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HOM MEASUREMENT RESULTS FOR CEPC 650 MHz 2-CELL CAVITY*

H. J. Zheng†, J. Y. Zhai, F. B. Meng
Key Laboratory of Particle Acceleration Physics and Technology, Institute of High Energy Physics, CAS, Beijing 100049, China

Abstract

CEPC will use a 650 MHz RF system with 240 2-cell cavities for the collider. The collider is a double-ring with shared cavities for Higgs operation and separate cavities for W and Z operations. The higher order modes (HOM) excited by the intense beam bunches must be damped to avoid additional cryogenic loss and multi-bunch instabilities. In this paper, the impedance budget, HOM damping and HOM power requirement for the CEPC collider ring are given. This HOM power limit and the fast-growing longitudinal coupled-bunch instabilities (CBI) driven by both the fundamental and higher order modes impedance of the RF cavities determine to a large extent the highest beam current and luminosity obtainable in the Z mode. Two prototypes of HOM coupler have been fabricated and installed on the 650 MHz 2-cell cavity. The higher order modes have been verified by bead pulling method. The Q_e for the HOMs have been also measured. A test bench with two 2-cell cavities is used to measure the real damping results and HOM propagating properties for a cavity string.

INTRODUCTION

CEPC is a proposed 100 km circular electron-positron collider operating at 90-240 GeV center-of-mass energy of Z, W and Higgs bosons. The luminosity goal for Higgs is 2 × 10^{-34} cm^{-2} s^{-1} and higher than 1 × 10^{-34} cm^{-2} s^{-1} for Z-pole. The conceptual design report (CDR) of CEPC has been published in August, 2018 [1]. CEPC parameters and lattice design for the collider are described in CDR. CEPC will use a 650 MHz RF system with 240 cavities for the Collider and a 1300 MHz RF system with 96 cavities for the Booster. There are two RF sections located at two long straight sections, respectively. Each RF section contains two Collider RF stations and one Booster RF station between the two Collider RF stations. Each of the 11 m-long Collider cryomodules contains six 650 MHz 2-cell cavities as shown in Fig. 1, and each of the 12 m-long Booster cryomodules contains eight 1.3 GHz 9-cell cavities.

Higher-order-modes excited by the intense beam bunches must be damped to avoid additional cryogenic loss and beam instabilities. This is accomplished by extracting the stored energy via coaxial HOM couplers mounted on both sides of the cavity beam pipe. The HOM absorbers are outside the cryomodule. From LEP2 and LHC experience of handling large higher-order-mode power in a multi-cavity cryomodule with coaxial HOM couplers [2, 3], the upper-limit of average HOM power produced in each 2-cell 650 MHz cavity is set to be 2 kW. Each cavity has two detachable coaxial HOM couplers mounted on the cavity beam pipe with HOM power handling capacity of 1 kW. Each cryomodule has two beamline HOM absorbers at room temperature outside the vacuum vessel with HOM power handling capacity of 5 kW each.

The design and vertical test of the 650 MHz 2-cell cavity have been finished [4]. The design, fabrication and low power test of the HOM coupler have been also completed, and wait for the low temperature test [5, 6]. This study focuses on the HOM measurement with cavity; the remainder of the paper is organized as follows: Sec. II introduces the HOM damping requirements. A 2-cell cavity with two stainless steel HOM couplers test bench, which is presented in Sec. III along with the measurement for HOM damping results and the recognition of the HOMs. In Sec. IV, a two 2-cell cavity with HOM coupler and absorber system is introduced to study the HOM propagating properties. Finally, the conclusions are summarized in the last section.

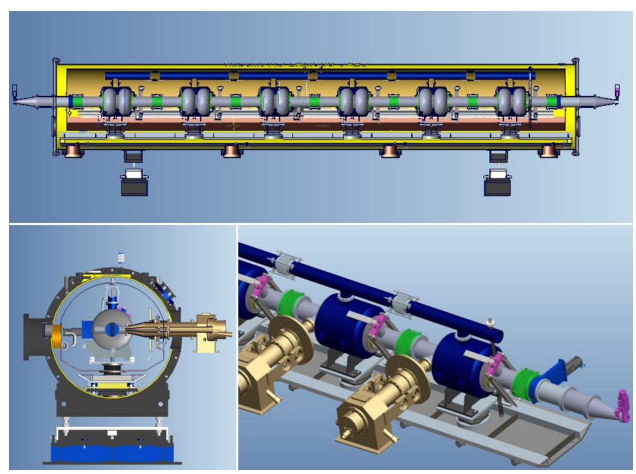

Figure 1: CEPC collider ring 650 MHz 2-cell cavity and cryomodule.

HOM DAMPING REQUIREMENT

The baseline of the collider is a double-ring with 650 MHz 2-cell cavities shared between the two collider rings as described in the introduction section. The beam parameters and RF parameters can be found in CDR [1]. 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. To keep the beam stable, the radiation damping time should be less than the rise time of the multi-bunch instability. The HOMs of the cavities must

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† zhenghj@ihep.ac.cn

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be damped sufficiently to prevent coupled bunch instabilities and to limit parasitic mode losses. To damp different polarization HOMs, at least two HOM couplers per cavity are needed. The cut-off frequency of the cavity beam tube for the monopole mode is 1471 MHz, so the couplers need to damp the HOMs at frequencies from 780 MHz to 1471 MHz.

The average power losses can be calculated as single pass excitation. As shown in Fig. 2, HOM power damping of 1.95 kW for each 650 MHz 2-cell cavity is required for the CEPC collider. Resonant excitation should be considered especially for the low frequency modes below cut-off. All the HOM power below the cut-off frequency should be coupled by the HOM coupler which mounted on the beam pipe and the propagating modes will be absorbed by two HOM absorbers at room temperature outside the cryomodule.

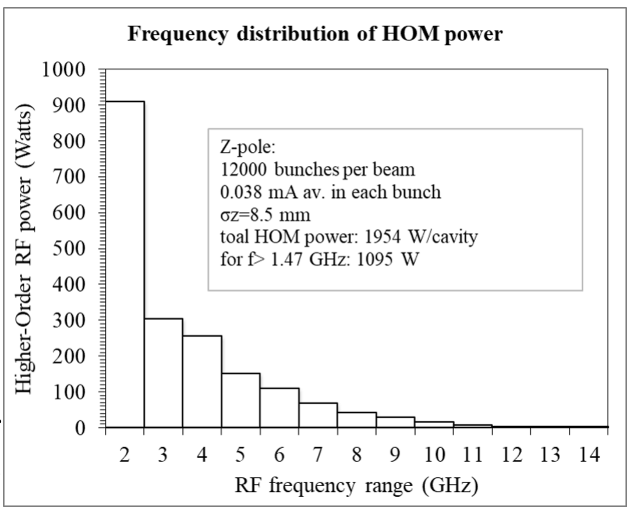

Figure 2: Frequency distribution of HOM power (Z-pole design).

A 2-cell single cavity model has been built using CST Microwave Studio [7]. The electric boundary condition has been used to get the electromagnetic parameters of HOMs. The threshold of the external quality factor for the HOMs with high R/Q is given in Table 1. The impedance thresholds are given by the longitudinal and transverse radiation damping time, without considering the HOM frequency spread and feedback. Besides, the R/Q for the modes above the cut-off frequency are not accurate, because of the electric boundary condition used. Therefore, the damping requirements shown in Table 1 are the most pessimistic case.

To keep beam stable, two loop HOM couplers are installed to damp the dangerous HOMs. The damped Q values for the 650 MHz 2-cell are simulated by CST Microwave Studio with electric boundary conditions. When give the impedance threshold, except for the radiation damping, a transverse feedback system of 5 turns and a longitudinal feedback system of one synchrotron oscillation period is considered. All modes below cut-off frequency, except TM011 mode for Z, can be damped. However, considering the full RF system, the threshold value greatly depends on the actual tolerances of the cavity construction. To find the total effects of all the RF cavities, we need to take into account the spread in the resonance frequencies of different cavities. For small frequency spread, this will result in an ‘effective’ quality factor Q of the whole RF system [8]. With a HOM frequency scattering of 1 MHz, all the transverse and longitudinal modes below cut-off frequency can be well damped for different operation scenarios. Figure 3 shows the impedance spectrum of the HOMs with different frequency scattering, and compared to the threshold of the radiation damping and possible feedback damping for Z, which is the most critical case. The dashed lines in Fig. 3 mean the cut-off frequencies for monopole mode and dipole mode.

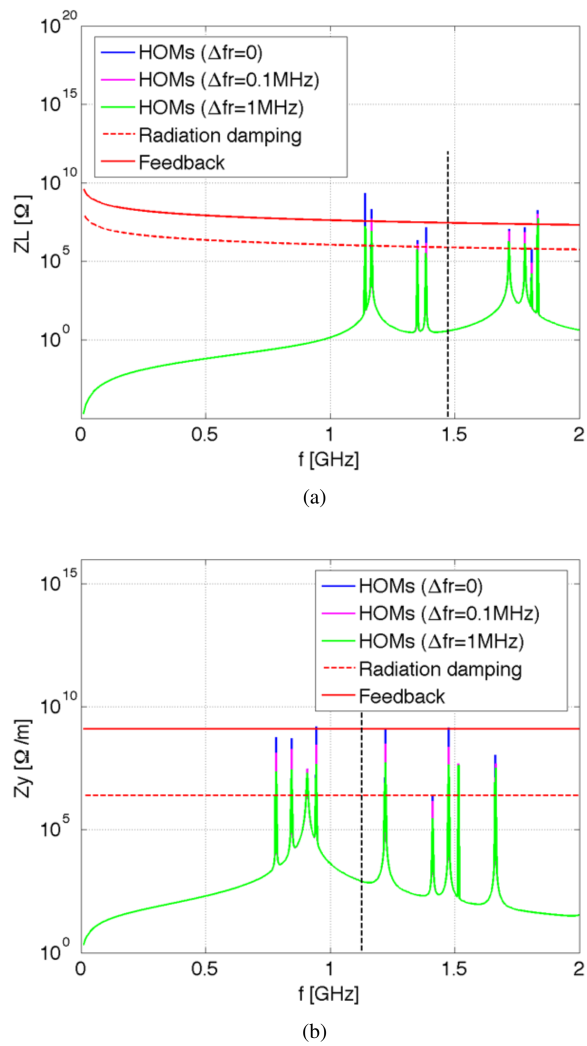

Figure 3: Impedance spectrum of HOMs compared to the threshold determined by radiation damping and feedback damping. (a) Longitudinal HOMs, (b) Transverse HOMs.

SINGLE CAVITY MEASUREMENT

A 2-cell cavity [4] with two HOM couplers [6] test bench was set up to measure the HOM characteristics using a network analyzer. The setup consists of a pulley-mounted driver

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Table 1: Damping Requirements of Prominent HOMs of the 650 MHz 2-cell Cavity

Mode	f (MHz)	R/Q^* (monopole Ω, dipole Ω/m)	Q_e (H)	Q_e (W)	Q_e (Z)
TM011	1165.574	65.2	1.9×10^5	1.8×10^4	2.6×10^2
TM020	1383.898	1.3	8.2×10^6	7.6×10^5	1.1×10^4
TM021	1717.475	19.9	4.3×10^5	4.0×10^4	5.8×10^2
TM012	1832.801	17.3	4.6×10^5	4.3×10^4	6.2×10^2
TE111	844.738	279.8	4.9×10^4	7.7×10^3	1.6×10^2
TM110	907.592	420.1	3.3×10^4	5.1×10^3	1.0×10^2
TE121	1475.553	125.8	1.1×10^5	1.7×10^4	3.5×10^2
TM120	1662.599	18.8	7.4×10^5	1.2×10^5	2.3×10^3

*Longitudinal R/Q with the accelerator definition and $k_{//mode} = 2\pi f (R/Q)/4$ [V/pC]. Transverse R/Q: $k_{\perp mode} = 2\pi f (R/Q)/4$ [V/(pC·m)].

motor to move the perturbing bead on a dielectric line ('fish line') through the cavity. The ports of the two HOM couplers were used as the excited input and output ports. The measurements of HOMs peak frequencies and Q were performed at room temperature. The test bench of the measuring device is shown in Fig. 4.

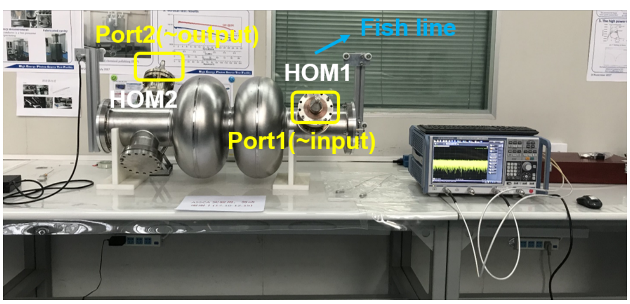


Figure 4: Test bench for HOM measurement.

Measurements of 2-cell Cavity HOMs Frequencies and Passbands

Due to the existence of two HOM couplers and machining errors for the cavity, these lead to complexity for the modes. A bead-pull method [9] was used to get the field profiles to identify different HOMs [10]. A fishing line was used to pull a Teflon bead through the RF cavity to measure the electromagnetic fields distribution on resonance inside as shown in Fig. 4. The measurement results of frequencies and pass-bands are shown in Fig. 5.

The electric field on axis for all the modes were measured by bead-pull method, and also simulated by CST. The measured field patterns were compared with the simulated results to determine the modes. The measured and simulated electric field distribution on axis for TM011-π mode and TM020-π mode are shown in Fig. 6 and Fig. 7 for example.

Measurements of 2-cell Cavity HOMs Q_e

The excitation signal was imported to the cavity by the HOM1 and the output signal was extracted by the HOM2 as indicated in Fig. 4. The measured microwave parameters were received from the network analyzer. The Q_e of the

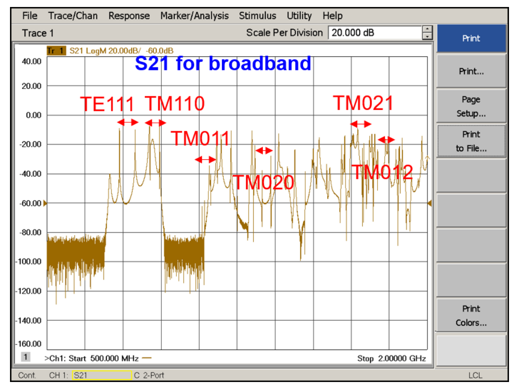
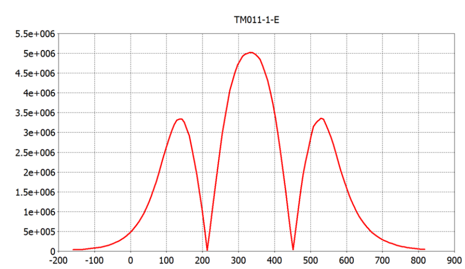
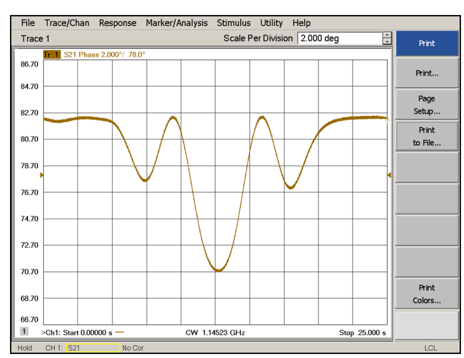


Figure 5: 2-cell cavity HOMs frequencies and passbands.



(a)



(b)

Figure 6: (a) Simulated electric field distribution on axis for TM011-π mode, (b) Measured electric field distribution on axis for TM011-π mode.

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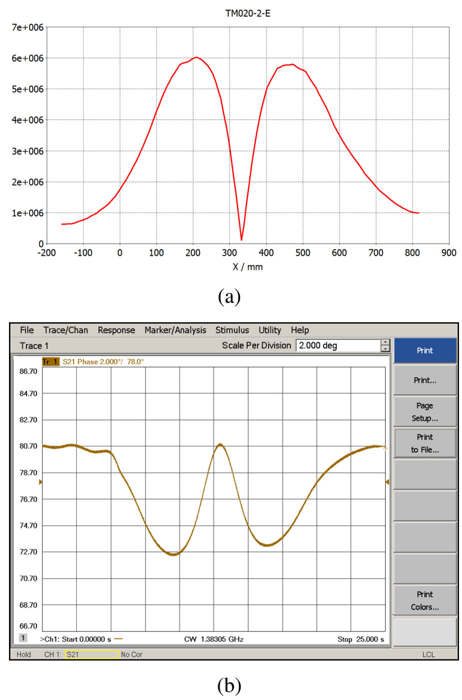

Figure 7: (a) Simulated electric field distribution on axis for TM020-π mode, (b) Measured electric field distribution on axis for TM020-π mode.

modes shown in Fig. 5 were measured. Two methods were used to measure Q_e, the impedance method and reflection method [11]. The reflection method has a limitation in that the coupling coefficient is not too small. The details of the different methods will not discussed in detail in this paper, which can be referred to [11].

The measured results of Q_e using these two methods compared with the simulated results are shown in Fig. 8. The Q_e values shown in Fig. 8 are the total Q_e for the two HOM coupler ports. The measured results by two different methods are in good agreement. The measured results for several modes are different from the simulated values, that mainly caused by the difference of the field distribution resulted from the machining. The measured Q_e results of the two ports for the fundamental mode are 1.4×10^{11} and 1.3×10^{10}, respectively. The Q_e for port1 is almost an order of magnitude larger than the Q_0 (1.5×10^{10}) of the cavity, while the Q_e for port2 is similar to the Q_0. That means the power of the fundamental mode transmit from the HOM coupler port is only about 30 W, which is acceptable. The main reason for the smaller Q_e value for port2 is that the unflatness of the field distribution for the fundamental mode. The damping for the fundamental mode will be better after the field flatness tune.

HOM PROPAGATING MEASUREMENT

To study the HOM propagation properties through multi-cavities, a two 2-cell cavities with HOM absorber and HOM couplers test bench was set up as shown in Fig. 9. The transmission properties from input port to HOM1 port was measured while HOM2 with matched load. The transmission properties from input port to HOM2 port was also measured while HOM1 with matched load. The extraction power efficiency from HOM1 and HOM2 is shown in Fig. 10. Obviously, the HOM power below the cut-off frequency can hardly be transferred through the second cavity to be absorbed by the HOM coupler 2. It should be noted that the loop antenna penetration depth into the beam tube for HOM2 is 10 mm shorter than HOM1, caused by the different cavity HOM tube length.

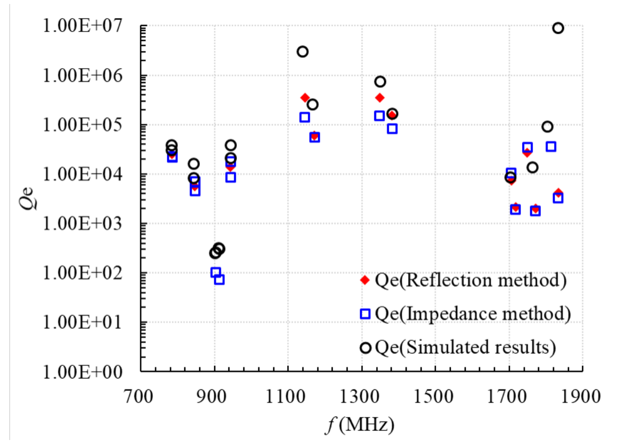

Figure 8: The measured results of Q_e compared with the simulated results.

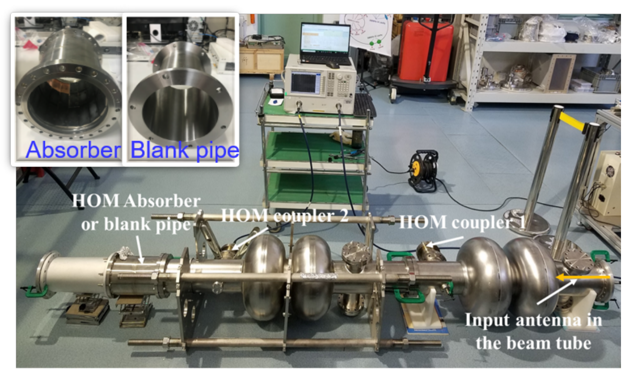

Figure 9: The two 2-cell cavities test bench.

To get the absorbing efficiency of the absorber, the absorber is attached to the end of the two cavity system. The cavity wall loss was subtracted by replacing the absorber with a blank flange. The measured HOM absorber absorbing efficiency is shown in Fig. 11. Apparently, the absorber mainly effects on the modes above the cut off frequency. The results may be different from the actual situation, because of the different boundary conditions. However, the results can reflect the performance of the absorber to some extent.

All the results shown above are the measured results, to figure out the HOM propagation properties through multi-cavities, more simulation work need to be done.

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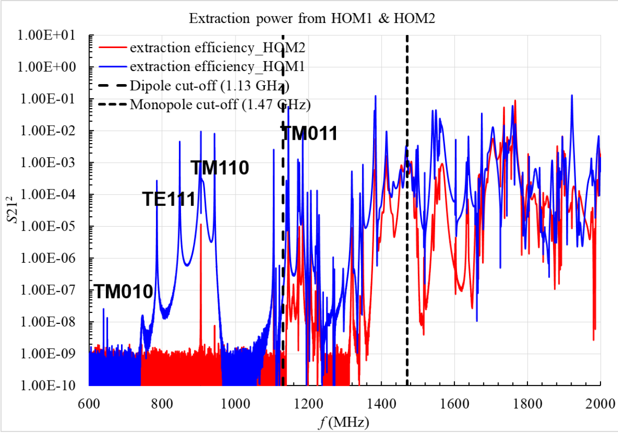

Figure 10: Extraction power efficiency of HOM1 & HOM2.

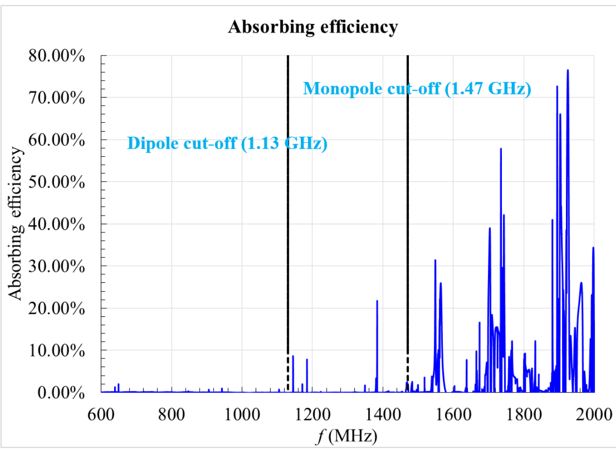

Figure 11: HOM absorber absorbing efficiency.

CONCLUSION

In this paper, the HOM damping requirements for CEPC are introduced. To keep the beam stable, two loop HOM couplers are planned to install on the 2-cell cavity. To check the damping results, a 2-cell cavity with two HOM couplers test bench is set up. Different methods are used to get the Q_e for different HOMs. The measured results seems good compared with the simulated results. The damping results for the fundamental mode are also meet the requirement. A two 2-cell cavities with HOM absorber and HOM couplers test bench is set up to study the HOM propagation properties through multi-cavities. The absorbing efficiency of the absorber and the extraction power efficiency of HOM couplers are achieved. To be clear with the HOM propagation properties through multi-cavities, more work need to be done.

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