COAXIAL BLADE TUNER FOR EUROPEAN XFEL 3.9 GHz CAVITIES

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Abstract

The European XFEL linac injector features a third harmonic section jointly realized by INFN and DESY in order to generate the high quality electron beam required for the short wavelength FEL operation. It hosts a 3.9 GHz 9-cell cavities cryomodule for the linearization of the beam phase space before the longitudinal bunch compression performed to increase the peak current for lasing. The cold tuning system for these cavities has been developed by INFN and it is inspired by the coaxial Blade Tuner already qualified for ILC cavities [1]. Design, fabrication and room temperature qualification of first tuner units produced are reviewed in this paper.

THE BLADE TUNER

Blade tuner is installed coaxially on the cavity helium tank and allows tuning the resonator frequency by varying its length. The tank is therefore split in two halves that are mechanically joined to the tuner ends; a bellow encloses the helium volume and allows the longitudinal strain.

The working principle of the Blade Tuner is based on the bending of titanium blades that deform from the rest position to a different configuration producing an elongation of the tuner itself. This deformation is generated by the rotation of the central rings with respect to the lateral ones. In order to reduce the relative rotation of the lateral rings to nearly zero, and to balance the torsional moments, the central rings rotate in opposite directions and the blades are assembled symmetrically with respect to the horizontal plane.

A schematic representation of the tuner kinematics is provided in Fig. 1, alongside with the Blade Tuner reference model designed for the ILC.

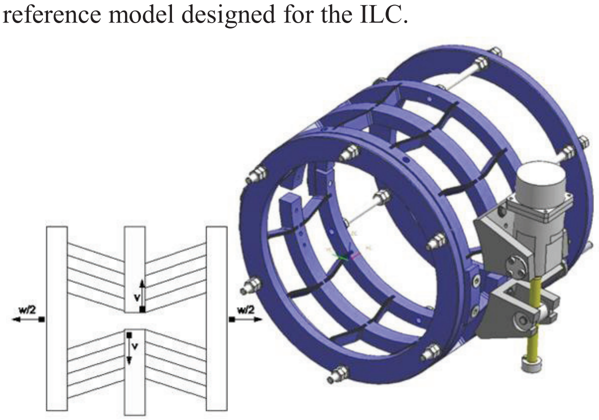

Figure 1: ILC Blade Tuner and its kinematics principle.

The rotation of the central rings is obtained by displacing in opposite directions the two edges on one side by means of a stepper motor drive unit. This electromechanical actuator will operate at cold, as for others XFEL cavities, and it's realized by a CuBe threaded spindle driven by a stepper motor through a mechanical reduction gearbox.

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) [2].

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.

Finally, main reference parameters and constraints relevant to tuner design are summarized in Table 1.

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
Tuning limit before cavity deformation	0.7 mm	Estimated (FEM)
Max. tuning range	1.5 Mhz	Derived/Estimated
Tuner to cavity strain efficiency	80 %	Estimated (FEM)
Tuning sensitivity	~ 5 Hz/stp.	Estimated (1.3 GHz)
XFEL drive unit accuracy	35.2 kstp/turn	By specifications
Motor spindle pitch	1 mm	By specifications
Ti Elastic module	$1.05\ 10^{11}$ Pa	
Ti Poisson module	0.37	
Ti tensile yield	$8.3\ 10^{8}$ Pa	

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

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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. 2, 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.

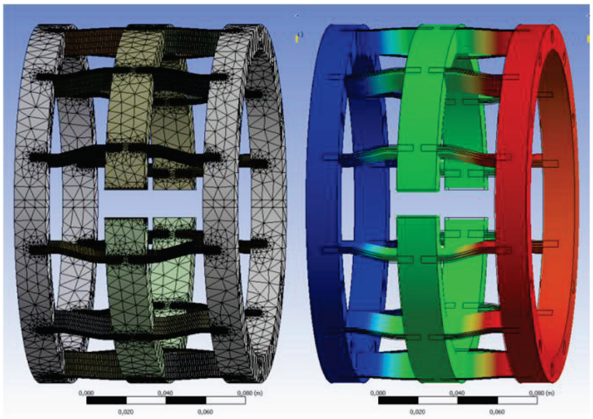

Figure 2: 3.9 GHz cavity tuner FE model developed for kinematics and stress analyses: mesh matrix (left), longitudinal strain distribution (right).

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. 3 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.

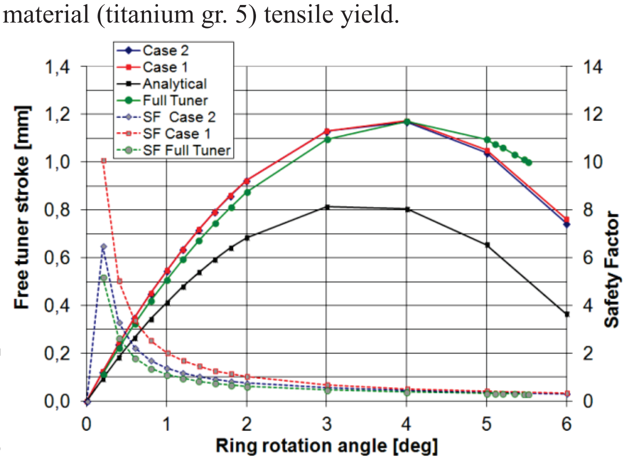

Figure 3: overview of results from the different FE analyses performed.

The discrepancy in absolute strain visible between FE and analytical models, about 0.3 mm, corresponds to the difference in length for the stretched blade in the two cases (straight connection vs. real shape).

PROTOTYPES

According to the baseline tuner design developed, three prototypes were manufactured and delivered by January 2013 (Fig. 4).

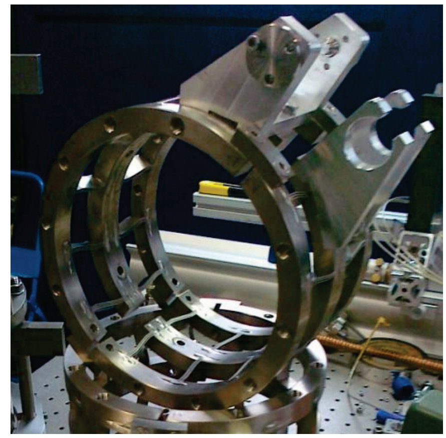

Figure 4: The 3.9 GHz cavity Blade Tuner.

Acceptance tests at room temperature (RT) then provided a first direct verification of expected stroke and stiffness. Measurements have been performed on a dedicated test bench featuring a stiff steel frame clamping a helium tank prototype on which tuner was installed.

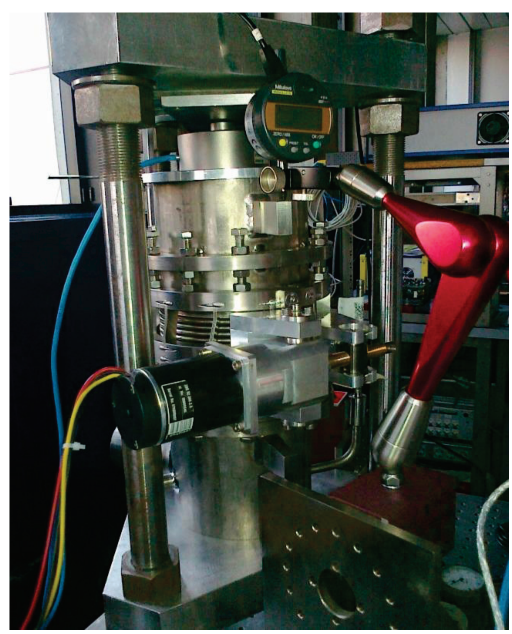

Figure 5: setup for room temperature acceptance test.

A load cell and three micrometer gauges completed the test device and allowed measuring longitudinal compressive force and strain and therefore tuning the frame stiffness in order to reproduce the mechanical constrain of the cavity. The entire setup during measurements is shown in Fig. 5, a RT stepper motor unit replicates the action of the XFEL one.

Finally, the equivalent external stiffness of the clamping frame resulted to slightly exceed the cavity nominal one, thus giving a "worst case" analysis. Firstly, collected data permitted a direct comparison of actual tuner stroke with performed simulations, as shown in Fig. 6 where longitudinal strain is plotted against motor spindle turns of the actual XFEL drive unit for the three prototypes tested (BT3H01 to 03).

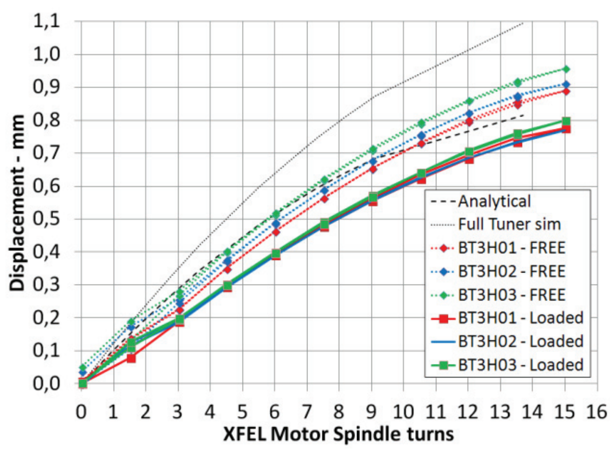

Figure 6: overview of room temperature tests on prototypes compared to simulations.

Unloaded (Free) curves have been obtained by operating the tuner in an open frame and can be directly compared to simulated and analytical data. This analysis reveals that the actual strain of the tuner, generated by the simultaneous deformation of 72 blades, averages down to finally resemble more the simple straight plate model than the full tuner simulated kinematics.

Tuner stiffness can then be derived as the load over the difference in strain between free and loaded case.

Finally, making use of the parameters shown in Table 1 through a simple spring model of the system [3] also the expected tuning range can be evaluated.

Table 2: Overview of Acceptance Test Results

Parameter	Design value	Measured value (* computed)
Tuner stroke	0.85 mm	0.78 mm @ 15 turns
Tuner-to-cavity efficiency	80 %	76 % @ 8 turns *
Tuner longitudinal stiffness	50 kN/mm	34 kN/mm @ 15 turns
Maximum load	4 kN	4.9 kN
Tuning range	1500 kHz	1450 kHz @ 15 turns *
Tuning resolution	~ 5 Hz/stp.	3 Hz/stp. @ 8 turns *
Steps to on-tune		230 kstp. *
External stiffness during test	5-6 kN/mm	6.2-6.6 kN/mm

An overview of all average acceptance test results is given in Table 2 on the assumption that the cavity on-tune frequency is achieved in the nominal working point of the tuner that is the middle of the tuning range.

Generally, the three units under test proved to perform homogenously, especially under cavity load and a good agreement is found comparing results to values expected by design. This anyway represents an estimation of tuner actual performances that will be proven during the first horizontal cavity cold test that is currently about to be scheduled.

PED CERTIFICATION

The XFEL linac is going to be certified according to the current directives related to pressure vessel (EU PED). Specifically, cavity modules including helium vessels and their ancillaries are required to ensure a MAWP (Maximum Allowed Working Pressure) of 4 bar absolute and this should happen without any loss in functionality.

Concerning the third harmonic cavity tuners, such a limit pressure load translates into the need to withstand a large part (about 80 %) of the tensile force (estimated to be about 5 kN) generated by the pressure difference. At the nominal working point the elongated cavity spring force (about 2 kN) partially compensates for it but this does not happen in the worst case, corresponding to a strongly detuned cavity.

A dedicated test bench is currently under development at LASA aiming to experimentally verify the functional limit of the tuner under traction. The setup will make use of the traction test machine (Instron 5500) already used for the qualification of cryomodule supporting posts [4].

CONCLUSIONS

A coaxial tuning system has been designed for the 3.9 GHz cavities of the third harmonic section of European-XFEL linac injector. The tuner design, inspired by the Blade Tuner already successfully qualified for the ILC, has been thoroughly verified by means of both analytical and finite element modelling and, afterwards, its expected performances have been confirmed by acceptance test routines on the first three prototypes produced.

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