MECHANICAL ANALYSIS OF THE XFEL 3.9 GHz CAVITIES IN SUPPORT OF PED QUALIFICATION*

M. Moretti, P. Pierini, INFN - LASA, Segrate, Italy
Andreas Schmidt, DESY, Hamburg, Germany

Abstract

We present the FEA stress analysis under different mechanical conditions of the XFEL 3.9 GHz superconducting cavities. The analysis is being performed in support of the necessary qualification according to the Pressure Equipment Directive European Norms, for the operating conditions set in the European XFEL project.

INTRODUCTION

This paper focuses on the stress analysis of the 3.9 GHz superconducting (SC) cavities for the Third-Harmonic system of the European XFEL project. This system is located right after the injector module, before the first bunch compressor, and it consists of a single module with 8 cavities plus 1 superconducting quadrupole.

All XFEL SC cavities need to be certified according to the Pressure Equipment Directive (PED 97/23/EC) for Category IV, with the formal approval by an appointed Notified Body (in this case the German TÜV Nord). For the 1.3 GHz cavities the procedure follows the certification process for a large scale production (Module B: EC Type Examination in which the design is assessed through the analysis of test pieces and Module F: Product Verification for the controls on the 800 series products) [1,2]. As materials (e.g. Nb, NbTi) are not foreseen by existing standards, a Particular Material Appraisal (PMA) has been issued by TÜV for this particular application. The 3.9 GHz cavities are approximately 1/3 of the size of the main resonators, with the same wall thickness, so they are considerably stiffer. Materials, welding schemes and procedures are similar to those followed for the main linac cavities. A new certification process with the involvement of the Notified Body was anyway necessary. This paper contains the structural analyses which have been carried out in support to the PED approval by TÜV.

The mechanical simulations are performed by means of the finite element (FE) code ANSYS, using an axisymmetric 2D model representative of the SC cavity in its helium tank. The first step is the calculation of the cavity stiffness and its comparison with the expected value, in order to find out if the FE model is valid and consistent. Then the minimum longitudinal cavity displacement that induces the achievement of the yield strength for the materials used for its fabrication is identified. Finally the stress analysis is performed by imposing the Maximum Allowable Working Pressure, which is set by the maximum pressure load distribution for a malfunction of the cryogenic system. Tuner stiffness and the thickness reduction on the welding regions are accounted for. The cavity design is validated according to the UNI EN 13445-3 standard.

DEVELOPMENT OF THE 2D FE MODEL

A rotational axisymmetric 2D model with 8-node-elements (PLANE 183) representative of the superconducting cavity in the helium tank has been implemented in ANSYS. The model is depicted in Fig. 1. An ideal linear elastic behavior is assumed for the materials. Material used for cavity fabrication has been authorized by TÜV through a PMA, following the 1.3 GHz cavity experience. Agreed material properties are summarized in Table 1.

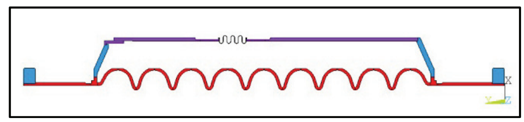

Figure 1: Axisymmetric 2D model.

Table 1: Material Properties

Material	Young's modulus (MPa)	Poisson's ratio	Density (kg/m^3)	Yield strength (MPa)
Ti-1	108000	0.34	4510	200
Ti-2	111000	0.34	4510	280
Nb-300	106000	0.40	8570	50
Ti-45Nb	62000	0.37	5700	480

In the first simulation the right flange of the cavity is constrained with no displacement, while the left one is stretched in the horizontal direction. The reaction on the left stretched flange is reported by the code and the cavity stiffness (corresponding to the stiffness of the whole system because of the negligible Ti-1 bellows rigidity) can be calculated. The result agrees with the expected value (K_{cav} ≈ 5500 N/mm). Then this verification confirms that the 2D FE model is valid and representative of the real superconducting cavity inside the helium tank.

MAXIMUM DISPLACEMENT

As a starting point, it is necessary to determine the maximum strain of the system without entering the plasticity range of the materials. A set of simulations is performed in order to identify the minimum horizontal cavity displacement that induces the achievement of the yield strength for the materials (Table 1). The right flange is constrained with no displacement, while the left one is stretched by varying Δy in the horizontal direction. The equivalent Von Mises stresses can be calculated by the code, focusing on the most stressed parts: Ti-1 compensator with yield strength equal to $R_{0.2}$ = 200 MPa (without considering the cold work hardening) and Nb-

ISBN 978-3-95450-132-8

300 superconducting cell iris with yield strength equal to $R_{0.2}$ = 50 MPa. The results are summarized in Fig. 2 and Fig. 3. As can be seen, the Ti-1 yield strength is never reached, not even stretching the cavity by the maximum displacement range allowed by the tuning system (that is 1 mm), while the Nb-300 yield strength is quickly reached by a horizontal displacement equal to 0.17 mm. Anyway these results are not relevant, because the stress linearization and verification according to the norm (UNI EN 13445-3) has to be performed.

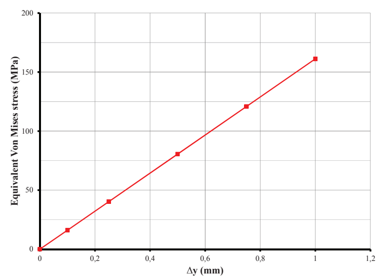

Figure 2: Equivalent Von Mises stress at the Ti-1 compensator as a function of Δy.

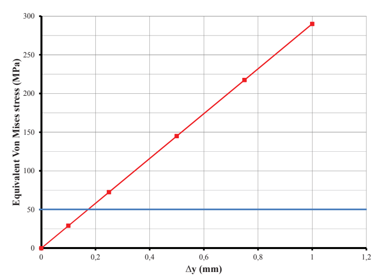

Figure 3: Equivalent Von Mises stress at the Nb-300 cell iris as a function of Δy.

STRESS ANALYSIS AND VALIDATION

An important step in the design certification process is the welds qualification. The extensive experience of the 1.3 GHz activity was used to define the minimum penetration of the welded joints. On the basis of conservative assumptions, in this simulation the reduction of the thickness on all welding sections has been implemented. Also the tuning system contribution is added by means of constraints on the two tuner rings.

A 4 bar pressure (MAWP condition) is applied on all surfaces in the inner volume of the helium tank, while the remaining structures are left at zero pressure: this pressure load distribution represents the extreme case for a malfunction of the vacuum system and it conservatively covers all the other cases. One flange ring of the tuning system is fixed in the cavity axial direction, while the axial displacement of the helium tank is limited to 0.3 mm at the opposite flange ring of the tuning system: a boundary condition of 0.3 mm is used at this position [3].

The model and the structural BCs are represented in Fig. 4. Fig. 5 shows the details of the meshing for the FE model.

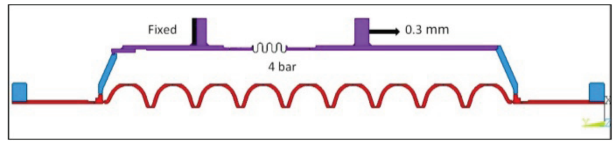

Figure 4: 2D model with indication of the BCs.

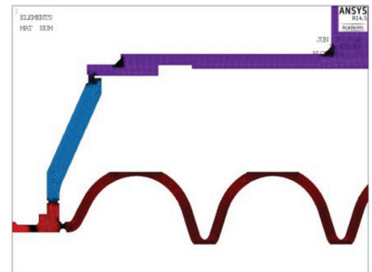

Figure 5: General view of the meshing for the 2D model.

Strength Analysis

The total displacement is reported in Fig. 6 and the maximum value is 0.336 mm.

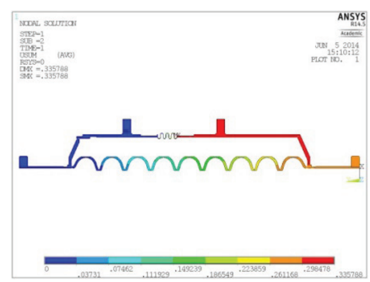

Figure 6: Total displacement in the 2D model.

The maximum value of the equivalent Von Mises stress in the cavity is 164 MPa and it occurs at the peak of the Ti-1 bellows convolutions, where the bending load is high because of the axial tensioning by means of the tuning system. In the cell iris sections the equivalent Von Mises stress reaches 136 MPa. The stresses are very low in most of the other welded regions compared to the yield strength of the related material (below 80 MPa according to the colored scale). Fig. 7 and Fig. 8 show the distribution of the equivalent Von Mises stress for the compensator and the iris sections, i.e. the main stressed parts of the assembly.

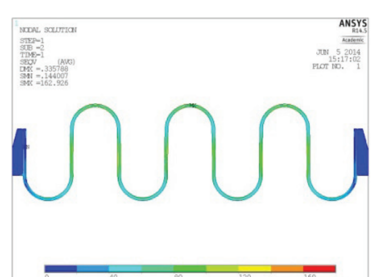

Figure 7: Von Mises stress at the compensator.

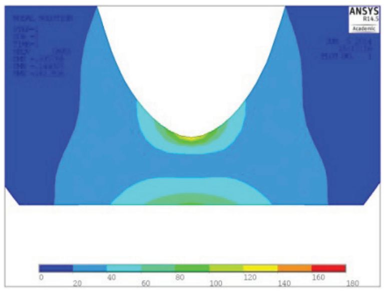

Figure 8: Von Mises stress at the cell iris.

Stress Linearization and Verification

Since the most stressed regions are the Ti-1 compensator peak and the Nb-300 cell iris, in the following sections the stress linearization, categorization and verification according to the European code EN13445-3 will be performed only in the two regions above [4]. Concerning the other welding regions, it was considered not necessary to perform the stress linearization and verification because of the low Von Mises stresses, that are far below the maximum allowable stress of the related materials.

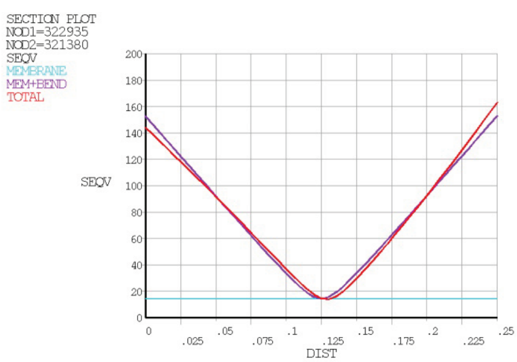

Figure 9: Linearized equivalent Von Mises stress through the wall thickness of the compensator peak.

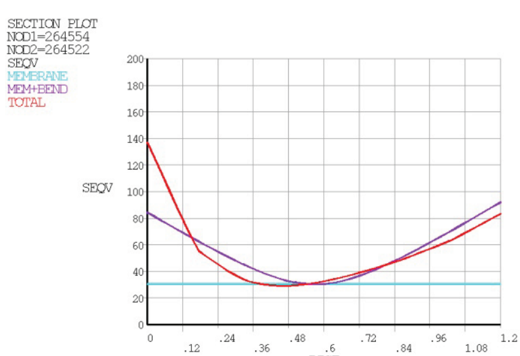

Figure 10: Linearized equivalent Von Mises stress through the wall thickness of the cavity iris weld.

Bellows Peak. The linearized equivalent Von Mises stress through the wall of the peak of the compensator convolutions is shown in Fig. 9. A membrane stress of 13 MPa deriving from the internal pressure can be observed. According to Appendix C of UNI EN 13445-3 code, it has to be classified as a general primary membrane stress and verified against the nominal calculation stress *f*. The latter one is derived from the Ti1 yield strength (200 MPa, without taking into account the cold work hardening) under consideration of a safety factor of 1.5: then the nominal stress has to be verified against the limit of 133 MPa. The maximum membrane plus bending stress is 152 MPa resulting from the high bending load due to the tuning system displacement. This stress has to be classified as a secondary membrane plus bending stress and verified against 3*f* (400 MPa). Then the calculated stresses on the bellows section are below the allowable stresses.

Cell Iris Weld: The linearized equivalent Von Mises stress through the cell iris thickness is depicted in Fig. 10. Here the membrane stress is 31 MPa and it has to be classified as a general primary membrane stress and verified against the nominal calculation stress *f*, which comes in this case from the Nb-300 yield strength (50 MPa) under consideration of a safety factor of 1.5: then the nominal calculation stress is 33 MPa. The maximum membrane plus bending stress is 92 MPa and it has to be classified as a secondary membrane plus bending stress and verified against 3*f* (100 MPa). Then the calculated stresses on the bellows section are below the allowable stresses.

CONCLUSIONS

The results of the strength analysis according to the EN 13445-3 code by means of the finite element method show that the extreme loading conditions define for the MAWP is uncritical for the system consisting of XFEL 3.9 GHz superconducting cavity inside the Helium tank, under consideration of the tuning system and the weld size reduction. Indeed the most stressed regions are the Ti-1 compensator peak and the Nb-300 cell iris, but the calculated linearized stresses are below the limits imposed by the norm. Concerning the other welding regions, it was considered not necessary to perform the stress linearization and verification because of the low Von Mises stresses, that are far below the maximum allowable stress of the related materials. The results of the strength analysis are summarized in Table 2.

Table 2: Strength Linearization and Verification

	Bellows Peak (Ti-1)		**Cell Iris (Nb-300)**	
	Actual stress (MPa)	*Max. Allowable (MPa)*	*Actual stress (MPa)*	*Max. Allowable (MPa)*
Max. Von Mises stress	164	--	136	--
General primary membrane stress	13	133	31	33
Max. membrane + bending stress	152	400	92	100

ISBN 978-3-95450-132-8

REFERENCES

[1] A. Schmidt et al., “PED requirements applied to the cavity and helium tank manufacturing”, SRF2013, Paris, France, September 2013; http://www.JACoW.org
[2] C. Astefanous et al., “Design and analysis of SRF cavities for pressure vessel code compliance”, PAC’11, New York, NY, USA, March – April 2011; http://www.JACoW.org
[3] A. Schulze, “FEM-Strength Analysis of the injector-module 3.9 GHz-Cavities”, Inspection Report 8110786360, February 2014.
[4] UNI EN 13445-3, “Unfired pressure vessels – Part 3: Design”, August 2004.