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LIMITATIONS OF THE EuXFEL 3RD HARMONIC CRYOMODULE IN HIGH DUTY CYCLE OPERATION

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Abstract

Future High Duty Cycle (HDC) operation scenarios of the European X-ray Free Electron Laser (EuXFEL) promise increased bunch repetition rate and photon delivery, at the cost of changing system requirements and moving away from the current mode of Short Pulse (SP) operation. To assess whether the third harmonic cryomodule design is also suitable for Long Pulse (LP) and Continuous Wave (CW) operation, key parameters of the spare module are examined at the Accelerator Module Test Facility (AMTF). For Radio-Frequency (RF) related energy efficiency, the cavity resonance tuning precision and the loaded quality factor tuning range are investigated. As performance indicators, limitations on attainable cavity gradient and RF stability are quantified. The results show that the module in its current design is insufficient for LP at high duty cycles and CW at the required operating points. The installed 3-stub tuners only yield maximum loaded quality factors between 5.3×10^6 and 1.9×10^7, and the mechanical cavity tuner prohibits tuning precision within the intended cavity half bandwidth. Also, some higher order mode couplers do not allow CW operation at required gradients. Nevertheless, closed-loop RF stability measured in single cavity control is comparable to that of the third harmonic system of EuXFEL.

INTRODUCTION

The European X-ray Free Electron Laser (EuXFEL) is a hard X-ray light source for matter and technology research providing the highest brilliance in the world. It is driven by a linear accelerator providing a bunched electron beam with energies up to 17.3 GeV. Therefore, 800 superconducting cavities are operated in Short Pulse (SP) operation mode with a Radio-Frequency (RF) flat top length of 650 µs at 10 Hz pulse repetition rate. Electron bunches are accelerated during these flat tops at a repetition rate of up to 4.5 MHz.

To optimize bunch train utilization, a High Duty Cycle (HDC) upgrade of the linac allows to increase both the bunch spacing and the number of bunches per second at the same time. Different scenarios include substantially longer flat tops of tens to hundreds of ms and reduced RF repetition rates, called Long Pulse (LP), or even Continuous Wave (CW) operation. However, such an upgrade demands careful evaluation of required modifications to the machine.

Numerous R&D activities have been carried out since 2007, mostly related to the cryomodules and periphery of TESLA-type 1.3 GHz accelerating cavities. However, implications to the 3.9 GHz third harmonic system of the EuXFEL were not investigated until 2017 [1], when the spare third harmonic cryomodule X3M2 was assembled.

The main focus of this work is determining the limitations of the third harmonics cryomodule in its current state for HDC operation. The resulting need for modifications depends on the specifications of the target operating point, which have not yet been decided.

CRYOMODULE X3M2

The third harmonic system at EuXFEL has been in operation since December 2015. It is used to linearize the longitudinal beam phase space curvature induced by the first accelerating module in the injector section, enabling to maintain beam quality in subsequent bunch compressors and the main linac. In the current EuXFEL setup, the 8 cavities of the cryomodule X3M1 are operated in vector sum, driven by a single klystron.

In 2018, the third harmonic spare module X3M2 passed the acceptance test for SP operation and has been installed in the Accelerator Module Test Facility (AMTF) since then. All cavities achieved electric field strengths of 20 MV/m without field breakdown.

To assess whether the module is suitable for LP and CW operation, the test bench was equipped with a 1 kW Solid State Amplifier (SSA), ready for operation since March 2023. The system is set up in single cavity control configuration. However, the available infrastructure is limited to provide 300 W drive power to the Fundamental Power Couplers (FPC).

LIMITATIONS AND STABILITY

Efficient HDC operation requires changes to several interdependent parameters of the system:

Without beam, the obtainable gradient E_{cav} depends on the provided driving power P_{drive}, the loaded quality factor Q_L, and the detuning Δf from cavity RF resonance,

$$E_{\text{cav}} = \frac{2}{l_{\text{cav}}} \cdot \sqrt{\frac{\left(\frac{r}{Q}\right) Q_L P_{\text{drive}}}{1 + \left(\Delta f \cdot \frac{2Q_L}{f_{\text{gen}}}\right)^2}} ,$$

where l_{cav} is the cavity length, (r/Q) the normalized cavity shunt impedance, and f_{gen} the generator frequency. The approach of reducing power demand through high loaded quality factors thus requires precise resonance control, as the impact of uncompensated disturbances on field stability increases. Besides, the maximum allowable gradient is bounded by the heat transport limit of the cryogenic system,

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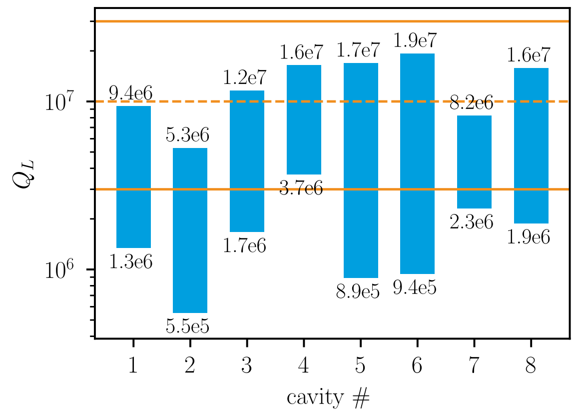

Figure 1: Q_L tuning range of X3M2 (SP specification: 3×10^6, reported minimum 2017 [1]: 1×10^7, target value: 3×10^7).

loaded by losses in cavity walls and their end groups. In this section, we present test results of the achievable loaded quality factor range, resonance tuner precision, coupler limits, and field stability.

Quality Factor Tuner Range

Other than in the 1.3 GHz system, the FPC on the third harmonic cavities are mechanically fixed. To adjust Q_L, 3-stub tuners are installed in the warm part of the waveguide. Phase shifts introduced by the tuners are unproblematic for operation in individual cavity drive configuration and therefore not analysed here. Quality factors are obtained experimentally in short pulse operation by exponential fitting of the RF amplitude decay, while individually moving the tuner stubs to alternating end stop positions. Results are shown in Fig. 1.

The desired Q_L of 3×10^7 is not achieved on any cavity, and only 5 out of 8 tuners yield loaded quality factors above 1×10^7. The lowest maximum Q_L are measured at 5.3×10^6 and 8.2×10^6, though all cavities were reported to reach 1×10^7 in 2017 [1]. At high average driving powers, the FPC are expected to heat up, reducing the loaded quality factor even further. However, the 3-stub tuners are located outside the cryomodule and therefore easily accessible for necessary modifications.

Resonance Tuner Precision

The cavities of the X3M2 cryomodule are equipped with a coaxial blade tuner, driven by a sensorless stepper motor attached to a harmonic drive gearbox [2]. Notably, neither a rotational encoder nor fast tuners are incorporated into the design, so resonance control is limited to quasi-static adjustments without motor position readback.

By driving a cavity in pulsed mode at low gradients, the current detuning is inferred from phase roll during field decay, while iteratively applying step commands to the tuner motor controller. Observed sensitivities show directional dependence with values between 2.8 and 4.5 Hz per step as

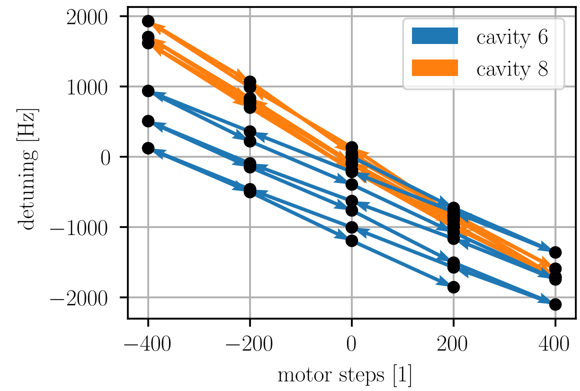

Figure 2: Variance and directional dependence of detuning sensitivity due to motor step loss at reduced current.

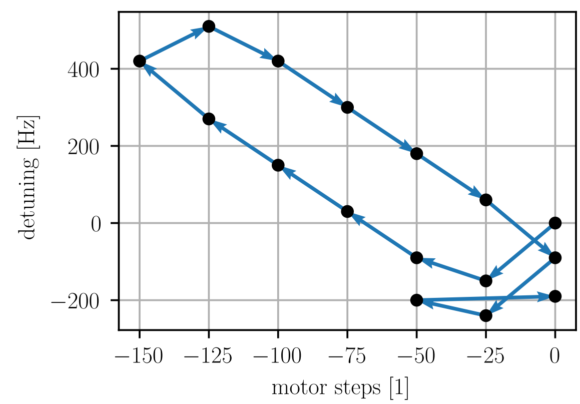

Figure 3: Hysteresis, motor direction inversion behavior, and step loss of cavity 4 at increased current.

shown in Fig. 2, inconsistent between subsequent measurements and different cavities. These results coincide with those presented in [3] obtained from the AH1 module installed at EuXFEL. The nominal sensitivity of 5 Hz per step can be partially recovered by increasing the motor driver current from 75 % (EuXFEL spec. to maximize lifetime) to 90 % of the motor coils rated maximum, indicating motor step loss.

Backlash in the assembly leads to hysteresis from 150 Hz to 1 kHz. Also, motor direction reversal with low step size shows a complex response by maintaining the previous detuning gradient. Additionally, stick slip friction in the tuner assembly blocks movements at position change commands up to 20 steps, where gearbox and threaded rod act as a torsional spring element. A recorded trajectory illustrating some of the named issues at increased motor current is depicted in Fig. 3.

The specified tuning accuracy of EuXFEL is <90 Hz. During operation, values within 60 Hz are achieved at X3M1, however the tuning procedure is error prone and time consuming. If Q_L is increased by a factor of 3 as part of the HDC update, the specification adapts accordingly to <30 Hz. The motor current may be increased to ease tuning, however stick slip friction effects cannot be avoided. Achieving

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long term stable detuning in the 30 Hz range seems hardly possible in a time efficient manner using the available tuner design, especially in presence of microphonics and coupler heating induced detuning.

It is therefore required to incorporate a fine tuner into the assembly to compensate the inaccuracy of the motor tuner, and to enable fast disturbance compensation. For LCLS-II, FNAL already designed a successor of the EuXFEL tuner including piezo elements [4]. However, changes to the tuner requires disassembly of the cryostring, making this upgrade a major effort.

RF Coupler Limits

Limitations of the current EuXFEL cryogenic installation and its implications are presented in [1], stating maximum allowable gradients in CW of 9.6 to 13.7 MV/m, depending on individual cavity quality factors. However, this estimate does not include additional heat loads, contributed by cavity end groups through losses in FPC and the two Higher Order Modes (HOM) couplers.

Other facilities, like LCLS-II [5] and SHINE [6], redesigned third harmonics couplers to withstand the higher loads during CW and reduce heating effects, as was done for the 1.3 GHz TESLA-type cavities at EuXFEL [7]. In contrast, the couplers of X3M2 are designed specifically for short pulse operation [8].

All cavities are tested for achievable gradient at maximum Q_L with several duty factors and in CW. The test bench infrastructure power maximum of 300 W does not allow gradients above 10 MV/m, however the HOM couplers located near the FPC show unacceptable heating at lower gradients already. In CW, in 4 out of 8 cavities HOM couplers are overheating at 5.5 and 5 MV/m, two more cavities even at 3 and 1.5 MV/m. At 50 % duty cycle, the latter two cavities' HOM couplers exceed the specified power limit at 4.8 and overheat at 3.7 MV/m, respectively, while all other cavities are gradient-limited by drive power.

Field Stability

Strict requirements on RF field stability are necessary to ensure precision and repeatability of beam phase space manipulations. Since HDC specifications are not yet available, recent intra-pulse amplitude and phase stability figures obtained by the X3M1 cryomodule in operation at EuXFEL are presented for comparison. The stability is evaluated at the flat top as Root Mean Square Error (RMSE) with respect to the setpoint.

Measurements are obtained at 4.5 MV/m (if possible) in closed loop using *a notch filter for passband modes and* proportional feedback. RF duty cycles of 0.7 %, 5 %, 50 % and 100 % are applied at a pulse repetition rate of 1 Hz. First tests gave poor results due to mechanical vibrations introduced through cryogenics, but improved significantly after lowering the pressure on the 4 K shield. The EuXFEL third harmonics system does not show comparable disturbances, so the effect is presumably test bench related. The final stability results are shown in Fig. 4, including a Pseudo Vector Sum (PVS) obtained by forming sample-by-sample mean voltages of all cavities.

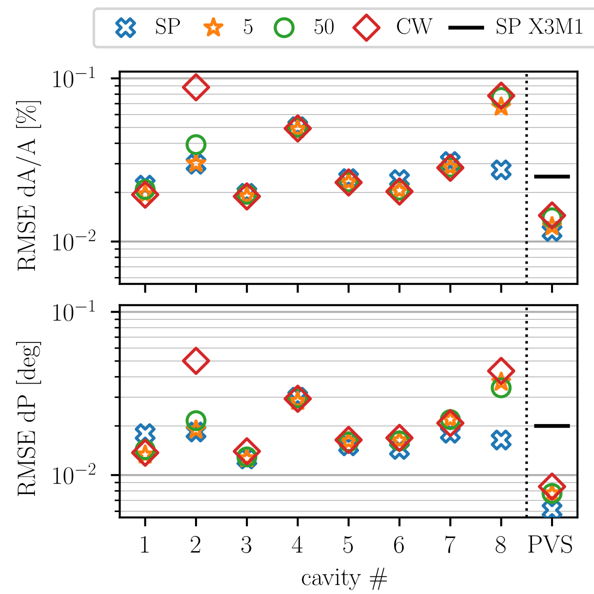

Figure 4: Closed loop intra-pulse amplitude and phase stability of single cavities and Pseudo Vector Sum (PVS) at selected duty cycles, vector sum stability of the operating EuXFEL 3rd harmonic module X3M1 given for comparison.

The obtained RF stability measurements are comparable to the presented EuXFEL figures, irrespective of the applied duty cycle. Outliers of cavity 4 and 8 with two to three times the RMSE of the remaining cavities require further investigation. As measurements of different cavities were taken sequentially, changes in the environmental parameters may have affected the obtained results. In PVS, the phase and amplitude stability of X3M2 are better than observed at EuXFEL.

CONCLUSION

The performed tests indicate that modifications of the third harmonic cryomodule are needed for a future HDC upgrade of EuXFEL. Future work should include investigation of the reason for HOM overheating. Also, options for further increasing the loaded quality factor are to be identified. For operation at high Q_L, especially the resonance tuner assembly requires modification.

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REFERENCES

[1] P. Pierini *et al.*, "Limits for the Operation of the European XFEL 3.9 GHz System in CW Mode", in *Proc. IPAC'17*, Copenhagen, Denmark, May 2017, pp. 1023–1026. `doi:10.18429/JACoW-IPAC2017-MOPVA066`

ISBN: 978-3-95450-219-6 ISSN: 2226-0366 doi: 10.18429/JACoW-LINAC2024-TUPB002

[2] R. Paparella, M. Bertucci, A. Bosotti, and C. Pagani, "Coaxial Blade Tuner for European XFEL 3.9 GHz cavities", in *Proc. SRF'13*, Paris, France, Sep. 2013, paper THP077, pp. 1101–1103.

[3] R. Paparella *et al.*, "Operational Experience of the European-XFEL 3.9 GHz Coaxial Tuners", in *Proc. SRF'17*, Lanzhou, China, Jul. 2017, pp. 240–244. doi:10.18429/JACoW-SRF2017-MOPB077

[4] J. P. Holzbauer *et al.*, "Tuner Testing of a Dressed 3.9 GHz Cavity for LCLS-II at Fermilab", in *Proc. IPAC'18*, Vancouver, Canada, Apr. 2018, pp. 2690–2692. doi:10.18429/JACoW-IPAC2018-WEPML008

[5] N. Solyak *et al.*, "3.9 GHz Power Coupler Design and Tests for LCLS-II Project", in *Proc. IPAC'18*, Vancouver, Canada, Apr. 2018, pp. 2727–2729. doi:10.18429/JACoW-IPAC2018-WEPML022

[6] Z. Y. Ma *et al.*, "Recent Progress of Fundamental Power Couplers for the SHINE Project", in *Proc. SRF'23*, Grand Rapids, MI, USA, Jun. 2023, paper WEPWB102, pp. 827–830. doi:10.18429/JACoW-SRF2023-WEPWB102

[7] D. Kostin, W.-D. Moeller, and J. Sekutowicz, "HOM Coupler Design Adjustment for CW operation of the 1.3 GHz 9-cell TESLA Type SRF Cavity", in *Proc. SRF'13*, Paris, France, Sep. 2013, paper THP059, pp. 1051–1054.

[8] T. Khabiboulline, I. Gonin, and N. Solyak, "New HOM Coupler Design for 3.9 GHz Superconducting Cavities at FNAL", in *Proc. PAC'07*, Albuquerque, NM, USA, Jun. 2007, paper WEPMN098, pp. 2259–2261. doi:10.1109/PAC.2007.4441216