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DESIGN OF A 166.6 MHz HOM-DAMPED COPPER CAVITY FOR THE SOUTHERN ADVANCED PHOTON SOURCE*

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Abstract

The Southern Advanced Photon Source (SAPS) aims to achieve ultra-low emittances and is expected to adopt low-frequency cavities (< 200 MHz) to accommodates on-axis injection. This paper focuses on the design of a 166.6 MHz HOM-damped normal conducting (NC) cavity for the SAPS. We propose a novel approach to achieve efficient HOM damping by optimizing the lowest frequency HOM and implementing a beam-line absorber in a coaxial resonant NC cavity. Notably, unlike beam-line absorbers for conventional NC cavities, the presence of a large beam tube in a coaxial resonant cavity does not affect the accelerating performance. This enables effective HOM damping while maintaining a high shunt impedance in a NC cavity. The numerical simulation results show that a compact copper cavity with effective HOM damping and excellent RF properties has been achieved.

INTRODUCTION

The Southern Advanced Photon Source (SAPS), planned for construction in the southern region of China, aims to become an advanced fourth-generation light source in the world. Its main parameters are listed in Table 1[1-2]. The recent lattice design of SAPS has successfully achieved a natural emittance of 32.5 pm, with an effective DA of 5 mm (horizontal) and 4 mm (vertical). Such a small DA is not enough for traditional off-axis injection schemes, which typically requires a DA of the order of 10 mm [3]. The on-axis longitudinal accumulation scheme is attractive due to its less demanding dynamic aperture requirement and the exempt from full-charge bunch delivery. However, a lower frequency RF system is required for a large separation between RF buckets since the state-of-art kicker has a total width of a few nanoseconds. In addition, lower frequency RF systems also have the advantages of low cost for RF power amplifiers and large acceptance, and have been used in many facilities, such as ILSF [4], MAX IV [5], Solaris [6], etc. Considering the technology readiness of 500 MHz HOM damped cavities and the fast kicker, a frequency of 166.6 MHz can be chosen for the fundamental cavity and 500 MHz for the third harmonic cavity.

Both normal conducting (NC) and superconducting (SC) options have been considered for the fundamental cavities during the design phase. The main parameters of these options are listed in Table 2. Due to the large RF power requirement and relatively small voltage requirement of SAPS, the number of cavities in the two schemes is very close. However, the NC option offers cost savings of at least 40% in construction expenses and requires less space in the straight section, which is valuable for synchrotron light sources. Compared with the SC option, the NC case can save at least 40% of the construction expenses and need less space of straight section, which is very precious for the synchrotron light sources. Furthermore, the NC scheme can enhance system stability by adding an additional cavity and can continue to operate even if one set of RF systems fails, although this is expensive for the SC option. Therefore, we decided to develop a HOM damped 166.6 MHz compact NC cavity for the SAPS, although the 166.6 MHz SC cavity has successfully developed in our institute [7].

Table 1: Main Parameters of SAPS

Parameter	Value
Beam energy (E_0)	3.5 GeV
Circumference	810 m
Natural emittance ($\varepsilon_{natural}$)	32.5 pm-rad
Energy loss per turn	0.898 MeV
Synchrotron tune (Q_s)	0.709E-03
Betatron tunes ν_x/ν_y	81.23/ 64.18
Momentum compaction (α_p)	1.37E-05
Damping time (x/y/z)	18.1/28.1/19.3ms

Table 2: NC and SC Options for the 166.6 MHz RF System

Parameter	NC	SC
Frequency	166.6 MHz	
Total RF power	778 kW	
Total RF voltage	2.0 MV	
Number of cavities	5	4
Cavity voltage/MV	0.4	0.5
Cavity length/m	~ 1.0	3.0
Total cavity wall loss/kW	110	~0.4
Total RF power/kW	906	778
Total AC power/MW	1.776	1.756

RF CAVITY DESIGN

Due to the low RF frequency, the implementation of cylindrical or spherical shapes for the cavity geometry would lead to an overly large design. Therefore, a quarter-wave cavity was chosen for the 166.6 MHz NC cavity. In an ideal quarter-wave cavity, the resonant frequencies of eigenmodes induced by a coaxial structure are $f_n =$

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$(2n+1)\cdot c/(4l)$ (n = 0,1, 2, …). Thus, the frequency of the first HOM is three times that of the fundamental mode. However, in actual cavities, a large accelerating gap is required to achieve an accelerating voltage of several hundred kV or more, which cannot be neglected and results in a reduced frequency gap between the first HOM and the fundamental mode. Furthermore, as the cavity diameter increases, the frequency of HOMs becomes closer to the fundamental mode due to the large accelerating gap, thus limiting the improvement of cavity performance as the diameter increases.

The first several HOMs caused by coaxial structure are mainly monopole, whose electronic fields along the axis are shown in Fig. 1. Although they are affected by the acceleration gap, their frequency and electromagnetic field are still dominated by the coaxial structure. According to the coaxial line principle, the electric field at the open end is the smallest and the shunt impedance is near zero if the cavity length is equal to an integer multiple of the half wave of HOM. With this concept, we can optimize the shunt impedance of the first while simultaneously improving the performance of the fundamental.

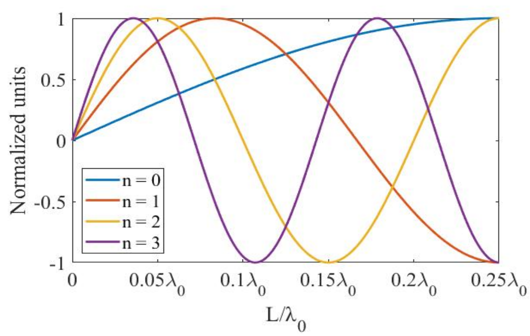

Figure 1: The electric field distribution of the first several HOMs along the axis.

The RF design and optimization process considered several key constraints. Firstly, to ensure practicality, the outer conductor diameter and length are kept below 1.0 m and 0.45 m, respectively. Secondly, the peak surface electric field (Ep) at the design voltage (Vc = 600 kV) is limited to 20 MV/m, which is 1.5 times the Kilpatrick breakdown limit at 166.6 MHz. A reasonable field enhancement factor (bravery factor) of up to 2 is applied, based on the experiences of other manufacturers and researchers, considering proper cleaning, heat treatment, and cavity baking [8]. Thirdly, to facilitate effective HOM damping through a beam-line absorber, the frequency of the first dangerous TM-like mode and TE-like mode should exceed 500 MHz and 400 MHz, respectively, ensuring a considerable frequency separation from the fundamental mode.

The optimized shunt impedance is approximately 8 MΩ (calculated as Rs = V^2/P), enabling the attainment of an accelerating voltage surpassing 600 kV, while sustaining a cavity power dissipation of 45 kW. These performance characteristics surpass those of cavities with similar structures. The first HOM, a monopole mode, exhibits a frequency of about 420 MHz, and its shunt impedance is optimized to be almost zero by matching the cavity's length to its half-wavelength. Consequently, the next HOM becomes the nearest dangerous HOM, with a substantial frequency separation from the fundamental mode. The frequency of the first dangerous TM-like mode and TE-like mode is 504 MHz and 441 MHz, respectively. The main parameters are listed in Table 3.

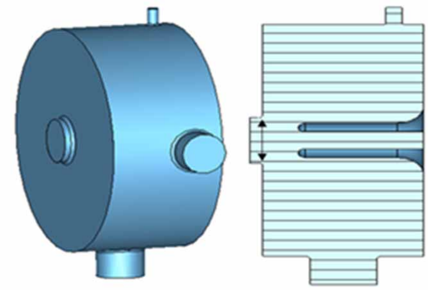
Figure 2: Cavity geometry and its cross-sectional view.

Table 3: Main Parameters of the 166.6 MHz NC Cavity

Parameter	Value
Frequency(f_0)	166.6 MHz
Cavity length (main body)	362 mm
Cavity diameter (no ports)	410 mm
Accelerating gap length	80 mm
Enlarged tube diameter	160mm
R/Q	257Ω
Shunt impedance $R_{sh}=V^2/(P_{in})$	7.76 MΩ
Quality Q	30200
Kilpatrick (k_p)	1.33
Frequency of nearest TM_like mode	504 MHz
Frequency of nearest TE_like mode	441 MHz

The cavity features multiple ports on its outer conductor, serving different purposes. One DN144 port is designated for the power input coupler, which utilizes a coaxial loop-type coupler with an alumina ceramic window. To accommodate frequency variations caused by temperature shifts, fabrication tolerances, and beam loading, two tuning plungers were designed. One plunger is manually operated, while the other is automatic. Each plunger can adjust the resonant frequency by approximately 200 kHz. The manual plunger sets the resonant frequency of cavity prior to operation, while the automatic plunger employs a stepper motor to adjust the resonant frequency during operation.

HOM INVESTIGATION AND DAMPING

Intense beam bunches in a storage ring can excite HOMs that may cause longitudinal and transverse coupled-bunch instabilities (CBI) by coupling the motion of different bunches. To maintain beam stability and prevent CBI, the HOM impedance of RF cavity must be damped below the CBI threshold level. The longitudinal and transverse CBI threshold of SAPS are 2.0 kΩ·GHz and 70 kΩ/m, respectively, which are calculated using the classic analytic formulas in the literature [9] according to the parameters in the literature [1].

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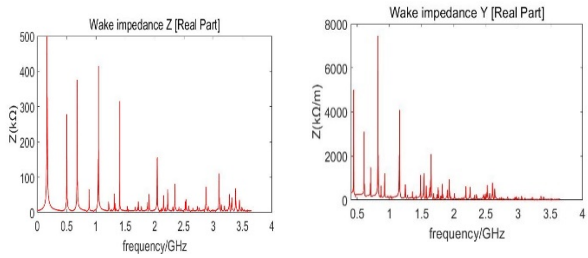


(a) (b)

Figure 3: (a)Longitudinal HOM impedance spectrum of the bare cavity. (b) Transverse HOM impedance spectrum of the bare cavity.

The impedance spectrum of HOMs in the cavity was calculated by using CST Microwave Studio and Particle Studio, as shown in Fig.3. Only HOMs with frequencies below the beam tube cutoff were considered because those above will propagate out of the cavity. The beam-pipe radius at both ends of the cavity is 31.5 mm, and its cutoff frequency is 3.65 GHz for the TM mode and 2.8 GHz for the TE mode. The impedances of most HOMs are above the CBI threshold of SAPS.

A beam absorber scheme was proposed for the NC cavity, as shown in Fig.4. Notably, this scheme is uncommon in NC cavities because increasing the beam tube aperture to extract the HOMs can substantially affect the performance of copper cavities with a hollow structure. Nevertheless, it is a viable option for coaxial structure NC cavities since their impedance is primarily determined by the internal and external radius and length of the cavity, and less by the size of the tube outside the cavity. Moreover, due to a large frequency separation between the first HOM and the fundamental mode, combined with the ability of the NC cavity to withstand power losses of several hundred watts with minimal impact on performance, allows for the absorber to be positioned near the cavity, resulting in higher absorption efficiency. Finally, a beam-line ferrite damper with a diameter of 456 mm is employed to damp the HOM, and a transition section of 150 mm is used to attenuate the accelerating mode, as shown in Fig. 5. The absorbing material used here for the HOM-damped cavity is ferrite-C48 with a thickness of 4 mm [10]. To reduce processing costs, the entire material-type structure was replaced with a solution involving small pieces spliced together. The cavity iris, with a 160 mm aperture diameter, facilitates HOM field propagation and fundamental mode rejection. Additionally, a taper with a length of 100 mm and a radius of 31.5 mm at the exit is used to reduce the low loss factor.

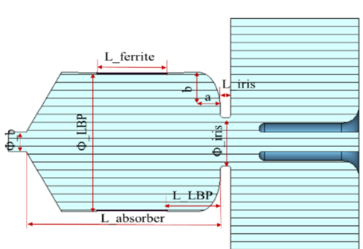
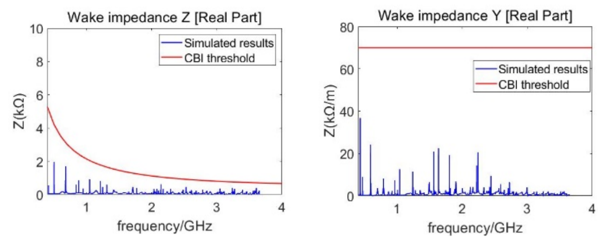


Figure 4: Cavity with beam-line HOM absorber.

With the beam-line ferrite damper, the cavity impedance spectrum is illustrated in Fig.5. The results indicate that the longitudinal and transverse HOMs have impedances of less than 2.0 kΩ and 50 kΩ/m, respectively. The impedance and quality factor Q_0 of the fundamental mode are reduced by approximately 1% due to the absorber, which is negligible. Therefore, the loss power caused by the absorber is less than 500 W when the cavity dissipates power at the design value of 45 kW.



(a) (b)

Figure 5: (a) Longitudinal HOM impedance spectrum of the 166.6 MHz cavity with absorber. (b) Transverse HOM impedance spectrum with absorber of the 166.6 MHz cavity with absorber.

THERMOMECHANICAL SIMULATION AND DESIGN

Thermal analyses of the cavity were performed using the ANSYS software, based on a maximum cavity dissipation power of 45 kW, corresponding to a 600 kV accelerating voltage along the cavity gap. In coaxial cavity structures, most of the power loss occurs on the inner conductor. To address this issue, a spiral-shaped water-cooled structure was designed for the inner conductor, with 12 cooling pipes placed inside the cavity mantle. The cooling pipes for the inner conductor and cavity mantle have diameters of 15 mm and 10 mm, respectively. The total volume flow rate was calculated to be 80 L/min, with a coolant velocity of 1.5 m/s, and a constant water temperature of 22°C was assumed. The simulation results indicated that the maximum temperature reached approximately 50°C, as shown in Figure 8, with a maximum thermal stress of 60 MPa. The multi-physical field analysis showed that this stress would result in a maximum thermal deformation of 0.11 mm and a frequency change of 90 kHz. However, with the tuners having an adjustment range of 400 kHz, the thermal deformation and frequency change values are acceptable.

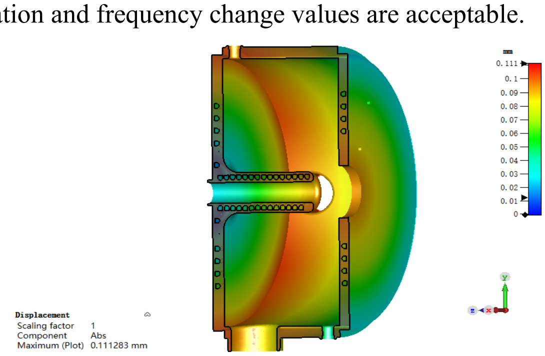


Figure 6: Cavity deformation as a result of thermal loss.

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The heat of the HOM absorbers is caused by the fundamental mode and the HOMs. The fundamental mode brings no more than 500 W of thermal power when operating at the design value. The total power of the HOMs be obtained by Eq. (7).

$$P_{HOM} = k_{HOM} \cdot q \cdot I_b \tag{7}$$

where the P_{HOM} is the HOM power, k_{HOM} is the loss factor of the HOMs, q is the bunch charge, and I_b is the beam current. The loss factor is calculated to be 1.94 V/pC for HOMs with a natural bunch length of 5.06 mm, and the HOM power is about 3.2 kW. Considering the fundamental loss power caused by the absorber and redundancy, the maximum heat load of the absorber in the design is 5 kW. The simulation results indicate that the maximum temperature of the ferrite does not exceed 54 °C under the condition that the temperature difference between the inlet and outlet water does not exceed 7 °C, as shown in Fig.7.

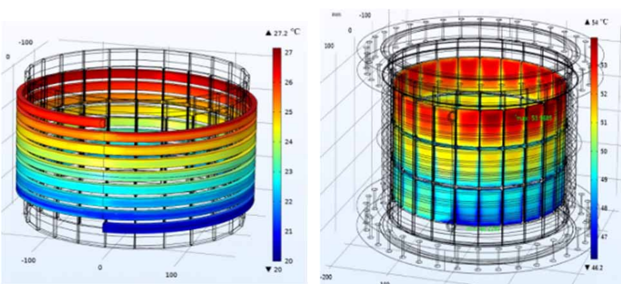

Figure 7: (a) Temperature distribution of the cooling pipe. (b) Temperature distribution of the ferrite.

CONCLUSION

This paper presents a novel approach to achieve effective HOM damping by optimizing the lowest frequency HOM and implementing a beam-line absorber in a coaxial resonant NC cavity. Unlike conventional NC cavities, by increasing the beam tube aperture in a coaxial resonant cavity to extract the HOMs does not compromise the accelerating performance, enabling efficient HOM damping while maintaining a high shunt impedance. Numerical simulations demonstrate that the 166.6 MHz HOM-damped NC cavity achieves a fundamental mode impedance of approximately 8 MΩ, which is superior to existing cavities with similar structure. The longitudinal and transverse HOM impedances are damped to below 2.0 kΩ and 50 kΩ/m, respectively, meeting the requirements for SAPS applications.

REFERENCES

[1] Y. Han *et al.*, "Preliminary study of the on-axis swap-out injection scheme for the southern advanced photon source", in *Proc. 12th Int. Particle Accelerator Conf. (IPAC'21)*, Campinas, Brazil, May 2021, pp. 1447-1449. doi:10.18429/JACoW-IPAC2021-TUPAB044

[2] X. Liu *et al.*, "Preliminary design of the full energy linac injector for the southern advanced photon source", in *Proc. 12th Int. Particle Accelerator Conf. (IPAC'21)*, Campinas, Brazil, May 2021, pp. 1454-1457. doi:10.18429/JACoW-IPAC-2021-TUPAB046

[3] G. Xu, J. Chen, Z. Duan, and J. Qiu, "On-axis Beam Accumulation Enabled by Phase Adjustment of a Double frequency RF System for Diffraction-limited Storage Rings", in *Proc. 7th Int. Particle Accelerator Conf. (IPAC'16)*, Busan, Korea, May 2016, pp. 2032–2035 . doi:10.18429/JACoW-IPAC2016-WEOAA02

[4] S. Ahmadiannamin *et al.*, "Design of 100 MHz RF cavity for the storage ring of the Iranian Light Source Facility (ILSF)", *Nucl. Instrum. Methods*, vol. 981, p. 164529, Aug. 2020. doi:10.1016/j.nima.2020.164529

[5] Å. Andersson *et al.*, "The 100 MHz RF system for the MAX IV storage rings", in *Proc. 2nd Int. Particle Accelerator Conf. (IPAC'11)*, San Sebastián, Spain, May 2011, pp. 193-195, paper MOPC051.

[6] A. I. Wawrzyniak *et al.*, "Solaris a new class of low energy and high brightness light source", *Nucl. Instrum. Methods*, vol. 411, pp. 4–11, 2017. doi:10.1016/j.ni-mb.2016.12.046

[7] P. Zhang *et al.*, "Development and vertical tests of a 166.6 MHz proof-of-principle superconducting quarter-wave beta= 1 cavity", *Rev. Sci. Instrum.*, vol. 90, p. 084705, 2019. doi:10.1063/1.5119093

[8] J. Bahng, E.-S. Kim and B.-H. Choi, "Design study of a radio-frequency quadrupole for high-intensity Beams", *Chin. Phys. C,* vol. 41. No. 7, pp.142-150, Jul.2017 . doi:10.1088/1674-1137/41/7/077002

[9] D. Einfeld, M. Plesko, and J. Schaper, "First multi-bend achromat lattice consideration", *J. Synchrotron Radiat.*, vol. 21, no.5, pp. 856–861, Sep. 2014. doi:10.1107/s160057751-401193x

[10] H. Hahn, E. M. Choi, and L. Hammons, "Ferrite-damped higher-order mode study in the Brookhaven energy-recovery linac cavity", *Phys. Rev. Accel. Beams,* vol. 12, p. 021002, Feb. 2009. doi:10.1103/PhysRevSTAB.12.021002