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

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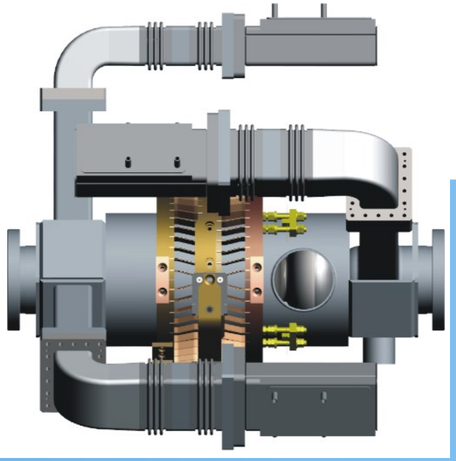
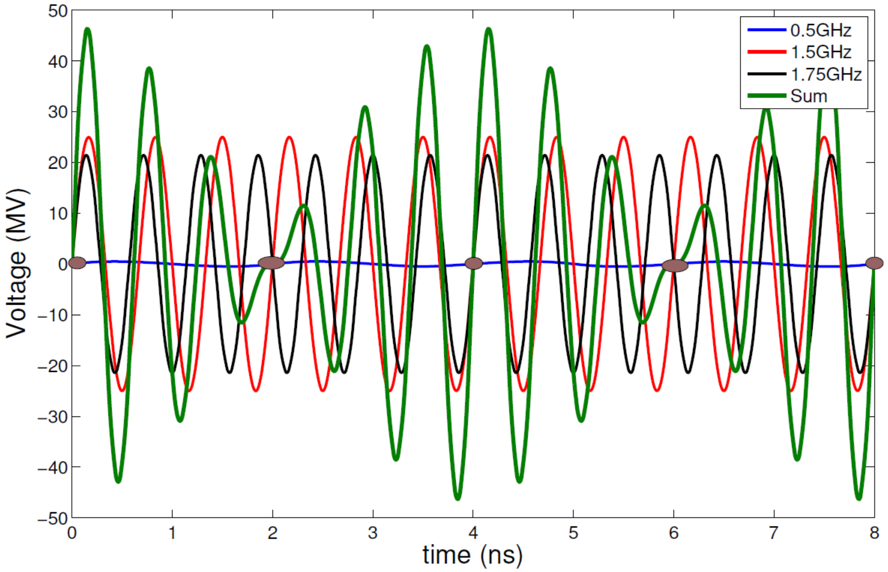
AGENDA



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

BESSY VSR scheme: the need for stable operation

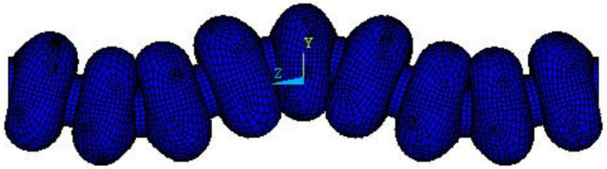
Beating of voltage at BESSY VSR caused by 3 cavities



- BESSY-VSR relies on exact synchronization of three (S)RF cavity systems
- The scheme itself has its inherent instabilities
- Any deviation in phase and amplitude will disturb the scheme → e.g. unwanted high current long bucket bunch shortening → increase loss of particles

VSR higher harmonic: Zero-crossing operation, with right tune highly unloaded system → operation at high Q → Narrow bandwidth → Easily to disturb:

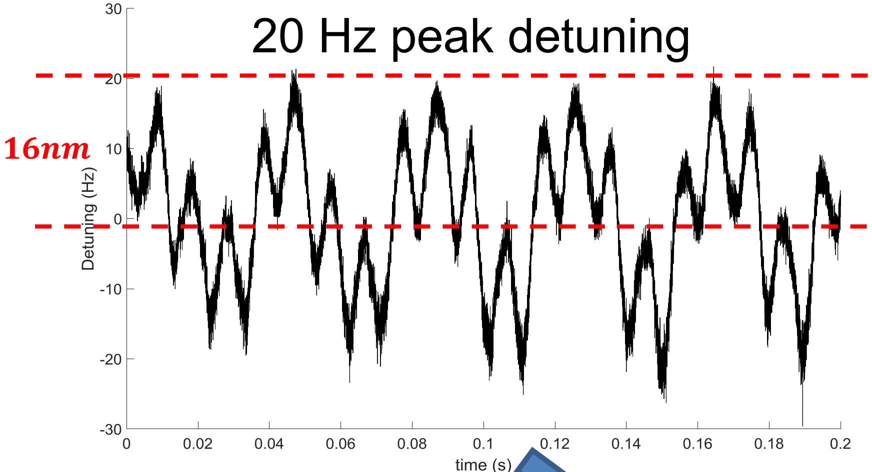
- Microphonics
- Dynamic Lorentz force detuning
- Highly mechanically resonant system

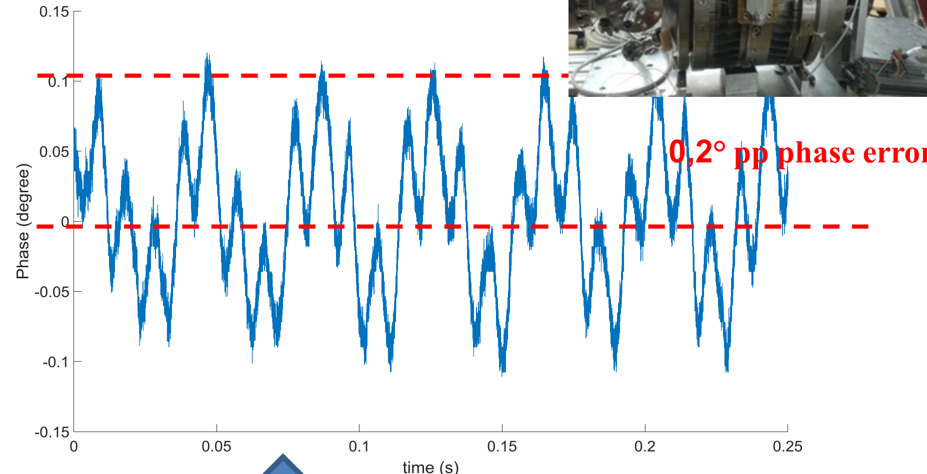


Let's demonstrate with a real example

Detuning influence to the cavity stability

Example: Gun 1.0 cavity of bERLinPro: Bandwidth 23 Hz





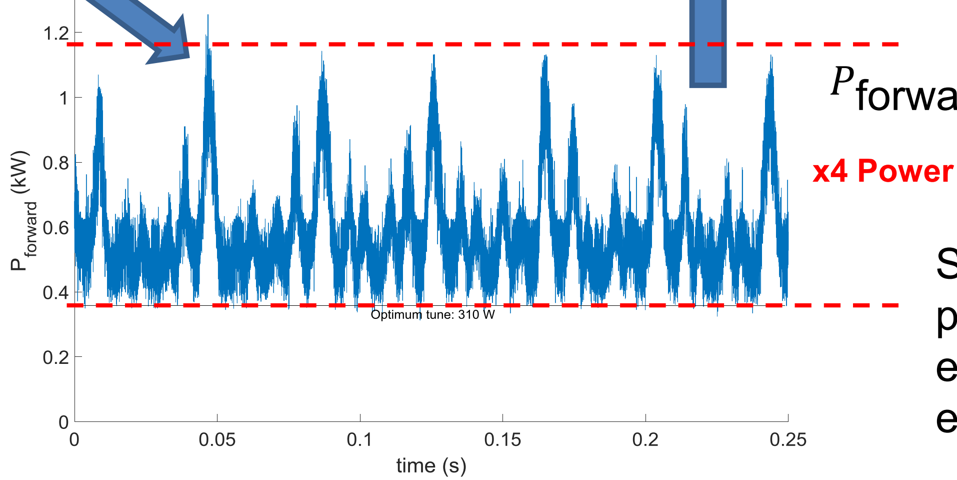
w/o beam-loading

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

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

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

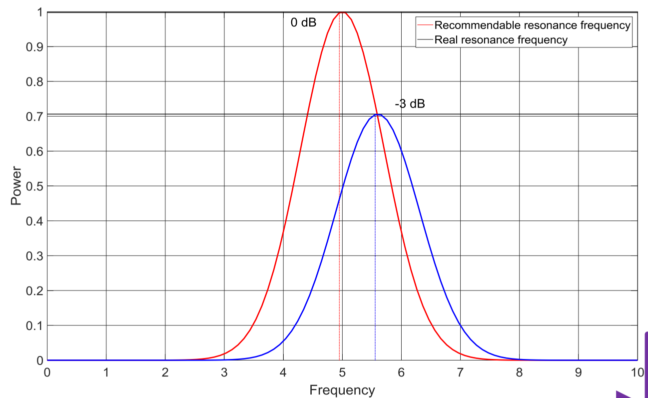
Precise field control is required, e.g. below 0.01 deg. in phase, 1e-4 relative amplitude



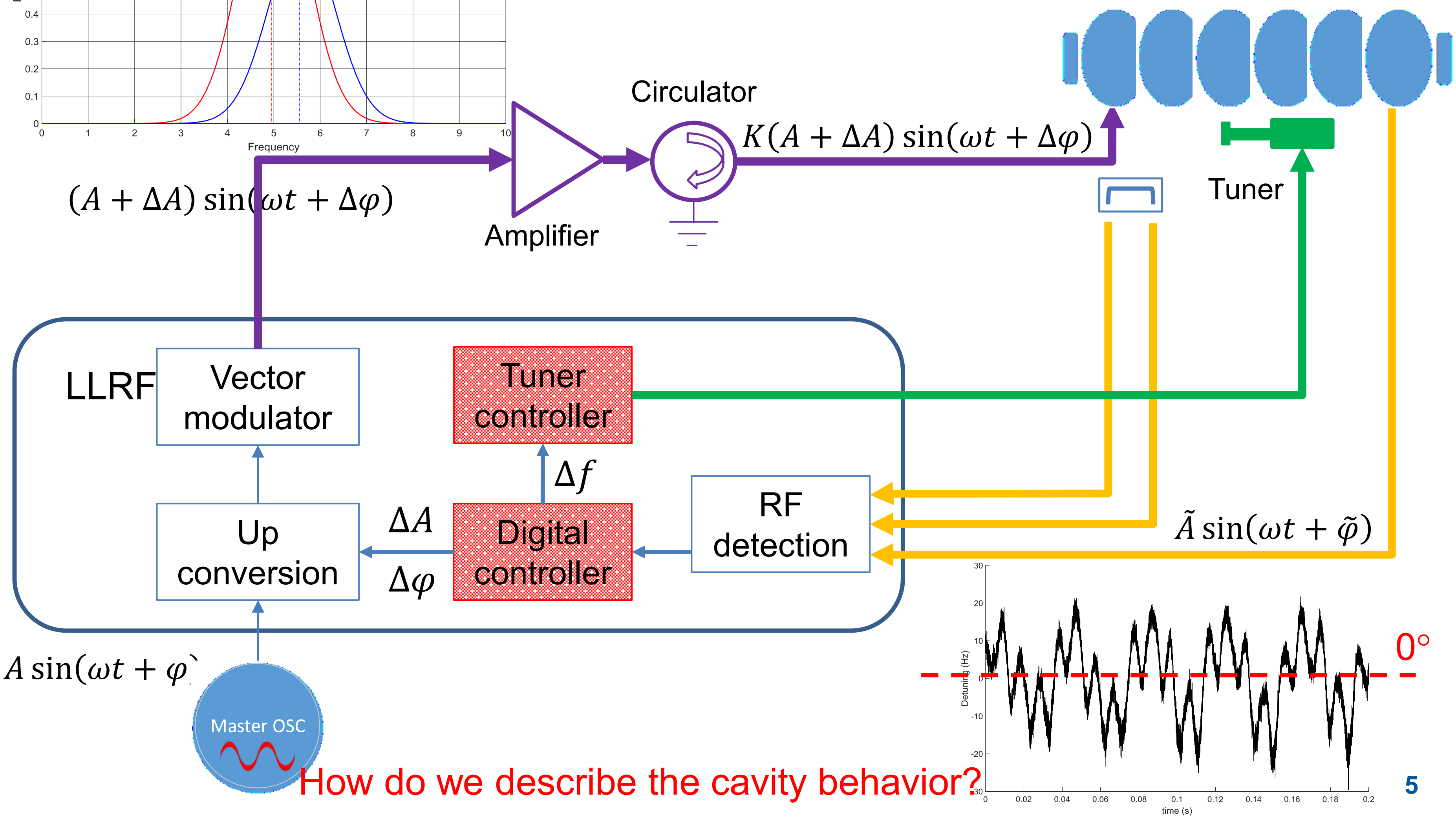
Stability paid by RF power, is limited and eventually not good enough!

How do we usually handle this?

LLRF scheme

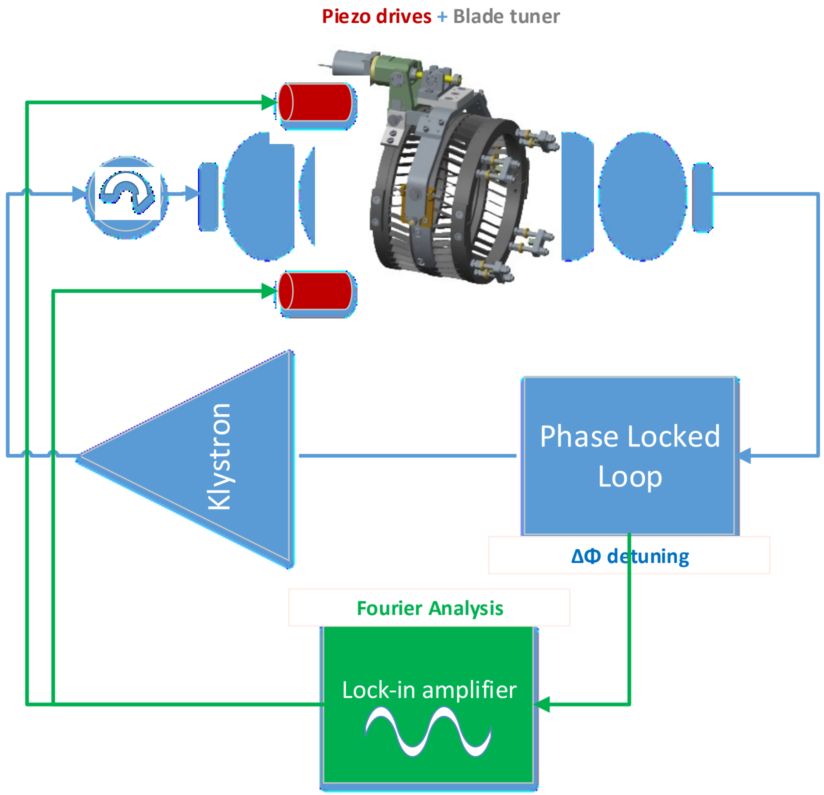


How do we generally control this?

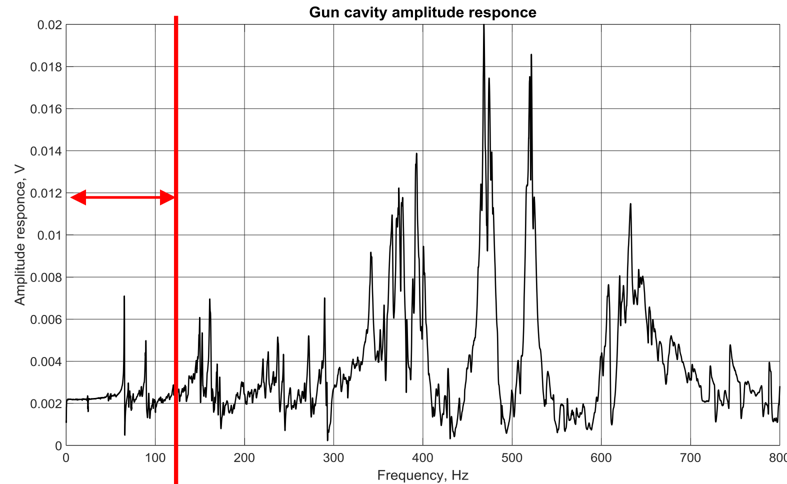


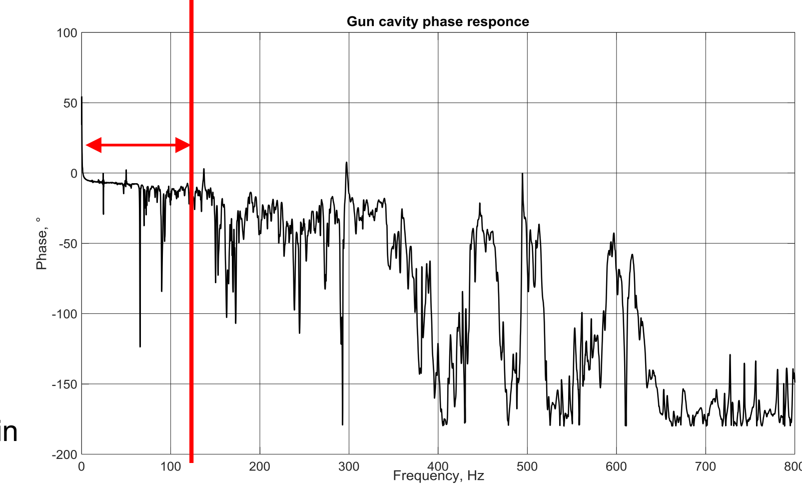
How do we describe the cavity behavior?

Mechanical properties of the cavity



Lorentz force and mechanical vibrations region of interest





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

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

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

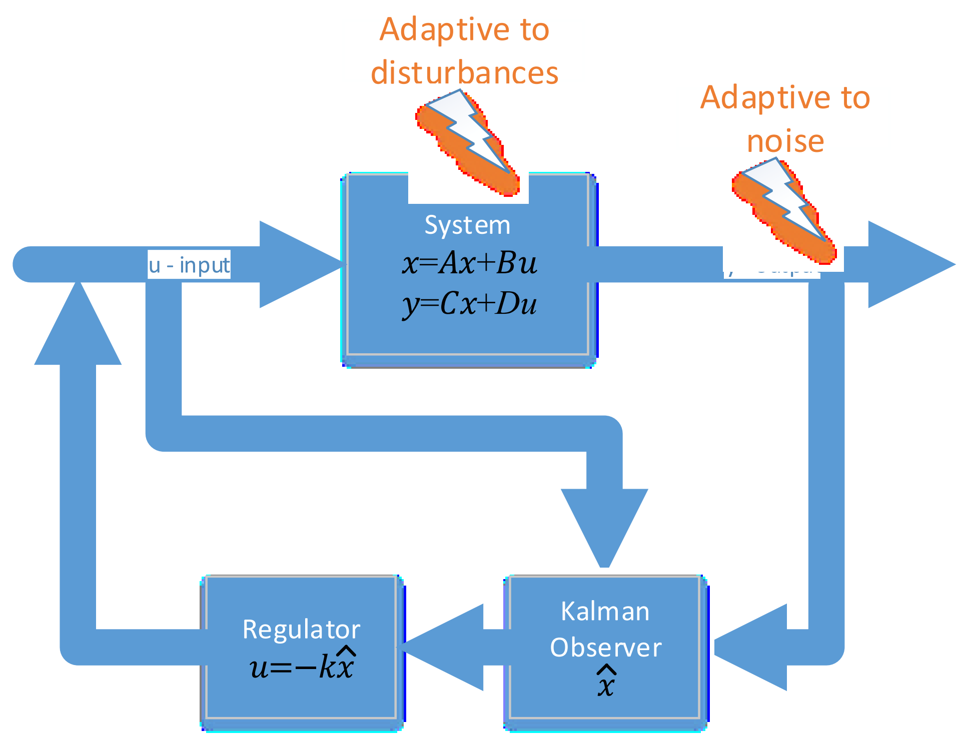
How control theory helps us to control cavity?

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!

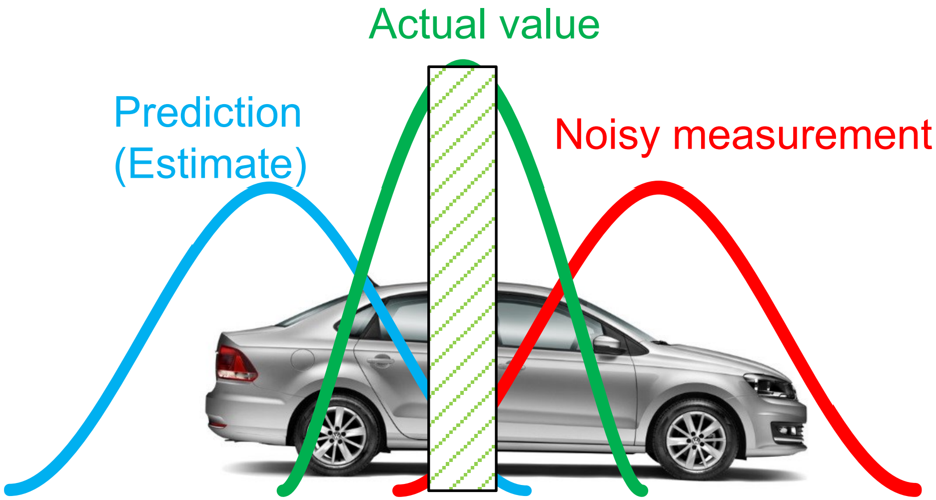
How does Kalman Observer work?

What is a Kalman filter? Definition

- Rudolf Emil Kálmán (1930 – 2016) - Hungarian-born American electrical engineer, mathematician and inventor
    - 1961-1972, the Apollo Project. First trajectory estimator using Kalman Filter

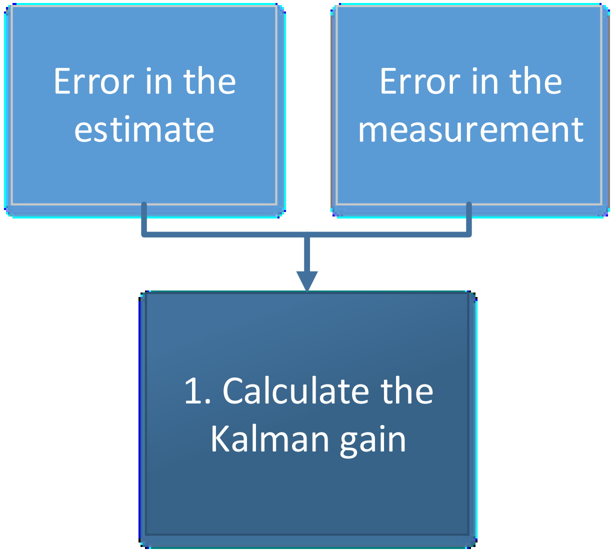
R. E. Kalman, "A new approach to linear filtering and prediction problems", *Transactions of the ASME–Journal of Basic Engineering*, 82

- Applications: NASA Space shuttles, Navy submarines, unmanned aerospace vehicles



The Kalman gain: a closer look

- Kalman Gain = K
- Error in the Measurement = E_{MEA}
- Error in the Estimate = E_{EST}



- $K = \frac{E_{EST}}{E_{EST}+E_{MEA}}$
- $0 < K \leq 1$

- Current Estimate = EST_t
- Previous Estimate = EST_{t-1}
- Measurement = MEA
- $EST_t = EST_{t-1} + K(MEA - EST_{t-1})$

Measurements	KG	Estimates
Measurements are accurate	**1**	Estimates are unstable
	0.9	
	0.8	
	0.7	
	0.6	
	0.5	
	0.4	
	0.3	
	0.2	
	0.1	
Measurements are inaccurate	**0**	Estimates are stable (small error)

- If $K \rightarrow 0$, $EST_t = EST_{t-1}$
- If $K \rightarrow 1$, $EST_t = K \cdot MEA$

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}

- X – State matrix $(X_t, \dot{X}_{t-1})$
- P – Process covariance matrix (error in the estimate)
- K – Kalman Gain
- R – Sensor noise covariance matrix (measurement error)
- Y – measurement of the state
- A, B, C – adaptation matrixes

State-space model for several modes

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Forced harmonic oscillations for the case of Lorentz force

$$\Delta\ddot{\omega}(t) + 2\varepsilon\omega\Delta\dot{\omega}(t) + \omega^2\Delta\omega(t) = \pm k2\pi\omega^2 E_{ACC}^2$$

Transition to the state-space representation

$$\Delta\ddot{\omega}(t) = -2\varepsilon\omega\Delta\dot{\omega}(t) - \omega^2\Delta\omega(t) \pm k2\pi\omega^2 E_{ACC}^2$$

Matrix state-space representation

$$\begin{pmatrix}\Delta\ddot{\omega}(t)\\ \Delta\dot{\omega}(t)\end{pmatrix} = \begin{pmatrix}-2\varepsilon\omega & -\omega^2\\ 1 & 0\end{pmatrix} \cdot \begin{pmatrix}\Delta\dot{\omega}(t)\\ \Delta\omega(t)\end{pmatrix} + \begin{pmatrix}\pm k2\pi\omega^2\\ 0\end{pmatrix} \cdot E_{ACC}^2$$

Discrete form of the state-space model

$$\begin{pmatrix}\Delta\dot{\omega}(t)\\ \Delta\omega(t)\end{pmatrix} = \begin{pmatrix}-2\varepsilon\omega\Delta t & -\omega^2\Delta t\\ \Delta t & 1\end{pmatrix} \cdot \begin{pmatrix}\Delta\dot{\omega}\\ \Delta\omega\end{pmatrix} + \begin{pmatrix}\pm k2\pi\omega^2\\ 0\end{pmatrix} \cdot E_{ACC}^2$$

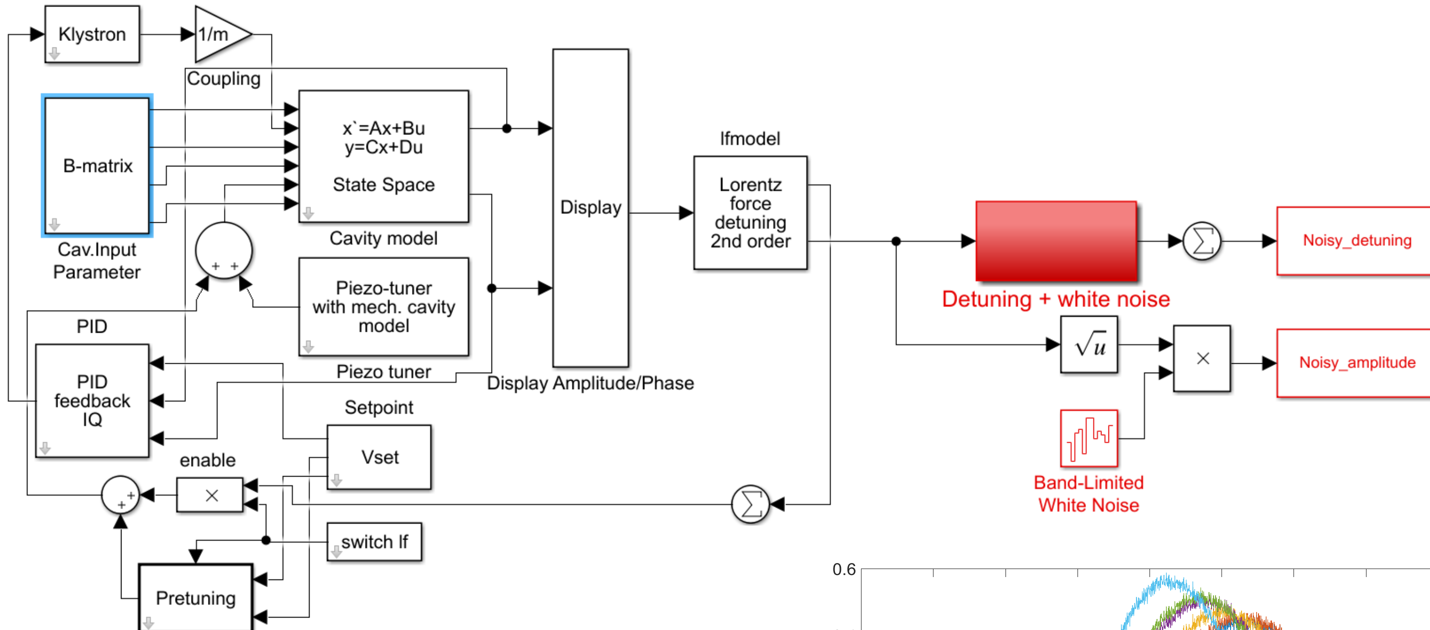
$$\Delta\ddot{\omega} = \frac{\Delta\dot{\omega}_t - \Delta\dot{\omega}_{t-1}}{\Delta t};\ \Delta\dot{\omega} = \frac{\Delta\omega_t - \Delta\omega_{t-1}}{\Delta t}$$

$$\sum \Delta\omega = \begin{pmatrix}0 & 1\end{pmatrix} \cdot \begin{pmatrix}\Delta\dot{\omega}\\ \Delta\omega\end{pmatrix}$$

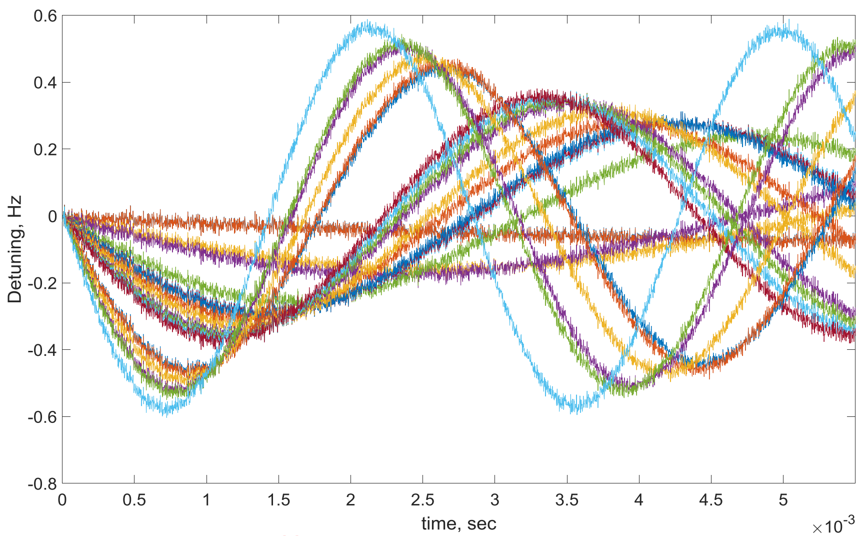
Example of 2 mechanical modes

$$\sum \Delta\omega = \begin{pmatrix}0 & 0{,}5 & 0 & 0{,}5\end{pmatrix} \cdot \begin{pmatrix}\Delta\dot{\omega}_1\\ \Delta\omega_1\\ \Delta\dot{\omega}_2\\ \Delta\omega_2\end{pmatrix}$$

Cavity behavior model as the KF input



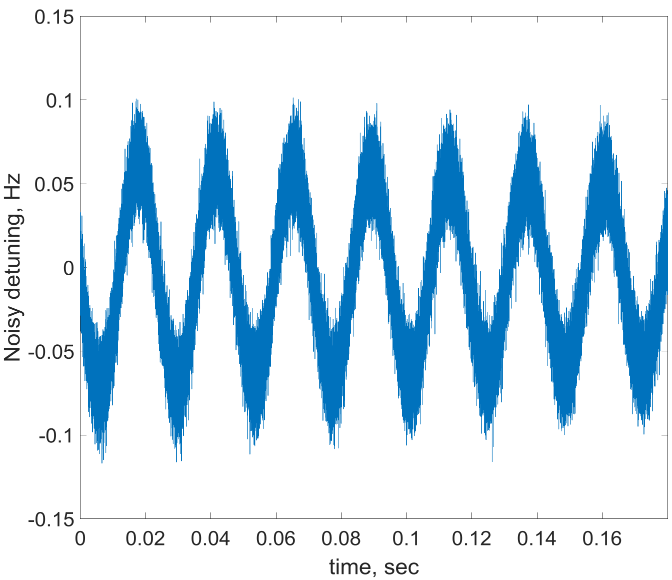
- 2nd order Lorentz Force detuning block describes up to 20 modes
- Individual noisy detuning of each mode generated
- Cavity field amplitude is generated

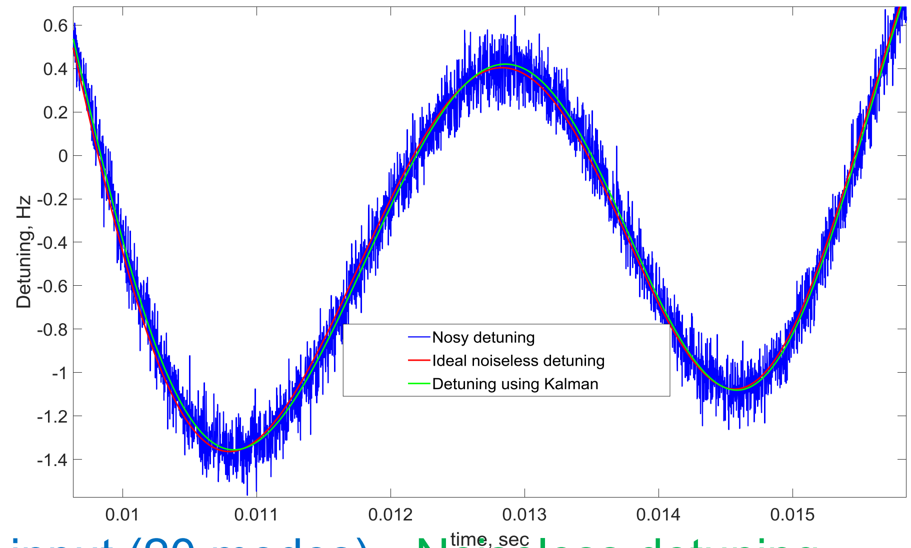


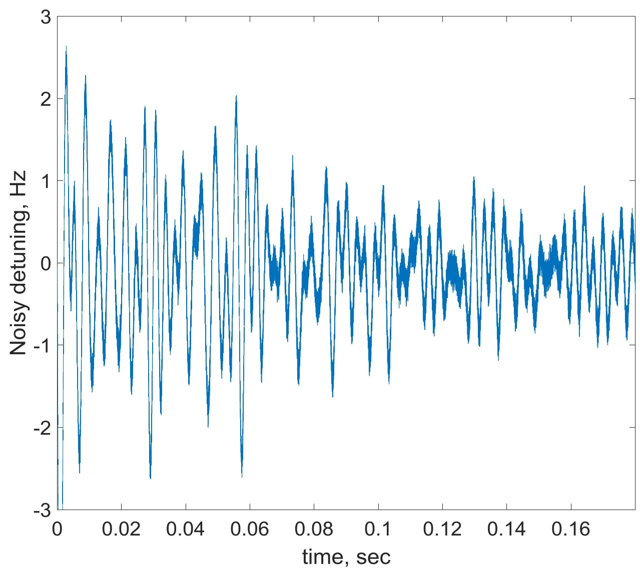
Lets test Kalman filter response under different input noises!

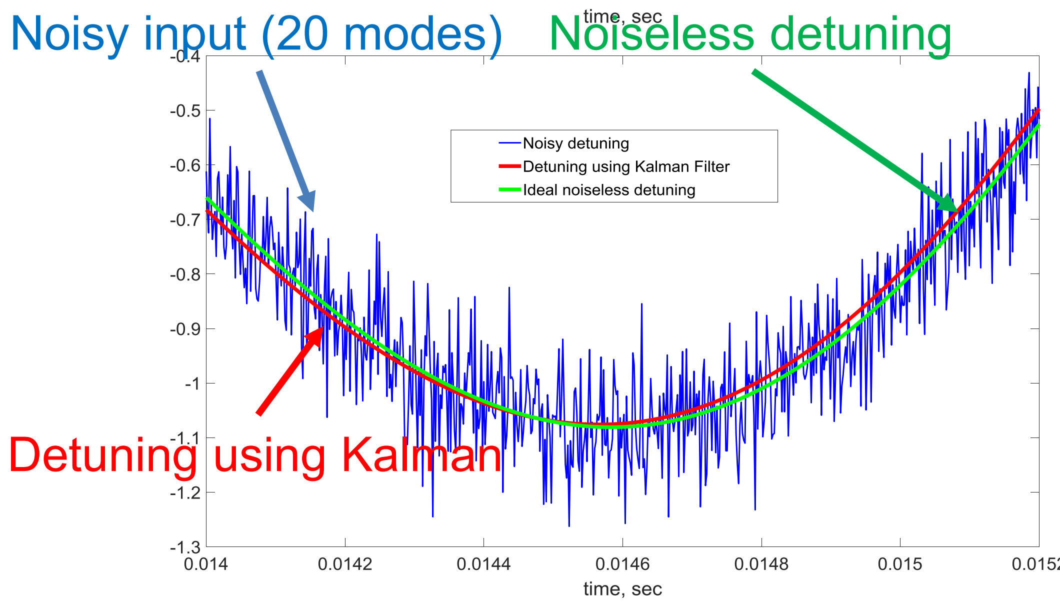
KF response to 20 noisy eigenmodes

20 eigenmodes are detuned





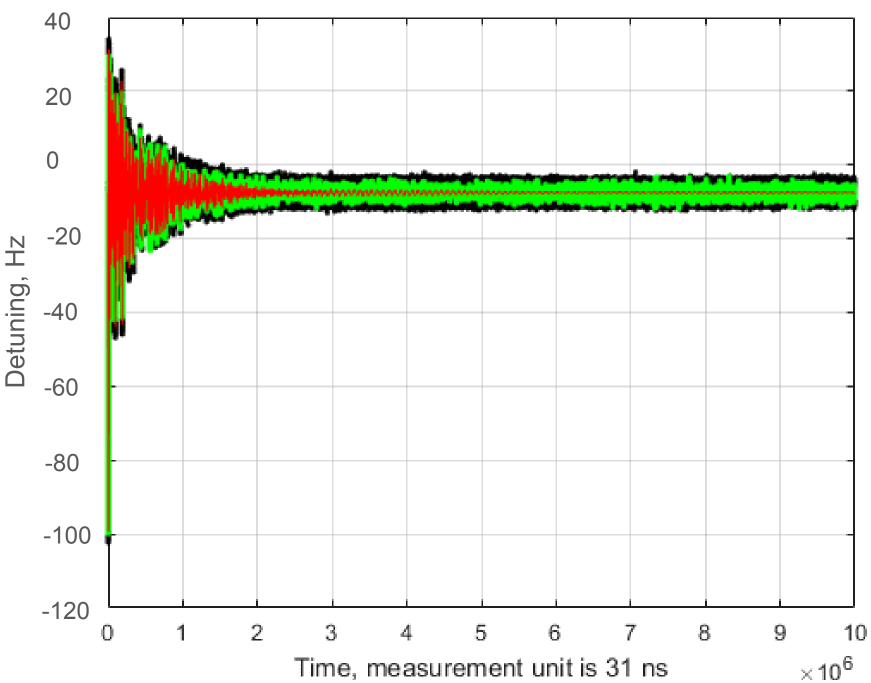




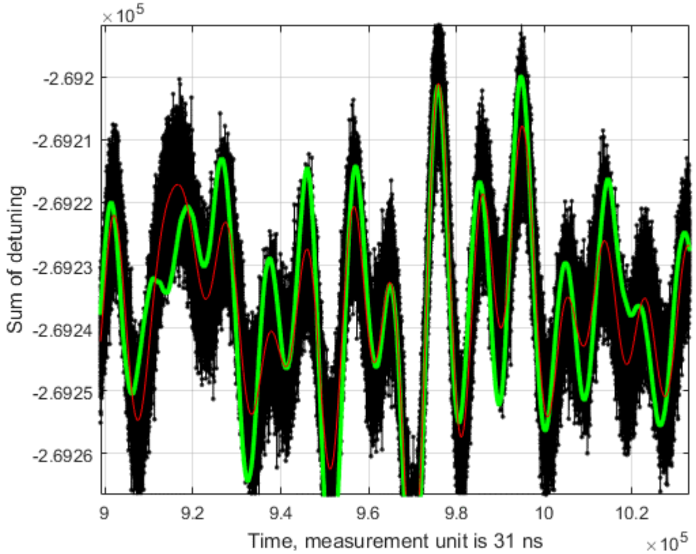
KF reaction to 2 sources of uncertainty: cavity field and detuning

Both: Detuning and field amplitudes are extremely noisy!

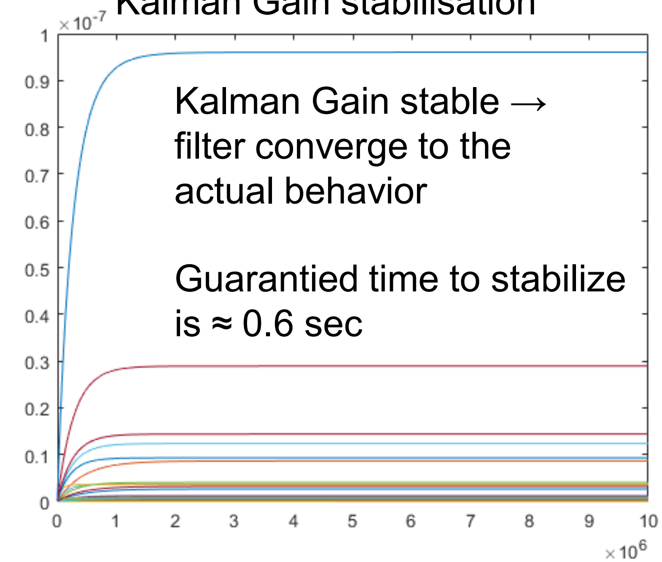
Input: noisy detuning and amplitude
SNR=20,1dB



Kalman filter reaction to the input noise



Kalman Gain stabilisation



Kalman Gain stable → filter converge to the actual behavior

Guarantied time to stabilize is ≈ 0.6 sec

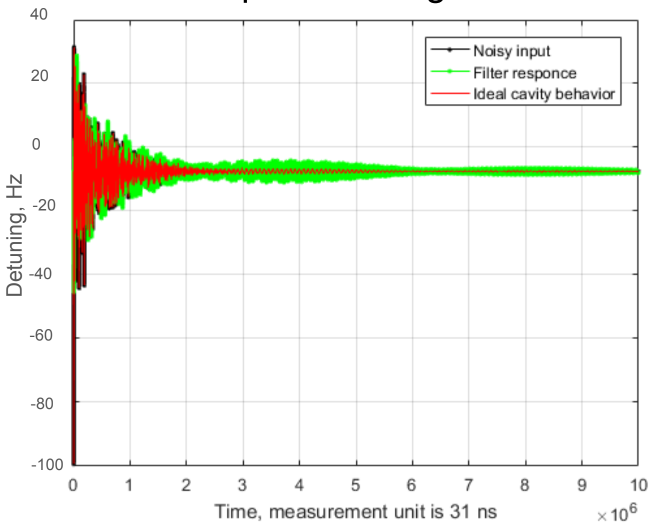
Result:

- Peak 100mHz difference → 0,4°
- Guaranteed time for Kalman Filter to become stable is 0,6sec

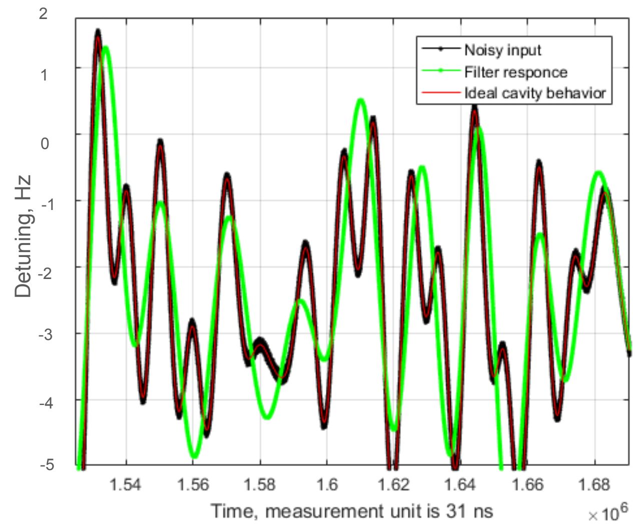
KF reaction to not fully described system state

System not fully described!

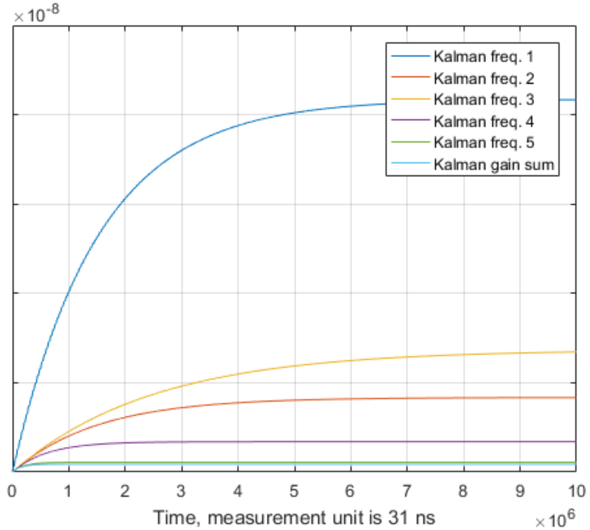
Input detuning



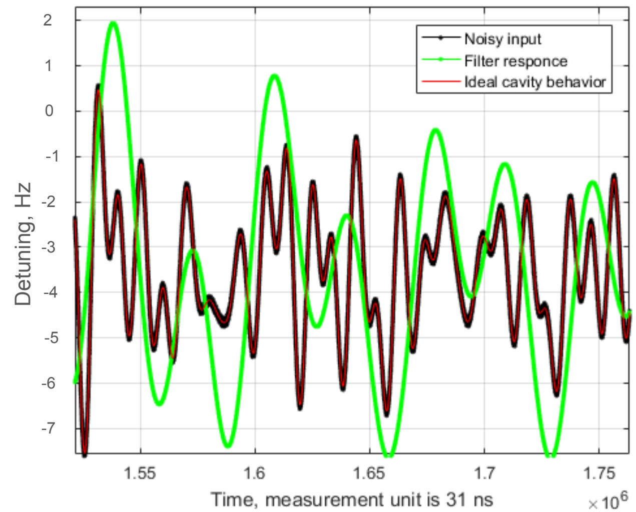
15 eigenmodes contribute to KF



Kalman gain stabilization



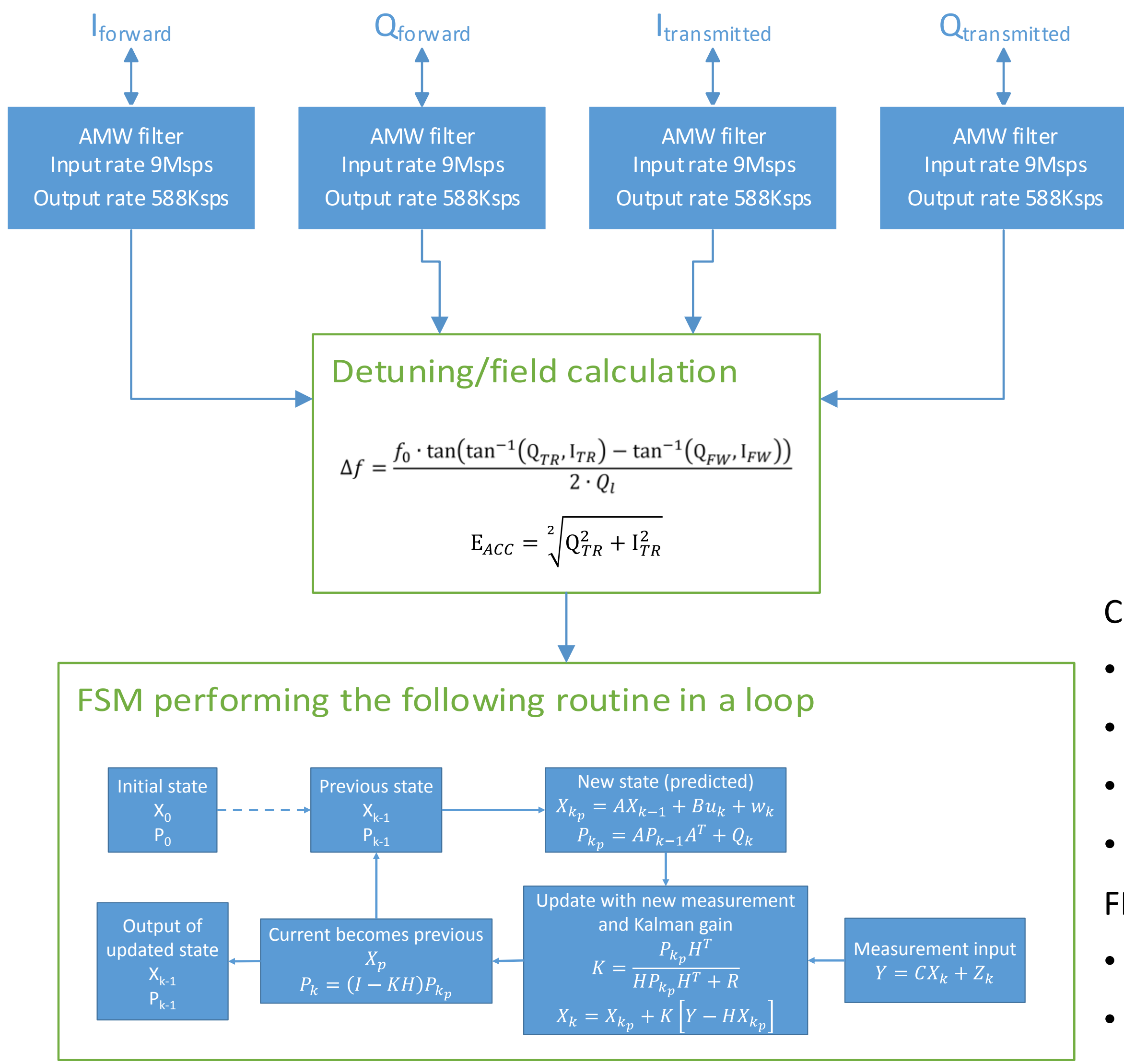
5 eigenmodes contribute to KF



Result:

- Kalman filter is able to work if the system is not fully described
- Introduction of new modes is possible and will be mitigated
- The good system identification is required

Complexity of mTCA development




СОЮЗ СОВЕТСКИХ СОЦИАЛИСТИЧЕСКИХ РЕСПУБЛИК

ГОСУДАРСТВЕННЫЙ КОМИТЕТ СССР
ПО ДЕЛАМ ИЗОБРЕТЕНИЙ И ОТКРЫТИЙ

АВТОРСКОЕ СВИДЕТЕЛЬСТВО

№ 1462297

На основании полномочий, предоставленных Правительством СССР, Государственный комитет СССР по делам изобретений и открытий выдал настоящее авторское свидетельство на изобретение:
"Матричное устройство для деления"

Автор (авторы): Водощенко Сергей Алексеевич

Заявитель:

Заявка № 4294151 Приоритет изобретения 5 августа 1987г.

Зарегистрировано в Государственном реестре изобретений СССР
1 ноября 1988г.

Действие авторского свидетельства распространяется на всю территорию Союза ССР.

Председатель Комитета

Начальник отдела

Complexities and developments:

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

FPGA firmware characteristics:

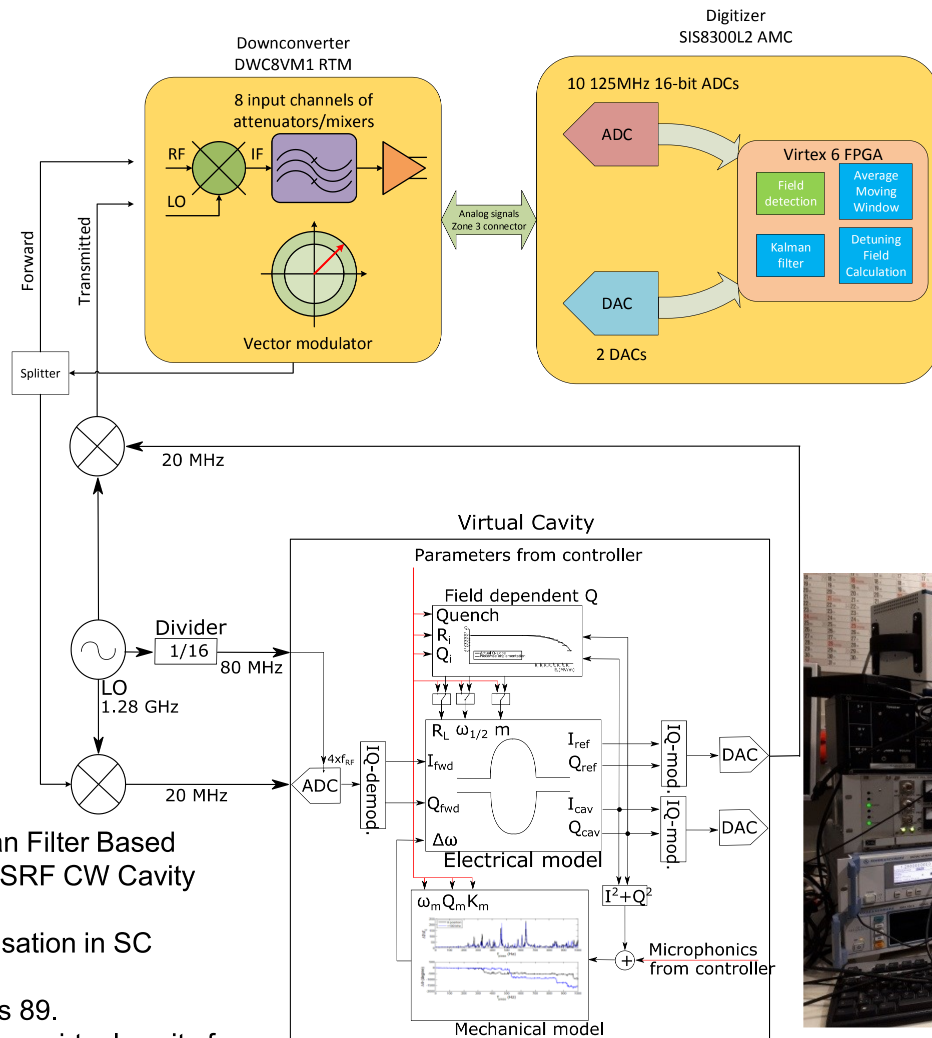
- Maximum processing rate 500Msps
- Able to process up to 1000 eigenmodes
- Actual piezo drive frequency is limited by 300Hz at 6uF and 140Vpp

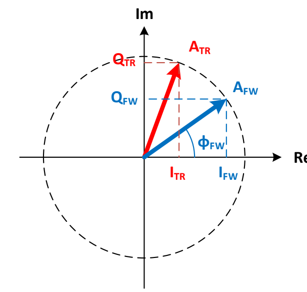
Testing hardware: cavity simulator + mTCA KF

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

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

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

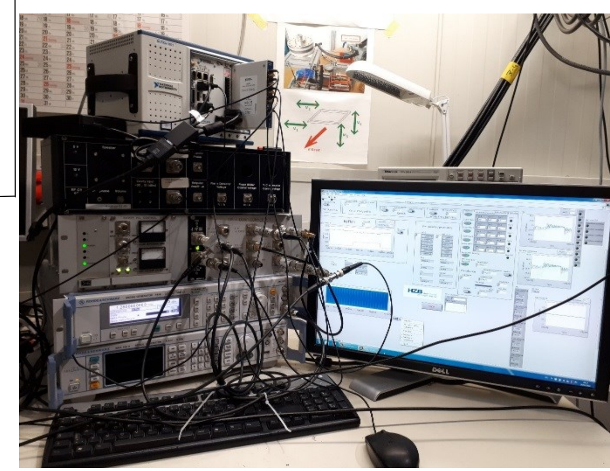




$$y(t) = Icos\omega t + Qcos\omega t$$

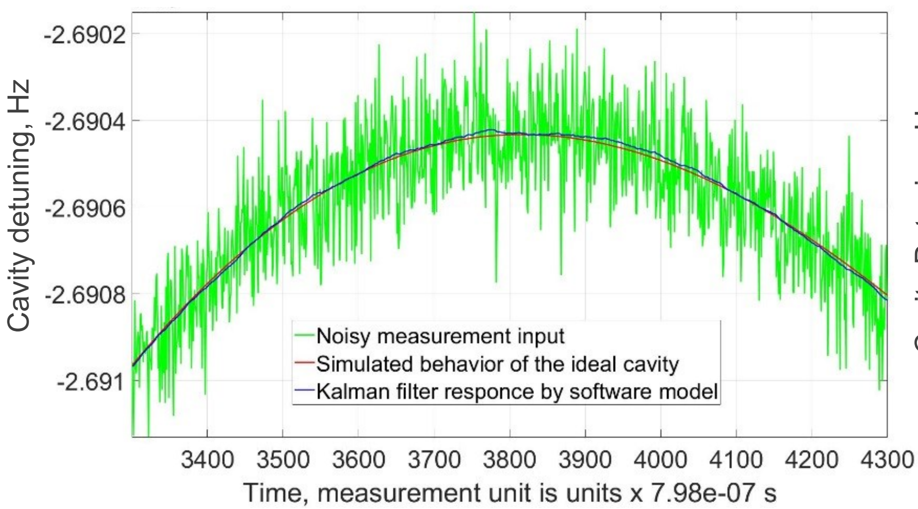
$$\varphi_0 = \text{atan}(\frac{Q}{I})$$

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



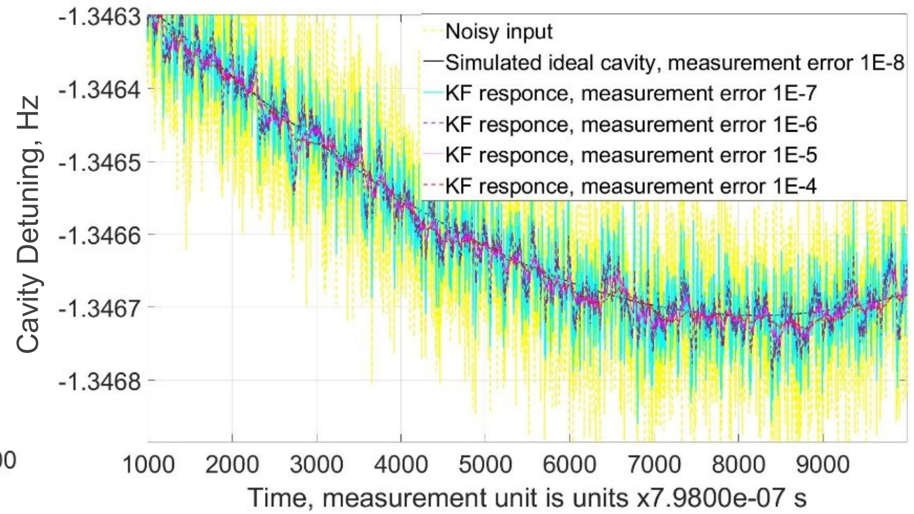
- IPAC 2018. “Developing Kalman Filter Based Detuning Control with a Digital SRF CW Cavity Simulator”
- IPAC 2017. “Detuning Compensation in SC Cavities Using Kalman Filters”
- Review of Scientific Instruments 89. “Superconducting radio-frequency virtual cavity for control algorithms debugging”

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

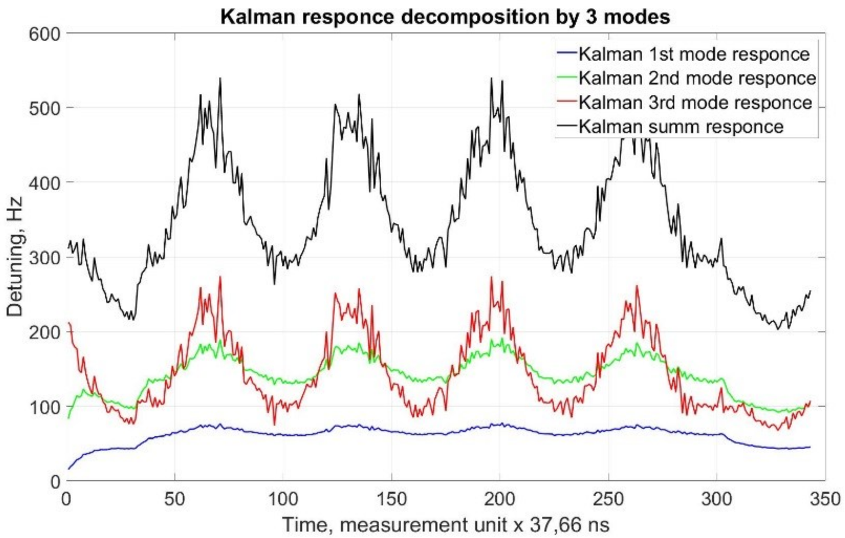
The initial error settings have influence on the proximity of the “real” produced curve to the “ideal”

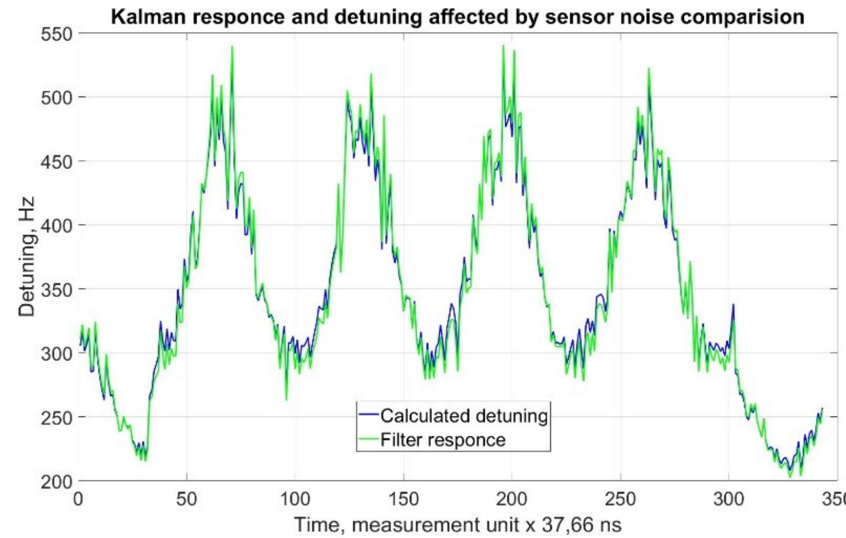


- Filter allows to find a sweet spot for the appropriate observation error

KF response real-time examination

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

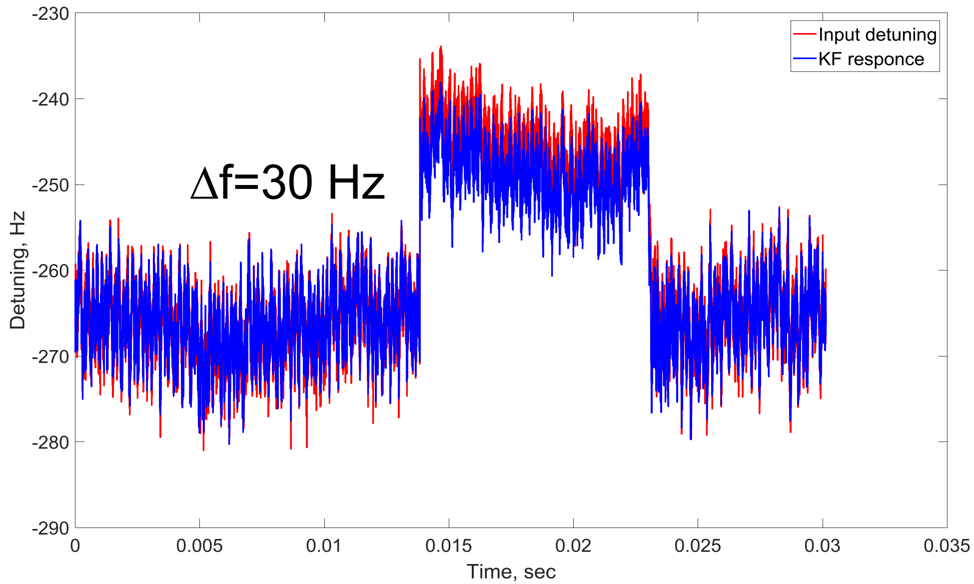




Mechanical modes contribution:
330 Hz – 20%; 460 Hz – 40%, 470 Hz – 40%

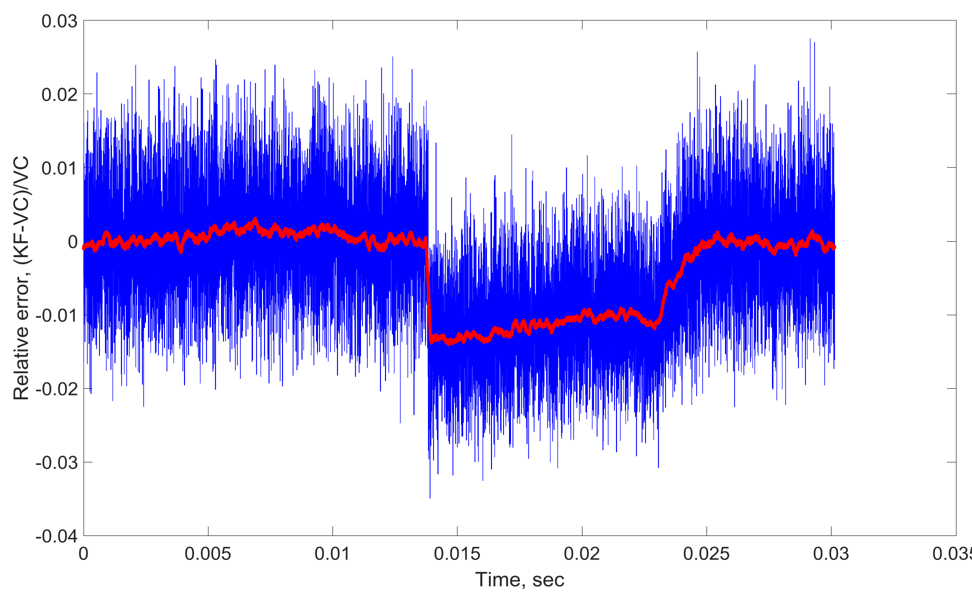
Kalman filter response consist of 3 modes.
The tracking precision is within 0,1 %

Kalman filter response to the rapid beam change

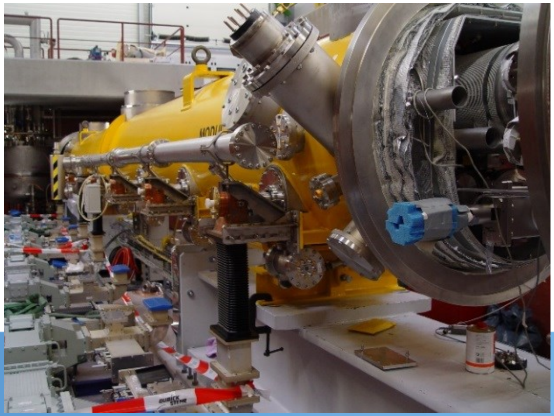


e.g. 1mbar pressure change in LHe system or non-synchronized Beam injection into BESSY II

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



Future works:



1. Kalman filter test in CMTB facility DESY. Planned for December 2018 (thanks to Dr. Mathieu Omet and Dr. Julien Branlard)
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

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Thank you for your attention!