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Study of Heavily Damped SC RF Cavity

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Abstract With reference to the KEKB 509 MHz superconducting (SC) cavity, a 500MHz SC cavity for the Beijing Electron Positron Collider upgrade project (BEPC Ⅱ) has been designed. Some simulations on the cavity have been made and some of cavity performances have been checked by the BEPC Ⅱ model cavity.

Key words superconducting (SC) cavity, higher order modes (HOMs), shunt impedance

1 Introduction

During last four decades, superconducting RF cavities have been developed gradually from lab bench to application in accelerators at various labs around the world. Their large scale applications in accelerators are listed in Table 1.

Table 1. SC cavity employed at circular accelerators[1]

Machines \ Items	Frequency	Material Cell No.	Cavity No.	Beam Current Beam Energy	Circumference Particles type
LEP Ⅱ (CERN)	352MHz	Nb/Cu 4-cell	288	6mA 100GeV	26.659km $e^- - e^+$
HERA (DESY)	500MHz	Nb 4-cell	16	50mA 32GeV	6.336km e-p
CESR Ⅲ (Cornell)	500MHz	Nb 1-cell	4	500mA + 500mA 5.3GeV	0.768km $e^- - e^+$
KEKB (KEK)	509MHz	Nb 1-cell	8	1100mA 8GeV	3.016km $e^- - e^+$

The development and application of SC cavities on particle accelerator have played an important role on the frontier of high beam energy and strong beam intensity. Because of the lower surface resistance of SC cavity, the unloaded quality factor Q_0 of SC cavity is about five orders higher than that of normal conducting (NC) cavity. Due to adopting the large beam pipe jointed the accelerating cavity, HOMs excited by beam current through the cavity can propagate along the beam pipe and further be damped deeply by the attached ferrite absorber. Thus the beam current threshold of instability can be enhanced remarkably.

The luminosity of the BEPC Ⅱ will be improved about two orders by increasing beam current and applying micro-β scheme. For this purpose, the beam current will be increased from several dozens milliampere to ampere order by using the double-ring structure. The beam instabilities induced by high intensity current will be a severe problem. How to overwhelm them becomes a key

Table 2. Main parameters related to the RF system in BEPC Ⅱ[2)].

Parameters	Symbol (Unit)	Colliding mode (e^+ and e^- rings)
Energy	E/GeV	1.89(<2.1)
Beam current	I/mA	910
Circumference	C/m	237.531
Natural energy spread	σ_e	$2.73E\times10^{-4}$
Tunes	$v_x/v_y/v_s$	6.57/7.61/0.034
Bunch length	σ_z/mm	15
Momentum compacting	α_p	0.033
Energy loss per turn	U_{loss}/keV	121 + (− 22)*
RF frequency	f_{rf}/MHz	499.8
Revolution frequency	f_{rev}/MHz	1.262
RF voltage	V_c/MV	1.5
Radiation damping time	$\tau_x/\tau_y/\tau_z$/ms	25/25/12.5
Beam power	P_{beam}/kW	130

* The value in the bracket is the part of the estimated parasitic modes loss.

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2) Wang Jiuqing, Wang Guangwei et al. Design Report of BEPC Ⅱ, Beijing, 2001

issue, especially the coupled bunch instability (CBI) induced by HOMs. Moreover, bunch length σ_z in the BEPC Ⅱ storage ring will be compressed from 50mm to 15mm to meet the requirements of the micro-β scheme[2]. Table 2 lists some parameters related to the RF system.

The bunch length σ_z can be calculated with following expression:

$$\sigma_z = \frac{\sigma_e}{\sqrt{2\cdot\pi\cdot f_{rf}}}\sqrt{\frac{c\cdot C\cdot\eta\cdot E}{((e\cdot V_c)^2 - U_{loss}{}^2)^{\frac{1}{2}}}} \quad (1)$$

here e is the electron charge, c the speed of light in vacuum and η the slippage factor; for the meaning of other variables, refer to Table 2. According to Eq. (1)[3], a frequency of 500MHz and a cavity voltage of 1.5MV will be applied to compress the bunch length. Since $U_{loss} \ll e\cdot V_c$, the bunch length is almost inversely proportional to $\sqrt{f_{rf}}$ and $\sqrt{V_c}$. The main virtue of the adoption of SC cavity lies on that its surface resistance is lower than that of the normal conducting (NC) cavity by about a factor of 10^5. At a given cavity voltage, the RF loss of SC cavity is negligible, and almost all of the microwave power can be transferred to the beam[4].

2 Structure optimization

Based on the KEKB 509MHz SC cavity, some modifications have been put forward to meet the frequency requirement of 500MHz for the BEPC Ⅱ.

2.1 Strategies of optimization

A typical cavity has a shape as shown in Fig. 1, whose structure has been developed successfully at High Energy Accelerator Research Organization (KEK), JAPAN, and proved that it can damp HOMs deeply during the KEKB operation. By tuning these dimensions, a set

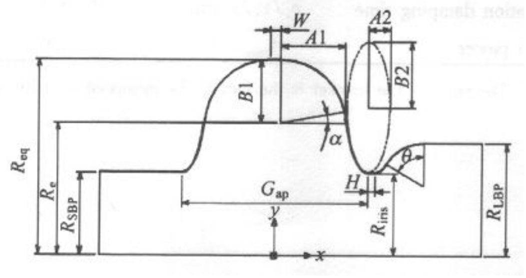

Fig.1. A typical cavity shape with a set of dimensions.

of suitable parameters can be obtained during the process, we find that each dimension has different influences on the cavity performance as follows:

G_{ap}: the cell length (effective accelerating gap), usually chooses $\frac{\lambda\cdot\beta}{4} \leqslant G_{ap} \leqslant \frac{\lambda\cdot\beta}{2}$,

here λ is the wavelength and β the relativistic velocity of accelerated particle.

α: wall slope angle, which influences the mechanical behavior of the cavity.

R_{SBP} or R_{iris}: small beam pipe (SBP) or coupling iris radius, which determines the cut-off frequency of HOMs.

R_{LBP}: large beam pipe (LBP) radius, which determines the cut-off frequency and HOMs loaded quality factor Q_L.

$A1$ & $B1$: semiaxis of the top ellipse, which is related to the peak magnetic field of H_{sp}.

$A2$ & $B2$: semiaxis of the bottom ellipse, which is related to the peak electric field of E_{sp}.

R_{eq}: equator radius, which determines the maximum force coming from liquid helium.

H: length of coupling iris, which influences the damping performance of HOMs.

W: equator length, the last free parameter.

The parameter W can be used to adjust the accelerating gap length to reach the required frequency at the extreme case, which can be eliminated like the Cornell cavity.

2.2 Choice of cavities

Two kinds of SC cavities and their accessories, which have been operated successfully on strong beam intensity accelerator, have been developed at Cornell and KEK, respectively. As the references and also considering the influence of various parameters on the cavity performances mentioned above, other four cavities with the fundamental frequency of 500 MHz have been considered during the BEPC Ⅱ SC cavity optimization. Some parameters for these cavities are listed in Table 3.

In Table 3, the Modified CESR Ⅲ cavity is similar as the CESR cavity in cell shape, while it has middle slope angle and proper equator length. It is expected that it can suppress the HOMs more deeply, but the accelerat-

Table 3. Parameters for the candidate cavities (default unit: mm).

Items \ Cavities	KEK KEKB	Cornell CESR Ⅲ	Enlarged equator	Scaled cavity	Modified CESR Ⅲ	Modified KEKB
Freq/MHz	508.887	499.765	499.8	499.8	499.8	499.8
$\alpha/(°)$	10	15	10	10	13	
W	13	0	36.2	10	8	
R_{eq}	262.83	273	262.83	268	271	270
$A1$	84.936	83	84.936	86	86	87
$B1$	84.936	83	84.936	86	86	87
$A2$	27.5	20	27.5	30	20	30
$B2$	80	20	80	90	40	90
H	4	-4	4	4	4	
R_{SBP} & R_{iris}	110	120	110	110	120	114
R_{LBP}	150	183**	150	150	160	150
$G_{sp}/2$	121.519	120.031	133.119	123.092	120.063	120.578
R/Q* /Ω	93.256	88.789	95.433	95.149	84.614	90.834
Transit time Factor* (void)	0.505	0.505	0.493	0.517	0.473	0.505
E_{sp}/E_{acc}* (void)	2.16	2.42	2.08	2.14	2.4	2.2
$\mu H_{sp}/E_{acc}$* /[mT/(MV/m)]	4.92	5.21	4.63	4.94	5.18	5.08

* Calculated by SUPERFISH. Here R/Q is effective characteristic impedance and E_{acc} the average effective accelerating electric field.

** Flute-tube structure.

ing mode performance goes down. The Modified KEKB cavity is based on the KEKB cavity. The radius of R_{SBP} is enlarged to propagate HOMs more easily.

For a high beam intensity accelerator, the important issue is to reduce the HOMs shunt impedance R_s during optimizing a cavity shape. Meanwhile, the other parameters such as cavity R/Q, transit time factor, E_{sp}/E_{acc} and $\mu H_{sp}/E_{ac}$ should also be considered carefully.

3 HOMs issues

Comparing with the other two B-factories (KEKB and CESR Ⅲ), the tunnel of BEPC Ⅱ is more compact, and the machine parameters of the BEPC Ⅱ are much different from others. By calculation, we found that the BEPC Ⅱ have more severe limitation to longitudinal HOMs shunt impedance $R_{s,long}$ than two B-factories.

3.1 Beam current threshold

The coupled bunch instability (CBI) mainly determines the beam current threshold I_{th} at a multi-bunch and high current intensity machine. It requires that the growth time of each HOM should be longer than the damping time of synchrotron radiation. Eq.(2) gives the relation of the product of the beam current threshold I_{th} and HOMs $R_{s,long}$ with the machine parameters in longitudinal[1] as

$$R_{s,long}\cdot I_{th}=\frac{2\cdot\left(\frac{E}{e}\right)\cdot v_s}{\alpha_p\cdot\tau_s\cdot n\cdot f}\cdot e^{\left(\frac{2\cdot\pi\cdot f\cdot\sigma_z}{c}\right)^2}. \quad (2)$$

For transverse direction, the HOMs $R_{s,trans}$ can also be expressed as

$$R_{s,trans}\cdot I_{th}=\frac{2\cdot\left(\frac{E}{e}\right)}{\langle\beta_{x,y}\rangle\cdot\tau_{x,y}\cdot n\cdot f_{rev}}\cdot e^{\left(\frac{2\cdot\pi\cdot f\cdot\sigma_z}{c}\right)^2} \quad (3)$$

where $\langle\beta_{x,y}\rangle$ is root mean square of the envelope function of betatron oscillation at the location of cavity along x or y direction, f the HOMs frequency and n the cavity number; for the meaning of other variables, refer to Table 2. The longitudinal limitations of HOMs $R_{s,long}$ at different beam current are shown in Fig.2.

The transverse magnetic (TM) monopole modes will basically influence the longitudinal beam current threshold, and the dipole TM and transverse electric (TE) modes will determine the transverse beam current threshold of CBI. The beam that moves along the cavity center can mainly excite the TM monopole modes of the cavity.

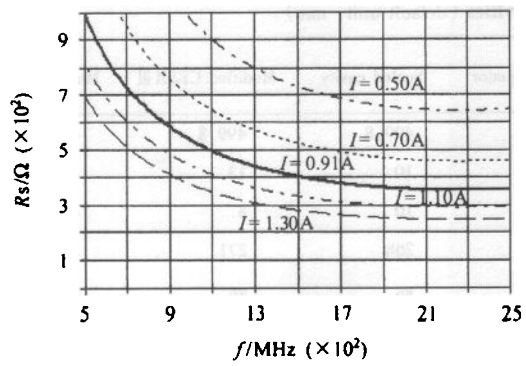

Fig.2. The shunt impedance limitation of HOMs vs. frequency at different beam current.

On the other hand, since the growth time of the instability of transverse resistive wall is several milliseconds, a correspondent transverse feedback system has been considered to damp the transverse CBI. So how to suppress the shunt impedance of the TM monopole modes is the key issue for the BEPC Ⅱ.

3.2 Shunt impedance of the TM monopole modes

The shunt impedance of the TM monopole modes for the enlarged equator cavity has been calculated by the code Clans. Some typical parameters of monopole modes are listed in Table 4.

Table 4. Some monopole modes parameters and their instability growth time

Mode Type	Freq. f/MHz	Loaded Q_l	Cavity $R/Q/\Omega^*$	Shunt Impedance R_s/Ω^*	Growth Time τ_g/ms
TM011	949	66	16	1056	6.56
TM020	1022	52	5.5	286	22.8
LTM01**	1168	39	7.0	273	21.6
TM030	1538	118	1.7	201	24.6
LTM02**	1985	115	0.91	105	42.6
STM01**	2214	81	1.2	97	45.4

* Here shunt impedance definition of linac is adopted.

** The letter L and S means LBP and SBP mode respectively.

From the results of Table 4, only TM011 mode at the frequency of 0.949 GHz is of dominant shunt impedance. Other monopole modes' R_s are lower than the limitation of longitudinal beam current. So the TM011 mode should be suppressed much more. On the other hand, since the synchrotron radiation damping time at the longitudinal direction is 12.5 ms, a longitudinal feedback system is needed to accumulate the beam to the design value. The damping time provided by the longitudinal feedback system should be shorter than the growth time of the most dangerous HOMs.

3.3 Reduction of the shunt impedance of the TM011 mode

To reduce the shunt impedance of the TM011 mode, the best way is to enlarge the radius of the coupling iris radius R_{iris} and the beam pipe radius R_{SBP} or R_{LBP}. But it will also spoil the accelerating mode performance and increase the static heat loss of cryostat. At last, a moderate R_{SBP}, R_{LBP} and R_{iris} should be chosen. Another method, which suggested by KEK experts, is to adjust the parameters of ferrite damper to reduce the shunt impedance of the TM011 mode. By moving the damper position and changing the damper size, a set of suitable damper parameters has been found. Fig.3 shows the R_s of the TM011 mode varies with the damper position.

When the damper is moved toward inside cavity, the R_s goes down continuously. But the minimum distance is limited by the power loss of the accelerating mode on the outer NC beam tube. The loss should be less than the allowable value of 1—2 W at the cavity voltage of 1.5MV. At present, a moderate distance of 878 mm has been chosen, a shorter distance has also been considered now.

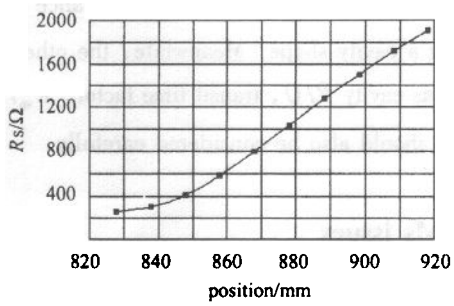

Fig.3. The shunt impedance of the TM011 mode vs. the distance from cavity center to the damper.

3.4 Measured results at the model cavity

By using the model cavity attached with the ferrite damper as shown in Fig.4, the quality factor of TM011 mode was measured at KEK. Fig.5 is the electric field pattern of the TM011 mode, it shows that the TM011 can propagate along the large beam pipe and be absorbed by the ferrite damper. According to the calculated result, Q_L decreases to 66.

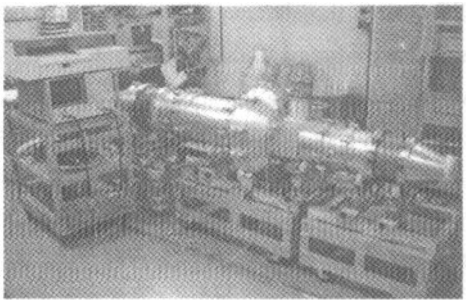

Fig.4. The measurement setup.

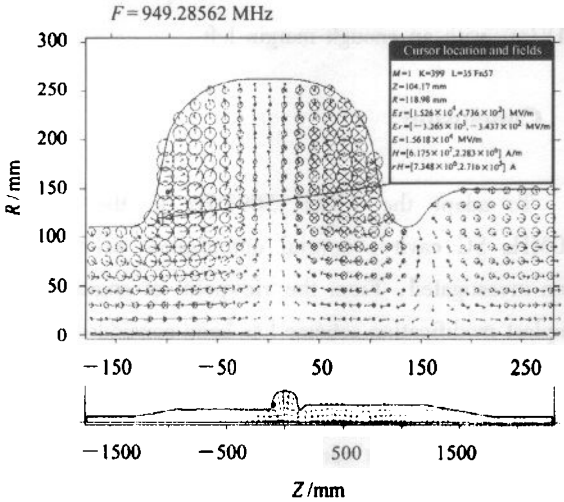

Fig.5. The electromagnetic field of the TM011.

Fig.6 shows the measured results. Comparing with the calculated results , the measured value is a little smaller than the calculated one, because Q_L is determined by the ferrite size and its properties. The ferrite film is only 4 mm in thickness, while, at the extreme case, the mesh of the computation model is 1 mm, which is too coarse to obtain an accuracy result.

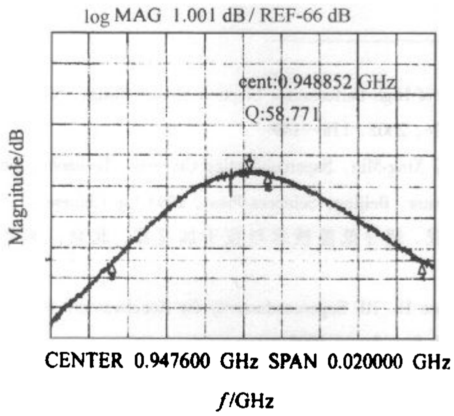

Fig.6. Measured Q_L of the TM011.

4 External quality factor

In a real machine, beam loading P_{beam}, cavity voltage V_c and effective characteristic impedance R/Q determine an optimal external quality factor Q_{opt} of the input coupler. According to the optimal external Q_{opt}, the dimension of the input coupler should be decided by simulation and measurement. For a coaxial input coupler, the inserting depth of the inner conductor should be settled according to the measured results.

For SC cavity, since the RF loss is negligible, the loaded Q_L is almost equal to the external Q_{ext} of the input coupler. One can simply get the optimal external Q_{opt} by[5]

$$Q_{opt} = Q_{ext} \approx \frac{V_c^2}{P_{beam} \cdot (R/Q)}. \tag{4}$$

For the BEPC Ⅱ SC cavity, it works at a cavity voltage of 1.5MV with the beam loading about 130kW and the cavity R/Q 95.433Ω for the enlarged equator case. From Eq.(4), one can get that the optimal Q_{opt} is about 1.8136×10^5. By moving the inner conductor of the coaxial input coupler in Fig.7, we have measured the external Q_{ext} of the input coupler at the model cavity as shown in Fig.8.

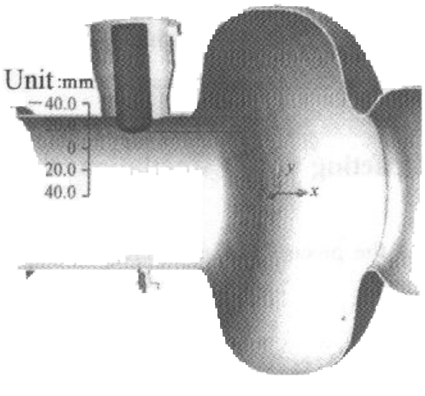

Fig.7. The inner conductor height of input coupler.

According to the fitting formula in Fig.8, the external Q_{ext} reaches the optimal point at the inner conductor height of 0.451mm. On the other hand, by calculating the S-matrix response of the input coupler port with a 3-D simulation code and deriving the external Q_{ext} of the input coupler, we also obtain the similar results.

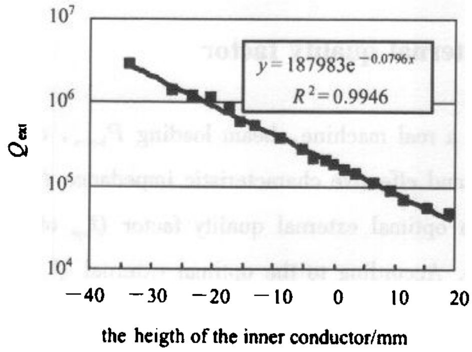

Fig.8. Measured Q_{ext} of input coupler.

5 Tuning sensitivity and the maximum displacement of the tuner

In order to compensate the varying beam loading or detune an idle cavity, the BEPC Ⅱ SC cavity should reserve a tuning range of ±200kHz by a tuner.

By changing the accelerating gap, the frequency shift of the fundamental mode has been calculated. For the enlarged equator cavity, the TM010 Mode's frequency varies from 500.029MHz to 499.693MHz when the cavity gap shrinks 1mm, the tuning sensitivity is 336kHz/mm. Since the revolution frequency of BEPC Ⅱ is in the order of MHz, if an idle cavity should be detuned, we need not care the revolution frequency. 150kHz detuning frequency is reasonable, and the tuning range can be chosen as ±200kHz. In this case, the moving distance of the tuner is 1.19mm for a 400kHz tuning range.

6 Multipacting (MP) simulation

During the process of the development and application of SC cavity, the electron MP was ever an obstacle to improve the accelerating field. By adopting the curving cavity shape and reducing the roughness of the inner surface of the cavity, it is effective to suppress the MP occurring and reduce the chance of an MP being excited[5].

We have done some simulations to identify the electron MP of SC cavity. The results show that the worst case occurs at the average effective accelerating gradient of E_{acc} = 7.7MV/m for the enlarged equator cavity. Normally, the BEPC Ⅱ SC cavity will be operated at E_{acc} = 5MV/m, with an enough margin left.

7 Conclusion

To adapt the KEKB 509MHz to the BEPC Ⅱ 500MHz SC cavity, several optimization schemes have been investigated. From the viewpoint of engineering, a simplest modification scheme has been considered seriously, based on the measured, calculated and simulated results of cavity performance. The new cavity for the enlarged equator length can satisfy the requirements of the BEPC Ⅱ. But in order to accumulate beam current to the design value, a superior longitudinal feedback system should be constructed. Now the engineering design of the BEPC Ⅱ SC cavity is under way.

All the work has been done under the careful supervision of Prof. S. Kurokawa, and the concrete tasks proceeded under the instruction of Prof. T. Furuya, Prof. Wang Guang-Wei and Pan Wei-Min. Furthermore, almost all of relevant persons of the BEPC Ⅱ and some of the KEK RF experts have taken part in the discussion of this project.

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深度抑制的超导高频腔研究

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摘要　参照 KEKB 509MHz 超导腔，同时考虑到许多方面因素的影响，为北京正负电子对撞机改造工程改频设计了一个 500MHz 超导腔，并且对腔的一些性能进行了模拟计算，同时利用铝模型腔对一些主要参数进行了测量和校核。

关键词　超导腔　高次模　分路阻抗

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