Calculation of the external quality factor of the high power input coupler for the BEPCⅡ superconducting cavity *

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Abstract It is very important to predict the coupling between the cavity and the high power input source in the coupler design. In this paper, a time domain method is used to calculate the external quality factor Q_{ext} for the BEPCⅡ superconducting cavity. A comparison between simulation results and experimental results is presented. The results of simulation and measurement of Q_{ext} have a good agreement within an error of 10%. The geometry parameters related with Q_{ext} are also studied.

Key words high power input coupler, external quality factor, superconducting cavity

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1 Introduction

It is very important to predict the coupling between the cavity and the high power input source in the coupler design. For the superconducting cavity, the optimal coupling in the presence of beam loading is[1]:

$$Q_{\mathrm{ext}} = \frac{V_{\mathrm{c}}^2}{P_{\mathrm{b}}(R_{\mathrm{a}}/Q_0)}\,, \tag{1}$$

where V_{c} is the cavity voltage, P_{b} is the power transferred to the beam, and R_{a}/Q_0 is a quantity decided by the cavity geometry. So for a series of the desired machine parameters, it is hoped that an optimal Q_{ext} will be found. For the BEPCⅡ superconducting cavity, V_{c}=1.5 MV, P_{b}=130 kW, R_{a}/Q_0=95.3Ω, and the optimal Q_{ext} is around 1.8×10^5.

Up to now there have been several methods to calculate the external quality factor. Some of them are based on the transmission line analytical theory. With the development of computer technology, more and more numerical methods are developed. Among them, two types of simulation techniques are often used: the frequency domain and the time domain[2].

In this paper, a time domain method[3] is used to study Q_{ext} of the BEPCⅡ high power coaxial input coupler. This method takes advantage of the built-in waveguide boundary condition, which makes the coupler-cavity system terminated with a matched load. First, the cavity is driven by an excitation signal which is then removed . Through calculating the natural decay time constant, the Q_{ext} can be calculated out directly. A comparison between the simulation results and the experimental results has been made for various antenna penetration depths, and the geometry parameters related with Q_{ext} have also been studied.

2 Calculation considerations and results analysis

When the cavity is left to "ring down", the stored energy satisfies[1]:

$$U = U_0 \exp\left(\frac{-\omega t}{Q_{\mathrm{L}}}\right)\,, \tag{2}$$

where U_0 is the stored energy when $t=0$. The energy in the cavity thus decays exponentially with a time

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constant[1]:

$$\tau_{\rm L}=\frac{Q_{\rm L}}{\omega}\,, \tag{3}$$

Based on the $\tau_{\rm L}$, the loaded quality factor can be received. For the superconducting cavity, the field decay is mostly determined by the power coupling out through the coupler port. The cavity boundary material is set as perfect conductor, so the energy decay is only determined by the coupling power, i.e. $Q_{\rm ext}=Q_{\rm L}$. In this method, the energy decay is recorded and the $\tau_{\rm L}$, ω, $Q_{\rm L}$ can be attained. Through calculating the natural decay time constant, the $Q_{\rm ext}$ can be calculated out directly.

We will not elaborate the method itself, but rather share some calculation considerations. For further details, please refer to Ref. [3].

The beam-pipe lengths on each side of the cavity are chosen to ensure that the fields in the beam-pipes will sufficiently evanesce up to the ends of the geometry. The length of the coupler coaxial line must be at least half of the wavelength so that the solution of the fundamental transmission line mode has been stabilized. The model solid material is set as vacuum and the boundary as perfect conductor. Two types of ports are set. A built-in waveguide port is added on the coupler coaxial port and a discrete port is added on the axis of cavity where the desired fundamental mode has a strong electric field component. In this time domain method, an excitation source must be added. The cavity is driven by a Gaussian pulse with the center frequency approximately around the resonant frequency of the system. The bandwidth of the excitation pulse should be appropriately chosen to cover the natural resonant frequency and avoid exciting the high order modes[2]. A probe is located at a particular position where the mode of interest has a strong component, but is not too close to the driving point[2]. The probe is used to record the field decaying after the excitation pulse is removed. Fig. 1 shows the energy decay curve as a function of time.

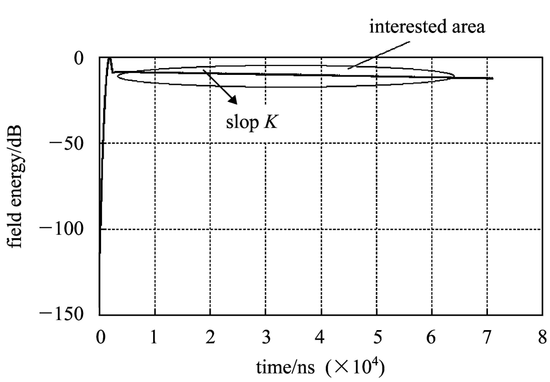

Fig. 1. Energy decay curve as a function of time.

The $Q_{\rm ext}$ is calculated from the slop of the energy decay curve K:

$$Q_{\rm ext}=-\frac{10\omega_0}{K\ln 10}\,, \tag{4}$$

A Fast Fourier Transform (FFT) of the field is used to find the resonant frequency. The resonant frequency can also be attained directly by counting the oscillation period of the time varying field signal over a period.

The simulation model is shown in Fig. 2.

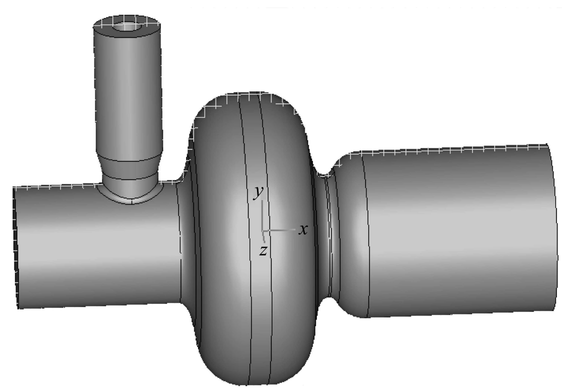

Fig. 2. The time domain method simulation model.

The following four geometry parameters shown in Fig. 3 have been studied. The $Q_{\rm ext}$ is mostly dependent on the antenna penetration depth. As shown in Fig. 4, a 30 mm penetration shift results in around one order of variation on $Q_{\rm ext}$ value. The simulation and measured results for various antenna penetration depths have been compared and are shown in Fig. 4. The results have a good agreement within an error of 10%. Here, the beam pipe wall is taken as the original point, with the penetration depth into the beam pipe as positive distance and out as negative distance.

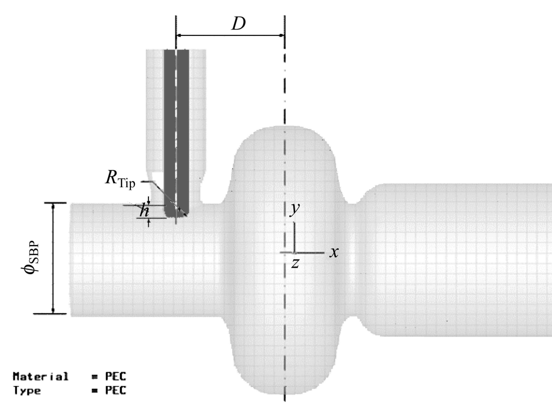

Fig. 3. 1) h (antenna penetration depth); 2) $R_{\rm Tip}$ (the antenna tip radius); 3) $\phi_{\rm SBP}$ (the small beam pipe diameter); 4) D (the distance between the coupler axis and the cavity equator perpendicular bisector).

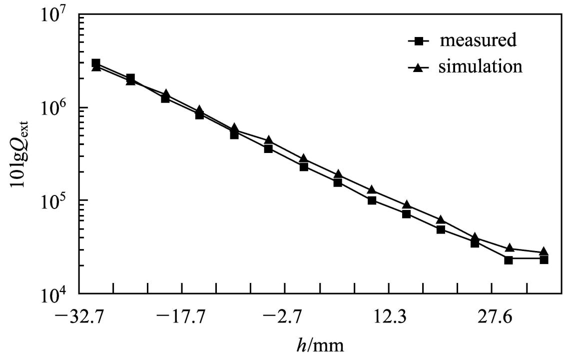

Fig. 4. The simulated $Q_{\rm ext}$ and measured $Q_{\rm ext}$ for various antenna lengths.

The $Q_{\rm ext}$ also varies with the other three geometry parameters. As shown in Fig. 5, as the antenna tip radius decreases from 15 mm to 10 mm, the $Q_{\rm ext}$ decreases about 10%. As shown in Fig. 6, a 20 mm decreasing of the diameter of the small beam pipe results in about 40% increasing of $Q_{\rm ext}$. As shown in Fig. 7, as the distance between the coupler axis and the cavity equator perpendicular bisector is increased from 215.25 mm to 225.25 mm, the $Q_{\rm ext}$ is increased by about 112.5%.

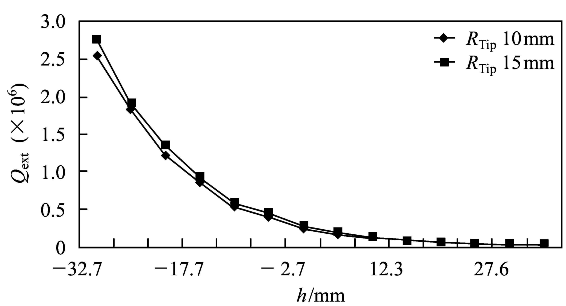

Fig. 5. Antenna tip radius impacts the $Q_{\rm ext}$.

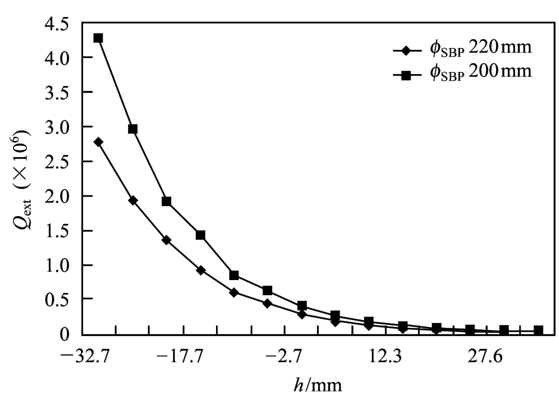

Fig. 6. The diameter of the small beam pipe impacts the $Q_{\rm ext}$.

The simulation of $Q_{\rm ext}$ will be used to aid the test and operational program in the positioning of the antenna penetration depth. For the BEPCII superconductor cavity, the expected $Q_{\rm ext}$ is about 1.8×10^5. Based on the simulation, the corresponding geometry parameters after cooling down are: D=215.25 mm, $R_{\rm Tip}$=15 mm, $\phi_{\rm SBP}$=220 mm, and the antenna penetration depth into the beam pipe is 2.146 mm. Based on the measured results, the corresponding antenna penetration depth is 2.043 mm. So the required antenna penetration depths given by the simulation and measurement should agree within 95%.

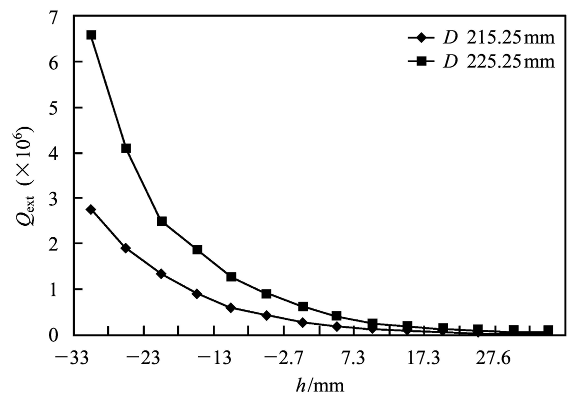

Fig. 7. The distance between the coupler axis and the cavity equator perpendicular bisector impacts the $Q_{\rm ext}$.

3 Summary

Among several kinds of methods to calculate the coupling between the cavity and high power input source, the time domain method used in this paper is one of the simplest ones, and it is suitable for both the strong and the weak coupling. Moreover, this method is efficient for both normal conducting cavity and superconducting cavity. Using this time domain method, $Q_{\rm ext}$ of the high power input coupler for the BEPCII superconducting cavity has been calculated. The results are nearly the same as the measured results for various antenna penetration depths. The geometry parameters impacting the coupling are also studied, which provide a foundation for the optimized design of high power coaxial coupler.

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