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THE 7 MeV APF DTL FOR PROTON THERAPY

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Abstract

A 7 MeV alternating phase focused (APF) drift tube linear (DTL) for proton therapy has been designed, and a design code has been developed based on a sinusoidal synchronous phase formula and a linearly increasing electrode voltage assumption. The design procedure includes the radio frequency quadrupole (RFQ) to drift tube linac (DTL) matching, and end-to-end simulation that conducted by Trace Win. Moreover, a cutting method has been performed to correct the integral electric field deviation of RF gaps.

INTRODUCTION

The Advance Proton Therapy Facility APTRON is a dedicated proton therapy facility located in Shanghai, China. The facility made up by a linac injector and a synchrotron of 24.6 m circumference, providing proton beam from 70 MeV to 250 MeV. Two fixed beam treatment rooms and one rotating gantry room is located downstream of the accelerator. A schematic layout of the facility is shown in Figure 1.

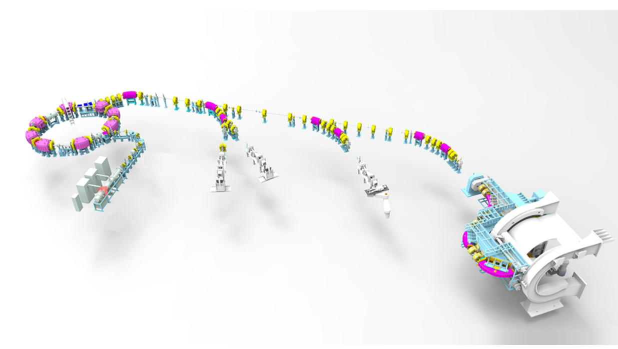

Figure 1: The bird's eye schematic view of the APTRON facility.

The alternating phase focused (APF) drift tube linac (DTL), together with a radio frequency quadrupole (RFQ), has been developed as the injector of the synchrotron ring. With its advantages of dimensions compactness and cost effectiveness, the APF DTL is an ideal choice for proton therapy facilities.

THE APF DESIGN CODE

The beam dynamics of the APF is solely depends on the electromagnetic field of the RF gaps, which determined by the synchronous phase sequence. In the past decades, several APF schemes has been proposed and developed. According to solid theoretical considerations as well as empirical rules, we choose the phase variation scheme that proposed by Yoshiyuki Iwata. In this scheme, the synchronous phase sequence is described by the following Equation (1) [1]:

$$\phi_s(n) = \phi_0 e^{-a\cdot n} sin\left(\frac{n-n_0}{b\cdot e^{c\cdot n}}\right), \quad (1)$$

where n is the number of the acceleration gaps; ϕ_0, a, b, c, and n_0 are free parameters.

Moreover, we add two hypotheses to our design strategy:

1. The potential of the electrodes are increasing monotonically and linearly.
2. The average electric field of the accelerating gaps is maintained.

Therefore, two extra parameter VE_0 and ΔVE, which stands for the voltage of the first electrode and the voltage growth of the successive electrode, together with the five Iwata formula parameters, could determine the structure of the APF.

Therefore, we developed the design code with the Iwata formula and the hypothesis to optimize the APF parameters automatically. The beam dynamics code is based on the BEAMPATH [2], and the parameters optimization algorithm is based on the nonlinear correlated stacking optimization method:

1. Estimate a set of initial parameters, generate the structure of the accelerator by the matrix transport method, feed the structure data into the BEAMPATH code, calculate the beam dynamics and evaluate the obtained results by a cost function.
2. Change two of the seven structural parameters described above to generate a new structure, feed the new structure data into the BEAMPATH and simulate the acceleration process. Compare the new results to the preceding results until all the possible parameter combinations have been considered and the best combination will be found.

THE APF DTL

The injection beam parameters for designing the APF DTL are obtained from the simulation results of a four-vane RFQ which serves as a pre-accelerator. Because the beam that extract from RFQ diverges horizontally but converges vertically while the horizontal and vertical focusing forces of the APF structure is totally identical, therefore a matching section is typically required to convert the injection beam from the RFQ into a symmetric one with symmetric properties in both the X and Y directions.

The injection and extraction energy of the APF is 3 MeV and 7 MeV, respectively. The cell number is 32 and the working frequency is 325 MHz; the on-axis acceleration field is 8.9 MV/m, corresponding to 0.5 times the Kilpatric limit.

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With the basic parameters described above, the APF DTL structure is determined automatically by executing our APF optimization code. The seven optimized parameters are ϕ_0 = 74, a = 0.007375, b = 1.925, c = 0.006625, n_0 = −8.25, VE_0 = 0.0805, and ΔVE= 0.00165.

Using these optimized parameters, the synchronous phases as a function of the gap number are shown in Figure 2.

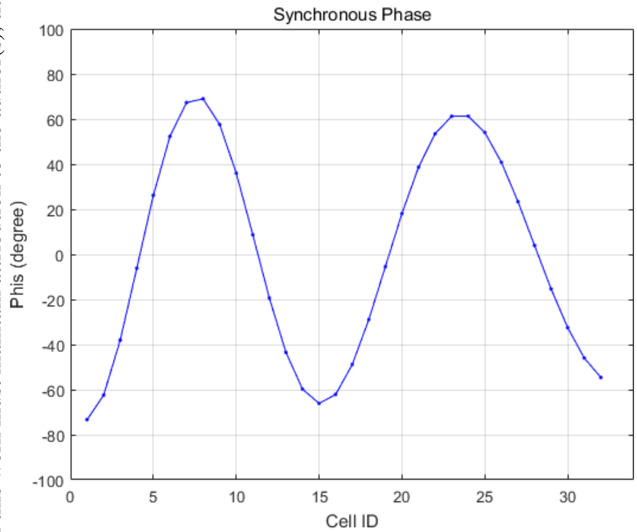

Figure 2: The synchronous phase sequence of the APF structure.

The physical parameters are summarized in the Table 1.

Table 1: The Basic Parameters of the APF DTL

Parameter	Value
Extraction structural energy	7.0000 MeV
Extraction beam energy	7.0428 MeV
Total length	1.5056 m
Total transmission	97.55 %
Effective transmission	67.90 %
Normalized RMS emittance X	0.2777 π mm mrad
Normalized RMS emittance Y	0.2660 π mm mrad
Total bunch length (2 RMS)	26.1476 mm
Momentum spread (2 RMS)	±2.835 %
Maximum surface field	26.0739 MV/m

ELECTROMAGNETIC DESIGN AND END-TO-END SIMULATION

With the APF structure above, the CST Microwave Studio code was used to compute the three-dimensional (3D) electromagnetic fields [3].

A comparison between the BEAMPATH analytical field and the CST numerical field is shown in Figure 3.

The difference between the analytical field that is used by the BEAMPATH and the simulation field calculated by CST is shown. As the integral electric field is our primary focus, the ratio between the BEAMPATH integral field and the CST integral field was compared. The coherency of the middle cells (cell 2 to cell 31) are less than 2 %, but the first and the last cell has about 10 % deviation from the design value. As showing in Figure 4.

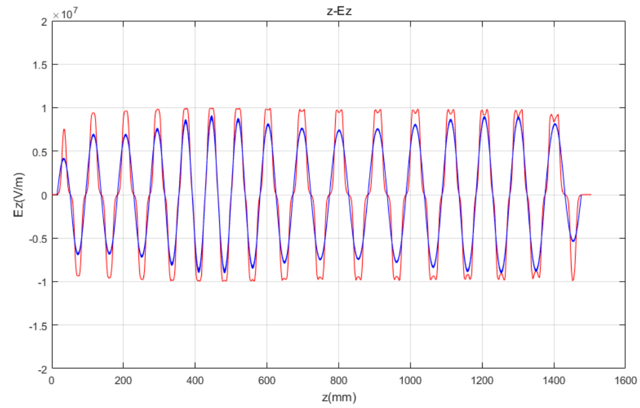

Figure 3: A comparison between the analytical fields used in BEAMPATH (blue) and the accurate 3D field generated by CST Microwave Studio (red).

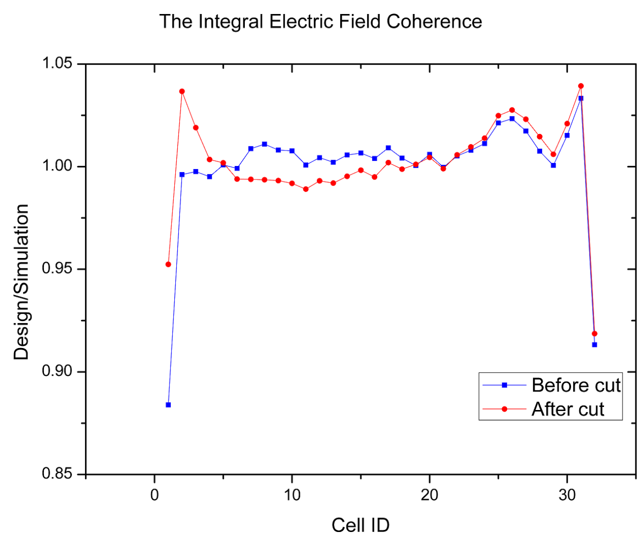

Figure 4: The integral field deviation between BEAMPATH and CST.

This deviation is cause by the half gap effect of the end cells, where the outer wall of the DTL cavity is electrical grounded. To correct this deviation, we keep the center of the first gap fixed ,and simultaneously cut the left side of the first tube and the right side of the second tube by 1.75 mm, as showing in the Figure 5. There we have the new integral electric field deviation showing in Figure 4.

The comparison shows this cutting method is an effective way to correct the integral electric field deviation, cutting the cells one by one, we had the integral electric field deviation of all cells below 2 %, and the effective transmission that calculated by Trace Win rise from 57.8 % to 66.8 % [4].

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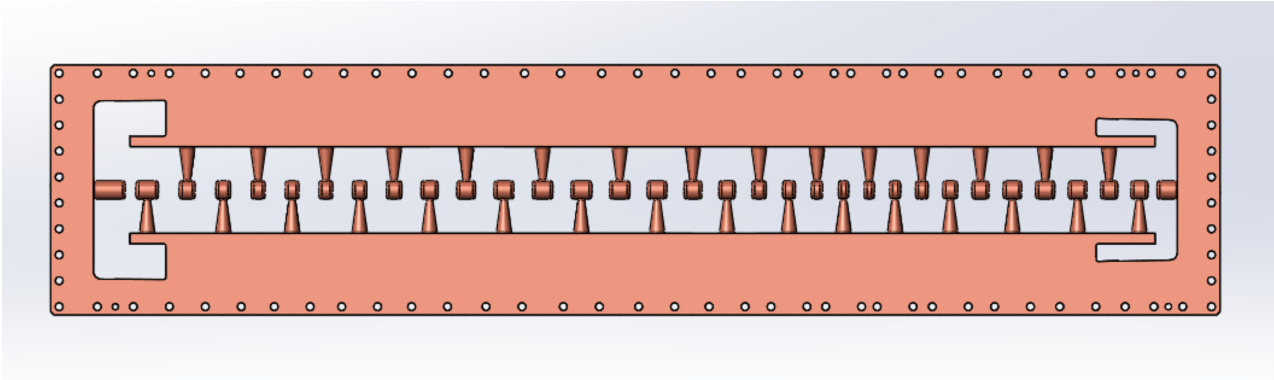

Figure 5: The tube and gap structure of the APF.

CONCLUSIONS

An effective APF DTL design and optimization code was successfully developed based on the Iwata synchronous phase formula and linearly electrode voltage assumption. Moreover, an APF DTL for proton therapy facility has been designed with consideration about various independent errors and joint error. Finally , an integral electric field deviation correction method was founded to rise the effective transmission from 57.8 % to 66.8 %.

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