LOWERING THE COST OF THE ILC SRF CAVITY HELIUM VESSEL *

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Abstract

From past work we found that within the cost of the String Assembly that dominates the overall cost of the cryomodules for ILC, the greatest cost elements are the helium vessel with the 2 phase pipe assembly, the niobium material, and the SRF cavity fabrication [1]. The cost of niobium is dependant upon market supply and demand and is essentially out of our control. We have carried out an aggressive study to reduce the cost of cavity fabrication in a high production environment [2], which leaves the helium vessel for further investigation.

It is recognized that significant cost savings may be realized if the helium vessel could be constructed of stainless steel instead of titanium material as is currently planned. To facilitate this change (AES) has developed a niobium to stainless steel transition assembly that will interface the helium vessel to the SRF Cavity at each end. Details of the design and analysis of the low cost helium vessel assembly are discussed along with potential cost reductions for the ILC high production run.

DISCUSSION

The objective of Phase I of this SBIR was to develop a preliminary design of a niobium to stainless steel transition and a conceptual design of the complete helium vessel that we demonstrate by analysis will meet the performance requirements. This result has been achieved. We have a preliminary design for the ILC helium vessel that departs slightly from a recent titanium configuration provided to AES by FNAL as shown in Fig. 1.

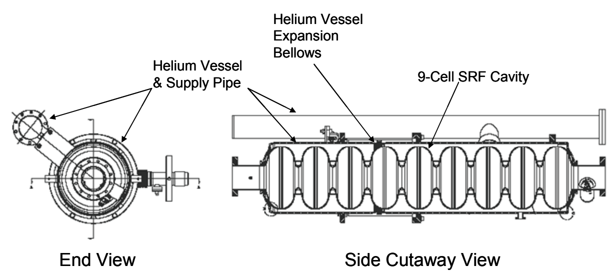

Figure 1: Preliminary Design for the ILC Titanium Helium Vessel and SRF Cavity Assembly.

We also have a detailed design for new end cap transitions from the SRF cavity that interface with the new helium vessel fabricated from stainless steel 316L. We further evaluated the SS slim line tuner under study at FNAL and INFN, and have found that it is compatible with the forces and displacements of the new helium vessel. This effort shows a potential cost savings of more than $100M ($US for CY 2009) for the ILC project.

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Niobium to Stainless Steel Transition

In the left hand side of Fig. 2 we show the current design configuration of the ILC end cell assembly with end cap. In this case, the niobium flange is welded to the Ni55Ti end cap which in turn is welded to the titanium helium vessel. These details were studied and resulted in the configuration shown to the right in Fig. 2 where the key element is the brazed assembly of the “niobium inner flange” with a “SS interface flange” resulting in a transition piece.

In the new design, the brazed transistion assembly is first e-beam welded to the end-cell and then is machined to accept the SS end cap by a second e-beam welding step. The SS end cap interfaces directly to the SS helium vessel by means of a TIG weld. Only one end group assembly is compared in Fig. 1. The other end group assembly has slightly different geometry but in principle is the same.

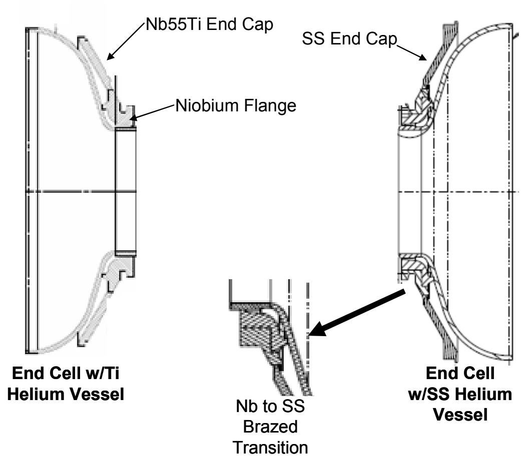

Figure 2: Comparison of ILC SRF Cavity End Cap Assembly Designs.

Figure 3 shows the sequence of steps required to make up the new end cap transition assembly. Three detailed parts are required to fabricate the end cap brazement (transition joint for niobium to SS); the inner niobium flange which is essentially the same as the existing ILC design, the new outer SS end cap rough machined ring that is brazed to the inner niobium flange, and the SS centering plug that is used during the brazing process to prevent the niobium part from loosening the braze material space during the brazing thermal cycle. Also shown is the copper braze foil. The brazement assembly is machined into an intermediate form followed by e-beam welding to the end cell assembly. One of our concerns about this approach was to not overheat or overstress the braze joint during e-beam welding of the transition assembly to the end half-cell.

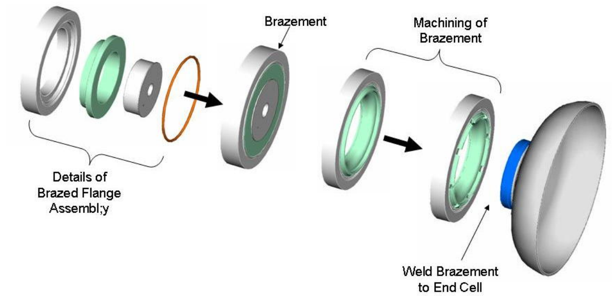

Figure 3: Sequence of Steps that make up the New End Cap Brazed Assembly.

Temperatures and Stresses While Welding

We examined the temperatures and stresses in the braze joint of a rough machined end group transition subassembly during its electron-beam welding to a niobium cavity end cell. The first weld is the "foot" weld of the niobium inner flange to the half-cell. This is comprised of a set of tack welds, a seam weld and finally a full penetration weld. Each of these welds is completed in a strategic order. There are eight "foot" locations spaced evenly around the circumference welded in the order of an eight bolt pattern. Heat loads were applied at the weld joint so that the total power deposited during the weld is consistent with the e-beam power. The braze joint was shown to be far enough away such that the melting-vaporizing-condensing and fusion cycle of the material will not affect the braze joint integrity. The joint material for this braze is copper with a melting point of 1083ºC. The analysis showed that the worst case joint temperature during the welding sequence was 646^{o}C.

In accordance with "The Brazing Book" by LucasMilhaupt, a properly made braze joint will in many cases be as strong as or stronger than the metals being brazed. Furthermore, it has been proven that failure of SS to niobium joints brazed with pure copper always fail in a fracture mode at the copper to niobium interface in a layer of iron rich compound with unknown properties [3]. This reference further confirms that the pure copper braze material changes during brazing to an alloy that is no longer represented by the properties of copper. Subsequently, a stress analysis was completed assuming a metallic bond between the stainless steel ring and the niobium interface piece.

Since the temperature gradients are high during the welding it is expected that the SS ring, the niobium inner flange and the niobium cavity will experience plastic strains. Temperature dependent bilinear elastic-plastic behavior was assumed for our model. The structural analysis compared strains to strain limits of the material. The failure strain limit for annealed SS is about 0.4 and for annealed niobium is greater. The results of the analysis showed that the strains throughout the assembly are all significantly less than 0.02, giving confidence to the ability of successfully performing the intended fabrication operation.

Interaction of Stainless Steel Helium Vessel, Coaxial Blade Tuner, and SRF Cavity

The difference in thermal expansion between the proposed stainless steel helium vessel and the niobium cavity was examined for the effects on the niobium to stainless steel transition pieces as well as the operation and loading of the coaxial tuner, bellows, and helium vessel. A finite element model was developed as shown in Fig. 4. The blade tuner and the piezoelectric tuner are represented by springs and local gaps that model the tuner movement. The bellows minimizes the load into the tuner when the tuner operates to extend the cavity. During cool down to operating temperature the SS helium vessel will contract much more than the SRF cavity. This will tend to unload the blade tuner which is not desirable because of the piezoelectric fast tuning elements which should always be in compression. Our approach to accounting for the differences in subassemblies contractions due to cool down necessitate pre-extending the cavity at room temperature during final assembly. This will strive to always have the tuner and helium vessel in compression. Final assembly tooling is therefore required to set the helium vessel extension so that upon cooling to 2 K the cavity will have contracted the same amount as if it were free.

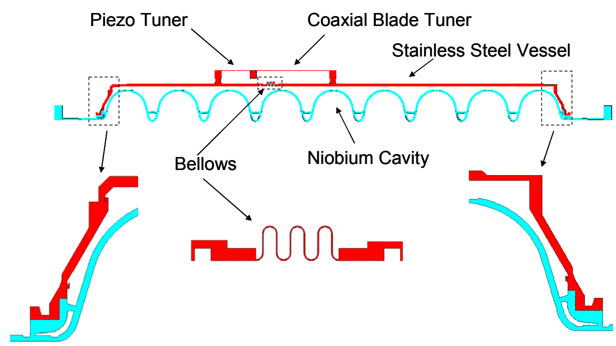

Figure 4: Finite Element Model for Component Interaction between Room Temperature and 2^{o}K.

During the analysis we found that it was necessary to increase the number of bellows convolutions in the helium vessel from the baseline design of 3 to 6 in order to reduce the local stresses in the bellows. We also found the system balanced all conditions of stress and displacements if we set the helium vessel room temperature pre-extension at 0.058". This resulted in a maximum load on the blade tuner of about 6kN, which decreases to about 1 kN as the system is cooled to 2^{o}K. We then used test data available from INFN for a coaxial-slim blade tuner made with SS rings and Inconel-718 blades [4] to establish that the load at a cavity displacement of 1mm at operating temperature would be about 6kN as well. This load is within the tuner design operating range.

Another issue that must be considered in more detail in Phase II of this project is if the tuner is fully extended to 1mm in the cold condition and we have a total loss of cryogenic cooling resulting in a rise of the system to room temperature, the total load on the tuner could go as high as 11.8kN, based upon the present AES structural analysis. This value is near the load limit of the tuner and should be acceptable; however, it might possibly result in some tuner blade buckling. A simple and yet effective solution to this remote problem would be to include a system control that would relax the tuner displacement if a warm-up condition is sensed. Such an administrative interlock would be quite simple and inexpensive, especially since the warm-up time transient is in fact rather slow.

Lastly, we compared the nominal extension (0.058') of the SRF cavity during helium vessel installation with typical displacements that are conducted during cavity tuning. The comparison shows that typical cell by cell cumulative extensions to the cavity can be much greater. This implies that we should not cause any detrimental effect upon a tuned cavity, but it will need to be confirmed during the Phase II testing and validation of the prototype that may result in some cavity tuning process modifications.

Confirmation of Potential Cost Reduction

The configuration was evaluated from a manufacturing and cost standpoint for traditional titanium construction as well as the lower cost stainless steel construction. Two potential fabricators (Titanium Fabrication Corporation, and Joseph Oat Corporation) were enlisted to provide technical support for this part of the effort. We found that the average difference in cost per unit for titanium vs. SS was more than $8K. This effort re-confirmed the upper level estimate from our previous cost estimating effort for a potential cost difference of $7500 per unit at the 6000 unit production level [1]. This difference now has more fidelity over our previous because the latest estimate is based upon a set of preliminary design detailed drawings and specifications that were not previously available.

A summary of helium vessel unit cost information is provided in Table 1.

Table 1: Avg. Unit Cost for Delivered Helium Vessels

MAT'L.	**Titanium**		**316L SS**	
QUAN.	6000	18000	6000	18000
COST	$33,090	$31,366	$24,175	$23,064
SAVINGS			-$8,915	-$8,302

The costs in the table are for US dollars in CY 2009 with inclusion of a material burden (G&A plus fee) that is based upon our original cost model for the ILC [1]. It became evident during this effort that further cost reductions may be achievable with more careful optimization of manufacturing approaches. This will be left for Phase II where we intend to fabricate one or more prototype helium vessels that with the support of Fermilab will be tested throughout ILC operating conditions with an SRF cavity and blade tuner.

In addition to the cost considerations of the helium vessel, we included a cost re-evaluation and comparison for the traditional niobium to Nb55Ti end cap assemblies that mate with the helium vessel vs. the new niobium to SS end cap assemblies for a production run of 6000 SRF cavities. We found that the revised end cap assemblies would be about $923 higher per set than the traditional design, which subtracts from the cost savings of the helium vessel. This cost was also based upon the same model previously used for ILC. The final difference in unit cost to the ILC project therefore becomes $7,992 and $7,379 for production runs of 6000 and 18000 units respectively. In terms of total contract cost savings to ILC we are looking at more than $100M savings.

CONCLUSIONS

We have shown that a SS version of the ILC helium vessel designed to be compatible with the constraints of the ILC system is technically feasible; however, there are some details that still require further validation that can only be proven by additional study and finally by test. This includes load testing of the brazed end cap assemblies early in the next Phase of the project, followed later by thermo-mechanical testing of a prototype helium vessel and cavity subsystem with blade tuner at temperatures from room ambient to 2^{o}K. The potential savings for the ILC project is more than $100M US.

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