AN IMPROVED SUPERCONDUCTING CAVITY DESIGN FOR LEP

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(Presented by J. Tückmantel)

1. INTRODUCTION

Several experiments have demonstrated the feasibility of superconducting (sc) cavities in storage rings. Based on the experience gained during these experiments, we have improved our cavity design with respect to RF properties and manufacturing simplicity. The following paper describes the basic guidelines used and the finally obtained cavity with its coupling scheme.

2. COMPUTATIONAL TOOLS

Up till now we have made all our cavity calculations with SUPERFISH [1], since this programme with its triangular mesh gives a good representation of the cavity surface and its results have been always reliable. The disadvantages of SUPERFISH are, that it calculates only monopoles and that the choice of the drivepoint is somewhat critical especially for multicell cavities and high frequency modes. Also one finds only modes for which the drive point is suitable and unexpected modes might get lost (which happened in fact). The new program URMEL 1.6 [2] can calculate monopoles and multipoles, finds all modes in consecutive order without missing one and avoids problems with the choice of a drive-point but offers actually only a rectangular mesh.

We tried to use this version of URMEL, however, it was considerably slower than SUPERFISH and multicells with narrow passbands could hardly be calculated. Therefore a new eigenvector processor (SAP) was developed and installed into URMEL at CERN [3]. The new version URMEL 1.8 is considerably faster and allows also to calculate narrow passbands with high precision in conserving the

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advantages of the basic concept of the program(*). This version allowed us to observe the reaction of the whole interesting mode spectrum on changes of the cavity shape with only two rather short jobs (two different boundary conditions at the centre plane).

The triangular mesh version of URMEL will become available only during 1984 [4]. Therefore we did the fine-tuning for the multimode compensation with SUPERFISH. Its triangular mesh follows the surface more exactly so that even small modifications are reproduced.

3. GENERAL CONSIDERATIONS

Superconducting RF cavities allow to store electromagnetic fields nearly without RF losses in the cavity walls. This property, which is very welcome for the accelerating mode, allows on the other hand the resonant build-up of Higher Order Modes (HOM) to levels, where the beam is perturbed and RF losses are created which have to be cooled away at liquid helium temperature. Therefore additional means have to be foreseen to attenuate this possible resonant built-up and by which the extracted energy is dumped into a "warm" load.

To sufficiently attenuate a mode, one has to guarantee a certain minimum amount of the field-component for which a coupling device is sensitive. For that purpose the position of the coupler on the cell has to be carefully chosen (e.g. [5]).

An additional problem is the field flatness of the HOMs for multicell cavities. A safe but elaborate solution is to use the single cell coupling-scheme on all cells, which guarantees sufficient coupling for all possible field profiles. On the other hand with field profiles not too different from those of an infinite structure, less coupling devices of stronger coupling on selected cells can be sufficient [6,7].

In this case one is bound to tight fabrication tolerances. An example for this fact is the CERN 5-cell cavity for the PETRA-test. All 5 cells were designed to have the same shape except for the end cell corrections. The first one was then made from two half-cells, but the field was limited to 5 MV/m by a quench at the crossing of two welds. Therefore the remaining four cells were produced with a central ring avoiding this crossing. During investigation of the HOM's of the

(*) In fact an upgraded version 1.8' was used for our calculation, this processor is also used in URMEL 2.0.

completed 5-cell cavity we detected that one TM_{011} mode with high R/Q was strongly concentrated in the special cell, the other being only weakly excited. Using a coupled resonator model [8] this severe field profile distortion could be traced back to a TM_{011} frequency offset of the special cell. The example shows that tuning cell frequencies correctly for the fundamental mode does not guarantee a good tune of the HOM. In this case nevertheless the presence of a coupling port on each cell allowed to find a modified arrangement of antenna- and loopcouplers for sufficient HOM damping.

If the decision to use only few coupling ports can be made it is especially attractive to put them onto the beam tube close to the cavity. For the fundamental mode this coupling scheme has been used successfully at Cornell and Wuppertal and will be tested soon for HOM [9,10].

4. THE LARGE BEAM TUBE CONCEPT

In the same line of thought lies the idea to use the beam tubes themselves as HOM couplers by opening them wide enough to serve as waveguides for all dangerous HOM [11]. It is assumed that once coupled into these guides the HOM will propagate away to be absorbed within the warm parts of the machine.

Comparing the proposed single mode cell geometry with the CERN 5-cell design we found for the fundamental mode:

(a) The R/Q smaller by a factor 0.55.

(b) The ratio of equatorial magnetic field and accelerating gradient higher by a factor 1.35.

At the present state of the art the dominant technical limitation of sc cavity fields is magnetic field heating of surface defects. Hence in adopting such a geometry one risks a substantial reduction of the obtainable gradients.

In considering this model also the question arises if in fact all HOMs couple strong enough to the beam tube. We therefore used URMEL and a calculation method described in [12] to scan the HOM spectrum for modes with a small beam tube damping effect. One such mode was in fact identified at 2.95 times the fundamental mode frequency. For a 5-cell cavity(*) its R/Q is 6 Ω and its $Q_{ex} = 5 \cdot 10^6$. For 9 cells(*) the corresponding values are 10 Ω and $1.5 \cdot 10^7$. Note that Q_{ex} increases more than proportional to the cell number. This is due to the well-known fact that the endcell perturbation by the beam tube causes a field unflatness which increases with the number of cells.

Having these drawbacks in mind and realizing that the very high degree of wakefield minimization inherent in this large beam tube design is not required for LEP [13] we chose to adopt a more conservative approach. We investigated the possibility to improve the existing CERN geometry such that couplers mounted onto the beam tubes provide similar damping figures as previously obtained in the PETRA experiment.

At the envisaged LEP frequency of 350 MHz, (and also at 500 MHz) wave guides as coupling elements are incompatible with cryogenic demands.

Therefore we intend to use as before small lumped circuit element couplers connected by coaxial lines to a warm load. These couplers will be mounted on the beam tube as close as possible to the end cells.

Comparing the strength of magnetic and electric fields at this coupler position one finds that an antenna coupler sensitive to the electric field is most suited. A construction similar to the one used on the 5-cell Petra test cavity [14], but with a fundamental mode rejection filter added, is under development.

To keep the cavity cells free from any coupling holes, also the power coupler of electric type will be mounted on the beam tube.

5. SINGLE-CELL CALCULATIONS

The first step is to find a single cavity cell as basis element which suits our needs better than the cell used in the PETRA-test.

(*) Since the field flatness of this mode and the fundamental one are independent no care was taken to get a flat fundamental mode for this study.

Single pass effects (wake fields)

With the suggested cavity shape at 350 MHz, no problems are expected for the beam stability in LEP [13].

Multi-pass effects (excitation of HOM)

The following goals are desirable but not all obtainable at the same time:

- High R/Q for the fundamental mode.
- Low E_p/E_{acc} and H_p/E_{acc} for the fundamental mode.
- Low R/Q for the HOMs.
- Strong cell to cell coupling for all modes (equivalent to low sensitivity to tolerances).
- No crossing of passbands at least for monopoles (for an isolated passband mechanical tolerances change only the relative excitation of the different cells, but maxima and zeros within cells remain at the same places. For two different superimposed field-patterns tolerances change also the excitation ratio within cells, thus maxima and zeros do not remain at fixed predictable positions).
- Shift modes away from the synchronous condition v = c.

These investigations were done with URMEL 1.8'.

Many iterations were done and here we summarize the main results (for a 500 MHz cavity):

- We tried only shapes well adapted to the requirements of production, chemical treatment etc. and avoided too adventurous shapes carrying the intrinsic risk of other problems as e.g. multipacting.
- To get a higher intercell coupling for the fundamental mode, we increased the iris-diameter from 15 to 17 cm and reduced the iris-thickness from 5 to 4 cm. The ratio E_{peak}/E_{acc} becomes 2.3, B_p/E_{acc} = 39 G/(MV/m), (R/Q) = 120 Ω.
- This modified iris increases also the coupling of the interesting HOMs if one looks only on the difference $f_\pi - f_\sigma$. However, a calculation with a multicell unit terminated by ideal boundaries in two iris planes shows that the shape of the passbands gets more non-sinusoidal. Thus the difference between the two highest or lowest modes does not increase proportionally to the global coupling.

- If one changes the inclination of the "side-walls" of the cavity, one can increase or decrease simultaneously coupling and (R/Q) for the TM_{012}-mode.
- As far as the cell shape is concerned we have taken all the above considerations into account but came to a configuration only slightly different from the one we started with. The main change of our new multicell design resulted from a more general approach to the endcell tuning in a multicell structure.

6. MULTI-MODE END CELL COMPENSATION

To apply the beam tube coupler concept we have to construct a multicell cavity such that for all dangerous modes a sufficient field exists at the coupler location on the beam tubes. It is known that the presence of a beam tube changes the frequency of the end cells and that this may lead to a very weak excitation of these cells. This leads to the idea to correct the end cells for the presence of the beam tube not only at the fundamental mode frequency - as done up to now - but also simultaneously for a group of important HOMs (multi-mode compensation). Of course such a multiple corrective action is only possible for a few selected modes. We concentrated on the TM_{010} (obviously), the TM_{011} (highest R/Q) and TM_{012} (small passband with a rather high R/Q) and controlled later, if no problems arise for other modes.

In computer simulations an infinite structure can be truncated (at the iris) by an "electric" or "magnetic" mirror to form a n-cell cavity thus allowing the n modes $0, \pi/n, ..., (n-1)\pi/n$ or $\pi/n, 2\pi/n, ..., \pi$ according to the symmetry of the single cell field pattern. With an end cell correction one can try to simulate the electric or magnetic mirror case and we have to investigate for the three above modes, which of the two cases is the most adequate.

- TM_{010}: Obviously we want to have a flat π-mode. Since E_z is symmetric in a single cell for this mode-family, we have to simulate a magnetic mirror allowing the modes $\pi/n, 2\pi/n, ..., \pi$.

- TM_{011}: The member of this mode family which has the highest R/Q has also the highest frequency. To obtain good beam tube coupling, this mode should be flat; this is possible with a magnetic mirror yielding a flat 0-mode (E_z antisymmetric in a single cell).

- TM_{012}: Again the mode with the highest frequency is the most dangerous one, thus we try again to get a flat π-mode using a magnetic mirror (E_z symmetric in a single cell).

Since in all three cases we have to simulate a magnetic mirror, we have to tune the real end cells to the same frequency as an inner cell would have when terminated on both sides by magnetic mirrors. Ideally we would like to find geometry modifications of the end cells mutually independent in the sense that they change only the frequency of one mode. In reality we found only partially decoupled actions. The decrease of the end cell diameter as done normally to obtain a flat fundamental π-mode is not suitable since it acts on all three above modes in the same sense. In this context one should also note that using the same diameter for all cells allows a fabrication from only two different types of half cells (see Appendix). In contrast reducing the end cell length does (to first order) not change the fundamental mode but acts strongly on the other two and is therefore appropriate. Another interesting action is to make the beam tube (where it meets the end cell) wider than the inner iris openings. This assures a better penetration of all HOM to the coupler location and increases as required the fundamental mode frequency while its action becomes progressively weaker for the TM_{011} and TM_{012} modes.

Therefore we used these two geometry modifications to compensate the fundamental π- and the TM_{011} zero mode simultaneously. The resulting beam tube is wide enough to let the TM_{012} mode propagate and this allows a specific action on this mode: A beam tube diameter reduction to cut off this propagation at a certain distance from the end cell creates a reactive stub the length of which has now been chosen to optimize the interaction between TM_{012} π-mode and coupler. This is not the flat tuned case but represents a certain overcompensation of the end cells with the effect, that the two highest modes of the TM_{012} passband get very close in frequency and will probably be perturbed by already small tolerances. This is not dangerous for this particular case, since the two modes have opposite symmetry. When both modes should mix they would tend to cancel in one end cell, but - because of their opposite symmetry - add up in the other end cell. Therefore, if we have two couplers (anyway needed to get the dipole modes safely) one mounted on each end, we will always have sufficient coupling. This type of cavity as 500 MHz 4-cell unit is shown in the Appendix.

6.1 Coupling efficiency

In order to prove, that with this concept one can sufficiently attenuate the dangerous modes, we chose an antenna coupler of 5 cm probe diameter mounted as close to the end cell as mechanically possible, and sketched strongly simplified in fig. 1 (more details can be found in [14]).

Knowing the averaged electric field on the antenna plate from SUPERFISH or URMEL we calculated to first order the displacement current I_D into the input resistance R_{coup} of the probe. With R_{coup} estimated from a lumped circuit model of the envisaged coupler we then obtained extracted power $P = 1/2\, I_D^2 \cdot R_{coup}$ and external Q for the dangerous modes. A collection of such data calculated with SUPERFISH for a 500 MHZ 4-cell cavity is given in table 2. Table 3 contains URMEL data for the same cavity.

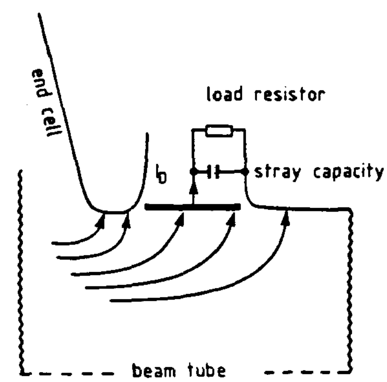

Fig. 1

6.2 An unexpected monopole mode

It should be mentioned that the contraction in the beam tube diameter allows a new type of mode which does not belong to a mode family known from the ideal single cell. For this mode the small diameter part of the beam tube represents the resonator, the cavities on the right and left sides playing the role of the terminating cut-off tubes. Since its R/Q is small and the electric field in the coupler region large, this mode represents no danger for the concept.

This mode was found automatically by URMEL since no mode gets lost, even unexpected ones. However, no so-called "iris mode" was found.

6.3 Multipoles

URMEL gives the new possibility to calculate multipole modes for cavities with axial symmetry. Therefore we were able to check if the coupling scheme - made for monopoles - gives also sufficient coupling for dipoles and quadrupoles. It turned out that only one dipole mode with high (R/Q) has a low but still sufficient coupling. Therefore we believe that with one antenna coupler on each beam tube, positioned on different angles, we will get sufficient coupling for mono- and multipoles.

The computed data for dipoles and quadrupoles are collected and represented in tables 4 and 5.

7. NUMBER OF CELLS

Perturbation effects get more and more serious if one increases the number of cells. At the probable frequency of 350 MHz a 5-cell cavity with cryostat will be very big and difficult to handle. Therefore we think that 4 cells will be a good operational unit at 350 MHz. This unit fits also well in the existing machine design matched to 5-cell Cu-cavities. Therefore we worked out this concept and the RF data obtained are collected in the tables at the end of this note.

8. CONCLUSION

The cavity and its coupling scheme described above is a design fitting the LEP requirements better than our first operational cavity used in the test at PETRA. Comparing the new geometry to the preceding design we obtained substantial improvements:

- Higher cell-to-cell coupling for all modes thus making the cavity performance more independent from fabrication tolerances.

- The same HOM attenuation can be obtained with less couplers, thus also less holes with vacuum joints, RF connections, etc.

- The coupling ports on the beam tubes are in a region, where the field of the fundamental mode is already strongly reduced compared to the former position. Therefore requirements for welds and surface quality for the couplers and the ports are strongly reduced. Also dust particles dropped from the coupling ports do not fall into the cells.

- The absence of coupling ports on the cells allows a much cheaper and more reliable fabrication of the cells, an easier cryostat design and a simple installation of a diagnostic system (T-maps) if a cavity has to be repaired. Also the multipacting observed in the 5-cell cavity at the coupling ports is suppressed.

- Keeping the cell diameter constant allows a fabrication with only two - instead of at least three - dyes for a multicell.

The only two moderate trade-offs are a 10% reduction in R/Q for the fundamental mode and a 15% increase in E_p/E_{acc}. This latter point is insignificant. Many of the recent measurements show that the resulting peak fields will not cause field emission problems up to accelerating gradients of 5 MV/m or even more.

In adopting the LEP frequency of 350 MHz our cavities and cryostats get bigger but we have less cells and less couplers for the same accelerating voltage, wakefields become smaller (larger absolute openings) and the R/Q per unit length of the HOM is lower. The loss in R/Q per unit length for the fundamental mode is largely overcompensated by the better Q_o values at lower frequencies (the BCS part of the surface resistance decreases with ω^2). The dominance of these BCS losses at 4.2°K has been confirmed by our measurements [15].

It is envisaged to test this concept with 3-cell units made from copper and niobium.

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APPENDIX

500 MHz 4-CELL CAVITY WITH MULTIMODE END CELL COMPENSATION

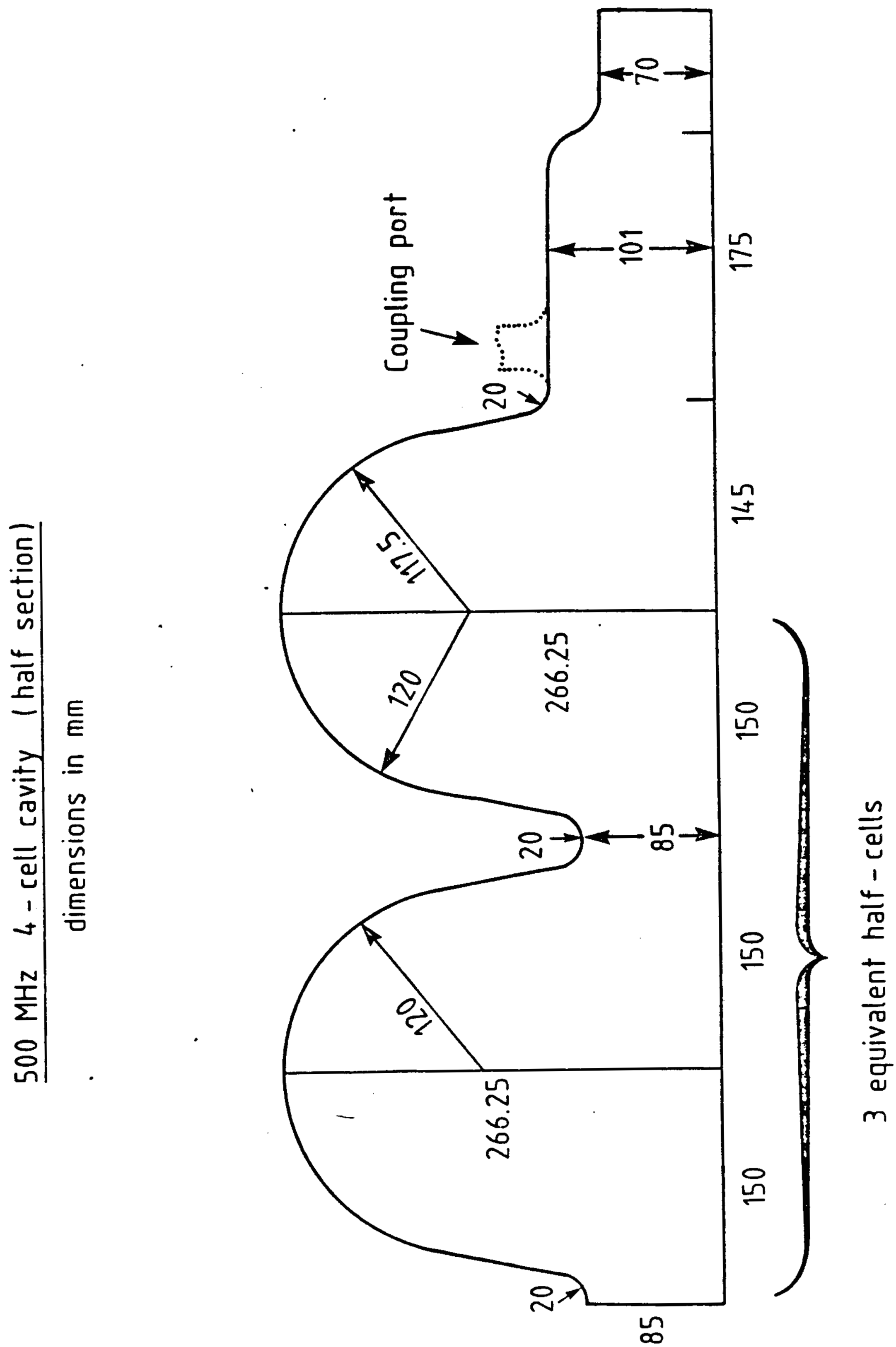

TABLE I

RF-data of 500 MHZ single cell with ideal boundaries
(SUPERFISH)

$$K = \frac{f(\pi) - f(0)}{0.5 * (f(\pi) + f(0))}$$

$$E_{peak} / E_{acc} = 2.33 \text{ for } TM_{010}\pi$$

$$B_{peak} / E_{acc} = 39 \text{ G/(MV/m) for } TM_{010}\pi$$

Mode	f(0) (MHz)	f(π) (MHz)	K (%)	(R/Q) (0) (Ohm)	(R/Q) (π) (Ohm)
TM_{010}	490.446	499.165	1.76	174.4	120.6
TM_{011}	906.762	882.326	-2.73	30.6	93.6
TM_{020}	1036.344	1070.327	3.32	0.34	10.8
TM_{021}	1397.760	1311.349	-6.38	26.3	19.5
TM_{012}	1408.835	1423.485	1.03	44.2	9.3

TABLE 2

RF-data of 500 MHz 4-cell cavity with multimode compensation (SUPERFISH)

<E> is the averaged electric field at the coupler location for 1 J stored energy. R_{coup} is the resistance the coupler represents at the specified frequency (realistic estimate). The Hom-coupler is assumed as circle of 5 cm diameter Q_{ext} is the external Q-value for one coupler

Mode		f (MHz)	<E> MV/m	(R/Q) (Ohm)	Q_{ext}	R_{coup} (Ohm)
TM_{010}	π	499.31	0.28	464.	-	-
	3π/4	496.96	0.33	0.	-	-
	2π/4	494.88	0.29	0.	-	-
	π/4	491.82	0.15	0.	-	-
TM_{011}	3π/4	885.87	0.18	0.	245,000	150
	2π/4	894.25	0.34	6.4	68,000	
	π/4	903.17	0.47	48.5	35,000	
	0	907.24	0.37	108.	57,000	
TM_{020}	π	1066.8	0.21	0.2	188,000	120
	3π/4	1057.1	0.37	0.3	61,000	
	2π/4	1046.8	0.42	1.4	48,000	
	π/4	1039.2	0.29	0.	100,000	
TM_{021}	3π/4	1320.0	0.57	0.3	27,000	90
	2π/4	1340.6	1.08	0.4	7,500	
	π/4	1363.7	1.38	1.3	4,500	
	0	1385.7	1.21	0.2	5,800	
TM_{012}	π	1427.9	0.52	22.7	39,000	70
	3π/4	1427.8	0.51	5.2	41,000	
	2π/4	1419.0	0.35	22.8	87,000	
	π/4	1413.8	0.70	0.3	22,000	

TABLE 3

Monopole-modes calculated by URMEL 1.8' for the cavity in the Appendix

Mode	f (MHz)	(R/Q) (Ohm)
TM_{010}	492.360	0.0
TM_{010}	495.670	0.7
TM_{010}	499.055	0.0
TM_{010}	500.347	461.3
TM_{011}	886.415	0.0
TM_{011}	895.114	5.1
TM_{011}	904.402	48.0
TM_{011}	909.116	111.7
TM_{020}	1029.930	0.3
TM_{020}	1038.059	2.2
TM_{020}	1049.631	0.2
TM_{020}	1060.306	0.3
Tube-mode	1222.672	0.8
Tube-mode	1222.766	4.5
TM_{021}	1301.7890	0.7
TM_{021}	1325.873	0.2
TM_{021}	1352.325	0.1
TM_{021}	1373.738	1.6
TM_{012}	1406.729	0.0
TM_{012}	1416.143	5.1
TM_{012}	1412.679	8.0
TM_{012}	1412.725	31.1
TM_{030}	1488.342	2.2
TM_{030}	1501.321	0.2
TM_{030}	1536.419	2.8
TM_{030}	1579.338	1.0

TABLE 4

Dipole-modes calculated by URMEL 1.8' for the cavity in the Appendix
V_{acc} calculated at 3.5 cm off axis

Mode	f (MHz)	(R/Q) (Ohm)
Dipole- 1	626.986	0.2
Dipole- 2	636.685	1.0
Dipole- 3	653.443	8.3
Dipole- 4	674.783	7.2
Dipole- 5	701.873	2.1
Dipole- 6	716.712	11.0
Dipole- 7	727.181	7.4
Dipole- 8	731.960	0.6
Dipole- 9	941.769	0.7
Dipole-10	941.986	0.0
Dipole-11	967.947	0.0
Dipole-12	974.104	0.3
Dipole-13	976.182	25.6
Dipole-14	1068.063	0.3
Dipole-15	1085.839	0.1
Dipole-16	1108.340	2.1
Dipole-17	1133.957	0.0
Dipole-18	1162.575	0.9
Dipole-19	1167.291	1.5
Dipole-20	1180.200	0.1
Dipole-21	1181.813	0.6
Dipole-22	1184.558	0.8
Dipole-23	1270.501	0.3
Dipole-24	1271.098	0.4
Dipole-25	1274.686	0.0
Dipole-26	1274.935	0.8
Dipole-27	1313.444	1.5
Dipole-28	1330.465	0.4
Dipole-29	1373.047	0.2
Dipole-30	1418.289	0.3
Dipole-31	1457.614	0.2
Dipole-32	1527.819	0.5
Dipole-33	1530.520	1.8
Dipole-34	1552.465	1.0
Dipole-35	1562.148	0.4
Dipole-36	1573.212	0.0
Dipole-37	1591.817	0.0
Dipole-38	1596.933	1.5

TABLE 5

Quadrupole modes calculated by URMEL 1.8' for the cavity in the Appendix
V_{acc} calculated at 3.5 cm off axis

Mode	f (MHz)	(R/Q) (Ohm)
Quadrupole- 1	870.710	0.1
Quadrupole- 2	872.020	0.1
Quadrupole- 3	873.894	0.0
Quadrupole- 4	875.699	0.0
Quadrupole- 5	959.413	0.0
Quadrupole- 6	960.489	0.0
Quadrupole- 7	963.021	0.0
Quadrupole- 8	965.366	0.2
Quadrupole- 9	1231.218	0.1
Quadrupole-10	1235.713	0.9
Quadrupole-11	1243.492	1.0
Quadrupole-12	1254.187	0.3
Quadrupole-13	1327.285	0.3
Quadrupole-14	1335.247	0.5
Quadrupole-15	1356.641	0.0
Quadrupole-16	1375.953	0.0
Quadrupole-17	1394.341	0.0
Quadrupole-18	1399.787	0.0
Quadrupole-19	1403.866	0.0
Quadrupole-20	1405.116	0.0
Quadrupole-21	1456.182	0.8
Quadrupole-22	1459.688	0.0
Quadrupole-23	1465.048	0.0
Quadrupole-24	1475.613	0.0
Quadrupole-25	1550.766	0.0
Quadrupole-26	1552.055	0.0