Preliminary study on the RF tuning of CSNS DTL

YIN Xue-Jun(殷学军)[1,2] LI A-Hong(李阿红)[1] XIAO Yong-Chuang(肖永川)[1] CHEN Qiang(陈强)[1] LIU Hua-Chang(刘华昌)[1] GONG Ke-Yun(巩克云)[1] FU Shi-Nian(傅世年)[1]

[1] Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China
[2] Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China

Abstract: In the R&D of the CSNS Drift Tube Linac (DTL), the first unit tank with 28 drift tubes has been developed. The axial accelerating field is ramped from 2.2 MV/m to 3.1 MV/m in this tank. The required field flatness is less than ±2% with the standard deviation of 1% for the beam dynamics; the field stability should be less than 1% for machine stable operation. After successful alignment, RF tuning was carried out focusing on the field profile measurement. Four slug tuners and eleven post couplers were applied in this procedure. The ramped field and required stability had been achieved by fine adjustment of the slug tuners and post couplers. In this paper, the preliminary tuning results are presented and discussed.

Key words: Alvarez DTL, RF tuning, bead perturbation, field measurement

PACS: 29.17.+w, 41.20.Jb, 06.50.D **DOI:** 10.1088/1674-1137/38/2/027002

1 Introduction

The CSNS Alvarez DTL working at 324 MHz will accelerate the H^- ion from 3.0 MeV to 80.0 MeV [1]. The first unit tank (∼2.8 m in length) was consisted of 29 accelerating cells, including 28 full drift tubes and two end plates. In this tank, the axial accelerating field is designed as ramped from 2.2 MV/m to 3.1 MV/m. To make the DTL tank operate stably and against any perturbation caused by machining errors and the small deformation due to thermal load, slug tuners and post couplers were utilized for the RF tuning procedure. For our case, four slug tuners and eleven post-couplers were used.

The field flatness needs to be $\leqslant \pm 2$ % with the standard deviation of 1% based on the beam dynamics consideration. Noting that the tuning was performed in the air but that the machine operates under a vacuum, so the air effect should be compensated for. The estimated frequency change due to the evacuation is about −100 kHz [2]. In addition, the difference between the tuning temperature (21 ℃) and the operating temperature (26 ℃) can provide an additional frequency change of 20 kHz when the frequency sensitivity on the temperature is assumed to be about 4 kHz/℃ [3]. Therefore, the target tuning frequency is set to be about 323.920 MHz ±5 kHz at 21 ℃. Furthermore, the maximum local frequency shift is expected to be no more than 8 kHz, which implies the local temperature perturbation is less than about 2 ℃. The beam loading can also cause the frequency shift, but will be less than 2 kHz. Therefore, the required stability is determined to be less than 100%/MHz, which means that the field stability sensitivity is less than 1% with 10 kHz perturbation.

To operate DTL effectively, basic parameters such as the resonant frequency, field flatness and field stability need to be tuned by following the requirements, which include four steps: first, field flatness tuning with the slug tuners; second, careful field stability adjustment with the post couplers; third, field flatness recovery by rotating the post couplers; and finally fourth, resonant frequency adjustment by moving all slugs uniformly, where accurate measurements of the field profile are crucial.

2 Perturbation measurement

2.1 Field profile measurement with bead-pull method

In the DTL tank, the field profile can be measured by the bead-pull method based on Slater's perturbation theorem [4]. It has been shown that the change in resonant frequency due to the bead perturbation is proportional to the relative change in stored energy:

$$\frac{\Delta\omega}{\omega_0}=\frac{\Delta U}{U}=\frac{-\int_{V_0}(\Delta\varepsilon E\cdot E_0^*+\Delta\mu H\cdot H_0^*)\mathrm{d}v}{\int_{V_0}(\varepsilon_0 E\cdot E_0^*+\mu_0 H\cdot H_0^*)\mathrm{d}v}, \tag{1}$$

where U is the stored energy in the cavity whose volume is V_0, ΔU is the stored energy change, E and E_0^*

Received 2 April 2013

are the perturbated and unperturbated electric field and H and H_0^* are the perturbated and unperturbated magnetic field respectively. ε_0 and μ_0 are the permittivity and permeability of a vacuum. $\Delta\varepsilon$ and $\Delta\mu$ are the permittivity and permeability difference between the bead and the vacuum.

For the case of a small sphere bead with radius r, where the perturbed field can be approximated by an unperturbed field, it can be shown that:

$$\frac{\Delta\omega}{\omega_0}=-\frac{\pi r^3}{U}\left[\frac{\varepsilon_r-1}{\varepsilon_r+2}\varepsilon_0|E_0|^2+\frac{\mu_r-1}{\mu_r+2}\mu_0|H_0|^2\right], \tag{2}$$

where ε_r and μ_r are the relative permittivity and relative permeability.

By noting that the magnetic field strengths on the z axis are zero since the DTL tank is operating in TM010 mode, then Eq. (2) reduces to

$$\frac{\Delta\omega}{\omega_0}=-\frac{\pi r^3}{U}\left[\frac{\varepsilon_r-1}{\varepsilon_r+2}\varepsilon_0|E_0|^2\right]. \tag{3}$$

For a spherical metal bead ($\varepsilon_r\to\propto,\mu_r\to 0$), Eq. (3) can be simplified further to

$$\frac{\Delta\omega}{\omega_0}=-\frac{\pi r^3\varepsilon_0}{U}|E_0|^2. \tag{4}$$

Here, the frequency shift due to the spherical bead is proportional to the square of the field intensity on the spot where the bead is located. With this relation, the field profile can be obtained by measuring the frequency shift as the bead is moved through the cavity.

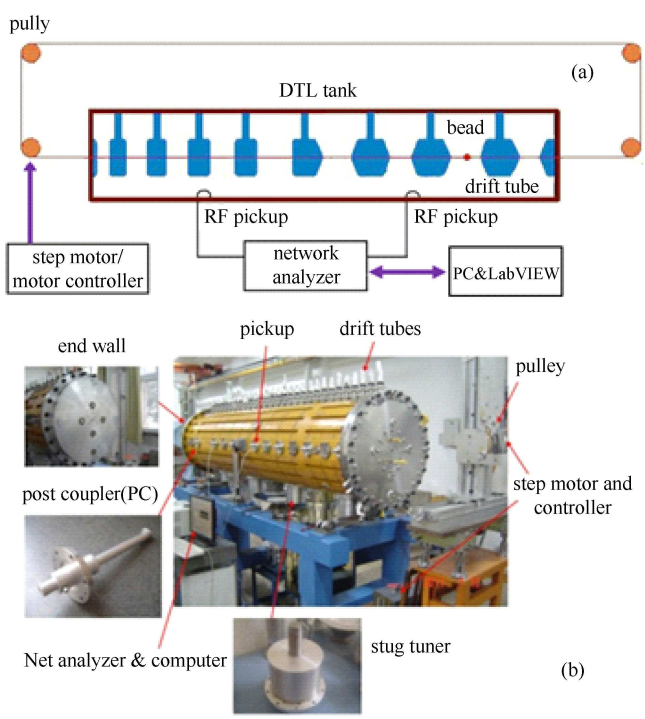

Fig. 1. DTL RF tuning setup. (a) The schematic diagram of a field-measurment; (b) the apparatus photo of DTL RF tuning.

2.2 DTL tuning setup

Figure 1(a) shows the schematic diagram of the field-measuring apparatus of DTL tank 1 based on Slater's perturbation method. A spherical hollow bead with a 3.0 mm diameter is used. The bead is transferred by a step motor and the speed is adjusted to complete the measurement in three minutes, which gives a spatial resolution of about 0.5 mm. The phase shift is measured using the vector network analyzer and the computation is carried out on the computer so that the derived field can be obtained, integrated, plotted and compared. The error caused by the bead shifting from the axis is estimated using the field distribution near the axis. A bead center shift of up to ±0.2 mm including the sag when it moves is acceptable.

Figure 1(b) shows a photo of the overall tuning setup with tuning elements, such as slug tuners, post couplers and RF pickups etc. During the flatness tuning and stability tuning, the movable slugs and the post couplers, which are made of aluminum, are used.

3 RF tuning results

3.1 Field flatness tuning with slug tuners

Equation (4) in the previous analysis shows that the local resonant frequency shifts are proportional to the local electric field energy in the opposite direction; the local resonant frequency can be modified by changing the insertion length of the slug tuner. Therefore, it is feasible to tune the DTL tank to have a ramped field profile by adjusting the position of the movable slug tuner.

As mentioned above, the required field flatness is ±2% with the standard deviation of 1%. To tune field flatness effectively, the frequency changes due to the perturbation caused by the slug tuners should be measured. The four slug tuners are initially set in constant length in the tank at 50 mm. The measured frequency spectrum is shown in Fig. 2. As shown in this figure, the working frequency is 323.4517 MHz, which corresponds to the TM010 mode. The two nearest neighbor frequencies, which are 319.437 MHz and 327.315 MHz, are also

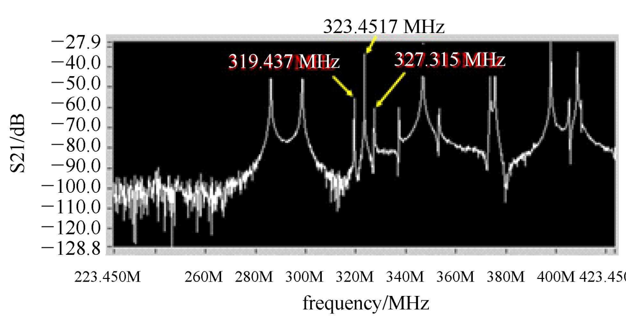

Fig. 2. The frequency spectrum.

measured, and the frequency intervals Δf correspondingly are 4.01 MHz and 3.86 MHz respectively.

The effect of slug tuner's position on the resonant frequency is measured carefully and plotted in Fig. 3. We can find that the resonant frequency shift is linearly proportional to the insert depth of the slug tuner, especially at the range of 10–80 mm. The measured sensitivities for each slug ranged from 1.6 to 6.7 kHz/mm. Further, the frequency shifts caused by the insert length of the tuner are different depending on the positions of the tuners in the tank. Tuner1 at the low energy end only caused a 100 kHz shift but tuner4 at the high energy end has a 670 kHz shift.

After fine tuning with the slug tuners in several iterations, the required field flatness was achieved. The field profiles before and after the slug tuning are plotted in Fig. 4. As can be seen, the field flatness decreases from 11.46% to 2.21% after tuning.

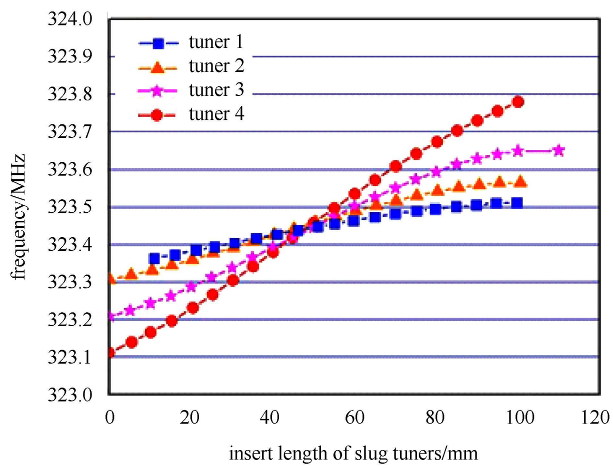

Fig. 3. The frequency shift caused by slug tuners.

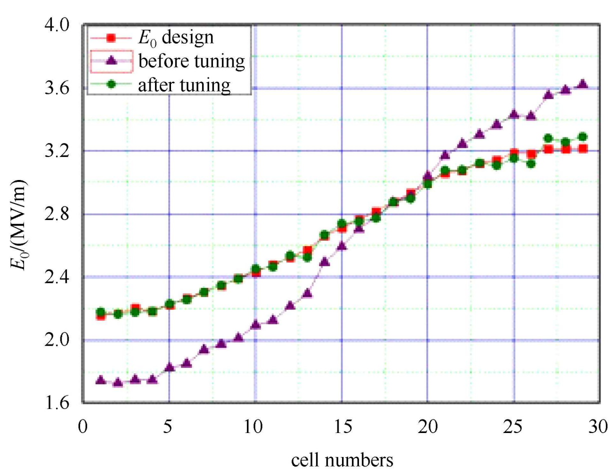

Fig. 4. The field profiles before and after tuning.

3.2 Field stabilization tuning by post couplers

The RF structure with many cells like DTL is very sensitive to the perturbation, such as fabricating errors and the small deformation due to powerload on the cavity wall, which would cause a large change in the field profile. To make the accelerating field profile insensitive to such perturbation, post couplers (PCs) are used in DTL cavities to create a secondary coupled resonator system, which can form the post coupler modes (PC modes) in the frequency spectrum at a lower frequency band than the operating frequency 324 MHz.

Initially, the post couplers are inserted as far as possible. The frequency spectrums of PCs mode are much lower than the operating mode frequency. After this, the post couplers are gradually extracted and the PC frequency spectrum moves from the low band to the high band during this extraction. When the PCs highest mode PC1 is adjusted to near the symmetric position in the frequency spectrum to the first higher order mode of TM mode, such as TM011 with respect to the operating modeTM010, the perturbation effects from both post coupler modes and higher order modes cancel each other out, which will lead to the field stabilization [5].

So, after obtaining the flat field profile, the necessary field stabilization tuning is performed. To measure the degree of the field stabilization quantitatively, the stability parameter-Tilt Sensitivity (TS) [6] is defined as:

$$\mathrm{TS}[\%/\mathrm{MHz}]=\frac{E_{\mathrm{m}}-E_0}{E_0}\times\frac{1}{\Delta f[\mathrm{MHz}]}100\%. \tag{5}$$

Where E_{m} and E_0 are perturbed and unperturbed electric fields respectively and Δf is the amount of frequency perturbation. In our measurement, two kinds of perturbation, such as ± 20 kHz, are introduced by extracting and inserting two movable slug tuners located at both ends of the tank, as shown in Fig. 5. Both perturbations make about 2% tilt of the field distribution without post couplers.

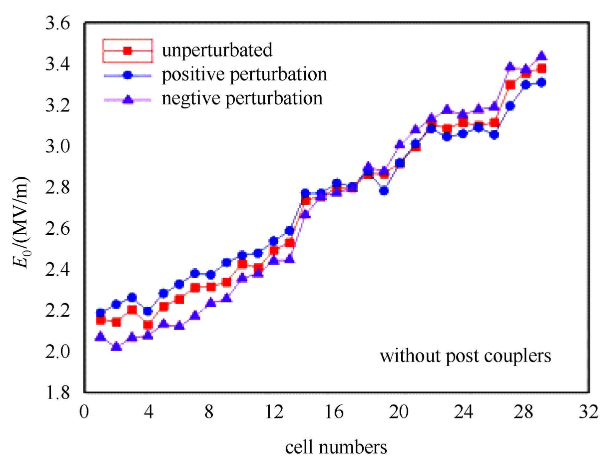

Fig. 5. The field profile with and without perturbation.

When the field stabilization is performed by tuning with the post couplers, all post couplers are set at the same position initially and then gradually extracted outward until the required tilt sensitivity is obtained. Fig. 6 shows the measured frequency spectrum when the initial stability was achieved.

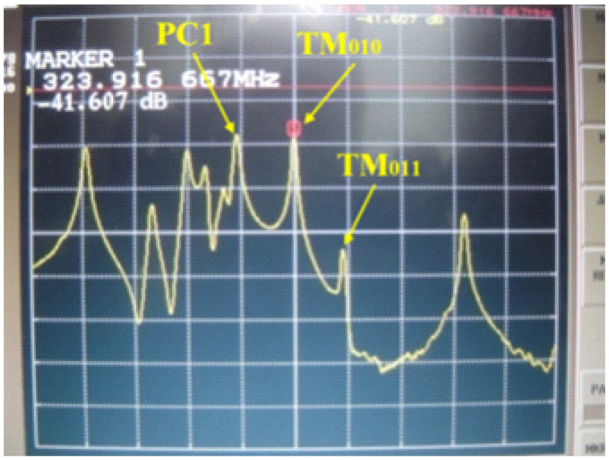

Fig. 6. The measured frequency spectrum.

As can be seen in Fig. 6, the post coupler modes are located in the lower band with respect to the operating mode TM010. In our tuning results, both of the frequency spacings of the PC1 mode and the TM011 mode with respect to the operating mode TM010 are ~5.82 MHz. The measured dispersion curves of TM modes and PCs modes after getting field stability are shown in Fig. 7. The system, composed by two chains of coupled resonators, has two bands of frequencies: the TM band and the PC band. Since the first unit DTL tank has eleven Post-Couplers, in the PC band there are eleven resonating modes correspondingly.

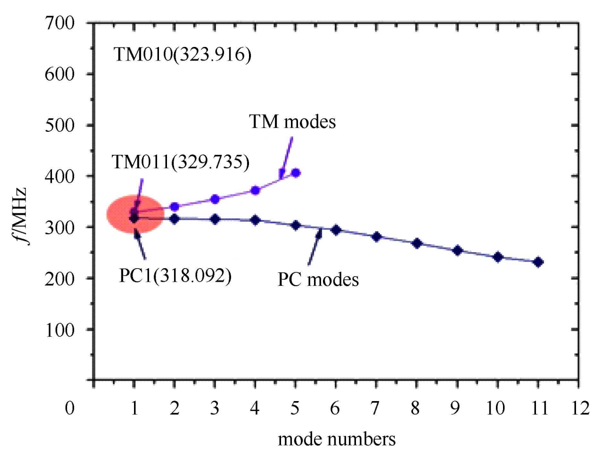

Fig. 7. Dispersion curves of TM and PCs modes.

It should be pointed that the flatness of the field profile would be somewhat distorted during the field stabilization, which can be recovered by rotating the tip attached at the end of each post coupler. Of course the rotating angles and direction of each tip are not the same. After that, the field flatness and the stability were tuned by tuning the slug tuners and post-couplers iteratively. This completes the coarse tuning and the fine tuning is conducted with the tilt sensitivity measurement. Finally, the field flatness profiles with and without perturbations are obtained, as presented in Fig. 8. The tuning results are summarized in Table 1. The field flatness was less than 1.89%(⩽2% in design) with a standard deviation of 0.87%; the stability error decreased from 250%−−165%/MHz to 99%−−62%/MHz corresponding 2.5%−−1.65% to 0.99%−−0.62%.

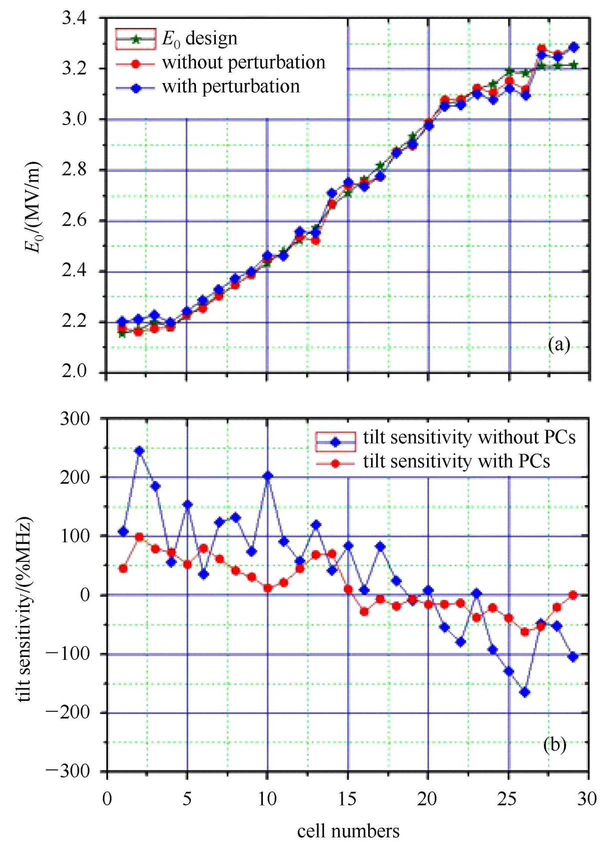

Fig. 8. CSNS DTL1RF tuning results for cold measurement. (a) Field flatness; (b) tilt sensitivity.

Table 1. The CSNS DTL1 RF tuning results.

	designed	measured
frequency/MHz	323.920±5 kHz	323.917
field flatness	⩽±2%	<1.89%
tilt sensitivity	⩽1%(100%/MHz)	0.99%−−0.62%

4 Conclusions

In the R&D of CSNS Alvarez DTL, careful RF tuning measurement was carried out. The field-measuring apparatus based on Slater's perturbation theorem was set up. The main measurement procedure includes the frequency measurement, the field flatness tuning and the field stability tuning. The measured sensitivities were from 1.6 to 6.7 kHz/mm for four slug tuners. After some iteration fine tuning, the field flatness $\leqslant$1.89% and the tilt sensitivity <1% were successfully achieved. In the near future, the frequency perturbation caused by slugs, RF pickups and RF power couplers should be considered in the stability parameter. The error of the measurement system should not be neglected. Finally, it should be beneficial to improve the environment within the RF tuning measurement system.

References

1 YIN X J, GONG K Y, PENG J, SONG H, XIAO Y C, LI A H, LIU L, FU S N. The R&D Status of DTL for CSNS. Science China Physics, Mechanics & Astronomy, 2011. 54
2 Naito F, Ikegami M, Kato T et al. Mechanical and RF Properties of the DTL for the JAERI/KEK Joint Project. Proc. of LINAC2002. Gyeongju, Korea1, 2002. 359–361
3 Wangler T P. Principles of RF Linear Accelerators. Johnwiley & Sons, Inc, 1998
4 David M.Pozar. Microwave Engineering and Applications. Pergamon Press, 1980
5 Natio F, Tanaka H, Ikegami M et al. Tuning of the RF Field of the DTL for the J-PARC. Proc. of PAC 2003. Portland, USA, 2003. 2835–2837
6 Alharbi N et al. Field Stabilization with Post Couplers for DTL tank 1 of Linac 4. CARE-Note-2006-012-HIPPI