LORENTZ FORCE DETUNING ANALYSIS FOR LOW-LOSS, REENTRANT AND HALF-REENTRANT SUPERCONDUCTING RF CAVITIES

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Abstract

Several new superconducting RF cavity shapes have been developed during the last few years in which the surface magnetic field is decreased relative to the TeSLA cavity shape, with the goal of reaching a higher accelerating gradient. This study will compare the Lorentz force detuning characteristics of the TeSLA, "low-loss," "reentrant," and "half-reentrant" cavity middle cells, and explore possible methods for stiffening the structures.

INTRODUCTION

The RF design of a superconducting elliptical cavity requires a trade-off in the optimization of the cell shape between the region of high electric field and the region of high magnetic field. In practice, the cavity performance may be limited not by the RF characteristics, but by detuning due to the Lorentz force, bath pressure fluctuations, or microphonics; Lorentz force detuning is of concern primarily for pulsed accelerators such as the proposed International Linear Collider. Hence the structural properties must also be taken into account in the cavity design. A half-reentrant (HR) cavity (1300 MHz, β = 1) is being developed at Michigan State University [1] for use in a superconducting linear collider and other applications. The electromagnetic performance of the half-reentrant cell shape is similar to that of a fully reentrant cavity, but a multi-cell HR cavity can be cleaned using traditional techniques.

This paper reports on structural analyses of the HR cavity for the mid-cell. The shift in the resonant RF frequency due to the Lorentz force was calculated as a function of wall thickness, with and without stiffening rings. The results for the HR cavity were compared with simulations for the TeSLA [2], Cornell reentrant [3] and ICHIRO "low-loss" [4] cavities to better understand the behaviour and trends. The response of these cavities to a helium bath pressure differential was reported earlier [5].

Figure 1 shows the Cornell reentrant, ICHIRO low-loss, and HR middle cells in comparison with the TeSLA shape. The RF parameters are compared in Table 1 (the RF design having been done independently by different groups). A comparison of the ratio of peak surface magnetic field to accelerating gradient shows the clear advantage all high-gradient cells relative to the TeSLA geometry. The B_{pk}/E_{acc} ratio is about the same for the ICHIRO and HR cavities (note that the Cornell re-entrant cavity has a higher B_{pk}/E_{acc}, but also higher cell-to-cell coupling; an alternative Cornell design with smaller cell-to-cell coupling is similar to the other high-gradient cells).

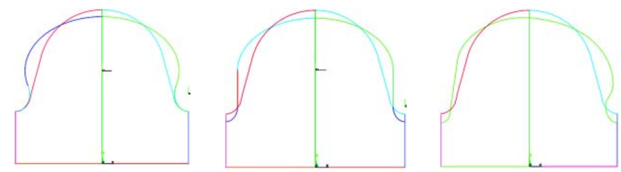

Figure 1: Mid-cell geometries.

Table 1: Some RF parameters of TeSLA and high gradient cavities (E_{pk} = peak surface electric field; B_{pk} = peak surface magnetic field; E_{acc} = accelerating gradient). An operating field of B_{pk} = 100 mT is assumed for the sake of comparison.

	TeSLA	Cornell	ICHIRO	HR	
E_{pk}/E_{acc}	2	2.4	2.23	2.41	
B_{pk}/E_{acc}	4.26	3.78	3.6	3.55	mT/(MV/m)
B_{pk}/E_{pk}	2.13	1.58	1.61	1.47	mT/(MV/m)
B_{pk}	100	100	100	100	mT
E_{pk}	46.9	63.5	61.9	67.8	MV/m
E_{acc}	23.5	26.5	27.8	28.2	MV/m

The Lorentz detuning coefficient is defined in terms of the cavity frequency f and the accelerating gradient E_{acc} as $K_L = df/dE_{acc}^2$. As K_L is defined in terms of the E_{acc}, but the Lorentz force is due to the surface field, a cell shape with lower ratios of surface fields to accelerating gradient will tend to have a smaller K_L.

The ANSYS codes [6] were used for the simulations. We assumed the same mechanical properties for the cavity walls and connecting (stiffening) rings (niobium with Young modulus = 105000 N/mm^2 and Poisson ratio ν = 0.38).

REGULAR CELLS WITHOUT STIFFENING

The response of the cavity to the Lorentz force was simulated. The simulations were done with the cell-to-cell junction constrained by symmetry. The goal for these calculations was not to achieve the best accuracy, but rather to understand the behaviour and trends.

The Lorentz force changes the cavity shape and shifts the RF frequency of the accelerating mode. The deformation is similar for all of the cells that are left-right symmetric (TeSLA, reentrant, and ICHIRO); the main deformation occurs along the straight segment joining the curved segments of the equator to the curved segments of the iris. The deformation happens mostly in the region of high electric field (Figure 2). The larger displacement for the ICHIRO cavity is due to the lower rigidity, which results from the straight segment being vertical.

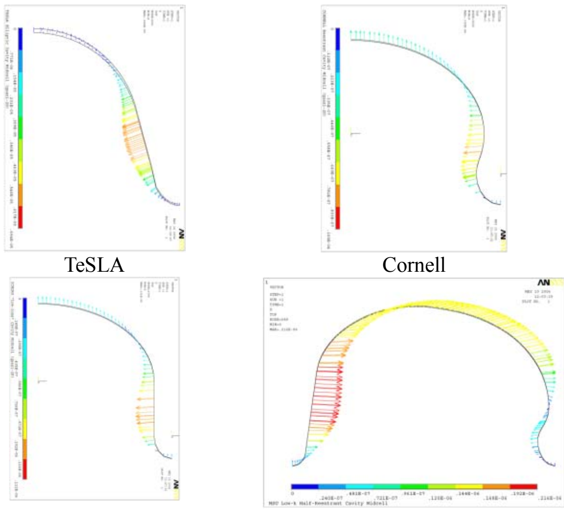

Figure 2: Cell deformations caused by the Lorentz force.

Because it is not left-right symmetric, the deformation of the HR cell is much bigger than that of the symmetric cells. The deformation occurs primarily in the region of high magnetic field. But the asymmetric cell shape produces deformations that are directed almost entirely along the cavity axis. The net effect is mostly self-cancellation: the volume of the cavity decreases on the non-reentrant side and increases on the reentrant side. The compensation effect results in a K_L value similar to the other cases. The deformation and frequency shift both depend on the thickness of the cavity wall, so the wall thickness was varied in the simulations (Figure 3). Note that, after the cavity is formed and etched, the wall thickness may be significantly different from the initial thickness of the sheet niobium.

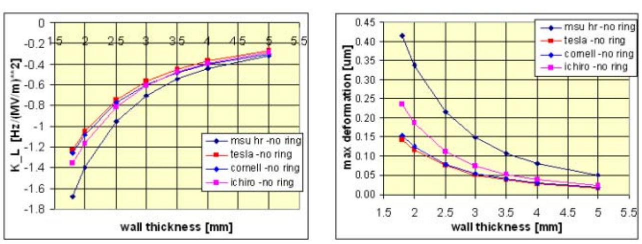

Figure 3: Mid-cell response to Lorentz force pressure (no stiffening rings).

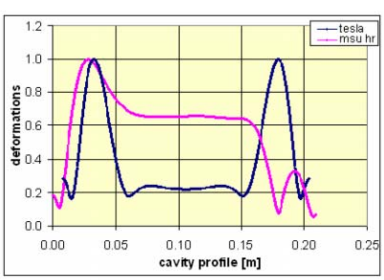

Figure 4: TeSLA and HR cell deformations caused by Lorentz force pressure along cell profile (no stiffening rings).

The deformation as a function of distance along the cavity wall (Figure 4) illustrates the cell behaviours discussed above. Even for the much larger deformations for the HR cavity, the frequency shift is approximately the same as for symmetric and more rigid cells.

REGULAR CELLS WITH STIFFENING

A stiffening ring can be used to change the frequency shift; this is part of the design for the TeSLA cavity and others. The same stiffening method can be applied to the HR cell (Figure 5). The difference is that the ring strengthens the iris region in the case of the HR cavity. The lower deformation of the TeSLA cavity is explained by the fact that its equator region is much more rigid. Still, all of the high gradient cells have about the same K_L as the TeSLA cell (Figure 6); this is due to their lower E_{pk}/E_{acc} and B_{pk}/E_{acc} ratios.

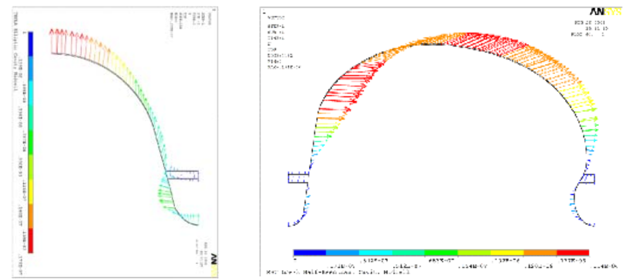

Figure 5: TeSLA and HR cell deformations caused by Lorentz force pressure (with stiffening rings).

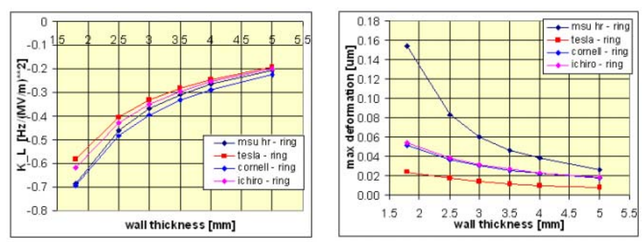

Figure 6: Mid-cell response to Lorentz force (with stiffening rings).

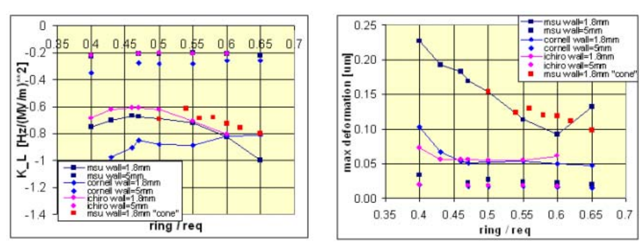

Figure 7: Stiffening ring position optimisation.

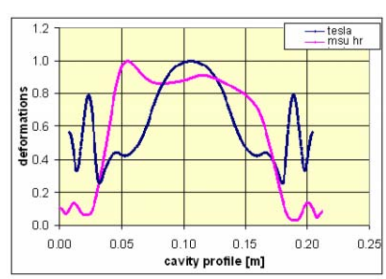

Figure 8: TeSLA and HR cell deformations caused by the Lorentz force along the cell profile (with stiffening rings).

The ring position optimisation shows similar results for most cases (Figure 7). The Cornell reentrant cell differs because it has no straight segment, and hence the position of the ring is less crucial. This is an advantage of the re-entrant geometry: the ring position may be chosen for convenience in welding. Again, the HR cell has bigger displacement but with different behaviour than the others.

For symmetric cells, the stiffening ring reduces the cavity wall displacement in the iris region, making the deformation along the cavity profile more evenly distributed between the iris and the equator (Figure 8).

Since the HR cell has one reentrant side, it is worth checking whether the "reentrant side ring" position is also less crucial, as was the case for the fully reentrant cell. The red points in Figure 7 correspond to a HR cell when the "left ring" is at the position r_{ing}/r_{eq} = 0.5 and the position of the "right ring" is being changed (r_{ing} = radius of the stiffening ring; r_{eq} = radius of the cavity equator). Similar to the Cornell reentrant cavity, the HR right ring position can be chosen in a wide range with no effect on K_L. Since the right ring is moved up, the equator becomes more rigid and the maximum cell deformation is lower. Thus, for the HR cell, the stiffening ring could be cone-shaped instead of being the traditional cylindrical shape. The effect is most clearly seen with a wall thickness of 1.8 mm. For more practical wall thicknesses of 3-4 mm, the dependence of K_L on the "right ring" position is even less. One example of the deformation for a cone-shaped stiffening ring is shown in Figure 9.

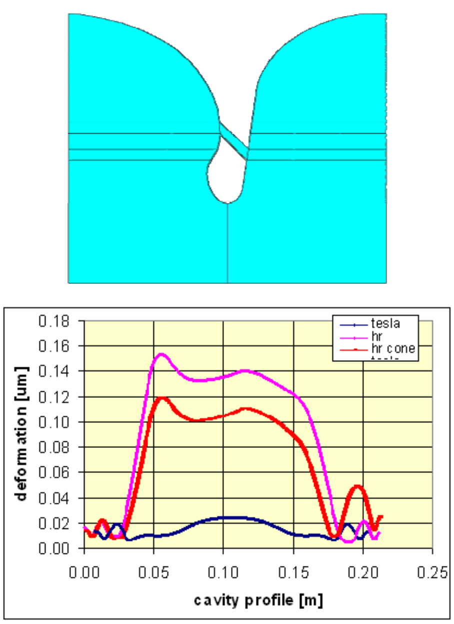

Figure 9: TeSLA and HR cell deformation caused by the Lorentz force along the cell profile (with stiffening rings and cone-shaped stiffening rings).

CONCLUSION

The Lorentz force detuning of different high-gradient cavity mid-cells is about the same and very close to the TeSLA mid-cell case. Hence the various cell shapes should all be suitable for use in a pulsed accelerator. The helium vessel should be designed to minimise the shift in frequency due to end cup deformations. Several high gradient cavities have been prototyped; prototyping of a single-cell version of the HR cavity is in progress. Because the HR cavity is partly non-reentrant, a multi-cell HR cavity can be cleaned using traditional techniques.

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