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HIGHER ORDER MODE DAMPING FOR 166 MHz AND 500 MHz SUPERCONDUCTING RF CAVITIES AT HIGH ENERGY PHOTON SOURCE

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Abstract

Superconducting rf cavities have been chosen for High Energy Photon Source, a 6 GeV diffraction-limited synchrotron light source under construction in Beijing. The main accelerating cavity adopted a quarter-wave β=1 structure operating at 166 MHz while the third harmonic cavity utilized the single-cell elliptical geometry at 500 MHz for the storage ring. The high beam current (200 mA) requires a strong damping of higher order modes (HOMs) excited in the superconducting cavities. To meet the beam stability requirements, enlarged beam pipes with a diameter of 505 mm for the 166 MHz cavity and 300 mm for the 500 MHz cavity were chosen to allow all HOMs to propagate along the beam tubes and to be damped by beam-line absorbers. This paper presents the HOM damping scheme and the cavity impedance analysis results. In addition, power losses due to HOMs were also evaluated for various operation modes (high charge and high luminosity) of the HEPS main rf cavities.

INTRODUCTION

High Energy Photon Source (HEPS) is a 6 GeV synchrotron light source to be built in Beijing [1, 2]. It will have a ~1.3 kilometer circumference and promises ultra-low emittance. Electron beam is firstly accelerated to 500 MeV by a linac prior to its injection into a ~450 m booster ring. The beam energy is then ramped up to 6 GeV followed by a top-up injection into the storage ring. The main beam parameters are listed in Table 1. The beam current is 200 mA with a 4.4 MeV energy loss per turn for HEPS phase I stage with 14 ID beam lines. This gives a total beam power of 880 kW to be provided by the radiofrequency (RF) system. However, considering the early commissioning of the machine, the requirements of HOM damping are calculated with bare lattice. A double-frequency RF system has been conceived for the storage ring with 166.6 MHz as the fundamental and 499.8 MHz as the third harmonic [3]. Five quarter-wave shape 166 MHz SRF cavities will provide the required 5.5 MV RF voltage and ~900 kW of beam power. Two single-cell elliptical SRF cavity use of the mature 500 MHz design will be the third harmonic cavity [4]. The beam parameters related to RF are given in Table 1. Two scenarios are given for the storage ring: fundamental RF without and with harmonic system. Much smaller synchrotron tune can be foreseen in the latter case.

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Table 1: The Beam Parameters of the HEPS Strorage Ring (No Harmonic Cavity, for Bare Lattice)

Parameter	Unit	no ID
Circumference	m	1360.4
Beam energy (E_0)	GeV	6
Beam current (I_b)	mA	200
Bunch length (σ_z)	mm	5.06
Energy loss per turn	MeV	2.64
Beam power	kW	528
Revolution frequency (f_{rev})	kHz	220.37
Sychrotron tune (Q_s)		8.194e-4
Momentum compaction (α_p)		1.88e-5
Damping time (τ_x)	s	10.85e-3
Damping time (τ_y)	s	20.62e-3
Damping time (τ_z)	s	18.76e-3
β function at linear section (β_{x-high})	m	7.38
β function at linear section (β_{y-high})	m	7.08

HOM DAMPING REQUIREMENTS

In a storage ring, the beam instabilities in both the longitudinal and transverse directions caused by the RF system are mainly from the cavities themselves. The HOMs excited by the intense beam bunches must be damped to avoid additional cryogenic loss and coupled-bunch instabilities (CBI). To keep the beam stable, the impedance budget and the HOM damping requirements are given. Two different rf systems are considered when given the impedance budget. One includes only the fudamental rf system with 166.6 MHz SRF cavities, the other includes the third harmonic rf system with 499.8 MHz cavity. The impedance threshold in the case without harmonic cavity to cause CBI can be calculated using the classic analytic formulas [5]:

$$Z^{th}_{\parallel,total}[\Omega] = \frac{1}{f_{\parallel,HOM}} \cdot \frac{2 \cdot E_0 \cdot Q_s}{I_b \cdot \alpha \cdot \tau_z}, \tag{1}$$

$$Z^{th}_{x,total} = \frac{2 \cdot E_0}{f_{rev} \cdot I_b \cdot \beta_x \cdot \tau_x}, \tag{2}$$

$$Z^{th}_{y,total} = \frac{2 \cdot E_0}{f_{rev} \cdot I_b \cdot \beta_y \cdot \tau_y}, \tag{3}$$

where $Z^{th}_{\parallel,total}$, $Z^{th}_{x,total}$ and $Z^{th}_{y,total}$ are total longitudinal and transverse impedance threshold, $f_{\parallel,HOM}$ is the HOM modal frequency, E_0 and I_b are beam energy and beam current, Q_s is the synchrotron tune, α is the momentum compaction factor, f_{rev} is the bunch revolution frequency, β_x and β_y are the

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maximum β functions at the RF cavity location, τ_x, τ_y and τ_z are radiation damping time in three directions. The total longitudinal and transverse impedance threshold can then be calculated using Eqs. (1) , (2) and (3) with parameters listed in Table 1. The longitudinal impedance threshold per cavity is shown in Fig. 1 as the magenta curve. If HOMs are damped where their impedance values are below the magenta curve, CBI will not emerge. At this moment, bunch elongation by harmonic cavities are not considered.

It is relatively complicated if considering the third harmonic cavities. An active RF cavity with resonant frequency near a harmonic of the fundamental RF cavity may increase Landau damping of synchrotron oscillations and increase the bunch length, thereby suppressing CBI and increasing the Touschek lifetime. Once third harmonic cavities are installed, bunches in the storage ring will be lengthened, thus change the tune (Q_s) and eventually alter the longitudinal CBI impedance threshold. To evaluate instabilities in the storage ring with harmonic cavities, the algorithm described in the literature [6] is applied. The impedance threshold with the harmonic cavities is shown in Fig. 1 as the blue line. Much lower impedance threshold can be observed for HOMs with frequency lower than 2.1 GHz, thus more stringent HOM damping requirements are needed.

HOM DAMPING FOR 166 MHz SRF CAVITIES

Cavity Impedance Spectrum of HOMs

To achieve the damping requirements for HEPS storage ring, the cavity with an enlarged beam pipe design was proposed. The stored energy will be extracted via HOM absorbers that are installed outside the cryomodule. The 166.6 MHz cavity containing HOM absorber and tapers were considered in the present study, and the model is shown in Fig. 2. The radius at the exit of the taper is 31.5 mm. The whole cavity impedance spectrum was simulated with CST Microwave Studio and Particle Studio. To obtain accurate impedance results, the impedance under 1 GHz which refered as narrow band impedance was get by CST Microwave Studio, and impedance above 1 GHz was get by CST Particle Studio. Fig. 1 shows the cavity impedance spectrum and the longitudinal impedance threshold with and without harmonic cavities. Considering the simulation speed and accuracy, the results of the impedance are composed of three parts. The impedance under 941 MHz was get from CST Eigenmode solver, the impedance between 941 MHz and 10239 MHz was get from CST wakefield solver, and the impedance between 10239 MHz and 23060 MHz was get from ABCI. All the impedance of HOMs are under the impedance threshold, except for the second monopole (M2) mode. The impedance for M2 mode is 1.28E4 Ω while the impedance threshold is 1.14E4 Ω.

HOM Power Analysis

The loss factor is calculated to be 2.5 V/pC for HOMs with a natural bunch length of 5.06 mm. The average power losses can be calculated as single pass excitation by

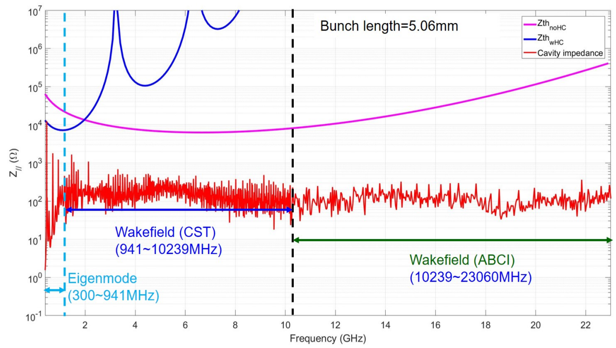

Figure 1: The cavity impedance and longitudinal impedance threshold with and without harmonic cavity for 166.6 MHz cavity.

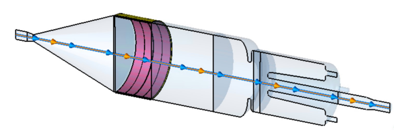

Figure 2: The 166.6 MHz cavity model containing HOM absorber and tapers.

$$P_{HOM}^{avg} = k_{HOM} \cdot q \cdot I, \tag{4}$$

where k_{HOM} is the loss factor for HOMs, q is the bunch charge and I is the beam current. The total average HOM power are summarized in Table 2 for different beam operation.

Table 2: The Parameters and Average HOM Power for Single Module. 'HC' Stands for High Charge Mode, 'HL' Stands for High Luminosity Mode

Parameter	Value (HC)	Value (HL)
Bunch rms length (σ_z) [mm]	5.06	5.06
k_{HOM} [V/pC]	2.54	2.54
Beam current [mA]	200	200
Bunch number	63	680
Bunch charge [nC]	14.41	1.33
P_{HOM}^{avg} [kW]	7.32	0.68
P_{HOM}^{real} [kW]	6.91	0.62

The accurate estimations of the HOM power loss are required to determine parameters of the HOM absorbers. The power loss is depended both on the beam parameters and the geometry design of the cavities, and it can be calculated by [7]

$$P_{HOM}^{real} = J_A^2 \sum_{k=-\infty}^{+\infty} Re[Z_{\parallel}(k\omega_0)] \mid \hat{J}_k \mid^2, \tag{5}$$

where J_A is the average beam current, $Z_{\parallel}$ is the longitudinal impedance, $\hat{J}_k$ is the normalized Fourier harmonic of the

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beam current at the kth revolution harmonic, $\omega_0 = 2\pi f_0$, and f_0 is the revolution frequency.

There are two different operation mode for the HEPS storage ring in different stage, which are referred to as 'high charge' and 'high luminosity'. The storage ring contains a total number of 756 rf buckets. For high charge operation mode, the beam containing of 63 bunches with a simple uniform filling scheme is considered. The distance between heads of the bunches is 12 rf bucket. For high luminosity operation mode, the beam contains 680 bunches which are evenly filled followed by an abort gap length of 76 rf bucket. The HOM power of the two different operation mode with the real filling patterns (P_{HOM}^{real}) are listed in Table 2. The results show that the HOM power loss slightly decreases after considering the actual filling pattern.

The modes of the cavity are orthogonal, so the total power dissipated in HOMs is the sum of the power absorbed by each mode. The HOM power given in Eq. (4) is the average HOM power obtained by assuming that the 'bunch spacing time (T_b)/decay constant (T_d)' of all higher order modes is the same. In the worst case, resonant excitation occurs when the beam frequency differs from the resonance of the excitation field by an integer multiple, and the beam power loss is expressed by [8]

$$P_{HOM}^{res} = I^2 \cdot \frac{R}{Q} \cdot Q_L, \tag{6}$$

Although, the probability of resonant buildup is small, if it does happen, the resulting mode excitation is severe. It is important that all potentially dangerous modes are carefully examined to ensure that resonant excitation is avoid. Eq. (6) is used to calculate the beam power loss for monopole modes under 1 GHz when resonance occurs, and the results are shown in Table 3. As known from the calculation results, if the M2 mode resonates, the mode contributes a HOM power of 1.02 kW. Therefore, the resonance of M2 mode should be avoided in practical operation.

Table 3: The Monopole Modes under 1 GHz

Mode	f (MHz)	R/Q (Ω)	Q_L	P_{HOM}^{res} (W)
M2	463.7246	44.5	576	1024.7
BT-M1	479.3997	6.8	34	9.2
BT-M2	556.5063	4.0	27	4.3
BT-M3	640.6204	0.8	19	0.6
M3	706.1134	24.1	148	142.8
BT-M4	818.0295	7.5	19	5.8
BT-M5	904.9142	7.9	29	9.3
M4	927.3574	8.8	271	95.0

HOM DAMPING FOR 500 MHz SRF CAVITIES

The veteran KEKB-type 500 MHz single-cell geometry is adopted as the third harmonic cavity. The cavity rf geometry is the same as the 499.8-MHz superconducting cavities used at BEPCII. In view of the HEPS's lifetime, a design optimization of the cavity with improved mechanical properties has been done [9]. To damp all the HOMs, a small ferrite absorber with diameter of 220 mm and a large absorber with diameter of 300 mm will be installed in each side of the cavity beam pipes as shown in Fig. 3. The radius at the exit of the tapers are 31.5 mm. The damped results for all the monopole modes under 2 GHz compared with the impedance threshold are shown in Fig. 4. The simulated results shown that all the HOMs are well damped.

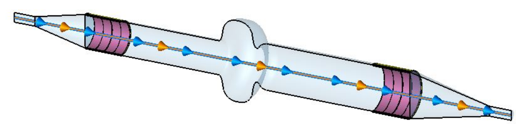

Figure 3: The 499.8MHz cavity model containing HOM absorber and tapers.

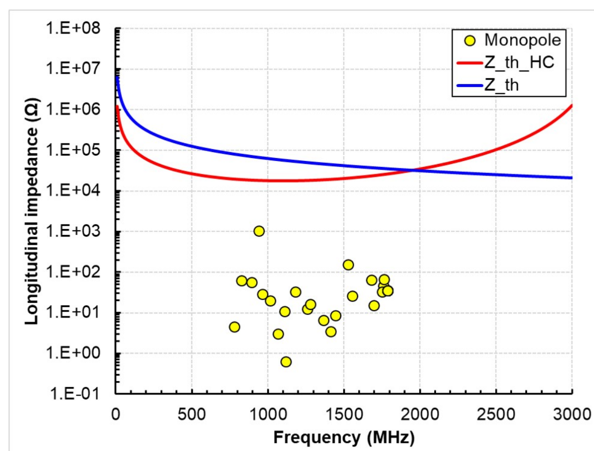

Figure 4: The cavity impedance and longitudinal impedance threshold with and without harmonic cavity.

FINAL REMARKS

To prevent the multi-bunch instability caused by the higher order modes of the superconducting cavity, an enlarged beam pipe with ferrite absorber design was adopted for 166.6 MHz cavity. All the HOMs can meet the beam stability requirements except that M2 mode is slightly higher than the threshold. The higher order modes of the third harmonic cavity with the same geometry design as BEPCII are well damped.

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REFERENCES

[1] Y. Jiao *et al.*, "The HEPS project", *J. Synchrotron Radiat.*, vol. 25, pp. 1611–1618, 2018. doi:10.1107/S1600577518012110

[2] Y. Jiao *et al.*, "Progress of Lattice Design and Physics Studies on the High Energy Photon Source", presented at the 12th Int. Particle Accelerator Conf. (IPAC'21), Campinas, Brazil, May 2021, paper MOPAB053.

[3] P. Zhang *et al.*, "Development and vertical tests of a 166.6 MHz proof-of-principle superconducting quarter-wave β=1 cavity", *Review of Scientific Instruments*, vol. 90, p. 084705, 2019. doi:10.1063/1.5119093

[4] P. Zhang *et al.*, "Status and Progress of the RF System for High Energy Photon Source", presented at the 12th Int. Particle Accelerator Conf. (IPAC'21), Campinas, Brazil, May 2021, paper MOPAB380.

[5] F. Marhauser, D. M. Dykes, P. A. McIntosh, and E. Weihreter, "HOM Damped 500 MHz Cavity Design for 3rd Generation SR Sources", in *Proc. 19th Particle Accelerator Conf. (PAC'01)*, Chicago, IL, USA, Jun. 2001, paper MPPH033, pp. 846-848.

[6] R. A. Bosch, "Instability Analysis of an Active Higher-Harmonic Cavity", in *Proc. 17th Particle Accelerator Conf. (PAC'97)*, Vancouver, Canada, May 1997, paper 6V034.

[7] K. Ivan *et al.*, "High order mode power loss evaluation in future circular electron-positron collider cavities", *Phys. Rev. Accel. Beam*, vol. 21, p. 071001, 2018. doi:10.1103/PhysRevAccelBeams.21.071001

[8] H. Padamsee *et al.*, *RF superconductivity for accelerators*, United States: Wiley-VCH, 2008.

[9] H. J. Zheng *et al.*, "Design optimization of a mechanically-improved 499.8 MHz single-cell superconducting cavity for HEPS", *IEEE Trans. Appl. Supercond.*, vol. 31, p. 3500109, 2021. doi:10.1109/TASC.2020.3045746