Design of a triple-spoke cavity

for 352 MHz and β=0.48

E. Zaplatin[1], R. Maier[1], M. Pap[1], R. Toelle[1]

1) FZJ, Jülich, Germany

Abstract

For use in a pulsed linear accelerator a 352 MHz cavity is designed and will be built for comparison with other cavity types. This report covers some features of cavity RF design and investigations of the cavity stiffening options.

1. RF Aspects of Cavity Design.

The basics of the electrodynamics of the spoke-type cavity are well known and have been discussed many times elsewhere [1]. The electrodynamic design of any SC RF cavity aims to optimise the cavity geometry to reach the highest accelerating efficiency, in other words to minimize values of peak electrical and magnetic fields on the cavity surface relative to the accelerating electrical field on the cavity axis (B_{pk}/E_{acc} and E_{pk}/E_{acc}). The good separation of electrical and magnetic fields in the space gives a freedom to the cavity shape design. On the other hand, we limited ourselves with the case when the circumference of the spoke in any cross section is the same (except for the base cone).

The design of the end cell of multi-spoke cavity is defined by two factors – to reach the minimum of magnetic field on the spoke surface and the design of the cavity end cup. The first affects also the distribution of the electrical field along the multi-gap cavity but its profile can be corrected by the end gap length reduction. The end cup design mainly comes from its mechanical properties. The geometry and parameters of the cavity are shown in Fig.1 and Table 1.

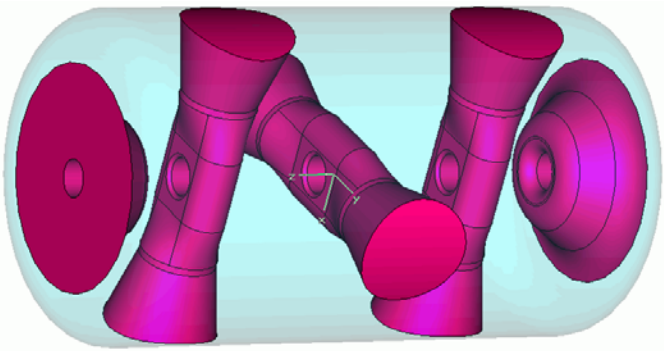


Figure 1: 4-gap H-cavity geometry.

Table 1: Some Parameters of HIPPI Triple-Spoke Cavity

Frequency	MHz	352.9
β=v/c		0.48
R aperture	cm	2.5
$\beta\lambda/2$	cm	20.44
Cavity radius	cm	21.7
Cavity length	cm	78
QR_s	Ohm	93
E_{pk} / E_{acc}		4.65
B_{pk} / E_{acc}	mT/MV/m	10.97
B_{pk} / E_{pk}	mT/MV/m	2.36

The role of the cone in the spoke base for electrodynamics is to increase the spoke diameter right in the region of the maximal B_{pk}. That moves B_{pk} from the outer spoke region closer to the middle of the spoke. It is not important for a square cavity shape, as the cross section here is nearly the same but plays an important role for the round cavity as it shifts B_{pk} away from the outer cavity wall.

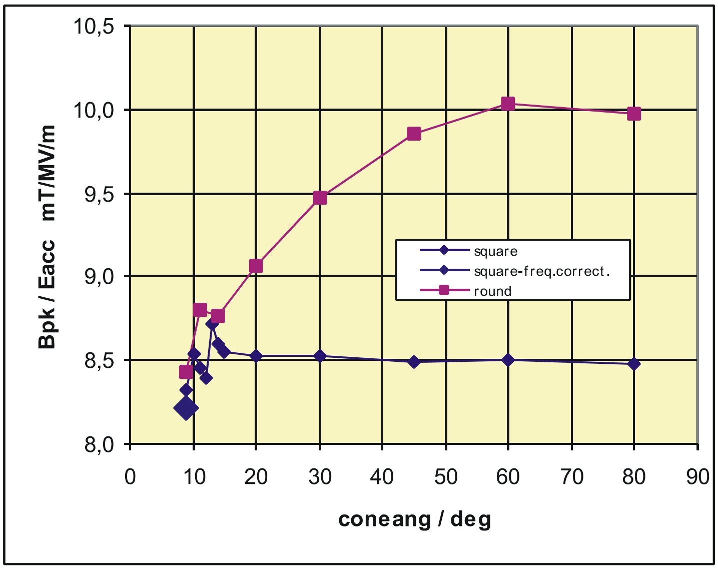


Figure 2: Peak magnetic field dependence on base spoke cone angle

For simulations the cone geometry in the spoke base is parameterised in such way that the diameter at the cone base is always equal to the biggest spoke dimension in the mid region. The change of the cone angle (coneang) results in the change of cone length. By coneang=60^{o} the whole cone geometry is outside of the round cavity, which corresponds to the straight cylindrical shape of the spoke base (Fig.2). The results means that with the use of the spoke with the cone on its base makes the outer cavity wall shape unimportant. On the other hand, the cylindrical cavity is more attractive because of its higher rigidity and technologically simpler to manufacture.

The position of the coupler on the cavity and its type (electrical or magnetic) should be checked in terms of the Q_{ext} simulations. The position of the E-field coupler opposite to the mid-spoke looks attractive because of the symmetry of its position. The magnetic field in this region equals zero. This port is designed for CF63 and will fit the coupler developed by IPN Orsay. A second access or coupler port for CF100 is located on the other side (Fig.3).

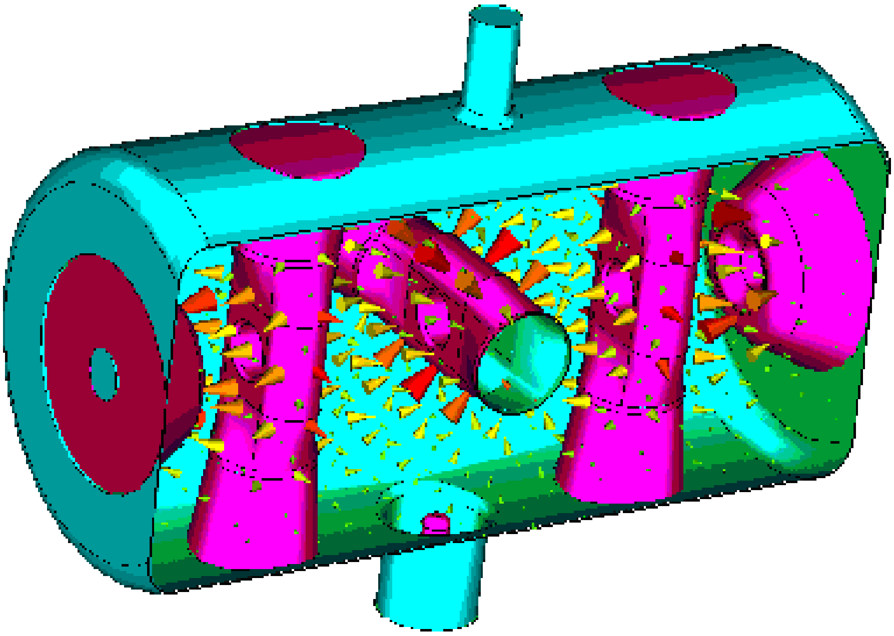


Figure 3: 4-gap H-cavity with electrical coupler and vacuum port.

Table 2: CW power requirements for the coupler for two accelerating field options and B_{pk}=80 mT.

Lcav	beam	Eacc	
m	mA	8 MV/m	10 MV/m
0.78	20	**108.10 kW**	**135.12 kW**

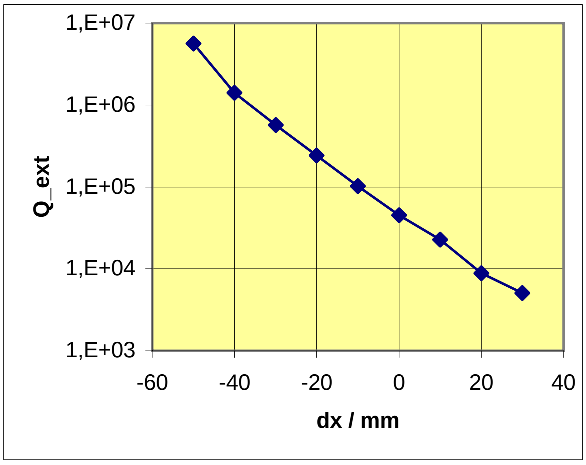
Bpk	**80**	mT
Epk	35.34	MV/m
E0T	8.96	MV/m
Voltage	7.28	MV
Pbeam	121.07	kW
Qext	3.2E6	

Simulations with MAFIA indicate the sufficiency of the coupling. For our beam-field parameters (Table 2) the E-field coupler should be installed deep (around 40 mm) inside the coupler port (Fig.4).

Table 3: Single-point multipacting in coaxial lines.

	CERN	HIPPI		
Z0/Ohm	75	75	75	**75**
Dout/mm	103	70	90	**100**
MP order / kW				
7	48	10.2	28.0	**42.6**
6	52	11.1	30.3	**46.2**
5	88	18.8	51.3	**78.2**
4	176	37.5	102.6	**156.4**
3	234	49.9	136.4	**207.9**
2	448	95.6	261.2	**398.0**
1	640	136.5	373.1	**568.6**

The main consideration of the coupler coaxial line size selection is multipacting. Multipacting levels can be scaled from known levels [2]. Table 3 gives the lowest seven single-point multipacting levels for the CERN LEP2 couplers and for three potential line choices. The last option (75 Ohm, 100 mm) seems to fit our requirements.



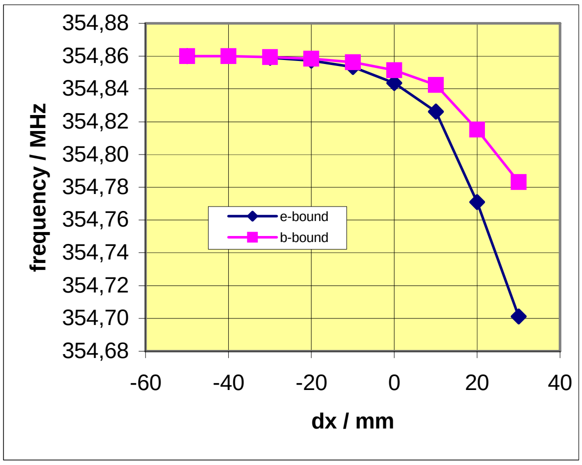
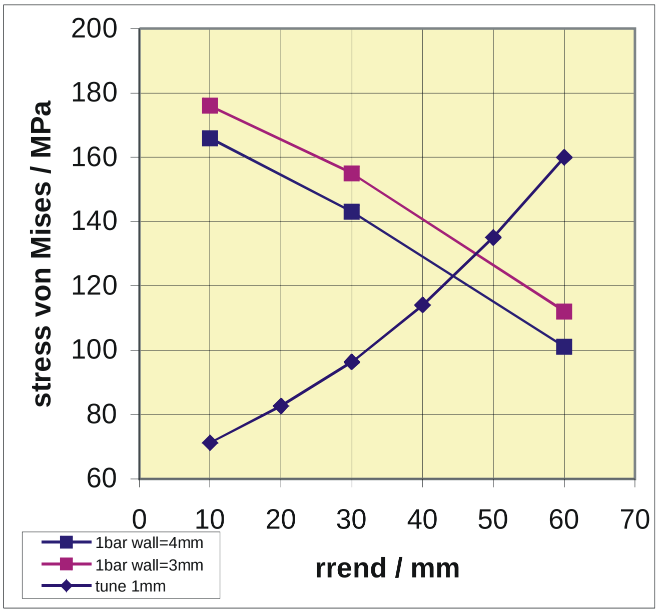


Figure 4: Q_{ext} and cavity frequency shift depending on coupler tip position relative to the cavity wall

The most flexible elements in a cavity are the end cups. This flexibility is used for reasonable deformations for cavity tuning. On the other hand, because of this flexibility the end cups are the most affected parts by vacuum loads. Fig.5 shows stresses von Mises from



1 mm end cup tuning shift and 1 bar external loads depending on the cavity end cup radius (rrend). Also the cavity end cups define the six first cavity mechanical eigenmodes.

Figure 5: Stress v. Mises on cavity end cup

2. Cavity in FZJ Test Cryostat.

The very first cavity investigation in terms of the mechanical properties is its mechanical eigen modes. We use the criterion of 200 Hz for the first mode that would be sufficient for the cavity rigidity. To improve the cavity rigidity the stiffening rings on both cavity ends are used (Fig.7). The stiffening rings are 3 cm high and 2.5 cm wide. The cavity fixation in four points by every ring is arbitrary and in fact not practical but it allows investigating the modes that are related only to the cavity. Here we should notice, as it could not be the ultimate cavity RF design, there cannot be a structural one either. Each time one should optimize the structure design with respect to the cavity future application and real cavity working environments. Since we decided not to use a separate LHe vessel but to measure the cavity in a bath cryostat, the results of the experimental mechanical conditions will depend mainly on the cavity fixation inside the cryostat.

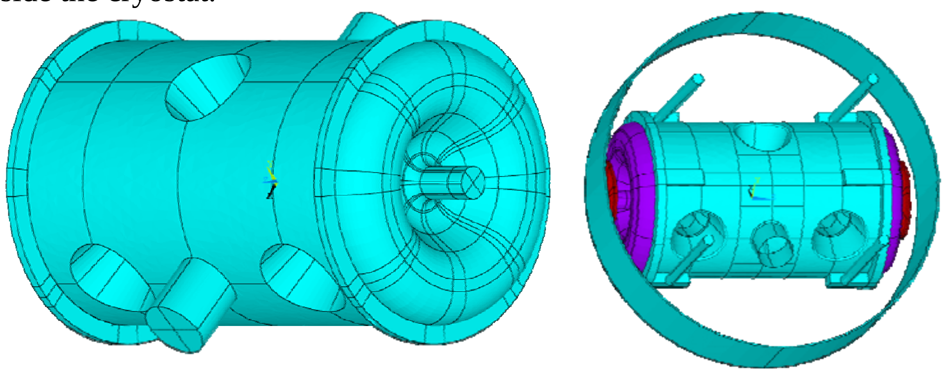


Figure 7: Triple-spoke cavity with stiffening ring and tentative installation in FZJ cryostat.

Table 5: Cavity eigen modes with unstiffened end-cup.

	w. ring	no ring
Mode	Freq / Hz	Freq / Hz
1	261	155.1
2	294.5	251.2
3	298.6	253
4	298.7	274.8
5	418.2	353.7

The FZJ test cryostat that is planned to be used for the cavity measurements is a vertical bath cryostat. Provisionally, the cavity is to be mounted to the upper flange by means of four rods connected to the cavity walls (Fig.7). In this case the cavity rigidity is defined mainly by the rigidity of the rods. To show the structural cavity properties the simulations of the cavity modal analysis with the completely fixed joints, which are supposed to be used for the connection of the rods to the cavity, have been provided (Table 5). The lowest cavity mechanical eigen mode is around 261 Hz, indicating sufficient cavity rigidity. Without the stiffening ring the first eigen mode frequency is lowered to 155 Hz as the cavity becomes more flexible in the transverse directions.

The further strategy of such type cavity design should include integrated simulations of RF and mechanical properties, so-called coupled analysis. The main idea and advantage of the coupled analysis (CA) with numerical codes like ANSYS is to use the same meshed model through all kind of simulations. Such CA in our case is helpful for cavity resonance frequency change calculations caused by different mechanical loads. The use of the same mesh during simulations or later the same but deformed mesh should increase the accuracy of the results.

Let‘s move the tuner from the cavity ends (beam ports) and apply the tuning pressure to the cavity walls close to the central spoke where the magnetic field is close to its maximal value. The slow cavity tuning is mainly required for the cooldown-to-cooldown difference compensation and 1 bar pressure frequency shift compensation. ANL practical experience shows that 20-50 kHz will be sufficient. Our simulations result in 75 kHz/mm tuning sensitivity for the relatively local pressure application (just in three mesh nodes, Fig.8). If required, the tuning zone can be made larger. There are advantages to install the tuner in this place rather as usual at the cavity ends – first, one saves space between the cavities that reduces accelerator length, and second, the required tuning force is much lower as it should not deform the stiffened end cup but only the 3-4 mm thick Nb wall. Disadvantage is that the tuning sensitivity is lower.

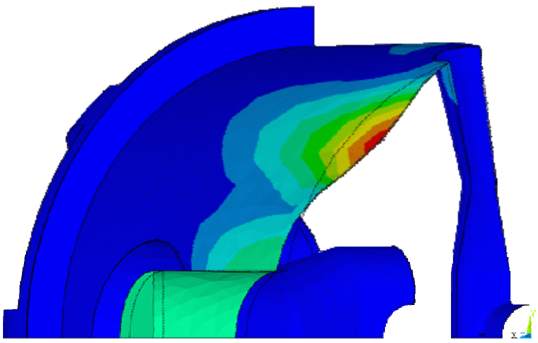


Figure 8: Option of triple-spoke cavity tuning close to the mid-spoke.

As soon as the tuner is moved to the middle of the cavity, the end cups can be stiffened as much as it is required.

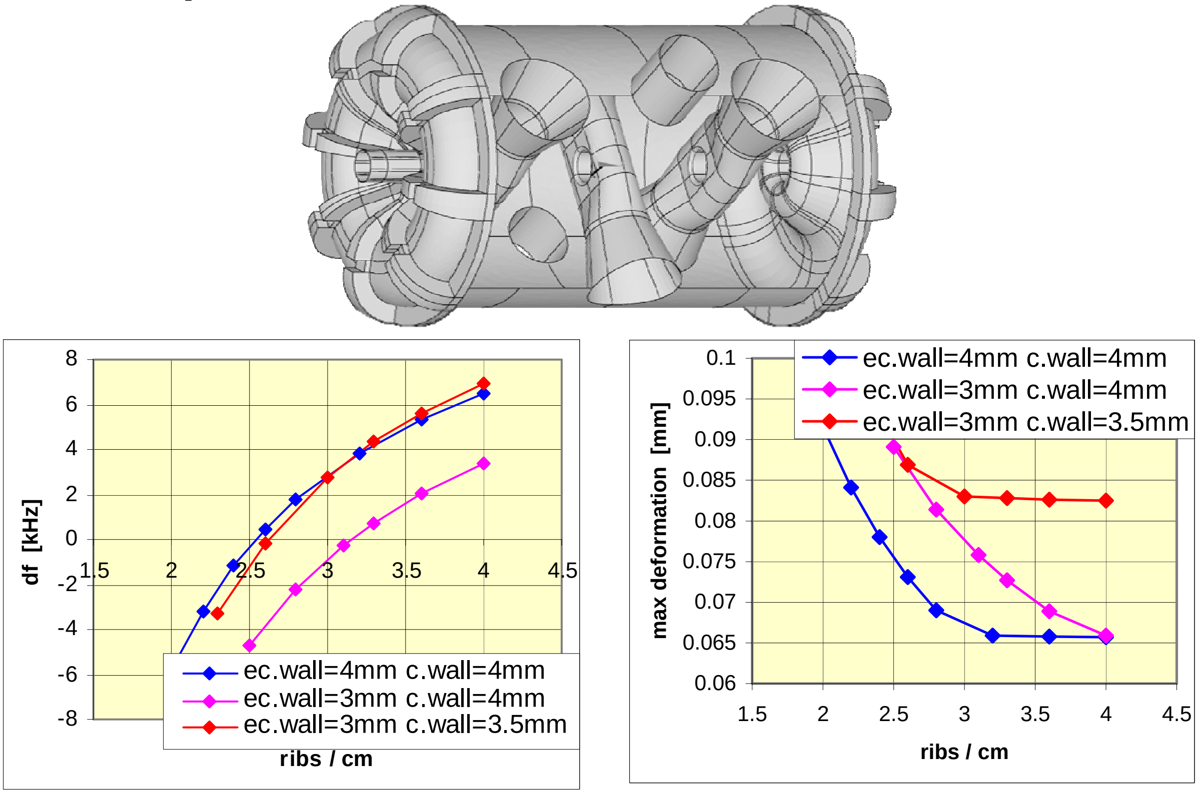


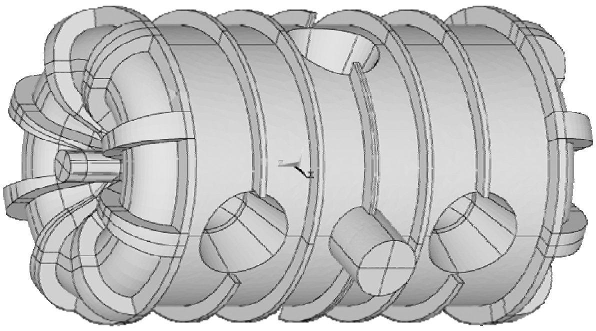
Figure 9: Triple-spoke cavity with stiffening end cup ribs and cavity reaction on 1 bar external loads vs. rib heights

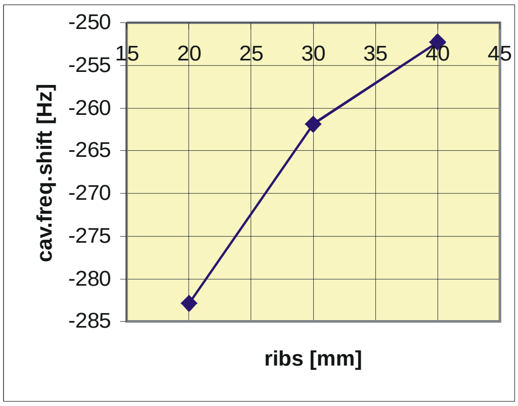
Let's consider the option with additional end cup stiffening ribs (Fig.9).Here the rings are 4 cm high and 2.5 cm wide. The ribs are 10 degrees wide, and should follow the end cup surface increase with radius. Thus the end cup rigidity increases with radius.

Assuming that the end cups do not move at all, the frequency shift from 1 bar pressure would be defined mainly by the magnetic field volume change (cavity inductance reduction). The end cup displacement caused by 1 bar pressure results in the last gap's length reduction (cavity capacitance increase). It means, both effects work in opposite directions concerning the cavity frequency change. Hence, one can find an end cup stiffening that would result in an end cup deformation compensating the frequency change because of magnetic field volume change. The rib height variation shows exactly this effect with the frequency shift crossing the zero line (Fig.9). An uncertain factor here is the end cup wall thickness. So we investigated two different cases for end cup wall thickness (3 and 4 mm for end cup, the rest of the cavity including spokes is 4 mm). One can see in the graphs that the maximum deformation moves from the end cup to the cavity wall. It is impossible to a priori predict the final effective wall thickness. Thus one should foresee the possibility to adjust the structure to the final conditions. One option is to build the ribs as high as possible and after initial measurements to reduce their thickness in the region of the main deformations making them less rigid. This method is rather close to the conducted simulation of the rib height variation. Another option is to make a slit-like cut in the same region as indicated in Fig.9. Most probably both methods can be applied.The uncertainty with the cavity wall thickness changes the results of the structure optimizations. This makes the possibility of the final structure adjustment highly necessary. The use of the tuner in the place of the maximum magnetic field means the ideally complete fixation of the wall in this place. This results in a lower frequency shift caused by magnetic field change and as a result „overcompensation“ by the end cup displacement. In this case to reach the complete compensation one should either provide bigger end cup stiffening or one could use the tuner as an additional tool for cavity frequency shift adjustment. Fig.8 shows the case when all four places around spoke are connected to the tuner and fixed. In practice, the slow tuner could be connected to only two opposite places (this corresponds to 75 kHz/mm tuning sensitivity for our cavity). A third place could be used for the fast tuner. That means, at least three of four tuning places will be fixed.

The action of the Lorentz forces in the region of the magnetic field is directed outside, which is opposite to the action of the 1 bar pressure. It means that the effects of cavity wall and end cup deformations have to be added. In this case the use of the tuners (say, cavity wall fixation in these places) reduces Lorentz force cavity detuning.

For further LFD reduction one could use small ribs (1 cm x 2.5 cm) on the cavity walls in the regions of maximal deformations (Fig.10). LFD rib installations will also affect the cavity frequency shift caused by 1 bar pressure. LFD ribs should be installed as the tuner will compensate the bigger LHe pressure detuning and LFD will be lower. Let‘s finally note, that investigations and optimizations of all effects are within 0.1 mm, which means strong uncertainties between simulations and the final cavity geometry as the tolerances on cavity manufacturing are within 0.5 mm. Nevertheless, the final practical cavity adjustment is possible if the methods of fine-tuning are included in the mechanical cavity design beforehand.With a use of LFD ribs the dependence on the cavity wall thickness for the frequency shift is negligible.





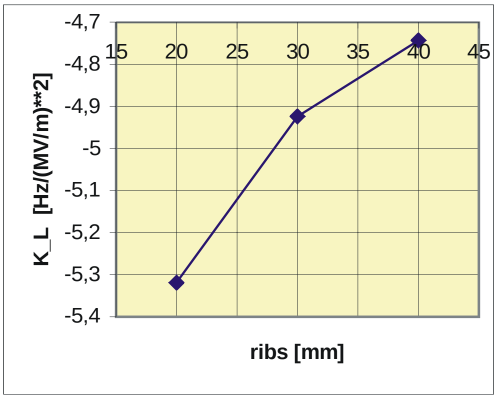
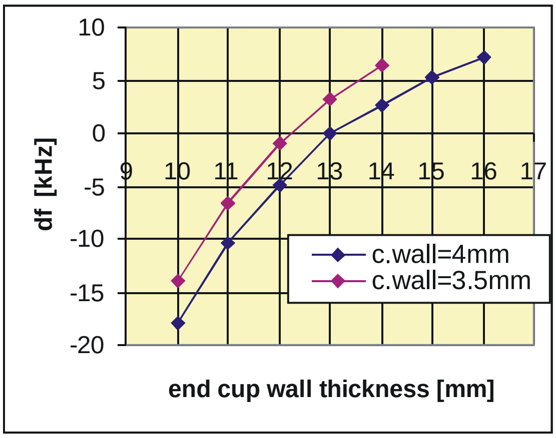


Figure 10: Triple-spoke cavity with stiffened end cup and Lorentz force ribs and cavity reaction on Lorentz forces vs. rib heights.

Another way of the end cup stiffening is to use the plasma sprayed copper coating technique. This innovative method has been used by ORSAY for SC RF elliptic cavity stiffening (see for instance [3]). The action is the same as using the end cup ribs but the copper thickness is lower than the rib height (Fig.11, 12).



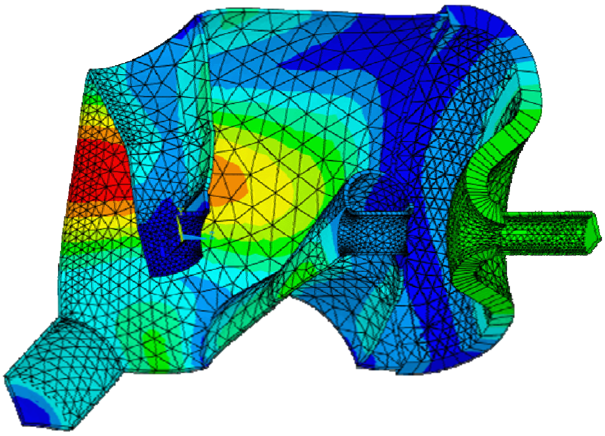
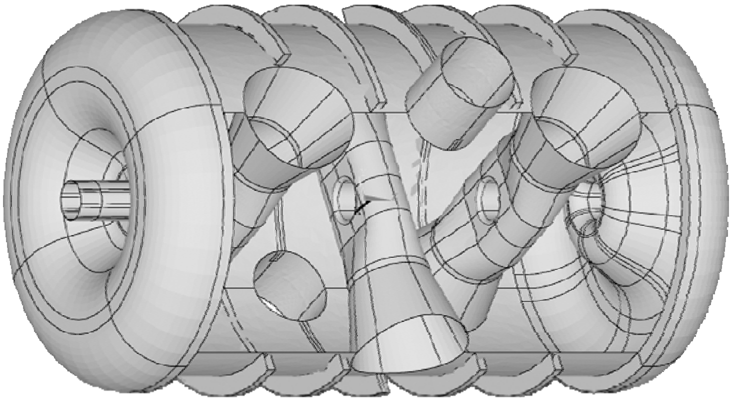


Figure 11: Triple-spoke cavity 1-bar pressure simulations with variable thickness of end cup.



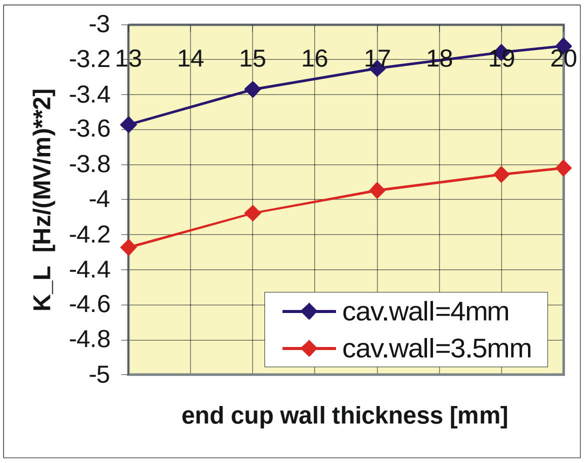


Figure 12: Triple-spoke cavity static LFD simulations with variable thickness of end cup.

References

[1] E. Zaplatin et al., "Low-β SC RF Cavity Investigations", SRF'2001, Tsukuba, Japan, 2001.
[2] J. Tuckmantel et al., "Improvements to Power couplers for the LEP2 Superconducting Cavities", Proceedings of the PAC'95, Dallas, USA (1995).
[3] S. Bousson et al. „Inert Gaz Plasma Spraying for Cavity Stiffening using Copper Coating", Proceedings of SRF2001, Tsukuba, Japan (2001)

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