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MICROPHONICS PASSIVE DAMPING

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Abstract

Different types of external loads on the resonator walls predetermine the main working conditions of the SRF cavities. The most important of them are very high electromagnetic fields that result in strong Lorentz forces and the pressure on cavity walls from the helium tank. For pulsed operation, the Lorentz forces usually play the decisive role for the cavity design. For CW operation, the liquid helium vessel pressure instability even for 2K operations is the source of large microphonics. All deformations resulting from any type of external loads on cavity walls lead to shifts in the working RF frequency in the range of hundreds of kHz. Taking into account high Q-factor of SC cavities such a large frequency shift takes the cavity out of operation.

Here we present and discuss the achievements and problems of microphonics passive damping in different type SRF cavities.

INTRODUCTION

One of the critical issues for new SC accelerators with modest beam current is small beam loading. Optimum coupling to the planned beam current would require relatively narrow cavity bandwidths. The thin walls of the SC RF cavities, and the narrow operating bandwidths, make them susceptible to detuning due to variations of the helium bath pressure, Lorentz pressure or to mechanical vibrations (microphonics). As the cavities detune, additional RF power is required to maintain the accelerating gradient. Sufficient reserve RF power has to be provided to compensate for the peak detuning levels that are expected, and not just for the average detuning. For narrow bandwidth cavities, providing sufficient reserve RF power can significantly increase both the acquisition cost and the operational cost of the machine. To mitigate the level of microphonics all possible passive measures must be employed in combination with other approaches. Under microphonics passive damping (MPD) we understand the common resonator-helium vessel structure design satisfying the ultimate requirements on low dependence of the resonance frequency shift on the cavity wall loading with a simple tuning procedure.

TECHNICAL APPROACH

For better understanding of the SC RF cavity behavior under vacuum load, different elliptical cavity middle cell shapes (Cornel reentrant [1], ICHIRO “low-loss” [2], MSU half-reentrant (HR) [3]) were investigated, in comparison with the well-developed TESLA-shape [4] cavity (Fig. 1).

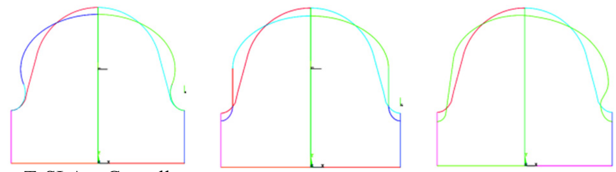

Figure 1: Mid-cell geometries.

The response of the cavities to a pressure differential was calculated with vacuum inside the resonator and ambient pressure is outside. The simulations were done with the cell-to-cell junction constrained by symmetry. The pressure differential changes the cavity shape and shifts the RF frequency of the accelerating mode. Inward deformation near the iris (the region of high electric field) increases the capacitance and hence reduces the frequency. Inward deformation near the equator (high magnetic field region) reduces the inductance and hence increases the frequency. Thus, the effects tend to cancel one another.

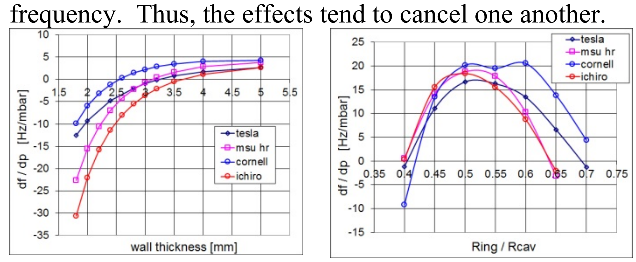

Figure 2: Middle cell frequency shift response to external pressure (left - R_{ing}/R_{cav} = 0.55, right - *wall thickness = 2.8 mm*).

The cavity rigidity depends on thickness of the cavity wall (Fig. 2, left). The frequency shift is approximately zero for a non-stiffened cavity with a wall thickness of about 3 mm. The frequency shift is different for each of the investigated geometries because of their different shape rigidity. A stiffening ring can be used to change the cell rigidity, thus varying the ratio between frequency shift from cavity capacitance and inductance change to produce a substantial reduction in df/dp. There are two places for the ring position where the frequency shifts reaches zero (Fig. 2, right). However, the higher ring position also results in an overall too high cavity rigidity, which causes in a large increase in the tuning force.

The response of an elliptical cavity middle cell to the external pressure differential was also investigated for a lower resonant frequency (650 MHz), in the framework of Project X (now PIP-II) [5], for two cavity types with β=0.91 and β=0.61.

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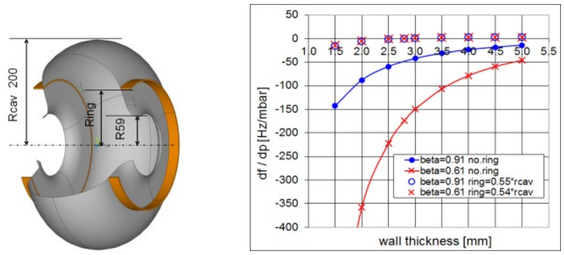

Figure 3: Project X β=0.91 middle cell cavity geometry (left) and simulation results (right).

Since the Project X cavity is rather large, the large cell slope surface is strongly affected by the external pressure, and the volume change near the iris region is larger than at the equator (Fig. 3), which results in a permanent negative frequency shift for non-stiffened middle cells. The proper choice of the stiffening ring position can balance the electrical and magnetic energy change (Fig. 4), resulting in two locations that will produce a zero frequency shift. On the other hand, the ring position also affects the Lorentz force detuning [6]. However, differing from the pressure differential case, the Lorentz forces at the dome region are directed outward the cavity volume. That is why the choice of the ring position is a trade-off between these two effects, since their optimizations result in the different ring positions. For the pulsed accelerators like TESLA, the ring was placed primarily to minimize the Lorentz force detuning (R_{ing}/R_{cav}=0.5, Fig. 4, right).

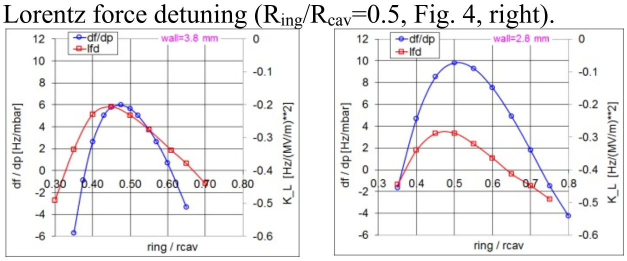

Figure 4: Middle cell simulation summary for Project X β=0.91 (left) and TESLA (right).

Instead of adding a stiffening ring, a special shape of the iris thickness can also be used to change the frequency shift (Fig. 5). This option eliminates the requirement for the installation of stiffening rings.

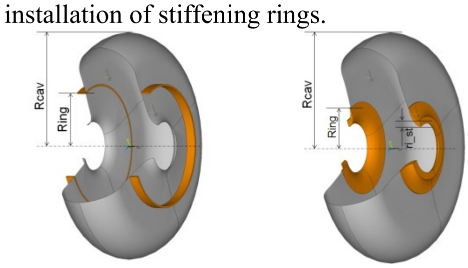

Figure 5: Elliptical middle cell geometry (β= 0.61), with ring and iris stiffening options.

Increasing the cavity iris wall thickness (Fig. 5, right) makes this region more rigid, which primarily serves to minimize the Lorentz force detuning. This stiffening option also results in a flat LFD optimum that gives the freedom to make the optimum choice for df/dp (Fig. 6). However, this type of iris stiffening can increase the cost of the resonator fabrication.

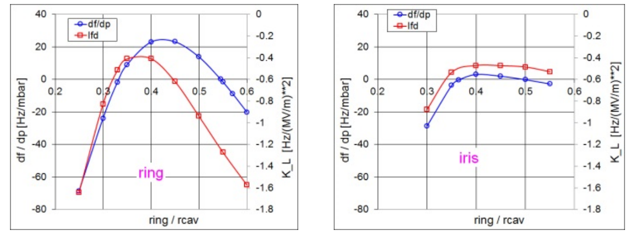

Figure 6: Project X elliptical middle cell geometry (β= 0.61) with ring and iris stiffening optimizations.

LOW-BETA SC RF RESONATOR STIFFENING EXPERIENCE

Historically, the self-compensation frequency shift design for multiple-gap resonators was first investigated for the naked (i.e., without helium vessel) low-beta triple-spoke cavities, which are designed with three half-wave loading elements.

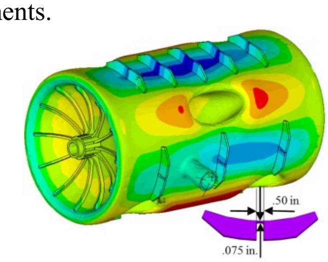

Figure 7: ANL RIA 325 MHz, β=0.5 Triple-Spoke Resonator end cup stiffening.

Such TEM accelerating cavities are characterized by a better separation of electrical and magnetic fields in the structure volume that makes easier to distinguish frequency shifts due to either electric or magnetic field distortions. This, in turn, allows an implementation of additional elements for optimal cavity mechanical design. The procedure of the TEM resonator structural design clearly illustrates the basics of the design, which balances deflections of the cavity walls in areas with magnetic fields (increasing frequency) with deflections in areas with electric fields (decreasing frequency).

For the proposed ANL RIA Driver linac and FNAL 8 GeV proton-driven upgrade, a Triple-Spoke Resonator (TSR) (325 MHz, β=0.5) has been developed [7] (Fig. 7). This cavity was designed to minimize the total RF frequency shift due to changes in the liquid helium bath pressure (df/dp) by adding stiffening ribs to both the end cups and the cylindrical wall of the cavity. The end cup ribs have a special profile that was optimized according to the end cup deformations. In actual construction, some of the ribs were made slightly oversized to allow for post-construction fine-tuning, by cutting away part of each rib. After modifying the support ribs, the RF frequency shift was measured to be 2.43 Hz/mBar whereas the modeled result predicted 4.08 Hz/mBar shift (beam pipes fixed).

The similar approach is used to design the 352 MHz, β=0.48 TSR in the framework of the European High Intensity Pulsed Proton Injector (HIPPI) project at the Re-

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search Center in Juelich, Germany (FZJ) [8]. Since this cavity was designed for pulsed operation, the primary goal of its design was the minimization of the Lorentz force detuning (LFD). For the mechanical design, additional end cup ribs were considered as an option to provide the required stiffening. The ribs are 10° wide and the proper choice of the rib heights can result in the complete frequency shift compensation (df/dp=0) with the final adjustment by making cuts in the region of the main deformations to make the ribs less rigid. The Lorentz force detuning during the high power test at 4.2 and 2K was measured, showing the same value of KL_exp = –5.5 Hz/(MV/m)^2 with KL_calc = –4.1 Hz/(MV/m)^2 at both 4.2K and 2K (beam pipes free).

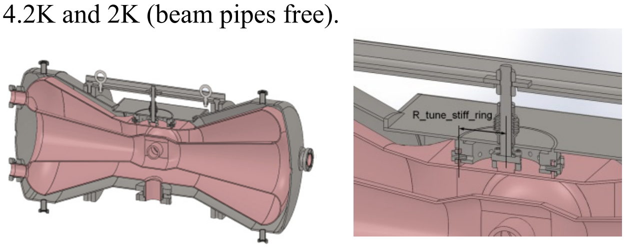

Figure 8: FZJ HIPPI triple-spoke cavity frequency shift due to external loads vs. rib height for different end cup wall thickness.

For the high-intensity proton accelerator complex proposed at Fermi National Accelerator Laboratory, Euclid TechLabs has developed a superconducting conical Half-Wave Resonator (162.5 MHz, β=0.11) [9]. The main objective of this project was to demonstrate a common resonator-helium vessel design with high mechanical stability, based on the idea of balancing the cavity frequency shifts caused by external loads. To use the outer conductor walls for cavity tuning deformations effectively, the central part of HWR is made asymmetric, with a planar surface on one side. This planar surface is used for tuning by deformation (Fig. 8). The tuner ring, connecting the cavity and helium vessel tuning plates, is installed around the bellows and provides compensation for the external pressure deformation of the cavity tuning wall (Fig. 9, left).

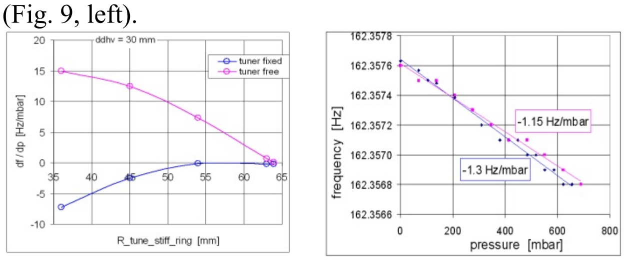

Figure 9: FZJ HIPPI triple-spoke cavity frequency shift due to external loads vs. rib height for different end cup wall thickness.

The side-tuning procedure results in tune sensitivity up to 80 kHz/mm, with an acceptable stress of 350 MPa/mm and tuning pressure of less than 1 kN/mm. The helium vessel was pressurized to test df/dp under cryogenic conditions. These df/dp measurements confirm the numerical simulations, and are consistent with room temperature df/dp measurements (Fig. 9, right).

MULTI-CELL SC RF ELLIPTICAL CAVTY

A conceptual design for the self-compensation of the frequency shift for multi-cell elliptical resonators was used first to optimize the bellows position for the cryomodule design for RIA [10, 11] at Michigan State University.

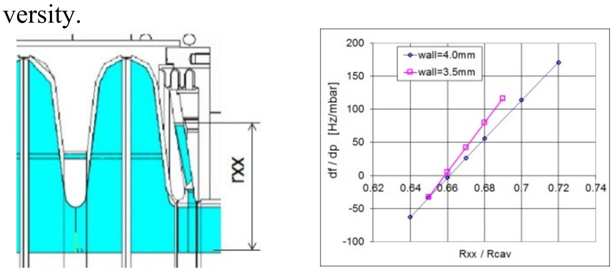

Figure 10: MSU 6-cell 805 MHz, β=0.47 elliptical cavity with helium vessel (left, only end sides shown) and bellows position optimization (right).

A helium vessel design was considered for 6-cell 805 MHz, β=0.47 elliptical cavities (Fig. 10, left). Bellows are included in the helium vessel to accommodate the motion produced by the tuner. When the cavity and cryostat are under vacuum, the pressure differential is exerted not only on the cavity walls, but also on the inside surfaces of the helium vessel, including the end dishes. One of the dishes is firmly attached to the outer cylinder of the helium vessel, and the other is connected via the bellows. Depending on the radius of the bellows (r_{xx}, Fig. 10, right), the inward force on the cavity walls will be either larger or smaller than the outward force on the end dish. Thus, the cavity will be either shortened or stretched. There is a particular bellows radius for which the shift in frequency with pressure is zero. This is an idea that was later realized at the Euclid HWR (Fig. 8).

High Frequency Multi-Cell SC RF Elliptical Cavity Helium Vessel Design

The detailed investigation of the cavity stiffening, together with helium vessel design, has been provided for bERLinPro Energy Recovery Linac (ERL) [12] and for Cornell ERL [13]. Both projects use 7-cell elliptical cavity (1300 MHz, β = 1.0) surrounded by a helium vessel (HV) (Fig. 11). The bERLinPro structure includes a coaxial tuner, power coupler and five HOM waveguides, which are connected to the beam pipes close to their transition with the cavity. All of the waveguides firmly join the outer HV cylinder. The stiffening rings are installed between cavity cells including end cells connected with waveguides. This design ensures the very rigid end parts of the structure. Both beam pipe ends are supposed to be completely free. The outer HV cylinder is split in two halves. The tuner occupies the gap between these halves. This secures the symmetric resonator deformation while tuning. The tuner in the Cornell structure is installed at the end of the HV cylinder, providing an asymmetrical

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cavity deformation. The tuning sensitivity is similar for both projects and is about 350 kHz/mm, with a tuning force of from 3 kN to 100 kN, depending on the ring position [13].

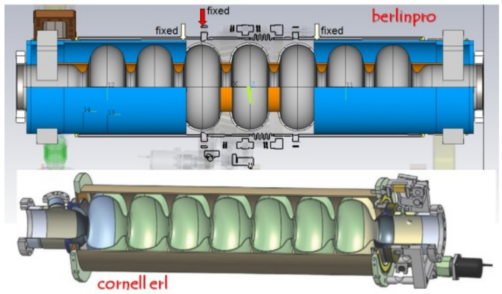

Figure 11: bERLinPro and Cornel ERL 7-cell elliptical cavities in provisional helium vessels with HOM waveguides, tuners and power couplers.

During simulations of both projects, the pressure differential is exerted on the cavity walls and on the inside surfaces of the helium vessel, including the end flanges. Several options for cavity stiffening were investigated.

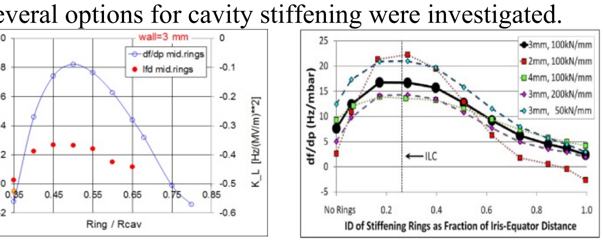

Figure 12: Simulation results for bERLinPro (left) and Cornell ERL (right) 7-cell cavity in helium vessel, showing variation of df/dp and LFD (bERLinPro) with position of the middle rings.

The simulation results for the dependences of df/dp on stiffening ring positions are shown on Fig. 12. There are two df/dp=0 stiffening ring positions that are similar to the single middle cell calculations. The preferable choice is a no ring option (R_{ing}/R_{cav}=0.35 for bERLinPro), since using the installation of rings close to the dome would result in a higher tuning pressure. The same results were obtained for the International Linear Collider (ILC) [13]. However, the final design of the ILC resonator was for the rings in a location with close to the highest value of df/dp. This is a result of it being optimized for pulsed operation, with the objective of minimizing the Lorentz force detuning coefficient. An accelerating field profile is not affected, either by the tuning or by the pressure differential. The mechanical stresses are well below the room temperature plastic deformation limit.

However, the low frequency of the mechanical eigenmodes that would be a major source of microphonics is a serious problem with the unstiffened cavity. External vibrations can excite mechanical resonances of cavities in a cryomodule. To minimize the level of microphonics, it is important to maximize the frequencies of the mechanical resonant modes of the cavity. The detailed investigations of the mechanical resonant cavity vibrations of the bERLinPro and Cornell ERL resonators were carried out using different simulation models, starting with the simplest of the naked resonators and variation of the cavity structural constraints. From the ANSYS results, an increase of the radius of the inner stiffening rings only slightly affects the frequency of the first resonant mode (transversal). For very small stiffening ring radii, the frequencies of the lowest mode lie dangerously close to 60 Hz. The second mode frequency (longitudinal) is strongly depends on the ring positions and is around 200 Hz.

Low Frequency Multi-Cell SC RF Elliptical Cavity Helium Vessel Design

The in depth investigation of the 5-cell elliptical cavity (650 MHz, β = 0.91) has been provided first in the frame of FNAL Project X [14-16], and later for PIP-II [17]. The latest version of the helium vessel design makes use of the bellows at the end flange to provide the balancing between electric and magnetic stored energies distortions, like at the MSU 805 MHz 6-cell cavity (Fig. 13).

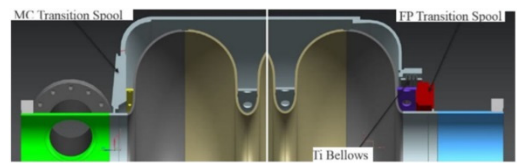

Figure 13: FNAL PIP-II 5-cell elliptical resonator (650 MHz, β=0.92) in provisional helium vessel (top), and optimized dressed cavity ends (bottom).

The baseline design for the β=0.92 cavity utilized an end lever tuner for better efficiency of the cavity tuning. The main coupler end and the field probe end of the helium vessel have slightly different joint designs, due to the cavity installation sequence and the variations in the cavity length. The main coupler end of the vessel is considered a fixed position relative to the main coupler port of the cavity.

The dependence of the frequency shift was investigated in terms of the tuner stiffness and in case where the tuner stiffness is higher than 60 kN/mm, df/dp is less than 12 Hz/mbar. To decrease LFD, the helium vessel stiffness was increased with the implementation of thicker end dishes (Fig. 13). With a simulated tuner stiffness greater than 60 kN/mm, LFD will be not higher than -0.75 $Hz/(MV/m)^2$.

The same scope of theoretical investigation was made for the FNAL PIP-II β=0.61 resonator [18]. The main task was to design the structure stiffening scheme to coincide the minimal values of df/dp and LFD. In the resulted structure, the end flanges of the helium vessel are connected to the cavity beam pipes. There is a slot in the HV left end flange imitating the connection of the tuner. The stiffening rings are installed between the cavity cells and connected end cells with vessel end flanges. The tuner end ring is supposed to be completely fixed, not taking into account the tuner stiffness. The pressure differential is exerted on the cavity walls and the inside surfaces of

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the helium vessel. This type of model configuration results in the best constraint conditions with low ring position (R_{ing}/R_{cav} = 0.33 for β=0.61 and R_{ing}/R_{cav} = 0.41 for β=0.92), in order to satisfy df/dp=0 and minimal Lorentz force detuning (Fig. 14).

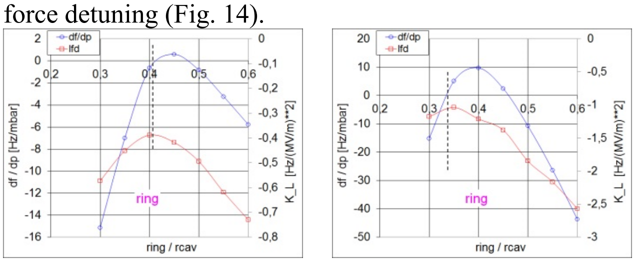

Figure 14: FNAL elliptical 5-cell cavity (β = 0.92, left) and (β = 0.61, right) stiffening optimization with ring.

SRF elliptical cavities for β=0.61 have an inherently more flexible shape, and its ultimate stiffening with the same stiffening scheme is less effective than for β=0.92 cavity. Primary was an idea that an installation of the second set of the rings should enhance the overall cavity rigidity. However, because the difference in LFD value for the one and two ring options is not essential, and the complexity of production of the cavity with two rings is higher, the use of the one-ring option is preferable. The same conclusion is for β=0.92 cavity [17] – for 2 rings, LFD~-0.275 Hz/(MV/m)^2, whereas for 1 ring, LFD~-0.38 Hz/(MV/m)^2. Still, the mechanical eigenmodes are a serious source of microphonics in this structure. The lowest mechanical mode frequency is around 30 Hz.

Low Frequency Multi-Cell SC RF Elliptical Cavity Tuning

The use of stiffening rings on the connecting cells with the outer helium vessel walls, together with HV constraints, results in a rather rigid structure. This scheme ensures perfect conditions for df/dp minimization without affecting the field profile. On the other hand, it creates problems for the resonator tuning using a lever tuner installed on one side of the structure, since high structure rigidity results in a higher tuning force, and in strong distortion of the accelerating field profile, even with only 1-mm tuner shift. It is important to keep the structure stiffening scheme symmetrical, in order to maintain a symmetrical field profile, with minimal distortions caused by cavity deformation due to the external helium pressure. At the same time, the whole structure should be constrained in the way that the tuning force applied at one cavity end also results in homogeneous resonator deformations along the length of the structure.

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