MULTI-SPOKE CAVITY END REGION ANALYSIS

E. Zaplatin, FZJ, Juelich, Germany

Abstract

The end region design of the multi-spoke cavities defines the homogeneity of the accelerating electrical field distribution along cavity axes. Using electrostatic representation of the cavity the last (end) cavity gap should be made half long of the others. Such conclusion is not absolutely valid. An electrostatic approach that is used for this decision is true only for the loading electrodes (spokes) since their dimension along the beam line is much smaller than a wavelength. On the other hand, the end region that compiles the last spoke, end gap and the end electrode (or the shape of the cavity end cup) should be designed based on electrodynamics problem. Here we present the results of numerical simulations of end region electrodynamics problem and experimental data of the four-spoke 500 MHz, β=0.5 cavity measurements. The main result of this work is that the end gap of the multi-spoke cavity might be of the same length like others with the certain end region design. The comparison of the usual (half length end gap) and full length end gap cavities has been made based on the simulation results for the triple-spoke 352 MHz, β=0.48 cavity. An option of the end region with RFQ electrodes is discussed.

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The end region design of the multi-spoke cavities defines the homogeneity of the accelerating electrical field distribution along cavity axes. Using electrostatic representation of the cavity the last (end) cavity gap should be made half long of the others. Such conclusion is not absolutely valid. An electrostatic approach that is used for this decision is true only for the loading electrodes (spokes) since their dimension along the beam line is much smaller than a wavelength. On the other hand, the end region that compiles the last spoke, end gap and the end electrode (or the shape of the cavity end cup) should be designed based on electrodynamics problem. Here we present the results of numerical simulations of end region electrodynamics problem and experimental data of the four-spoke 500 MHz, β=0.5 cavity measurements. The main result of this work is that the end gap of the multi-spoke cavity might be of the same length like others with the certain end region design. The comparison of the usual (half length end gap) and full length end gap cavities has been made based on the simulation results for the triple-spoke 352 MHz, β=0.48 cavity. An option of the end region with RFQ electrodes is discussed.

1 NUMERICAL SIMULATIONS

To simplify the problem understanding, an alternative approach is to represent the designed multi-gap structure (Fig.1) by a chain of coupled circuits (CC). This model is appropriate for describing the fields and computing the dynamic range of the accelerating structure. An advantage of the CC model is that it doesn't require specific dimensions, so that conclusions drawn with this model are rather general. At the same time, the lack of the specific cavity dimensions taken into account during circuit calculations is a disadvantage since for our purpose of the end region cavity design the real shape of the region is very important (Fig.2). Additionally, the usual representation of the multi-gap cavity by a chain of coupled circuits takes into account only the coupling between adjacent cells. In our case of the cross spoke cavities the coupling between the neighboring cells is done through the magnetic field that links all the cells in the single cavity (H-type cavity feature, Fig.3). Anyway, generally the spokes represent the inductances and the gaps are the capacitances for CC. The mid cells are approximately identical and their own frequencies are about the same. This defines an equal cell-to-cell voltage distribution. The own resonance frequency of the end cell differs as the inductance of the end electrode and the end cup wall less than the spoke inductance. This results in the last gap voltage drop. There are two ways to correct this frequency – to increase either capacitance (end gap reduction) or the inductance (end cup shape modification) of the cell. In reality because of the strong cell-to-cell coupling these speculations are not absolutely correct. But as a start up to solve the problem they are valid.

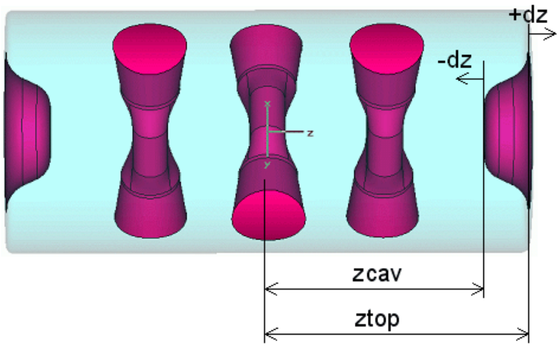


Figure 1: Triple-spoke cavity geometry.

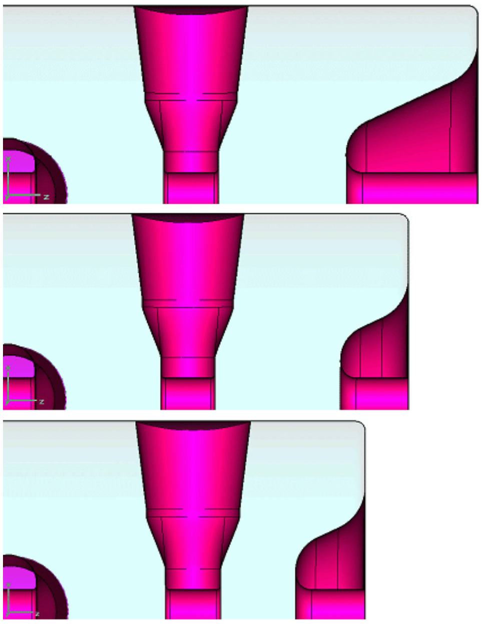


Figure 2: Triple-spoke cavity end region simulation.

Let's start an analysis of the structure with equal gap lengths and rather arbitrary end cup shape (Fig.2, middle picture). As expected, an electrical field distribution along cavity axes is very much inhomogeneous (Fig.4, mid picture of the cavity and blue curve on the Fig.5). To correct that let's first go usual way and reduce the end gap length. This increases the capacitance of this gap, which changes frequency and as a result equalizes the electric field distribution (Fig.4, bottom picture and Fig.5, red curve). Making these calculations we kept the end cup shape the same. It is worthwhile to notice that such gap reduction results not only in capacitance grow but also in inductance change. This caused again by the strong cell-to-cell coupling in the cavity and redistribution the structure RF current. In fact, it is impossible to provide pure separate change either capacitance or inductance in RF cavity by the modification of the geometry.

The second way to correct e-field profile is to increase the cavity length keeping the end gap length the same but modifying the end electrode (an extrusion following the cavity length increase, Fig.2, top picture). This provides the same effect making electrical field distribution along the cavity axes homogeneous (Fig.4, top picture and Fig.5, magenta curve).

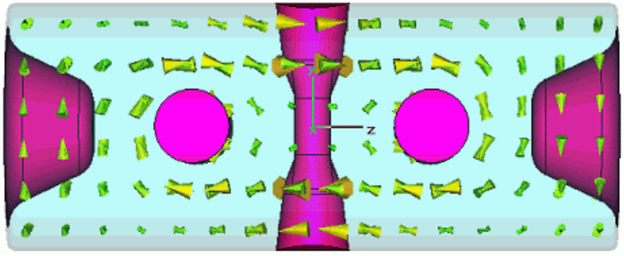


Figure 3: Triple-spoke cavity magnetic field distribution.

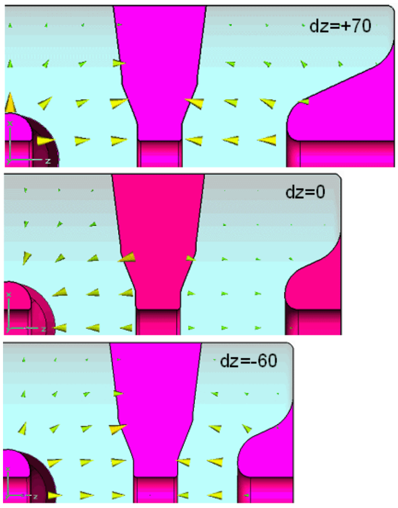


Figure 4: Triple-spoke cavity electric field distribution for different end regions.

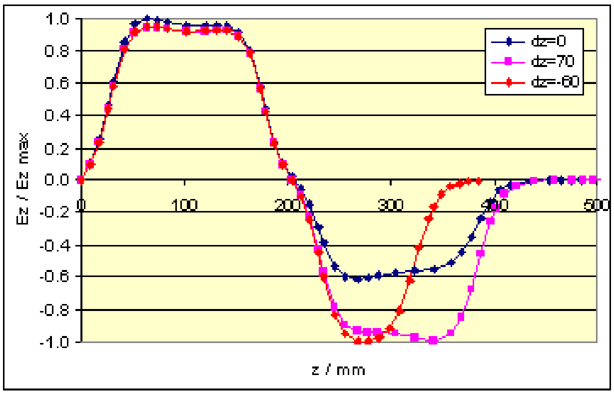


Figure 5: Field profile along cavity axis.

Fig.6 plots show the behavior of different cavity parameters. A value “dz” corresponds to the cavity geometry change – the negative value of dz shows the end gap length reduction and the positive dz is the cavity length increase. This corresponds to dz=0 for the initial geometry of the equal gaps and arbitrary end cup shape (Fig.1).

As expected, the behaviour of the cavity frequency reflects the same effect from both modifications. At the same time the cavity capacitance and inductance changes are rather complicate and not completely independent.

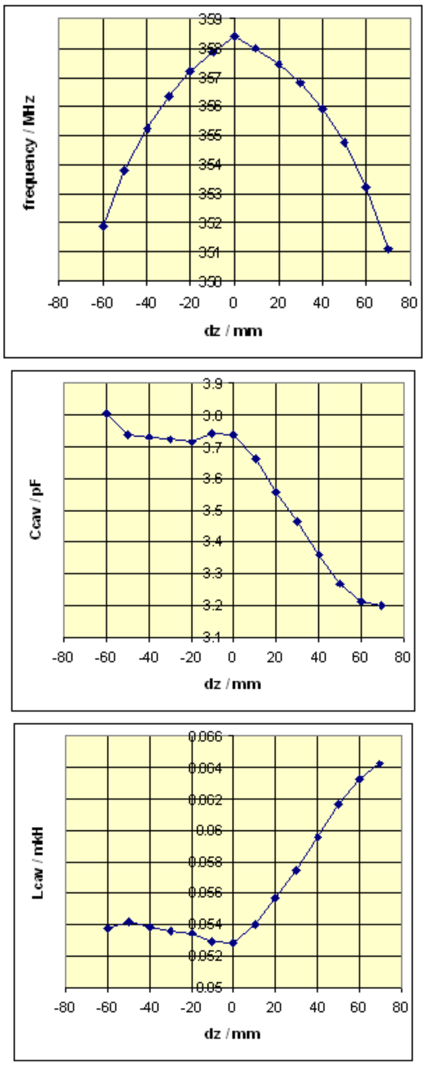


Figure 6: Triple-spoke cavity parameters by end region change.

The ratio of peak surface electric and magnetic fields to accelerating field (E_{pk}/E_{acc} and B_{pk}/E_{acc}) are the most important parameters characterizing superconducting structures. Their behaviors for both modifications are shown on Fig.7. Here, the cavity length definition for E_{acc} evaluation corresponds for „us“ is zcav (the dimension between end electrodes, Fig.1) and for „eu“ is zcell= N*βλ/2, where N is the number of gaps (NF straight line on the first plot). The parameter ztop corresponds to the whole cavity length (Fig.1). Because of the cavity symmetry along beam path all these values on the presented plot are divided by two.

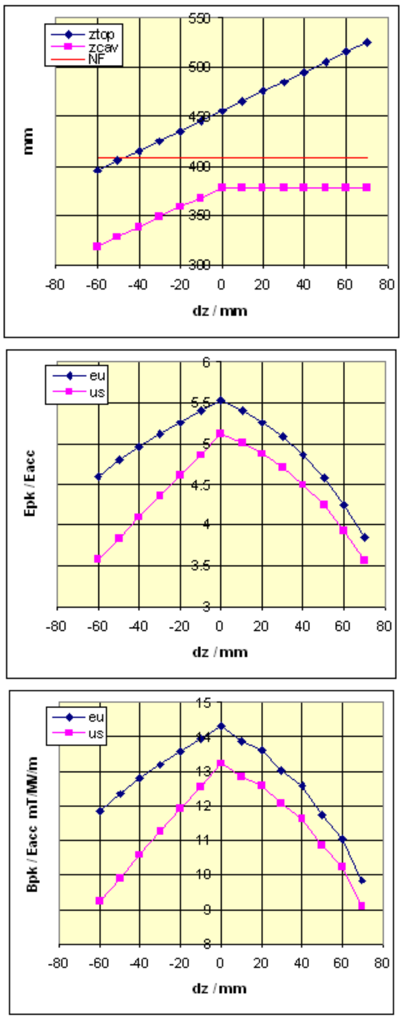


Figure 7: Triple-spoke cavity parameters by end region change.

The second order parameters of the cavity (Fig.8) are calculated using data for the copper cavity. The Q of a structure is proportional to the ratio of the stored energy to power dissipation. The stored energy depends on cavity volume and the dissipated power on cavity surface. In other words, the Q is being increased as the cavity inductance grows and capacitance falls. At the same time the geometry factor G=Q*R$_S$, which is cavity size and material independent reflects the cavity shape improvements.

The shunt impedance (R_{sh}) is a direct measure of the power dissipation in the cavity and thus showing the cavity accelerating efficiency. For superconducting structures it has a direct impact on the requirements for the cryogenic system. This parameter shows also an improvement for the equal gap structure.

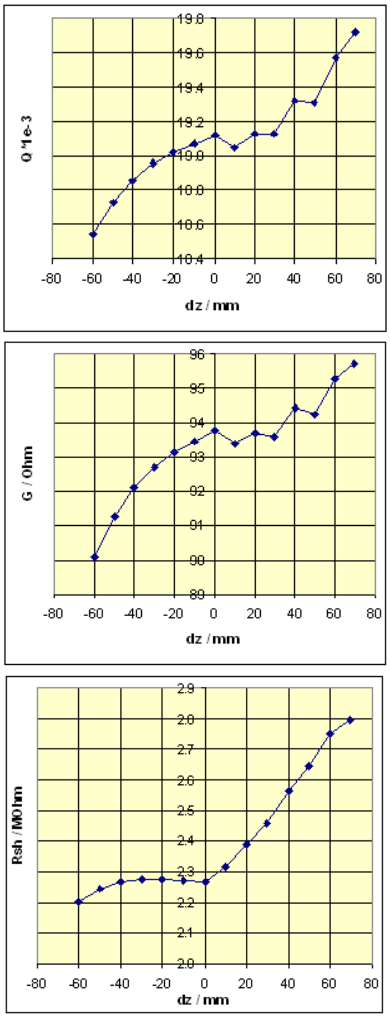
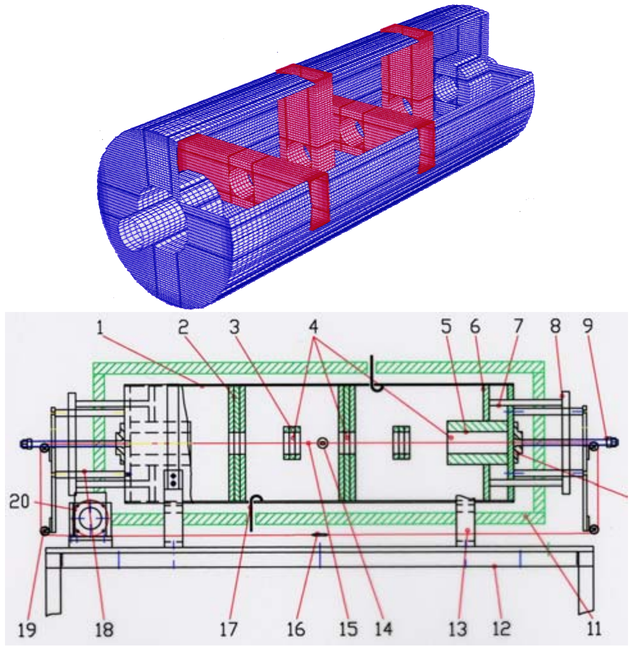


Figure 8: Triple-spoke cavity parameters by end region change.

2 EXPERIMENTAL CAVITY MODEL

A crossed-spoke cavity has been studied in FZJ some years ago [1]. The numerical simulations were provided with MAFIA [2].

A simple model of five-gap spoke cavity has been built to check cavity basics [3-4]. The model is a cylindrical pipe with four rectangular spokes, which can be placed either in cross or ladder way (Fig.9, Table 1). The circumferential wall of the cavity model was machined out of a commercial brass pipe, the spokes and the end plates are of copper. The RF contact between sliding cut plates and cavity walls are performed via spiral springs. A cavity radius is 158 mm, a spoke length along an accelerating path is 45 mm, $\beta\lambda/2$=150 mm, a spoke width is 90 mm, a cavity aperture 60 mm is kept constant along the whole cavity. The end plates are movable which allows change cavity frequency and field distribution along cavity. The coupling and measurement loops have been placed in the central gap.



1-cavity wall (brass)
2-vertical spoke (45 mm thick)
3-horizontal spoke (45 mm)
4-beam holes (60 mm)
5-drift tubes
6-adjustable short plate
7-sliding rod
8-nut
9-spindle
10-spindle bearing
11-thermal shield
12-support
13-cavity hold
14-perturbing bead (Al)
15-spring
16-spring
17-RF coupling loop
18-sheave support
19-return sheaves
20-5-phase step motor

Figure 9: MAFIA four-spoke cavity geometry and an experimental stand.

Table 1: Some Parameters of Multi-Spoke Cavity Model.

accel. π-mode freq.	MHz	461
number of spokes		4
cell length	mm	150
gap length	mm	105
cavity inner diam.	mm	316
cavity inner length	mm	1050
apperture	mm	60

Table 2: Calculated and Measured Four-Spoke Cavity Model Frequencies

frequency / MHz		Q_0
MAFIA	measured	measured
463	459.84	5500
475	470.34	6000
495	490.48	6000
534	530.12	6000
595	589.96	4000

A perturbation method has been used for the cavity e-field distribution measurement. The calculated and measured cavity frequencies for five modes of fundamental mode band are within less then 1% to each other (Table 2). The measured e-field distribution differs from the simulations within 5% that is defined by the accuracy of the end plate positions (Fig.10).

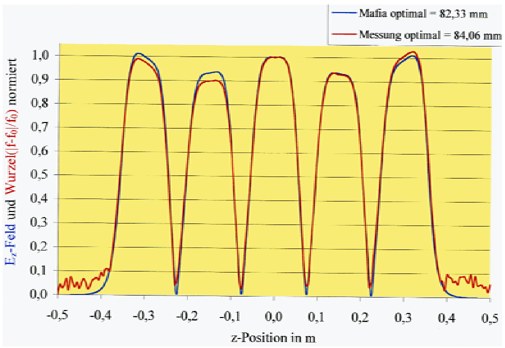


Figure 10: Calculated and measured field profile along cavity axes.

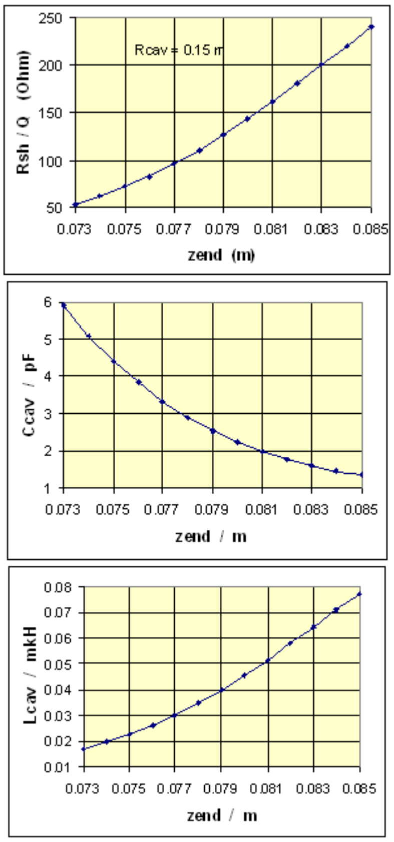


Figure 11: The cavity model parameters (calculated).

3 END-REGION WITH RFQ ELECTRODES

A "full-length" (βλ/2) end gap can be effectively used for RFQ finger-like electrode installations. An idea to use such electrodes in SC technology and the proof of principle for spoke-type cavity has been reported in [5-6]. The RFQ electrode installation in the end region means addition capacitance that is equivalent to the cavity end-gap length reduction. So, the "full-length" end gap can be used without end cup geometry modification. In this case the end gap is playing the combined function for acceleration and focusing of particles.

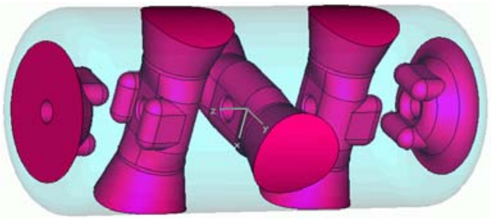


Figure 12: Triple-spoke cavity with RFQ end region.

The main task for such geometry optimisation is to find the electrode shapes that wouldn't affect the achieved acceleration efficiency of the cavity without electrodes. The possible electrode configurations are shown on Fig. 12 with corresponding accelerating field distributions on Fig. 13. The electrode shapes still need to be optimised but the very first simulations show that E_{pk}/E_{acc} and B_{pk}/E_{acc} ratios for the cavities with RFQ end gaps look promising (Table 3, E_{acc} is normilized on N_{gaps}*(βλ/2)).

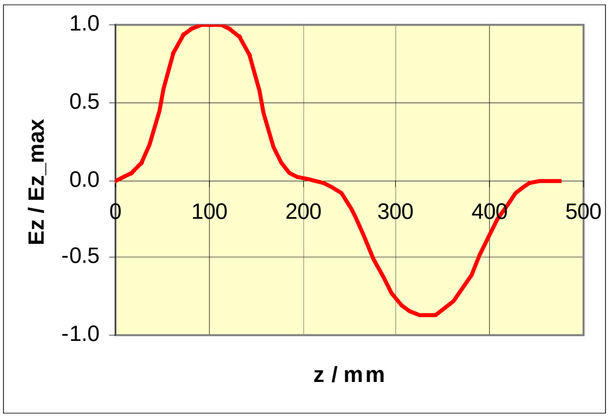


Figure 13: Field profile along cavity axis with RFQ end region.

Table 3: E_{pk}/E_{acc} and B_{pk}/E_{acc} for RFQ end region

RFQ electrodes	y-symm
E_{pk}/E_{acc}	5.47
B_{pk}/E_{acc} [mT/MV/m]	10.64
no RFQ electrodes	
E_{pk}/E_{acc}	4.27
B_{pk}/E_{acc} [mT/MV/m]	11.96

4 SUMMARY

1. The end gap length of the multi-spoke cavity might be of any length. The end cup shape then can provide accelerating electric field homogeneity.
2. The cavity with equal gaps has an advantage in terms of cavity second order parameters (Q, R_{sh}, G).
3. As the multi-spoke cavity tuning is made by the end gap change, the cavity with equal gaps has disadvantage of about two times lower tuning sensitivity.
4. “Not compensated” full-length end gap can be used for RFQ finger-like electrode installations.

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