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STATUS OF CRYOMODULE TESTING AT CMTB FOR CW R&D

J. Branlard*, V. Ayvazyan, A. Bellandi, J. Eschke, C. Gümüs,
D. Kostin, K. Przygoda, H. Schlarb, J. Sekutowicz
DESY, Germany

Abstract

The CryoModule Test Bench (CMTB) is a facility to perform tests on superconducting accelerating modules. The 120 kW Inductive Output Tube (IOT) installed in the facility allows driving the eight superconducting cavities inside the module under test in a vector-sum or single cavity control fashion with average Continuous Wave (CW) gradients higher than 20 MV/m. The scope of these tests is to evaluate the feasibility of upgrading the European X-ray Free Electron Laser (EuXFEL) to CW operation mode. Following the successful tests done on a prototype module XM-3, the initial performance results on production module XM50 will be presented in this paper. Because of EuXFEL requirements, XM50.1 is equipped with modified couplers that allow a variable Loaded Quality factor (Q_L) to values higher than $4{\times}10^7$. A cost relevant open question is the maximum Q_L that can be operated at, while maintaining the system within the EuXFEL field stability specifications of 0.01 % in amplitude and 0.01 deg in phase. Because of this, the LLRF system capability of rejecting microphonics and RF disturbances, as well as Lorentz Force Detuning (LFD) related effects in open and closed loop is of prime interest.

INTRODUCTION

The continuous wave (CW) upgrade scenario of the European X-ray free electron laser (EuXFEL) relies on operating the series cryomodules designed for pulse operation in CW [1]. Only the first 17 cryomodules would be modified to provide the higher helium flux required to cool down the higher dynamic load inherent to CW operations. The 2-phase pipe in the cryomodules of the rest of the linac (80-90 cryomodules) remains unchanged from the pulsed operation design. A fundamental question is how these cryomodules will perform in CW. What is the expected dynamic load? Can we optimize the cool down procedure to maximize the cavities Q_0? Is operation at 1.8K instead of 2K a viable option? What range of Q_L can we achieve with the current couplers? Pushing towards higher Q_L certainly helps with lowering the required input power but can then the field stability requirements of 0.01% and 0.01deg . in amplitude and phase be maintained? A series of R&D tests is on-going at DESY to provide an answer to theses technical questions, essential for the design and overall cost of the upgrade [2]. Until now, all CW tests were performed on XM-3, a prototype cryomodule which is not approved for EuXFEL installation. This module provided valuable insight on the potential of a CW EuXFEL, and interesting results regarding the use of large grain SRF cavities [3]. Testing a series production cryomodule (XM50) is even more interesting, as the results can directly apply the EuXFEL.

* julien.branlard@desy.de

CRYOMODULE MODIFICATION

The series XFEL cryomodule XM50 which had been set aside during the XFEL installation (due to problems during the first string assembly), was reassembled and is now referred to as XM50.1.

As for the XFEL pre-series cryomodule XM-3, all 8 couplers of XM50.1 were modified by inserting a modified iso-vac flange, shown in blue in Fig. 1, moving the warm part of the coupler 5 mm further away from the 70K window. The motorized coupler allows for an additional 5 mm displacement [4].

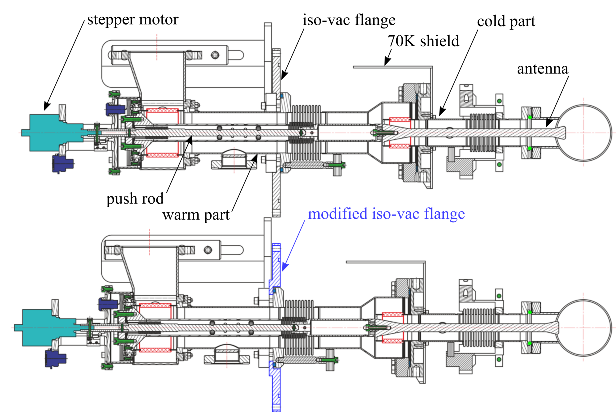

Figure 1: Unmodified XFEL power coupler (top) and with the modified iso-vac flange (bottom), shifting outwards the warm part of the coupler.

By stretching outwards the warm part of the coupler, this modified flange effectively pulls the coupling antenna further away from the cavity central axis, hence shifting the Q_L range towards higher values. The stretching of the bellows puts an upper bound on this modification.

PULSED TESTS AT AMTF

As for the series EuXFEL cryomodules, XM50.1 was first tested in pulsed mode at the Accelerating Module Test Facility (AMTF). This horizontal cryomodule test is essential: it validates the assembly work, proves the leak tightness in warm and cold conditions, checks higher order mode rejection, static and dynamic heat load and allows to assess the maximum operational gradient, either limited by power, break down or field emission. The performance of the reassembled cryomodule is reported in [5]. Further RF control tests are also performed to evaluate some of the metrics important for CW operation: frequency tuner sensitivity,

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external coupling range, piezo sensitivity, Lorentz force detuning coefficients and compensation and frequency of the sub-fundamental modes ($8\pi/9$ and $7\pi/9$).

Table 1: Frequency Tuner Sensitivity [-Hz/step]

C1	C2	C3	C4	C5	C6	C7	C8
0.45	0.47	0.48	0.48	0.45	0.47	0.46	0.48

Table 1 lists the tuning coefficients measured over a kHz range around resonance. The sensitivity matches perfectly the expected value for standard EuXFEL cryomodules. It also worth mentioning that very little backlash was observed (< 50 Hz), as illustrated in Fig. 2.

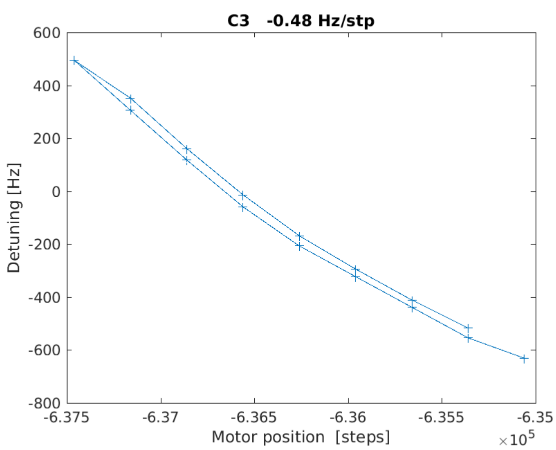

Figure 2: Frequency tuner scan for cavity 3 of XM50.1.

The Q_L range is measured by running the motorized couplers from negative to positive end-switch. At the first measurement, some couplers did not achieve the expected maximum Q_L. The negative end-switches were then carefully adjusted to extend the motor excursion. The results are summarized in Table 2. After end-switch adjustment, all couplers can reach $Q_L \geq 4 \times 10^7$.

Table 2: Coupler Tuning Range [$\times 10^6$]

	C1	C2	C3	C4	C5	C6	C7	C8
min	2.2	1.2	1.9	1.0	1.5	1.1	1.4	1.9
max	41	115	45	116	32	99	36	39
max*	64	104	60	93	46	74	58	51

The piezo-electric fast tuners are also checked for tuning range (1 kHz expected) and polarity (i.e. positive bias induces a positive detuning). The results for XM50.1 are summarized in Table 3, for both piezos at each cavity displayed as two rows. The total range corresponds to a ±65 V DC bias.

Also on the lower side for cavity 1, the measured piezo tuning range is within the acceptance threshold (1 kHz ± 100 Hz). After successful completion of the pulsed

Table 3: Piezos Total Tuning Range [Hz]

C1	C2	C3	C4	C5	C6	C7	C8
987	1055	1077	973	901	902	1046	977
905	1025	953	973	936	932	981	950

test, the module was warmed up and transported to the CryoModule Test Bench (CMTB) for CW operation.

PRELIMINARY TESTS

Investigation of IOT Start up Transients

The inductive output tube (IOT) at CMTB is the second prototype developed in collaboration with CPI for the 1.3 GHz CW tests at DESY. While the IOT has demonstrated 80 kW output power, it is presently limited to 35 kW maximum output power. This lower power is not a limitation since for the current high Q_L power tests, 2 kW per cavity suffice to reach the target CW gradient of 18 MV/m. However investigations are on-going to recover the IOT maximum output power. Another effect is being studied related to transients appearing on the amplitude and phase of the IOT output signal during ramp up. While these transients are not a problem for CW operation, they need to be understood (and possibly mitigated) for long pulse operation (i.e. pulses of 100 msec and longer with duty ratios up to 60%). Figure 3 illustrates this phenomenon showing the amplitude transients as a function of the RF duty cycle. A similar behavior is observable on the phase.

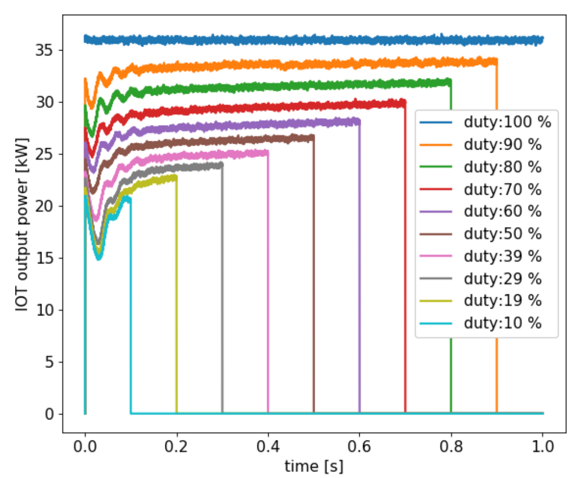

Figure 3: IOT amplitude transient as a function of duty cycle.

These effects are most likely related to a thermal effect at the cathode. Increasing the operation duty cycle minimizes the amplitude of transients oscillations. A discussion with the vendor is on-going to understand how to mitigate the issue.

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Demonstration of the IOT Linearizer Module

To linearize the IOT, a pre-distorter block was implemented inside the LLRF main controller firmware. After characterization, the IOT non linearity can be rectified in amplitude and phase. The results of IOT linearization are shown in Fig. 4. A linearity improvement factor of 100 in amplitude and 50 in phase is obtained. The benefits are a linear actuator chain, improving the system robustness and simplifying controls and setup.

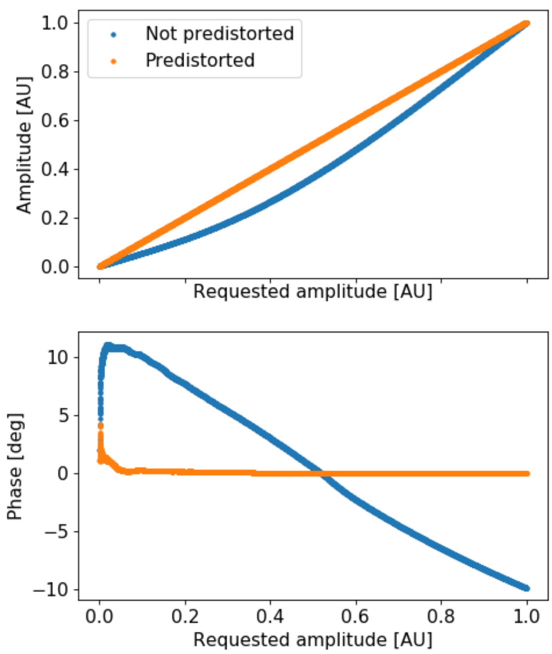

Figure 4: IOT amplitude (top) and phase (bottom) linearized using the pre-distortion module in the LLRF main controller firmware.

CW TESTS AT CMTB

The background microphonic spectrum at CMTB was measured using the piezo sensors mounted on all eight cavities of XM50.1 (see Fig. 5). The dominant frequency is 49 Hz, "well known" at CMTB, coming from vacuum pumps. Other harmonics of the 49 Hz are also visible. Around 200 Hz, the cavity fundamental mechanical mode is excited from the background noise.

Figure 6 illustrates the long term behavior of the background microphonics spectrum over 6 hours during day time for cavity 4 of XM50.1. The frequency content from cavity to cavity differs, even if some frequencies like the 49 Hz is visible on all spectra. This is a strong indication that any noise cancellation technique requires to be adjustable and customized to individual cavities. The need for automation and configuration scripts is evident for a CW XFEL.

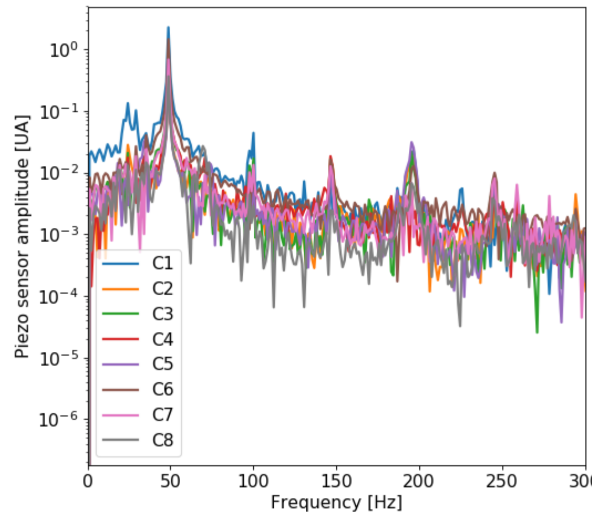

Figure 5: Background microphonics measured with piezos installed on all eight cavities of XM50.1, once installed at CTMB.

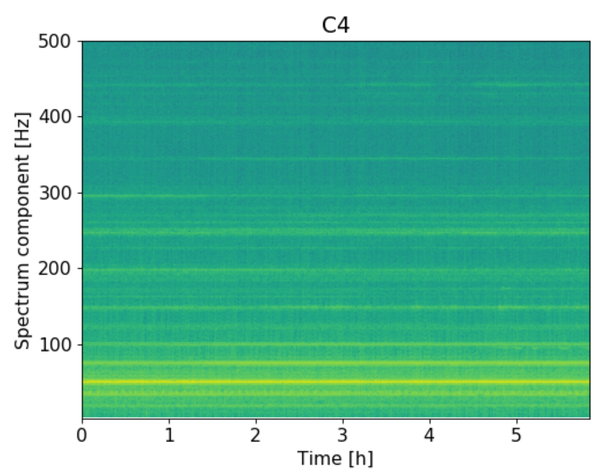

Figure 6: Long term measurement of the background microphonics spectrum of XM50.1 cavity 4.

For each cavity, a frequency sweep on one piezo was used to mechanically excite the cavity. The transfer functions of the piezo sensor identifying the main resonant modes are shown in Fig. 7. Commonly observed mechanical modes are consistently found for all cavities around 200, 280 and 390 Hz, in agreement with other published results [2, 6].

OUTLOOK

Technical problems at CMTB delayed the IOT operation on the module, so that RF related results could not be reported in this contribution. Fortunately, XM50.1 will stay at CMTB for several months allowing to continue the R&D effort towards a CW upgrade of the European XFEL. Developing new diagnostics for online Q_L and detuning measurement is of particular interest. Microphonics measurement and compensation is another very interesting topic. Oper-

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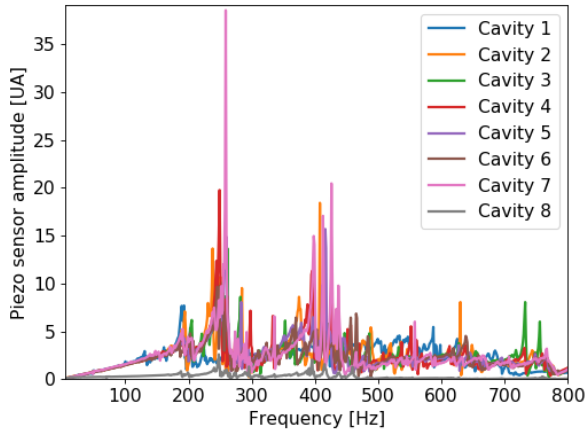

Figure 7: Main mechanical modes for all eight cavities of XM50.1, measured using a frequency sweep piezo excitation.

ating high Q_L ($\geq 4 \times 10^7$) cryomodules at relatively high gradient (> 16 MV/m) in vector sum is a challenge which requires advanced cavity resonance control. This R&D effort aims at demonstrating exactly this approach, which we see as a key milestone for the feasibility of the XFEL CW upgrade.

ACKNOWLEDGEMENTS

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