STRUCTURAL MECHANICS OF SUPERCONDUCTING CH CAVITIES*

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Abstract

The superconducting (sc) CH-structure (Crossbar-H-mode) is a multi-cell drift tube cavity for the low and medium energy range operated in the H_{21}-mode, which has been developed at the Institute for Applied Physics (IAP) of Frankfurt University. With respect to different high power applications two types of superconducting CH-structures (f = 325 MHz, β = 0.16, 7 cells and f = 217 MHz, β = 0.059, 15 cells) are presently under construction and accordingly under development.

The structural mechanical simulation is a very important aspect of the cavity design. Furthermore, several simulations with ANSYS Workbench have been performed to predict the deformation of the cavity walls due to the cavity cool-down, pressure effects and mechanical vibrations. To readjust the fast frequency changes in consequence of the cavity shape deformation, a new concept for the dynamic frequency tuning has been investigated, including a novel type of bellow-tuner.

INTRODUCTION

Superconducting structures have to fulfill strict mechanical requrements to assure a stable operation of a cavity. The walls of superconducting cavities are kept very thin to maintain the cooling. Due to these thin walls superconducting cavities are very susceptible to external ascendancies. The caused mechanical deformations can change the resonance frequency of the cavity in the range of several hundred kHz. The sources of cavity detuning include the Lorentz Force, pressure variations of the helium bath and mechanical vibrations of external equipment (e.g. vaccum pumps). To control the effects of the mechanical deformations of the cavity shape due to external forces the mechanical analysis is an important basic appliance. For all mechanical simulations of the sc CH cavity we use ANSYS Workbench to analyze the cavity deformation [1].

To control the frequency variations of prospective sc CH cavities during operation a novel tuning concept was worked out. Dynamic capacitive bellow tuners welded inside the cavity are provided reaching a tuning range of several hundred kHz to compensate the dynamic frequency shift [2]. To analyze their mechanical behavior, several static structural simulations have been carried out where a bellow tuner model was exposed to a range of static forces.

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STRUCTURAL MECHANICAL ANALYSIS

The investigated cavity is a sc 325 MHz CH cavity which is designed and optimized for high power applications (see Fig. 1). It consists of 7 accelerating cells and has a design gradient of 5 MV/m [3]. Its frequency is the third harmonic of the UNILAC at GSI. The structural mechanical simulations with ANSYS Workbench have been made to investigate the deformation of the cavity walls and the resulting frequency variations due to external effects.

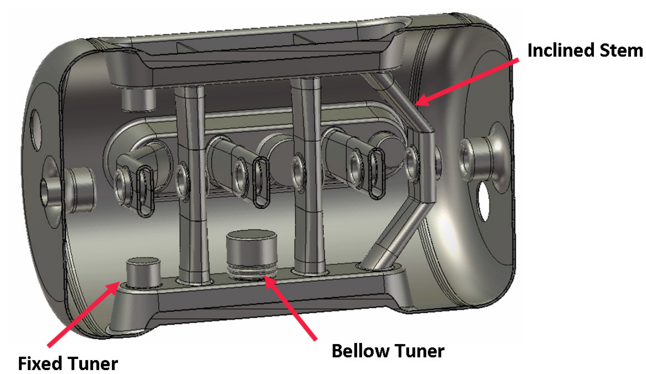

Figure 1: Layout of the sc 325 MHz CH cavity [4].

The complete 325 MHz CH cavity is produced of niobium sheets (thickness 3 mm). The following physical properties of niobium are used for the mechanical simulations:

- Young's modulus: $E = 1.05 \times 10^{11}$ Pa
- Density: $\rho = 8570$ kg/m^3
- Poisson's ratio: $\nu = 0.38$
- Yield stress: 470 MPa (@ 4K)

Cool-Down and Evacuation

The initial step of the mechanical simulation is the structural deformation analysis of the sc 325 MHz CH cavity due to evacuation and cool-down to 4.2 K. For the ANSYS analysis model to calculate the deformation caused by evacuation the attachments at each end of the cavity are chosen to be the fixed support. The end caps are completely fixed against deformations in any direction. For the case of the cavity cool-down only one end cap is fixed. In this case the applied load is the temperature of 4.2 K, while the atmospheric pressure on the surface of the cavity walls is the applied load for the analysis of evacuation effects. The following figures show the simulation results, which give a representation about the mechanical behaviour of the 325 MHz CH cavity (see Figs. 2 and 3).

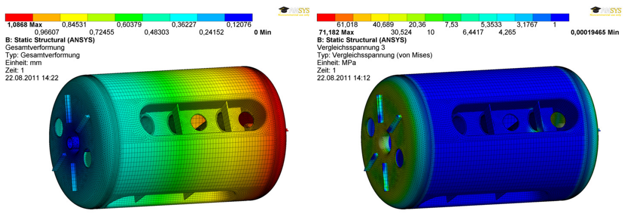

Figure 2: Displacements of the sc 325 MHz CH cavity under Cool-Down (left) and appearing material stress (right).

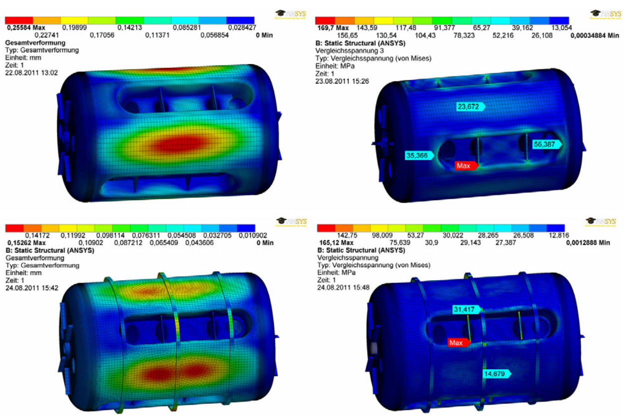

Figure 3: Deformation and max. von-Mises stress of the cavity due to evacuation without stiffening ribs (top) and with stiffening ribs (bottom).

Table 1: 325 MHz CH cavity under cool-down to 4.2 K and evacuation

Parameter	Cool-Down (4.2 K)	Evacuation	Evacuation (stiffeners)
Displ.	1.08 mm	0.256 mm	0.153 mm
Max. stress	71.18 MPa	65 MPa	40 MPa
Δf	530 kHz	230.7 kHz	137 kHz

The results of the cavity cool-down show that the maximum displacement is around 1.08 mm, which will lead to a frequency shift of about 530 kHz. In that case the peak von-Mises stress was found to be 71.18 MPa, which is still acceptable in comparison to the yield stress of niobium (470 MPa). In the real design of the cavity additional attachments like coupling and tuning ports may stiffen the geometry, which will lead to a smaller frequency shift. The pressure of 1 bar on the cavity walls without stiffening ribs leads to a total displacement of 0.256 mm and a maximum von-Mises stress of around 65 MPa. The causing frequency shift is in the range of around 230.7 kHz. The stiffening ribs added to the cavity walls reduce the maximum displacement and consequently the frequency change (see Table 1).

NOVEL FREQUENCY TUNING CONCEPT

For the prospective sc 325 MHz and sc 217 MHz CH cavities [5] a new dynamic frequency tuning concept is foreseen. Additionally to the cylindrical static tuners, several dynamic capacitive bellow tuners are welded into the girders to act against slow and fast frequency variations by changing their height. The goal of the slow tuners, driven by stepping motors, is to readjust the frequency changes caused by cavity cool-down to 4.2 K and evacuation effects. In addition, one of these slow tuners is based on a fast reacting piezo actuator to compensate frequency changes due to microphonic excitations and Lorentz Force Detuning. This tuning device including slow and fast dynamic bellow tuners is sufficient for frequency tuning during beam operation. The final design of the 3-cell bellow tuner is shown by Figure 4.

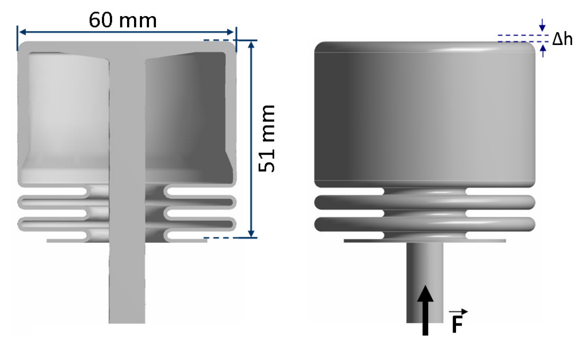

Figure 4: Design of the novel dynamic 3-cell bellow tuner for the sc 325 MHz CH cavity.

Table 2: Required frequency shift of the dynamic bellow tuners for sc CH cavities

Parameter	Frequency shift	Driven by
Slow bellow	150 kHz/mm	Step motor
Fast bellow	150 Hz/μm	Step motor + Piezo

RF simulations of the sc 325 MHz CH cavity show that a frequency shift of 150 kHz/mm is achievable at a working point of 51 mm tuner height for each dynamic bellow tuner. Table 2 shows the required frquency shift and furthermore the drive system of the different tuner types.

MECHANICAL SIMULATIONS

The main tuner design optimization goal of the structural mechanical analysis is to reduce the appearing material stress. To achieve the desired frequency shift of 150 kHz the stroke of the bellow tuner has to be 1 mm. The following 3-dimensional contour plot illustrates the maximum stroke and the appearing von-Mises stress of the bellow tuner (see Fig. 5).

The restricting boundary condition for the 3-cell bellow tuner model is the lowermost ring which is fixed to limit

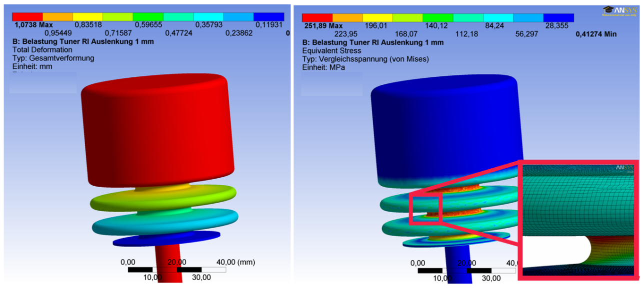

Figure 5: Maximum stroke (left) and max. von-Mises stress (right) of the dynamic bellow tuner.

the degree of freedom. After pushing on the bottom of the central rod with a force of 380 N and the causing stroke of 1 mm ANSYS Workbench determines the peak von-Mises stress to be around 251.9 MPa, which appears between each cell. This calculated value is clearly smaller than the yield stress of 470 MPa and assures a stable operation of the bellow tuner.

MODAL ANALYSIS AND ELASTIC BUCKLING

The next step of the structural mechanical analysis is the investigation of the dynamic properties of the bellow tuner. The main purpose of the modal analysis is to determine eigenfrequencies that the structure will naturally resonate at. It is imperative that the natural frequencies of the bellow tuner do not match the signal bandwidth of the piezo actuator which is in the range of several hundred Hz. For this purpose the modal analysis is an important method to find out where stiffening elements are needed to eliminate the most dangerous eigenmodes.

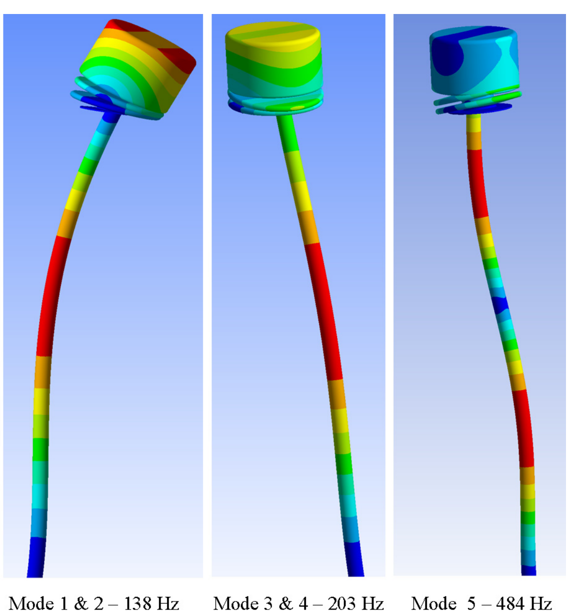

Figure 6: First mechanical eigenmodes of the dynamic bellow tuner.

Figure 6 shows the lowest natural frequencies and the corresponding eigenmodes of the bellow tuner. For the first dangerous natural frequencies the main direction of oscillation appears in the middle of the rod ($l_{rod} = 400mm$). Another problem that may appear is the effect of elastic buckling. The applied load at the centroid of the cross section at the end could lead to an instability and thereby to a deformation of the long tuner rod. The critical load for a rod length of 400 mm is calculated to be around 3180 N. In comparison to the required force for the maximum stroke of the bellow tuner this value is clearly higher. To avoid both effects, the vibration and the effect of buckling, the rod must be supported by stabilizing elements during operation.

SUMMARY & OUTLOOK

Presently the sc 325 MHz CH cavity is under construction at Research Instruments (RI), Bergisch-Gladbach. In 2012 it is foreseen to test the cavity and the new tuning device including a piezo based bellow-tuner with beam at the GSI UNILAC, Darmstadt. For the first sc 217 MHz CH cavity including dynamic bellow tuners of the proposed sc cw LINAC further structural mechanical and rf simulations are in progress at present. To investigate and demonstrate the cavity capabilites a full performance test in 2013/2014 with beam at the GSI HLI is planned.

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