HOMs simulation and measurement results of IHEP02 cavity *

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Abstract: In accelerator RF cavities, there exists not only the fundamental mode which is used to accelerate the beam, but also higher order modes (HOMs). The higher order modes excited by the beam can seriously affect beam quality, especially for the higher R/Q modes. 1.3 GHz low-loss 9-cell superconducting cavity as a candidate for ILC high gradient cavity, the properties of higher order mode has not been studied carefully. IHEP based on existing low loss cavity, designed and developed a large grain size 1.3 GHz low-loss 9-cell superconducting cavity (IHEP02 cavity). The higher order mode coupler of IHEP02 used TESLA coupler's design. As a result of the limitation of the mechanical design, the distance between higher order mode coupler and end cell is larger than TESLA cavity. This paper reports on measured results of higher order modes in the IHEP02 1.3 GHz low-loss 9-cell superconducting cavity. Using different methods, $Q_{\rm e}$ of the dangerous modes passbands have been obtained. The results are compared with TESLA cavity results. R/Q of the first three passbands have also been obtained by simulation and compared with the results of the TESLA cavity.

Key words: 1.3 GHz 9-cell superconducting cavity, low-loss shape, higher order modes, $Q_{\rm e}$, experimental measurements

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1 Introduction

The layout of the IHEP02 1.3 GHz low-loss 9-cell superconducting cavity [1] is shown in Fig. 1. In order to damp higher order modes (HOMs), two HOM couplers are mounted respectively at the upstream and downstream beam tube. Distances from the HOM couplers to the end cells are 65 mm and 50 mm, which are different from TESLA cavity [2]. The length of the upstream beam tube is also different from the downstream beam tube.

Damping of HOMs in the ILC linear collider is necessary. Parasitic modes excited by the accelerated beam may lead to loss of beam quality and additional power dissipation. For HOMs with frequency lower than the cut-off frequency of the beam tube, their power loss must be extracted by external load. When moving relativistic particles encounter geometric variations along the structure, such as RF accelerating cavities, vacuum bellows, and beam diagnostic chambers, there are wakefields after the particles go through [3]. Long range wakefields are important for the beam dynamics of a long train of bunches in a linear accelerator since these wakefields can cause multibunch instabilities. The long range wakepotential can be represented as a sum over contributions from HOMs. The transverse long range wakefield mainly considers the influence of dipole modes, which requires the $Q_{\rm e}$ of the HOMs to be less than 10^5 [4]. In this paper, we present the simulation results of R/Q and measured $Q_{\rm e}$ of HOMs.

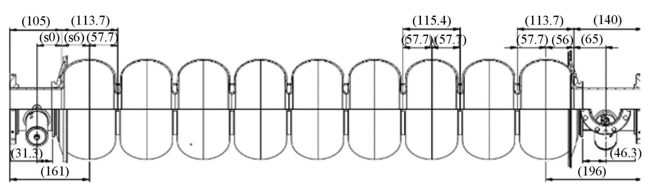

Fig. 1. Layout of IHEP02 9-cell cavity.

2 Simulation results of R/Q

The ratio R/Q is a very important quantity related to the interaction of the beam and cavity. The higher the value of R/Q the larger the energy change between beam and cavity. For monopole HOMs, the beam energy loss will be higher. For dipole modes, the transverse displacement of the beam will be larger The displacement may cause emittance increase or even worse beam loss.

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It becomes very important to measure modes with large R/Q.

An important parameter describing the transverse beam-cavity interaction is transverse shunt impedance. From the Panofsky–Wenzel theorem [3], the transverse momentum change of the particle passing through a cavity excited in a single mode is proportional to a parameter $(R/Q)_\perp$. In this paper, for dipole modes, $(R/Q)_\perp$ is defined as:

$$\left(\frac{R}{Q}\right)_\perp = \frac{\left|\int E_z \mathrm{e}^{\mathrm{j}\omega z/c}\mathrm{d}z\right|^2}{k^2 r^2 \omega U} = \frac{V_{//}^2}{k^2 r^2 \omega U}. \quad (1)$$

The unit of $(R/Q)_\perp$ is ohms. k is the wave number. ω is the frequency of the mode. U is the energy stored in the cavity. r is the distance from the axis. $V_{//}$ is the accelerating voltage of a cavity which is defined as:

$$V_{//} = \int_0^d E_z \mathrm{e}^{\mathrm{j}\omega z/c}\mathrm{d}z, \quad (2)$$

d is the length of the cavity. In this paper, we define a new $(R/Q)_\perp$ called $(R/Q)'_\perp$ as:

$$\left(\frac{R}{Q}\right)'_\perp = \frac{V_{//}^2}{r^2 \omega U}. \quad (3)$$

The unit of $(R/Q)'_\perp$ is Ω/cm^2.

Energy generated by HOMs can be coupled by HOM couplers and absorbed by external load. HOMs energy loss can be divided into two parts, power dissipated in the cavity walls P_0 and power coupled by the external circuit P_e. It is better to have small Q_e in order to damp the HOMs sufficiently.

$$Q_\mathrm{e} = \frac{\omega U}{P_\mathrm{e}}. \quad (4)$$

The Q_e of dangerous mode can be obtained by measuring the microwave parameters of the 1.3 GHz 9-cell cavity. The measured results affect how to optimize the HOM coupler structure in the future.

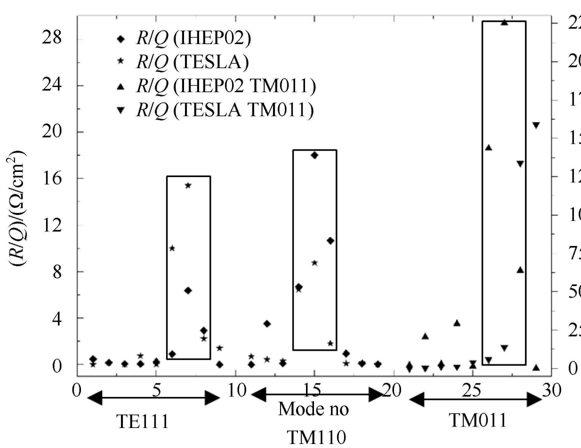

Fig. 2. HOMs R/Q.

The R/Q of the first three HOMs passbands have been simulated. The results of R/Q compared with TESLA cavity results are shown in Fig. 2. In Fig. 2, the modes in the box represent the most dangerous three modes which have the largest R/Q in that passband. The most dangerous modes need to be measured carefully. From the result, we can see that the dangerous modes in the IHEP02 1.3 GHz low-loss cavity are almost the same as for the TESLA cavity, except for the TM011 mode. This difference is mainly because of the different design of these two kinds of cavities.

3 Structure of HOM couplers

There are three major varieties of HOM couplers [3]: waveguide, coaxial, and beam tube. Considering the purpose of the 1.3 GHz superconducting cavity, it requires the connection between the cavities to be short. The coaxial type was chosen, because of their more compact size [4]. The coupler used for IHEP02 1.3 GHz low-loss 9-cell superconducting cavity is shown in Fig. 3. According to the rules of excitation, the frequencies of modes TE111, TM110 and TM011 are all under the cut-off frequency of the beam tube whose radius is 40 mm.

In order to sufficiently attenuate the HOMs, there were two HOM couplers mounted respectively upstream and downstream [2]. The position of the HOM coupler was 65 mm from the edge of the end cell on the upstream side and 50 mm from the edge of the end cell on the

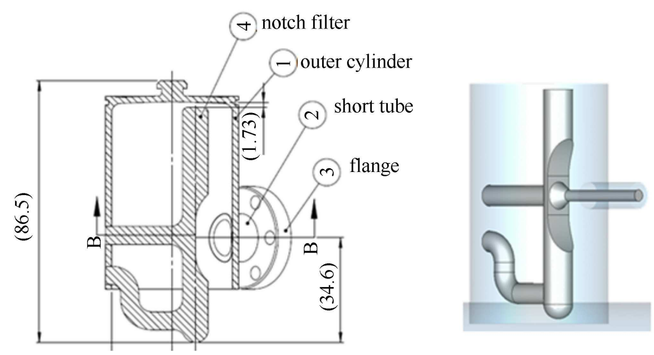

Fig. 3. (color online) Profile and model of HOM couplers.

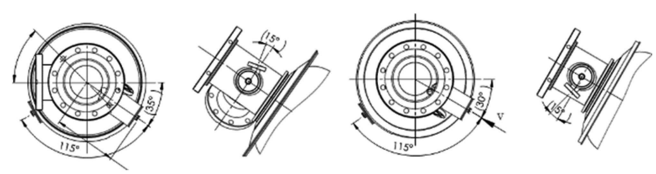

Fig. 4. The left two pictures show the upstream coupler position and the right two pictures show the downstream coupler position.

downstream side. The design value of the insertion length of the coupling loop tip was 30.25 mm from the beam axis. The mounted angle of the upstream coupler and downstream coupler are shown in Fig. 4.

4 HOMs measurements

The HOMs characteristics were measured using a network analyzer. 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. A schematic diagram of the measuring device is shown in Fig. 5.

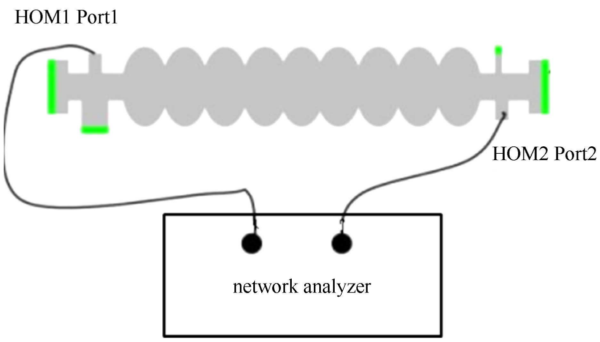

Fig. 5. (color online) Schematic diagram of the HOM measurement.

4.1 Measurements of IHEP02 cavity HOMs frequencies and passbands

The measurement results of frequencies and passbands are shown in Fig. 6. The most dangerous modes are identified.

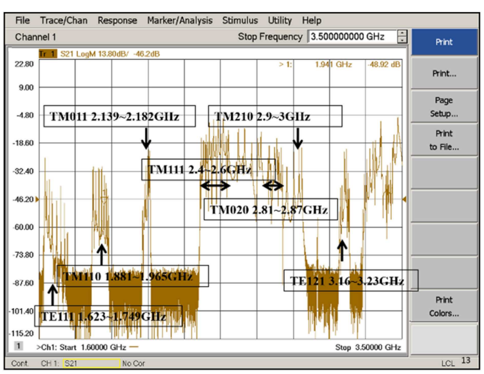

Fig. 6. (color online) IHEP02 cavity HOMs frequencies and passbands.

4.2 Measurements of IHEP02 cavity HOMs Q_e

The excitation signal was imported to the cavity by the upstream HOM coupler and the output signal was extracted by the downstream HOM coupler. The measured microwave parameters were received from the network analyzer. The bead pulling method [3] was used to measure the field profile.

The Q_e of the first three modes with frequencies under the beam tube cut-off frequency were measured. Q_e of the mode TM111 was also measured even though its frequency was above the beam tube cut-off frequency. There was a mode during TM111 passband with the largest R/Q not only of the modes of this passband but also of all calculated modes [5, 6].

Three methods were used to measure Q_e, the impedance method [7, 8], reflection method [9] and transmission method [10]. The reflection method has a limitation in that the coupling coefficient is not too small. The transmission method was used for one port weak coupling. The calculations for these methods are as follows.

a) Impedance method

The normalized impedance for an equivalent circuit is

$$\overline{z}=\frac{1}{\frac{1}{\overline{r}}+\mathrm{j}\left(\omega\overline{C}-\frac{1}{\omega\overline{L}}\right)}=\frac{1}{\overline{g}+\mathrm{j}\overline{b}},\tag{5}$$

where $\overline{r}$ is equivalent resistance, $\overline{C}$ is equivalent capacitance, and $\overline{L}$ is equivalent inductance.

The unloaded quality factor is

$$Q_0=\frac{\omega_0 W_0}{P_c},\tag{6}$$

where ω_0 is resonance frequency, W_0 is energy stored in the cavity, and P_c is power dissipated in the cavity at resonance.

The external quality factor is

$$Q_e=\frac{\omega_0 W_0}{P_e},\tag{7}$$

where ω_0 is resonance frequency, W_0 is energy stored in cavity, and P_e is power dissipated in the external circuit.

Defining half power points:

$$P_{c1,2} = 1/2P_c,\tag{8}$$

$$P_{e1,2} = 1/2P_e,\tag{9}$$

from (5)–(9), we can get

$$\overline{b}_{1,20} = \pm\overline{g},\tag{10}$$

$$\overline{b}_{1,2e} = \pm 1.\tag{11}$$

The reflection coefficient is:

$$\varGamma=\frac{\overline{z}-1}{\overline{z}+1}\tag{12}$$

and the voltage standing wave ratio (VSWR) is:

$$S=\frac{1+|\varGamma|}{1-|\varGamma|}.\tag{13}$$

Then from (5), (12), (13), the resonant VSWR is

$$S_0 = \overline{r}(r>1),\tag{14}$$

$$S_0 = \frac{1}{\overline{r}}(r<1).\tag{15}$$

From (5) ~ (15), the VSWR at the half power points of Q_0 and Q_e are

$$(S_{1/2})_0=\frac{2+\beta^2+\sqrt{4+\beta^4}}{2\beta}((S_{1/2})_0<S_0), \tag{16}$$

$$(S_{1/2})_e=\frac{1+2\beta^2+\sqrt{1+4\beta^4}}{2\beta}, \tag{17}$$

where β is the coupling coefficient.

In some cases, the resonant VSWR is so large that it is not easy to measure. In other cases, the VSWR curve is asymmetric. We can solve these problems by measuring arbitrary VSWR values. First, we get the resonant VSWR S and frequency ω_0 by VSWR curve. Then, we find an arbitrary VSWR value near the resonant VSWR. The calculations are as follows.

$$Q_0 = \frac{\omega_0}{\Delta\omega}\sqrt{\frac{(S_x-S_0)(S_xS_0-1)}{S_x}}(\beta>1), \tag{18}$$

$$Q_0 = \frac{\omega_0}{\Delta\omega}\sqrt{\frac{\left(\frac{S_x}{S_0}-1\right)\left(S_x-\frac{1}{S_0}\right)}{S_x}}(\beta<1), \tag{19}$$

$$\beta = S_0(\beta>1), \tag{20}$$

$$\beta = \frac{1}{S_0}(\beta<1), \tag{21}$$

$$\frac{Q_0}{\beta} = Q_e, \tag{22}$$

$$\frac{Q_0}{1+\beta} = Q_L, \tag{23}$$

where S_x is an arbitrary VSWR.

b) Reflection method

Measuring the resonant frequency ω_0, loaded quality factor Q_L, and reflection parameters S_{11}(dB) and S_{22}(dB), we then get

$$Q_0=(1+\beta_1+\beta_2)Q_L \tag{24}$$

Here S_{11} and S_{22} are reflection parameters for Port 1 and Port 2 as shown in the Fig. 5. β_1 and β_2 are coupling coefficients for Port 1 and Port 2. There are three different cases for different coupling coefficients.

1) Port 1 and Port 2 are both under coupling:

$$\beta_1 = \frac{1-10^{\frac{S_{11}}{20}}}{10^{\frac{S_{11}}{20}}+10^{\frac{S_{22}}{20}}}, \tag{25}$$

$$\beta_2 = \frac{1-10^{\frac{S_{22}}{20}}}{10^{\frac{S_{11}}{20}}+10^{\frac{S_{22}}{20}}}. \tag{26}$$

2) Port 1 is under coupling and Port 2 is over coupling. Port 1 and Port 2 are both over coupling, however $\beta_2>\beta_1+1$

$$\beta_1 = \frac{1-10^{\frac{S_{11}}{20}}}{10^{\frac{S_{11}}{20}}-10^{\frac{S_{22}}{20}}}, \tag{27}$$

$$\beta_2 = \frac{1+10^{\frac{S_{22}}{20}}}{10^{\frac{S_{11}}{20}}-10^{\frac{S_{22}}{20}}}. \tag{28}$$

3) Port 1 is over coupling and Port 2 is under coupling. Port 1 and Port 2 are both over coupling, however $\beta_1>\beta_2+1$

$$\beta_1=\frac{1+10^{\frac{S_{11}}{20}}}{10^{\frac{S_{11}}{20}}-10^{\frac{S_{22}}{20}}}, \tag{29}$$

$$\beta_2=\frac{1-10^{\frac{S_{22}}{20}}}{10^{\frac{S_{11}}{20}}-10^{\frac{S_{22}}{20}}}. \tag{30}$$

c) Transmission method

Measuring the resonant frequency ω_0, loaded quality factor Q_L, reflection and transmission parameters S_{11}(dB) and S_{21}(dB), then

$$Q_0 = (1+\beta_1+\beta_2)Q_L, \tag{31}$$

$$P_r = P_{in}\Gamma^2=P_{in}10^{\frac{S_{11}}{10}}, \tag{32}$$

$$P_t = P_{in}T^2=P_{in}10^{\frac{S_{21}}{10}}, \tag{33}$$

$$P_{in} = P_r+P_t+P_0. \tag{34}$$

Here S_{11} is reflection parameter for Port 1 as shown in the Fig. 5. S_{21} is transmission parameter from Port 1 to Port 2. β_1 and β_2 are coupling coefficients for Port 1 and Port 2. There are two different cases for different coupling coefficients.

1) Port 1 is under coupling.

$$\beta_1 = \frac{(1-10^{\frac{S_{11}}{20}})^2}{1-10^{\frac{S_{11}}{10}}-10^{\frac{S_{21}}{10}}}, \tag{35}$$

$$\beta_2 = \frac{10^{\frac{S_{21}}{10}}}{1-10^{\frac{S_{11}}{10}}-10^{\frac{S_{21}}{10}}}. \tag{36}$$

2) Port 1 is over coupling.

$$\beta_1 = \frac{(1+10^{\frac{S_{11}}{20}})^2}{1-10^{\frac{S_{11}}{10}}-10^{\frac{S_{21}}{10}}}, \tag{37}$$

$$\beta_2 = \frac{10^{\frac{S_{21}}{10}}}{1-10^{\frac{S_{11}}{10}}-10^{\frac{S_{21}}{10}}}. \tag{38}$$

The measured results of Q_e using these three methods compared with the TESLA design goal are shown in Fig. 7. Modes in the box are the most dangerous modes in that passband. Although the frequency of the TM111 mode is above the cut off frequency of the beam tube, it has two dangerous modes [5, 6]. The TM111 mode also needs to be measured. The measurement results show a good damping with all the modes under 10^5. The lengths from HOM coupler to the end cells of the IHEP02 cavity are 65 mm and 55 mm while they are 45 mm for the TESLA cavity. The damping of the TM110 mode in the IHEP02 cavity is better than in the TESLA cavity.

The Q_e are lower than the TESLA BBU limit, mainly because of the different cavity designs. These measured results give a good basis for the next HOM coupler optimal design.

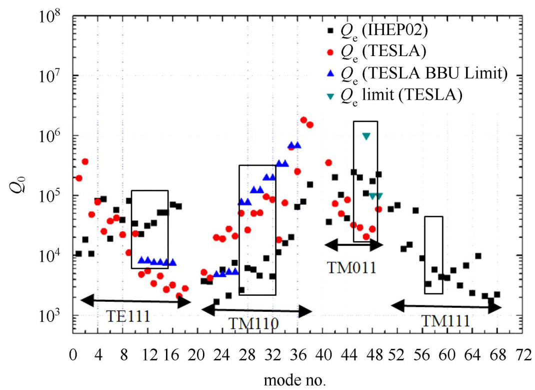

Fig. 7. (color online) Q_e of IHEP02 cavity compared with TESLA results.

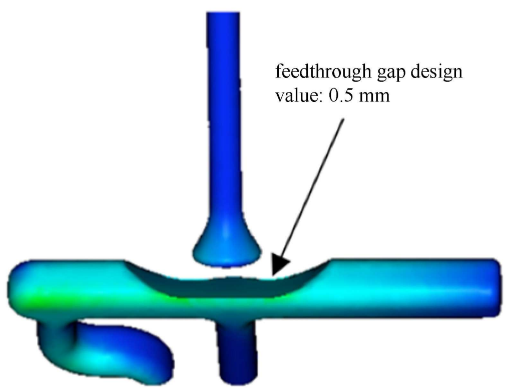

Fig. 8. (color online) Definition of feedthrough gap.

In order to get the relationship between Q_e and feedthrough gap, Q_e values with different gaps were also measured. The fifth mode of TM110 (5Pi/9) was chosen for measurement. The design value of feedthrough gap is 0.5 mm. The definition of feedthrough gap is shown in Fig. 8. The measured values are shown in Fig. 9. These measured results give a good foundation for the HOM coupler feedthrough gap design.

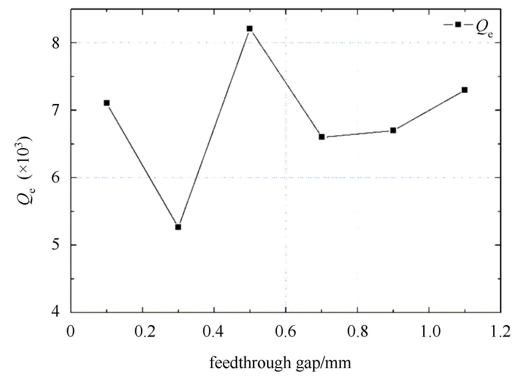

Fig. 9. Measurement results of $Q_e\sim$ feedthrough gap.

5 Conclusion

In this paper, different methods of measurement of Q_e and the corresponding measurement results are presented. $(R/Q)_\perp$ simulated results are also obtained for the first three HOMs passbands. The measurement results show that:

1) There is very good damping for the dipole passbands TM110 and TM111, with the Q_e of these modes all under the TESLA BBU limit.

2) The Q_e values of the monopole passband TM011 are near the Q_e limit of TESLA.

3) The damping of the first dipole passband TE111 should be improved to keep Q_e below the TESLA BBU limit.

The measurement results provide good guidance for the optimization of HOM coupler design in the future.

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