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HOM DAMPING WITH AN ENLARGED BEAM TUBE FOR HEPS 166.6 MHz SC CAVITIES

X. Hao*, Z. Li, F. Meng, P. Zhang, X. Zhang
Institute of High Energy Physics(IHEP),Chinese Academy of Sciences(CAS),Beijing, China

Abstract

The 166.6 MHz superconducting cavities have been proposed for the High Energy Photon Source (HEPS) storage ring, which is initiated by the Institute of High Energy Physics in Beijing. Their higher order modes (HOMs) have to be damped sufficiently in order to limit coupled-bunch instabilities and parasitic mode losses. In order to keep the beam stable, the impedance budget and the HOM damping requirement are given. As one HOM damping option, an enlarged beam tube allows HOMs to propagate and subsequently be absorbed by downstream HOM dampers installed on the inner surface of the beam tube. And the conventional coaxial HOM coupler, which will be mounted on the big beam tube, is planned to extract the HOM power below the cut-off frequency of the beam pipe.

INTRODUCTION

High Energy Photon Source (HEPS) is a 6 GeV kilometer-scale light source [1], and the main beam parameters are listed in Table 1. Prior to its official construction, a test facility namely HEPS-TF has been approved in 2016 to R&D and prototype key technologies and components [2].

Table 1: Beam Parameters of the HEPS Storage Ring

Parameter	**Value**
Circumference	1300 m
Beam energy(E_0)	6 GeV
Beam current(Ib)	200 mA
Total energy loss per turn	2.5 MV
Beam power	500 kW

A 166.6 MHz RF system has been chosen to be the fundamental RF system for the HEPS storage ring to accommodate the newly proposed novel injection scheme [2]. The current R& D has been focused on the 166.6 MHz superconducting (SC) cavity [3]. Due to the low RF frequency and high beam current, higher order modes (HOM) damping becomes one of the key challenges of the 166.6 MHz SC cavities. This paper will focus on the HOM damping requirements and present a preliminary design of a HOM coupler.

THE HOMS AND THEIR 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. To keep the beam stable, the radiation damping time should be less than the rise time of the multi-bunch instability. Thus HOMs of the cavities must be sufficiently damped to prevent coupled bunch instabilities and to limit parasitic mode losses. To damp different HOMs with different polarizations, at least two HOM couplers per cavity are needed. In this paper, only one HOM coupler has been use for the cavity to extracting monopole mode and one dipole polarization.

Figure 1 shows the RF model of the recently designed 166.6 MHz cavity namely proof-of-principle (PoP) cavity [2, 3]. This cavity serves as a starting point for the following HOM studies.

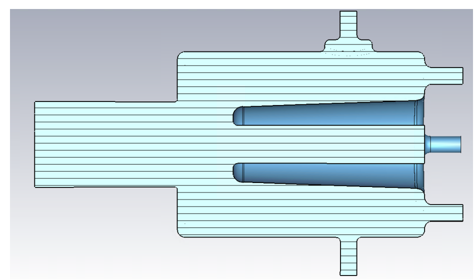

Figure 1: The 166.6 MHz PoP cavity.

The Monopole and Dipole Modes

HOMs in the cavity are calculated by using CST MWS [4]. The frequency convergence is below 10 kHz for every mode. The results are listed in Table 2 for monopole modes, Table 3 for dipole modes. The R/Q for monopole and dipole mode is calculated by [5].

Table 2: The List of Monopole Modes

Mode	**Freq [MHz]**	**R/Q [Ω]**
M1	166.860	135.8
M2	464.623	70.1
M3	700.789	46.5
M4	921.376	7
M5	1195.580	3.3
M6	1347.644	13
M7	1483.832	8
M8	1556.6	13
M9	1744.500	5
M10	1819.567	12.6
M11	2011.997	8.2

$$\frac{R}{Q}[\Omega] = \frac{|V|^2}{\omega U} \tag{1}$$

* haoxr@ihep.ac.cn

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Table 3: The List of Dippole Modes

Mode	Freq [MHz]	R/Q [Ω/cm^2]	R/Q [kΩ/m]
D1.1	431.9	0.32	0.36
D1.2	432.98	0.42	0.46
D2.1	643.063	0.57	0.42
D2.2	644.854	0.64	0.47
D3.1	874.476	0.85	0.46
D3.2	874.992	0.92	0.50
D4.1	1012.701	1.146	0.24
D4.2	1013.597	1.159	0.24
D5.1	1255.47	0.188	0.07
D5.2	125 548	0.199	0.07
D6.1	1419.12	0.045	0.015
D6.2	1419.40	0.068	0.023
D7.1	1612.28	0.26	0.77
D7.2	1619.92	0.005	0.001
D8.1	1642.65	1.04	0.003
D8.2	1647.12	0.257	0.0037
D9	1687.315	0.08	0.02
D10.1	1773.73	0.723	0.194
D10.2	1785.33	0.71	0.19
D11.1	1790.37	0.17	0.046
D11.2	1791.029	0.116	0.03
D12.1	1831.83	0.001	0.002
D12.2	1834.667	0.033	0.008
D13.1	1914.813	0.09	0.02
D13.2	1920.97	0.09	0.02

$$\frac{R}{Q}[k\Omega/m] = \frac{c}{\omega}\frac{1}{r^2}\frac{|V|^2}{\omega U} \tag{2}$$

The Threshold for HOMs

Assuming all cavities have identical impedances and every HOM frequency coincides with beam spectral line, the impedance threshold can be calculated as

$$R_L^{thresh} = \frac{2(E_0/e)\nu_s}{N_c f_L I_0 \alpha_p \tau_z} \tag{3}$$

$$R_T^{thresh} = \frac{2(E_0/e)}{N_c f_{rev} I_0 \beta_{x,y} \tau_{x,y}} \tag{4}$$

where R_L^{thresh} and R_T^{thresh} are longitudinal and transverse impedance threshold, N_c is the total number of cavities, f_L is the longitudinal HOM frequency, E_0 is the beam energy, Q_s is the synchrotron tune, Ib is the average beam current, α is the momentum compaction, $\tau_{x,y,z}$ is the damping time, f_{rev} is the beam revolution frequency, $\beta_{x,y}$ is the β function at the cavity.

The threshold impedances were then calculated and shown in Fig. 2 and Fig. 3. Finally the damping requirement of HOMs are calculated in terms of Q_L for each HOM and listed in Table 4 and Table 5.

Table 4: The List Monopole HOM Threshold

Mode	Freq [MHz]	Rth[kΩ]	Q_L^{th}
M1	166.860		
M2	464.623	87.6	2.5×10^3
M3	700.789	87.4	3.8×10^3
M4	921.376	43.4	1.2×10^3
M5	1195.580	43.4	2.6×10^3
M6	1347.644	37.5	5.8×10^3

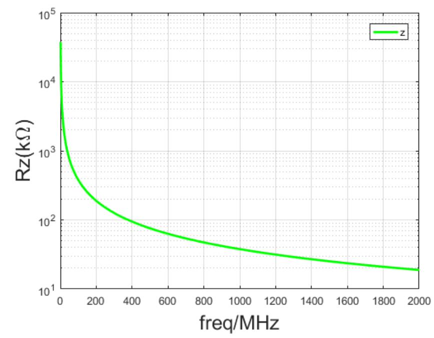

Figure 2: The longitudinal impedance threshold.

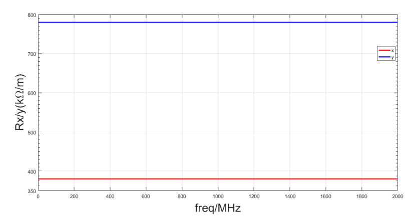

Figure 3: The transverse impedance threshold.

HOM COUPLER DESIGN SCHEME

The Enlarged Tube HOM Coupler

At first, considering an enlarged tube, as shown in Fig. 4. The tube itself is a high-pass filter. As long as the tube can extract M2 and D1, the structure can extract all other HOMs. However, the radius of the tube needs to be 260 mm. It's too big for the cavity. The results for the preliminary optimization of the pipe are shown in Fig. 5.

Table 5: The List of Dipole HOM Threshold

Mode	Freq [MHz]	Rth[kΩ]	Q_L^{th}/x, y
D1.1	431.9	381	2.1×10^3
D1.2	432.98	381	1.6×10^3
D2.1	643.063	381	1.8×10^3
D2.2	644.854	381	1.6×10^3
D3.1	874.476	381	1.6×10^3
D3.2	874.992	381	1.5×10^3
D4.1	1012.701	381	3.2×10^3
D4.2	1013.597	381	3.2×10^3

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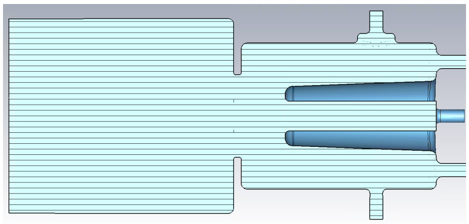

Figure 4: The enlarged tube HOM coupler.

$$TM01 : f_c = 3e^8 \times \frac{2.405}{2\pi * R} \tag{5}$$

$$TE11 : f_c = 3e^8 \times \frac{1.841}{2\pi * R} \tag{6}$$

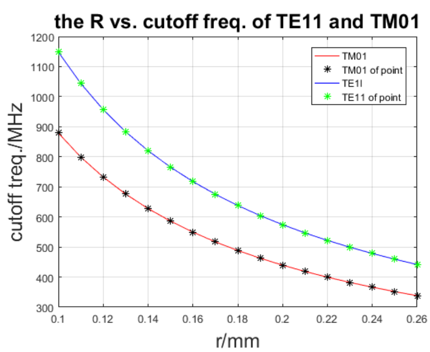

Figure 5: The cutoff frequency of TE11 and TM01 w.r.t. the tube radius.

Combined Big Tube and Coaxial

Considering the project requirement, the big tube coupler radius should be less than 150 mm. Resonant excitation should be considered especially for the low frequency modes below cut-off frequency. There modes need to travel through the coaxial HOM coupler. The coaxial HOM coupler structure is shown in Fig. 6 and the parameters of the structure is shown in Table 6.

The 3D geometry is optimized by using CST MWS codes. Sweeping the main parameters and optimizing the structure, eligible parameters of the structure have been found and is shown in Table 6. Finally the frequency and Qext of the HOMs are calculated and listed in Table 7.

Combined with the notch filter, the structure can achieve the design goal. However, the structure has the big disadvantage: the probe is long thus might disturb the beam.

Table 6: List of Parameters Shown in Fig. 6

Name	Value	Name	Value
R-tube	150 mm	**L-tube**	500 mm
xc	50 mm	**L-probe**	100 mm
R-coaxial	50 mm	**L-coaxial**	200 mm
R-iris	110 mm	**L-iris**	120 mm

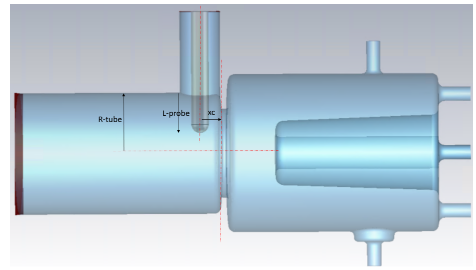

Figure 6: The big tube HOM coupler.

In Table 6, "R-tube" and "L-tube" are the radius and length of the big tube. "R-probe" is the length of the probe. "xc" is the distance from coaxial HOM coupler to cavity. "R-coaxial" is the radiu of the coaxial HOM coupler and "L-coaxial" is the length of the coaxial-HOM coupler. "R-iris" and "L-iris" are the radius and the length of the iris.

Table 7: Result of Optimization

Mode	Freq [MHz]	Qe
M1	167.23	2.1e4
M2	466.197	1890
M3	704.9	997
D1	429.3	1489
D2	632	32

Combined Enlarged Tube, Coaxial and Coaxial-In

In order to mitigate the perturbation from the coaxial probe, a shielding structure has been designed as shown in Fig. 7. The optimized geometric parameters are listed in Table 8.

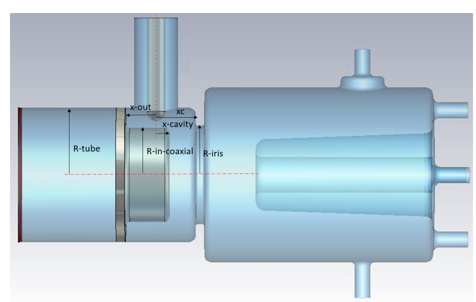

Figure 7: The coaxial-in structure.

In Table 8, R-coaxial-in is the radius of the shielding structure and x-out is the distance from the large part of the shielding structure to the center of the coaxial antenna. x-cavity is the distance from the narrow part of the shielding structure to central shaft of the coaxial-HOM coupler, d is the wall thickness of the shielding.

Finally the frequency and Qext of the HOMs are calculated and listed in Table 9, the fundamental mode has a high Qe value indicating an effective notching. On the other hand, the next monopole mode has beenextracted out of the cavity

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Table 8: The List of Parameters for Coaxial-in Structure

Name	**Value**	**Name**	**Value**
R-tube	150 mm	**L-tube**	500 mm
xc	90 mm	**L-probe**	30 mm
R-coaxial-in	105 mm	**x-out**	70 mm
R-iris	110 mm	**L-iris**	20 mm
d	20 mm	**x-cvity**	30 mm

well. However, the extraction of the first dipole mode is not ideal and require further optimization.

Table 9: The Results After Optimization

Mode	**Freq [MHz]**	**Qe**
M1	167.23	1.5e9
M2.1	452.49	413
M2.2	472.32	849
M3	709	1.5e4
D1	429.3	6e4
D2	628.46	913

CONCLUSION

In this paper, higher order modes and their associated damping requirements are listed for the 166.6 MHz superconducting RF cavities. Due to high beam current, HOMs need to be damped to Qext of $10^3 - 10^4$. A preliminary design of the HOM coupler based on an enlarged beam tube and a coaxial antenna with beam shielding structure is presented. Proper fundamental mode suppression and monopole HOM extraction are achieved. However the first dipole mode is above the impedance threshold thus require further optimizations.

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