

Design of a 450 MHz $\beta=0.2$ single spoke cavity at PKU

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Abstract The design of a 450 MHz $\beta=0.2$ superconducting single spoke cavity has been finished at Peking University. A theoretical model and a numerical simulation are used to study the relationship between the RF performance and the geometric parameters of the cavity. In this paper, the optimization of the spoke cavity is described in detail. The RF simulation gives the optimum parameters E_{pk}/E_{acc} of 2.65 and B_{pk}/E_{acc} of 5.22 mT/(MV/m). The mechanical properties of the cavity are also studied. Two stiff ribs are used to offer a credible mechanical stability.

Key words spoke cavity, low and medium β , superconducting linear accelerator

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1 Introduction

A spoke cavity is a TEM-class accelerating structure for low and medium β particles. Compared to a TM-class elliptical cavity for the same velocity range, the spoke cavity has many significant advantages^[1]. The spoke cavity operates at about half of the frequency of an elliptical cavity with the same transverse size. Since the BCS surface resistance of superconductors has a quadratic dependence on the frequency, operating at lower frequency requires less refrigeration and has the potential to operate at higher temperature. The lower operating frequency also offers a broader velocity acceptance and a higher voltage gain. In addition, the large cell-to-cell coupling results in a greater robustness with respect to mechanical tolerances. Because of its advantages for low and medium β particles, many new worldwide facilities have been proposed using spoke cavities. The AEBL (Advanced Exotic Beam Laboratory)^[2] is proposed at ANL, and will use 134 spoke cavities at 345 MHz. The Eurisol (European Isotope Separation On-Line) facility will use roughly 22 spoke cavities at 352 MHz^[3]. Applications for the ADS (Accelerator Driven System) for nuclear waste transmutation or for tritium production also propose the use of spoke cavities^[4].

Based on our experience of superconducting cavities at PKU, we have conducted research on spoke

cavities and designed a $\beta=0.2$ spoke cavity. The operating frequency of 450 MHz has been chosen because it is convenient for operating at 4.2 K. A 2-gap single spoke structure has a wider velocity acceptance, especially for very low β particles. It is also easier to study the fabrication process.

2 RF design

The goal of the RF (radio frequency) design of the superconducting cavity is to get a lower heat load and a higher accelerating gradient, which are determined by a higher R/Q_0 (R is the shunt impedance and Q_0 is the quality factor) and lower peak surface fields (E_{pk}/E_{acc} and B_{pk}/E_{acc}). For most cases, the performance limitation in a spoke cavity is the thermal-magnetic quench with little or no field emission^[4], which leads us to put more care to minimize B_{pk}/E_{acc} . Generally, E_{pk}/E_{acc} should be slightly less than 3^[5], and the best perspective results for a spoke cavity are about 2.5 for E_{pk}/E_{acc} and 5 mT/(MV/m) for B_{pk}/E_{acc} ^[4]. The peak surface fields must be balanced with the shunt impedance, which is mainly determined by the cavity type.

A MWS (microwave studio) is used to conduct the RF simulation. Fig. 1 shows cut-away views of the spoke cavity model in the MWS and the main geometric parameters used for the optimization.

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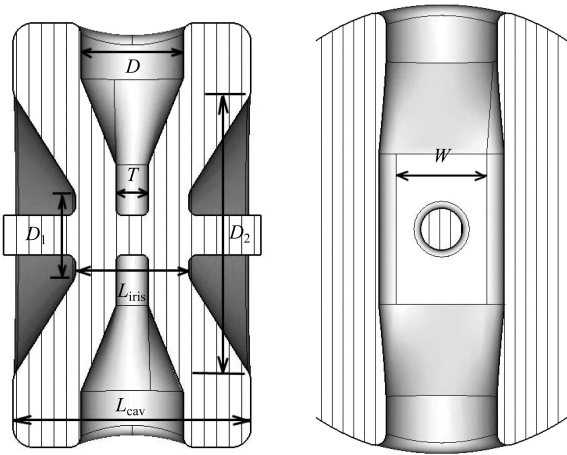


Fig. 1. Cut-away views of the spoke cavity model in the MWS and the main geometric parameters.

2.1 Basic parameters of the spoke cavity

The length of a 2-gap single spoke cavity is determined by the structure's β and the frequency of the desired mode^[6]: the length from iris to iris is $2/3\beta\lambda$, where λ is the free-space wavelength of the accelerating mode. The diameter of the cavity is of the order of $\lambda/2$. Beam dynamics considerations lead us to choose an aperture diameter of 30 mm.

2.2 Optimization of the peak surface field and the shunt impedance

To optimize a spoke cavity, many parameters can be changed. Usually, the cavity's diameter is used to set the frequency, while all others are used to minimize the peak surface fields and maximize the shunt impedance.

Before optimizing the geometry, the spoke cavity is simplified as a capacitive-loaded TEM resonant line model to study the RF properties. The resonant transmission line is a simple way of generating voltages that can be used to accelerate particles. The capacitive-loaded $\lambda/2$ transmission line is shorted at both ends, and the maximum voltage is in the middle, while the maximum current is at both ends of the inner conductor.

The main part of a spoke cavity is the spoke bar, consisting of the spoke base which is connected to the cavity body and the spoke aperture which is connected to the beam pipe. The optimization of the spoke base, including the shape and the dimension, will minimize the peak surface magnetic fields and thus the surface currents. While the optimization of the aperture region, including the thickness and the width, will minimize the peak surface electric fields. So the optimizing processes can be separated into two

independent parts. In addition, the influence of the end walls should be considered.

Spoke base: For spoke base optimization, cylindrical and elliptical cross sections have been studied^[7]. The cylindrical one is chosen, because it has a more homogenous surface magnetic field distribution, while the other exhibits a strongly inhomogeneous distribution with higher peaks.

The diameter of the spoke base (D) is optimized to get a lower B_{pk}/E_{acc} . The variation of B_{pk}/E_{acc} and R/Q_0 with D/L_{cav} is shown in Fig. 2.

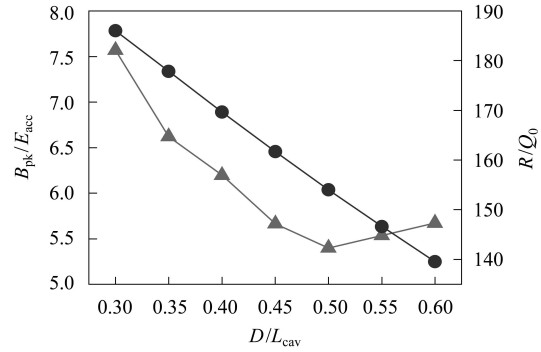


Fig. 2. B_{pk}/E_{acc} (triangles) and R/Q_0 (circles) vs. D/L_{cav} .

In Fig. 2, the B_{pk}/E_{acc} first decreases and then increases as the diameter of the spoke base increases. It is not difficult to understand that increasing the surface area of the spoke base will decrease the surface magnetic flux density for a given total flux. But a too large spoke base decreases the space of the magnetic flux, which causes the B_{pk}/E_{acc} increasing again.

On the other hand, R/Q_0 decreases as D/L_{cav} increases. From the transmission line model, R/Q_0 is proportional to $\ln(b/a)$ (a , b are the diameters of the inner and outer conductors). So the higher R/Q_0 must be considered to balance with the lower B_{pk}/E_{acc} . Finally, we choose D/L_{cav} as 0.43.

Spoke aperture: For optimization of the spoke aperture region, cylindrical, elliptical and race-track shape cross sections have been studied^[7]. Compared to the cylindrical shape, the others offer lower peak surface electric fields and higher transit time factors. They also allow the perimeter of the spoke at the aperture region to be similar than that at the base. This will reduce the production costs and efforts significantly. In addition, the race-track shape exhibits a fairly homogenous peak surface electric field around the periphery of the spoke, which is chosen as the best solution.

To optimize the aperture region with the race-track shape cross section, we need to change the thickness (T) in the beam direction and the width (W)

normal to the beam direction, while the length from iris to iris (L_{iris}) is a constant. The RF results are shown in Fig. 3.

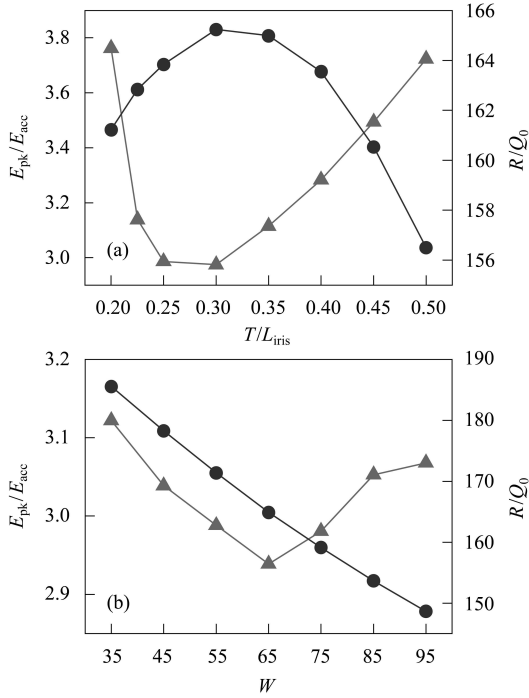


Fig. 3. (a) $E_{\text{pk}}/E_{\text{acc}}$ (triangles) and R/Q_0 (circles) vs. T/L_{iris} . (b) $E_{\text{pk}}/E_{\text{acc}}$ (triangles) and R/Q_0 (circles) vs. W .

As the thickness increases, $E_{\text{pk}}/E_{\text{acc}}$ first goes down and then goes up. Increasing the thickness will decrease the gap length between the inner and outer conductors, then increase the electric field for a given voltage between the two conductors. So the peak surface electric field increases with a larger thickness. On the other hand, when the gap length is too large, the accelerating field on the axis of the beam aperture will decrease, which causes $E_{\text{pk}}/E_{\text{acc}}$ to go up with decreasing thickness.

Increasing the width of the spoke will increase the surface area of the electric field, and decrease the surface electric field density. This causes the $E_{\text{pk}}/E_{\text{acc}}$ to go down. But if the width becomes too large, the surface electric field will centralize to both ends of the race-track, which causes the $E_{\text{pk}}/E_{\text{acc}}$ to go up again.

At last, we choose T/L_{iris} as 0.28 and W as 65 mm.

End wall: Normally, a spoke cavity uses re-entrant shaped or dish-shaped end walls. Here, we have studied both of them. MWS models are shown in Fig. 4.

The two types of end walls are of nearly the same quality concerning the peak electric surface fields. But the re-entrant shape leaves more space between the spoke base and the end wall for the magnetic

flux which decreases the peak magnetic surface fields. With the dish-shaped end wall limit, the diameter of the spoke base can not be too large. This also restricts the cavity with dish-shaped end walls reach lower $B_{\text{pk}}/E_{\text{acc}}$.

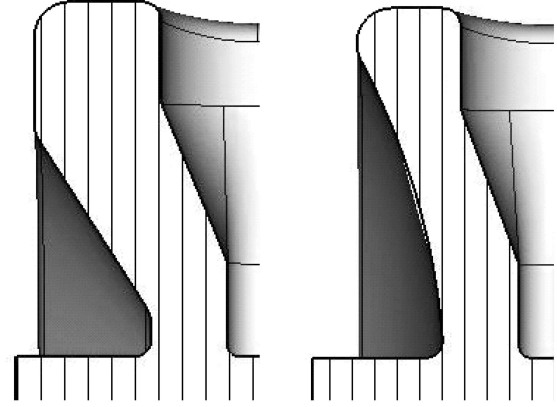


Fig. 4. Cut-away view of the re-entrant shaped (left) and dish-shaped (right) end walls.

For the re-entrant shaped end wall, the diameters of both bottoms of the cone (which helps to get a better peak fields and better shunt impedance) should be considered. $D1$ is defined as the diameter of the small bottom, which is more sensitive to $E_{\text{pk}}/E_{\text{acc}}$, while $D2$ is that of the large bottom, which is more sensitive to $B_{\text{pk}}/E_{\text{acc}}$. The variation of $E_{\text{pk}}/E_{\text{acc}}$ and R/Q_0 with $D1$ and that of $B_{\text{pk}}/E_{\text{acc}}$ and R/Q_0 with $D2$ are shown in Fig. 5.

$D1$ can be easily chosen at the minimum point of $E_{\text{pk}}/E_{\text{acc}}$ in Fig. 5(a). From Fig. 5(b), we can observe that $B_{\text{pk}}/E_{\text{acc}}$ decreases and R/Q_0 increases as $D2$ decreases. But smaller $D2$ leads the electric field to centralize to the small bottom of the cone, which increases the $E_{\text{pk}}/E_{\text{acc}}$. The influence of the peak surface electric field must be considered when $D2$ is decided.

Other parameters: After all of the above processes, the cavity total length should be considered, which is related to $B_{\text{pk}}/E_{\text{acc}}$. Increasing the cavity length will increase the space for the magnetic flux, and decrease the $B_{\text{pk}}/E_{\text{acc}}$. On the other hand, the length from iris to iris is a constant, equal to $2/3\beta\lambda$, so the cavity length can not be too large for mechanical stability and manufacturability.

Blend edges will help to decrease the peak surface fields, and get better $E_{\text{pk}}/E_{\text{acc}}$ and $B_{\text{pk}}/E_{\text{acc}}$. For manufacturing reasons, the sharp areas also need to blend. Besides all of this, we need to consider the height between the spoke base and the aperture region. It has little effect on the peak surface field, but can offer better shunt impedance.

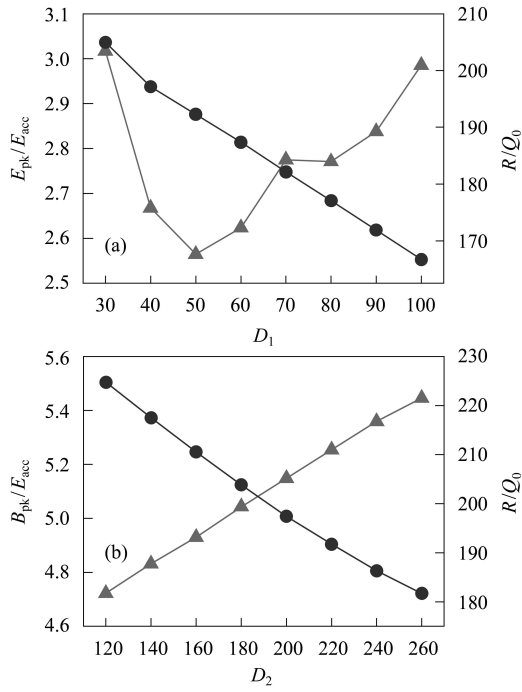


Fig. 5. (a) E_{pk}/E_{acc} (triangles) and R/Q_0 (circles) vs. D_1 . (b) B_{pk}/E_{acc} (triangles) and R/Q_0 (circles) vs. D_2 .

2.3 Cleaning ports

Two cleaning ports have to be added to the

periphery of the cavity. These ports permit good cleaning access to the cavity. All experience on the TESLA cavity indicates that chemical polishing and high-pressure rinsing are necessary to increase the cavity performance in terms of achievable field levels. For this cavity, a diameter of 45 mm for the cleaning ports is enough. One port will also be the input coupler port in the future.

Cleaning ports are located at 45° with respect to the spoke bar^[6] or perpendicular to the spoke bar^[8]. The RF parameters show nearly no difference between these two conditions and a cavity with no clean ports. But to eliminate power dissipation on the normal conducting flanges when the cavity operates at 4.2 K, the port tubes length should be longer for the first condition, because the magnetic field at this position is still strong. The second condition needs only short port tubes, where both the electric and magnetic field are weak enough. We choose our cleaning ports to be perpendicular to the spoke bar.

2.4 Final geometry

After the optimization of all these parameters and adding cleaning ports, the final geometry parameters of the spoke cavity are given in Table 1.

Table 1. The main geometry parameters of the spoke cavity.

cavity diameter	spoke diameter at base	spoke thickness at aperture	spoke width at aperture	iris-to-iris length	cavity length	aperture diameter	cleaning port diameter
324.4 mm	79.6 mm	25 mm	65 mm	88 mm	185 mm	30 mm	45 mm

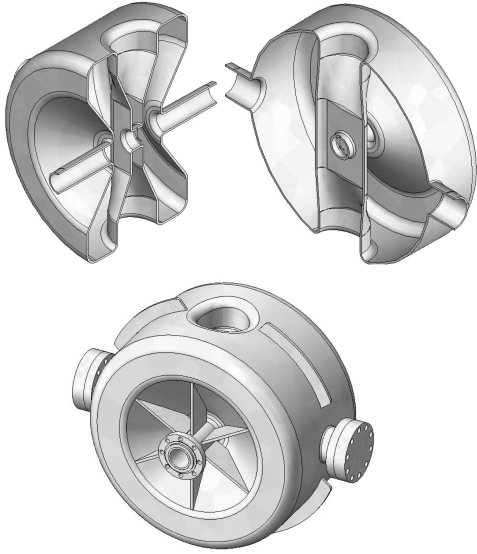


Fig. 6. The cut-away views of the final geometry and the whole cavity model with stiff ribs and flanges.

The final models of the spoke cavity are shown in

Fig. 6.

2.5 RF parameter

The major RF performance parameters are listed in Table 2. We use more than 1000000 mesh cells (more than 70 lines per wavelength) to reduce the possibility of errors caused by the software. E_{acc} is scaled with the iris-to-iris length, $2/3\beta\lambda$. The quality factor is calculated assuming a surface resistance of 100 n Ω at 4.2 K. R/Q_0 is defined as $R/Q_0 = V_{acc}^2/\omega U$.

3 Mechanical studies

For the mechanical study, we use CAD software (SolidWorks) and structural analysis software (ANSYS) to do the simulations. The material properties of niobium used are^[9]:

- Density 8560 kg/m³,
- Young's modulus 107000 MPa,
- Poisson ratio 0.359.

Table 2. RF parameters of the spoke cavity.

Q_0 for 100 nΩ at 4.2 K	$T(\beta)$ at $\beta=0.2$	$T_{\max}(\beta)$ at $\beta=0.217$	G/Ω	$(R/Q_0)/\Omega$	$E_{\text{pk}}/E_{\text{acc}}$	$(B_{\text{pk}}/E_{\text{acc}})/$ (mT/(MV/m))	P_{cav} at 4.2 K and $E_{\text{acc}} = 7.5$ MV/m
7.30×10^8	0.8015	0.8079	73.0	178.7	2.65	5.22	3.34 W

3.1 External vacuum load

The cavity has been evaluated for an external load of 2 atm, while the flanges on both beam pipes are fixed. The stiff ribs reduce the stresses and deformations of the structure. Six radial niobium stiff ribs are used in the re-entrant region, and four niobium stiff ribs are presented on the cylindrical portion of the cavity. The thickness of all the stiff ribs is 4 mm. Table 3 gives the results of equivalent stress and displacement for the cavity with or without stiff ribs.

Table 3. Equivalent stress and displacement under 2 atm pressure.

	peak equivalent stress/MPa	peak displacement/ mm
without stiff ribs	308.2	0.221
with stiff ribs	55.3	0.060

These stiff ribs significantly reduce the stress at the iris, and move the maximum stress point from the cavity body to the stiff ribs. It also leaves enough places in the tuning region to facilitate a controlled displacement for cavity tuning.

3.2 Tuning sensitivity

Tuning the cavity changes the capacity in an equivalent circuit by pushing the end flanges. The pushing is limited to produce stresses less than the niobium yield strength (50 MPa^[9] at room temperature). The maximum displacement between both end walls is 0.55 mm and the corresponding frequency shift is about 650 kHz.

3.3 Mechanical resonance

The calculation of the mechanical resonance modes is performed by fixing the ends of both beam tubes. The frequencies of the lowest six modes are listed in Table 4.

Table 4. Mechanical resonance modes of the cavity.

mode	frequency/Hz
1	92
2	213
3	335
4	375
5	452
6	483

The lowest mode seems not to be dangerous. Because of the torsion around the beam axis, this mode does not cause a frequency shift. All others are longitudinal and deleterious. Stiff ribs should also heighten the frequencies of these deleterious modes to reduce the influence of microphonics.

4 Summary and outlook

We have finished the RF design and mechanical studies of the 450 MHz $\beta = 0.2$ single spoke cavity at PKU. The cavity is expected to have a good performance with $E_{\text{pk}}/E_{\text{acc}} = 2.65$ and $B_{\text{pk}}/E_{\text{acc}} = 5.22$ mT/(MV/m). The cavity will be under construction very soon. Studies of the main coupler, high order mode and beam dynamics are our following work.

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