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DYNAMICS DESIGN ON 70-250MeV PROTON LINAC*

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Abstract

Charged proton beams have broad application prospects, and research on compact S-band proton linear accelerators is increasingly heating up in recent years. For radiation therapy, to achieve the conventional penetration range of water-equivalent tissues, protons with energy of 70 to 230 MeV are required. The design of electromagnetic structure is closely related to particle dynamics design. A flexible and controllable particle dynamic tracking code (PDT) through both traveling wave and standing wave acceleration has been compiled to simulate particle trajectory and satisfy automatic tuning of the various components in the entire acceleration chain. The linac with a total length of approximately 7.89 m composed of 16 tanks of backward traveling wave structures and permanent magnet quadrupole lenses was designed, operating at an RF frequency of 2.856 GHz with a target acceleration gradient of 30 MV/m, and accelerating proton beam from 70 MeV to 250 MeV while maintaining low emittance and high transmission efficiency.

INTRODUCTION

Proton linear accelerator is widely used in basic research, medical treatment, and industrial manufacturing, among other fields. It can be used in the manufacture of microelectronic devices, surface modification of materials. Currently, it's mainly concentrated in the field of radiation therapy. Compared with advanced photon therapy technologies such as intensity-modulated radiation therapy and volumetric arc therapy, proton therapy can significantly reduce the dose of radiation to normal tissue surrounding the tumor, reducing the possibility of inducing second primary tumors [1]. Traditional proton therapy equipment is bulky, difficult to install and manufacture, and expensive, making it difficult to be widely promoted. Currently, research into miniaturization and compactness of proton linear accelerator is underway worldwide.

Currently, the main high-gradient RF acceleration structures include the TeV Energy Superconducting Linear Accelerator (TESLA) structure [2], Coupled Cavity Linac (CCL) [3], and Backward Traveling Waveguide (BTW) structure [4] is used in the TULIP project, which is dedicated to developing a compact proton linac capable of achieving an accelerating gradient of 50 MV/m, and peak surface electric field and shunt impedance within acceptable ranges even in low-β configurations. Due to the scarcity of simulation software for proton acceleration using traveling wave architecture, we utilized our own compiled open-source particle dynamic tracking code (*PDT*) based on traveling wave acceleration to conduct preliminary dynamic design of a 70-250 MeV BTW proton linac.

PDT CODE

Compared with the abundant available design tools for standing wave proton linac, the design tool for tracking protons through traveling wave structures is relatively hard to find. Most particle tracking programs are designed to handle standing waves or use the superposition of two standing waves to approximate traveling waves, making them unsuitable for BTW structures. Additionally, these programs often function as closed systems, limiting customize and expand the solver capabilities according to our specific requirements.

Due to the unique demands of proton therapy, it is necessary to adjust the kinetic energy of the output particles within a certain range while maximizing the transmission efficiency. This implies that the PDT code not only needs to simulate the particles trajectories through acceleration channel but also incorporate the beam matching functionality [5]. *TraceWin* is capable of calculating the transfer matrix of a given structure and handling standing wave electromagnetic field map represented by real numbers, whereas PDT code accepts not only real numbers but also traveling wave with complex numbers. Since the electromagnetic structure design and particle dynamics design are closely related, it is important to find a starting point.

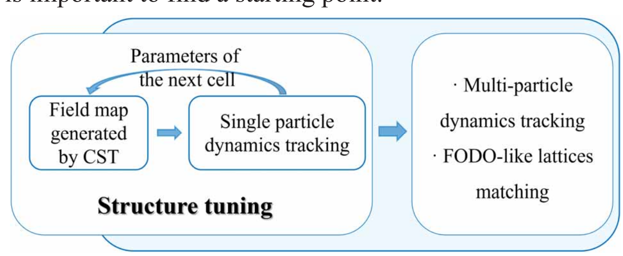

Figure 1: The Simplified scheme of PDT code architecture.

The commonly used simulation software CST studio suite [6] makes it feasible to extend the use of the program to traveling wave structures. CST is used to model and tune the single cell for calculating the electromagnetic field map, while MATLAB serves as the core of the code. The whole solving process is mainly divided into two modules. Since the RF structure design and particle dynamics design are closely related, it is important to find a starting point. In the first part, it makes full use of automated MATLAB and CST co-simulation to track the dynamics of a single particle in the longitudinal direction and tune waveguide structure as an interactive multi-run simulation. has added

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this module to create appropriate wires to enable communication between MATLAB and CST, for speeding up the design process. Another module incorporates longitudinal and transverse multi-particle tracking, as well as transverse focusing of FODO-like lattices approximate matching for bunched beams to maximize the transmission. Its modular design permits adjustment and extend of functions for different design requirements, including seeking the optimal starting point for energy modulation, and optimization of elements parameters.

Finally, the benchmark with the *TraceWin* shows its accuracy both in energy gain and envelopes are good. The simulation model integrative framework is proposed as in Fig. 1.

LINAC DESIGN

Protons with the kinetic energy of 70 MeV are decided inject into a compact BTW linac with an accelerating gradient of 30 MV/m, operating at frequency of 2.856 GHz. The linac is composed of several different tanks, and each tank consists of multiple same BTW cells, as the particle reference velocity β in each tank does not change significantly, which refers to a small unit cell length change. Nevertheless, β between tanks changes greatly which cannot be ignored, the length of the BTW cells in the adjacent tank needs to be adjusted with it.

Structure Tuning

After completing the modeling of the low β BTW single cell structure in CST, the geometry of the regular BTW structure is showed in Fig. 2. Then optimize the geometric parameters, such as the nose cone and coupling holes, to better the characteristics including the shunt impedance, transit time factor and filling time. Based on this prototype and some input data, such as particle species, initial kinetic energy, synchronous phase, operating mode, acceleration gradient, and target output energy, PDT calculates the cell length, optimal number of cells and particle energy in each tank, and obtains the corresponding electromagnetic field maps of every unit cell generated by CST.

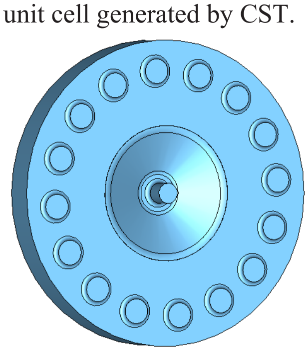

Figure 2: Model diagram of BTW accelerating structure.

A compact 16 accelerating tanks linac is chosen, with a constant number of 19 cells per tank operating at 5/6π mode. The optimal incident phase is obtained through the optimization algorithm in PDT code and the synchronous phase is chosen to 10 degrees. The TTF of particles in each tank is above 0.905, which achieves the desired acceleration efficiency. The total length of waveguide is 7.17 m, which is designed for the main acceleration cavity.

Lattice Design

The transmission efficiency is directly related to the transverse emittance of the beam. Meanwhile, the cavity has the impact of defocusing for particles along transverse direction when linac boost the particles longitudinally. For a constant aperture of the RF structure, the excessive particle radial distance in general can lead to particle loss. In the following, we derive the condition to maximize the transmission of a beam line composed of permanent magnetic quadrupole structures (PMQs), for a given lattice geometry.

Traditionally, in a FODO lattice structure, the tanks have a fixed length, and the magnetic elements are designed accordingly for beam focusing and defocusing. This allows for a relatively straightforward matching of the transverse ellipses. When the lengths of the tanks increase with acceleration and the relativistic β increases, the matching process becomes more complicated, requiring a more comprehensive analysis and optimization approach to ensure proper beam dynamics and stability. Optimize the magnetic field gradients of the quadrupole lens and calculate the transfer matrix by PDT code to find the optimal matching point between the magnetic field gradient and the Twiss parameters. This process involves iteration and numerical techniques to converge on the optimal matching value.

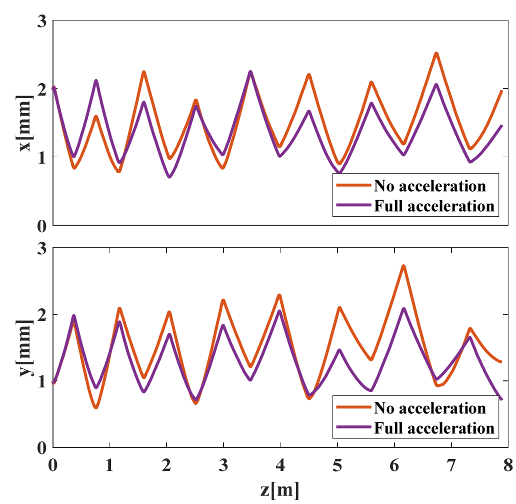

Figure 3: Transverse beam envelop with full acceleration and no acceleration.

To achieve the maximum acceleration efficiency, each tank requires the particle to enter with an individually calculated optimal incident phase. Consequently, drifts must be incorporated between the tanks to ensure alignment between the exit phase of the preceding tank and the incident phase of the subsequent tank. If the length of the quadrupole lens, which is 0.03 m, exceeds the required ideal drift length, an extension of one wavelength of the period should be considered. This adjustment is necessary to ensure that the drifts is appropriately sized to achieve the desired matching between the tanks.

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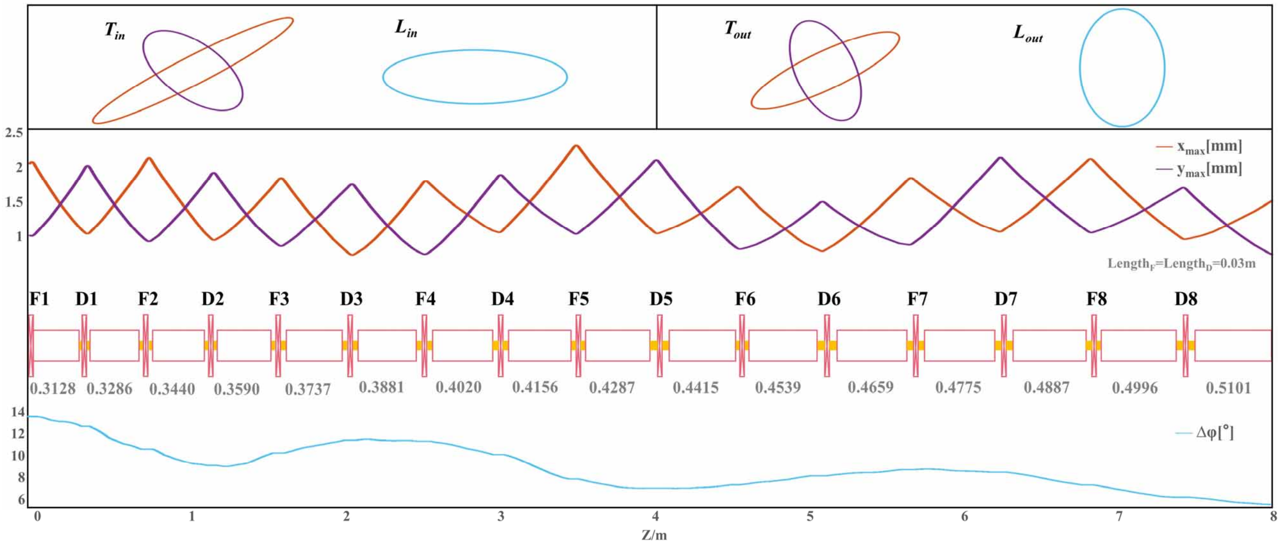

Figure 4: Configuration of the overall structure of linac (F and D are PMQs), with the envelope throughout the acceleration (x_{max}, y_{max}, $\Delta\varphi$), the phase-space ellipses at the beginning and the end of the acceleration (T is transverse while L is longitude).

The transverse beam envelops of two extreme cases with on acceleration and full acceleration are successfully limited to an acceptable range and are shown in Fig. 3. The overall length of the acceleration channel is 7.89 m.

PARTICLE TRACKING RESULTS

The distribution modes of the beam particles in phase space include Gaussian and Kapchinskij-Vladimirskij (K-V) distribution for typical numerical simulating. K-V distribution is chosen that provides clearer boundaries in an intuitive way, which is good for studying particle focusing phenomena and envelope matching in the phase space ellipsoid. Fig. 4 shows the normalized phase-space ellipses of the multiple particles with scale [mm·mrad] at the beginning and the end of the linac. The results show that transverse ellipses can almost be matched after eight complete lattice structures. This suggests that the beam's transverse characteristics, such as the beam size and shape, are close to being properly aligned and matched to the lattice structure.

The small amplitude oscillation of the longitudinal envelope in Fig. 4 is related to the oscillation of the optimal incident phase synchronous phases. In addition, the overall amplitude of the longitudinal envelope follows Adiabatic Phase Damping, which means that the phase spread decreases as the energy increases. This is due to the effect of energy dispersion.

CONCLUSION

A flexible tool *PDT* code that works for a variety type of particles and electromagnetic field maps is certainly free to include any element as we desired to. It's used for a S-band compact proton linac dynamic design. The result achieves a close match of the transverse ellipses after lattice structures, it indicates that the accelerating and focusing channel is properly designed and configured to preserve the beam quality and optimize its performance.

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