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MECHANICAL DESIGN AND FABRICATION ASPECTS OF PROTOTYPE SSR2 JACKETED CAVITIES*

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Abstract

A total of 35 superconducting SSR2 spoke cavities will be installed in the PIP II SRF linac at Fermilab and a total of 8 prototype SSR2 cavities will be manufactured for the prototype cryomodule. In this paper, the mechanical design and fabrication aspects of the prototype jacketed SSR2 cavity will be presented. Radio Frequency (RF) and mechanical design activities were conducted in parallel directly on the jacketed cavity in order to minimize the number of design iterations. Also, the lessons learned from other spoke cavities experiences (i.e. SSR1 at Fermilab and ESS double spoke at IPNO) were considered since the early stage of the design.

INTRODUCTION

The Single Spoke Resonator type 2 (SSR2) Superconducting Radio Frequency (SRF) cavity operates at a temperature of 2 K with a nominal electromagnetic frequency of 325 MHz. A total of seven SSR2 cryomodules are planned to be integrated in the PIP-II linac superconducting section [1] and each of them includes five SSR2 jacketed cavities and three superconducting solenoids. Several design iterations of the RF volume, with the aim of mitigating the multipacting while preserving the cavity electromagnetic performances, have been carried out and a final version has been selected [2]. This version of RF volume at 2 K, of which a cut out section is shown in Fig. 1, is then used as an input for the mechanical design of the bare cavity and the surrounding liquid Helium (He) vessel which, as it will be shown in this paper, is carried out simultaneously.

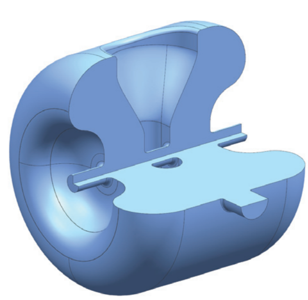

Figure 1: Cut out section of the SSR2 RF volume.

The bare cavity, which is a Niobium (Nb) shell, and the system called jacketed cavity, which comprises of the bare cavity and the He vessel, are required to satisfy specific mechanical technical requirements, some of which are summarized in Table 1.

Moreover, the bare cavity alone should be able to withstand a leak check (1 bar differential pressure), and the jacketed cavity must be integrated in the cavity string and the cryomodule. Thus its overall dimension depends on the total length available for the vacuum vessel and the interfaces with external components shall be taken into account.

Table 1: Mechanical Technical Specifications for the SSR2 Jacketed Cavity

Parameter	Value
df/dP, $\frac{Hz}{mbar}$	<25
Lorentz Force Detuning (LFD), $\frac{Hz}{MV/m^2}$	<4
Longitudinal stiffness, $\frac{kN}{mm}$	16
Operating frequency tuning sensitivity, $\frac{kHz}{mm}$	>250
Maximum Allowable Working Pressure (MAWP) RT / 2 K, bar	2.05 / 4.1

Therefore, the jacketed cavity shall be optimized to maintain mechanical stability, acceptable response to microphonics and He pressure fluctuations. To facilitate cavity operation in the optional pulsed regime, the LFD coefficient shall be minimized to a reasonably achievable value. In addition, the jacketed cavity needs to be tunable (the lower the longitudinal stiffness the better) and it must be manufacturable. The total cost must also be taken into account during the design process.

MECHANICAL DESIGN

The mechanical design of an SRF jacketed cavity is a constrained multi-objective optimization problem, in which:

- The geometry is the subject of the optimization.
- The requirements represent the objectives to be minimized, maximized or satisfied. Some of these often result in contradictory conditions (e.g. a stiffer cavity as a lower LFD coefficient and pressure sensitivity but the tunability is worse).

The RF volume is considered as a starting point, and its shape and dimension are to be assumed as frozen. This represents a constraint on the shape and dimension of the bare cavity inner surface. For the jacketed cavity system a total of four geometrical variables can be identified: Nb shell thickness, bare cavity stiffeners (geometrical shape and

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location), location of the interfaces between the bare cavity and the He jacket, geometrical shape and thickness of the He jacket.

In addition to the geometrical variables, the bare cavity stiffeners and the He jacket can be manufactured from different materials. However, as it is shown in the *Lessons Learned* paragraph of this section, the material selection for these elements is carried out based on previous single and double spoke cavity designs.

Once the possible design variables, constraints and objectives have been identified, in order to maximize the effectiveness and efficiency of the design process, the design of the bare cavity and the He jacket is carried out simultaneously as a integrated system opposed to trying to optimize the bare cavity first and only secondly the He jacket which may have led to unnecessary design iterations.

Lessons Learned

The lessons learned from the design and fabrication of a similar single spoke jacketed cavity at Fermilab [3] and of a double spoke jacketed cavity at IPNO [4] is used as a starting block for the design of the jacketed SSR2 cavity. Specifically:

- He vessel is manufactured from Titanium (Ti) Gr.2.
- Interfaces between He vessel and bare cavity and stiffening elements are chosen to facilitate the manufacturing process and only afterwards are optimized to satisfy the technical requirements.
- Bare cavity flanges will have through holes.
- Only one type of jacketed cavity.

Past experience with He vessels made from Stainless Steel has shown a possible magnetization of the TIG welds and the formation of oxides near the welded joints. Furthermore, from the manufacturing point of view, the Stainless Steel to Nb brazed joint can be avoided since Ti can be electron-beam welded to the bare cavity directly.

Avoiding the blind holes on the cavity flanges is imperative when trying to avoid beam vacuum particles contamination during the assembly operations held in a cleanroom. Moreover, they could trap water during the multiple wet cleaning operations that the cavity undergoes before the cleanroom assembly. The stagnation of water in a confined space could lead to the oxidation of the fasteners used to seal the cavity ports.

The Single Spoke Resonators type 1 (SSR1), of which the cryomodule is being assembled at Fermilab [5], have two different designs for the He vessel. Thus, the jacketed cavities positions cannot be swapped with each other during the cavity string assembly. In the case some cavities of the same type do not meet the gradient and Q_0 requirements during cold test, it is not possible to proceed with the assembly. Having only one type of jacketed cavity for the SSR2 cryomodule can, for the above mentioned reason, reduce the risk related to faulty cavities.

Materials

As discussed in the *Lessons Learned* paragraph, the He vessel will be manufactured from Ti Gr.2. This grade of Ti is not magnetic, has excellent mechanical properties and it is very resistant to oxidation which make it suitable to be used in the cleanroom. It is also a material allowed by the ASME [6] code for the fabrication of pressure vessels.

The bare cavity shell is entirely fabricated from RRR grade Nb with the exception of the four cavity flanges which are made from Ti Gr.5. This grade of Ti, that shares with the Gr.2 the non-magnetic and oxidation resistant properties, has a greater yield and ultimate strength as well as greater hardness, which make it suitable to be used as a Ultra High Vacuum (UHV) sealing surface.

No Nb-Ti (NbTi) alloy is used on the SSR2 cavity. An Electron Beam Weld (EBW) of the Ti Gr.2 and Gr.5 directly to the Nb will be used to join the He vessel and the cavity flanges respectively to the bare cavity. Avoiding the NbTi can reduce the total cost associated with the procurement of the SSR2 cavities. Extensive Non Destructive Testing (NDT) and Destructive Testing is performed in [7] and [8] on a EBW joint between RRR grade Nb and Ti Gr.5. Tests are also repeated after an heat treatment at 600 ºC for 24h and at 800 ºC for 2h, showing that the heat treatment does not alter the mechanical strength of the joint.

Reinforcement Setting and Cavity Geometry

Figure 2 shows a cut out section of the SSR2 jacketed cavity, while Fig. 3 shows the details about the reinforcements welded on the bare cavity and the interfaces with the He vessel. All the set of reinforcements and interfaces was optimized together with the shape of the He vessel to satisfy all the mechanical requirements and to facilitate the manufacturing. As can be noticed in Fig. 3, the beam pipes flanges stand out from the recesses of the He vessel. These recesses can cause turbulence and disrupt the linearity of the cleanroom air flow [9], thus moving the flanges outside can help to avoid particles contamination during the cleanroom assembly.

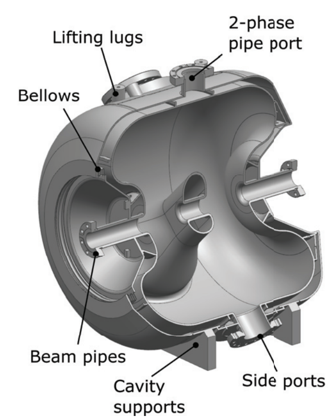

Figure 2: Cut out section of the SSR2 jacketed cavity.

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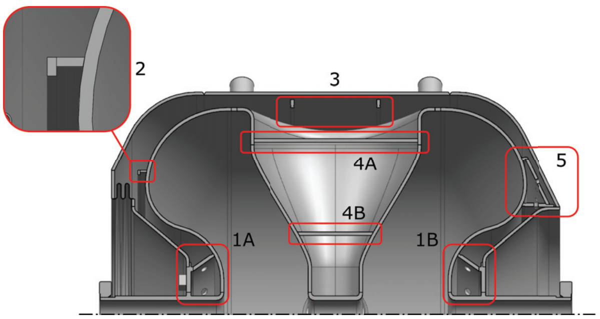

Figure 3: Section of the SSR2 jacketed cavity. The iris stiffeners, in details 1A and 1B, reduce the stresses due to pressure in the He space together with the spoke outer rib in detail 4A. The L rib ring and L rib disk in detail 2 help reduce the stress during the leak check of the bare cavity and the leak check of the He space. The reinforcements in details 3, 4B and 5 reduce the LFD coefficient.

Manufacturing Considerations

An exploded view of the bare cavity and of the jacketed cavity are shown in Fig. 4 and Fig. 5 respectively. All the components of the bare cavity will be manufactured from R04220-Type 5 RRR grade pure Nb according to [10]. The same type of Nb sheet is used to form the components showed in Fig. 4 with the sole exception of the beam pipes and the side port tubes which are machined directly from tubes. The manufacturing process of the bare cavity consists of forming, machining and EBW of various components, including the transitions between Nb and Ti. On the other hand, the He vessel components will be TIG welded.

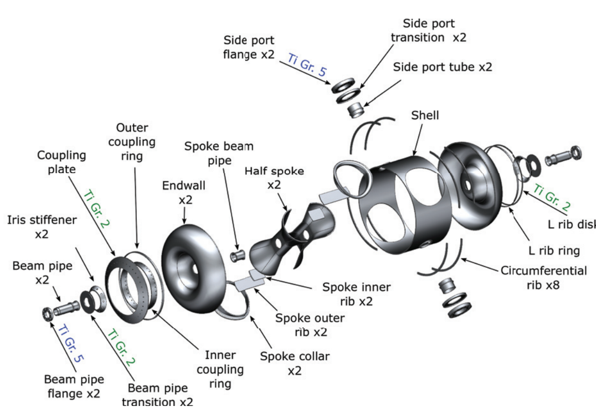

Figure 4: Exploded view of the SSR2 bare cavity. The components with no indication about the material are made from RRR grade Nb.

In order to satisfy the mechanical requirements (Table 1), a minimum thickness for the Nb sheet to be employed for the fabrication must be selected. The value of 3.75 mm for the bare cavity shell was selected as a result of the optimization of the whole jacketed cavity geometry. Using this as minimum final value and taking into consideration the thickness reductions due to manufacturing and cavity processing, the thickness of the Nb sheets to begin with can be selected.

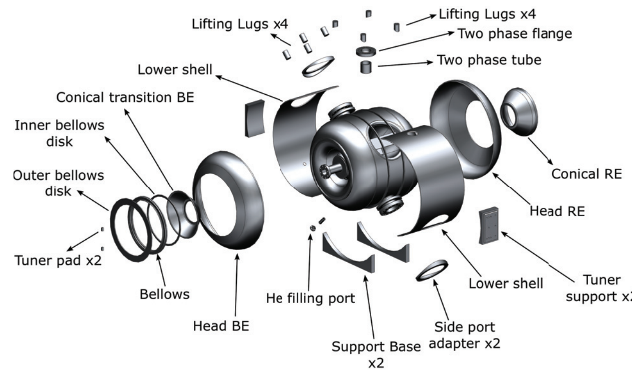

Figure 5: Exploded view of the SSR2 jacketed cavity.

Table 2 shows the contributions to the thickness reduction of each process and the resulting Nb sheet thickness.

It is expected that the formed Nb components will exhibit a thickness reduction that depends on the depth of the final piece. On the endwalls, for example, this reduction will be at its maximum. The difference in thickness of the final pieces will require a machining of the areas to be joined by EBW. The usual thickness of Nb to be joined by a full penetration one-sided EBW that guarantees a flat under bead on the RF side is 3.2 mm [11]. To guarantee the structural soundness with a reasonable margin, as shown in the *Structural Analysis* section, it has been chosen to perform 4 mm thick full penetration one-sided EBW that will be developed prior to the fabrication of the bare cavity.

Figure 6 shows a detail of the EBW joint. The bulk of the material can have very different thicknesses due to the forming process and for this reason a wide tolerance of 0.7 mm is used. The groove is machined from the opposite side with respect to the RF surface. Figure 7 shows a detail of the beam pipe and the side port for the jacketed cavity.

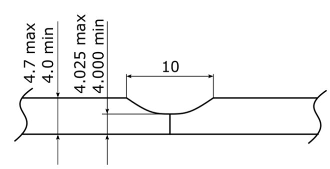

Figure 6: Detail of the EBW joint for the Nb components.

Table 2: Niobium Thickness Reduction Due to Fabrication and Processing

Thickness (mm)	**Material removed (µm)**	**Process**
3.75	-	Minimum required thickness
3.77	20	Cleaning of sheets as received
3.78	10	Localized BCP before weld
3.96	180	Bulk BCP
4.04	75	3 Light BCP
4.70	670	Forming

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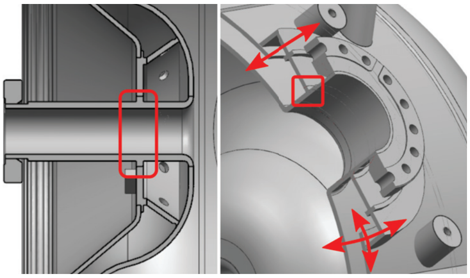

Figure 7: On the left, a detail of the beam pipe and its connection to the He vessel. A collar is machined on the Nb tube to distance the joint between Nb and Ti. As a matter of fact, the Ti could contaminate the RF surface during the welding and the superconducting properties could be lost. On the right, a detail of the side port. Also in this case a collar is machined on the Nb side tube to prevent Ti contamination on the RF side. The interface between the side tube and the He vessel is composed of two Ti components: the side port transition and the side port adapter. This configuration creates three degrees of freedom, allowing to compensate possible misalignment due to the welding.

STRUCTURAL ANALYSIS

Figure 8 shows the set of analysis performed on bare and jacketed cavity. The scope of these analyses is the optimization of the geometry of He vessel and the shape and position of all the stiffeners. The analysis are divided in elastic analysis and elasto-plastic analysis where the MAWP is established. The contributions of gravity and He hydrostatic are negligible and thus they are not implemented into the analysis. The tuner stiffness is simulated using a spring with 70 kN/mm connected between the beam pipe transition and the lower shells.

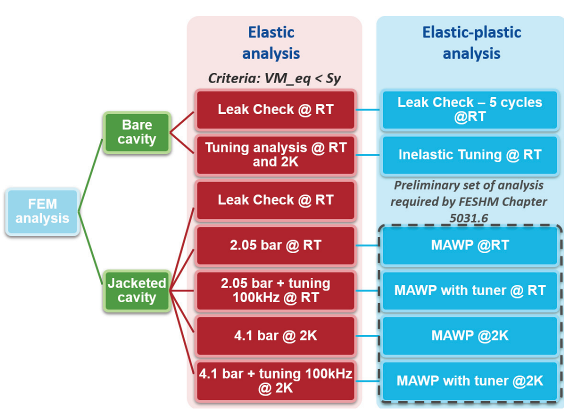

Figure 8: Overview of FEM Analysis performed on bare and jacketed cavity.

The stiffeners are optimized using the Direct Optimization system on Ansys Workbench [12]. Employing the MOGA (Multi-Objective Genetic Algorithm) provided by Ansys, it is possible to select dimensional limits for the stiffeners and, using the maximum Von Mises (VM) stress and longitudinal stiffness as constraints, the optimal configuration is found. Figure 9 shows an example of the correlation between maximum VM stress, cavity longitudinal stiffness as function of the height of the L ring rib. The trends go in opposite directions, thus a compromise on this dimension is chosen. The other geometrical parameters yield similar trends which are not shown in this paper, but are used to identify an optimal configuration.

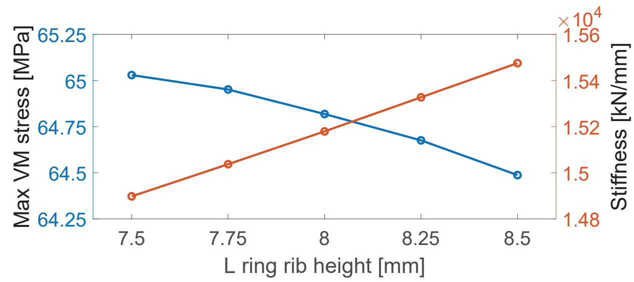

Figure 9: L ring rib optimization. correlation between ring height, maximum stress and cavity stiffness.

Material Properties

Table 3 shows the material properties used for the material employed in the analysis. The true stress - true total strain curves used in the elasto-plastic analysis are calculated using to Ramberg-Osgood equation according to ASME VIII-2 Annex 3-d [6].

Table 3: Material Properties for FEA

Material	Temp K	Yield strength MPa	Ultimate strength MPa	Young modulus GPa
Nb	295	65	150	104.8
	2	317	600	118
Ti gr. 2	295	275	344	107
	2	834	1117	117

Elastic Analysis

Elastic analysis are used to evaluate the structural integrity of the jacketed cavity. The VM stress shall not go beyond the yield strength of the material. Leak check analysis are carried out applying 1 bar differential pressure across the bare cavity shell. Figure 10 shows that the greatest stresses are on the endwall on the tuner side, particularly on the L rib disk. Here $\sigma_{VM}^{max} > S_y$, so plastic deformation is expected and thus an elasto-plastic analysis is performed to check the plastic deformation entity in this region.

The second elastic analysis involves the tunability of the cavity. The stiffness of both endwalls at Room Temperature (RT) and at 2 K is calculated applying a displacement on the beam pipe transition. The longitudinal stiffness on the tuner side at 2 K is 17.3 kN/mm, while on the non-tuner side is

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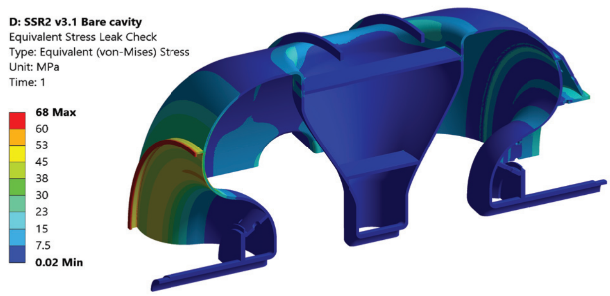

Figure 10: Equivalent VM stress during leak check.

72 kN/mm, for this reason the SSR2 cavity will be tuned (elastically and inelastically) from one side only. Gradually increasing the load on the beam pipe transition allows to find the force corresponding to $\sigma_{VM}^{max} = S_y^{Nb} = 65$ MPa. For the SSR2 cavity this force is 10 kN or 0.65 mm of BP deformation. Considering the sensitivity of the cavity (315 kHz/mm [2]) the elastic tuning range for the SSR2 jacketed cavity is 200 kHz. Figure 11 shows the results for the most critical loading conditions at RT: 2.05 bar He pressure, tuning of 100 kHz on the beampipe; and 2K: 4.1 bar He pressure, tuning of 100 kHz on the beampipe, stresses due to the cooldown.

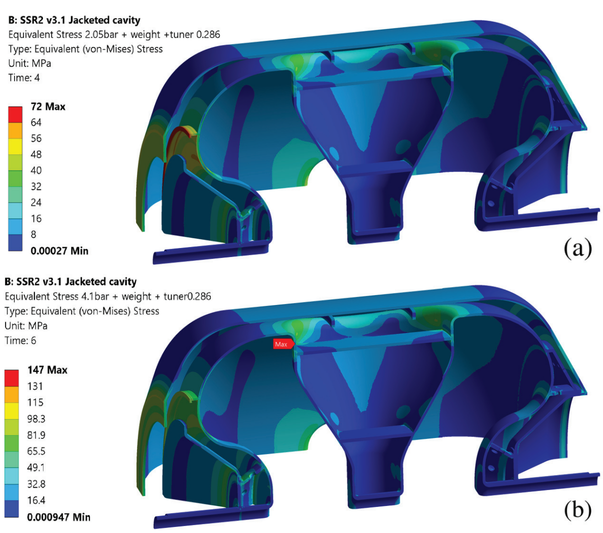

Figure 11: Equivalent VM stress on jacketed cavity (a) at RT with 2.05 bar of He pressure; (b) at 2 K with 4.1 bar of He pressure.

High stresses are localized on geometrical discontinuities. Stress Classification Lines (SCL), shown in Fig 12, are used on these points, according to the ASME Sec. VIII Div. 2 [6], to verify that the maximum membrane + bending stresses are below the allowable value defined by the ASME code.

Elasto-Plastic Analysis

The first elasto-plastic analysis simulates five consecutive leak checks (LC). The result is that after the first LC, where plastic deformation occurs, the residual displacement on

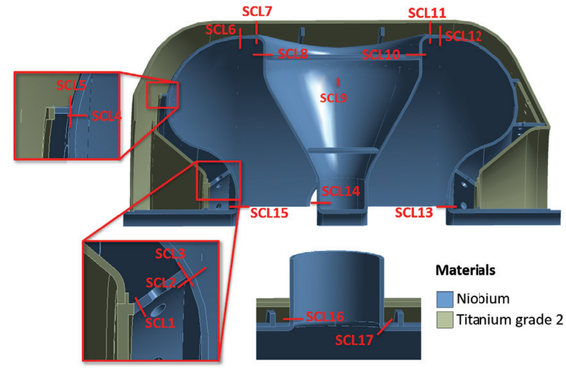

Figure 12: Position of the SCL on the SSR2 cavity.

beam pipe flange is 85 µm which corresponds to 27 kHz of frequency shift. Due to the strain hardening effect, from the 2nd to the 5th LC the frequency shift is negligible. The cavity welding process induces permanent distortions on the cavity walls, with corresponding frequency shifts. To adjust the frequency the cavity is permanently deformed using a fixture. Figure 13 shows the correlation between the force to be applied on the beam pipe transition and the residual frequency shift.

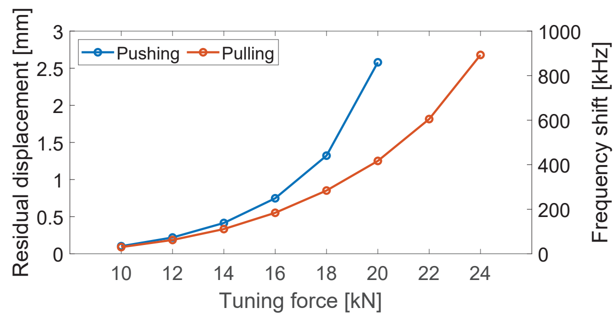

Figure 13: Inelastic tuning of SSR2 cavity.

Another elasto-plastic analysis is used to evaluate the MAWP for the most critical loading conditions, at both RT and 2K. This analysis consists of increasing the He pressure until the plastic collapse of the cavity is reached. The MAWP is then calculated dividing the ultimate pressure by a factor indicated by the ASME code [6] which depends from the loading conditions. At RT the MAWP is 2.76 bar and at 2K is 12.4 bar.

CONCLUSION

In this paper the mechanical design of the SSR2 jacketed cavity has been presented. Manufacturing aspects and structural soundness have been taken into account simultaneously from the first design iteration. The use of the past design and fabrication experience, gained during the development of the single spoke resonators at Fermilab and double spoke resonators for ESS has allowed to converge on a solution that satisfies all the mechanical requirements and implements new technological processes.

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