

# RF RECOMMISSIONING OF THE EUROPEAN XFEL LINAC AFTER ITS FIRST THERMAL CYCLE

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## Abstract

The superconducting linac at the European X-ray Free-Electron Laser (EuXFEL) in Hamburg Germany has been operating at 2 K since its initial cool-down in 2016. After nearly ten years of user operation at cryogenic temperature, the linac was warmed up for the first time in summer 2025 for its first long maintenance period and successfully cooled down again in December 2025. This marks the first complete thermal cycle of all superconducting RF cavities since the start of linac operation in 2017. To avoid mechanical stress on the SRF cavities, frequency detuning before warm-up and retuning after cool-down were required. This contribution describes the approach taken for detuning and retuning all 784 cavities, statistics about the subsequent re-conditioning effort, and the RF recommissioning of the SRF linac.

## DETUNING AND RETUNING

To allow installation of redundant cryo-valves and avoid thermal cycling the linac for future cryo-safety tests, a six-month long intervention and maintenance period (LIMP) was scheduled from June 2025 till January 2026. In preparation of this first warm up since beginning of operation in 2017, all 776 1.3 GHz and eight 3.9 GHz superconducting cavities were detuned, retuned and subsequently conditioned for the RF startup after the LIMP.

### Cavity Detuning

Cavities were not detuned to their warm-tuner position (also known as parking position) but rather to an intermediate detuning, referred to as *safe* position defined as a detuning large enough to avoid unrecoverable plastic deformation due to a thermal cycle. The safe positions were set to either 100 or 200 kHz below the 1.3 GHz resonant frequency, depending if the detuning when the cavity is warm is less or larger than 300 kHz. The motivation to detune “only” to safe is to minimize tuner motor movement to optimize their life expectancy. The detuning operation was done in a semi-automated way, using an emergency software tool developed and used during the covid pandemic, called ED2S (emergency-detune-to-safe) [1]. This one-button tool drives all selected motors to a pre-defined motor position, without actually checking if the cavities are being detuned. Since the pre-LIMP detuning was not an

emergency, it was decided to perform the operation with RF on, so that the resonant frequencies could be tracked as cavities were being detuned. The procedure consisted of driving all cavities at a moderate gradient, disabling all feedback and automation algorithms, set the target detuning to safe and launch the ED2S tool. The total detuning took 40 minutes, followed by a systematic check (and adjustment when needed) of the final frequency (FFT of the cavity probe signal). During the process, two motor drivers (4%) failed (one blown fuse and one power supply failure). 47 cavities (6%) were masked from ED2S, mostly out of precaution and were detuned manually. Overall, the entire process could be successfully completed within an eight-hour shift for a crew of eight people, including a 2.5-hour tunnel access to repair the two tuner drivers. Three cavities needed special care: one cavity required an unusually high number of motor steps to reach its destination. The problem was later identified as slippage in the stepper motor rotor and could be addressed by increasing the driver current. The other two cavities stopped at a detuning closer to 100 kHz rather than the targeted 200 kHz due to a software error, which turned out to be a non-issue.

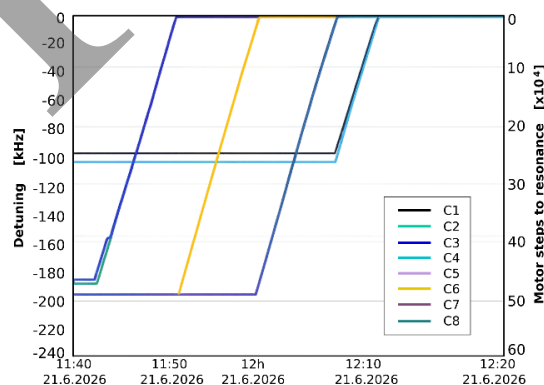


Figure 1: Resonant frequency tracking during retuning of station A11, module 4, cavities 1 to 8.

Tracking the cavity frequency during detuning and retuning allowed to measure the motor sensitivities. We found the behaviour to be very linear over the detuning range, with an average of  $-0.466 \pm 0.0098$  Hz/motor step for cavity 1 of every cryomodule and  $-0.443 \pm 0.0061$  Hz/motor step for all other cavities (C2-C8). A plausible explanation comes from cryomodule design, since the tuner is assembled differently for cavity 1 due to the presence of a gate valve at the beginning of the cavity string.

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## Cavity Retuning

After the completion of the LIMP, the EuXFEL linac was successfully cooled down and the cavities could be tuned back to resonance in January 2026. As for the detuning, re-tuning was performed in a semi-automated way, using ED2S with RF on but in a supervised way, with an operator assigned to monitor four cryomodules at a time and intervene if necessary. Since the E2DS tool does not actually check tuning of the cavities, we wanted to avoid having a cavity being tuned over its resonance (i.e. more than 100 kHz above resonance) as this could potentially damage the tuner and the cavity. This operation, including fine tuning using piezos could be carried out within one shift (8 hours) with a crew of 10 operators. Only one motor driver failure occurred during the retuning. Figure 1 shows as an example the resonant frequency tracking during the retuning of cryomodule 4 of RF station A11, where 0 kHz denotes the 1.3 GHz resonance. Cavities 1 and 4 had a safe detuning offset of -100 kHz, the other six of -200 kHz. Note that the E2DS checks this before moving motors and decides to start with cavities requiring longer tuning, (i.e. more motor steps). The tool doesn't move all cavities all at once to avoid failures due to over-current.

This tuning activity was also the opportunity to study the impact of tuner motor movement on piezos. Any longitudinal mechanical deformation of the cavity induces a voltage on the piezo. The piezo voltage persists throughout the tuning process and its polarity indicates whether the cavity is elongated or contracted. This is illustrated in Fig. 2, showing bi-directional motor movements and the corresponding induced piezo voltage. The motivation for this measurement is to provide insight on motor movement if detuning is performed without RF (in case of a real emergency for example). Using the logged piezo voltage, one could reconstruct the detuning process and confirm if the cavity was indeed detuned to its destination.

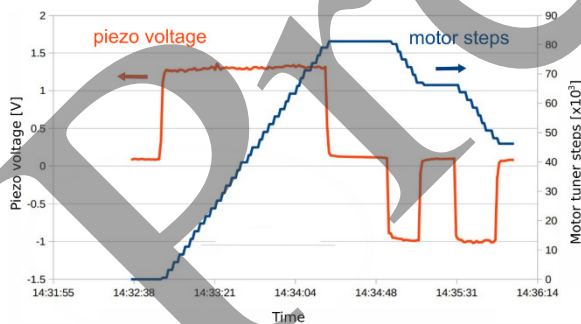


Figure 2: Voltage induced on the piezo during the motor movement required for cavity tuning.

## CONDITIONING AND RF STARTUP

### Multipacting Processing

Following cavity tuning, cold conditioning took place. Since the cavity vacuum had not been vented (or compromised) during the LIMP, there was actually no need to re-condition the couplers, only cavity multipactor processing was required. Although not automated, this activity could be carried quite fast, performed during day shifts with one

station assigned to each operator. Approximately 80% of the stations required some level of processing. Most could be processed in less than 3 hours (the fastest took half an hour, the longer seven hours). While two full weeks had been reserved for this task, 90% of the stations were fully processed within three days and completion was achieved after a week. The multipacting processing procedure consisted of setting up the station (32 cavities) in short pulse (750  $\mu$ sec fill time, 100  $\mu$ sec flat top) to minimize the dynamic heat load, disabling all feedback and automation, and gradually increasing the station gradient setpoint while monitoring coupler vacuum, electron emission and radiation sensors. Figure 3 (a) shows the effect of conditioning on vacuum, with each peak corresponding to an increase of the station setpoint. Figure 3 (b) shows the radiation profile monitored by the gamma counter readouts located under the cryomodule. For this particular station, conditioning could be completed with 1.5 hours. Once the station had reached its maximum setpoint for short pulses, the flat top length was gradually increased until the maximum duration (650  $\mu$ sec) was reached, with similar care as during the gradient ramp-up.

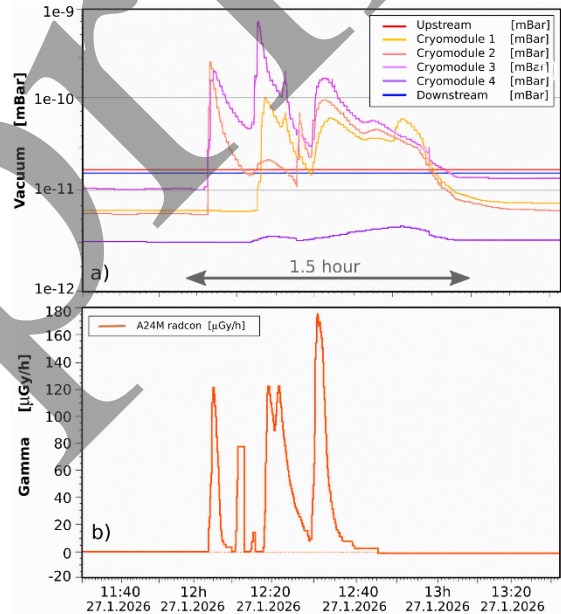


Figure 3: Coupler vacuum profile during multipacting processing (a) and corresponding activity on the radiation monitor (b) for RF station A24.

The quench detection software needed to be disabled during multipacting processing, as the software in its current state cannot distinguish a quench from a multipacting event. The signature on the RF decay of a cavity experiencing multipacting is illustrated in Fig. 5 (a) and the corresponding loaded quality factor ( $Q_L$ ) values for this cavity are shown in Fig. 5 (b). The threshold for quench detection is indicated by the dashed orange line (typically 10% below nominal  $Q_L$  value). The  $Q_L$  values computed for pulses with multipacting events, indicated with red dots, all fall below this threshold.

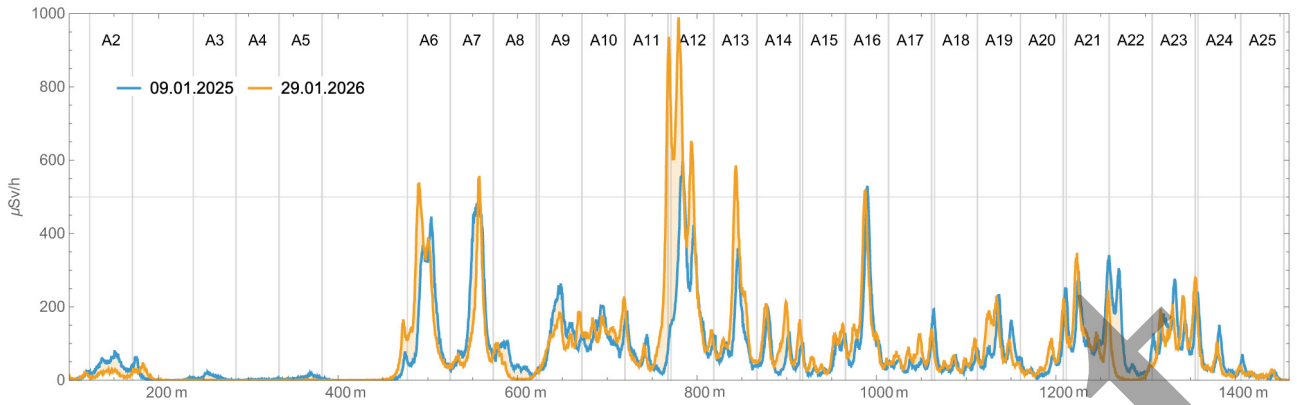


Figure 4: XFEL tunnel neutron scans (2025 - 2026 comparison).

Some data could be recorded during multipacting processing. Future work will be done to train AI models on this data in order to improve the quench detection software discriminating quenches from multipacting events.

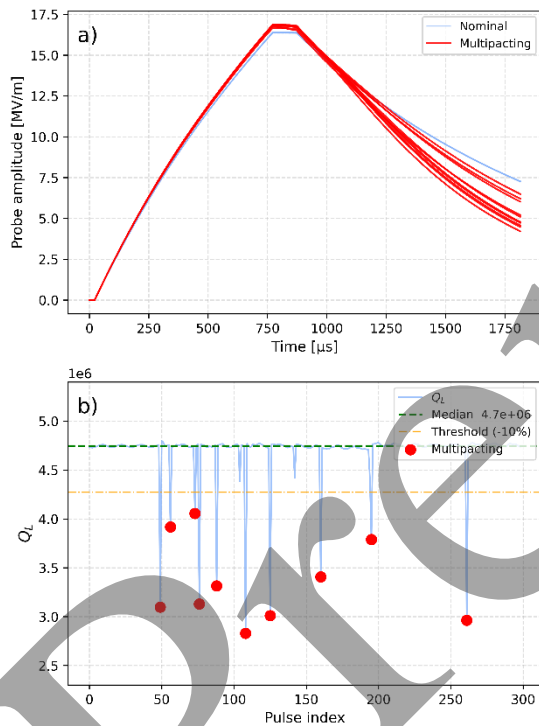


Figure 5: a) Nominal cavity probe waveform (blue) compared to pulses where a multipacting event took place (red); b) corresponding loaded quality factor with the quench detection threshold indicated in orange.

### Recovering the Linac Maximum Energy

All stations could be successfully processed within a week, allowing all cavities to be set to their maximal operational gradient. A tunnel radiation survey using MARWIN [2] showed a radiation profile similar to before the LIMP, with the exception of a radiation peak around RF station A12, in excess of the administrative limit of  $500 \mu\text{Sv/h}$ , see Fig. 4. We used our standard procedure for field emitter identification: successively de/retuning cavities by  $\sim 1 \text{ kHz}$  while monitoring the radiation peak with MARWIN. This

allowed identifying the culprit: A11.M4.C1 (cavity 1 of cryomodule 4 in station A11), producing excessive dark current, accelerated and scattered at the quadrupole at the end of A11 (hence its peak observed at the beginning of A12). This new field emitter is the only one to be reported following the LIMP and the 2025 thermal cycle of the linac. The other orange peaks above the  $500 \mu\text{Sv/h}$  threshold (A6, A7, A12 and A13) were coming from operating these stations at higher gradients during the 2026 scan (orange) compared to 2025 (blue). A11.M4.C1 was detuned (standard procedure for new field emitter) and the neighbouring cavities in A11 could absorb the gradient loss by operating approx.  $0.5 \text{ MV/m}$  higher than before the LIMP so that the total energy gain of station A11 remained unchanged. The total energy of the EuXFEL after the LIMP could be demonstrated to be around  $17.3 \text{ GeV}$ . This is the same energy as for the last high energy run before the LIMP in April of 2025. As a final remark, there were no changes done to the waveguides or klystrons during the LIMP. All high-power systems started without issues in January 2026, with the exception of the multi-beam klystron at station A1. One of its seven cathodes failed; the klystron is now running with only six beams, instead of seven. The gain loss could be compensated with an increase of the modulator high-voltage (6300 to 8200V).

## CONCLUSION

Detuning of the EuXFEL cavities to the so-called *safe* position (instead of tuner parking position) worked out extremely well. Cavity retuning and conditioning after cool down could also be performed much faster than anticipated. The maximum energy of the accelerator could be fully recovered after this first thermal cycle. While a next planned warm up is not expected to happen anytime soon, future work includes improving the automation level, in particular for cavity multipactor processing, and developing more advanced diagnostics (i.e. more accurate multipacting versus quench detection).

## ACKNOWLEDGEMENTS

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