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MECHANICAL DESIGN AND ANALYSIS OF SRF GUN CAVITY USING ASME BPVC SECTION VIII, DIVISION-2, DESIGN BY ANALYSIS REQUIREMENT*

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Abstract

A prototype SRF gun is currently being designed at FRIB, MSU for the Low Emittance Injector of the Linac Coherent Light Source high energy upgrade at SLAC. This employs a 185.7 MHz superconducting quarter-wave resonator (QWR). The mechanical design of this cavity has been optimized for performance and to comply with ASME Section VIII, Div 2, Design by analysis requirements. This paper presents the various design by analysis procedures and how they have been adopted for the SRF gun cavity design.

INTRODUCTION

At the FRIB facility, MSU, there is an ongoing design and fabrication process for a cryomodule prototype intended for the high-energy upgrade of LCLS-II [1].

Figure 1, illustrates the SRF Gun cavity, which serves as the main element of the cryomodule. The cavity consists of a niobium resonator cavity encompassed by a titanium vessel. Operating at 4K, the titanium vessel holds superfluid helium gas. In addition to providing mechanical support to the cavity, the vessel plays a role in its tuning. Further information regarding the tuner and its mechanical analysis can be found in a separate reference [2]. The vessel is designated as a Pressure Vessel due to its capability to withstand pressures exceeding atmospheric pressure. While the exterior of the niobium RF resonator cavity is cooled by the helium gas, its interior remains in a vacuum state during beam line operation.

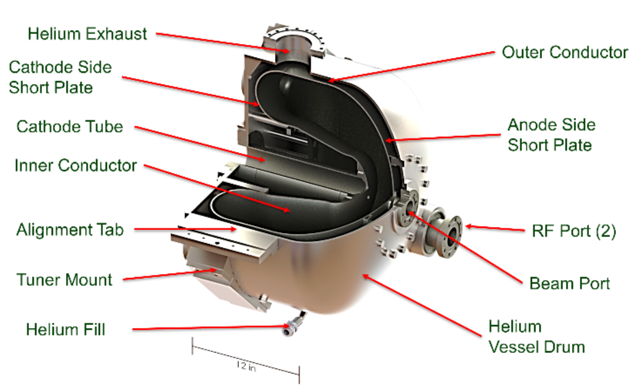

Figure 1: SRF Gun Cavity with key components.

MATERIALS

The SRF Gun Cavity assembly is constructed of four materials: Pure niobium, Ti-45Nb alloy, Grade 2 titanium, and 316L Stainless Steel. Of these materials, only Stainless Steel and Grade 2 Ti are approved by the Code [3], and hence has properties and allowable stresses available from Section II, Part D.

The room temperature material properties and allowable stresses for this analysis are identical to those established before for FRIB cavities.

At cryogenic temperatures, the yield and ultimate stress of Nb, Ti, and SS increase. The properties for these materials at cryogenic temperature were determined through previous work. However, no low-temperature data was available for Ti-45Nb alloy, so its room temperature properties were used for all temperatures. It is expected that, like the other materials, Ti-45Nb alloy would exhibit a significant increase in strength at cryogenic temperatures.

The most critical mechanical property for Niobium is its room temperature yield strength. As Niobium is the weakest material at room temperature and would be the first to yield in a hypothetical pressure scenario, we specify a minimum yield strength of 60 MPa for fine-grain Niobium to our vendors. Tensile tests conducted on Nb samples confirmed this minimum value, showing consistent yield strengths of around 60 MPa or more at room temperature [4]. The yield strength of these samples did not significantly change after baking at 600°C for 10 hours. Previous studies [5] aimed to determine the temperature at which niobium retains its mechanical properties while expelling most of the hydrogen present. They found that baking at 600°C is suitable, and a sharp decline in yield strength occurs at temperatures starting from around 650°C and above, as acknowledged by the authors of [6].

Based on this information, a yield strength of 60 MPa is used for BPVC calculations, which is consistent with all FRIB cavities designed and analyzed for a 60 MPa yield at room temperature

Table 1 presents the material properties employed for the SRF Gun Cavity analysis. Non-pressure boundary components such as the nose and stiffening rings utilize coarse-grain niobium for ease of fabrication and manufacturing. A yield strength of 30 MPa is assumed for these coarse-grain niobium components.

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Table 1: Material Properties for SRF Gun Cavity

Material	Temp K	Yield Strength MPa	Ult. Strength MPa	Young Modulus GPa
Nb	RT	60	160	105
	4K	317	448	118
SS 316L	RT	180	503	199
	4K	350	1228	213
Ti Gr-2	RT	275	344.7	105
	4K	833	1027.3	117
Ti-45-Nb	RT	475.78	546	62
	4K	475.78	546	68

WELDS

The electron beam process is utilized for welding in the Nb and Nb-to-Ti transitions, while the TIG (GTAW) process is employed for Ti-Ti and Nb-Ti to Ti welds. The finite element model does not include explicit representation of the welds. Instead, all weld joints are assumed to be bonded in the contact conditions, and the weld strength is de-rated based on the joint efficiencies specified in Div1-Table UW-12 [7]. Detailed information regarding this can be found in the FRIB Engineering note [8], specifically in the section titled "Weld Joint Overview." Due to the lack of prior knowledge regarding the weld fusion zone, a very fine mesh is used in the cavity assembly model to accurately capture the developed stresses in the weld areas. It should be acknowledged that certain weld geometries may not fully comply with ASME Section VIII, Div. 2, and part 4.2.

LOAD CASES

In order to explain the various load cases and the pressure volumes, a cavity cut section is shown in Fig. 2.

There are three volumes which may be pressurized or evacuated:

1. The volume outside the helium vessel typically evacuated for insulation
2. The He volume inside the helium vessel
3. The volume through which the beam passes on the inside of the Nb cavity itself.

The pressures in these volumes are denoted as P1, P2, and P3, respectively. With regards to pressure, typical operation involves an insulating vacuum, a beam vacuum, and a pressurized He volume. The maximum allowable working pressure for the He volume is set at 0.227 MPa for RT and 0.41 MPa for 4K. Atypical operations may occur if the insulating or beam vacuums are spoiled, and the He space simultaneously evacuated. This reverses the normal operational stress state of the device, producing an external pressure on the Ti shell, and an internal pressure on the Nb cavity; however, this pressure is limited to a maximum differential of 14.7 psid. This loading state is not covered here.

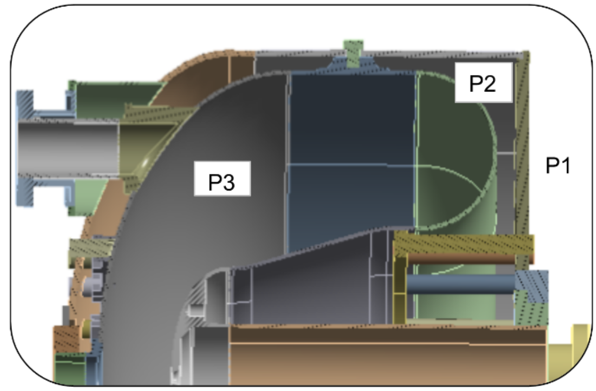

Figure 2: Cut section of the SRF Gun cavity with pressure areas/volumes.

The cavity is subjected to five basic loads:

1. Gravity
2. He liquid head
3. Thermal contraction
4. Tuner extension
5. Pressure (internal and external)

Three of these loads gravity, liquid head, and pressure produce both primary and secondary stresses. The remaining loads thermal contraction and tuner extension are displacement-controlled loads which produce secondary stresses only. Thermal contraction will not be considered in this stress analysis because the titanium vessel, niobium resonator cavity and the interconnecting Ti 45 Nb flanges have almost identical coefficients of thermal expansion, resulting in no mismatch stresses between the interconnected structures. He liquid head is negligible and is not considered. The first four load cases (LC1 though LC4) as shown in Fig. 3, will be covered for all Design by Analysis steps.

RT	Gravity P2 = 0.227 MPa P1=P3=0 MPa	Warm Pressurization
RT	Gravity P2 = 0.227 MPa P1=P3=0 MPa T = 0.14mm	Warm Pressurization + Tuner Extension
4K	Gravity P2 = 0.41 MPa P1=P3=0 MPa	Cold Pressurization
4K	Gravity P2 = 0.41 MPa P1=P3=0 MPa T = 0.14mm	Cold Pressurization +Tuner Extension
RT	Gravity P1=P3=0.1 MPa P2= 0 MPa	Helium Space Leak Check
RT	Gravity P2=P1=0.1 MPa P3= 0 MPa	Cavity Space Leak Check
RT	Gravity P2=0.1 MPa P3= 0 MPa	Bare Cavity Leak Check

Figure 3: SRF Gun Cavity load cases.

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The last three load steps are during cavity fabrication to test for weld leaks. These are not covered here but the cavity has been checked for these loads and passes the Code. However special fixturing is required to hold the bare cavity in space without damaging it.

FINITE ELEMENT MODEL

The cavity model was developed in solidworks and then imported as a .step file to ANSYS WB for FEA. Mechanical properties used are as per Table1. Material assignment is shown in Fig. 4.

Two types of FEA models were generated: Fine mesh model with around 4.5 million nodes and a coarse mesh model with 2.5 million nodes. The fine mesh model is used for majority of the analysis except buckling. Buckling analysis is very computationally demanding. Hence a slightly simplified model with coarser mesh was employed for the buckling solution. The FEA models were generated so as to maximize the hexahedral elements and minimize tetrahedral elements.

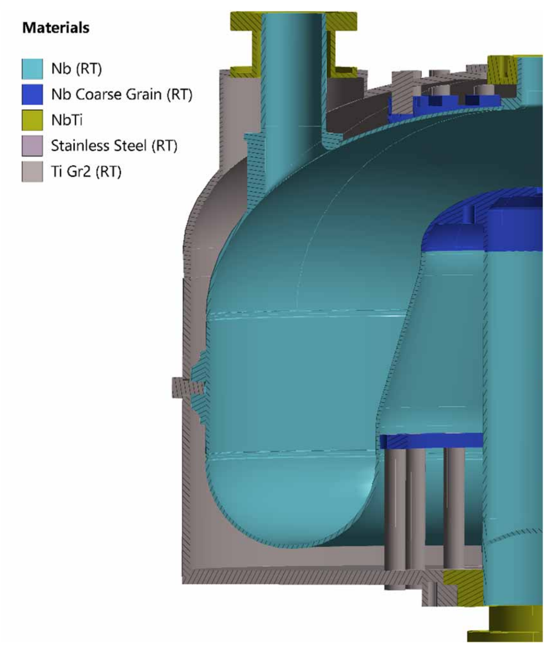

Figure 4: Cut section of the SRF Gun cavity showing the material assignment.

During the manufacture of the cavity, especially during forming, there is a noticeable thinning of cavity walls [9]. Etching also removes some material (~180 micron) from the cavity, this also leads to thinning of the Nb cavity walls. A conservative estimate of the final wall thinning based on above mentioned factors is incorporated into the FEA model.

DESIGN BY ANALYSIS

Design by analysis section of the BPVC Section VIII, Div.2: Part 5 lays down certain requirements and rules which have been followed for the numerical (FEA) analysis presented here. Figure 5, shows the four major analysis types that need to be conducted and requirements met for the cavity to be safe for operations per the code. The analysis types are further elaborated in sections ahead.

Protection against Plastic Collapse

Section 5.2 of the code provides three alternative analysis methods for evaluating protection against plastic collapse. Elastic stress analysis method which involves stress linearization though thickness at various key locations, has been used in the past for various cavities at FRIB. This method, although computationally efficient, is tedious and time consuming for a complex geometry. Stress linearization has to be done at various key locations sometimes involving stress concentration locations. This makes picking the right location for stress linearization line quite important.

Figure 5: BPVC Section VIII, Div.2: Part 5, Design by Analysis Requirement.

Limit Load Analysis Method (Section 5.2.3) has been used here for the analysis and results presented. This is a pass/fail criteria based on FEA model convergence. Limit-load analysis addresses the failure modes of ductile rupture and the onset of gross plastic deformation (plastic collapse) of a structure. Displacements and strains indicated by a limit analysis solution have no physical meaning. Protection against plastic collapse using limit load analysis is based on the theory of limit analysis that defines a lower bound to the limit load of a structure as the solution of a numerical model with the following properties:

1. The material model is elastic-perfectly plastic with a specified yield strength.
2. The strain-displacement relations are those of small displacement theory.
3. Equilibrium is satisfied in the undeformed configuration.

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The load case combinations and load factors are as per Table 5.4 of the code. The assessment procedure is followed as outlined in section 5.2.3.5 of the code. Elastic perfectly plastic plots have been used in ANSYS with tangent modulus set to zero. Large displacements has been turned off in ANSYS as per the code. Since this is a pass/fail criteria, the actual results like displacements and strains indicated by the solution have to physical meaning.

The Table 2 shows the analysis results for all the load case combinations analyzed. The FEA model solutions for all cases converged, hence meeting the criteria.

Table 2: Limit load analysis. Design loads, load case combinations and model convergence results.

Temp	Load Case	Design Load Combination	Convergence
RT	LC1	1.5(P2+Gravity)	Yes
RT	LC2	1.3(P2+Gravity+T)	Yes
4K	LC3	1.5(P2+Gravity)	Yes
4K	LC4	1.3(P2+Gravity+T)	Yes

Protection against Local Failure

As per Section 5.3 of the code, two analysis types can be used to assess these criteria:

1. Elastic Analysis-Triaxial Stress limit
2. Elastic Plastic Analysis-Local Strain Limit

We have utilized Section 5.3.2, Elastic Analysis. As per this, "In addition to demonstrating protection against plastic collapse, the following elastic analysis criterion shall be satisfied for each point in the component"

$$(\sigma1+\sigma2+\sigma3) \leq 4S \text{ or } (\sigma1+\sigma2+\sigma3)/4S \leq 1 .$$

To get the results, a user defined output is requested with ($\sigma_1+\sigma_2+\sigma_3$). σ denotes the three principal stresses and the S is the allowable stress value as per the code. The results are shown in Table 3. The results only show the inner Nb cavity. At every node on the outer resonator bodies for all the four cavity assembly types, the criteria are satisfied.

FEA results satisfy the above mentioned criteria for every node except for a few nodes at rinse port transition weld and the cavity boss weld. These were proven to be caused by sharp edges and are numerical errors, which can be ignored. Elastic plastic analysis of a sub-model was used to confirm this.

Table 3: Protection against Local Failure Results for Niobium Cavity

T	Load Case	Design Load Combination	$\sigma_1+\sigma_2+\sigma_3$ MPa	4S MPa	$\sigma_1+\sigma_2+\sigma_3$ <4S
RT	LC1	P2+Gravity	<160	160	Yes
RT	LC2	P2+Gravity+T	<160	160	Yes
4K	LC3	P2+Gravity	341	845	Yes
4K	LC4	P2+Gravity+T	333	845	Yes

Protection against Collapse from Buckling

The code allows for two different types of analysis: Bifurcation buckling analysis or Elastic-plastic collapse analysis. The bifurcation buckling analysis can be performed with either elastic or elastic-plastic properties. The analysis here is conducted with elastic properties.

For bifurcation buckling analysis, a minimum design factor of $\Phi_B = 2/\beta_{cr}$ is used as per the code. For unstiffened and ring stiffened cylinders and cones under external pressure β_{cr}= 0.80, or Φ_B = 2.5.

The Eigenvalue buckling analysis was conducted in ANSYS with pre-stresses turned ON. This changes the initial stiffness matrix for the buckling solver. Since buckling is governed by the stiffness matrix (depends on the initial pressure and the Elastic Modulus of the material), buckling pressure at room temperature and cryogenic temperatures is almost the same. This is because the modulus of elasticity for Nb increases only by 1% at cryogenic temperatures.

The code suggests to evaluate all buckling modes to determine the minimum buckling load. The current analysis evaluated first two buckling modes. The results presented are for the lowest buckling mode (lowest load or lowest applied pressure). Full model is always considered to capture all the symmetric and non-symmetric buckling modes. It was previously found that using a half or a quarter symmetric model, many buckling modes were not captured hence giving erroneous results.

Table 4 shows the eigenvalue buckling load factor derived from ANSYS simulations for the four load cases. All of them are more than the required value of Φ_B = 2.5.

Table 4: Load Multiplier for Eigenvalue Buckling Analysis

Temp	Load Case	Design Load Combination	Load Multiplier
RT	LC1	P2+Gravity	11.2
RT	LC2	P2+Gravity+T	11.16
4K	LC3	P2+Gravity	7
4K	LC4	P2+Gravity+T	6.9

Protection against Collapse from Cyclic Loading

To show protection against failure from cyclic loading, a fatigue screening analysis and a ratcheting assessment is needed.

Fatigue Assessment The fatigue screening analysis is performed to check if additional fatigue analysis is needed. Two methods are provided in section 5.5.2 of the code, Method A and Method B. Method A has been used in the past for all FRIB cavities and has been used here for this case. The number of cycles in Method A are limited based on the criteria provided in Table 5.9 of the code. In addition to the required cycles, additional cycling due to tuner activity is also considered. The modified criteria then become:

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$$N_{\Delta FP} + N_{\Delta PO} + N_{\Delta TE} + N_{\Delta Ta} + N_{\Delta Tuner} \leq 1000 .$$

The results of the screening criteria, shown in Table 5 show that the cavity has less total cycles during its lifetime than the screening criteria, therefore requiring no fatigue analysis

Table 5: Method A Fatigue Screening Cycles

Type of cycle	Number
$N_{\Delta FP}$	33
$N_{\Delta PO}$	0
$N_{\Delta TE}$	66
$N_{\Delta Ta}$	33
$N_{\Delta Tuner}$	300
Total Cycles	432

Ratcheting Assessment Ratchetting, also known as cyclic creep, is a behavior in which plastic deformation accumulates due to cyclic mechanical or thermal stress. While Fatigue analysis is concerned with avoiding the initiation and propagation of cracks that could eventually cause a sudden fracture. Ratcheting is a failure mode typically associated with components that are subjected to pressure loading and simultaneously large cyclic thermal stresses. The SRF gun cavity is made of niobium and the outside vacuum vessel is made of Titanium Gr-2. These have very similar CTE and hence the induced thermal stresses are negligible. So in our case thermal stresses are not considered.

Two analysis methods are allowed by Div. 2 for the ratcheting assessment: Elastic Stress Analysis (Part 5.5.6) and Elastic-Plastic Stress Analysis (Part 5.5.7). For SRF Gun, an elastic-perfectly plastic stress analysis was used since a model for the analysis that accurately represents the component geometry, boundary conditions, applied loads, and material properties was already developed for previous analyses.

The analysis for protection against ratcheting is performed by application, removal and re- application of the applied loadings to show that the structure eventually shakes down to elastic action, i.e., that the incremental increases in plastic deformations from each cycle are small and diminishing as the number of cycles increases. The finite element model was subjected to 7 load cases. If any one of the following conditions is met, the ratcheting criteria are satisfied

- Structure should have an elastic core
- Repeated cycles result in no change in geometry
- There is no plastic action

Two load cases were considered for checking ratcheting:
Load Case I

- MAWP = 0.227 MPa varied
- Tuner Displacement = 0.14mm varied
- First Load Step pressure = 1.15 * MAWP = 0.262 MPa
- Gravity load included in all load steps

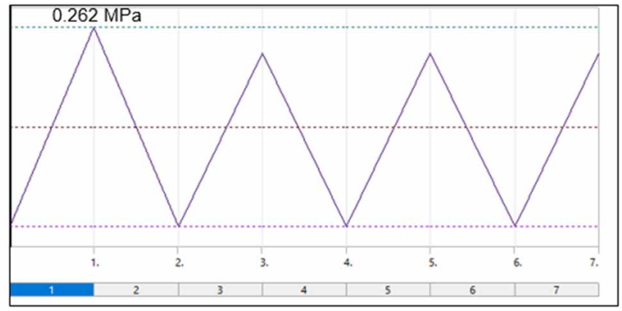

Figure 6: Load case I showing the pressure cycling. Tuner displacement is also cycled along with pressure.

Table 6: Displacements at the End of each Load Cycle

End of Load Cycles	Max FEA model displacement (mm)
1	0.183
2	0.007
3	0.177
4	0.007
5	0.177
6	0.007
7	0.177

Figure 6 shows the Load case I cycles. Table 6 shows the maximum displacements of the cavity after each load step. Analysis shows that there is no change in dimension between the last and next to last cycles (load cases 5 and 7), demonstrating convergence. This indicates that the structure has an elastic core and no permanent change in overall dimensions. The actual plastic strain after the 7 load cycles was found out to be 0.02% at the rinse port weld corner. Everywhere else the plastic strain was zero, demonstration no plastic action. Load Case II is same parameters without tuner displacements and shows no plastic action as well.

CONCLUSION

Structural analysis of SRF Gun cavity and supporting helium vessel design shows that it meets the ASME BPVC, Section VIII, Div. 2, Part 5 by satisfying the following requirements:

1. Plastic collapse – satisfied by a limit load analysis according to 5.2.3.
2. Local failure – satisfied by an elastic stress analysis performed according to 5.3.2.
3. Buckling – satisfied by a linear buckling analysis performed according to 5.4.1.2(a).
4. Fatigue assessment – the need for a fatigue analysis is assessed according to 5.5.2.3.
5. Ratcheting assessment – satisfied by elastic plastic stress analysis as per 5.5.7.2

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