WP2: LLRF

Berlin meeting, April 23, 2025

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WP2: Low Level RF controls 23.04.2026

DESY, HZB, CNRS
Convener & deputy: Julien Branlard (DESY) & Christian Schmidt (DESY)
Main contacts with other partners: Axel Neumann (HZB), Christophe Joly (CNRS)

WP02's task with iSAS

Main goal:

Investigate and demonstrate techniques to achieve efficient field-control of narrow-bandwidth SRF cavities

through

- improved **algorithms** to achieve **RF field control**
- improved **algorithms** to achieve **resonance control**
- improving efficiency of **RF sources** and their usage
- investigation of what can be achieved with **FE-FRT** for resonance control
- improving **diagnostics** (detuning measurement and fault detection) making use of **AI / ML**

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Task 2.1: Coordination of R&D on LLRF – *M1-M48*

Candidate declined position → load on other members

2026 milestone M24 — due/submitted Feb 2026 ✓

Milestone M24 coming up → risk analysis (contact Adèle regarding form of deliverable)

WP02 meeting next week for status update

Task 2.2: Efficient field control for high loaded-quality factor cavities – *M1-M48*

Test ongoing, publication pending – On-track for milestone M30

2026 milestone M30 — due Nov. 2026

Task 2.3: Vibration analysis and detuning control of cavities – *M1-M36*

Measurement on-going, report this year

Task 2.4: Integrated LLRF control using Ferro-Electric Fast Reactive Tuners– *M13-M48*

Task 2.5: Energy efficient supervisory control and fault diagnosis– *M1-M48*

No recent progress. Next point of focus

2026 milestone M33 — due Aug. 2026

WP2 – LLRF: status/evolution of Task 2.1

Coordination of R&D on LLRF – *M1-M48*

- **Past developments**
  - Organization of meetings, deliverables, document sharing structure, …
- **Current developments**
  - Euclid Techlabs is WP2's industrial partner
    - overlap with FE-FRT development
  - DESY iSAS hire
    - Mona, Bachelor student to support with iSAS related cryomodule tests and data analysis
    - Plans to follow up with a consulting position for a soon-to-be retired RF expert
  - Preparation for iSAS 1st reporting period review on June 1st
    - RP1 submitted

Mona Eberenz

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2026 milestone M33 **due Aug. 2026**

WP2 – LLRF: status/evolution of Task 2.2

Efficient field control for high loaded-quality factor cavities – *M1-M48*

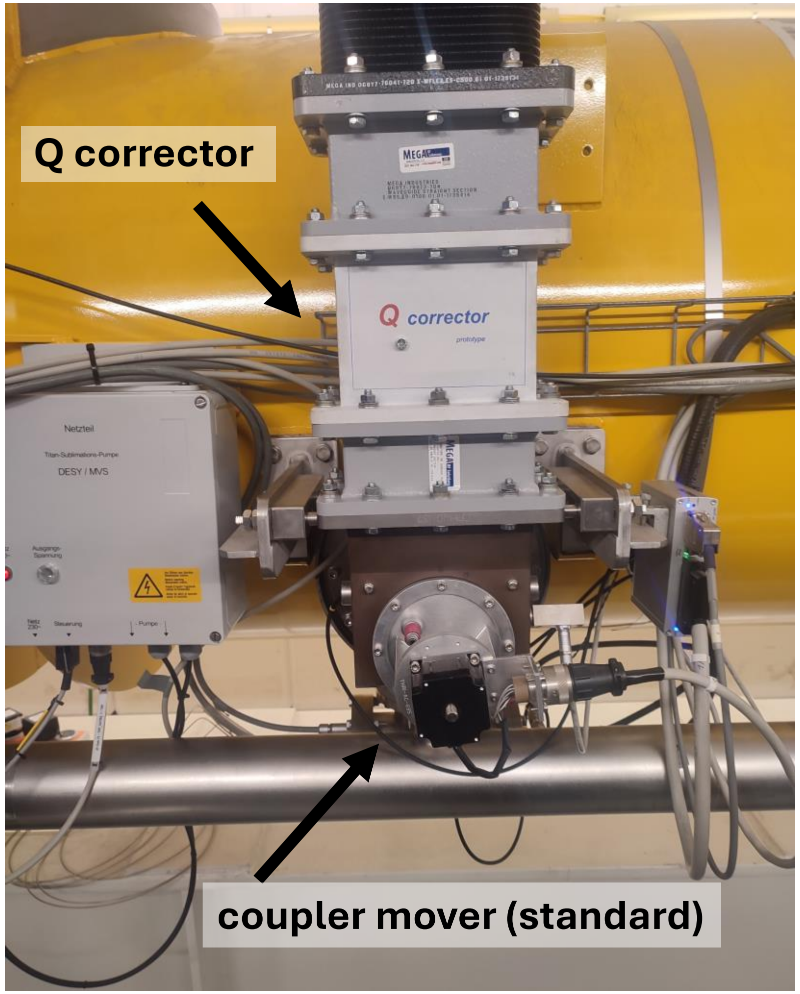
- **Past developments**
  - Developed **prototypes** to externally shift the Qext to higher range

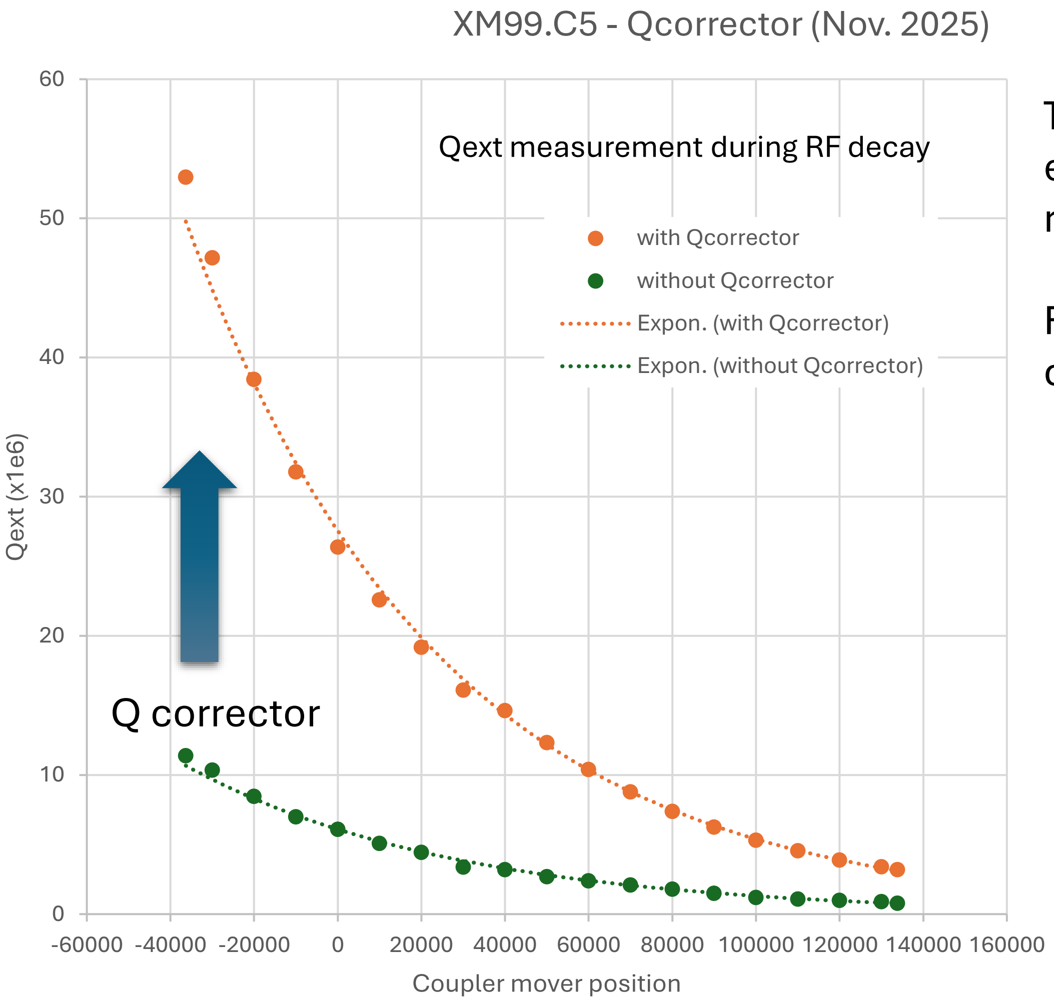
- **Current developments**
  - Tests with Q-corrector show **factor 5 reduction** in forward power for only 8% coupler temperature increase (**slides 7-8**)
  - Developed **techniques** to **drive high loaded-quality factor** (narrow bandwidth) cavities (not using self-excited loop or PLL), adapted to pulsed and vector sum operation (i.e. interesting for XFEL upgrade) (**slides 9-10**)

WP2 – LLRF: status/evolution of Task 2.2

Efficient field control for high loaded-quality factor cavities – *M1-M48*

Developed prototype to shift Q_{ext} to higher values (i.e. narrower cavity bandwidths)





The Q corrector can effectively shift the Qext range

For e.g. for a standard L3 cryomodule

Qext = [1e6 – 1e7]

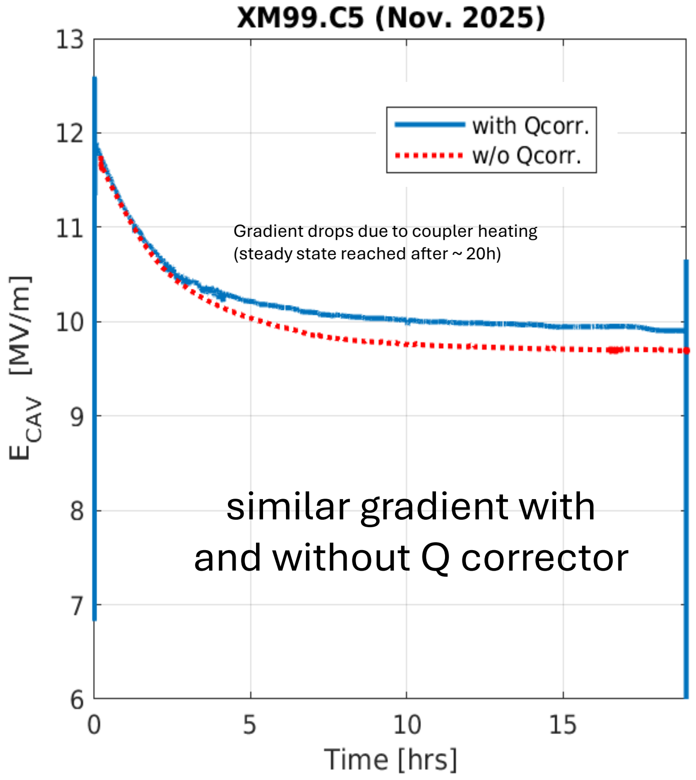
↓

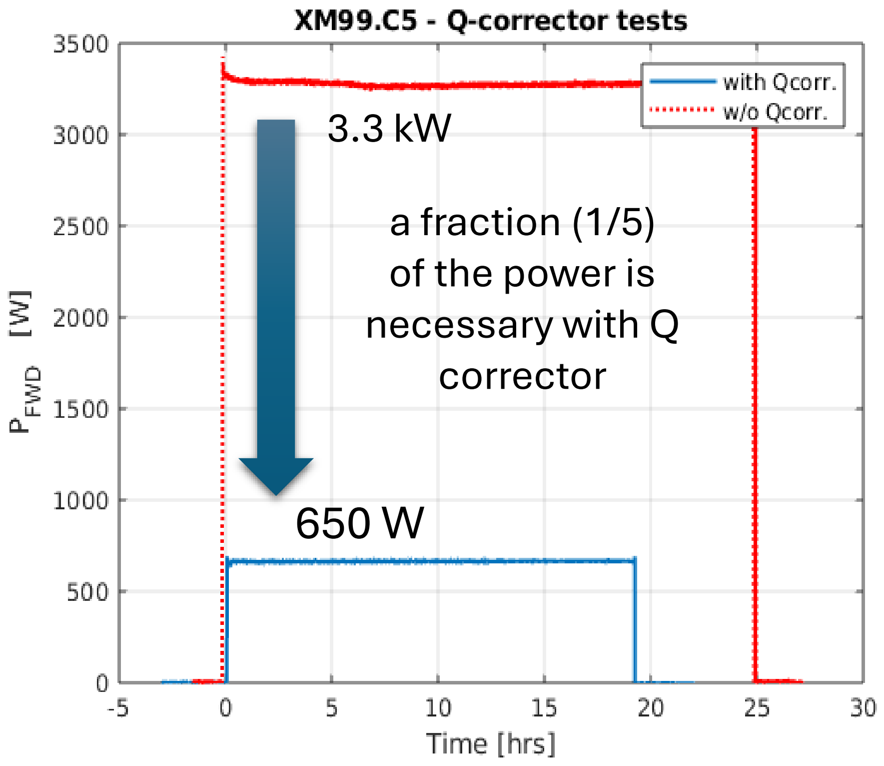
Qext = [3e6 – 5e7]

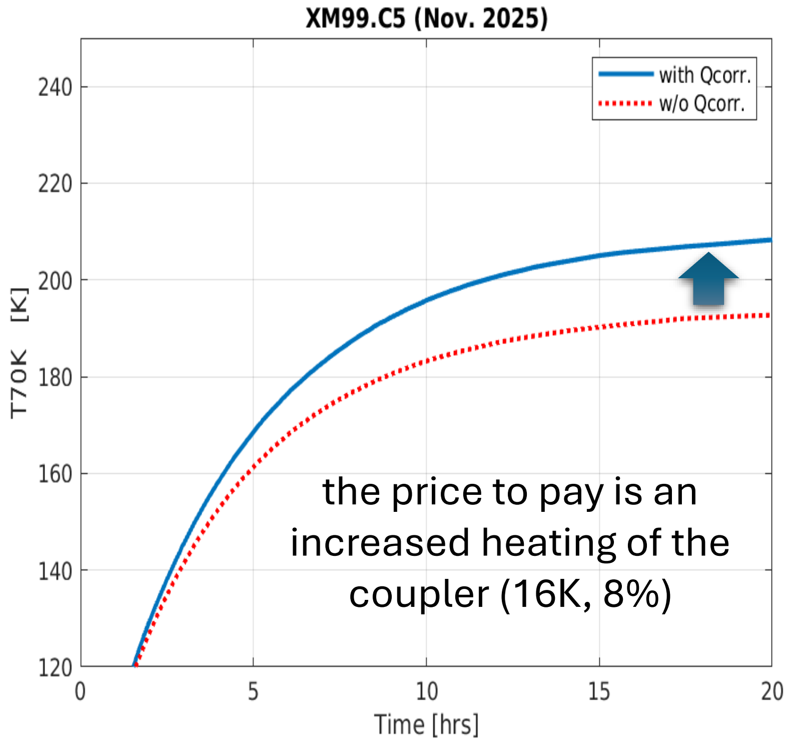
WP2 – LLRF: status/evolution of Task 2.2

Efficient field control for high loaded-quality factor cavities – *M1-M48*

Operating at higher Qext can potentially bring significant RF power savings







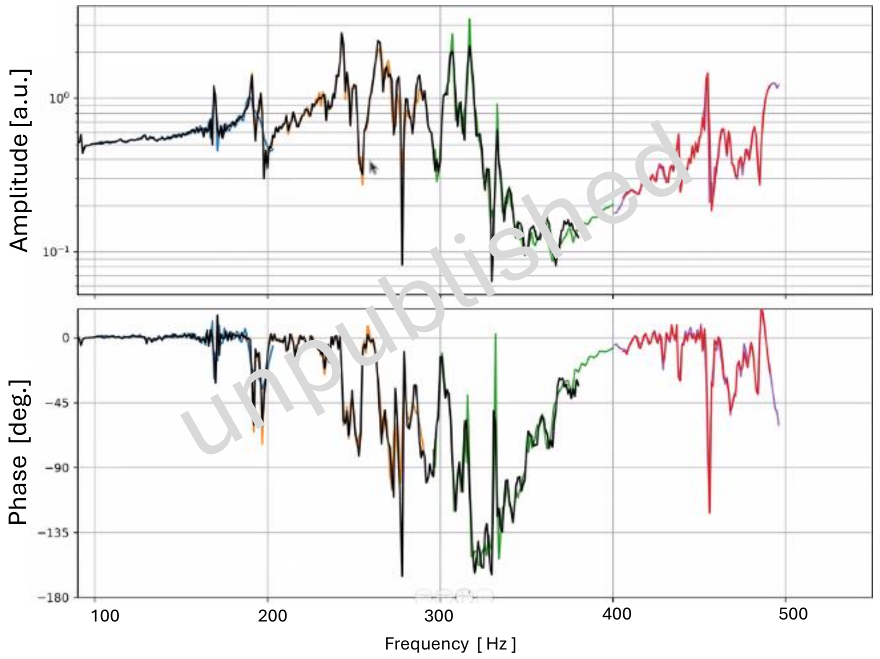
Currently : investigate if coupler heating is safe for coupler ?

WP2 – LLRF: status/evolution of Task 2.2

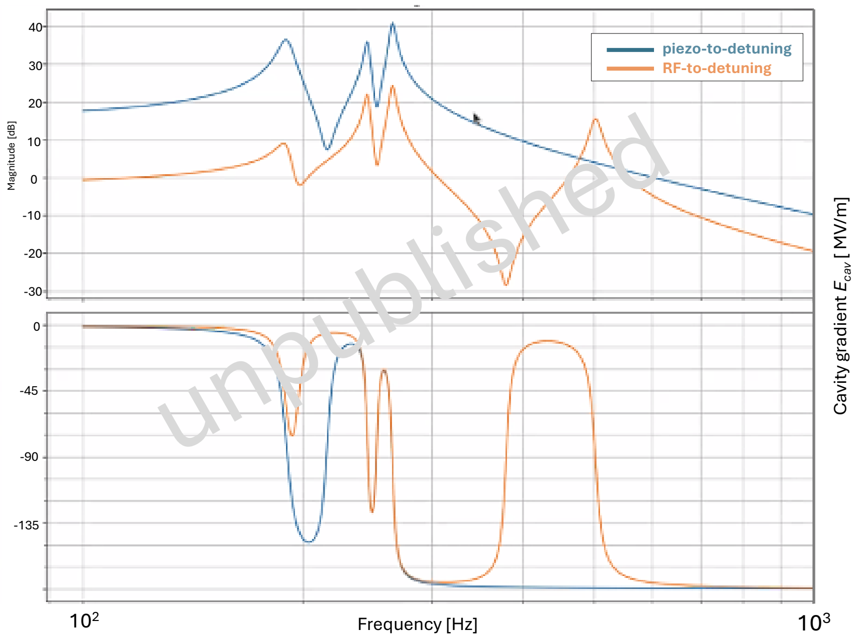
Efficient field control for high loaded-quality factor cavities – *M1-M48*

- **Current developments**
  - **Resonance filling : model-based approach**

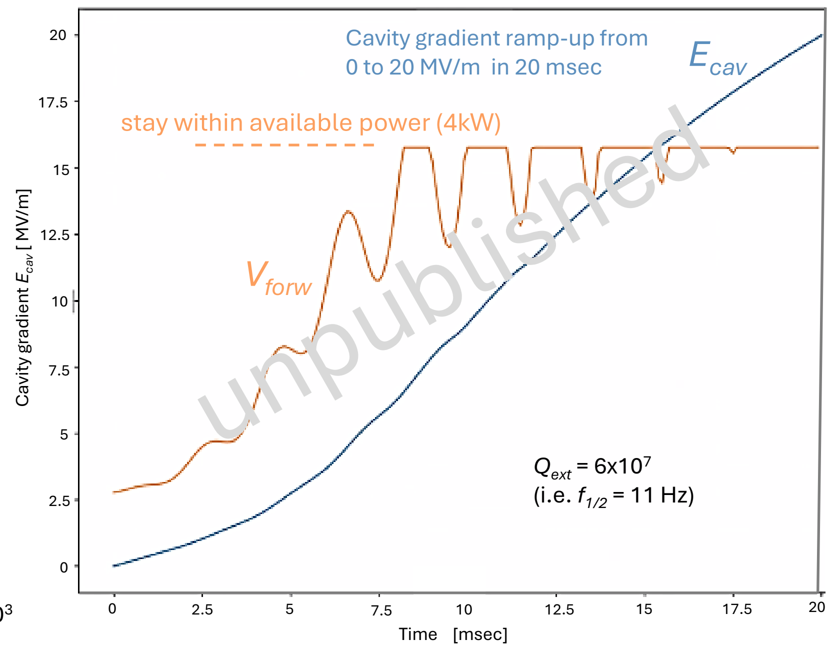
Step 1: identify **RF-to-detuning** and **piezo-to detuning** transfer functions



Step 2: fit **model** to experimental transfer function



Step 3: compute **piezo** and **RF drive** (given power limit) to bring cavity to target setpoint in allocated time



Currently acquiring experimental data. Next publish !

Courtesy : Bozo Richter

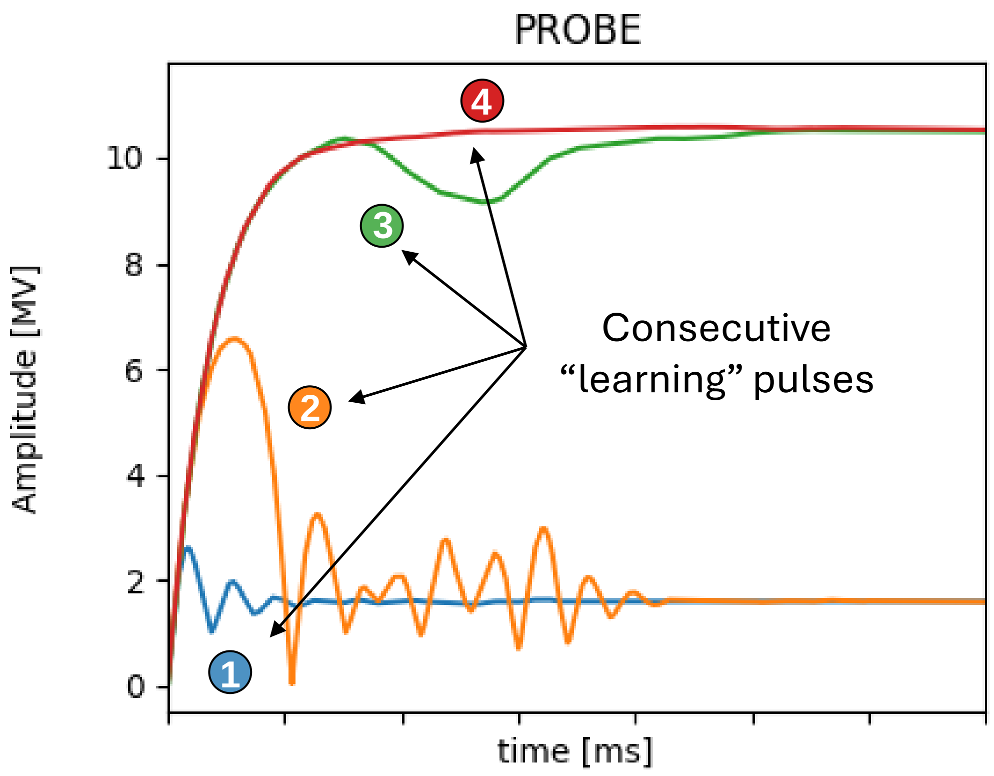
WP2 – LLRF: status/evolution of Task 2.2

Efficient field control for high loaded-quality factor cavities – *M1-M48*

- **Current developments**

Adaptive resonance filling

- Cavities with narrow bandwidth experience during field ramp-up a detuning induced by Lorentz forces equivalent to **tens of bandwidths** (i.e. several 100 Hz compared to BW ≈ 20 Hz)
- The frequency of the RF **must** be modulated to always drive the cavity on resonance during the fill time (in pulsed mode): so called "**resonance filling**"
- Use iterative learning techniques to learn this frequency modulation in a robust and reproducible way



Demonstrated at DESY's cryomodule test stand (paper in preparation)

Courtesy : Bozo Richter

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No recent progress. Next point of focus

2026 milestone M33 due Aug. 2026

WP2 – LLRF: status/evolution of Task 2.3

Vibration analysis and detuning control of cavities – *M1-M36*

- **Past developments**
  - Energy efficient Lorentz force detuning compensation at EuXFEL →presented at Padova 2025 + published at IPAC 2025
  - Developed an observer-based measurement of cavity detuning → accepted for publication at Phys Rev Accel & Beam

- **Current developments**
  - Assessment of microphonics level at XFEL
    - relevant information for EuXFEL CW upgrade
    - (**slides 13-15**)

  See poster from J. Einstein Curtis

  - Exploring AI-based method to achieve detuning compensation
    - **(slides 16-19)**

  To be presented and published at IFAC 2026

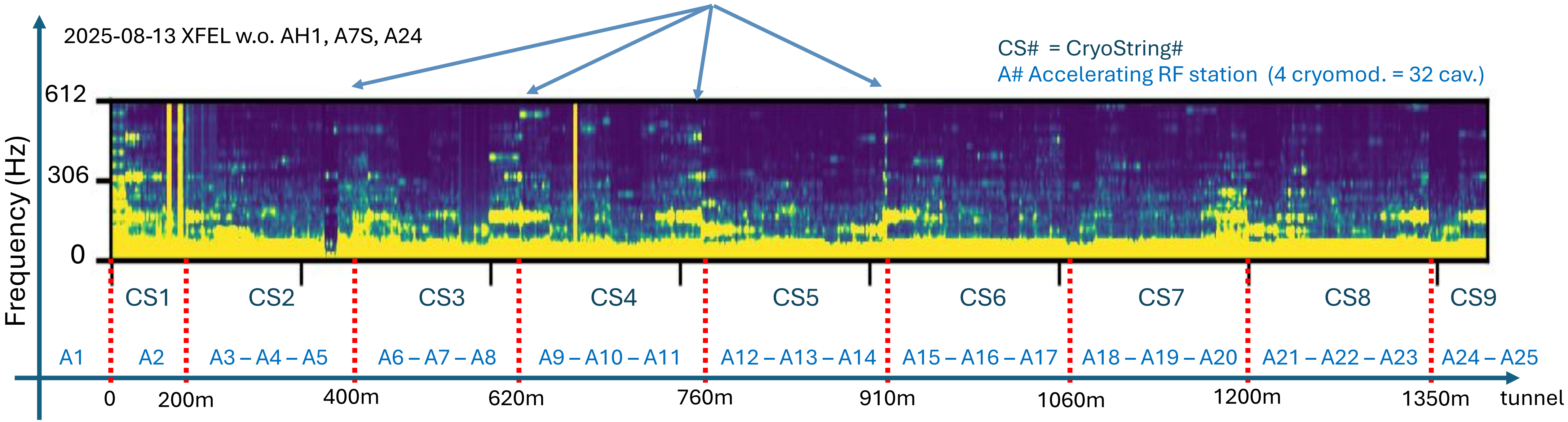
  - Implemented an narrow bandwidth active noise compensation algorithm, tested in CW at LCLS-II (SLAC)
    - **(slide 20)**

  To be presented and published at IPAC 2026

WP2 – LLRF: status/evolution of Task 2.3

Vibration analysis and detuning control of cavities – *M1-M36*

- Current developments
  - **Assessment of microphonics level at XFEL**
  - Microphonics measured without RF, using installed piezos during last year summer shutdown
  - Identified vibration source at **cryostring junction** (propagating up-/down-stream) coming from flow sensor



Courtesy Josh Einstein-Curtis

WP2 – LLRF: status/evolution of Task 2.3

Vibration analysis and detuning control of cavities – *M1-M36*

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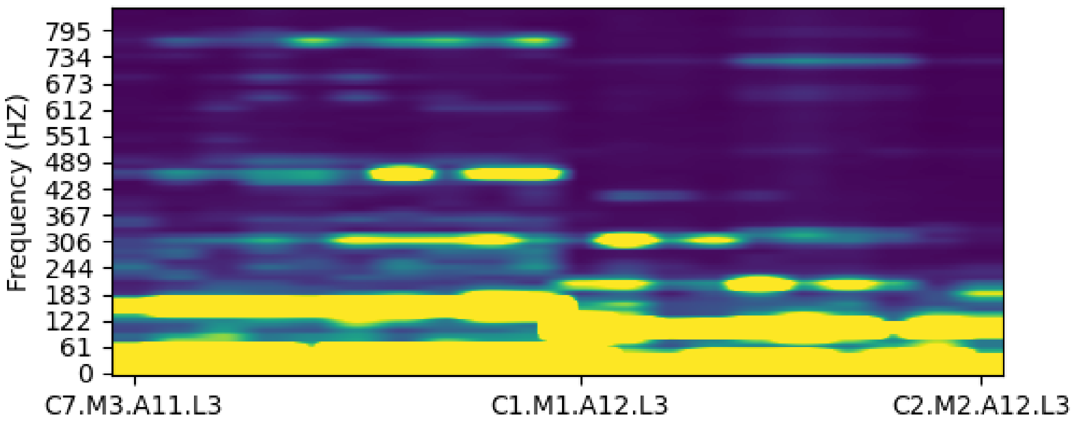
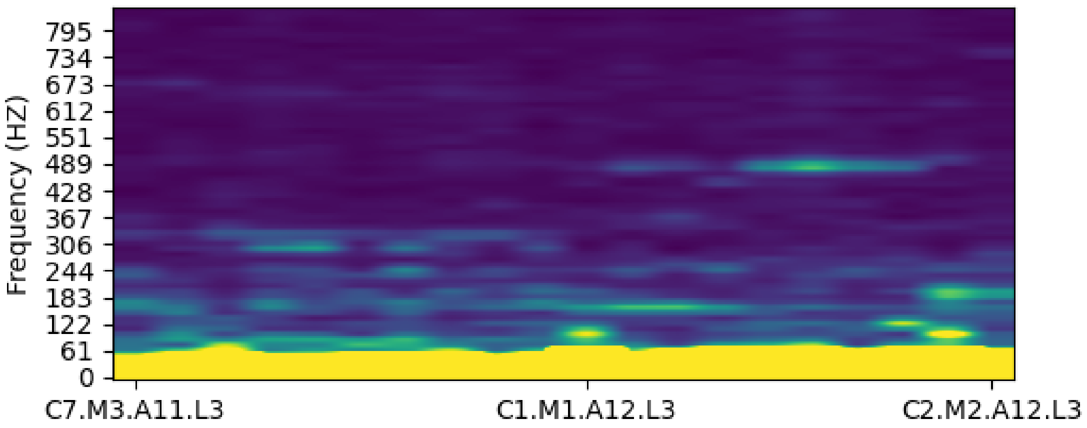
See poster from J. Einstein Curtis

Flow sensor ON



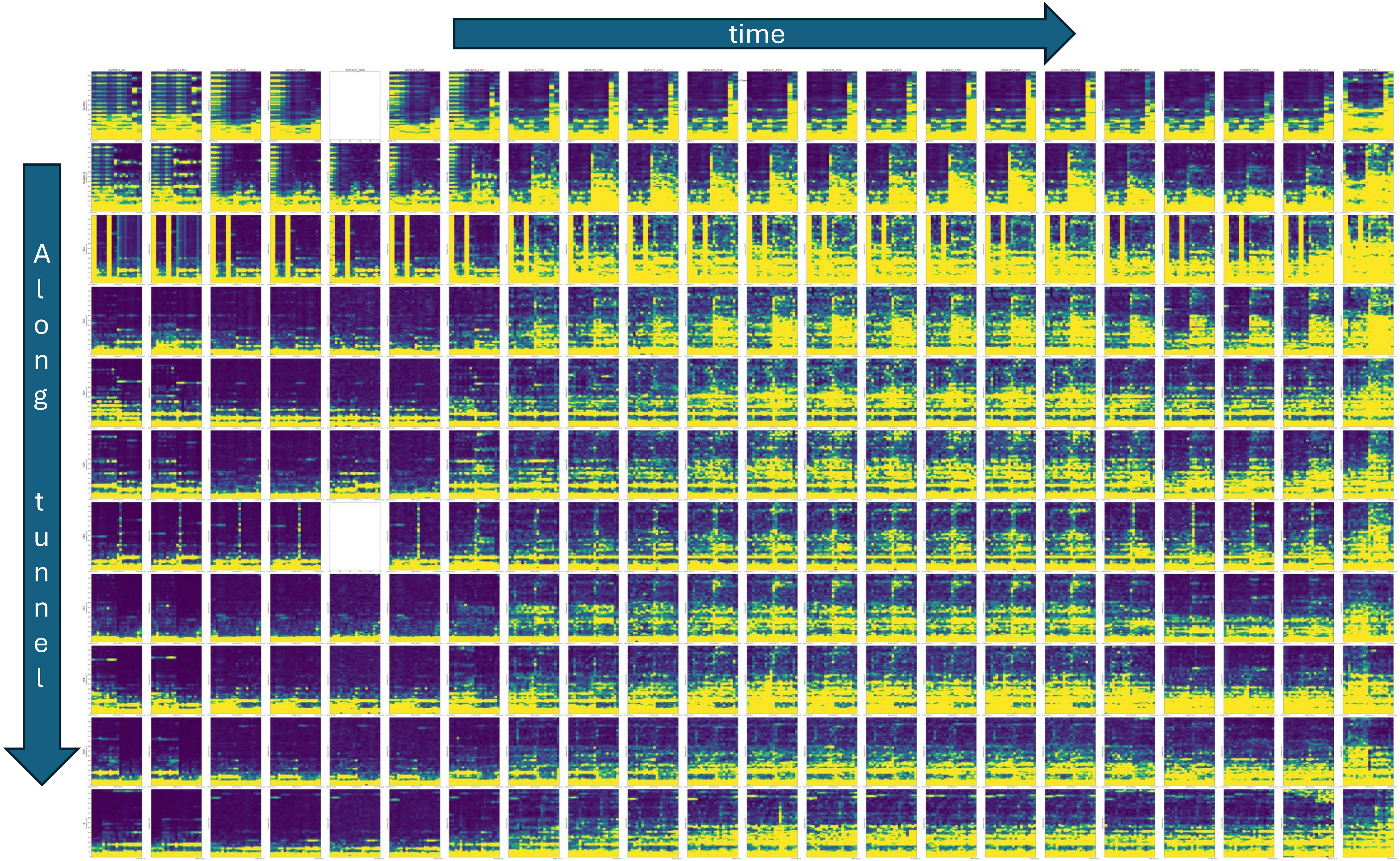
Flow sensor OFF



Coriolis flow sensor

Courtesy Josh Einstein-Curtis

- No direct impact on current operation of the EuXFEL but valuable information for the upgrade.

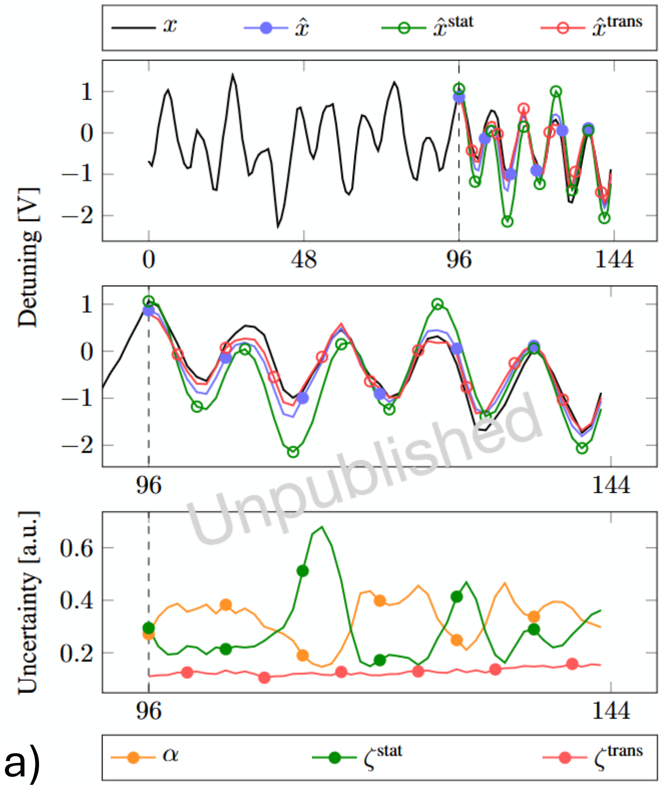

time
Along tunnel

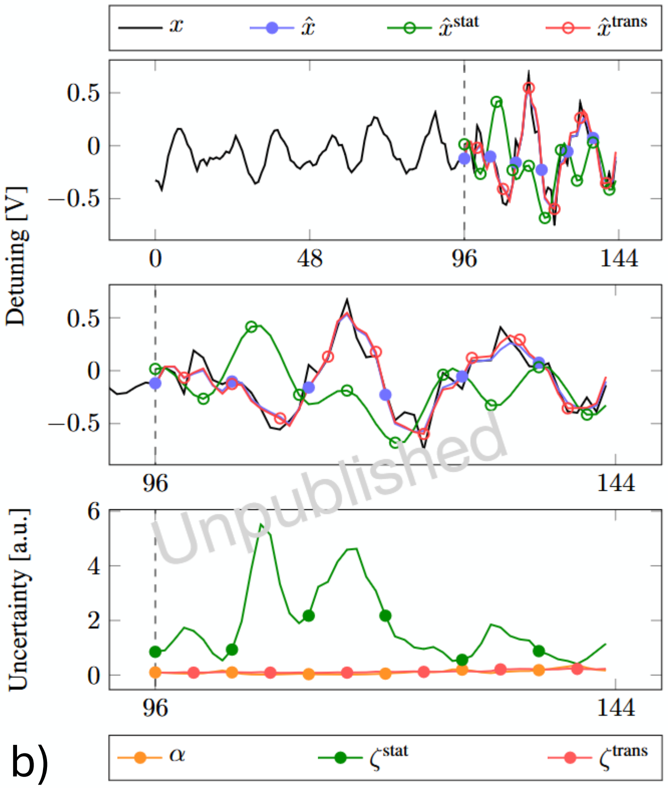
WP2 – LLRF: status/evolution of Task 2.3

Vibration analysis and detuning control of cavities – *M1-M36*

- **Current developments** — 1. **AI-based** detuning compensation

Exploration of AI-based methods for RF detuning compensation

a) 

b) 

- Designed a hybrid dynamical model architecture
  "*KIND: a Kalman-inspired adaptive estimator for SRF cavity detuning*" , accepted
  To be presented (+ proceeding) at IFAC 2026
- Proved stability under recursive model rollout
  "*Stable multi-step rollouts via uncertainty guided hybrid dynamics*", under review

Figure: Rollout behavior of a KIND model on measured SRF gun cavity data.
(a) On nominal data: hybrid model parts - stationary and transient - track the ground truth.
(b) On transient data: compared to transient model part, nominal part misses the right dynamics.
In both cases hybrid parts are correctly blended to produce the final prediction.

Courtesy A. Maalberg

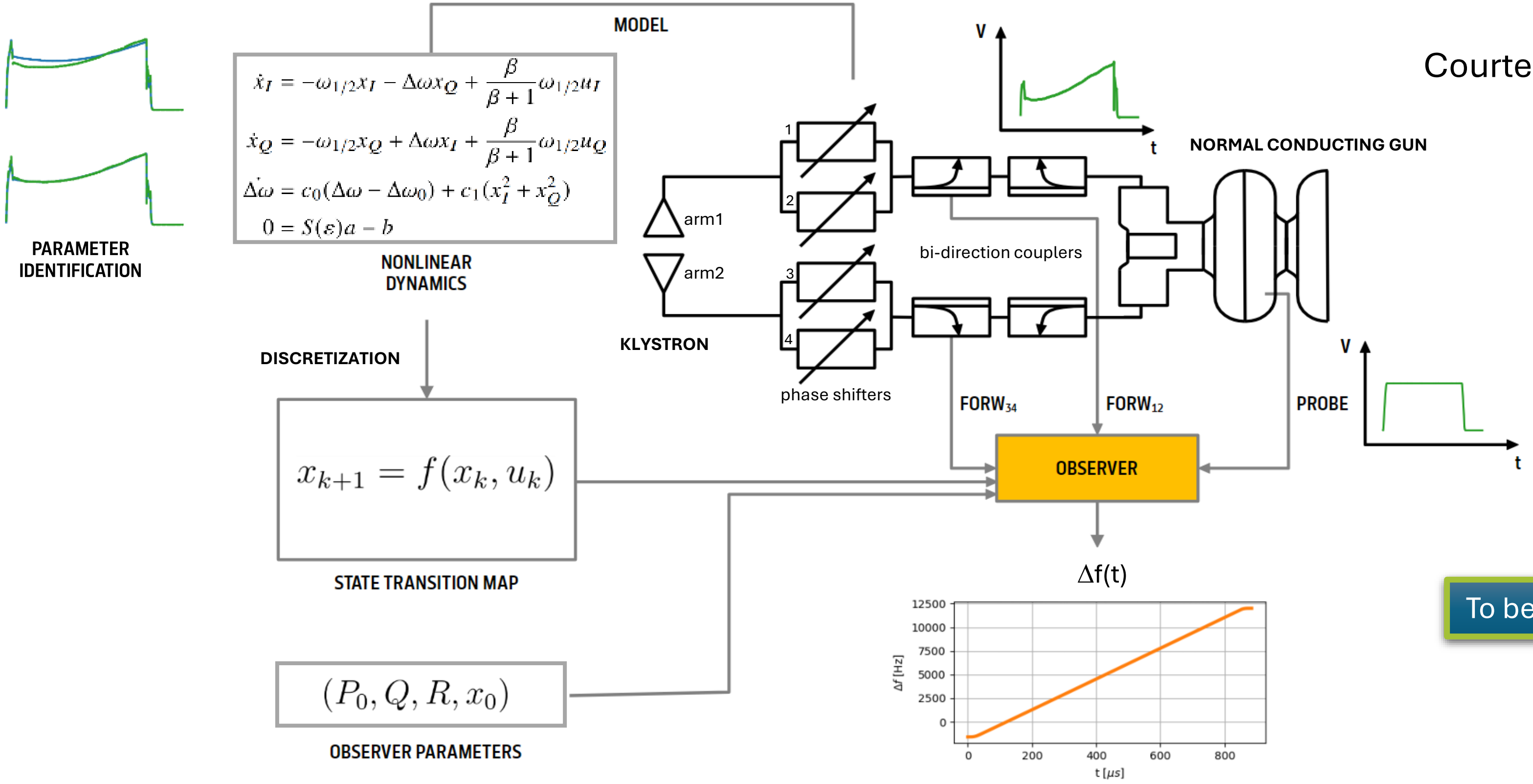
WP2 – LLRF: status/evolution of Task 2.3

Vibration analysis and detuning control of cavities – *M1-M36*

- **Current developments** — 2. **observer-based** detuning estimation

Exploration of <u>observer-based</u> methods for RF detuning computation, at the EuXFEL NRF gun

- One challenge comes from the double input coupler architecture of the NRF gun
- After parameter identification, a model-based observer provides online detuning estimation



Courtesy M. Herrmann

To be presented (+ proceeding) at IPAC 2026

WP2 – LLRF: status/evolution of Task 2.3

Vibration analysis and detuning control of cavities – *M1-M36*

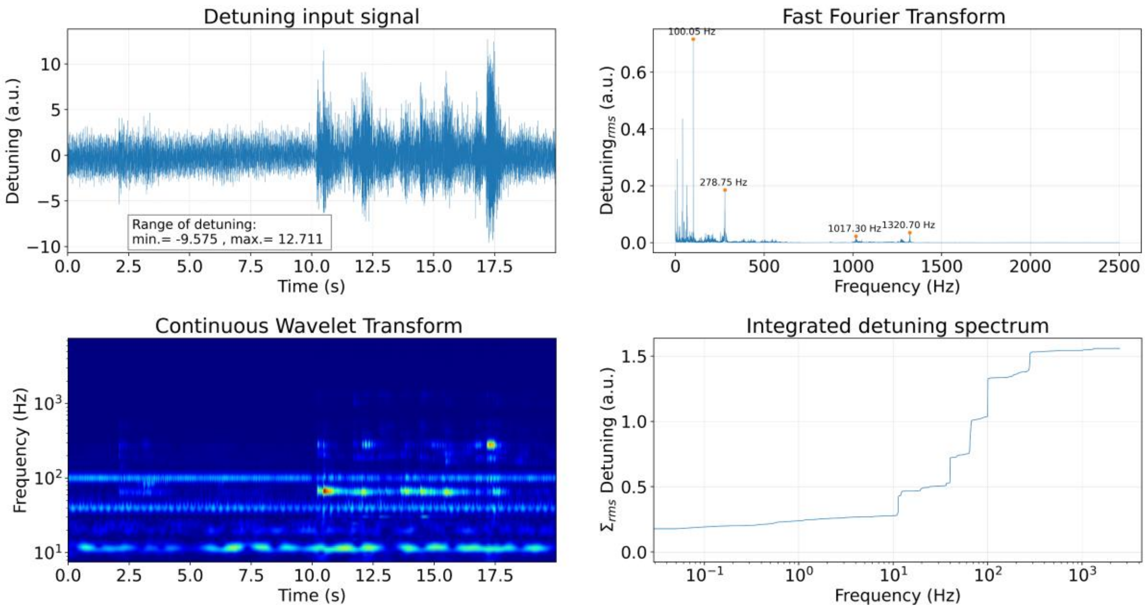
- **Current developments**

3. **wavelets-based** detuning estimation

Exploration of <u>wavelets</u> for RF detuning computation, at SeaLAB, HZB

- Classical Fourier analysis provides a global description that does not retain temporal information.
- Short-time Fourier transform (STFT) introduce time localization by applying the transform over sliding windows, but uses a fixed window length, leading to a trade-off between time and frequency resolution that remains constant across all frequencies.
- Benefit of continuous wavelet transform (CWT): provides **a time-frequency representation with adaptive resolution**.

Microphonics measured at SEALab's photoinjector



$$T(a,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} x(t)\psi^*\left(\frac{t-b}{a}\right) \mathrm{d}t,$$

$$\psi(t) = \frac{1}{\sqrt{\pi B}} e^{2\pi i F t} e^{-t^2/B}$$

Morlet wavelet offers a well-defined central frequency and is particularly suitable for analyzing oscillatory signals

Courtesy P. Echevarria

To be presented (+ proceeding) at IPAC 2026

WP2 – LLRF: status/evolution of Task 2.3

2026 milestone M33

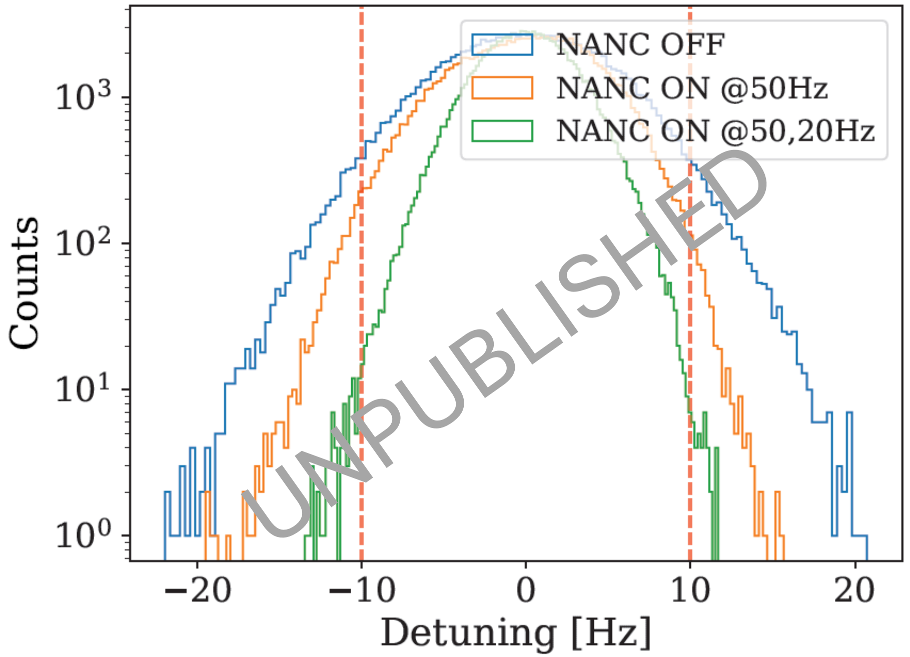
Vibration analysis and detuning control of cavities – *M1-M36*

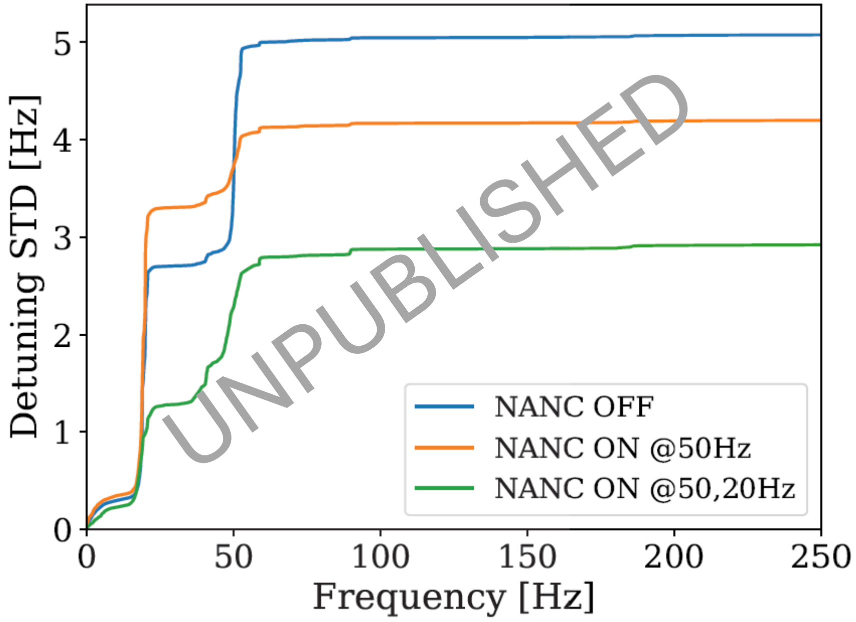
• Current developments

Microphonics suppression to allow higher gradient operation

- Developed a Narrow Bandwidth Active Noise Cancellation (NANC) algorithm and demonstrated at SLAC (LCLS-II)
- With NANC off, the cavity could operate at **max 9 MV/m**
- With NANC ON, the cavity can be operated **at 16 MV/m** (78% improvement!)

Courtesy B. Richter, J. Diaz





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No recent progress. Next point of focus

2026 milestone M33 due Aug. 2026

WP2 – LLRF: status/evolution of Task 2.4

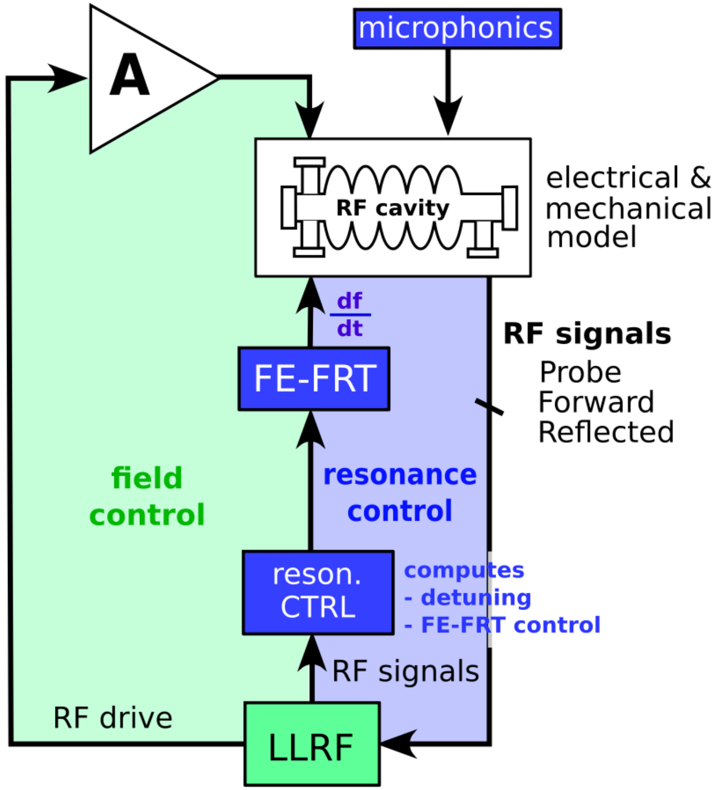
Integrated LLRF control using Ferro-Electric Fast Reactive Tuners– *M13-M48*

- **Past developments**
  - …

- **Current developments**
  - **Goal is to integrate a ferro-electric fast reactive tuner (FE-FRT) with a digital LLRF system**
    - Hardware development 2026/27 within WP1
    - Measure FE-FRT voltage response and temperature dependence
    - Evaluation of existing MTCA hardware as potential FE-FRT driver
  - **Development of Matlab/Simulink model of RF control loop to simulate resonance control**
    - Using FE-FRT voltage response, include it in LLRF control simulation environment
    - Set back : joint-PhD program on this topic stopped
    - Work taken over by colleagues from IJCLab and LPSC
  - **RF and resonance control using FE-FRT**
    - High-voltage amplifier transfer function measurement using capacitive load (to emulate FE-FRT))
    - Controller development on RF SoC on going, HZB
    - First measurements at HoBicat, HZB

Roadmap toward milestone

Synergy with WP1



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2026 milestone M33 **due Aug. 2026**

WP2 – LLRF: status/evolution of Task 2.5

Energy efficient supervisory control and fault diagnosis– *M1-M48*

- **Past developments**
  - 1st milestone delivered and approved : (D35) ML implementation plan

- **Current developments**
  - Development of SSPA test stand to investigate efficient operation depending on working point
    - Details next slide

      2026 milestone M33 **due Aug. 2026**
  - AI-based diagnostic for LLRF (presented at IPAC last year, full article submitted for peer-review
    - Details next slide

WP2 – LLRF: status/evolution of Task 2.5

Energy efficient supervisory control and fault diagnosis– *M1-M48*

- **Current developments**
  - Development of SSPA test stand to investigate efficient operation depending on working point

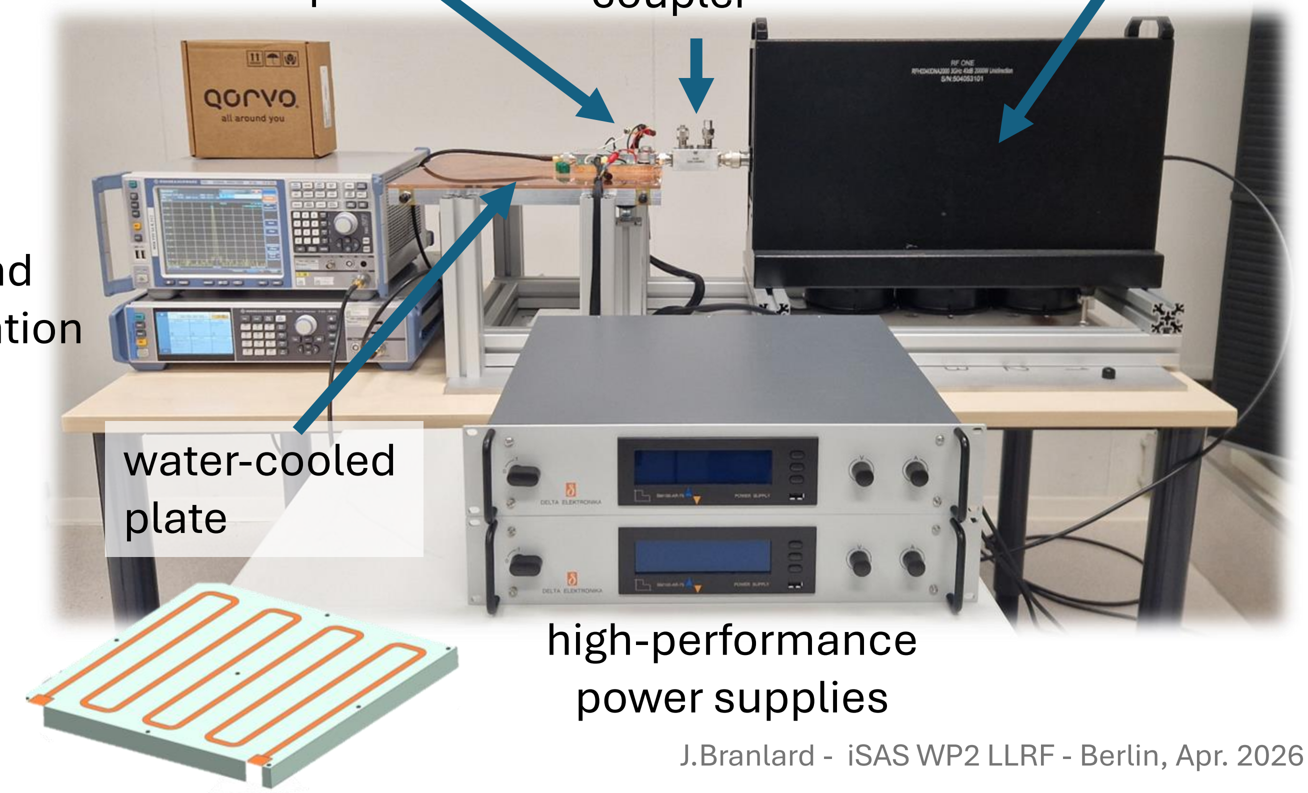
Courtesy H. Pryschelski

1kW GaN amplifier

high-power bi-directional coupler

2 kW load

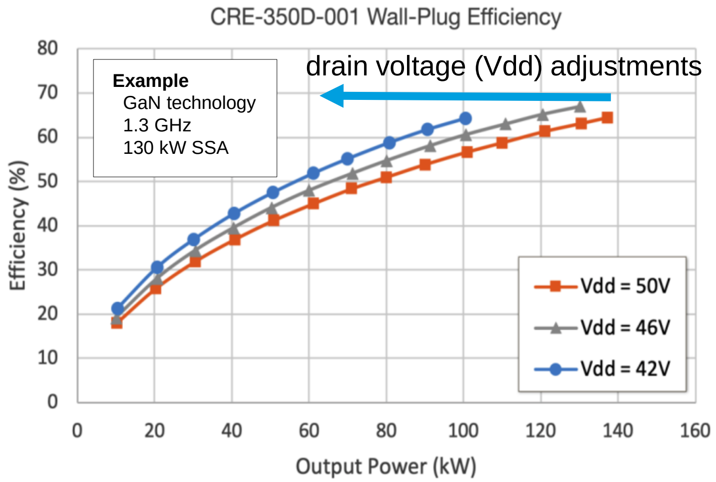
1.3 GHz source and instrumentation



high-performance power supplies

Preparation of a SSA test stand

- GaN 1 kW prototype
- Cooling / load / power supply
- Experiment with pulsed/CW operation
- Understand efficiency optimization with drain voltage adjustments

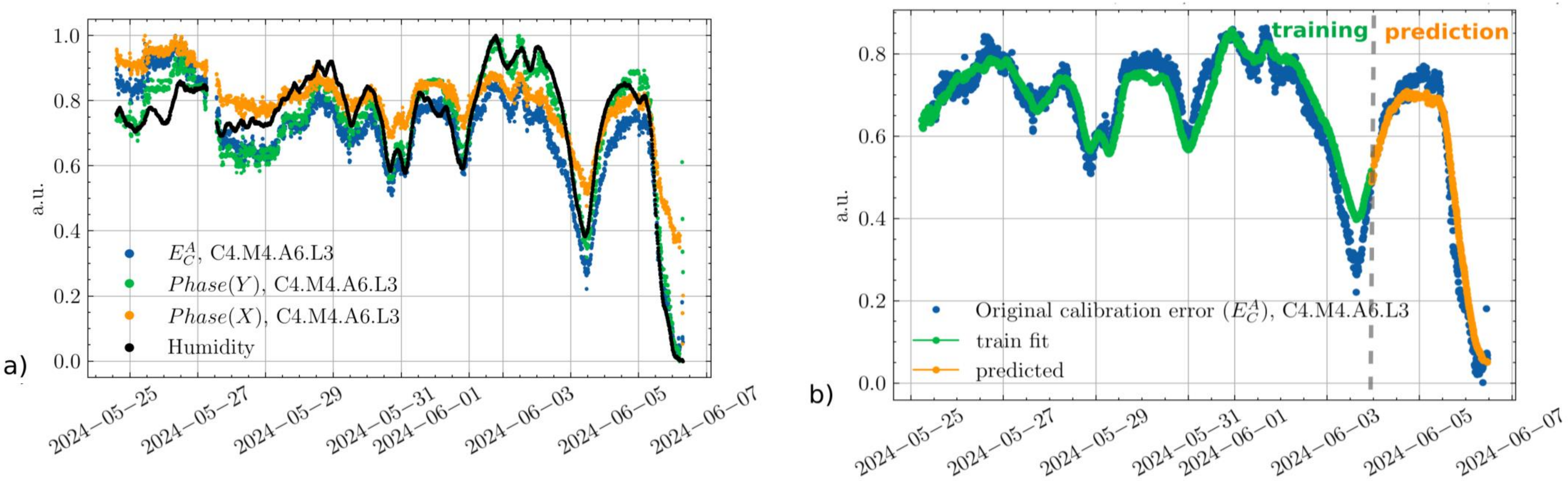


Reference: *"High-efficiency industrial 130 KW CW solid-state RF amplifier for 1.3 GHz"*, M. Nedos, N. Pupeter *et al.* in proc. IPAC 2023

WP2 – LLRF: status/evolution of Task 2.5

Energy efficient supervisory control and fault diagnosis– *M1-M48*

- **Current developments**
  - AI-based diagnostic for LLRF (presented at IPAC last year, full article submitted for peer-review



  - a) Strong correlation between RF waveform calibration coefficients and relative humidity
  - b) Using weather forecast, a trained model can predict 2 days in advance the calibration error!

First results presented at IPAC 2025, full article submitted for peer-review

WP2 – LLRF: points of attention

- Points of attention
  - Discussions on future involvements for the call HORIZON-INFRA-2026-TECH01
  - Suggested topics with application for large scale accelerator operation
    - Cryoelectra / DESY : optimization of SSPA parameters for efficient pulsed operation (EuXFEL upgrade)
    - DESY / CERN framework development for anomaly detection (link to LLRF)
    - HZB topics related to AI, FE-FRT and RF sources
    - ➔ **All 3 have links to LLRF**

WP2 – LLRF: plans to achieve milestones & deliverables

- Milestones & deliverables **on track?** → **yes**

D35 ML implementation plan

D5 Report uphonics study and ML-based mitigation

D6 Report on LLRF/SSA interface study

D7 Report on RF control studies

D9 Report on RF control studies

D8 Report on RF control studies

2024 | 2025 | 2026 | 2027 | 2028

M40 Impact analysis WP2

M6 Energy-efficient SSA oper.

M7 Detuning control techniques

M8 Field control for high Qext cavs.

M9 demo ML and anomaly detect.

M10 demo uphonic FE-FRT compensation

Dx Deliverables

Mx Milestones

Accounted for

Thank you for your attention !

2025 iSAS meeting in Padova, Italy

BACKUP

WP2 – LLRF: plans to achieve milestones & deliverables

- Milestones & deliverables **on track? → yes**

Timeline in project months (M)				M/D	#	Related WP	Related task	Description	Status	Risk level
Y1	M6	August	2024	D	35	WP2	2.1 Coordination of R&D on LLRF	ML implementation plan	Accounted for	On track
Y2	M24	February	2026	M	40	WP2	2.1 Coordination of R&D on LLRF	Impact risk analysis WP2	Submitted	On track
Y3	M30	August	2026	M	6	WP2	2.5 Energy efficient supervisory control & fault diagnosis	Demonstration of energy-efficient SSA operation	In progress	On track
Y3	M33	November	2026	M	7	WP2	2.3 Vibration analysis & detuning control of cavities	Demonstration of detuning control techniques	In progress	On track
Y3	M36	February	2027	M	8	WP2	2.2 Efficient field control for high loaded-quality factor cavities	Demonstration of RF control for CW/LP ops	In progress	On track
Y3	M36	February	2027	D	5	WP2	2.3 Vibration analysis & detuning control of cavities	Report on microphonics study & ML-based mitigation	In progress	On track
Y3	M36	February	2027	D	6	WP2	2.5 Energy efficient supervisory control & fault diagnosis	Report on interface study of LLRF with SSA	In progress	On track
Y4	M42	August	2027	M	9	WP2	2.5 Energy efficient supervisory control & fault diagnosis	Demonstration of ML and anomaly detection	In progress	On track
Y4	M45	November	2027	M	10	WP2	2.4 Integrated LLRF control using ferro-electric fast reactive tuners	Demonstration of FE-FRT microphonics compensation	In progress	On track
Y4	M46	December	2027	D	7	WP2	2.2 Efficient field control for high loaded-quality factor cavities	Report on LLRF RF control studies	In progress	On track
Y4	M47	January	2028	D	9	WP2	2.5 Energy efficient supervisory control & fault diagnosis	Report on anomaly detection & LLRF optimization	In progress	On track
Y4	M48	February	2028	D	8	WP2	2.4 Integrated LLRF control using ferro-electric fast reactive tuners	Report on integration of FE-FRT in LLRF	Not started	On track

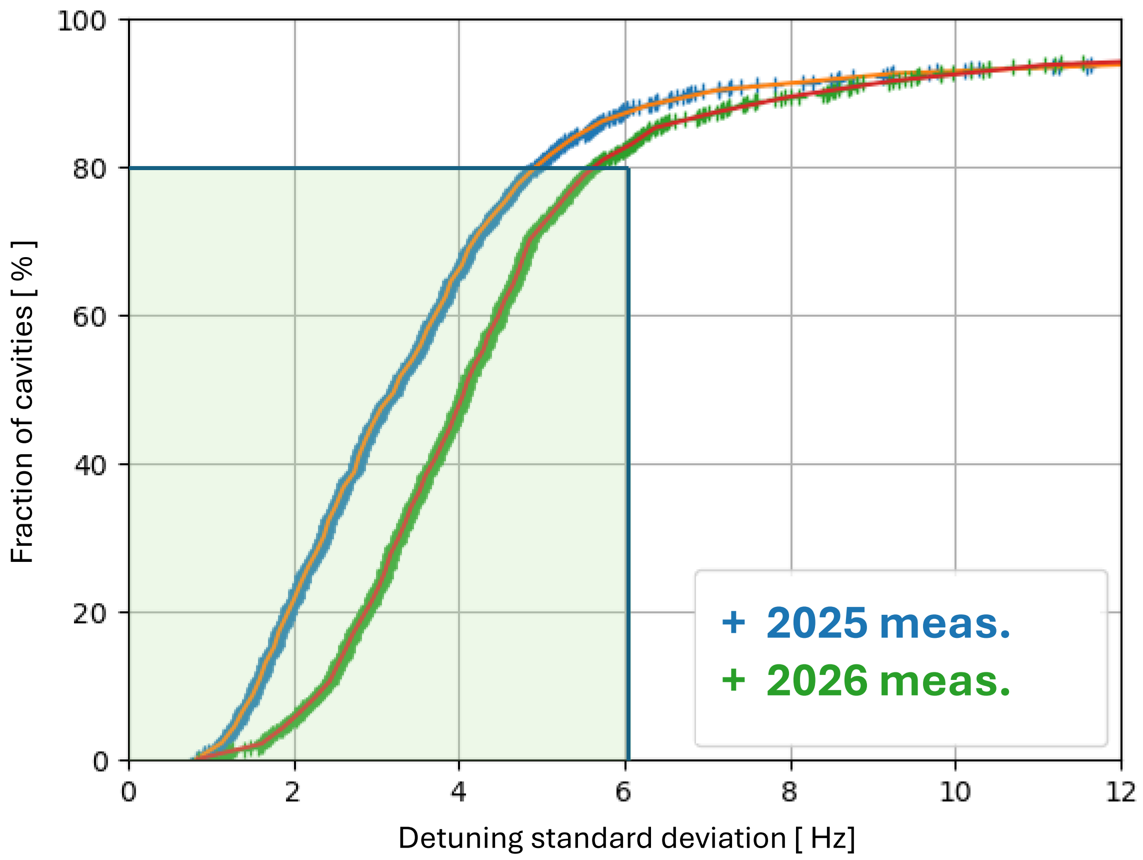
- Plans to **achieve** milestones & deliverables
  - Delay risks to be anticipated? **→ some unknowns but nothing critical. Plan B as back up**
  - Cooperation with other WP(s) to be reactivated? **→ clearly potential to increase collaboration, not always easy in practice due to daily "emergency" in home institute + budget / travel restrictions**
  - Risk mitigation measures to be implemented? **→ risks were identified and mitigations strategies presented in official impact risk analysis (milestone M40 submitted in Feb. 2026)**

WP2 – LLRF: status/evolution of Task 2.3

Vibration analysis and detuning control of cavities – *M1-M36*

- **Past developments**
  - …

- **Current developments**
  - Assessment of microphonics level at XFEL
  - 80% of cavities are below 6 Hz (rms)



Why is bandwidth and resonance control crucial for efficiency

Bandwidth (Qext) and Resonance (Δf) control

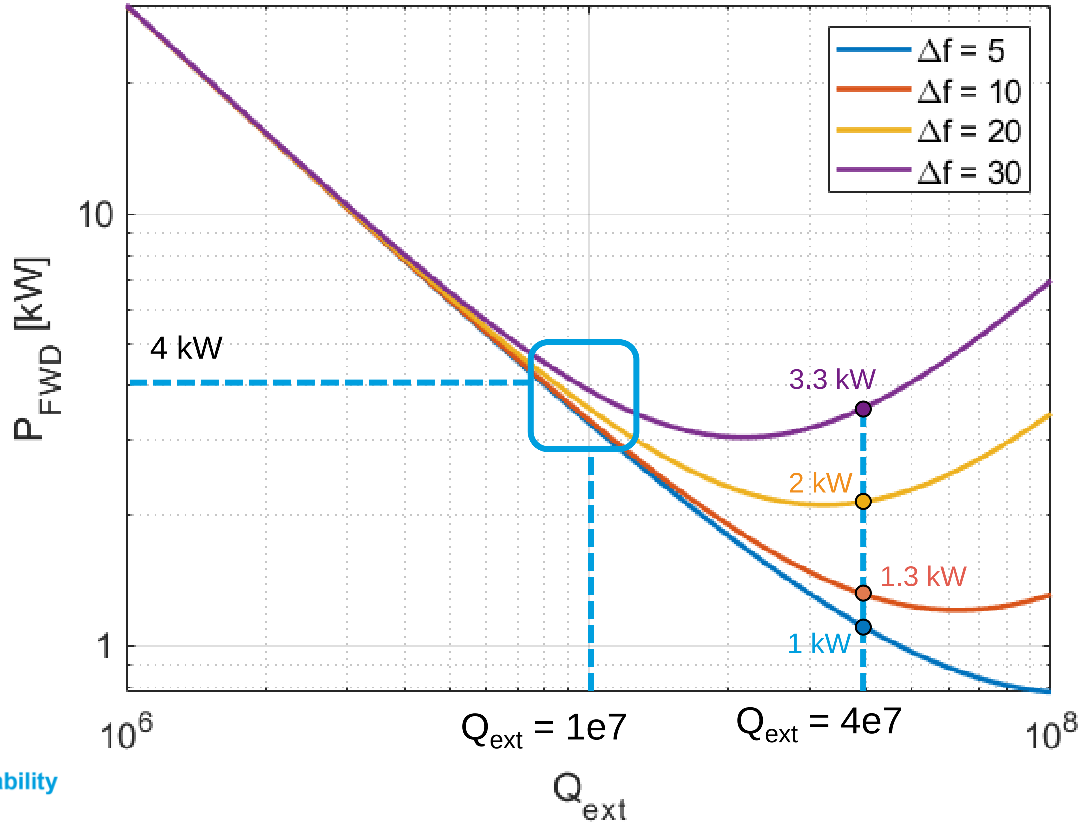
Operating at **higher Qext** (narrower bandwidth)

- reduces the power needs **IF** resonance control can be guaranteed
- makes resonance control extremely challenging

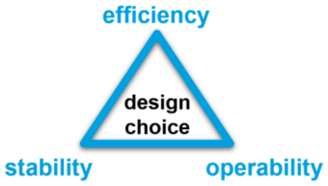
$$P_{\mathrm{rf}} = \frac{V_{\mathrm{acc}}^2}{4\frac{r}{Q}Q_{\mathrm{ext}}}\left[\left(1 + \frac{\frac{r}{Q}Q_{\mathrm{ext}}I_b\cos\phi_b}{V_{\mathrm{acc}}}\right)^2 + \left(\frac{2\delta_f Q_{\mathrm{ext}}}{f_0} + \frac{\frac{r}{Q}Q_{\mathrm{ext}}I_b\sin\phi_b}{V_{\mathrm{acc}}}\right)^2\right]$$

Parameters for SRF gun

r/Q = 208 Ohm
V_{acc} = 5 MV (energy gain from the gun at 50 MV/m -> 5 MeV)
I_b = 100 uA (100 pC at 1 MHz)
ϕ_b = 0 deg.



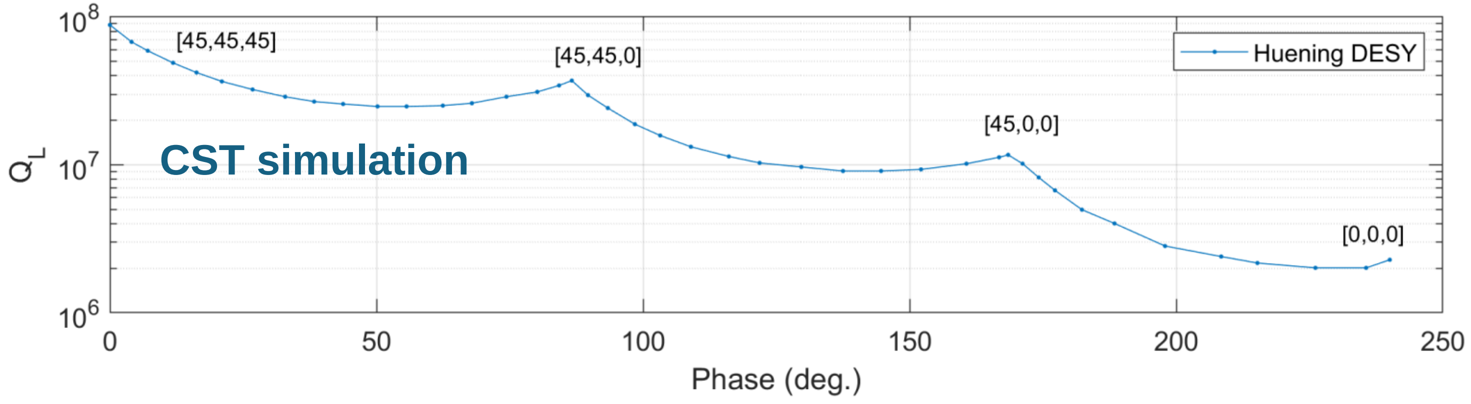
The challenge is to find the **highest Qext** one can operate the cavity at while still **meeting the resonance control goals** and without compromising **operability** and **reliability** of the system.

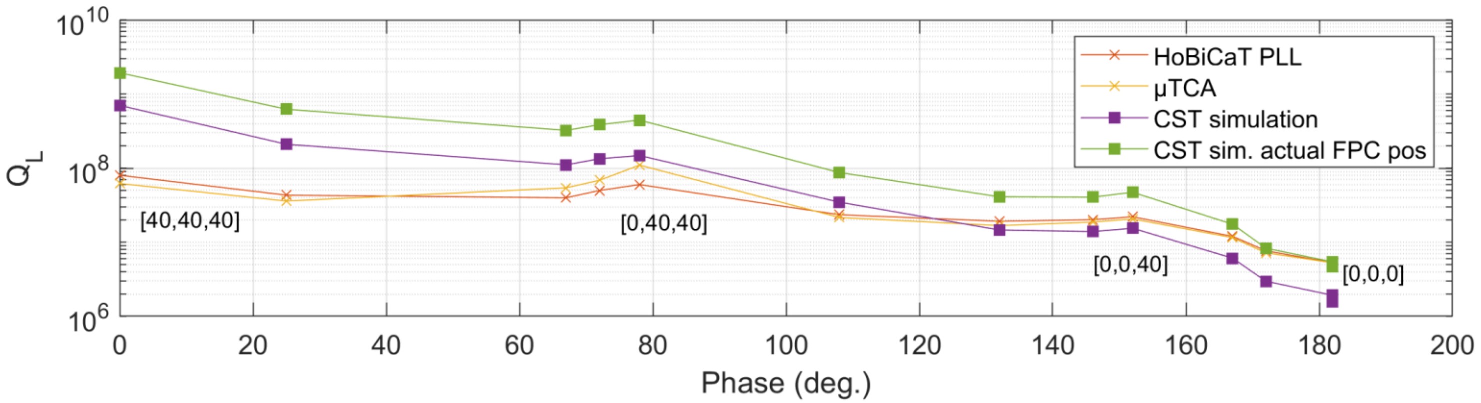


Extending the Qext range

First test with 3-stub tuner at HobiCat

- (HZB) re-measured Qext change with 3-stub tuner at HobiCat (had already been done a long time ago…)
- Cross checked results with CST simulations.





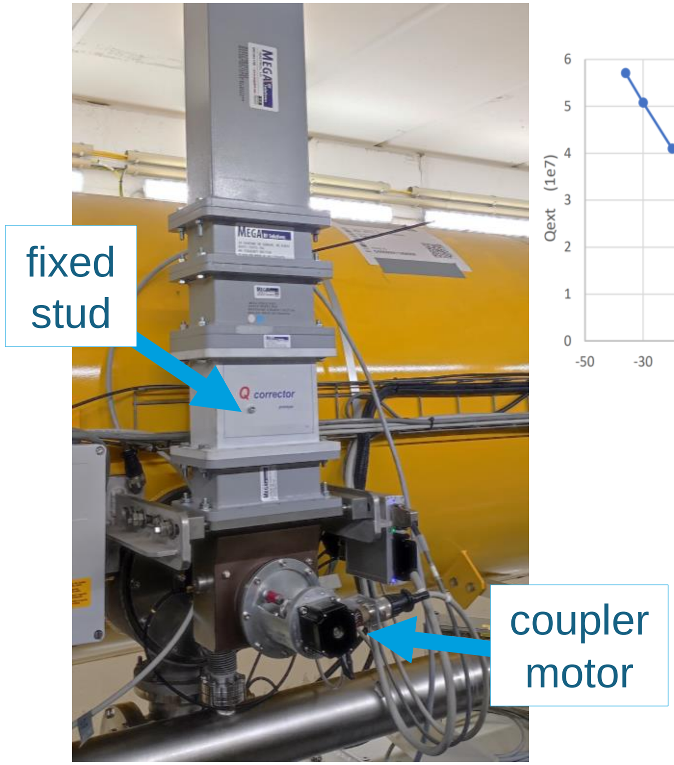
Courtesy A. Neumann

3-stub tuner

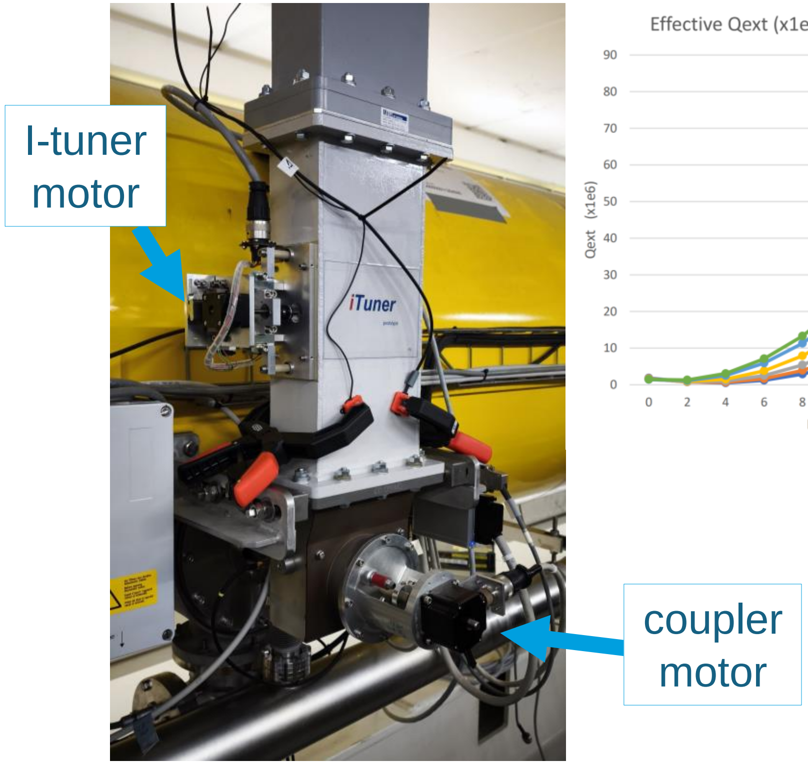
Developed 2 prototypes to extend the Qext range

Waveguide components to increase Qext range

Q-corrector (fixed)

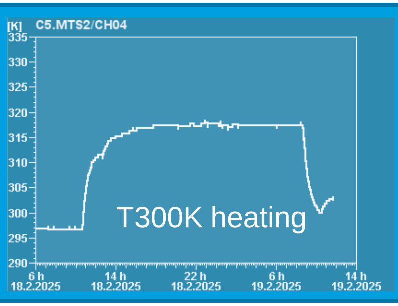


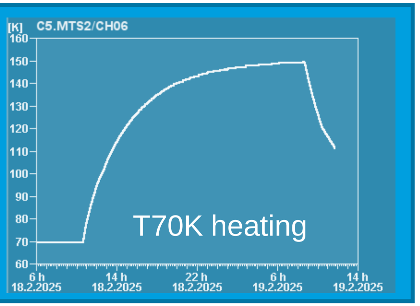
Iris-tuner (variable)



Courtesy V. Katalev

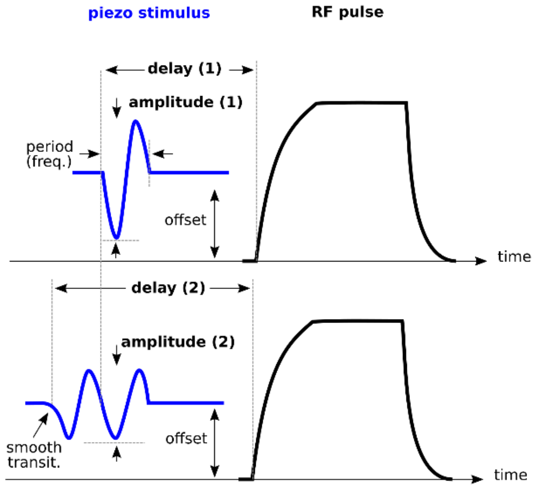
- Several devices are being developed to **increase** or **shift** the **Qext tuning range**
- High-power test started
- Currently investigating induced heating of coupler





WP2 – LLRF: status update

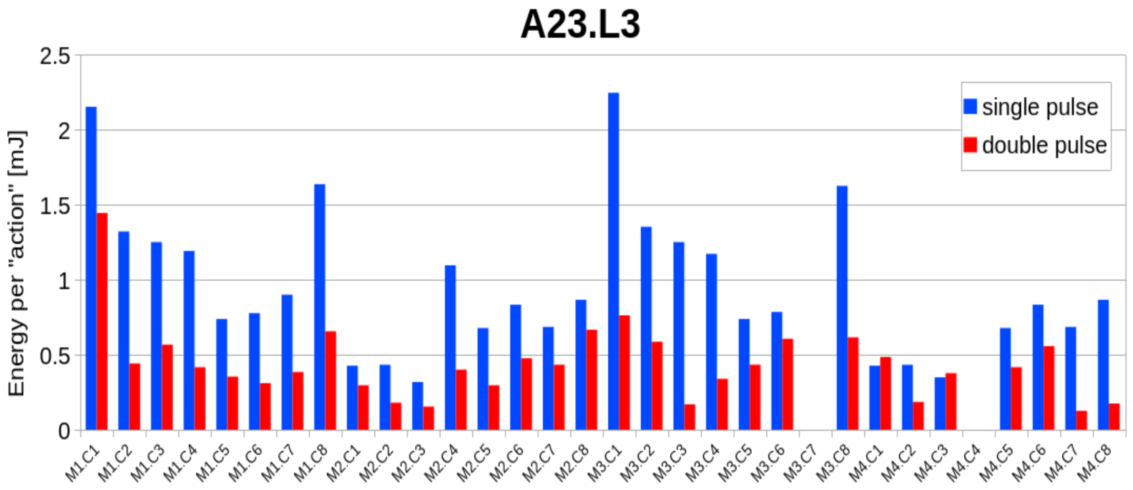
Example 1: improving efficiency of resonance control algorithms (DESY)



Piezo stimulus used to compensate Lorentz force detuning in pulsed operation at EuXFEL.

1. **Bayesian optimization of piezo stimulus parameters** (delay, amplitude, offset)
2. **Using a double sine excitation** (instead of just 1)
3. **Smoothing the leading edge** (to minimize inrush current)

= net energy saving factor of 2

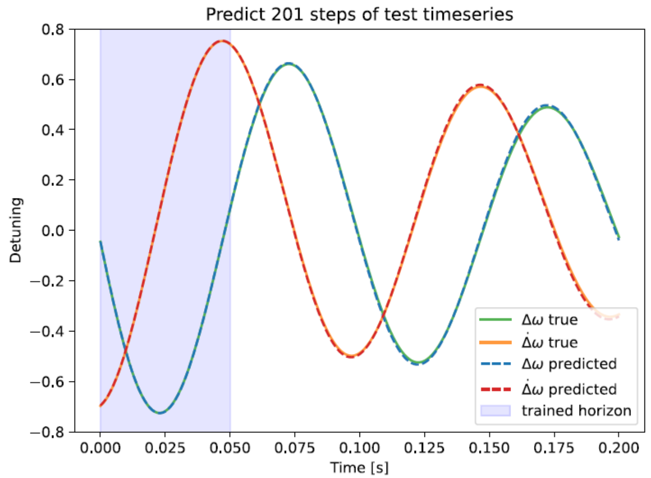


Presented at IPAC 2025: "Optimization of Piezo Operation for Superconducting TESLA Cavities at EuxXFEL", M. Grecki *et al.*

Example 2: developing machine learning–based diagnostics for SRF cavities (HZB)

Deep learning of cavity detuning

- Can one use **machine learning** (auto encoders) to **predict detuning** in CW
- Use **deep learning** to adapt the cavity model to real-time variations
- Use Koopman filter to make dynamics of the system appear linear
- Simulated **detuning data**, then used to train and test model

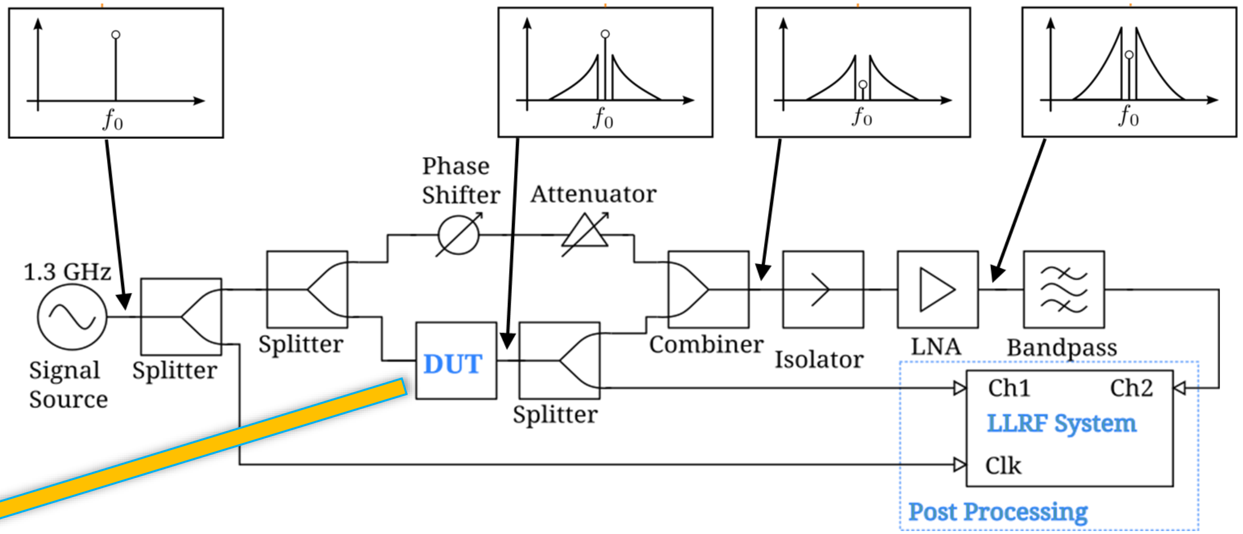


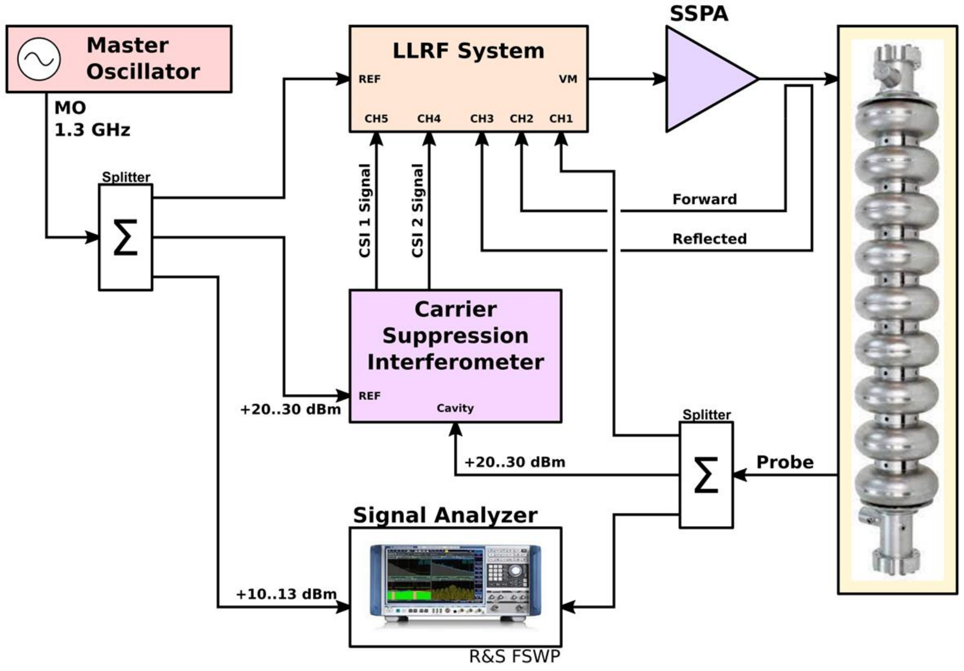
Carrier Suppression Interferometer

Concept

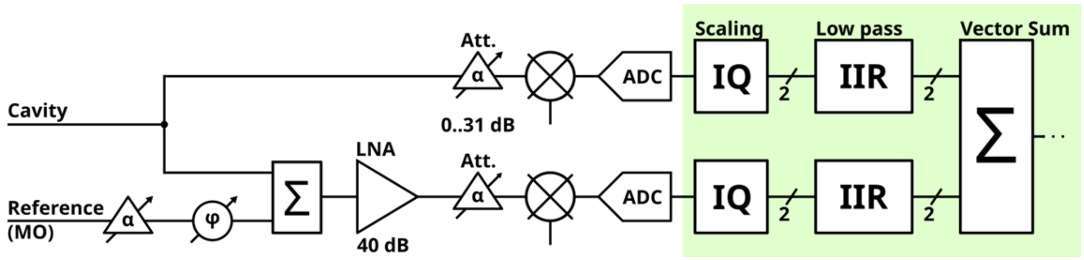
Courtesy: M. Hoffmann

- Overcome noise limits of the post-IQ system
- CSI performance scales with RF input power
- Source → very low amplitude noise !
- Replace the DUT with the LLRF system





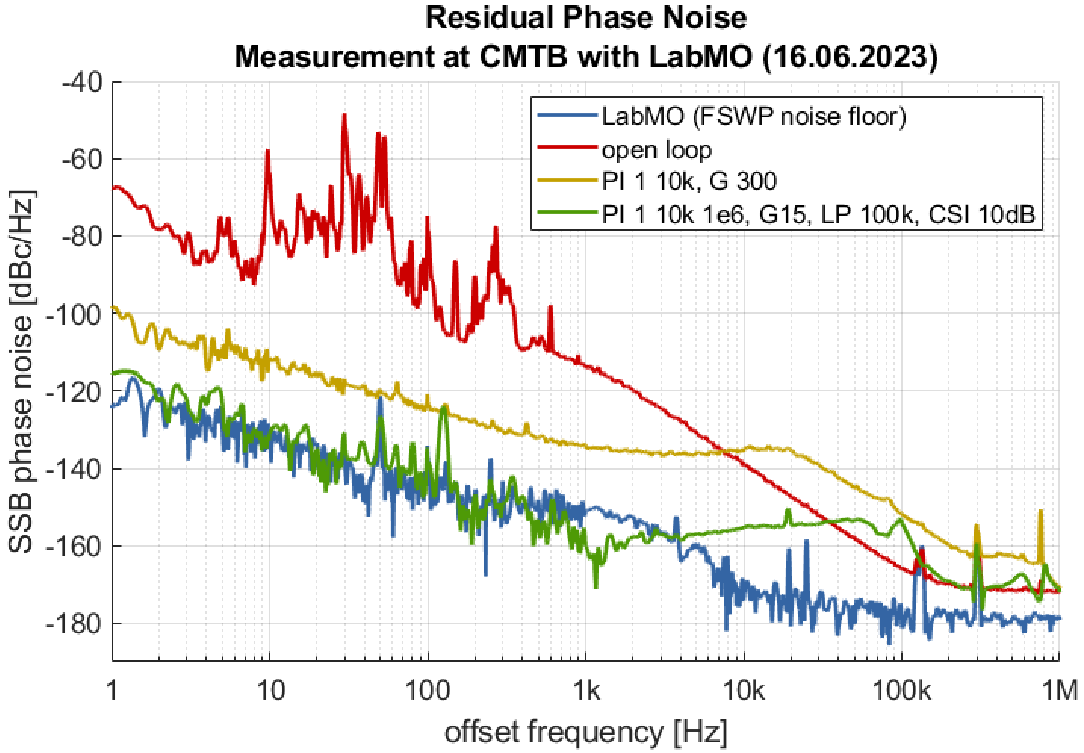
- CSI signal contains no carrier
  - no absolute information of amplitude and phase
- CSI signal as amplified error signal
  - Combination of CSI and standard measurement as controller input

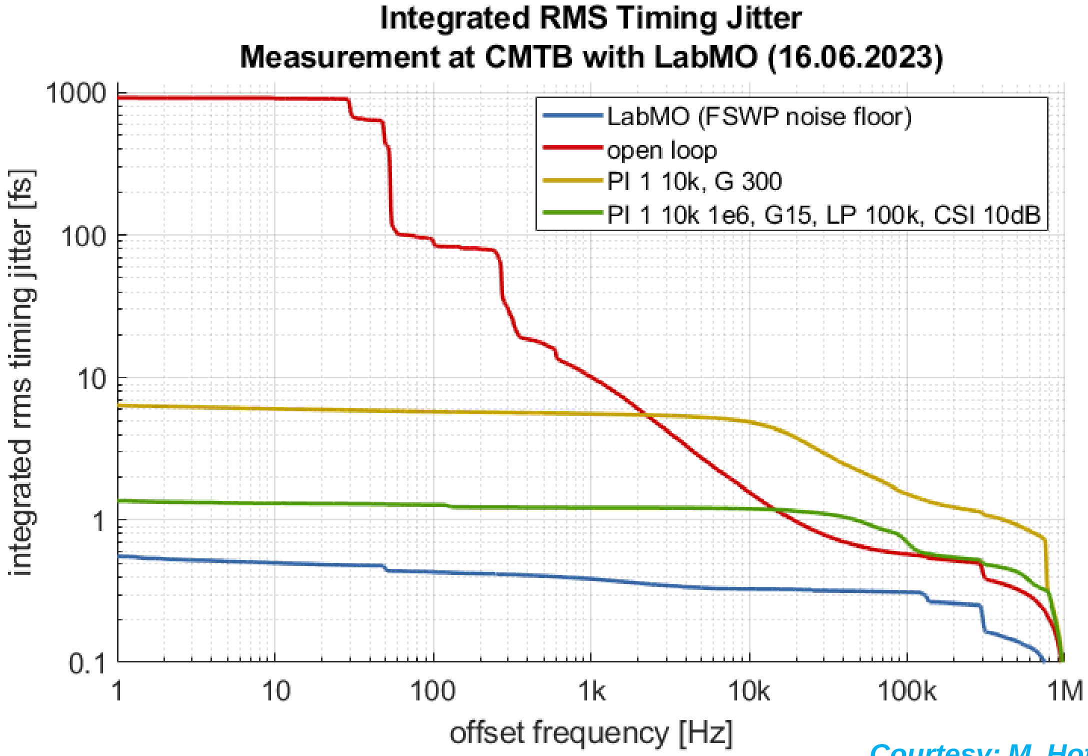


Measurement Results from CMTB

Lab MO as Reference (best results)

- Cavity at Q_L ~ 10^7 (f_{12} = ~ 65 Hz)
- Open loop vs. PI controller vs. CSI with PI
- Reached noise floor of FSWP
- Requires stable condition of the cavity (steady state CW)
- Cavity tuning (PZT) to maintain operation at resonance





Courtesy: M. Hoffmann

WP2 – LLRF: status/evolution of Task 2.3

Vibration analysis and detuning control of cavities – *M1-M36*

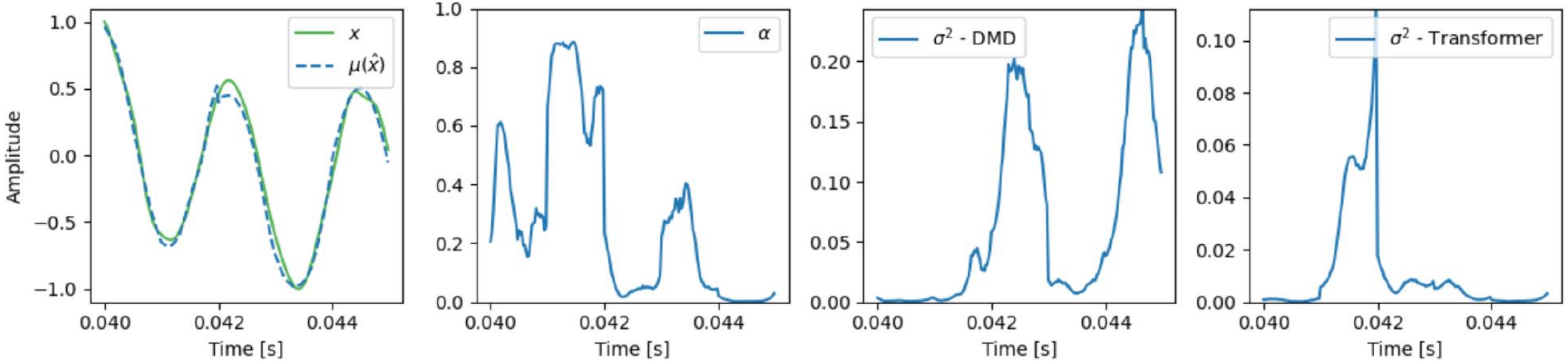
- **Current developments**

1. **AI-based** detuning compensation

Exploration of AI-based methods for RF detuning compensation

- Designed a hybrid model that learns detuning dynamics from data (accepted for presentation at IFAC2026)
- Derived a stability theorem (paper under review)

Courtesy A. Maalberg



Demonstration of estimating “real-world” time series by blending Dynamic Mode Decomposition (DMD) and Transformer (deep-learning architectures) predictions with an adaptive alpha (similar to Kalman gain)

To be presented (+ proceeding) at IFAC 2026