DESIGN AND TESTING OF THE VSR BLADE TUNER AND ACTUATORS

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Abstract

The VSR DEMO SRF 1.5 GHz cavities require a large tuning range of 1 MHz to allow for the desired operation, including a cavity parking mode. The tuning system composed of blade tuner, stepper motor, release mechanism, and pre-loaded piezos installed into frames features mostly components already validated and used for other applications. However, the operational demands for the VSR application require adaptation of some of the components and testing to assess performance during augmented operation. Here the results of all component tests, most performed at cryogenic temperature, are presented.

TESTS OF TUNING COMPONENTS

The tuning system for the VSR cavities is shown in Figure 1. The blade tuner design [1] was adjusted for the purpose of delivering sufficient stroke and tuning force. The design changes were approved with simulations and durability was assessed with a test specimen. The stepper motor's expected operation exceeds the guaranteed lifetime by a factor of ten. Tests conducted with a test bench at cryogenic temperature prove the motor's longevity and help to quantify its heating properties. A cold test of the encapsulated piezos yield the available piezo stroke. A test of the release mechanism at cryogenic temperature is prepared.

Operational Requirements

To meet the operational demands of the BESSY II storage ring a pair of VSR cavities needs to be either tuned very closely to the resonant frequency of 1.5 GHz (VSR mode) or tuned off the resonance by about ±350 kHz (parking mode) [2]. The required tuning range of 1 MHz adds up from the 700 kHz required for operation, ±100 kHz accounting for master-clock frequency shifts, and ±50 kHz allocated for fabrication tolerances. Required tuning for VSR cavities for one year operation as summarized in Table 1 was extrapolated from general operational data of BESSY II, in particular experiences with the Landau cavities. The table lists required tuning above 3 kHz frequency shift only, i.e. to be covered by the motor. Fast, and smaller detuning needs to be compensated by the piezos, demanding for a stroke of 4 µm in cold. The required lifetime of the tuning system was set to five years.

Simulated cavity frequency sensitivity of about 800 kHz/mm and cavity stiffness of 8 kN/mm at room temperature set the required tuning stroke of 1.5 mm with some margin and the max. force of 12 kN to tune the cavity.

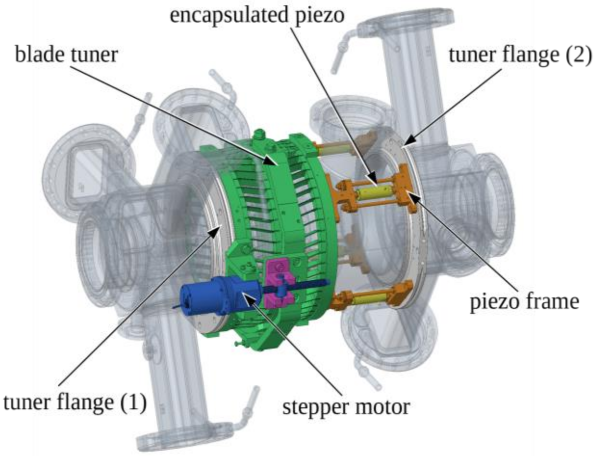

Figure 1: VSR DEMO cavity with tuning system.

Due to the large tuning range, the cavity experiences high stresses with peaks close to the iris and at the contact with the stiffening rings. Peak stress values exceed the cavity's material elastic limit at room temperature, but not at cryogenic temperature. A stuck travelling nut on the motor spindle would require for warm-up to replace the motor but would at the same time endanger the cavity's further usage. To mitigate this risk, a releasing mechanism that is activated at cryogenic temperature is required.

Table 1: Tuning of VSR cavity for BESSY II operation

Operational Mode	**Tuning Range [kHz]**	**Occurrences [1/y]**
Cool down / Warm up	1000	4
Change of Operation (VSR or parking mode)	500	200
Momentum Acceptance	90	20
Seasonal Drift and Contingency Measurements	30	6
Ramp-up Beam Current	11	104
Small Detuning Events	≤10	437

Blade Tuner

To achieve the required stroke, deliver sufficient force and stiffness the existing blade tuner design was adopted based on the original coaxial blade tuner system [1] and further developed through detailed simulations. Compared

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to the design for TESLA cavities, a larger number of longer blades, welded in pairs, are used. Due to the uneven load and stress distribution on the blades, with peak values close to the welded joint [3] a test piece was examined to assess the lifetime performance. The specimen resembles a tuner section with three blade pairs on each side of the middle ring (Figure 2) and was tested at room temperature in cycles of alternating full deflection. A calibrated set of spring washers generated a compressive load on the specimen's blades equivalent to the one induced by the actual VSR cavity. Both displacement and force diagnostics were installed in the specimen holder (Figure 2). Additionally, the pneumatic actuator used to operate the test piece recorded its displacement and generated force.

Analyses performed on load distribution [3] returned a worst-case, peak load value per blade of about 175 N (max tuning range on most solicited blades). Thus, an accelerated lifetime test (ALT) setup was configured for a target peak load of 1050 N at full stroke of 1.5 mm. A workload cycle was designed based on the demands in Table 1 summarizing in loops of varied stroke the different operational cases and repeated to resemble the required lifetime. The specimen survived the complete test with no visual alteration of the blades and full consistency in the stroke and load behaviour at the test's start and end. After successful testing the production of three blade tuners at Zanon Research & Innovation SRL was released which were delivered in Summer 2021.

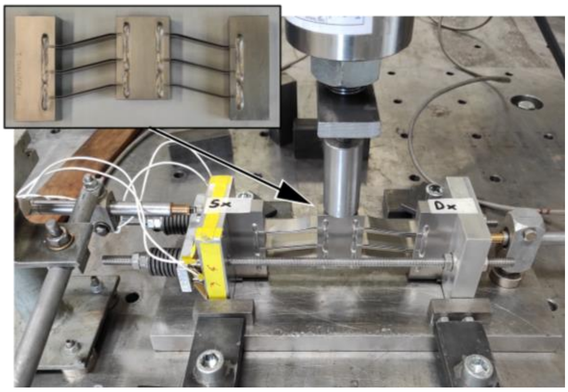

Figure 2: Blade tuner specimen in its holding frame during ALT, with actuating head (top centre), and stroke load sensors (on the sides).

Stepper Motor for Blade Tuner Actuation

The blade tuner is actuated by Phytron's LAV stepper motor (200 steps/rev.) equipped with a planetary gear box providing a 50:1 transmission ratio [4]. The system of blade tuner and stepper motor allows for a tuning resolution of 2.1 Hz/step. The blade tuner's transmission ratio of 38:1 result in required stroke and force at the motor spindle of 57 mm and 320 N. To provide sufficient effective stroke, the spindle length was increased to 120 mm. The stepper motor is developed for in-vacuum and cryogenic applications, but the manufacturer guarantees for operation of 30 Msteps only. The necessary steps for five-year operation are approx. tenfold. A dedicated motor test was setup to prove reliability of the motor for such extended usage. A test for LCLS II HE has proven motor operation of more than 400 Msteps [5]. In contrast to that test the ALT performed for the VSR application is executed concentrating small movements at defined locations on the spindle, run nearly continuously not requiring intermediate cooling pauses, and executed at speeds up to 400 steps/s.

Since the VSR DEMO cavities are still in the prototype manufacturing stage, the motor test is executed with a testbench instead. This mechanical setup actuates four springs in parallel resembling the cavity stiffness. It features a high-resolution eddy current distance measurement resolving the last 5 mm at maximum deflection with submicrometre precision. The testbench is installed into HoBiCaT cryostat [6] and connected to the 4 K-piping return flow. Temperature sensors are placed on the copper intercept of the motor, on the copper braid connecting to the 4 K-piping, and on the travelling nut (Figure 3).

From the operational demands in Table 1 a testing scheme was developed covering nearly 300 Msteps requiring 17 days of integrated testing time. The test was executed with a script running defined loops while monitoring the temperatures of motor, travelling nut, and power stage, and pausing if set thresholds were exceeded. For the testing sequence three positions on the spindle were defined: upper and lower location (as for parking mode), and middle location (as for VSR mode). Changes of operation and small detuning events given in Table 1 were allotted to these three positions, concentrating the wear on the spindle as in planned operation.

First, the ALT confirmed motor longevity of 287 Msteps with no visual degradation of the thread on spindle and nut. But in a preliminary testing attempt the travelling nut failed after a few cycles. Inspection of the failed part by the manufacturer revealed the cracks of the threaded TECASINT insert originated in insufficient bonding of insert and steel body. Phytron therefore adapted the very manufacturing step, and the travelling nuts will be replaced for the ten motors purchased in 2020. The subsequent test was performed with a replaced nut. Albeit the results in [5] and [7] indicate the ball bearings inside the motor being the components most affected by the ALT, not spindle or travelling nut. Accordingly, the next step is to disassemble the tested motor to assess wear of the inside components.

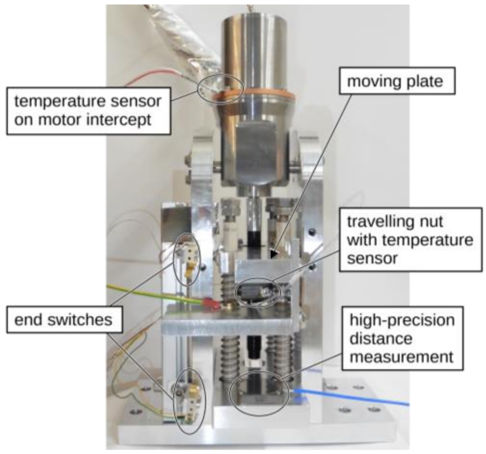

Figure 3: Stepper motor in the testbench with diagnostics.

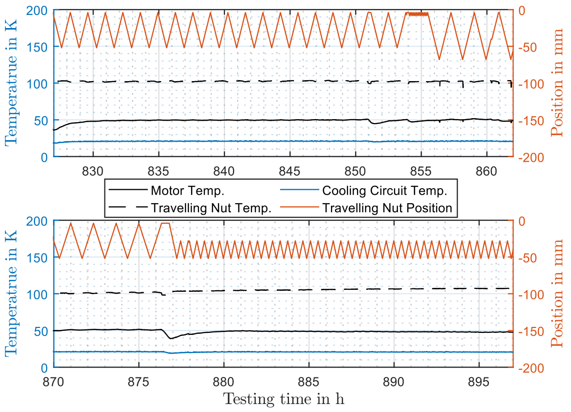

Figure 4: Temperatures during motor test at 200 steps/s (top) and 300 steps/s (bottom).

Second, the ALT has proven continuous motor operation is possible at speeds up to 340 steps/s. The motor then has to be run with half the nominal current, i.e. 600 mA. During this operation the temperature at the motor's copper intercept increased by ca. 30 K, stabilizing at about 50 K (Figure 4). The gradient over the copper braid settled at 30 K after approx. 6 h of operation (Figure 4). Due to the very poor thermal connection of the travelling nut its temperature never dropped below 85 K but also never showed severe heating (Figure 4).

Third, the test has shown that speeds up to 400 steps/s are possible for motor operation up to 2 h, without overheating. However, the tested time was too short to reach a thermal equilibrium state, and the effect of high speed on wear increase is unclear. The manufacturer recommends max. 333 steps/s for continuous operation.

Fourth, evaluation of the high-resolution distance measurement revealed an overall good performance regarding position repetition accuracy (Figure 5). But the targeted stroke of 0.5 mm for this loop was consistently deceeded (Figure 5), and this behaviour is not yet understood. All in all, it became obvious that the mechanical setup is not ideal for in-depth investigation of movement precision and step-loss since the moving plate can tilt. A setup with a cavity would be a more suitable approach: kinematically fully determined, and with indirect high-resolution position measurement derived from frequency detuning.

The ALT has qualified the motor for the targeted application. Next, tests assessing the motor performance regarding repetition accuracy, step-loss and the correlation to speed are projected in a setup with the blade tuner to assess the behaviour of the whole tuning system.

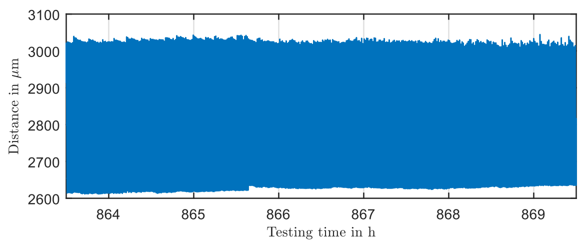

Figure 5: Distance travelled by the nut with targeted stroke of 0.5 mm at speed of 200 steps/s.

Piezos and Housing Frame

Four encapsulated piezos of type P-844K075 by Physik Instrumente GmbH are used for fast and fine tuning. Their performance has been qualified already for LCLS II [8]. To assess the cold stroke, the piezos were tested with a TESLA cavity at 1.8 K. The calculated value of 4.1 µm at 100 V retrieved from the hysteresis curve with assumed tuning sensitivity of 315 kHz/mm is just above the requirement.

For the VSR application, a new frame to house the piezos was designed to bridge the clearance of 160 mm between tuner and cavity flange. It facilitates adjustable preloading of the piezo capsule with spring washers and offers length adaption above 5 mm to account for manufacturing tolerances of tuner and cavity. A prototype frame was built (Figure 6), warm and cold tests are pending.

Release Mechanism

To prevent a permanent deformation of the cavity in case of a stepper motor failure and subsequent warm-up a releasing mechanism is designed to be incorporated into the tuner leverage. This release would be performed at temperature below 80 K and the cavity can then be warmed up with a dedicated scheme without damage caused by tuning or pressure induced stress. A viability study of the trigger showed that a bolt with a pyrotechnical release is the most promising solution for application in vacuum and cryogenic environment [9]. The separating bolt produced by PyroGlobe GmbH (Figure 6) is for in-vacuum application and was tested by the manufacturer at 220 K. The envisaged installation environment of the bolt is at approx. 10 K and a test to prove the pyrotechnical load can be ignited also close to the absolute zero is necessary. Such test is prepared and will be performed in HoBiCaT.

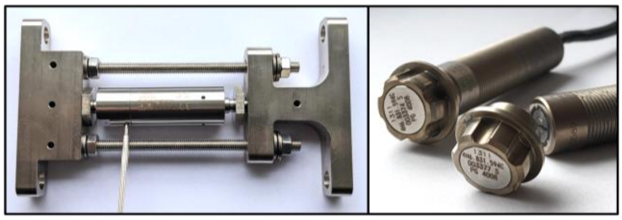

Figure 6: Encapsulated piezo in the housing frame (left), and separating bolt before and after trigger (right).

CONCLUSION

The components of the tuning system for the VSR cavities were assessed and tested individually. A specimen test of the blade tuner was successful, and the stepper motor was run for the required number of steps ten times beyond the guaranteed lifetime. The encapsulated piezos have delivered the required stroke and a warm test with the new frame design is prepared.

Next, the assembled components will be tested to assess the tuner system's overall performance. Such test will be conducted first in warm and then be repeated at cryogenic temperature. In parallel, the releasing mechanism will undergo approval followed by design integration into the blade tuner leverage.

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