COMPENSATION FOR THE STEM EFFECTS OF THE END CELLS FOR THE J-PARC SDTL STRUCTURE

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Abstract

The effects of a lack of half stems on the end plates of SDTL tanks on both the resonant frequency and the field distribution were studied. It was found that the frequency deviation of the end cell for the J-PARC SDTL last tank caused by the lack of a half stem on the end plate is about 0.87 MHz, and that the deviation of the field distribution due to two half stems is about ±3%. A simple compensation method was proposed in which a disk of 1.5 mm in thickness and 250 mm in radius was added to the originally flat end plate. The effects of the added disks were estimated by both MAFIA and analytical calculations; both the resonant frequency and the field distribution were correctly adjusted. This compensation method has large merits of simple fabrication and low cost. It was applied to the SDTL tanks of the J-PARC proton linac. The validity of the new compensation was confirmed by measurements and tuning of the SDTL tanks of the J-PARC.

KEY WORDS: SDTL, proton linac, stem effect, end cell, field distribution, compensation, J-PARC

1. Introduction

An Alvarez drift-tube linac (DTL, Fig. 1) is widely used for accelerating low-energy proton beams. It is a complicated and sophisticated structure, since drift-tubes contain focusing magnets. A separated-type drift-tube linac (SDTL, Fig. 2) was proposed [1] as an accelerating structure for the medium-energy region because of both a high shunt impedance and simplicity of construction. A higher shunt impedance can be realized by eliminating focusing devices from the drift tubes and reducing the drift-tube diameter. The focusing elements are placed between two adjacent SDTL tanks. This scheme is usually adopted in a high-energy proton linac of a coupled-cavity type. The required focusing period for the SDTL should be determined based on the focusing strength, which depends upon both the strength of the focusing device and the focusing periods in terms of the unit-cell length. A focusing period of seven was selected for the J-PARC SDTL [2], implying an SDTL tank of five cells. Since one of the merits of the

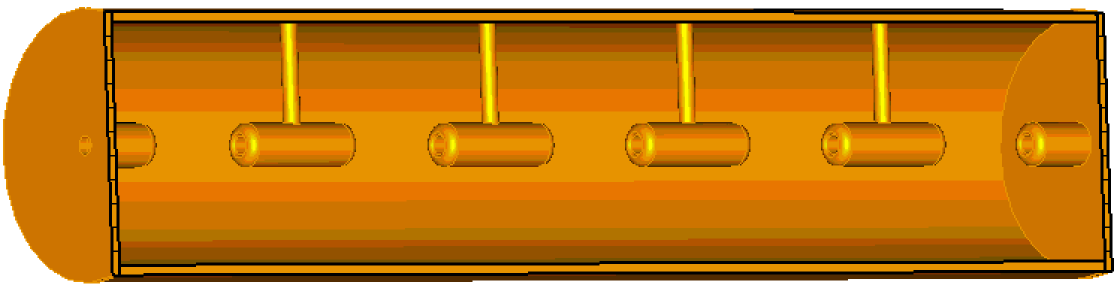

Fig. 1 Inside view of an Alvarez-type DTL tank. A drift tube usually contains a focusing quadrupole magnet.

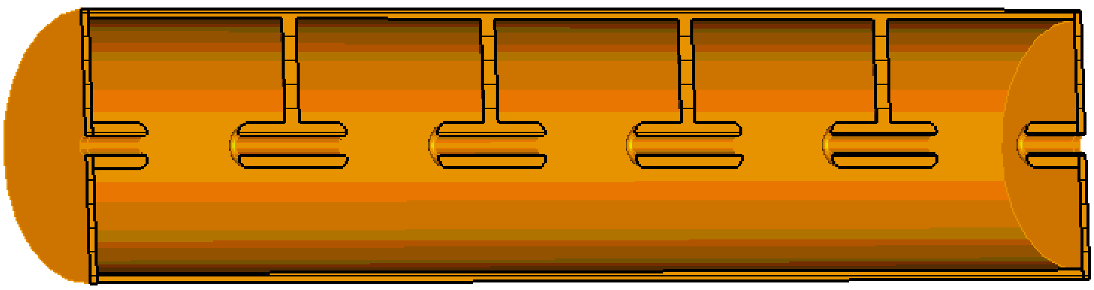

Fig. 2 Cross-sectional view of an SDTL tank. There is no focusing magnet in the drift tube.

SDTL structure is simplicity of both the rf properties and mechanical issues in construction, no kinds of stabilizing devices (post couplers or multi-stems) are usually installed. Thus, realizing the designed accelerating field distribution, which is closely related to the local-frequency perturbation, is one of the important issues [3]. The Alvarez-type structure is a heavily loaded cylindrical tank, operating in the TM010 mode. A normal unit cell, defined so as to include an accelerating gap, consists of two tubes of half size and two half stems (Fig. 3). Careful attention is required for both end cells, in which there is usually no half stem on the end plate (Fig. 4). Since the perturbation caused by a stem is not very small, both the resonant frequency and the accelerating field distribution in a five-cell SDTL tank are strongly influenced if there is no compensation for the half stem, corresponding to the virtual half stem on the end plate. In this report, a new simple compensation method is proposed, and some results of both analytical and numerical analyses are presented.

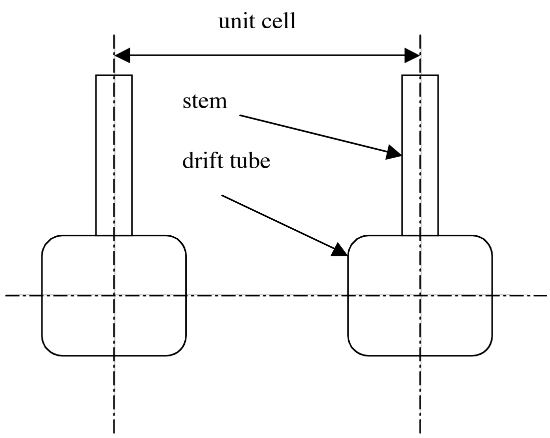

Fig. 3 Configuration of a unit cell of the SDTL (normal cell).

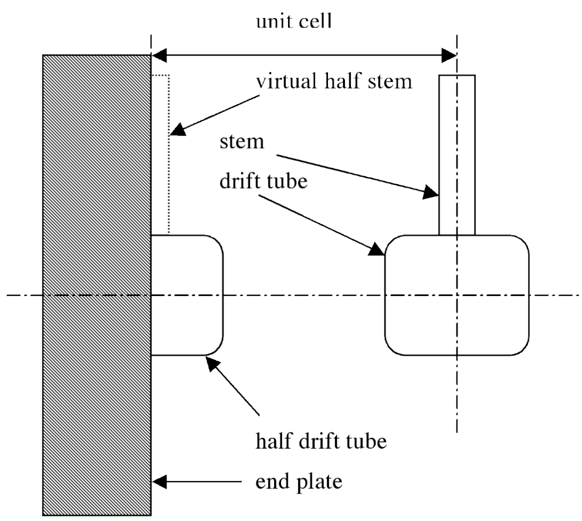

Fig. 4 Configuration of a unit cell of the SDTL (end cell).

2. Frequency perturbation due to the stem

The frequency shift due to a stem in a unit cell of J-PARC SDTL was calculated with SUPERFISH, using a perturbation technique. Typical SDTL parameters are summarized in Table 1. The calculated results for each cell of the SDTL tanks are plotted in Fig. 5. Typical frequency shifts are equal to 1.814/1.741 MHz for a particle energy of 50/190 MeV.

Table 1 Typical parameters of unit cells of the SDTL tank for the J-PARC linac.

Frequency	324	MHz
Tank diameter	520	mm
Drift tube diameter	92	mm
Stem diameter	36	mm
Cell length	0.29 ~ 0.51	m
Tank length	1.47 ~ 2.56	m
Energy	50 ~ 190	MeV

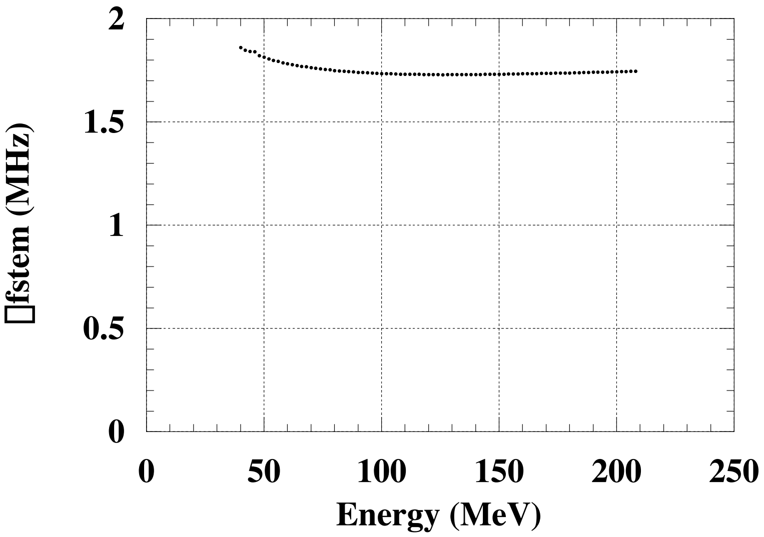

Fig. 5 Shift of the unit-cell frequency due to a stem of 36 mm in diameter for the J-PARC SDTL.

The volume of the stem, as the volume of perturbation, is constant for all SDTL cells. However, as one can see from Fig. 5 and Table 1, the frequency shift due to the stem decreases more slowly than the cell length (and cell volume) increases. It takes place due to a change in the operating-mode field distribution with the particle-energy increasing. The fundamental unit-cell design of the SDTL was performed so that the resonant frequency of the normal cell includes the contribution of the stem. Thus, if there is no contribution of a half stem on an end plate, a lack in a frequency shift of

0.91/0.87 MHz in the end cell for the first/last SDTL tank takes place.

3. Field distribution in the SDTL tank

A design field distribution in the SDTL tank is uniform. The field distribution would be deformed if there were to be a large frequency perturbation locally, since there are no stabilizing devices in the SDTL. The calculated field distribution by using a perturbation method [4, 5] (Appendix) for an equivalent cylindrical tank is plotted in Fig. 6, assuming that there was a frequency shift of -0.87 MHz in both end cells for the SDTL last tank. The calculated deviation of the field distribution was about ±3%. The above-mentioned results were also confirmed by a MAFIA calculation. Figure 7 shows the accelerating field distribution of the SDTL last tank without any end-cell compensation, calculated with MAFIA; the deviation of the field distribution is about ±3.4%. Taking advantage of the near symmetry of the geometry in the longitudinal direction, the simulation was made for a half of SDTL tank. For different tanks, the field perturbation is proportional to the square of the cavity length (see Appendix) and is maximal for the last SDTL tank. For the first shortest tank, we can expect a field perturbation of ±1.5%. Since the estimated deviation of the field distribution of about ±(1.5 – 3)% is not negligibly small, some compensation is required for the SDTL tank.

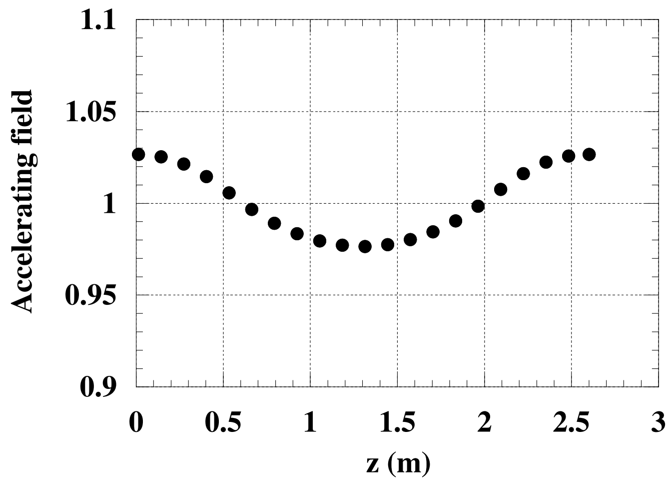

Fig. 6 Field distribution in the cylindrical tank, calculated with the perturbation method. The length of the tank is equal to that of the SDTL last tank. A frequency shift of -0.87 MHz in both end cells is assumed. It is assumed that the accelerating field in the gap of the SDTL is proportional to the calculated one.

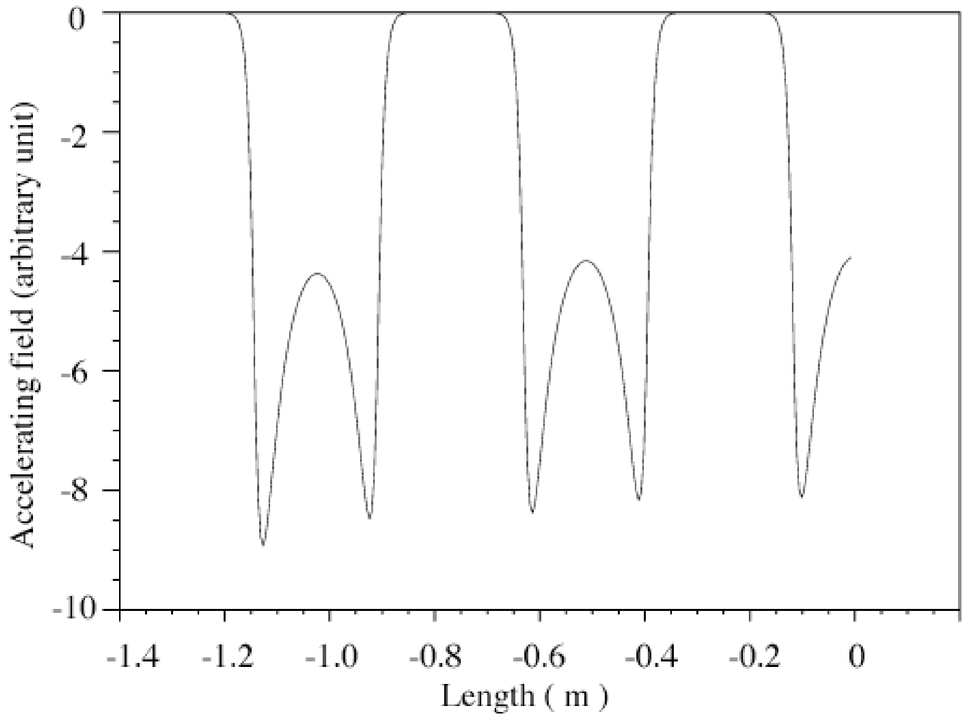

Fig. 7 Accelerating field distribution of the last SDTL half tank without any end-cell compensation, calculated with MAFIA. The relative accelerating fields, indicated at the gap center, are -4.37, -4.16 and -4.09 for the 1st, 2nd and 3rd gaps, respectively.

4. Method of compensation for half stems in both end cells

Several compensation methods have been investigated. The first one is to add half stems on the tank end plates. The second one is to decrease the tank diameter locally in the end cells. The third one is to add special local tuners to increase the end-cell frequency. These methods were rejected due to more complicated cavity construction and increasing costs. Generally, there is the possibility to compensate for the frequency shift and decrease the field perturbation with the existing cavity tuners. However, it results in a deeper insertion of the tuner (associated with increasing rf-losses), more complicated cavity tuning and reduced field perturbation, not eliminated. Finally, a new method of frequency compensation for both end cells was proposed (Fig. 8). Here, a thin circular disk is added on the end plate: the thickness and the radius of the disk are chosen so that the frequency shift due to the increase in the volume of the end plate

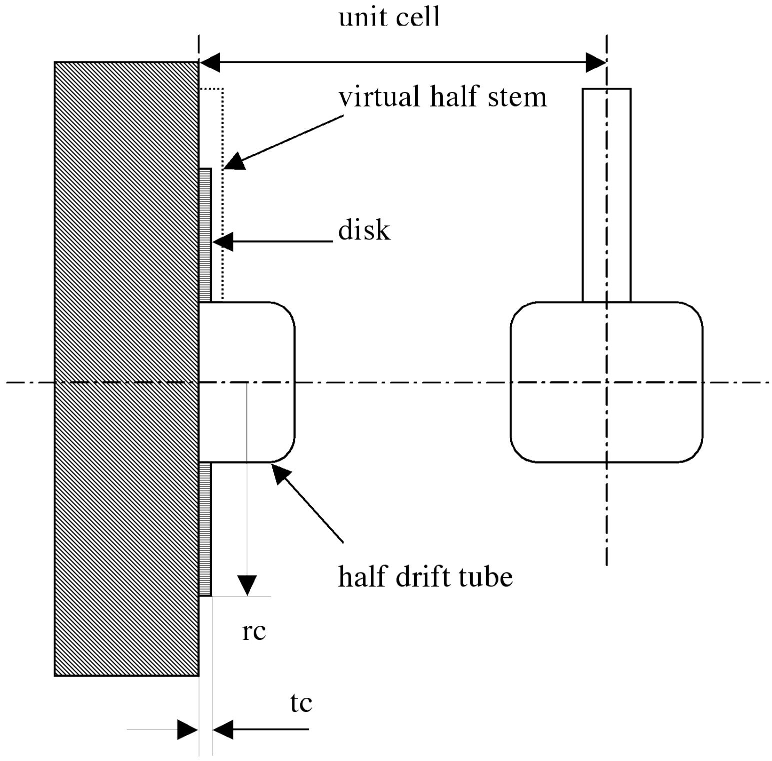

Fig. 8 Configuration of a unit cell of SDTL (end cell). A disk (thickness,tc; outer radius,rc; inner radius=drift tube radius) is added for compensation, instead of the virtual half stem on the end plate.

should be approximately equal to that of the virtual half stem on the end plate. In order to maintain an unchanged cell length and the gap length, the outer radius of the disk (rc) should be less than the radius of the tank. Figure 9 shows the frequency shift of the end cell as a function of the inner radius of the disk when tc=1 mm and rc=250 mm. As for the inner radius of the disk, the equal radius of the drift tube was selected because of simplicity of fabrication. After investigating the frequency shift for the other tanks, a set of tc=1.5 mm and rc=250 mm was selected. For further construction simplification, the same geometrical parameters (tc, rc) of the disk were applied for all of the tanks. In this case, the compensation of the frequency is not accurate for each tank: for example, it is smaller than the accurate value by about 40 kHz for the first tank. However, it can be seen from Fig. 9 that the errors in frequency compensation are so small that it requires a small tuning range of the resonant frequency by a tuner, and that the deviation of the field distribution is much less than the required tolerance (±1%).

From the viewpoint of fabrication, it is a large advantage that this compensation

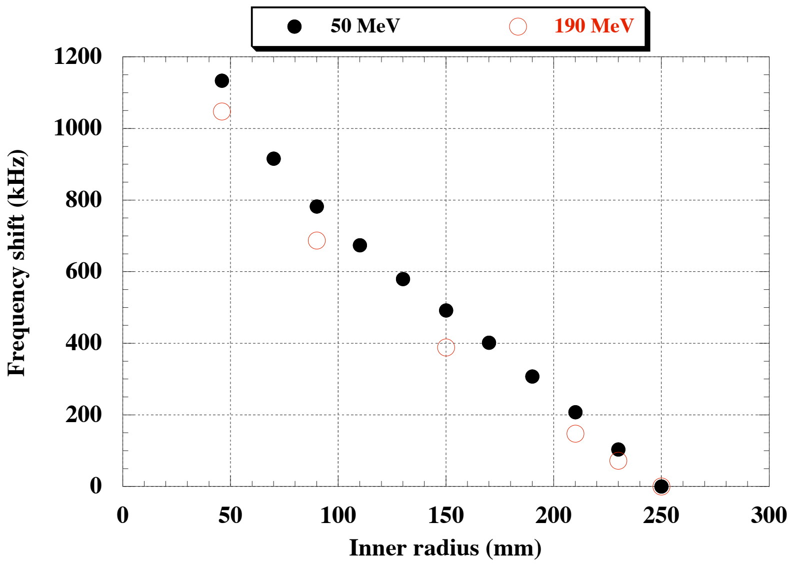

Fig. 9 Frequency shift due to the compensation disk on the end plate as a function of the inner radius of the disk for both the first (50 MeV) and the last (190 MeV) cells of the SDTL. A thickness of 1 mm and an outer radius of 250 mm of the disk are fixed in the calculation.

method gives no additional and high-cost fabrication process, which would be expected in adding a half stem on the end plate.

5. Calculated results with MAFIA

The effects of the local-frequency shift on the field distribution would be largest in the SDTL last tank, because the length is the longest among all SDTL tanks and the induced perturbation on the field distribution is proportional to $(L/\lambda)^2$ according to eq. (5) in Appendix, where L is the tank length and λ the free-space wavelength. Thus, some simulations were made for the SDTL last tank by using MAFIA. The calculated accelerating field distribution without any end-cell compensation is already shown in Fig. 7, and the corresponding calculated results with end-cell compensation by adding a half stem on the end plate is shown in Fig. 10. Here, a uniform field distribution was achieved, which was expected, since all of the local cell frequencies are equal. Next, figure 11 shows the compensated field distribution by adding a thin circular disk on the

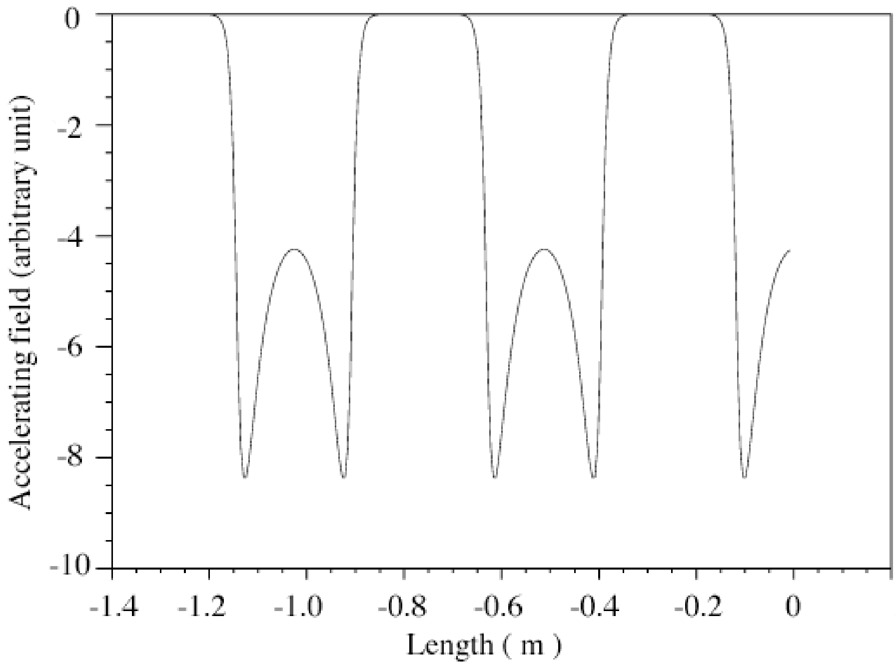

Fig. 10 Accelerating field distribution in the last compensated SDTL half-tank by adding a half stem on the end plate, calculated with MAFIA. The relative accelerating fields, indicated at the gap center, are -4.240 for all gaps, since there is no perturbation of the local frequency.

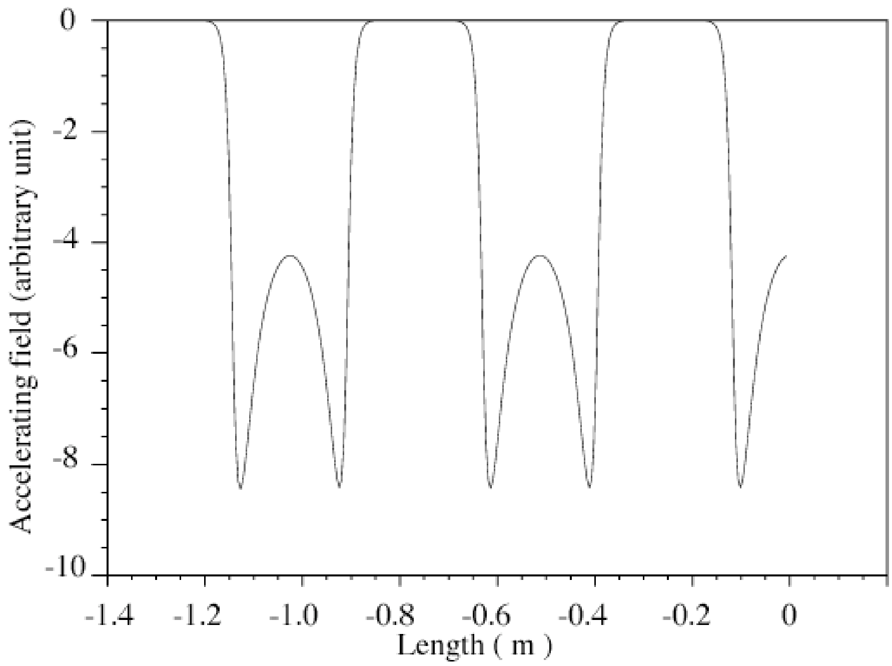

Fig. 11 Accelerating field distribution in the last compensated SDTL half-tank by adding a thin circular disk on the end plate, calculated with MAFIA. The thickness and the radius of the disk are 1.5 mm and 250 mm. The relative accelerating fields, indicated at the gap center, are -4.240, -4.236 and -4.235 for 1st, 2nd and 3rd gaps, respectively.

end plate; the thickness and radius of the disk are 1.5 mm and 250 mm, respectively. It can be seen from Fig. 11 that the field deviation is almost perfectly compensated, resulting in a uniform field distribution. Therefore, it can be concluded that the effects of the compensation with a disk of 1.5 mm are almost equal to those by adding a half stem on the end plate. When a disk of 1.0 mm in thickness is used in the simulation, the deviation of the field distribution is ±0.58%.

6. Conclusion

The effects of a lack of half stems on the end plates of the SDTL tanks on both the resonant frequency and the field distribution were studied. It was found that the frequency deviation for the J-PARC SDTL last tank caused by lack of a half stem on the end plate was about 0.87 MHz, and that the deviation of the field distribution from the designed uniform one due to two half stems was about ±3%. A simple compensation method was proposed in which a disk of 1.5 mm in thickness and 250 mm in radius was added to the originally flat end plate. The effects of the added disks were estimated by both the MAFIA and analytical calculations; both the resonant frequency and the field distribution were correctly adjusted. This compensation method has large merits of simple fabrication and low cost. It was applied for the SDTL tanks of the J-PARC proton linac. The simplicity of fabrication was confirmed in the construction, and the validity of the new compensation method was also confirmed by the field measurements and tuning of the SDTL tanks of the J-PARC [6].

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Appendix: Calculation of the field distribution in An Alvarez drift-tube linac with the perturbation theory.

The distribution of the accelerating field in an Alvarez DTL (TM010 mode) can be simulated analytically. The basic assumption is that the field distribution for all gaps in a DTL is proportional to the corresponding field distribution in a hollow cylindrical tank. If there were some deviations of the local frequencies along the tank (z-direction) from the basic distribution of the local frequencies, they would cause both a shift of the total resonant frequency and a deviation of the field distribution from the basic one. Here, we consider small perturbations on the local frequencies. Since the resonant frequency of the TM010 mode (f_r) is theoretically determined by the radius of the cylindrical tank, any kinds of perturbations on the local resonant frequency can be expressed in terms of the shift in the local radius (a(z)). We thus consider the varied local radius, expanded by a Fourier series as

$$a(z) = a_0\left[1 + \sum_{i=1} P_i \cos\frac{i\pi z}{L}\right], \tag{1}$$

where L is the tank length, and assume P_i << 1. The electric field (E(z)) in the tank is also expanded by a Fourier series as

$$E(z) = J_0(k_z r)e^{j\omega t}\left[1 + \sum_{n=1} E_n \cos\frac{n\pi z}{L}\right], \tag{2}$$

where J_0 is a Bessel function of zeroth order ($J_0(x) \approx 1 - \frac{x^2}{2^2}$). The wave number ($k_z$) is determined by

$$k_z = x_{01}/a(z), \tag{3}$$

where $x_{01} = 2.405$ is first root of J_0(x) for the TM01-mode.

The electric field is described by the differential wave equation in cylindrical coordinates as

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial E}{\partial r}\right) + \frac{\partial^2 E}{\partial z^2} + \frac{\omega^2 E}{c^2} = 0, \tag{4}$$

where $\omega=2\pi f_r$ and c is the speed of light. The relation between E_n and P_n can be derived from eqs. (1) – (4), and by taking the first-order terms ($1/a(z) \approx \frac{1}{a_0}\left(1 - \sum_{i=1} P_i \cos\frac{i\pi z}{L}\right)$),

$$E_n = \frac{8L^2}{\lambda^2 n^2} P_n, \tag{5}$$

where λ is the rf wavelength, given by f_r/c. Relation (5) indicates that the effects of a perturbation are proportional to $(L/\lambda)^2$. The local resonant frequency can also be expressed in a Fourier series as

$$f(z) = f_0\left(1 + \sum_{i=1} F_i \cos\frac{i\pi z}{L}\right). \tag{6}$$

From eqs. (1),(3) ,(6) and $k_z = \omega/c$ for the TM010 mode, the following relations can be derived:

$$f_0 = \frac{2.405c}{2\pi a_0}, \tag{7}$$

$$P_i = -F_i. \tag{8}$$

Then, we have the relation between the coefficients of the electric field and the local frequency as

$$E_n = -\frac{8L^2}{\lambda^2 n^2} F_n. \tag{9}$$

Next, we consider the new local-frequency perturbation to the initial local-frequency distribution (f(z)). The j-th perturbation of the local frequency of Δf_j is given in a range from $z=h_j-s_j/2$ to $z=h_j+s_j/2$. Then, the new local-frequency distribution is expressed in a Fourier series as

$$f'(z) = f_0'\left(1 + \sum_{i=1} F_i' \cos\frac{i\pi z}{L}\right). \tag{10}$$

By integrating eq. (10), we obtain the following relations:

$$f_0' = f_0 + \sum_{j=1}^{M} \frac{s_j}{L}\Delta f_j , \tag{11}$$

$$F_i' = \frac{f_0 F_i}{f_0'} + \sum_{j=1}^{M} \frac{4\Delta f_j}{i\pi f_0'} \cos\frac{i\pi h_j}{L} \sin\frac{i\pi s_j}{2L}, \tag{12}$$

where M is the number of local-frequency perturbations.