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A tuning system for BEPCⅡ *

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Abstract: The tuning system plays a very important role when a superconducting cavity is in operation. It cooperates with other control loops to adjust the cavity frequency with high precision, reduce the reflection power, guarantee the stability of beam, and ensure the safety of the superconducting cavity. This paper focuses mainly on the tuning system working principle, the working state and problems that Beijing Electron Positron Collider (BEPCⅡ) has encountered during operation.

Key words: tuning system, 500 MHz cavity tuner, frequency tuner

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1 Introduction

The tuning system is an essential part of the Superconducting Radio Frequency (SRF) system for BEPCⅡ, which consists of a tuner and a tuning loop. The frequency of BEPCⅡ superconducting cavity is 499.8 MHz, with the temperature of 4.2 K. It works at continuous wave (CW) mode, while the maximum current is 911 mA. Because of beam effects, helium pressure and microphonics, the actual frequency deviates from the working frequency, which will result in the increase of incident and reflection power, and even cause beam loss. To ensure that the cavity works well, the cavity frequency should be adjusted constantly by a tuning system [1, 2].

BEPCⅡ had adopted a KEKB-type tuner. Stretching the cavity to change its frequency ensures that the cavity is always working on resonance. So the beam can run normally and also save energy. Some key problems of BEPCⅡ tuning system are analyzed in this article.

2 Mechanical structure and working principle of the tuner

2.1 The mechanical structure of the tuner

As Figs. 1(a) and (b) show, the tuner is composed of a main motor and a piezoelectric oscillator. The main motor has a large stroke in the resonant frequency, while the operation is slow. On the other hand, the piezoelectric oscillator has a small stroke and fast operation. The piezoelectric oscillator is wrapped with a layer of 5 mm lead sheath to shield radiation. The main parameters of the tuner are listed in Table 1 [3].

Table 1. Main parameters of the tuner.

type	motor	piezo
tuning rate	low	fast
stroke	4 mm	∼40 μm
cavity tuning sensitivity	330 kHz/mm	
tuning range	660 kHz	6.6 kHz
resolution	μm	several tens of nm
operating temperature	room temperature	room temperature
number	1	1
harmonic drive ratio	1:50	–
type or max load	PK596AE1-H50 (0.72°/step)	–

Figure 2 (a) is the schematic diagram of the tuner. The motor tuner consists of a stepping motor and a reduction gear box. The reduction ratio of the reduction

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gears is 48:72. The screw pitch of the piezoelectric oscillator support platform is 4 mm.

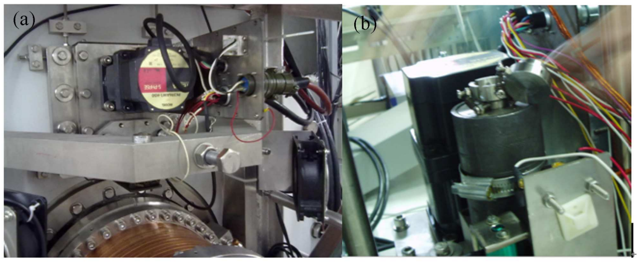

Fig. 1. (a) The 500 MHz tuner on the cryomodule; (b) the tuner components.

The theory formula of piezoelectric oscillator support platform displacement is:

$$S = cp \times \left(\frac{0.72^\circ}{360^\circ}\right) \times \frac{1}{50} \times \frac{48}{72} \times 4, \tag{1}$$

S: displacement of piezoelectric oscillator support platform; cp: pulse numbers.

According to Formula (1), the theoretical resolution of the main motor we can get is 0.1 μm. The displacement resolution of the motor can be improved by adjusting the motor driver. However, the resolution is lower than the theoretical resolution of the motor tuner due to manufacturing and installation errors. Also, backlash of gears is inevitable.

Figure 2(b) is the displacement curve of the piezoelectric oscillator during the voltage change from 0 to 900 V. The sensitivity is about 27 nm/V, the hysteresis phenomenon exists during a round trip.

2.2 The working principle of a mechanical tuner

The fixture of the tuner on a cryomodule is shown as Figs. 3(a) and (b). The tuner arms are connected with the cavity end flange. The frequency of the cavity must

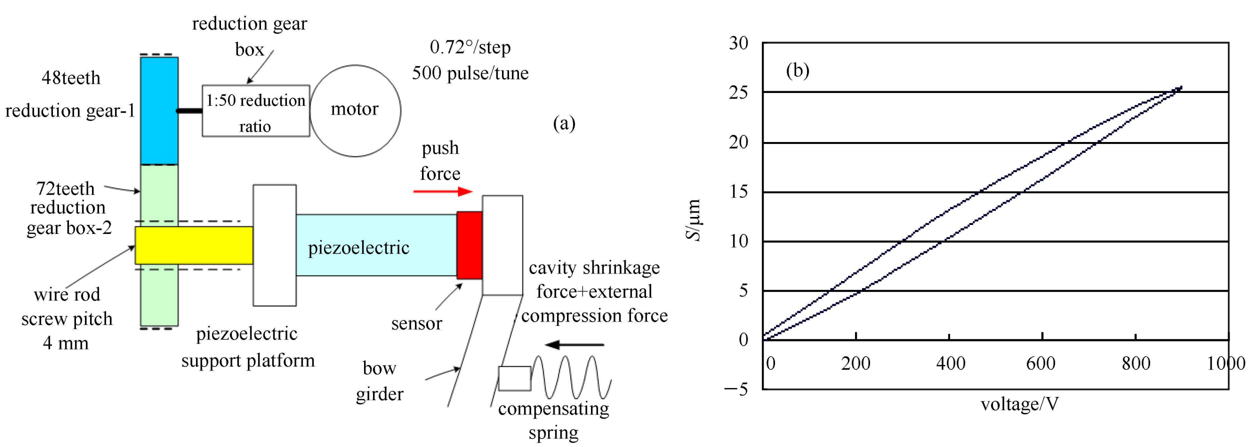

Fig. 2. (a) The schematic diagram of the tuner; (b) piezoelectric oscillator voltage vs. displacement curve.

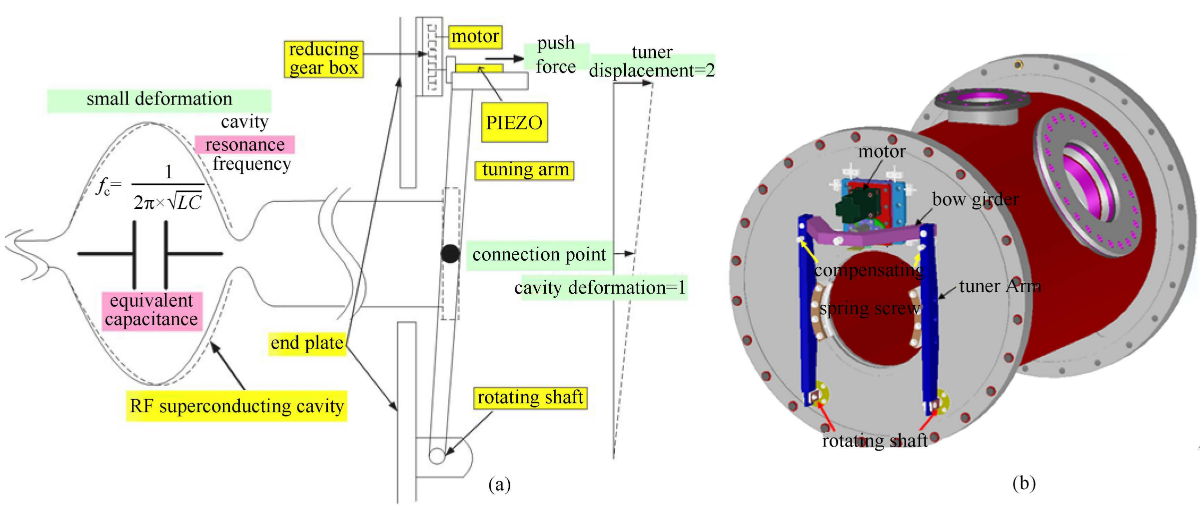

Fig. 3. (a) The actuator tuning diagram; (b) the 3D graph of the tuner and cryomodule.

be lower than the working frequency in the initial state. Through preloading, the cavity is adjusted to the working frequency. The preload of BEPC II cavity is about 120 kg. When the tuner operates, the cavity keeps stretching. The motor and piezoelectric oscillator pushes the tuner arms to stretch the cavity. According to the lever principle, the cavity displacement is half the displacement of the tuner.

According to the cavity electromagnetic field perturbation theory, when the cavity is stretched in the axis, the frequency of the cavity will elevate. The cavity also can be simplified into a capacitor module. The frequency changes with the length of cavity.

3 The tuning loop analysis

The tuning loop controls the frequency of the cavity based on the Radio Frequency (RF) phase error between the incident RF signal and the cavity RF field. The tuner phase error signal is processed in a servo amplifier module that provides a Proportion Integration (PI) feedback control function. The tuner controller uses the PI feedback control signal to drive the stepping motor or piezo-tuner.

Figure 4 divides the tuner phase error into four ranges: (1) the stepping motor dead-band and piezo-tuner range, (2) the overlap range, (3) the stepping-motor range and piezo-tuner dead-band, and (4) the tuner-speed-limiting range. Settings like these can reduce motor wear and improve the frequency precision [4].

When the tuner phase error is within ±1°, the piezo-tuner driver generates a voltage, proportional to the tuner phase error, to change the cavity frequency, while the stepping motor stays in a stop state. When the tuner phase error is in an overlap range, both the piezo-tuner and stepping-motor drivers generate drive signals to change the cavity frequency. When the tuner phase error is in the stepping motor range, only the stepping motor driver clock signal is generated to change the cavity frequency; the driver clock frequency is linearly proportional to the tuner phase error. When the tuner phase error exceeds a limiting setting, the driver clock frequency is limited to a constant, so the moving speed of the stepping motor tuner is also limited. Details of the tuning loop are presented in Fig. 5.

4 The actual working state analysis of the tuner system of BEPC II

The main factors that influence the frequency of BEPC II cavity are beam loading, helium pressure and microphonics. The frequency changed by beam loading can be computed by Formula (2).

$$\Delta f = (I_b \sin\Phi_s / 2V_{rf})(R/Q) f_{rf}. \quad (2)$$

R/Q=95.3, I_b is the beam current intensity, f_{rf} is the working frequency of the cavity 499.8 MHz [5].

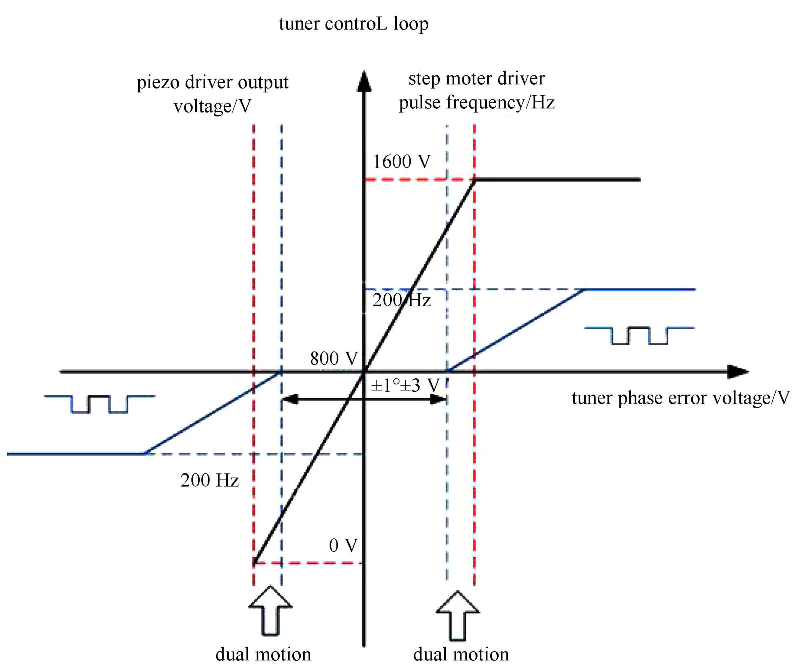

Fig. 4. The tuner phase error voltage vs. the stepping motor clock/piezo driver signal.

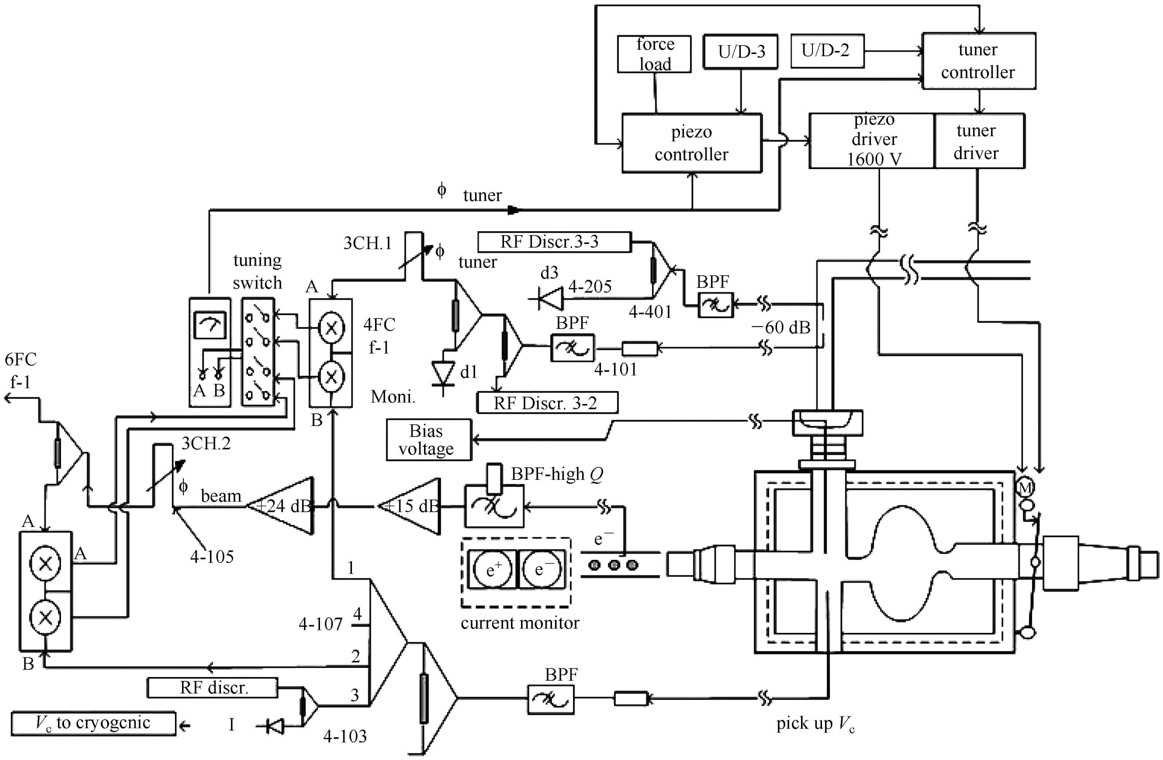

Fig. 5. The tuning loop of the KEKB-type SRF cavity of BEPCⅡ.

The frequency changed by helium pressure is about 250 kHz/bar. The frequency of the cavity changes by about 40 Hz due to the external mechanical perturbations and the change of vacuum degree.

According to Formula (2) we know that a 900 mA electron beam (@$E_0=1.89$ GeV, V_c=1.5 MV) leads to the cavity detuning by about 14 kHz. In order to keep resonance, the tuner force reduces, then the cavity rebounds, and the frequency of the cavity decreases to offset the beam impaction. The spring-back displacement of the cavity is about 42.4 μm. Considering the injection time electron is 10 min, the cavity will spring back 71 nm/s, the frequency decrease by about 23.4 Hz/s. According to Formula (1), 1 mm displacement of the motor tuner needs about 9375 pluses. So 1 mm displacement of the cavity needs 18750 pulses. Given the injection rate, the tuner needs 1.33 pluses/s.

As Fig. 6 shows, during the process of positron and electron injection, due to the fast injection rate, the phase error is beyond the range of ±1°, only the motor tuner works, the piezo-tuner is in stop state. After the injection is finished, the piezoelectric oscillator voltage goes up to its maximum value quickly. During the start stage, the beam declines, the piezo-tuner and motor tuner both work, but during the last stage, only the piezo-tuner works. To ensure the stability of beams a negative detuning angle is usually set.

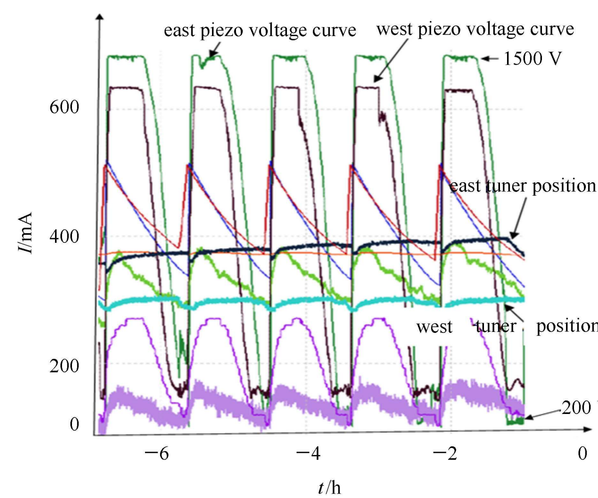

Fig. 6. The tuner working state of BEPCⅡ.

5 Problems encountered by BEPCⅡ tuning system

The reflection power of BEPCⅡ west cavity is abnormal. The minimum reflection power is larger than 10 kW, and the reflection power curve is nearly flat, as shown in Fig. 7. In order to eliminate the hidden dangers many experiments have been done. At last, it was found that the tuning working point deviated from the reson-

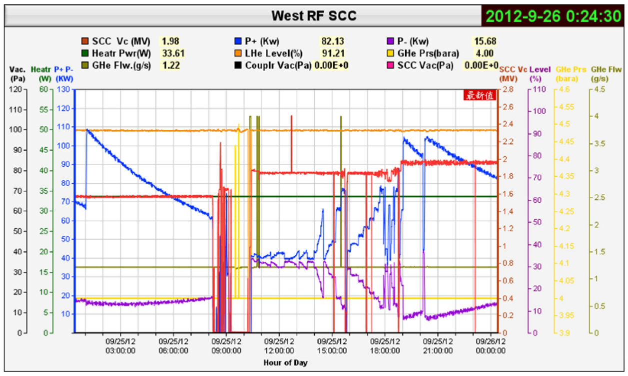

Fig. 7. The BEPCⅡ west cavity matching point curve.

ance point. Adjusting the tuning point to the resonance point by moving the phase shifter, the reflection power can be lower than 10 kW. When the cavity voltage is decreased, the reflection power can even decrease to about 2 kW.

On March 27, 2012, the electron beam lost frequently, and the motor tuner working position needed constant manual adjustment before beam injection. Fig. 8(a) shows the beam and power curves when the beam is lost. Due to the tuner problem the incident power increased rapidly, the cavity voltage decreased and the beam was lost. Fig. 8(b) shows that when the e-beam decreased, the motor tuner run abnormally and that the tuner position changed suddenly. Through inspection, it was found that the spring screw blocks the motion of tuner arm. When the tuner's push force was greater than the block force, the position of motor tuner changed suddenly.

On September 21, 2012，when BEPCⅡ west cavity was run in synchronization mode, the tuning range of tuner was limited. Through inspection, it was found that the pedestal tilted to the south side of the cavity, resulting in the upper part of the tuner arm being inclined to the cavity. Through removing the mechanical spacing shim, the tuner could work temporarily. Due to the tilting of the tuner arms, the cavity might be deformed in the axis. This is very dangerous to the cavity. In such a case, the cavity needs to be warmed up in order to adjust the tuner arm.

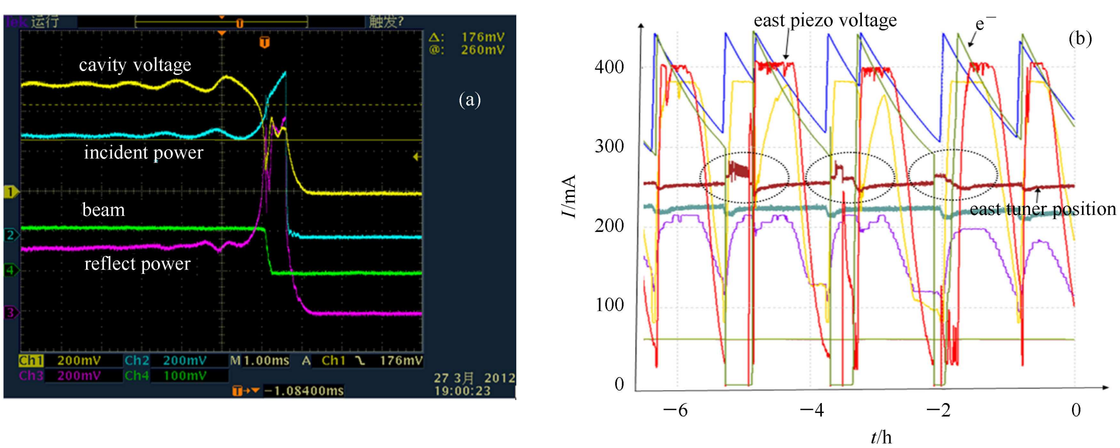

Fig. 8. (a) The beam and power curves when the beam was lost; (b) the curves of the motor and piezo.

6 Conclusion

The KEKB-type tuning system used by BEPCⅡ has worked well for six years. In order to control the frequency of the cavity better, we need to understand the beam and tuning system. The piezo-tuner needs further research to compensate the frequency of the cavity quickly. We have manufactured two sets of tuners and will test them on BEPCⅡ later.

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