ISBN: 978-3-95450-211-0 doi:10.18429/JACoW-SRF2019-TUP106

MECHANICAL TUNER FOR A 325 MHz BALLOON SINGLE SPOKE RESONATOR

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Abstract

TRIUMF has designed, fabricated and tested the first balloon variant of the single spoke resonator at 325 MHz and β=0.3. TRIUMF has also designed and built a mechanical tuner as part of the development. The tuner employs a nutcracker lever pressing at the beam ports driven by a scissor jack. The scissor is actuated through a tube coupling to a warm ball-screw and servo-motor located outside the cryostat. The design and warm tests of the tuner will be presented.

INTRODUCTION

The RISP project [1] is a radioactive ion beam project located in Daejeon Korea. The project includes a heavy ion linac to accelerate ions up to 238U to 200MeV/u with 400kW of beam power. The same accelerator will also be capable of accelerating light ions with proton currents and final energy of 0.66mA and 600MeV. The driver linac has two sections, SCL1 and SCL2. SCL2 is comprised of two cavity variants, SSR1 and SSR2. SSR1 is a β=0.3 single spoke balloon resonator designed at TRIUMF [2].

A mechanical tuner is required to tune the SSR1 cavity to its operational frequency after cooldown and to maintain the cavity frequency within the RF bandwidth as internal and external forces act to detune the cavity. TRIUMF is commissioned to design, build and test the mechanical tuner.

SPECIFICATION

Cavity frequency tuning is accomplished via squeezing the cavity at the beam pipes and adjusting the gap between the beam port irises and the spoke. The frequency sensitivity of the cavity in this area is 467Hz/μm based on finite element analysis (FEA). The mechanical properties of the SSR1 cavity are given in Table 1 and form the baseline of the tuner design. The design challenge is that the cavity is relatively stiff and the tuning sensitivity is relatively high so a strong tuner with high resolution is required.

The tuner is designed to provide adequate coarse frequency tuning range to compensate uncertainties in fabrication and thermal contraction during cooldown while allowing enough precision to maintain the cavity comfortably within the cavity bandwidth (60Hz) during operation due to slow helium pressure fluctuations, Lorentz force detuning (LFD), and other slow detuning effects. Fast detuning due to microphonics is compensated by choosing sufficient bandwidth in the RF coupler set-up although the tuner design allows a piezo to be included in the warm drive shaft for potential active compensation.

The mechanical tuning range is primarily determined by the range of the resonant frequency uncertainty due to cooldown. This uncertainty has been chosen as <180kHz. Other detuning compensation requirements including detuning for switched off cavities are well within the above range. This together with the spring constant of the cavity, 14kN/mm, sets the gross specifications for the tuner strength shown in Table 1. The resolution of the tuner is set by the requirement that the tuner is capable to adjust the frequency in the center of the bandwidth. A resolution of 1.5Hz is chosen which corresponds to 2.5% of the bandwidth.

The cavity will operate at 2K in superfluid helium at a pressure of 31mbar. The typical stability of the pressure in helium bath should be ≤ ±0.3mbar. The expected sensitivity to helium pressure fluctuations is ~10Hz/mbar for an expected detuning of ≤ ±3Hz. These tend to be slow variations and should be easily compensated by the tuner.

Table 1: SSR1 and Tuner Design Parameters

Parameter	Value	Unit
SSR1 rf frequency	325	MHz
Cavity bandwidth	60	Hz
Tuning sensitivity	467	Hz/μm
Tuning force	33	Hz/N
Spring constant	14	N/μm
Coarse tuning range	180	kHz
Displacement range	0.39	mm
Maximum Force	5500	N
Resolution	<1.5	Hz
Position resolution	<3.2	nm

CONCEPTUAL DESIGN

TRIUMF has past experience and success with designing and operating tuners with warm motors external to the vacuum tank [3,4]. The choice allows straightforward motor servicing and the ability to add a piezo fast actuator for a retro-fit without warm-up. In the case of the SSR1 tuner a nutcracker mechanism fits around the cavity to supply a tuning force on the beam flanges during operation. The cavity is a spring load with the tuner as a lever. The nutcracker is squeezed through a scissor mechanism that is in turn activated though an actuating rod assembly connecting the warm motor external to the cryomodule to the scissor.

Due to complexities of the SSR1 cryomodule design RISP requested TRIUMF to design for a horizontal access from tuner motor to tuner. In order to adapt the nutcracker to existing hardware on the cavity (fundamental feedthrough and rf pick-up) the nutcracker was positioned at a 45^0 angle to the horizontal. The interface of the tuner to the cryomodule is shown in Fig. 1. The components of the SSR1 tuner are shown in Fig. 2.

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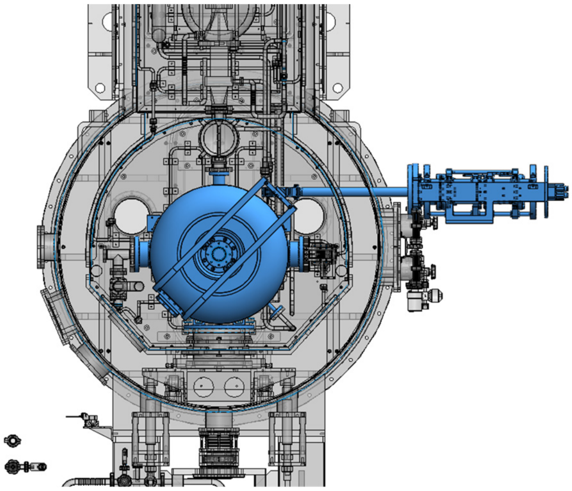

Figure 1: The SSR1 cavity and tuner installed in the SSR1 cryomodule.

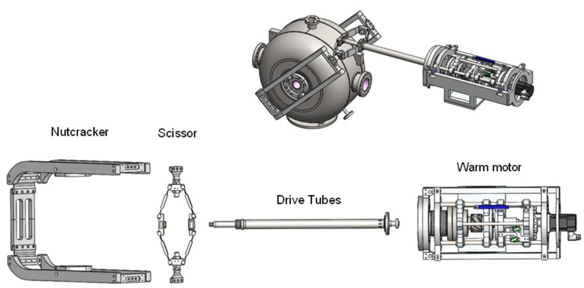

Figure 2: The components of the TRIUMF SSR1 tuner.

DETAIL DESIGN

Detailed tuner design was modeled in SolidWorks and validated using ANSYS FEA simulations along with structural and thermal calculations. The design methodology flowchart is shown in Fig. 3.

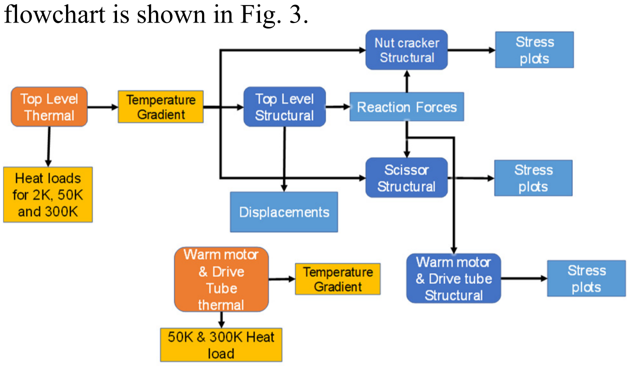

Figure 3: SSR1 design methodology.

The tuner mechanism will operate only in compression under constant elastic load from the cavity. C-flex i-30 pivot bearings [5] are selected for the beam port pivots to allow rotation and radial loads without friction. This creates a drive system with theoretically zero backlash. Limit switches and a mechanical hard stop prevent the cavity and tuner components from being overdriven. The reaction force and displacement results from FEA simulation are shown in Fig. 4. The mechanical advantage in force is 5:1 and in displacement is 25:1.

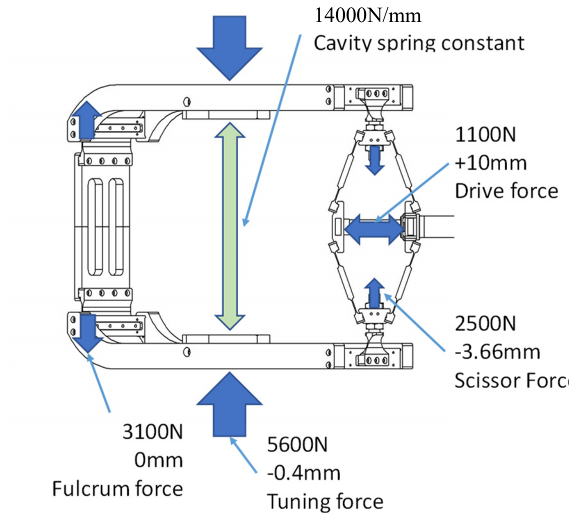

Figure 4: The forces and displacements on the SSR1 tuner components under maximum load.

Stresses, Material Choice and Thermal Analysis

All flexures are under tension and bending loads, therefore, the maximum von-Mises stress happens on the tension side extreme fibers of the bending faces. The scissor arm flexure experiences a maximum stress of 348MPa under full load. The fulcrum flexures experience a maximum stress of 54MPa while the nutcracker arm shows a maximum von-Mises stress of 77MPa on the compression side due to the stress riser of c-flex bore.

The stresses inform the choice of materials. The nutcracker arms are made from 316L SS. The C-flex pivot bearings (SS) are used on the connection between the nutcracker arm and the beam port interface. The scissor arm and flexures and the fulcrum flexures are made from Ti grade 5. Ti grade 5 has a minimum fatigue limit no lower than 410MPa at 10^9 fully reversing cycles [6,7]. If we consider our worst case scenario to be $<10^7$ cycles of 0 to 350MPa, the scissor arm flexure is within safe limits.

The heat load to the 2K system by conduction is calculated at 0.1W with 1.3W as the load to the 50K thermal intercept. A typical plot displaying thermal temperatures of the nutcracker assembly is shown in Fig. 5. Values from the thermal analysis are used to apply thermal boundary conditions to all structural simulations.

Assembly

The tuner is designed to be installed around the cavity after the cavity string (a 3 cavity sequence) is assembled. The C-Flex Pivot bearings are LN2 shrink fit into the nutcracker arm bores. Next the flange rings are attached to the cavity. The rings are split to fit around the beamline. The nutcracker arms are slid between the cavities and the C-flex is engaged with the flange rings (Fig. 6).

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Next the scissor and fulcrum end cross arms are installed followed by the fulcrum flexures and end plate. The last step is to tighten the C-Flex clamping screws on flange ring bosses.

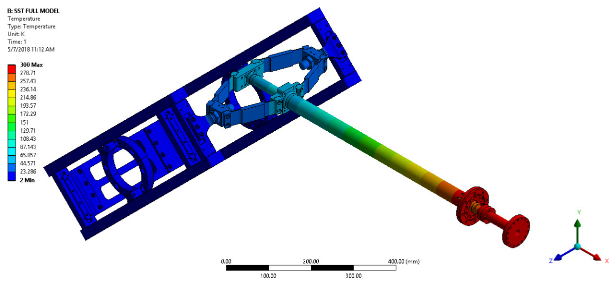

Figure 5: Thermal analysis of the SSR1 tuner.

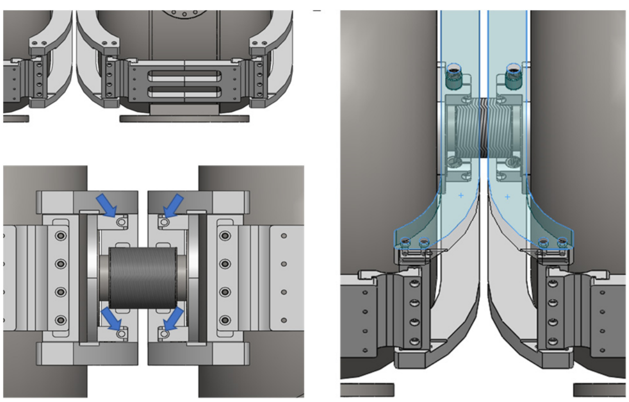

Figure 6: A few details of the tuner assembly around the cavity string.

The warm end flange is attached to the cryomodule along with the carriage flange. To make the connection between warm drive and cold tuner, the drive tube weldment can be inserted through the motor carriage and threaded into bronze nuts on the scissor blocks. This allows the connection to be made with limited access to the cold tuner when the hermetic string is inside the vacuum tank and thermal shielding.

The inner carriage is pre-assembled on the bench and then is attached to the outer carriage through silicone rubber dampers between the frame and inner carriage to isolate the tuner from ambient vibrations. Finally the Potentiometer, limit switches and hard stop are installed to complete the assembly.

All carriage components slide freely along the tuner drive axis on linear ball guides. A linear force is produced from the servo motor turning a ball screw. This force then pushes against the inner drive tube and pulls on the outer drive tube which expands the scissor actuating the cold tuner. When the ball screw nut is sufficiently retracted, the drive system fully disengages allowing the cavity and cold tuner to move during cooldown.

Motor and Ball Screw

The motor and ball screw were chosen based on previous experience at TRIUMF with similar applications in ISAC-II and ARIEL. A Kollmorgen AKM31E-ANCNR-00 motor is chosen with a rated torque of 1.2Nm. The motor is equipped with a rotary resolver which is interpreted by a Kollmorgen AKD drive that produces an emulated encoder signal with a resolution of 2^{16} counts per revolution. This equates to a minimum cavity displacement of 1.18nm/count corresponding to a cavity frequency step of 0.56Hz/count. A linear potentiometer is added to the warm tuner shaft to compliment the rotary resolver and allow for absolute positioning.

A ball screw (**NSK** W1601MA-1PY-C3Z2) is selected for its low coefficient of friction to allow the tuner to back drive to a relaxed position in the event of a power failure or during warm-up with a force of 60-200N depending on the bearing pre-load. It has a basic dynamic load rating of 3510N and a static load rating of 8450N with a pitch of 2mm and a diameter of 16mm.

TUNER TESTING

The stiffness of the cavity is expected to be 14kN/mm based on simulations. The measured spring constant of the first prototype SSR1 was 10kN/mm. The difference is most likely due to the thinner shell wall in the prototype [2] compared to that used in the simulation. The tuner testing is done with a spring that replicates the spring constant of the cavity. The spring is shown in Fig. 7. The measured spring constant for the spring is 12.4kN/mm close enough to the cavity constant to be a representative load.

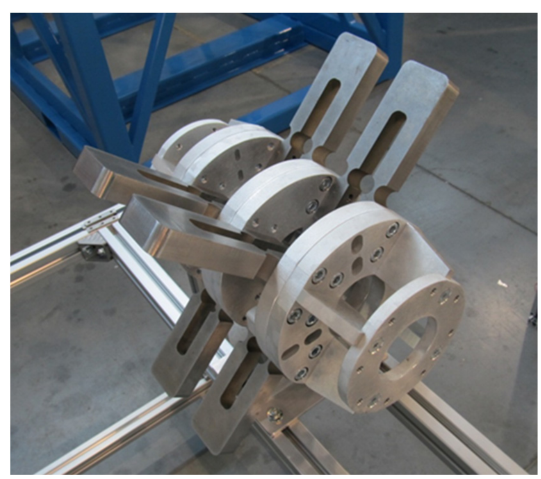

Figure 7: The mechanical spring used to replicate the cavity during tuner acceptance testing.

The tuner assembly (Fig. 8) is mounted in a Bosch frame (Fig. 9) in order to perform the warm qualification tests. The motor is driven by a Kollmorgan AKD driver and Workbench software. A linear variable displacement transducer (LVDT) is placed between the spring ends to measure the change in length of the spring as the motor is driven.

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The specification document indicates that the mechanical tuning range shall be ≥180kHz. Based on the cavity frequency sensitivity a demonstrated deflection of 0.4mm corresponds to 190 kHz tuning range. Tuner tests showed that a scissor deflection of 12 mm is required to generate the 0.4 mm cavity deflection – a 30:1 mechanical ratio (Fig. 10). The motor current ranged linearly from 0 to 1.6A to cover this tuning range. At 12.4kN/mm, a deflection of 0.4mm corresponds to a maximum tuning force of 5kN.

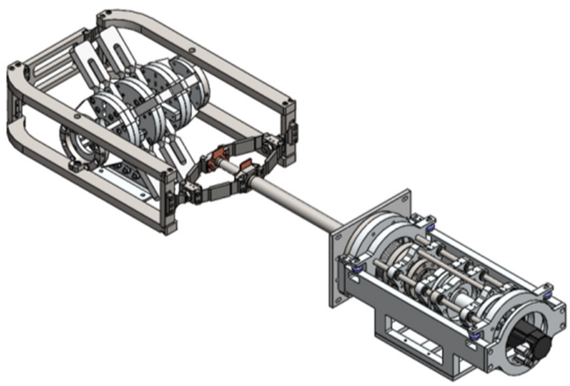

Figure 8: The test set-up. Illustrated is the spring, the nutcracker, the scissor, the actuator and the motor housing

In order to measure the tuner response a saw-tooth drive signal at 5Hz was used to drive the motor. The displacement of the cavity spring was measured with the LVDT device at ±0.5μm. The displacement corresponds to a cavity rf frequency variation of ±230Hz. The drive signal and the resultant spring displacement are shown in Fig. 11. The results show excellent tracking between the drive signal and the response with no measureable backlash.

The room temperature results confirm accurate tracking at less than 10% of the full test range corresponding to ±50nm range. A cold test that would measure rf frequency directly is required to measure the response at the sub 10nm range to test the full resolution. This test will be conducted later at RISP.

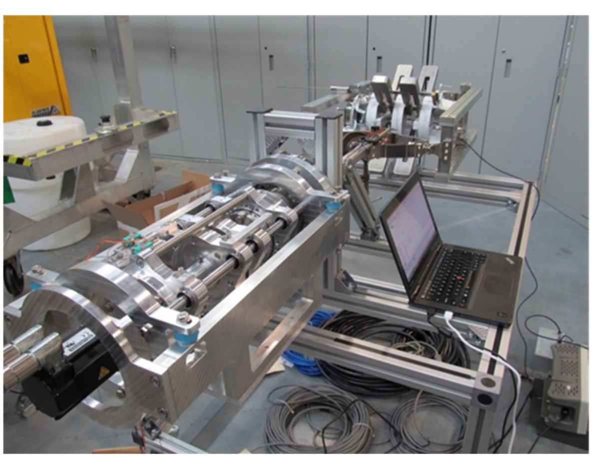

Figure 9: The tuning test center with spring, nutcracker bars, scissor device, actuator arm and motor assembly.

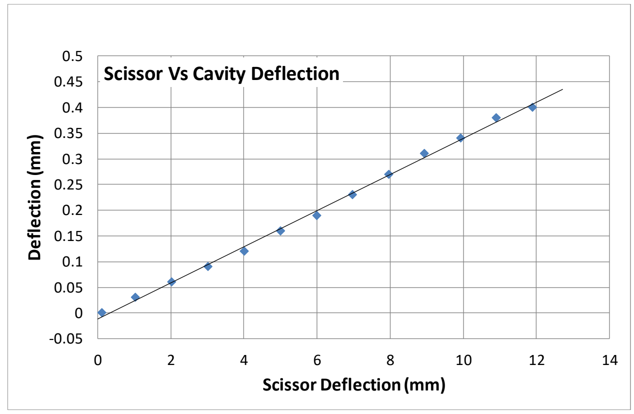

Figure 10: Tuning range test showing that the tuner can tune over the full 0.4mm range.

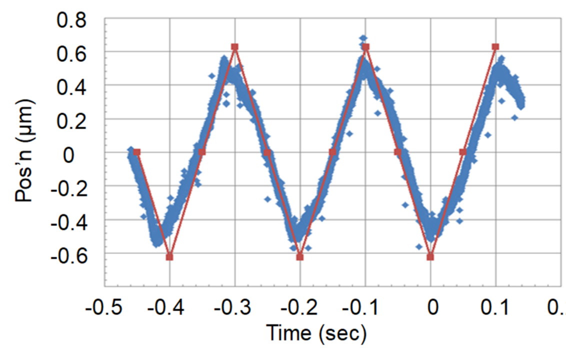

Figure 11: Small motion test. A 5 Hz drive signal is input to the motor and the response signal from the LVDT is superimposed for a displacement of ±0.5μm.

CONCLUSION

A nutcracker style tuner with scissor mechanical force through a shaft to a warm motor has been designed, fabricated, assembled and tested at TRIUMF. The TRIUMF designed SSR1 tuner was tested at room temperature with results consistent with the design specifications. Cold testing will be done at RISP.

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