Design of a 325 MHz SC Spoke040 cavity at IHEP

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Abstract: A spoke cavity is a TEM-class superconducting resonator with particular advantages: compact structure and high shunt impedance. The 325 MHz β=0.40 (β=v/c, v is the velocity of particle and c is the velocity of light) single spoke cavity (Spoke040) is adopted for the Chinese ADS (Accelerator Driven Sub-critical System) project. The physics and mechanical design has been accomplished, and the fabrication of a prototype is currently in progress. In this paper, the optimization processes for the main radio frequency (RF) and mechanical parameters are analyzed in detail. Two kinds of cavity end-walls (flat and convex) are compared. The convex end-wall is preferred in order to improve mechanical performance of the cavity. Two prototypes of the Spoke040 cavity are in the machining stage, and should be finished in early 2014. Vertical testing is also under preparation.

Key words: single spoke cavity, superconducting, RF, mechanical performance

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1 Introduction

The first 325 MHz β=0.12 superconducting single spoke (Spoke012) cavity was tested with $E_{\rm acc}$= 5.0 MV/m@$Q_0=8.5\times10^8$ ($E_{\rm acc}$ is the acceleration gradient and Q_0 is the intrinsic quality factor) at 4.2 K at IHEP, a milestone for the R&D of spoke cavities in China [1]. A spoke cavity is proposed to accelerate heavy particles with velocity from β=0.15 to β=0.75 [2]. A series of Spoke040 cavities will be applied to the Chinese ADS (Accelerator Driven Sub-critical System) linac to accelerate the 10 mA proton beam from 34 MeV to 178 MeV (0.26< β < 0.54), positioned next to Spoke021 cavities and then elliptical cavities [3].

Based on the experience of superconducting cavities at IHEP, we committed to the R&D of the Spoke040 cavity. The radio frequency (RF) and mechanical properties were studied with CST microwave studio and Ansys workbench. $E_{\rm peak}/E_{\rm acc}$=3.68 and $B_{\rm peak}/E_{\rm acc}$=8.31 were achieved for a Spoke040 cavity with convex end-walls, showing mechanical properties that are much better for overcoming deformation and pressure.

2 RF design

The purpose of RF design is to reduce the heat load and over-fulfilled accelerating gradient, which result from high R/Q_0 (R is the shunt impedance) and good peak surface fields $E_{\rm peak}/E_{\rm acc}$ and $B_{\rm peak}/E_{\rm acc}$ [3]. Generally, $E_{\rm peak}/E_{\rm acc}$ should be slightly less than 3 [4]. Several requirements were defined for the Spoke040 cavity by the Chinese ADS project, including: 325 MHz frequency; proton beam energy in the range 34–178 MeV ($0.26 < \beta < 0.54$); $\beta_{\rm g}$ = 0.40; total length < 614 mm (including the liquid helium bath and tuner); $V_{\rm cmax}$=2.86 MV ($V_{\rm c}$=$E_{\rm acc}\times\beta\lambda$, $E_{\rm acc}$=7.7 MV); and, $E_{\rm peak}$<32.5 MV/m, $B_{\rm peak}$<65 mT.

The principles for RF optimization can be summarized as follows: minimize $E_{\rm peak}/E_{\rm acc}$ and $B_{\rm peak}/E_{\rm acc}$; maximize R/Q (Q is the quality factor) and G (G is the geometric factor); minimize length and radius to achieve a compact structure for the best use of the already existing vertical test (V.T.) facilities; and, simplify the structure.

2.1 Basic parameters of the spoke cavity

The basic parameters for the resonator $\beta_{\rm g}$ = 0.40 f=325 MHz determine the main geometric dimension for the Spoke040 cavity [4], which are: length of the cavity $L_{\rm cav}=2/3\times\beta_{\rm g}\lambda\approx250.0$ mm, and diameter from gap center to gap center $L_{\text{g-g}}=\beta_{\rm g}\times\lambda/2=185.0$ mm. The beam tube $R_{\rm beam}$=50 mm is required by beam aperture dynamics. The main geometry has been studied before [5–7].

For the first steps, we studied how the basic geometric dimensions would influence the RF parameters. The

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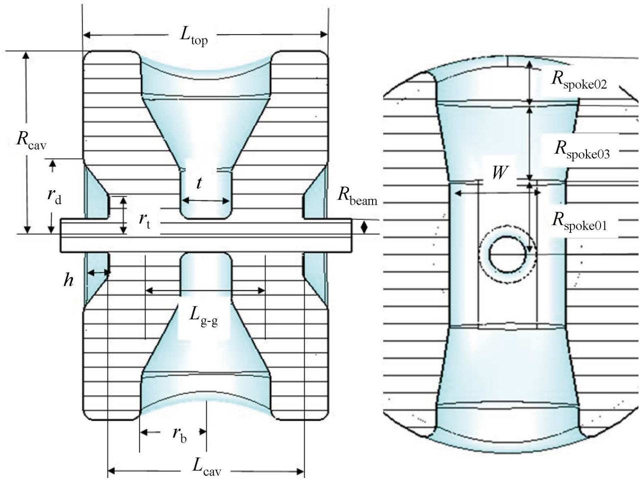

Fig. 1. Cut-away views of the spoke cavity model in the MWS, and its geometric parameters.

basic TEM mode of high frequency microwaves in a cylindrical resonator can be used to accelerate charged particles, and the maximum value of electric field is distributed along the axis centre line. Higher $E_{\rm acc}$ is the goal of the RF design for the Spoke040 cavity.

Firstly, we consider the resonator as a cylinder intersecting with a cylindrical spoke to get a two-gap accelerating electric field, as shown in Fig. 2.

The value of $L_{\rm cav}$ is required by the TEM mode and allows little flexibility, so d (d is the diameter of the cylindrical spoke) was changed to study the RF parameters, as shown in Fig. 3. $E_{\rm peak}/E_{\rm acc}$ and $H_{\rm peak}/E_{\rm acc}$ first decrease and then increase with the increase of d. On the other hand, $G{*}R/Q$ first increases and then decreases. Larger values of d leads to better TTF (TTF is the transit time factor). In the first step, d=120 mm was chosen for smaller $E_{\rm peak}/E_{\rm acc}$ and $H_{\rm peak}/E_{\rm acc}$.

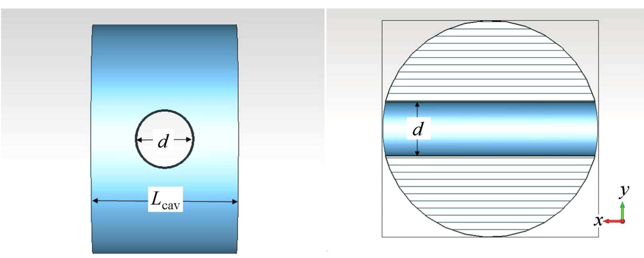

Fig. 2. View of cylinder spoke.

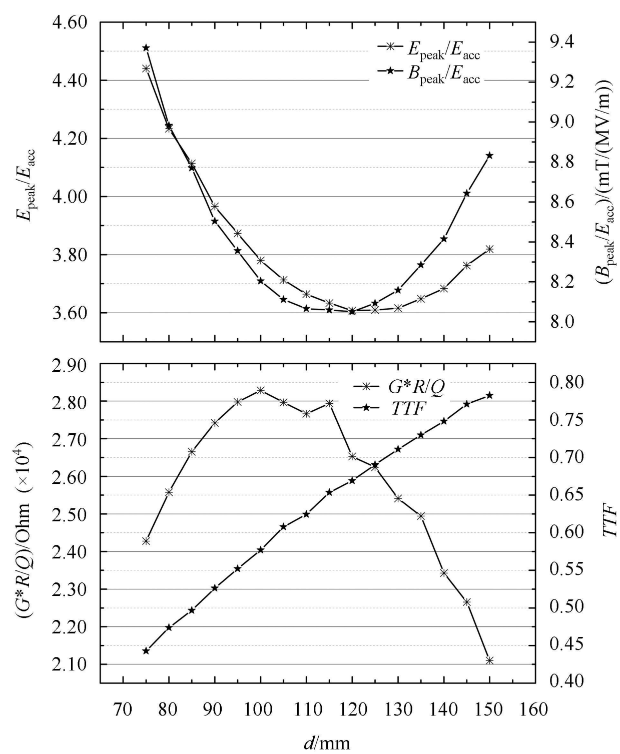

Fig. 3. $E_{\rm peak}/E_{\rm acc}$, $B_{\rm peak}/E_{\rm acc}$, $G{*}R/Q$ and TTF vs. d.

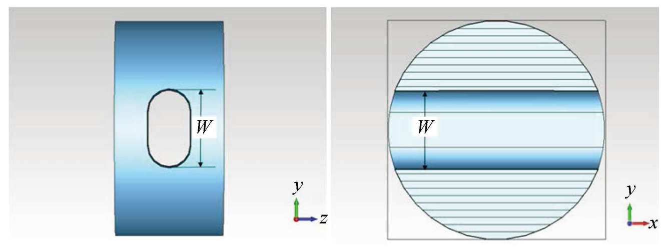

Fig. 4. View of track spoke.

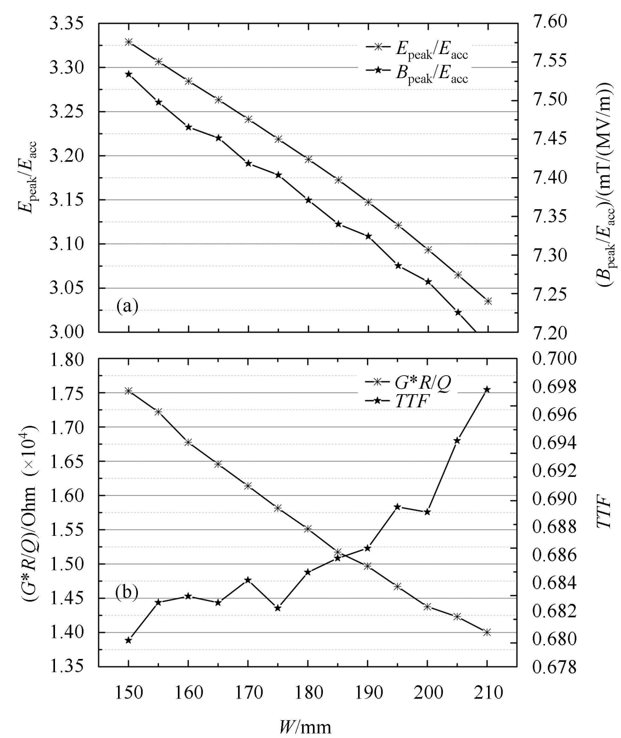

Fig. 5. $E_{\rm peak}/E_{\rm acc}$, $B_{\rm peak}/E_{\rm acc}$, $G{*}R/Q$ and TTF vs. W.

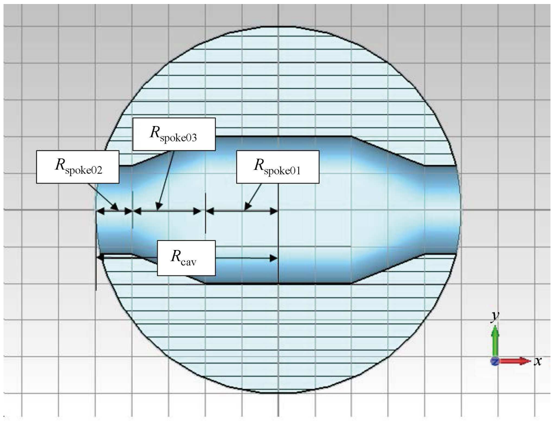

Fig. 6. View of final spoke.

For the same accelerating voltage V_c, a shorter gap means higher E_{acc} ($V_c = E_{acc} * \beta\lambda$). We therefore constructed a track spoke to get higher E_{acc}, as shown in Fig. 4.

The radius of the track was chosen as $d/2 = 60$ mm, and the width of the track (W) was changed to study the RF parameters. With respect to cylinder type, the track type has better E_{peak}/E_{acc} and H_{peak}/E_{acc}, but smaller $G*R/Q$ and TTF. In Fig. 5, with the growth of W, E_{peak}/E_{acc} and H_{peak}/E_{acc} and TTF increase substantially, while $G*R/Q$ show the opposite behaviour. We choose $W = 0.8 \times L_{cav} \approx 200.0$ mm for the next steps.

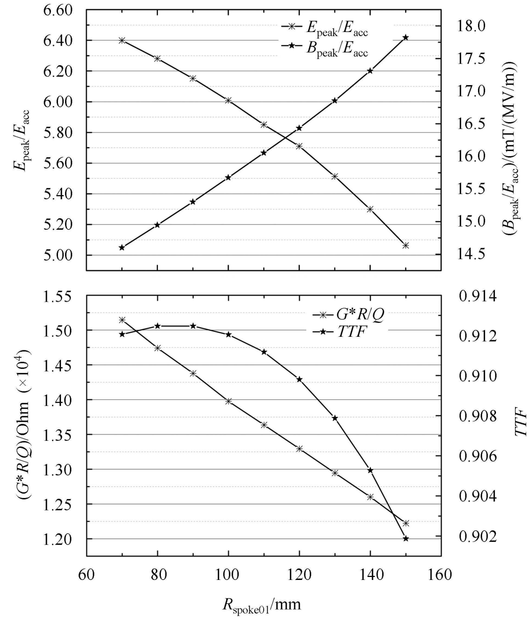

Fig. 7. E_{peak}/E_{acc}, B_{peak}/E_{acc}, $G*R/Q$ and TTF vs. $R_{spoke01}$.

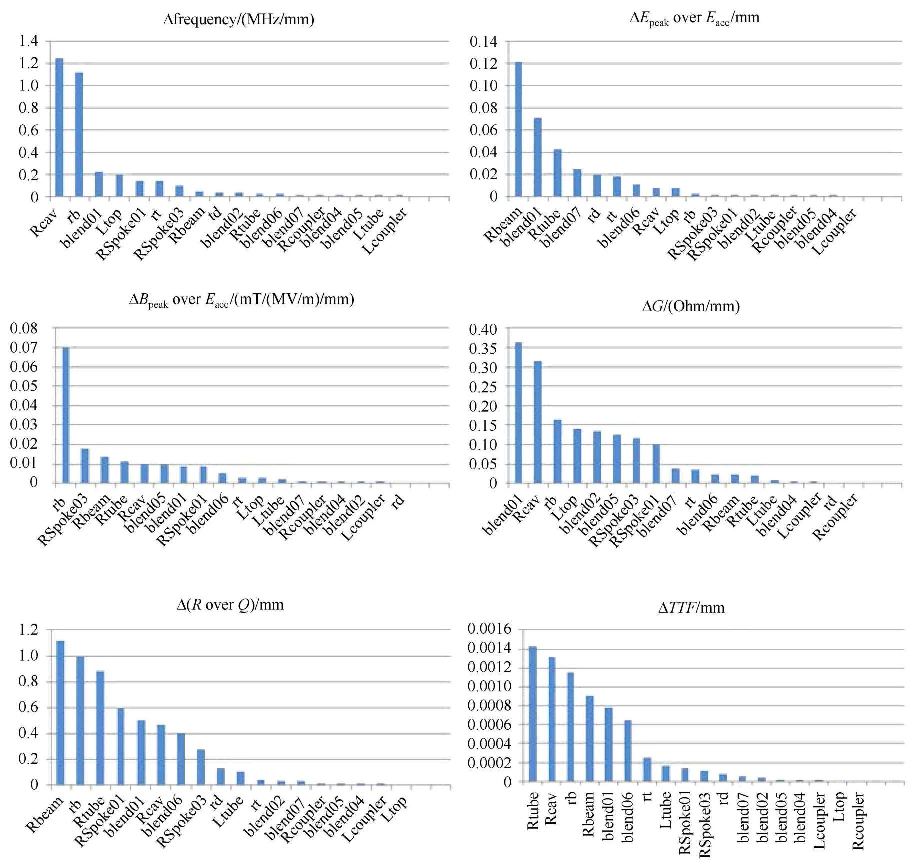

Fig. 8. RF parameter sensitivity to various geometric values.

While the cylinder spoke has a lower B_{peak}, the track type can give higher E_{acc}. Early researchers introduced a transition spoke (Fig. 6) to get lower $E_{\text{peak}}/E_{\text{acc}}$ and $H_{\text{peak}}/E_{\text{acc}}$ and higher $G*R/Q$ and TTF. With $R_{\text{spoke03}}=R_{\text{cav}}/3$ (R_{spoke03} is the transition length of the spoke), the rate of track to cylinder was changed gradually. In Fig. 7, a larger track means smaller $E_{\text{peak}}/E_{\text{acc}}$, while a larger cylinder can bring better $G*R/Q$ and TTF. Lastly, the end-walls, tubes and arcs were added to acquire basic RF parameters for the complete Spoke040 cavity, as shown in Fig. 1.

2.2 Sensitivity analysis

Using the dominant dimensions from Section 2.1, we changed one dimension slowly and fixed the others to analyze RF sensitivity to geometric perturbation. The tiny changes of the RF parameters caused by every millimeter were counted in Fig. 8. Taking r_{d} (end wall bottom radius) as an example: when $\Delta r_{\text{d}}=1$ mm, $\Delta f=1.1$ MHz, $\Delta(E_{\text{peak}}/E_{\text{acc}})=0.02$, $\Delta(B_{\text{peak}}/E_{\text{acc}})=(0.07\ \text{mT/MV})/\text{m}$, $\Delta(R/Q)=1$, $\Delta G = 0.15\ \Omega$, $\Delta TTF = 0.001$. This indicated that r_{d} strongly influences $B_{\text{peak}}/E_{\text{acc}}$, f and R/Q, weakly influences TTF and G, and rarely influences $E_{\text{peak}}/E_{\text{acc}}$. These provide effective criteria for optimization of the RF details.

We summarize the basic process of EM design and optimization for RF details in Fig. 9 and Fig. 10.

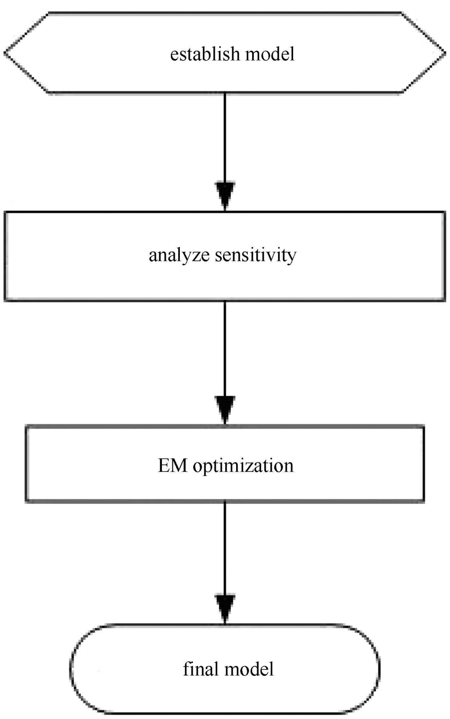

Fig. 9. Workflow for EM design.

In Fig. 10, the workflow for optimizing the main RF parameters is given. The determination index in judging areas are controllable, and more criteria can also be added as RF is required. $B_{\text{peak}}/E_{\text{acc}}$ is considered prior to $E_{\text{peak}}/E_{\text{acc}}$ because field emission has been identified as the principal ceiling in recent years. For the first few cycles, a less stringent index is necessary in order to simplify the process and save time, but this must be made increasingly stricter to refine the promising RF parameters for the final superconductivity cavity.

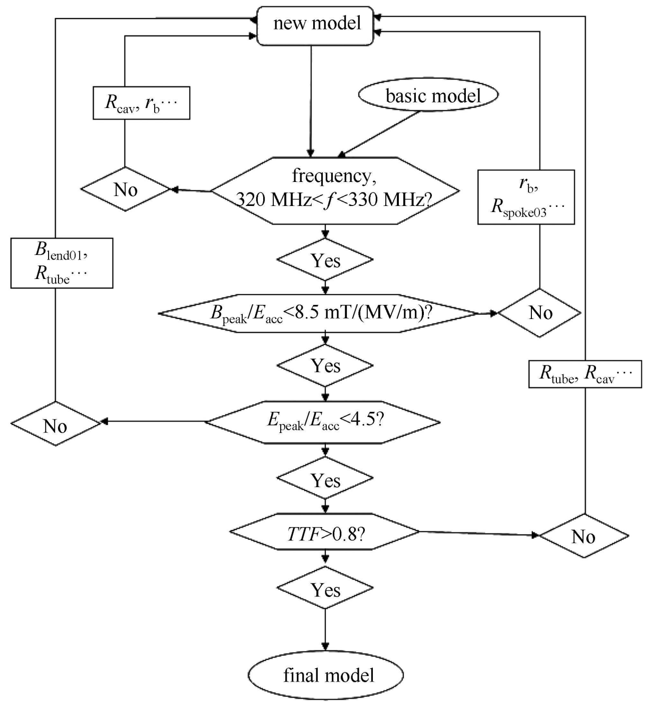

Fig. 10. Optimizing of details.

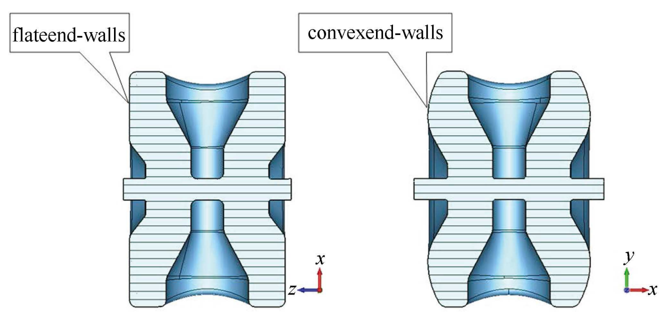

Fig. 11. Cut-away view of flat and convex end-walls.

Table 1. Geometric parameters of flat and convex end-walls for Spoke040.

	L_{top}/mm	L_{cav}/mm	R_{cav}/mm	W/mm
flat	370	292	278	160
convex	386.6	292	278	160
	R_{beam}/mm	r_{d}/mm	r_{t}/mm	r_{b}/mm
flat	25	110	60	98
convex	25	120	60	98

2.3 RF behaviour for flat and convex end-walls

The Spoke040 cavity's mechanical properties will face unprecedented challenges because it is the biggest of the three spoke cavities in the Chinese ADS. Convex end-walls were introduced to meet tuning requirements.

Table 2. Main RF parameters of flat and convex end-walls for Spoke040.

RF parameters/	flat	convex
f/MHz	324.41	324.44
$E_{\mathrm{peak}}/E_{\mathrm{acc}}$	2.82	3.68
$(B_{\mathrm{peak}}/E_{\mathrm{acc}})$/mT/(MV/m)	6.25	8.31
Q	22923.0	22795.6
$(R/Q)/\Omega$	247.22	250.41
TTF	0.817	0.821

The energy storage capacity of the convex type is compensated by appropriately increasing L_{top} and r_{d}. $E_{\mathrm{peak}}/E_{\mathrm{acc}}$=3.6 and $B_{\mathrm{peak}}/E_{\mathrm{acc}}$=8.31 mT/(MV/m) were obtained for the convex end-walls Spoke040 cavity.

3 Mechanical studies

The purpose of the mechanical study is to make df/dp as low as possible and obtain enough tuning range. We imported the SAT file of the Spoke040 cavity from CST microwave studio to Ansys workbench 14.5 to study the mechanical parameters. Naked shells were simulated at T=22 ℃ with different thickness, pressure and port modes. The material properties of Nb, which was the material used, are: density 8600 kg/m^3, Young's modulus 1.03E11 Pa, Poisson ratio 0.38. The results are shown in Fig. 12 and Table 3.

Table 3. Mechanical parameters for naked Spoke040 cavity with ports locked

	flat		
peak stress/MPa	3.0 mm	3.5 mm	4.0 mm
1.0 atm	556.56	347.88	448.58
1.5 atm	834.85	521.81	672.86
2.0 atm	1113.1	695.75	897.15
deformation/mm	3.0 mm	3.5 mm	4.0 mm
1.0 atm	0.46617	0.46611	0.37654
1.5 atm	0.96476	0.69916	0.56481
2.0 atm	1.2863	0.93221	0.75308
	convex		
peak stress/MPa	3.0 mm	3.5 mm	4.0 mm
1.0 atm	309	362.2	389.48
1.5 atm	463.5	543.3	584.22
2.0 atm	618	724.39	778.96
deformation/mm	3.0 mm	3.5 mm	4.0 mm
1.0 atm	0.42168	0.33315	0.26586
1.5 atm	0.63251	0.49972	0.39879
2.0 atm	0.84335	0.66629	0.53172

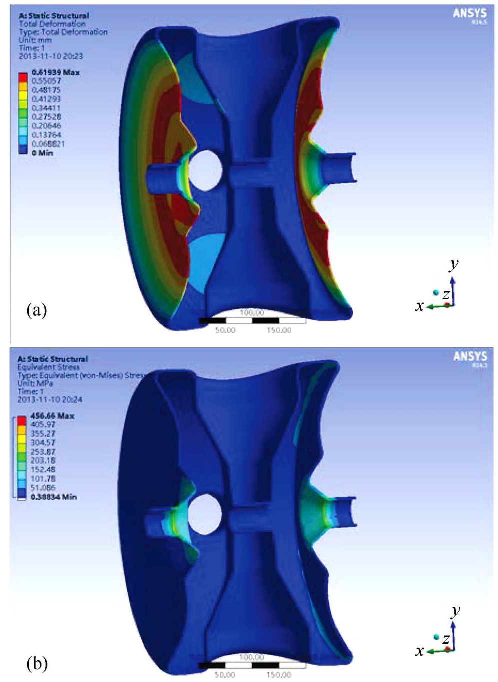

Fig. 12. Deformation (a) and stress (b) for convex end-walls Spoke040 with shell thickness=3.0 mm, pressure=1.0 atm and all ports locked.

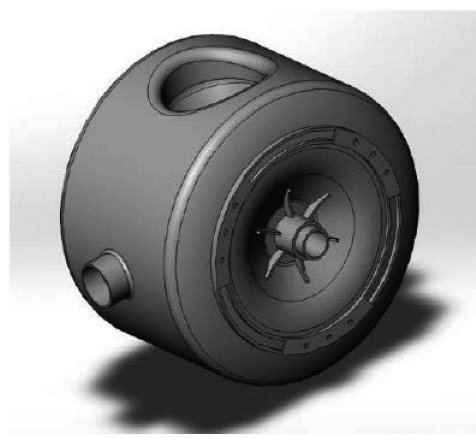

Fig. 13. Schematic of Spoke040 cavity with stiff ribs.

Table 4. Margin specifications.

parameters	ports free	ports locked
peak stress/MPa	85	38
peak deformation/mm	1.32	1.136
(df/dp)/(kHz/torr)	−0.67	−0.044

Deformation and pressure were mainly found to be symmetrical around the beam tube, and the maximum index appeared at the join between tube and end-walls. Considering material extensibility and hardness, a 3.0 mm Nb plate was selected. The convex type exhibits better mechanical performance. Stiff ribs were added to lower df/dp, as shown in Fig 13 and Table 4 [8]. Two tuners will be adopted to extend the tuning range to over 200 kHz.

4 Conclusion

The optimization of a superconducting single spoke cavity has been studied. The design of a Spoke040 cavity with convex end-walls has been completed, meeting the requirements for beam dynamics and giving better mechanical performance than previous cavities. The fabrication of two Spoke040 prototypes has begun, and vertical testing will be conducted later in 2014.

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