OPTIMIZATION OF SPIRAL-LOADED CAVITIES USING THE 3D CODE OPERA/SOPRANO*

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Abstract

Rebunching cavities are today routinely used for matching a beam of charged particles between different accelerator structures, and thus optimizing the overall transmission and beam quality. At low resonance frequencies, unnecessary large dimensions of these cavities can be avoided by using spiral-loaded cavities. The optimization of these structures is a complicated process in which a wide range of different parameters have to be modified essentially in parallel. In this contribution, we investigate in detail the characteristics of a model structure with the 3D code OPERA/SOPRANO. This includes the optimization of the structure in terms of the spiral geometry for a given resonance frequency, the investigation of power losses on the inner surfaces, and the possibility of cavity tuning by means of a tuning cylinder.

INTRODUCTION

Spiral-loaded cavities are today routinely used in many accelerator facilities around the world [1], [2]. Mainly as buncher and post accelerator elements to vary the temporal profile and the final energy of the beam [3]. The big advantage of this structure is its compact size as compared to quarter-wave resonators. These small structures allow changing the energy as well as the velocity distribution in a beam very efficiently and thus providing an efficient matching between different sections of an accelerator or shaping of the longitudinal beam profile in front of an experiment. Different types of spiral-loaded cavities have already been realized in the past, differing in number of accelerating gaps and in the winding of the spiral arms.

In this contribution, we consider a single arm normal conducting structures as it was already built up [4]. It consists of a cylindrical external tank and three drift tubes on the symmetry axis. The middle drift tube is attached to the spiral arm. A model of this structure is shown in Fig.1 and the design parameters for the initial model are found in Tab.1. A particularity of this type of structure is the ratio of the radii, where the small radius equals half of the large radius. In order to efficiently accelerate charged particles in such a structure, the distance between the midgaps needs to be an integer multiple of half an RF period. The geometry of this structure can be described by the following equation

$$L = \frac{n\beta\lambda}{2} \quad (1)$$

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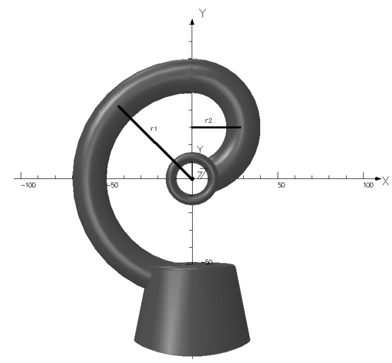

Figure 1: Model of the spiral arm with hidden tank walls and marked spiral radii.

where $\beta = \frac{v}{c}$, λ the wavelength and L is the distance between the middle of two gaps which is also referred to as the cell length.

Table 1: Design values of cavity tank and spiral arm

Design Parameter	Size [mm]
Cavity length	150
Cavity radius	100
Cavity wall thickness	5
Drift tube length	60
Drift tube thickness	10
Gap width	15
Aperture radius	10
Blend radius	2.5
Spiral radius r1	60
Spiral radius r2	30
Spiral thickness	20

In the frame of this study, we built up a model of a well-known cavity, which was then simulated and analyzed by using the different modules of OPERA [5]. This allowed us to benchmark the results of this code with previous data and results from other simulation codes. In our investigations, we used the eigenvalue solver SOPRANO to determine the relevant resonance frequencies. The solver can be used to find the different resonance modes of a cavity structure with either perfect conducting boundaries or realistic metal surfaces by solving the Helmholtz equation via the Galerkin method and subsequently solve the sparse generalized eigenvalue problem.

FIGURES OF MERIT

In order to compare the simulation results with other structures several characteristic values are computed, which are defined according to [6]. First we define the quality factor Q as

$$Q = \frac{\omega U}{P} \qquad (2)$$

where ω is the angular frequency of the mode, U is the stored energy in the system and P the average power loss.

$$U = \frac{1}{2}\mu_0 \int |\mathbf{H}|^2 \, dV \qquad (3)$$

$$P = \frac{1}{2}R_s \int |\mathbf{H}|^2 \, dS \qquad (4)$$

R_s is the average surface resistance of the material. The quality factor indicates the power losses in the structure.

A second figure of merit that is independent of the excitation level of a cavity is the shunt impedance and the shunt impedance per unit length

$$r_s = \frac{V_0^2}{P}, \quad Z = \frac{r_s}{l} \qquad (5)$$

where V_0 is the accelerating voltage

$$V_0 = \left| \int_{-L}^{0} E_z(z)dz \right| + \left| \int_{0}^{L} E_z(z)dz \right| \qquad (6)$$

and E_z is the the accelerating field. It expresses how much energy is needed establish a certain average E-field inside the cavity.

SIMULATION RESULTS

For all simulations we used the same boundary conditions and mesh settings to allow for simple comparison of the results. In order to get a volume mesh error smaller than 10^{-6} around 10^5 linear tetrahedrons were used to mesh the complete model body. A minimum of 1 GB RAM is required for running OPERA solver, which takes about 5 minutes at a CORE 2 DUO workstation using only one core.

Initial model

The results of the first three modes of the initial model can be found in Tab.2 where the OPERA function to compute the Q value was used. The higher Q value at the second resonance is due to the surface resistance, which decreases with the square root of the frequency. At the third resonance the Q value increases more than expected from the change of the surface conductivity. That is on one hand due to a different field distribution in the cavity, which cannot be used for beam acceleration, because there is no change in sign between the two gaps. On the other hand the second modes is a $3\lambda/2$ oscillation which leads to much lower maximum fields. The accelerating field distribution on beam axis and the surface power losses of the first mode are shown in Fig.2 and Fig.3. It can clearly be seen that the main power losses are located along the spiral where the highest surface currents occur.

Table 2: Simulation results of initial model

Mode	1	2	3
Frequency [MHz]	234.283	607.945	838.894
Q (Copper)	5,993	9,503	16,059
r_s [MΩ]	3.30	1.67	3.44
Z [MΩ/m]	22.02	11.12	22.19

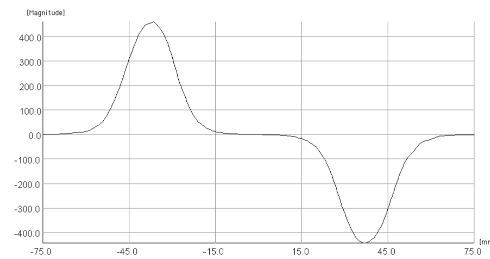

Figure 2: Accelerating field distribution on beam axis at the first resonance.

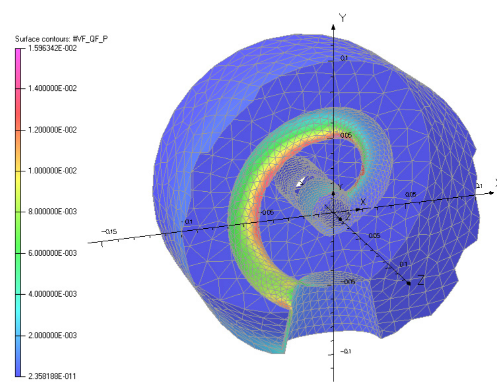

Figure 3: Power loss on surface at the first resonance frequency.

Rotation of the Spiral Arm

The frequency tuning of spiral-loaded cavities is typically done by shortening of the spiral arm. In such an R-R/2 structure the drift tube remains centred in the cavity even after rotation, which allows for a simple tuning of the structure to the desired resonance frequency. In order to determine this dependency, we rotated the spiral arm in steps of one degree in the range of $-90°$ up to $90°$ and shortened it continuously. For each iteration step, we then calculated the effect on the resonance frequency. Thereby $-90°$ correspond to the longest spiral arm, $90°$ to the shortest one and zero degree to the initial model. By reducing the length of the spiral arm, the inductance of the system is reduced, which leads to a higher resonance frequency.

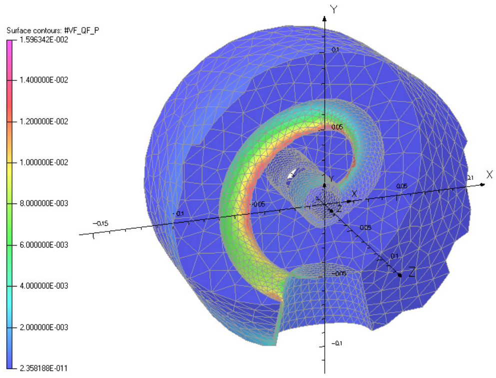

Figure 4: Resonance frequency as a function of the effective spiral arm length.

In Fig.4 the change of the first resonance frequency as a function of the rotation angle is displayed. The resonance frequency can be adjusted very smoothly over a range of more than 100 MHz, which underlines the flexibility of this structure.

Influence of a tuning cylinder

During operation the resonance might get detuned by several effects like temperature drift, stress on the structure, aging processes or errors due to the driver. By introducing a tuning cylinder the resonance frequency can be fine-tuned to compensate these errors. The effect of a tune cylinder depends on its shape and insertion position. By introducing a tuning cylinder the resonance frequency can be fine-tuned over a range of aprox. 1 MHz to compensate these errors. During this process, the effective volume of the cavity is changed. Depending on the cylinder shape and its insertion position, a change in the inductance or capacity of the system is obtained. Depending on this coupling, the frequency can be changed according to $\omega \propto (LC)^{-1/2}$. In order to study these effects several simulations with different setups and varying insertion depths of up to 20 mm were performed. We concentrated on the following two parameters: cylinder radius (20, 25 and 30 mm) and the position of the cylinder. It can be seen that a strong influence of the tuning cylinder can only be found at the $0°$ position of the cylinder. Here, the resulting change is one order of magnitude higher than at the other two positions. This can be explained by the higher field level in this area, which is then displaced by the tuning cylinder. In total the frequency decreases to 7 MHz, which is more than enough to compensate detuning causes by heating or other effects. The change of resonance frequency as function of the insertion depth of the tune cylinder is shown in Fig.5 for the three different positions.

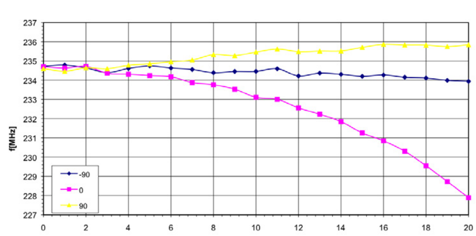

Figure 5: Resonance frequency as function of tune cylinder inserting depth at different positions and the same radius of 30 mm.

COMPARISON OF THE RESULTS

The results of the shunt impedance of the initial model fit well with the simulation results and the built structure in [4]. Also the resonance frequencies found with SOPRANO are in the estimated range. Q values in the order of 10^4 can be considered as typical for such copper structures as well as a shunt impedance of some MΩ. In summary, these results are in very good agreement to earlier simulations and measurements and qualify OPERA for the design and simulation of such cavities.

CONCLUSION AND OUTLOOK

OPERA/SOPRANO proved to be a useful tool to find resonance modes in complex 3D structures within a given frequency range and to investigate the properties of such structures in some detail. The code allowed us to analyze the 3D EM field distribution and in particular the influence of a tuning cylinder, which allowed for benchmarking against measurements.

The next step will be to develop a fully parameterized model of a spiral-loaded cavitiy which will allow for a flexible optimization of the whole structure to most different boundary conditions. By using OPERA's internatl optimizer we are aiming for substantially improving the layout of these structures.

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