LLRF controls and RF operations.

SRF 2019 Tutorial


SRF 19 DRESDEN

19th International Conference on RF Superconductivity

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for the DESY LLRF team

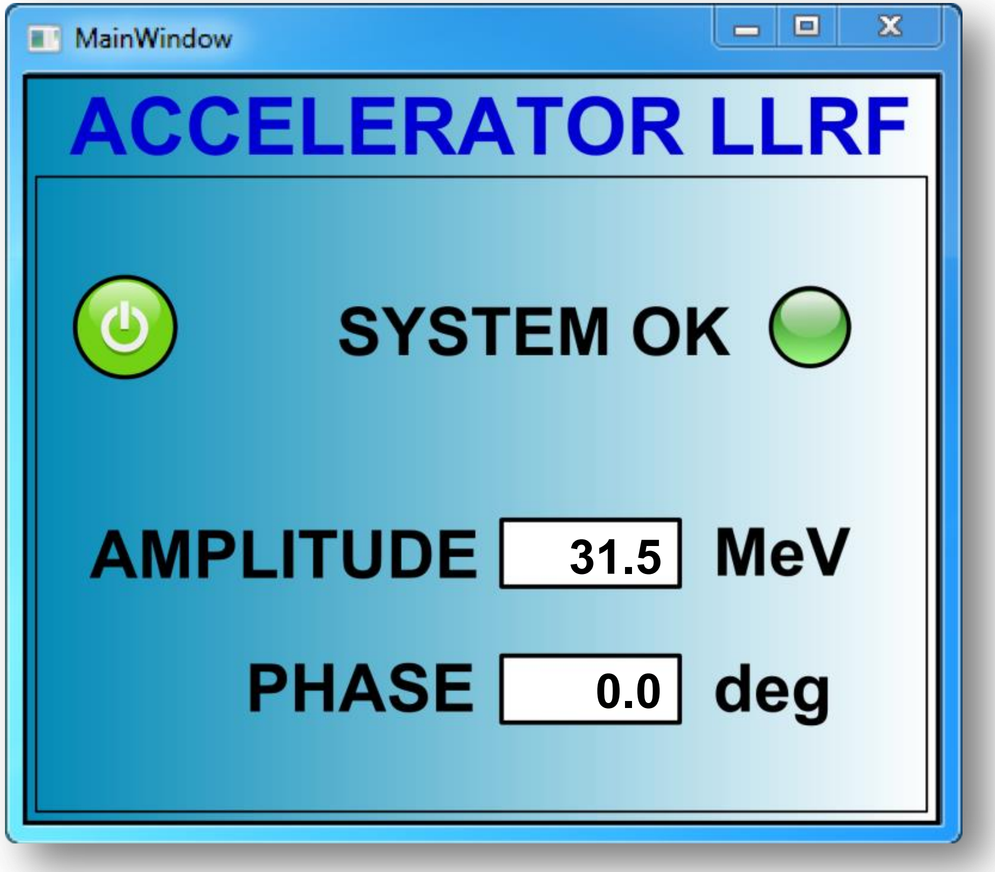
Dresden, 29.06.2019

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

What is a LLRF system for?

Interface to the “ultimate LLRF” system



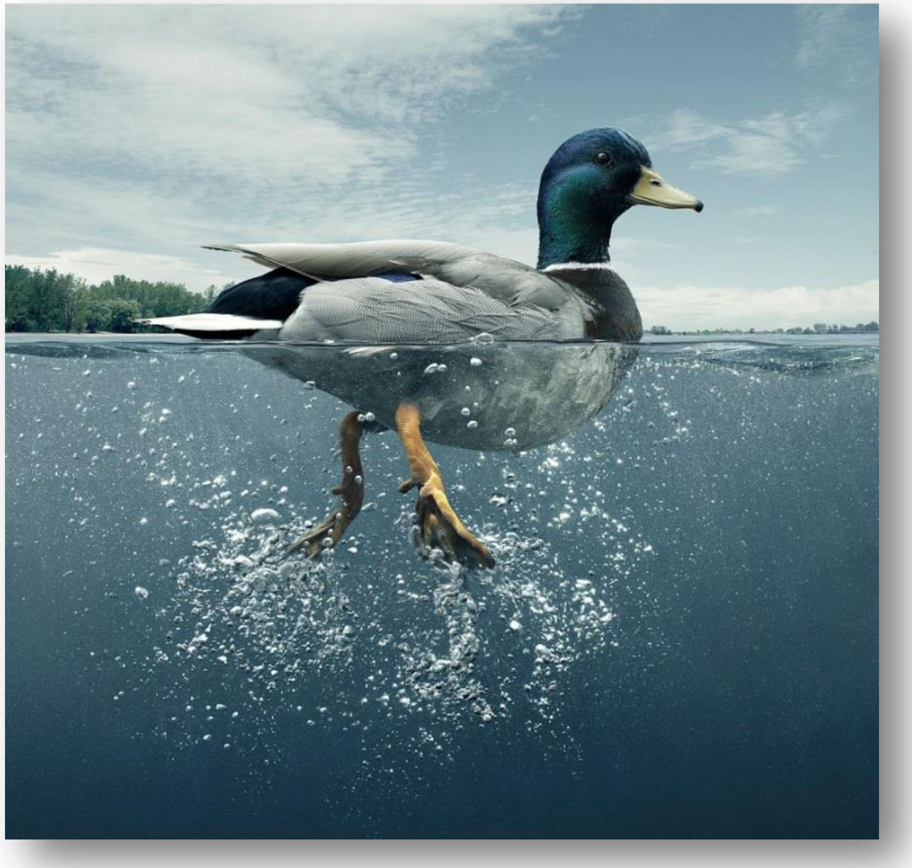
MainWindow

ACCELERATOR LLRF

SYSTEM OK ●

AMPLITUDE 31.5 MeV

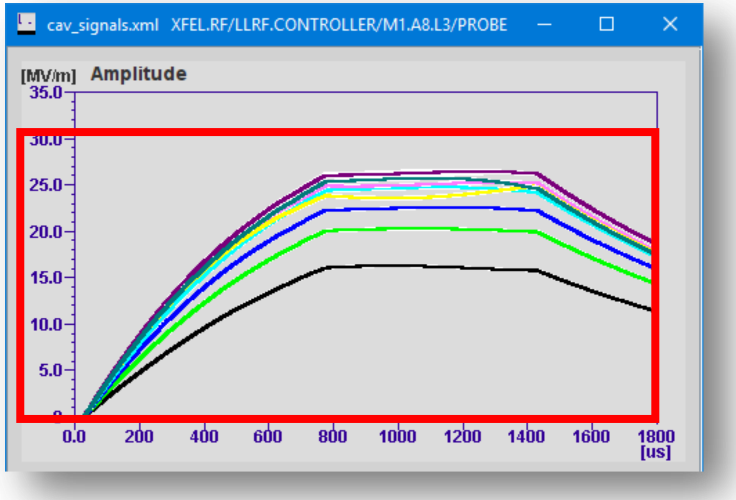
PHASE 0.0 deg

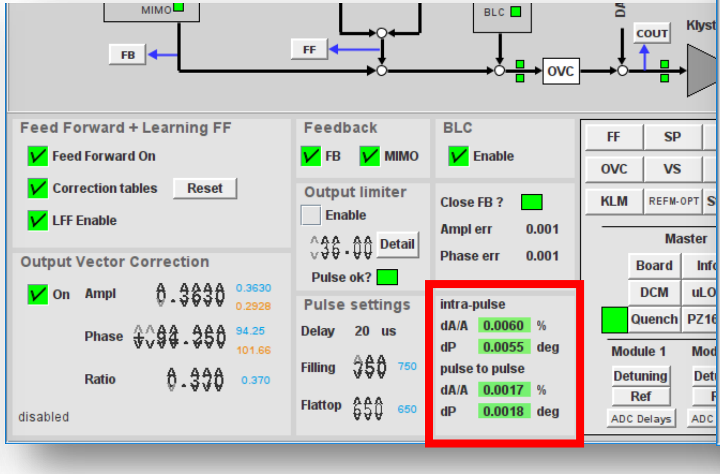


What is a LLRF system for?

Main functionality

- It allows operator / other actors to **set** the **accelerating voltage and phase** for a given RF station
- It **Maintains** the desired amplitude and phase across the flat top at the **required stability**
- Provides **calibrated** (engineering units) **waveforms** for all cavities (Forward, Reflected, Probe)





Feed Forward + Learning FF
☑ Feed Forward On
☑ Correction tables Reset
☑ LFF Enable

Output Vector Correction
☑ On Ampl 0.3630 0.3630 0.2928
Phase 94.250 94.25 101.66
Ratio 0.370 0.370
disabled

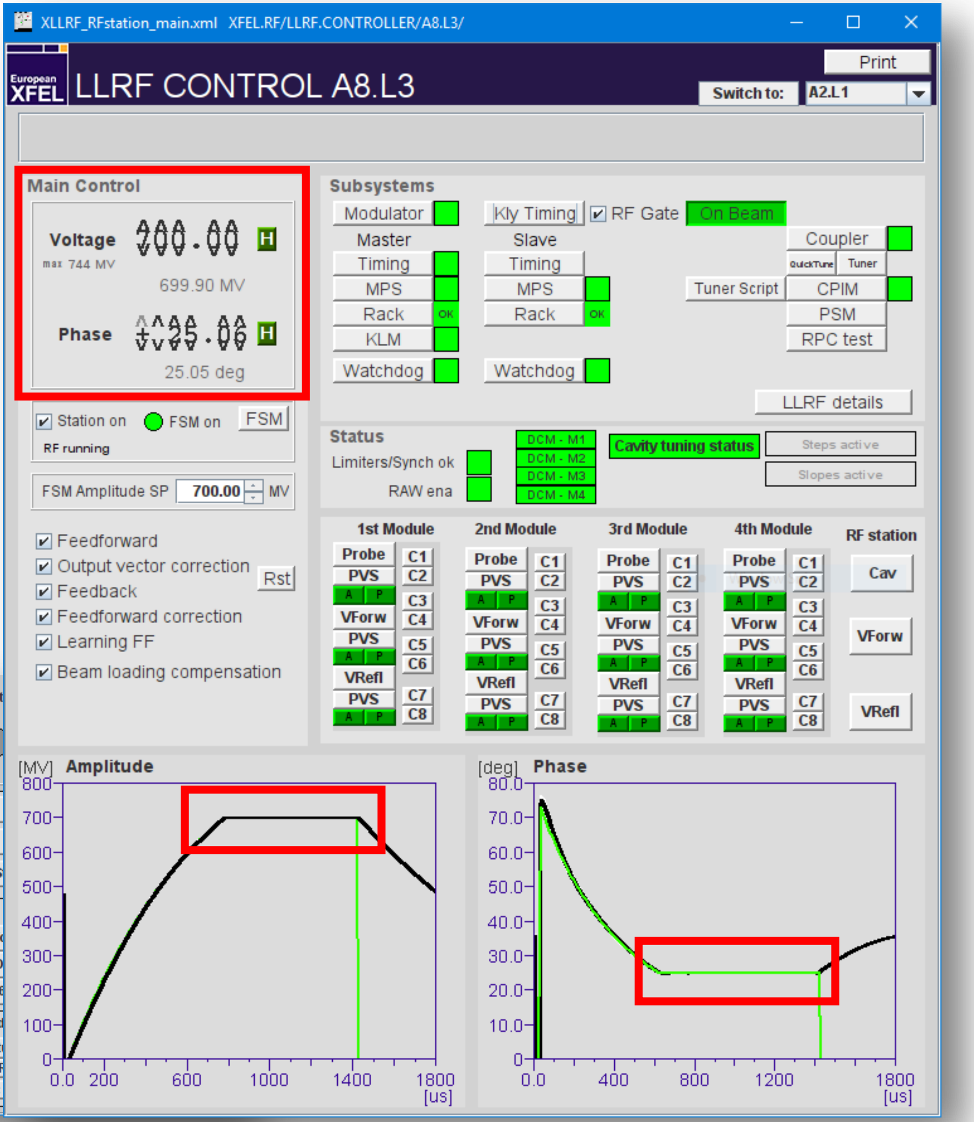
Feedback
☑ FB ☑ MIMO

Output limiter
☐ Enable
36.00 Detail
Pulse ok? 🟩

Pulse settings
Delay 20 us
Filling 750 750
Flattop 650 650

BLC
☑ Enable
Close FB ? 🟩
Ampl err 0.001
Phase err 0.001

intra-pulse
dA/A 0.0060 %
dP 0.0055 deg
pulse to pulse
dA/A 0.0017 %
dP 0.0018 deg



LLRF CONTROL A8.L3
Switch to: A2.L1

Main Control
Voltage 200.00 H
max 744 MV
699.90 MV
Phase 25.06 H
25.05 deg

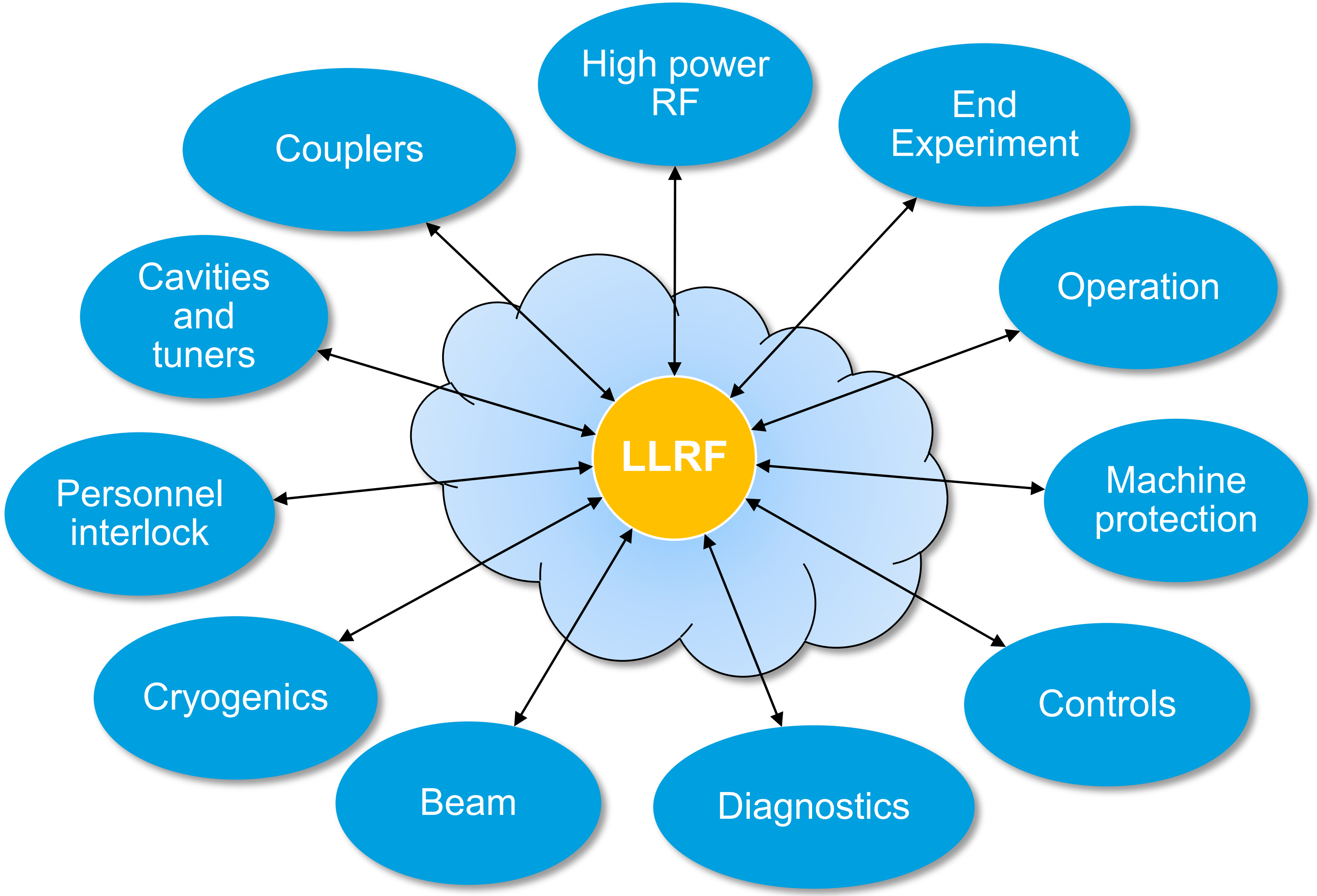
☑ Station on ● FSM on FSM
RF running
FSM Amplitude SP 700.00 MV

☑ RF Gate On Beam
Limiters/Synch ok 🟩
RAW ena 🟩

☑ Feedforward
☑ Output vector correction Rst
☑ Feedback
☑ Feedforward correction
☑ Learning FF
☑ Beam loading compensation

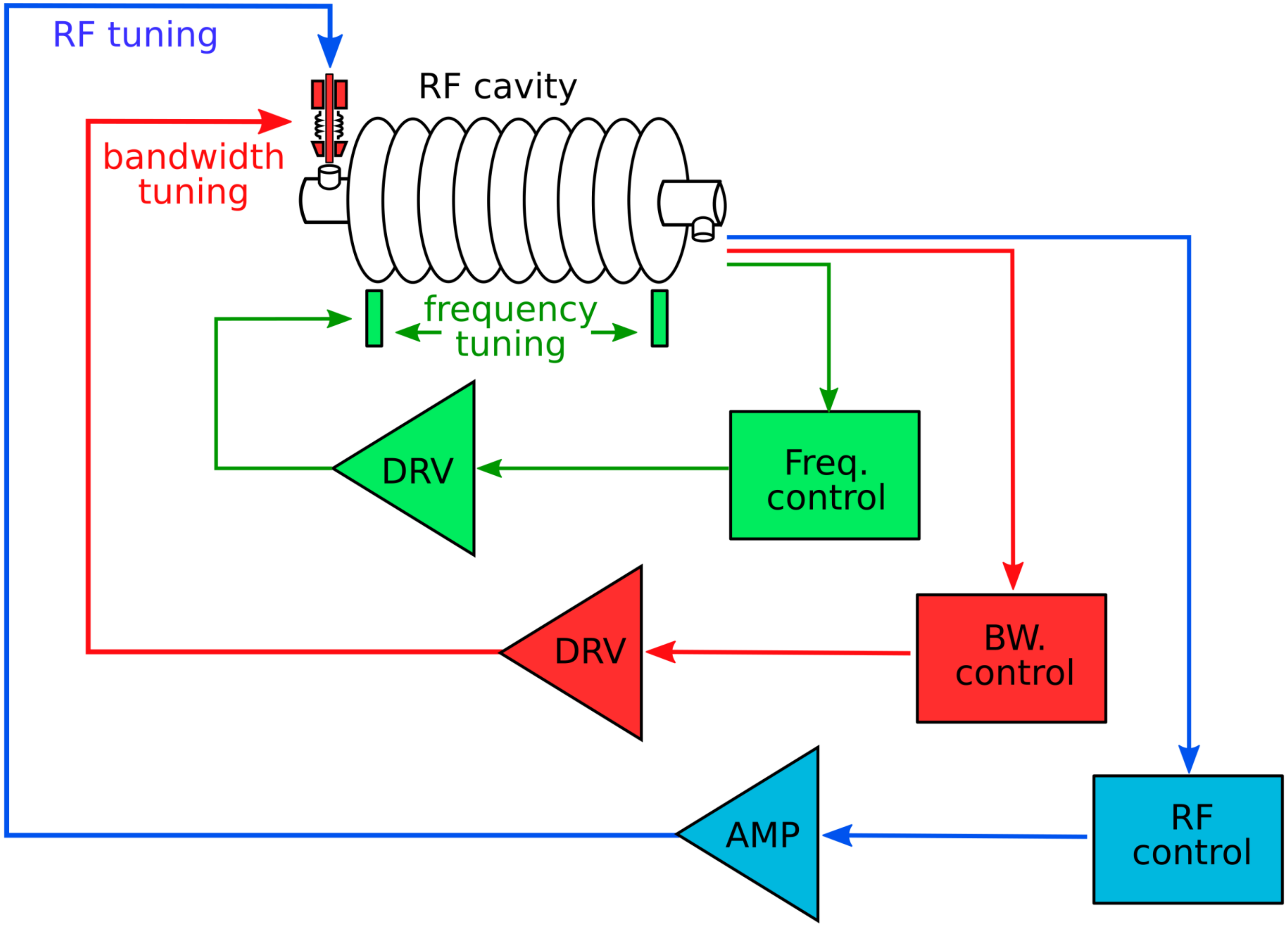
LLRF

Where does it start ? Where does it end ?



LLRF

LLRF controls



What I will try to cover in this talk

“RF controls crash course”

RF cavities

- Some basics about the cavity electrical and mechanical system and its modelling

RF power couplers

- Why, how ?
- Impact of changing the external coupling

Frequency tuners

- Fundamentals of tuners, slow, fast
- Some examples and practical considerations

LLRF system

- The basic blocks of LLRF
- Practical case simulation demo

RF operations

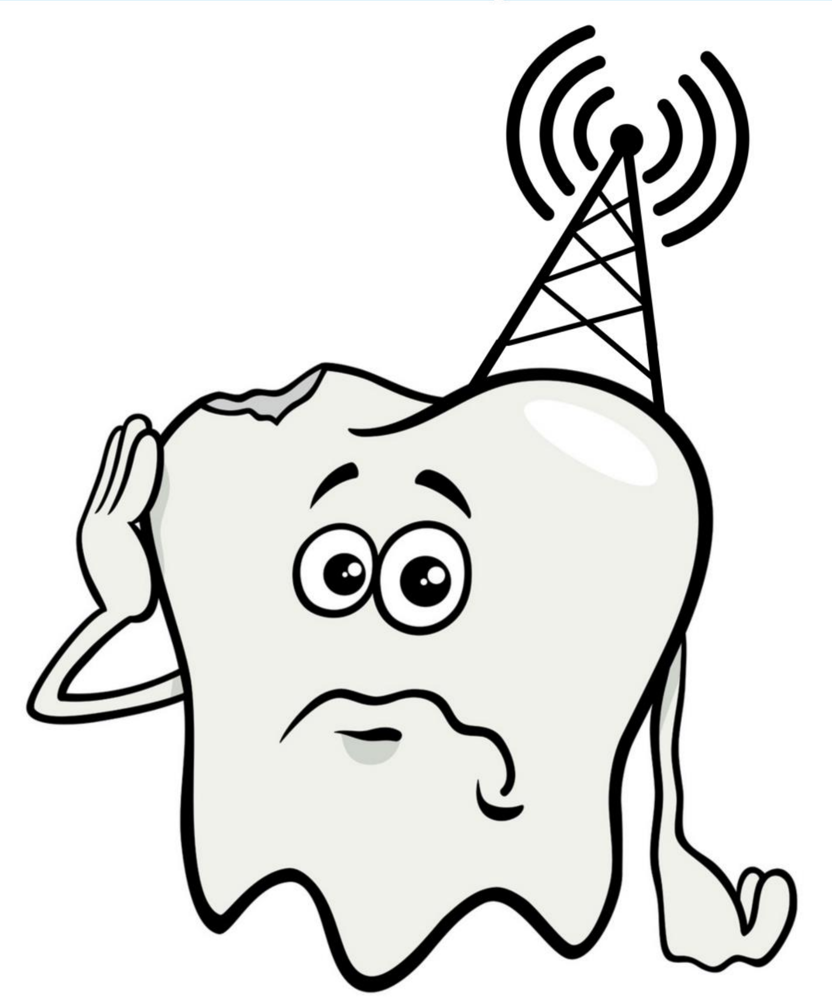
- Some examples of operation study or cases

Cartoon Fundamentals by Carlos Gomes Cabral

Note:

Due to my background and work environment, most examples in this tutorial are inspired from **pulsed** **linac** **electron** machines.

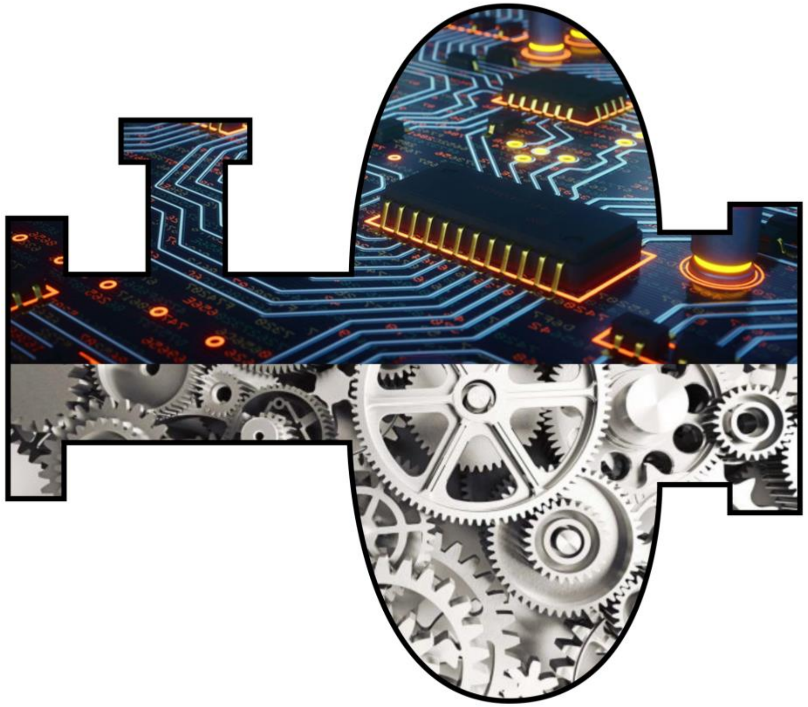
RF cavities



RF cavities

Copper (NRF) cavities

Niobium (SRF) cavities



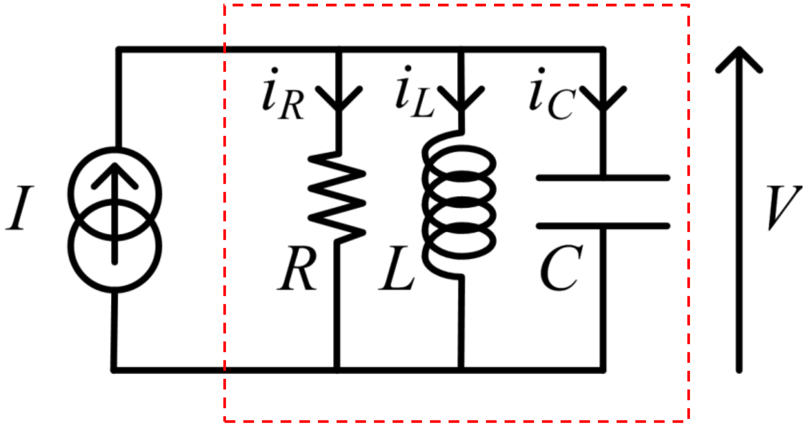
Coupled **electrical mechanical** system

Cavity as an Electrical System

The standard RLC model (simplified)

$$\boxed{i_R + i_L + i_C = I}$$ (1)

$$\boxed{\begin{aligned} i_R &= \frac{V}{R} \\ \frac{di_L}{dt} &= \frac{1}{L}V \\ i_C &= C\frac{dV}{dt} \end{aligned}}$$ (2)



(1) ➔ $$\frac{di_R}{dt} + \frac{di_L}{dt} + \frac{di_C}{dt} = \frac{dI}{dt}$$

(1) & (2) ➔ $$\frac{1}{R}\frac{dV}{dt} + \frac{1}{L}V + C\frac{d^2V}{dt^2} = \frac{dI}{dt}$$

➔ $$\boxed{\frac{d^2V}{dt^2} + \frac{1}{RC} \times \frac{dV}{dt} + \frac{1}{LC} \times V = \frac{1}{C} \times \frac{dI}{dt}}$$

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

2nd order linear differential equation has a solution in the form of

$$\boxed{V(t) = V_{CAV}(t) \times \sin(\omega_{RF}t)}$$

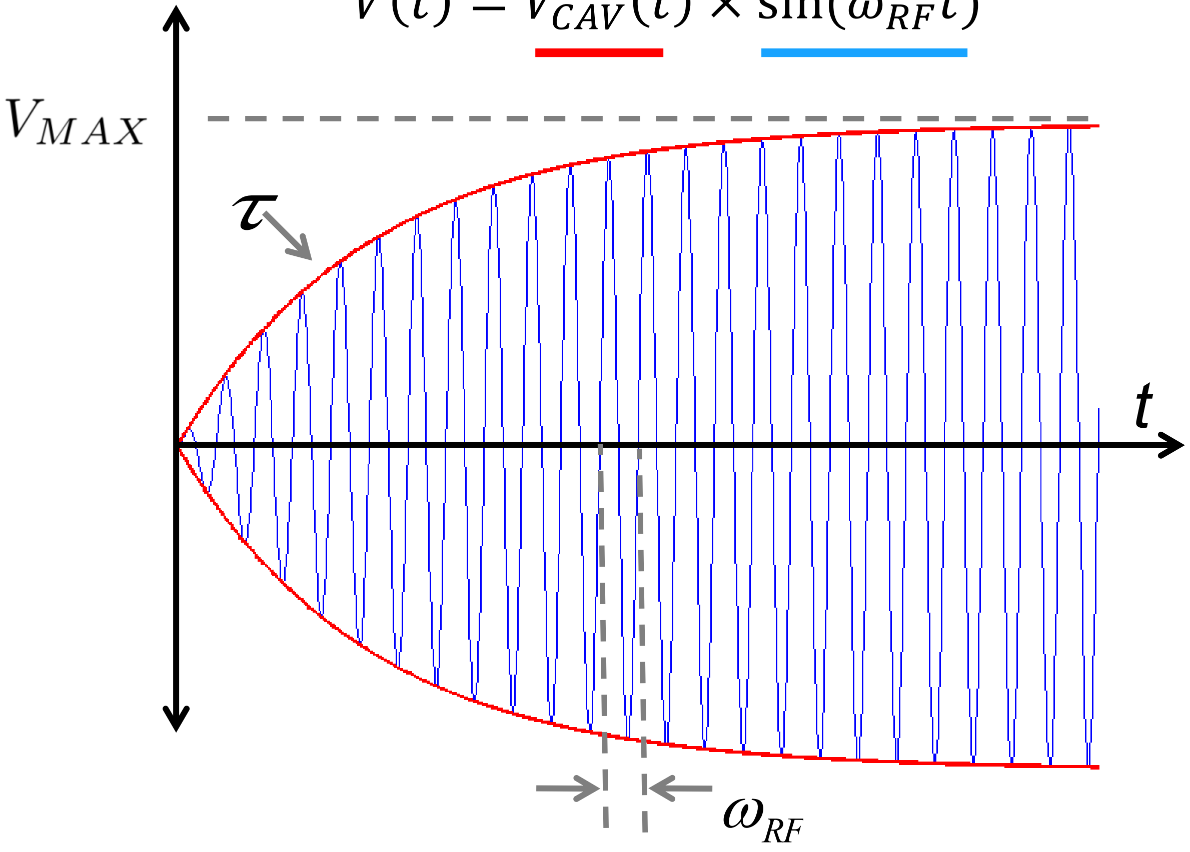
envelope

carrier

Cavity as an Electrical System

The envelope equation

$$V(t) = \underbrace{V_{CAV}}(t) \times \underbrace{\sin(\omega_{RF} t)}$$



V_{CAV} : envelope

$$\boxed{V_{CAV} = V_{MAX}(1 - e^{-\frac{t}{\tau}})}$$

τ is the **cavity time constant**

it depends on the **cavity bandwidth**

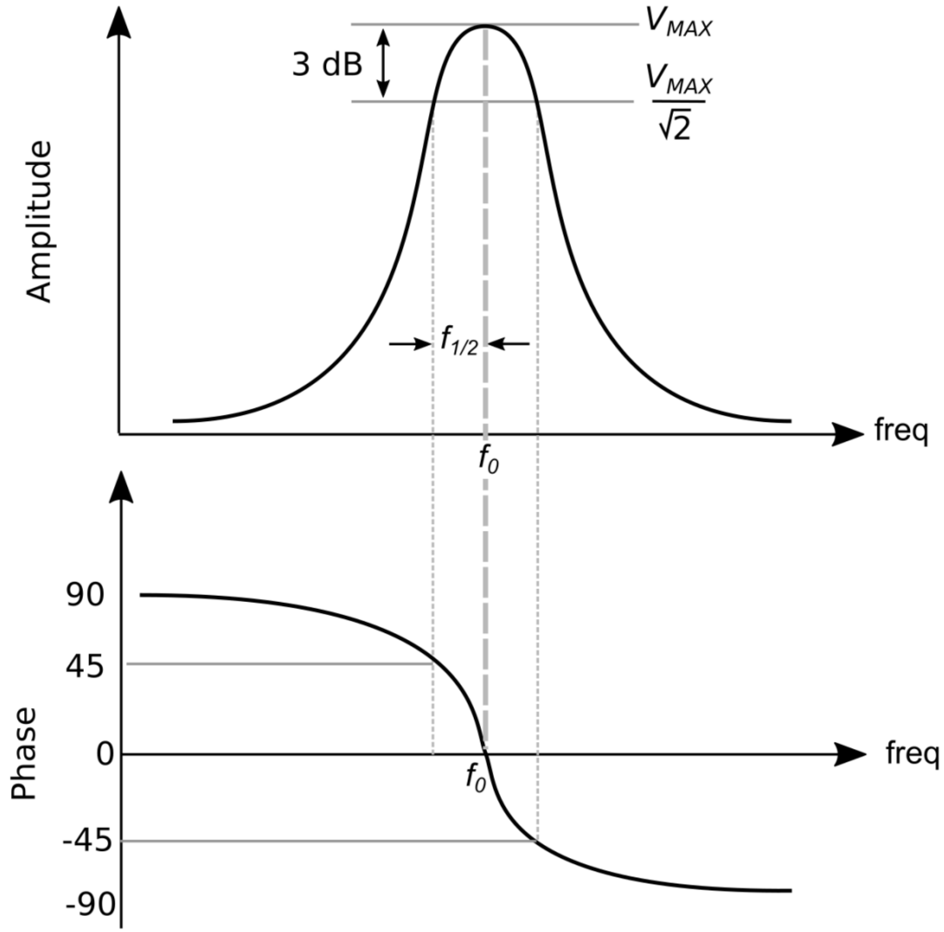
$$\tau = \frac{1}{2\pi f_{1/2}}$$

cavity half bandwidth
(i.e. half of the cavity bandwidth)

Cavity as an Electrical System

In the frequency domain

- Cavity behaves as a **band pass filter**
  - Center frequency **f_0**
  - Half bandwidth **$f_{1/2}$**

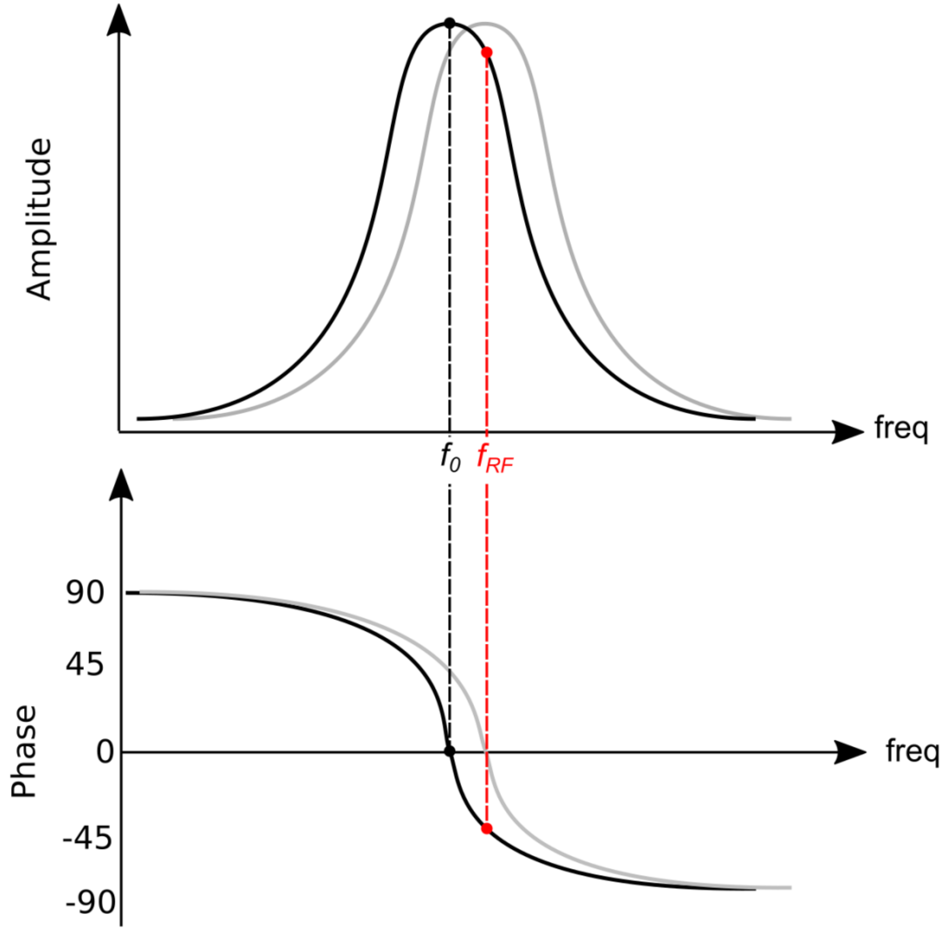


Cavity as an Electrical System

In frequency domain

- Cavity behaves as a **band pass filter**
  - Center frequency f_0
  - Half bandwidth $f_{1/2}$
- We can define **detuning** as the difference between the **cavity center frequency** (f_0 = resonance frequency) and the frequency of the **RF drive** (f_{RF})

$$\Delta\omega = \omega_0 - \omega_{RF} = 2\pi(f_0 - f_{RF})$$



Cavity as an Electrical System

Some figures of merit

Quality factor Q_0

$$Q_0 \equiv \frac{\text{Energy stored in cavity}}{\text{Energy dissipated in cavity walls per radian}} = \frac{\omega_0 U}{P_{diss}}$$

Shunt impedance R_{sh}

$$R_{sh} \equiv \frac{V_c^2}{P_{diss}} \quad \text{in } \Omega$$

V_c = cavity “accelerating” voltage

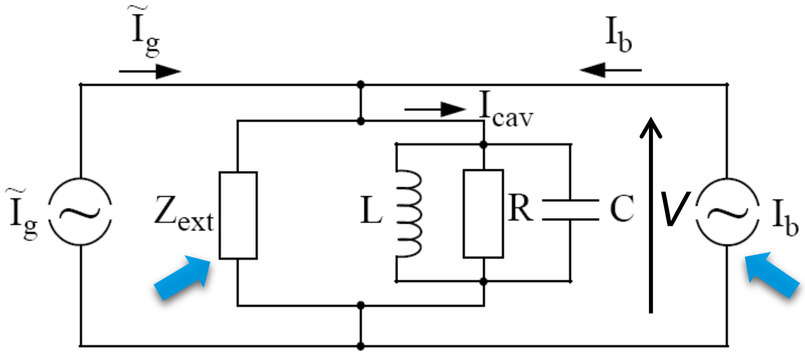
R_{sh}/Q_0 “R over Q”

$$\frac{R_{sh}}{Q_0} \quad \text{in } \Omega$$

→ defined by cavity geometry only

Cavity as an Electrical System

The standard RLC model (with coupling and beam)



- Same as before but now:
  - $I = I_g + I_b$
  - $R_L = R \,//\, Z_{ext}$

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

$$\boxed{\ddot{V}(t) + \frac{\omega_0}{Q_L}\dot{V}(t) + \omega_0^2 V(t) = \frac{\omega_0 R_L}{Q_L}\dot{I}(t)}$$ using $$\boxed{\begin{array}{c}\frac{1}{R_L C} = \frac{\omega_0}{Q_L} \\ \frac{1}{LC} = \omega_0^2\end{array}}$$

- 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:

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

Cavity as an Electrical System

State space representation

- Starting from the same differential equation

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

- Separate *V(t)* and *I(t)* into Re{} and Im{} parts

$$\begin{aligned} \mathbf{V}(t) &= (V_r(t) + iV_i(t)) \cdot e^{i\omega t} \\ \mathbf{I}(t) &= (I_r(t) + iI_i(t)) \cdot e^{i\omega t} \end{aligned}$$

- Simplifications for SRF cavities, near resonance

$$\begin{aligned} \dot{V}_r + \omega_{1/2} V_r + \Delta\omega\, V_i &= R_L\, \omega_{1/2}\, I_r \\ \dot{V}_i + \omega_{1/2} V_i - \Delta\omega\, V_r &= R_L\, \omega_{1/2}\, I_i \end{aligned}$$

- Introducing the following matrices:

$$\begin{aligned} \mathbf{A} &= \begin{pmatrix} -\omega_{1/2} & -\Delta\omega \\ \Delta\omega & -\omega_{1/2} \end{pmatrix} \\ \mathbf{B} &= \begin{pmatrix} R_L\omega_{1/2} & 0 \\ 0 & R_L\omega_{1/2} \end{pmatrix} \\ x &= \begin{pmatrix} V_r \\ V_i \end{pmatrix} \\ u &= \begin{pmatrix} I_r \\ I_i \end{pmatrix} \end{aligned}$$

- The cavity equation can be expressed in the state space formalism

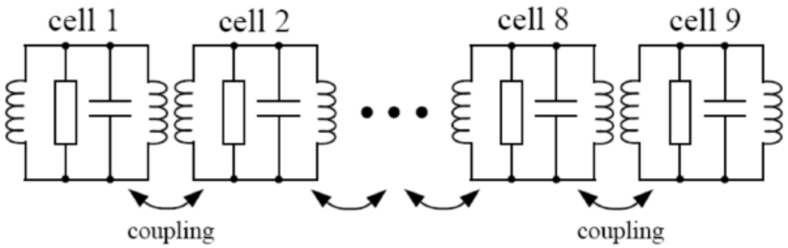
$$\boxed{\dot{x}(t) = \mathbf{A} \cdot x(t) + \mathbf{B} \cdot u(t)}$$

See: T. Schilcher's PhD Thesis for complete reference: "*Vector Sum Control of Pulsed Accelerating Fields in Lorentz Force Detuned Superconducting Cavities*", DESY, 1998

Cavity as an Electrical System

Sub-harmonic modes

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

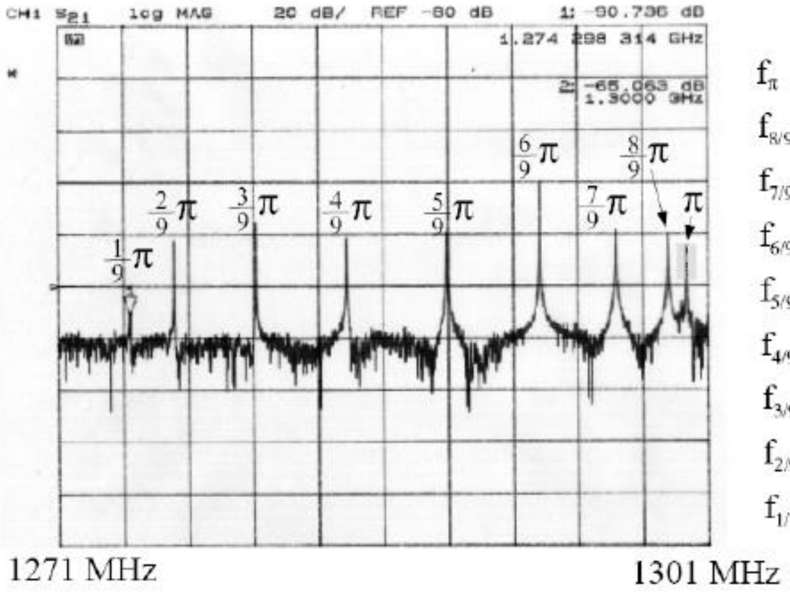


Modelled with 9 magnetically coupled resonators (RLC circuits)

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

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:	$\approx 10^{10}$
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

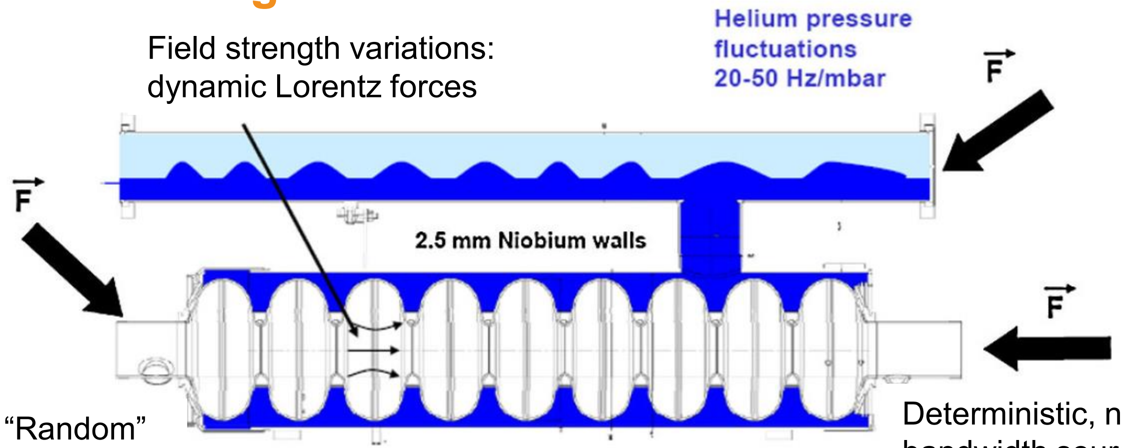
$f_{1/9\pi}$ = 1274.387 MHz

Courtesy: S. Pfeiffer

Cavity as a Mechanical System

Cavity mechanical modes, microphonics and sources of detuning

- **Detuning** can come from
  - Random external sources (external)
  - Deterministic external sources (external)
  - Helium bath fluctuations (external)
  - Lorentz force deformations (internal)



Field strength variations: dynamic Lorentz forces

“Random” broadband machinery noise

Deterministic, narrow bandwidth sources: vacuum pumps, water cooling pumps

Source: A. Neumann, “Analysis and active compensation of microphonics in continuous wave narrow-bandwidth superconducting cavities”, PRST-AB, 2010

- Detuning **mechanical modes** modelled by 2nd order differential equation

- Each mode *m* has its own **frequency** (ω_m), **quality factor** (Q_m) and **coupling** to the cavity field (K_m)

frequency

detuning contribution of mode m

Lorentz force detuning constant

$$\boxed{\frac{d^2\Delta f_m}{dt^2}+\frac{\omega_m}{Q_m}\frac{d\Delta f_m}{dt}+\omega_m^2\Delta f_m = \underbrace{-\omega_m^2 K_m\left(\frac{V_{cav}}{l_{cav}}\right)^2}_{\text{LFD}}\underbrace{+\omega_m^2\mu_m}_{\text{other mechanical driving forces (e.g. piezo)}}}$$

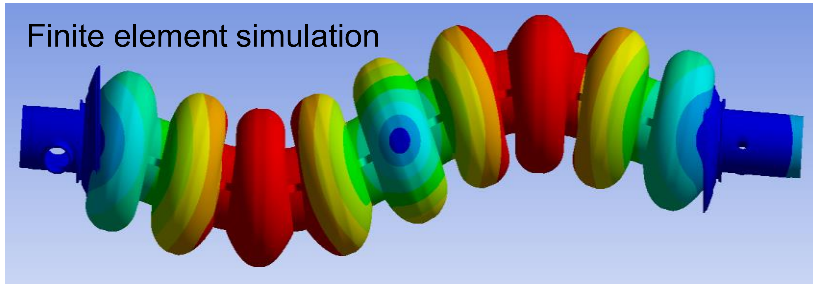
quality factor

Cavity as a Mechanical System

Cavity mechanical modes, microphonics and sources of detuning

- Finite element analyses can accurately predict the **cavity eigenmodes**

Cavity first eigenmodes
59 – 60
150 – 152
202
266 – 270
391 – 398
402



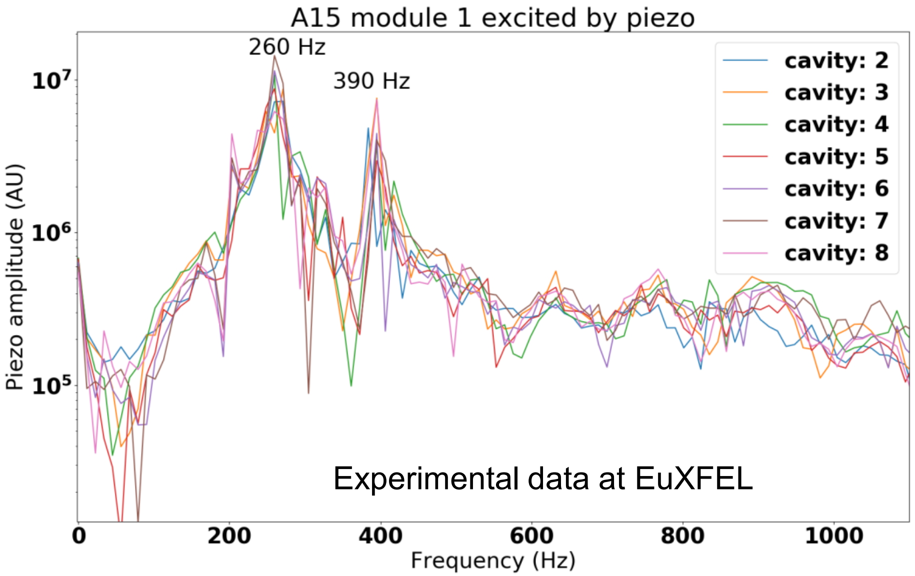
Source: S. Barbanotti, “Modal analysis of the XFEL 1.3 GHz cavity and cryomodule main components and comparison with measured data”, SRF 2019

- The modes can be observed **experimentally**
  - Exciting a piezo with a frequency sweep

OR

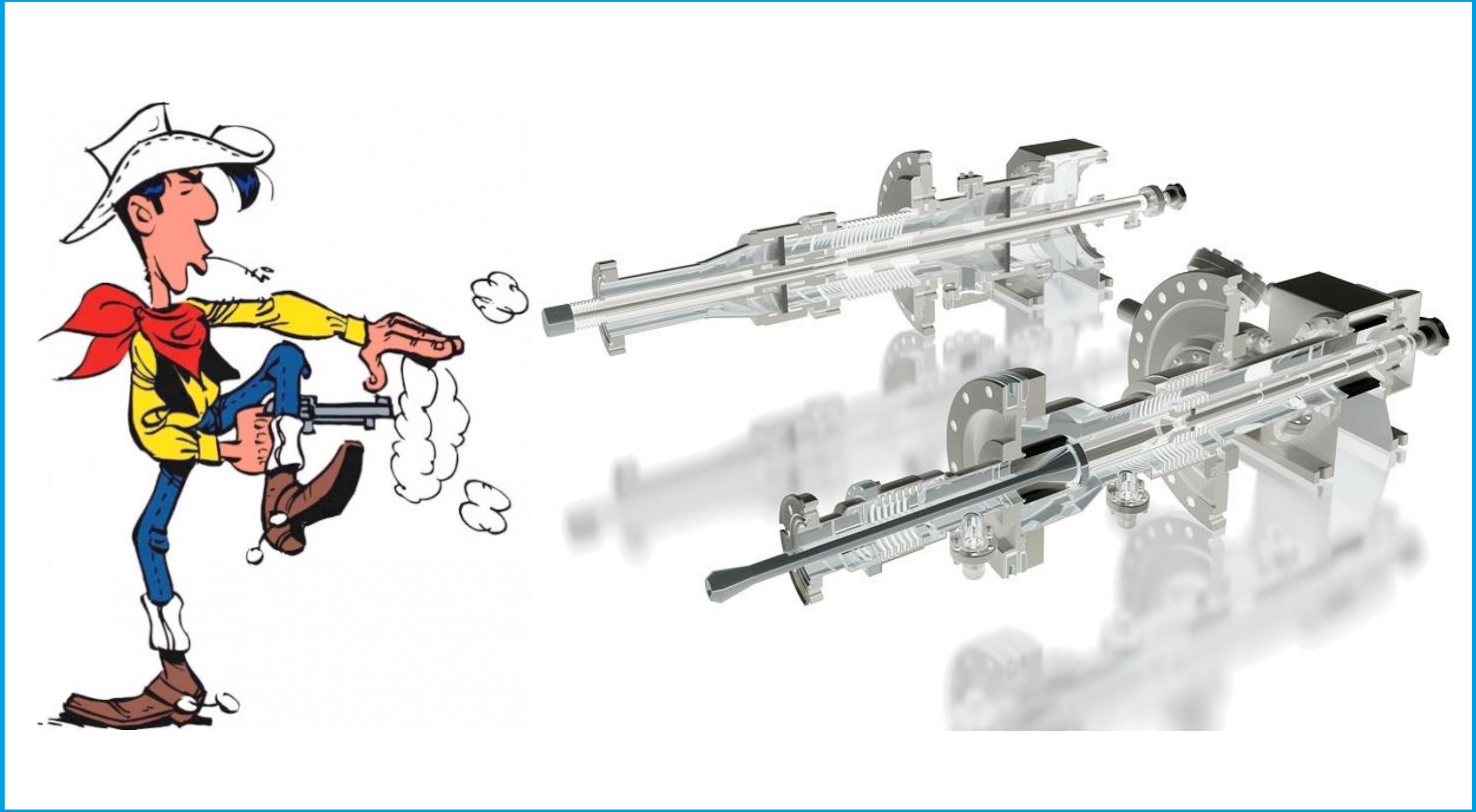
  - Using the pulsed RF as external stimulus

  - Measuring the piezo sensor response



Source: A. Bellandi, “LLRF R&D towards CW operation of the European XFEL”, Linac 2018

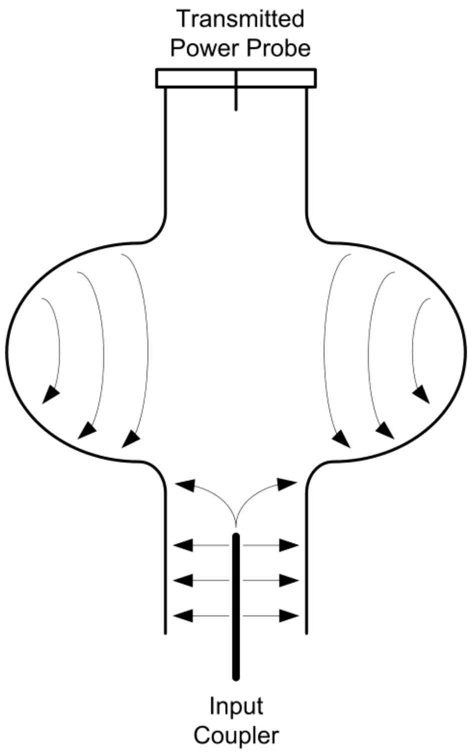
RF couplers



Coupler: Graphics Copyright: Rey.Hori / Mamoru Horiuchi. All rights reserved. ©Rey.Hori, 1995-2017
Lucky Luke: Graphics Copyright: Morris & Goscinny, 1946

Cavity coupling

Coupling power in and out of a cavity



Input coupler

- An antenna carries power from an RF source to the cavity
- The strength of the **input coupler** is adjusted by changing the penetration of the center conductor

Output coupler (pick up)

- the **transmitted power probe** (fixed coupler) picks up power transmitted through the cavity

Measurable "resulting" quality factor (**loaded** Q)

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

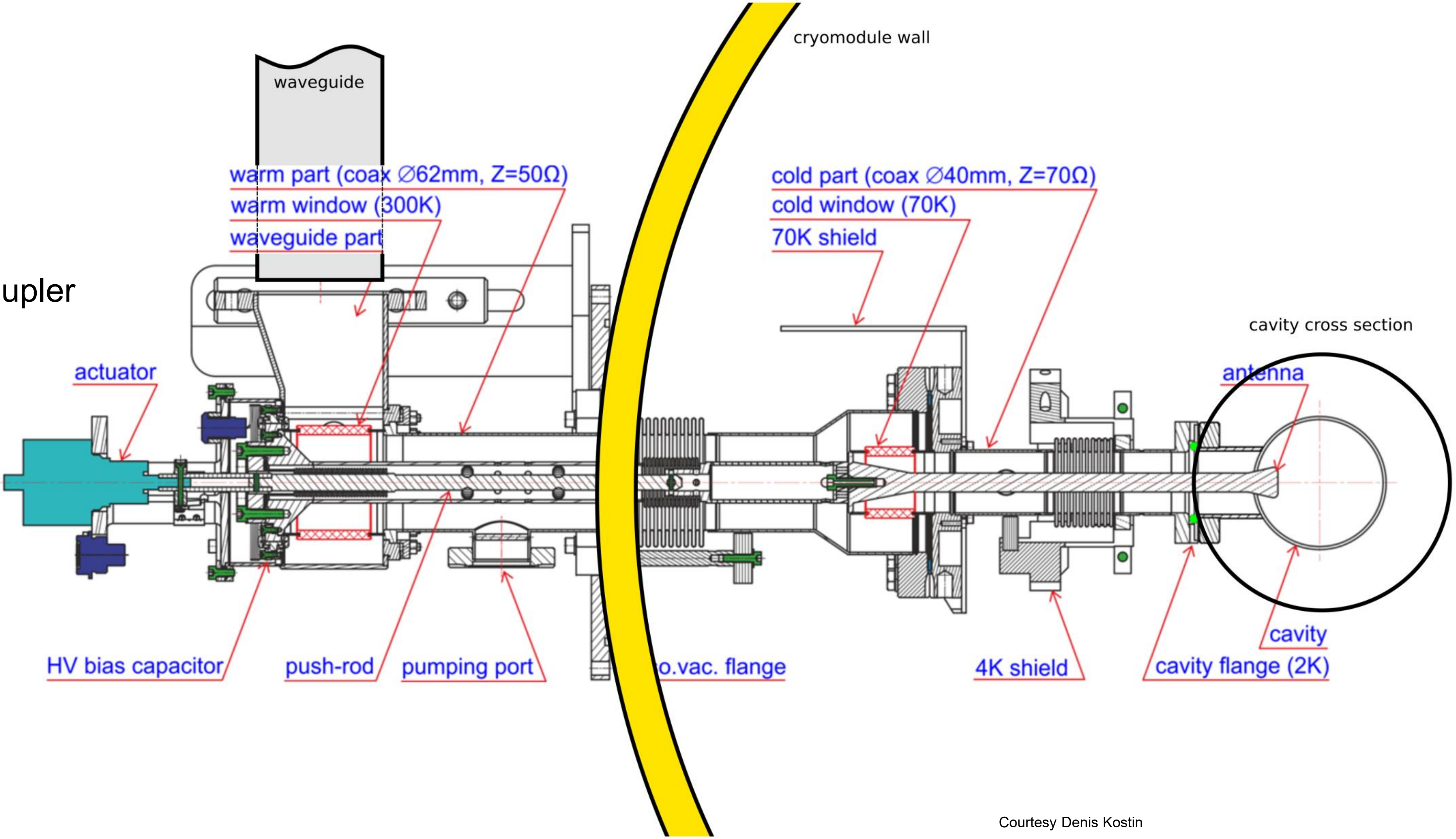
External quality factor modified by the coupler antenna position

Cavity **unloaded** quality factor

Cavity coupling

Example: fundamental input power coupler (FPC) for EuXFEL

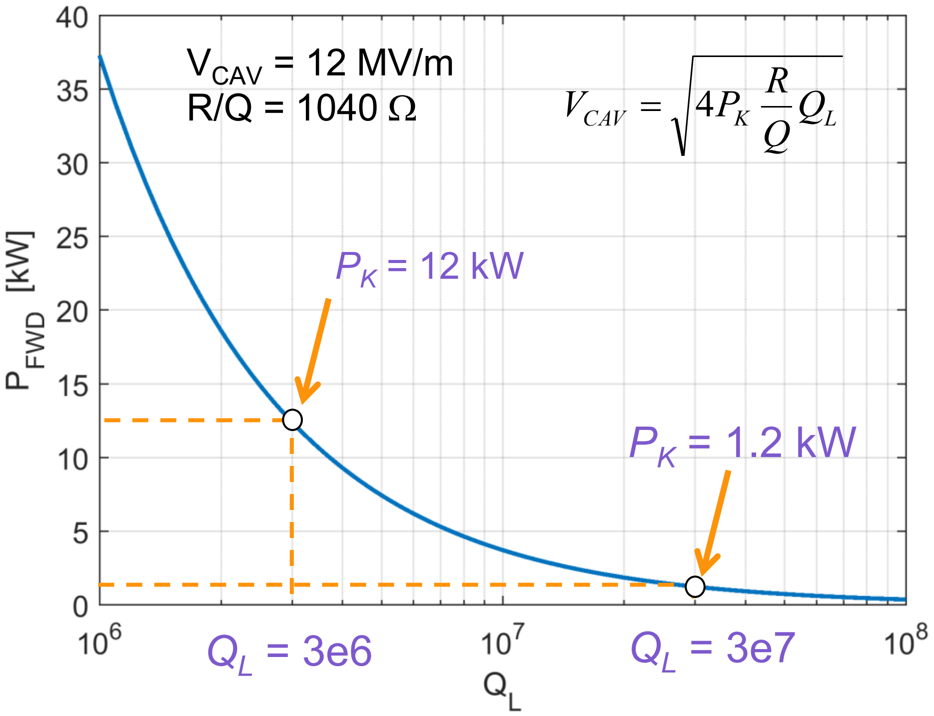
TTF –type coupler



Courtesy Denis Kostin

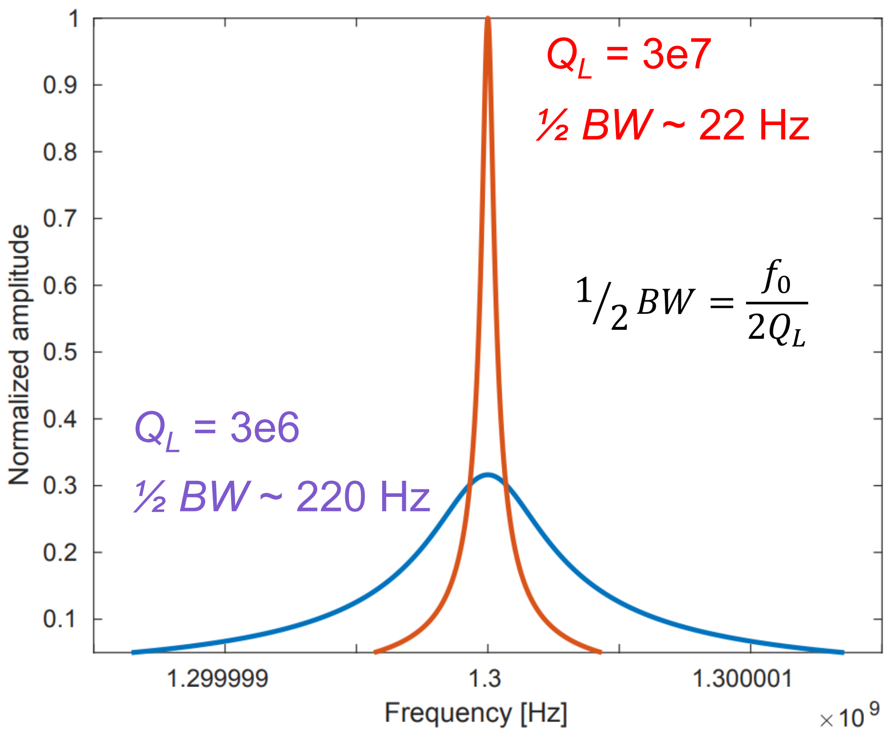
Cavity coupling

Changing Qext



With higher Q_L, **less power** is required to achieve same gradient.

Δf (cryo) ≈ 1 Hz (for a well-regulated cryo bath)



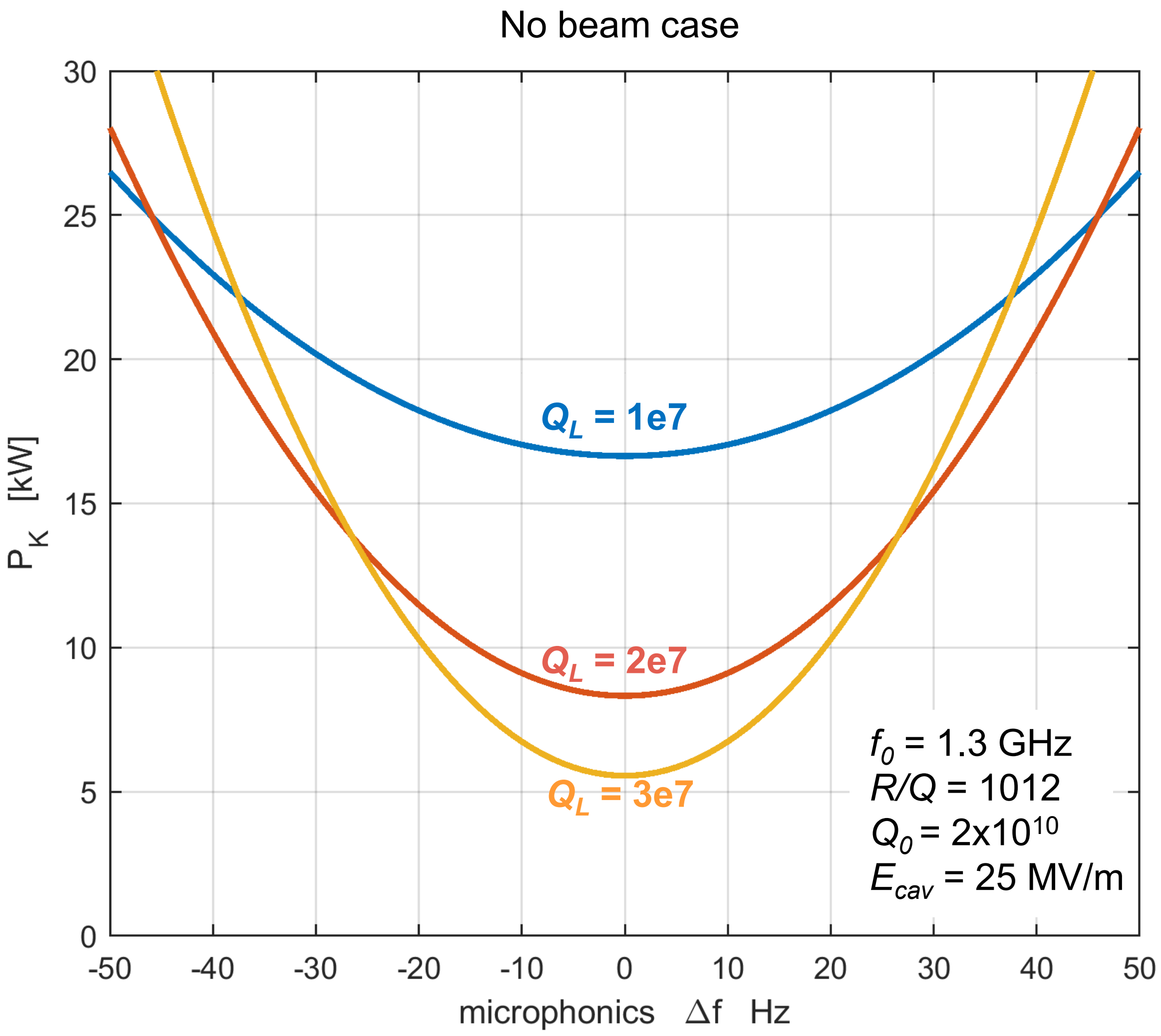
courtesy A. Bellandi

Increasing Q_L decreases the cavity bandwidth, making it **more sensitive to microphonics**.

Cavity coupling

Q_L , microphonics and power

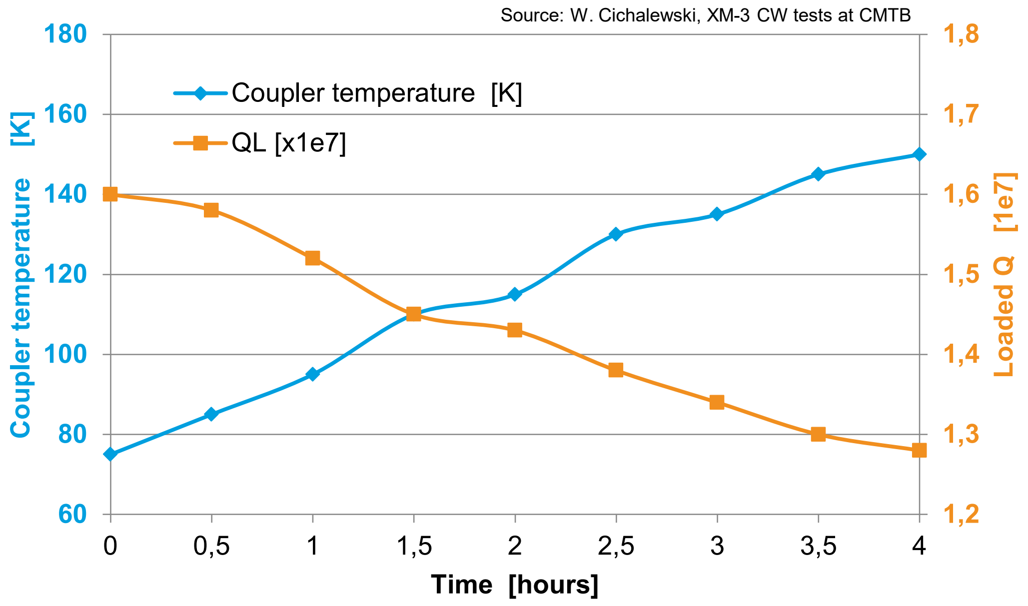
- Changing coupling has an impact on the **cavity sensitivity to microphonics**
- This translates into **RF power cost**, required for field regulation
- Example:
    - Plot shows the power required as a function of microphonic detuning for different values of Q_L



Cavity coupling

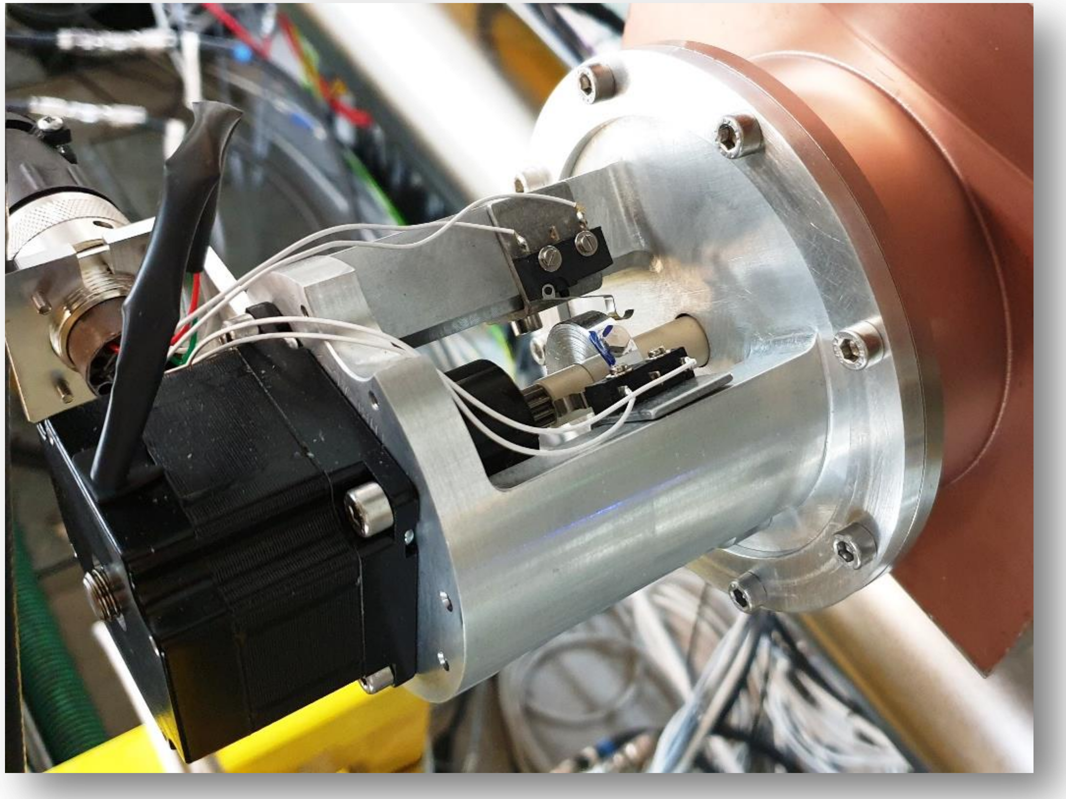
Adjustable coupler

- Coupler heating



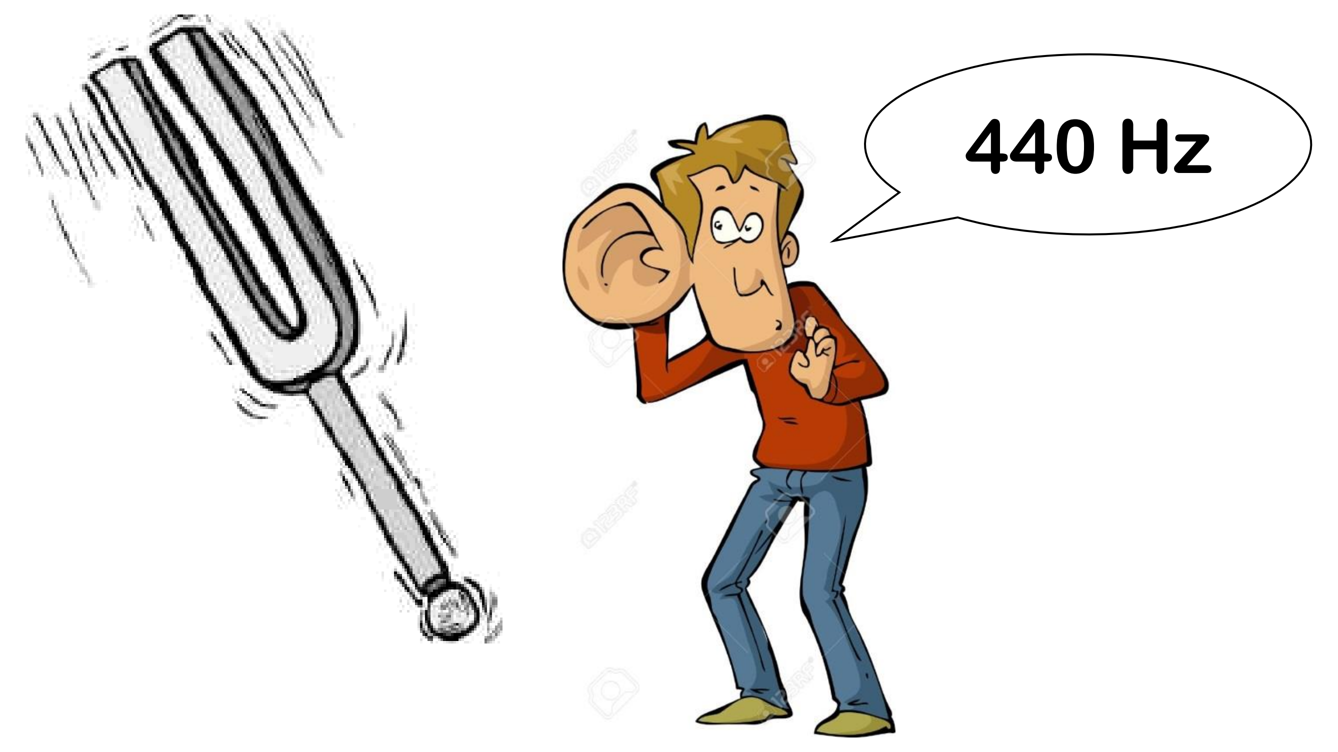
- Couplers heat up during operation, dilating the antenna, effectively lowering the loaded Q
- As a consequence, more power is needed to maintain the same gradient
- This further increases the coupler temperature, etc…

- Motor with end-switches



End switch on motorized coupler tuners on XM50.1 at DESY

Frequency tuners



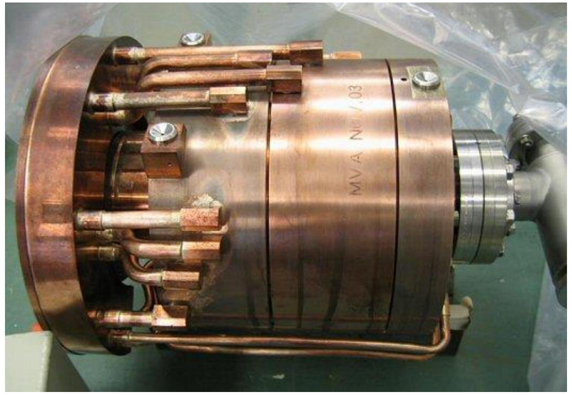
Tuning the cavity resonant frequency

- Resonance control is a fundamental part of the cavity RF system
  - Eg. copper cavities heat up and change frequency
  - Eg. synchrotrons often change frequency and cavities must track sometimes in the GHz/s rate

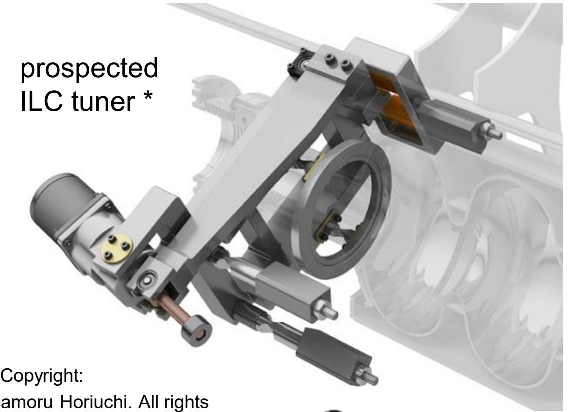
- SRF cavities have high loaded Qs and are thus more sensitivity to microphonics and Lorentz Force Detuning

- Tuning may be accomplished
  - by changing the cavity dimensions by temperature (i.e. water cooled normal conducting cavities)
  - by mechanical force, squeezing the cavity (i.e. motorized brackets)
  - electrically, using ferrite stubs (i.e. 3 stub tuners also affect Q_L and phase)

water cooled gun at PITZ



prospected ILC tuner *



* Graphics Copyright: Rey.Hori / Mamoru Horiuchi. All rights reserved. ©Rey.Hori, 1995-2017

3-stub tuner

Tuning the cavity resonant frequency

Slow and fast tuners

Slow tuners

Work over a large frequency range
Once on frequency they are only used to correct slow drifts

Note the mode dampers for the B and E strings

Fast tuners

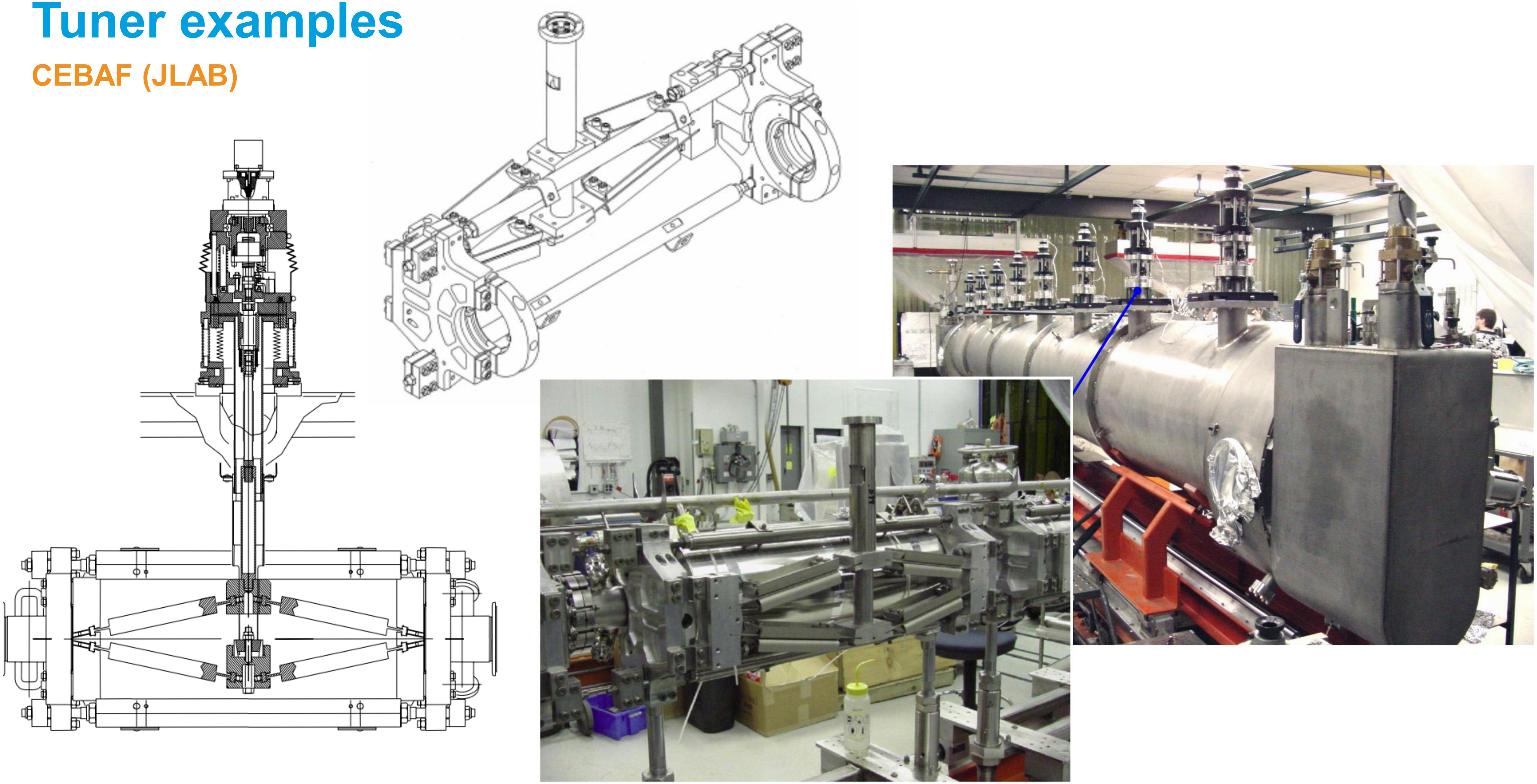
Used for fast dynamic resonance frequency modulation to compensate for microphonics or Lorentz Force Detuning

Stratocaster whammy bar

Courtesy B. Chase, FNAL

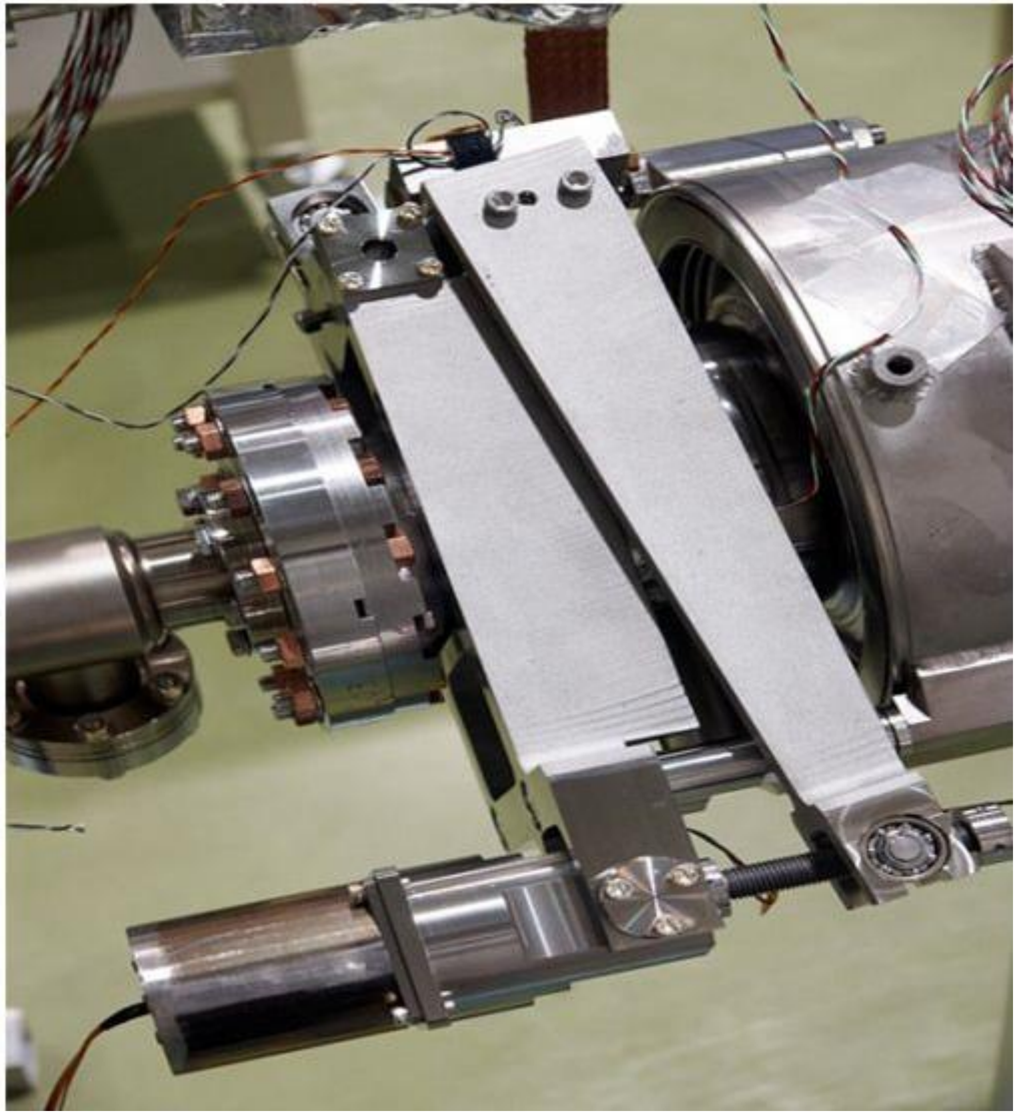
Tuner examples

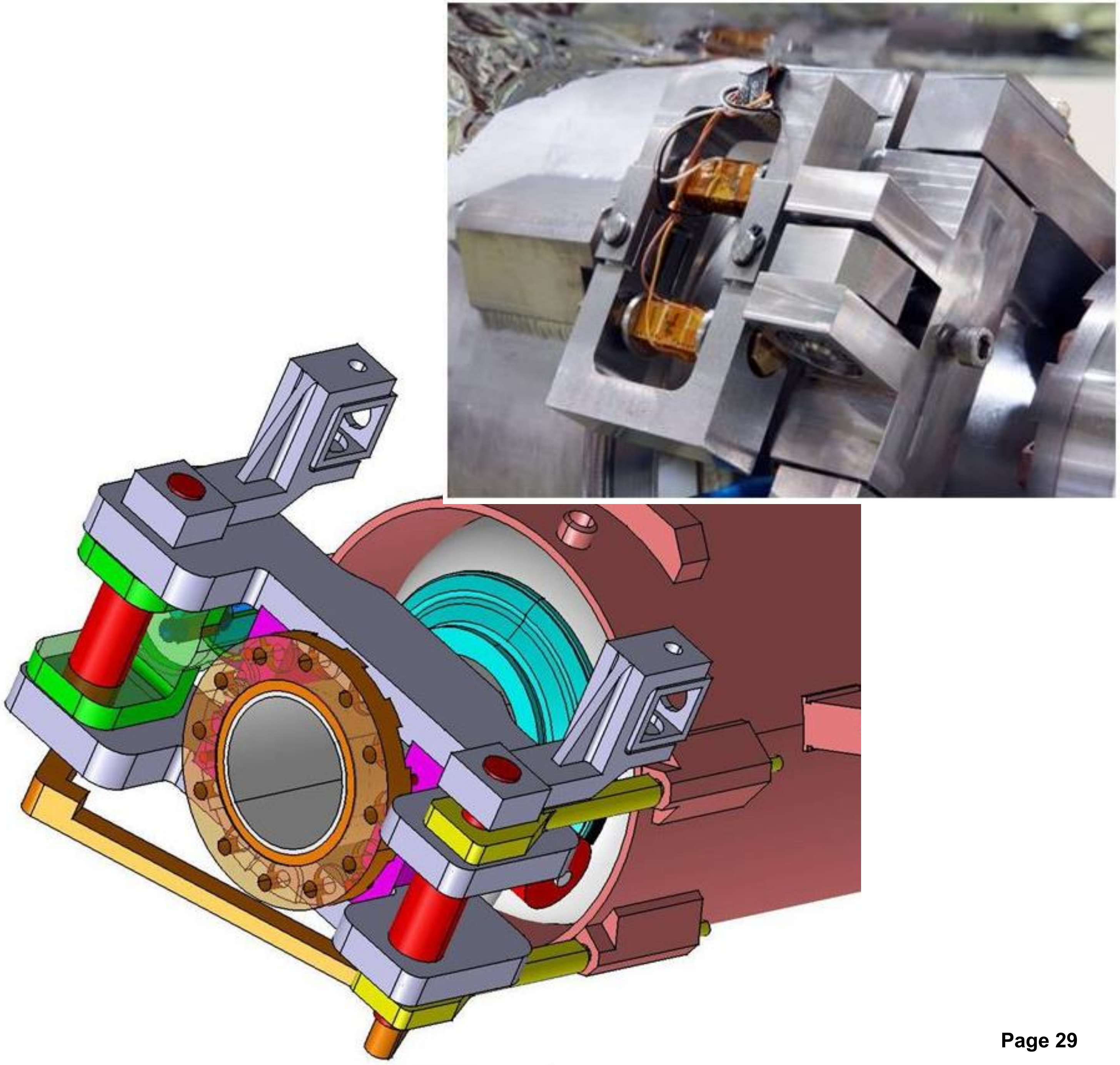
CEBAF (JLAB)



Tuner examples

Saclay type (EuXFEL)

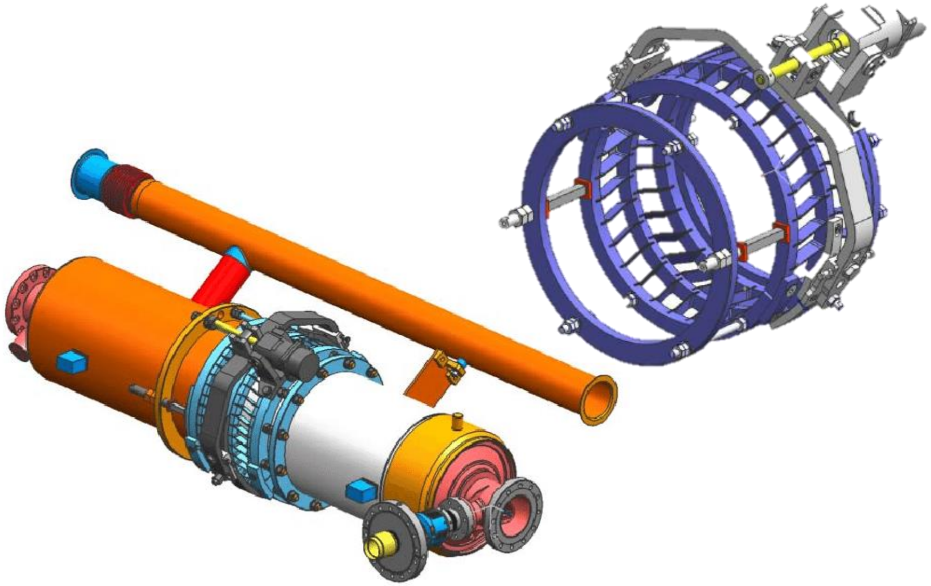




Tuner examples

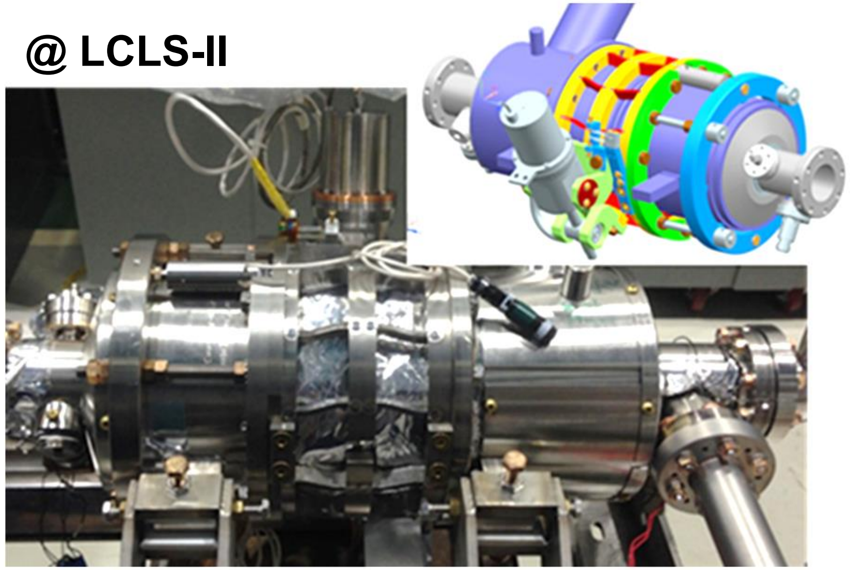
(Slim) blade tuner

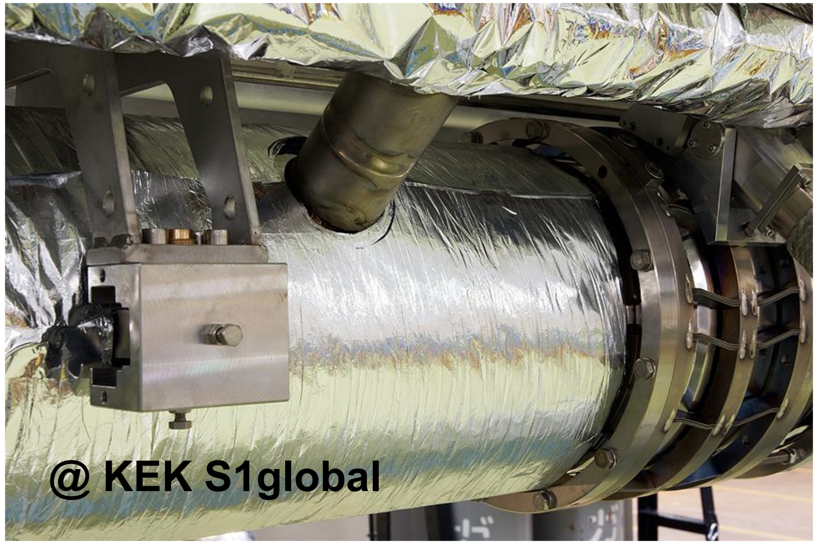
Blade tuner
First design



Slim blade tuner
Improved design
More economical
Tested in S1Global (KEK)
Used in 3.9 GHz EuXFEL
Used in 3.9 GHz LCLS-II with piezo

@ LCLS-II

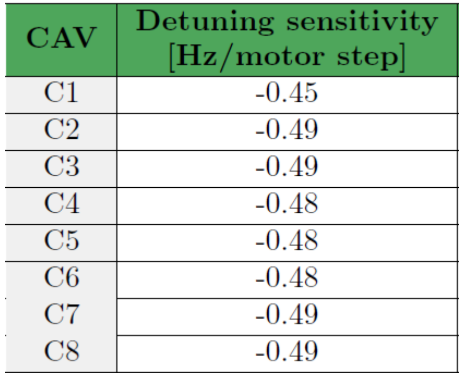




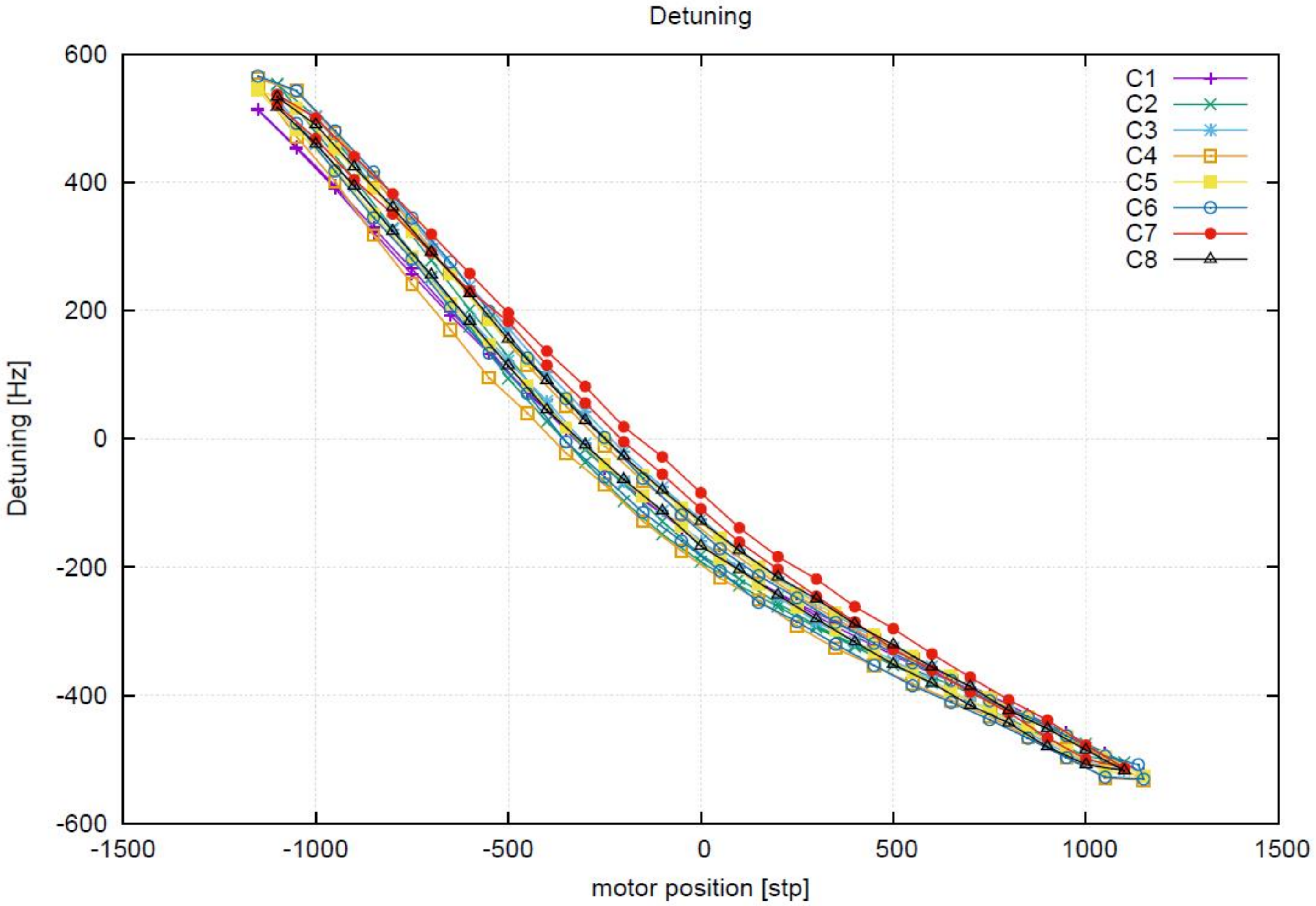
Tuners (continued)

Main characteristics

- Push / pull techniques
- Tuner pre-load
- **Motor sensitivity**
- Tuner backlash
- Motor lifetime



CAV	Detuning sensitivity [Hz/motor step]
C1	-0.45
C2	-0.49
C3	-0.49
C4	-0.48
C5	-0.48
C6	-0.48
C7	-0.49
C8	-0.49

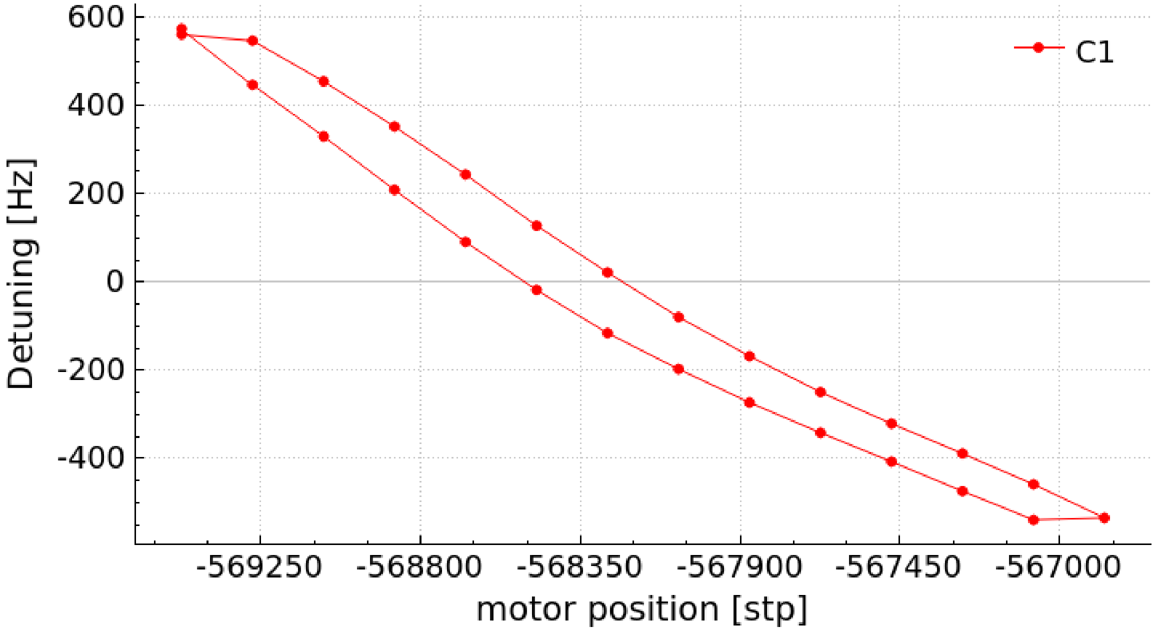


Example: EuXFEL XM36 tuner tests

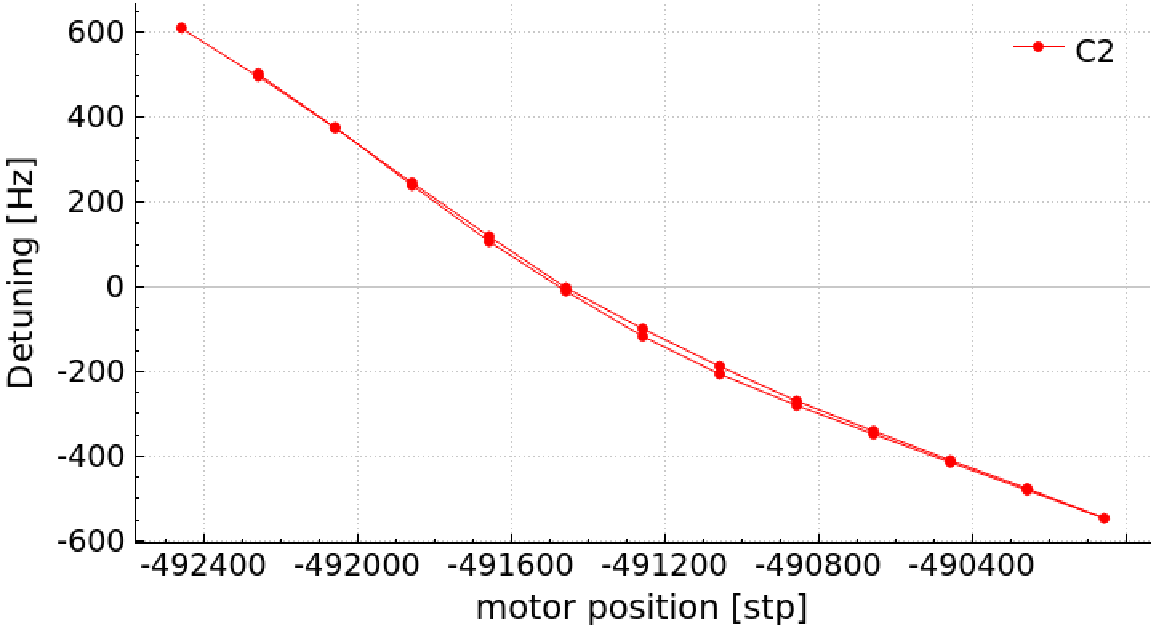
Tuners (continued)

Main characteristics

- Push / pull techniques
- Tuner pre-load
- Motor sensitivity
- **Tuner backlash**
- Motor lifetime



Example:
EuXFEL XM57 C1 and C2 tuner tests

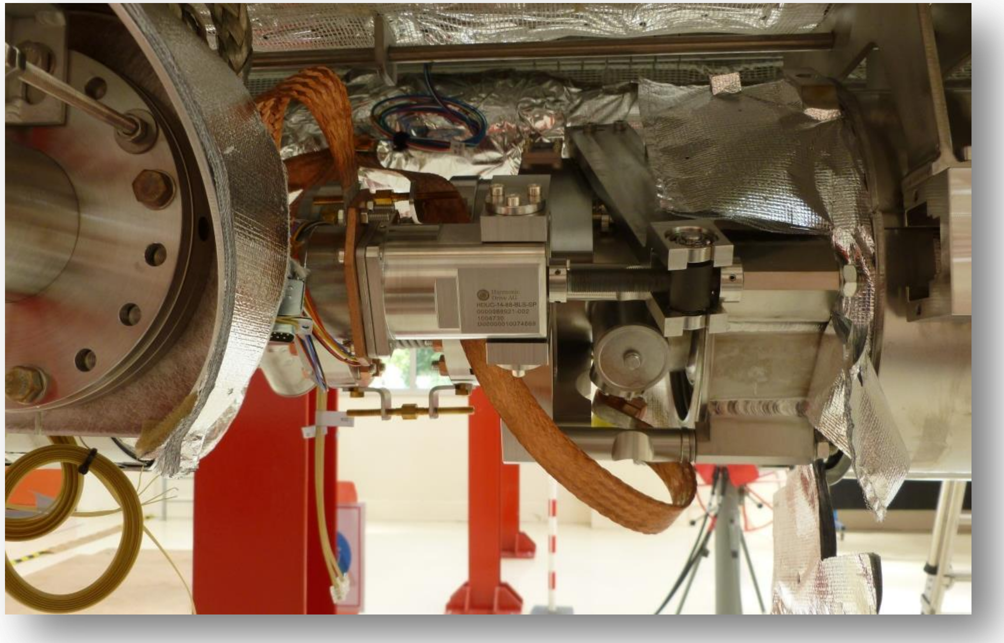


Tuners (continued)

Main characteristics

- Push / pull techniques
- Tuner pre-load
- Motor sensitivity
- Tuner backlash
- **Motor lifetime**
  - Limit motor drive (in time, in steps)
  - Avoid motor over heating (cooling with cooper braids)

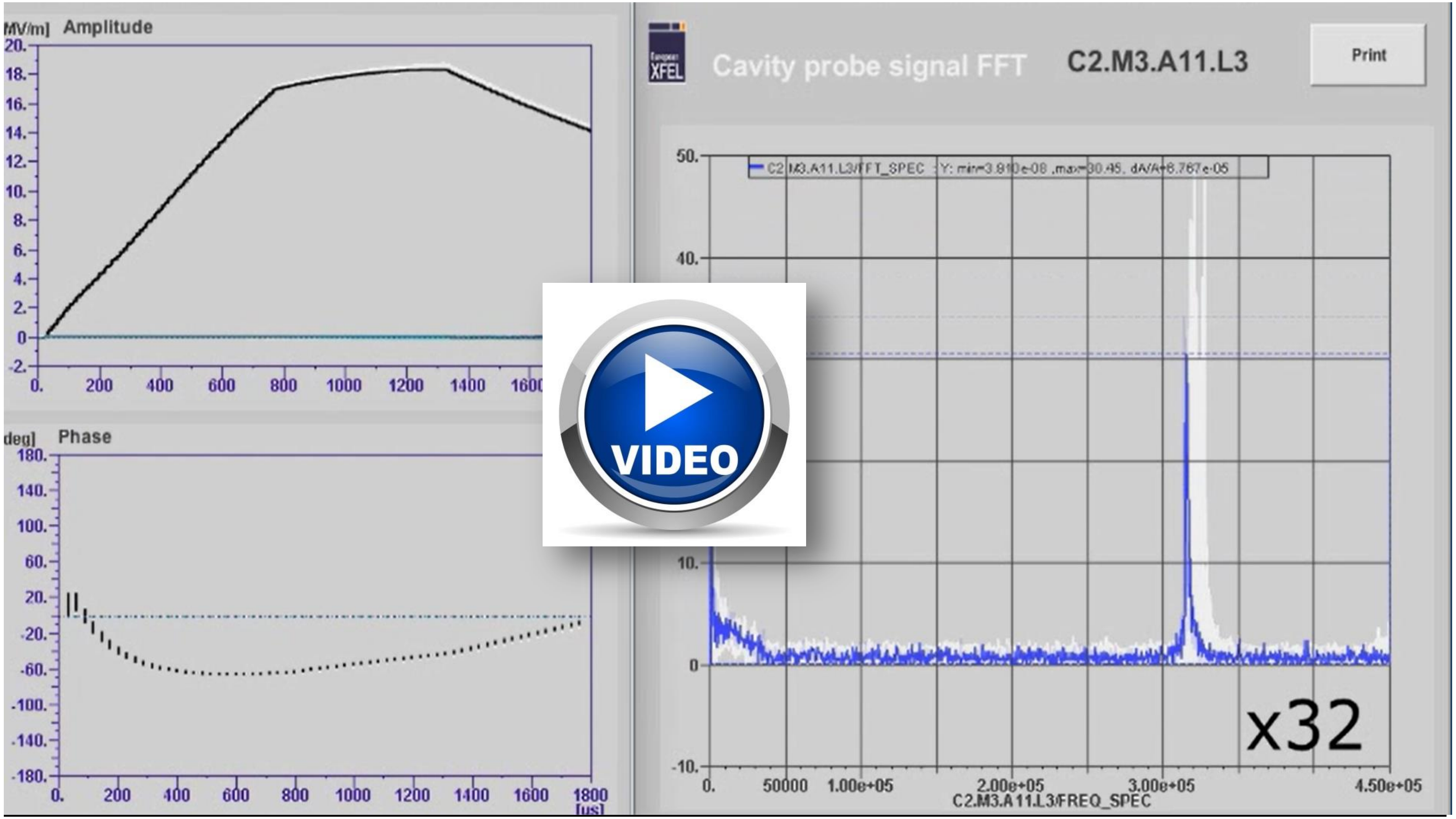
- Example: Eu-XFEL tuners
  - Expected lifetime ~ 15-20 million steps
  - Moving from parking position < 1 million steps (typ. 400-600 k steps)
  - → maximum 15-20 thermal cycles (> 20 years)
  - → 1 or 2 already used during cryomodule tests



Cavity tuning

Using “slow tuner”

- Tuning from parking position



video time = (32x then 8x) actual time

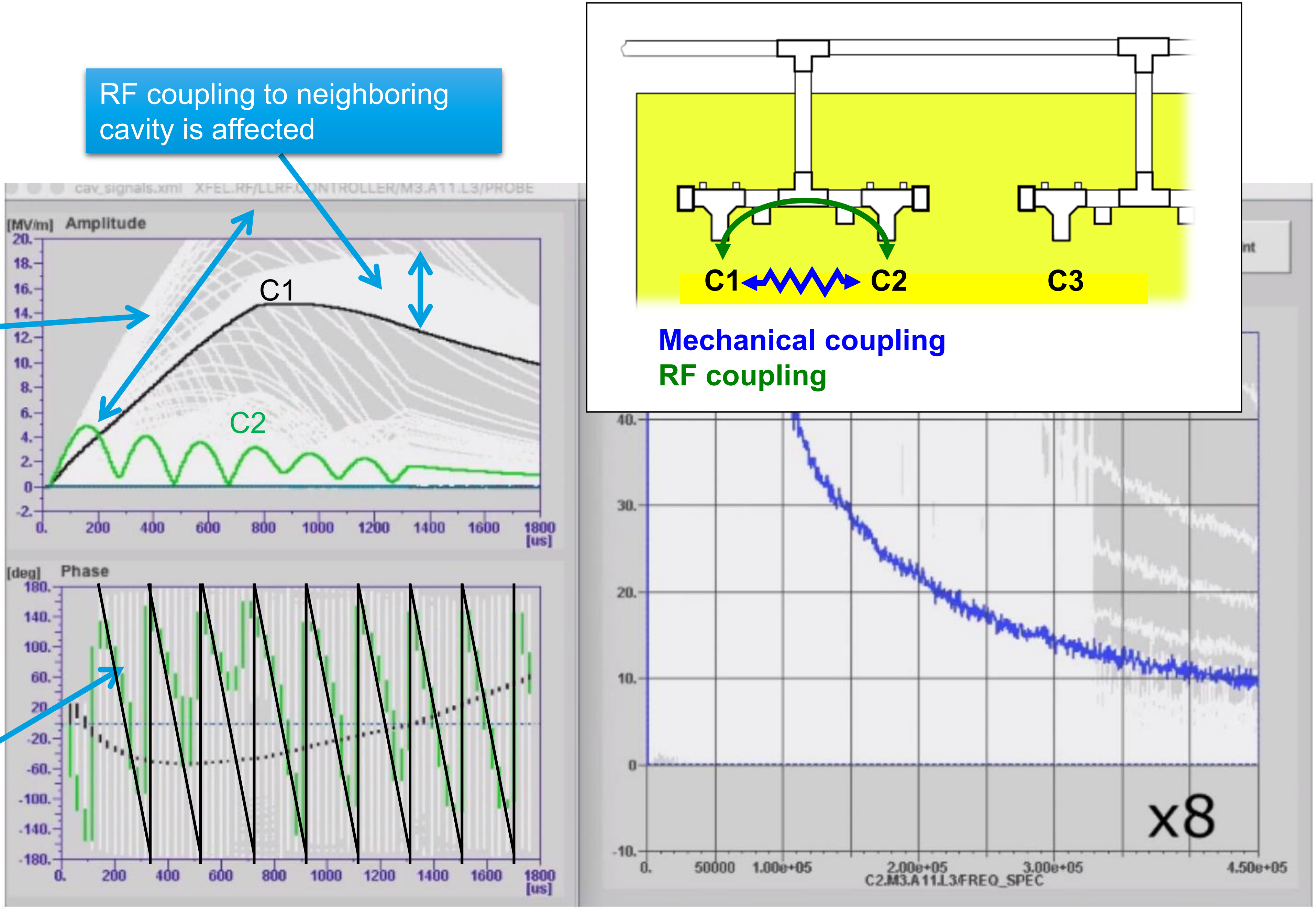
Cavity tuning

Using “slow tuner”

RF coupling to neighboring cavity is affected

Detuning is visible from cavity amplitude

Detuning is visible from cavity phase $\frac{d\varphi}{dt}$



Cavity tuning

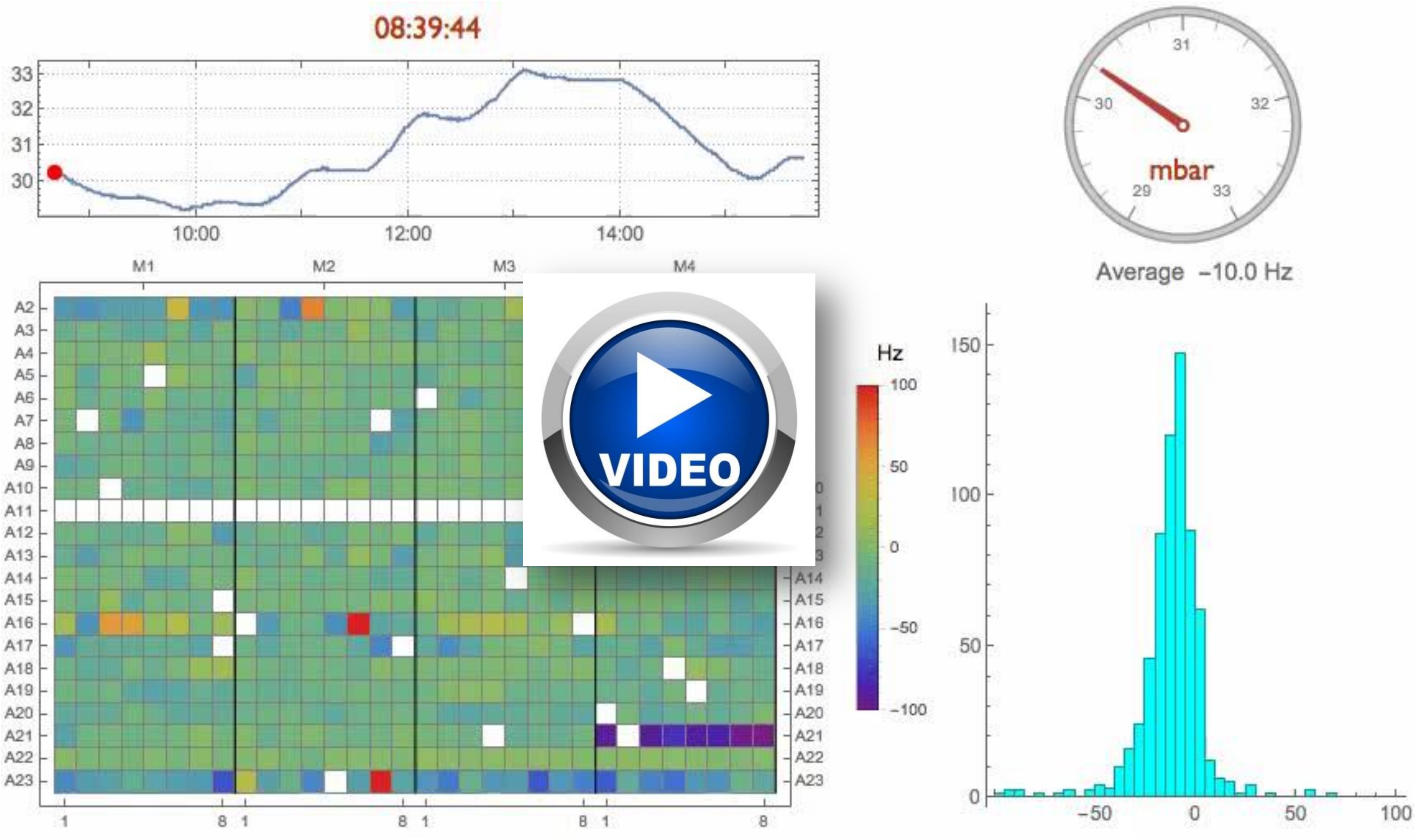
Impact of cryogenic bath

Study @ XFEL

- Vary the helium bath pressure
- Observe cavity detuning (800)

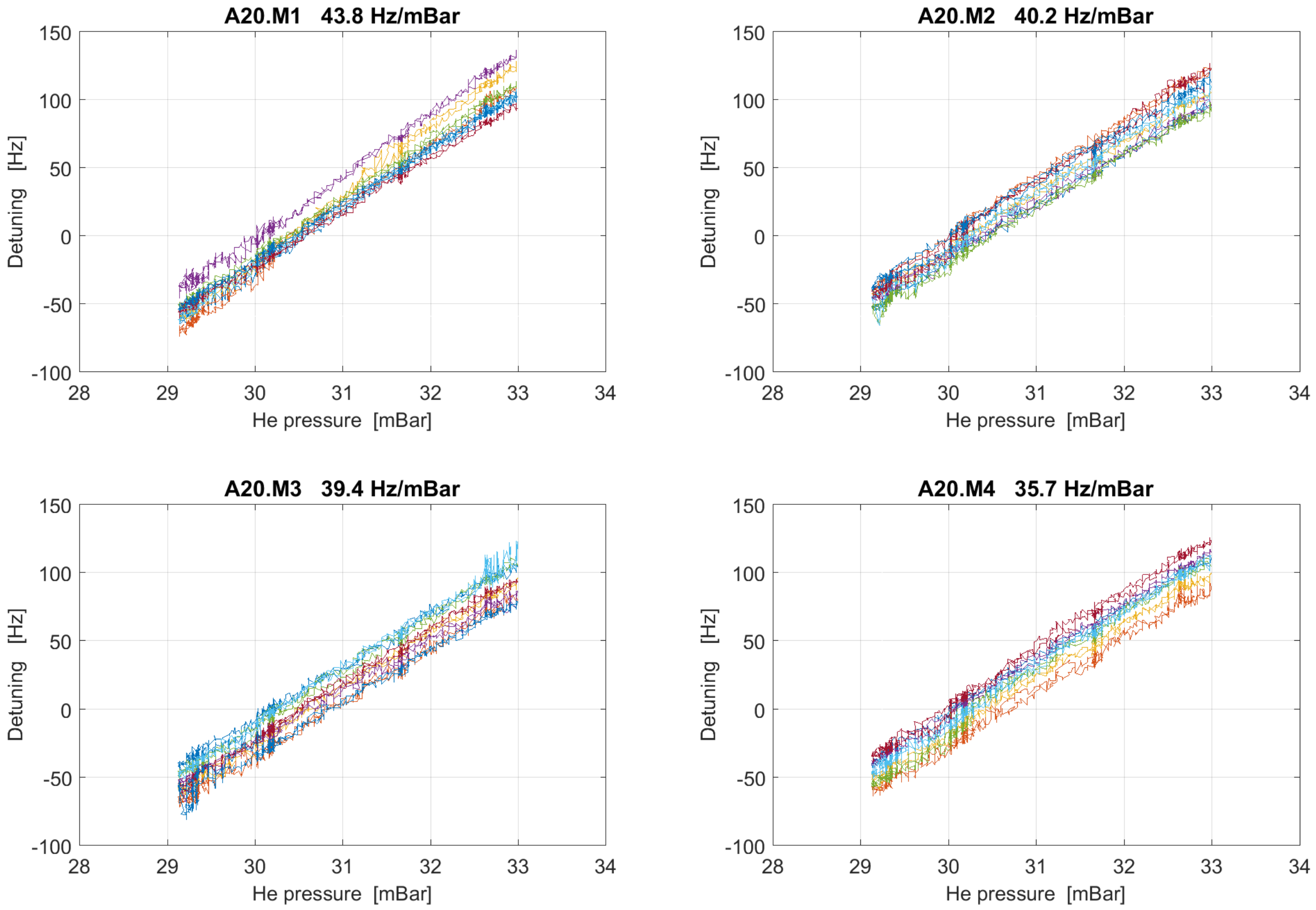
Goal

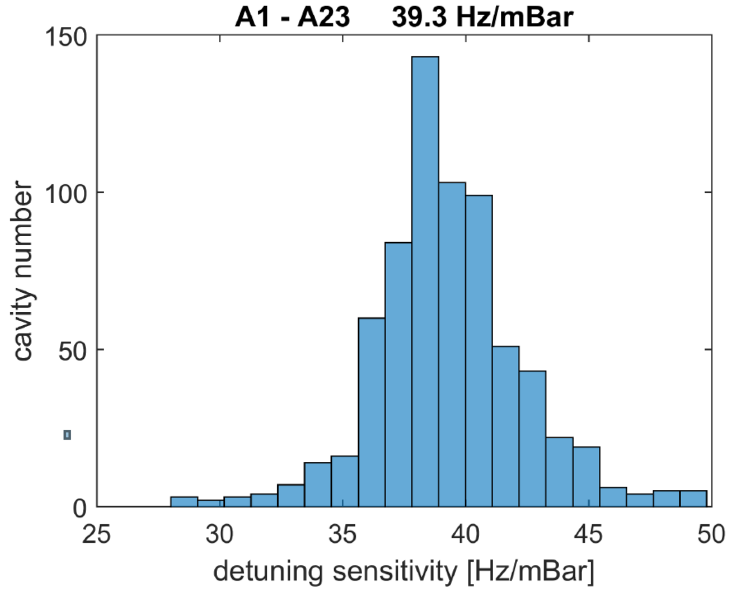
- Derive the cavity tuning sensitivity to He pressure fluctuations (i.e df/dp)
- Set safety RF operation thresholds regarding helium excursions



Cavity tuning

Impact of cryogenic bath





40 Hz/mBar for 1.3 GHz cavities

62 Hz/mBar for 3.9 GHz cavities

L.L.R.F.
Low Level Radio Frequency

LLRF

Low level radio frequency

Low Level = low power

- mW – W

High Power

- kW – MW

10^{-3}

mW

10^{0}

W

10^{3}

kW

10^{6}

MW

LLRF

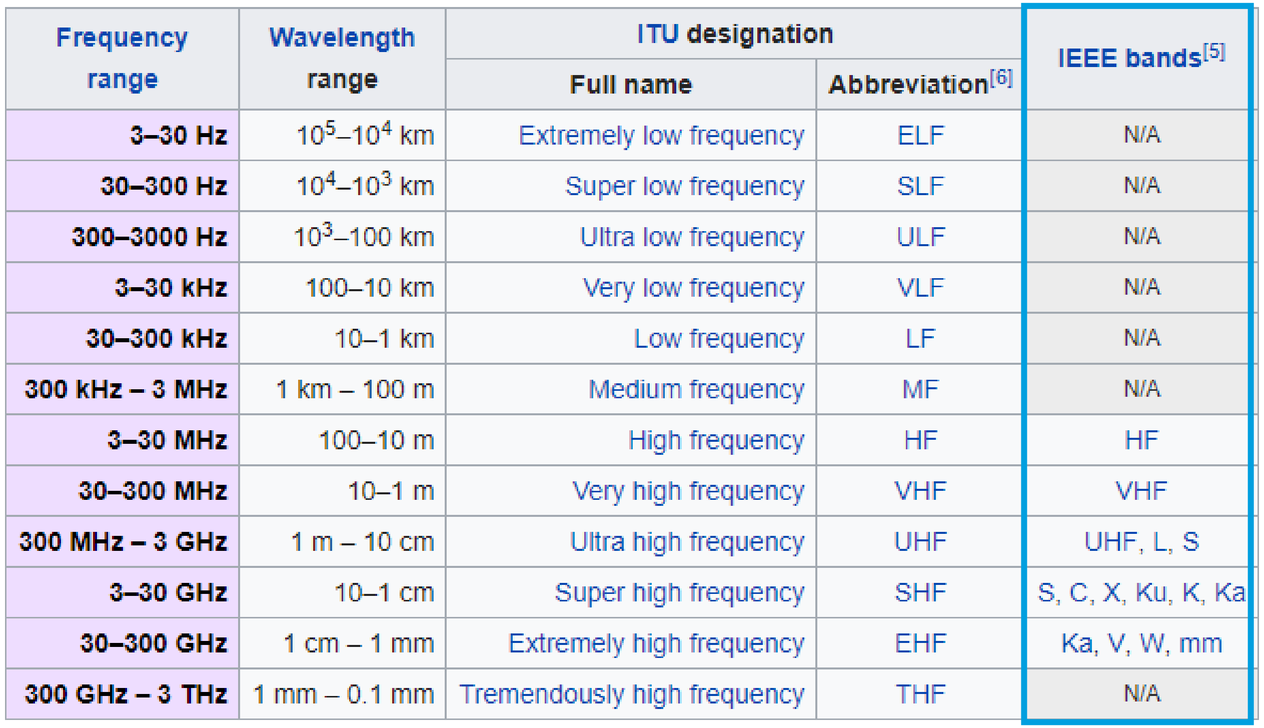
Low level radio frequency

Radio frequency (**RF**) is the oscillation rate of an alternating electric current or voltage or of a magnetic, electric or electromagnetic field or mechanical system in the frequency range from around twenty thousand times per second (**20 kHz**) to around three hundred billion times per second (**300 GHz**).

This is roughly between the **upper limit of audio frequencies** and the **lower limit of infrared frequencies.**

These are the frequencies at which energy from an oscillating current can radiate off a conductor into space as **radio waves**.

Source: Wikipedia



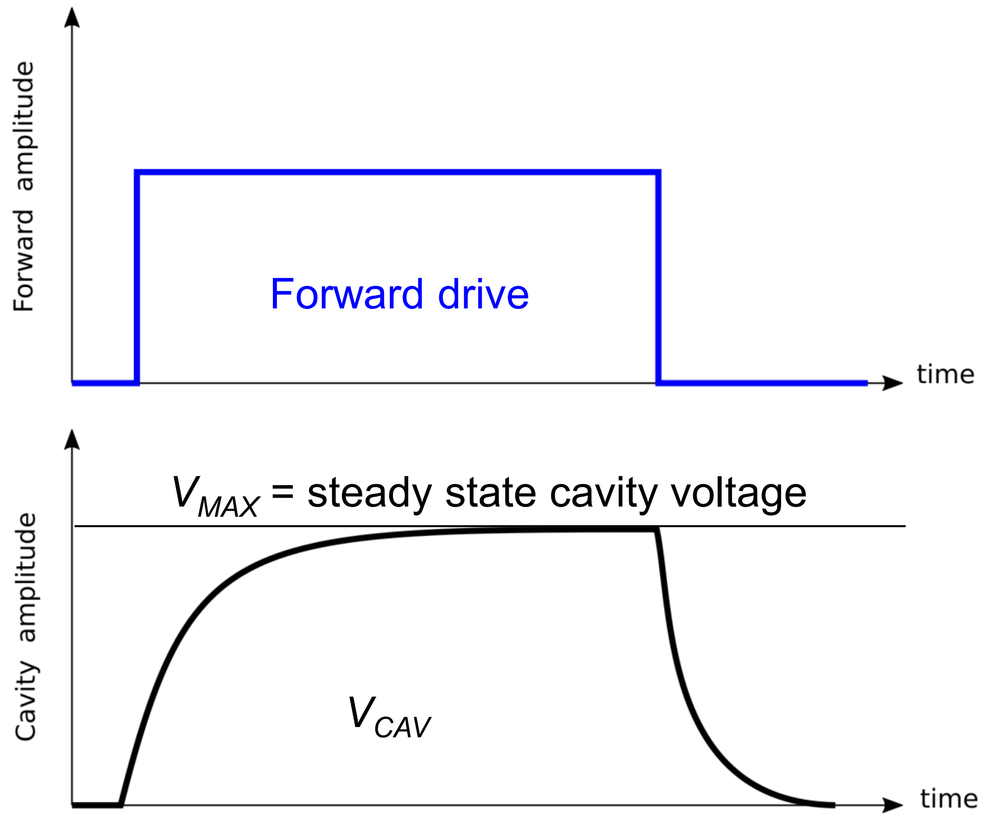
Frequency range	Wavelength range	ITU designation		IEEE bands[5]
		Full name	Abbreviation[6]	
3–30 Hz	10^5–10^4 km	Extremely low frequency	ELF	N/A
30–300 Hz	10^4–10^3 km	Super low frequency	SLF	N/A
300–3000 Hz	10^3–100 km	Ultra low frequency	ULF	N/A
3–30 kHz	100–10 km	Very low frequency	VLF	N/A
30–300 kHz	10–1 km	Low frequency	LF	N/A
300 kHz – 3 MHz	1 km – 100 m	Medium frequency	MF	N/A
3–30 MHz	100–10 m	High frequency	HF	HF
30–300 MHz	10–1 m	Very high frequency	VHF	VHF
300 MHz – 3 GHz	1 m – 10 cm	Ultra high frequency	UHF	UHF, L, S
3–30 GHz	10–1 cm	Super high frequency	SHF	S, C, X, Ku, K, Ka
30–300 GHz	1 cm – 1 mm	Extremely high frequency	EHF	Ka, V, W, mm
300 GHz – 3 THz	1 mm – 0.1 mm	Tremendously high frequency	THF	N/A

L band: 1-2 GHz
S band: 2-4 GHz
C band: 4-8 GHz
X band: 8-12 GHz

LLRF System

Feed Forward

- Cavity response to a square pulse



Q_L affects the cavity rate of filling

Q_L is there

$$\tau = \frac{Q_L}{2\omega_0}$$

$$V_{CAV} = V_{MAX}(1 - e^{-t/\tau})$$

$$V_{MAX} = 2\sqrt{P_{FWD}\frac{R}{Q}Q_L}$$

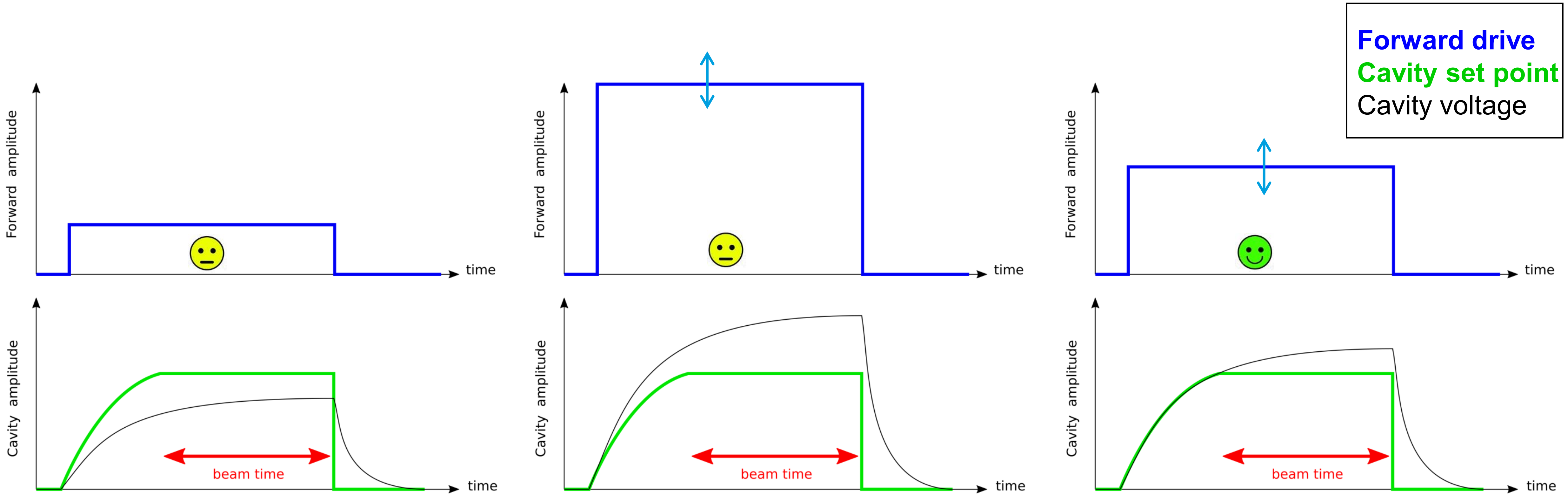
Q_L is there

Q_L affects the cavity maximum voltage (for a given forward power)

LLRF System

Feed Forward

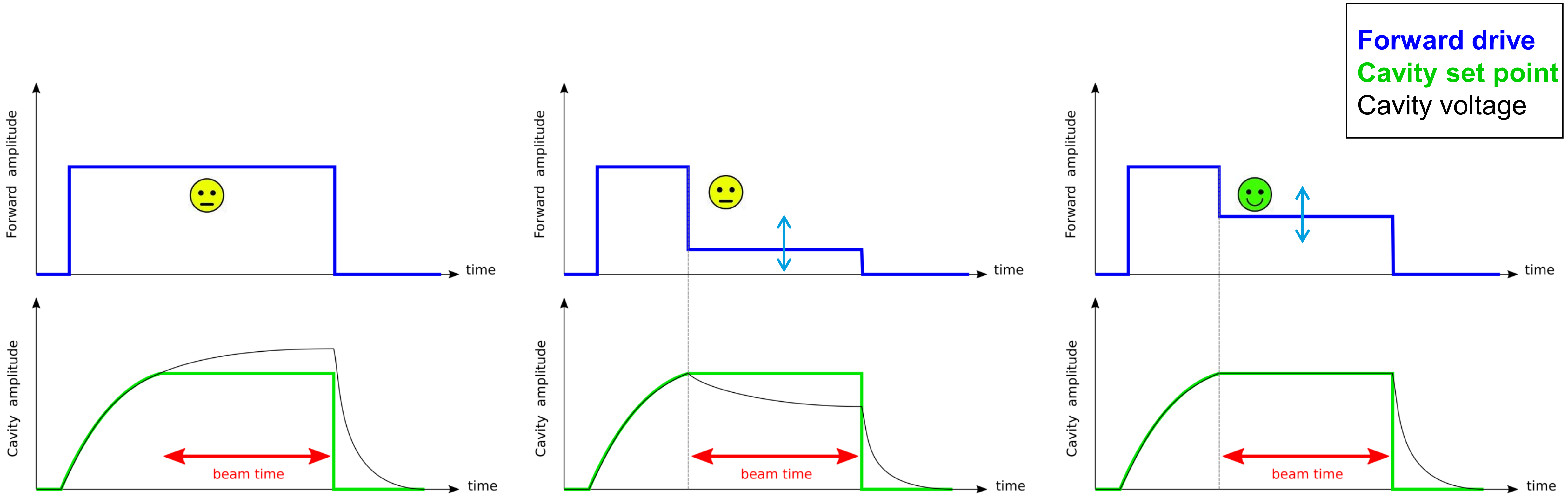
- Adjust amplitude of the **forward drive** to match the set point gradient **at the beginning of the beam time**



LLRF System

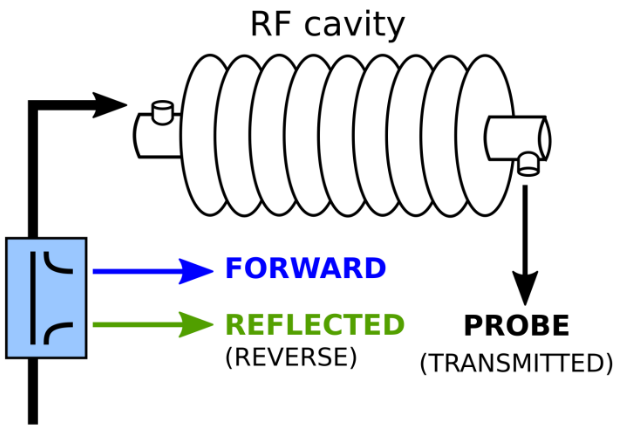
Feed Forward

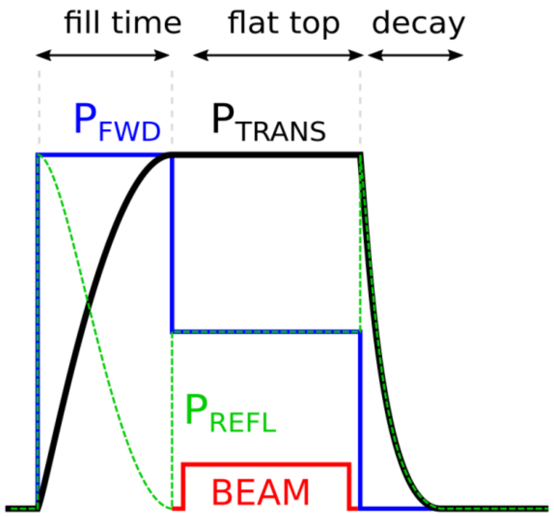
- Adjust the drive **during the beam time** to **maintain a flat accelerating gradient**



LLRF System

Forward, Reflected and Probe Signals





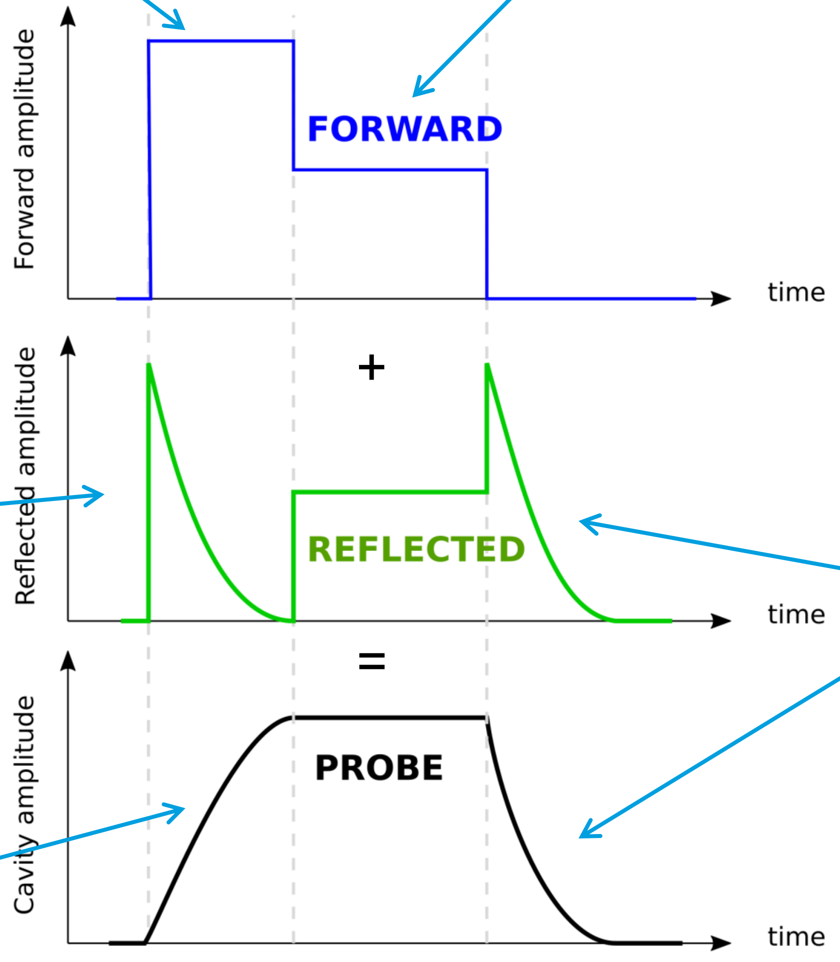
High forward power to fill cavity as fast as possible

Drop forward power when target gradient is reached (i.e. don't fill till steady state)

Forward power is first reflected (impedance mismatch)

Cavity "empties" itself at the same rate from each pick up

Cavity "fills up" (low pass filter to a step response)

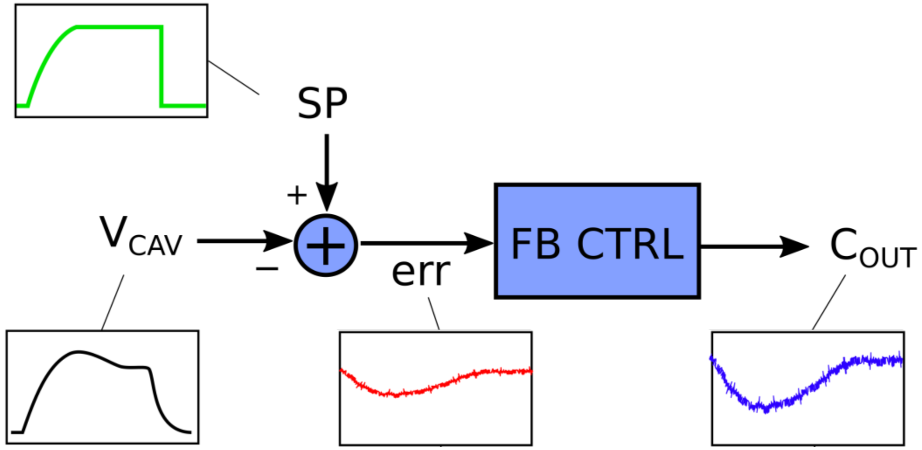


LLRF System

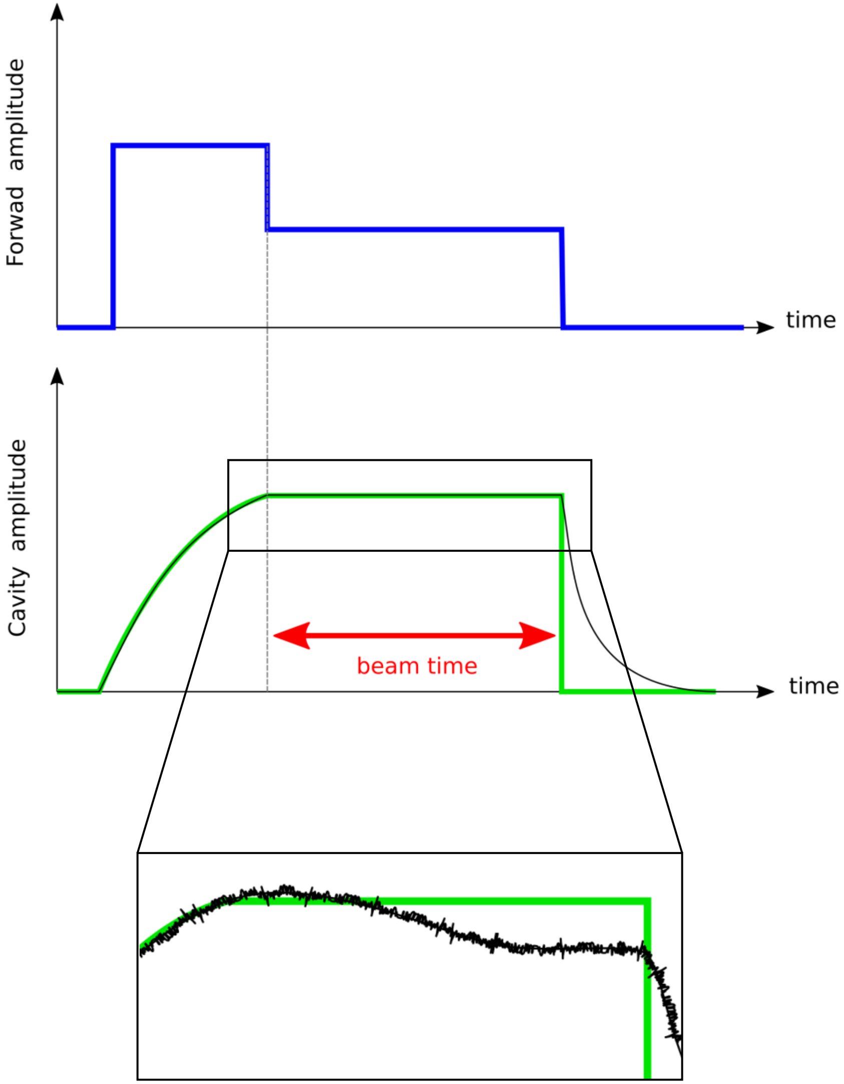
Why do we need feedback?

- *“Feed forward only gets you in the ball park, but you need feedback to achieve the regulation required by the beam”*

- Compute error: err = SP – V_{CAV}



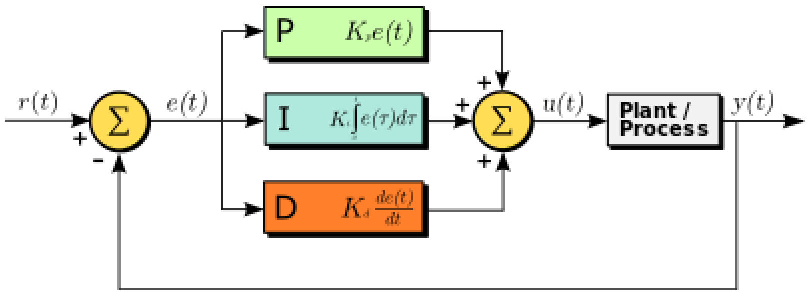
- Simplest feedback is proportional : $C_{OUT} = K_P * err$



LLRF System

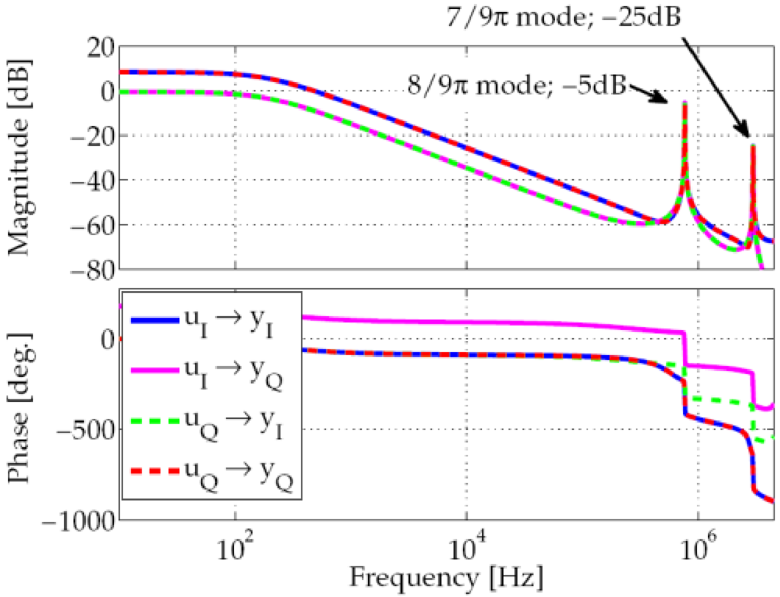
Feedback

- **Classic feedback controllers**



  - **P: proportional controller** output scales with the input error
  - **I: integral controller** minimizes the steady state error left from the proportional controller correction
  - **D: differential controller** tries to minimize rapid error changes

- **Modern feedback controller**
  - e.g. 2x2 MIMO controller (can do PID and more…)
    - Cancellation of one pass band mode
    - Cancellation of cross coupling between inputs

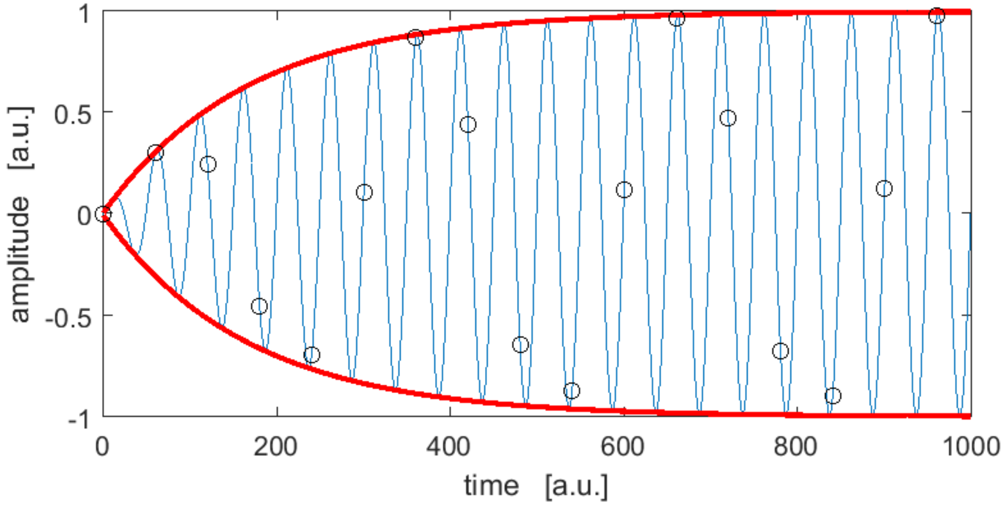


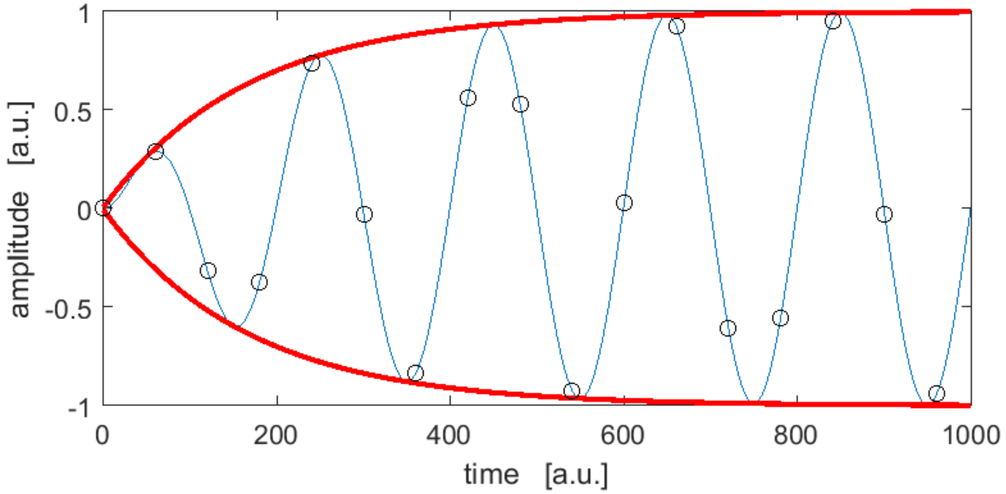
Reference : S. Pfeiffer: "*LLRF controls and Feedback*", CERN Accel. School on FELs & ERLs, Hamburg, 2016
S. Pfeiffer: "*Advanced LLRF system setup tool for RF field regulation of SRF cavities*", SRF, 2019

LLRF System

Down Conversion

- Transfer envelop information of the cavity signals to a lower carrier frequency, easier to digitize
  - RF frequency: 1.3 GHz
  - Typical ADC sample frequencies 60-150 MSPS
  - Typical down converted frequencies: 10-60 MHz





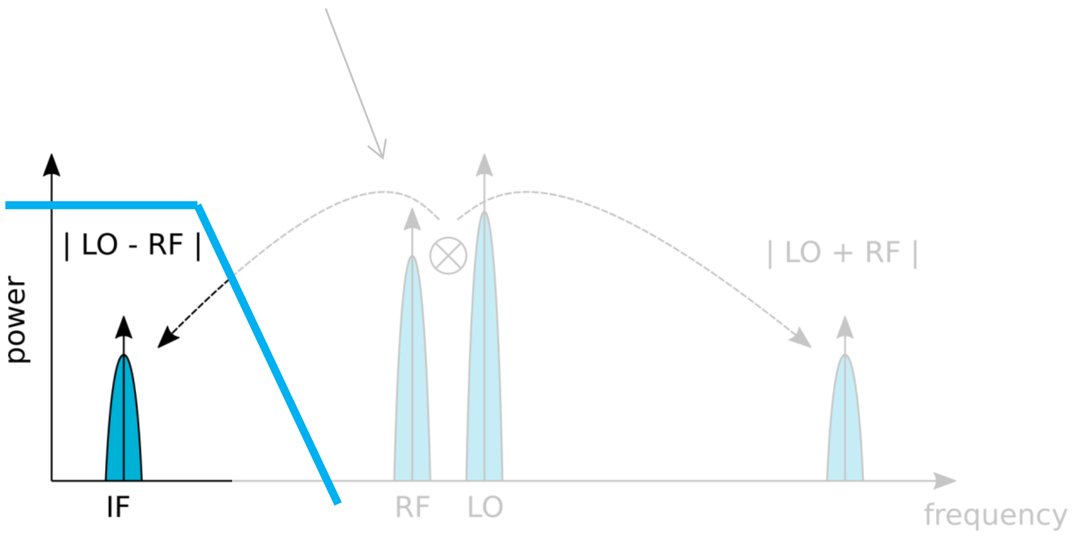
LLRF System

Down Conversion

- Frequency translation

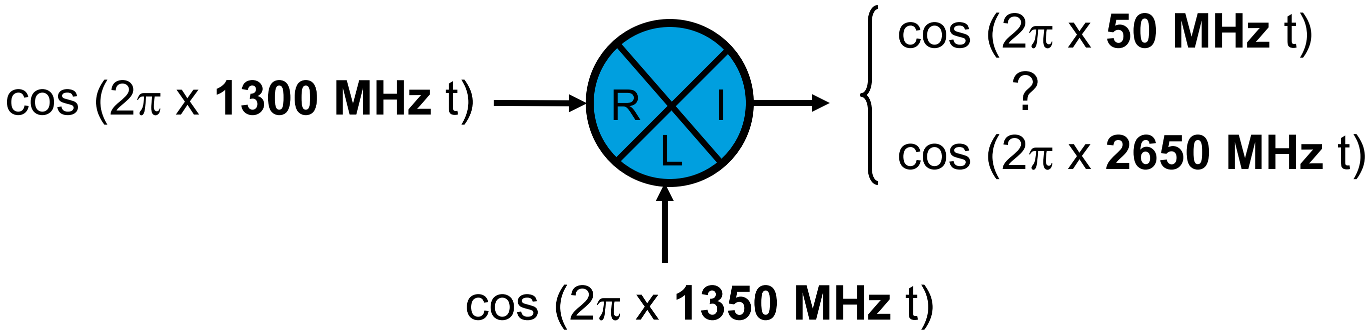
  from Radio Frequency **RF**
  to Intermediate Frequency **IF**
  via a Local Oscillator **LO** signal


Source: RF microwave


Cavity signal with relevant information (probe, forward, reflected) at RF frequency

- The fundamental component allowing for this operation is the **RF mixer**

- The corresponding operation is a **frequency multiplication**



cos (2π x **1300 MHz** t)

cos (2π x **1350 MHz** t)

cos (2π x **50 MHz** t)
?
cos (2π x **2650 MHz** t)

⇨

$$\cos a \cos b = \frac{1}{2}\cos(a+b) + \frac{1}{2}\cos(a-b)$$

$$\sin a \sin b = \frac{1}{2}\cos(a-b) - \frac{1}{2}\cos(a+b)$$

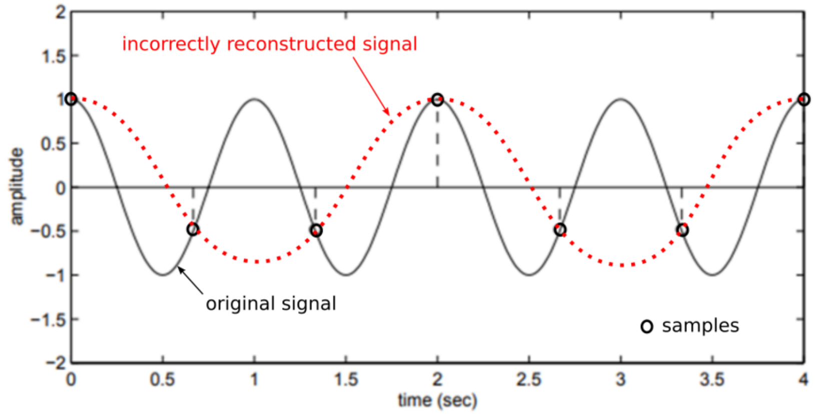
$$\sin a \cos b = \frac{1}{2}\sin(a+b) + \frac{1}{2}\sin(a-b)$$

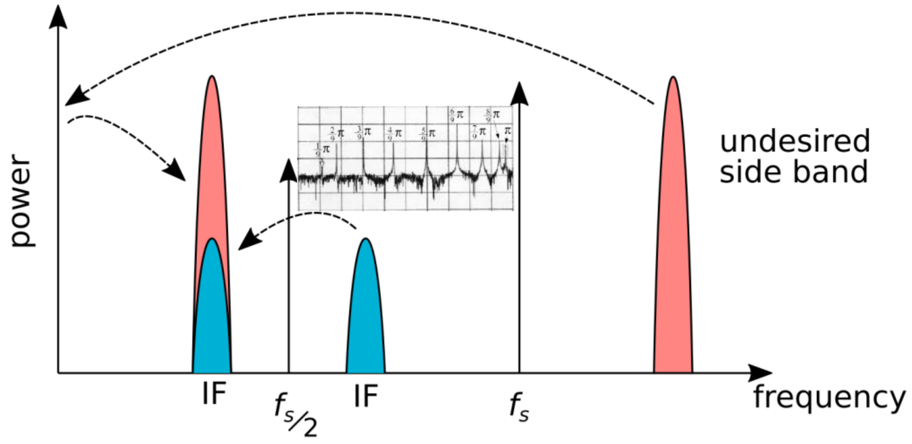
$$\cos a \sin b = \frac{1}{2}\sin(a+b) - \frac{1}{2}\sin(a-b)$$

LLRF

Sampling

- Sampling frequency
  - Under-sampling looses information
  - avoid undesired information (noise, side bands), folding onto the carrier information
- Nyquist frequency
  - *“the minimum rate at which a signal can be sampled without introducing errors, which is twice the highest frequency present in the signal.”*
  - In practice, under sampling is OK if the signal bandwidth is within 1 Nyquist zone





- ADC range
  - ADC saturation loses amplitude information
  - ADC range under usage deteriorates the signal to noise ratio

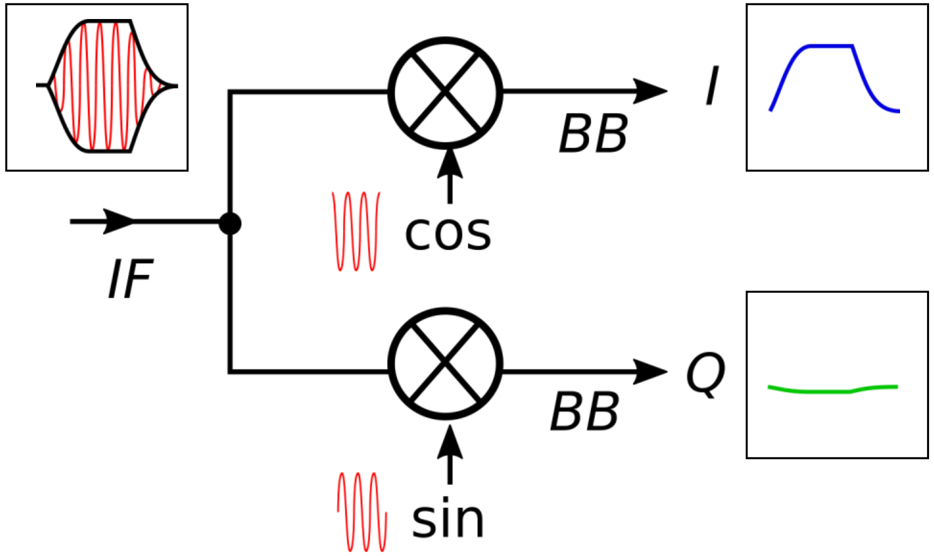
optimization of ADC dynamic range

Typically condition signal to stay at 70-80% of max ADC range

LLRF System

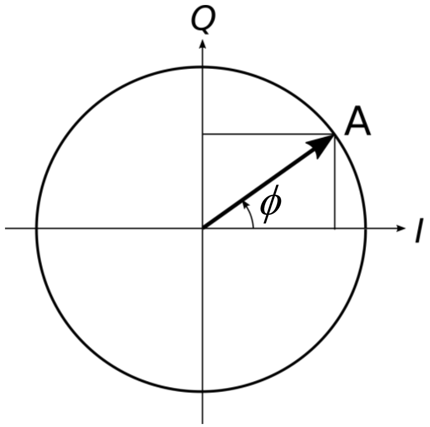
I Q detection

- I Q detection
  - At IF sampling, **multiplication by IF sine and cosine** tables



  - In practice, digital scaling and rotation is also taking place at this stage → **digital signal calibration**

- Phasor diagram

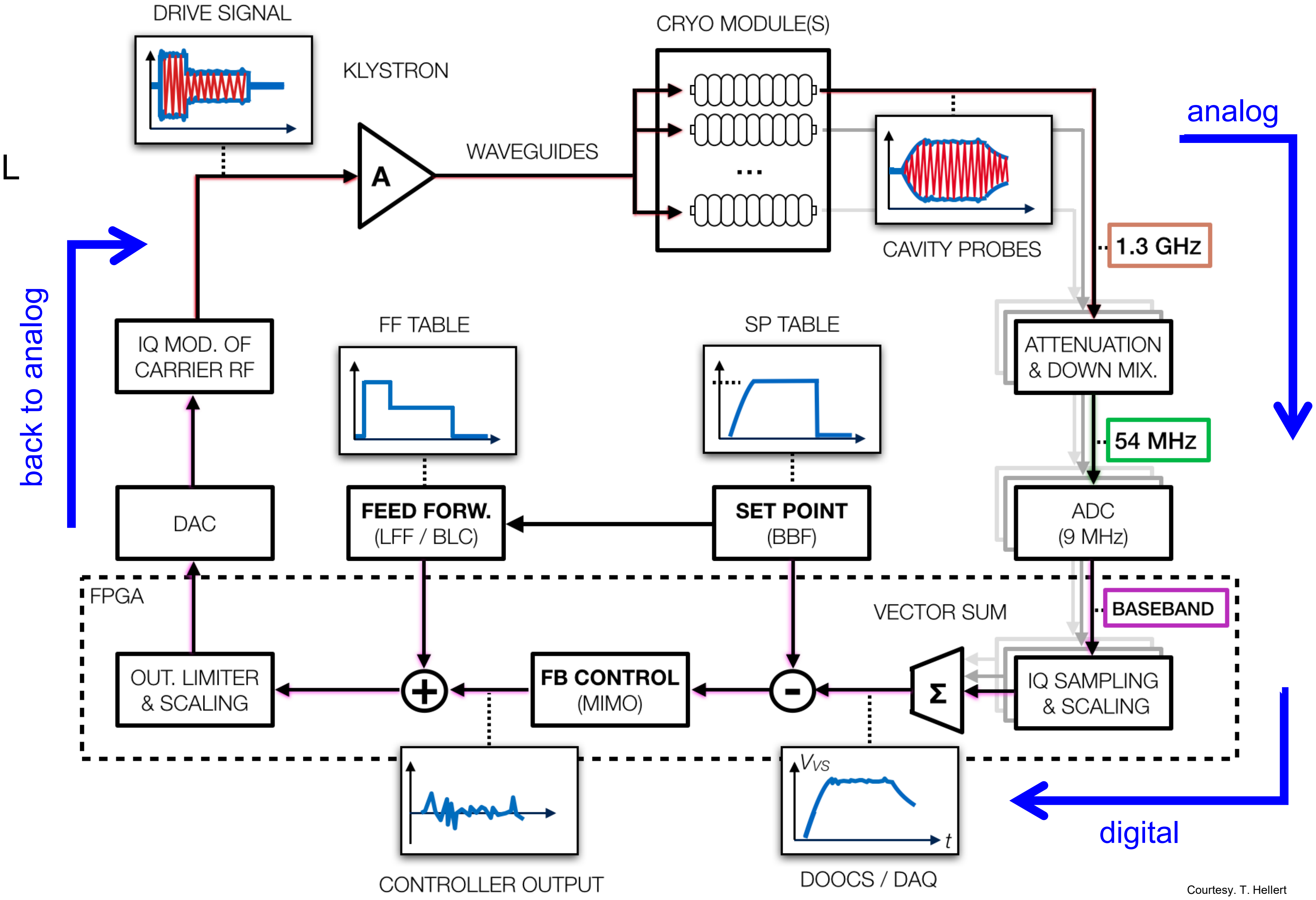


$$I = A \cdot \cos\phi$$
$$Q = A \cdot \sin\phi$$
$$A = \sqrt{I^2 + Q^2}$$
$$\phi = \text{atan2}(Q, I)$$

LLRF system

The complete loop

- Example from EuXFEL



Courtesy. T. Hellert

LLRF system

The bird's eye overview

- Typical layers in system architecture
- The functionalities descried earlier are spread over several layers
- E.g. set point

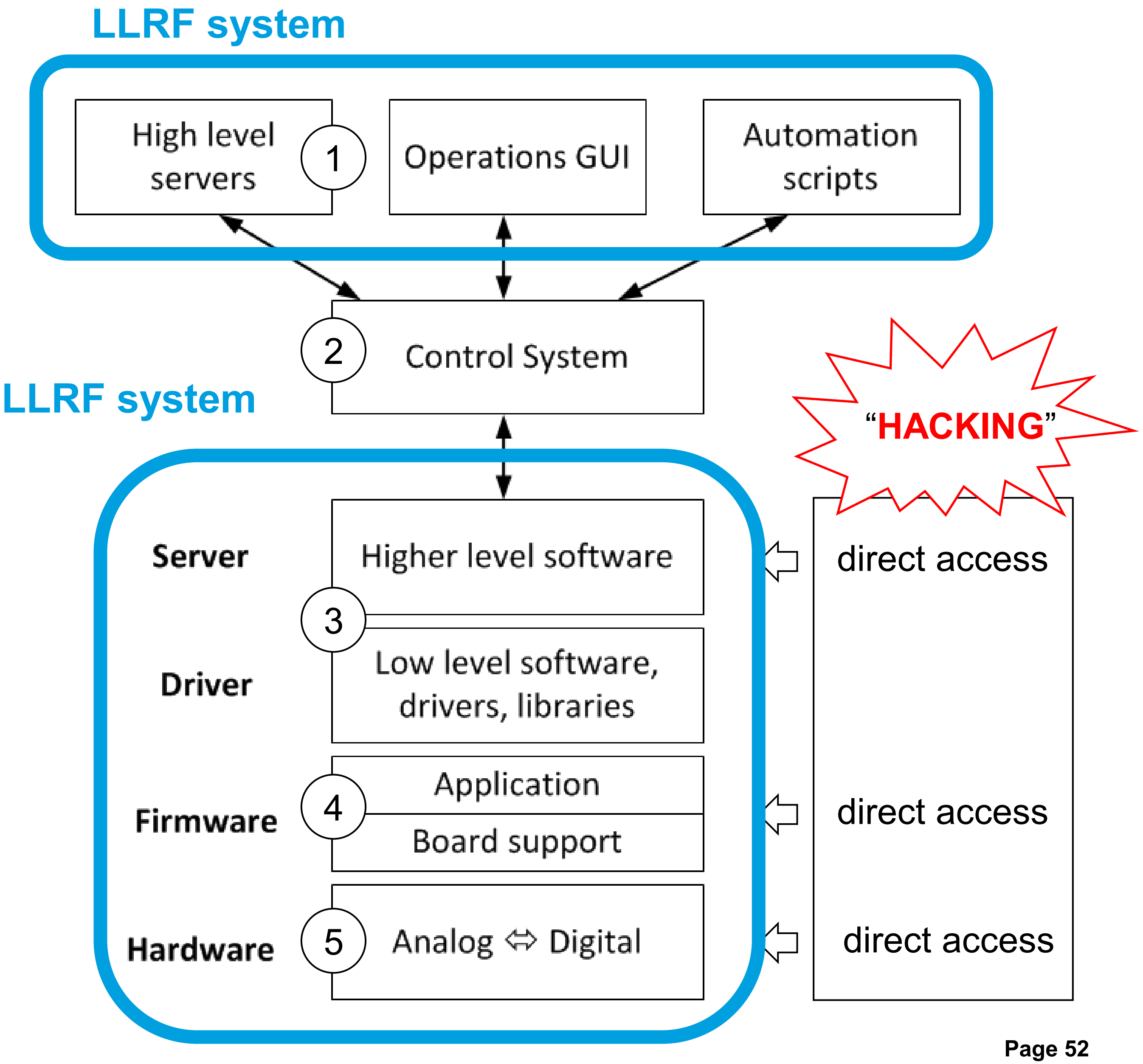
① User can change the SP via GUI (new value, slope etc…) OR energy server can request a SP change

② The request is sent over the control system to the LLRF controller server

③ The LLRF controller server computes the new set point tables and writes them to firmware registers via the driver

④ The firmware feedback mechanisms adapt the drive to this new request

⑤ The hardware drive signal is modified accordingly

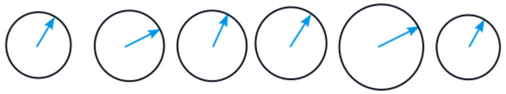


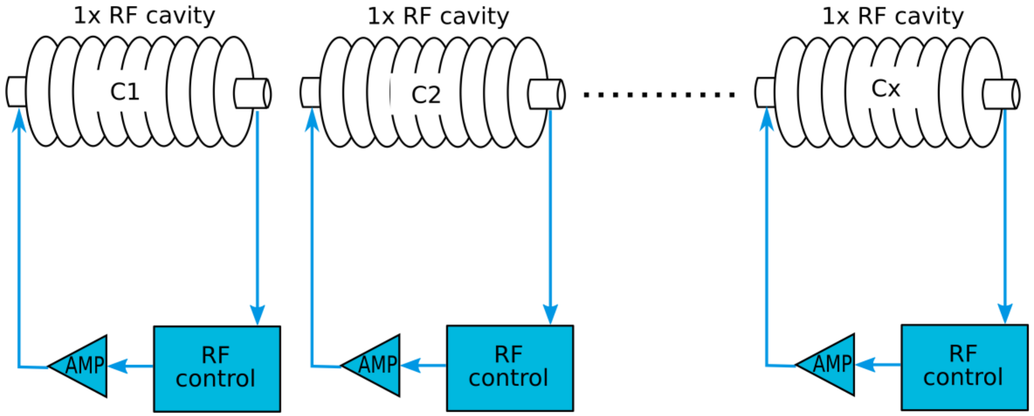
Single Cavity versus Vector Sum RF regulation

Single Cavity

- **One high power actuator per cavity**
- i.e. Solid State Amplifier (SSA)
- Example: LCLS-II

- Pros
  - Simpler regulation

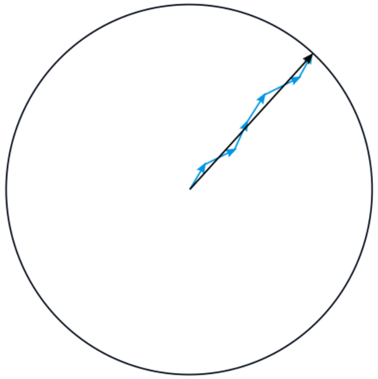


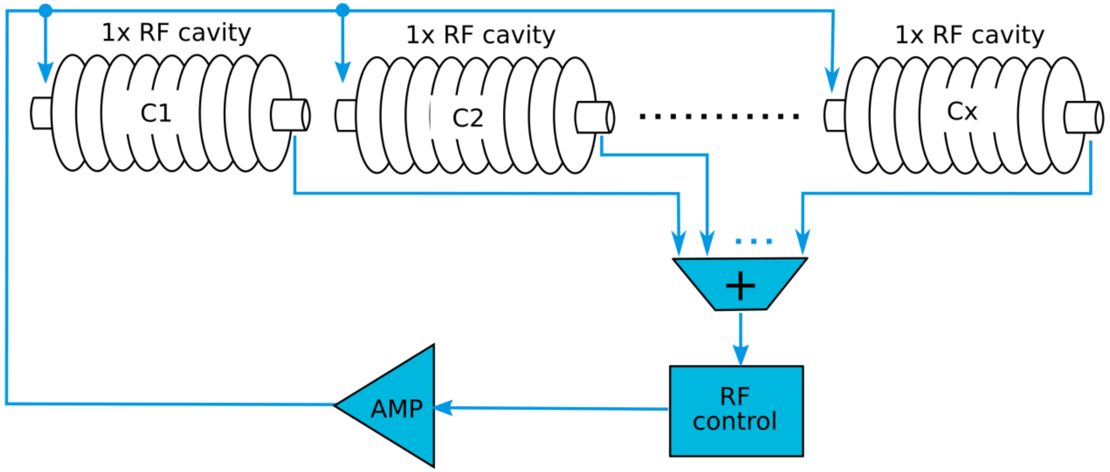


Vector Sum

- **One high power actuator per many cavities**
- i.e. pulsed klystron
- Example: Eu-XFEL

- Pros
  - Cost reduction





Pulsed versus Continuous Wave (CW) operation

Note: the beam is always pulsed

Benefit of Short Pulse (SP) operation

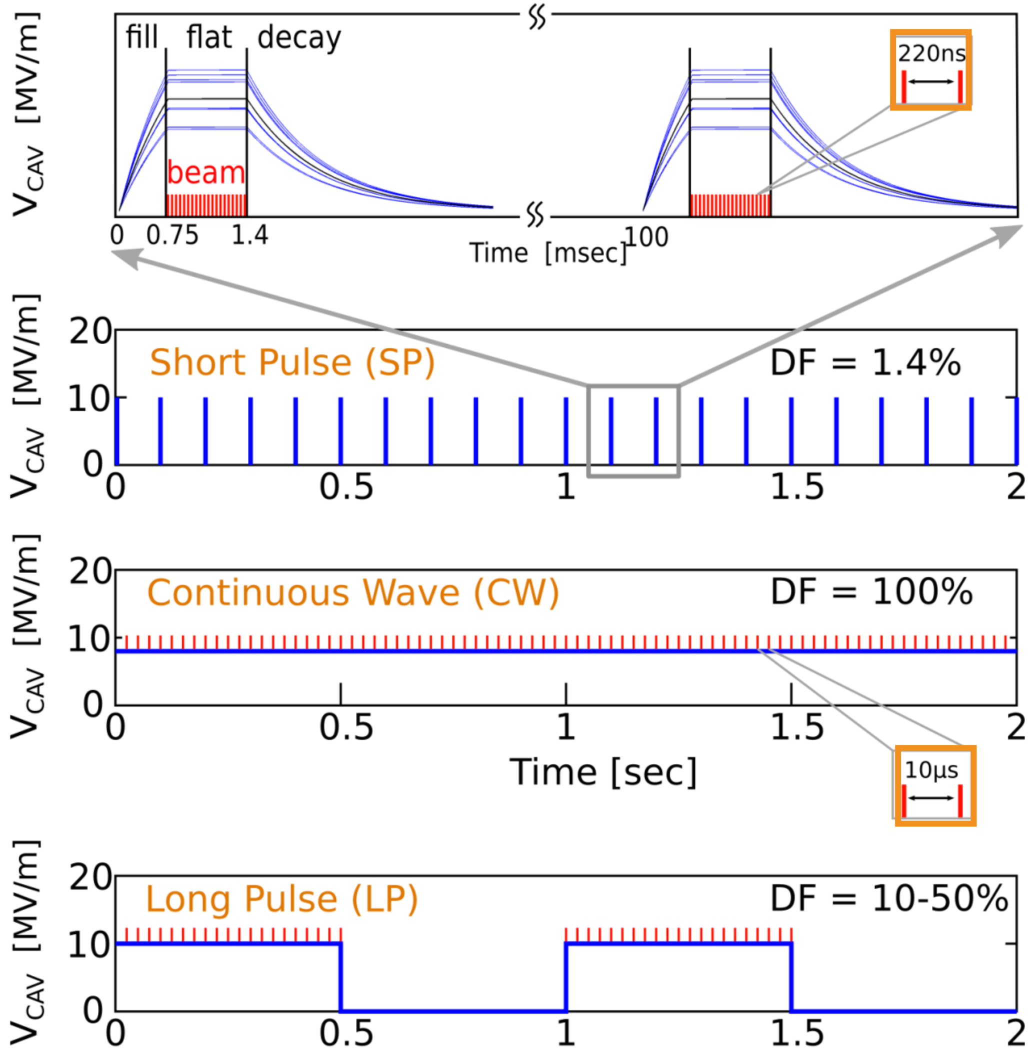
- Lower dynamic heat load → cryo ☺
- Higher energies → eg. shorter wavelength for FEL

Benefits of Continuous Wave (CW) operation

- Flexible beam patterns for detectors
- Slower repetition rate lasers
- Fill-transients no longer an issue

Benefits of Long Pulse (LP) operation

- Still high duty factor (DF = 10-50%)
- Higher gradients than CW with same heat load



E = 17.5 GeV

N_{bunch}/s = 27k

E = 8 GeV

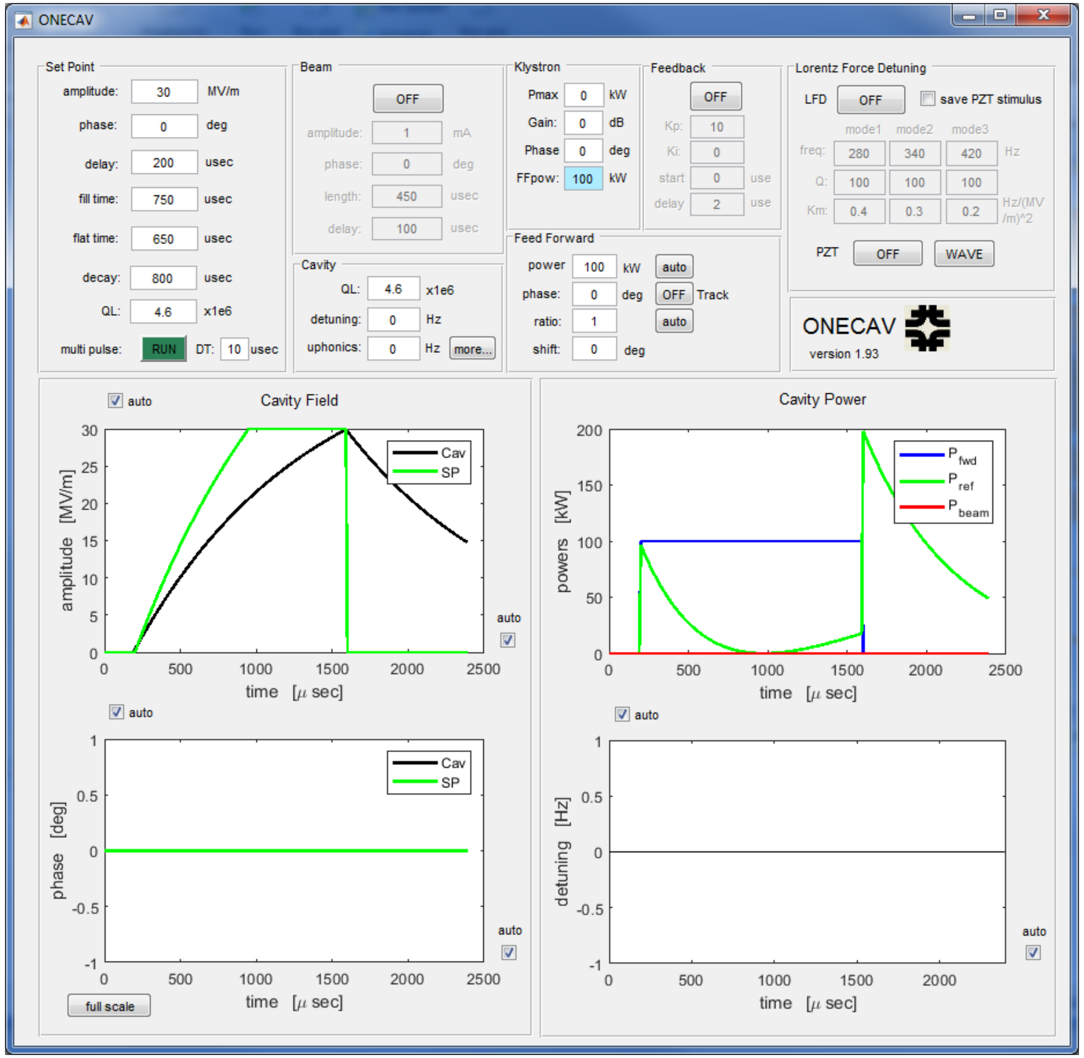
N_{bunch}/s = 100k

E = 10 GeV

N_{bunch}/s = 50k

LLRF System

DEMO: ONECAV simulation



ONECAV

Set Point
amplitude: 30 MV/m
phase: 0 deg
delay: 200 usec
fill time: 750 usec
flat time: 650 usec
decay: 800 usec
QL: 4.6 x1e6
multi pulse: RUN DT: 10 usec

Beam
OFF
amplitude: 1 mA
phase: 0 deg
length: 450 usec
delay: 100 usec

Cavity
QL: 4.6 x1e6
detuning: 0 Hz
uphonics: 0 Hz

Klystron
Pmax 0 kW
Gain: 0 dB
Phase 0 deg
FFpow: 100 kW

Feedback
OFF
Kp: 10
Ki: 0
start 0 use
delay 2 use

Feed Forward
power 100 kW
phase: 0 deg
ratio: 1
shift: 0 deg

Lorentz Force Detuning
LFD OFF
☐ save PZT stimulus

	mode1	mode2	mode3	
freq:	280	340	420	Hz
Q:	100	100	100	
Km:	0.4	0.3	0.2	Hz/(MV/m)^2

PZT OFF

ONECAV
version 1.93

- MATLAB simulator available for download
  - DESY intranet: http://www.desy.de/~branlard/
  - On request: julien.branlard@desy.de
  - Useful to understand cavity behavior under RF control
  - Comments, bug fixes are welcome!
- Demo covers:
  - FF control
  - Probe, forward and reflected signals
  - Impact of detuning
  - Feedback
  - Proportional and integral gains actions
  - Beam and beam loading
  - Impact of changing Q_L
  - Long pulse and power overhead

RF operations

Source: gifsec.com

RF operations

Routine operation

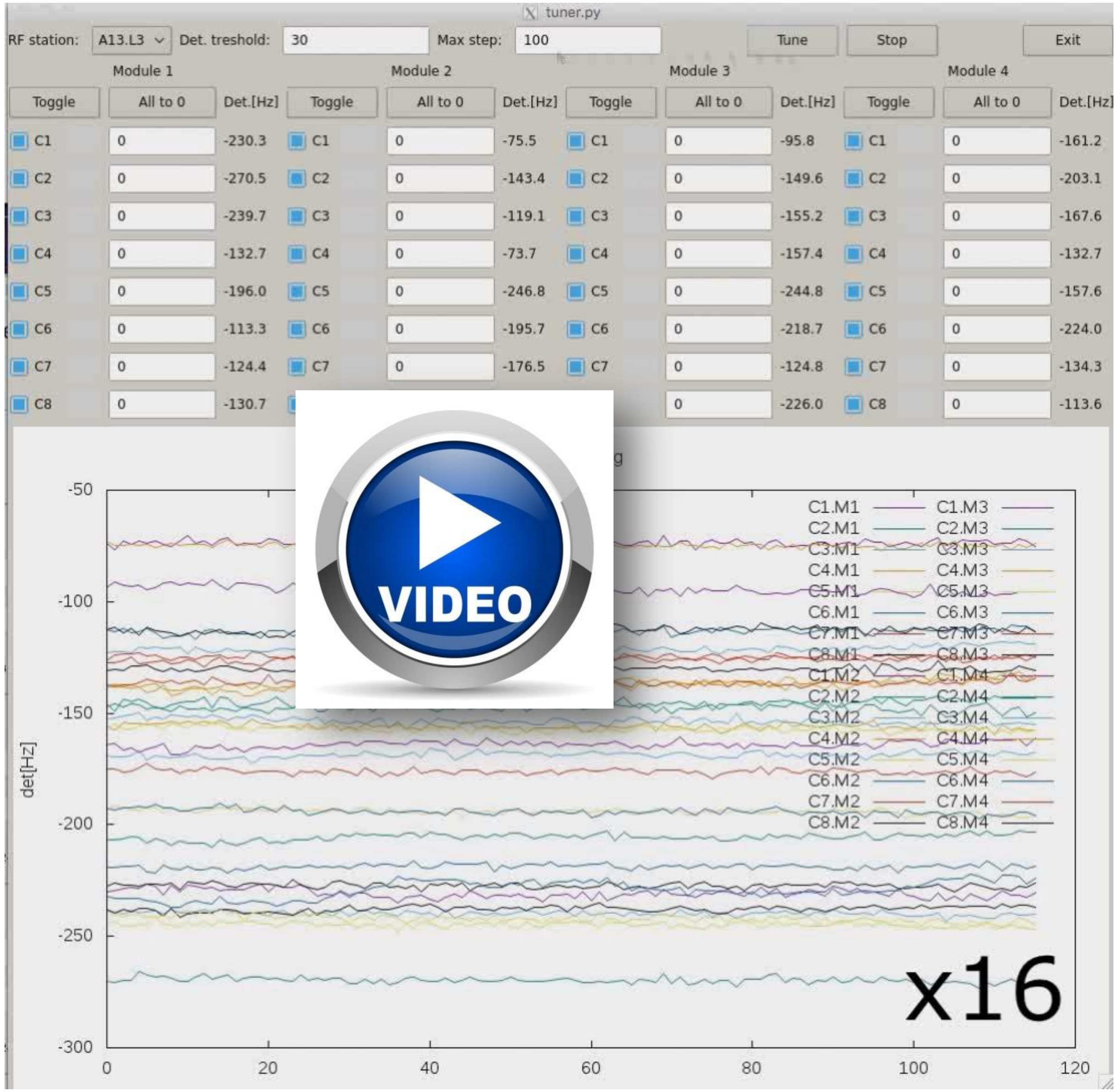
- RF operation covers many aspects of what was presented until now
  - An RF station ramping up / ramping down
  - Cavity fine tuning
  - Energy feedback server adjusting set point
  - Calibration procedures using beam
  - RF trips investigation (post mortem DAQ analysis, finding the root cause)
  - Dedicated study (e.g. additive beam arrival time jitter induced by individual components)
  - Etc…

- Only present a couple of examples here

Cavity coarse tuning

Using tuner motor

- Example taken from EuXFEL
- 32 cavities to be tuned
- Initial detuning ranging from -50 to -300 Hz
- Goal is: | detuning | < 30 Hz
- Script adjusted 32 cavities in < 1 min



RF station: A13.L3 Det. treshold: 30 Max step: 100

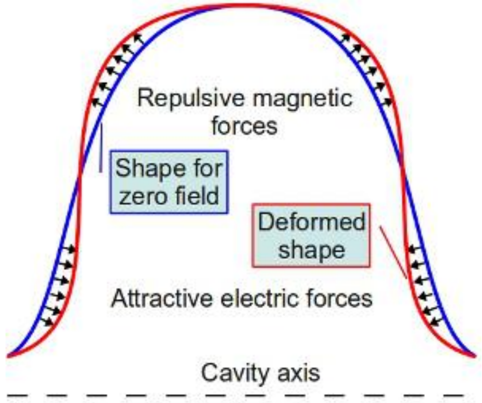
Module 1			Module 2			Module 3			Module 4		
Toggle	All to 0	Det.[Hz]	Toggle	All to 0	Det.[Hz]	Toggle	All to 0	Det.[Hz]	Toggle	All to 0	Det.[Hz]
☑ C1	0	-230.3	☑ C1	0	-75.5	☑ C1	0	-95.8	☑ C1	0	-161.2
☑ C2	0	-270.5	☑ C2	0	-143.4	☑ C2	0	-149.6	☑ C2	0	-203.1
☑ C3	0	-239.7	☑ C3	0	-119.1	☑ C3	0	-155.2	☑ C3	0	-167.6
☑ C4	0	-132.7	☑ C4	0	-73.7	☑ C4	0	-157.4	☑ C4	0	-132.7
☑ C5	0	-196.0	☑ C5	0	-246.8	☑ C5	0	-244.8	☑ C5	0	-157.6
☑ C6	0	-113.3	☑ C6	0	-195.7	☑ C6	0	-218.7	☑ C6	0	-224.0
☑ C7	0	-124.4	☑ C7	0	-176.5	☑ C7	0	-124.8	☑ C7	0	-134.3
☑ C8	0	-130.7					0	-226.0	☑ C8	0	-113.6

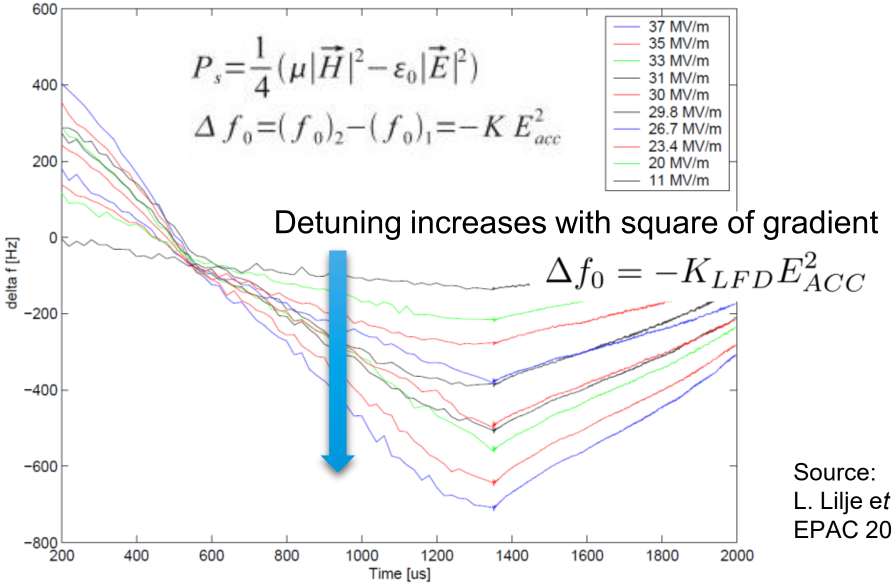
video time = 16 x actual time

Cavity “fine” tuning

Use of piezo in pulsed mode

- Lorentz Force detuning





$$P_s=\frac{1}{4}(\mu|\vec{H}|^2-\varepsilon_0|\vec{E}|^2)$$

$$\Delta f_0=(f_0)_2-(f_0)_1=-K\,E^2_{acc}$$

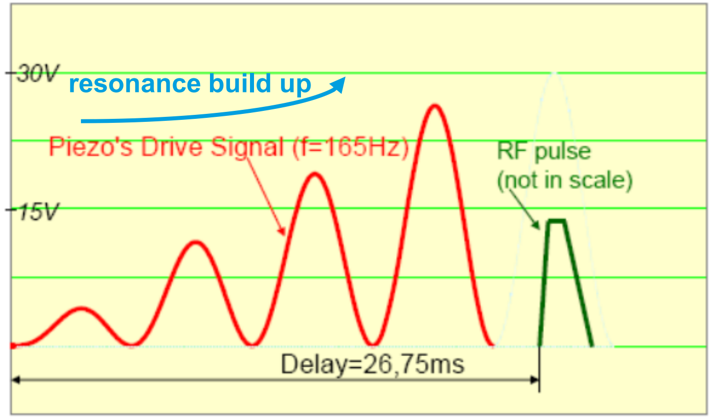
Detuning increases with square of gradient

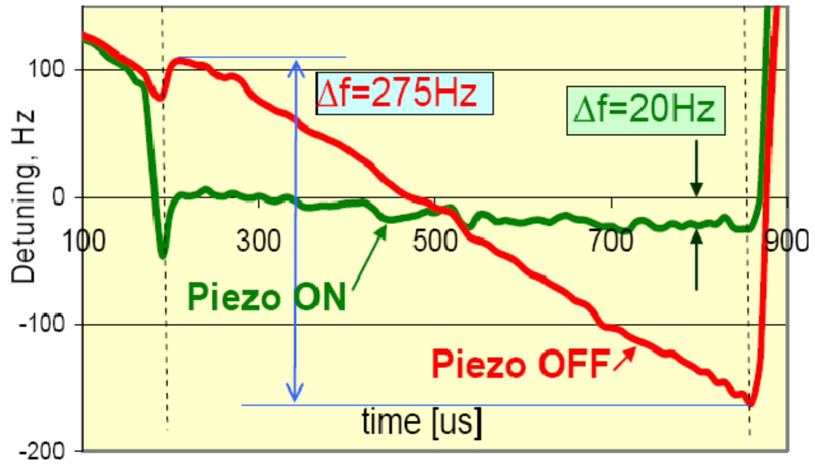
$$\Delta f_0 = -K_{LFD}E^2_{ACC}$$

Source:
L. Lilje *et al.*
EPAC 2006

- Lorentz force detuning compensation using piezo

Piezo stimulus:
- Frequency
- Delay
- AC amplitude
- DC offset



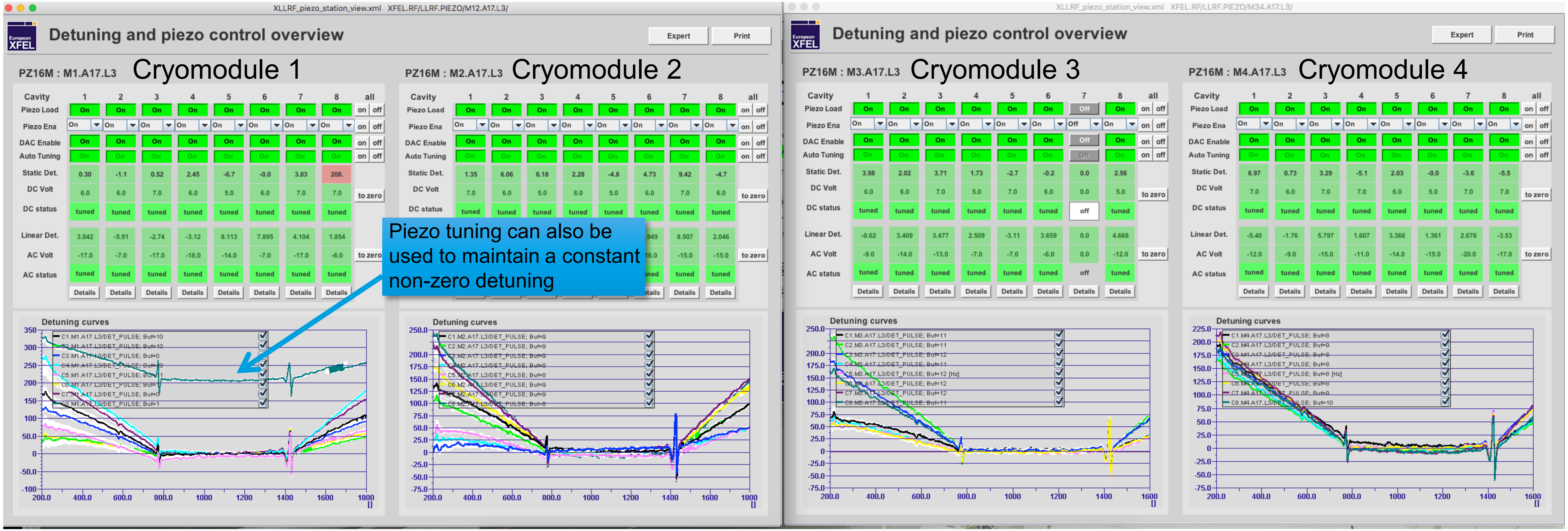


Example from FNAL 2007
R. Carcagno *et al. SRF 2007*

Cavity “fine” tuning

Another example of Lorentz force detuning compensation

- Example from EuXFEL: (station A17)
  - 32 cavities, LFD compensated



XLLRF_piezo_station_view.xml XFEL.RF/LLRF.PIEZO/M12.A17.L3/

Detuning and piezo control overview

Expert | Print

PZ16M : M1.A17.L3 Cryomodule 1

Cavity	1	2	3	4	5	6	7	8	all
Piezo Load	On	On	On	On	On	On	On	On	on off
Piezo Ena	On	On	On	On	On	On	On	On	on off
DAC Enable	On	On	On	On	On	On	On	On	on off
Auto Tuning	On	On	On	On	On	On	On	On	on off
Static Det.	0.30	-1.1	0.52	2.45	-6.7	-0.0	3.83	208.	
DC Volt	6.0	6.0	7.0	6.0	5.0	6.0	7.0	7.0	to zero
DC status	tuned	tuned	tuned	tuned	tuned	tuned	tuned	tuned	
Linear Det.	3.042	-5.91	-2.74	-3.12	8.113	7.895	4.104	1.854	
AC Volt	-17.0	-7.0	-17.0	-18.0	-14.0	-7.0	-17.0	-6.0	to zero
AC status	tuned	tuned	tuned	tuned	tuned	tuned	tuned	tuned	
	Details	Details	Details	Details	Details	Details	Details	Details	

PZ16M : M2.A17.L3 Cryomodule 2

Cavity	1	2	3	4	5	6	7	8	all
Piezo Load	On	On	On	On	On	On	On	On	on off
Piezo Ena	On	On	On	On	On	On	On	On	on off
DAC Enable	On	On	On	On	On	On	On	On	on off
Auto Tuning	On	On	On	On	On	On	On	On	on off
Static Det.	1.35	6.06	6.18	2.28	-4.8	4.73	9.42	-4.7	
DC Volt	7.0	6.0	5.0	6.0	5.0	6.0	7.0	6.0	to zero
DC status	tuned	tuned	tuned	tuned	tuned	tuned	tuned	tuned	
Linear Det.	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	949	8.507	2.046	
AC Volt	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	16.0	-15.0	-15.0	to zero
AC status	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	ned	tuned	tuned	
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	tails	Details	Details	

Piezo tuning can also be used to maintain a constant non-zero detuning

XLLRF_piezo_station_view.xml XFEL.RF/LLRF.PIEZO/M34.A17.L3/

Detuning and piezo control overview

Expert | Print

PZ16M : M3.A17.L3 Cryomodule 3

Cavity	1	2	3	4	5	6	7	8	all
Piezo Load	On	On	On	On	On	On	Off	On	on off
Piezo Ena	On	On	On	On	On	On	Off	On	on off
DAC Enable	On	On	On	On	On	On	Off	On	on off
Auto Tuning	On	On	On	On	On	On	Off	On	on off
Static Det.	3.98	2.02	3.71	1.73	-2.7	-0.2	0.0	2.56	
DC Volt	6.0	6.0	7.0	5.0	7.0	6.0	0.0	5.0	to zero
DC status	tuned	tuned	tuned	tuned	tuned	tuned	off	tuned	
Linear Det.	-0.62	3.409	3.477	2.509	-3.11	3.659	0.0	4.668	
AC Volt	-9.0	-14.0	-13.0	-7.0	-7.0	-6.0	0.0	-12.0	to zero
AC status	tuned	tuned	tuned	tuned	tuned	tuned	off	tuned	
	Details	Details	Details	Details	Details	Details	Details	Details	

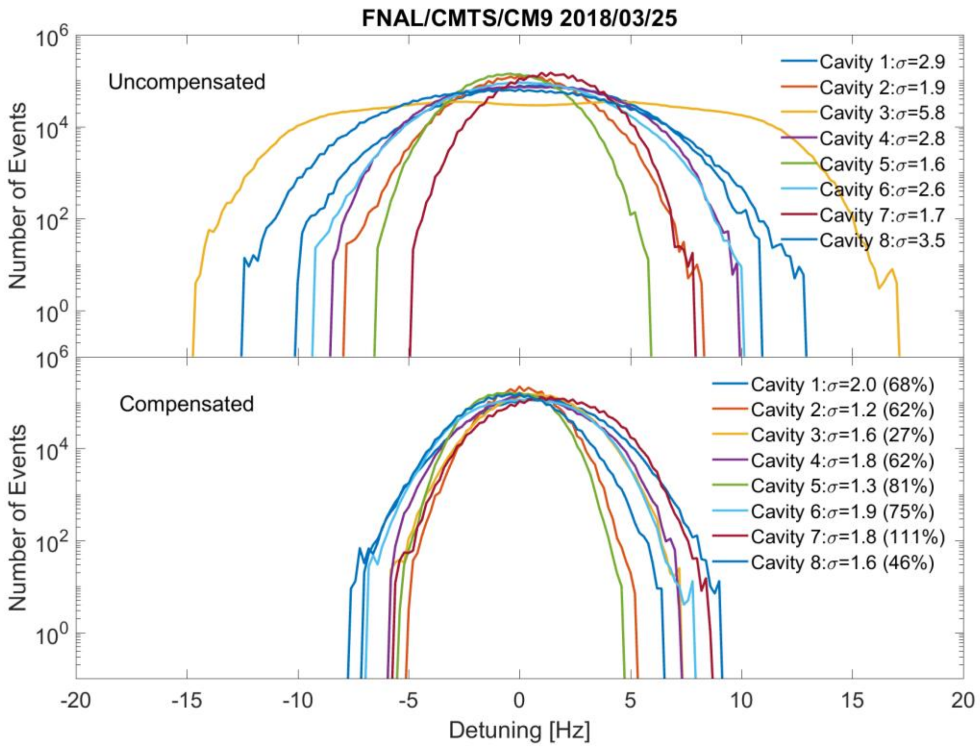
PZ16M : M4.A17.L3 Cryomodule 4

Cavity	1	2	3	4	5	6	7	8	all
Piezo Load	On	On	On	On	On	On	On	On	on off
Piezo Ena	On	On	On	On	On	On	On	On	on off
DAC Enable	On	On	On	On	On	On	On	On	on off
Auto Tuning	On	On	On	On	On	On	On	On	on off
Static Det.	6.97	0.73	3.29	-5.1	2.03	-0.0	-3.6	-5.5	
DC Volt	7.0	6.0	7.0	7.0	6.0	5.0	7.0	7.0	to zero
DC status	tuned	tuned	tuned	tuned	tuned	tuned	tuned	tuned	
Linear Det.	-5.40	-1.76	5.797	1.607	3.366	1.361	2.676	-3.53	
AC Volt	-12.0	-9.0	-15.0	-11.0	-14.0	-15.0	-20.0	-17.0	to zero
AC status	tuned	tuned	tuned	tuned	tuned	tuned	tuned	tuned	
	Details	Details	Details	Details	Details	Details	Details	Details	

Cavity “fine” tuning

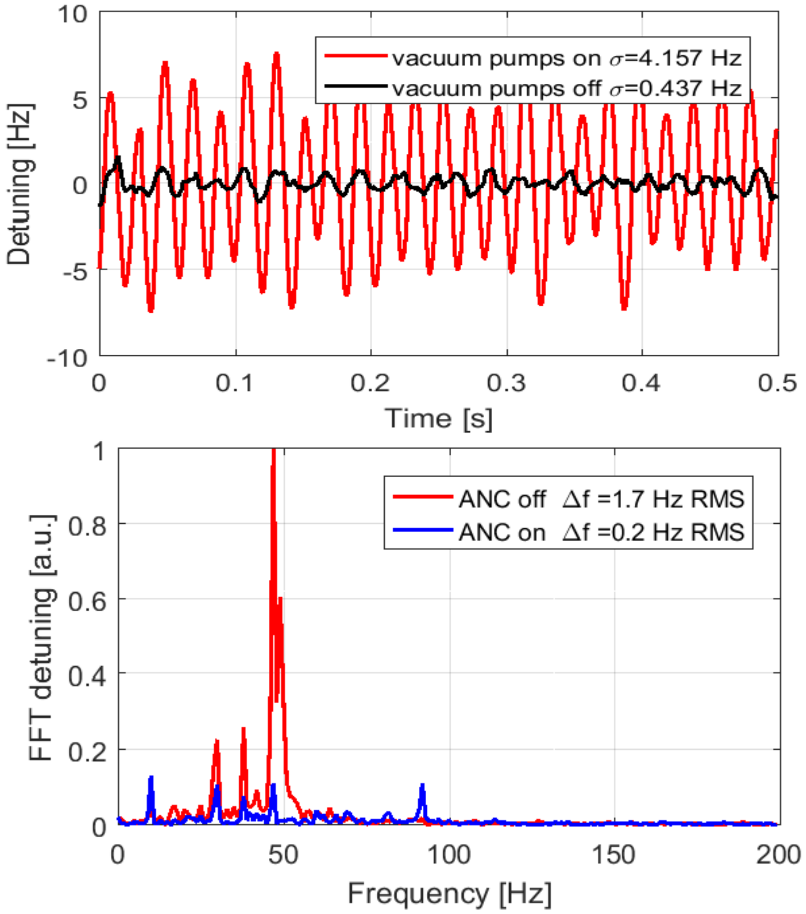
Microphonics and microphonics compensation

- Transfer function / noise spectrum techniques



Source: W. Schappert “Active Resonance Control Algorithm Development for LCLS-II”, 2nd microphonics workshop, 2018

- Active noise compensation (notch filter) techniques



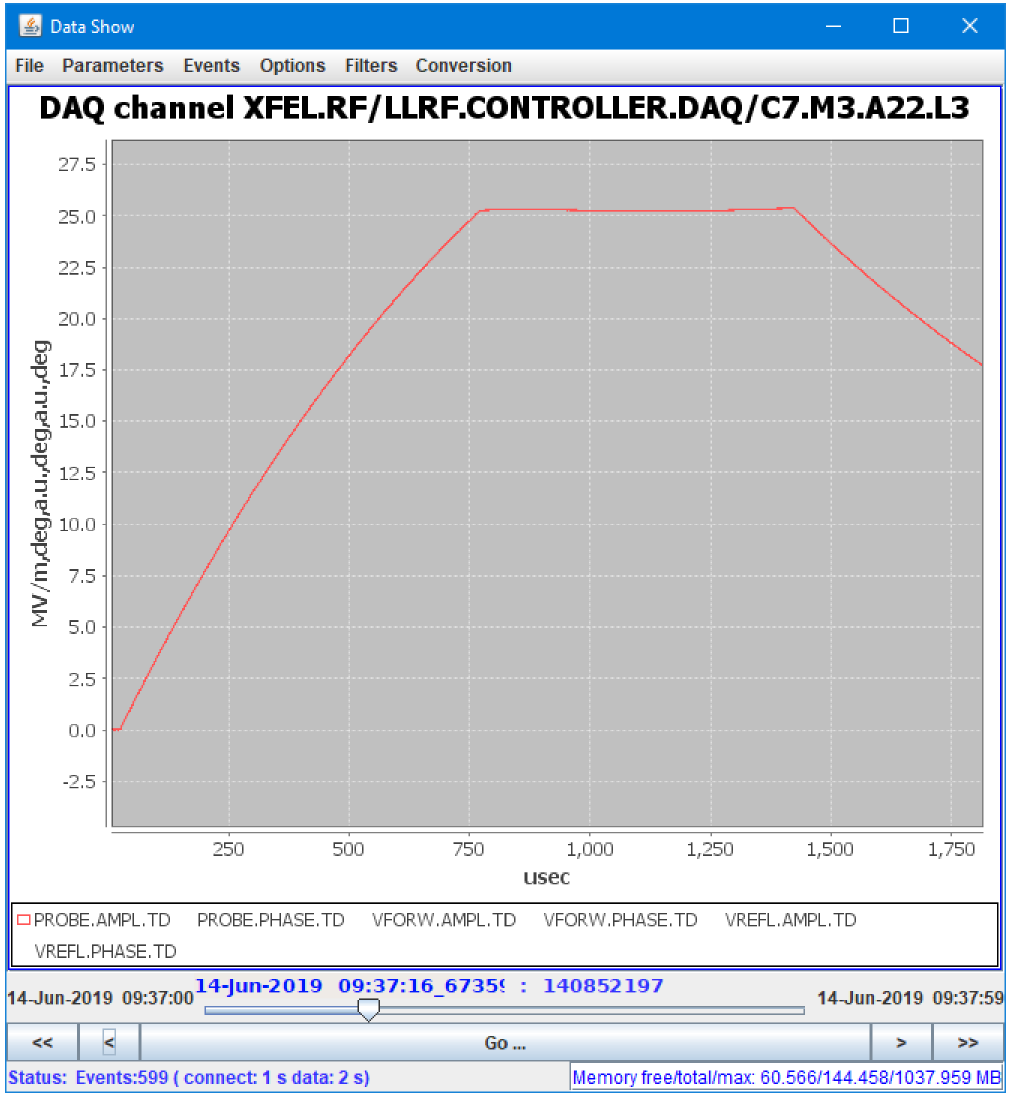
Source: R. Rybaniec *et al.* “FPGA based RF and piezo controllers for SRF cavities in CW mode”, IEEE Real Time Conference 2016

RF operation

Experience of a cavity quench

Data retrieved from the DAQ system at EuXFEL on 14 Jun. 2019

Quench triggered (by slowly increasing the gradient) to test the quench detection / reaction mechanism



14-Jun-2019 09:37:00 14-Jun-2019 09:37:16_6735 : 140852197 14-Jun-2019 09:37:59

Status: Events:599 (connect: 1 s data: 2 s)

Memory free/total/max: 60.566/144.458/1037.959 MB

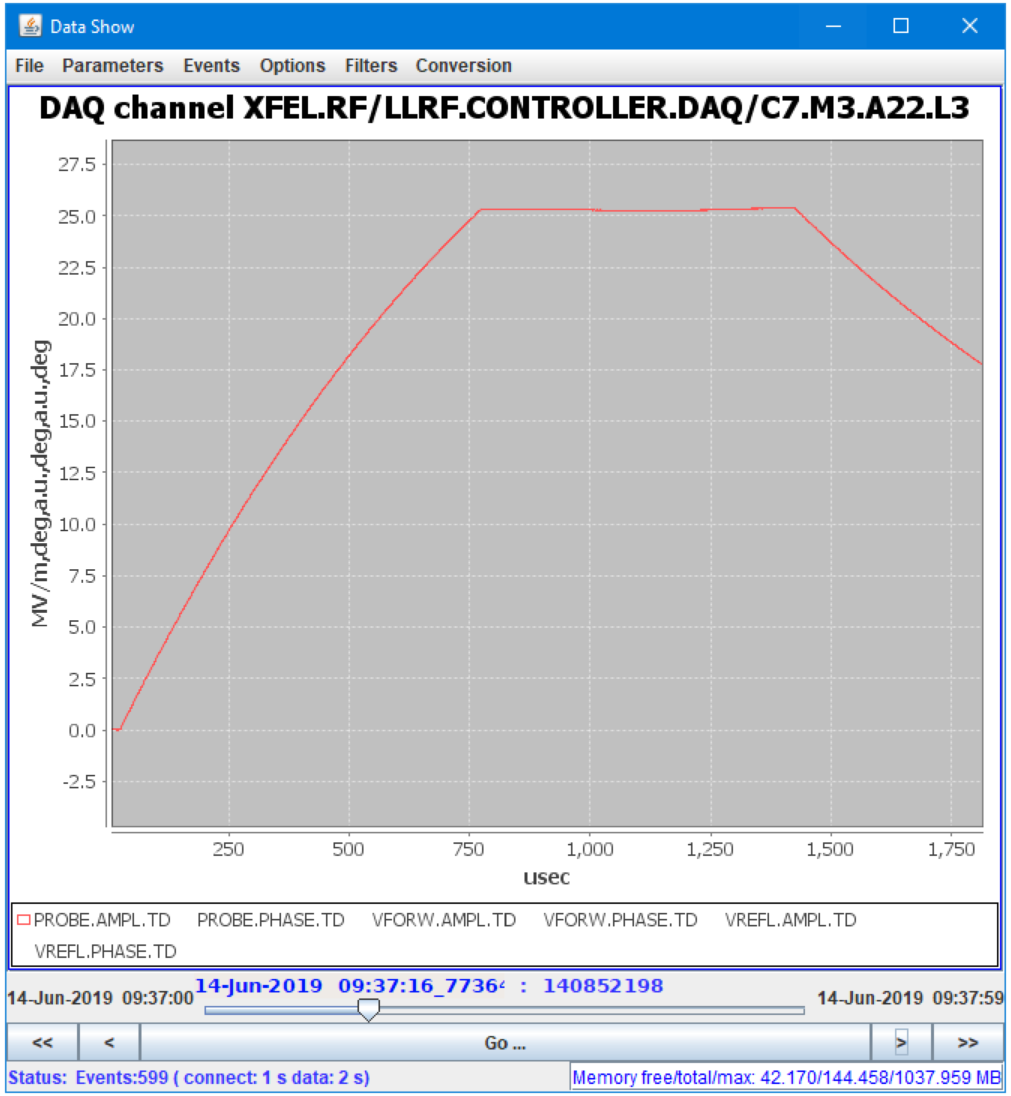
Pulse 1

Q_L = 4.6e6

RF operation

Experience of a cavity quench

Gradient is slowly increased



DAQ channel XFEL.RF/LLRF.CONTROLLER.DAQ/C7.M3.A22.L3

☐ PROBE.AMPL.TD PROBE.PHASE.TD VFORW.AMPL.TD VFORW.PHASE.TD VREFL.AMPL.TD VREFL.PHASE.TD

14-Jun-2019 09:37:00 14-Jun-2019 09:37:16_7736‹ : 140852198 14-Jun-2019 09:37:59

Status: Events:599 (connect: 1 s data: 2 s) Memory free/total/max: 42.170/144.458/1037.959 MB

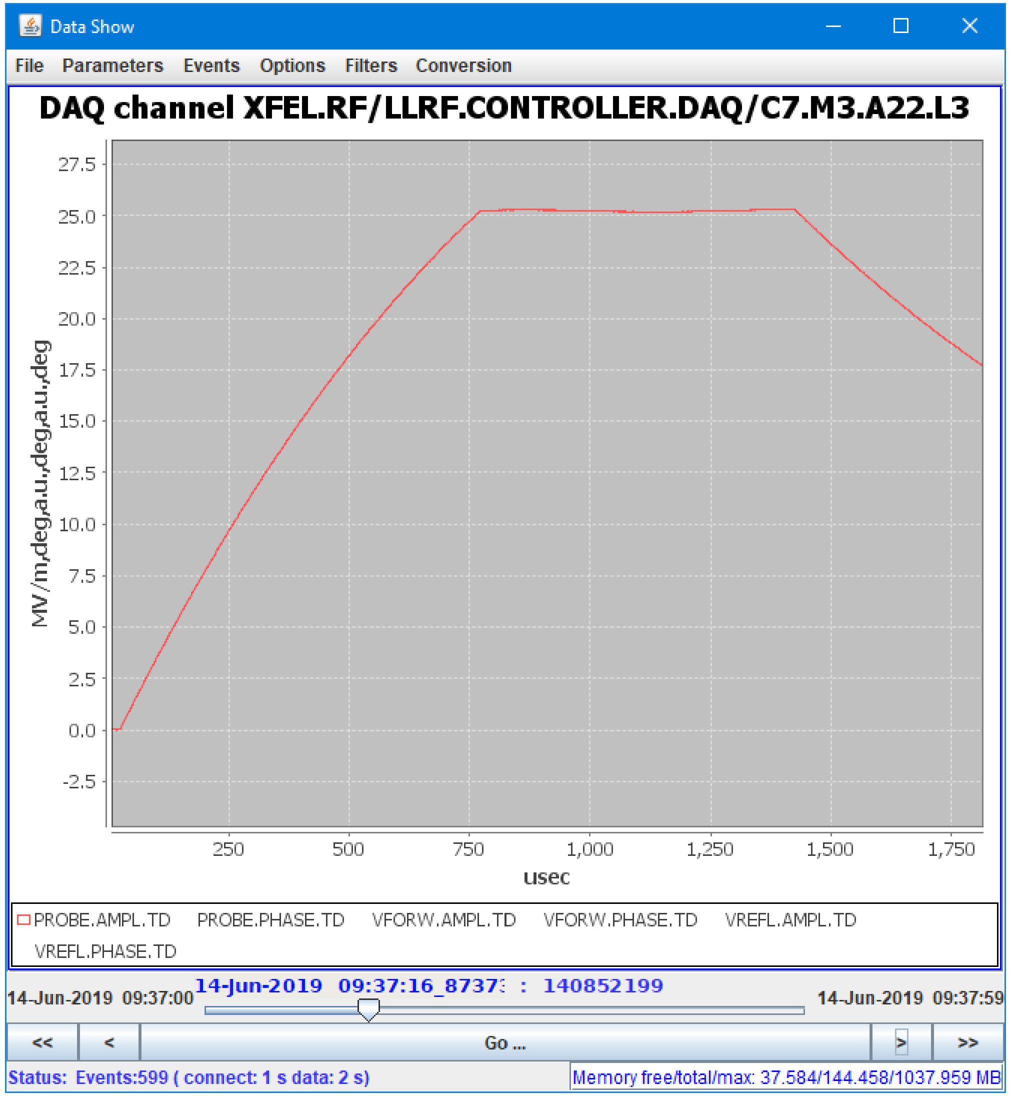
Pulse 2

Q_L = 4.6e6

RF operation

Experience of a cavity quench

Gradient is slowly increased



DAQ channel XFEL.RF/LLRF.CONTROLLER.DAQ/C7.M3.A22.L3

14-Jun-2019 09:37:00

14-Jun-2019 09:37:16_8737 : 140852199

14-Jun-2019 09:37:59

Status: Events:599 (connect: 1 s data: 2 s)

Memory free/total/max: 37.584/144.458/1037.959 MB

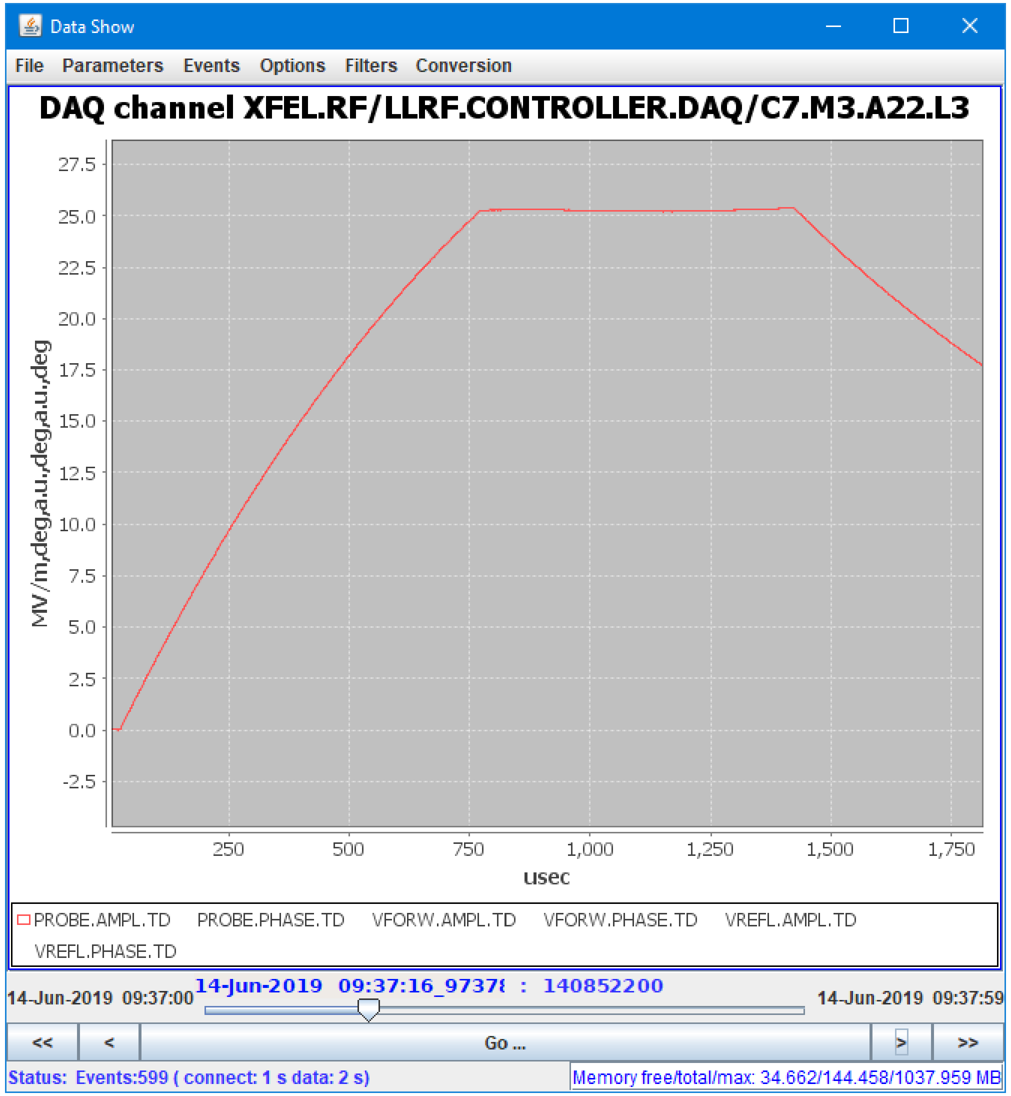
Pulse 3

Q_L = 4.6e6

RF operation

Experience of a cavity quench

Gradient is slowly increased



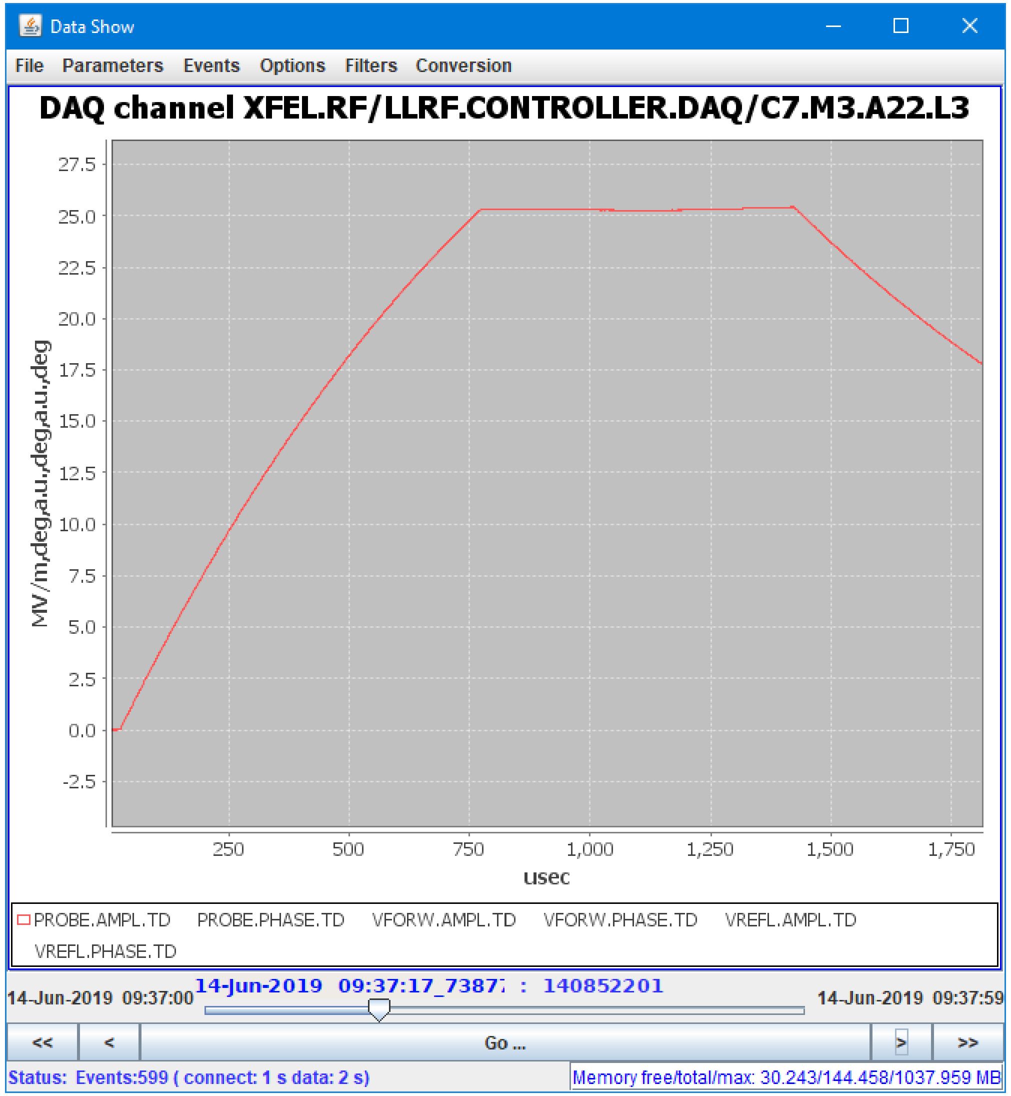
Pulse 4

Q_L = 4.6e6

RF operation

Experience of a cavity quench

Gradient is slowly increased



Status: Events:599 (connect: 1 s data: 2 s)

Memory free/total/max: 30.243/144.458/1037.959 MB

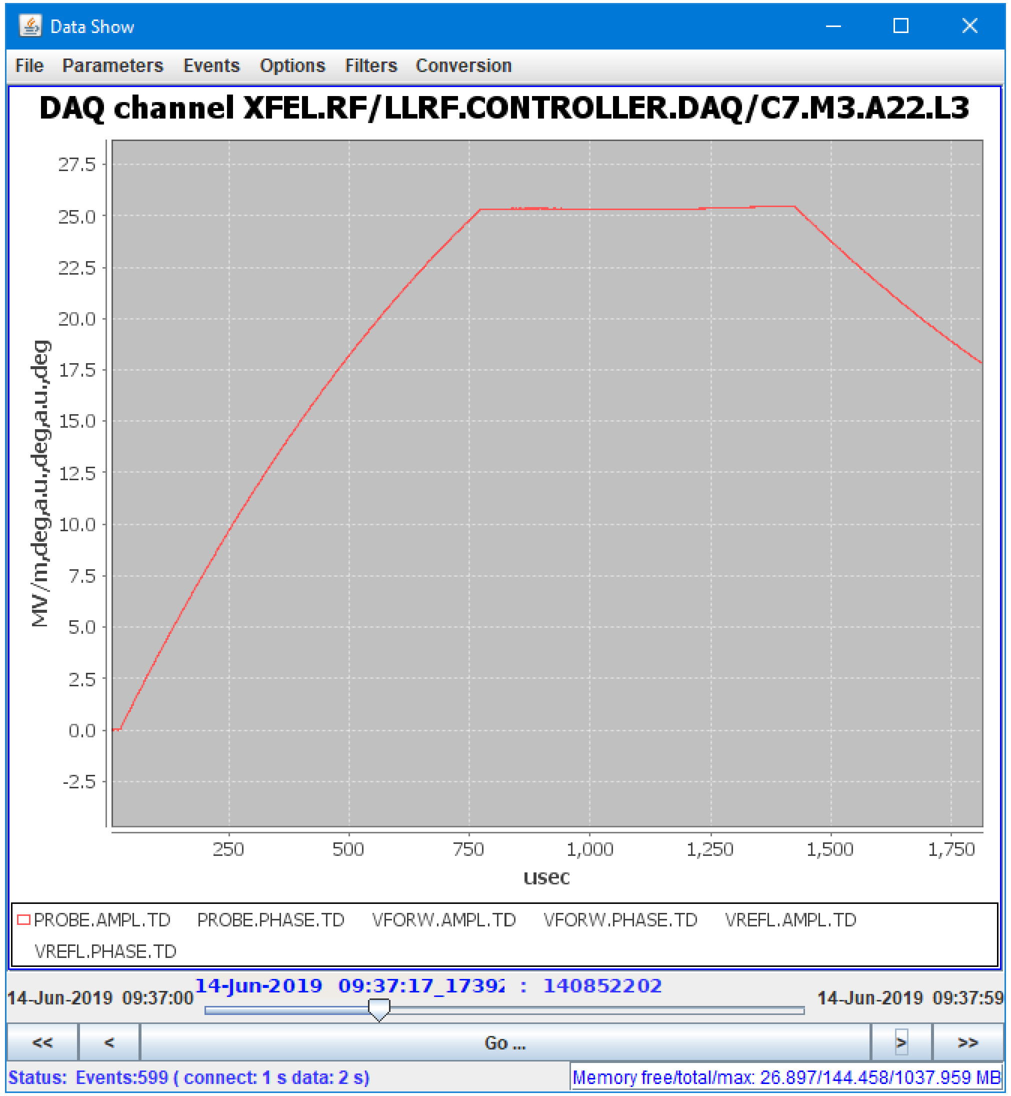
Pulse 5

Q_L = 4.6e6

RF operation

Experience of a cavity quench

Gradient is slowly increased



Pulse 6

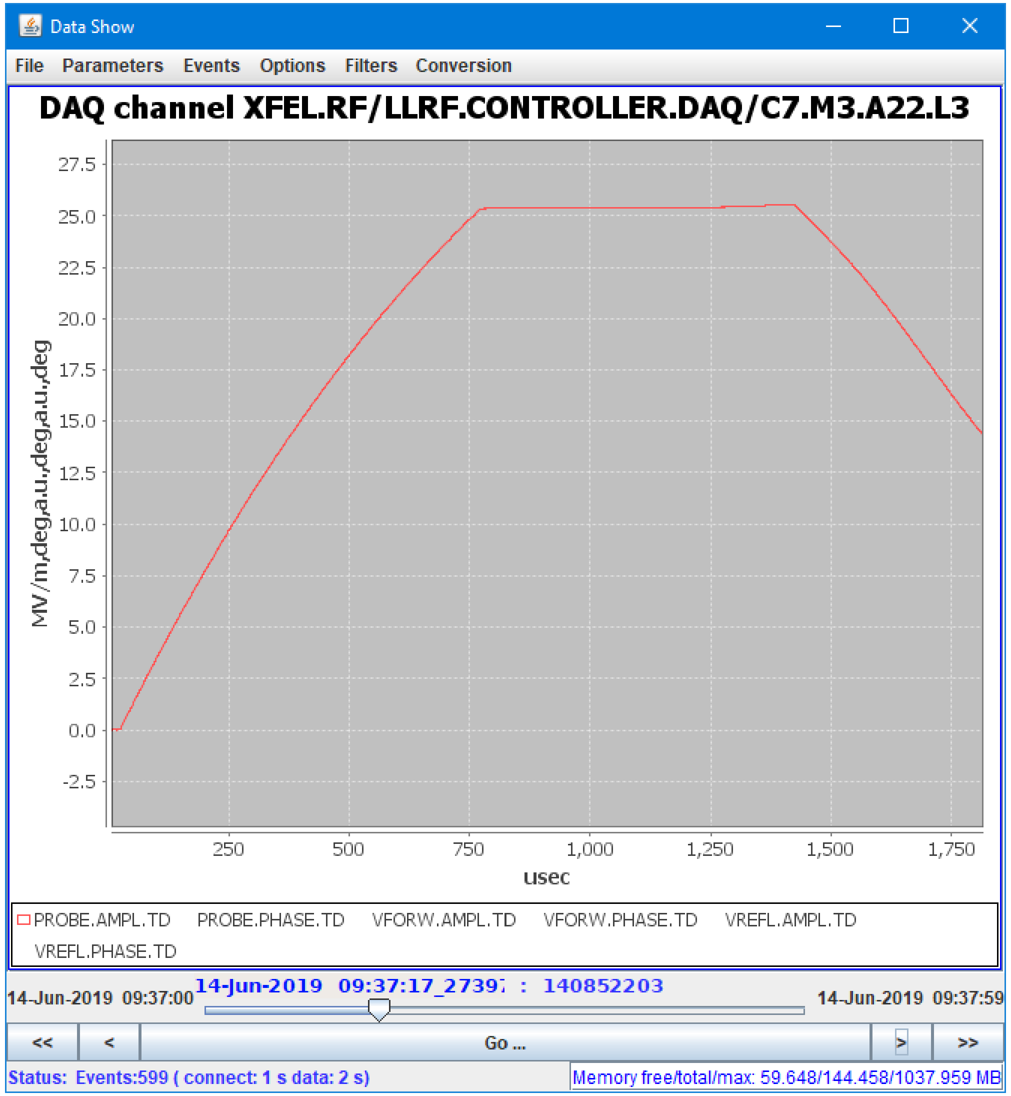
Q_L = 4.6e6

RF operation

Experience of a cavity quench

First indication of a quench visible during the cavity decay

Q_L value drops but flat top gradient is still preserved



14-Jun-2019 09:37:00 14-Jun-2019 09:37:17_2739 : 140852203 14-Jun-2019 09:37:59

Status: Events:599 (connect: 1 s data: 2 s)

Memory free/total/max: 59.648/144.458/1037.959 MB

Pulse 7

Q_L = 4.3e6

RF operation

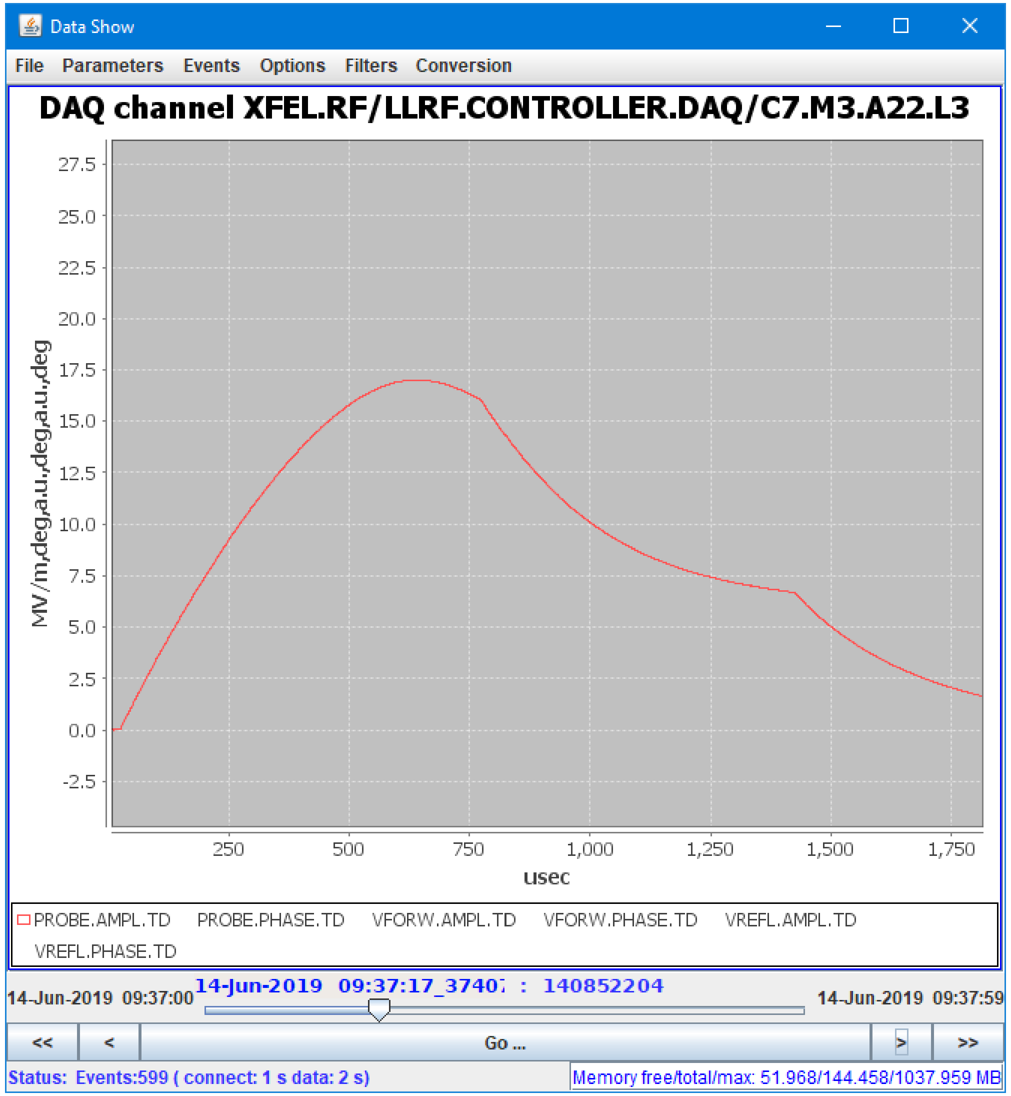
Experience of a cavity quench

Gradient collapses: “**break down**” to normal conducting conditions

Note: this exercise is done in **open loop**

Closed loop operation would generate a sudden increase in forward power to compensate for the gradient loss

→ possible sparks at coupler



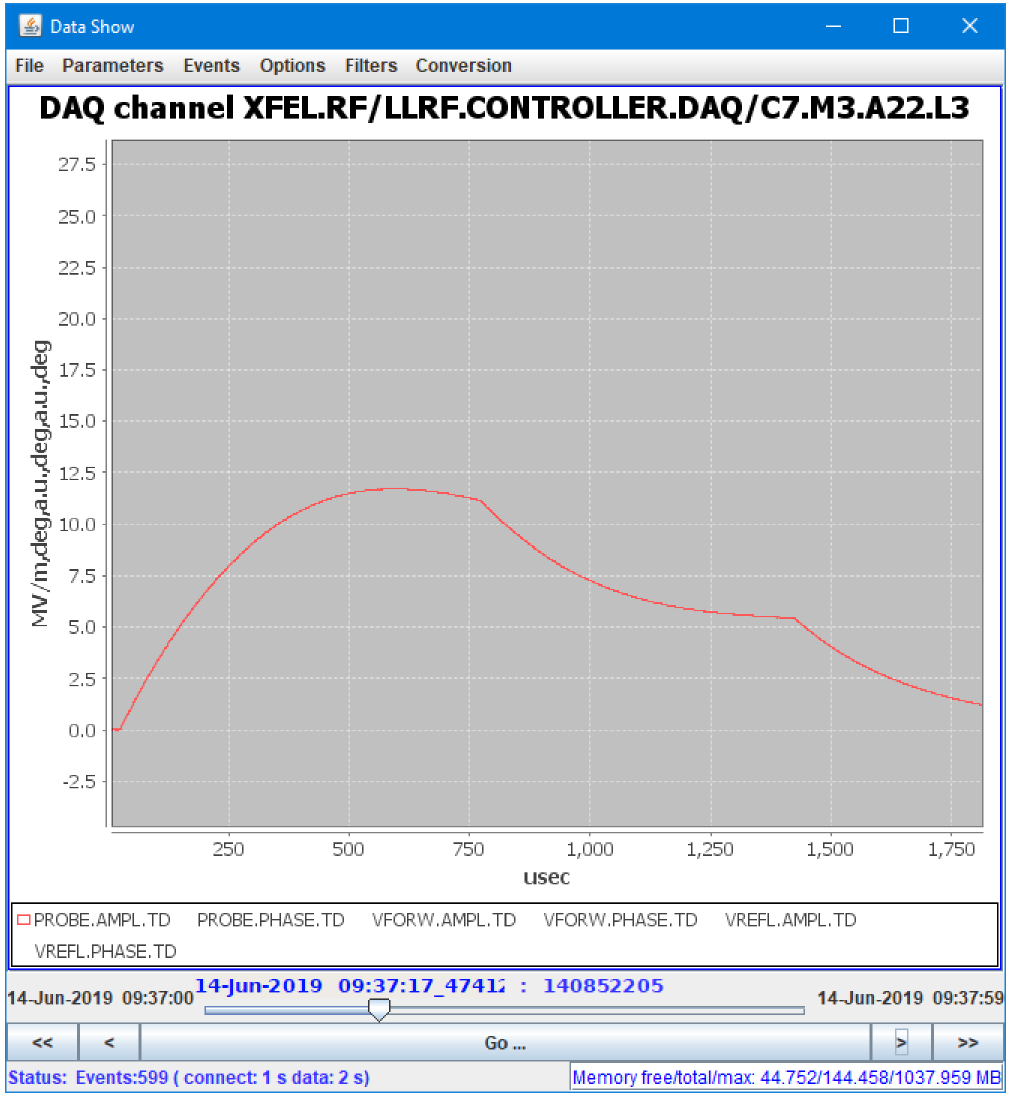
Pulse 8

Q_L = 1.0e6

RF operation

Experience of a cavity quench

Gradient collapses further



DAQ channel XFEL.RF/LLRF.CONTROLLER.DAQ/C7.M3.A22.L3

14-Jun-2019 09:37:00 14-Jun-2019 09:37:17_4741 : 140852205 14-Jun-2019 09:37:59

Status: Events:599 (connect: 1 s data: 2 s)

Memory free/total/max: 44.752/144.458/1037.959 MB

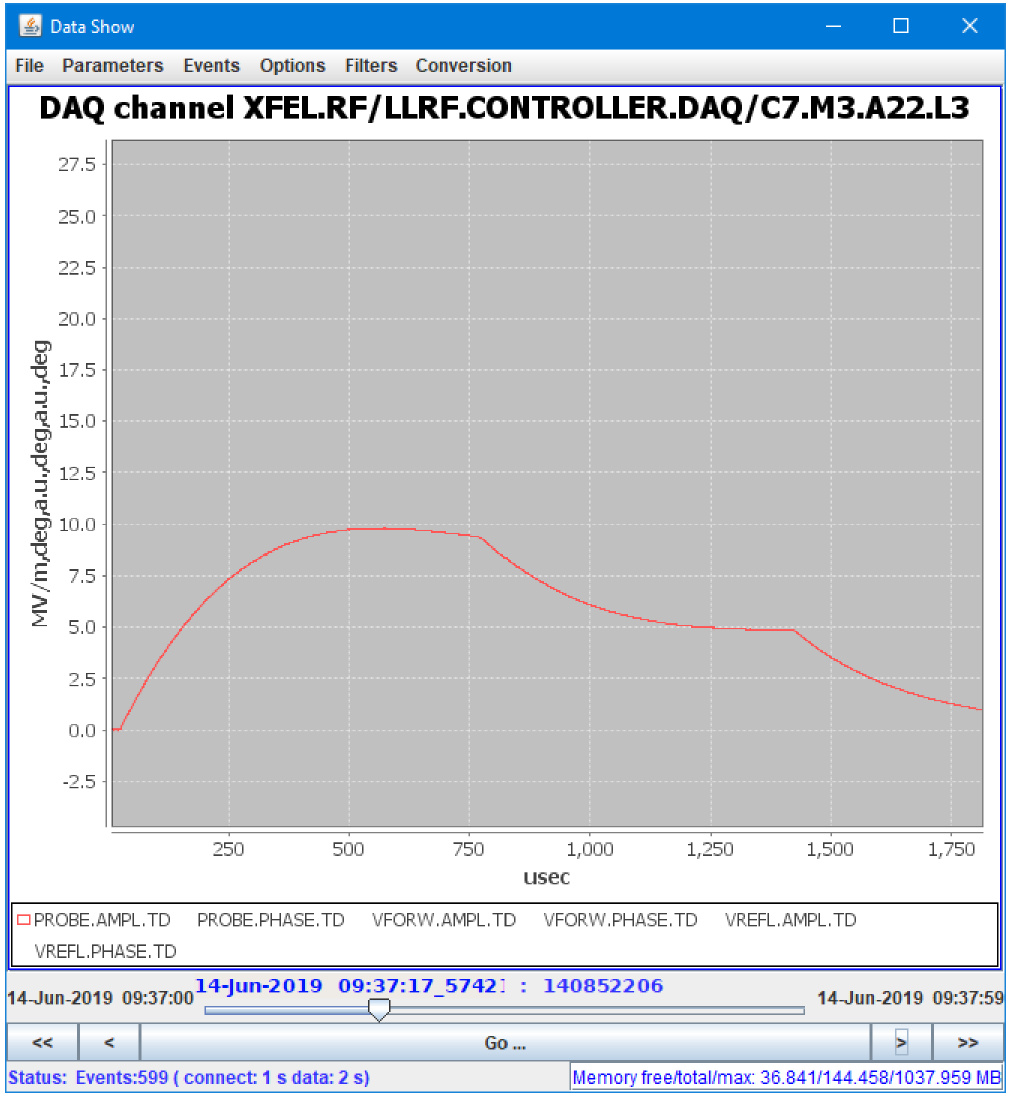
Pulse 9

Q_L = 1.0e6

RF operation

Experience of a cavity quench

Gradient collapses further



Status: Events:599 (connect: 1 s data: 2 s)

Memory free/total/max: 36.841/144.458/1037.959 MB

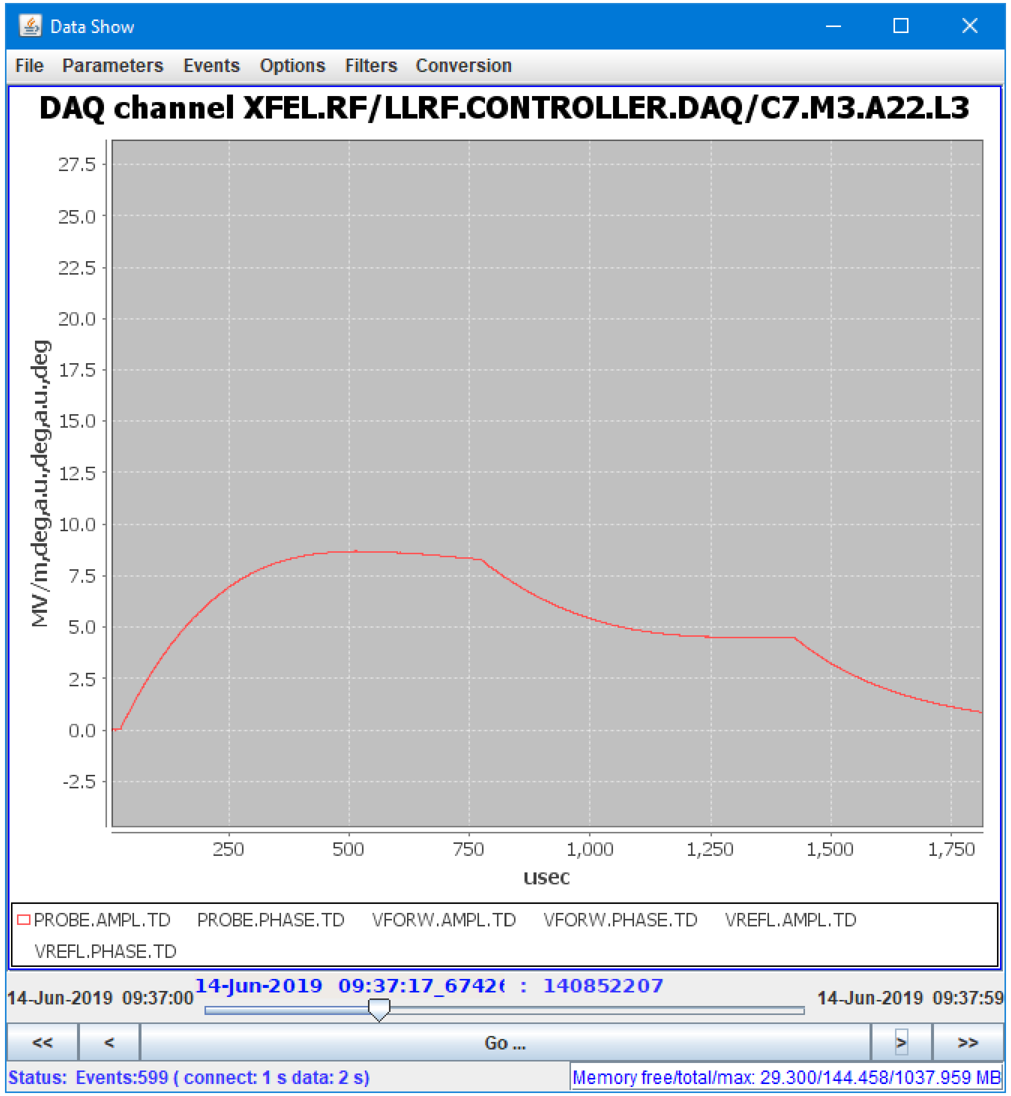
Pulse 10

Q_L = 1.0e6

RF operation

Experience of a cavity quench

Gradient collapses further



Status: Events:599 (connect: 1 s data: 2 s)

Memory free/total/max: 29.300/144.458/1037.959 MB

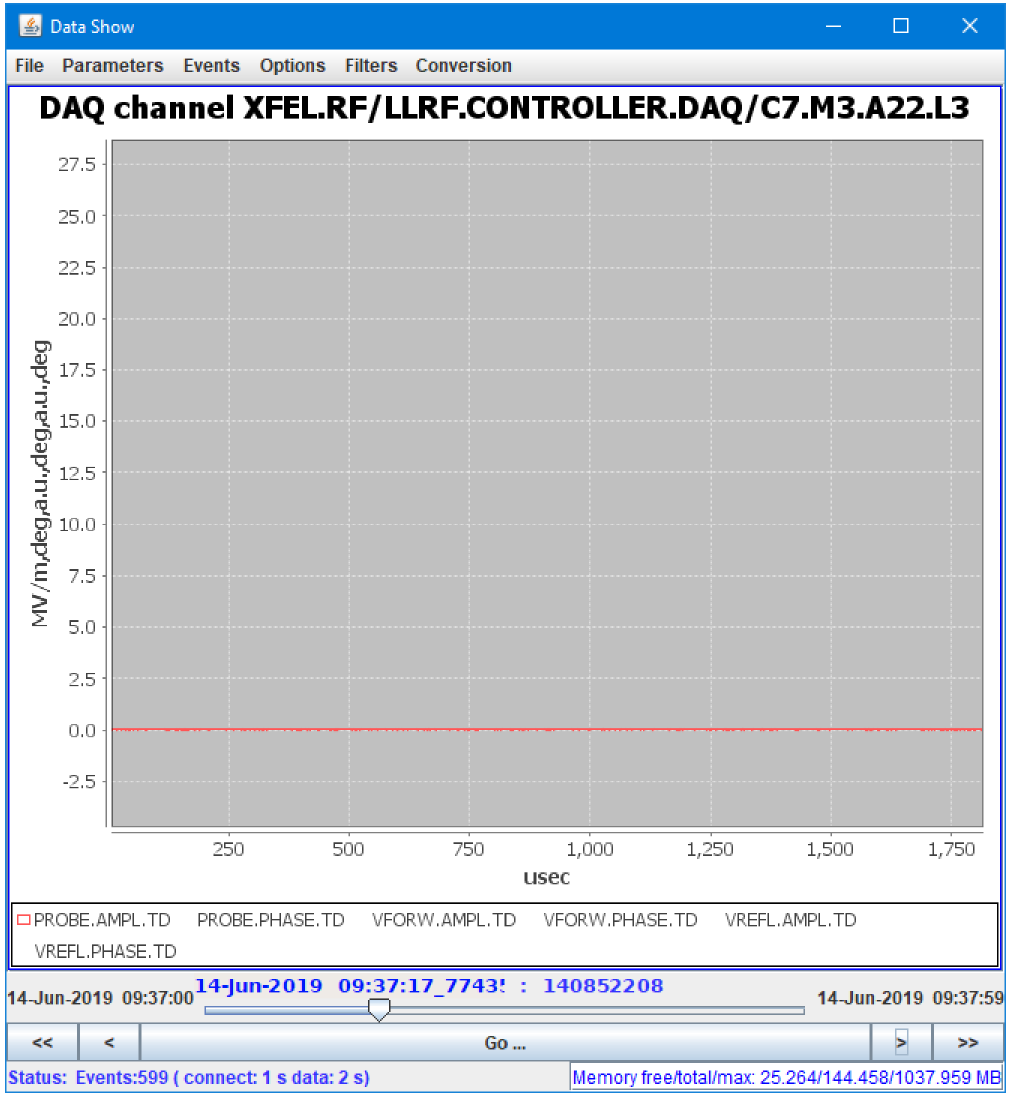
Pulse 11

Q_L = 1.0e6

RF operation

Experience of a cavity quench

RF operation is interrupted



14-Jun-2019 09:37:00

14-Jun-2019 09:37:17_7743! : 140852208

14-Jun-2019 09:37:59

Status: Events:599 (connect: 1 s data: 2 s)

Memory free/total/max: 25.264/144.458/1037.959 MB

Pulse 12

Q_L = ….

RF operation

Experience of a cavity quench

- What does a **quench** mean in terms of **additional dynamic heat load** ?

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

observed Q_L change due to quench:
4.6e6 → 1e6 (= 3.6e6)

Set to 4.6e6

Q_0 must have been in the 1.3e6 range (from 2e10) **➔ 4 orders of magnitude change!**

- Nominal operation dynamic heat load
  HL = 0.3 W / cavity
- **Quench**: Q_0 drops by 4 orders of magnitude
- Instantaneous heat load increases by > 3 orders of magnitude!

Duty Factor:
1 msec @ 10 Hz = 1%

$$HL = DF \times \frac{(V_{CAV})^2}{\frac{R}{Q} Q_0}$$

25 MV/m x l_{cav} ≈ 26 MV

Quench **➔ 8 MV !!!**

≈ **0.3 W**

Quench **➔ 490 W !!!**

1012 Ω

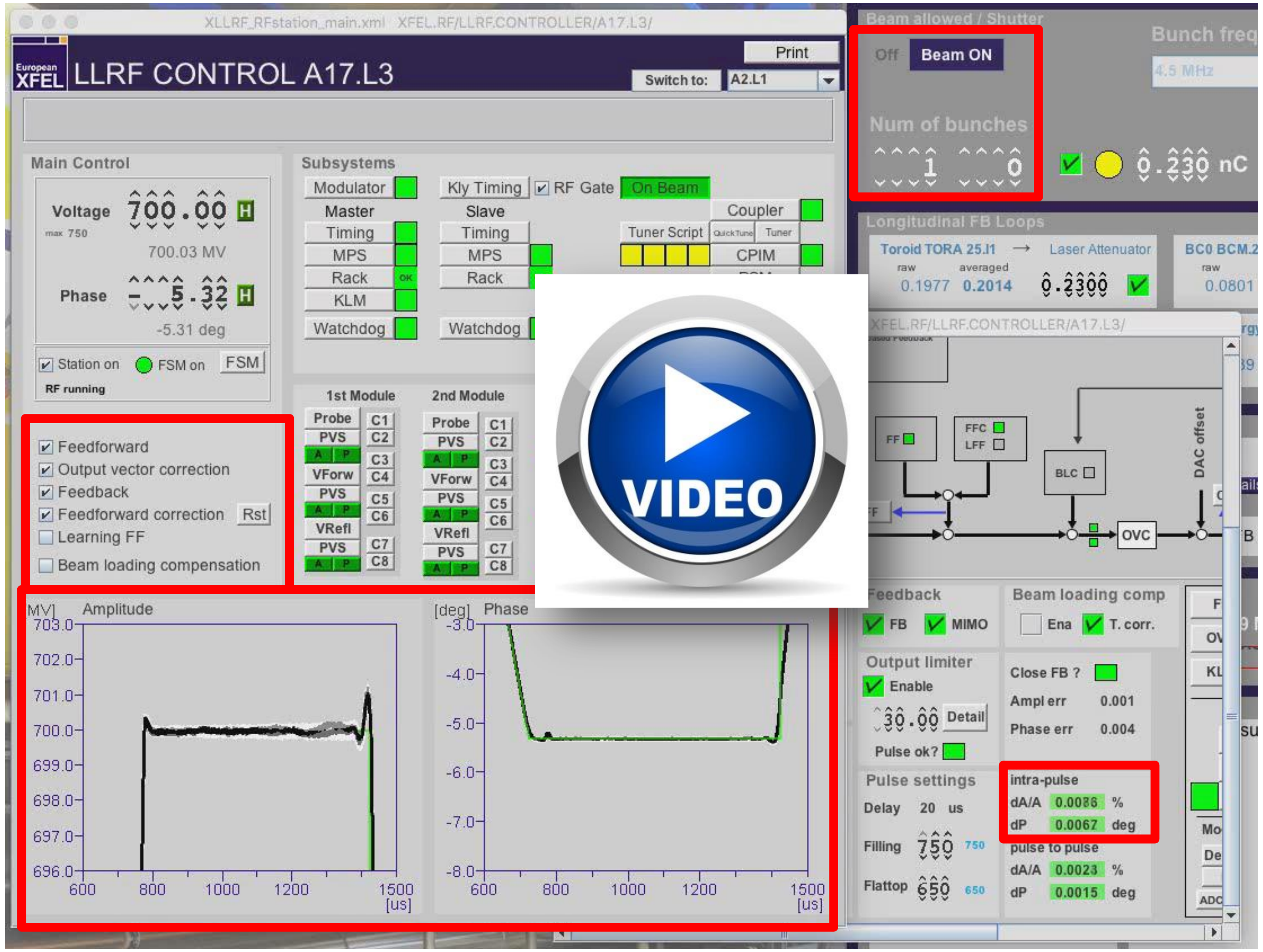
2e10

Quench **➔ 1.3e6 !!!**

RF operation

Beam loading compensation

- Compensates beam loading, assuring same energy gain for all electrons along bunch trains



LLRF CONTROL A17.L3

Voltage 700.00 (max 750) 700.03 MV

Phase -5.32 -5.31 deg

☑ Station on ● FSM on

☑ Feedforward
☑ Output vector correction
☑ Feedback
☑ Feedforward correction Rst
☐ Learning FF
☐ Beam loading compensation

Num of bunches 1 0 ☑ 0.230 nC

Toroid TORA 25.I1 raw 0.1977 averaged 0.2014 → Laser Attenuator 0.2300 ☑

BC0 BCM.2 raw 0.0801

Feedback: ☑ FB ☑ MIMO

Beam loading comp: ☐ Ena ☑ T. corr.

Output limiter: ☑ Enable 30.00

Ampl err 0.001
Phase err 0.004

Pulse settings:
Delay 20 us
Filling 750 750
Flattop 650 650

intra-pulse
dA/A 0.0086 %
dP 0.0067 deg

pulse to pulse
dA/A 0.0023 %
dP 0.0015 deg

Requirements
dA/A ≤ 0.01%
dP ≤ 0.01 deg.

Summary

Anybody awake ?

RF cavities fundamentals

- RLC model, envelope equation, detuning, sub harmonics, mechanical model, microphonics

RF power couplers

- Input power coupler, why and how changing Q_{ext}, impact on bandwidth, on power, heating of couplers

Frequency tuners

- Why tuning is important, slow and fast tuners, tuner figures of merit, “real world” examples, impact of Helium pressure

LLRF system

- LLRF versus HPRF, feed forward, feedback, down conversion, sampling and ADCs, IQ detection, system level description, single regulation, vector sum, pulsed and CW operation

Demo

- Simple examples using simulator

RF operations

- RF tuning, LFD compensation, quench, beam loading compensation

Thank you!

I wish everyone a fruitful conference and a pleasant stay in Dresden.

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