Design of a higher harmonic cavity for the SSRF storage ring[*]

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Abstract   Higher harmonic cavity used in the third generation synchrotron light source increases the Touschek lifetime. The higher harmonic cavity of Shanghai Synchrotron Radiation Facility (SSRF) is a 1.5 GHz passive superconducting cavity. Its higher order modes (HOM) are extracted by a ferrite HOM damper out of the cryostat. Multi-cell cavity is chosen concerning the voltage. The harmonic cavity dynamics, beam dynamics with passive harmonic cavity and the design of single cell cavity are included in this paper.

Key words   SSRF, higher harmonic cavity, superconducting RF, HOM damper

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1   Introduction

The SSRF ring is a 3.5 GeV synchrotron light source under construction in Shanghai, China. The designed emittance of the SSRF storage ring is very low while the current remains high (300 mA). A large quantity of electrons are limited in a narrow phase space, as a result the Touschek lifetime in the 3rd generation light source is the dominant[1]. The higher the electron density, the lower the Touschek lifetime is. The top-up injection gives no essential help to increase the lifetime of the storage ring. We decided to add the third harmonic cavities for bunch lengthening which has earlier proven to increase the Touschek lifetime without deteriorating the brightness. The higher harmonic cavities working at a voltage of about 1/3 of the voltage of the main cavities give a nearly zero slope for the total voltage at operation phase. This lengthens the electron bunches by a factor of about 2, reduces the charge density and thereby increases the Touschek lifetime. Furthermore, another effect of the harmonic cavities is to give rise to a spread in synchrotron frequency of the bunches leading to strong Landau damping[2].

The higher harmonic cavity's resonate frequency is integer times of the accelerating frequency, or within several revolution frequencies around the main RF frequency. Harmonic cavity adjusts the energy gain of different particles in a bunch or different bunches in a bunch train, to control the dynamics of the particles.

2   Double RF systems dynamics

In a storage ring which consists of both a fundamental RF cavity with main RF voltage V_c and a harmonic cavity with harmonic voltage V_{nc}, the electron bunch experiences RF voltage $V(t)$ which can be expressed as:

$$V(t) = V_c \sin(\omega_{\mathrm{RF}}t + \phi_s) + V_{nc}\sin(n\omega_{\mathrm{RF}}t + n\phi_r), \quad (1)$$

$$U_0 = eV_c \sin\phi_s + eV_{nc}\sin n\phi_n, \quad (2)$$

where n is the integer ratio of higher harmonic cavity to fundamental RF frequency and $\phi = \omega_{\mathrm{RF}}t$.

In order to maximize the bunch length, $V(\tau)$ should be omitted at the center of the bunch; To avoid a second region of phase stability close by, the second derivation of $V(\tau)$ needs to be omitted too[3]. So the harmonic voltage and phase angle can be calculated:

$$\frac{V_{nc}}{V_c} = \frac{1}{n^2}\sqrt{n^2 \cos^2\phi_s + \sin^2\phi_s}, \quad (3)$$

$$\phi_n = \frac{1}{n}\tan^{-1}\left(\frac{1}{n}\tan\phi_s\right). \quad (4)$$

When the potential well is flattened near the bunch center and the RF acceptance is slightly increased, the synchrotron oscillation frequency is[3]

$$\omega_{ns} = \omega_s \frac{\pi}{2K(1/\sqrt{2})} \left[\frac{n^2-1}{6} \right]^{1/2} \phi_{max} , \qquad (5)$$

where ω_s is the synchrotron frequency without harmonic cavity, and $K(1/\sqrt{2})=1.85407$ is the complete elliptic integral of modulus $1/\sqrt{2}$.

3 Passive harmonic cavity

The harmonic voltage generated by a cavity with shunt impedance R_{sh}, tuning angle Ψ_h and bunch factor F_n, can be expressed as:

$$V_h = 2I_b F_n R_{sh} \cos\Psi_h e^{j\Psi_h} , \qquad (6)$$

$$\tan\Psi_h = -2Q\frac{n\omega_{RF} - \omega_{res}}{\omega_{res}} , \qquad (7)$$

$$\Psi_h = \frac{\pi}{2} + n\phi_h . \qquad (8)$$

For the SSRF case, tuning the fundamental mode of harmonic cavity to be higher than the harmonic of nf_{RF} makes sure that the cavity lengthens the bunch length. Otherwise the bunch will be shortened. Generally, negative slope of cavity voltage indicates the electrons' bunching, while positive slope indicates debunching. In Fig. 1, we add a harmonic voltage to the main RF voltage $V_1(t)$, only when the cavity frequency is larger than nf_{RF} (the solid red curve in

Fig. 1. The harmonic cavity's voltage and tuning.
(a) — $V(\phi)$, ------ $V_1(\phi)$, ······ $V_2(\phi)$;
(b) — $V_1(t)$, ------ $V_{equat}(t)$, ······ $V_{small}(t)$.

Fig. 1), the slope at the bunch center is negative, which adds a trend of bunch lengthening. Otherwise, the bunch is shortened.

In passive mode, the harmonic cavity voltage is adjusted by tuning. When $\delta f \gg fr/Q_0$, the induced voltage can be calculated by[4]:

$$V \approx I_b \cdot \frac{R}{Q} \cdot \frac{f_{res}}{\delta f} . \qquad (9)$$

We use the SSRF parameters shown in Table 1. According to Eq. (9), $V_{nc} = 1.3$ MV if $V_{RF} = 4$ MV. If V_{RF} reaches 6 MV in the most favorable condition with 3 ACCEL super-conducting cavities as the main RF cavities, the optimized V_{nc} should be 1.94 MV. The nominal harmonic voltage is set to be 1.5 MV.

Table 1. Nominal SSRF storage ring parameters.

energy	3.5 GeV
circumference	432 m
multi-bunch beam current	200—300 mA
single-bunch beam current	5 mA
RF frequency	500 MHz
harmonic number	720
momentum compaction	0.00042
energy spread	0.001
radiation loss	1.450 MeV
main RF voltage	> 4.0 MV
nominal bunch length	4 mm

Concerning the tuning range, we use the typical value $R/Q = 50$ Ω/cell, $f_{res} = 1.5$ GHz. For multi-bunch operation, if we use a single cell cavity, δf needs 12.5 kHz; if there are 3 cells, tuning should be 37.5 kHz to gain a total voltage of 1.5 MV. In single-bunch operation, these cavities generate 0.03 MV, which is enough to lengthen the single bunch.

There are two super-conducting harmonic RF systems being operated at Swiss Light Source (SLS) and Elettra. As our reference, SLS's working point is 35 kHz with 200 mA, getting a voltage of 0.8 MV[5]; Elettra's working point is 64 kHz with 320 mA, a voltage of 0.56 MV is reached[6].

4 Cavity design

In order not to introduce new instabilities to the storage ring, High Order Modes (HOM) is one of the core concerns of the harmonic cavity for the SSRF storage ring.

There are several methods to damp HOM in the superconducting RF cavities, including the coaxial type, the beam pipe absorber type[7], and the choke mode absorber[8], etc. The HOM absorber uses ferrite or silicon carbon on the beam pipes connected with cavities, to damp the HOM power. In order to damp all the HOMs, all the modes besides the fundamental mode, should be able to propagate along the beam
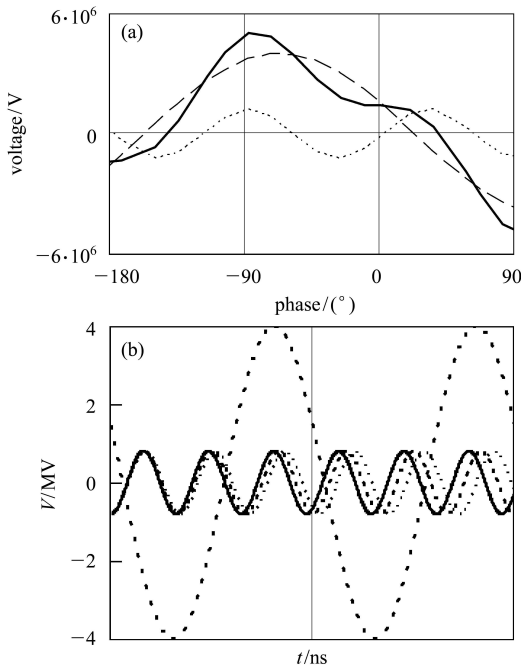
pipe to reach the HOM absorber location. This type of cavity is called "single mode cavity". But there are still two lowest frequency dipole modes. Wide beam pipe has lower cutoff frequencies of propagating waves. However, attaching wide beam pipe to the cell lowers these dipole modes too. There are two solutions: to enlarge the beam pipe like KEK-B cavity and to flute beam pipe like CESR cavity.

Every mode has its own cutoff frequency in a round beam pipe. The lowest monopole mode is TM_{01} and the lowest dipole mode is TE_{11}. We consider their frequencies as the cutoff frequencies of monopole modes and dipole modes. We choose the enlarged beam pipe method. Extensive calculations show that when the beam pipe is enlarged to lower the cutoff frequencies, the first monopole cutoff frequency decreases faster than the dipole one. In the design scheme, the beam pipe is not enlarged. The condition under which the first monopole mode's frequency equals the monopole cutoff frequency is considered as the critical condition. After the beam pipe is enlarged, all the modes can propagate out of the cavity.

4.1 Single cell optimization criteria

A passive higher harmonic cavity in the storage ring is narrow-band impedance. The cavity voltage is determined by the beam current component I_b and harmonic cavity impedance Z_L at the same frequency.

Some quantities are used in the following section. V_c is the cavity voltage, R_{sh} is the shunt impedance of the cavity, Q_0 is the quality factor of fundamental mode, G is the geometry factor of the cavity, and R_s is the surface resistance of superconductor, which can be improved by surface treatment.

1) Maximize $G \cdot R/Q$

Since the superconducting technology is adopted, heat loss capacity of the cryostat, which is determined mainly by cavity dissipation loss, dominates the cavity's running and maintenance expense. Although the cavity is in "superconducting" state, the RF surface resistance doesn't vanish. It is crucial to minimize the energy loss of the cavity. The applicable equation is as below:

$$P_c = \frac{V_c^2}{R_{sh}} = \frac{V_c^2}{Q_0 \cdot (R/Q)} = \frac{V_c^2 \cdot R_s}{G \cdot (R/Q)}, \qquad (10)$$

2) Higher order modes elimination

The first monopole mode's frequency is kept higher than the monopole cutoff frequency of the round beam pipe. The reason is explained earlier in this chapter.

4.2 Shape determination

Since this is a CW cavity, elliptical shape is chosen. The single cell's basic variables are defined in

Fig. 2. Simulations using SUPERFISH, CLANS / CLANS2, and MAFIA are performed to determine the proper shape of the single cell.
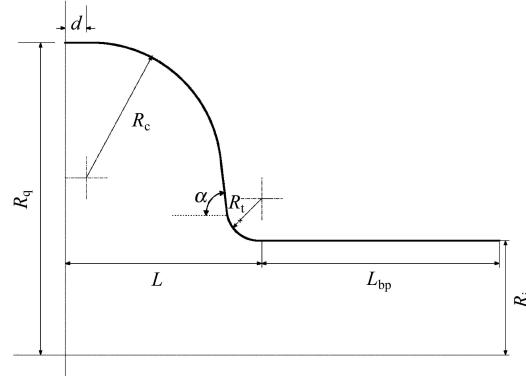

Fig. 2.   The single cell variables.

4.2.1 Slope angle

The inner cavity's space is largely determined by the slope angle α, see Fig. 2. The bigger the α is, the higher the impedance. Concerning drainage in surface treatment, we choose $\alpha = 90°$, which is also called "low loss"[9] angle.

4.2.2 Iris radius R_i and iris transition radius R_t

R_i is one of the most important parameters. It changes the RF characteristics dramatically.

Calculations based on a 1.5 GHz pillbox model are done with respect to the enlarging R_i, shown in Fig. 3(a). It is obvious that R/Q and $G \cdot R/Q$ both decrease with R_i's increase. A sharp crash down of geometry factor G occurs in the very beginning, probably because of the increase in surface area caused by the opening of the beam pipe. Fig. 3(b) shows that the frequency difference between the first monopole HOM (Fhom1) and cutoff frequency of round beam pipe (Fmono) increases quickly in the beginning, but declines to very small slope at the turning point towards positive. According the principles of optimization, we need to compromise between these two conditions.

As referred above, the multi-cell design is adopted, so the cell length should be half of the wavelength, i.e. 100 mm for 1.5 GHz. The slope angle is chosen as 90°; both of the iris transition (R_t) and top arc (R_c) are treated as circular arc; Equator radius (R_q) is tuned to the proper frequency which is 1498 MHz$< f <$1500 MHz in the SSRF case.

Then $G \cdot R/Q$ and frequency differences are considered respectively with changing the iris radius (R_i) and iris transition radius (R_t), which shows the specific local feature in Fig. 3. The maximum surface magnetic field is also calculated. In Fig. 4(a), the region above the abscissa, where the frequency differences are positive, is believed to be excluded from the danger of HOM after putting an enlarged beam pipe

and HOM absorber outside the cavity. So the region below the umbrella-shaped dotted curve Fig. 4(b) is the "safe" range.

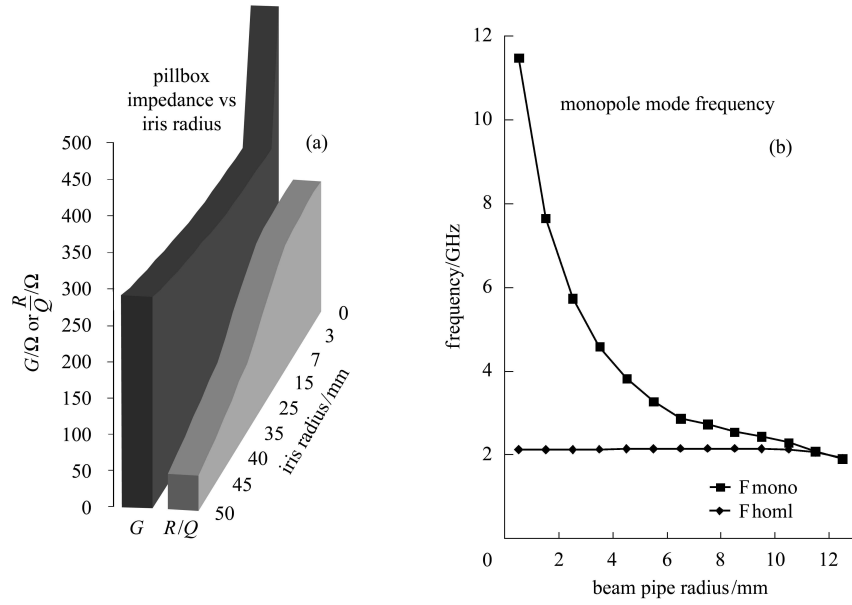Along the critical line in the lower two graphs, both $G \cdot R/Q$ and B_{sp}/E_{acc} alter within 4%. The authors choose $R_i = 41.5$ mm, $R_t = 16$ mm, because the impedance $G \cdot R/Q$ has the largest value in the "safe" range, see the star in Fig. 4(b).

Fig. 3. Investigation of pillbox model.
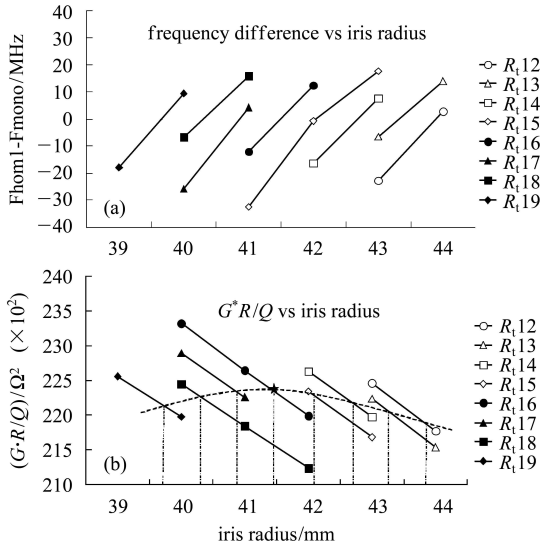(a) Impedance vs. iris radius; (b) The frequency difference of the first monopole HOM.

Fig. 4. Various considerations of the cavity shape. R_t is the transition curve radius in Fig. 2.

4.2.3 Straight section on the equator

The single cell cavity will be formed by two punched half cells. Electron beam welding (EBW) will be used to connect the two halves along the cavity equator. For convenience, a short straight section is kept on the equator in the design step. Less than 1% amplitude change is observed when d varies within 6 mm. Finally, we choose $d = 2$ mm. A longer straight section might result in mechanical instability of the cavity.

4.2.4 Final shape of the single cell cavity

With all the above considerations, we have reached an optimized shape for the single cell (Fig. 5). Table 2 lists all the related parameters.
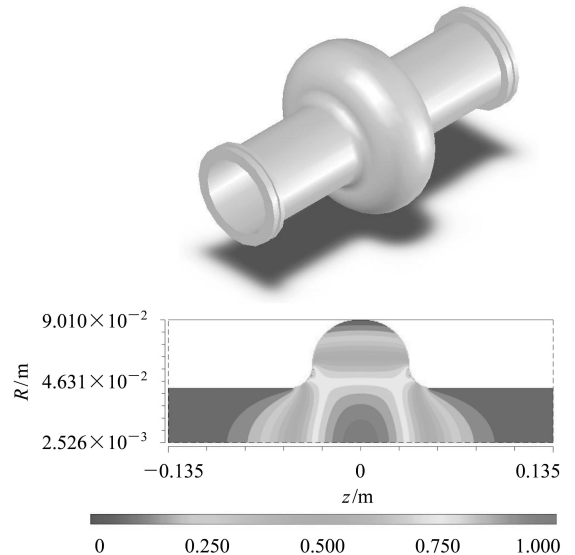

Fig. 5. The single cell cavity shape and fundamental mode field.

Table 2. Parameters of a single cell HHC cavity.

frequency	1499.693 MHz
fundamental mode	TM_{010}
cavity voltage	0.5 MV
R/Q	82.97 Ω
G	269.1 Ω
$G\cdot R/Q$	22328
E_{sp}/E_{acc}	2.04
B_{sp}/E_{acc}	4.95 mT/(MV/m)
cell length	100 mm
slope angle	90
iris radius	41.5 mm
iris circular radius	16 mm
beam pipe length	85 mm
equator radius	90.1 mm

5 Conclusion

A higher harmonic cavity is designed for the SSRF storage ring. As the first step, a single cell cavity is being manufactured, both with niobium and copper in the beginning of 2007. The single cell is a "low loss" cavity, its shape is optimized to have large shunt impedance ($R/Q = 82.97\ \Omega$) and low dissipated power in the same voltage and surface treatment conditions, and the higher order modes will be eliminated by adding enlarged beam pipes.

One single cell cavity is designed to provide 0.5 MV voltage. In order to reach the nominal voltage 1.5 MV, we need three single cell cavities or one 3-cell cavity. The single-cell approach is a more expensive way, because the cavities need 3 cryogenic systems and more power. Therefore the multi-cell cavity is chosen for the SSRF storage ring. Further study of the multi-cell cavity is being undertaken.

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