TRIM TUNING OF SPS-SERIES DQW CRAB CAVITY PROTOTYPES *

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Abstract

The final steps in the manufacturing of a Superconducting Radio-Frequency (SRF) cavity involve careful tuning before the final welds to match the target frequency as fabrication tolerances may introduce some frequency deviations. The target frequency is chosen based on analysis of the deviation induced by remaining processing steps, including acid etching and cool down. The baseline fabrication of a Double-Quarter Wave (DQW) crab cavity for the High Luminosity Large Hadron Collider (HL-LHC) envisages a first tuning before the cavity subassemblies are welded together. To produce a very accurate final result, subassemblies are trimmed to frequency in the last machining steps, using a clamped cavity assembly for RF measurements. This paper will describe the trim tuning of two SPS prototype DQW crab cavities fabricated by Niowave.

INTRODUCTION

The design of the SPS-series cavity includes the development of several tuning methods to tune the cavity frequency at different stages of its fabrication, preparation and operation. The installed cavity, operating at 2 K and delivering a 3.4 MV deflecting voltage to a 450 MeV SPS beam, must operate at (400.79 ± 0.06) MHz [1].

The very first tuning of a DQW cavity is envisaged before the main cavity subassemblies are welded together, by the so-called trim tuning method. This tuning intends to correct frequency deviations introduced by fabrication tolerances.

TARGET FREQUENCY

The target frequency for the manufactured SPS-series cavity, 400.29 MHz at ambient conditions, was calculated taking into account the expected frequency shift introduced by different operations such Buffered Chemical Polishing (BCP), coupler insertion, evacuation and cooldown. Table 1 summarizes the frequency shifts associated to each operation. These frequency shifts were based on simulations and estimations.

THE DQW CAVITY SUBASSEMBLIES

The fabrication model prepared by BNL and CERN for the SPS-series DQW crab cavity was adapted to reflect the volume changes experienced by the cavity within BCP and cooldown.

Niowave Inc. prepared parts to fabricate two SPS-series DQW cavity prototypes. Each cavity was divided in three main subassemblies before trim tuning: one center subassembly and two end cap subassemblies (also known as top and bottom subassemblies). The parts were formed out of 4 mm-thick niobium sheets. The subassemblies for one cavity prototype are shown in Fig. 1.

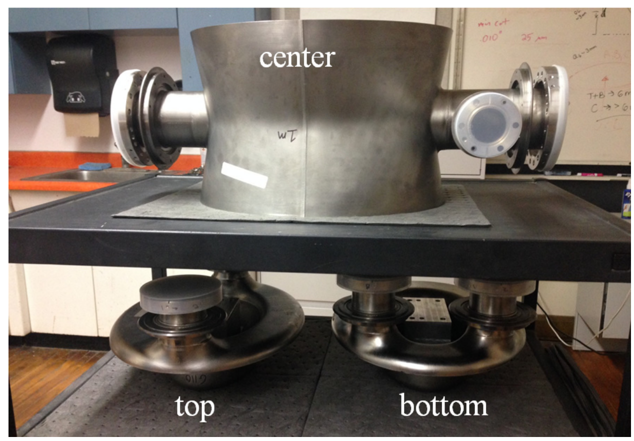

Figure 1: Cavity subassemblies.

Extra material was left on the edges of each subassembly. By trimming part of this extra material, both cavity height and distance between cavity plates were reduced. The cavity frequency is very sensitive to both geometric parameters. According to CST simulations, the frequency decreases by 0.98 MHz per trimmed millimeter (that is, the frequency goes down by reducing the length of extra material).

Table 2 summarizes the initial extra material left on the edges of each subassembly, about 27 mm total per cavity. Few tenths of mm could be trimmed passed the nominal edge location in case that the cavity frequency had to be further reduced. The amount of material that can be trimmed beyond the nominal edge location was limited by the blending of the cavity dome outer perimeter.

Table 2: Initial Extra Material Left in the Subassembly Edges for Prototype #1

Subassembly	Extra material (mm)
Top	3.80
Center (top edge)	9.34
Center (bottom edge)	10.23
Bottom	3.87

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Table 1: Expected Frequency Shifts and Cavity Frequency Evolution for a SPS-series DQW Crab Cavity

Operation	Frequency shift (kHz)	Expected frequency (MHz)
Last two welds (transversal shrinkage and penetration)	-890	400.29
Bulk BCP (150 µm)	-127	400.16
Light BCP (30 µm)	-24	400.14
Coupler insertion (FPC, 3 HOM dampers, pickup)	-90	400.05
Permittivity change due to evacuation	+134	400.18
Cool-down (inside helium vessel with tuning system)	+609	400.79

TRIM TUNING GOAL AND STRATEGY

The frequency shift associated with the last two welds is a decrease of 0.89 MHz. This estimated shift is based on an expected transverse shrinkage of 0.5 mm per weld (resulting in a cavity height reduction of 1 mm) and a penetration of the weld bead of 0.5 mm.

The primary goal of the trim tuning was then to bring the clamped subassemblies to target frequency within an acceptance range of ±0.20 MHz. The target frequency for the clamped assembly of a DQW cavity was 401.18 MHz for a temperature of 293 K, an atmospheric pressure of 1013.25 mbar and a humidity of 60%.

Trim tuning of the DQW subassemblies was executed in phases. Firstly, some trimming steps to flatten the subassembly edges, symmetrizing the cavity body and bringing the center subassembly to nominal height. Then, starting from symmetric subassemblies, the same amount of material was removed from both end cap subassemblies so that symmetry of the cavity body was preserved. Several trimming steps were performed to approach the target frequency and better define the trim tuning sensitivity in the range of interest. Next, the thickness of the weld joints was machined to 3 mm in order to ease welding and reduce weld bead penetration. This local thickness reduction should not compromise the structural integrity of the cavity according to ANSYS simulations [2]. Measurements of the subassemblies themselves were used to create a profile that would match each part, with imperfections from stamping and previous welding, together to create a final matched weld joint with thickness tolerance of 0.2 mm. Following the trimming, the final phase intended then brings the cavity to target frequency in a few small steps.

After each trimming step the parts were stacked and clamped to check the fundamental (operational) mode frequency of the assembly. Clamping had to be sufficient to ensure a good RF contact without deforming the cavity volume. Thus, clamping was progressively increased while monitoring the assembly frequency. The last frequency recorded before any evidence of elastic deformation corresponded to the frequency of the clamped assembly. The clamped assembly is shown in Fig. 2. The clamping mechanism was designed to provide force evenly distributed on all accessible subassembly surfaces.

Input and pickup probes had weak coupling for negligible impact on the frequency measurement of the clamped assembly. The DQW cavity at room temperature was the main contributor to the loaded quality factor. The clamped DQW assembly showed a broad resonant peak (compared to the peak at 2K) with a bandwidth of about 70 kHz. The frequency of the clamped assembly was measured with a precision up to 1-2 kHz. Clamping introduced an uncertainty of about ±10 kHz. Meteorological conditions (temperature, humidity and atmospheric pressure) were monitored during frequency measurements and the measured value corrected accordingly. In general the frequency variation was below 20 kHz. The trimming resolution was about 0.2 MHz given a minimum trim step of 0.2 mm.

Figure 2: Clamped subassemblies.

Reaching the theoretical Q required well degreased, flat, matching edges, and appropriate clamping to ensure full RF contact. The quality factor that can be obtained with clamped subassemblies is within 10% of the theoretical value. The geometry factor G of a DQW cavity is 87 Ohm. The surface resistance R_s of pure niobium at 293 K and 400 MHz is 0.015 Ohm for an assumed electrical conductivity of 7×10^6 S/m. The expected quality factor Q of the welded DQW cavity was about 5800 ($Q = G/R_s$).

The instantaneous trim tuning sensitivity (derivative of the frequency with respect to length) started from a lower value than expected and reached the calculated value as the cavity volume got closer to nominal dimensions (see slope in Fig. 3). Both prototypes showed similar frequency evolution. The process of trim tuning of the clamped assemblies for both prototypes demonstrated the control required for cavity production.

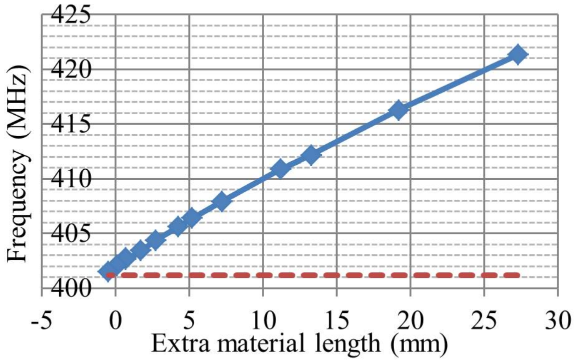

Figure 3: Frequency evolution during trim tuning for one of the prototypes. The red dashed line corresponds to the target frequency for the clamped DQW assembly.

FINAL ASSEMBLY

After trim tuning and thinning at Niowave, the cavity subassemblies were electron-beam welded together at Jefferson Lab. The frequency was measured at three different stages: 1) clamped assembly before welding, 2) assembly after tack welding, and 3) welded cavity. Table 3 lists the frequency for both cavity prototypes for each stage. Tack welding introduced a positive frequency shift. The full welding then reduced the cavity frequency, but in a smaller amount than expected. The dome of one of the cavities was significantly deformed after welding. The process of welding may have led to such deformation and could explain the mismatch of the predicted and measured frequency shifts.

Frequency and metrology controls made during trim tuning and welding of the CERN SPS DQW cavity parts would later confirm this hypothesis and reveal a precise method to tune the cavity. The welds that join center and end cap subassemblies narrowed the joint perimeter and pushed the end cap subassemblies away, displacing the capacitive plates outwards. The CERN cavity was set back into shape and tuned to target frequency by pushing down the rim of the cavity dome in the end cap subassemblies [3].

Table 3: Frequency (in MHz) of the two US SPS DQW Cavity Prototypes at Different Assembly Stages

	Prototype #1	Prototype #2
Clamped assembly	401.35	401.34
After tack welding	401.79	401.51
EB-welded cavity	401.60	401.39

CONCLUSION

A careful trim tuning was planned and executed for the two SPS cavity prototypes. The strategy allowed bringing the clamped assembly to target frequency within the acceptable range. Welding turned out to induce a non-predictable frequency shift. The frequency shift was significantly different from the expected value and it differed more than 0.2 MHz from one prototype to the other. Dimensional controls on the CERN SPS DQW prototypes evidenced the cavity deformation due to welding and shed light about a tuning method for returning the cavity into shape and tuning to target frequency.

The trim tuning method described in this paper may lead to an offset of the flanges and preparatory rings with respect to the nominal value. The location of the flanges and rings will be measured after the cavity is completed and the helium vessel interfaces will be adjusted to the measured location.

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