ISBN: 978-3-95450-191-5 doi:10.18429/JACoW-SRF2017-MOPB076

ANALYSIS OF THE PRODUCTION, INSTALLATION AND COMMISSIONING OF THE EUROPEAN-XFEL FREQUENCY TUNERS

R. Paparella†, A. Bosotti, D. Sertore, INFN/LASA Segrate (MI), Italy
C. Cloué, C. Madec, T. Trublet, CEA/IRFU, Gif-sur-Yvette, France
C. Albrecht, A. Bellandi, S. Barbanotti, J. Branlard, K. Jensch, L. Lilje, DESY, Hamburg, Germany

Abstract

In the European-XFEL superconducting linac, mechanical frequency tuners equipped with stepper motors and piezoelectric actuators provide cold tuning of each of the 768 1.3 GHz cavities. More than 820 complete tuning systems were fabricated and pre-assembled in industry, tested at several stages before and after assembly and successfully commissioned during cryo-module cold tests at AMTF (DESY). Quality control strategy adopted to preserve the well-assessed tuner reliability through such a large-scale industrial production is critically reviewed and the lessons learned are presented in this paper. The statistical analysis of the large set of data acquired up to the recent commissioning of the entire linac is then summarized.

THE E-XFEL TUNING SYSTEMS

Cold tuning systems for the main linac cavities at 1.3 GHz has a largely assessed design and has been extensively tested at DESY from TTF to the currently operating FLASH linac [1]. It features a double asymmetric leverage mechanics and its stretching action on the cavity is actuated by a stepper-motor driven unit working at cold. Two piezoelectric ceramic stacks are installed in a single preloading frame to counteract dynamic tune disturbances (Fig. 1).

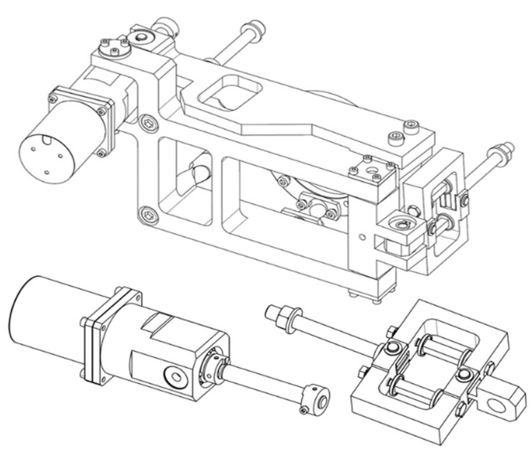

Figure 1: E-XFEL tuner with drive unit and piezo subsets.

QUALIFICATION OF VENDORS

Given the assessed design and performances, focus since the initial stage has been on the preservation of manufacturing and assembling quality going to industrialization phase. Key choices at this stage have been:

- Minimize the number of parts to be procured. The whole system has been divided into three subsets: mechanics (leverage, joints), drive unit (motor, gearbox, shaft and nut), piezo system (actuators, frame).
- Get the most out of industrial partner know-how. Both actuators (piezo and motors) were installed into their respective units by the manufacturer themselves, units were then delivered as "ready-to-use" at the cryomodule installation stage at CEA (France).
- Competition between vendors. Prototypes from any possible provider were tested at labs and at least two vendors were qualified by DESY for each subset.
- Introduce and additional quality control stage upon tuner assembly on string at CEA. This check should be performed by non-expert personnel.

All the several in-house developments through the years at DESY as well as at partner labs were gathered and transferred to interested companies in order to avoid a sole-supplier dependency scenario and evaluate different technical alternatives.

Qualification of Motor Drive Vendors

Support was provided to companies to apply the dry-lubricant coating recipe developed at DESY and to provide a cryogenic test of each produced unit.

Two technical options were evaluated for both stepper motor and gearbox components against the expected workload of 14 MSteps: Sanyo Denki and Phytron for the former, Harmonic Drive and Phytron planetary gear for the latter case.

Qualification of Piezo Vendors

Assembly and pre-loading of piezo stacks is the crucial stage of any piezo-actuated systems and for any cold tuning system before E-XFEL these operations have been usually "hand-crafted" by lab experts.

Several companies were, at the time, already qualified for the production of cryogenic proof multi-layer piezo stacks but the E-XFEL requirements set a further step. In order to benefit from a scenario where the piezo manufacturer itself integrates the actuators, the ability to assemble the whole mechanical fixture was then asked to companies.

Qualification of Mechanics Vendors

Drawings and tolerances of E-XFEL tuner mechanical components, initially supplied by CEA and adapted to a local supplier in France, underwent a significant simplifications and relaxation through the interaction with contacted large-scale, high precision machining companies.

† E-mail: rocco.paparella@mi.infn.it

ISBN: 978-3-95450-191-5 doi:10.18429/JACoW-SRF2017-MOPB076

While incoming acceptance control of most parts took place at CEA the one of piezo fixture components has been set as in charge directly to the piezo company.

SPECS AND REQUIREMENTS

The detailed list of requirements and specifications that has been finally conceived for the call-for-tender stage is reported in Table 1 and Table 2 for the two critical subsets, the drive unit and the piezo unit respectively.

Table 1: Drive Unit Requirements and Specifications

820 Motor Drive Units	
Lifetime	14 MSteps expected workload, 50 MSteps maximum 30 h maximum runtime
Load	200 N axial load on spindle 0.3 Nm maximum torque
Requests	Coating of parts, both dry-lubricant and hardening Mechanical assembly of the whole drive unit
Acceptance	Cryo-test at liquid Nitrogen temperature (77 K) on 100% of produced units
Packaging	ESA standard for dry-lubricated gears Hermetically sealed, double plastic bag with inert gas desiccant gel, humidity indicator
EDMS	Factory Acceptance Test (FAT) reports uploaded to EDMS [2]

Table 2: Piezo Unit Requirements and Specifications

824 piezo fixture units	
Handling	UHV and Cryo compatibility
Radiation	Radiation hardness proved up to an integral fluence higher than 10^{14} n/cm^2 (20 y of operation) [3]
Cabling	ETFE twisted cables Centre soldering on PZT stacks with cable stress relief Insulation by Kapton tape around each stack
Requests	Incoming QC on fixture mechanics Highest quality for machining and surface finishing of piezo support plates
Acceptance	"Burn-in" test on 100% of produced units Test done at room temperature (RT)
EDMS	Factory Acceptance Test (FAT) reports uploaded to EDMS [2]

PRODUCTION, TESTS AT FACTORIES

Once again with focus on the two most critical subsets of the tuning systems, the drive and the piezo units, the production stage is here briefly described.

Motor Drive Units

Contract has been awarded to Harmonic Drive, Limburg, Germany [4], providing a coated HD gearbox with 1:88 reduction ratio energized by Sanyo-Denki stepper motor installed in the completely functional unit.

Several feedbacks from the manufacturer have been implemented in the final process, including a revised motor bearing coating, 1 mm spindle pitch in place of the original 1.5 mm and the effort on minimizing exposure of units to air (humidity) by both using ESA compliant packaging and reducing vented module time window.

In addition to dimensional checks, a functional test of each assembled unit is performed at the company both at room temperature (RT) and at cold (CT) so that main parameters can be directly compared. The measurements performed in each test are:

- Motor temperature in operation. On average, motor temperature during cold test set to about 95 K.
- Motor windings impedance and inductivity
- Current threshold for insurgence of step-loss. Performed by lowering the coil current from the nominal 1 A while the 200 N spindle load is applied.

Globally, FAT results successfully returned the picture of a very homogeneous production batch. Scatter in electrical coil parameters values was for instance about 2% (standard deviation over average value) so well below the data-sheet references (10 % for impedance, 20 % for the inductivity).

Step-loss current threshold rises significantly on average in cryogenic operation (Fig. 2) and, for few units, gets close to the nominal operating current of 1 A.

This scenario thus exposes these motors to the risk of slipping in presence, for instance, of a low-performing driver or a longer than usual cabling.

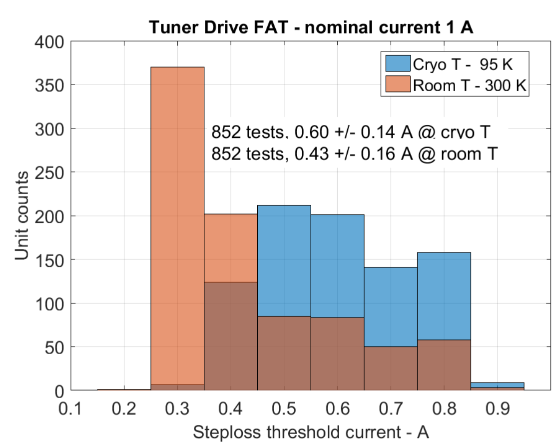

Figure 2: Step-loss current threshold FAT results.

ISBN: 978-3-95450-191-5 doi:10.18429/JACoW-SRF2017-MOPB076

Piezo System Units

Contract has been awarded to Physik Instrumente, Karlsruhe, Germany [5] providing its multi-layer actuator model P-888.90, 38 µm stroke / 3.8 kN blocking force nominal performances at the rated 120 V voltage.

Also in this case, feedbacks from the manufacturer were taken into account and led to a different stack support plates design (higher thickness and explicit surface quality required) and a better wires fixation.

In addition to the internal QC during the stack production, a Factory Acceptance Test has been required on the assembled piezo fixtures. Measurements are performed at room temperature since margins exist once at cold due to the specific features of PZT ceramic [6].

A fatigue routine has been settled and is applied to each piezo stack once assembled in the frame, it consists of:

- DC test. The full rated voltage of 120 V is driven statically for 2 hours.
- AC test. The stack is energized with a 1 kHz half-wave sinusoidal pulse with 100 Hz repetition rate until 1 million cycles are achieved.

The following physical parameters of each piezo stacks are measured after this "burn-in" test and compared to their pre-test values:

- Electrical capacitance
- Leakage current at nominal maximum voltage
- Stroke at nominal maximum voltage

Homogeneity of these parameters through the produced batch parameters resulted to be compatible with a typical data-sheet tolerance level of 20% (Table 3).

Table 3: Piezo Parameters, before vs. after Burn-in Test

1644 Tests, Stats for 95% CL				
Parameter	**Specs**	**Before**	**After**	**Delta**
Capacitance [µF]	13 ± 2.6	12.9 ± 1.5	13.0 ± 1.5	0.1 ± 1.2
Max. leakage current [µA]	8	2.6 ± 1.8	2.6 ± 2.0	0.01 ± 1.5
Max. stroke [µm]	38 ± 3.8	22.6 ± 3.6	22.9 ± 3.8	0.3 ± 4.0

As Table 3 shows, robustness of installed piezo stack performances is confirmed by both the adherence to nominal values and by the statistically negligible difference across the "burn-in" test ("Delta" is the statistics of unit-by-unit, before/after differences) (Table 3). Company reported then that 3 units out of the 1648 globally produced failed during the fatigue test and were replaced.

The specifications for maximum piezo stroke refer to an unloaded stack, the reduced value for the stroke of installed piezo is the effect of piezo frame stiffness (about 65 kN/mm, as induced from nominal piezo stiffness of 100 kN/mm).

QUALITY CONTROL STRATEGY

The several measurements and checks on subcomponents at the companies and at CEA are followed, once the tuner is assembled, by additional measurements on the system as a complete and functional unit. The goal being to cross-check that tuner main functionalities are preserved through the later stages.

Automatic Test Routine at Module Assembly

Along the cold-mass assembly procedure at CEA, after the cavity string completion in clean-room, tuners are installed. Three time windows for further tuner test have been identified along the module stages:

- Phase 1: on exposed cavity string, after first alignment. Factory cabling from both motor and piezo actuators are used.
- Phase 2: cold mass is assembled and still exposed. Final cabling configuration is used, without connectors.
- Phase 3: complete cryo-module, ready for shipment.

As additional constraints, the assembling personnel (not RF experts) should perform the measurement in a stage where the use of VNA was not foreseen. In addition, its impact should be minimized to preserve both the actuators integrity and the on-going alignment.

Finally, a test routine has been conceived and its electronic equipment realized capable to cross-check tuner actions indirectly and its focus being the identification of eventual loose mechanical assembly or cabling errors. While an LVDT displacement sensor is installed when possible (Phase 1) to verify cavity strain, piezo mechanical coupling and electrical polarity is passively controlled through reverse piezoelectric effect [7]. The following sequence of measurements is therefore automatically provided by the test control electronics:

- Motor is displaced in tuning direction (increasing frequency, stretching cavity) by 2 turns.
- Differential LVDT sensor stroke is measured on 2nd turn (the first turn is discarded to achieve a better homogeneity).
- Differential piezo charging, resulting from their compression, is also measured on the 2nd turn.

Although effective on dedicated test benches, the test routine results proved ultimately to be not reliable enough and heavily scattered to provide a physical characterization of performances of installed tuners. Nonetheless it properly served as a "wake-up call" check specially for Phase 1 and 2 at the ramping-up of module assembly, when exchanged cable polarity and bad pin soldering were often revealed.

Finally, each cavity tuner has been tested at least once with 2535 tests globally recorded and 5 cryomodules missing a test phase. Indeed, 166 out of 800 cavities triggered a critical alarm and required fixing and further testing, the vast majority (150) in the Phase 2 measure when the final cabling from each tuner to the vessel motor port was under test.

Constraints and problems prevented the measurement to be performed homogeneously for each module and only 385 cavities had a fully automated test routine at all 3 phases ("auto-mode", no manual measurements). The final control done at the ready-for-shipment cryomodules (Phase 3) scores the highest "auto-mode" rate (620 out of

ISBN: 978-3-95450-191-5 doi:10.18429/JACoW-SRF2017-MOPB076

800 cavities) and the best data consistency, allowing for instance exposing a slight inhomogeneity between position 1 tuner (gate-valve side, mirrored tuner) and the others in the string (Fig. 3) later confirmed by other QC stages.

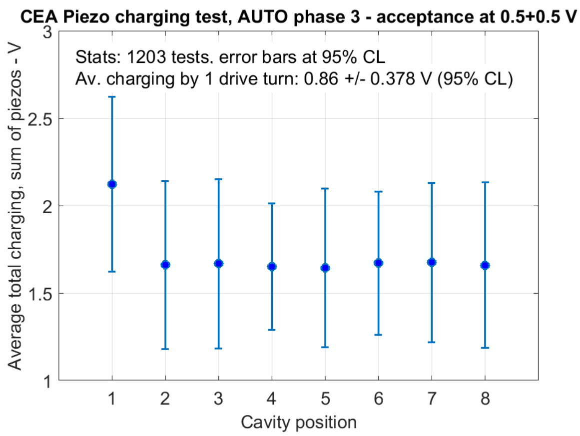

Figure 3: Piezo charging, "auto-mode" tests on Phase 3.

QC at Later Stages, Incoming Acceptance

Once the cryomodule is complete and delivered to DESY, two additional verifications of tuner functionalities are scheduled.

An Incoming Cryomodule Inspection is provided upon delivery at room temperature. Electrical capacitance of each actuator is measured via the flanged connector port of the module and cavity frequency shift in response to a single motor drive turn is measured. Results are compared to nominal values at first, or to values measured at previous stages if needed.

Globally, the average frequency shift for the batch of 791 cavity tests available as of today sets to 15.6 +/- 2.43 kHz/turn (95% CL); negatively affected in terms of scatter by the limited resolution of the room temperature cavity frequency measure.

Considering the nominal tuner parameters (35200 steps/turn, 1:25 leverage ratio) the former result translates to a tuning sensitivity of 0.44 +/- 0.07 Hz/step; already significantly higher than the value expected from E-XFEL TDR [1] of 0.36 Hz/step (tuning sensitivity at 315 kHz/mm).

QC at Later Stages, AMTF Cold Test

The final cross-check before installation in the tunnel take place at the Cryomodule cold-test at AMTF facility in DESY [8]. An exhaustive evaluation of cold tuner performances and parameters in view of linac operations is performed including the measurement of:

- Piezo electrical capacitance during cool-down, at 300 K, 70 K and 2 K temperature.
- "steps-to-tune", i.e. the amount of motor steps required to drive the cavity from cool-down position to operating frequency (at 2 K).
- Drive unit tuning sensitivity and hysteresis. Motor executes +/-1200 steps around working point at 2 K.
- Cavity frequency shift in response to a piezo DC scan from -65 V to +65 V at 2 K.
- The complete parameter set for the Lorentz Force detuning (LFD) compensation: static and dynamic coefficients, best compensating pulse shape, residual detuning (at 2 K).

Analysis of tuner sensitivity data across the 770 tuner tests available as of today possibly confirms the inhomogeneity of position 1 cavity tuner mechanical coupling to cavity (Fig. 4).

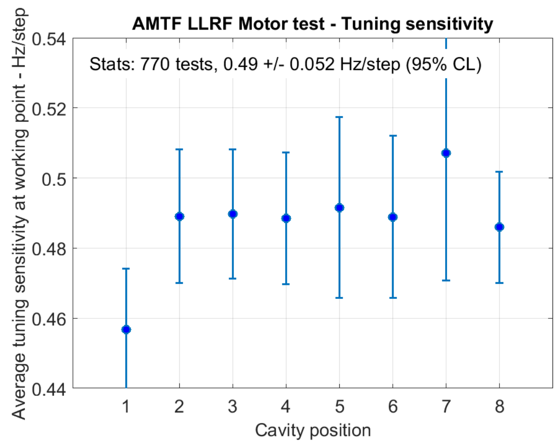

Figure 4: Drive unit tuning sensitivity, AMTF.

Worth pointing out that the global average cold tuning sensitivity value around nominal frequency is even higher than the Incoming Acceptance one (at RT), leading to an effective cavity longitudinal tuning coefficient as high as 430 kHz/mm. None of the units tested showed a critically low sensitivity, the lowest one recorded being 0.38 Hz/step.

For completeness, hysteresis around the nominal working point as measured in the AMTF motor cold tests resulted to be highly scattered and on average equal to 87 +/- 127 steps; well below the maximum acceptable value set at 300 steps.

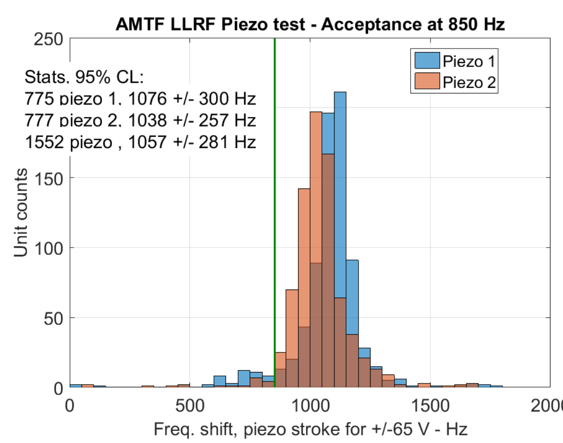

Figure 5: Piezo DC tuning range stats, AMTF test. Green line represents acceptance threshold.

DC fine tuning capability for the 1552 piezo units cold-tested at AMTF out of 1600 as of today confirmed to be granting the required range (850 Hz) with margins although a significant scatter in performances is observed (Fig. 5) together with an apparent offset between the two stacks in the fixture.

ISBN: 978-3-95450-191-5 doi:10.18429/JACoW-SRF2017-MOPB076

Only 6 piezo stacks, among those cold tested, exhibited a significantly low sensitivity (< 50 % of acceptance threshold). These are distributed among four cryomodules (XM10, XM14, XM17, XM25) but never in the same fixture.

KNOWN ISSUES

After all 800 cavities left CEA module assembly stage with functional tuning systems, issues have been identified later on upon AMTF cold test and, for a subset of cases, prevented tuners to be actuated. Each of the reported events (8 motors, 6 piezo) resulted to be related to the integrity of the vessel feed-through connectors: pressed cables, damaged plug, bad soldering, missing thermo-retractable tubes.

Initial information coming from the ongoing commissioning [9] are then starting to integrate the depicted scenario.

Table 4: Reported Missing Tuner Tests, AMTF

AMTF Missing Tests: 30/800 Drives, 48/1600 Piezo		
Unit	**Lack**	**Report entry**
XM1.C5	Drive	SW bug, no data
XM5.C1	P1&2	Short at flange connector
XM7.C1	All	Extremely detuned cavity
XM8.C1	All	Stuck tuner
XM11.C1	All	High field emission
XM20.C8	All	Damaged coupler
XM22	All	String vacuum leak
XM27.C1	P1&2	Cavity coupler leak
XM27	Drives	String vacuum leak
XM39	All	String vacuum leak
XM48.C2	P1	Piezo not responding
XM80.C1	P1	Bad soldering at flange
XM93.C1	All	Stuck tuner

Overall, 30 stepper motor based drive unit and 48 individual piezo stacks missed their cold characterization upon LLRF tests in AMTF. Most of these missing measurements is found to be a consequence of issues in other areas or in tuner-related components outside the modules (Table 4).

Ultimately, clues of a hard-failure of cold tuner hardware might be possibly stated, starting from AMTF results, for:

- XM8.C1 motor drive. Under investigation, module out of the tunnel.
- XM93.C1 motor drive. Possibly solved, feedback awaited from the module in the tunnel (off-line).
- XM5.C1 piezo 1 and 2. Later solved by re-soldering at vessel feed-through connectors flange.
- XM48.C2 piezo 1. Possibly solved, feedback awaited from the module in the tunnel (missing piezo driver).

Reversed Piezo Polarity

Inverted polarity in piezo stacks cabling, although not a highly critical issue, has been the most recurrent problem reported along cryomodules assembly and test.

Surprisingly, this issue has not been detected by any of previous QC stages, including the automatic test routine at module assembly whose sensing capability has been routinely cross-checked by reversing cables on purpose (with errors always detected). At all, 67 (out of 1600) stacks in 8 modules (XM9, XM10, XM13, XM14, XM67, XM68, XM99, XM100) showed reversed polarity at AMTF cold test with a set of distinctive features:

- Inspection at vessel flanges always revealed correct cabling (red on plus, black on minus).
- A regular pattern is found: either all (or almost all) piezo 1 or 2 with reverse polarity in the same module.
- Besides polarity reversion, a significantly lower stroke is observed for these stacks.
- Involved stacks where not coming from homogeneous production batches.

Missing any specific clue about the events behind these issues, cable were swapped and re-soldered at the vessel feed-through flange before transport to tunnel.

CONCLUSIONS

At the moment of writing, all the 89 1.3 GHz cryomodules operating in the European-XFEL (88 in the linac, 1 in the injector) shows fully functional static cold tuners, for a total of 712 motor-based drive unit. Eight more modules are in the tunnel (XM 24, XM 91, XM 93, XM 94, XM 95, XM 96, XM 97, XM 98), they are already cooled-down but without RF and not yet commissioned; lastly, five are currently off the tunnel (XM 8, XM 46, XM 50, XM 99, XM 100).

As reported by [9], a large fraction of the motor initial checks failed, being then identified as a motor driver related issue. The step-loss current threshold critically approaching at cold the nominal current (Figure 2) could have had an impact on this. Finally, piezo driver production has been heavily delayed therefore more time is needed for a feedback on the fast actuator status in the linac.

REFERENCES

[1] M. Altarelli *et al.*, "The European XFEL Technical Design Report", DESY, Rep. DESY-2006-097, July 2006.

[2] EDMS, *https://teamcenter.desy.de*

[3] M. Fouaidy *et al.*, "Radiation hardness tests of piezoelectric actuators with fast neutrons at liquid helium temperature", CARE-Note-07-004-SRF.

[4] Harmonic Drive, *https://harmonicdrive.de*

[5] PI, *https://www.physikinstrumente.com/en*

[6] R. Paparella, Ph. D. Thesis, "Università degli Studi di Milano", CARE-Thesis-08-001-1.

[7] A. Bosotti *et al.*, "A Fully Automated Device For Checking XFEL Piezo-Tuner Installation", *Proceedings of SRF2009*, Berlin, Germany, paper THPPO049, pp. 693-697.

[8] K. Przygoda *et. al*, "Testing Procedures for Fast Frequency Tuners of XFEL Cavities", *Proceedings of IPAC2015*, Richmond, VA, USA, paper WEPMN030, pp. 2991-2993.

[9] J. Branlard *et al.*, "Installation and First Commissioning of the LLRF System for the European XFEL", *Proceedings of IPAC2017*, Copenhagen, Denmark, paper THOAA3, pp. 3638-3641.