

TUNING PROCESS OF SSR1 CAVITY FOR PROJECT X AT FNAL*

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Abstract

SSR1 is a family of single spoke resonators to be used in Project X at Fermi National Laboratory. These cavities operate in CW regime having nominal frequency of 325 MHz and optimal beta of 0.22. SSR1 cavities will accelerate H⁻ ions after the Half Wave Resonator (HWR) section from 9 MeV to 32 MeV. In the near future this cavity will be used in Project X Injector Experiment (PXIE), which contains the ion source, the LEBT, the MEBT, the RFQ of Project X, and a cryogenic temperature section, having one HWR and one SSR1 cryomodule. SSR1 cavities have been built and tested at FNAL, the preparation of these resonators includes RF tuning which is the main focus of this paper. The frequency of the cavity is carefully chosen prior to the vertical test, and it is adjusted before welding the helium vessel to obtain 325 MHz nominal frequency for the dressed cavity in operating conditions. Several SSR1 cavities have been tuned at FNAL, the procedure, the hardware and the data are presented.

INTRODUCTION

SSR1 cavities have been built and tested at Fermilab [1] [2]. During cavity production it is necessary to set frequency goals throughout the entire process, to match the final target frequency of 325 MHz for a cold jacketed SSR1. After assembling and welding of the niobium, the cavity arrives at Fermilab and undergoes several quality control steps: visual inspection, CMM measurements, RF QC and leak check. The frequency is monitored throughout the entire cavity processing; when the cavity is received from the vendor several measurements are taken: fundamental frequency, high order modes frequencies, and field flatness. SSR1 cavity processing includes baking at high and low temperature and chemical polishing, bulk and light BCP. The leak check and the chemical processing are two main causes of frequency shifts. During the vacuum check the cavity geometry is deformed by the atmospheric pressure, which shrinks the structure inducing permanent plastic deformations, even though very small. The average Δf for SSR1 due to the leak check is -80 kHz. The bulk BCP removes 150 μm in average from the cavity surface, while the light chemical processing results in 30 μm material removal. For both processes the frequency variation is not negligible, the Δf produced by the bulk BCP has been averaged over 10 cavities and it is 150 kHz, while the one due to light BCP is 30 kHz. Transition ring and helium vessel welding makes the frequency change as well; the two processes have been recently started at FNAL. All these are causes

of frequency deviations; in order to control and compensate for these shifts it is necessary to tune the cavities with a proper fixture.

SSR1 BARE CAVITY TUNING

The first tuning step of SSR1 comes for the preparation to the vertical test, the frequency is adjusted to 324.6 MHz in order to reach approximately 325 MHz once the cavity is cooled down to 2 K in the test dewar. Usually the cavity received from the vendor has a resonant frequency of 325.6 (± 0.2) MHz, after the leak check, first bake and chemistry it is usually higher by 70 kHz. The total frequency shift to apply is approximately 1 MHz, taking into account the cavity sensitivity 540 kHz/mm and the spring constant 23 kN/mm, the tuning requires a robust fixture capable of delivering forces of several tens of kN. Figure 1 shows the tuning machine for SSR1 cavities, it consists in a box equipped with two rods which allow pushing or pulling on the cavity beam pipes. Two load cells measure the forces applied on each rod, four displacement gauges give reading of the deformations the cavity is subject to, and they are mounted between the beam pipes and the coupler ports. A set of antennae is mounted on the coupler ports to allow recording the frequency step by step with a network analyser.



Figure 1: SSR1 tuning machine with a cavity in it.

To understand how the frequency changes when the tuning machine acts on the resonator, let us keeping in mind Slater's rule:

$$\frac{\Delta f}{f_0} = \frac{1}{4W} \int_{V_i}^{V_f} (\epsilon_0 E^2 - \mu_0 H^2) dV. \quad (1)$$

W is the stored energy in the cavity in initial conditions, V_i is the volume before tuning and V_f is the volume after deformations are applied. Since the rods are acting on the beam pipes the high electric field area is modified, consequently the change in cavity volume will have the same sign of the change in frequency: bigger volume means higher frequency.

Tuning procedure

Before starting tuning the cavity, it has to be installed in the machine, which means have it fit centred in

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between the two rods to avoid any asymmetric deformation of the cavity structure. The tuning consists in applying a force on the cavity and then release the pressure coming back to relaxed position. This is done in several steps, gradually, to avoid any abrupt change in the cavity geometry; RF measurements are taken for the stressed and relaxed conditions at each cycle. This process is repeated until the target frequency is achieved. Figure 2 shows the frequency of SSR1-112 during the tuning, one can see how for small forces applied the process is reversible and the frequency in the relaxed state is equal to the one before pushing or pulling. When the force overcomes the elastic limit of the material the cavity starts yielding, and as result the frequency for the relaxed cavity changes.

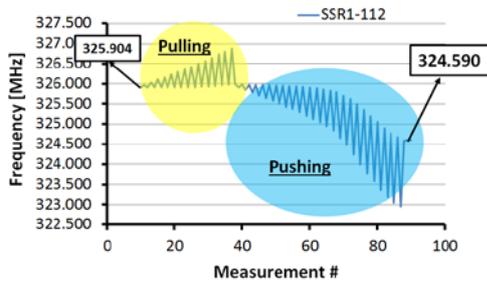


Figure 2: SSR1-112 frequency during tuning.

Frequency of the relaxed cavity is represented by the lower values for the pulling and higher values for the pushing. Despite the desired negative frequency shift, the first part of the tuning involves pulling which makes the frequency become higher. The reason why the tuning starts with pulling is to increase the elastic range of the material by stretching it; the frequency is not modified significantly usually a shift ranging from +80 to +100 kHz is sufficient. After the first pulling the real tuning by pushing starts, many cycle are usually required and the total force required can reach over 7000 lb_f .

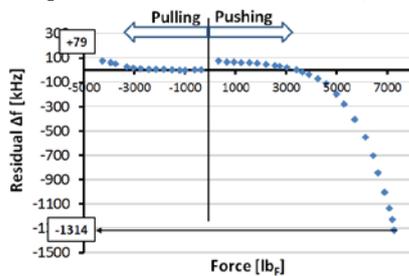


Figure 3: relaxed cavity frequency shift vs. force.

The figure above shows the Δf due to plastic deformation of the cavity, the pulling required almost 4300 lb_f while the pushing over 7200 lb_f , the non-linearity of the last part of the plot is due to the yield of the material. When the value of frequency for the relaxed cavity is approaching the target, it is extremely important to increase the force by small steps since the material is yielding, and the frequency changes much faster with the applied force. During the tuning it is possible to measure physical quantities related to cavity displacements, force

applied and frequency shifts, in general it is interesting to look at frequency sensitivity as a function of the displacement and cavity spring constant. The frequency sensitivity $\frac{\Delta f}{l}$ measured in kHz/mm can be calculated from the plot of the frequency as a function of the average displacement, reported in figure 4. One can see two lines, one for the relaxed, one for the loaded cavity. The average of the parameter $\frac{\Delta f}{l}$ for all the cavities tuned is 460.7 kHz/mm, which is lower than the one predicted by simulations (540 kHz/mm). This mismatch is partly due to the residual asymmetry in the deformation induced by the rods; the error in evaluating the displacements is also not negligible: from time to time the gauges move from the reference position and they have to be readjusted.

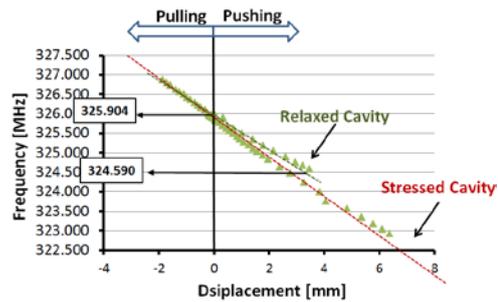


Figure 4: SSR1-112 frequency vs. average displacement.

Figure 5 shows the average displacement as a function of the force applied, from this plot it is possible to extract the spring constant value of the cavity evaluated as $\frac{\Delta F}{\Delta l}$, where ΔF is the difference in force applied; it is expressed in kN/mm, its average value is 22.2 kN/mm.

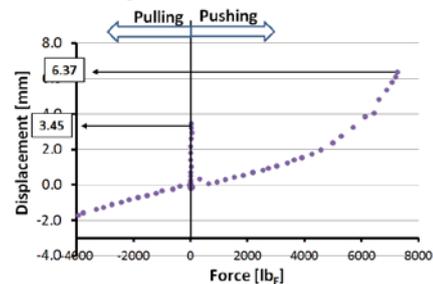


Figure 5: average displacement vs. force.

Tuning after transition ring weld

In the latest design of SSR1 helium vessel [3] a transition ring is used to attach the niobium cavity to the stainless steel vessel [4]. The ring is attached to the cavity by electron beam welding, see figure 6, this operation is done after the resonator qualifies from the VTS. Recently Fermilab received two SSR1 cavities which had the transition ring welded, SSR1-107 and SSR1-108. The frequency shift expected was very small, while the effective shift was around 500 kHz. The cause of this shift is the contraction of the accelerating gap on the transition ring side; the weld induces the material to shrink while it cools down, pushing the beam pipe in and consequently reducing the resonant frequency.



Figure 6: SSR1 cavity with transition ring.

To prove this, bead pull measurements were taken on SSR1-108 before and after the weld, the normalized field amplitude plots are presented in figure 7, up side refers to the side of welding. Looking at figure 7(a) the maximum of the accelerating field is on the down side, opposite to the weld side, while for figure 7(b) the higher point appears on the transition ring side. Higher field means shorter gap, so this is an evidence of the shrinkage due to the weld.

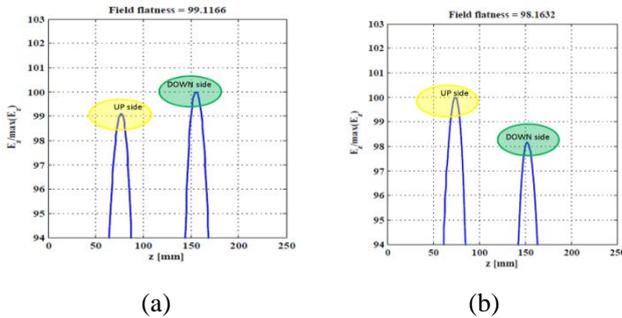


Figure 7: SSR1-108 field flatness before (a) and after (b) transition ring weld.

SSR1-107 has been tuned to compensate for the effects of the transition ring weld, following the procedure described in the previous paragraph but applying asymmetric forces to bring the gap length back to original value.

SSR1 DRESSED CAVITY

Fermilab recently received the first SSR1 cavity with helium vessel, in order to monitor the resonant frequency measurements have been taken during the entire welding process. Figure 8 shows the frequency history of SSR1-107 during the welding of the stainless steel helium vessel; the main steps are highlighted on the graph. The most critical procedure is the welding of the beam tubes to the vessel which brings up the resonator frequency significantly. The welds on the outer helium vessel shell do not induce significant shift, while the two ports (coupler and vacuum) may interfere with the helium vessel parts and put stress on the cavity: the lower peak in the yellow part of the graph is due to the ports pressing against the vessel parts, they have been machined during the welding procedure to solve this issue. The first cavity ended up having a total frequency shift of 264 kHz during the dressing process, the procedure and the design of the

helium vessel parts will be revised in order to obtain lower shrinkage effect on the cavity geometry.

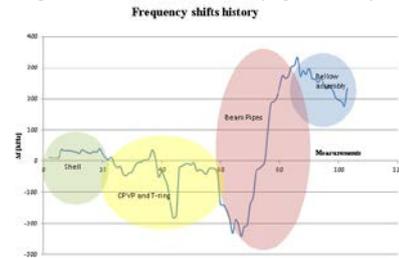


Figure 8: frequency shifts induced by helium vessel welding.

Once the resonator has been dressed it does not fit in the tuning machine, a new fixture has been created to adjust the dressed SSR1 frequency: it consists in two stainless steel bars connected to the helium vessel on the tuner plates. Figure 9 shows the dummy tuner that will be used to adjust the frequency of the jacketed cavities; the device will allow tuning by pushing and pulling, unlike the real tuner device for SSR1 which will be able to compress the cavity only [3]. One rod is installed on each bar to allow tuning on the cavity wall, only on the side opposite to the transition ring, which has been connected to a bellow to allow movement.



Figure 9: SSR1-107 dummy tuner assembly.

CONCLUSIONS

Over ten SSR1 bare cavities have been tuned successfully at Fermilab, a new helium vessel design has been introduced and the first prototype has been built. The tuning procedure has been described and all the issues have been addressed. Currently tests and measurements are in progress on SSR1-107, to characterize all the features of the jacketed cavity; tuning will be done using the dummy tuner fixture, to assure that the target 325 MHz frequency is achieved.

REFERENCES

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