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Virtual SRF Cavity: testing SRF cavity without the hassle of liquid Helium and Klystrons

Pablo Echevarria, on behalf of LLRF team

Superconducting radio-frequency virtual cavity for control algorithms debugging

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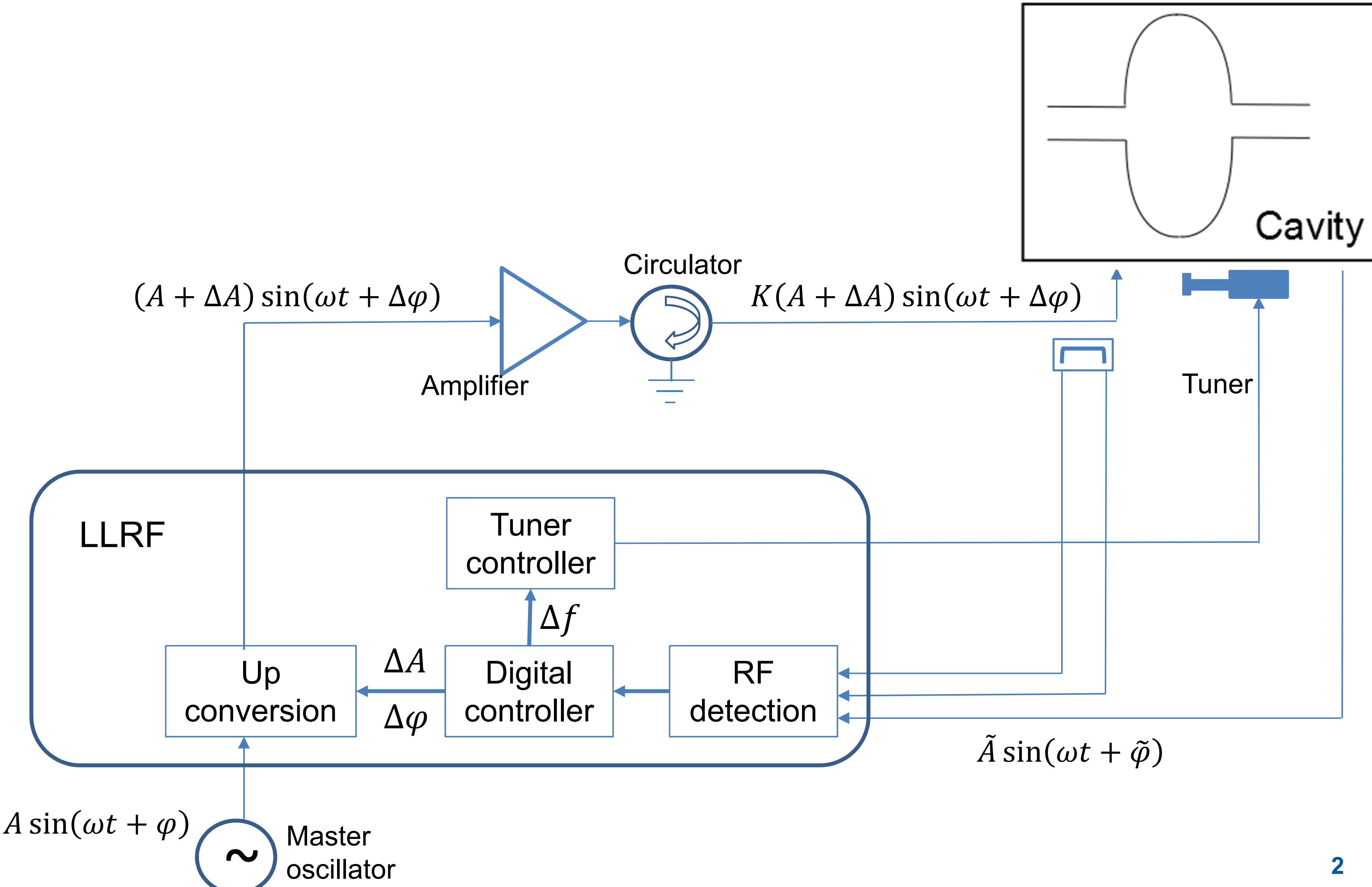
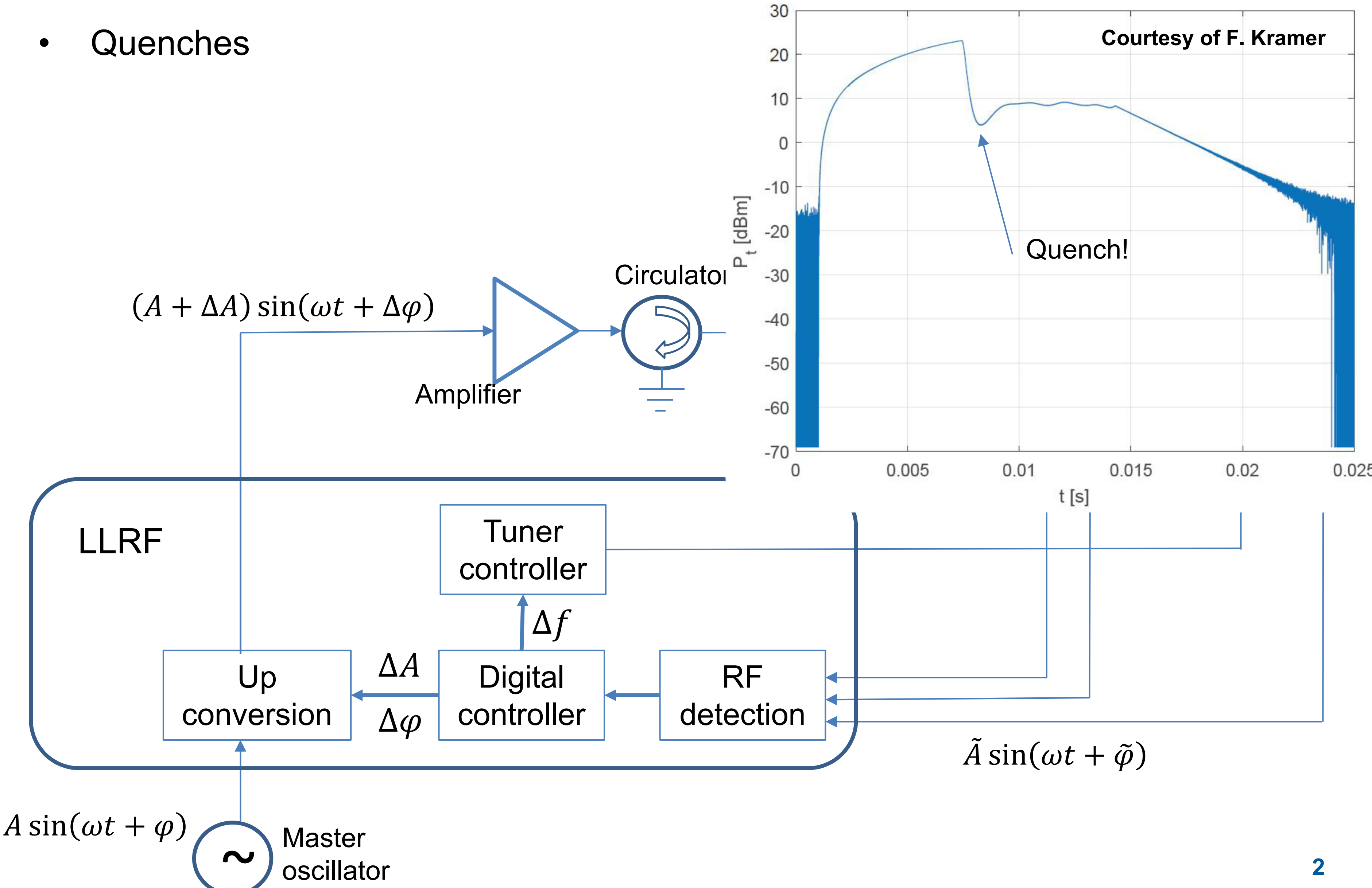
SRF Conference
3rd July 2019

Motivation



Cavity
Circulator
$(A+\Delta A)\sin(\omega t+\Delta\varphi)$
$K(A+\Delta A)\sin(\omega t+\Delta\varphi)$
Amplifier
Tuner
LLRF
Tuner controller
Δf
Up conversion
ΔA
$\Delta\varphi$
Digital controller
RF detection
$\tilde{A}\sin(\omega t+\tilde{\varphi})$
$A\sin(\omega t+\varphi)$
Master oscillator

- Quenches


Courtesy of F. Kramer
Quench!
P_t [dBm]
t [s]
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
0
0.005
0.01
0.015
0.02
0.025
$(A + \Delta A)\sin(\omega t + \Delta\varphi)$
Amplifier
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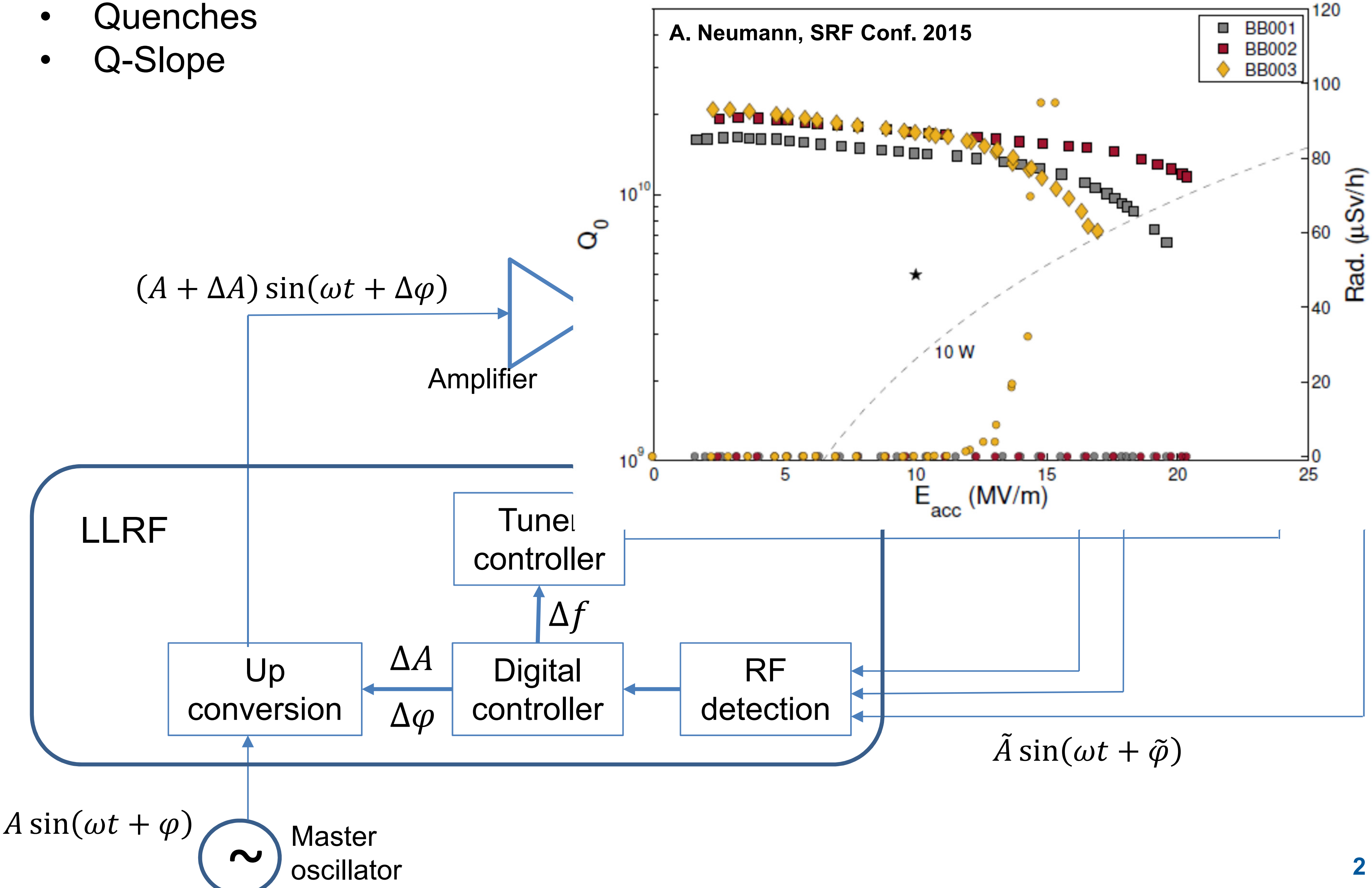
Master oscillator

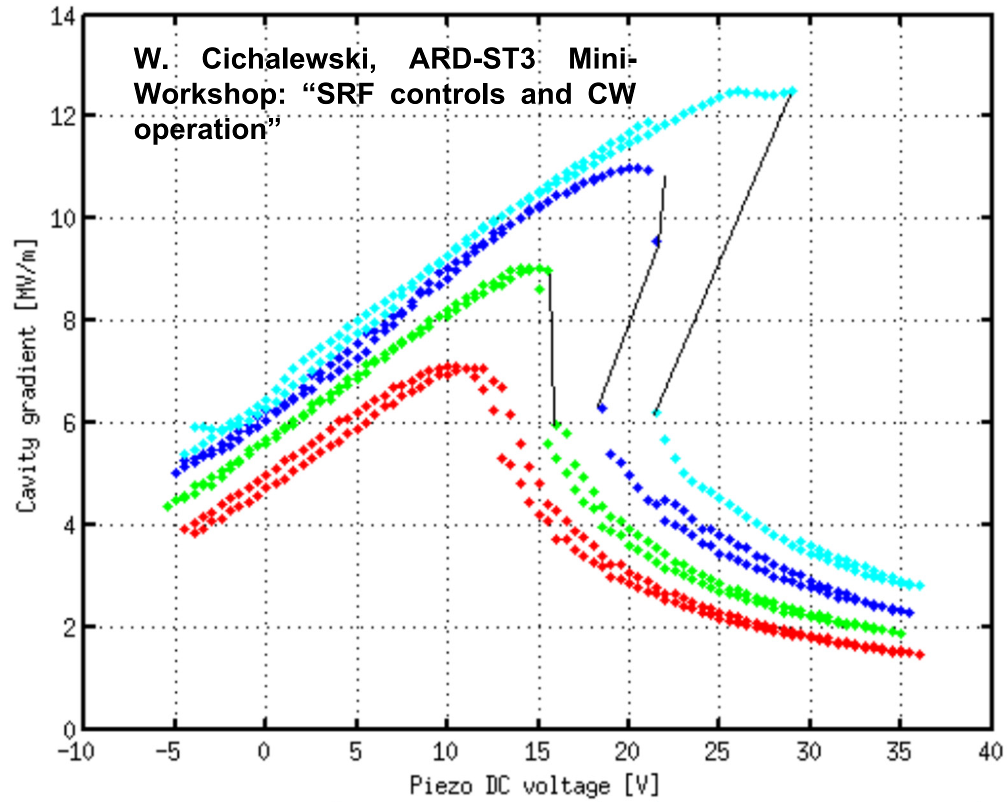
Motivation

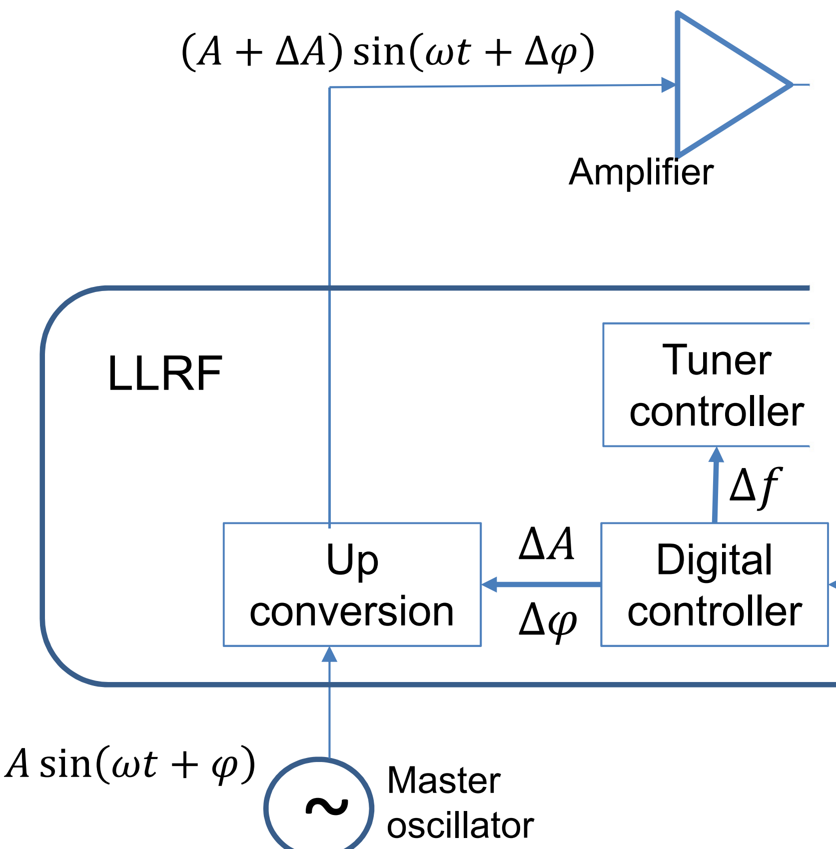
- Quenches
- Q-Slope



Motivation

- Quenches
- Q-Slope
- Lorentz force detuning

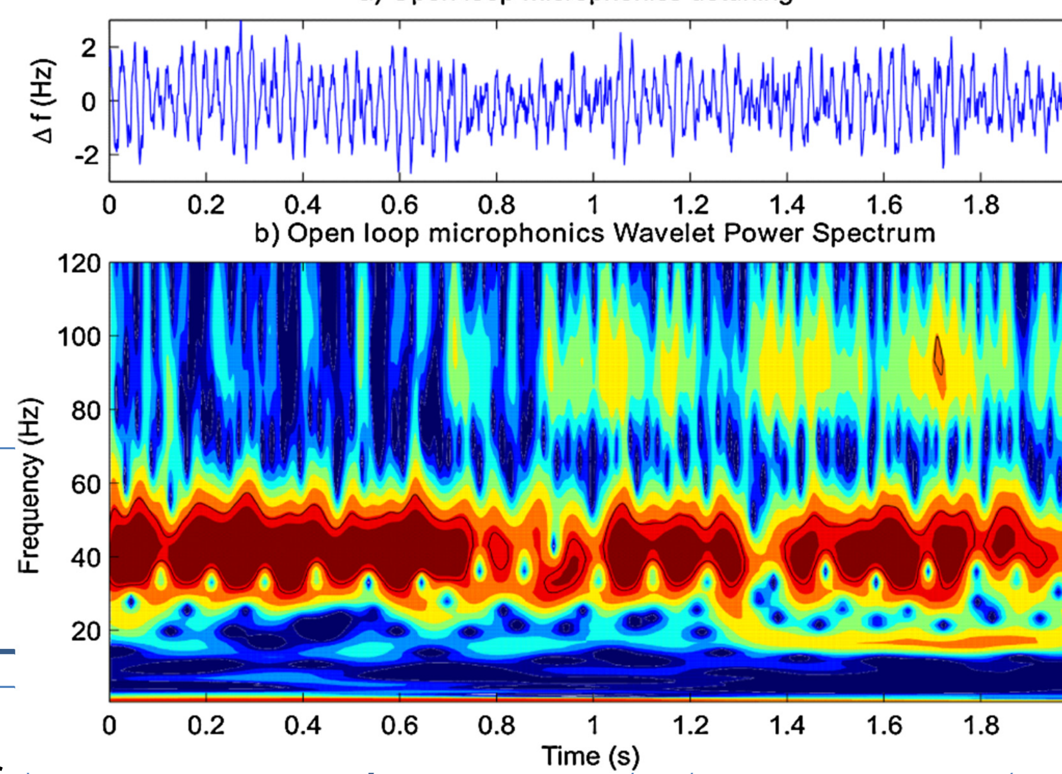


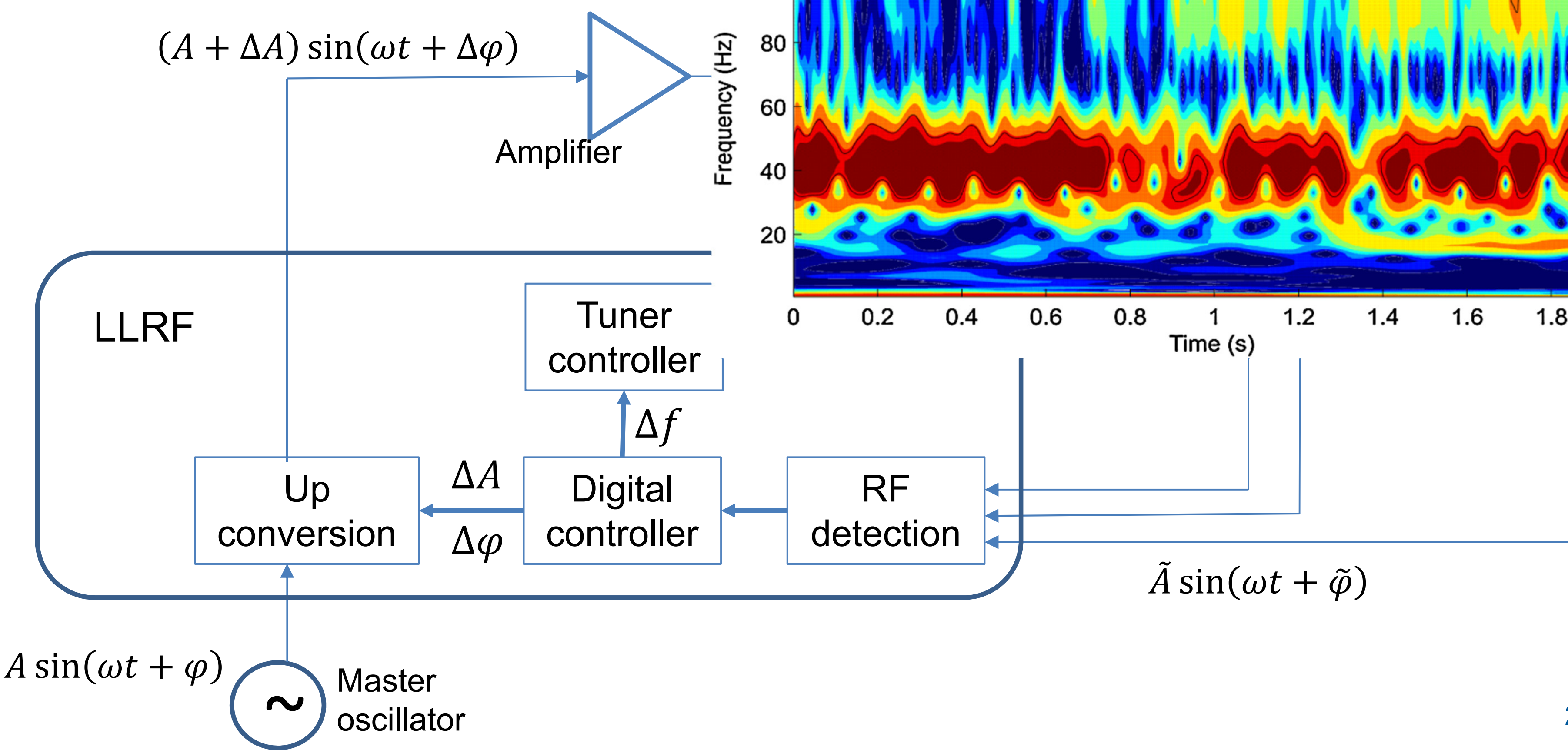


Motivation

- Quenches
- Q-Slope
- Lorentz force detuning
- Microphonics
- …

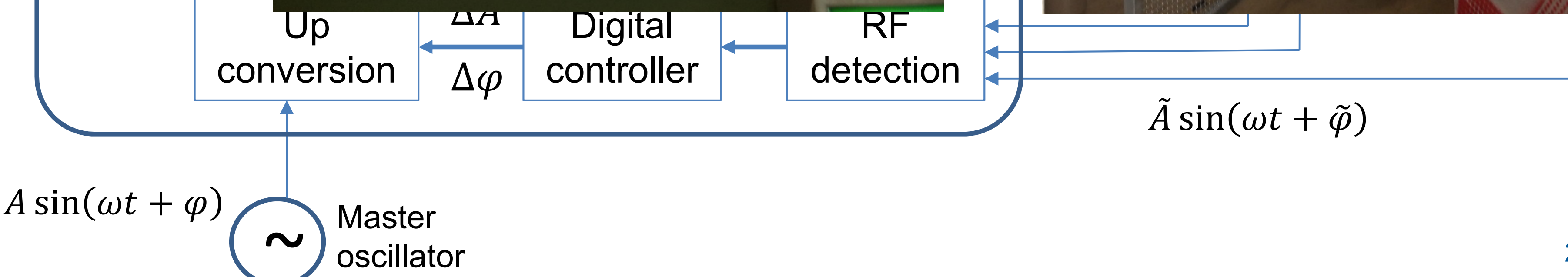
A. Neumann, Phys. Rev. Let. Acc. And Beams, 2010





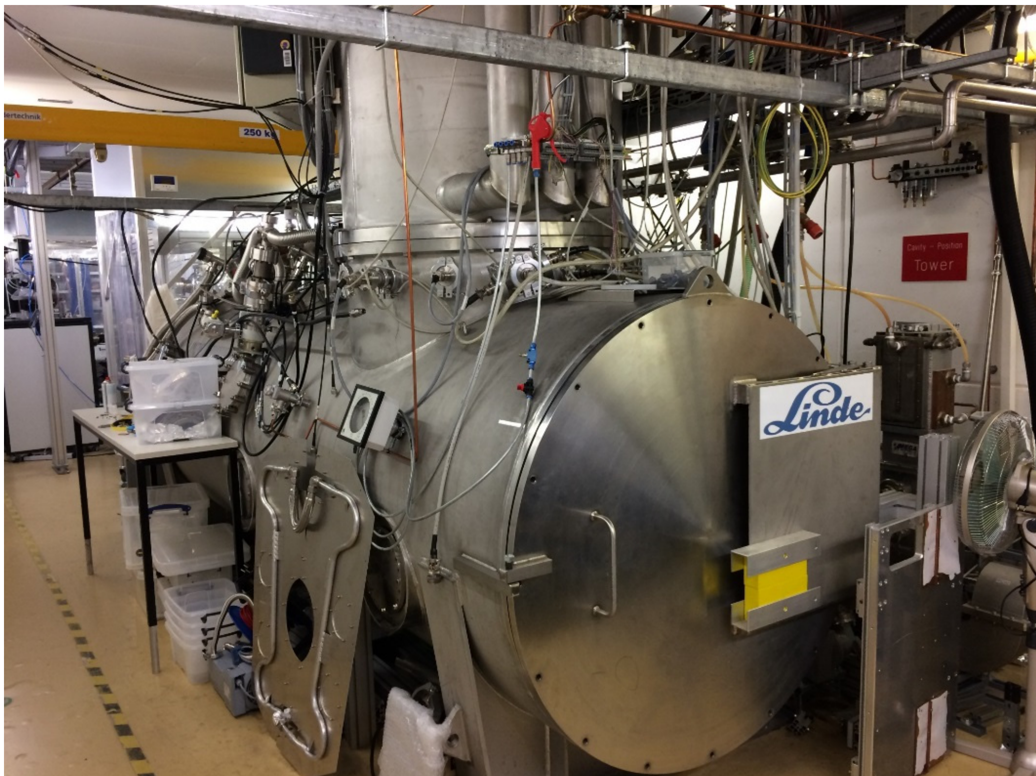
Motivation

- Radiation



Motivation

- Radiation
- Cryogenics



$A +$

on

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

$A\sin(\omega t + \varphi)$

Master oscillator

Motivation

- Radiation
- Cryogenics
- High power RF

Up conversion

ΔA

$\Delta\varphi$

Digital controller

RF detection

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

$A\sin(\omega t + \varphi)$

Master oscillator

Motivation

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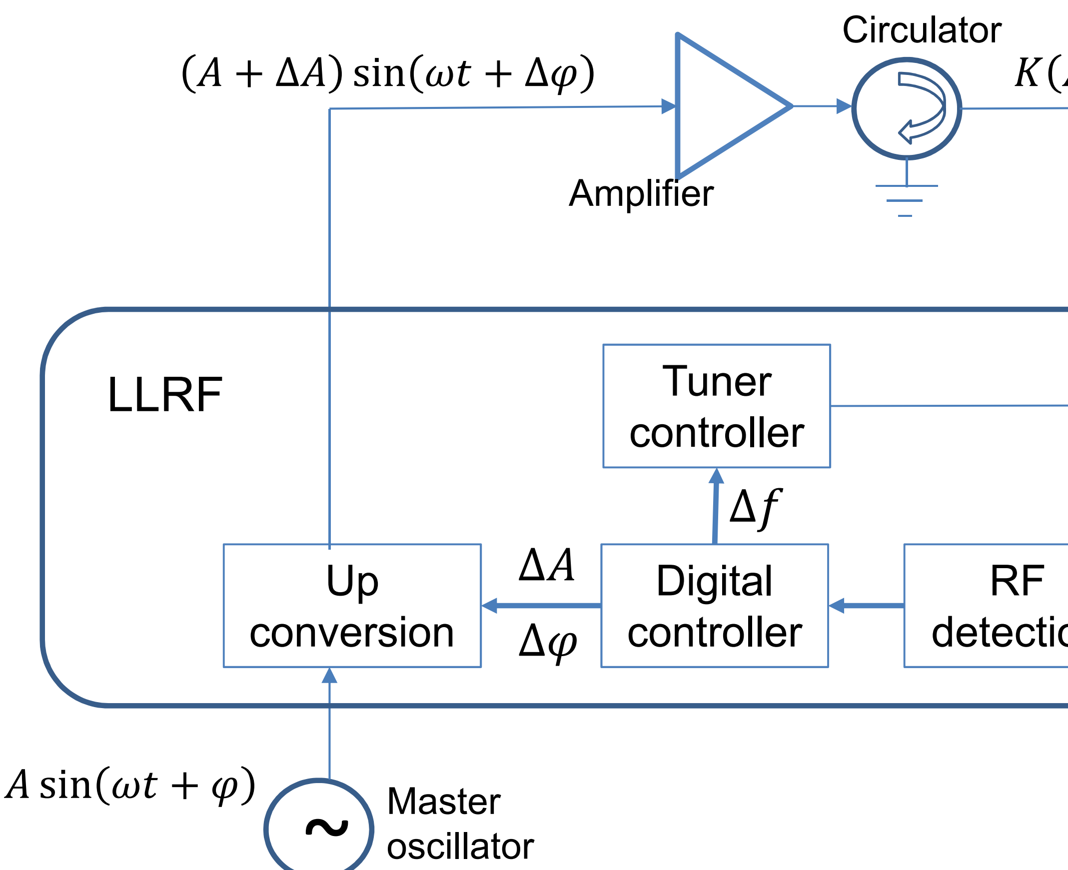
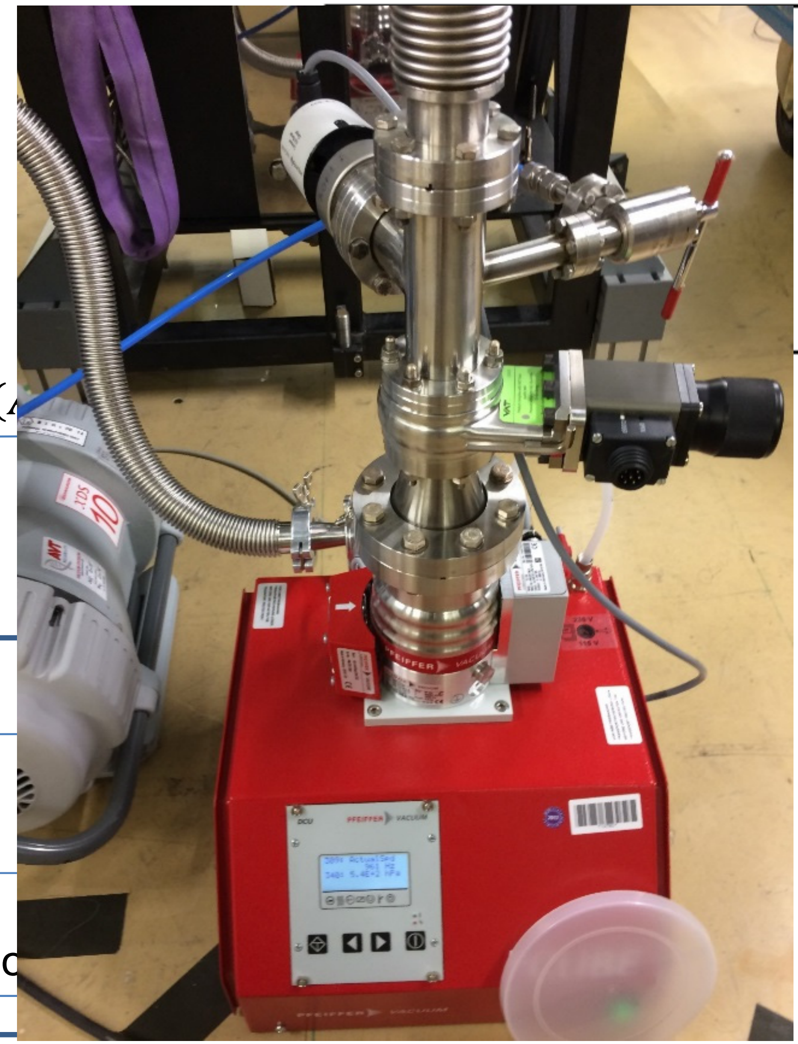
- Radiation
- Cryogenics
- High power RF
- UHV





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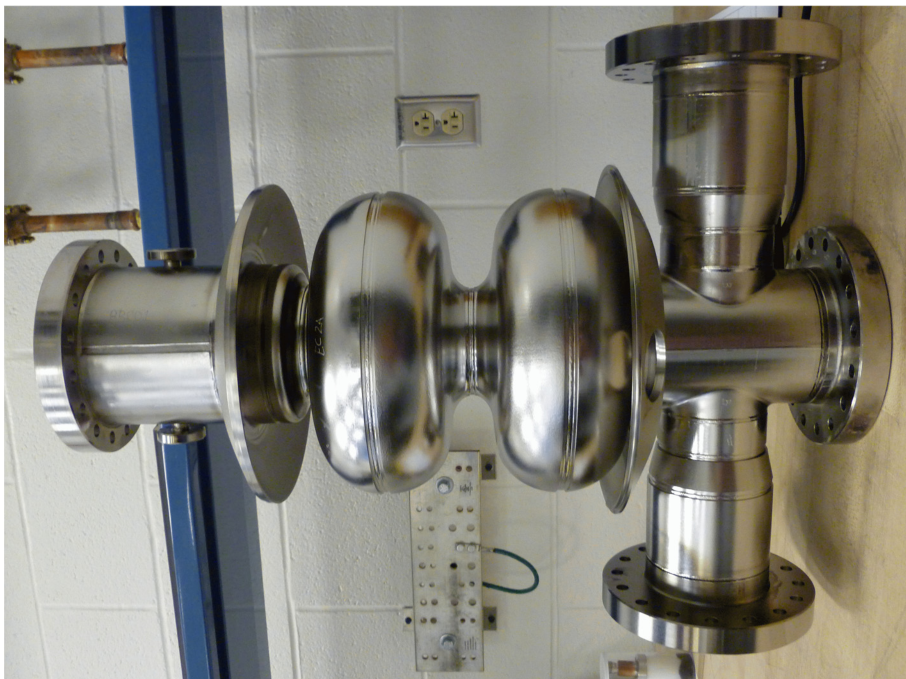
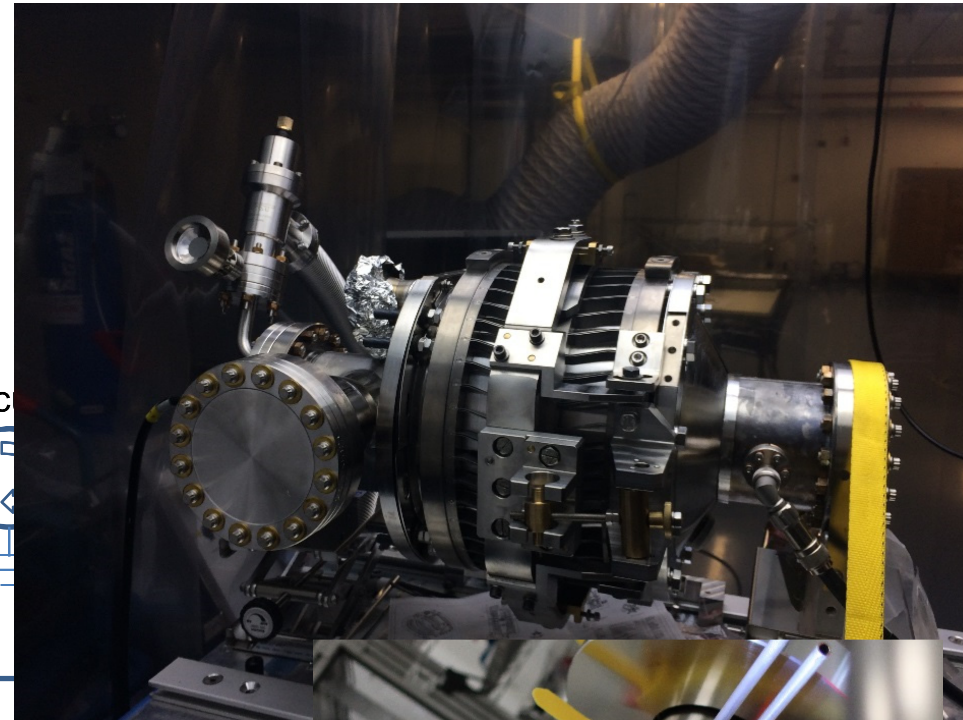
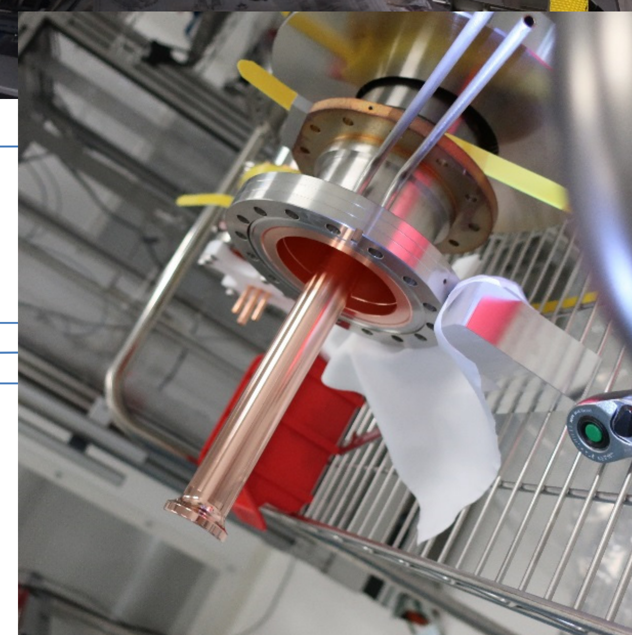
- Radiation
- Cryogenics
- High power RF
- UHV
- Cavities!





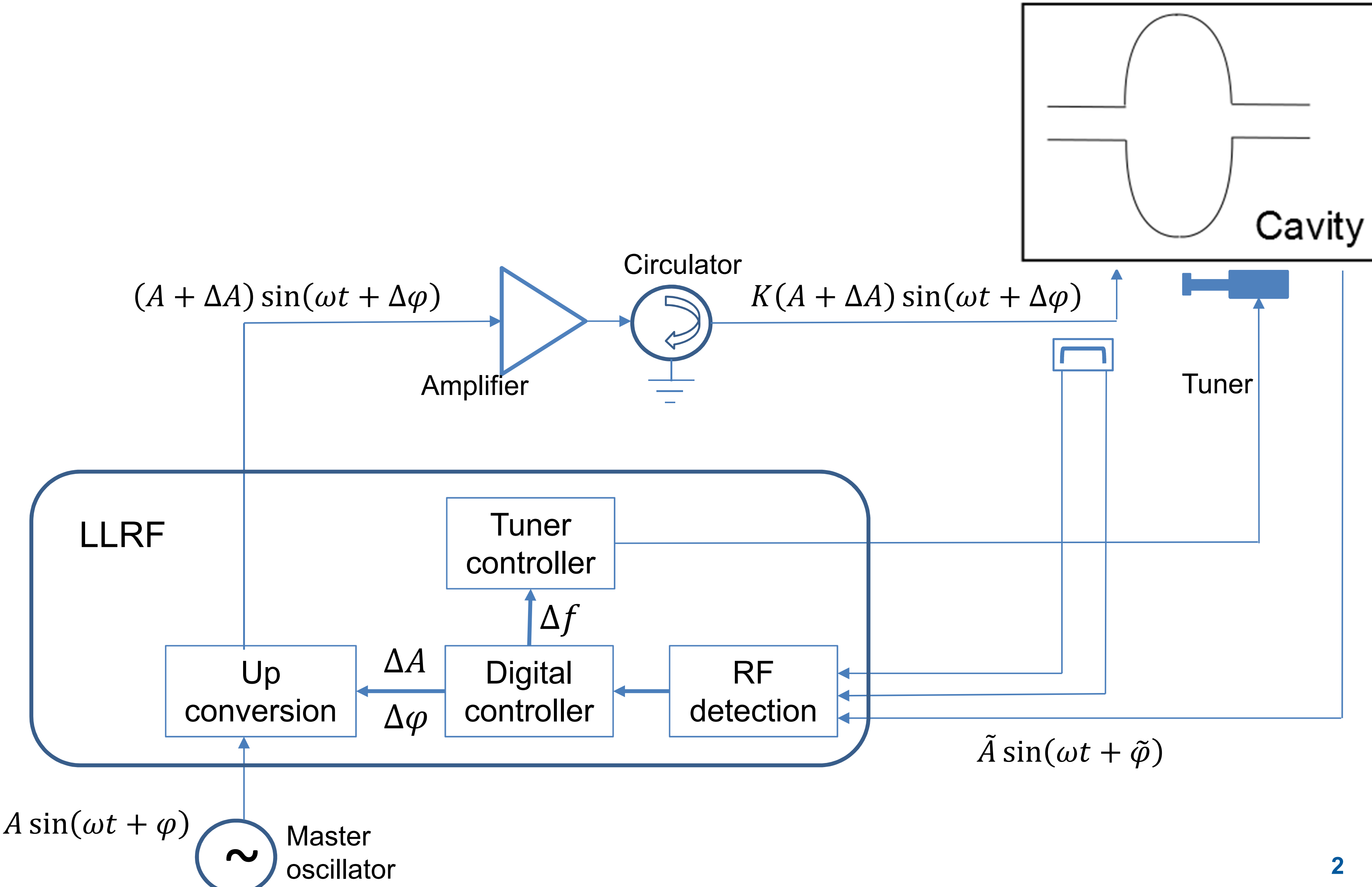


RF detection

$A \sin(\omega t + \varphi)$

Master oscillator

Motivation



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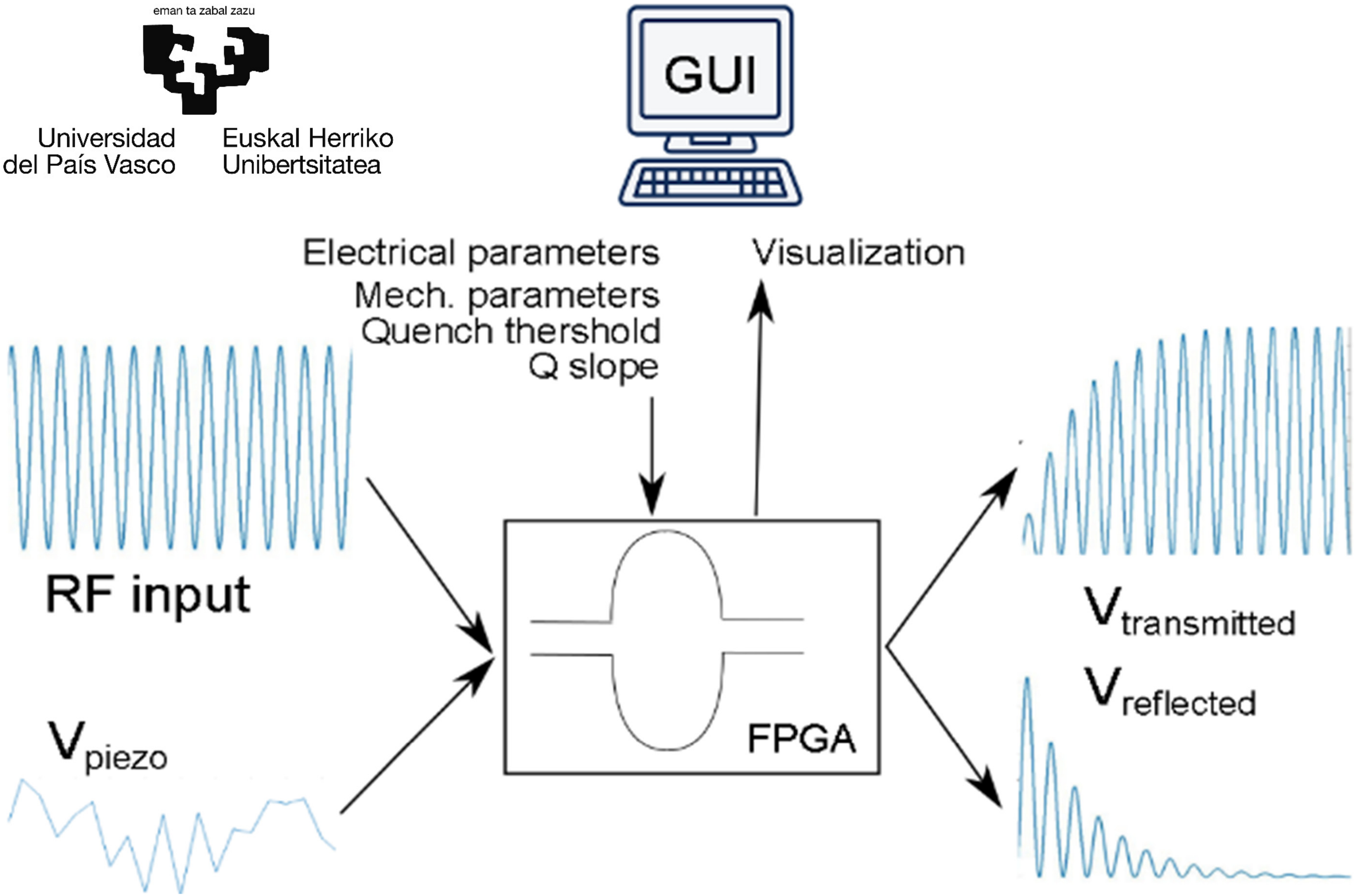
Master oscillator

Motivation

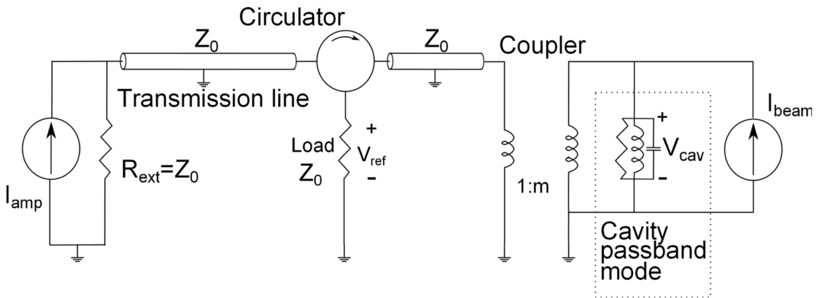


GUI
Electrical parameters
Mech. parameters
Quench thershold
Q slope
Visualization
RF input
V_{piezo}
FPGA
$V_{transmitted}$
$V_{reflected}$

Outline

- Electrical model for transmitted and reflected voltages
- Realistic SRF behaviour:
  - Quench
  - Field dependent Q
  - Mechanical modes: Lorentz force detuning and microphonics
  - Piezo tuner model
- Some applications.
  - Kalman filter debuging
  - Quench detection algorithms
  - Operator training on LLRF EPICS panels
- Conclusions and some possible upgrades

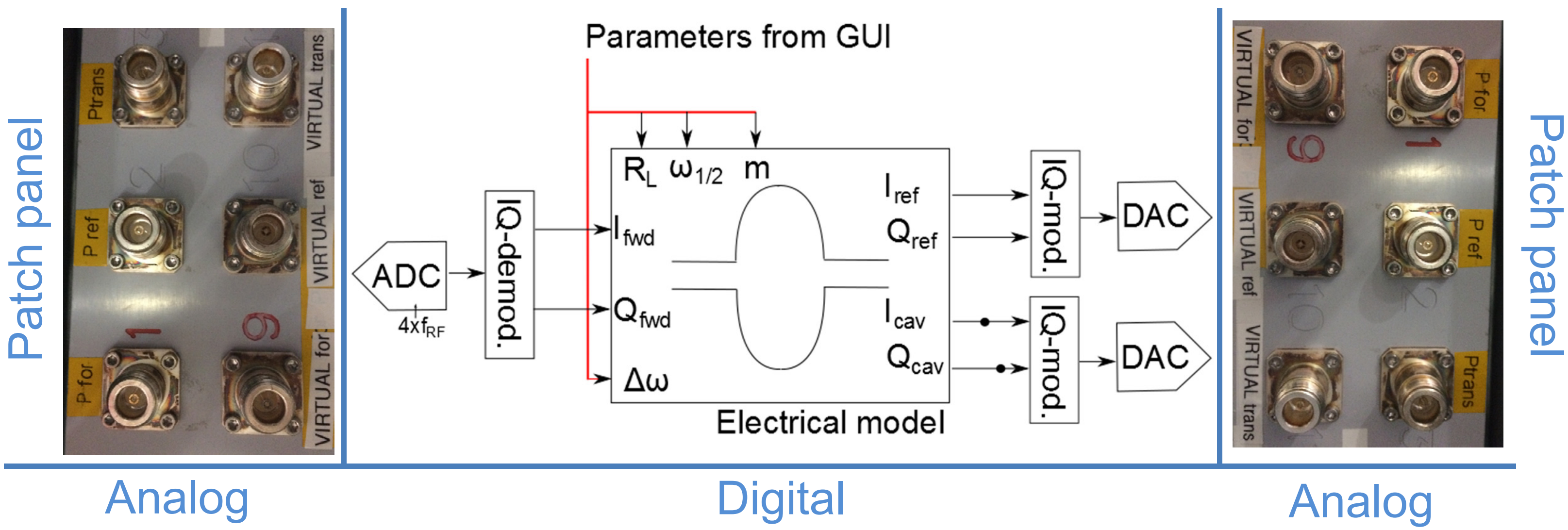
Electrical model



$$\frac{d}{dt}\begin{pmatrix} V_{cav}^I \\ V_{cav}^Q \end{pmatrix} = \begin{pmatrix} -\omega_{1/2} & -\Delta\omega \\ \Delta\omega & -\omega_{1/2} \end{pmatrix}\begin{pmatrix} V_{cav}^I \\ V_{cav}^Q \end{pmatrix} + \begin{pmatrix} R_L\omega_{1/2} & 0 \\ 0 & R_L\omega_{1/2} \end{pmatrix}\frac{1}{m}\begin{pmatrix} I_{amp}^I \\ I_{amp}^Q \end{pmatrix}$$

$$V_{ref} = \frac{V_{cav}}{m} - \frac{Z_0 I_{amp}}{2}$$

- All parameters are defined by: f_0, Δf, Q_0, Q_{ext} and r/Q
- $\begin{pmatrix} I_{amp}^I \\ I_{amp}^Q \end{pmatrix}$ obtained with IQ-demodulation of the ADC input
- V_{cav} and V_{ref} are IQ-modulated to generate the RF signal
- User can choose what signal to send to the DACs



Electrical model: transmitted voltage

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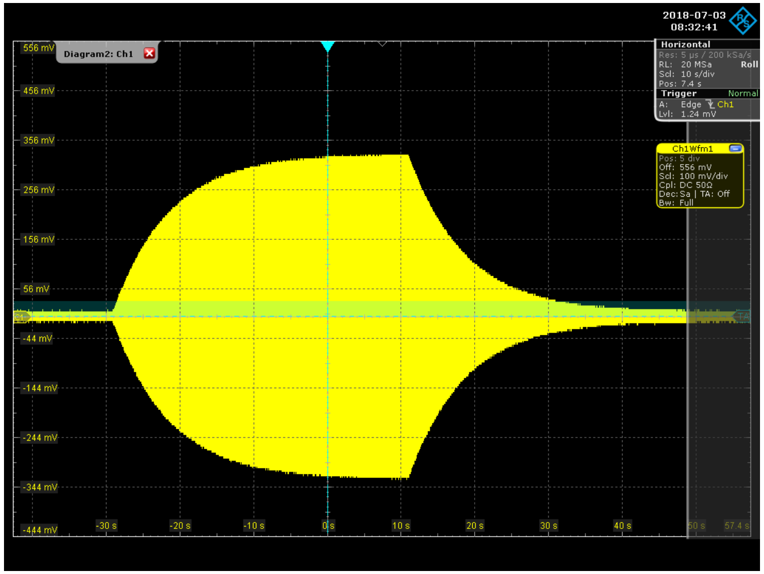
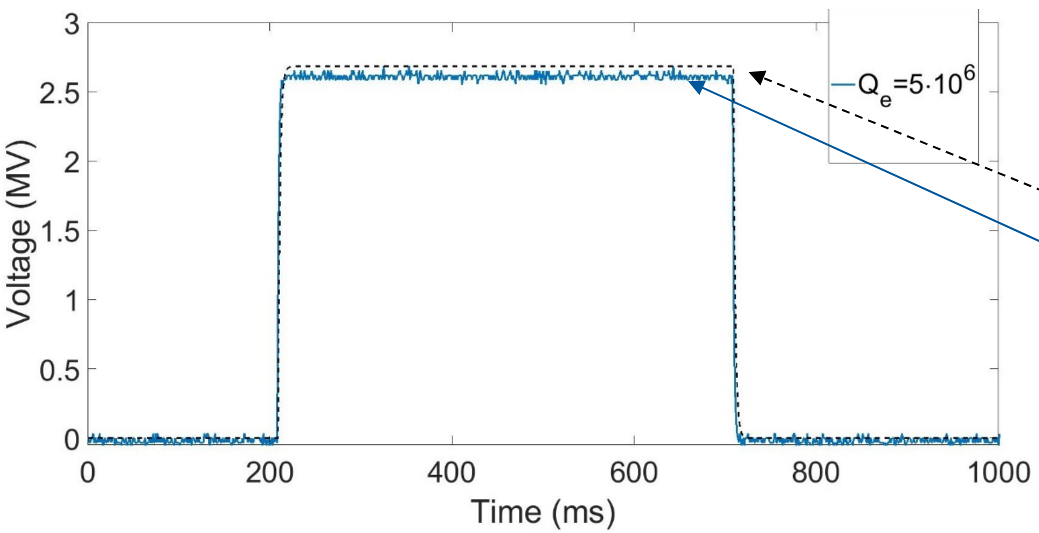
TABLE I. Measured and theoretical fall time and maximum voltage without detuning as a function of Q_{ext} for $Q_0 = 5 \times 10^{10}$, $r/Q = 1000\ \Omega$, $\Delta f = 0$ Hz, and $f_{RF} = 1.3$ GHz.

	T_{fall}		V_{cav}^{max}	
Q_{ext}	Meas.	Theo.	Meas. (MV)	Theo. (MV)
5×10^6	1.13 ms	1.22 ms	2.66	2.68
5×10^7	12.0 ms	12.23 ms	8.22	8.48
5×10^8	117 ms	121.2 ms	25.46	26.57
5×10^{10}	5.9 s	6.121 s	66.84	68.04



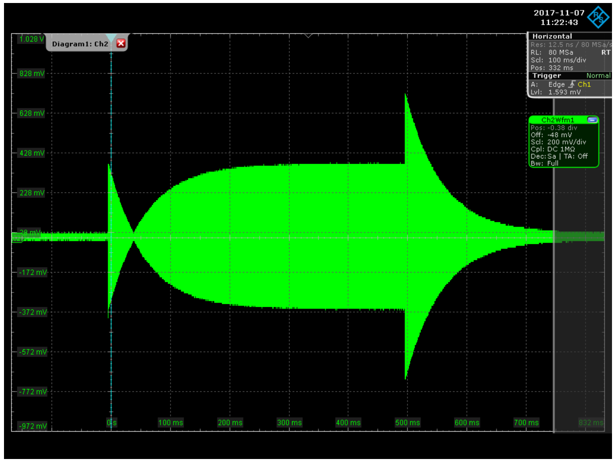
Actual RF output of a critically coupled cavity



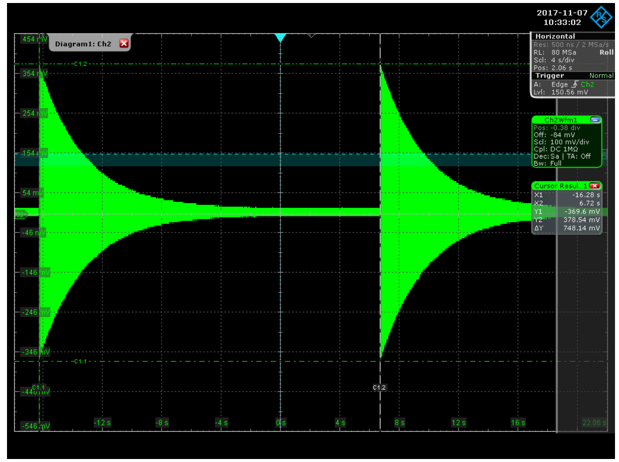
Theoretical response

VC output measured from scope

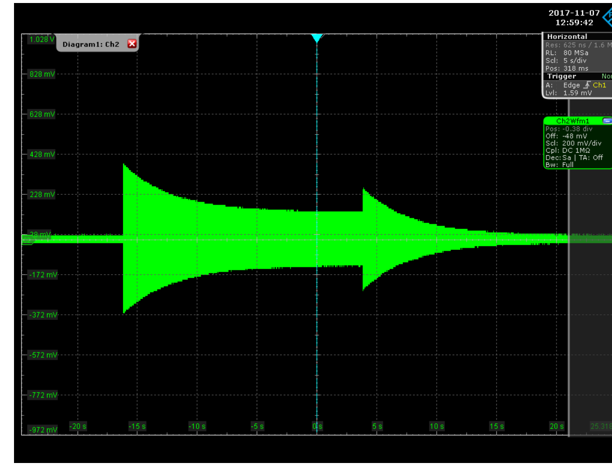
Electrical model: reflected voltage



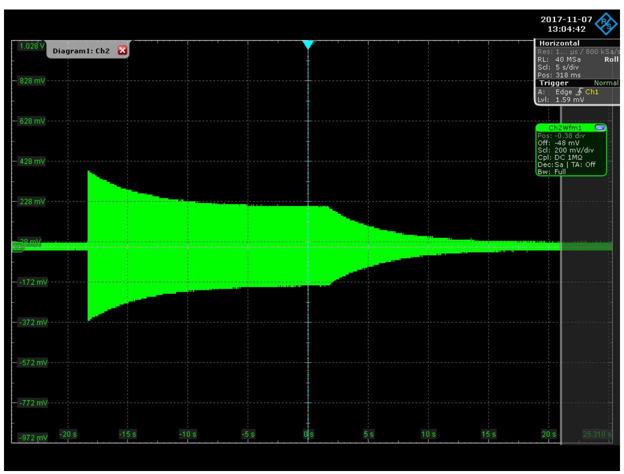
β >1



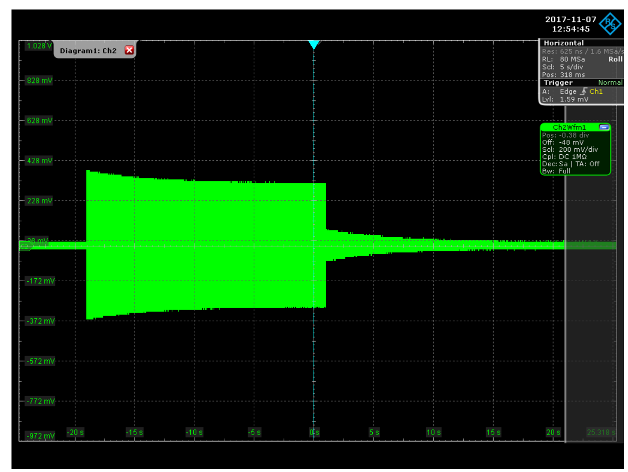
β =1



1>β >1/3

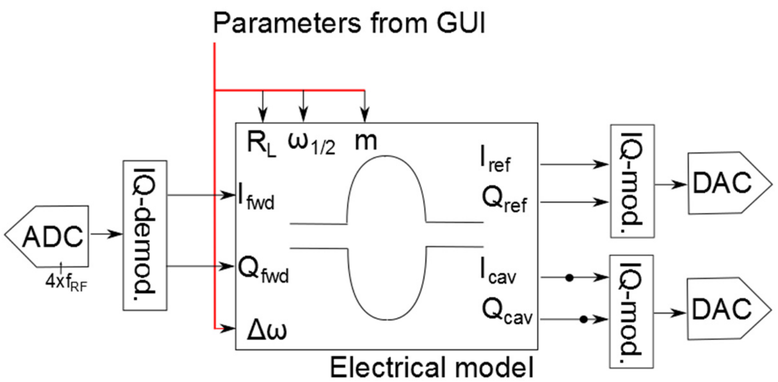


β =1/3



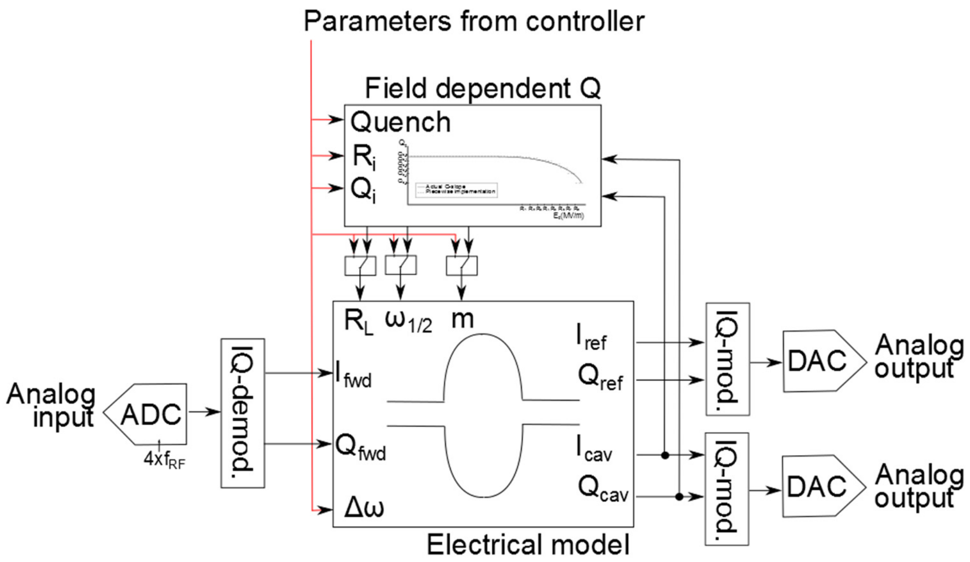
β <1/3

Realistic SRF behaviour



FPGA changes the parameters in real time

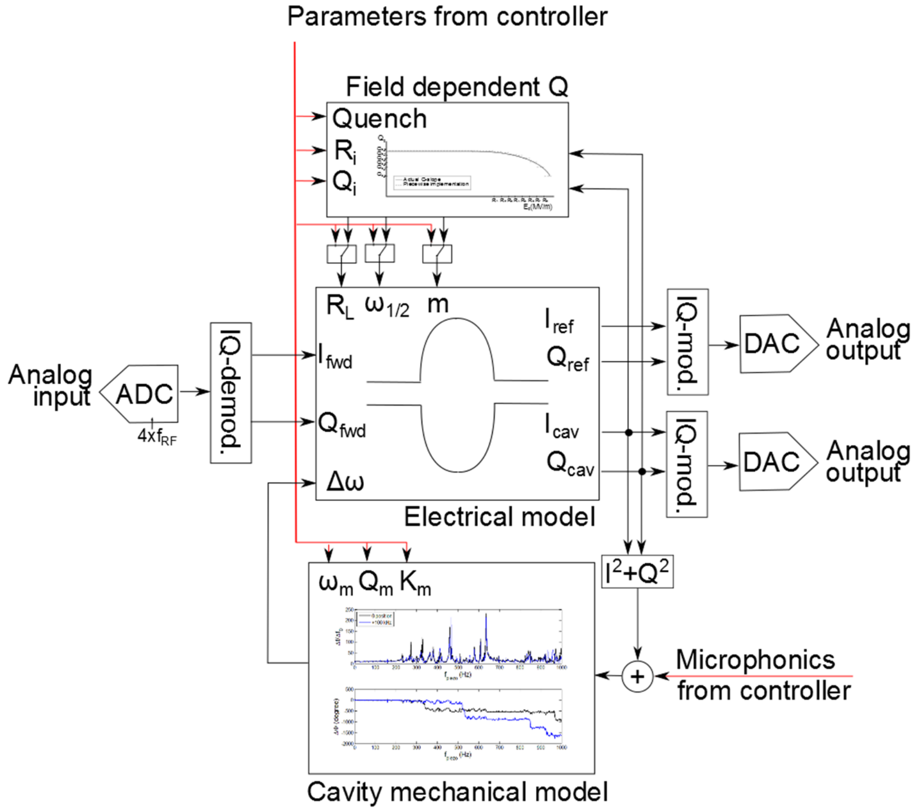
Realistic SRF behaviour



Q-slope and quench

FPGA changes the parameters in real time

Realistic SRF behaviour

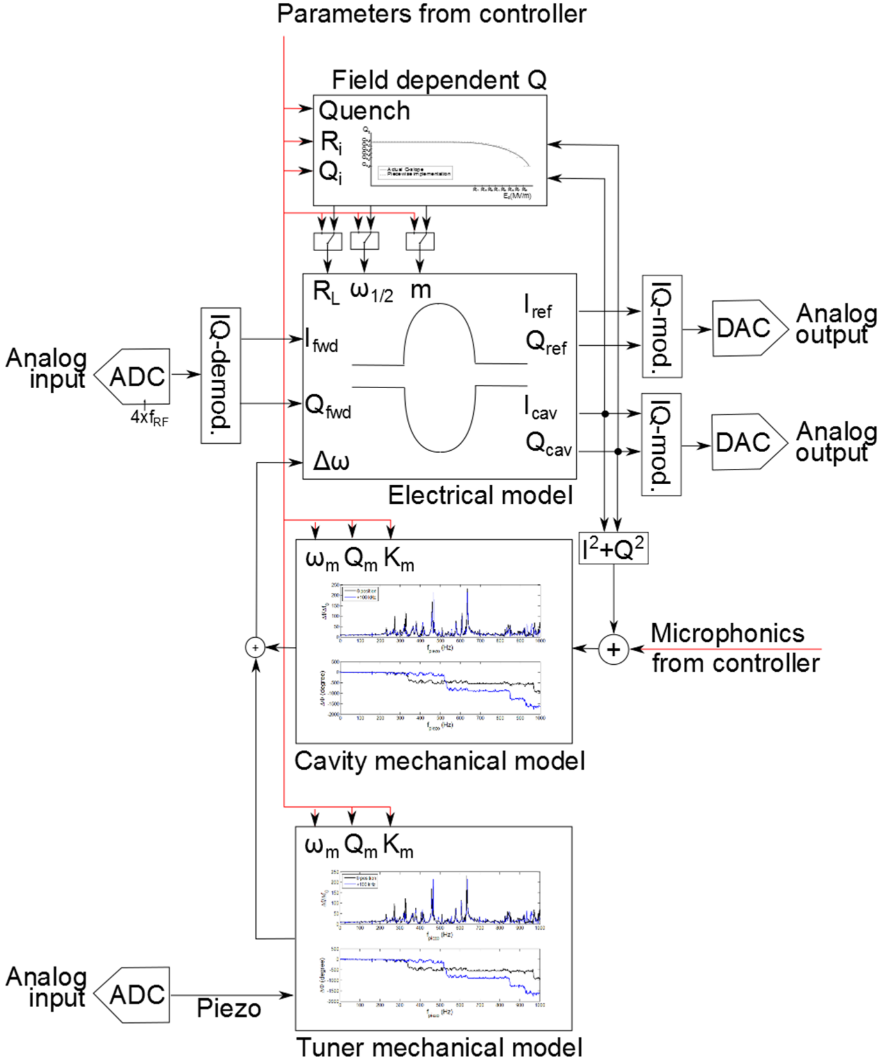


Q-slope and quench

Lorentz force detuning and microphonics

FPGA changes the parameters in real time

Realistic SRF behaviour



Q-slope and quench

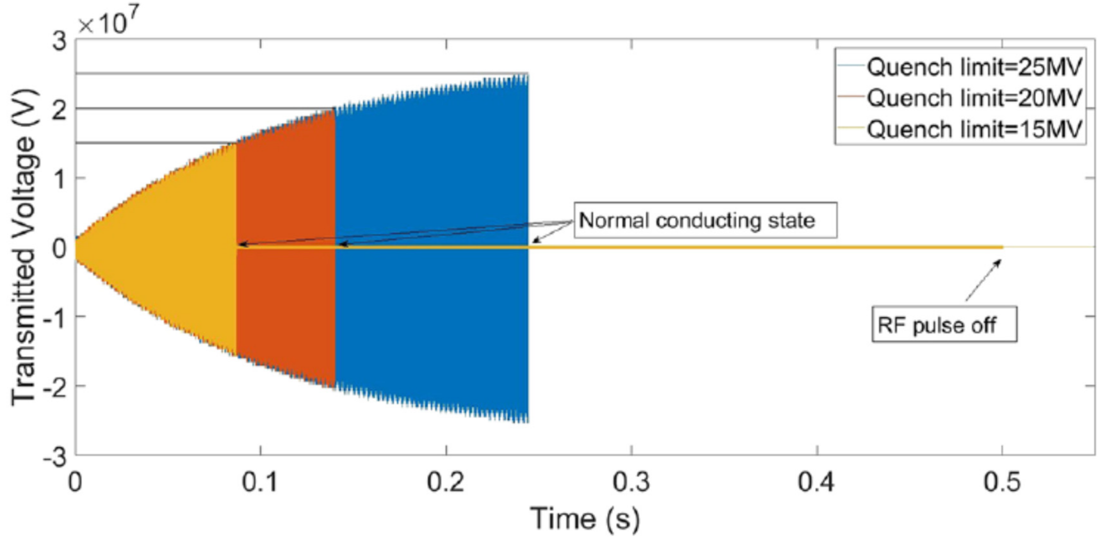
Lorentz force detuning and microphonics

Piezo tuner mechanical mode

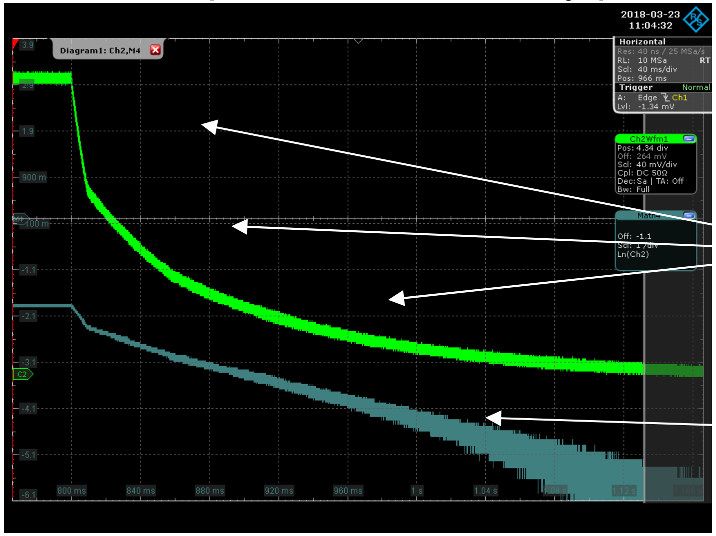
FPGA changes the parameters in real time

Realistic SRF behaviour

- Quench threshold is set by user. Once reached parameters are set to normal conducting



- *Vcav* is used to address a look-up table where cavity parameters are stored → Q-slope



Decay with three Q_0 values

Logarithm of decay

Realistic SRF behaviour

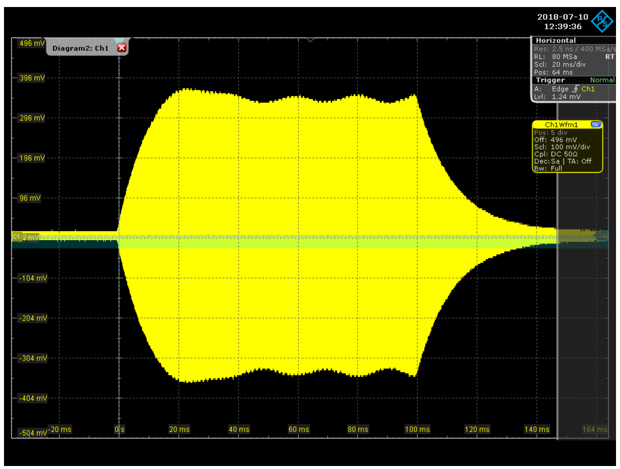
- Lorentz force detuning and microphonics defined by up to 5 mechanical modes

$$\frac{d}{dt}\begin{pmatrix}\Delta\omega_m(t)\\ \Delta\dot{\omega}_m(t)\end{pmatrix} = \begin{pmatrix}0 & 1\\ -\omega_m{}^2 & \dfrac{\omega_m}{Q_m}\end{pmatrix}\begin{pmatrix}\Delta\omega_m(t)\\ \Delta\dot{\omega}_m(t)\end{pmatrix} + \begin{pmatrix}0\\ -\omega_m{}^2\end{pmatrix}\left(K_{m1}E_{\mathrm{cav}}{}^2 + K_{m2}M_c\right)$$

Microphonics

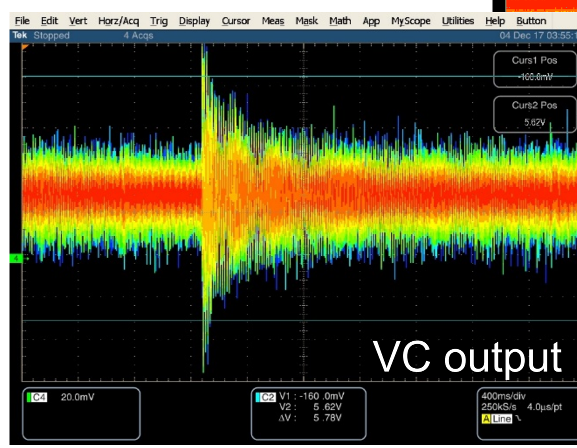
Field in cavity

- Microphonics: white noise, step, impulse or sinusoidal signals



LF detuning with 50Hz mech. Mode*

SRF gun „hit“ by cryogenics



Actual VC outputs

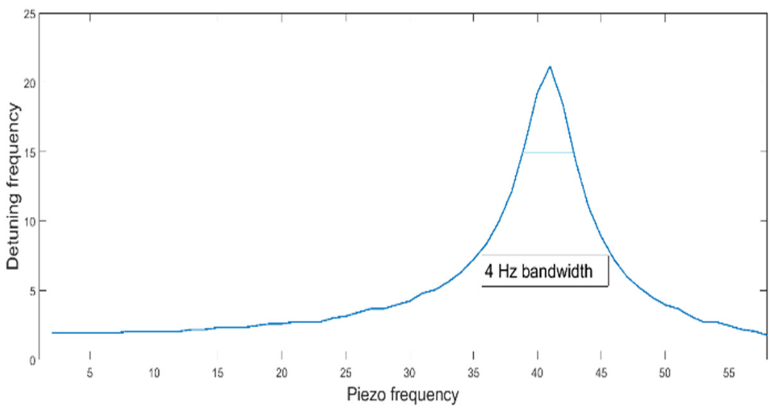
Detuning after impulse microphonics with 5 modes

Realistic SRF behaviour

- Lorentz force detuning and microphonics defined by up to 5 mechanical modes

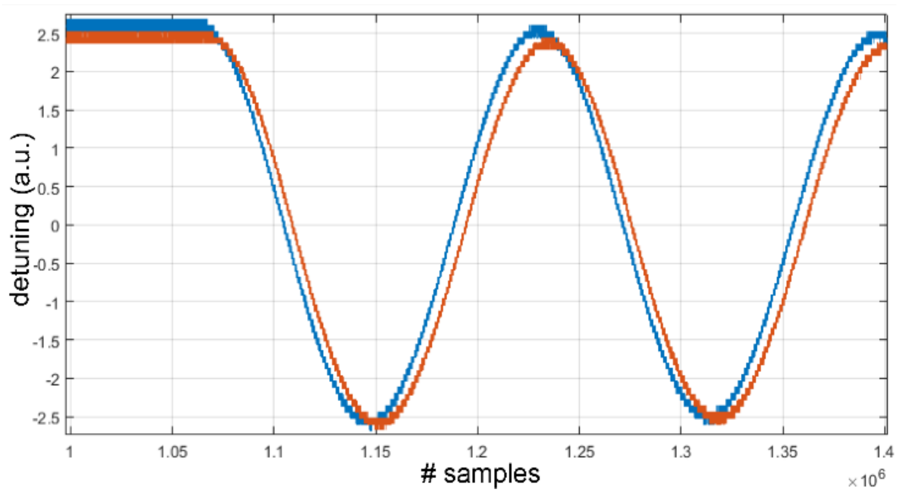
$$\frac{d}{dt}\begin{pmatrix}\Delta\omega_m(t)\\ \Delta\dot{\omega}_m(t)\end{pmatrix}=\begin{pmatrix}0 & 1\\ -\omega_m{}^2 & \frac{\omega_m}{Q_m}\end{pmatrix}\begin{pmatrix}\Delta\omega_m(t)\\ \Delta\dot{\omega}_m(t)\end{pmatrix}+\begin{pmatrix}0\\ -K_m\omega_m{}^2\end{pmatrix}\left(E_{\text{cav}}{}^2+M_c\right)$$

- Microphonics: white noise, step, impulse or sinusoidal signals
- Similar block for piezo tuner emulation: 5 mechanical modes + DC component + Delay

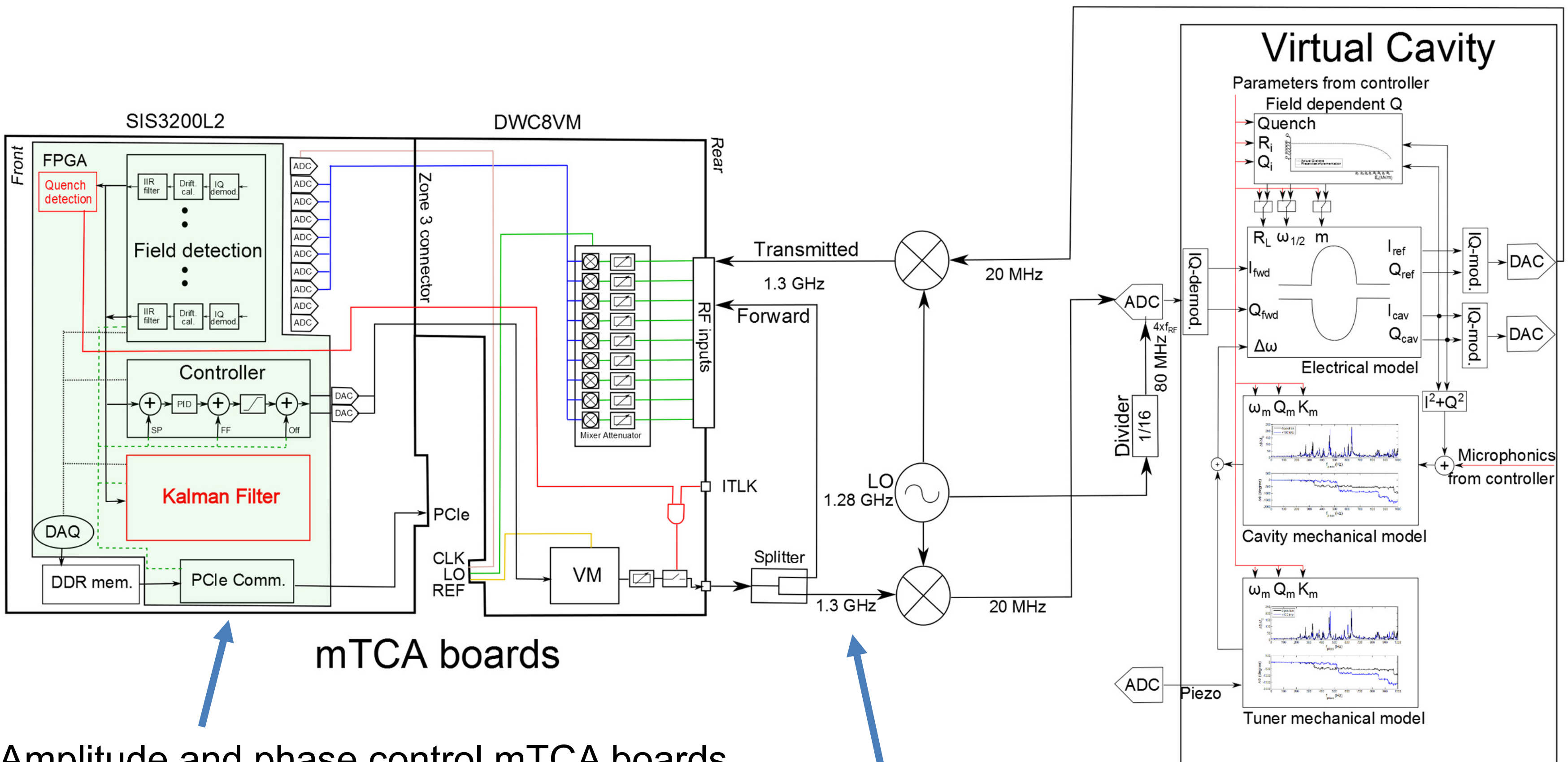


Measured detuning vs. Piezo input frequency for 1 mode @ 40Hz and Q=10

Measured detuning without and with 50ms delay



Some applications



mTCA boards

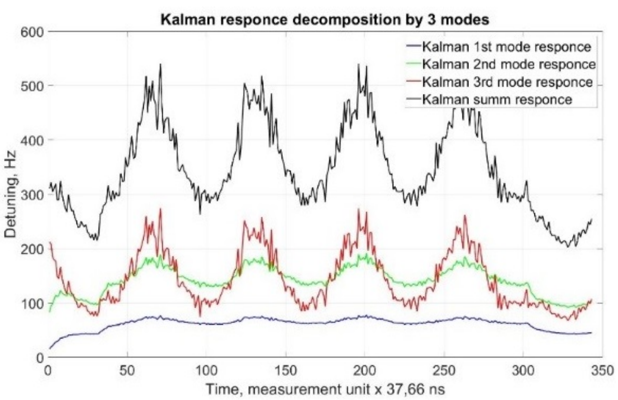
Amplitude and phase control mTCA boards

Up/Down Converter to/from 1.3GHz

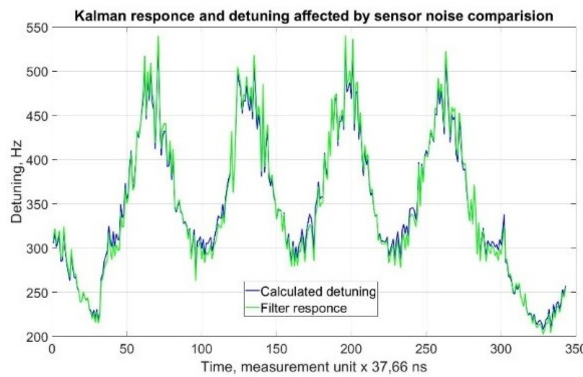
Virtual cavity connected to an mTCA.4 LLRF control boards

Some applications

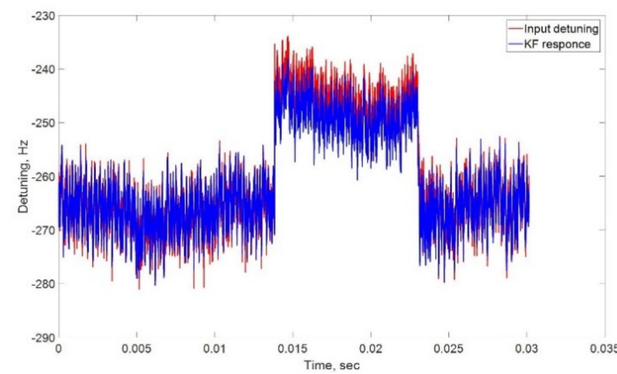
- **Kalman filter debugging**. Estimation of detuning in noisy enviroments for optimal detuning control. [A. Ushakov, IPAC18]
  - Debugged with Virtual Cavity with three mechanical modes



Kalman modes estimation



Comparison with VC detuning

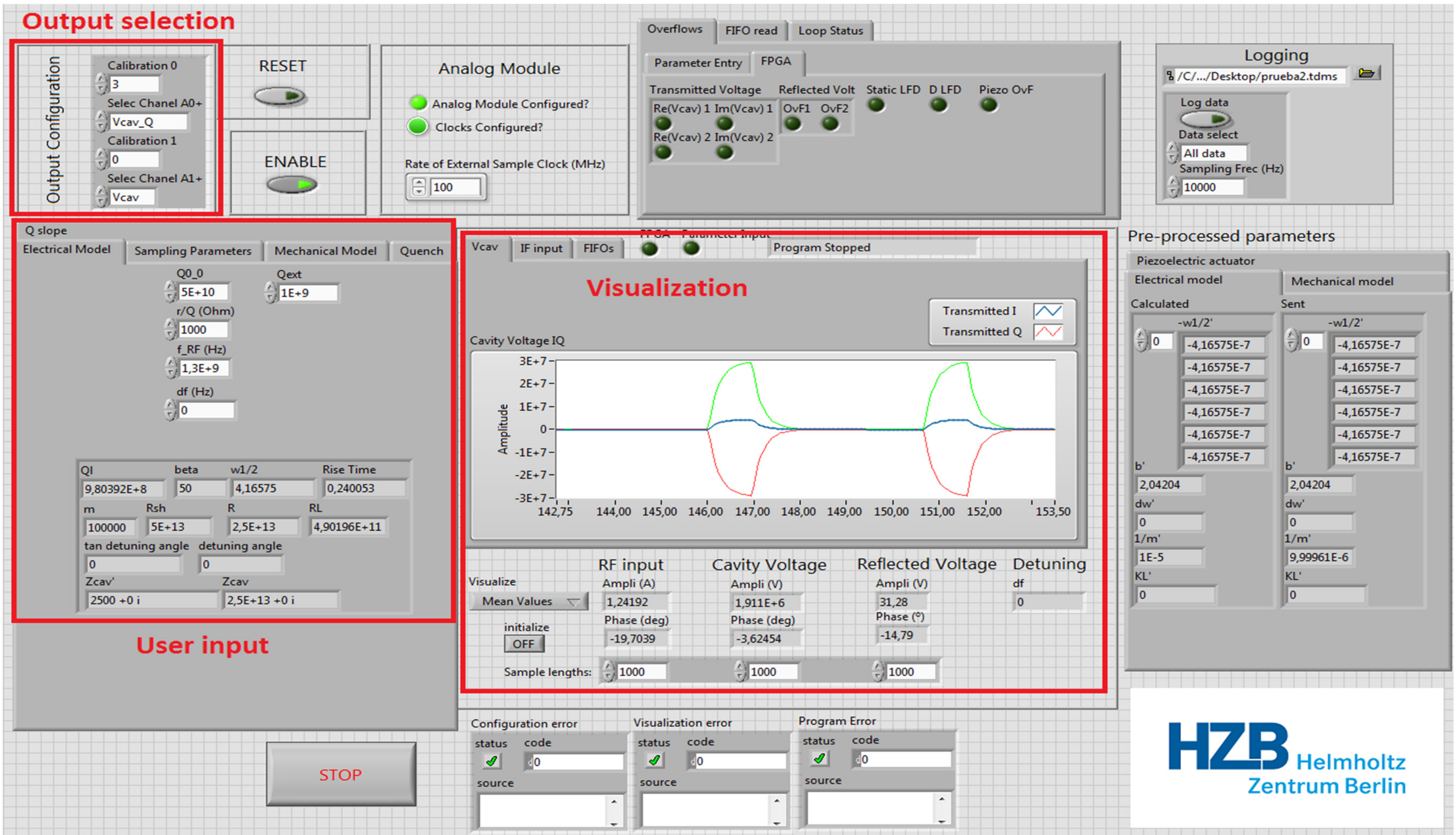


Kalman estimation after stepwise microphonics

- **Quench detection algorithms:** LLRF signals can be used to estimate in real time cavity parameters. If a sudden change in $\omega_{1/2}$ is detected → switch off RF
  - Simulated for all HZB SRF cavities (bERLinPro and BESSY-VSR) [P. Echevarria, IPAC19]
  - To be implemented in mTCA.4 and tested with the Virtual cavity

Some applications

- **LLRF operator training:**
  LLRF servers + ChimeraTK Control System Adapter + EPICS panels



- **Teaching:** GUI panels can be modified to hide information to students!

Some applications

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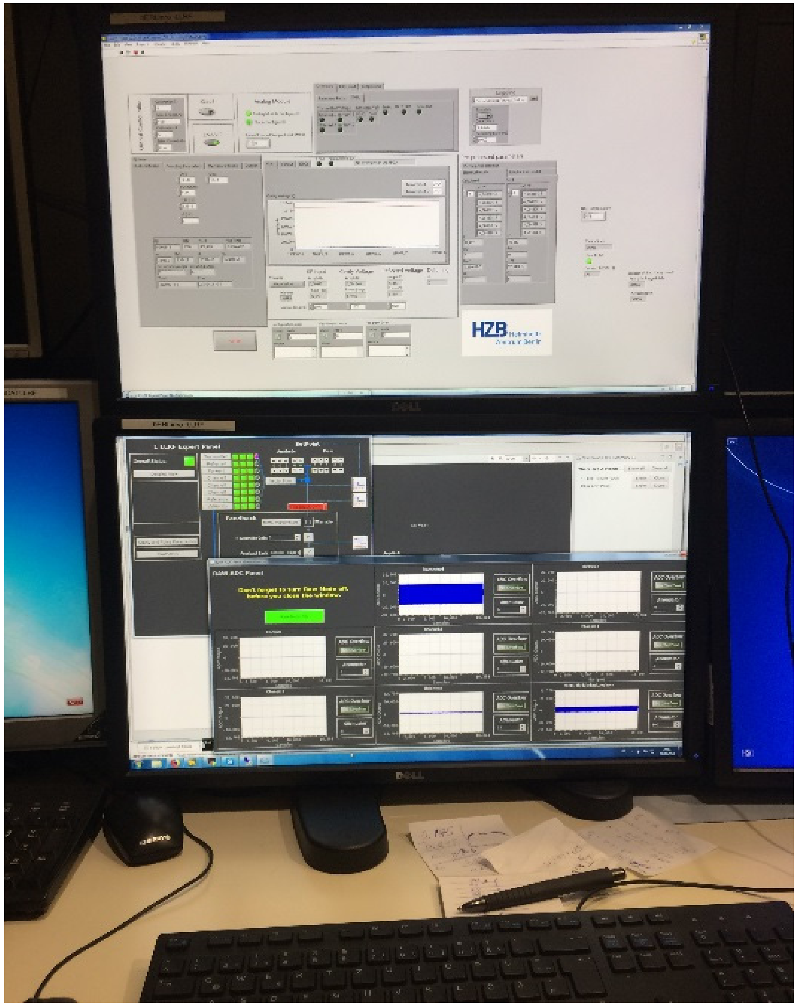

(thanks to M. Hierholzer (DESY)!)

- **Teaching:** GUI panels can be modified to hide information to students!

Conclusions and possible upgrades

- Using a Virtual Cavity for control algortihms debugging saves time and money
- The presented Virtual Cavity mimics:
  - Fundamental cavity behaviour for transmitted and reflected voltages
  - Quenches
  - Q-slopes
  - Lorentz force detuning
  - Microphonics
  - Piezo-tuner behaviour
- Wide range of user-selectable parameters
- Already used for:
  - Kalman filter detuning estimation
  - LLRF panels training
- To be used following this year: Quench detection algorithms
- Possible upgrades:
  - Multiple passband modes
  - Virtual Cryomodule: several cavities to debug Vector Sum LLRF control
  - Recorded real microphonics signal
  - Amplifier non linearities
  - Beam loading
  - …

Thanks for your attention!