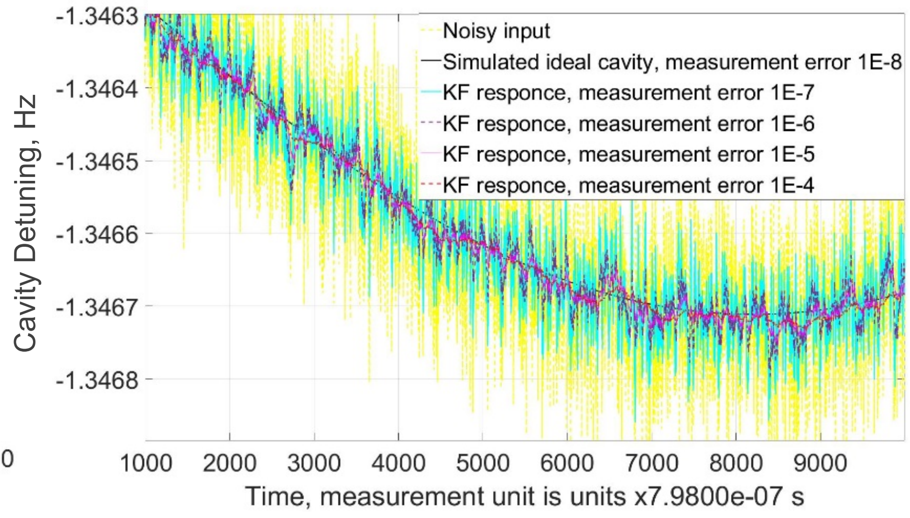
Lessons learned

Ideal Kalman Filter reaction slightly differs from the data obtained from mTCA HW



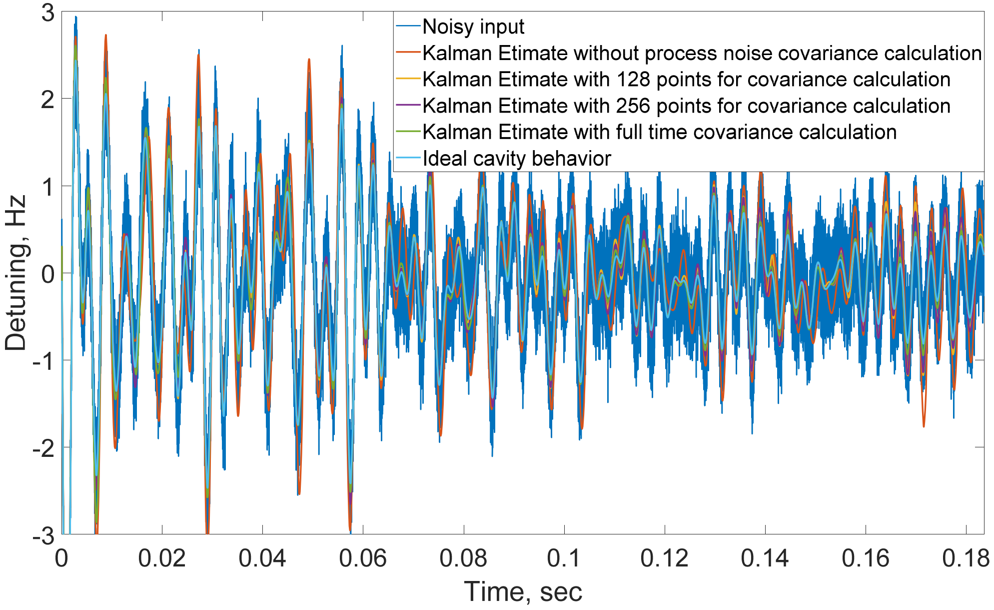
- Reaction with some deviation from ideal.
- Stands intrinsic hardware noises: attenuators, downconverters, not-scaled amplitude of field

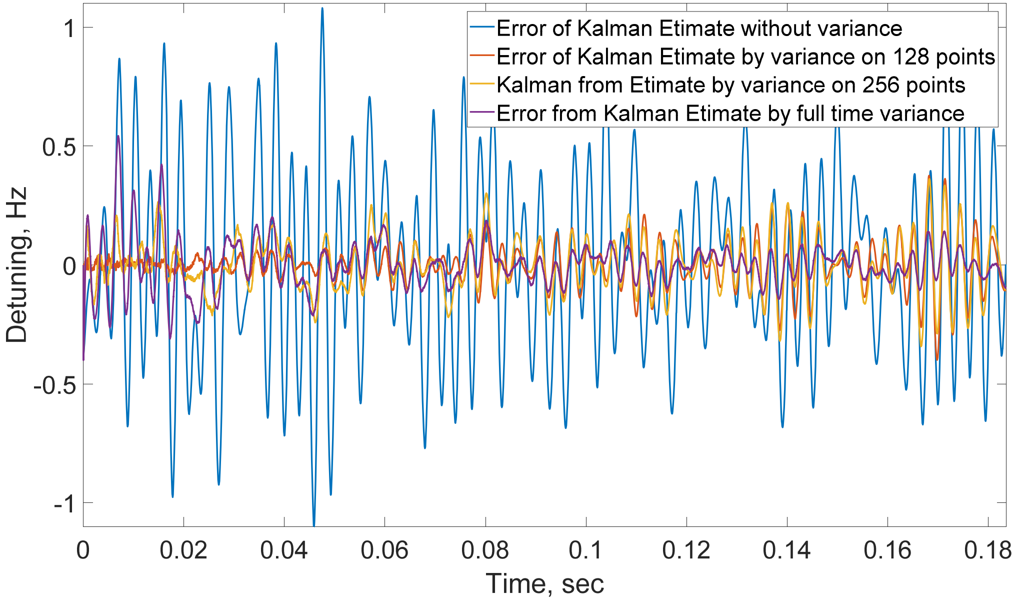
The initial error settings have influence on the proximity of the "real" produced curve to the "ideal"



- Filter allows to find a sweet spot for the appropriate observation error

Kalman filter optimization for 20 modes

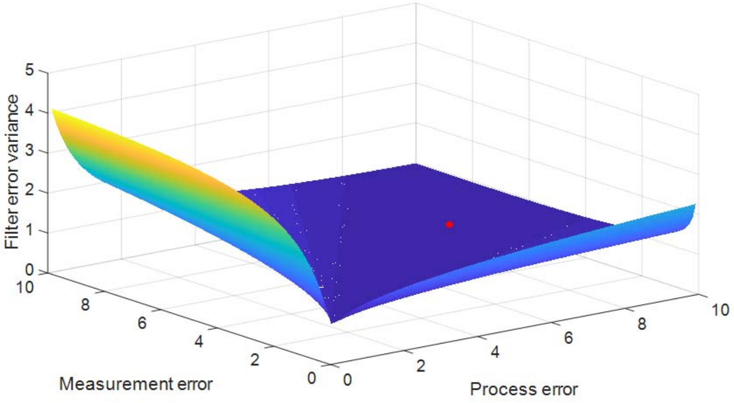




It is impossible to ignore the variance component in the process covariance matrix calculation: the error is significant

Difference between process covariance matrixes on 128 and 256 points is not significant

Best error variance is 0,967

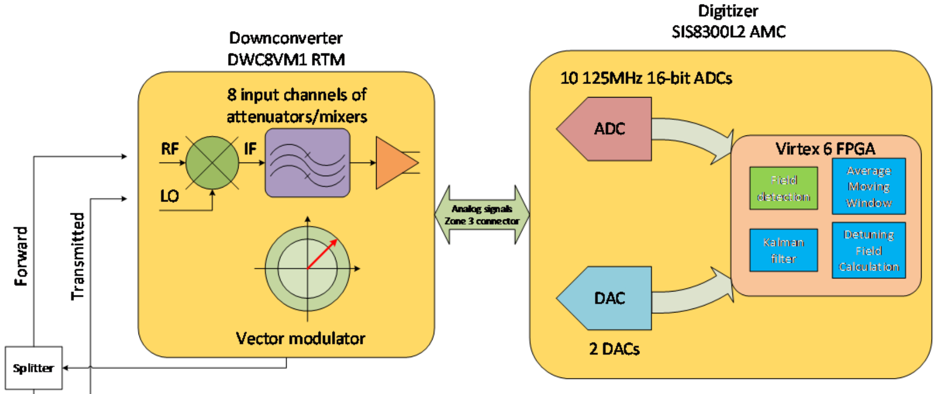


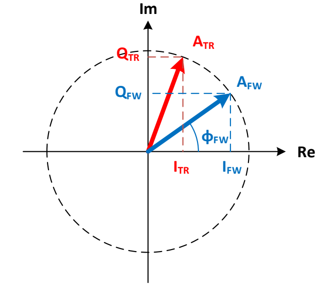
Testing hardware: cavity simulator + mTCA KF

$$A_{IF} = \frac{1}{2} A_{LO} A_{RF} \begin{pmatrix} \sin((\omega_{RF} - \omega_{LO})t + (\varphi_{RF} - \varphi_{LO})) \\ + \sin((\omega_{RF} + \omega_{LO})t + (\varphi_{RF} + \varphi_{LO})) \end{pmatrix}$$

Lower sideband F_{IF}=1,354-1,3GHz=54MHz
1st Nyquist image

$$\varphi_{IF} = \varphi_{RF} - \varphi_{LO}$$

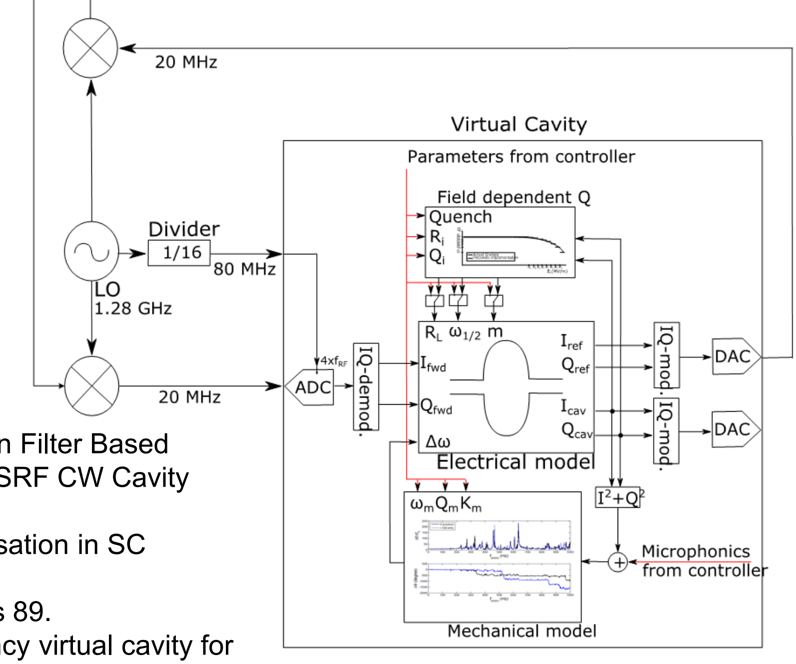




$$y(t) - I\cos\omega t + Q\cos\omega t$$

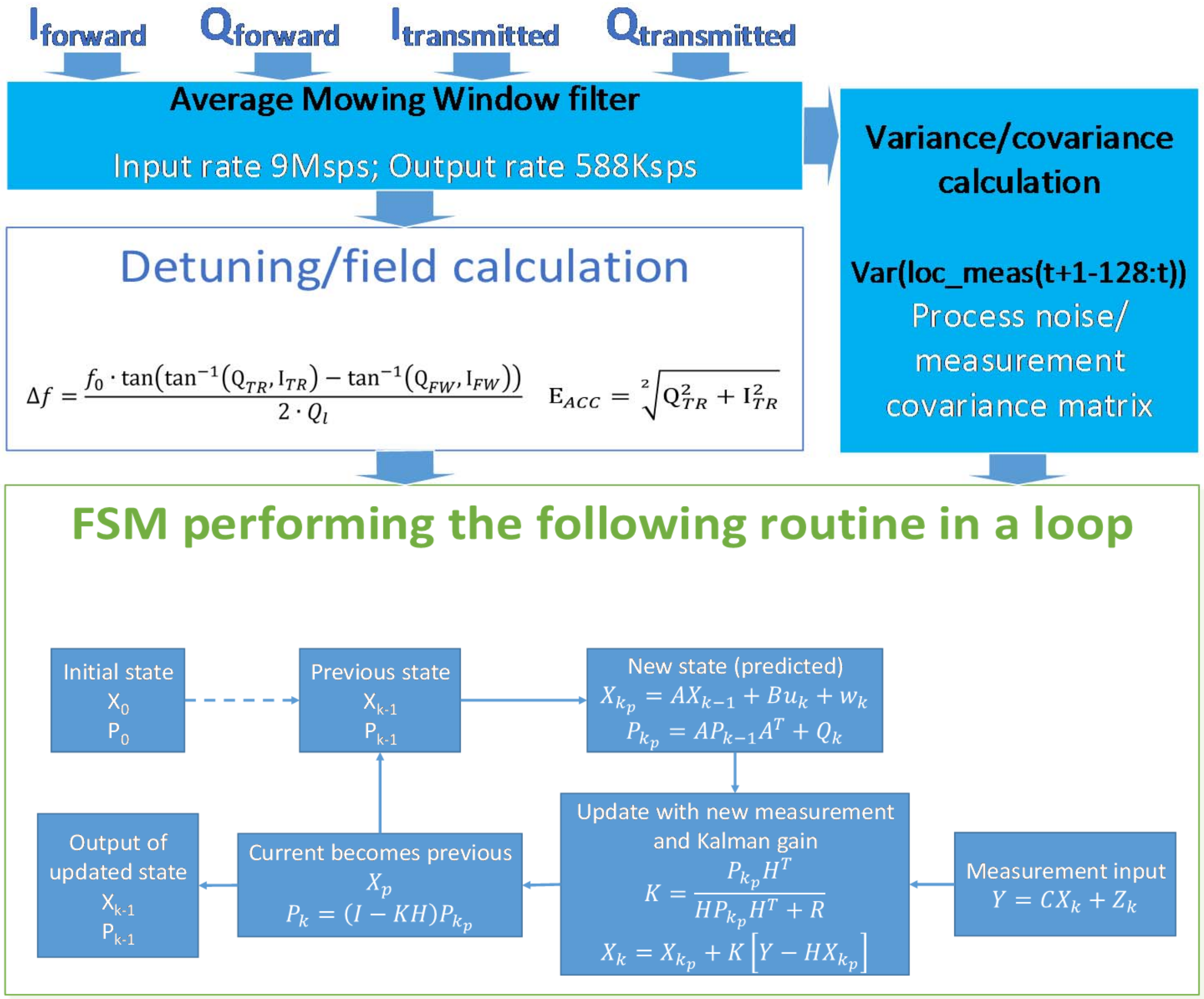
$$\varphi_0 = \mathrm{atan}\left(\frac{Q}{I}\right)$$

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



- IPAC 2018. “Developing Kalman Filter Based Detuning Control with a Digital SRF CW Cavity Simulator”
- IPAC 2017. “Detuning Compensation in SC Cavities Using Kalman Filters”
- Review of Scientific Instruments 89. “Superconducting radio-frequency virtual cavity for control algorithms debugging”

Developed firmware for mTCA



$I_{forward}$ $Q_{forward}$ $I_{transmitted}$ $Q_{transmitted}$

Average Mowing Window filter

Input rate 9Msps; Output rate 588Ksps

Variance/covariance calculation

Var(loc_meas(t+1-128:t))

Process noise/ measurement covariance matrix

Detuning/field calculation

$$\Delta f = \frac{f_0 \cdot \tan\left(\tan^{-1}(Q_{TR}, I_{TR}) - \tan^{-1}(Q_{FW}, I_{FW})\right)}{2 \cdot Q_l} \qquad E_{ACC} = \sqrt[2]{Q_{TR}^2 + I_{TR}^2}$$

FSM performing the following routine in a loop

Initial state
X_0
P_0

Previous state
X_{k-1}
P_{k-1}

New state (predicted)
$X_{k_p} = AX_{k-1} + Bu_k + w_k$
$P_{k_p} = AP_{k-1}A^T + Q_k$

Update with new measurement and Kalman gain
$$K = \frac{P_{k_p} H^T}{H P_{k_p} H^T + R}$$
$$X_k = X_{k_p} + K\left[Y - HX_{k_p}\right]$$

Measurement input
$Y = CX_k + Z_k$

Current becomes previous
X_p
$P_k = (I - KH)P_{k_p}$

Output of updated state
X_{k-1}
P_{k-1}

Complexities and developments:

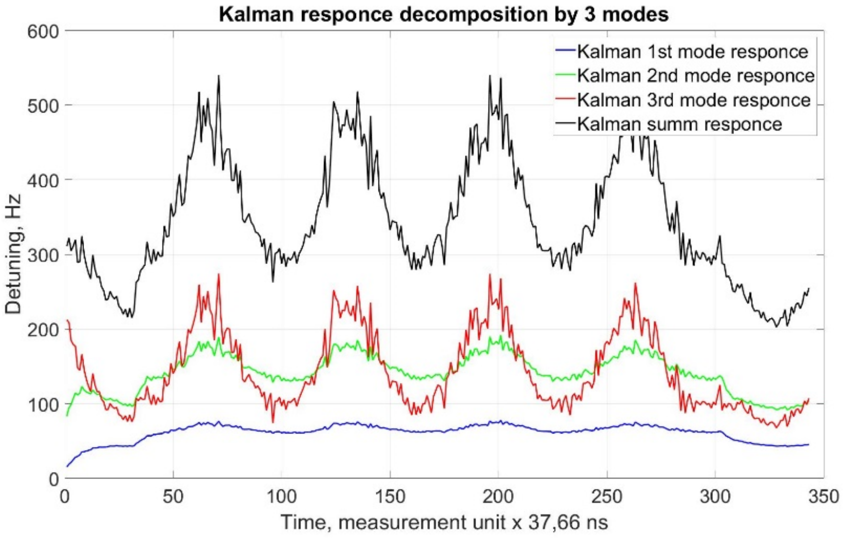
- Floating point library developed
- Matrix operations library developed
- Detuning and field calculation math
- Additional average moving window filters

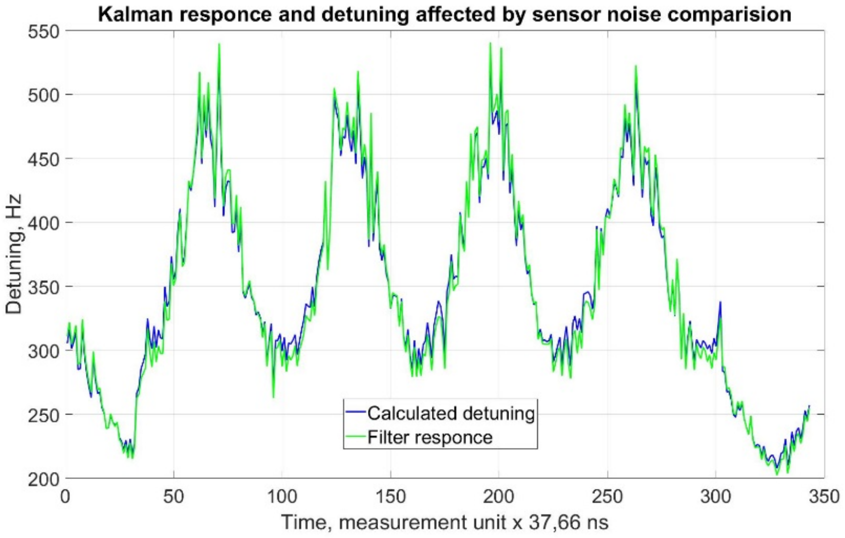
FPGA firmware characteristics:

- Maximum processing rate 500Msps
- Able to process up to 1000 eigenmodes
- Actual piezo drive frequency is limited by 300Hz at 6uF and 140Vpp
- 15Hz/V for Gun cavity

KF response real-time examination

Input: cavity oscillation depends on 3 mechanical modes:
330, 460, 470 Hz

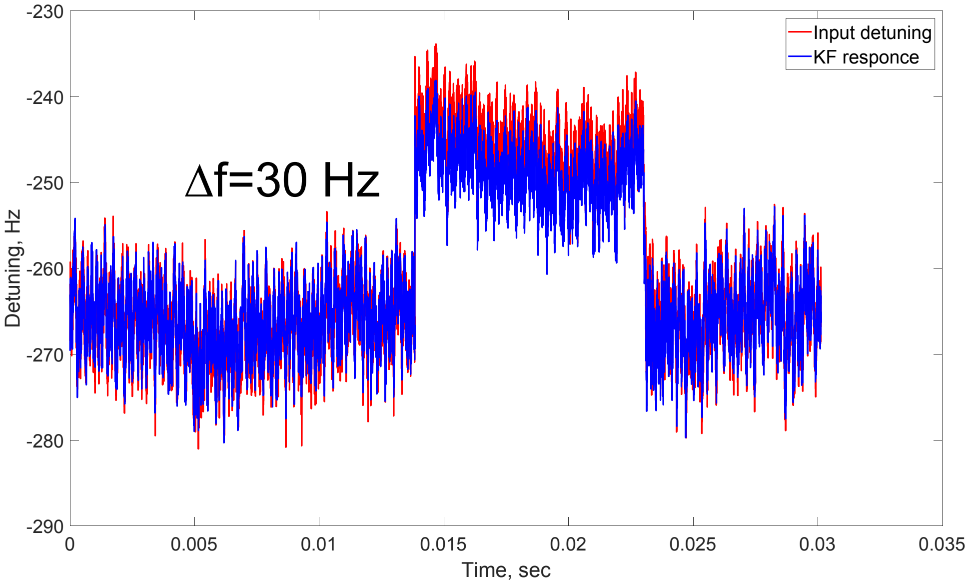




Mechanical modes contribution:
330 Hz – 20%; 460 Hz – 40%, 470 Hz – 40%

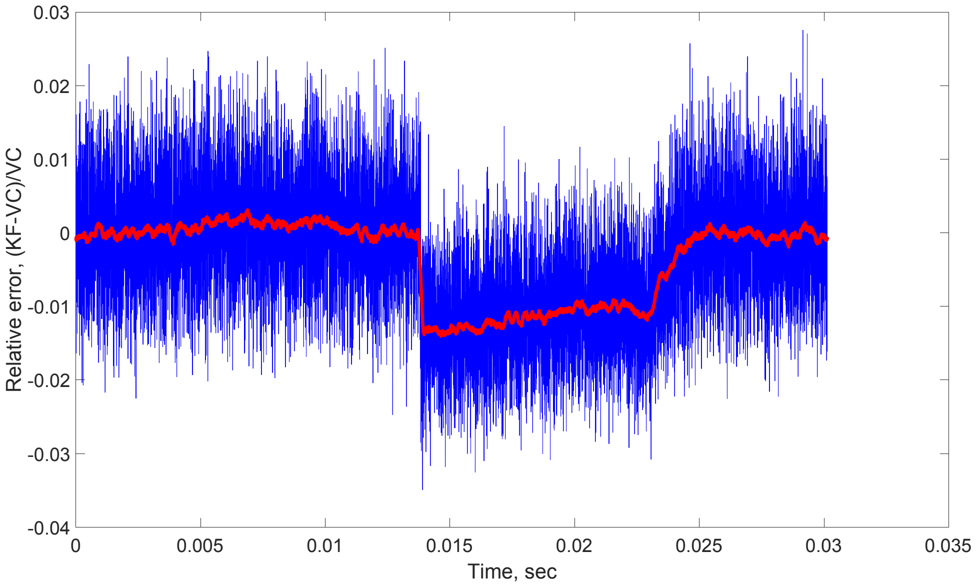
Kalman filter response consist of 3 modes.
The tracking precision is within 0,1 %

Kalman filter response to the rapid beam change

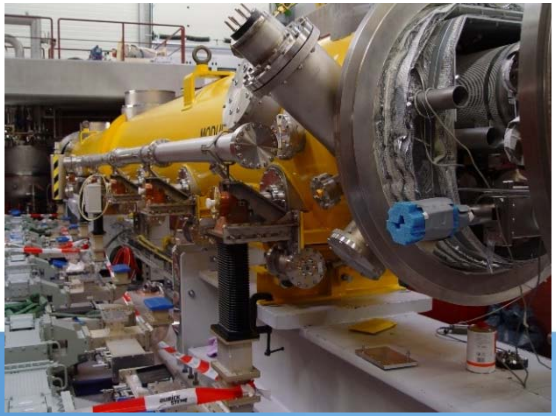


e.g. 1mbar pressure change in LHe system or non-synchronized Beam injection into BESSY II

Kalman filter reacts to the stiff transition with 2µs delay. Keeps tracking within 2% of error



Future works:



1. Kalman filter test planned in CMTB facility DESY for December 2018
2. Close the control loop with a real cavity
3. HZB “in house” mTCA firmware portfolio development related to the specific of our application
4. Transient beam loading control investigation by Kalman Filter

Thank you for your attention!