Design and test of frequency tuner for a CAEP high power THz free-electron laser *

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Abstract: Peking University is developing a 1.3 GHz superconducting accelerating section highpower THz free-electron laser for the China Academy of Engineering Physics (CAEP). A compact fast/slow tuner has been developed by the Institute of High Energy Physics (IHEP) for the accelerating section to control Lorentz detuning, compensate for beam loading effect, microphonics and liquid helium pressure fluctuations. The tuner design, warm test and cold test of the first prototype are presented, which has a guiding significance for the manufacture of the formal tuner and cryomodule assembly.

Key words: 1.3 GHz cavity tuner, frequency tuner, THz-FEL

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1 Introduction

The China Academy of Engineering Physics (CAEP) is building an 8 MeV high power THz free-electron laser, which adopts 2 4-cell superconducting accelerating cavities to accelerate electrons. The cavity operates at a frequency of 1.3 GHz and a temperature of 2 K. It works in continuous wave (CW) mode, while the maximum current is 5 mA. Fig. 1 shows the schematic of the superconducting accelerating section [1].

As with other pulsed superconducting cavities, for example the 1.3 GHz 9-cell cavity for the International Linear Collider (ILC), each 4-cell cavity will be equipped with a slow tuner to compensate for static detuning and a fast tuner to compensate for the dynamic detuning due to the Lorentz force, beam loading effect, microphonics and liquid helium pressure fluctuations. The slow tuner for the 4-cell cavity uses a normal stepper motor while the fast tuner employs piezo actuators [2–4].

The 4-cell cavity is considerably stiffer than a 9-cell cavity for ILC and FEL, so the tuner must be capable of applying stronger force to the cavity flanges than the 9-cell cavity tuner. At the same time, the tuner will be mounted to the internal magnetic shield so as to strictly limit the tuner remanence, and the 2 K heat leakage of the tuner is strictly limited also. Furthermore the plan for the superconducting accelerating section provides only limited space for a tuner. Therefore, because of these reasons the design of a suitable tuner is very challenging.

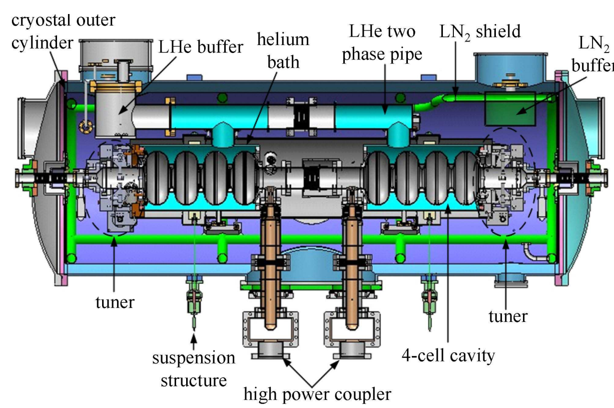

Fig. 1. The whole schematic of the superconducting accelerating section.

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2 Tuner requirements

The tuner must be able to compensate for the following effects [2].

(1) Static variations in the resonant frequency of the cavities due to manufacturing tolerances.

(2) Dynamic detuning of the cavities by the Lorentz force during the RF pulse (the accelerating section works in pulse mode during the start stage).

(3) Slow variations of the cavity resonant frequency due to the helium pressure fluctuations, beam loading and microphonics.

The primary factors that drive the design of the tuner are as follows:

(1) The spring constant of the 4-cell cavity (with helium bath) is about 16 N/μm.

(2) The tuning sensitivity of the cavity is 770 Hz/μm.

(3) The tuner installed space is limited by pickup and HOM port.

(4) The cavity requires that the magnetic field at any position of the central line of the tuner be less than 10 mGs (as shown in Fig. 9, the tuner is wrapped up by magnetic shielding).

(5) The heat leakage of the two tuners should be less than 0.3 W due to the limit of the 2 K cryogenic system.

Given the manufacturing tolerances for the cavities, the tuner must be able to statically retune the cavity over a range of 800 kHz centered on the nominal operating frequency of 1.3 GHz.

Based on simulations, at an accelerating gradient 13 MV/m, the Lorentz force is expected to detune the cavity by about 200 Hz. This detuning is significant when compared with the loaded width of the cavity resonance of 260 Hz (@$Q_{\rm L}=5\times10^6$). If the Lorentz force detuning is not compensated, an additional RF power will be required to achieve the desired accelerating gradient.

About 50 Hz detuning will be led by 5 mA beam loading, when the cavity works in CW mode with 4 MV cavity voltage.

At the planned operating temperature of 2 K slow fluctuations in the pressure of the surrounding liquid helium bath can change the resonant frequency of the cavity over periods of several minutes. An ANSYS model estimated the sensitivity would be: $\Delta f/\Delta P$=100 Hz/mbar. The cryogenic system will be able to regulate the helium pressure to within ±0.1 mbar. Pressure variations of this magnitude can shift the resonant frequency by up to ±10 Hz.

Furthermore, in the event that the cavity should fail, the tuner must be able to statically detune the cavity by about 200 kHz to limit any beam-cavity coupling (about 55 kW power output from 5 mA beam at resonant frequency).

3 Tuner design

The major elements of the tuner are shown in Fig. 2. The tuner is amounted on the pickup end. Four annular

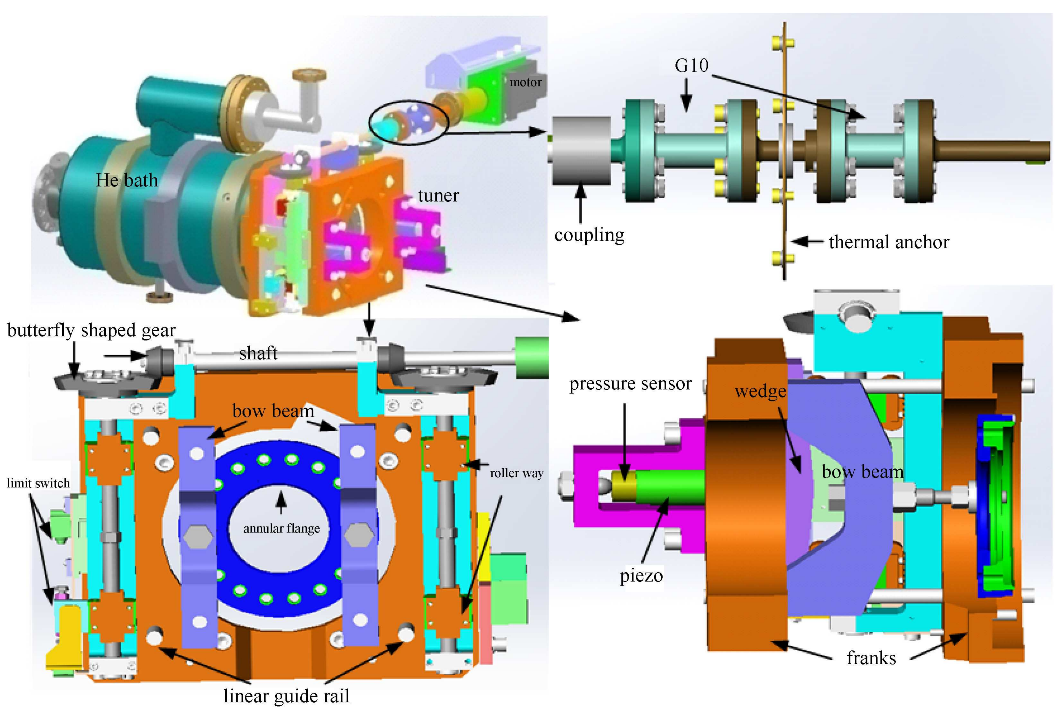

Fig. 2. Details of the 4-cell cavity tuner design.

flanges are fixed with the cavity brim. Two bow beams connect the front flange and annular flange together. A stepper motor controls the position of each roller way via a harmonic drive assembly and screw gear mechanism. The gear set is chosen to provide a reduction ratio of 3:1, and the wedge is to provide a ratio of 15:1 between the displacements of the roller way and the front flange of the motor tuner [5].

The motion of the wedge is transmitted to the front flange of the motor tuner by two piezo actuators. Through two bow beams fixed on the front flange the cavity is stretched. To accommodate the large forces required to stretch the cavity two actuators were used at each end.

To deliver the required static tuning range of 260 kHz to 800 kHz, the motor tuner must displace the cavity by about 351 to 1039 μm. The static load on each piezo will change by ~5.5 kN or 15.7% of piezo blocking force. To ensure that the load on the piezo remains between 10% and 50% of the blocking force, the tuner is designed to always apply tensile force on the cavity flanges across the entire tuning range.

Piezo actuators were selected to provide the cold stroke of 4 μm. To avoid shear forces on the actuators and simplify the connection with the arms, the piezo actuators that have been encapsulated in custom stainless steel housing were chosen.

On the roller way two limit switches are installed, which are designed to limit the stroke of the motor tuner.

During warm test or cold operation, the force applied to the cavity flanges can be monitored using two pressure sensors installed at the end of the piezo acturators.

The tuner has been designed so that it can be assembled and tested as an independent unit before it is mounted on the cavity. Once testing is completed, the assembly is installed on the helium vessel and initial piezo preload is set using adjustment screws.

As Fig. 3(a) shows, the mechanical deformation of the tuner is about 53 μm under the load of 21300 N. The ratio of deformation of the tuner and cavity is 1:25. The max stress of the tuner is about 79 MPa as shown in Fig. 3(b), which meets the mechanical safety required.

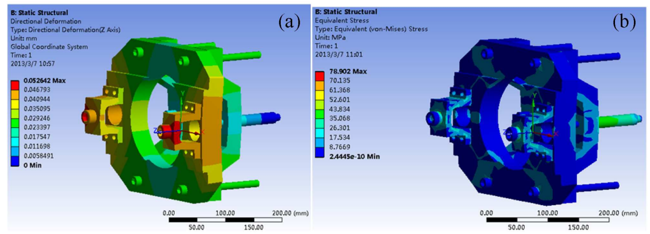

Fig. 3. Simulation of the stress and deformation.

4 Test results

Figure 4 shows the test stand of the tuner. A prototype tuner was installed on the helium vessel of the 4-cell cavity. The performance of the tuner was tested under room temperature and 80 K liquid nitrogen temperature [5, 6].

Fig. 4. The test stand of the tuner.

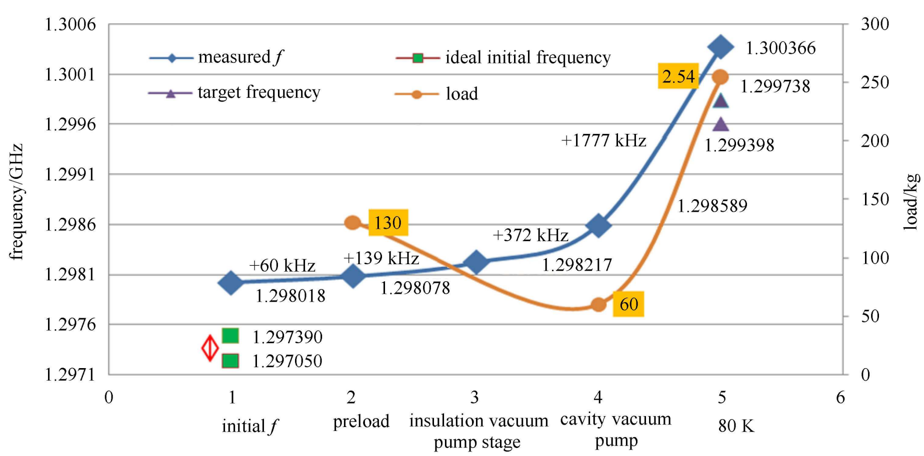

Fig. 5. The load and frequency during cooling-down.

During the cooling-down stage, the frequency and load of the cavity were changing as Fig. 5 shows. The preload is 130 kg, while after the cavity was evacuated the preload decreased to 60 kg. During the decreasing of the temperature the load of the cavity would increase to 254 kg. The frequency of the cavity changed about 1.78 MHz during cooling-down, and the final frequency was over working frequency (1.3 GHz) at 80 K temperature. So it should be tuned to a certain range between 1.29705 and 1.29739 GHz during the pretuning stage in order to keep the frequency within a suitable tuning range and the load force of the cavity is between 17% and 50%.

4.1 Motor tuner test result

To evaluate the performance of the tuner at room temperature, the resonant frequency of the cavity was monitored using a networking analyzer as the stepper motor was operated. During motor operation, the forces on the cavity flanges were monitored by the pressure sensors and the displacement of the cavity was measured with dial gauges.

Figure 6(a) is the room temperature test result of the motor tuner. The max stroke of the tuner is about 3.386 mm. At 80 K liquid nitrogen temperature, the tuning max range of the motor tuner can reach 812 kHz as Fig. 6(b) shows. The max force is about 25.7% of the blocking force.

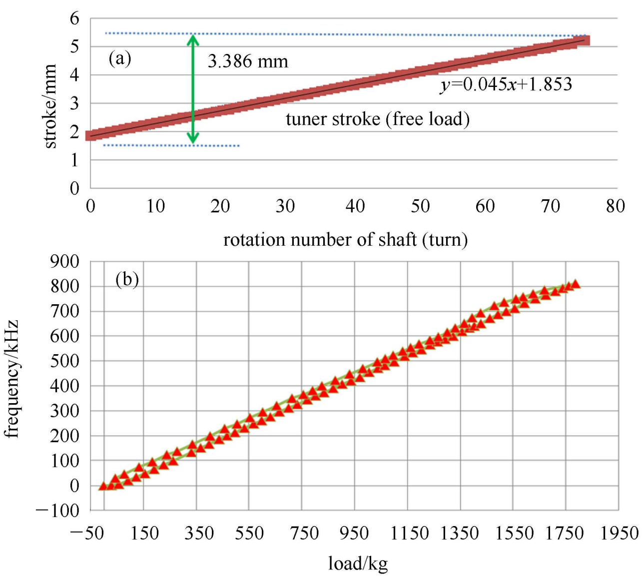

Fig. 6. The tuning range of the motor tuner.

Using slow keys of the tuner controller to control the motor, the minimum amount of frequency change of the cavity measured is about 50–60 Hz as shown in Fig. 7. As the IQ phase has 0.06 degrees of jitter, which corresponds to the frequency jitter of 52 Hz, the resolution of the motor tuner measured was limited by the precision of phase detection.

4.2 Piezo tuner test result

The performance of the piezo tuner was evaluated by measuring the stroke and tuning range.

As shown in Fig. 8(a), the stroke of the piezo tuner is about 60 μm at free load and room temperature, the corresponding frequency change of the cavity should be

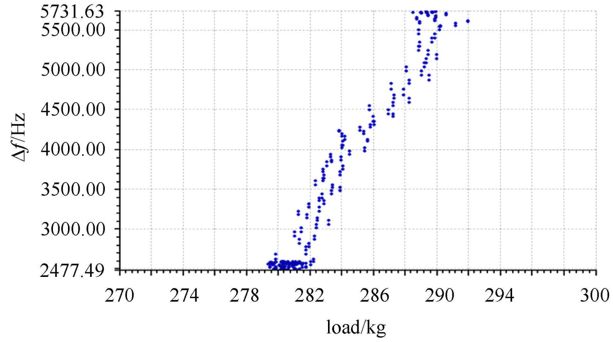

Fig. 7. The resolution of the motor tuner.

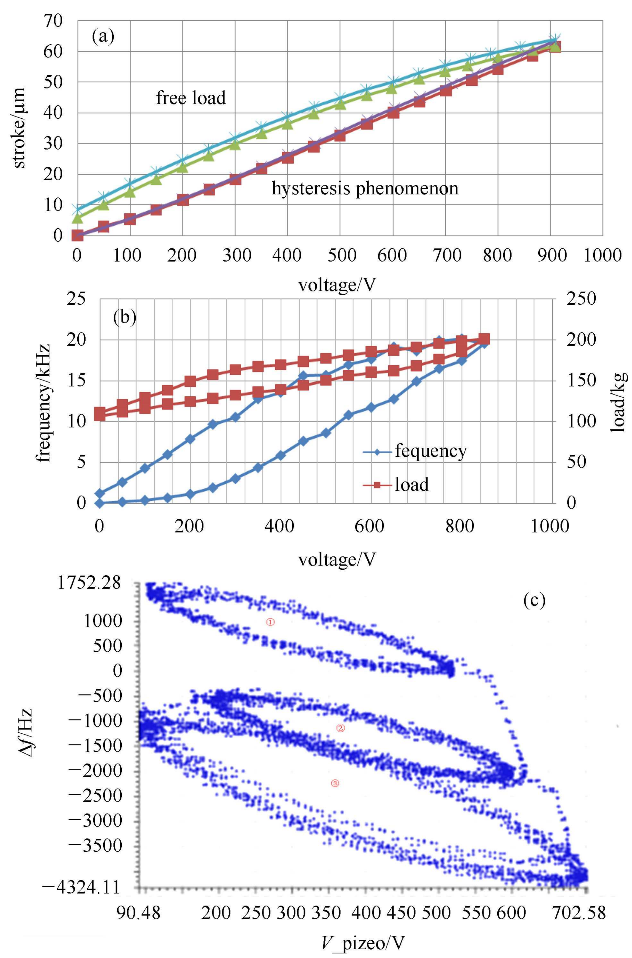

Fig. 8. The test curve of the piezo tuner.

42 kHz, while in fact the frequency change of the cavity is only about 20 kHz as shown in Fig. 8(b). Nearly half of the displacement is consumed by mechanical clearance. Therefore, the assembly process of the tuner requires that each part be fixed tightly.

The piezo tuner was tested at 80 K liquid nitrogen temperature as Fig. 8(c) shows. The sine signal was magnified by a high voltage amplifier to drive the piezo tuner. As Curve ① the tuning rang is about 1.8 kHz at the offset voltage of 300 V and scan voltage range ±200 V, Curve ② shows the tuning rang is also 1.8 kHz at the offset voltage of 400 V and the scan voltage range ±200 V， while Curve ③ displays the tuning rang at about 3.3 kHz at the offset voltage of 400 V and the scan voltage range ±300 V. So the tuning range of the piezo tuner meets the requirements at offset voltage of 400 V and scan voltage range ±300 V.

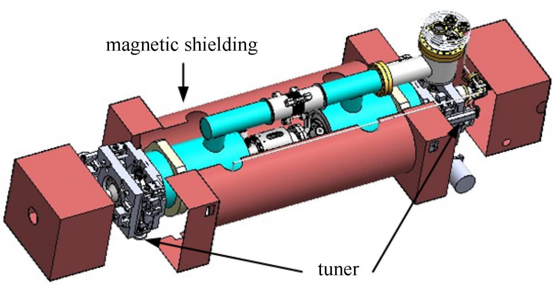

Fig. 9. The magnetic shielding of the cavity and tuner.

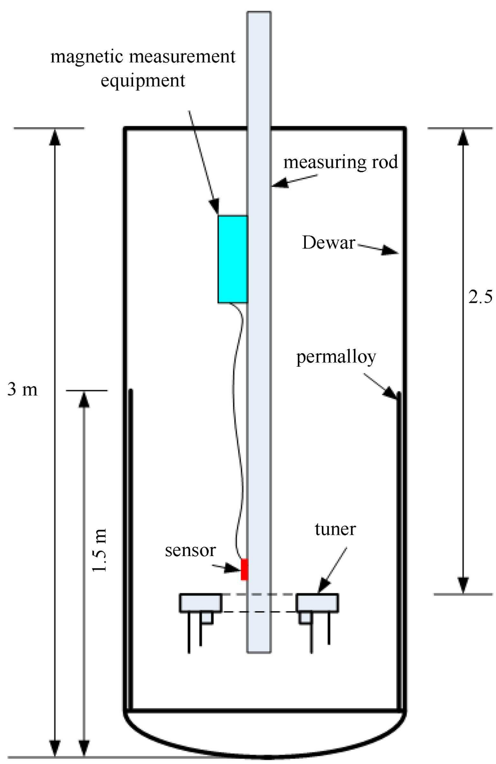

Fig. 10. The schematic diagram of the magnetic field measurement of the tuner

4.3 Axial magnetic field measurement

The tuner and cavity are wrapped by magnetic shielding as Fig. 9 shows. Because the value of residual magnetism has great effect on the superconducting cavity Q_0, so it needs to limit the axial magnetic field of the tuner.

The mechanical structure of the motor tuner is made of 304 stainless steel. The magnetic field of the tuner was measured by a Gauss magnetic measurement instrument in a vertical test Dewar, as shown in Fig. 10.

The test results of the magnetic field are shown in Fig. 11. The upper end of the Dewar is zero position.

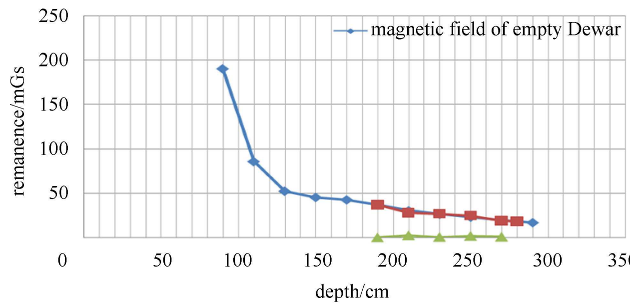

Fig. 11. The magnetic field measure results.

The inner intensity of the magnetic field of Dewar decreases with the increase of depth. From the depth of 0 cm to 130 cm the intensity of the magnetic field decreased rapidly; when the depth was over 130 cm it decreased slowly and tended to be stable. The strength of the magnetic field of the tuner leads less than 3 mGs, which meets the requirements of the axial magnetic field of the tuner no more than 10 mGs.

Important tuner parameters are summarized in Table 1.

Table 1. The tuner design and performance parameters.

parameter	designed	measured
cavity spring constant/(N/μm)	16	∼15
cavity sensitivity/(Hz/μm)	770	∼700
piezo sensitivity/(Hz/V) (room temperature)	46.2	23.5
gear set	1:3	1:3
wedge	1:15	1:15
maximum piezo load/N	16000	17860
motor tuning range/kHz	800	812
piezo tuning range/kHz	⩾2	3.3
axial magnetic field of tuner	<10 mGs	∼3 mGs
heat leakage/W	<0.3	—
piezo preload/N (initial piezo load)	1300	1300
number of piezo	2	2
harmonic drive ratio	1:50	1:50

5 Conclusion

The tuning range and axial magnetic field of the tuner have satisfied the design requirements through room temperature and 80 K liquid nitrogen temperature test. Due to the limit of the test conditions, the dynamic performance and resolution of the tuner did not function. The work performance of the tuner needs further research.

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