ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-WEPMN030

TESTING PROCEDURES FOR FAST FREQUENCY TUNERS OF XFEL CAVITIES

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Abstract

The XFEL accelerator will be equipped with 100 accelerating modules. Each accelerating module will host 8 superconducting cavities. Every single cavity will be equipped with a mechanical tuner. Coarse tuning will be supported by a step motor. A fine tuning will be handled by double piezoelectric elements installed inside a single mechanical support, providing actuator and sensor functionality or redundancy. Before the main linac installation, all its subcomponents need to be tested and verified. The AMTF (Accelerator Module Test Facility) has been built at DESY to test all XFEL cryomodules. In total 1600 piezos need to be tested. Test procedures for fast frequency tuners have been developed to check their basic performance in cryogenic conditions (tuning range, acting and sensing abilities). High level applications have been first developed and next adopted to perform fully automated tests including report generation and data base storage. After the successful completion of the acceptance tests, the cryomodules will be prepared for tunnel installation.

INTRODUCTION

The 36 accelerating modules equipped with 1.3 GHz superconducting (SC) resonant cavities have been delivered to DESY since February 2014. The 26 (including 3 pre-series) cryomodules have been tested using AMTF test stand. The AMTF test stand has been equipped with 3 independent RF stations supported by cryogenic subcomponents, RF waveguide distributions and RF sources. The each RF station has been installed with LLRF control system based on MTCA.4 technology [1].

The pre-series and a few of first regular series of XFEL modules have been fully tested with both piezo tuners installed per single cavity including: DC scans, LFD compensation and microphonics measurement. The rest of the tests of regular XFEL 1.3 GHz modules have been reduced mainly due to time limitation (e.g. to train operators, limited space at storage buffer, sharing resources with 3 GHz modules) and technical problems (broken couplers, RF source problems, cabling issues).

The piezo DC scans have been proposed for checking not only the typical tuning range foreseen for the Saclay II model of the piezo tuner but also locating piezo looseness (mechanical mistake during piezo assembly), shorts on the cables and inside connectors or mistakes in cabling pinout (reversed piezo polarity). The acceptance criterion for piezo tuning range has been agreed to not be less than 850 Hz of cavity absolute static detuning value.

Lorentz force detuning (LFD) compensation can play crucial role not only for regular operation at high RF gradient conditions (above 30 MV/m) but also to evaluate the quench limit conditions for each cavity per accelerating module [2]. The actuator functionality of supporting piezo elements applied for each cavity has been checked. The LFD factor has been measured for each cavity for both middle (between 10 and 15 MV/m) and high gradient (between 19 and 30 MV/m) operating conditions. The acceptance test threshold has been initially set to be below 10 Hz of static and dynamic detuning values and next relaxed due to time constraints foreseen for the tests (less than 50 Hz).

The sensor functionality of each piezo element has been evaluated to study the main sources of the mechanical vibrations that can additionally modulate resonance frequency of the cavity. The dominated frequency component for all tested cavities has been located at 50 Hz (see Fig. 1).

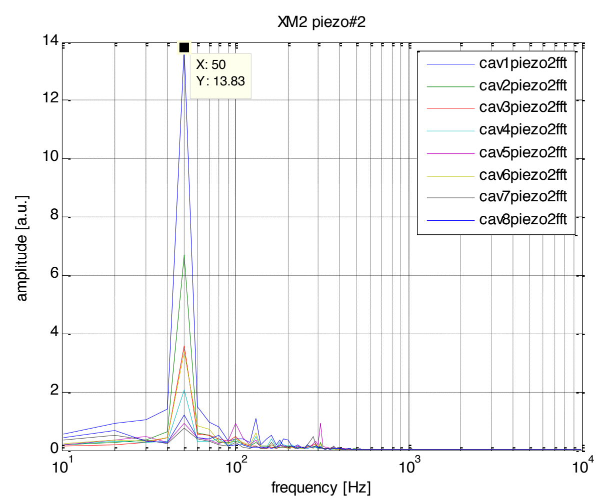

Figure 1: Microphonics measurement at XM-2 module.

Due to limited time the test procedure has been excluded from the regular tests.

LLRF CONTROL

The single RF station at AMTF has been installed together with LLRF control system designed according to MTCA.4 standard. The LLRF control system has been packed inside 9U, 12-slot crate equipped with cooling units, redundant power supply (PS), MTCA Carrier Hub (MCH), CPU and HDD, Advanced Mezzanine Card backplane (AMCB). In addition, the crate is equipped

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with three 10-channel RTM downcoverters (DWC), three 10-channel AMC based fast ADC digitizers, single AMC controller (TC) and RTM vector modulator (VM) boards setup, single AMC-RTM machine protection system (MPS) setup and timing module (TM) based on AMC standard. The AMC modules communicate over the backplane using low latency serial links (throughput up to 3 Gbps). The piezo tuners are driven and sensed using 19 inch 16-channel piezo driver (PZ16M) box connected to MTCA.4 system using fibre optics. The cavity voltage (P_{RB}), forward (P_{FWD}) and reflected (P_{REF}) power from 8 SC cavities (24 RF signals) are mixed to intermediate frequency (IF) of 54 MHz using analog downconversion scheme. The analog signals are digitized (with 81.25 MHz), filtered, demodulated to In-phase and Quadrature (IQ) components and finally converted to amplitude and phase (AP) information. The multiply input and multiply output (MIMO) and proportional RF feedback (RFB) and piezo controllers are implemented inside powerful Virtex 5 FPGA series from Xilinx. The RF source is driven with analog vector modulation scheme that closing RF feedback loop.

The piezo controller partially implemented on the supported CPU using Distributed Object Oriented Control System (DOOCS) is responsible for cavity detuning calculation (using cavity equation) and adaptive feedforward algorithm implementation. The LFD correction signal is calculated, sent to internal FPGA memory and finally applied to analog power amplifiers that drive piezo actuators. The piezo sensors data are stored inside external memory and sent back to CPU for monitoring purpose.

The LLRF controller is synchronized to RF field using 10 Hz repetition rate trigger (RF Trig) generated according to frequency derived from 1.3 GHz reference signal. The IQ components are sent between AMC boards over the backplane using 9 MHz strobe signal. The piezo controller synchronization signal (Pre Trig) is shifted in time by 20 ms in advance to RF field trigger.

Whenever accelerating module is in cool-down or warm-up condition, the interlock (INTL) signals are activated to open RF gates that prevent RF source driving using VM or piezos driving using PZ16M unit.

TESTING PROCEDURES FOR PIEZO TUNERS

Testing procedures for piezo tuners have been developed and tested using Matlab® environment. After successful maintenance with XFEL pre-series modules, all accepted tests have been ported to official DESY control system based on DOOCS servers.

Piezo DC Scans

The cavity can be course tuned with step motor based mechanical tuner with a range of hundreds of kHz. Nevertheless, this tuning is slow and cannot be applied with 10 Hz repetition rate of the RF field. When applying DC bias voltage to a piezo tuner, cavity tuning can be achieved much faster (in a milliseconds) but in a limited range (hundreds of Hz). The main idea of the piezo DC scan procedure is to identify and check if the measured piezo tuning range is acceptable (>800 Hz). The PZ16M box has been hardware protected to limit DC voltage range that can be applied to piezos to ±65 V. In addition each piezo element has been installed with voltage suppressor (max. ±100 V) and discharging resistor (charge stored inside piezo can significantly detune cavity during cabling). The main steps for the test are:

- Switch on RF (apply step to RF source),
- Set PZ16M to act on the first piezo element (remotely by switching relay),
- Apply small DC bias voltage to piezo element with user defined step,
- Measure cavity static detuning value (middle point of the flattop region) and average it over several RF pulses if needed,
- Check if DC bias voltage range didn't exceed user defined boundaries,
- Set PZ16M to act on the second piezo element and repeat the test procedure for it (measure all cavities),
- Switch off RF.

LFD Compensation

The cavity fine tuning is done using a fast piezo actuators than can react in milliseconds time advance to the RF field pulse duration (flattop region of the RF field pulse).

The LFD compensation has been implemented using adaptive feedforward control scheme [3]. The cavity detuning is calculated according to electromechanical model of the system using cavity voltage, forward and reflected power parameters. Than the user defined harmonic excitation is calculated and generated to drive the piezo element (see Fig. 2).

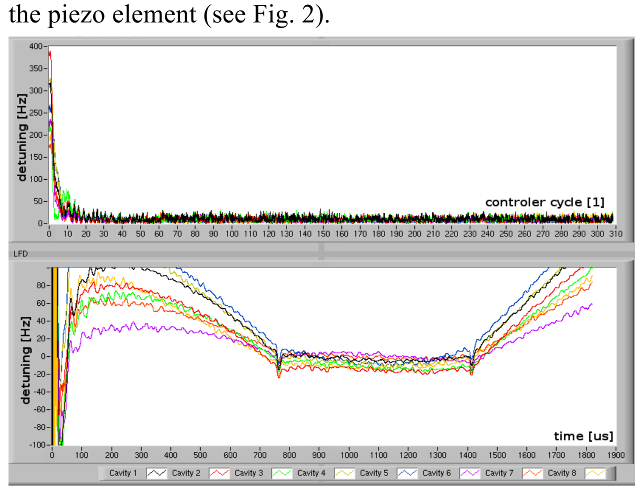

Figure 2: LFD compensation measured over 310 steps of adaptive feedforward algorithm.

As it was experimentally proved, the static and dynamic detuning parameters are coupled to DC and AC voltages applied to the piezo actuator. The crucial role plays also correct setup of the compensation pulse

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frequency and its time advance to the RF filed. The frequency parameter is mainly coupled to the mechanical resonance of the cavity environment and it can be directly identified using piezo sensor to RF measurements. The time advance to the RF field parameter can be calculated using a simple system identification procedure. The idea is to scan piezo pulse delay with a small AC positive and negative voltage applied and search for local minimum of the dynamic detuning function of the cavity. The main steps for the LFD compensation are:

- Switch on RF,
- Set PZT to act on the first piezo element,
- Relax cavity static detuning with step motor tuner,
- Measure piezo excitation frequency parameter,
- Perform piezo correction pulse delay parameter identification,
- Start AC and DC parameters adaptation algorithm,
- Measure cavity dynamic (difference between filling and decay detuning value) and static detuning parameters and average them over several RF pulses if needed,
- Check if mean square error (MSE) of dynamic detuning reached boundary, if not correct AC voltage value,
- Check if MSE of static detuning reached boundary, if not update piezo DC bias voltage,
- If both MSE criterions meet stop adaptation algorithm,
- Set PZ16M to act on the second piezo and repeat system identification procedures and AC and DC voltages adaptation algorithm (measure all cavities),
- Switch off RF.

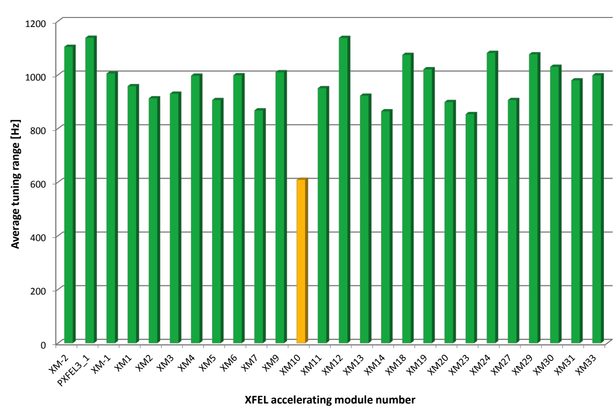

Figure 3: The cavity tuning range measurement of XFEL modules using piezo actuators.

RESULTS AND CONCLUSION

The demand capacity of AMTF test stand has been met during 14 months of operation experience (3 modules per 3 weeks including cool and warm up processes). During regular operation one module has been reported to be broken with power coupler (cavity 1 at XM27) and returned for repairing. Several modules have been discovered to have electrical shorts and wrong polarity with the piezo connections (e.g. several cavities at XM5 and XM9) which results in damage of chosen PZ16M box driving channels. Several modules have been reported to have vacuum problems which prevents its high gradient operation for certain cavities. The piezo tuning range and LFD factor (ratio between cavity detuning without and with piezo compensation) trends have been recorded for 26 XFEL modules (see Fig. 3 and Fig. 4).

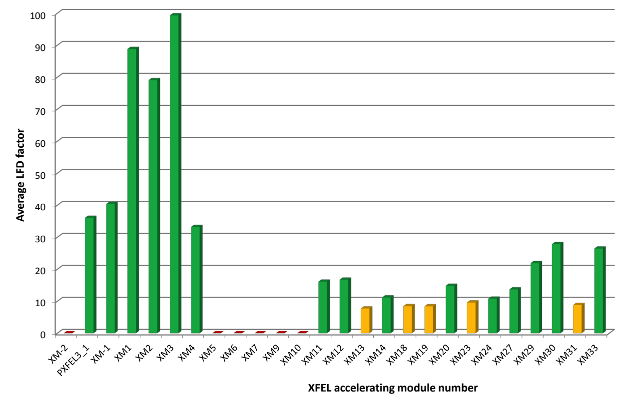

Figure 4: The LFD factor measurement of XFEL modules using piezo tuners.

The XM10 module has been noticed to have relatively small piezo DC scan range. Due to the fact, it has been decided to be assembled for low gradient operation stations at XFEL linac.

The LFD factor has the maximum value for the measurements done by LLRF experts with optimized piezo pulse parameters. Its decrease by factor of 2 has been observed when LFD compensation has been carried out by regular operators without enough optimization.

During 14 months of AMTF operation, the 52 piezo elements have been successfully tested with its main functionality. None of the piezo elements have been broken or reported to have mechanical looseness. The modules with piezo cables short or wrong polarity have been reworked before main tunnel installation. The modules which have been not fully tested are stored and will be measured in extra time or using spare Cryomodule Test Bench (CMTB) facility.

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