ISBN: 978-3-95450-194-6 ISSN: 2226-0366 doi:10.18429/JACoW-LINAC2018-MOPO079

CAVITY DESIGN OF A 7MeV 325MHz PROTON APF IH-DTL FOR A COMPACT INJECTOR*

X. Li[1], Y.H. Pu†, X.C. Xie, M.H. Zhao, Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai, China
F. Yang, Shanghai APACTRON Particle Equipment Co., Ltd, Shanghai, China
[1]also at University of Chinese Academy of Sciences, Beijing, China

Abstract

An Interdigit H-mode Drift-Tube-Linac (IH-DTL) with Alternating-Phase-Focusing (APF) method working at 325 MHz was designed. With the RF field established properly in the cavity, protons can be accelerated from 3 MeV to 7 MeV successfully. In this paper, the process of designing such an APF IH-DTL cavity is going to be presented. Also, the characteristics of the cavity and parameters studying of RF are going to be demonstrated.

INTRODUCTION

Over the recent decades, with the development of particle accelerator physics and related technologies, using energetic particles such as protons, electrons provided from them to treat cancers is more and more efficient and practical. Because of protons' unique Bragg peak, proton accelerators attract a lot of attention.

As a key member, Shanghai Institute of Applied Physics (SINAP) work together with other two members to establish a joint company named Shanghai APACTRON Particle Equipment Co., Ltd to manufacture the Advance Proton Therapy Facilities. To be competitive, we are going to improve the facility in many aspects. A 7 MeV injector is one of main components which are being improved by us now.

Usually, this typical injector consists of a compact Electron-Cyclotron-Resonance Ion Source (ECRIS), a Radio-Frequency-quadrupole (RFQ) and a Drift-Tube-Linac (DTL), the RFQ and DTL accelerates protons from 40keV to 3 MeV and then to 7 MeV respectively. Traditional DTL is quite bulky, heavy, high-cost and difficult-to-maintain which limits its popularization as an injector for medical facility.

IH-DTL working with APF have the advantages of compact, cost-efficient and easy-to-maintain, so we adopt it as a candidate for our compact injector. Interdigit H-mode as an idea was first proposed in the 1950s by J. P. Blewett [1]. High shunt impedance is one of its main features, so this type of structure's RF power consumption is much lower than that of a conventional Alvarez-type DTL with energy lower than 10 MeV. Unfortunately, due to the slow development of three-dimensional(3D) electromagnetic (EM) field solver and rather complicated cavity structure, this advanced structure didn't have a good development over the past decades.

Entering the 21st century, well-developed 3D EM solvers like CST, HFSS, etc. make it practical to get the precise field distribution and optimize the cavity dimensions and RF characteristics [2]. Also, we exported the 3D RF field from CST microwave studio and got rather good results using a third-part code TraceWin [3].

In the following sections, a latest design of the APF IH-DTL for a compact injector is going to be presented. It concludes considerations of the cavity, the RF characteristics and geometric dimensions, the comparison between the calculated-voltages and required-voltages from beam dynamics.

APF IH-DTL

There are several linear accelerators adopting APF IH-DTL cavities [4-6]. Regarding to the principle of APF, A sequence of negative and positive phases alternatively appear between adjacent two electrodes(tubes). When the particles go through these different gaps and the tubes along the longitudinal axis, the negative phases they meet will focus the particle bunches longitudinally but defocus them radially. Conversely, the positive phases will focus the particles bunches radially but defocus them longitudinally. After several sinusoidal like periods of the phase sequence, we can get the particles focused successfully both in longitudinally and radially. Figure 1 shows the principle of APF [7]. Then the additional focusing elements in the case of conventional DTL can be saved in the APF LINACs. These features can significantly reduce the construction and maintenance cost of the radio therapy facilities adopting APF IH-DTL as its injector.

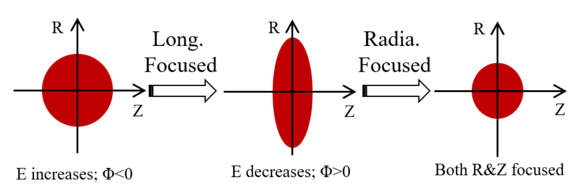

Figure 1: Demonstration of focusing principle of APF.

Unlike TM_{010} mode in the conventional DTL, TE_{111} mode is excited in an IH-DTL cavity. Alternatively introducing tubes supported by the stem connecting to the opposite wall, we can get the longitudinal accelerating E-field at π mode in Fig. 2.

† corresponding author: Tel: +86 130 6260 1189
E-mail address: puyuehu@sinap.ac.cn

ISBN: 978-3-95450-194-6 ISSN: 2226-0366 doi:10.18429/JACoW-LINAC2018-MOPO079

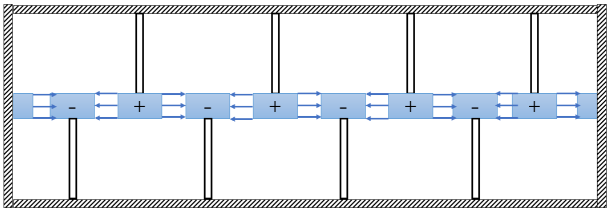

Figure 2: A drawing for principle of IH-DTL.

DESIGN OF APF IH-DTL CAVITY

The job of RF design of a cavity is to get the voltages distribution between adjacent tubes along longitudinal axis required by beam dynamics. Based on principle of IH-DTL cavity, E-field directly excited by the structure like in Figure 2 can't be suitable to accelerate particles efficiently. Besides, there is no any additional elements can be employed to focus particles, the motion inside the cavity is strongly determined by the electromagnetic (EM) field distribution in the cavity. And as mentioned previously [8], the EM-field distribution would depend strongly on the whole structure of the cavity, including the diameters of the cavity, the widths of the ridge, the shapes of the End-Ridge-Cut, the shapes of the stem, the diameters of the drift tubes, tuners, vacuum pipes, RF power feed coupler, etc. Dimensional changes occur on anyone of those structures can change the distribution of EM-field. So, looking for an efficient designing procedure among above variables is a challenge. We choose CST MWS as the 3D EM solver to establish model, calculate and optimize the cavity [5].

The frequency of the cavity depends on the capacitance and inductance of the whole IH-DTL structure. The following Eq. (1) shows the relation among them. Capacitance mainly comes from gaps of the tubes and that of the two ridges; correspondently, inductance mainly depends on the cross-section area enclosed by the cavity wall, tubes' outer radii, two ridges' height.

$$f \propto \frac{1}{\sqrt{L_e C_e}} . \tag{1}$$

Because the velocity at the exit is 1.52 times of that at the entrance, it causes the length of the unit cells and the gap increasing, then it makes the capacitance decreasing from the entrance to the exit, the results is the E-field would peak near the entrance of the cavity. In order to get the maximum shunt impedance, a uniform E-field distribution is the goal we are working for. It is easy to reach this by reducing the radius at the entrance or increase the radius at the exit.

Even then, the first and last few cells can't establish the same E-field as it at the middle of the cavity, this is ascribed to the characteristic of TE111 mode. Here we can use End-Ridge-Cuts (ERC) to enhance the E-field by increasing magnetic flux. Figure 3 shows the End-Ridge-Cuts, now the mode looks like TE11(0).

To get larger beam transmission, the inner radii of the drift tubes are determined to be 6mm. In our cavity, the maximum E-field should be no more than 1.6 times of E_{Kilpat}, which comes from the Kilpatric criterion. Regarding to the frequency 325 Mhz, the maximum E-field is about 29 MV/m, namely the bravery factor is 1.6. The most probably area where RF breakdown happens easily is around the outer edge of the tubes. So, we chamfer the outer edge of the tube with the radius of 4 mm, and the outer radius of the tube is 13 mm. To get optimum value of quality factor, the inner edge of the tube is chamfered with radius of 1 mm.

When designing the support stems, the main concern is the structural maximum E-field on the tube, the vertical component of E-field, the quality value and the heat transmission efficiency. So, we adopt tapered stems which has large base and small top to meet the above four requirements, as shown in Figure 3.

The following procedure is the designing procedure we developed for an APF IH-DTL cavity:

1. Construct a structure model based on the cell table, which determines the cell length, namely the synchronous phases sequence.
2. Segmentally adjust the diameters of the cavity to make the axial longitudinal E-field uniform.
3. Adjust the width of the End-Ridge-Cut to refine the E-filed near the both ends of the cavity.
4. Tune the resonant frequency of the cavity to 325 MHz by adjusting the diameter of the cavity.
5. Iterate the step 2- 4 to refine the uniformity of axial longitudinal E-field and frequency of the cavity.
6. Refine chamfering radius of the outer edge of the drift tubes to make sure the maximum E-field is less than 29 MV/m (1.6times E_{Kilpat})
7. Export the 3D EM distribution to re-calculate the beam dynamics with a third-part code like TraceWin. Optimize the geometry and dynamics by doing co-iteration with each other.
8. Add the tuners, Couplers, Vacuum pipes. Iterate the step 2-4 if necessary. Redo the step 7 to make a check.
9. After the mechanical design of the cavity, re-construct the model in CST MWS. Make sure the E-field distribution and voltage distribution meet the requirement of dynamics.

Table 1: The Main Parameters of the APF IH-DTL

Parameters items	Value	Unit
Frequency	325	MHz
Length	1514.6	mm
Input energy	3	MeV
Output energy	7	MeV
Unit cells number	32	-
Inner radius of the cavity	95.6-116	mm
Outer radius of the tube	13	mm
Inner radius of the tube	6	mm
Bravery factor of the cavity	1.53	-
Quality factor (0.8)	8900	-
Establishing field power (0.8Q)	195	kW
Woking mode	TE11(0)	-

ISBN: 978-3-95450-194-6 ISSN: 2226-0366 doi:10.18429/JACoW-LINAC2018-MOPO079

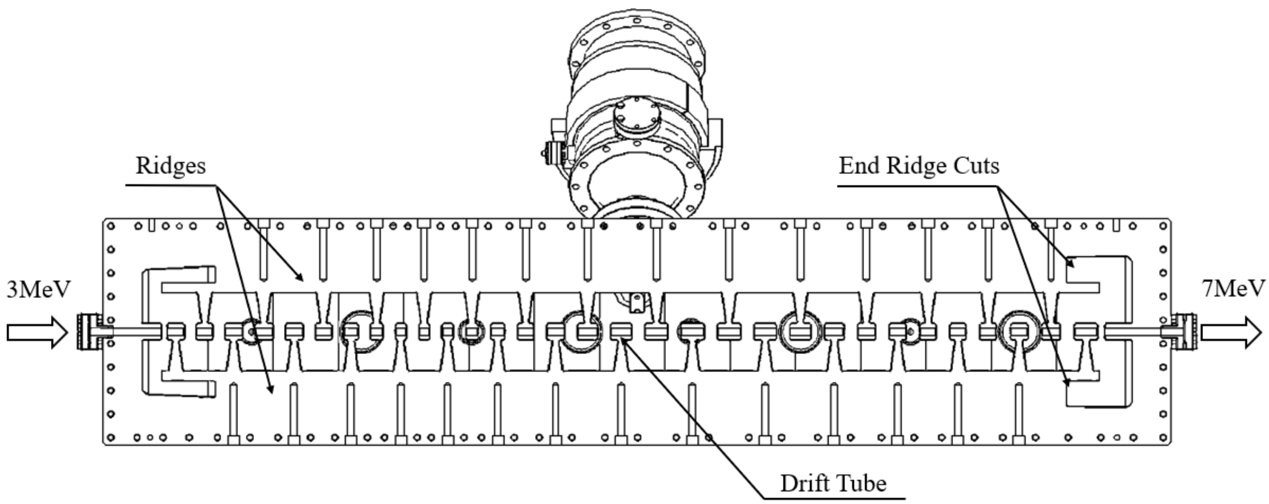

Figure 3: Cross-section drawing of the APF IH-DTL cavity.

Based on the above study of the cavity designing, we successfully get the cavity structure of APF IH-DTL working at 325 MHz as shown in Figure 3.

Results of the Design

After co-iteration between cavity optimization and beam dynamics tracking, some key RF characteristics parameters can be calculated with post-processing templates. Some of these main parameters of are summarized in Table 1.

Draw a line along the Z axis from the beginning to the end of the cavity, longitudinal component of E-field distribution can be plotted by the post-processing template too. Figure 4 shows uniformity of the E_Z. we can see the uniformity is rather good, which keep a good coincidence with the quality factor.

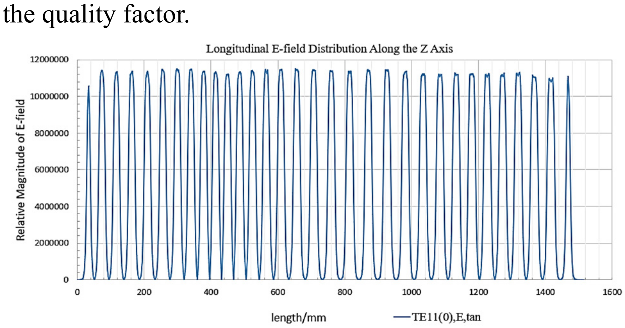

Figure 4: Longitudinal E-field distribution along the Z axis.

Integrating voltage is visual and useful way to see if the cavity meets requirements from the dynamics or not. According to the definition of the integral voltage, we get the gap voltages cell by cell orderly and plot them as the function of the gap number. A comparison between the calculated and dynamics is shown in Figure 5.

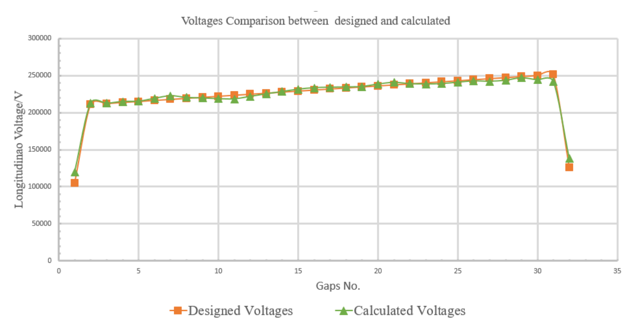

Figure 5: A comparison of voltage between the designed from dynamics and calculated by CST MWS. The triangle and square show the calculated and designed respectively.

CONCLUSION

We developed a useful way to design an APF IH-DTL cavity, according to this procedure, we designed a cavity working at 325 MHz, its corresponding E-field and integral voltage distribution were plotted by post-processing template of CST. Meanwhile, exported 3D EM field was used to track the protons with a third-part code TraceWin, the results met the expectations from the dynamics very well. According to the plan, we are going to do the machining work soon and the cold test and tuning of the cavity.

ACKNOWLEDGEMENTS

This work was supported by the National Key Research and Development Program of China (grant number 2016YFC0105408).

REFERENCES

[1] J.P. Blewett, CERN Symposium 159 (1956).

[2] CST, https://www.cst.com/

[3] D. Uriot and N. Pichoff, “Status of TraceWin Code”, in *Proc. 6th Int. Particle Accelerator Conf. (IPAC’15)*, Richmond, VA, USA, May 2015, pp. 92-94.

ISBN: 978-3-95450-194-6 ISSN: 2226-0366 doi:10.18429/JACoW-LINAC2018-MOPO079

[4] R.A. Jameson, "Practical design of alternating-phase-focused", in *Proc. RuPAC'12*, St. Petersburg, Russia, September 2012, paper MOACH02, p. 12.

[5] Y. Iwata *et al.*, "Alternating-phase-focused IH-DTL for an injector of heavy-ion medical accelerators", *Nucl. Instr. Meth.*, A vol. 569, pp. 658-696, 2006.

[6] K. Yamamoto *et al.*, "Experimental verification of an APF linac for a proton therapy facility", *Nucl. Instr. Meth.*, B vol. 269, pp. 2875-2878, 2011.

[7] S. Ogata, "Design and Analysis of APF-Linac with 'PiMLOC'", private communication, Shanghai, China, Sep. 2014.

[8] U. Ratzinger, "H-Type Linac Structures", CERN Accelerator School, Lufthansa Training Center, Seeheim, Germany, May, 2000, pp. 351-380, 2005.