A new tuning procedure for the DTL RF field pattern

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Abstract The DTL tank is a multi-cell cavity. In a fabricated tank, the measured average axial field E_0 for each cell may obviously deviate from the designed value. It is generally thought the deviation is due to the errors in fabrication and assembly. But it is not always true. In this paper, it is shown that the deviation may already exist before fabrication in some cases. It is partly due to the imperfection of the current design procedures. A new design method is introduced to reduce the deviation in the design stage.

Key words DTL, deviation, average axial field, tuning

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1 Introduction

The drift tube linac (DTL) is a structure that consists of tanks containing many drift tubes to form cells, and each cell is slightly longer than the previous one due to the increase of the particle velocity. Fig. 1 illustrates its typical structure. A DTL cell starts and ends in the middle of two adjacent drift tubes. The cell length is $\beta\lambda$, where β is the synchronous particles' velocity, and λ is the RF wavelength. Synchronous particles refer to the particles appearing in the center of successive gaps at the synchronous phase ϕ_s[1], with a phase shift of 2π between adjacent cells. As a proton beam moves along the axial direction, it drifts inside the drift tubes which shield the RF field during the portion of the period that will decelerate the beam. When the beam passes by the gaps, which refer to the longitudinal space between drift tubs, it is accelerated during the accelerating portion of the period. The electric field is roughly parallel to the tank axis and concentrated near the longitudinal axis by drift tubes.

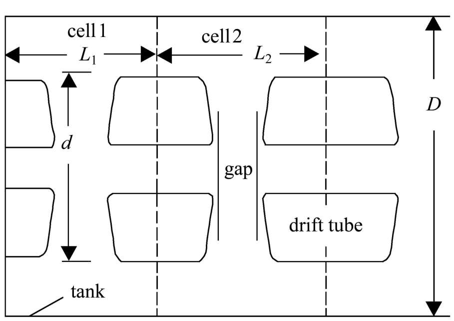

Fig. 1. Schematic diagram of the DTL.

In a DTL cell, the synchronous particle gains energy δW:

$$\delta W = qE_0TL\cos\phi_s\,, \tag{1}$$

where q is the charge of the particle, E_0 is the average axial electric field:

$$E_0 = \frac{1}{L}\int_{-L/2}^{L/2} E_z \mathrm{d}z\,, \tag{2}$$

E_z is the longitudinal component of electric field, T is the transit-time factor, and L is the cell length.

The DTL design usually consists of two steps and uses two codes, DTLFISH[2] and PARMILA (Phase and Radial Motion in Ion Linear Accelerators)[1]. First, for a series of given β values, DTLFISH tunes some representative cells to a desired resonant frequency. Half cell length is used because the cell is supposed to be symmetric, as DTLFISH does not consider the velocity increase of the particles in the gap. DTLFISH stores T and other properties of each cell in SFDATA tables, tabulated as a function of β.

In the second step, the beam-dynamic code PARMILA considers the velocity increase of particles in the gap and generates asymmetric cells, in which the right half of the cell is longer than the left one. Given the energy of the synchronous particle at the end of cell $N-1$, according to Eq. (1), PARMILA

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calculates the cell length L_N, gap length g_N, gap position of cell N and the energy of the synchronous particle at the end of that cell. The ratio g_N/L_N for the cell is interpolated from the SFDATA table and thus the cell resonates at the working frequency f_0. The variations of E_0 and ϕ_s along a tank are input by the designer and they affect the energy gain and thus the cell length. In this paper, we use E_{0D} to stand for the designed E_0 value in PARMILA code. Obviously the beam dynamics of a DTL accelerator depends on E_{0D}.

DTL is usually fabricated directly using the cell data given by DTLFISH and PARMILA. However, a general problem appears: the measured E_0 for each cell in a fabricated tank deviates a lot from the designed E_{0D}. Here, we use E_{0M} to stand for the measured value. This deviation will affect the net accelerating voltage and the peak surface field. Engineers used to think the deviation is attributed to the errors in fabrication and assembly. The problem is usually solved by using slug tuners and post couplers. Tuning work often costs a lot of time and the inserted tuners lower the Q value of the tank.

We found that the deviation, in fact, already exists before the fabrication. It is because that the E_{0D} in PARMILA are decided by the designer and the designer doesn't know the cell geometries beforehand. Then PARMILA uses the input E_{0D} to generate cell geometries of a tank, by interpolating the cell data from DTLFISH that do not account for E_{0D} variation information. In a tank, the field distribution in each cell is affected by the field in other cells, and the E_0 of each cell is not only related with the input power, but also with the cell geometries. As a result, the deviation between the E_{0M} and the E_{0D} appears.

To solve this problem, we suggested a new design procedure in this paper, so as to tune the deviated field back to the design pattern. The new procedure can obviously reduce the deviation and improve the precision of the DTL design. In the second section, an example tank is designed to clearly show the problem. Then the problem is overcome with a new procedure presented in Section Three. Finally the fabricated DTL tank in SNS project is taken as an example to further demonstrate the issue.

2 DTL cavity design for CSNS

The proton linear accelerator for the China Spallation Neutron Source (CSNS) project consists of a 3 MeV radio-frequency quadrupole linac (RFQ) and a 132 MeV DTL. The DTL has been proposed to construct in two phases. Its energy is chosen as 81 MeV for Phase Ⅰ and 132 MeV for Phase Ⅱ. The specifications of the DTL for CSNS are given in Table 1. The design of the DTL is based on a 30 mA beam current.

Table 1. Specifications of CSNS DTL accelerator.

ion	H^-
frequency	324 MHz
input energy	3 MeV
input beam	12.46 π·mm·mrad (transverse)
un-normalized total emittance	571.5 π·deg·keV (longitudinal)
output energy	132 MeV
duty factor	1.05%
I_{peak}/mA	15(1st phase), 30(2nd phase)

The 132 MeV DTL consists of 7 tanks. The design parameters of each tank from PARMILA are shown in Table 2. The E_{0D} designed for the 1st tank is different from that for other tanks. In other tanks, the E_{0D} is constant along the tank. But in the 1st tank, the E_{0D} is linearly ramped from cell 1 to cell 24, and then keeps constant until the exit end of the tank, as plotted in Fig. 2, with cycles (○). In DTL cells, the points of maximum surface field are near the drift tube noses. At the low energy section of the tank, the gaps are short, so small E_{0D} is chosen to avoid RF breakdown. As particle energy increases, the gap length increases too. A larger E_{0D} is more advisable for a high accelerating efficiency at the high energy section of the tank.

Table 2. Design parameters of CSNS DTL tanks.

tank number	1	2	3	4	5	6	7	total
output energy/MeV	21.76	41.65	61.28	80.77	98.86	115.8	132.2	132.2
length/m	7.99	8.34	8.5	8.85	8.69	8.57	8.67	59.6
number of cell	61	36	29	26	23	21	20	216
RF driving power/MW	1.41	1.41	1.39	1.45	1.45	1.45	1.49	10.05
total RF power/MW	1.97	2.01	1.98	2.03	1.99	1.96	1.98	13.92
accelerating field/(MV/m)	2.2 to 3.1	3.1	3.1	3.1	3.1	3.1	3.1	
synchronous phase/(°)	−30 to −25	−25	−25	−25	−25	−25	−25	

After the DTL is designed with PARMILA, we use the MDTLFISH (Multi-cell DTL Fish)[2] code to simulate the 1st tank with 61 cells all together. The E_0 for each cell are got by integrating the E_z along the axis in a cell length. Here we use E_{0S} to stand for the simulated E_0 value in MDTLFISH code, as indicated by the bullets (•) in Fig. 2. It obviously deviates from the E_{0D} and the difference is illustrated by the ratio of

E_{0S} to E_{0D}, as plotted with the solid curve in Fig. 2. The ratio range is rather large: from 0.92 to 1.25. This result confirms that the E_0 distribution pattern in the tank generated by PARMILA doesn't agree with the designed E_0 distribution pattern. A new step should be added to the design procedure, which is simulating the tank generated by PARMILA, finding out the deviation, and tuning the tank to reduce the deviation.

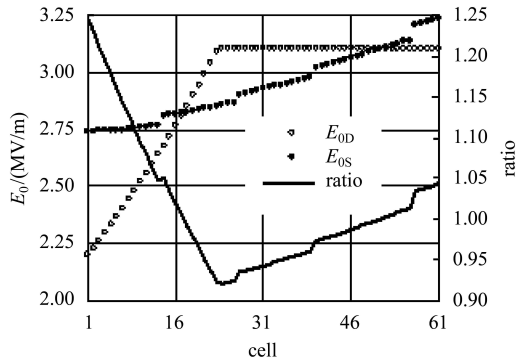

Fig. 2. The E_0 distribution pattern of DTL-1 for CSNS.

3 RF field tuning

As shown in Fig. 2, the tuning goal for the 1st tank is to reduce the E_{0S} at the low energy end and increase the E_{0S} in the middle of the tank. The effect of local frequency perturbation on the E_0 distribution pattern is utilized.

3.1 Effect of local frequency perturbation on a chain

In a linac tank, cells may have local configuration deformation that introduces a local frequency deviation from the resonant frequency $f(z)=f_0+\delta f(z)$, where f_0 is the resonant frequency of the structure. As a result, the field is perturbed. In the case the perturbation is small $\delta E_0 \ll E_0$, the effect of local frequency perturbation on the field satisfies[3, 4]:

$$\frac{\mathrm{d}^2}{\mathrm{d}z^2}\left(\frac{\delta E_0}{E_0}\right)\approx\frac{8\pi^2}{\lambda_0^2}\left(\frac{\delta f}{f_0}\right). \tag{3}$$

Here, λ_0 is the free space wavelength, δf is the frequency perturbation, and δE_0 is the field perturbation. The boundary conditions are $\mathrm{d}(\delta E_0/E_0)/\mathrm{d}z=0$ at the tank ends.

Figure 3 is an example performed from Eq. (3). Figs. 3(a) and (b) show a tank without perturbation: uniform frequency distribution and uniform E_0 distribution along the tank respectively. After adding a local frequency perturbation like Eq. (4):

$$f=\begin{cases} f_0+\dfrac{m}{m+1}\Delta f & (0\leqslant z\leqslant L_1) \\ f_0 & (L_1<z<L_2) \\ f_0-\dfrac{1}{m+1}\Delta f & (L_2\leqslant z\leqslant L_3) \\ f_0 & (L_3<z<L_\mathrm{T}) \end{cases}. \tag{4}$$

the E_0distribution changes as expressed by Eq. (5):

$$\frac{\delta E_0}{E_0}=\begin{cases} \dfrac{m}{m+1}\dfrac{8\pi^2}{\lambda_0^2}\dfrac{\Delta f}{f_0}\dfrac{z^2}{2} & (0\leqslant z\leqslant L_1) \\ \dfrac{m}{m+1}\dfrac{8\pi^2}{\lambda_0^2}\dfrac{\Delta f}{f_0}L_1\left(z-\dfrac{1}{2}L_1\right) & (L_1\leqslant z\leqslant L_2) \\ \dfrac{1}{m+1}\dfrac{8\pi^2}{\lambda_0^2}\dfrac{\Delta f}{f_0}\left[L_3z-\dfrac{z^2}{2}+\dfrac{1}{2}(L_1L_2-L_1L_3-L_2^2)\right] & (L_2\leqslant z\leqslant L_3) \\ \dfrac{1}{m+1}\dfrac{4\pi^2}{\lambda_0^2}\dfrac{\Delta f}{f_0}(L_3^2-L_2^2+L_1L_2-L_1L_3) & (L_3\leqslant z\leqslant L_\mathrm{T}) \end{cases}, \tag{5}$$

where

$$m=\frac{L_3-L_2}{L_1}. \tag{6}$$

The biggest field perturbation is

$$\left(\frac{\delta E_0}{E_0}\right)_{\max}=\frac{1}{m+1}\frac{4\pi^2}{\lambda_0^2}\frac{\Delta f}{f_0}(L_3^2-L_2^2+L_1L_2-L_1L_3). \tag{7}$$

Figures 3(c) and (d) show the perturbed frequency and E_0 distributions respectively.

3.2 Field tuning

According to the guidance of Eq. (7), the frequencies of the first 3 cells and the other 3 cells in the middle of the 1st tank are tuned by adjusting their gap length in the MDTLFISH simulation. The frequencies of cell 1, 2, 3 are tuned from 324 MHz to 327.24 MHz, and the frequencies of cell 22, 23, 24 are tuned from 324 MHz to 321.8 MHz. In average, there is little resonance frequency shift in the tank. In Fig. 4, the bullets (•) show the E_{0S} after tuning, which is close to the E_{0D} (○) now. The ratio of two fields ranges from 0.97 to 1.04, within ±4%, which becomes much less than that in Fig. 2 and not difficult to be tuned by tuners and post couplers.

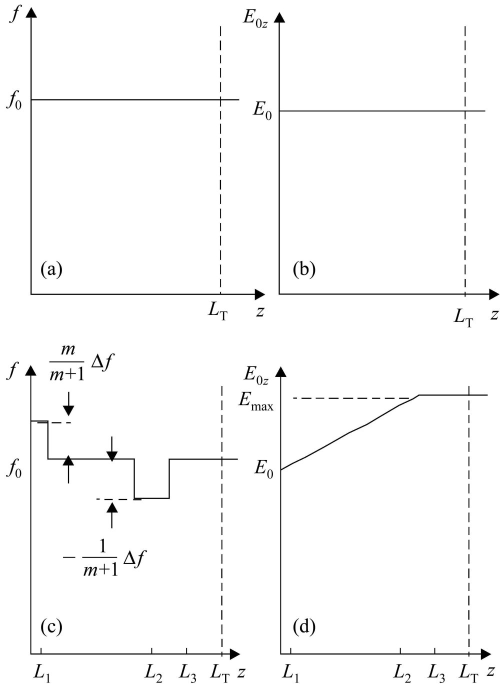

Fig. 3. An example of the effect of local frequency perturbation on a cell chain. (a) Frequency distribution of the unperturbed tank. (b) E_0 distribution pattern of the unperturbed tank. (c) Frequency distribution of the perturbed tank. (d) E_0 distribution pattern of the perturbed tank.

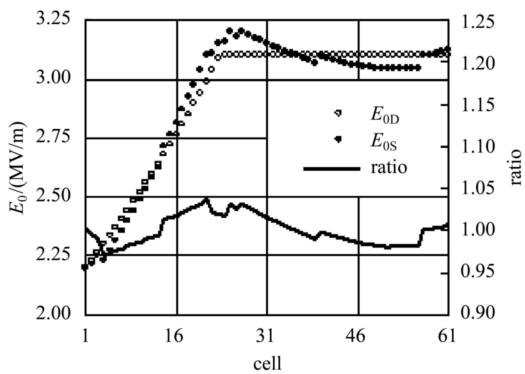

Fig. 4. The E_0 distribution pattern of DTL-1 for CSNS, after tuning.

Now a new problem appears. Although the E_0 for each cell is tuned right, the transit time factor T of the tuned cell is changed because we have adjusted the cell gap. Referring to Eq. (1), particles will not reach the original designed energy after they pass through these cells. To solve this problem, we return to PARMILA code to correct the SFDATA tables with new T and other parameters. Running PARMILA again, the code generates a new tank by interpolating from new SFDATA tables. The E_{0D} and the E_{0S} for this new tank are shown in Fig. 5. Comparing Fig. 5 with Fig. 4, it can be seen there is no observable difference in E_{0S}, because we have not changed the tank a lot.

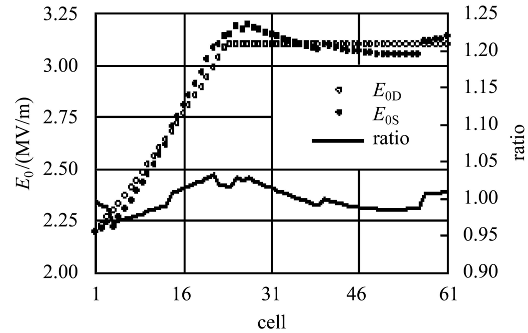

Fig. 5. The E_0 distribution pattern of DTL-1 for CSNS, after correcting.

4 DTL for SNS

The deviation problem also exists in the SNS DTL. We simulated its 1st tank, and the E_{0S} (•) are shown in Fig. 6(a). (Design parameters for the SNS DTL can be found in SUPERFISH installation subdirectory). The cycles (○) show the E_{0D}, and the solid curve shows the ratio of these two fields. The rather large ratio is almost equal to the measured result in the SNS DTL cavity tuning report[5].

We tried the same method to tune the SNS DTL cavity. Tuning the frequency of cell 1 from 402.5 MHz to 414 MHz and the frequency of cell 60 from 402.5 MHz to 396 MHz, the E_{0S} is approaching the E_{0D} as shown in Fig. 6(b). The solid curve shows the ratio of these two fields, and it is almost equal to unit.

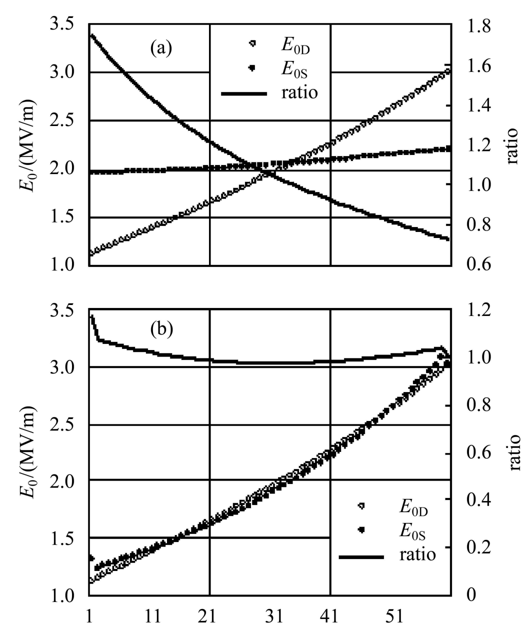

Fig. 6. The E_0 distribution pattern of DTL-1 for SNS. (a) Before tuning. (b) After tuning.

5 Conclusions

In this paper, we find that the present DTL design procedure remains a drawback that produces a different E_0 pattern from the expected one in design. So a new tuning step is proposed to add to the current design procedure. Some examples from CSNS DTL and SNS DTL are presented to show what the problem is and how to solve it. More efforts are demanded to revise the source codes so as to avoid such drawback in DTL design.

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