LLRF TESTS OF XFEL CRYOMODULES AT AMTF: FIRST EXPERIMENTAL RESULTS

J. Branlard*, V. Ayvazyan, M. Grecki, H. Schlarb, C. Schmidt, DESY, Hamburg, Germany
W. Cichalewski, K. Gnidzinska, A. Piotrowski, K. Przygoda, DMCS, Łódź, Poland
W. Jałmużna, EicSys, GMBH, Poland

Abstract

In preparation for the series production of cryomodules for the European X-ray Free Electron Laser (XFEL), three pre-series cryomodules and several prototypes are produced and tested at the Cryomodule Test Bench (CMTB) and at the Accelerating Module Test Facility (AMTF) in DESY. Among the numerous tests performed on the modules, the low-level radio frequency (LLRF) tests aim at characterizing the performance of the modules from an RF controls perspective. These integration tests must take into account cavity tuners, cavity motorized couplers, gradient quench limits, microphonics, piezo control and the overall gradient performance of the cryomodule under test. In this paper, the LLRF-specific tests are summarized and the first experimental results obtained at CMTB and AMTF are presented.

INTRODUCTION

DESY's Accelerating Module Test Facility (AMTF) hosts two vertical cryostats (VTS), three accelerator cryomodule test stands (XATB1, 2, and 3) and a waveguide assembly test facility (WATF). In the VTS, the gradient performance of individual cavities is measured before they are sent to CEA Saclay, France for cryomodule assembly. The complete cryomodule is then shipped back to DESY and installed in one of the cryomodule test stands for a complete check-up. After passing acceptance tests, the cryomodule is moved to the WATF where a customized power waveguide distribution system is mounted onto the module according to individual cavity performance. The modules are then either stored or installed into the XFEL tunnel, based on their performance, availability of storage space and installation schedule constraints. After mechanical inspection, cryogenic and RF connectivity, the following RF tests are performed:

- Cavity fundamental mode spectra measurements.
- Higher order modes (HOM) couplers spectra.
- Calibration of cold RF cables.
- Warm coupler conditioning.
- Coupler conditioning during cool-down.
- Loaded Q measurements and adjustment.
- Cavity gradient calibration.
- Cavity gradient performance measurement.
- Cryomodule dynamic heat-load measurement.

On top of these RF measurements, dedicated low level radio frequency (LLRF) tests are performed:

- Piezo capacitance measurement (before and during cooldown).
- Microphonics measurement.
- Piezo scans (cavity detuning transfer function).
- $8\pi/9$ and $7\pi/9$ mode identification
- Cavity tuner motor characterization.
- Cavity loaded Q motor characterization.
- Lorentz force detuning compensation.
- Closed-loop nominal gradient operation.

More details about the LLRF tests design is reported in [1]. This paper focuses on the first results obtained with the prototype and pre-series XFEL cryomodules, namely PXFEL3_1, XM-3 and XM-2.

LLRF CRYOMODULES TESTS

Piezo Capacitance Measurement

The piezo impedance is a reliable indicator for aging or for any potential damage occurring during cool-down and warm-up. The expected capacitance should range from $\simeq 12\ \mu$F when the piezo is warm to $\simeq 4\ \mu$F when it is cold. Monitoring of the piezo impedance is performed parasitically during the cryomodule cool-down and warm-up sequence using a measurement module placed in series with the LLRF piezo driver. Fig. 1 shows the resistance and capacitance of a piezo as a function of time during cool-down.

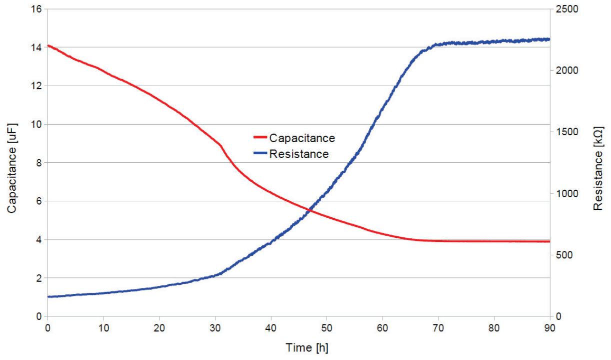

Figure 1: Piezo impendance during cryomodule cool-down.

Piezo Scans

The first goal of this test is to characterize in time and frequency domain the sensitivity of individual cavities to microphonics using piezo sensor data. A cavity *ringing*

---

* julien.branlard@desy.de

significantly more than the average would trigger an alert as potentially problematic. The second goal of this test is to identify the main mechanical modes of the cavity-tuner system. This can be done by exciting cavities with piezos using different frequencies to identify mechanical resonance modes. Fig. 2 (a) shows the typical piezo DC bias scan, and the resulting cavity detuning. With this test, the full piezo DC range is exercised and its maximum tuning range is derived. Fig. 2 (b) shows the FFT of a piezo sensor data, identifying the main mechanical resonance modes of the cavity-tuner system. Each cavity tuner is equipped with two piezos; their sensor or driver functionalities can be swapped. All piezo tests are then repeated for the default sensor and for the default actuator.

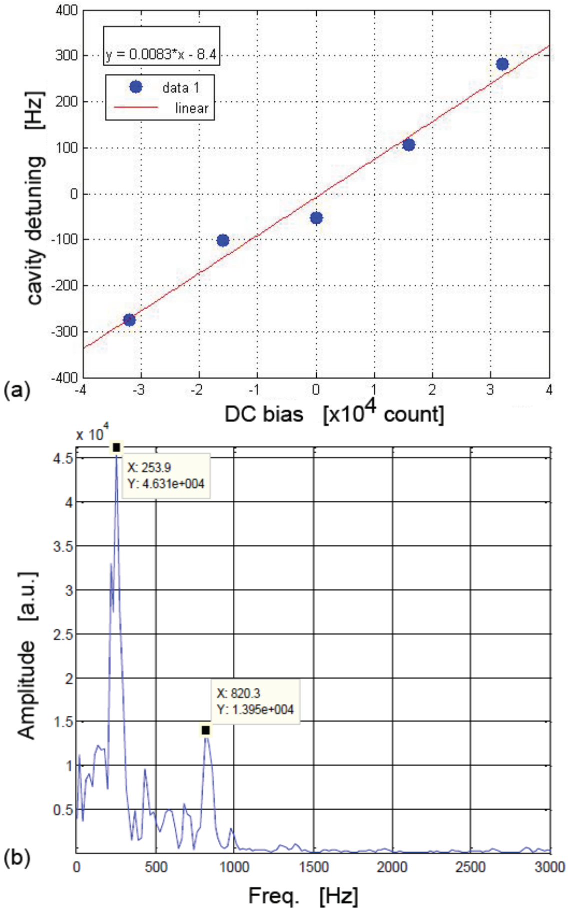

Figure 2: Full range (± 70V) piezo DC scan (a) and FFT of piezo sensor data (b) showing cavity mechanical resonance.

Cavity $8\pi/9$ and $7\pi/9$ Modes

The measurement of these two sub-fundamental accelerating modes for every cavity is essential to derive the filter coefficients used in the LLRF controller to notch out the $8\pi/9$ component for individual cavities and the $7\pi/9$ in their vector sum. The cavities are excited with a broadband small-signal disturbance, their probes are measured and Fourier-transformed to obtain the sub-fundamental frequencies and amplitudes. The probe data is sampled at 9.027 MHz resulting in a 4.5 MHz Nyquist zone which is wide enough to observe the $8\pi/9$ and the $7\pi/9$ modes. Figures 3 (a) and (b) show for a given cryomodule the 8 cavity frequency peaks observed for the $8\pi/9$ and $7\pi/9$ modes respectively. The outcome of this test are the notch filter center frequencies and bandwidths for all cavities.

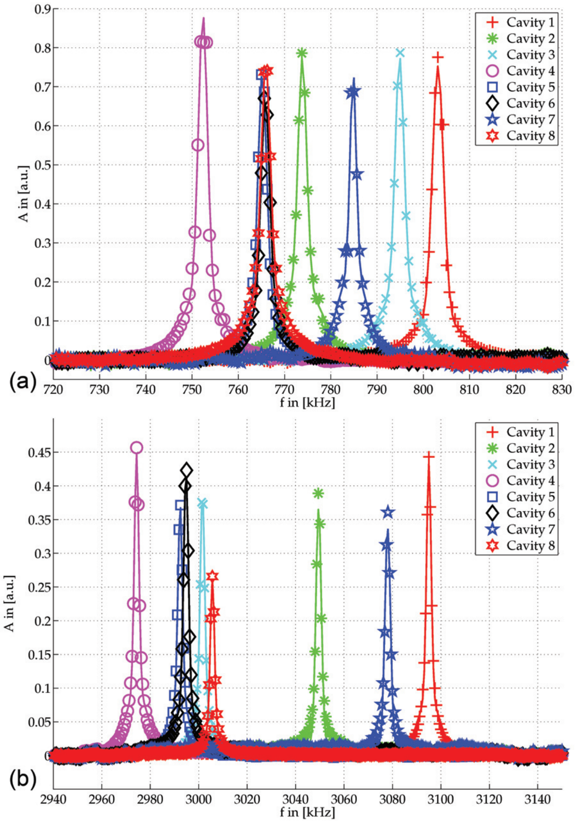

Figure 3: Sub-harmonic resonance peaks for eight cavities: (a) $8\pi/9$ and (b) $7\pi/9$.

Cavity Tuner Motor Characterization

In this test, the cavity tuner motor is exercised around cavity resonance. The scan sequence goes as follows: after initial checks (cavity on resonance, piezo tuning automation switched off, tuner motor is responsive, etc..), the motor is moved in one direction until the cavity is detuned by a specify amount (typically 1-2 kHz), then the motor direction is reversed until the cavity is detuned by the same amount in the other direction. The motor direction is reversed one more time and the cavity is brought back to resonance. Fig. 4 illustrates this scan, for a tuner showing a strong hysteresis profile. The cavity loaded Q or Q_L is also recorded during the scan to identify possible coupling between cavity detuning and Q_L, as described in [2]. The outcome of this test is the cavity tuning transfer function, along with parameters to quantify the hysteresis behavior.

Cavity Loaded Q Motor Characterization

In a similar way to the tuner motor scans, the motorized power input couplers are exercised to derive the cavity

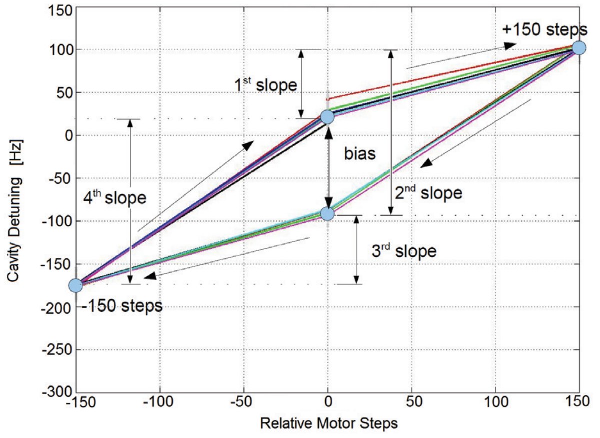

Figure 4: Scan of the cavity frequency tuner, showing cavity detuning as a function of motor position.

loaded quality factor transfer function (Fig. 5). The maximum and minimum Q_L values are also extracted from this scan. Adjusting Q_L proved to be an essential tool when trying to flatten cavity gradients loaded with beam current above 3mA [3], and is planned as a tuning parameter for XFEL high beam current operation.

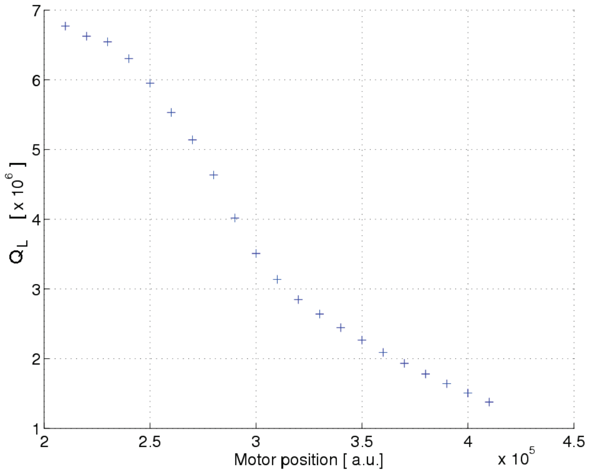

Figure 5: Scan of the cavity coupler tuner, showing cavity Q_L as a function of motor position.

Lorentz Force Detuning Compensation

Lorentz force detuning compensation is essential for high performance cavities. In the example of Fig. 6, the tested cavity is experiencing Lorentz force detuning greater than 700 Hz. By piezo compensation, its 800 μsec flat top gradient is maintained above 42 MV/m. During this test, the parameters used to compensate Lorentz force detuning are recorded (amplitude, frequency and delay of piezo stimulus) and a detuning constant specific to each cavity is calculated.

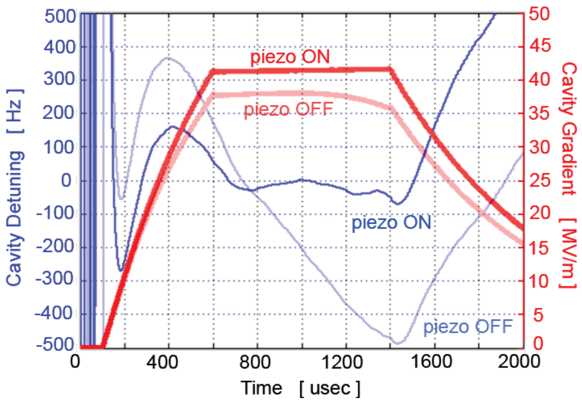

Figure 6: Piezo compensation of > 700 Hz Lorentz force detuning at 42 MV/m.

Closed-Loop Nominal Gradient Operation

The goal of this integral test is to set and maintain the cryomodule in nominal operating conditions, while monitoring its long term behavior. Forward, reflected and probe signals are recorded, the vector sum amplitude and phase regulation performance is measured and the dynamic heat load and X-ray radiation levels are logged.

CONCLUSIONS

To complete the assessment of the XFEL cryomodules, a series of tests are performed to identify and characterize the cavity and cryomodule parameters relevant for LLRF control of the module. The tests are described here and the first results with the XFEL pre-series modules are presented. Full automation of these tests requires complex exception handling. Currently, these tests are performed under the supervision of a LLRF expert along with a cryomodule operator. Test results are stored in a database, along with the corresponding cavity data. The outcome of these tests allow to derive LLRF parameters such as cavity 8π/9 mode filter coefficients, cavity tuner mechanical resonance modes, coupler and tuner motor characteristics.

Some of these tests need be repeated after tunnel installation: (1) to verify that the cryomodule sustained no damage during transport and installation into the tunnel and (2) to characterize the waveguide distribution system assembled after the AMTF tests. Indeed, one should expect such effects as coupling between adjacent cavities to change once the cryomodule is equipped with its customized power distribution waveguide system.

REFERENCES

[1] J. Branlard *et al.*, ”LLRF Testing of Superconducting Cryomodules for the E-XFEL”, IPAC12, New Orleans, USA.

[2] J. Branlard *et al.*, ”Superconducting Cavity Quench Detection and Prevention for the E-XFEL”, ICALEPCS 2013, San Francisco, USA.

[3] J. Branlard *et al.*, “LLRF Automation for the 9mA ILC Tests at FLASH”, Linac 2012, Tel Aviv, Israel.