# MECHANICAL DESIGN OF THE HWR CAVITIES FOR THE SARAF SRF LINAC

N. Misiara, L. Boudjaoui, G. Ferrand, P. Hardy, F. Leseigneur, C. Madec, N. Pichoff
CEA/DRF/IRFU/SACM-SIS, Gif-sur-Yvette, France

*Abstract*

SNRC and CEA collaborate to the upgrade of the SARAF accelerator to 5 mA CW 40 MeV deuteron and proton beams (Phase 2). CEA is in charge of the design, construction and commissioning of the superconducting linac (SARAF-LINAC Project). The SCL consists in 4 cryomodules. The first two identical cryomodules host 6 half-wave resonator (HWR) low beta cavities ($\beta$ = 0.09) at 176 MHz. The last two identical cryomodules will host 7 HWR high-beta cavities ($\beta$ = 0.18) at 176 MHz. The fully equipped cavity includes the niobium cavity with its helium tank, the couplers and the frequency tuning system. In this paper, the mechanical design and the foreseen qualification procedures for both cavities and tuning systems are presented with compliance, to the best extent, to the rules of Unfired Pressure Vessels NF-EN 13445 (1-5) standards.

## INTRODUCTION

The SARAF-LINAC project, managed by CEA (France), integrated to the SARAF-Phase 2 project managed by SNRC (Israel) has been introduced in [1].

This paper focuses on the mechanical design, complying with the European Pressure Equipment Directive (PED), and more specifically to EN-13445. The mechanical design of the Frequency Tuning System (FTS) is also detailed.

Figure 1 shows the cavity with its helium tank, power coupler and frequency tuning system.

## PRESSURIZED EQUIPMENT

### *EN-13445 and Design Cases*

The vessel made of niobium constituting the cavity and the He-tank made of titanium are considered as pressure vessels. Materials (Nb, Nb-Ti alloy and Ti), nominal operating conditions (4.45 K) and shapes of the cavities are not covered by the European Standard EN-13445-3, however, this standard was used as guidelines for the mechanical design.

Multiple cases were considered, however, only the most critical cases were computed, called design cases, according to the guidelines of the EN-13445-3. The definition of the design cases is detailed in Table 1. The nominal helium pressure is 1.2 bar and the burst disc opening pressure is 2 bar.

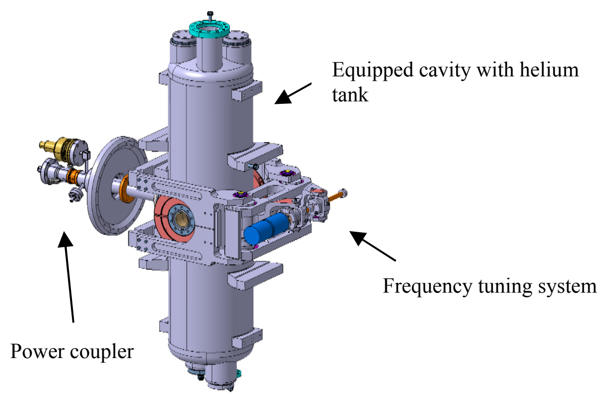


Figure 1: On the top, fully equipped low-beta (LB) cavity with power coupler and tuning system. . On the bottom, fully equipped high-beta (HB) cavity.

Design case 1 corresponds to the pressure test performed on the cavity (Nb-vessel and helium tank assembled) at 2.86 bar at room temperature. The standard defines the test pressure as being 1.43 times the maximum pressure.

Design case 2 corresponds to the test of the FTS on the cavities at 4.45 K. The pressure considered is the opening pressure of the burst disc, i.e. 2 bar.

Table 1: Detail on the Design Cases

| | Design case 1 | Design case 2 |
|---|---|---|
| *Geometry* | LB and HB cavities | Full-equipped LB and HB cavities |
| *Type* | Test case | Normal case |
| *Temperature* | 300 K | 4.45 K |
| *Loading* | Test pressure: 2.86 bar | Helium pressure: 2 bar FTS effort |

As long as the cavity is not at cryogenic temperature (4.45 K), the FTS will remain disengaged by the main security controller.

### *Material Properties*

The material properties considered for the mechanical simulations are detailed in Table 2.

Table 2: Material Properties

| Material | Temp [K] | Young mod. [GPa] | Sy [MPa] | Su [MPa] |
|---|---|---|---|---|
| *Nb (ASTM B393)* | 4.45<br>293 | 105 | 317<br>40 | 600<br>95 |
| *Ti Gr 2 (ASTM B265-06)* | 4.45<br>293 | 107 | 834<br>275 | 1117<br>345 |
| *NbTi (ASTM B265-06)* | 4.45<br>293 | 62 | -<br>410 | -<br>450 |

The material properties presented come from previous studies ([2], [3] and [4]) and are used for simulations. The standard requires to undertake a qualification process on the material after being delivered to verify that the material specifications are met.

## NUMERICAL SIMULATIONS

### *Finite Element Analyses (FEA) Model and Meshing*

The standard proposes two methods to design the structure. First, an analytical method ("Design by Formulae") proposes models and formulas to design pressure vessels for specific geometries, materials and working conditions. For cavities, as none of the previous parameters are covered by the standard, the "Design by Formulae" method could not be followed. Therefore, the second method, the numerical method (Design by Analysis) was performed using FEA software ANSYS Workbench. A complete 3D model using bulk elements has been computed and was used to validate the design, as requested by the standard. In order to increase the accuracy of the linearization process, at least two elements through the thickness of the walls are requested.

### *Linearization*

The European standard imposes to linearize the stress field into the pressure vessel walls in order to separate the different stresses into 3D elements. Depending on the considered case (normal, exceptional or test case), the criteria on allowable stress differs as detailed in Table 3. Linearization process is already implemented in ANSYS, therefore it is only necessary to check if the previous criteria are met. European standard details the admissible stresses to be considered depending on the location on the structure, welding coefficient and control method.

Table 3: Values of Admissible Stress Depending on Temperature and Case Type

| Material | Temp[K] | S [MPa] normal case | S [MPa] exceptional case |
|---|---|---|---|
| *Nb* | 4.45<br>293 | 211<br>26.5 | 302<br>38.1 |
| *Ti Gr 2* | 4.45<br>293 | 465<br>143.5 | 794.3<br>261.9 |
| *NbTi* | 4.45<br>293 | -<br>187.5 | -<br>390.4 |

## TEST PRESSURE SIMULATIONS

The thickness of the Nb parts has been minimized while maintaining the structural integrity during the test pressure simulations (see Table 1). For this purpose, the thickness was reduced (with a limit of 2 mm), increasing locally the stresses on the walls. When the stresses was close to the maximal acceptable stresses (see Table 3), the thickness was rounded to the upper closest value in mm. Table 4 details the final minimum local thickness of the different sheets to meet the requirements of the standard.

The following simulations, with the frequency tuning system, were computed with these optimized thicknesses.

Table 4: Vessel and Tank Parts Thicknesses

| | Low $\beta$ cav. | High $\beta$ cav. |
|---|---|---|
| *Nb – Outer conductor and torus* | 2 mm | 3 mm |
| *Nb – Inner conductor* | 2 mm | 2 mm |
| *Ti – Cylindrical shell* | 3 mm | 4 mm |
| *Ti – Torispherical shell* | 4 mm | 4 mm |

## FREQUENCY TUNING SYSTEM (FTS)

### *Cavity Sensitivity*

The frequency was defined to 176 MHz in nominal operations. The FTS is designed to overcome detuning due to manufacturing defects including the chemical treatment, thermal shrinkage of the structure, pressure deformation etc. A first bench of coupled mechanical/RF simulations carried out the cavity sensitivity to the tuner [5], [6]. Table 5 presents the tuning parameters of the cavities.

Table 5: Tuning Parameters of the Cavities

| | Low $\beta$ cav. | High $\beta$ cav. |
|---|---|---|
| *BP sensitivity [kHz/mm]* | 653 | 158 |
| *Required BP Displacmt [mm]* | 0.15 | 0.63 |
| *Tuning Range [kHz]* | 0-100 | 0-100 |

(BP: Beam Port)

### *Mechanical Design*

The FTS design is based on IFMIF Linac [7] and is presented in Figure 2. The objective is to deform reversibly the HWR at 4.45K by applying an effort on the beam ports. Pairs of flexible arms apply the effort generated by a stepper motor, on both beam ports simultaneously. A kinematic chain composed of the arms, an eccentric and additional levers, increases the effort applied on both beam ports. The principal characteristics of the FTS are gathered in Table 6.

Table 6: FTS Main Parameters

| | BP disp. [mm] | Motor axial load [N] | Effort on BP [kN] |
|---|---|---|---|
| *LB* | 0.2 | 200 | 3.5 |
| *HB* | 0.65 | 320 | 12.3 |

Figure 2 shows the HB and LB FTS, before being installed on the cavities.

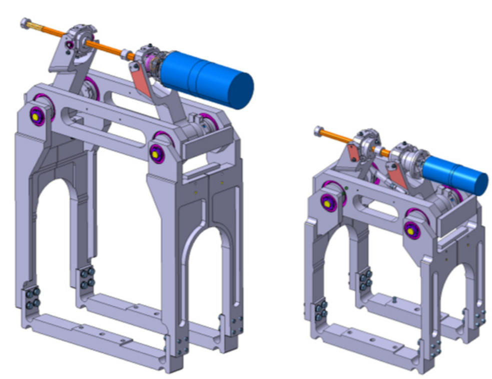

Figure 2: High- and low-beta FTS (on the left and on the right respectively).




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The FTS will apply the effort on the cavity using intermediate interface flanges. In order to limit the rotation of the beam ports while the FTS is pushing on the flanges, the effort is concentrated as close as possible around the beam axis with pushing studs (see Figure 3.A). An adjusting strut (Figure 3.B) was designed to avoid undesired movements of the structure when it is not engaged yet, for example during installation or maintenance.

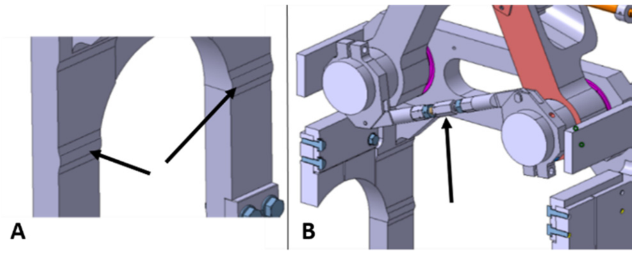



Figure 3: A: Pushing studs B: Adjusting strut.

Stainless steel (AISI316L), has been chosen for the constitutive parts of the low- and high-beta FTSs. Stainless steel is stiffer than titanium, introducing less elastic deformations. A heat treatment will be applied on the parts to reduce their magnetization (especially the bearings).

The loading has been separated into 3 steps:

1. Cooling, from 293 to 4.45 K of the entire structure;
2. Helium pressure applied into the vessels (2 bar) ;
3. FTS load applied on the flanges (3.5 and 12 kN).

In this way, it is possible to isolate the contribution of each of them. Figure 4 presents the displacement field of the HB cavity and its CTS at cold temperature, when the CTS is engaged and pushes on the cavity.

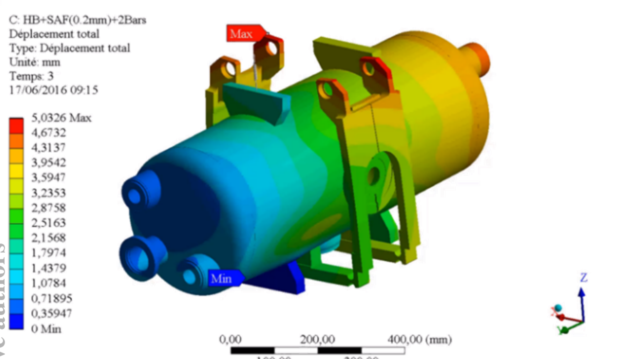
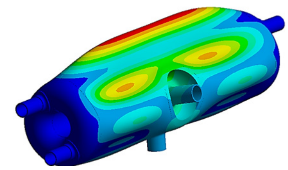
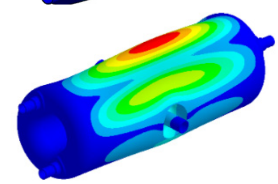



Figure 4: Displacement field of the High-beta fully-equipped cavity.

## BUCKLING

The Nb-vessel is submitted to an external pressure, therefore the inherent risk of failure by buckling must be studied. The criterion to be met is a minimal load multiplier of 3. The larger the first eigenmode load multiplier, the lower the risk to see failure by buckling to occur. This criterion is not given by this specific standard, but a load multiplier of 3 is a commonly used value.

Table 7: First Buckling Eigenmode and Load Multiplier of LB and HB Cavities

| Mode | Load multiplier | Critical load (MPa) | |
|---|---|---|---|
| *1* | 7 | 1.4 |  |
| *1* | 5.8 | 1.16 |  |

In both cases, as presented on Table 7, the minimum load multiplier of 3 is exceeded, validating the design of the Nb-vessels for buckling.

## CONCLUSION

The design of the equipped cavities is validated for the SARAF phase II Linac. The cavities were designed in compliance to European standard guidelines. Final design of the components were validated in June 2016 by SNRC. We are launching the call for tender for prototype manufacturing. Test of the first cavity prototypes is expected in September 2017.

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