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OPERATIONAL EXPERIENCE OF THE EUROPEAN-XFEL 3.9 GHz COAXIAL TUNERS

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Abstract

The European-XFEL injector hosts a third-harmonic section composed by a module with eight 3.9 GHz cavities equipped with a coaxial frequency tuner inspired by INFN-LASA Blade Tuner design. The 3.9 GHz tuning system met specifications during all the injector runs in 2016 up to the recent commissioning of the entire linac; it matched the required tuning range and frequency sensitivity although higher than expected cavity detuning was experienced during pressure transients in the cryogenic system. An analysis of all collected experimental data is reported in this paper together with the strategy developed to provide a sound and effective retuning routine to the control room operator.

INTRODUCTION

The 3rd harmonic 3.9 GHz section at the European XFEL (E-XFEL) injector provides linearization of the longitudinal beam phase space after the first accelerating section. To compensate the effect of the space charge, a long bunch is generated in the RF gun. The subsequent RF acceleration in the first 1.3 GHz module produces cosine sinusoidal curvature in the longitudinal phase space of the incoming bunch. To remove this effect, a 3.9 GHz module is placed afterwards to linearize the longitudinal phase space and prepare the beam for the following compression and acceleration stages.

The E-XFEL third harmonic module is an 8-cavity module that provides a maximum voltage of 40 MV, corresponding to an accelerating field higher than 15 MV/m per cavity. All the cavities are operated close to 180° phase with respect to the incoming beam.

INFN Milano–LASA has provided, as in-kind contribution, the main components of the 3rd harmonic module now in operation in the E-XFEL tunnel [1].

The coaxial tuner used on the FNAL ACC39 module was scaled from the INFN blade tuner design originally proposed for the TESLA collider. Progresses at INFN on the blade tuner concept for ILC led to the development of a simpler, lighter and cheaper device (the "slim" tuner), that has been extensively characterized.

TUNER DESIGN

Assuming as a reference the slow-tuning mechanics geometry of the ILC Blade Tuner, a baseline 3.9 GHz cavity tuner model has been designed. The prototype design has been extensively characterized through different levels of simulation up to a 3D FE (Finite Element) model of the whole tuner; this allowed carefully estimating and understanding global kinematics and safety factors. Resulting layout is showed in Fig. 1, where the FE mesh (0.6 M elements, 0.16 M knots) is presented together with an example of longitudinal strain distribution along the tuner.

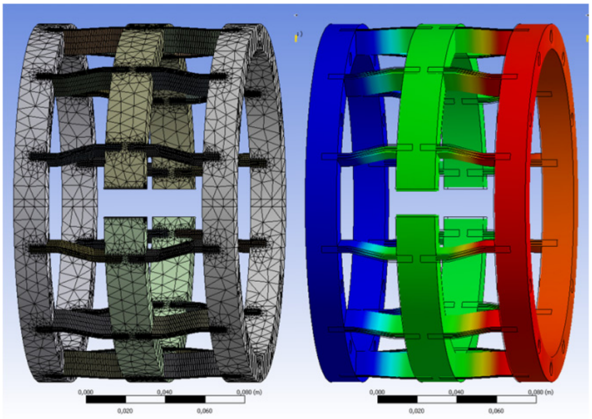

Figure 1: 3.9 GHz cavity tuner FE model developed for kinematics and stress analyses: mesh matrix (left), longitudinal strain distribution (right).

Full-body FE model results (“Full Tuner” case) were evaluated against selected reference cases:

- Case 1 - Single blade 3D FE “cartesian” model, were torsional effect is assumed to be negligible.
- Case 2 - Free single blade 3D FE model, including blade torsion.
- Analytical model - blade geometry is simplified down to a straight plate connecting the two rings.

An overview of analyses results is shown here below in Fig. 2 for what concerns the evaluation of tuner stroke and corresponding safety margin, defined as the ratio between the highest nodal stress in simulation over the material (titanium gr. 5) tensile yield.

The discrepancy in absolute strain visible between FE models and analytical case, about 0.3 mm, corresponds to the difference in length between the simplified blade used in the model compared to the actual shape at the maximum stretching.

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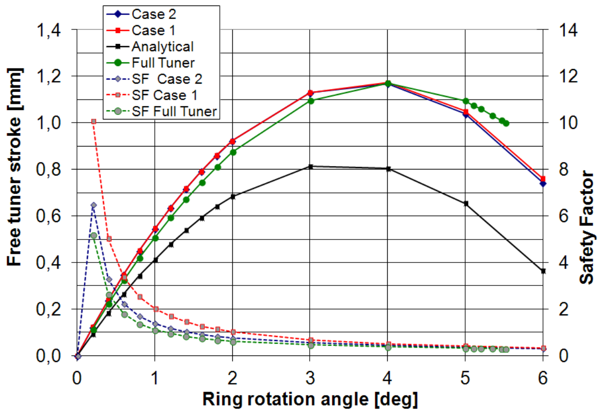

Figure 2: overview of results from the different FE analyses performed.

TUNING THIRD HARMONIC CAVITIES

XFEL third harmonic cavities are, to a first order, a scaled version of the main linac 1.3 GHz cavity. More specifically, technical challenges must be faced as the higher surface resistance (scaling with f^2), design of main and HOM couplers or the complexity of mechanical handling associated to the reduced geometrical dimensions (also scaled by 1/3).

Table 1: 3.9 GHz Tuner Specs and Reference Parameters

Parameter	Value	Comment
Longitudinal Cavity Stiffness	5.4 kN/mm	Measured on prototypes
Equivalent stiffness of cavity end cones	50 kN/mm	Estimated (FEM)
Cavity Tuning Sensitivity	2.3 MHz/mm	Measured on prototypes
Cavity strain for plastic deformation	0.7 mm	Estimated (FEM)
Maximum tuning kinematic range	0.8 mm	Measured
Maximum allowed tuning range	0.3 mm	PED Specifications
Max. tuning range	0.7 MHz	Derived
Tuner stiffness	> 100 kN/mm	Estimated
External stiffness	> 30 kN/mm	Estimated
Tuner to cavity strain efficiency	> 85 %	Estimated (FEM)
Tuning sensitivity	5 Hz/stp. 4.6 -5.2 Hz/stp	Goal/Design Measured
XFEL drive - motor	200 stp/turn	Stepper motor
XFEL drive - HD	1:88	Reduction ratio
XFEL drive unit	35200 stp/turn 70400 µstp/trn	Standard µstepping, 2x
Drive spindle pitch	1 mm	

For what directly concerns frequency cold tuning, due to the much stiffer mechanical behaviour of the 3.9 GHz structures and the moderate accelerating gradients needed for their operation (about 15 MV/m), no fast compensating tuning action is needed to handle dynamic Lorentz Force Detuning effects under pulsed operation. Therefore, differently from ILC tuner, fast piezo actuators are not part of the tuner design.

To maximize hardware and software homogeneity along the linac, tuners for the third harmonic section make use of the same stepper motor drive unit already developed jointly with manufacturer for the XFEL 1.3 GHz cavities.

Main reference parameters and constraints relevant to tuner design are summarized in Table 1.

TEST ON VERTICAL INSERT

Cavities 3HZ004 and 3HZ012 installed inside the He Tank and provided with frequency tuner have been successfully tested in vertical cryostat at LASA before being shipped to DESY to be installed inside their cryomodule (Fig. 3).

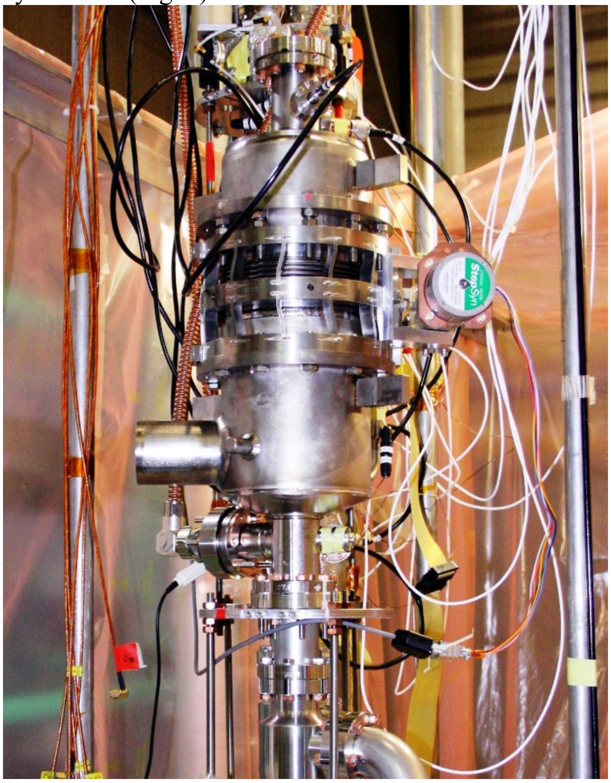

Figure 3: Dressed 3HZ004 upon vertical test.

The purpose of the cavity dressed test was to check possible performance worsening due to He Tank installation and/or mechanical interferences between the He Tank and the cavity that would prevent during cooldown the reaching of the nominal resonant frequency of 3.9 GHz (achieved with the tuner action). Both cavities repeated the performances obtained during the vertical tests of the naked cavities, i.e. $E_{acc} > 20$ MV/m and $Q_0 > 2 \cdot 10^9$. The tuners were installed in their neutral positions, i.e. the length of the cavity is not changed by the tuning installation procedure. The "free" cavity frequencies were f = 3899.666 MHz for 3HZ004 and 3899.434 MHz for 3HZ012 cavity. The about 6 MHz positive frequency shift gained by the cavity passing from 300 K to 2 K has been preserved and not altered by any interference with the He-Tank.

During both tests, tuner motors were connected to an external driver to measure tuner range and sensitivity. Both test were executed from neutral position (install position) to a maximum of six turns.

The frequency shift after six turns was about 1200 kHz for both cavities, corresponding to 0.5 mm of cavity longitudinal displacement. The initial tuning sensitivity sets to about 170 kHz/turn, corresponding to about 4.8 Hz/step assuming the reference motor driver configuration of 35200 steps/turn.

INJECTOR COMMISSIONING

European-XFEL injector commissioning started in December 2015, and all eight cavities of the third-harmonic module, named AH1, were successfully tuned from parking position after cool-down to the operating frequency. Once motor driver configurations have been debugged its parameters have been set to the final configuration of 70400 µsteps per turn, corresponding to an additional micro-stepping factor 2 compared to the 1.3 GHz cavity tuner drives. The maximum coil current limit is instead unchanged at 1 A.

The on-tune procedure took two steps, at first cavities were driven in close proximity of the 3.9 GHz frequency (within 2 kHz) with VNA control directly from the tunnel, then by means of LLRF Probe FFT panel [2] fine tuning is finally achieved. Table 2 resumes the former procedure and the tuning sensitivity measured upon tuning to resonance.

Table 2: VNA Controlled Tune to Resonance

Pos.	Cavity	Start freq. [MHZ]	µsteps to tune	Average Sensitivity [Hz/µstep]
1	3HZ010	3899.430	225400	2.51
2	3HZ005	3899.731	109500	2.46
3	3HZ012	3899.541	177000	2.60
4	3HZ013	3899.555	171500	2.60
5	3HZ008	3899.588	159000	2.59
6	3HZ007	3899.765	103500	2.27
7	3HZ004	3899.821	70400	2.54
8	3HZ011	3899.835	61000	2.70

Following successful injector commissioning, all AH1 cavity tuners were set back to parking position to allow for a safe warm-up of the section in summer 2016 prior to the connection of the whole linac string of the machine.

Before commencing warm-up operations, the long-range tuning capabilities at cold have been cross-checked for three selected AH1 cavity tuners. Measurements have been performed by means of a VNA equipment directly connected to the RF ports in the tunnel on cavities (C1, C7 and C8) with significantly different pre-load conditions.

Data available for cavities 3HZ004 and 3HZ010 in particular (Fig. 4) confirm the robustness of the tuning action in terms of coarse range and sensitivity, results from three different testing scenarios (VT at LASA, AMTF cryoadapter and AH1) indeed consistently overlap.

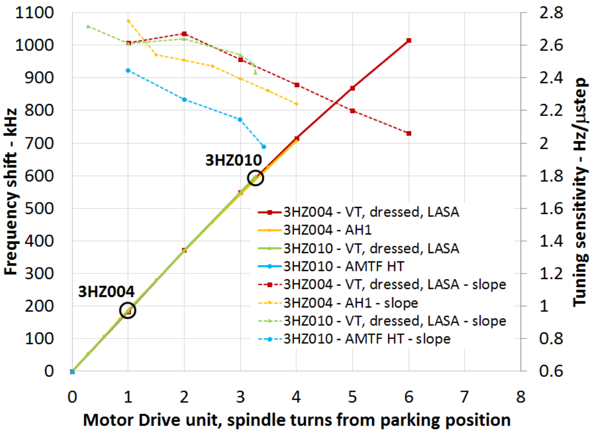

Figure 4: comparison of tuning range and sensitivity.

The working point along the tuner kinematic curve is highlighted in the plot for the two cavities, with 3HZ010 (C1) being the overall farthest one from its neutral point.

In January 2017 AH1 cavities have been successfully re-tuned back to operating frequency and are steadily operating since then.

CRYO TRANSIENTS AND DETUNING

Data for long third-harmonic cavity runs at cold became firstly available with the commissioning of the injector. Extended operations in the linac environment revealed what seemed a higher than expected sensitivity of the cavity small-range tune to the stability of resonator cryogenic scenario.

Detuning Events at The Injector

AH1 cavities tune at the bandwidth scale exhibited alternating sequences of periods with small and steady error interrupted by rapid detuning variations in both directions.

This introduced the need for a more frequent than expected re-tuning of cavities to cancel the detuning before that either LLRF limiters action or, ultimately, klystron saturation occurs (currently set to about 60 kW out of 80 kW nominal power).

Findings arose through the investigation of features and causes of such an issue are here summarized:

- The time corresponding to the beginning of cavity tune digression is often very well correlated to a variation of injector 2-phases helium line operating pressure from its set-point at 30.6 mbar.
- In most of the cases where 2 K line pressure saw instead no significant variation, either other cryogenic channels did (2 K return line at JT valve, temperature sensors) or actions/changes on the cryogenic plant were occurring (Fig. 5, lower plot).
- Cavities on the 1.3 GHz injector module A1 experience a similar and correlated detuning with a reduced impact that finally requires no corrective actions.

- In both A1 and AH1 modules a slope in the detuning amount of each cavity is appearing, larger at the end facing the feed-box and smaller at the end-cap. For instance, AH1.C8 experiences, on correlated events, about ten times higher detuning than A1.C1 (Fig. 5, upper plot).
- The former slope, moreover, almost perfectly overlap for the AH1 case with the mechanical preload of each tuning system that is proportional to the steps-to-tune required (Table 2). For instance, C7 and C8 have a smaller compressing load from the cavity spring-load effect and are more prone to an higher perturbations sensitivity compared to C1.
- The cavity pair C2-C6 is crucial since their mechanical pre-load is almost identical while C6 typically experiences much higher detuning. This consideration paves the way to a model in which the crucial role is played by the pressure/temperature gradient along the joint string of A1 and AH1.

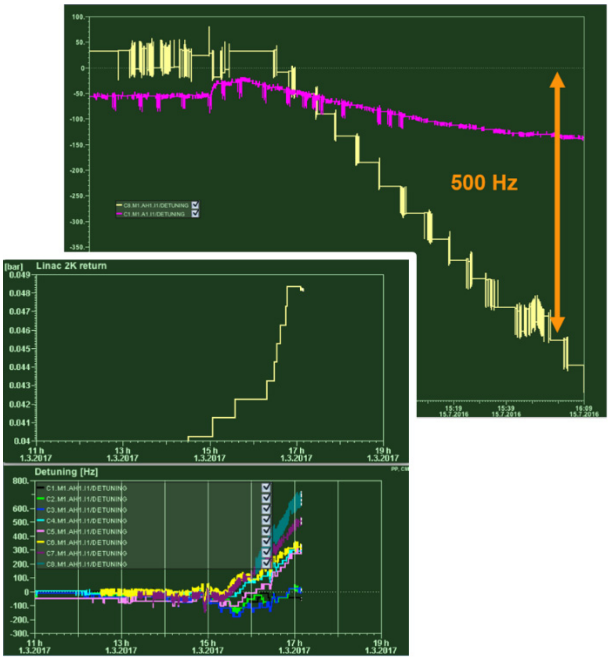

Figure 5: Upper plot: correlated detuning at A1.C1 (above) and AH1.C8 (below). Lower plot: JT 2K return line pressure (above) rise causing AH1 detuning (below).

Qualitatively, the impact of this detuning issue was significantly reduced by switching from the cryo-plant configuration used during injector commissioning (with cold compressor used far from its nominal set-point) to the final linac operation.

Pressure Sensitivity Studies

Although a deeper understanding of the actual cavity pressure conditions in AH1 is still required, a further study of the third-harmonic resonators pressure sensitivity has been triggered by these findings.

Firstly, Table 3 resumes all experimental evidences collected for the cavities in AH1. Results from naked and dressed cavity vertical tests (VT) at LASA (frequency shift upon sub-cooling from 2.0 K to 1.8 K) can be then compared to the values acquired in AH1 during a typical pressure instability occurrence leading to cavity detuning. Specifically, the selected 26.7.2017 event corresponds to a steady pressure rise of about 9 mbar within 5 minutes, C6 and C7 are missing since they were already out of the range of the detuning computation routine.

Table 3: Pressure Sensitivity Measurements, [Hz/mbar]

Pos.	Cavity	VT naked	VT dressed	AH1 event on 26.7.2016
1	3HZ010	-26.3		58
2	3HZ005	-49.7		55
3	3HZ012	-20.1	-7.2	54
4	3HZ013	-1.5		54
5	3HZ008	-21.5		59
6	3HZ007	-50.2		
7	3HZ004	-12.2	-7.5	
8	3HZ011	-21.8		57

Naked cavities during vertical tests, although substantially free, were indeed connected to titanium frame (holding second sound detectors) whose actual stiffness is uncertain and that might have contributed to the observed scatter in values. The pressure sensitivity range observed in AH1 is indeed confirmed

Pressure sensitivity in a cryomodule environment was expected to be, at a first order, about 1.8 times the one of the 1.3 GHz cavity that is indeed in the range of 20-30 Hz/mbar. This result, aligned with AH1 values (Table 3), is achieved by simply comparing the end-cone area, the stiffness and the tuning sensitivity of the two cavities.

Additionally, a FE model of the third-harmonic resonator has been used to simulate expected sensitivity to the variation of pressure in the helium tank as a function of the external cavity stiffness. This latter expresses the rigidity of resonator mechanical constraint, modelled as the mechanical series of cavity end cones and tuner. For the 3.9 GHz cavity it can be estimated from values in Table 1 to be about 35 kN/mm, with a limited excursion of +/- 2 kN/mm along the tuning range (related to actual blade angle).

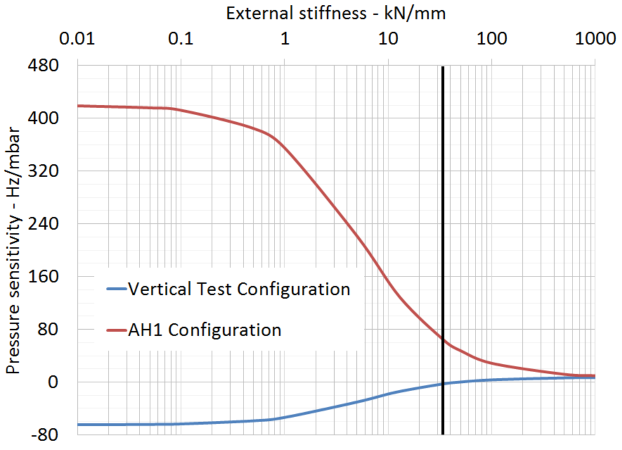

Figure 6: Simulated pressure sensitivity.

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Figure 6 shows model results for both the vertical test and the AH1 horizontal test scenarios. In the free cavity regime (left end), largest contribution to sensitivity comes by the compressing action on beam pipe flanges (VT case) and by the stretching action on tuner bellow (AH1 case).

The estimated external stiffness for the dressed cavity (35 kN/mm) intercepts the two curves at about -3 Hz/mbar (VT) and 62 Hz/mbar (AH1), thus in reasonable agreement with experimental findings (Table 3). During VT at LASA tuner were at their lowest (in frequency) and neutral point with any preload, thus small-range stiffness might have been lower than nominal.

SMALL RANGE TUNING STUDIES

In parallel to the investigation of reported detuning events, a deeper characterization of the small-range action of the AH1 tuners has been performed. The purpose being mainly to maximize the effectiveness of cavity re-tuning process made by the control room operator through a better understanding of motor drive unit sensitivity and residual hysteresis at the scale of the usual corrective action (< 300 µsteps).

Two main issues are affecting the functionality of any stepper-motor actuated drive unit in general, as indeed for the E-XFEL drive unit in use at AH1 (that is the same of the 800 1.3 GHz cavities):

- Step-loss at motor start, ultimately related to excessive friction and torque required compared to the actual current settings. Step-loss coil current threshold rises significantly in cryogenic operations [3].
- Backlash upon motion reversal, generated by both the motors itself and the reduction gearbox installed.

AH1 tuners motors were moved in loop within a range +/- 300 µsteps from tuned position, the stroke of each single movement command has then been varied (20, 50, 100, 150, 300 µsteps) and the number of motor start-ups changed accordingly for the same loop range. Resulting curves are shown in Fig. 7.

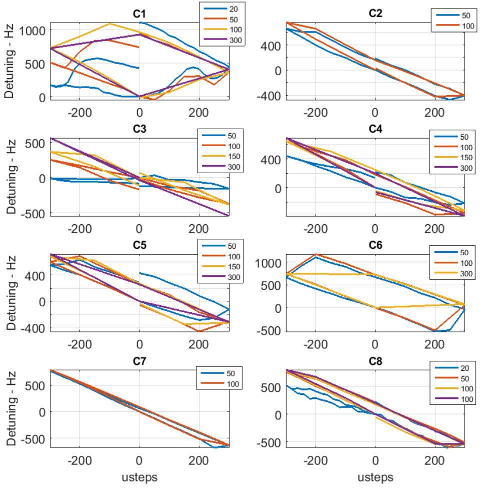

Figure 7: Small range loops curves.

A negligible offset between start and stop frequency ("closed" loop) proves a similarly negligible amount of step-loss, confirmed moreover by the loop slope approaching the nominal tuning sensitivity. The projection on the "steps" axis of the "closed" loop area measures instead the impact of backlash at each direction reversal.

A summary of collected data is shown in Table 4, unfortunately any clear correlation with, for instance, the mechanical preload (i.e. the "steps-to-tune") emerges.

Table 4: Small-range Measurements Results

Pos.	**Cavity**	**Backlash [µsteps]**	**"Closed" loop thr. [#µsteps]**	**Steps-to-tune [µsteps]**
1	3HZ010	530	100	225400
2	3HZ005	85	50	109500
3	3HZ012	-20	300	177000
4	3HZ013	100	150	171500
5	3HZ008	130	150	159000
6	3HZ007	300	50	103500
7	3HZ004	40	50	70400
8	3HZ011	80	50	61000

It can then be inferred that, given the motor driver configuration in use at the moment of testing (July 2016), commanding a single motor action with less than 50 µsteps has to be avoided: this would result in a significant and cavity-varying loss step fraction and ultimately lead to an unpredicted small-range sensitivity.

The amount of backlash effect is also comparable to the tuning range considered, this suggests that the information about the direction of motion of the last performed movement should be available for the control room operator to be aware of the effects of a motion reversal.

Measured parameters could be assessed into a devoted tuning routine capable to automatically accounting for both step-loss and backlash.

CONCLUSIONS

The coaxial tuners for the 3.9 GHz cavity of E-XFEL AH1 injector module met specifications and properly fitted design model expectations. A detailed characterization of their performances and limitations is underway and an optimized control room operator user interface is under development.

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