

Resonant filling for long pulse operation of EuXFEL using iterative learning based feed forward



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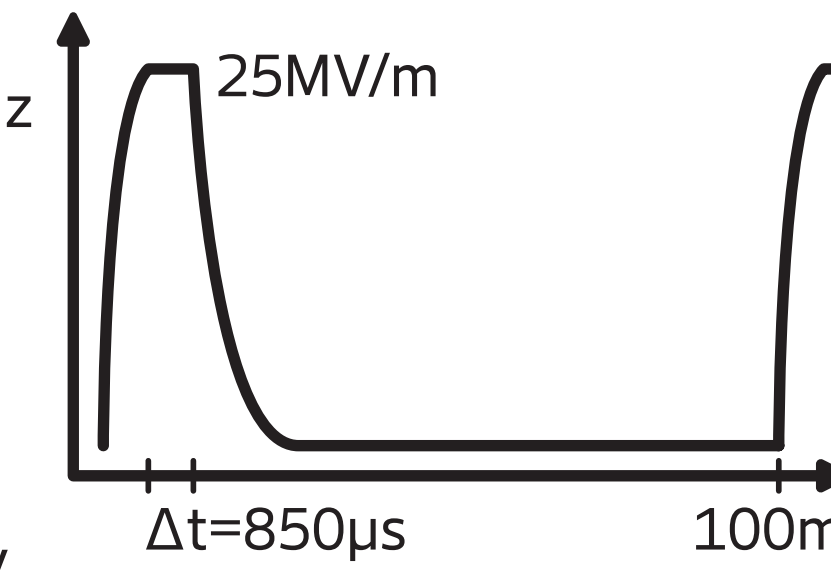
Motivation

- **future operation scenario** of the European XFEL (EuXFEL):
 - **long pulse (LP) mode** - increased RF pulse lengths (see right)
 - **narrower RF bandwidths** for energy efficiency
- Peak power limitation of RF amplifiers: **fill times** of several milliseconds surpassing **period of mechanical resonances** of TESLA cavities
- single cavity RF regulation
 - RF drive phase adjustable to **match phase** shift due to **Lorenz force detuning**
 - idea: fill on resonance by **iterative learning control (ILC)** on RF phase
- vector-sum RF regulation
 - common RF drive does not allow per cavity individual dynamic phase alignment
 - idea: ILC on mechanical cavity tuners - match cavity detuning to common RF phase

Pulsed RF at EuXFEL

Short Pulse (commissioned)

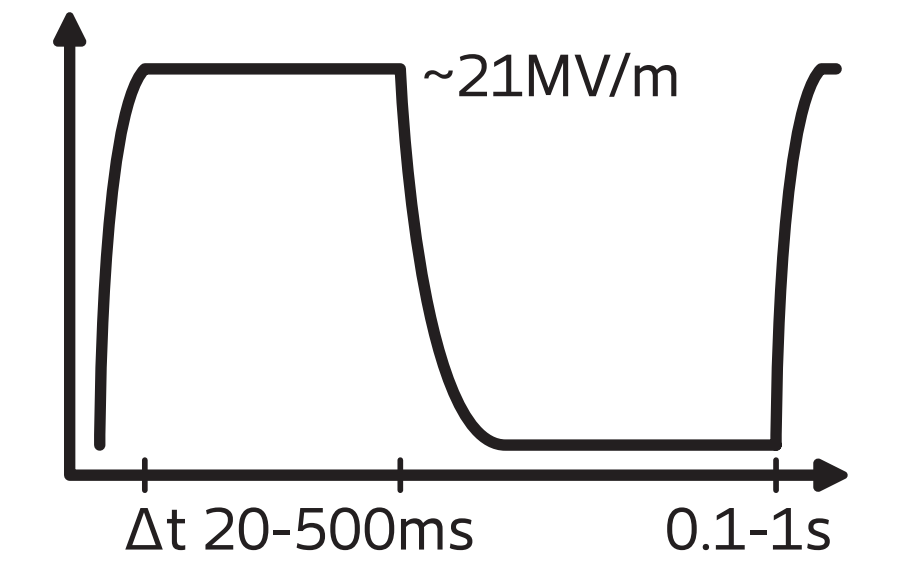
- 800 TESLA cavities @ 1.3GHz
- RF rep. rate 10Hz
- flattop duty cycle 0.65%
- QL = 3.5e6



- Klystron, 300kWp per cavity
- vector sum control of 32 cavities

Long Pulse (upgrade scenario)

- > 800 TESLA cavities
- rep. rate 1 to 10 Hz
- flattop duty cycle 10 - 50%
- QL 2e7-6e7



- SSA, 4-8 kWp per cavity
- vector sum of 8 or single cavity control

1. Reference Trajectories

Assumptions

- no excitation of cavity mechanical modes
- constant forward power
- known cavity parameters
 - $k_{lfd} \left[\frac{\text{Hz}}{\text{MV}^2} \right]$ Lorenz force detuning constant
 - $\omega_{1/2} = \frac{\pi f_0}{Q_L} \left[\text{rad/s} \right]$ cavity half bandwidth

Trajectory generation

- cavity voltage during on resonance filling ($t \geq 0$)

$$V_{cav}(t) = a(1 - e^{-\omega_{1/2}t})$$

- Lorenz force detuning

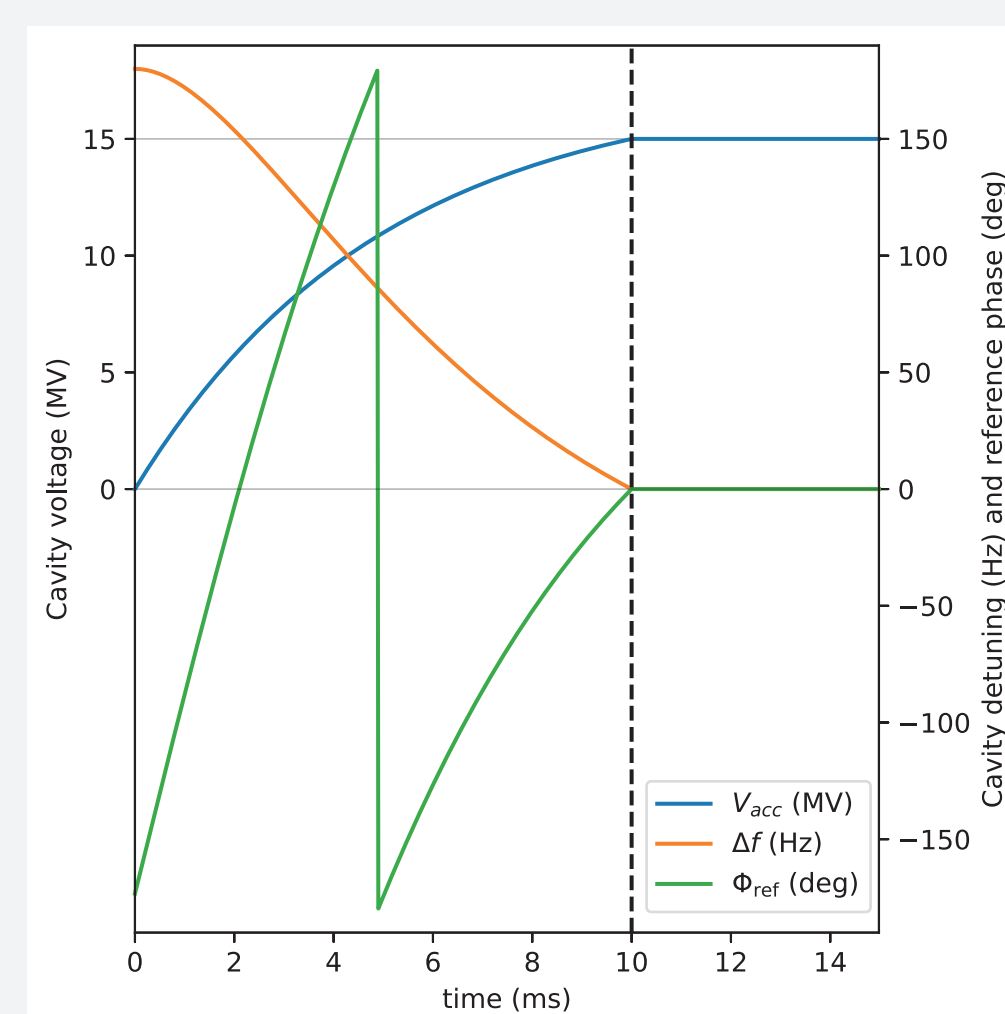
$$\Delta f_{lfd}(t) = k_{lfd} V_{cav}^2(t)$$

- reference detuning (zero at flattop)

$$\Delta f_{ref}(t) = \Delta f_0 + \Delta f_{lfd}(t)$$

- reference RF forward phase

$$\Phi_{ref}(t) = \Phi_0 + 2\pi \int \Delta f_{ref}(\tau) d\tau$$



Limited fill time

- final Vcav depends on forward power and QL
- here: step down forward power
 - non-smooth detuning
 - excites mechanical modes

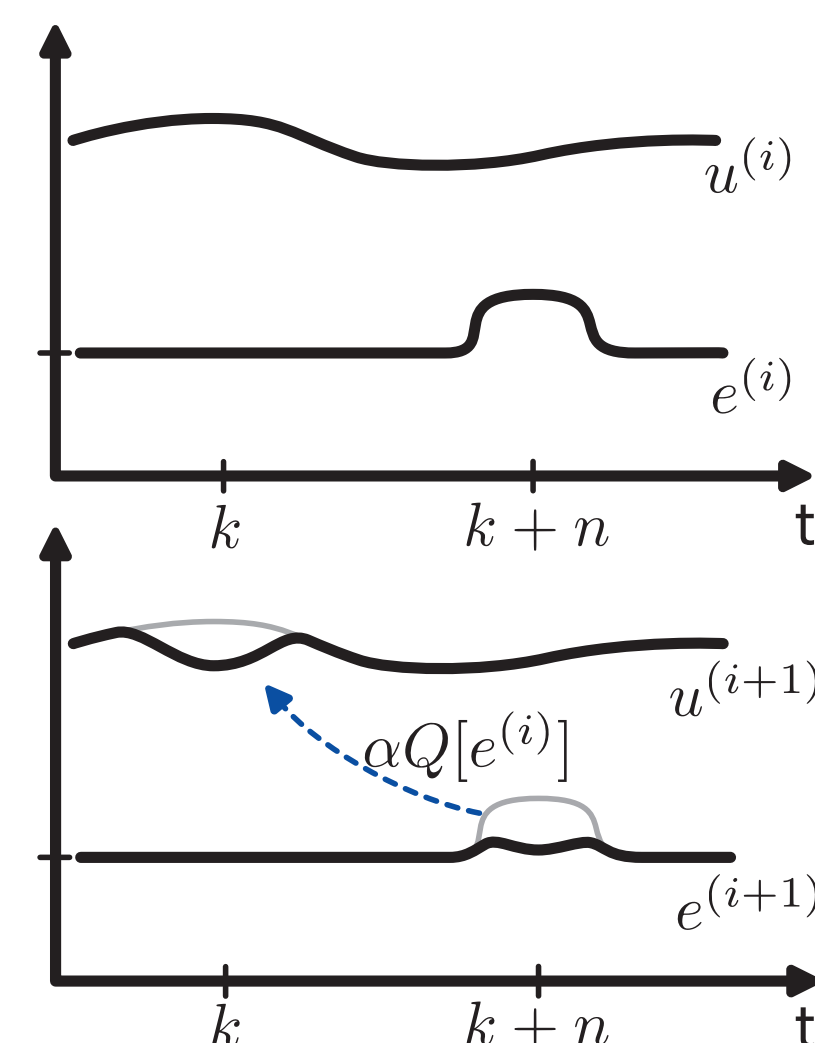
2. Iterative Learning Control (ILC)

- iterative feed forward adaption scheme
- requires repetitive reference tracking experiment
- here: model free SISO

$$u_k^{(i+1)} = u_k^{(i)} + \alpha Q [r_{k+n}^{(i)} - y_{k+n}^{(i)}]$$

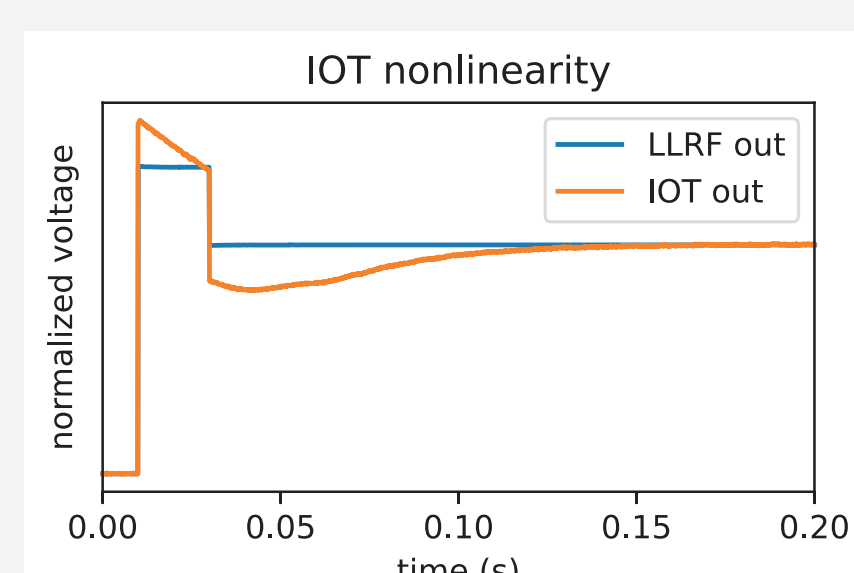
u: control drive r: reference y: plant output
i: repetition index k: sample index e: error r-y
 α : adaption rate Q: error filter n: delay offset

- n-step ahead adaption to account for delay from u to y
- 2 free parameters: adaption rate α and delay offset n



3. Experimental Setup

- Facility: DESY Cryomodule Test Bench (CMTB)
- installed cryomodule changed between tests
 - separate LLRF systems
 - single cavity and vector sum control
 - generator driven for deterministic fill time
 - shared RF amplifier: 40kW CW capable IOT
 - connected to 8 cavities via waveguides
 - nonlinear thermal effects in pulsed mode
 - piezo drive system
 - 40ms feed forward table @ 25.1kHz
 - intra-pulse feedback disabled
 - detuning calculated inter-pulse (RF based observer)



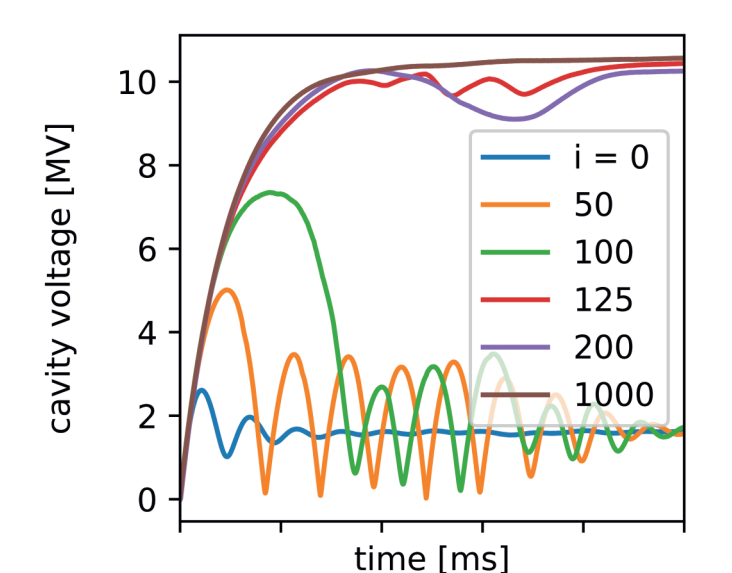
4. Phase Tracking ILC for single cavity control

- preprocessed Φ_{cav} as time-varying ILC reference
- flat initial RF feed forward phase
- RF feed forward phase as ILC control drive
- constant piezo voltage

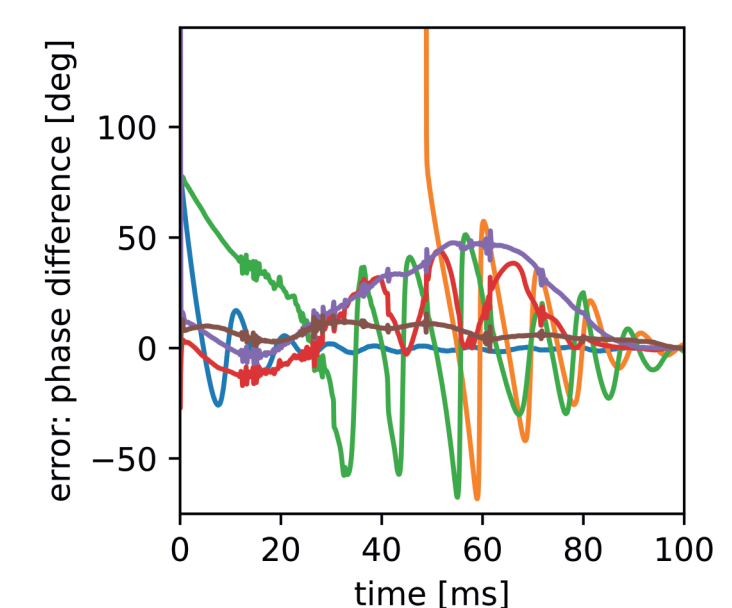
- delay offset n=1 (no delay)
- preprocessing of Φ_{cav}
 - lowpass filtering to suppress noise
 - linear extrapolation at $V_{acc} < 1\text{MV/m}$
- amplifier linearization by ILC
 - separate ILC for amplitude and phase
 - desired RF feed forward as reference
 - LLRF out as control drive

Experiment

- cryomodule XM50.1, cavity 5
- QL 4e7
- fill time: infinite (800ms)
- rep. rate: 1Hz
- target cavity voltage: 10MV/m



- very slow convergence rate
 - flat initial RF phase
- noise artifacts appearing
- implementation revision required
 - initialize with Φ_{ref}
 - reduce pulse length



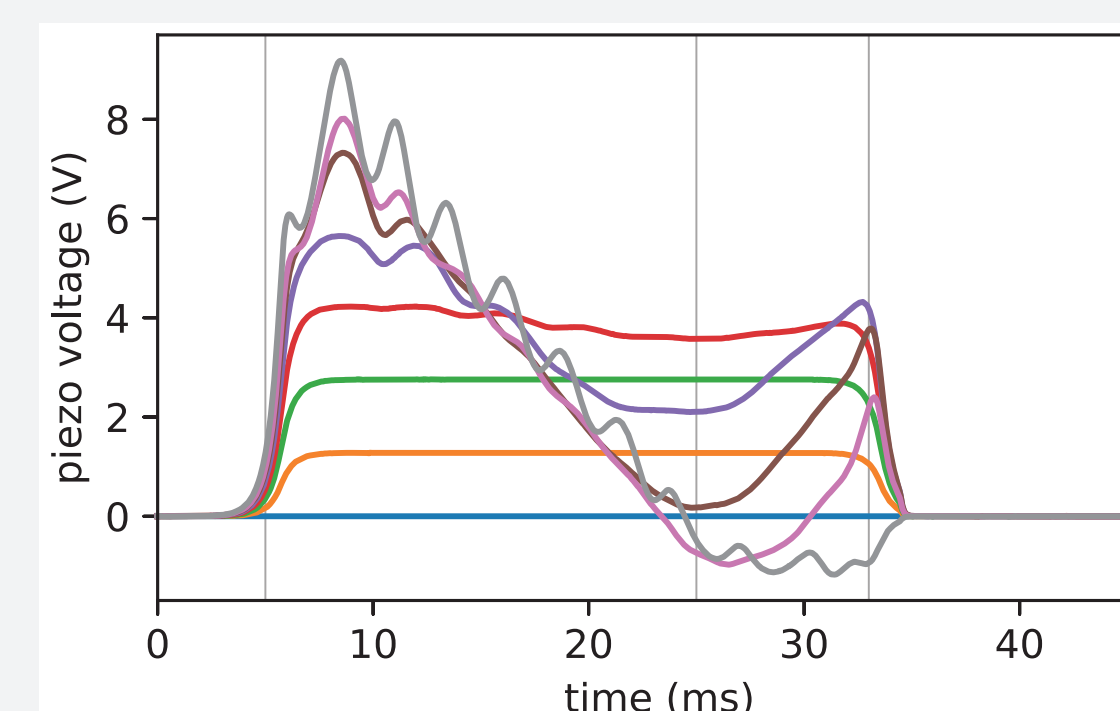
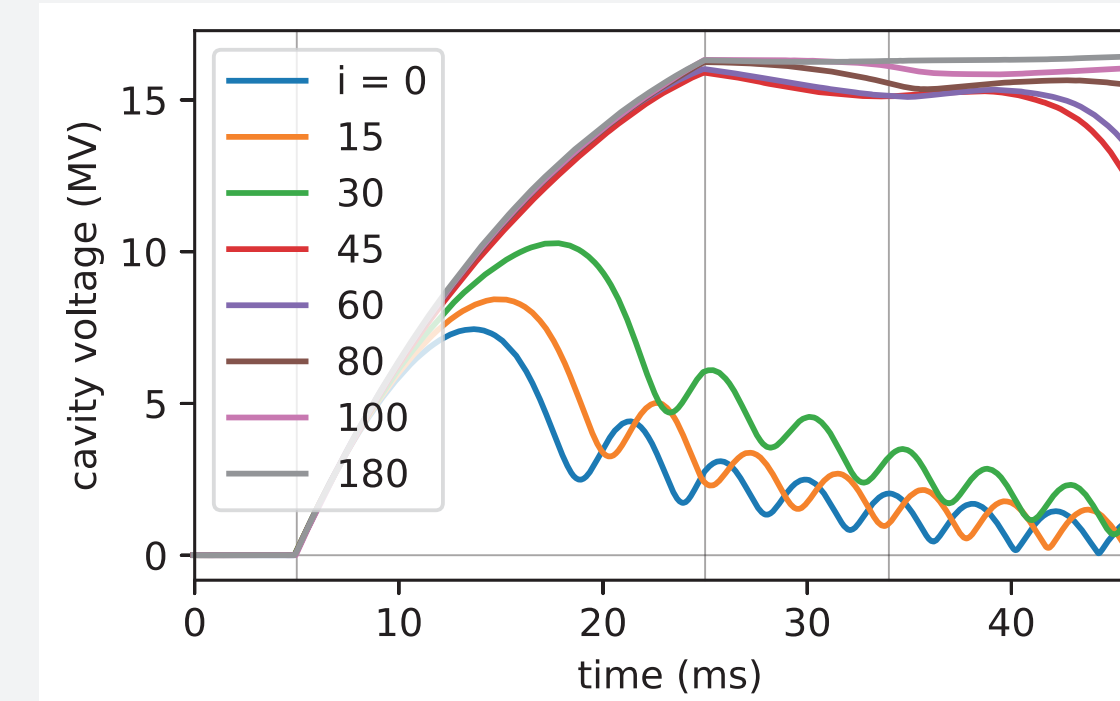
5. Tune Tracking ILC for vector sum control

- Φ_{ref} as common RF feed forward phase
- Δf_{ref} as ILC detuning reference
- piezo voltage vp as ILC control drive

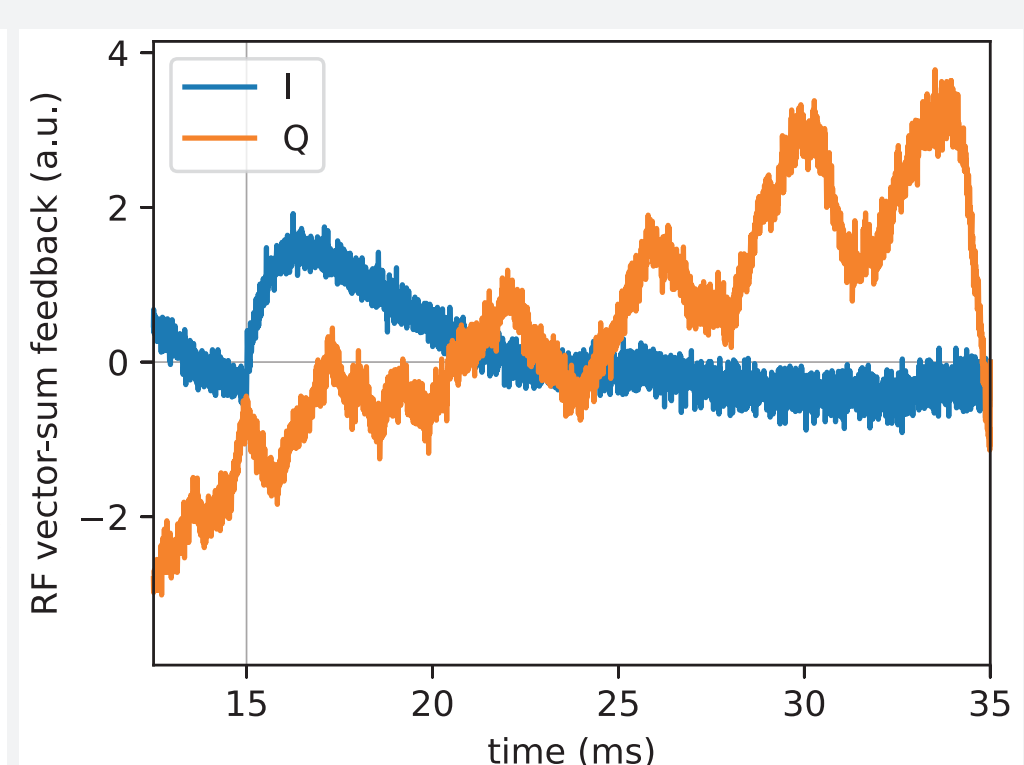
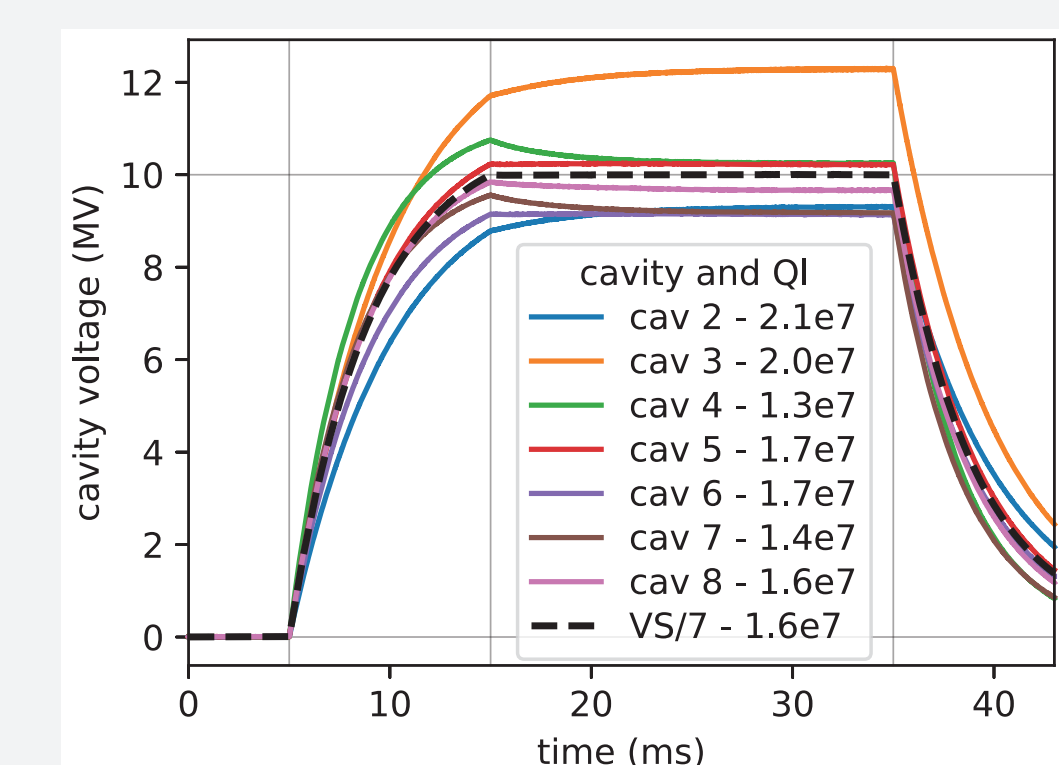
- delay offset ~2.6 ms (heuristic)
- clamping learning step size (0.1V / iter)
- low pass filtering ILC error (filtfilt, 300Hz)
 - smooth actuation beginning and end
 - noise reduction
- one-shot inversion amplifier linearization

Experiment 1: single cavity

- cryomodule XM50.1, cavity 6
- QL 6e7, $k_{lfd} = -0.95\text{Hz/MV}^2$
- reference generation for $k_{lfd} = -0.8\text{Hz/MV}^2$
- target V_{acc} 16MV (unstable at 18MV)
- initial detuning: 0V piezo drive at flattop

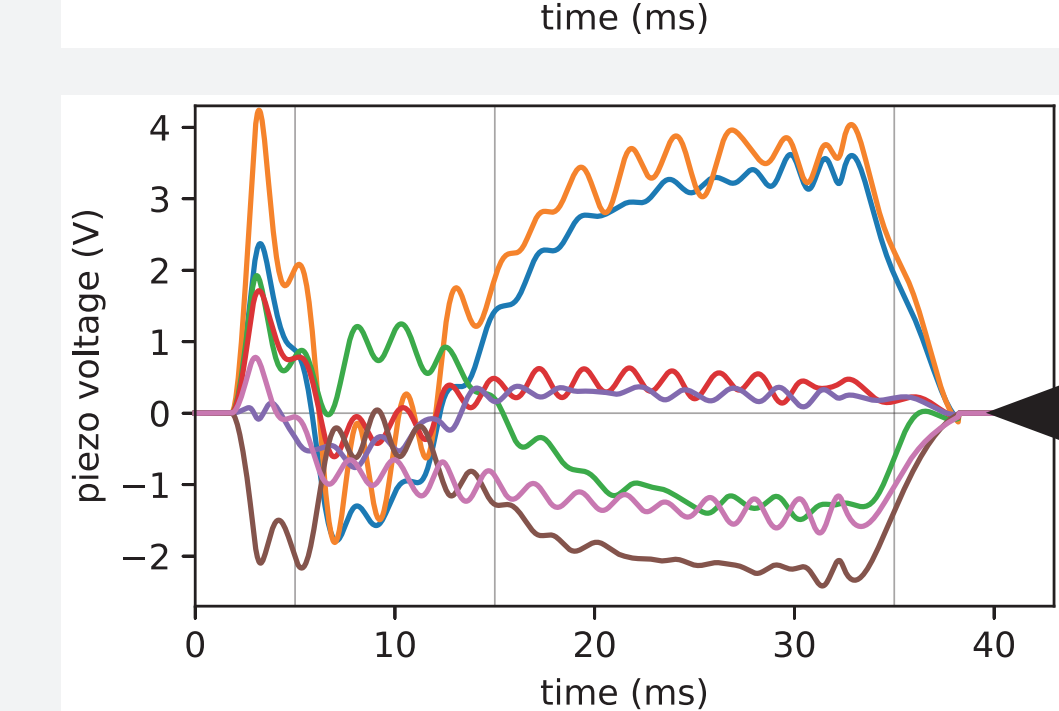
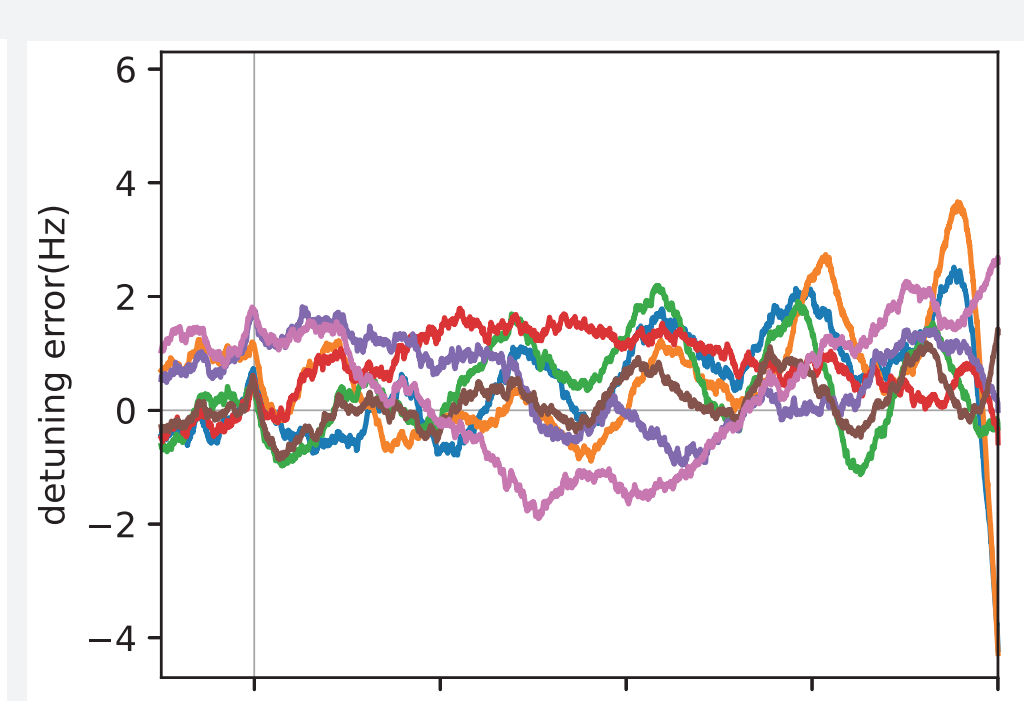
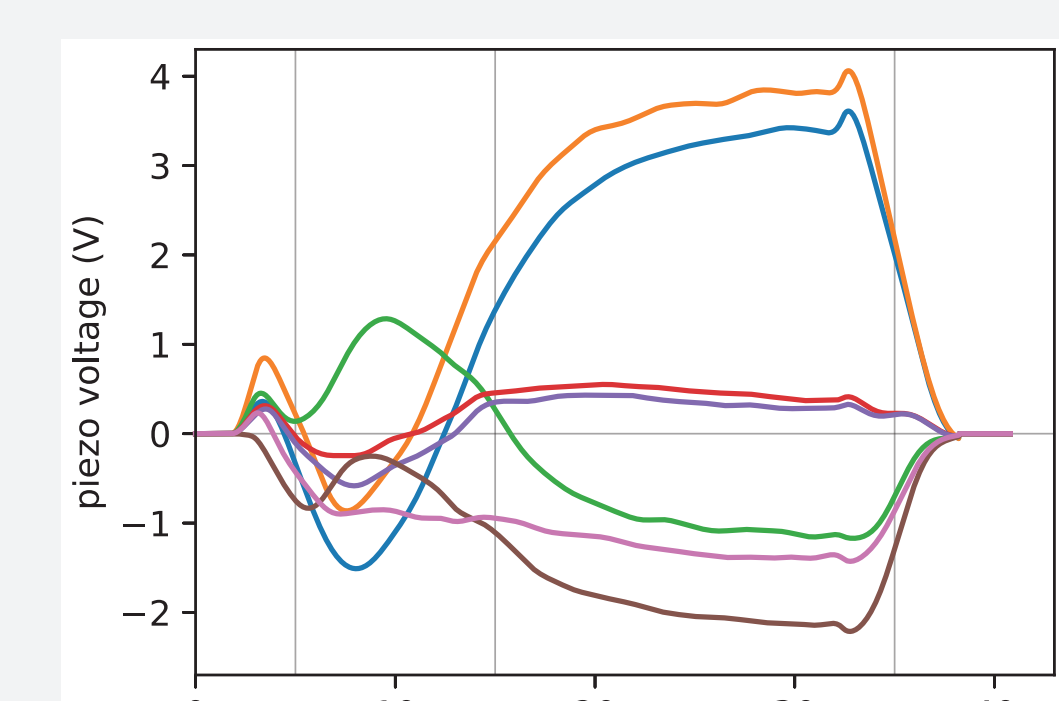


Experiment 2: multiple cavities and proportional RF feedback



- cryomodule XM8 at its max. QL
- 7 cavities in vector sum
- target average V_{acc}: 10MV
- QL spread 1.3e7 - 2.1e7
- forward power spread 1.7-2.2kWp
- fill time 10ms

- reference $k_{lfd} = -0.9\text{Hz/MV}^2$
- initial detuning: all cavities at 90Hz
- VS field stability (20-34ms)
 - 0.025% dA/A
 - 0.058deg dP



- stability to be improved by feedback resonance control
- higher gradients to be tested
- incorrect initial detuning leads to
 - growing oscillations
 - piezo voltage diverging

Conclusion

- applied feed forward adaption schemes generally suitable
- adaptation speed generally low, hyperparameter tuning needed
- divergence of piezo adaptation must be addressed (static part)
- further testing at QL 6e7 and V_{acc} towards 21MV needed
- closed loop piezo control required to improve field regulation

Future Work

- proper amplifier linearization
- piezo offset automation
- smooth output enforcement, boundary conditions, and limits for ILC
- phase tracking feed forward initialization
- forward power trajectory optimization for smooth detuning setpoint

- systematic approach to set ILC delay offset
- spectral analysis of error signals for systematic filter design
- increase piezo table lengths
- retest on high QL cryomodule at V_{acc} 21MV

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