Design and simulation of a new type of 500 MHz single-cell superconducting RF cavity

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Abstract: This paper illustrates the design and simulation of a unique 500 MHz single-cell superconducting radio frequency cavity with a fluted beam pipe and a coaxial-type fundamental power coupler. The simulation results show that the cavity has a high r/Q value, a low peak surface field and a large beam aperture, so it can be a candidate cavity for high current accelerators. With the help of a fluted beam tube, almost all the higher order modes can propagate out of the cavity, especially the first two dipole modes, TE_{111} and TM_{110}, and the first higher monopole mode, TM_{011}. The external quality factor of the coaxial fundamental power coupler is optimized to 1.2×10^5, which will be useful when it is applied in the light source storage ring.

Key words: 500 MHz superconducting cavity, higher order modes, input coupler, simulation

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1 Introduction

At present, most of the world's synchrotron radiation light sources choose two types of 500 MHz superconducting radio frequency (SRF) cavities: KEKB and CESR, which were researched and fabricated successfully at the High Energy Accelerator Research Organization (KEK) and Cornell University in the 1990s [1], respectively. The KEKB-type cavities have a cylindrical large beam pipe (LBP) and are designed to propagate higher order modes (HOMs) towards the beam axis and damp them by ferrite absorbers bonded on the inner surfaces of beam pipes on both sides of the cavity [2]. In addition, the input coupler for the KEKB SRF cavity has almost the same design as that of the TRISTAN SRF cavities [3], which can handle an input power as high as 1 MW and have the ability to change the coupling in a small range by changing the penetration depth of the inner conductor. The CESR-type cavities propagate HOMs with a fluted beam tube [4] (FBT), which has four special flutes that reduce the cutoff frequency of dipole modes and the round beam tube (RBT), whose cutoff frequency is high enough to exceed the resonant frequency of the fundamental mode but less than the second monopole HOM resonant frequency. The fundamental power coupler is of rectangular waveguide-type, and has a fixed coupling with a maximum input power of around 300 kW [5].

The optimization goals include, for example, lower electromagnetic surface fields (E_p/E_{acc}, H_p/E_{acc}), lower cryogenic losses, stronger HOM damping, or lower loss factor. Some of these objectives are mutually exclusive. Therefore, we have to compromise to reach an optimal result in the actual design. The innovation of this design is to combine the preponderant accessories of the two types of cavity, the high

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power transmission capability of the coaxial input coupler of KEKB, and a large beam aperture of CESR and low loss factor of CESR's FBT [3].

2 Structural optimization

A typical cavity has a shape with the set of dimensions as shown in Fig. 1, and by tuning these dimensions and taking the performance influences of each dimension into account [6], a set of suitable geometrical parameters can be obtained during the optimization processes.

Comparing the performance parameters of KEKB [7] and CESR [7], it is not difficult to find that CESR has a larger beam aperture which satisfies the needs of high current accelerators. It can also be found that performances such as the shut impedance r/Q, E_p/E_{acc}, H_p/E_{acc} of KEKB are better than those of CESR. Based on the KEKB 509 MHz SRF cavity and the CESR 500 MHz SRF cavity, some modifications and optimizations have been put forward to meet the frequency and other performance requirements. We adopted CESR's 240 mm large beam aperture to make it suitable for strong beam accelerators and the bottom ellipse, which is similar to KEKB's, to minimize the value of E_p/E_{acc}. At the same time, we had to modify the equator length d and the equator radius R_{eq} to catch the operation frequency and other performance parameters. Therefore, we came up with a new type of 500 MHz single-cell SRF cavity shape with very good performance parameters, as shown in Table 1. It can be found that the main parameters, such as r/Q, E_p/E_{acc} and H_p/E_{acc}, of the new type of 500 MHz SRF cavity are better than those of CESR, and that the 240 mm beam aperture is much better for high current accelerators than KEKB's beam aperture of 220 mm.

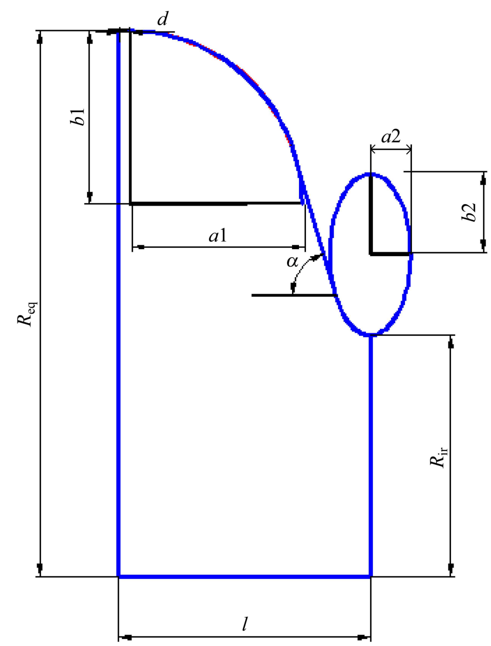

Fig. 1. A typical cavity shape with a set of dimensions.

Table 1. The parameters of the referenced cavities and the new type of cavity (default unit: mm).

items	new type	CESR	KEKB
R_{ir}	120	120	110
R_{FBT}/R_{LBP}	183**	183**	150
R_{eq}	269.2	274	262.83
l	120.04	120.2	121.519
$a1/b1$	89/89	82.6/82.6	84.936/84.936
$a2/b2$	20/40	20/20	27.5/80
d	4.9	0	6.5
$\alpha/(°)$	80	75	80
Freq/MHz	499.65	499.765	508.887
r/Q*/Ω	90.5	88.789	93
T_s*(void)	0.499	0.505	0.505
E_p/E_{acc}*(void)(***)	2.36	2.45	2.16
H_p/E_{acc}*/(mT/(MV/m))	4.94	5.26	4.92

*Calculated by SUPERFISH. Here, r/Q is the effective characteristic impedance and E_{acc} is the average effective accelerating electric field. **Flute-tube structure. *** The values of E_p/E_{acc}, H_p/E_{acc} are calculated with the cell length ($2l$), which is half the accelerating mode's wavelength ($\lambda/2\approx$300 mm).

3 HOM damping methods

Because of the harm caused by HOMs, HOM damping is one of the most crucial technologies in cavity design. The first two dipole modes, TE_{111} and TM_{110}, and the first higher monopole mode, TM_{011}, are considered to be the most harmful and to generate major power due to their high impedance, so the three main HOMs must be propagated out and damped. As the FBT of CESR has a lower loss factor and moderate cutoff frequency [3], based on HOM damping of the CESR 500 MHz cavity, the HOM damping method of using FBT for the new type of cavity was chosen. The most harmful HOMs, TE_{111}, TM_{110} and TM_{011}, whose resonant frequency are higher than the cutoff frequency of the beam tubes, can propagate out and be damped by ferrite absorbers bonded on the inner surface of the beam tubes. The geometrical parameters of the FBT structure are as shown in Fig. 2 and Table 2. Table 3 shows the cutoff frequency of some of the modes of RBT and FBT, and Table 4 shows the frequency of some of the resonant modes.

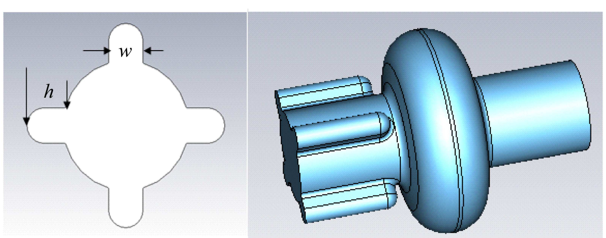

Fig. 2. A typical fluted beam pipe shape and a 3D model.

Table 2. The dimensions of the FBT structure (mm).

item	value
pipe length	260
coupling iris radius ($R_{\rm ir}$)	120
flute height(h)	63
flute weight (w)	60
chamfer angle (R_edge)	12.7

Table 3. The partial cutoff frequency (MHz) of RBT and FBT.

mode	RBT	FBT
TE_{11}	730.1	569.1
TM_{01}	954.9	926.7
TM_{11}	1516.6	1468.0

Because of the beam hole, the TM_{110} cavity mode is partially TE_{111}-like. Thus both trapped modes (TM_{110} and TE_{111}) couple to the fluted beam pipe via the TE_{11} waveguide mode, and it is only necessary to lower the propagation frequency of the TE_{11} mode to below that of the two trapped cavities [8]. Analyzing Table 3 and Table 4, it is not difficult to find that the new type of cavity with the use of FBT is successful in propagating the most harmful HOMs, such as TE_{111}, TM_{110} and TM_{011}, out of the cavity.

Table 4. Partial resonant frequency (MHz).

mode	resonant frequency
TE_{111}	625.2
TM_{011}	942.1
$TM_{110} \rightarrow TE_{11}$ in FBT	676.8

A smaller external quality factor, $Q_{\rm ext}$, means a shorter damping time and a larger current to disturb the beam. The optimization goal of the SRF cavity is to reduce the $(r/Q)*Q_{\rm ext}$ values for the HOMs. Assuming ideal RF absorbers on the FBT and RBT, which means that all HOMs propagating through the waveguide ports on the beam tube will be absorbed completely, we can get the $(r/Q)*Q_{\rm ext}$ values of the HOMs, which will be used to compare with the beam instability threshold value of the Shanghai Synchrotron Radiation Facility (SSRF), as shown in Fig. 3. The $(r/Q)*Q_{\rm ext}$ values of the HOMs are all below the SSRF threshold values, so no instability is induced.

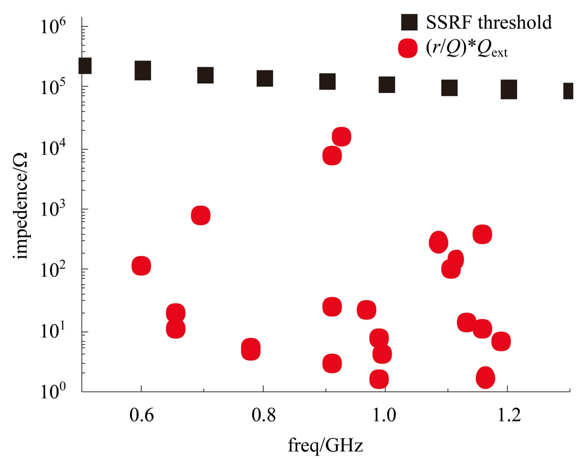

Fig. 3. Comparison of the SSRF threshold and the $(r/Q)*Q_{\rm ext}$ values of the HOMs.

4 Fundamental power coupler

The fundamental power coupler is used to transmit power to the SRF cavity from the power generators. The efficient transfer of power from a generator to a "load" (cavity and beam) is the primary task of a coupler.

It is very important to predict the coupling between the cavity and the high power input source of the coupler design. In real machines, beam loading $P_{\rm beam}$, cavity voltage $V_{\rm c}$ and effective characteristic impedance r/Q determine an optimal external quality factor $Q_{\rm opt}$ of the input coupler. Based on the optimal external $Q_{\rm opt}$, the dimension of the input coupler should be decided by simulation and calculation. For a coaxial coupler, the distance between the coupler axis and the iris D_2, the antenna penetration depth L and the external form of the coupler can be settled to meet the $Q_{\rm opt}$ requirement with the help of a 3D electromagnetic code.

For the SRF cavity, RF loss is negligible, and the loaded $Q_{\rm L}$ is almost equal to the external $Q_{\rm ext}$ of the input coupler. One can simply get the optional external $Q_{\rm opt}$ by [9]

$$Q_{\rm opt}=Q_{\rm ext}\approx\frac{V_{\rm c}^2}{P_{\rm beam}\cdot(r/Q)}. \tag{1}$$

The structural dimensions [9] of the input coupler are shown in Fig. 4. As shown in Fig. 5, when L=4 mm and D_2 increases from 80 mm to 90 mm, the $Q_{\rm ext}$ increases by about 45%. Fig. 6 shows that the $Q_{\rm ext}$ decreases by about 82% with L increasing from -12 mm to 12 mm, while the D_2 is 88 mm. We can obtain suitable $Q_{\rm ext}$ by varying L and D_2. In addition, the calculated $Q_{\rm ext}$ results of the different external forms of the power input coupler have been compared and are shown in Fig. 7 and Fig. 8. The external quality factor of the SRF modules operated at SSRF is $(1.7\pm0.3)\times10^5$, while we need to obtain the $Q_{\rm ext}$ of 1.2×10^5 at this new SRF cavity, which is a stronger coupling than that of the SRF modules operated at the SSRF storage ring. The simulations show that this can be achieved when D_2=88 mm, $L=-3.55$ mm under the straight type of coaxial input coupler. However, the coupling can still be varied in a small range by changing the penetration depth of the inner conductor to the beam pipe.

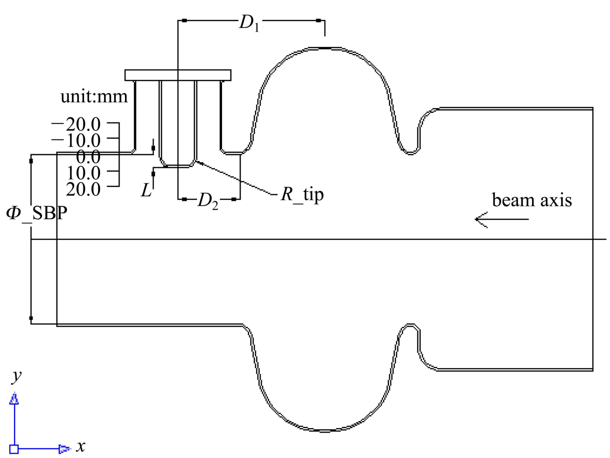

Fig. 4. Schematic of the cavity structure (L: antenna penetration depth; R_tip: antenna tip radius, set as 15 mm; Φ_SBP: small beam pipe diameter, set as 240 mm; D_2: distance between the coupler axis and the iris).

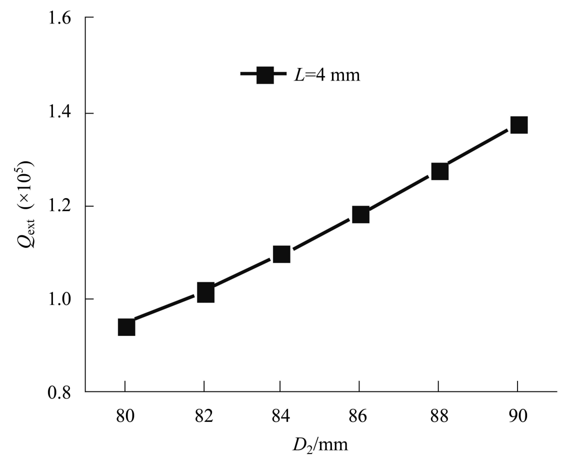

Fig. 5. The distance between the coupler axis and the iris (D_2/mm) impacting the $Q_{\rm ext}$.

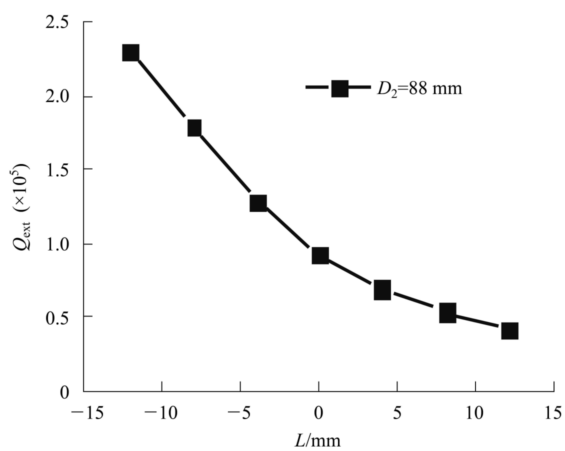

Fig. 6. Antenna penetration depth (L/mm) impacting the $Q_{\rm ext}$.

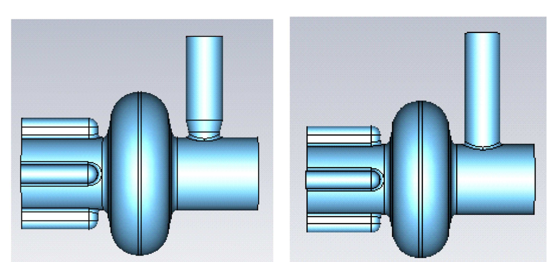

Fig. 7. Taper-type (left) and straight-type (right) input couplers.

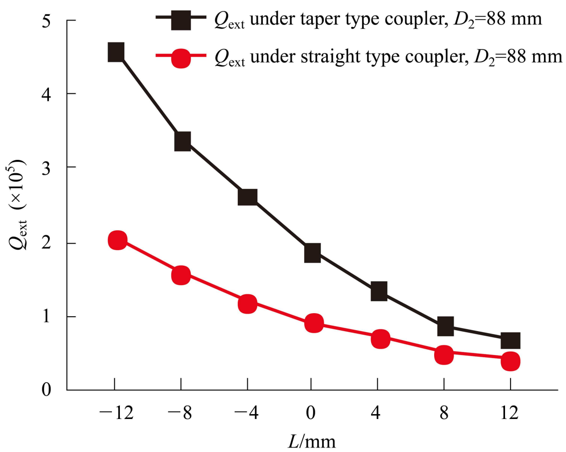

Fig. 8. Comparison of the $Q_{\rm ext}$ of different types of input coupler.

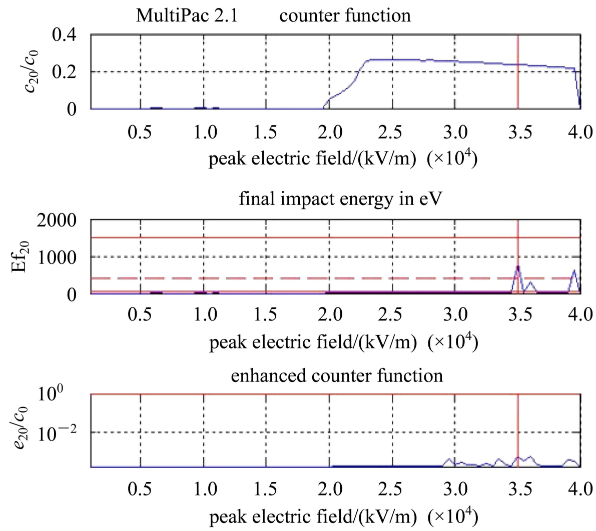

Fig. 9. The enhanced counter function.

5 Multipacting simulation

During the development and application processes of the SRF cavity, electron multipacting (MP) was always an obstacle to improving the accelerating field. Adopting a curving cavity shape and reducing the roughness of the inner surface of the cavity is effective in suppressing MP occurrence and the chances of an MP being excited [10].

We performed simulations to identify the electron MP for the inner cell of the new type of 500 MHz single-cell SRF cavity with MultiPac software [11]. The enhanced counter function result is much less than one, which shows that when the peak electric field changes from 0–40 MV/m, there is no obvious electron MP in this new type of SRF cavity, as shown in Fig. 9.

6 Conclusions and discussion

The preponderant accessories of the two typical cavity types (KEKB & CESR) were combined and a unique type of 500 MHz single-cell cavity was designed and optimized, adopting a fluted beam tube, a large beam aperture and a coaxial type fundamental power coupler. Based on the calculated and simulated cavity properties, the new type of 500 MHz single-cell cavity can meet the requirements of a higher accelerating gradient, a higher r/Q value, and a lower peak surface field. The use of FBT can propagate the most harmful HOMs, such as TE_{111}, TM_{110} and TM_{011}, out of the cavity. The $Q_{\rm ext}$ of the cavity-coupler system was chosen to be 1.2×10^5, and the D_2 of 88 mm and L of -3.55 mm under the straight type of coaxial fundamental power input coupler were fixed. Furthermore, the simulations show that there is no obvious electron MP in this unique type of SRF cavity. A feasibility study has been gradually carried out in the preliminary stage of the cavity fabrication.

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