# LLRF TESTING OF SUPERCONDUCTING CRYOMODULES FOR THE EUROPEAN XFEL

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*Abstract*

During the installation phase of the European XFEL (2014), an average of one superconducting cryomodule per week will be tested and validated before being installed into the XFEL tunnel. Extensive tests will be carried out in order to assess the RF performance of each cryomodule. A series of low level RF (LLRF) tests are planned as part of this validation phase, and will assess the cryomodule effective operating gradient, tuning range, compensation of Lorentz force detuning and microphonic behavior. These tests will be carried at DESY, in the Cryomodule Test Bench (CMTB) during the early stage of cryomodule production, and later at the Accelerating Module Test Facility (AMTF). Due to the pace and quantity of the modules to be tested, these tests have to be fully automated. This contribution presents the LLRF tests for the XFEL cryomodule validation, the challenges associated with automation, along with the first experimental results obtained on pre-series cryomodules tested at CMTB.

## AMTF

The Accelerating Module Test Facility (AMTF) construction is now in its final stage. The main hall hosts two vertical cryostats (VTS), three accelerator cryomodule test stands and a waveguide assembly test facility (WATF). In the VTS, the gradient performance of individual cavities is measured before they are sent to 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 the acceptance tests, the cryomodule is moved to the WATF where a costumed power waveguide distribution system is attached to the module according to individual cavity performance [1]. The modules are then either stored or installed into the XFEL tunnel, based on their performance, availability of storage space and installation schedule constraints. The AMTF hall floor plan is shown in Fig. 1.

## LLRF TESTS

The cryomodule performance assessment can be summarized as: ”at which gradient and with what regulation performance can one control this cryomodule?”. Many parameters come into play in this assessment and are of crucial importance for LLRF control. Each module will be tested for the following parameters: individual cavity quench voltage, range and characteristic of the cavity slow tuning motors, performance of the piezo actuators and sensors, sensitivity to microphonics, identification of other cavity $\pi$ modes, performance and characteristics of the cavity loaded Q motor, Lorentz force detuning compensation and finally, sustained nominal cryomodule operation. Some of these tests can be performed in parallel, simultaneously for all cavities; others have to be done sequentially. Due to the paired power distribution scheme used between of cavities [1], it is also planned to check the properties of paired cavities simultaneously (e.g. tracking any detuning observed on cavity 3 when moving the tuner motor of cavity 4). Acceptance criteria are defined for most of these tests but might be refined as more experience is gained with cryomodule testing. For all these tests, the basic functionality of motors, polarity of piezos, probe connections, etc... will already have been tested and is a prerequisite to the LLRF tests. The cryomodule is also expected to be at 2° K; cryogenic, personnel and technical interlocks are active.

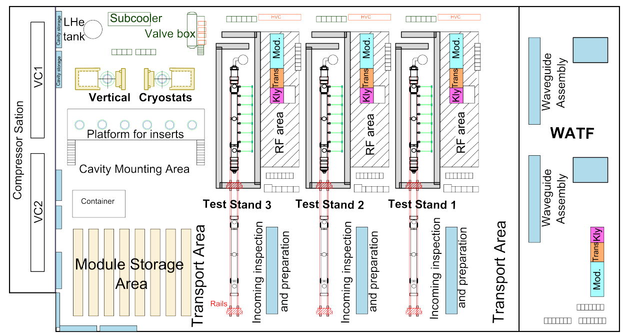


Figure 1: Floor plan of the AMTF hall.

### *Cavity Static Tuning*

The goal of this test is to fully characterize the cavity slow tuner. The procedure consists of operating the cavity at low gradient (5-8 MV/m) so as to stay away from Lorentz force detuning, and record the detuning while exercising individual cavity motors. In particular, one looks for backlash effects occuring when changing motor tuning direction, motor tuner non-linearities and a quantitative assessment of any observed hysteresis effect. The deliverable is a complete motor characterization for all cavities inside the cryomodule, which can be used later as a reference transfer function between cavity tuning and motor position.

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### *Piezo Characterization*

The goal of this test is to exercise the full range of operation of piezo and characterize the detuning response of all cavities. For this test, both piezos of every cavity are exercised sequentially as sensor and actuator. Initial diagnostics such as piezo sensors background noise and piezo capacitance are first measured. Then, operating cavities at low gradient (5-8 MV/m), individual piezos are scanned with their full DC bias range (+/-70 VDC) while recording the achieved detuning. The scan is then repeated using DC and AC stimuli on the piezo, scanning the full frequency range of the AC component. The piezo drive waveforms and corresponding detuning is archived.

### *Microphonics Studies*

This test and the previous one can be coupled. Cavities are assumed to be on resonance and operating with low RF power. The first goal is to characterize in time and frequency domain the sensitivity of individual cavities to microphonics using piezo sensor data. A cavity "ringing" 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 resonant modes.

### *Quench Threshold Identification*

This test assumes the availability of a quench detection server, triggered by a sudden drop in loaded Q, and turning RF off at the following RF pulse. For optimal cryomodule operations, several cavity gradient thresholds are typically used: quench gradient, near-quench gradient and safe-operation threshold. During normal operations, automatic servers take different actions should a cavity gradient exceed one of these thresholds. It is therefore crucial to measure precisely (i.e. with an accuracy of 0.1-0.2 MV/m) the gradient at which a cavity quenches, when operated at its full nominal flat top length of 800 $\mu$sec. In this test, each cavity is taken individually to its quench limit. The scheme consists of detuning all cavities but one using piezo DC bias, and close the feedback loop around the measured cavity, all others being excluded from the vector sum. Running in feedback mode allows to maintain flat top and compensate for Lorentz force detuning with RF power. A first ramp-up with 1 MV/m steps is performed until a quench is detected and the RF safely turned off. After a brief cryogenic recovery time, a second ramp-up is performed using smaller gradient increments (0.1 MV/m). The two measurements are correlated and archived, along with the forward, reflected and probe waveforms leading to the two quenches. Near-quench and safe-operation thresholds are calculated for every cavity as a function of their measured quench threshold. The proposed waveguide power distribution can also be cross-checked with this measurement.

### *Other $\pi$ Modes Identification*

Prior to string assembly, all cavities are fully scanned and the frequency of their nine $\pi$ modes is measured. This data is archived and tracks each cavity. It allows for spreading the 8$\pi$/9 modes of all 8 cavities to smear out their effect when picking the cavities for string assembly. The cryomodule measurement described here repeats these cavity modes identification, firstly to correlate measured results with reported data, secondly, to derive the filter coefficients used in the LLRF control system to notch out the 8$\pi$/9 frequency for all cavities and the 7$\pi$/9 for the vector sum. The approach for this test consists of driving with proportional feedback one cavity at a time, all others being excluded from the vector sum. The proportional gain is increased until instabilities are observed and the probe signal are then recorded and Fourier transformed. 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 and the 7$\pi$/9 modes.

### *Loaded Q Characterization*

All XFEL cavities are equipped with motorized coupler antennas, effectively changing the loaded Q ($Q_L$) of the cavities. It is foreseen to adjust $Q_L$ to flatten cavity gradients tilts induced by high beam loading, as demonstrated during the 9 mA International Linear Collider tests at FLASH [2]. For this purpose, a precise characterization of the cavity $Q_L$ is necessary. In this test, the coupler motor is exercised through its full range, triggering of end-switches is confirmed and the transfer function $Q_L$ versus motor position is measured. As time permits, this test would be repeated at different gradients. Special care is also taken to measure any hysteresis effects when reversing the motor position. The deliverable of this test is a complete $Q_L$ - motor position transfer function for each cavity, and a set of parameters used in the automatic $Q_L$ server, such as end switch motor positions and available $Q_L$ range.

### *Lorentz Force Detuning*

This simple test is used to measure the Lorentz force detuning constant for each cavity, and verify the ability to compensate for it using piezos. The module gradient is ramped up and the detuning of each cavity is measured as a function of gradient. Detuning constants are measured, any abnormal detuning behavior triggers an alert. The piezo compensation algorithm is then turned on and the detuning of individual cavity is tracked and logged. For a successful test, Lorentz force detuning is compensated to 1 Hz or less, pulse to pulse microphonics to 10 Hz or less.

### *Cryomodule Nominal Operation*

The purpose of this final test is to have the cryomodule undergo sustained nominal operations for several hours (8 hours minimum, as time permits). The cryomodule is then operated at 25 MV/m, with nominal pulse timing parameters (500 $\mu$sec fill, 800 $\mu$sec flat top), with nominal feedback gains and active Lorentz force detuning compensation. Due to the absence of beam, all cavity $Q_L$ are kept to their nominal $3 \times 10^6$. An important outcome of this test is to derive the optimal parameters for the MIMO RF field controller. Cryomodule amplitude and phase regulation performance are also measured and logged, along with the forward and reflected power waveforms to archive the cryomodule nominal power profile.

## SERVER ARCHITECTURE

To perform each of the tests described above, a set of applications organized as a high-level software framework is under development. These applications will be implemented as multiple middle-layer servers in the DOOCS control system [3]. These middle-layer servers call a set of external low-level servers which handle hardware device functionalities like coupler motor, high power RF management, piezo control etc..., essential for hardware components configuration and operation. One of the most important device server is the LLRF controller server, which sets operation parameters for RF field control.

In parallel, a data archiver is being developed to store measurement results and to gather cryomodule performance key parameters. The main archiver for AMTF test results is the DAQ system (currently used for on-line FLASH data storage) [4]. Intermediate reporting and data evaluation is handled by a diagnostic server currently under development.

The overall management of these LLRF tests is handled by a sequencer. This software coordinates the sets of measurements for each XFEL module and compiles results into an acceptance report. The sequencer is also responsible for exception handling. Defining the scope of exceptions and possible handling scenarios is currently in progress. This work requires in-depth knowledge of the system behavior and possible fault sources, which are documented and organized in a UML format. A finite state machine approach is likely to be used to program the required operation procedures and exception handling scenarios.

## FIRST RESULTS

Some of the procedures described earlier have been tested, either directly at FLASH, or at CMTB. Figure 2 shows a cavity tuner motor backlash measurement. From the cavity resonance position, the tuner motor is moved 150 steps in each direction and the resulting detuning is measured. Typical figure of interest from this measurement are the four detuning slopes and the backlash bias. Figure 3 shows a quench threshold identification sequence. The gradient is increased by 1 MV/m steps until a quench occurs. Note that in this particular example, the flat top start time is also delayed due to saturation of the DAC during the fill time.

## SUMMARY

An overview of the cryomodule characterization tests, relevant for LLRF operations has been described. Due to the tight scheduling of cryomodule production and validation before installation into the tunnel, these tests have to be automated. Although implementation details can not be given in such an overview, the concepts and procedures have been presented, including the software architecture describing the organization between the different tests servers. Preliminary results from testing the first cryomodule prototypes have also been presented. The experience from testing the first XFEL pre-series modules at AMTF scheduled before the end of 2012 will be very valuable to refine acceptance criteria and LLRF test procedures.

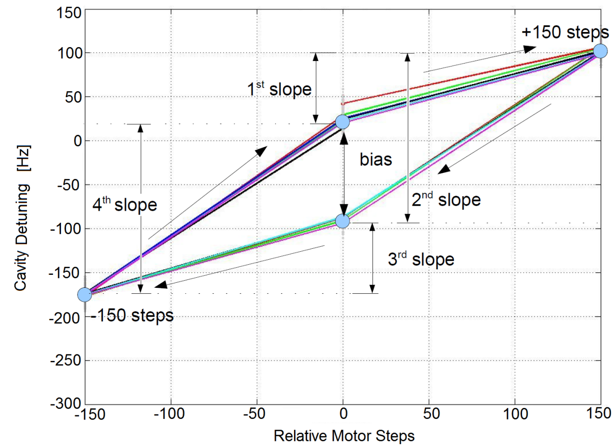


Figure 2: Backlash measured on frequency tuners.

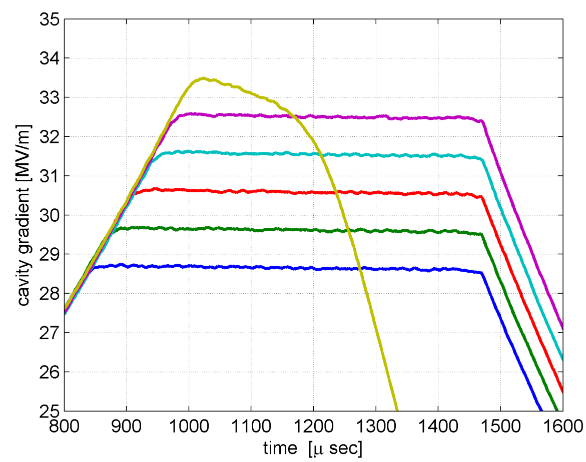


Figure 3: Quench threshold identification.

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