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Mechanical Design and Fabrication Studies for SPL Superconducting RF Cavities

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Abstract

CERN's R&D programme on the Superconducting Proton Linac's (SPL) superconducting radio frequency (SRF) elliptical cavities made from niobium sheets explores new mechanical design and consequently new fabrication methods, where several opportunities for improved optimization were identified. A stainless steel helium vessel is under design rather than a titanium helium vessel using an integrated brazed transition between Nb and the SS helium vessel. Different design and fabrication aspects were proposed and the results are discussed hereafter.

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MECHANICAL DESIGN AND FABRICATION STUDIES FOR SPL SUPERCONDUCTING RF CAVITIES

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CERN’s R&D programme on the Superconducting Proton Linac’s (SPL) superconducting radio frequency (SRF) elliptical cavities made from niobium sheets explores new mechanical design and consequently new fabrication methods, where several opportunities for improved optimization were identified. A stainless steel helium vessel is under design rather than a titanium helium vessel using an integrated brazed transition between Nb and the SS helium vessel.

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INTRODUCTION

The SPL is an R&D effort coordinated by CERN in partnership with other international laboratories, aimed at developing key technologies for the construction of a multi-megawatt proton linac based on state-of-the-art RF superconducting technology, which will serve as a driver for new physics facilities such as neutrinos and Radioactive Ion Beams (RIB). Amongst the main objectives of this R&D effort, is the development of 704 MHz bulk niobium β=1 elliptical cavities, operating at 2 K with a maximum accelerating field of 25 MV/m, and the testing of a string of cavities integrated in a machine-type cryomodule.

In an initial phase, at CERN, four β=1 cavities will be supplied and will need to be tested together as they would operate in a machine-type cryo-module [1]. Fig. 1 presents the cavity together with its helium tank, main coupler [2], HOM coupler, tuner, and cold magnetic shielding in the configuration that will be tested at CERN in the cryo-module.

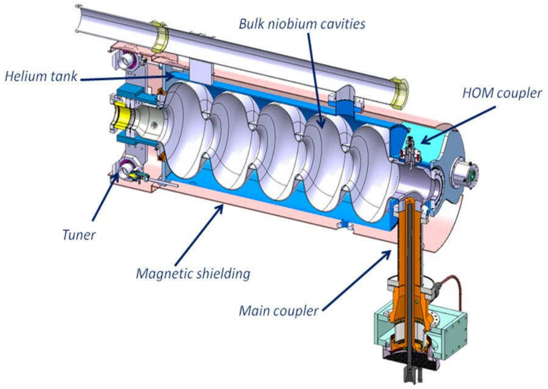

Figure 1: SPL β=1 cavity in its helium tank.

CAVITY

The main design properties of the β=1 cavities are summarised in Table 1, for a 50 Hz pulsed operation, 20 mA current and 0.8 ms beam pulse length.

Table 1: β=1 Cavity, Main Design Properties and Operation.

Property	Units	Value
Cavity material	-	bulk niobium
Gradient	MV/m	25
Quality factor Q_0	-	$5 \cdot 10^9$
R/Q	-	570
Operating Temp.	K	2
Cryog. duty cycle	%	8.22
Dynamic heat load	W	20.4

MATERIAL

Cavities will be manufactured using high purity niobium. CERN has placed an order to purchase 570 kg of pure niobium in the form of sheets and tubes. The whole of the material supply goes through an extensive series of tests:

- Ultrasonic inspection, for continuity faults and for attenuation variations (attenuation specification < 20%);
- Surface roughness, Rt (specification Rt ≤ 15 µm).
- Hardness, HV10 (specification < 60 HV10);
- Microstructure, for grain size and uniformity;
- Electrical residual resistivity ratio RRR, in bulk material (specification RRR > 300);
- Tensile properties, longitudinal and transverse to rolling direction (specification tensile strengths > 140 MPa, yield strengths between 50 MPa to 100 MPa, elongation at break > 40%).

MANUFACTURING

A copper cavity mock-up is under fabrication at CERN with the same geometry as the future niobium cavities. This mock-up, aiming to be used for real-scale HOM measurements, is also used to set all the manufacturing parameters and to identify any difficult steps. The processes of fabrication such as mechanical design, shaping, and welding of half-cells were done by CERN.

To produce accurate shapes, spinning has been chosen as a shaping technique for the half-cells as well as the end groups (Fig. 2).

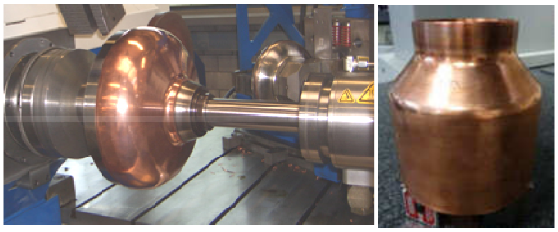

Figure 2: Spinning of Cu half-cell and end group.

The inner surface of the spun half-cells was then machined by turning to improve shape accuracy.

Twenty-two half-cells were produced and checked, with the achieved shape accuracies being summarized in Table 2.

Table 2: Shape Accuracy of Copper Spun Half-Cells.

	Final shape accuracy
Average shape accuracy	± 150 µm
Shape accuracy min. deviation	± 120 µm
Shape accuracy max. deviation	± 250 µm

Helium Tank

Two choices of material were studied for the helium tank: stainless steel and titanium. Titanium has the advantage of having the same thermal contraction as niobium (to the order of 1.5 mm*m^{-1} from ambient temperature to 2 K), while the thermal contraction of stainless steel is approximately double. The use of a stainless steel tank would induce either the need for a larger tuner range than a titanium tank or larger thermal stresses to the cavity. However, stainless steel is more easily manufacturable and costs are therefore reduced [3].

One of the driving elements for the mechanical design was the transitions from the helium tank to all the adjacent components, in particular the main coupler. This analysis is detailed in the following paragraphs. The baseline for the β=1 cavities that will be tested in a cryo-module at CERN is a stainless steel helium tank.

Niobium to Titanium Transitions

Both titanium and stainless steel helium tanks have been designed and their feasibility checked.

An alloyed version of titanium was preferred to pure titanium. The grade 5 titanium Ti6Al4V is significantly stronger than the commercially pure titanium while having the same stiffness and thermal properties. This grade is heat treatable, already used in many cryogenic applications and has an excellent combination of strength, corrosion resistance, weldability and fabricability. Its mechanical properties allow its use for manufacturing of ConFlat (CF) flanges, cheaper than the NbTi flanges usually utilized when titanium helium tanks are chosen.

One possible solution for the interfaces of the accelerating cavity to the helium tank is a welding between Nb and Ti6Al4V.

The electron beam (EB) process was used for welding high purity (RRR≥300) niobium to a titanium alloy (Ti6Al4V). Analysis of the welding before and after outgassing heat treatment (800° C/2h) was based on non destructive testing (dye penetrant and X-Rays), mechanical tests before and after heat treatment (tensile tests and micro-hardness profiles), macro and micro-structural assessment via optical and scanning electron microscopy (SEM). The cross-section of weld macrostructure is shown in Fig. 3.

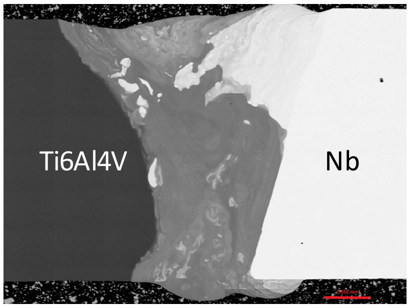

Figure 3: Macrograph of EB weld of niobium to Ti6Al4V.

The average tensile strength before Heat Treatment (HT) was 152.7 ± 2.7 MPa with an average elongation at break of 24.8 ± 2.7%. After HT, the average tensile strength was 158.8 ± 2.2 MPa with an average elongation at break of 26.6 ± 0.1%. All of the samples broke in the bulk niobium.

The hardness of the weld metal zone ranges from 201 to 311 HV0.05, which is an intermediate value between the hardness of both parent metals.

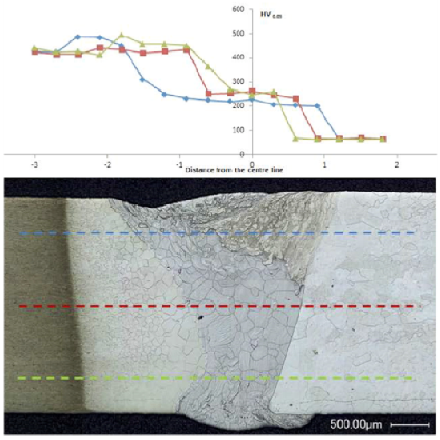

Figure 4: Hardness profile across the weld.

Samples after HT did not show substantial differences in the hardness values compared to the samples before HT (Fig. 4).

Energy Dispersive Spectroscopy (EDS) semi-quantitative analyses were performed to assess the composition of the weld bead. There is no remarkable composition difference in the samples after HT.

Results showed no weld defects or mechanical weakness. As a first conclusion, this transition from Grade 5 titanium to pure niobium, by EB welding, could safely be used for our application.

A qualification of welding procedures according to ISO 15614-11 is ongoing. Included in this qualification are: visual examination, radiographic examination, surface crack detection, metallographic characterization, hardness test, transverse & longitudinal bend tests and transverse tensile test (at room temperature as well as at 77°K).

Niobium to Stainless Steel Transitions

Fusion welding of niobium and stainless steel was difficult to implement because it generates brittle phases (intermetallics) in welds. Moreover, the physical and mechanical properties of the two base metals present big differences in thermal conductivity and linear expansion coefficients, which would lead to a large temperature gradient and thermal stress in the joint during the welding. On the other hand, brazing can eliminate the problems in fusion welding because the base metals remain in the solid state during joining. This brazing technique has been developed at CERN and many successful examples have been reported [4] [5].

In addition to the well-mastered niobium to stainless steel brazing technique, a R&D programme has been started at CERN aiming to explore electron-beam welding possibilities between niobium and stainless steel. Based on its advantages of high-energy density, precisely controllable heating position and radius, EB welding is the most frequently utilized fusion-welding technique in the field of dissimilar metals joining. A pure copper (OFE Cu, 1 mm thick) interlayer sheet was adopted in the present work to join niobium and 304 L stainless steel by EB welding.

The first passage acted on the copper layer near the interface between niobium and copper, the second passage acted on the interface between copper and stainless steel with identical beam parameters for both of them. Microstructure observation and composition measurements are ongoing. In the preliminary tests, according to this configuration, the macrograph of the weld is characterized by full penetration as shown in Fig. 5. Furthermore, it could also be seen that there was solid solution of copper uniformly distributed in weld, which improves the plasticity of the joint. Absence of intermetallics that might fragilise the weld is still to be carefully checked.

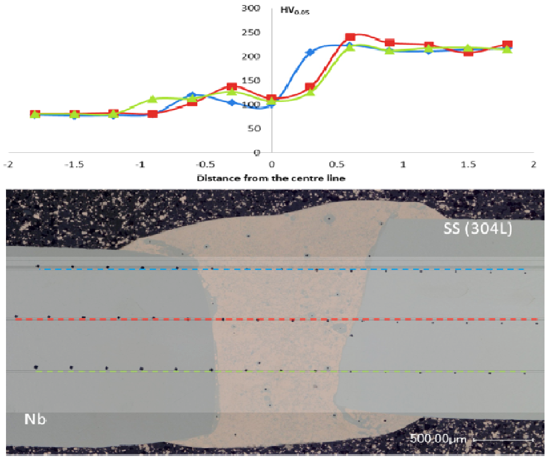

Figure 5: Macrograph & hardness profile of the weld.

CONCLUSION

A string of four SPL superconducting β=1 RF cavities are planned to be installed by 2013 in a so-called Short cryo-module and will be tested at CERN in a machine-type configuration, powered by high-power RF. Extensive studies have already been done with respect to the mechanical aspects of the cavities and helium tank, and the construction of these four cavities is foreseen by the end of 2012.

Within the framework of the SPL R&D study, innovative mechanical solutions have already been explored and a number of R&D studies are still ongoing with several promising results already having been obtained.

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