ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-SUPCAV010



# DESIGN OF THIRD-HARMONIC SUPERCONDUCTING CAVITY FOR SHEN-ZHEN INDUSTRY SYNCHROTYON RADIATION SOURCE *

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*Abstract*

Shenzhen industry synchrotron radiation source is the fourth generation of medium energy light source with beam energy of 3GeV. It has the characteristics of low emittance and high brightness. In the design, the beam lifetime is one of the most important parameters. The main factor that affects its beam lifetime is the scattering of electron collisions inside the beam. To solve this problem, a harmonic radio frequency system is used. The third harmonic superconducting elliptical cavity is designed to stretch beam length to improve beam quality and beam lifetime. The present work is mainly about the shape optimization of 1.5 GHz 2-cell third harmonic superconducting elliptical cavity. Firstly, the principle of harmonic cavity in dual high frequency system is introduced, and the resonant frequency and acceleration gradient of superconducting cavity are given. Then, CST, electromagnetic field simulation software is used to optimize the cavity parameters to obtain the high performance and high frequency parameters that meet the requirements.

## INTRODUCTION

The beam lifetime in low-medium energy third and fourth generation synchrotron light sources is typically dominated by large-angle intrabeam (Touschek) scattering. Much attention has been paid to the use of harmonic rf systems to lengthen the bunches and improve the lifetime [1, 2]. Under ideal conditions, one expects lifetime improvements of a factor of 2–4, depending on the machine parameters. As shown in Fig 1, the high-order harmonic cavity is a high-frequency cavity whose resonant frequency is a multiple of the main high-frequency cavity. The addition of a high-order harmonic cavity can make the slope of the cavity pressure encountered by the center of the cluster zero, which makes the cluster elongated longitudinally, reduces the cluster charge density, thereby reducing Toschek scattering and increasing beam life. At the same time, the high-order harmonic cavity can cause frequency dispersion in the beam cluster, which can suppress the longitudinally coupled beam instability through Landau damping [3, 4]. For synchrotron radiation light source, a second high-frequency system is added to make the high-frequency accelerating electric field seen by the beam cluster superposition of the main high-frequency cavity pressure and the harmonic cavity pressure, and the electron density and length of the beam cluster are changed, thereby modulating and improving the beam quality and life .

At present work, we have studied the high-frequency cavity used in the third harmonic cavity system of Shenzhen Light Source. The content of this article is the design and optimization of the 1.5 GHz superconducting third harmonic cavity.

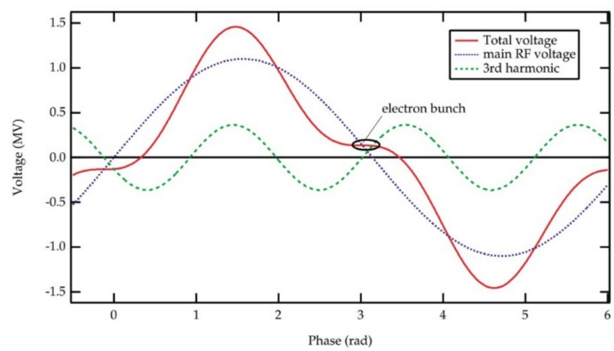


Figure 1: RF voltage seen by the bunch for main rf and higher harmonic cavity.[3]

## PERFORMANCE PARAMETERS OF SRF CAVITY

### Accelerating Gradient

The ratio of the accelerating voltage of the resonant cavity to the effective length d of the cavity is defined as the accelerating gradient (*E*acc). The accelerating gradient characterizes the energy gain per unit length of charged particles. The accelerating gradient is defined as follows:

$$E_{acc} = \frac{V_{acc}}{d}. \quad (2.1)$$

In accelerators, the definition of the effective length of the resonant cavity is different. The usual definition is:

$$d = \frac{N}{2}\beta\lambda\,, \quad (2.2)$$

where $N$ is the number of acceleration gaps, $\beta$ is the relative velocity of the particles, and $\lambda$ is RF wavelength.

### Quality Factors

The intrinsic quality factor of the resonant cavity can be used to reflect the power loss of the resonant cavity, which is defined as:

$$Q_0 = \frac{\omega \cdot W}{P_c}, \quad (2.3)$$

* Work supported by Shenzhen Development and Reform Commission
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where $W$ is the energy storage of the resonant mode in the resonant cavity, $\omega$ is the resonant frequency, and $P$c is the power loss of the resonant cavity in the resonant mode.

### *Surface Resistance*

The surface resistance of superconducting cavity mainly comes from two terms: the residual resistance $R$res, practically constant vs. temperature $T$, and the BCS term rapidly increasing with frequency ($\sim f^2$ ) and decreasing exponentially with $T$. The residual resistance is a measure of the surface quality, *e.g.*, purity of the superconductor, roughness, type of oxidation, inclusions on grain boundaries and so on. The general rule is the cleaner the surface the lower the residual resistance.

$$R_s = R_{res} + R_{BCS} \tag{2.4}$$

$$R_{BCS} = 0.0002 \cdot \frac{1}{T} \cdot \left(\frac{f[\mathrm{GHz}]}{1.5}\right)^2 \cdot exp\left(-\frac{17.67}{T}\right). \tag{2.5}$$

### *Geometric Factor*

The geometric factor is a ratio of the stored energy and surface integral of $H^2$. Higher geometric factor means higher intrinsic quality factor and lower energy dissipation for the same surface ‘quality’.

$$G = \frac{\omega W}{\frac{1}{2}\int_S H^2 ds} = \frac{\omega W \cdot R_s}{P_c} = Q_0 \cdot R_s. \tag{2.6}$$

### *Characteristic Impedance*

The beam characteristic impedance relates the stored energy and maximum accelerating voltage acting on the particle. One should note that *(R/Q)* depends on the cavity geometry, resonant mode field pattern, and on assumed trajectory. It is a measure of how effective the beam–cavity energy exchange is. This effectiveness is higher when *(R/Q)* is larger.

$$(R/Q) = \frac{V_{acc}^2}{\omega W} \tag{2.7}$$

### *Ratio of Peak Electric and Magnetic Field to Accelerating Gradient*

The maximum accelerating electric field established in the RF cavity is limited by the surface peak electric field ($E$peak) and the surface peak magnetic field ($B$peak). When designing and optimizing the superconducting cavity, it is necessary to minimize $E$peak/$E$acc and $B$peak/$E$acc to increase the highest electric field acceleration gradient that the superconducting cavity can achieve.

$$\eta_E = \frac{E_{peak}}{E_{acc}}. \tag{2.8}$$

$$\eta_B = \frac{B_{peak}}{E_{acc}}. \tag{2.9}$$

## OPTIMIZED DESIGN OF SUPERCONDUCTING CAVITY CAVITY

The goal of superconducting cavity shape optimization is to obtain smaller losses and higher acceleration gradients, and to avoid the occurrence of cavity shapes that limit the acceleration performance of the superconducting cavity [5].

$$P_c = \frac{1}{2}\int_S R_s H^2 ds = \frac{V_c^2}{(R/Q)\cdot G} \cdot R_s. \tag{2.10}$$

Among them, $P$c is the power loss of the superconducting cavity; $R$s is the surface resistance; $V$c is the accelerating cavity pressure of the superconducting cavity. Therefore, when the surface resistance and the required acceleration chamber pressure are constant, the higher the values of $G$ and *(Q/R)* are, the smaller the power loss of the corresponding superconducting chamber will be, which can save the liquid helium used for superconducting chamber refrigeration and reduce the operation cost.

### *The Shape of the Superconducting Cavity*

In an electron storage ring with an energy of 3 GeV, the electron speed is close to the speed of light, so the $\beta$ value of the cavity is approximately 1. According to the target's high-frequency parameter requirements, the optimization direction of the ellipsoidal cavity can be divided into three categories. As shown in Fig. 2, (a) TESLA cavity type that minimizes the peak electric field ratio to reduce the possibility of field emission; (b) RE cavity type that minimizes the peak magnetic field ratio to achieve a higher accelerating gradient ; (c) LL cavity with low power loss [6].

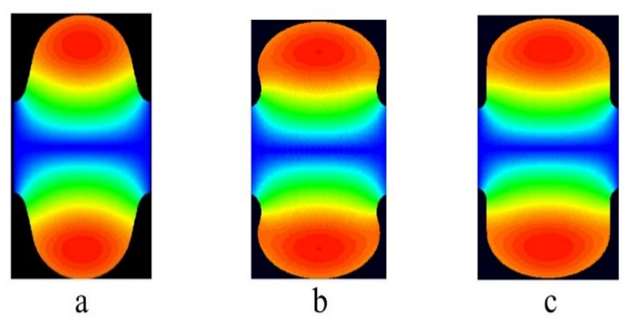


Figure 2: Three types of superconducting elliptical cavity [6].

Based on the actual requirements of the third-harmonic superconducting cavity, we have determined a 2 cell cavity type scheme, and the working mode is TM010-π mode. Since the accelerating cavity pressure required by the third harmonic superconducting cavity is 1 MV, it only needs to reach an accelerating gradient of 5 MV/m. When optimizing the cavity, we chose a solution similar to the LL cavity. Schematic diagram of the parameters of the ellipsoidal half cavity (see Fig. 3).

### *Preliminary Design of the Superconducting Cavity*

The frequency of the third harmonic superconducting cavity is 3 times that of the main high frequency, $f$=1500 MHz. According to *Eq*. (2.2), the half-bowl length $L$ of the ellipsoidal cavity is 50 mm. For beam dynamics considerations, Riris chooses between 35 mm and 40 mm (see Fig. 4).

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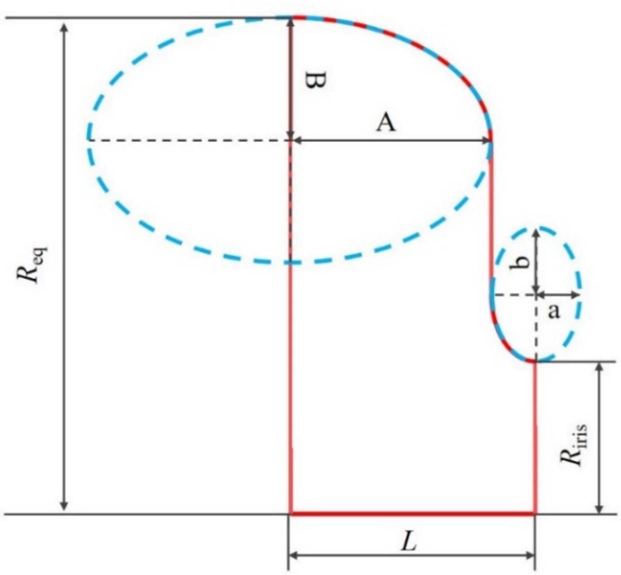


Figure 3: Schematic diagram of half cell.

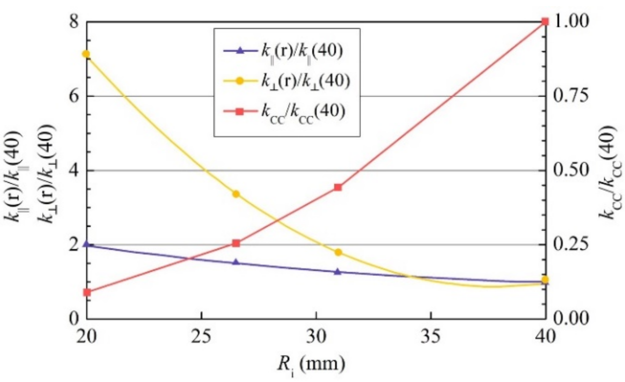


Figure 4: longitudinal $k_{\parallel}$,transvers $k_{\perp}$ loss factors and cell-to-cell coupling $k_{cc}$. [5].

## *SC Parameter Sweeping*

Use CST microwave studio [7] to scan and optimize parameters to obtain the influence of geometric variables on high-frequency parameters.

Figure 5 shows the scanning results of *R*eq parameters. The value of *R*eq has little influence on the $\eta_E$ and $\eta_B$, but great influence on the resonant frequency of the cavity. In the final parameter selection, the value of other two parameters is taken as the optimization goal. The resonant frequency of the third harmonic cavity is adjusted to the target frequency by changing the radius *R*eq at the equator.

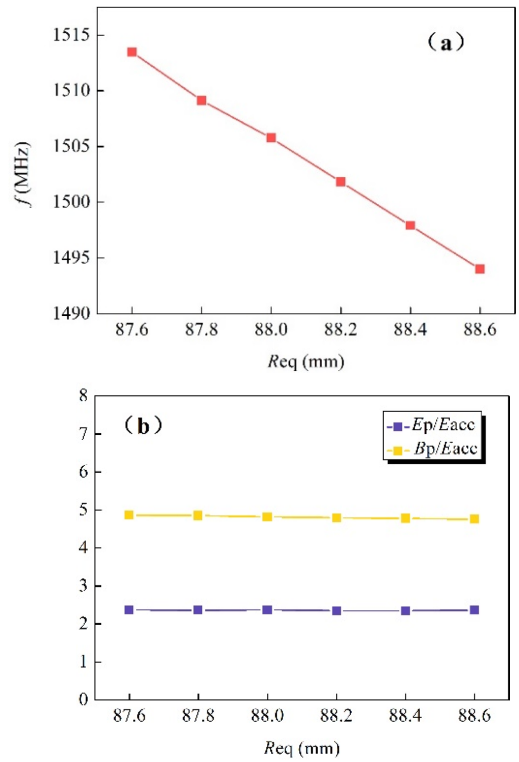


Figure 5: (a) Influence on frequency corresponding to *R*eq; (b) Ratio of the peak electromagnetic field corresponding to *R*eq.

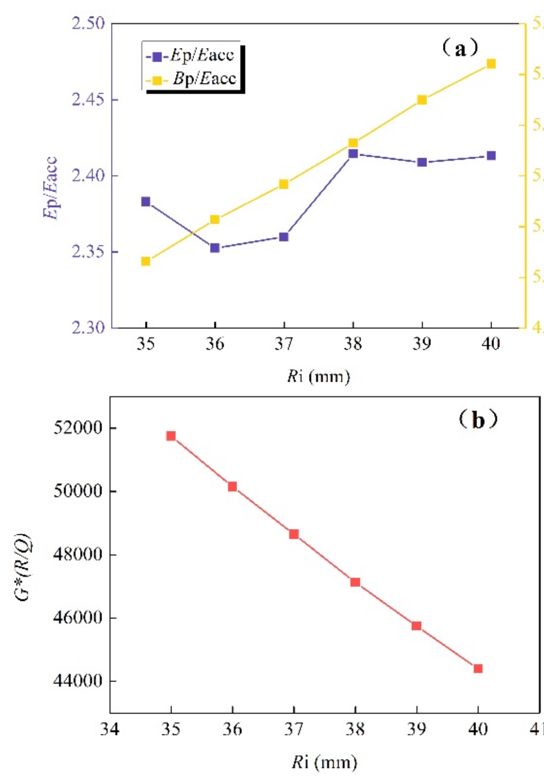


Figure 6: Dependence of G**(R/Q)*, $\eta_E$, and $\eta_B$ of the accelerating mode on the iris radius.

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Steps in the process of optimizing the geometric parameters of the superconducting cavity:

First determine the iris radius. As shown in Fig. 6, *R*i is a very powerful variable for the inner-cell optimization. When *R*i is smaller, *(R/Q)* is bigger but $\eta_E$ and $\eta_B$ get smaller. Unfortunately, *R*i also impacts HOM impedances $k_\perp$, $k_\parallel$, which become larger, and $k_{cc}$, which becomes smaller, for smaller *R*i. Figure 4 illustrate dependencies of these parameters on *R*i for a 1.5 GHz elliptic inner cell. In this work, we determined that *R*i is 38 mm. Next we determined a/b, where a is a constant (10 mm), change the value of b (see Fig. 7). As the value of b increases, $\eta_E$ increases monotonously, however, $\eta_B$ has a minimum value at b=15 mm. Considering comprehensively, we determine that the value of d is 15 mm, which leads to a/b=1/1.5. The values of a and A are determined at the same time, because the sum of a and A is *L*. According to dependence of *(R/Q)*, $\eta_E$, and $\eta_B$ of the accelerating mode on the a (see Fig. 8), a is determined to be 12 mm. At the end the value of B is determined. Figure 9 shows that the value of B has almost no effect on the electromagnetic parameters. Considering the mechanical properties, the B value is determined to be 25 mm, (A/B=38/25).

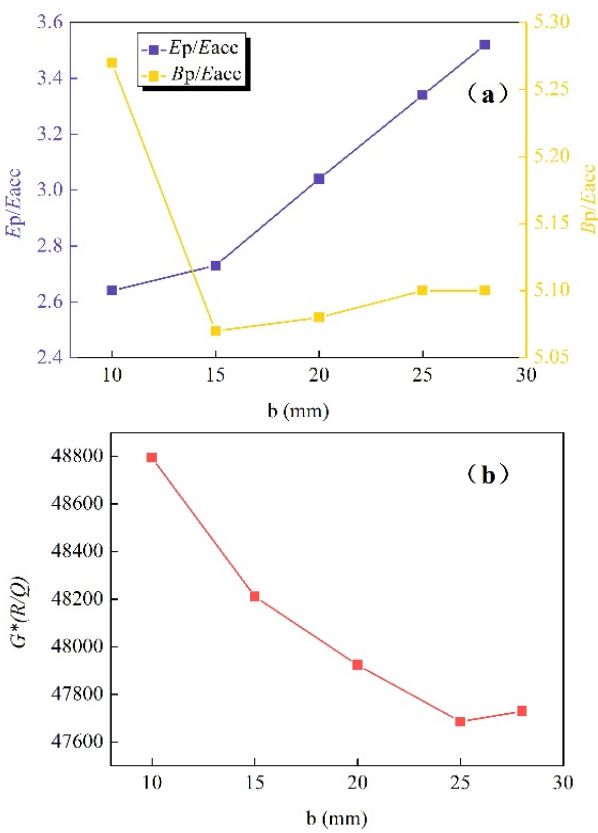


Figure 7: Dependence of G**(R/Q)*, $\eta_E$, and $\eta_B$ of the accelerating mode on the ratio of a and b.

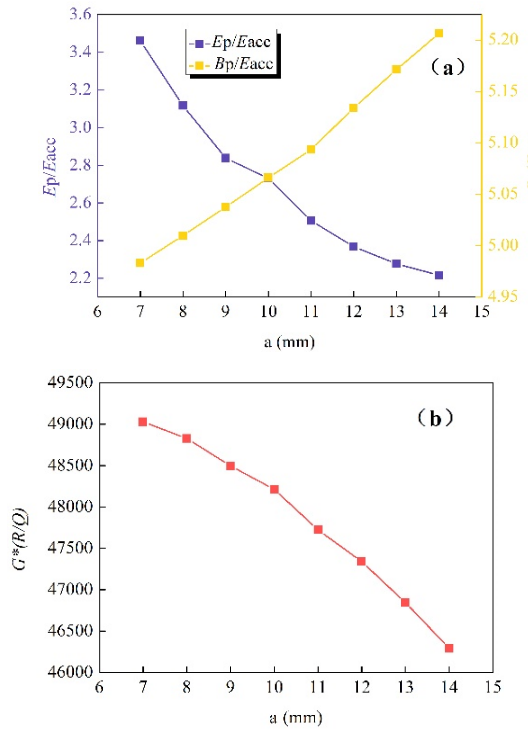


Figure 8: Dependence of G**(R/Q)*, $\eta_E$, and $\eta_B$ of the accelerating mode on the ratio of a.

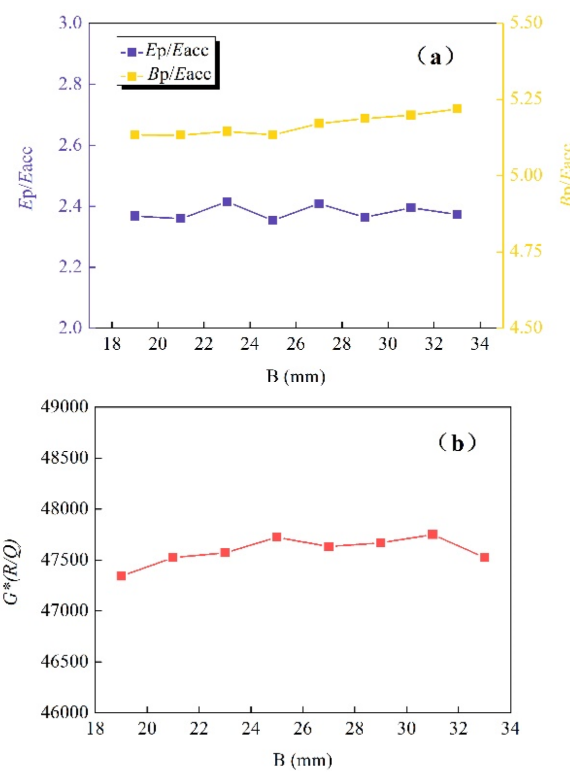


Figure 9: Dependence of G**(R/Q)*, $\eta_E$, and $\eta_B$ of the accelerating mode on the ratio of B.

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### *Superconducting Cavity Optimization Results*

Through parameter optimization, this paper finally determined the cavity parameters of the 1.5 GHz 2-cell superconducting cavity, as shown in Table 1, the length of a single cell is 100 mm, and the corresponding high-frequency electromagnetic field parameters are shown in Table 2.

Table 1: Geometric Parameters of Superconducting Cavity

| **Parameters** | **Value** |
|---|---|
| Cavity length (mm) | 440 |
| Cell length (mm) | 100 |
| *L* (mm) | 50 |
| *R*eq (mm) | 88.3 |
| *R*i (mm) | 38 |
| a/b | 12/18 |
| A/B | 38/25 |

Table 2: RF Parameters of Superconducting Cavity

| **Parameters** | **Value** |
|---|---|
| 0 mode frequency（MHz） | 1468.83 |
| PI mode frequency（MHz） | 1499.90 |
| *G*（Ω） | 178 |
| *R/Q*（Ω） | 272 |
| *G**（*R/Q*）（$\Omega^2$） | 48123 |
| *Bpeak / Eacc*（mT/(MV/m） | 5.13 |
| *Epeak / Eacc* | 2.35 |

## CONCLUSION

In this work, several parameters of 2-cell third harmonic superconducting elliptical cavity were designed and optimized, and its geometric parameters and radio frequency parameters were determined. On the basis of meeting the fundamental mode frequency of 1499.9 MHz, the third harmonic superconducting cavity has low loss, the *(G*R/Q)* value is as high as 48123 $\Omega^2$, and the surface peak electric field ratio *E*peak / *E*acc=2.35, the peak surface magnetic field ratio *B*peak / *E*acc = 5.13 mT/(MV/m). If the peak magnetic field of the high-purity niobium cavity is 200 mT and the maximum peak electric field is 100 MV/m, the theoretical acceleration gradient can reach 39 MV/m respectively.

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