SPL 704MHz β = 0.65 CAVITIES MECHANICAL DESIGN FOR EUCARD

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Abstract

Within the framework of EUCARD (European Coordination for Accelerator Research&Development), supported by European Union, IPN Orsay is in charge of the design of a 704 MHz 5-cell elliptic superconducting cavity for the intermediate energy section (β = 0.65) for accelerating high intensity proton beams in pulsed mode. This study offers a new option to replace the injector of the Large Hadron Collider at CERN with SPL (Superconducting Proton Linac) project.

For this cavity's design, a compromise between the requirement of high technological performance and the constraint of the cavity's cost should be found. As middle β elliptical cavities have a big ratio between equator radius and iris radius, the Lorentz forces detuning factor is higher than for a high β elliptical cavity. As a consequence, the cavity wall thickness should be increased and one or two stiffening rings between cells are necessary. Both increase the cost of cavity which should be imperatively minimized since more than fifty β 0.65 cavities are considered for SPL linac.

To do these optimizations, the simulation of Lorentz forces detuning has been carried out first since the operating mode is pulsed. Finite Element Method (FEM) models have been developped in Cast3m, aiming to reduce frequency shift by optimization of stiffening rings. Thanks to the platform developed at IPN Orsay, the 3D modeling for mechanical calculations are performed on the set which includes coupler and high mode ports and helium vessel. The final design of 704 MHz β 0.65 niobium cavities with optimized wall's thickness according to mechanical constraints imposed by SPL specifications are presented in this paper.

INTRODUCTION

Based on SPL superconducting linac design parameters, the electromagnetic design is optimized first with Superfish [1]. Then 3D modeling with Microwave Studio has been performed in order to optimize coupler port position. The maximum peak surface electric field is 50 MV/m , the maximum peak magnetic field is 100 mT. Other essential parameters are given in table 1.

The principal challenge is the high accelerating gradient for middle β. As the frequency shift due to Lorentz forces increases with square of the accelerating gradient, for E_{acc} = 19 MV/m, and $Q_{ext} \approx 10^6$, the frequency shift

Table 1: Some SPL superconducting linac design parameters

Parameter	Values
Frequency	704.4 MHz
$\beta = v/c$	0.65
R/Q	290 Ω
Q_0	$> 10^{10}$
Accelerating gradient	19 MV/m

must be kept less than bandwidth δf:

$$\delta f = f_0 \left(\frac{1}{Q_0} + \frac{1}{Q_{ext}}\right) \tag{1}$$

As $Q_0 \gg Q_{ext}$, $\delta f = f_0 \frac{1}{Q_{ext}}$ the frequency shift should not exceed 704 Hz. In other term, the Lorentz detuning coefficient $K = \Delta f/(E_{acc})^2$ should be smaller than 1.9.

LORENTZ FORCES DETUNING AND CAVITY STIFFENING

First, FEM modeling of the cavity shape is performed in Cast3m, [2]. Then, the electromagnetic fields on the cavity's wall, simulated with Superfish, have been interpolated on Cast3m modeling. Figure 1 shows the vector representation of radiation pressure on the cavity wall.

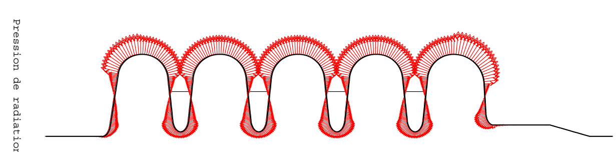

Figure 1: Radiation pressure on $\beta 0.65$ cavity.

The resulting cavity shape change under radiation pressure while cavity is totally fixed is computed. Finally the frequency shift Δf_0 is computed thanks to a specially developed module according to Slater's formula:

$$\frac{\Delta f_0}{f_0} = -\frac{1}{4W} \iiint_{\Delta V} (\mu_0 H^2 - \epsilon_0 E^2) dV \tag{2}$$

where: W is the total electromagnetic energy stored in the resonator, E and H are the electromagnetic surface fields and ΔV the cavity volume variation due to deformation, f_0 is the fundamental mode of the unperturbed cavity.

A very high numerical precision is required at this step because the cavity deformation ($\Delta l = 0.2\,\mu$m) is very small compared to the cavity scale (1 m).

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The stiffening rings are added cell to cell, (figure 1). This system permits to reduce mechanical deformations. However, the frequency shift reduction is function of the stiffening rings position as show figure 2, the cavity wall thickness is fixed to 4 mm.

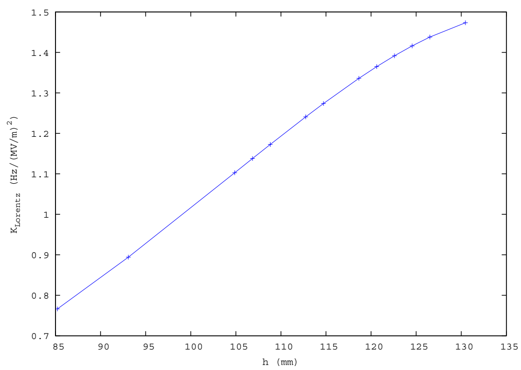

Figure 2: Lorentz forces coefficient as function of stiffening rings position.

From this curve, we can choose $h = 94$ mm from beam axis to guarantee $k = 0.9\,\mathrm{Hz}/(\mathrm{MV/m})^2$, which means $\Delta f_0 = 325$ Hz at 19 MV/m. Still, Lorentz forces detuning depends also on cavity's fixing, the formulation 2 gives the frequency shift when cavity is totally fixed. In reality, the cavity is linked to its cold tuning system and together integrated to a helium vessel. As a consequence, another component of frequency shift, which depends on stiffness of helium vessel and cold tuner should be added to Δf_0.

$$\Delta f_t = \Delta f_0 + \Delta f_1$$

with:

$$\Delta f_1 = \frac{\partial f}{\partial L} \times \frac{\partial L}{\partial F} \times F$$

where $\frac{\partial f}{\partial L}$ is the frequency variation generated by 1 mm longitudinal displacement, F the force necessary to make such displacement, $\frac{\partial F}{\partial L}$ is the stiffness of the cavity plus tuner plus helium tank.

Generally, the stiffness of the cavity is much smaller than the stiffness of the tuner connected to helium vessel, it's important to size the tuner and the helium vessel with a stiffness as high as possible in order to reduce Δf_1.

The frequency longitudinal sensibility $\frac{\partial f}{\partial L}$ is simulated with Cast3m, as well as F. These simulations are very important to determine the cavity wall thickness. As the table 2 show, even with stiffeners, if the wall thickness is 3 mm, the total Lorentz forces coefficient exceeds in this case $1.9\,\mathrm{Hz}/(\mathrm{MV/m})^2$ (limit imposed by bandwidth).

Another mechanical stress on the cavity is external pressure. In situ, the fluctuations of pressure helium bath on the cavity under vacuum generate mechanical deformations which contribute also to frequency shift. The simulations show the dependence of these frequency shift as function of stiffening rings position, figure 3. The remark is that

Table 2: Optimization of cavity wall's thickness

thickness	$\Delta f_0/E^2_{acc}$	$\Delta f_t/E^2_{acc}$
3 mm	$1.9\,\mathrm{Hz}/(\mathrm{MV/m})^2$	$2.45\,\mathrm{Hz}/(\mathrm{MV/m})^2$
4 mm	$0.9\,\mathrm{Hz}/(\mathrm{MV/m})^2$	$1.44\,\mathrm{Hz}/(\mathrm{MV/m})^2$

the dependence is opposite to the previous (figure 3). So the compromise is the point situated at the intersection of these two curves.

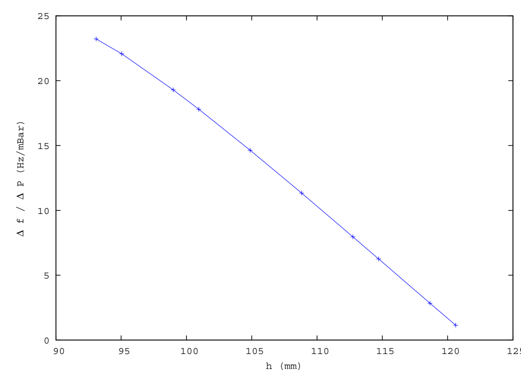

Figure 3: Frequency shift over pressure's variation as function of the stiffening rings position.

As result, the stiffening rings position is fixed to 94 mm from beam axis, in this case, the frequency shift due to bath's pressure variation is 22 Hz/mBar.

CAVITY STRUCTURE MODELING AND DESIGN

To simulate the mechanical stress and deformation of the cavity with coupler and HOM ports, also in the situation when the cavity is integrated to its helium vessel, 3D modeling is necessary. The 3D modeling of the cavity is made with Catia V5. A platform, developed at IPN Orsay, allows to adapt this modeling to FEM code Cast3m. The mechanical stresses under 2 bar external pressure have been simulated with Cast3m. The material properties of niobium used in simulations are the following:

Young's Module : 103 GPa
Poisson coefficient: 0.39
Volumic mass: $8600\,\mathrm{kg/m^3}$
elastic limit at 300 K: 50 MPa

The 3D simulations results concerning Von Mises stress distribution on the cavity wall (4 mm), without stiffeners and with stiffeners are presented at figures 4 and 5.

From simulations results, we can see a big difference of stress distribution on unstiffened or stiffened cavity. In the first case, the Von Mises stress distribution under 2 bar external pressure on the 4 mm cavity's wall is shown in figure 4, the critical region where stress peak is located is around

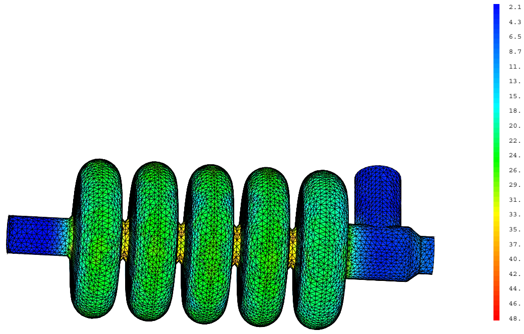

Figure 4: Von Mises stress on 4 mm cavity without stiffeners under 2 bar pressure.

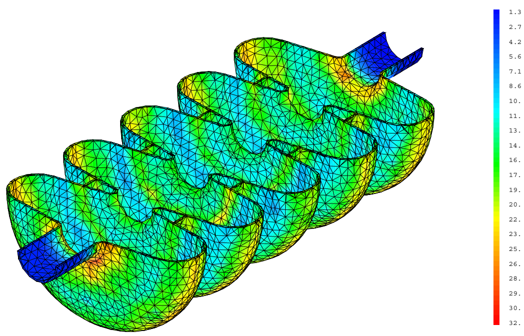

Figure 5: Von Mises stress on 4 mm cavity with stiffening rings under 2 bar pressure.

the iris, the maximum stress is 48 MPa. In the second case, the stress is more uniformly distributed, figure 5, the stress peak is located at the junction between stiffening rings and the cells and also between end cells and beam tube. The Van Mises stress level don't exceed 32 MPa.

The choice of 4 mm as cavity wall's thickness has been approved here by mechanical simulations. In fact, not only the mechanical behaviours of cavity under static external pressure, illustrated in figure 5, are satisfied if the wall thickness is 4 mm, but also if the cavity has been stretched or compressed under this pressure. The table 3 shows the maximum values of Von Mises stress on the cavity with stiffening rings in case that 2 Bar external pressure is applied to cavity and the cavity is stretched or compressed of 1 mm. It points out the weakness if the cavity wall's thickness is 3 mm, and the safety margin if the thickness is 4 mm.

Table 3: Cavity stretched or compressed under 2 bar external pressure

thickness	stretched under 2 bar	compressed under 2 bar
3 mm	$\sigma_{\max} = 31$ MPa	$\sigma_{\max} = 47$ MPa
4 mm	$\sigma_{\max} = 20$ MPa	$\sigma_{\max} = 35$ MPa

The mechanical simulations allow to conclude that 4 mm is an optimal thickness. Over this value, the reduction of mechanical stress would be less significant compared to the increase of the price of cavity, another disadvantage is the heaviness of the cavity.

MECHANICAL VIBRATIONS MODES

In pulsed regime, the cavity has its own mechanical eigen-modes which could be excited by the external noise or inner mechanical forces. For cavity design, it's important to push the first mode higher than 50 Hz, which is a critical frequency. For SPL cavity, two first eigen-modes are presented in the table 4. The simulations results show that with the stiffeners, the frequency of the first eigen-modes has been raised and moved away from 50 Hz.

Table 4: Eigenmodes

eigen-mode	without stiffeners	with stiffeners
1	58 Hz	75 Hz
2	115 Hz	151 Hz

INTEGRATION TO HELIUM VESSEL WITH TUNER

Concening the cavity's integration to helium vessel with tuner, a coordination with $\beta 1$ SPL cavity's design is decided. As a consequence, both β = 0.65 and β =1 have the same helium vessel and tuner. However, the interfaces between cavity and helium vessel also between cavity and tuner have been designed. In figure 6, some special elements such as Ti flange for transition with tuner and thick tube in niobium which facilitate niobium to titanium tank transition are illusted.

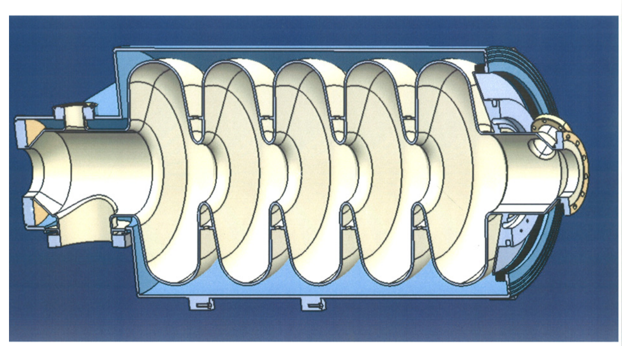

Figure 6: 704 MHz $\beta 0.65$ Cavity with helium vessel.

CONCLUSIONS AND PERSPECTIVES

Mechanical studies for 704MHz β = 0.65 cavity inside the EuCard programme have been successfully completed at IPN Orsay. The geometry and the stiffener optimizations have been discussed. The cavity integration to helium vessel with tuner have been done in collaboration with CEA and CERN. The first prototype manufacturing is now scheduled.

ACKNOWLEDGEMENTS

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REFERENCES

[1] F. Bouly, PhD thesis of University Paris-Sud, expected on Oct. 2011.

[2] Cast3m: http://www-cast3m.cea.fr.