Optimization of the three-dimensional electric field in IH-DTL*

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Abstract: The tuning process of the three-dimensional electric field near the beam axis is very important in the optimization of the Interdigital H-mode Drift Tube Linac (IH-DTL). The tuning of the longitudinal field distribution, the Kilpatrik (Kp) factor, and the transverse dipole field have been discussed in detail, combined with the radio-frequency tuning process of the 53.667 MHz short IH-DTL cavity, which was designed to accelerate $^{238}U^{34+}$ from 0.143 MeV/u to 0.289 MeV/u in the SSC-Linac injector project at the Institute of Modern Physics. The flatness criterion and the tube tuning method are discussed in order to meet the beam dynamics requirements. In the tube tuning process, the energy gain error in the cells should be reduced to less than ±2%, and the Kp factor should be reduced to 1.6. The transverse dipole field and the method that uses a "plunger" to dismiss this dipole field are evaluated. The experience gained from the first cavity optimization benefits the tuning process of the three remaining IH-DTL cavities in the SSC-Linac project.

Key words: IH-DTL, acceleration cell, transient time factor, Kilpatrik factor, transverse dipole field

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1 Introduction

As part of the SSC-Linac, DTL plays an important role [1]. The first IH-DTL for the SSC-Linac was designed to operate in 53.667 MHz CW mode. The basic design specification parameters are listed in Table 1.

The pre-fixed electric field distribution in the first DTL tank does not match the field used in the electrodynamics design exactly, which will be prejudicial to beam quality, in particular causing phase array mismatch. In adjusting the voltage distribution along the cavity, different flatness criteria are discussed.

1) An equal maximum electric field of every cell.

2) The voltage agrees with the designed value.

3) The energy gain agrees with the designed value.

These criteria are not compatible with each other, and one of them, with more accuracy, should be used in the tuning process. Several tuning methods are available for the IH-DTL [2], but the best one for this DTL is tube tuning because of its geometry structure.

Table 1. The major parameters of DTL tank 1.

parameter	value	unit
frequency	53.667	MHz
input energy	0.143	MeV/u
output energy	0.228	MeV/u
Q factor	13000	
structure power	15	kW
shunt impedance	197	MΩ
cell number	10	
total length	586	mm
DTL radius	530	mm

However, this method has a problem in that the gap with a shorter length has a higher peak surface electric field. Further analysis and optimization of the Kp factor should therefore be done.

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Different kinds of blends on the tubes were tried, and the blend parameters were adjusted to reduce the Kp factor in the third section in order to reduce the vacuum degree requirement in operation. The transverse dipole field is also very important to the quality of DTL. In the fourth section, the transverse electric field that exists in the acceleration gap and the method that uses a "plunger" to dismiss the transverse field are assessed, combined with single particle simulation by a VBA macro.

2 Voltage distribution adjustment along the cavity

2.1 The flatness criterion

The data generated by the beam optics code, LINREV [1], offer the voltage, the cell length, the gap length, the input energy and the output energy of every cell, with which the tubes and stems are created in the CST-MWS simulation environment [5]. The perfect electric field on the axis used in the LINREV code has an equal maximum electric field level and the same distribution curve shapes in every cell. The problem is that the simulation and qualitative analysis all show that the distribution curve shapes and the maximum fields are different in every cell with different cell lengths, especially in the cells with phase switch. Table 2 investigates the composite effects of gap modification by the parameter sweep method. Gap modification of a single cell changes the related field level and transient time factor quite effectively, without affecting the field distribution of other cells. But the voltage change is negligible compared with the transient time factor while the gap modification changes. This act does not coincide with the theory that the local capacity affects the local voltage due to short tank length [3].

The conclusion obtained from Table 2 is that using voltage or related field level as a scope for field distribution flatness is improper because the transient time factor is a function of gap length to cell length ratio. So it is necessary to get the unique energy gain of every cell by an equation,

$$V_{\rm eff} = \int_{-L_{\rm b}/2}^{L_{\rm b}/2} E(0,z)\cos(\omega t(z))\,{\rm d}z, \tag{1}$$

$$V = \int_{-L_{\rm b}/2}^{L_{\rm b}/2} E(0,z)\,{\rm d}z, \tag{2}$$

$$T = V_{\rm eff}/V, \tag{3}$$

$$\Delta E_{\rm k} = qV_{\rm eff}\cos\phi_0. \tag{4}$$

Where $L_{\rm b}$ is the cell length, ω is the frequency, $\Delta E_{\rm k}$ is the kinetic energy gain of one cell and ϕ_0 is the phase arrangement. The flatness is defined to be the degree of $\Delta E_{\rm k}$ coincidence with the designed energy gain in this paper, and $V_{\rm eff}$ is extracted from the 3D electric field result of the CST-MWS by a result template and VBA macro.

Table 2. The maximum electric field level ($E_{\rm zmax}$), voltage (V), effective voltage ($V_{\rm eff}$), and transient time factor (T) as a function of gap modification. A gap modification of −1 mm means a reduction in gap length by 1 mm on both sides of the gap.

modification/ mm	$E_{z\max}$/ (V/m)	V/V	$V_{\rm eff}$/V	T
−2	7.95×10^6	2.36×10^5	1.78×10^5	0.753622
−1	7.64×10^6	2.36×10^5	1.76×10^5	0.741724
0	7.34×10^6	2.35×10^5	1.71×10^5	0.729281
1	7.07×10^6	2.34×10^5	1.68×10^5	0.717558
2	6.78×10^6	2.34×10^5	1.65×10^5	0.704081

2.2 Tube tuning

The theory of tube tuning is based on the general perturbation theory for RF resonant cavity [4]. The initial gap length is fixed to 25 mm and the cell length gets longer as $\beta\lambda$ increases. The electric capacitance per unit length consists of two parts: the capacitance of the drift tube structure and the distributed capacitance between the tube support stems. Tube tuning changes the first part appreciably [2, 3].

Figure 1 shows the influence of gap modification over the longitudinal electric field on the beam axis, which is the same as the conclusion of Table 2.

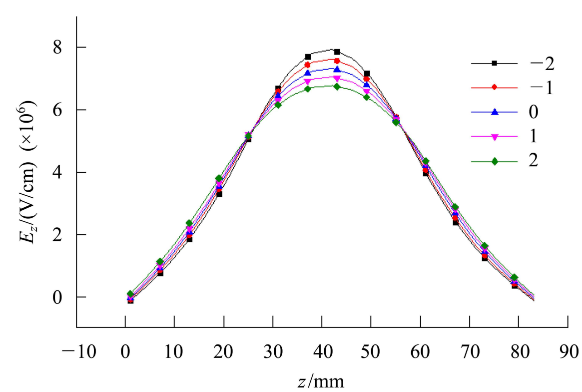

Fig. 1. Electric field distribution on the middle axis as a function of gap modification (cell no. 5).

In the tube tuning process, the center of the cell is fixed and the front tube and end tube are modified symmetrically in order to keep the phase arrangement. The final gap modification of DTL tank 1 for cells 1 to 10 are: 1.5, −1, −0.2, 0.4, 0.7, 0.7, 0.4, −1.5, −1, and 0. The tuning results are reviewed briefly in Fig. 2. The errors of $\Delta E_{\rm k}$ in most cells are minimized to a great level, but the $\Delta E_{\rm k}$ of cells 8, 9, and 10 are not so good because the sensitivity to gap modification is low with a −20° phase arrangement. For the last cell, the error of $\Delta E_{\rm k}$ does not dismiss, and even the gap modification is relatively large, considering the errors are not accumulated in the last cell, whose modification is given up.

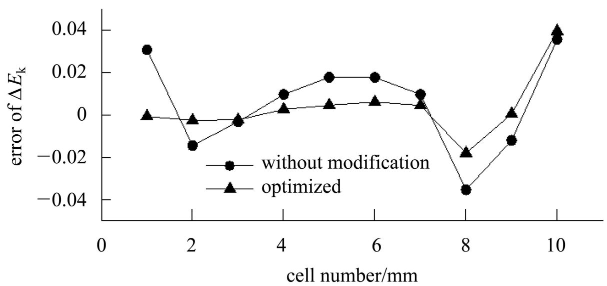

Fig. 2. The energy gain errors before and after gap modification.

One disadvantage is the considerable Kp factor increase because of the high local electric surface fields near the shortest gap, so the gap modification is limited in the range −1.5 mm to 1.5 mm.

2.3 The advantage of tube tuning

The tube tuning of one cell does not affect the electric field of the other cells, thus making cell by cell tuning possible. This method is also very sensitive; a 1 mm gap modification causes about 1.5% of the energy gain shift. The final distribution on the real cavity can be measured by the perturbation method, and from the field level one can estimate $V_{\rm eff}$ and $\Delta E_{\rm k}$. Tube tuning is a highly accurate method, and especially suitable for the final step of tuning.

3 The optimization of the Kp factor

The highest value of the surface electric field in the whole IH-DTL tank 1 is on the drift tubes. But the surface electric field on the tubes is not rotational symmetry because of the stems. This electric field distribution can be seen as two parts, a symmetry rotational electric fluxline from tube to tube, with the other electric fluxline from the tube to the stem of the opposite tube. The shape of stem, the tube blend, the gap length and the tube length all affect the maximum surface electric field distribution. As the gap modification is finished, the only variable parameter is the shape of the tube blend.

Figure 3 shows three different kinds of blends on the tube, and all of them have at least two parameters. The tuning process uses the fifth cell as the representative sample of all cells to find the best blend type. A parameter sweep on blend angle and blend scale has been done to get the lowest Kp factor for the three different kinds of blend.

Analysis shows that the second blend can get the lowest Kp factor of 1.45 by adjusting the blend scale to 5.6 mm and the angle to 45 degrees. But the third blend is accepted as the second one has manufacturing problems. The final optimization results of the Kp factor in the whole cavity for three blends are 1.72, 1.45, and 1.6. The third blend and the optimized parameter are applied to all cells and an average Kp factor of 1.6 is obtained. All the cells should be optimized separately to get the array of proper blend parameters, but in that case all the tubes will have different blends and therefore more difficulties in fabrication.

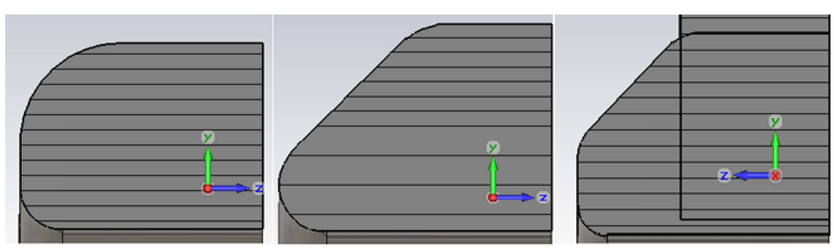

Fig. 3. Three different kinds of blend on the tube.

4 The transverse dipole field

The transverse dipole field exists in all IH-DTLs, and depends on the gap length and the capacity between two ridges. Fig. 4 shows the longitudinal and the transverse electric field map of DTL tank 1.

The value of the transverse field of DTL tank1 is about 3% of the longitudinal part, and this record

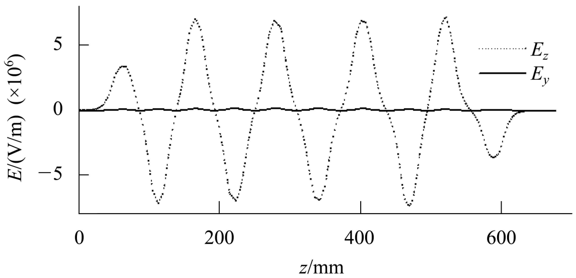

Fig. 4. The longitudinal (E_z) and transverse (E_y) electric fields of DTL tank 1 along the middle axis.

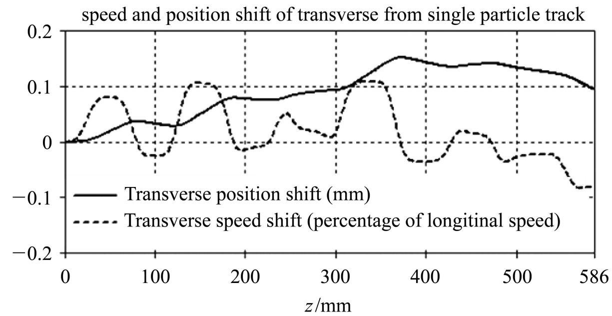

Fig. 5. The transverse position shift and transverse speed shift of the central particle, from the DTL entrance to the exit.

increases to 10% in DTL tank 4, whose gap length is up to 55 mm. The capacity of the two ridges is already minimized based on mechanical reasons. The transverse dipole field causes either a parallel displacement of the beam or an oscillation around the beam axis [3]. Theoretically, the transverse kinetic energy gain in one cell can be neutralized in the next cell. Single particle track simulation by CST-WMS and VBA macro has been done to find the influence of the transverse dipole field in DTL tank 1. Fig. 5 shows the transverse velocity and the position shift in the whole tank. The maximum position shift is 0.15 mm.

Drift tube geometry with bulges on the tube is usually adopted to reduce the electric dipole content and symmetrize the field around the beam axis [2]. The electric dipole field can reduce an order of magnitude, with the cost being an 8% additional power loss and a higher Kp factor. Judging and weighing up the effects and the unfavorable defects, this method is not applied in the final cavity design in our case.

5 Conclusion

In the flatness tuning process, gap length tuning prominently changes the transient time factor rather than the gap voltage for short DTL lengths. By slightly modifying the gap length, the energy gain error in cells 1–7 and 9 is reduced below ±0.5%. With a proper tube blend, the Kp factor is optimized to 1.6. The transverse dipole field is about 3% of the longitudinal field, and causes a transverse position shift of about 0.15 mm on the beam when a single particle is traced. Tube bulge is not applied to the final DTL design because of additional power loss, a higher Kp factor and difficulties in fabrication.

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References

1 HE Y, WANG Z J, XIAO C. Conceptual Design of Linear Injector For SSC Of HIRFL. Proceedings of IPAC2011. San Sebastián: Spain, 2011. 2610–2612

2 LU Y R, Ratzinger U, Schlitt B, Tiede R. Nuclear Instruments and Methods in Physics Research A, 2007, **582**: 336–344

3 Ratzinger U. H-type Linac Structure. CERN Accelerator School, Lufthansa Training Center, Germany, 8–16 May 2000

4 Klein H, Basic Concepts I. CERN Accelerator School for Particle Accelerators, Oxford, 1991, 112

5 http://www.cst.com/Content/Products/MWS/Overview.aspx. A specialist tool for the 3D EM simulation of high frequency components