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A 3 GHZ SRF REDUCED-BETA CAVITY FOR THE S-DALINAC*

D. Bazyl, H. De Gersem, W.F.O. Müller, TEMF, TU Darmstadt, Darmstadt, Germany
J. Enders, S. Weih, Institut für Kernphysik, TU Darmstadt, Darmstadt, Germany

Abstract

In order to reduce the energy spread and to be able to use a 200 keV spin-polarized electron source, the initial part of the injector linac of the superconducting Darmstadt electron linear accelerator S-DALINAC needs to be upgraded. The decisions on the cavity type, number of cells and value of geometric beta are motivated. The main part of this work is dedicated to the mechanical design of the cavity. A precise evaluation of the mechanical characteristics of an SRF cavity is necessary during the design stage. The dependence of the resonant frequency of the fundamental mode on external mechanical loads needs to be investigated for developing the tuning procedures. The results of the multiphysics simulations and of the optimization of the mechanical design are presented.

INTRODUCTION

In 2016 the S-DALINAC [1] was upgraded by a third recirculation ring. As a result, the operation of the S-DALINAC in the ERL regime became possible [2]. A number of projects aim at improving the overall performance of the accelerator. One of the critical tasks is to reduce the energy spread growth of the beam in the injector section. The SRF injector linac consists of one 5-cell $\beta = 1$ cavity and two 20 cell $\beta = 1$ structures. The 5-cell cavity is not suited to pre-accelerate the future 200 keV electron beam coming from the spin-polarized gun [3] up to the energy of 1 MeV.

A number of layouts were considered to replace the 5-cell cavity. The final choice of the cavity type is the six-cell reduced-beta cavity (see Fig. 1). It is worth to mention that a multi-cell cavity with a constant length of cells for a low energy electron beam is not a straightforward solution since synchronism condition between the RF field and the beam is not completely satisfied. However, detailed beam-dynamics studies have shown that for an optimal value of the number of cells, the geometric beta and the flat top peak electric field, the beam loses only ~10% of the energy in the first cell and hits the accelerating phase of the electric field in the following cells. Such a cavity can work efficiently with an accelerating gradient below 10 MV/m (further increase of the accelerating gradient becomes inefficient). The designed value of the accelerating gradient of the 6-cell cavity varies from 3.5 to 5 MV/m. Taking into consideration the cavity performance, the mechanical stability of the cavity during operation has a higher priority rather than achieving high accelerating gradients in the cavity since only 1 MeV of beam energy is required after the capture section. More details behind the motivation to choose this cavity type, number of cells and geometric beta can be found in [4].

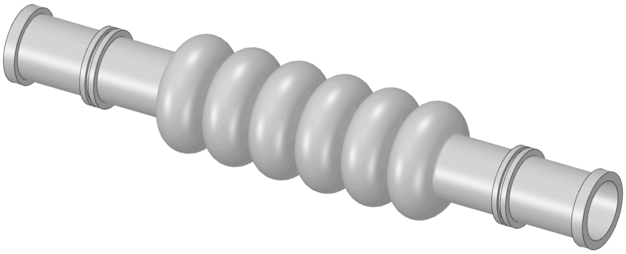

Figure 1: The layout of the 3 GHz 6-cell β=0.86 cavity.

The RF design was done using CST MWS [5] while the structural analysis of the cavity using Finite Element Analysis (FEA) was carried out in ANSYS [6].

RF Parameters

The RF characteristics of the cavity have changed since previously reported in [4] due to some modifications applied to the geometry of the cavity that will be discussed in further sections related to the mechanical design of the structure. The current RF characteristics for the updated cavity geometry are given in Table 1. For β-dependent parameters (e.g. Vacc, R/Q) average values are given since the beam velocity changes from cell to cell.

Table 1: RF Parameters of the 6-Cell Cavity

Parameter	**Value**
Mode	TM_{010}
Phase advance	π
Frequency, GHz	3
Accelerating voltage, MV	1.22
R-over-Q, Ω	308
Geometry factor, Ω	253
Accelerating gradient, MV/m	4.72

MECHANICAL MODEL AND FINITE ELEMENT ANALYSIS

During the operation external mechanical loads act on SRF cavity walls. The frequency shifts of the fundamental mode due to these stresses should be evaluated when considering the necessary tuner settings and range. At the same time stress caused by the operation of the tuner should not exceed the yield strength of the niobium (Nb) at cold temperature to avoid plastic deformation.

The wall thickness of the cavity was selected to be 2.8 mm (2.5 mm after polishing of the inner surface) by referring to the experience with the 3.9 GHz cavity used at the XFEL facility [7]. For elliptic cavities operated in CW mode in the frequency range of 3 GHz it is not necessary to implement stiffening rings because the cavity is rigid enough without

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them. The first version of the 6-cell cavity has the same iris radius in each cell. The cavity is designed for the existing input power coupler of which the end part uses a beam pipe as a transmission line. Due to that, the connection of the cavity to the beam pipes has an ellipsoidal shape. There was a request to design a cavity as rigid as possible. In that regard, the connection of the cavity to the beam pipes was changed to a smooth transition. This results in an increase in the cavity stiffness by 1 kN/mm. The FEA computations were carried out using ANSYS together with HFSS to estimate frequency shifts caused by deformations.

Boundary Conditions

To save FEA computation time the model shown in Fig. 2 was used since an elliptical cavity is axially symmetric. The cavity is fixed in all directions on the left-hand side (A) while it moves freely in the longitudinal direction on the opposite side (B). The model does not yet account for the cavity holders and the cryostat.

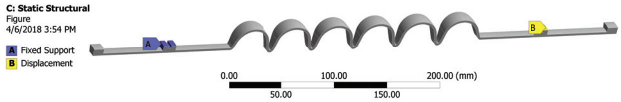

Figure 2: Boundary conditions used in FEA analysis.

The material properties of Nb at 2 Kelvin that were used in the simulations are given in Table 2.

Table 2: Niobium Properties Used in the Simulations

Parameter	Value
Temperature, K	2
Young's modulus, MPa	118
Poisson ratio	0.38

Longitudinal Stiffness

The longitudinal cavity stiffness was calculated by applying the force to the free cavity end. The estimated value yield to be:

$$K = 4.6\ \frac{\text{kN}}{\text{mm}} \tag{1}$$

Another important quantity to estimate the necessary tuner characteristics is the frequency shift per longitudinal length change of the cavity. The deformation caused by longitudinal displacement applied to the free cavity end leads to a frequency shift that is equal to:

$$\frac{df}{dl} = 2.1\ \frac{\text{kHz}}{\mu\text{m}} \tag{2}$$

Pressure Sensitivity

A pressure of 10 mbar was applied to the cavity walls. Figure 3 shows a plot of the resulting deformation of the cavity. The deformed mesh of the cavity is then sent to HFSS and the resonant frequency shift of the fundamental mode is evaluated. The calculated pressure sensitivity has the following value:

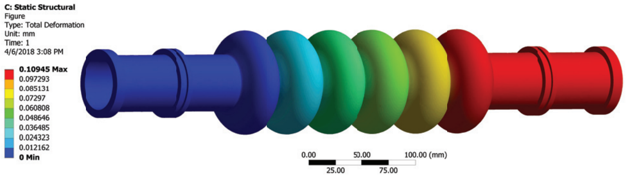

Figure 3: The cavity deformation caused by 10 mbar of pressure applied to the cavity walls.

$$\frac{df}{dp} = 30\ \frac{\text{Hz}}{\text{mbar}} \tag{3}$$

The pressure fluctuations in the cryostat of the 6-cell cavity do not exceed 10 mbar (~1.5 mbar average) [8]. Hence, this effect will almost be negligible for the designed cavity.

MICROPHONICS

External vibrations coming from the cryogenic system or even the white noise might excite mechanical vibrations of an SRF cavity. These vibrations detune the cavity and result in a frequency shift and in some cases require additional input RF power to compensate for the detuning attributed to the field level in the cavity. For CW operation of an SRF elliptical cavity, microphonics represent the largest disturbance of the resonant frequency. With respect to that and with respect to the fact that the available RF power amplifiers can only provide up to 500 W a modal analysis for the six-cell cavity preformed. The first six mechanical modes of the 6-cell cavity are given in Table 3. The deformation plots of the first four mechanical modes are shown in Fig. 4.

Table 3: Mechanical Modes of the 6-Cell Cavity

Mode	Frequency, Hz	Mode type
1	276	longitudinal
2	378	transverse
3	782	transverse
4	893	longitudinal
5	1173	transverse
6	1340	breathing

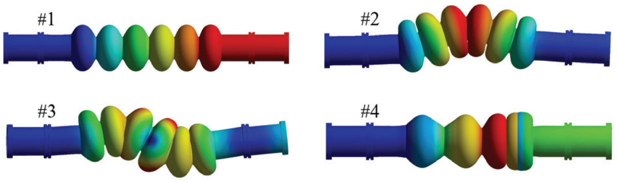

Figure 4: Deformations of the first four mechanical modes.

When analyzing the results one can see that the first longitudinal mode is located in the dangerous frequency range below 1 kHz. Since it is not planned to manufacture a prototype of the 6-cell cavity we will study the available experimental data concerning microphonics of the 20-cell cavity of the S-DALINAC and do the numerical predictions of the mechanical vibrations and compare the results. The obtained information will help to make sure that the results obtained for the 6-cell cavity are correct. In case there are excitation

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sources in the estimated frequency range they will be either isolated or, if that is not possible, the cavity geometry will be modified to shift the resonant frequency of the unwanted mechanical mode.

SUMMARY

The results of the investigation of the mechanical model of the six-cell cavity are summarized in Table 4.

Table 4: Mechanical Characteristics of the 6-Cell Cavity

Parameter	**Value**
Material	Nb
Temperature, K	2
Wall thickness, mm	2.5
K, kN/mm	4.6
df/dp, Hz/mbar	30
df/dl, kHz/µm	2.1

TUNER FRAME

The tuner frame of the S-DALINAC cavities is designed as a lever system where the force can be applied by a stepper motor (coarse tuner) and a fine tuner consisting of multiple piezo actuators. It is based on two plates with four titanium rods as supports between them. The input-coupler side of the frame is fixed to the cryostat, while the output-coupler plate is used to stretch and compress the cavity, respectively (see Fig. 5). The titanium rods also guide the cells, ensuring that the cavity deformation is only applied in longitudinal direction. After the cool-down of the accelerator, the coarse tuner is driven once to adjust the center of the resonance frequency. During operation the LLRF control system stabilizes the relative amplitude error and the rms phase error down to $7 \cdot 10^{-5}$ and 0.8° [9] using the fast piezo tuner for microphonics compensation. Since the cell region of the new capture structure is 8 mm longer compared to the current 5-cell structure, the length of the tuner frame has to adapted by replacing the titanium rods. Furthermore, the frame will be equipped with a new piezo tuner containing two actuators where each is specified for a push force up to 3 kN and a travel range of 90 µm. The other parts of the lever system and the coarse tuner can be reused.

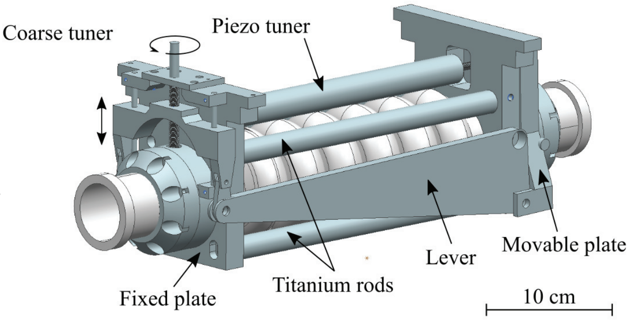

Figure 5: The 6-cell cavity equipped with the tuner frame.

CONCLUSION

The behaviour of an SRF cavity submitted to various mechanical loads was studied in order to determine the range of the necessary tuner parameters. Even though the model used in the computations went through some simplifications, the obtained parameters enable the necessary tuner characteristics range to be estimated. Nevertheless a more realistic model that will include the cavity, cavity holders, cryostat and the tuner will be studied before placing an order for the cavity.

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