DESIGN OF A β=0.175 2-GAP SPOKE RESONATOR*

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Abstract

In this paper, we present the electromagnetic and structural design of a low-β superconducting spoke resonator for a beam-test in the Low Energy Demonstration Accelerator (LEDA). This test is part of the Advanced Accelerator Applications (AAA) project. Recently, the sole use of superconducting resonators from 6.7 MeV on has been approved for this project. The beam test will use the lowest-β resonator from this accelerator design. The choices of the cavity dimensions are driven by its use immediately after the LEDA Radio-Frequency Quadrupole (RFQ). The frequency is 350 MHz, the length corresponds to a geometric β (β_g) of 0.175. Our design approach has been to carry out an integrated RF and mechanical design from the start. The final cavity is well understood in terms of RF and mechanical properties. The RF properties, like Q, R/Q, peak surface fields and acceleration efficiency are very reasonable for such a low-β structure. The design also includes power coupler, vacuum and pick-up ports and their influences. The mechanical design added tuning sensitivities, tuning forces, stiffening schemes and the understanding of stresses under various load conditions.

This presentation reflects changes in the coupling port and the beam aperture compared to a previously presented design [1].

1 CAVITY REQUIREMENTS

The choice of the test cavity's β is driven by the 6.7 MeV (β=0.12) beam energy at the end of the RFQ. To reduce the challenge given by this very low particle beam velocity, a short 2-gap structure has been chosen. Its large velocity acceptance allows the use of a slightly higher-β structure with lower peak surface fields and thus higher accelerating gradients. The frequency is also given by the RFQ. Advantages of spoke resonators are their high mechanical stability and their compact size. The diameter is approximately $\lambda/2$, thus a 350 MHz spoke is not larger than a 700 MHz elliptical cavity. In addition, gap-to-gap coupling in spoke resonators is achieved by off-axis magnetic coupling. Therefore, adequate coupling is achieved at smaller beam apertures, allowing higher acceleration efficiency. The choice of a small beam aperture drives the power-coupling scheme. Beam-pipe coupling, as used in elliptical resonators, only provides sufficient coupling for very small beam currents. Here the coupling needs to be done directly to the cavity body. As an implication of this, the coupler port has to be integrated into the cavity design, as it influences the cavity volume and thus the cavity frequency.

This approach also requires a cleaner environment than it is necessary for elliptical cavities. Any particles created in the coupler could end up directly in the high field region of the cavity. This could create field emission problems.

2 ELECTROMAGNETIC DESIGN

The goal of the electromagnetic design is the optimization of peak surface fields for a resonator with the proper frequency and a beam aperture compatible with the beam-dynamics requirements. The end product of this design is a production specification of the spoke resonator with all attachments that at 4.5 K, and after all processing steps will properly operate at 350 MHz. To achieve this goal the nominal structure not only had to be designed, but frequency changes due to cool-down, BCP and loading due to the coupler needed to be understood.

2.1 Basic Cavity Parameters

The length of a 2-gap spoke resonator is determined by the structure's β_g and the desired mode of operation [2]: the length over both gaps is 2/3 $\beta_g\,\lambda$, the distance from gap-center to gap-center is $\beta_g\,\lambda/2$. The diameter of the cavity is of the order of $\lambda/2$. The cavity aperture radius for the results presented here is 2.5 cm.

2.2 Optimization of the Peak Surface Fields

The major part of the optimization deals with minimizing peak surface fields. This affects the shape of the spoke and the shape of the cavity end-walls. Changes in the cavity frequency due to these geometry changes are compensated by adjusting the cavity diameter. The optimum spoke shape is cylindrical at the base, where it meets the outer cavity wall. This minimizes the peak magnetic fields. It is flat with a racetrack shaped cross section at the center of the spoke, where the aperture traverses the spoke. This minimizes the peak electric fields. For RF reasons, dish-shaped [3] or re-entrant, conical [4] end-walls are both reasonable. Figure 1 shows the resultant optimized geometry shape with re-entrant end-walls.

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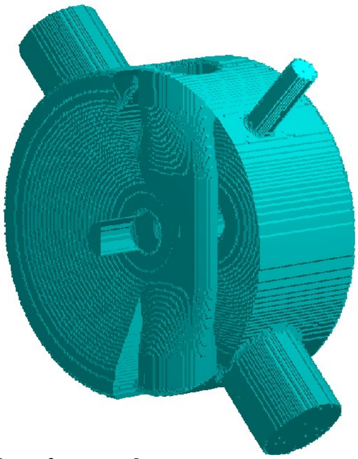

Figure 1: This figure shows a cut-away view of the MAFIA [5] model of the optimized spoke resonator. This model also includes coupler, cleaning and RF pickup ports, which are discussed later.

2.3 Completion of the Cavity Model

The optimization of the spoke shape can be done independent of other features of the cavity. Once it was established, the coupler, cleaning and pick-up ports have been added to the model to determine the cavity radius for the proper cavity frequency. The pick-up port is a minor perturbation, but the coupler port has to be chosen as large as possible to mitigate potential multipacting problems. The RF power will be coupled electrically into the cavity by a coaxial line. This is different from proposed magnetic coupling loops for previous designs, like the RIA [6] project. Magnetic coupling seems to be the first choice, as the dominant RF field at the outer cavity wall is magnetic. However, for large beam currents the power to be transmitted to the beam makes the thermal management of a magnetic loop very complex and expensive. Simulations and laboratory measurements on an ANL spoke resonator have shown that the electric field at the outer cavity wall is sufficient to deliver the beam power even for a 100-mA beam using a simple coaxial antenna. We have selected a 75-Ω coaxial line with a 103-mm diameter. Table 1 shows one-point multipacting levels for various coaxial line sizes and line impedances that have been derived by scaling from known multipacting levels.

Table 1: Multipacting Levels in Coaxial Lines

	103 mm, 75Ω	***103 mm, 50 Ω***	***76.2 mm, 75 Ω***	***76.2 mm, 50 Ω***
7	47 kW	32 kW	15.2 kW	10.1 kW
6	51 kW	36 kW	16 kW	11.4 kW
5	86 kW	60 kW	28.5 kW	19 kW
4	172 kW	118 kW	56 kW	37.3 kW
3	229 kW	152 kW	72.3 kW	48.2 kW
2	438 kW	300 kW	145.5 kW	97 kW
1	626 kW	428 kW	203.3 kW	135.5 kW

Multipacting levels above the thick black lines would be reached in the β=0.175 spoke cavity for a 100-mA beam at a 7.5-MV/m accelerating gradient. Levels above the broken thick lines would be reached at the highest beam energy where spoke resonators are proposed (109 MeV) [7]. The largest possible port fitting onto this cavity at 75 Ω (leftmost column) has the least potential for multipacting at the power levels required. This coaxial line is identical with the one used at CERN for the LEP2 [8] accelerator and has a proven performance up to 600 kW of CW power. We decided to add a second port of the same size opposite to the coupler port. This port will not be used in operation, but serves the purpose of having good cleaning access to the cavity. Recent RF tests of an ANL spoke resonator [9], done at LANL, indicate that good high-pressure rinsing after a chemical polish significantly increases the cavity performance in terms of achievable field levels.

2.4 Final Geometry

The final tuning of the spoke resonator has been done for the structure in Figure 1 assuming a 1 1/2" diameter pick-up port and two 103-mm diameter ports in the orientation indicated. The total effect of these ports on the cavity frequency is -2.8 MHz. Table 2 lists the major geometric dimensions of the cavity after the final tune. Figure 2 is a cut-away view of the basic geometric outline.

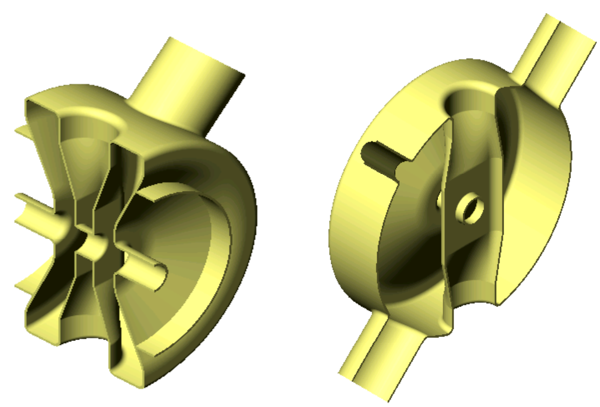

Figure 2: This is a cut-away view of the final cavity geometry with optimized spoke shape, all attached ports and the selected end-wall geometry.

Table 2: Geometric Parameters of β=0.175 Resonator

Cavity Radius	19.609 cm
Spoke Radius at Base	4.5 cm
Spoke Thickness at Aperture	3.5 cm
Spoke Width at Aperture	11.44 cm
Aperture Radius	2.5 cm
Cavity Length (gap-to-gap)	9.99 cm
Cavity Length (over all length)	19.99 cm
Coupler Port Radius	5.015 cm
Pick-up Port Radius	1.905 cm

It should be noted that the overall length of the cavity is twice the gap-to-gap length. This is due to the shape of the end-walls that extend beyond the full RF-gap length.

2.5 RF Parameters

The major RF performance parameters for the final geometry described above are listed in Table 3. E_0T and related numbers are scaled with the gap-to-gap length, not with the overall physical cavity length. This provides the proper relation between peak surface fields and the accelerating voltage in a single cavity. The overall length of the cavity is reflected in the real-estate gradient of the linac design. As the table shows, the peak surface fields of this low-β structure are in the same range as for the APT β=0.64 cavities, indicating the potential for a high accelerating gradient [10]. Also, the RF-losses into the cavity at 4 K are moderate and allow a reasonably sized cryo-system for this part of the accelerator.

Table 3: RF Parameters of β=0.175 Resonator

Q_0 (4 K)	1.21E+09	(for 70 nΩ)
T (β_g)	0.7765	(β_g=0.175)
T_{max}(β)	0.8063	(@ β=0.21)
G	84.7 Ω	---
E_{pk}/E_0T	2.82	---
H_{pk}/E_0T	73.8 G/MV/m	---
P_{cav} (4 K)	9.32 W	@ 7.5 MV/m
R/Q	134 Ω	

3 THE MECHANICAL DESIGN

The design strategy for this resonator included an integrated look at RF and mechanical properties. This was facilitated by being able to interchange cavity models between standard CAD software (SOLIDWORKS [11]), structural analysis software (COSMOS/M [12]), and MAFIA.

3.1 End-Wall Choice

Evacuated cavities with both dish-shaped and re-entrant end-walls have been evaluated for stresses under a two atmosphere external load. The re-entrant shape is better in terms of stresses under load and in terms of the achievable tuning range. These simulations also showed that a simple stiffening ring (Figure 2) on the end-wall is sufficient to reduce the stresses in the structure. Table 4 gives stresses and forces for several ring diameters. In addition, the frequency change due to the loaded structure deformation has been calculated with MICAV [13]. With little effort, it was possible to interface to the deformed structural COSMOS/M models. The maximum displacement in all 3 cases was 4.7 mils (0.119 mm).

Table 4: Structure with a 2-Atm Vacuum Loading

Ring - diameter	**Reaction-force [lbs]**	**VanMises Stress [psi]**	**Δf [kHz]**
28 cm	3875	5172	-94.98
26 cm	3776	5177	-87.96
24 cm	3743	5181	-74.94

3.2 Tuning Sensitivities

For the same stiffener positions, the tuning sensitivities were evaluated for fixed and moving stiffening-rings. The moving boundary condition refers to an independent movement of the stiffening ring with respect to the beam pipe flange, while the fixed boundary condition refers to a locked, common movement of stiffener and beam pipe flange. The movement is assumed to be symmetric from both ends of the cavity. The center of the cavity is always fixed. The movement has been limited to produce stresses less than the Niobium yield strength (7000 psi) at room temperature. This stress limit for the fixed boundary condition corresponds to an end-wall movement of 0.0055'' and a total frequency change of 142 kHz. For the free boundary condition the wall movement is 0.0133'' with a total frequency change of 602 kHz. The tolerable wall excursions in operation are increased by a) the operation of the cavities at 4 K and b) by the possibility to extend stresses beyond yield to a certain degree. Table 5 lists the results of the analysis.

Table 5: Tuning Sensitivity Results

Ring Dia-meter [cm]	**Boundary Condition**	**Tuning Sensitivity**	
		kHz/lb	kHz/mil
28	moving	- 0.3542	-45.148
28	fixed	- 0.3108	-25.845
26	moving	- 0.3914	-45.404
26	fixed	- 0.3504	-25.664
24	moving	- 0.4012	-46.076
24	fixed	- 0.3490	-25.370

All stresses due to vacuum loading and tuning are reasonably low, and tuning sensitivities are comparable. The 28-cm ring position was chosen for the design as it showed the lowest stresses under vacuum loading. With these results, the performance criteria for a cavity tuner are defined.

3.3 Mechanical Resonances

The calculation of the lowest mechanical modes of this spoke resonator show that it is a stiff structure. Table 6 gives the 5 lowest modes for the various stiffener positions. All the modes are longitudinal or torsional. The lowest ones for each case are above 270 Hz. All modes were calculated for the bare cavity with fixed flanges.

Table 6: Mechanical Resonances of Resonator in Hz

Stiffener	**F1**	**F2**	**F3**	**F4**	**F5**
28 cm	284	469	519	549	552
26 cm	271	468	516	548	548
24 cm	270	465	514	545	547

3.4 Cavity-Coupler Interaction

Two major operation scenarios are foreseen with this spoke resonator; low-current operation at 13.3 mA and high current operation at 100 mA. The coupling strength is different for these two options. Simulations have been done to find the coupler tip positions that match the beam loaded Q of the cavity. The importance of this result for the cavity design is in the resulting frequency change that has to be compensated for by the cavity tuner. Table 7 gives the required Q_{ext}, the corresponding tip position and the frequency change between these two coupler settings. The frequency change between the two scenarios can easily be compensated for by a tuner, without using up any significant tuning margin.

Table 7:Frequency Change in the Spoke Resonator for the High and Low Current Operation

	13.3 mA	**100 mA**
Q_{ext}	1.4e6	1.9e5
Tip Position	-20 mm	-7 mm
Δf	-	23 kHz
% of Nominal (RT) Range	-	16 %

4 SUMMARY AND OUTLOOK

A β=0.175 spoke resonator has been designed. An integration of the cavity with external components like the coupler, tuner and cryostat has been done. The RF properties indicate the potential for a high accelerating gradient. The mechanical properties show that this structure is stiff; which also implies a smaller tuning range than for elliptical cavities.

The detailed understanding of RF and mechanical properties has been applied to prepare design and fabrication specifications for this cavity. We are in the process of ordering two of these cavities from industry. We plan to have these tested vertically and with beam on the LEDA accelerator in the coming year.

5 ACKNOWLEDGEMENTS

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