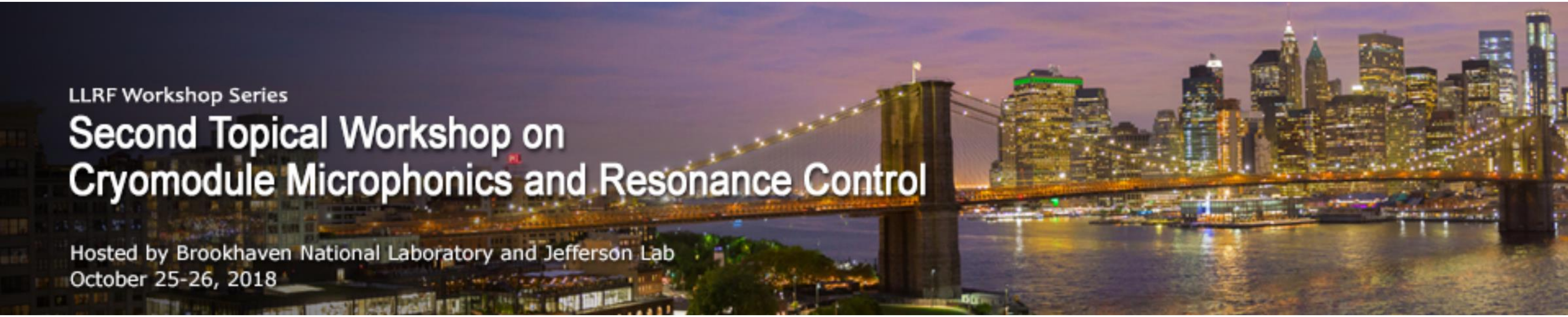
CW studies at DESY's cryomodule test bench.

R&D effort towards continuous wave operation of the European XFEL



Julien Branlard, for the LLRF team
New York City, 25.10.2018

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

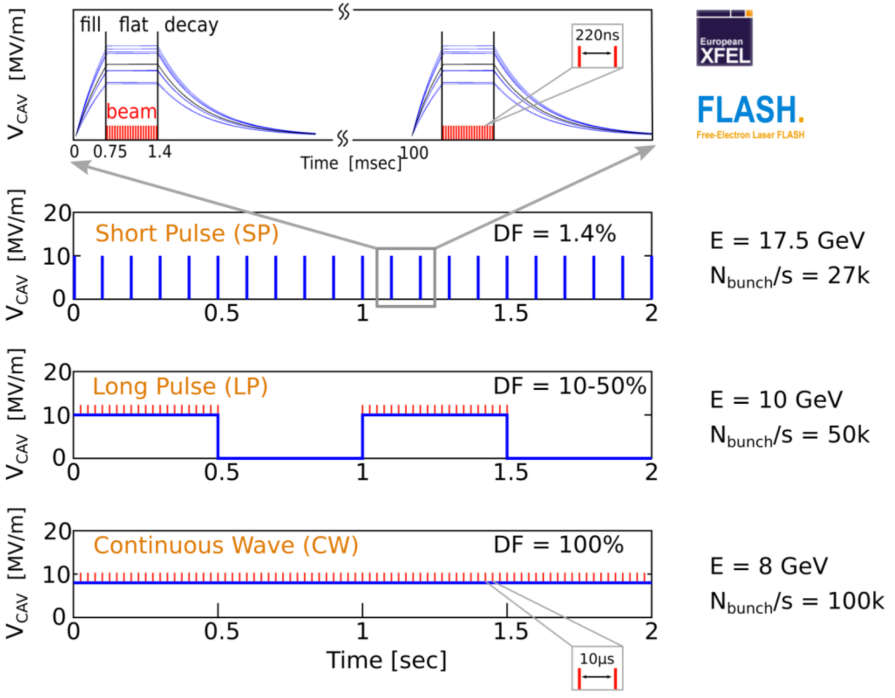
DESY.

CW studies at CMTB

Motivations for CW

CW upgrade of the European XFEL

- Feasibility study
- Possible beam energy = 8 GeV
- CW in addition to pulsed mode
- Long pulse also an option



Collaboration with other Helmholtz institutes (Germany)

HZDR (Dresden)

- ELBE: SRF FEL
- Single cavity regulation LLRF system
- Shared, HW, FW, server development
- Possibility to test with beam

HZB (Berlin)

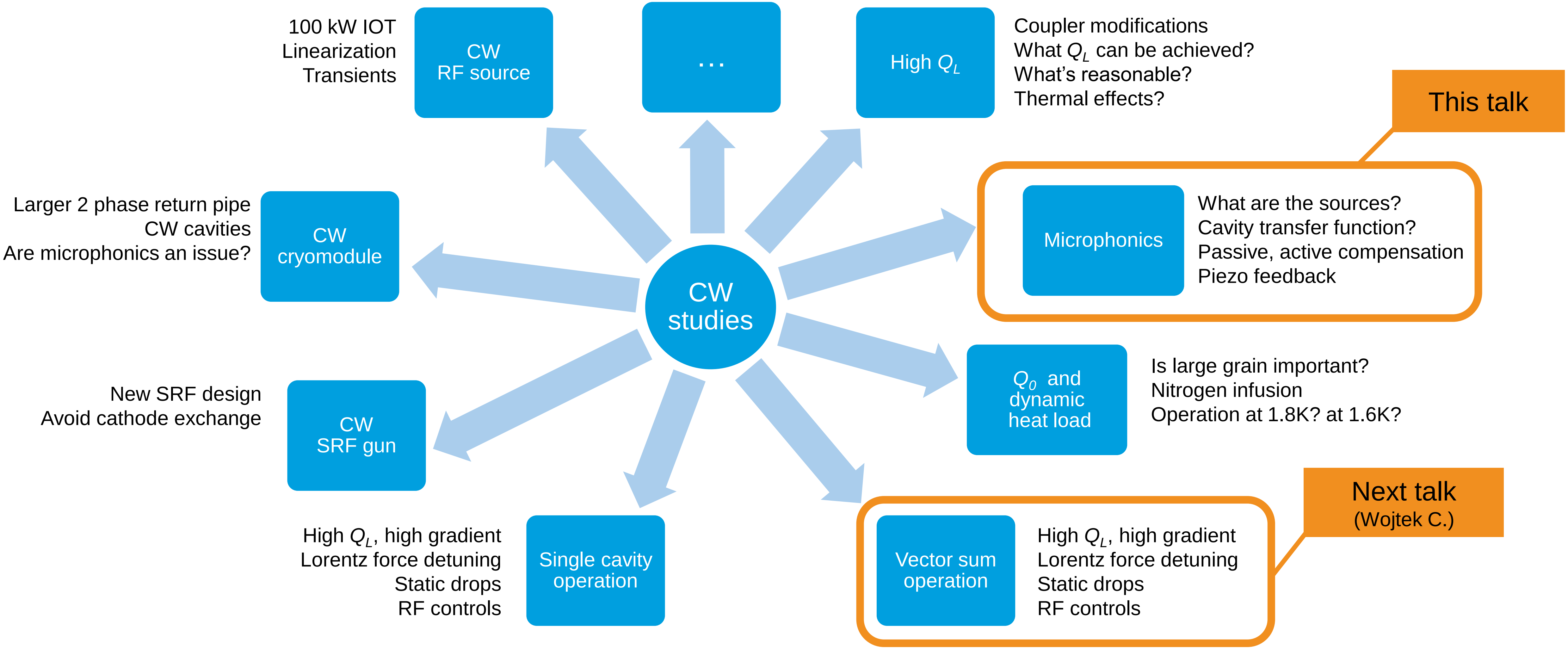
- bERLinPro: SRF ERL
- BESSY-VSR, storage ring
- LLRF, single cavity regulation
- Shared, HW, FW, server development

Talks tomorrow by A. Neumann and P. Echevarria

Accelerator R&D program funded by Helmholtz

CW studies at DESY

Simple overview

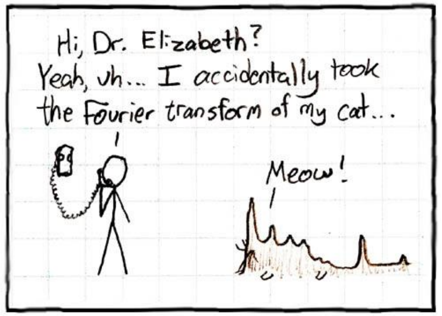


OUTLINE

Microphonics in the scope of CW studies at DESY

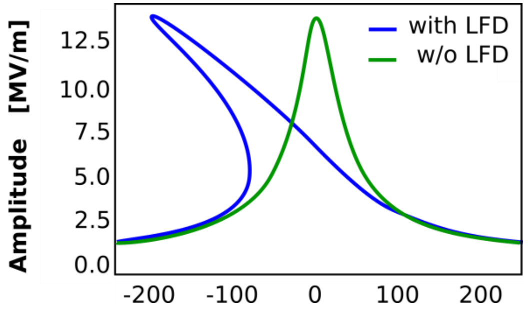
Microphonics and cavity modes measurements

- With piezo, with RF
- Frequency and stability analysis



Lorentz Force detuning and microphonics

- Static drops
- Piezo feedback



Suppression of microphonics

- Active noise cancellation
- Automation of parameter optimization

Outlook

- Summary
- Future tests at CMTB

Microphonics measurements

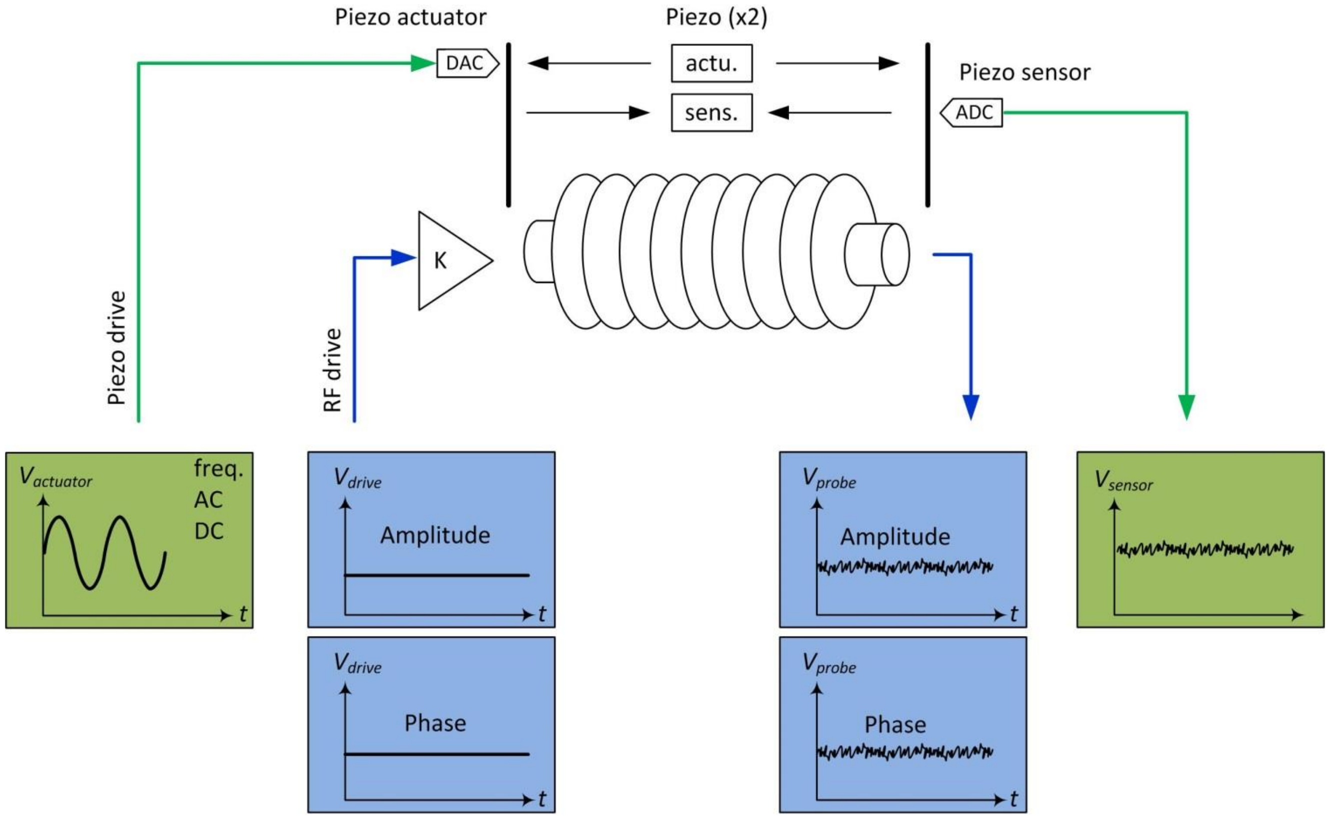
For particle accelerators

Sources of microphonics

- Natural vibrations (i.e. earthquakes)
- Human factors (i.e. trucks, foot steps)
- Accelerator operation (i.e. pumps, cryo bath)
  - RF
  - Piezo

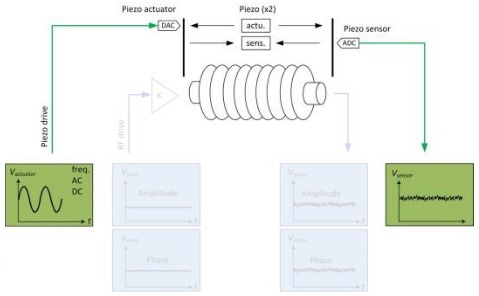
Measuring microphonics

- With beam
- With external sensors (i.e. accelerometers)
- With internal sensors (i.e. piezo)
- With RF (i.e. cavity probe)



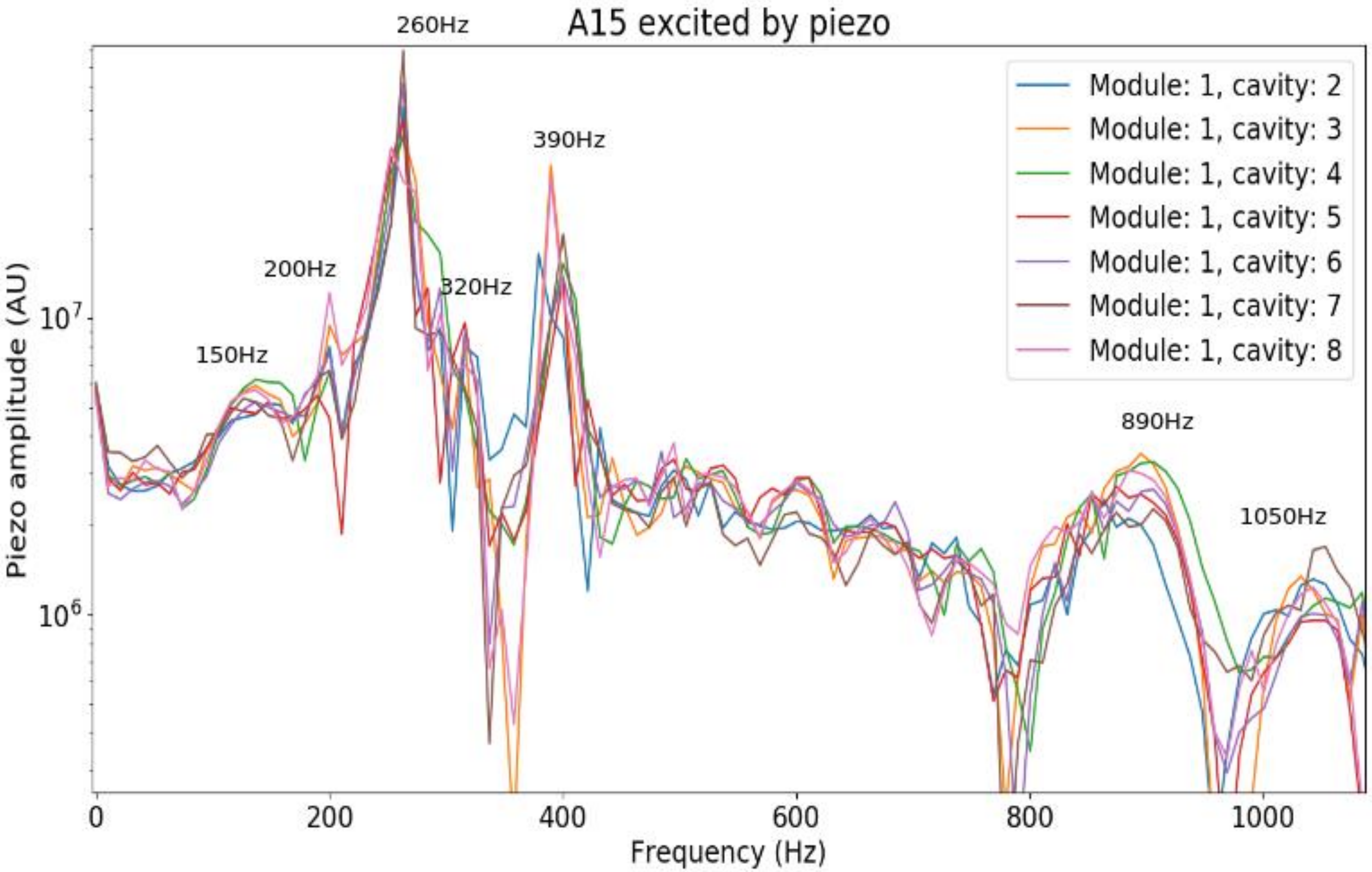
Measuring cavity mechanical modes

Transfer function: piezo → piezo



Measurement

- RF is off
- Excite piezo with sine waveform
- 2 periods at 300 Hz
- FFT of piezo sensor waveform



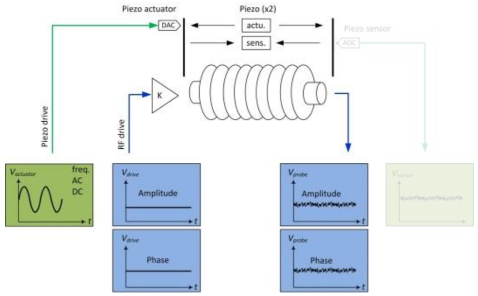
Courtesy A. Bellandi

Outcome

- Dominant resonant modes are found
- Here XFEL cryomodule ~ 260 Hz

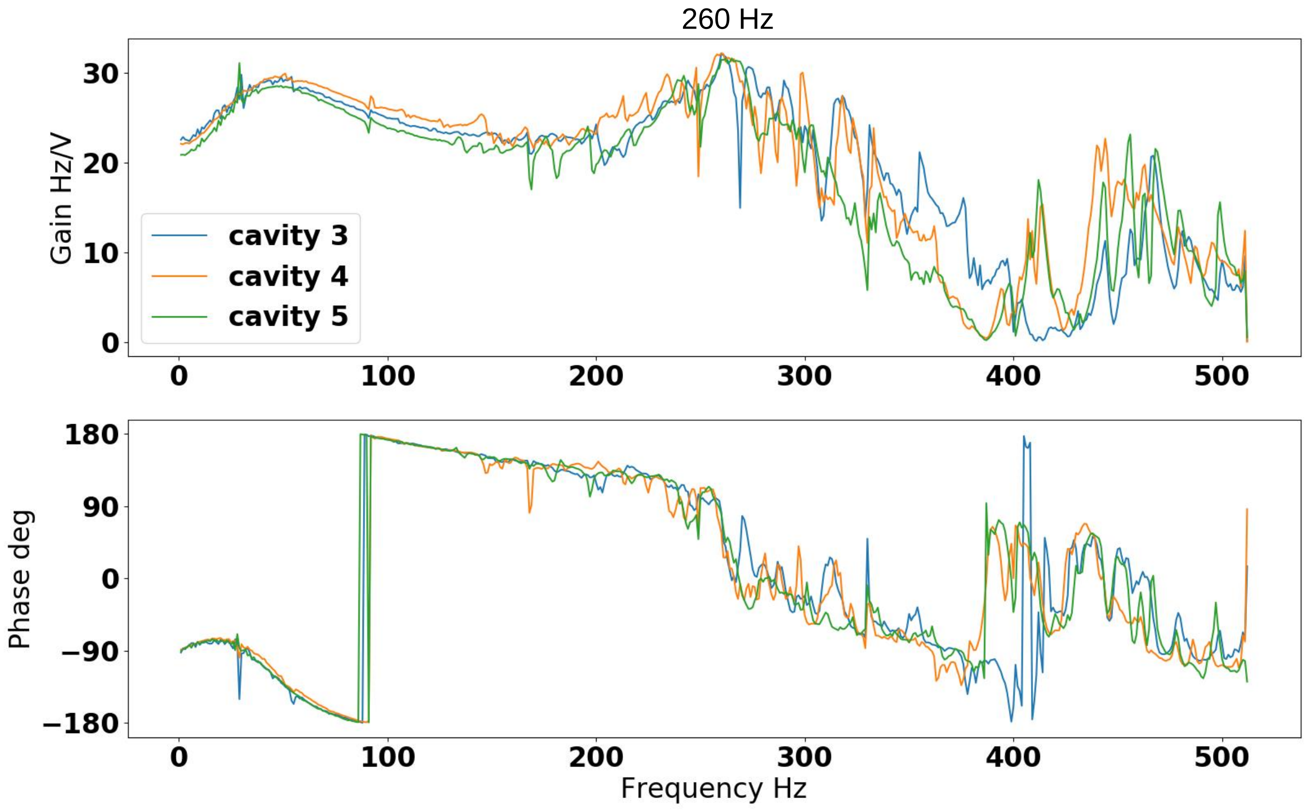
Measuring cavity mechanical modes

Transfer function: piezo → RF



Measurement

- RF is on
- Excite piezo with sine waveform
- FFT of **RF phase waveform**
- Sweep sine frequency



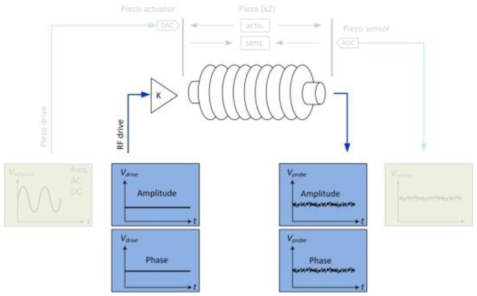
Outcome

- Dominant resonant modes are found
- Here XFEL cryomodule ~ 260 Hz

Courtesy A. Bellandi

Measuring microphonics – with RF

As a function of gradient

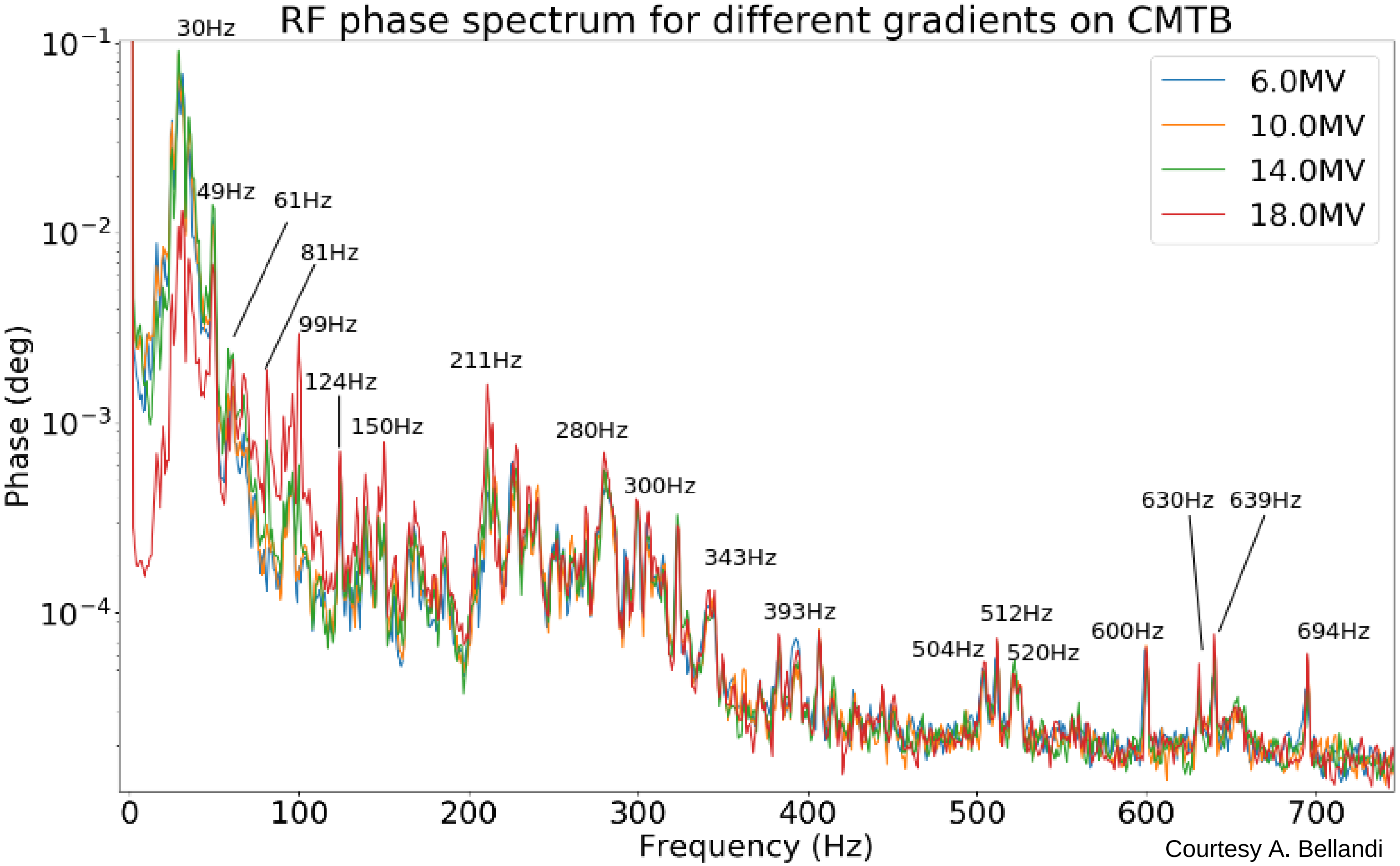


Measurement:

- RF is on, different gradients
- FFT of cavity **RF phase signal**

Outcome

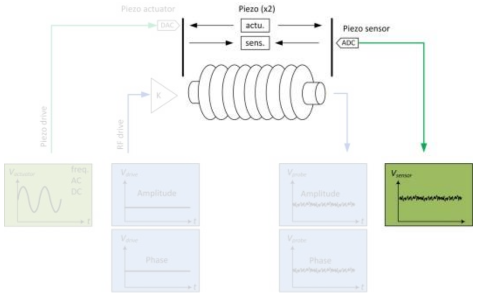
- CMTB: main freq: 30 Hz, 49 Hz (well known)
- Independent of gradient



Courtesy A. Bellandi

Measuring microphonics – without RF

As a function of time

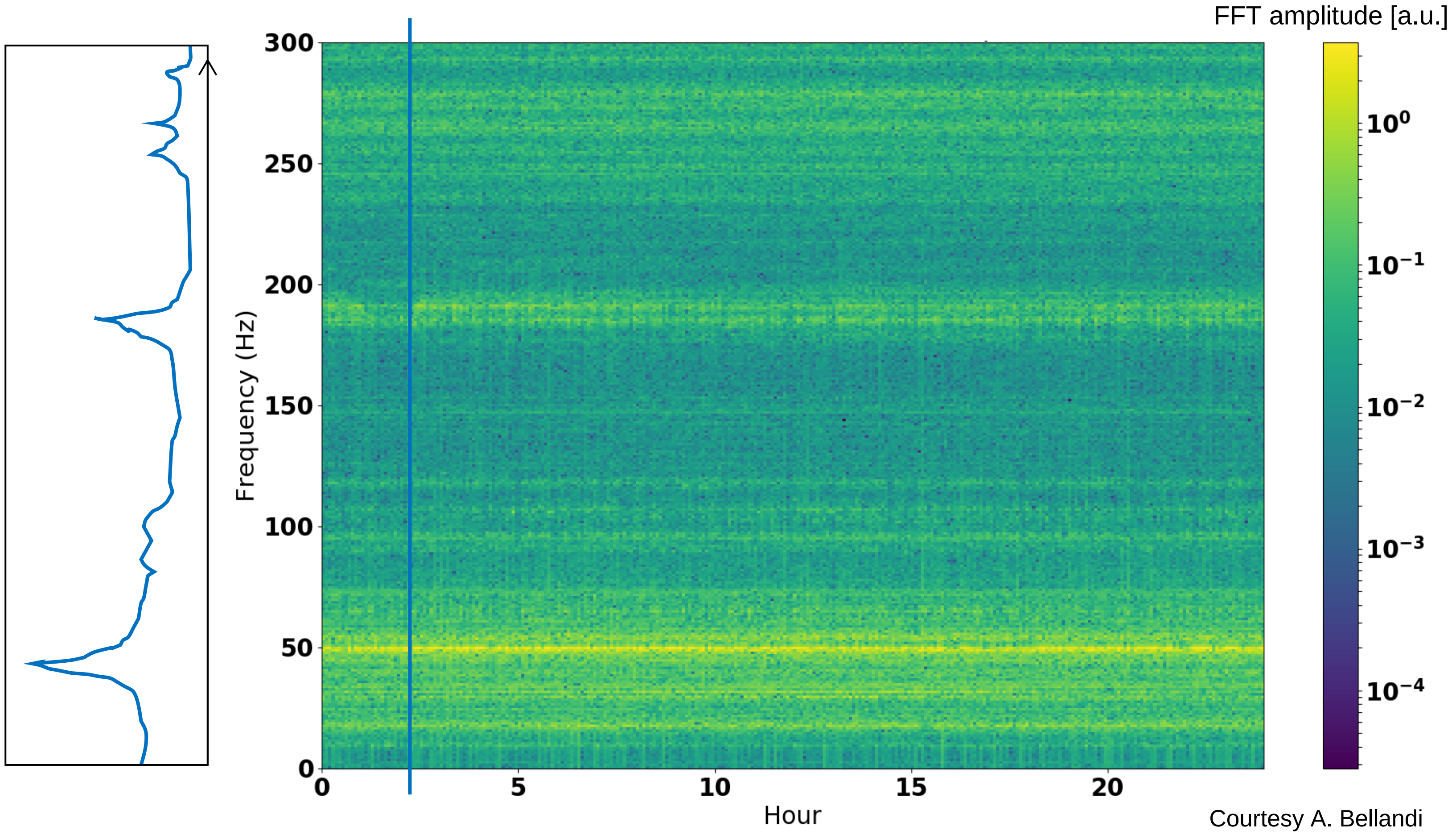


Measurement

- XM-3 at CMTB
- Data taken **with piezos**
- FFT amplitude of **piezo sensor**
- Spectrogram over 1 day

Outcome

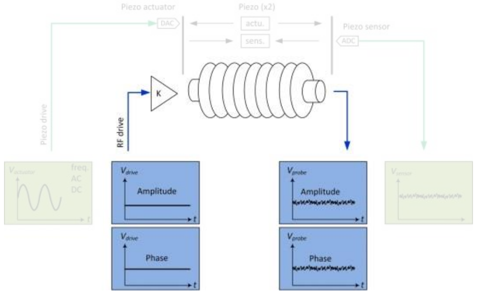
- Stable background conditions (in this example)



Courtesy A. Bellandi

Measuring microphonics – with RF

As a function of time

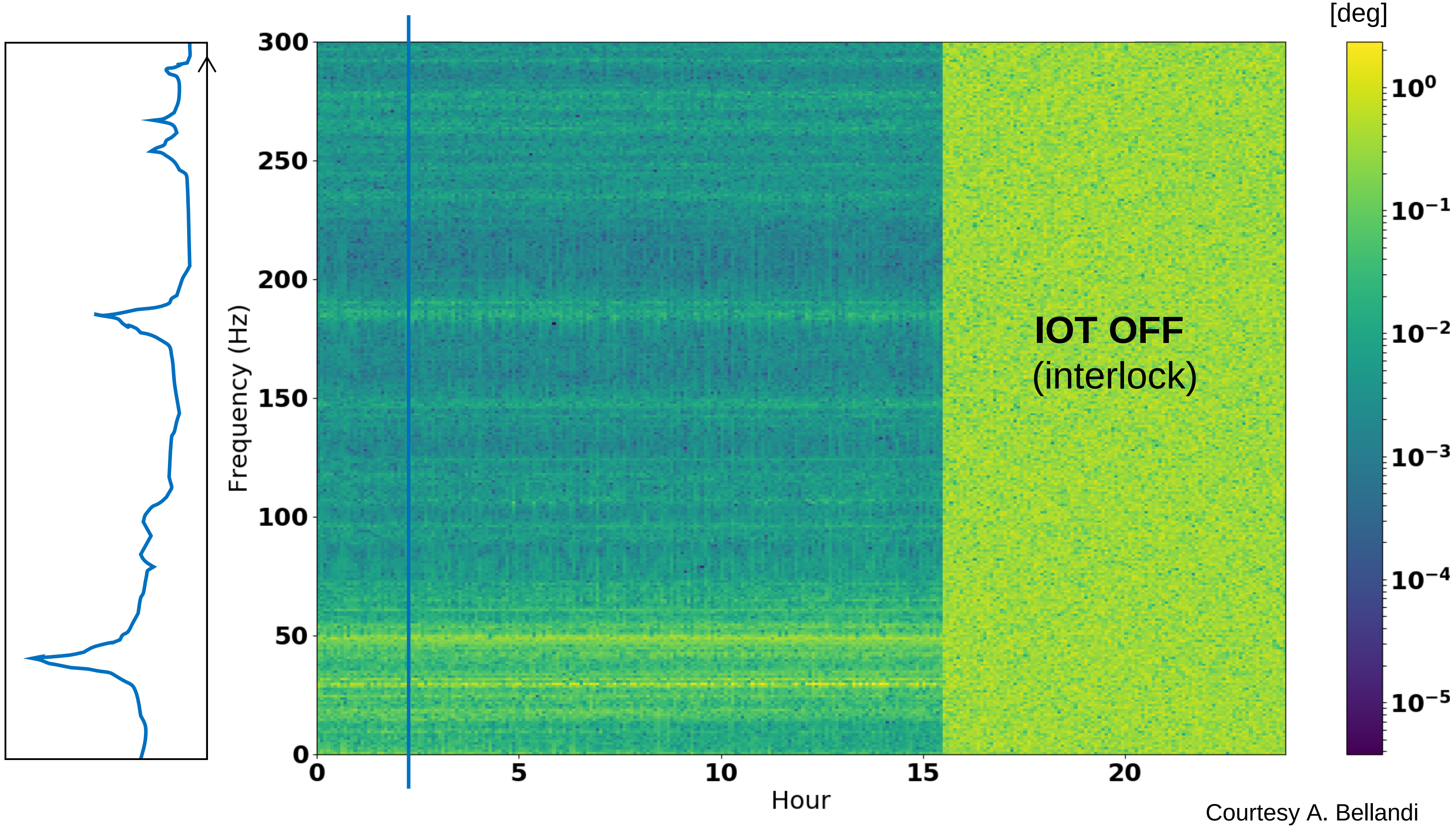


Measurement

- XM-3 at CMTB
- Data taken **with RF**
- FFT amplitude of **probe phase**
- Spectrogram over 1 day

Outcome

- Stable background conditions (in this example)



Courtesy A. Bellandi

Microphonics suppression

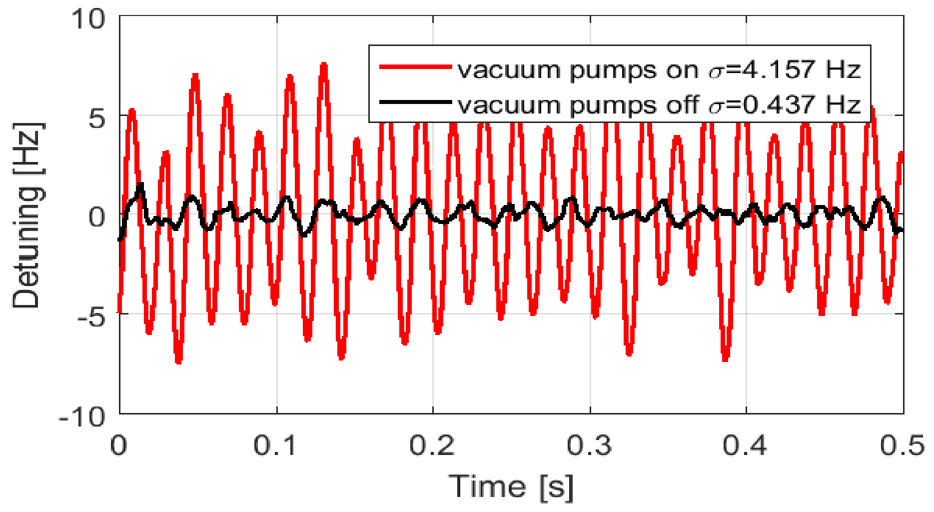
Using Active Noise Cancellation (ANC) techniques

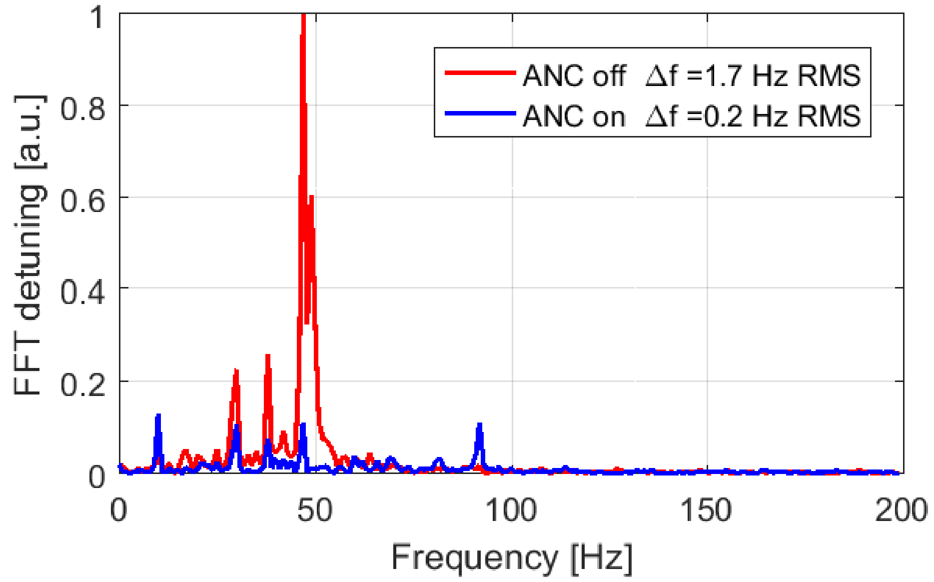
Source of microphonics

- Main contributor are **vacuum pumps** (essential for operation)
- Dominant frequencies around **30 Hz** and **49 Hz** for most cavities
- Impact increased with higher Q_L

Microphonics suppression

- Active Noise Cancellation (**ANC**) techniques were applied to notch these frequencies (adjusted for individual cavities)
- > 20 dB suppression can be achieved





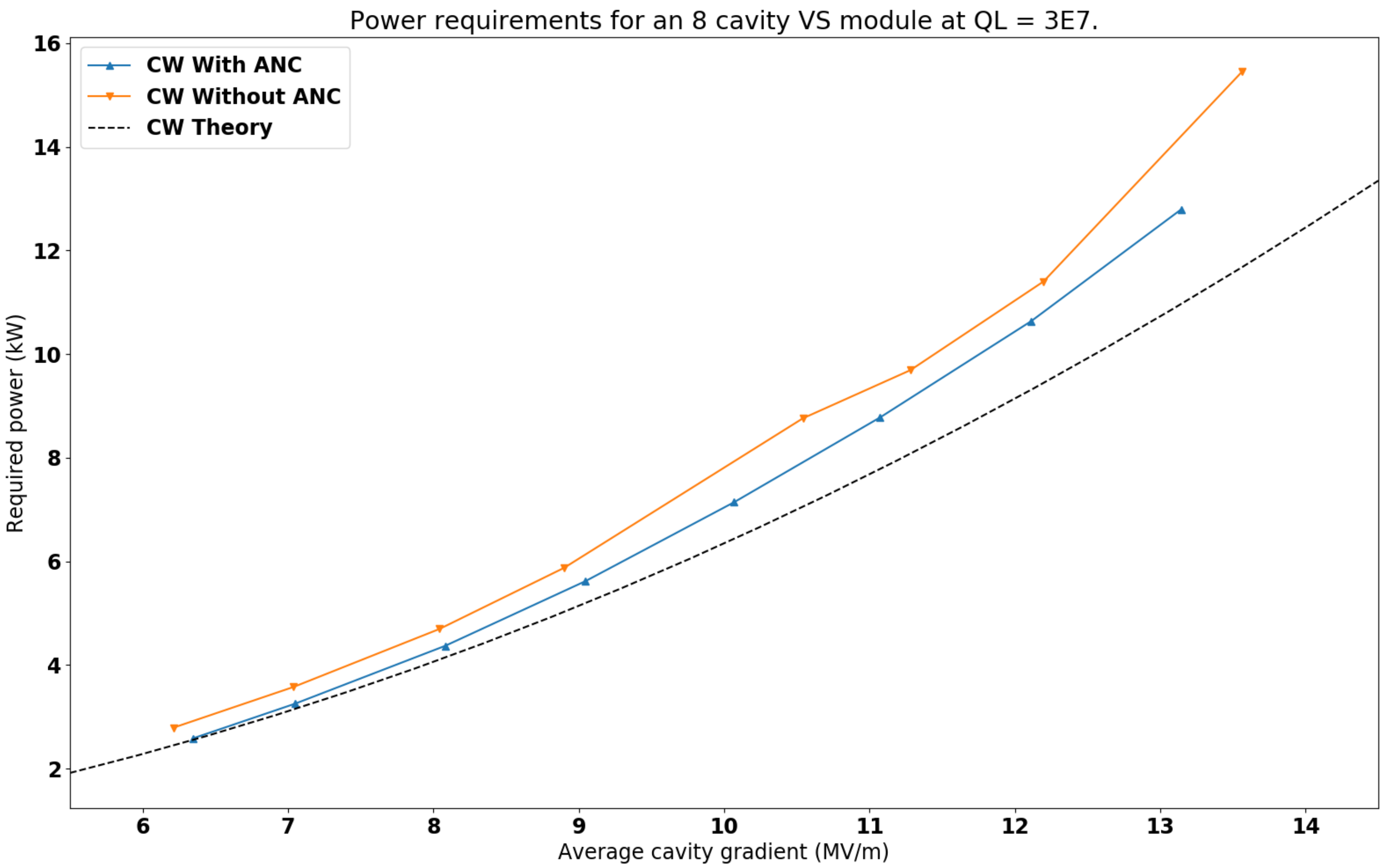
Reference:
R. Rybaniec *et al*. "FPGA-Based RF and Piezo controllers for SRF Cavities in CW Mode",
IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 64, NO. 6, JUNE 2017

ANC: power consumption

The impact of noise cancellation on forward power

ANC also helps with power consumption

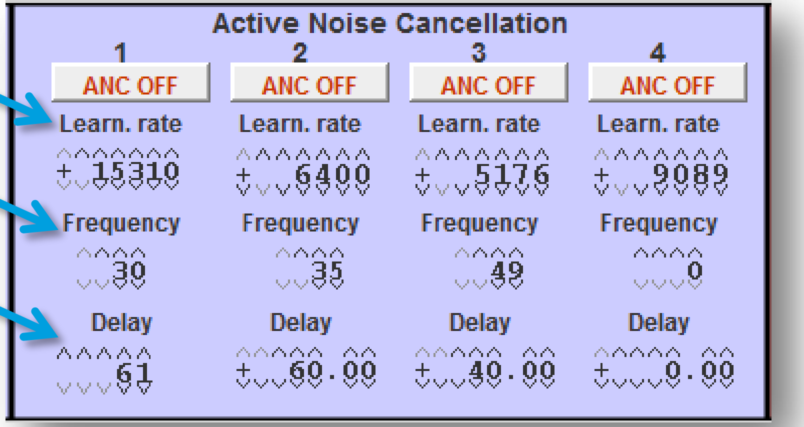
- Gradients between 6 MV/m and 13 MV/m
- ANC decreased the power consumption by 6% to 12%
- For low gradients the consumption for the ANC measurements approaches the theoretical minimum value



Courtesy A. Bellandi

ANC: parameter optimization

x800 for XFEL ! 😱

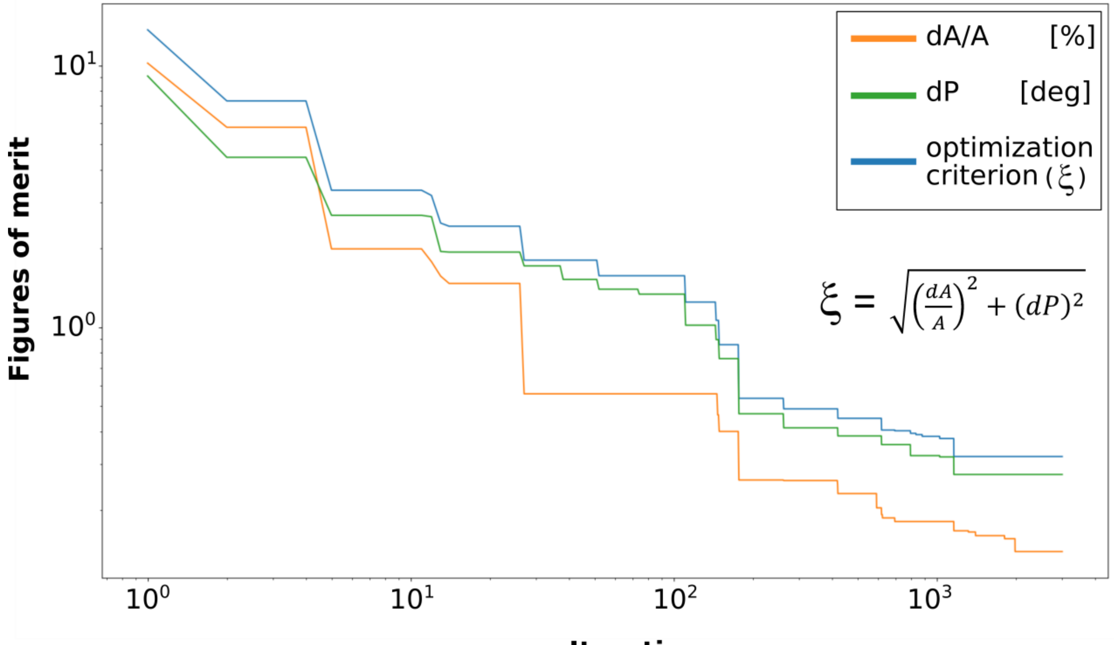


ANC optimization

- Done manually → not scalable
- Based on experience
- Likely change with time

Automation

- First attempt
  - Bayesian optimization algorithm
  - Time consuming
  - Positive outcome but not as optimal as manual tuning
- Work on-going
  - Improve optimization algorithm
  - Improve ANC scheme to include microphonics measurements

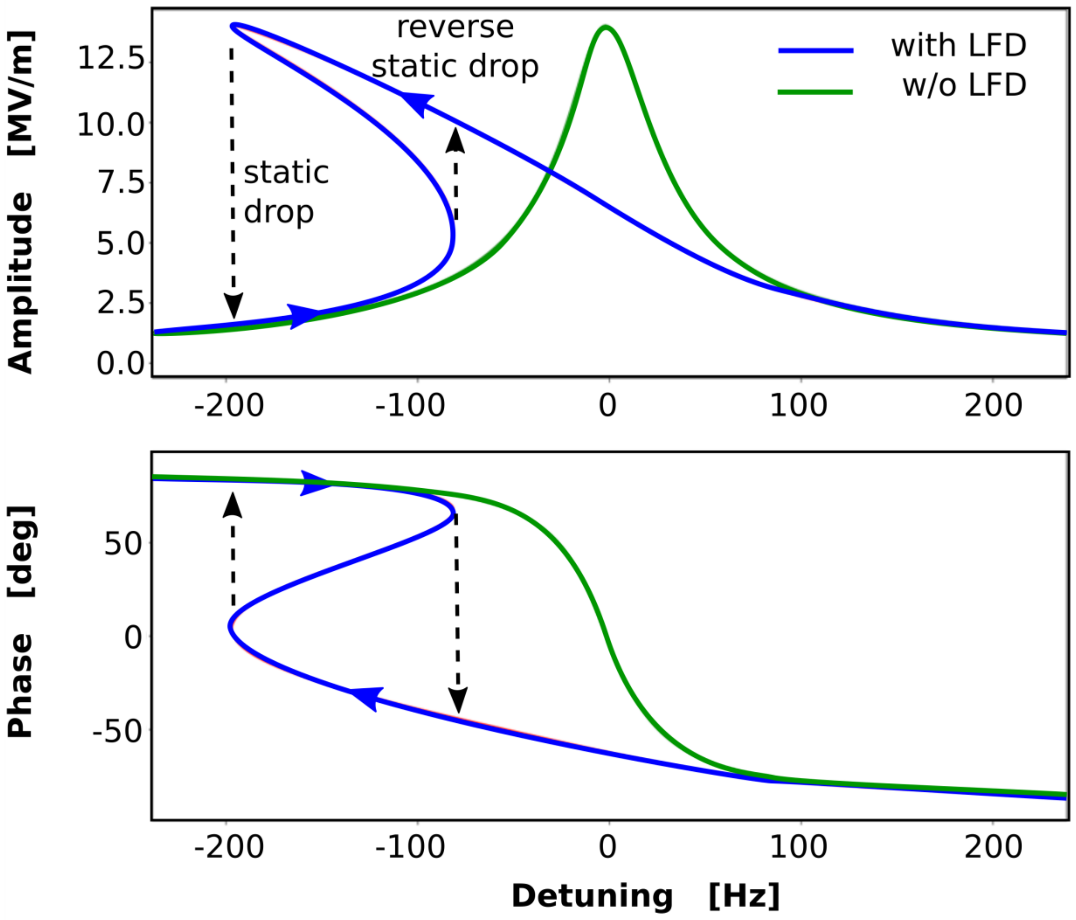


Courtesy A. Bellandi

Microphonics and LFD

1 / 3

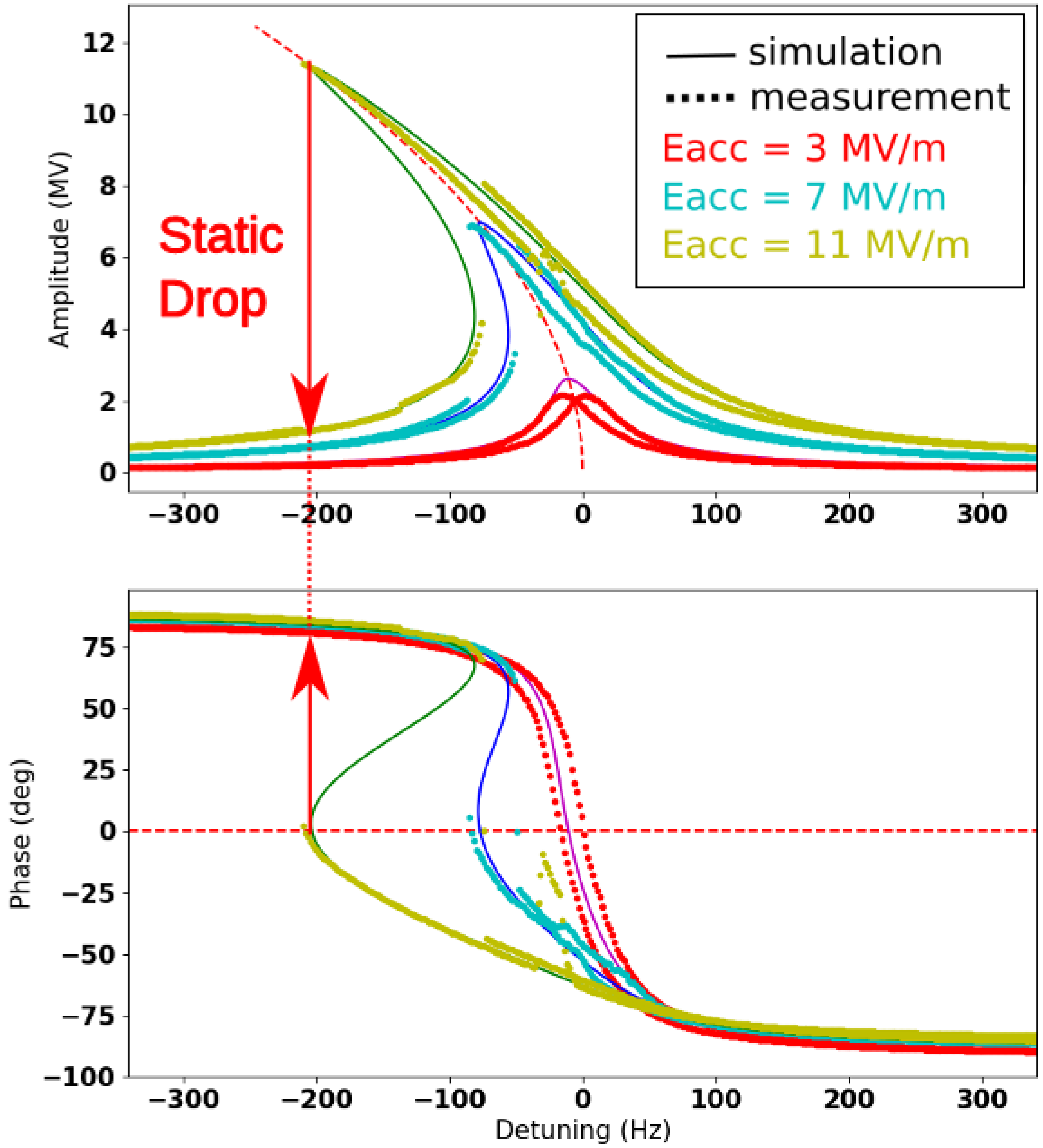
- Microphonics can/will make the cavity experience a static drop
- Effect is worsened for higher Q_L and higher gradients



Microphonics and LFD

2 / 3

- Microphonics can/will make the cavity experience a static drop
- Effect is worsened for higher Q_L and higher gradients

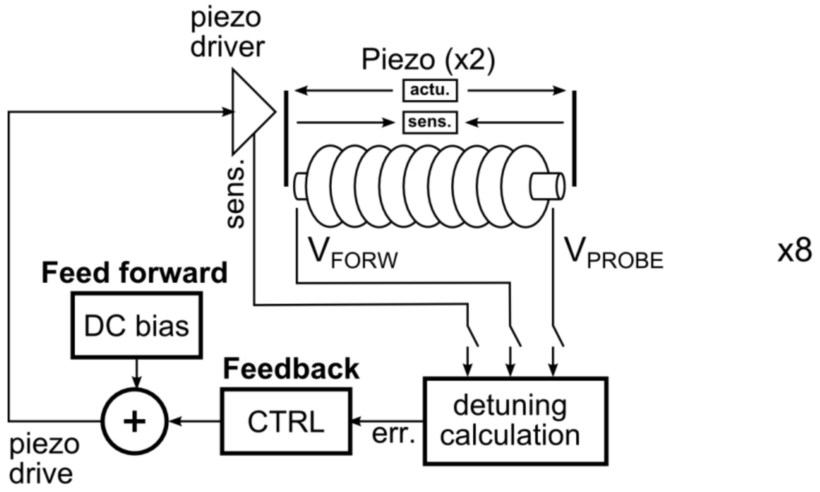


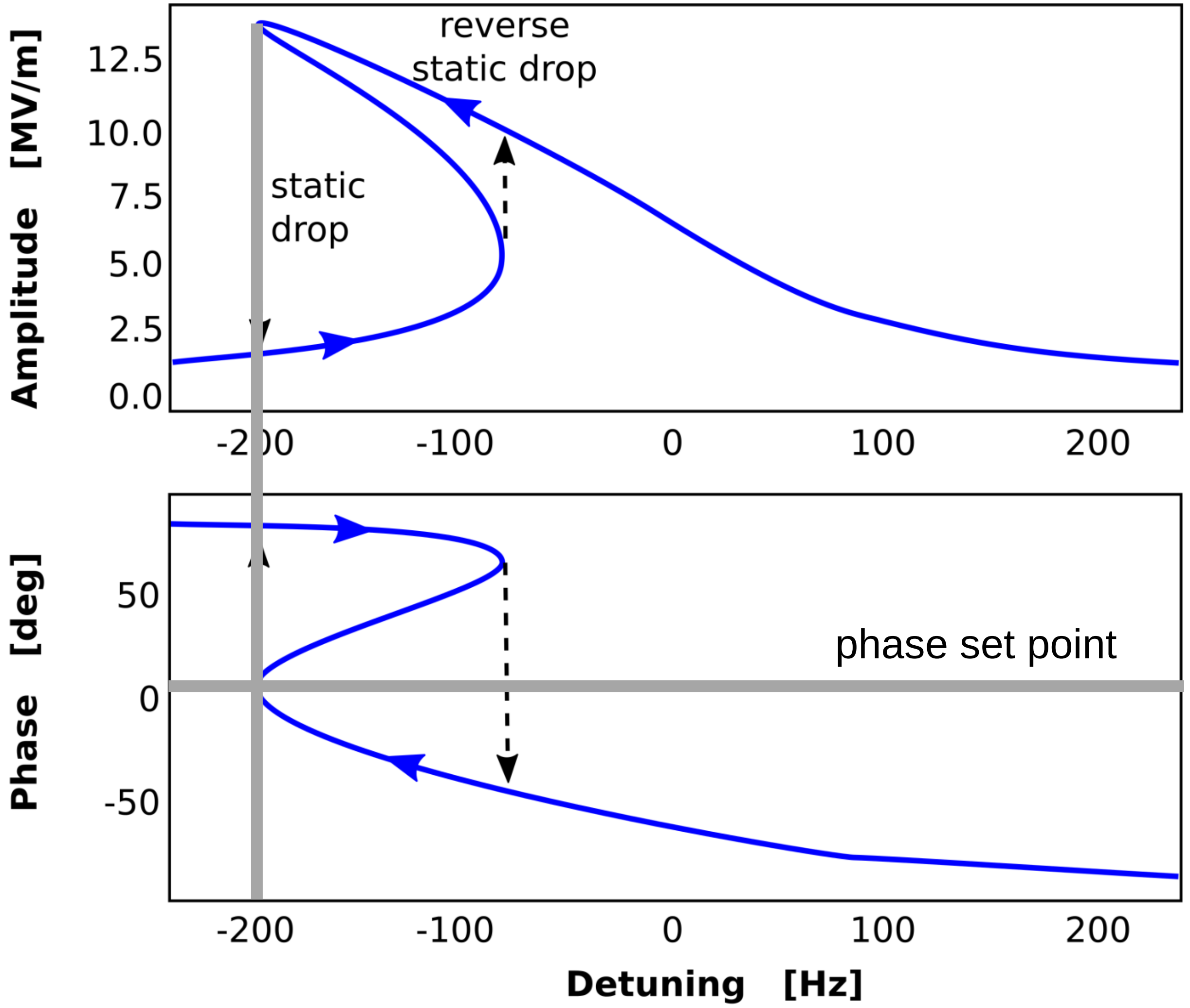
Courtesy A. Bellandi

Microphonics and LFD

3 / 3

- Microphonics can/will make the cavity experience a static drop
- Effect is worsened for higher Q_L and higher gradients
- In practice, **piezo integrator feedback** works against this effect
- Choose your working point wisely





Microphonics and LFD

3 / 3

- Microphonics can/will make the cavity experience a static drop
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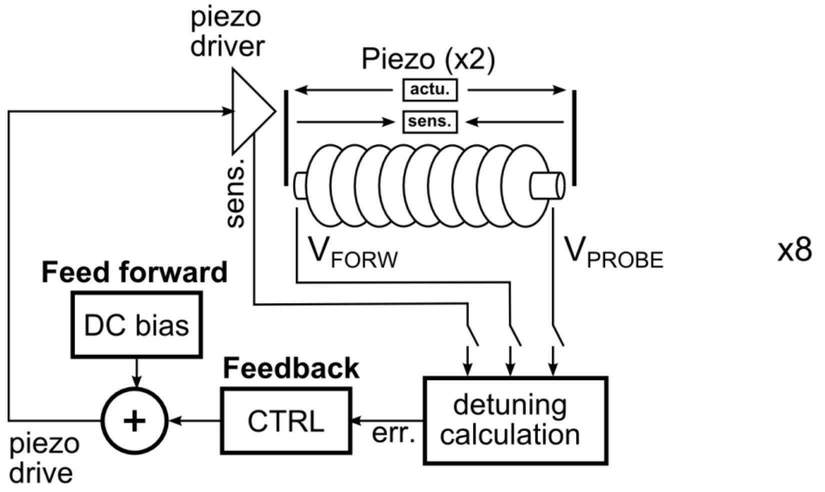
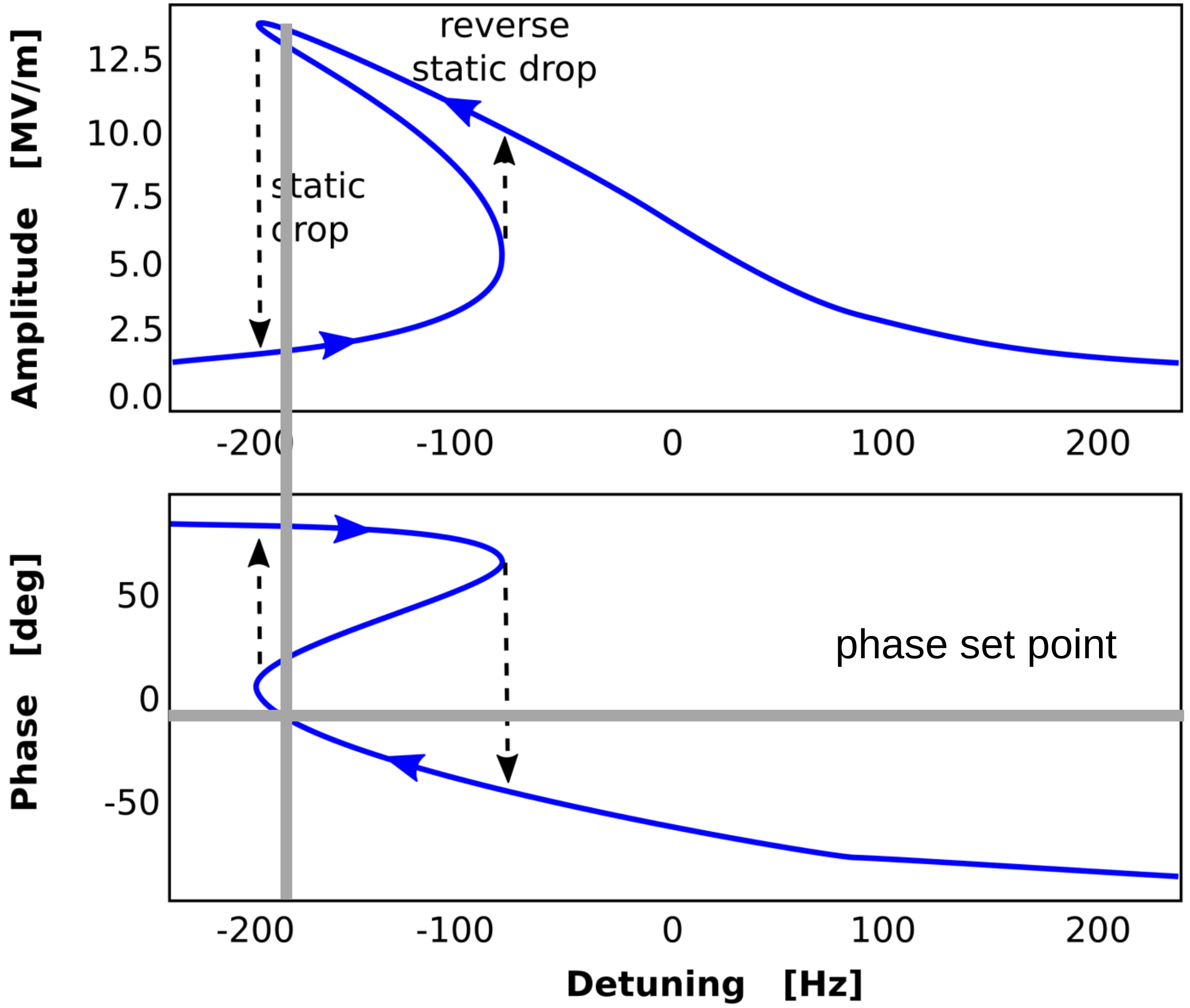


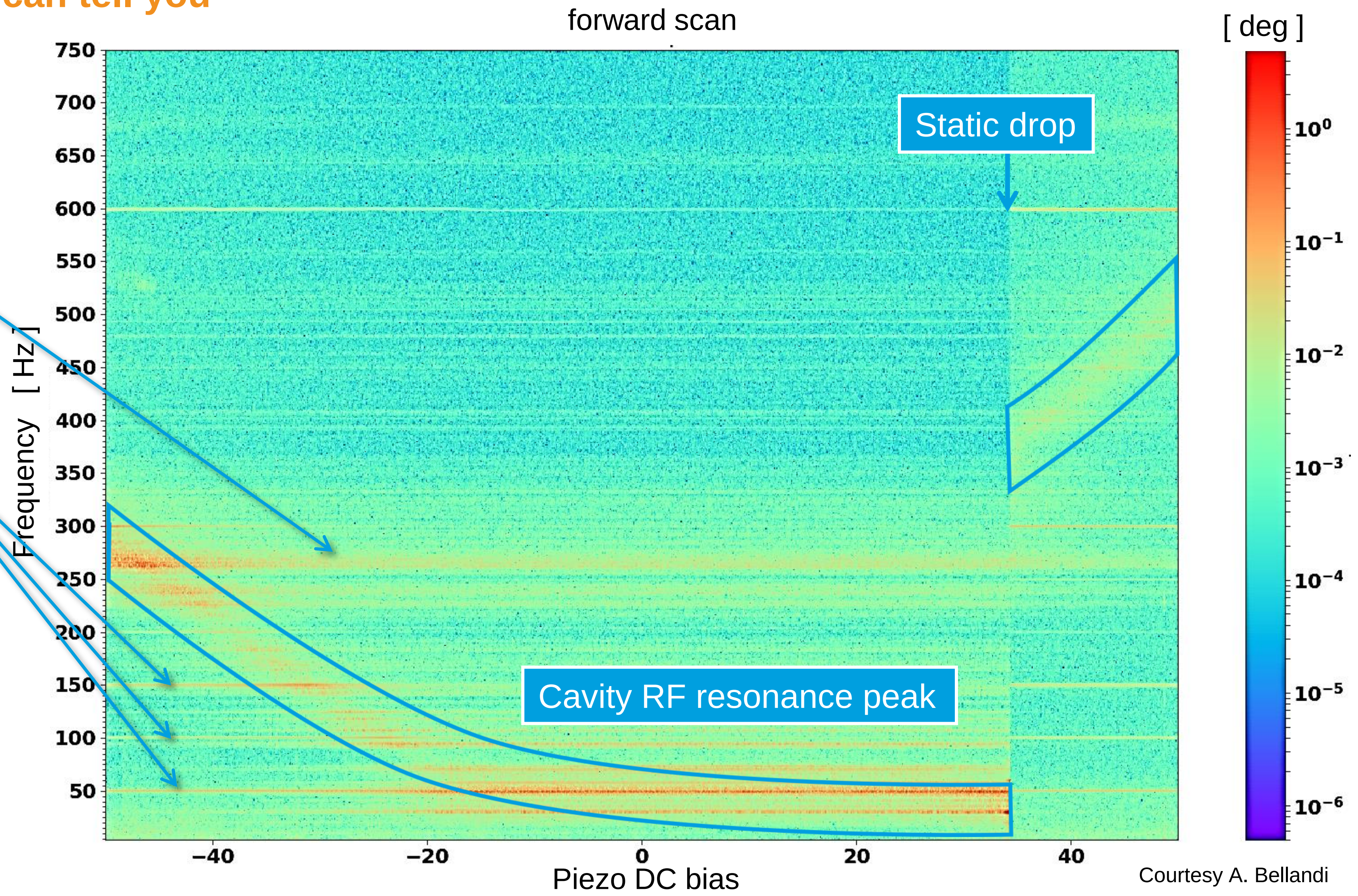


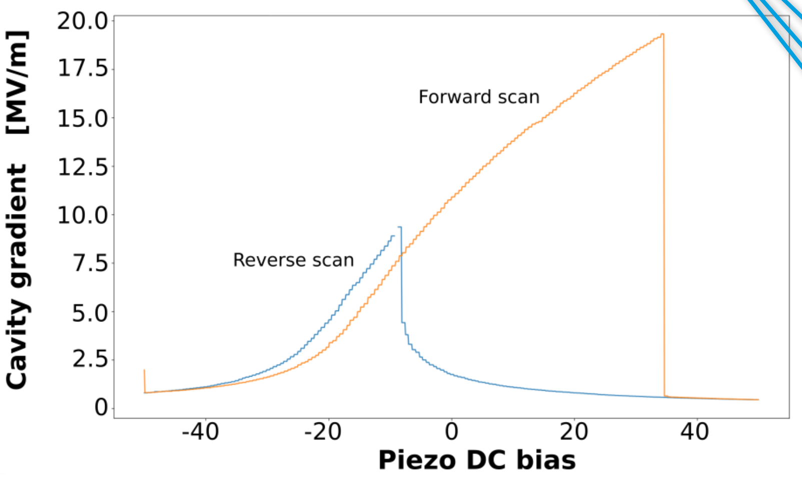
Cavity tuning

What the cavity phase spectrum can tell you

Cavity main mechanical mode: 260 Hz

Microphonics: 49 Hz and harmonics





Courtesy A. Bellandi

Summary

On going work towards CW operations

- Understand microphonics signature and how to measure them
- Characterize the cavity/tuner mechanical transfer function
- Good results in CW in terms of
  - RF stability (0.01%, 0.01 deg.)
  - At high Q_L (6-8x107)
  - At high gradient (>20 MV/m)

Next talk by W. Cichalewski

BUT

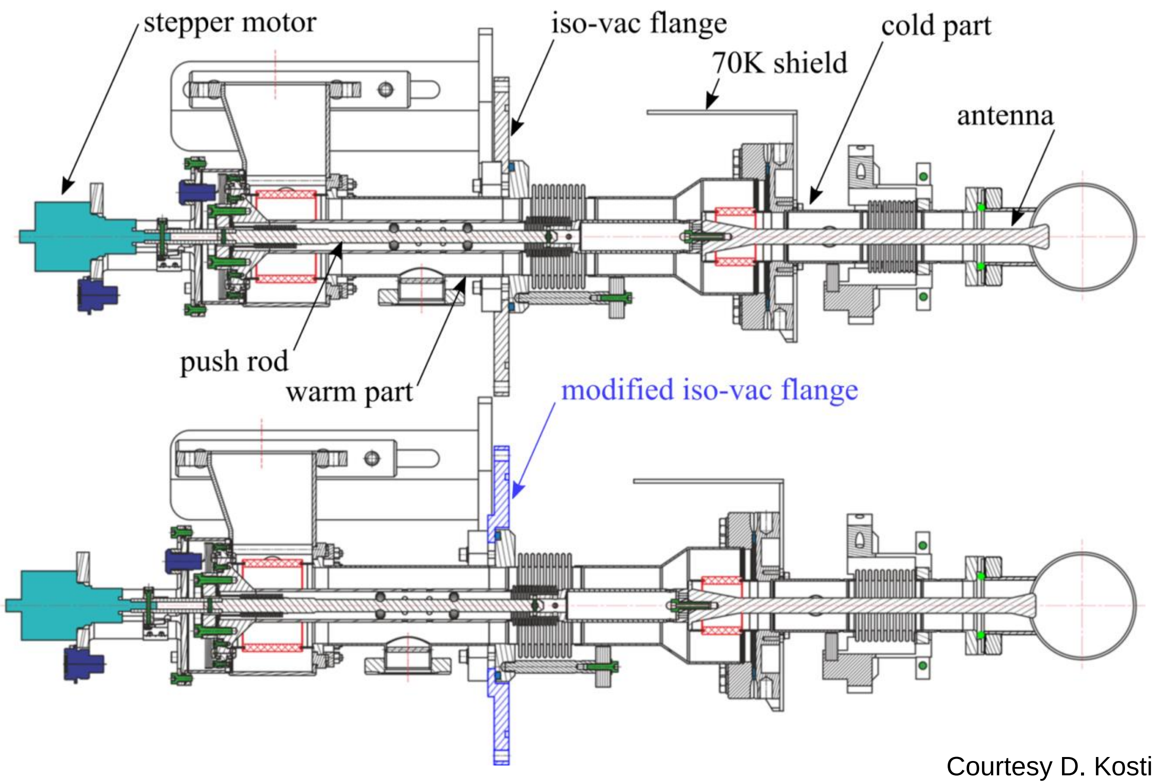
- Understand the limitations and how to go beyond
- Limitations of current active noise compensation approach (ANC)
  - Automate settings
  - Scale to 800 cavities
  - Adapt settings to changing environment

Summary

On going work towards CW operations

Upcoming tests at CMTB

- XM50 and XM46
- XFEL series cryomodules
- Modified with extended iso-vac flange for higher Q_L
- Difference with XM-3
  (fine versus large grain, series versus prototype)
- What heat load / Q_0 to expect
- Extremely relevant for a CW upgrade of the XFEL (main linac)



Courtesy D. Kostin

Thank you for your attention!

Special thank to my CW colleagues at DESY
Valeri Ayvazyan, Andrea Bellandi, Wojciech Cichalewski, Jürgen Eschke, Çagil Gümüş, Denis Kostin, Rüdiger Onken, Sven Pfeiffer, Konrad Przygoda, Jacek Sekutowicz, Christian Schmidt

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BACK UP SLIDES

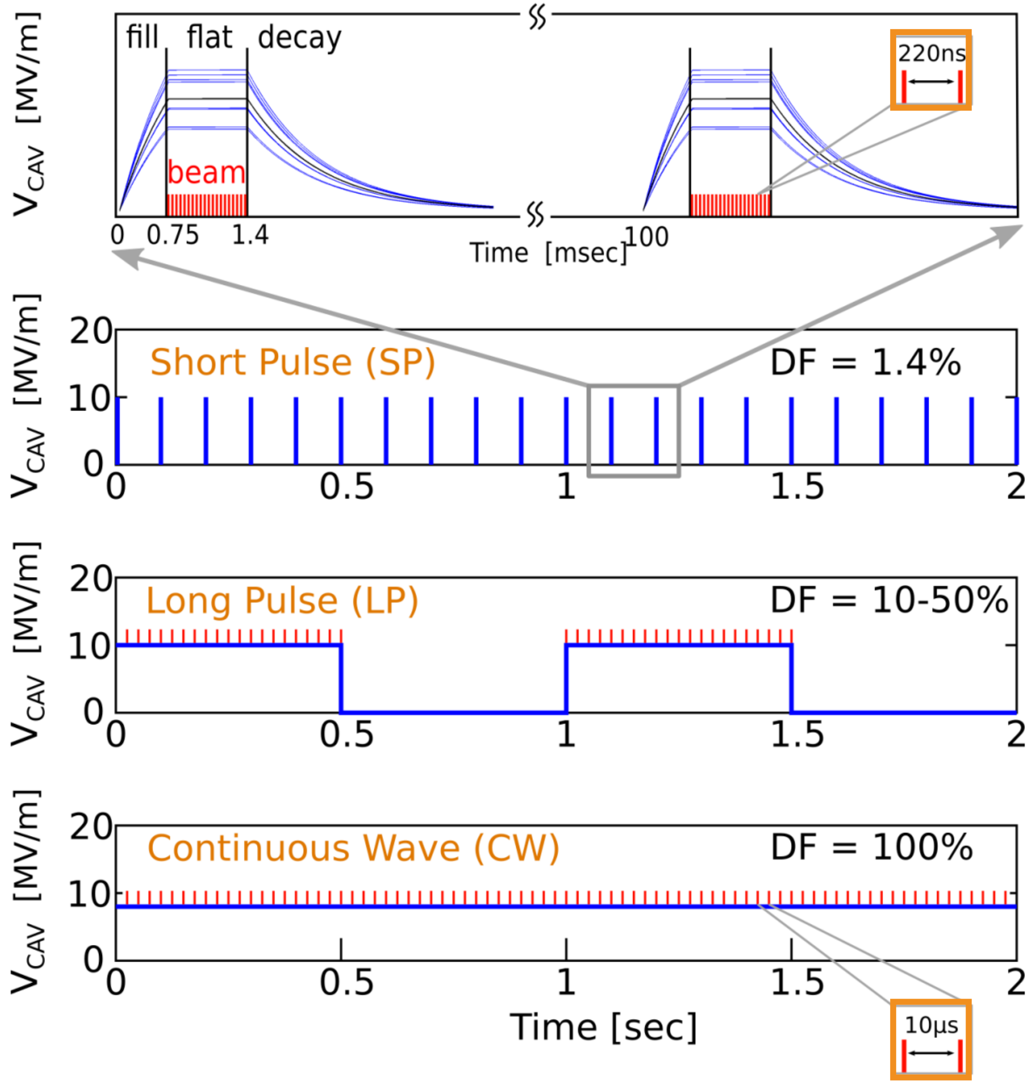
MOTIVATION FOR CW OPERATION

Benefits of Continuous Wave (CW) operation

- Flexible beam patterns for detectors
  Almost any macro pulse structure can be offered
- 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



European XFEL

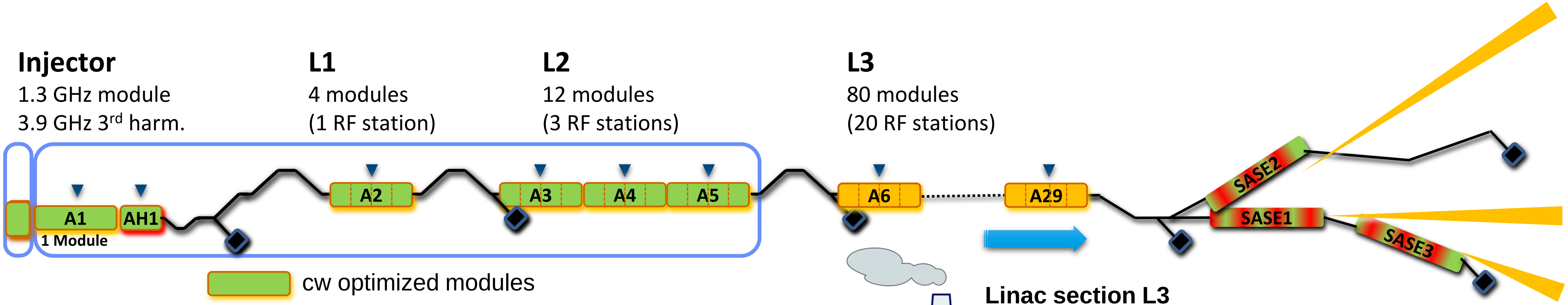
FLASH. Free-Electron Laser FLASH

E = 17.5 GeV
N_{bunch}/s = 27k

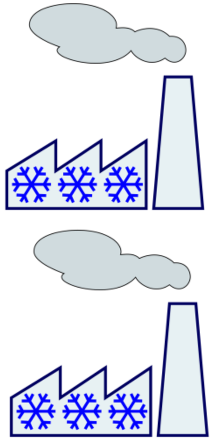
E = 10 GeV
N_{bunch}/s = 50k*
*up to 500 kHz for 20pC

E = 8 GeV
N_{bunch}/s = 100k*
*up to 1 MHz for 20pC

OPERATING THE XFEL IN CW



cw optimized modules



Linac section L3

- operated at moderate CW gradients
- lengthened by former A2 … A5

  80 + 12 modules

  24 RF stations

→ **Expected energy 8 GeV !**

1 – Replace the front-end cryomodules (17x)

- Larger cooling capability
- CW cavities

2 – Install CW capable RF sources

- 1x IOT per RF station

3 – Double the cryo plant (cost driver)

- 2.5 → 5kW

4 – Install CW capable gun:

- RF gun upgrade

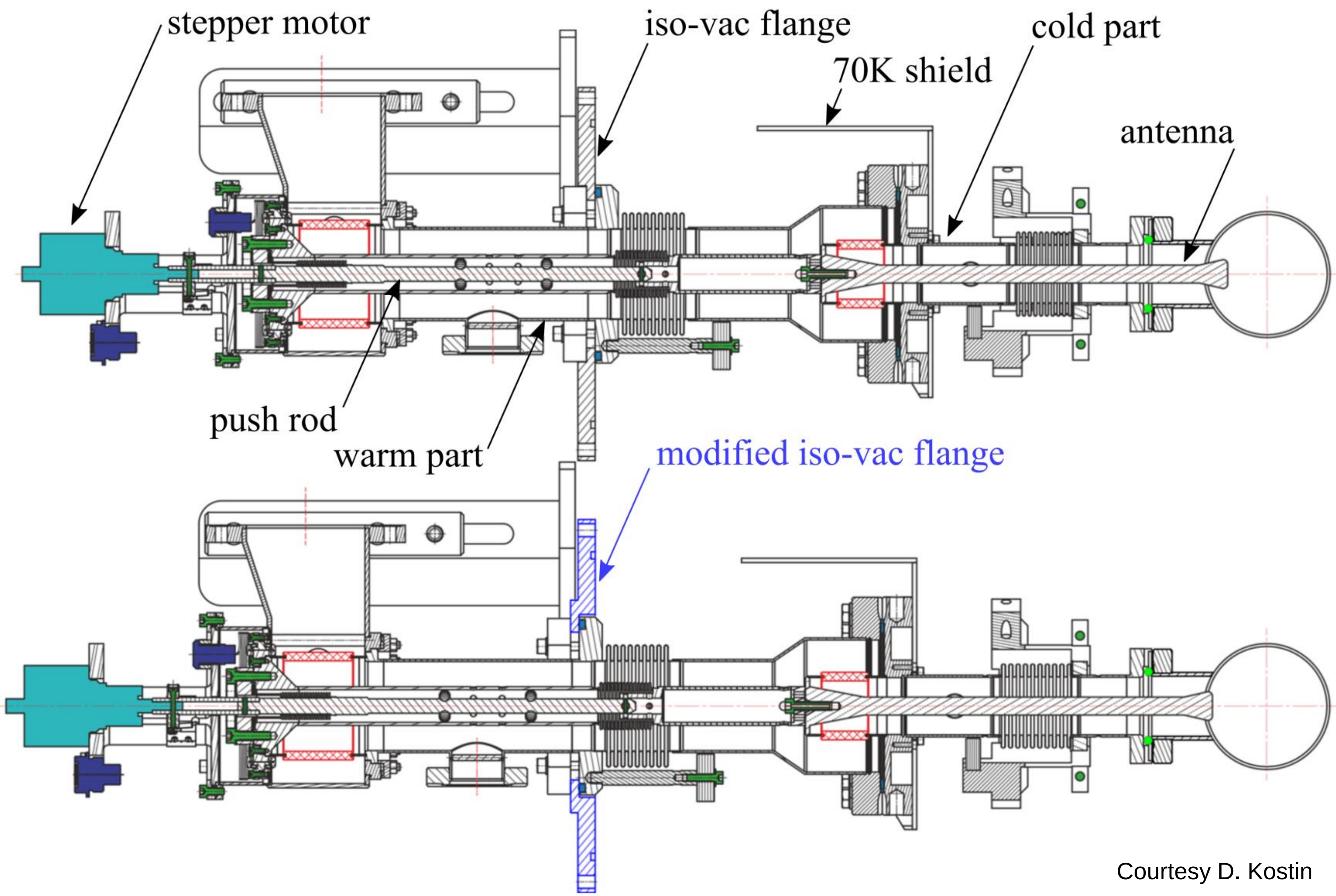
- **The former front-end cryomodules can be installed at the end of the linac to lengthen L3 (+4 RF stations)**
- **No further action required in L3 (>1km)**
- **The upgraded XFEL would be capable of short pulse long pulse AND continuous wave operation**

Coupler modifications

Modified iso-vac flange

Example of XM-3

Cavity	Q_L max (before)	Q_L min (after)	Q_L max (after)
C1	2.8E7	0.6E7	8.4E7
C2	1.9E7	0.5E7	6.8E7
C3	2.2E7	0.8E7	11.0E7
C4	2.0E7	0.6E7	9.1E7
C5	2.0E7	0.5E7	7.5E7
C6	1.9E7	0.4E7	6.6E7
C7	1.8E7	0.5E7	3.0E7
C8	2.0E7	0.5E7	3.0E7

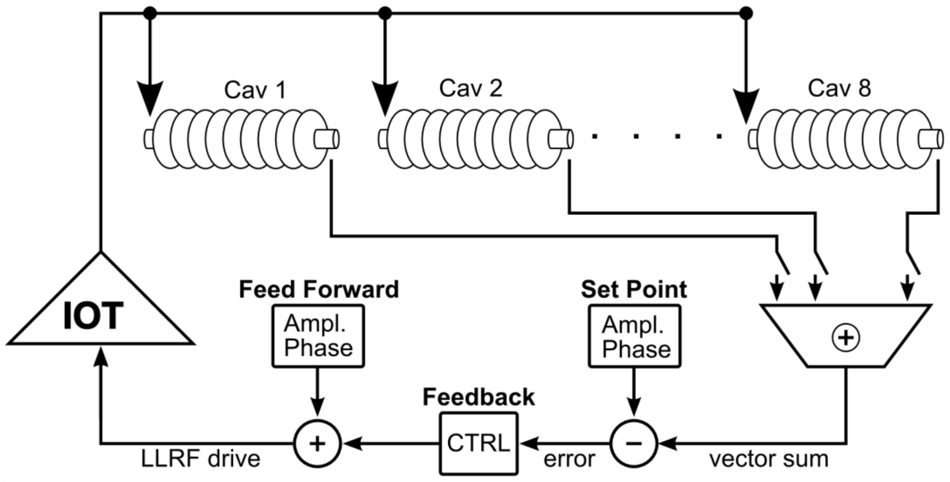


Courtesy D. Kostin

Control of acceleration field and cavity resonance

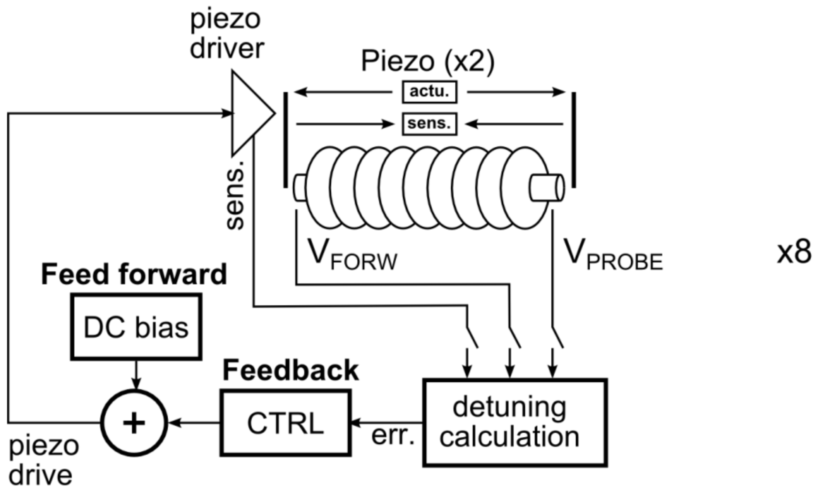
RF feedback

- Applied around individual cavities or to the vector sum
- Proportional / integral feedback controller
- Goal is to maintain gradient amplitude and phase
  - $dA/A \leq 0.01\%$
  - $dP \leq 0.01$ deg.



Piezo feedback

- Each cavity is equipped with a dual piezo frequency tuner
- Applied around individual piezo electric element
- Proportional / integral feedback controller
- Goal is to keep cavity on resonance to meet phase stability requirements
  - Δf << cavity half bandwidth



Results: RF Stability example

Vector sum regulation (CW)

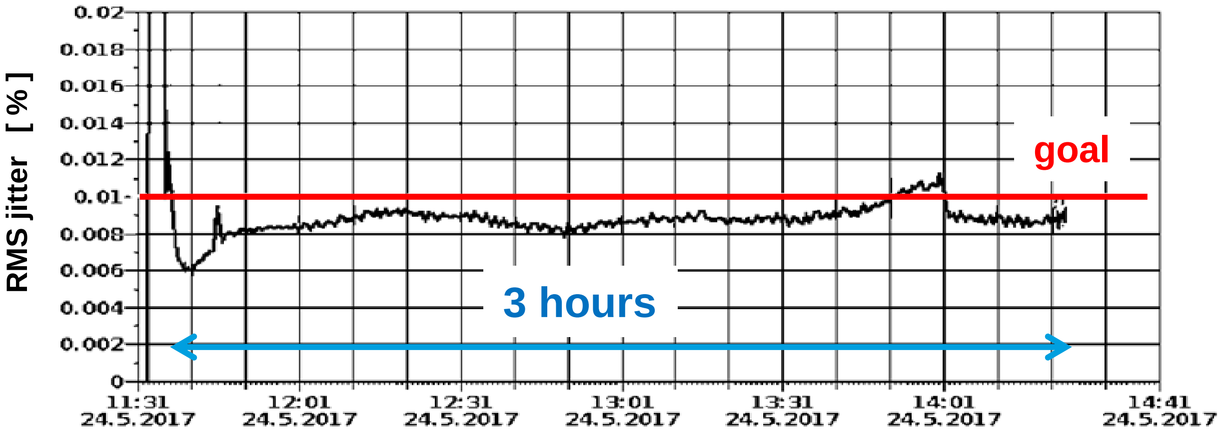
- E_{ACC} = 15 MV/m Q_L = 1.5-3x10^7 (43-22 Hz half bandwidth)
- Regulation performance (**May 2017**)
  - dA/A = 0.008 % dP = 0.008 deg.

- E_{ACC} = 16 MV/m Q_L = 3x10^7 (22 Hz half bandwidth)
- Regulation performance (**Dec. 2017**)
  - dA/A = 0.007 % dP = 0.010 deg.

Single cavity regulation (CW)

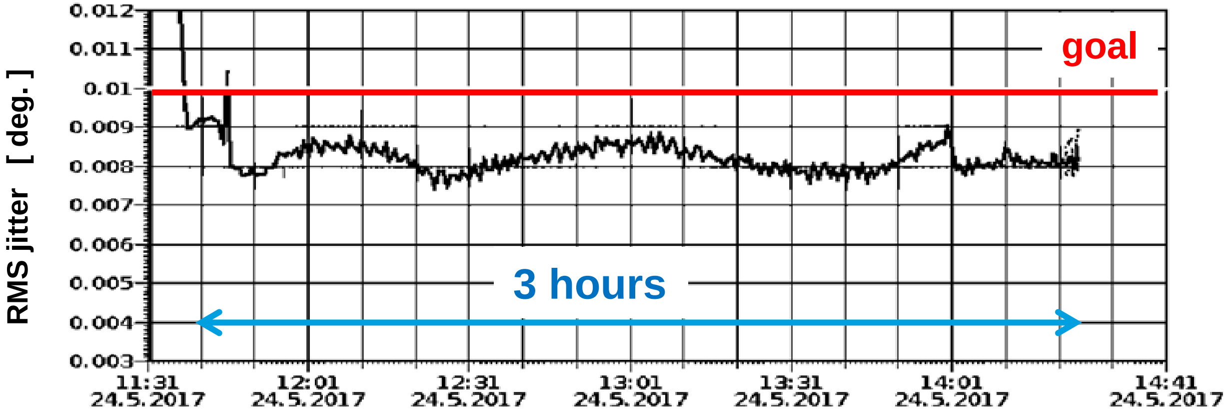
- E_{ACC} = 16 MV/m Q_L = 8.2x10^7 (8 Hz half bandwidth)
- Regulation performance (**Dec. 2017**)
  - dA/A = 0.015 % dP = 0.017 deg.

Vector sum amplitude stability (dA/A)

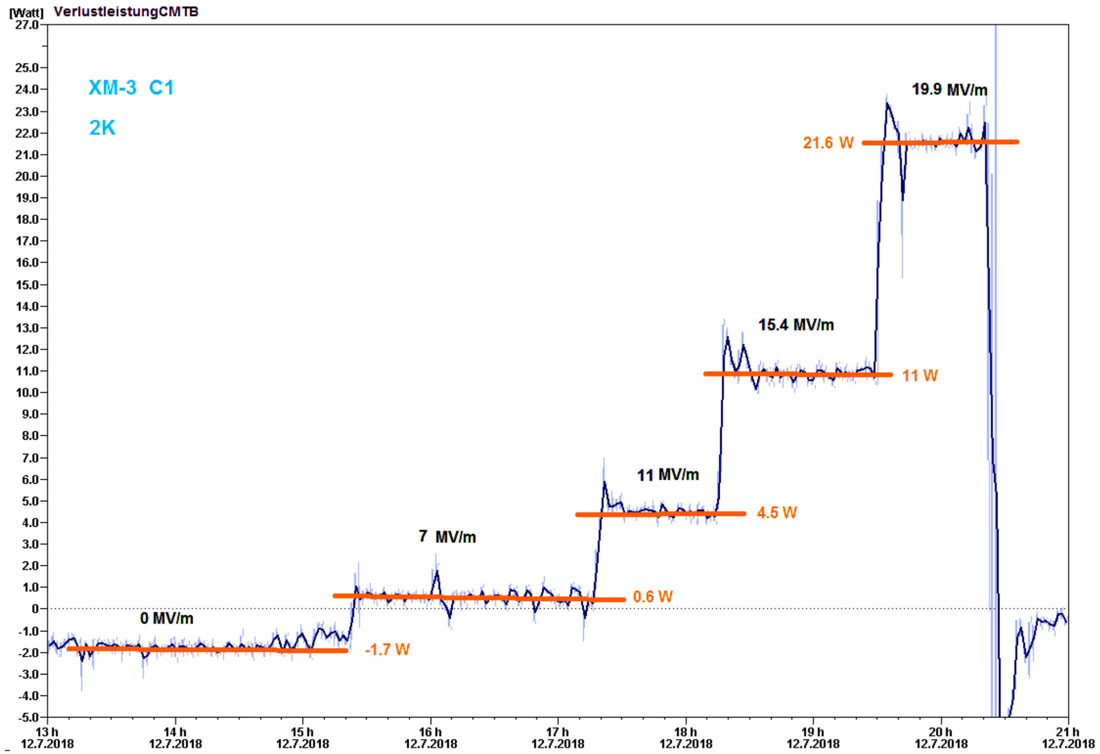


World Record !

Vector sum phase stability (deg.)

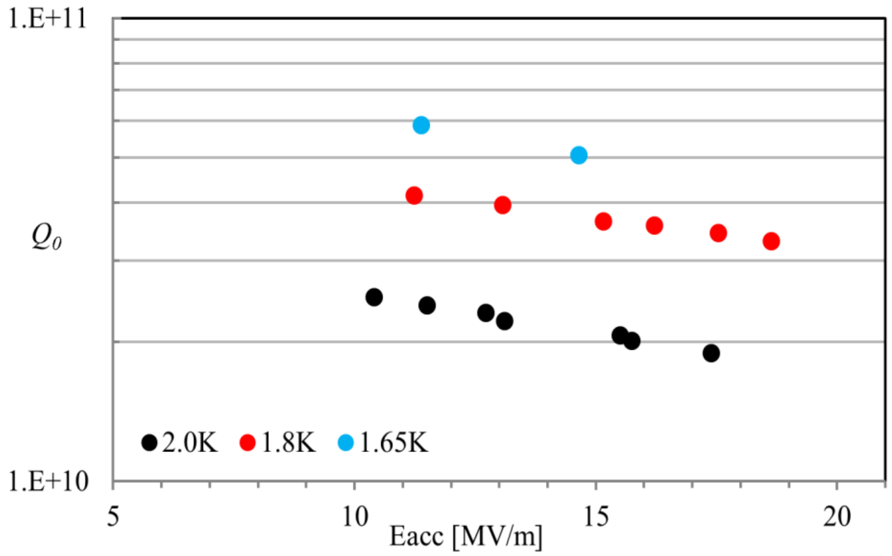


Heat load measurements



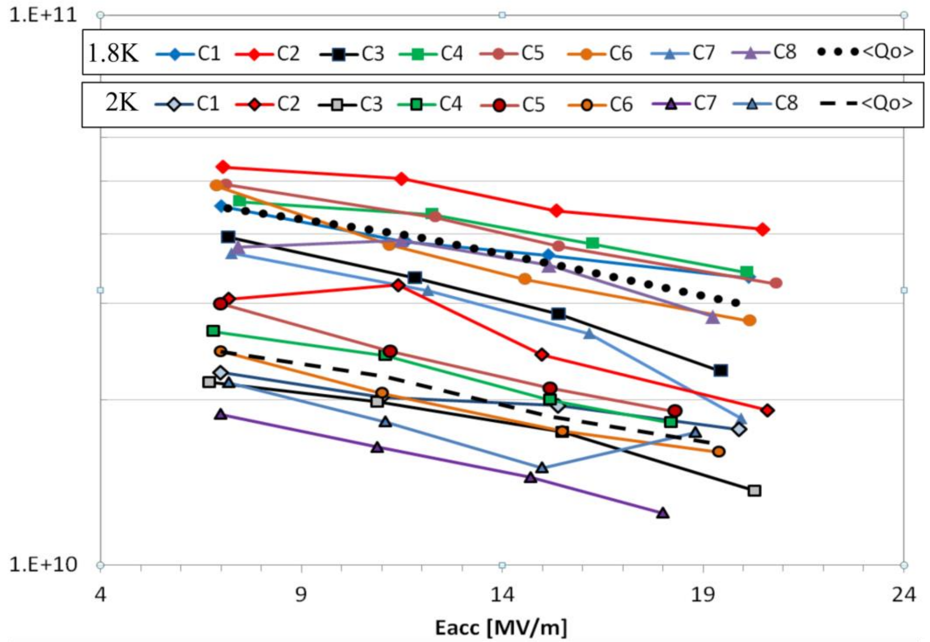
The goal was to investigate the potential benefit to operate large grain cavities at temperatures lower than 2K. In these measurements Q_0 is computed by measuring the difference in helium mass flow when one (or several) cavities are in operation.

Cryomodule heat load measurements



Q_0 vs Eacc for the whole cryomodule at 2K, 1.8K and 1.65K. The gain in Q_0 for 1.8K operation compared to 2K operation is about 80%. Further investigation is required to find out if operation at 1.8K will be more efficient for the first 136 cavities (17 cryomodules in the injector section of the European XFEL accelerator)

Single cavity heat load measurements

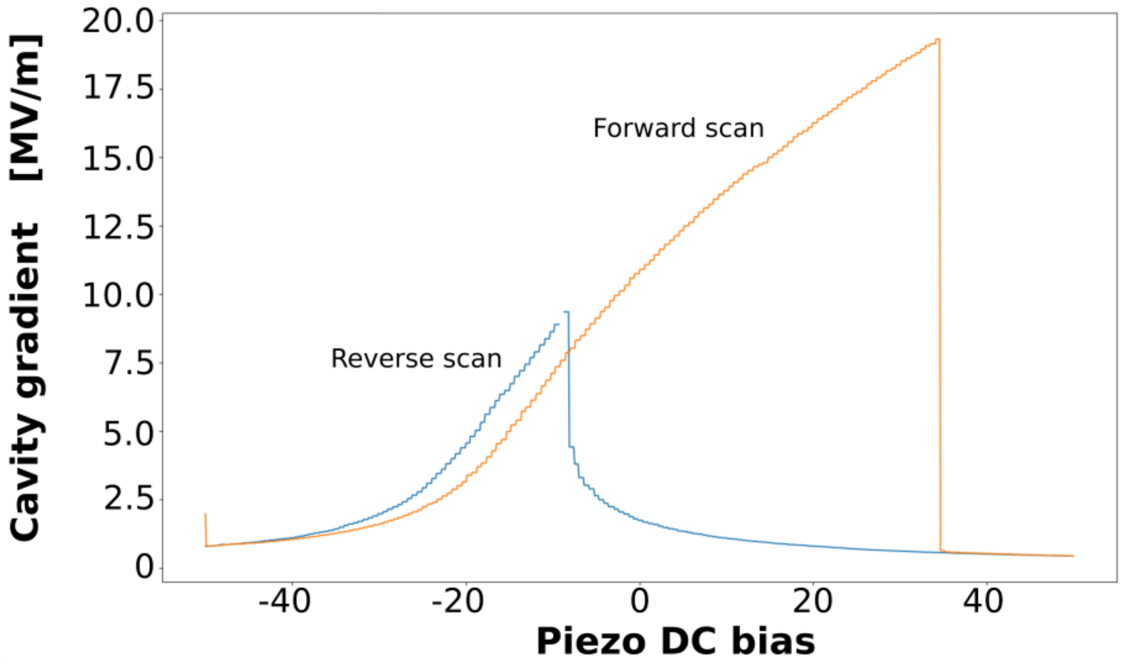


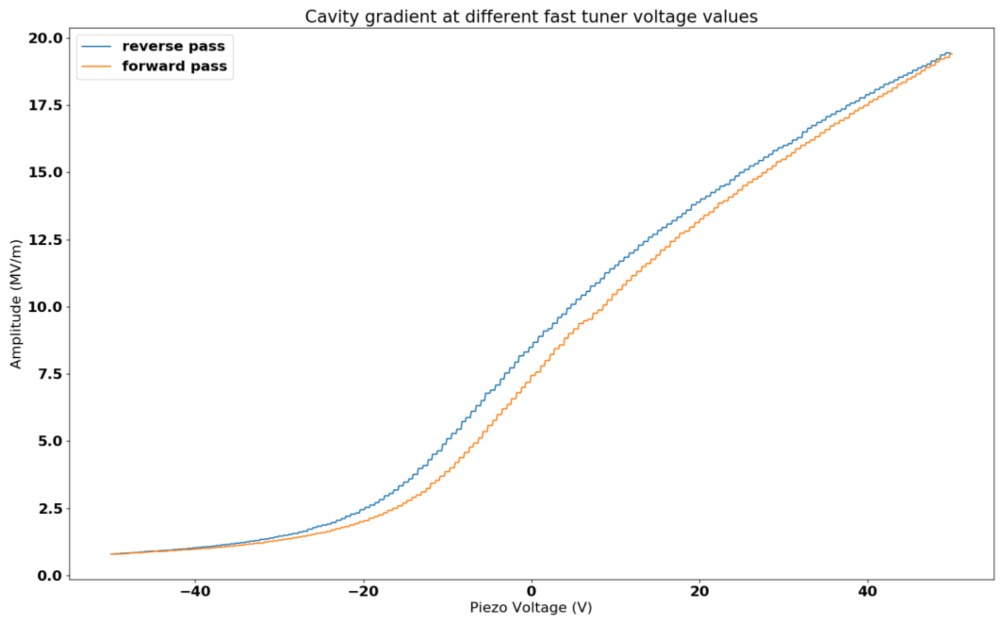
The main linac, extended from 84 to 96 cryomodules, could operate in CW around 8 MV/m. The dynamic heat load at this lower gradient is very low and operation at 1.8K would not be beneficial due to the static heat load

LFD and static drops

Hysteresis behavior when tuning the cavity

- The “delay” between the forward and the reverse scans are due to the hysteresis induced by the tuner backlash.
- If the scan is stopped just before the static drop, one can see the classic hysteresis curve.





Cavity mechanical modes

Mechanical cross talk between cavities

- The coupling between the excited cavity (C4) and the neighboring cavities (C3 and C5) become dominant around the cavity mechanical resonant frequency (~260 Hz)