Beam Dynamics Design of a Hybrid Single-Cavity Proton Linear Injector

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Date: 2025-05-07T13:42:51+00:00

Abstract

A proton linear accelerator serving as the injector for a medical synchrotron constitutes the proton source of a proton therapy facility, providing the main synchrotron ring with proton beams of sufficient current and adequate beam quality. This study proposes a Hybrid Single Cavity (HSC) type proton linear accelerator structure and conducts a beam dynamics design. This accelerating structure integrates a Radio Frequency Quadrupole (RFQ) and a Drift Tube Linac (DTL) within the same resonant cavity, aiming to improve structural compactness and achieve system simplification through the adoption of a single power source. The beam dynamics parameters of the RFQ were designed and optimized, and beam matching to the DTL was realized by adjusting the end cell structure; the DTL section employs an Alternating Phase Focusing (APF) scheme for dynamics design, and end-to-end charged particle simulations were performed for the entire structure. Simulation results demonstrate that under conditions of 425 MHz operating frequency and 75 kV inter-electrode voltage, the RFQ structure length is 255.151 cm, achieving a transmission efficiency of 84.86%; the DTL comprises 24 accelerating gaps with a length of 90 cm, attaining a transmission efficiency of 70.89%, with good beam envelope control, and the total length of the HSC accelerating cavity is 3.45 m. Beam dynamics studies indicate that this hybrid single cavity proton linear accelerator can effectively compress system length while ensuring beam quality and transmission efficiency, and due to the adoption of a single cavity, will simplify its power source system.

Full Text

Beam Dynamics Design of a Hybrid-Single-Cavity Proton Linac Injector

Vol. XX, No. X, XXX 20XX

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Abstract

[**Background**] As the proton source for synchrotron-based proton therapy systems, the compactness, simplicity, and robustness of the proton linac injector are critical for overall system acceptance, offering reduced footprints and improved performance. Traditional linac configurations combining a Radio Frequency Quadrupole (RFQ) and Drift Tube Linac (DTL) often result in relatively long system lengths and complex configurations. To address these challenges, a 425 MHz proton linac with a Hybrid Single Cavity (HSC) structure is proposed, integrating both RFQ and DTL structures into a single resonant cavity for a more compact and simplified design. [**Purpose**] This study aims to design and simulate the beam dynamics of an HSC-based proton linac injector, focusing on optimizing beam quality and transmission efficiency while minimizing overall system length. [**Methods**] The RFQ section was designed and optimized using the four-section method, with adjustments to the last cells at the output end to achieve beam matching with the subsequent DTL section. The DTL section was designed employing the Alternating Phase Focusing (APF) method. Comprehensive end-to-end beam dynamic simulation was conducted to evaluate the performance of the integrated HSC structure. [**Results**] Operating at 425 MHz with an inter-vane voltage of 75 kV, the RFQ section achieved a transmission efficiency of 84.86% with a structural length as short as 255.151 cm. The DTL section contains 24 drift tubes, with a length of 90 cm and a transmission efficiency of 70.89%, and the beam envelope is well controlled. The total length of the linac was reduced to 3.45 meters, making it much more compact than existing injectors for medical synchrotrons. [**Conclusions**] The HSC-based proton linac injector effectively balances beam quality and transmission efficiency while significantly reducing system length.

Keywords: HSC, RFQ, DTL, Proton Injector

Proton therapy has become a significant research direction in medical physics, leveraging the Bragg peak's depth-dose distribution characteristics and its advantage of minimizing damage to normal tissue. In proton therapy facilities, the accelerator is the core component. Based on different accelerator technologies, proton therapy facilities are mainly divided into two categories: cyclotron-based and synchrotron-based systems [1]. Cyclotrons can produce continuous proton beams and have the advantages of a long development history and mature technology, making them widely used in medical and industrial applications. However, cyclotrons have a fixed direct output energy. To meet the energy requirements for clinical treatment of target regions at different depths, a degrader must be installed in the beam transport line for energy modulation, which increases ionizing radiation and reduces beam utilization efficiency. In contrast, synchrotrons can directly extract variable-energy beams, avoiding the adverse effects caused by degraders. Due to these advantages, synchrotrons have shown continuously growing application potential in proton therapy [2, 3].

In synchrotron-based facilities, proton beams require pre-acceleration through an injector before entering the main accelerator. Pre-acceleration commonly employs linear accelerators, cyclotrons, or electrostatic accelerators, among which linear accelerators are widely adopted due to their excellent matching characteristics. Linear accelerator-based injectors are mainly divided into two types: single Radio Frequency Quadrupole (RFQ) linac structures and combined RFQ-Drift Tube Linac (DTL) structures. The former is suitable for low-energy beam injection (<3.5 MeV). Using a single structure reduces system complexity and construction costs, but the low-energy beam remains affected by space charge effects, leading to beam emittance growth. The latter raises the beam energy to 7 MeV through a combined RFQ-DTL structure. The higher injection energy facilitates particle accumulation in the synchrotron, improving beam intensity and treatment dose rate [4]. After decades of development, RFQ-DTL combined injectors have matured, but numerous challenges remain in achieving system compactness. To achieve compact system designs, researchers worldwide have explored different hybrid linac configurations. Germany's GSI and the Frankfurt Neutron Source (FRANZ) investigated a four-rod RFQ combined with an IH-DTL structure, eliminating the intermediate matching section and simplifying the structural design [5]. The Tokyo Institute of Technology proposed a Hybrid Single Cavity (HSC) structure that places the RFQ and IH-DTL in the same cavity for carbon ion injectors. This approach requires only one power source and auxiliary system, making the injector installation layout within buildings more flexible [6]. Lu Liang et al. from the Institute of Modern Physics, Chinese Academy of Sciences, developed an HSC injector prototype for carbon ions, successfully accelerating a 5.98 mA beam to 2 MeV/u. Although this prototype's acceleration efficiency was not high, its successful operation provided an experimental foundation for HSC practicality and serves as an important reference for subsequent structural optimization and practical applications [7].

This study designs an HSC structure for a proton injector, as shown in Figure 1 [Figure 1: see original paper]. Low-energy proton beams generated by the ion source are transported and matched through a Low Energy Beam Transport (LEBT) line into the RFQ, which is then accelerated to 7 MeV by this hybrid single cavity structure. In this design, the RFQ adopts a four-vane structure operating in TE210 mode, while the DTL employs a cross-bar H-mode DTL (CH-DTL) operating in the same mode. This study separately conducts beam dynamics design and optimization for the RFQ, DTL, and matching structure of the HSC to achieve structural compactness.

1 Injection Requirements

Considering engineering schedule factors, the first domestic proton therapy demonstration device adopted a PL-7i linear accelerator imported from AccSys. Its main technical specifications are listed in Table 1 . This injector provides 7 MeV proton beams for the synchrotron main ring and meets the requirements for beam stability and controllability in proton radiotherapy to support high-precision beam transport and treatment processes.

Table 1 Technical specifications of PL-7i proton Linac

Parameter	Requirements
Accelerated Particle	Proton
Final Energy and Energy Spread	$ $7.0 MeV (1%, HWHM)
Pulse Peak Current	>10 mA
Repetition Rate (adjustable)	0.1~10 Hz
Beam Pulse Width (adjustable)	20~100 s
Transportation Efficiency	<1.5 π· m·rad
Normalized Output Emittance (90%)	10~100%
Length (RFQ+DTL)	Beam Intensity Adjustment Range

2 Beam Dynamics Design

In the HSC structure adopted in this study, the RFQ and DTL are directly connected without intermediate beam matching elements; the matching function is accomplished by the last several cells of the RFQ. This study separately designs the beam dynamics for the two accelerating structures and then optimizes the matching structure.

2.1 RFQ Beam Dynamics Design

The RFQ beam dynamics design employs the classic four-section structure, including: Radial-Matching, Shaper, Gentle Buncher, and Accelerator sections [8], as shown in Figure 2 [Figure 2: see original paper]. In the radial matching section, only transverse focusing fields are provided between electrodes with zero longitudinal accelerating field, and the focusing strength increases from near-zero to its peak value, transforming time-independent phase ellipse parameters into time-dependent ones. Entering the shaper section, longitudinal electric fields and synchronous phase control are gradually introduced to establish longitudinal stability regions, enabling particles to gradually achieve phase synchronization and form initial bunches, creating conditions for subsequent bunching. The gentle buncher section is the core of the four-section theory, performing adiabatic bunching of the beam. By slowly increasing modulation depth and longitudinal field strength while maintaining essentially constant geometric length of the beam structure, the longitudinal distribution density of particles is gradually compressed, effectively suppressing space charge effects.

In the accelerator section, bunches are accelerated to the target energy while the RFQ electrodes continue providing certain transverse focusing fields to control beam emittance growth during acceleration and ensure beam quality [9].

2.1.1 Parameter Selection The transverse dimensions of the resonant cavity and accelerating cell length are affected by the operating frequency. Higher operating frequency results in smaller transverse dimensions and shorter accelerating cells, but also implies higher machining difficulty and error sensitivity. To ensure compactness of the medical accelerator device, an operating frequency of 425 MHz was selected. Considering transmission efficiency from the ion source to RFQ matching, direct RFQ-DTL matching, and potential efficiency reduction due to various errors, the RFQ input beam current was set to 20 mA to ensure sufficient accelerator output current. The RFQ input beam emittance was taken as the typical value of 0.2 mm • mrad from conventional ion source outputs [10]. The input beam energy directly affects the total length of the RFQ accelerating structure and cavity power consumption, but excessively high input energy significantly increases ion source design difficulty. Therefore, a more relaxed setting of 25 keV was adopted for the ion source. The input parameters used in various simulation software for this study are shown in Table 2 .

Table 2 Input parameters of RFQ for simulation

Parameter	Value
Particle	Proton
Number of macroparticles	25 keV
Input energy	20 mA
Input beam currents	$0.05282\ \mathrm{mm}/\pi \cdot \mathrm{mrad}$
Input beam c-s parameters:	$0.05282\ \mathrm{mm}/\pi \cdot \mathrm{mrad}$
Input transverse normalized rms emittance	$0.2\pi \cdot \mathrm{mm} \cdot \mathrm{mrad}$

Since resonant cavities operate at high voltage and are prone to sparking (discharge), the maximum electric field strength in the accelerating gap must be limited. This is typically determined based on the empirical formula given by Kilpatrick:

$$E_k = 1.64 \cdot f_{\mathrm{rf}}^{0.64}$$

where E_k is the Kilpatrick limit electric field strength in MV/m and f_{rf} is the operating frequency in MHz. According to this formula, at 425 MHz, the maximum electric field strength in the accelerating gap is $E_k = 19.91$ MV/m. However, with continuous improvements in machining precision and vacuum technology, the maximum surface electric field that resonant cavities can withstand in practical applications usually exceeds the Kilpatrick limit. Therefore, a correction factor p_K is typically introduced, representing the multiple by which the maximum electric field can exceed the Kilpatrick limit under modern process levels. The calculation formula is as follows [12]:

$$E_{\max} = p_K \cdot E_k$$

The value of p_K depends on the operation mode: typically $p_K = 1.2$ for continuous wave (CW) operation, but it can be appropriately increased in pulsed operation mode. Given that the duty cycle of the injector in this design is low and operates in pulsed mode, $p_K = 1.85$ was selected, resulting in a maximum surface electric field of approximately 36.84 MV/m [13].

The length of individual accelerating cells for both RFQ and CH-DTL is $\beta\lambda/2$. The RFQ output energy should not be selected too low; otherwise, the DTL gap and drift tube length would become too small, increasing difficulty for precision machining of drift tubes and cooling channel design. At 425 MHz, if the DTL input energy is between 2 MeV and 7 MeV, the length of individual accelerating cells ranges from 2.3 cm to 4.3 cm. After careful consideration, the RFQ section extraction energy was finally chosen as 3 MeV.

2.1.2 RFQ Optimization and Results After initial parameter setting, the optimization phase begins. RFQ dynamics design involves multiple key parameters, including average aperture radius r_0, inter-vane voltage V, number of radial matching cells, synchronous phase at the gentle buncher end, energy and modulation coefficient, and energy at the shaper end W_s. These parameters collectively determine the RFQ's acceleration efficiency, beam transmission efficiency, and structural dimensions.

To clarify the specific impact of each physical parameter on RFQ accelerating structure performance, key variables were analyzed. The analysis revealed that average aperture radius r_0 is a critical factor affecting focusing strength. Reducing r_0 significantly increases the focusing coefficient, thereby enhancing beam confinement, improving transmission efficiency, and effectively compressing structural length. However, excessively small apertures increase local electric field strength and sparking risk. Inter-vane voltage affects electric field strength; with constant r_0, increasing voltage improves transmission efficiency but raises maximum surface electric field. To simplify structural design and machining processes, this study adopted a constant voltage design. Combined with the relationship between operating frequency and average aperture, the inter-vane voltage was finally selected as 75 keV. The number of radial matching cells mainly affects RFQ acceptance, with negligible impact when exceeding 4 cells. In the shaper and gentle buncher sections, phase smoothly transitions from -90° to the acceleration phase. In the design program, the GB end phase and energy settings are influenced by initial energy and must be co-adjusted to maintain constant initial energy. Larger GB end modulation coefficient m yields higher acceleration gradient but reduces focusing strength, affecting transmission efficiency. Shaper end energy influences gentle buncher length, thereby affecting overall dimensions and transmission efficiency. Increasing RFQ end phase also improves acceleration efficiency but reduces bunching effectiveness.

Based on the above analysis, RFQ parameters were optimized, with the resulting design shown in Figure 3 [Figure 3: see original paper]. Simulation verification shows that under the optimized design, the RFQ's maximum surface electric field is 36.2 MV/m (below the surface voltage limit of 36.84 MV/m), with a total electrode length of 255.15 cm and an output beam energy of 3.02 MeV. The output beam's transverse normalized rms emittance is 0.19 mm · mrad, and longitudinal normalized rms emittance is 0.21 mm · mrad, with simulation results shown in Figure 4 [Figure 4: see original paper].

2.2 RFQ-DTL Matching

The RFQ structure achieves strong focusing through quadrupole electric fields, with alternating focusing in x and y directions. The DTL structure in this study, however, relies on transverse electric fields between drift tubes for simultaneous focusing or defocusing in both transverse directions, forming a weak focusing periodic structure similar to FODO-FODO [14]. Therefore, the phase space distribution of the beam at the matching section exit significantly impacts subsequent transport quality, making reasonable matching design crucial for overall beam quality. In conventional RFQ-DTL injector systems, a Medium Energy Beam Transport (MEBT) line is typically installed to achieve transverse and longitudinal phase space matching [15]. To achieve structural compactness and reduce accelerator total length, various compact matching designs have emerged recently, including integrating quadrupole magnetic lenses within the first four drift tubes of the DTL [16] or directly connecting RFQ and DTL without an intermediate matching section [17]. The HSC structure proposed in this study employs direct matching between a four-vane RFQ and CH-type DTL, where matching units consist of several specific transport cells at the RFQ end, achieving phase space matching with the DTL through optimized electrode parameters.

The RFQ section design did not initially consider matching units for the subsequent DTL structure, requiring separate beam dynamics optimization design for the matching section. During simulation, the transition drift section between RFQ and DTL was optimized in detail, involving parameters such as synchronous phase, number of cells, and length of the transition section to ensure smooth beam transition and efficient matching. Figure 5 Figure 5: see original paper shows the beam phase space distribution after adjusting RFQ end accelerating cell parameters, where the beam diverges in the x-direction and focuses in the y-direction. The matching unit consists of two RFQ accelerating cells, with phase space distribution after the matching section shown in Figure 5(b). The beam's normalized rms emittance in x and y directions remains at 0.201 and 0.198 $\pi \cdot$ mm · mrad, respectively, with essentially no emittance growth and good beam quality. The corresponding Twiss parameters are: $\alpha_x = -0.1127$, $\alpha_y = -0.1648$, $\beta_x = 0.1587$, $\beta_y = 0.0959$. These parameters indicate the beam is in a slightly divergent state, with small and similar β values in both transverse directions, facilitating efficient matching with the DTL structure. This condition helps reduce the DTL section's requirement for beam envelope modulation, avoiding emittance growth and beam spot oscillations caused by mismatch, thereby enhancing overall acceleration system stability and efficiency. Additionally, error analysis was conducted through numerical simulation studies of input beam parameter errors and structural machining errors. Results demonstrate robust and stable beam transmission performance within typical error ranges, further validating the feasibility and engineering adaptability of the designed structure.

2.3 DTL Beam Dynamics Design

2.3.1 APF Dynamics Design Method Conventional Alvarez-type DTLs operate in 0-mode with accelerating cell length of $\beta\lambda$, while H-mode DTLs operate in π-mode with cell length of $\beta\lambda/2$, significantly shortening the accelerating cavity length. For H-mode DTLs, two beam dynamics design schemes exist: KONUS (Kombinierte Null Grad Struktur) [18, 19] and Alternating Phase Focusing (APF) [20]. The KONUS scheme combines zero-phase acceleration, quadrupole focusing, and negative-phase bunching to achieve high acceleration gradient, but introduces focusing structures inside the cavity, increasing RF design difficulty. The APF scheme achieves collaborative control of beam acceleration, bunching, and focusing by alternately arranging synchronous phases of accelerating cells, generating transverse electric fields in accelerating gaps. This offers significant advantages in structural simplification and RF design [21]. Based on these considerations, the DTL structure of the HSC in this study adopts the APF beam dynamics design scheme.

The fundamental principle of the APF scheme is to artificially introduce periodic focusing and defocusing electric fields by alternately setting synchronous phases of accelerating gaps during acceleration, achieving effective transverse beam control. Without external magnetic elements, relying on focusing effects generated by phase arrangement can partially replace conventional magnetic quadrupole focusing systems. Beam transport behavior in gaps is highly sensitive to synchronous phase sequences. Proper phase function design helps control beam spot size evolution and envelope stability while mitigating longitudinal divergence trends caused by space charge effects, thereby ensuring beam quality while improving transmission efficiency.

Regarding synchronous phase arrangement patterns, extensive research and practical experience internationally have led to several representative phase distribution methods. Among them, the sinusoidal-like phase variation function proposed by Japanese researcher Yoshiyuki Iwata has become widely adopted due to its concise form and flexible parameter control, demonstrating excellent performance in multiple accelerator experiments. This study conducts beam dynamics design based on this method. Iwata's empirical phase distribution formula is as follows [22]:

$$\phi(n) = \phi_0 \times \exp(-an^b) \times \cos(2\pi n/c + \phi_0 n_0)$$

where ϕ_0 is the phase variation amplitude; a is the phase attenuation factor determining the decay speed of phase with increasing accelerating cell number n; b controls the periodicity of phase variation, with larger values resulting in fewer periods; c is the phase waveform modulation factor for fine-tuning local phase variation characteristics; and n_0 is the phase offset controlling the initial phase position. During the design process, adjusting the n_0 value can align the DTL's first accelerating gap synchronous phase with the RFQ end accelerating cell synchronous phase as closely as possible, achieving natural phase transition, improving DTL acceptance of RFQ output beams, and reducing emittance growth and loss rates during injection.

2.3.2 Optimization and Results Analysis Based on the aforementioned synchronous phase variation 规律, parameters within each DTL accelerating cell are shown in Figure 6 [Figure 6: see original paper]. The RF phase of a single accelerating cell varies from -90° to +90°, with the RF phase at which particles reach the accelerating gap center being the particle synchronous phase. Structural parameters for each DTL accelerating cell were calculated, including synchronous phase, gap length, drift tube length, and transit time factor, which serve as input parameters for subsequent charged particle simulation.

After completing preliminary matching design, the RFQ output beam was used as input conditions for beam dynamics simulation of the DTL structure. To enhance HSC structural compactness, an optimization program was further employed for systematic optimization of synchronous phase distribution [23]. By comparing key beam quality indicators such as beam envelope evolution, transmission efficiency, and output emittance under different phase distributions, the optimal synchronous phase arrangement was determined. This scheme achieves good acceleration efficiency while effectively suppressing beam emittance growth, demonstrating excellent transmission performance. Figure 7 [Figure 7: see original paper] shows the beam envelope, bunch length, and energy spread variations along the HSC structure axis. Figure 8 [Figure 8: see original paper] shows the exit phase space from end-to-end simulation, with an exit beam current of 12 mA, overall cavity transmission efficiency of 60.16%, DTL section transmission efficiency of 70.89%, and exit emittance of 0.28/0.32 $\pi \cdot \mathrm{mm} \cdot \mathrm{mrad}$, all meeting injection requirements.

Analysis of beam loss indicates that particles are primarily lost in the initial region of the DTL section, mainly due to: (1) Accelerating field distortion caused by poor matching between RFQ and DTL sections; (2) At 425 MHz operating frequency, to meet high-frequency structural requirements, cavity transverse dimensions, drift tube aperture, and length are reduced, affecting electric field uniformity in accelerating gaps and causing transverse divergence of central particles, making the beam transverse envelope approach drift tube aperture; (3) Acceleration and focusing cannot occur simultaneously in DTL structures, causing bunches to gradually expand longitudinally and affecting subsequent transport stability. By optimizing the transition structure, electrode aperture, gap length, and phase arrangement, the beam transverse envelope was successfully compressed, suppressing emittance growth and bunch expansion. Finally, using the optimization program to adjust parameters of the phase sequence formula significantly improved overall system transmission efficiency from 20% to 60.16% under 20 mA input beam conditions.

Conclusion

This study conducted beam dynamics design research for a proton linac injector based on the Hybrid Single Cavity (HSC) structure. This structure integrates a four-vane RFQ with a CH-type DTL in a single resonant cavity, offering advantages in structural compactness and simplified RF systems.

During the design process, to address matching difficulties and low transmission efficiency in conventional HSC structures, the RFQ end structure was first reconstructed by redesigning the end port as a transport section to achieve phase space matching. Simulation results show that RFQ output beam emittance exhibits essentially no growth, with normalized rms emittance values of 0.201 and 0.198 $\pi \cdot \mathrm{mm} \cdot \mathrm{mrad}$, respectively. The corresponding Twiss parameters demonstrate good transverse symmetry, meeting DTL section injection requirements. The DTL section employs the Alternating Phase Focusing (APF) scheme for dynamics design, achieving good beam transport through optimized phase sequences. The total HSC cavity length is 3.45 m, accelerating a 20 mA beam to 7 MeV with a transmission efficiency of 60.16%.

In summary, the HSC injector designed in this study achieves structural compactness and improved transmission efficiency while ensuring beam quality, providing a theoretical foundation and preliminary parameter support for subsequent electromagnetic design, thermal stability analysis, and practical engineering implementation of HSC structures.

Author Contributions

MI Chuan was responsible for HSC cavity dynamics design, data analysis, and manuscript writing and revision. XIE Xiucui was responsible for DTL phase sequence optimization and guidance on dynamics design and analysis. LIU Yonghao provided guidance on design procedures and result analysis. WAN Weishi provided guidance on dynamics calculations. All authors reviewed and modified the article.

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