PRELIMINARY DESIGN OF AN RF-FOCUSED INTERDIGITAL DRIFT TUBE LINAC

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Abstract

The development of compact and efficient low-energy linear accelerators is crucial for advanced scientific and medical applications. While H-mode Drift Tube Linacs (DTL) offer superior shunt impedance compared to conventional Alvarez structures, they traditionally suffer from transverse defocusing and longitudinal instability when operating at a 0° synchronous phase. This paper presents the comprehensive design and beam dynamics study of a Radio-Frequency Focused Interdigital (RFI) H-mode DTL. By modifying the drift tubes to include internal pole tips, transverse quadrupole focusing is achieved directly via the RF fields, eliminating the need for internal magnetic lenses. We evaluate three transverse focusing lattices (FDFD, FFDD, and FFFDDD) using TraceWin, determining the optimal balance between beam transmission and required focusing voltage. Furthermore, a single cell optimization was performed and a high effective shunt impedance of 259 MΩ/m has been achieved.

INTRODUCTION

In the low-to-medium $\beta(0.05< \beta <0.2)$, the Alvarez-type Drift Tube Linac (DTL) [1] operating in the TM010 mode served as the standard architecture for ion acceleration. However, the Alvarez-DTL suffers from a sharp decline in effective shunt impedance due to the insert of quadrupoles in drift tubes, which presents significant drawbacks in terms of power consumption and facility footprint. In contrast, H-mode linacs, which operate in the TE110 (Interdigital H-mode, IH) [2] or TE210 (Cross-bar H-mode, CH) modes, provide exceptionally high shunt impedance and highly compact structural dimensions within this low-β range.

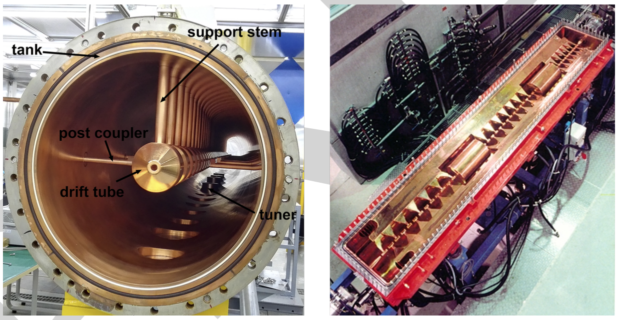

Figure 1: Alvarez-DTL structure for CSNS and IH-DTL structure for GSI HLI project.

Despite their superior RF efficiency, conventional H-mode accelerators encounter severe beam dynamics bottlenecks. The fundamental challenge arises from the strong transverse RF defocusing forces inherent in the acceleration gaps. To mitigate this without employing lenses in every drift tube, designers typically adopt the KONUS (Kombinierte Null-Grad Struktur) beam dynamics concept [3], where the beam is accelerated at a 0° synchronous phase. Over multi-gap sections, this lack of longitudinal confinement inevitably leads to beam filamentation, substantial longitudinal emittance growth. Furthermore, to periodically refocus the beam, external magnetic lenses such as Permanent Magnet Quadrupoles (PMQs) or Electromagnetic Quadrupoles (EMQs) must be inserted into specific drift tubes. Integrating these magnets into the heavily space-constrained vacuum environment—while simultaneously managing precision alignment and complex water-cooling systems—drastically escalates manufacturing complexity and overall construction costs.

To overcome these physics and engineering limitations, the Radio-Frequency Integrated (RFI) focusing H-mode DTL is proposed. By redesigning the geometry of the drift tubes to include internal electrode extensions, this structure generates a transverse electrostatic-like quadrupole field directly derived from the accelerating RF power. This innovation not only eliminates the need for internal magnetic lenses but also permits operation at negative synchronous phases, thereby restoring deep longitudinal stability. This paper systematically explores the realization of this structure, detailing the comparative selection of transverse focusing lattices, and the 3D electromagnetic optimization of the combined drift tube.

OPERATIONAL PRINCIPLE OF THE RFI H-MODE DTL

The innovation of the RFI H-Mode DTL lies in the geometry of its combined drift tubes. Conventional cylindrical drift tubes are replaced by an integrated structure featuring four internal electrode extensions (pole tips), as shown in Fig. 2. As the cavity is excited in the TE110 mode, these internal tips are alternately charged by the RF field, effectively generating a time-varying RF quadrupole field inside the drift tube.

Because transverse focusing directly generated from the RF field, the linac is no longer restricted to the 0° synchronous phase required by KONUS dynamics. Instead, it can stably operate at a negative synchronous phase, as shown in Fig. 2, thereby providing a stable longitudinal bucket to

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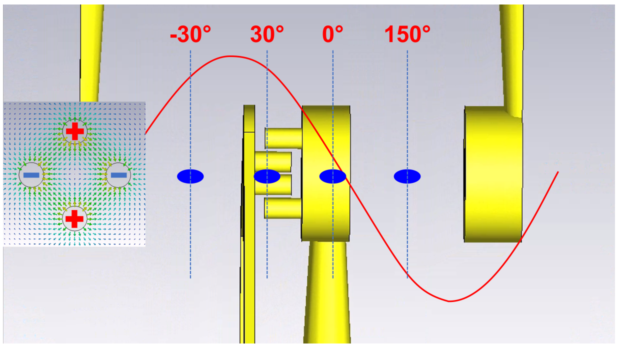

Figure 2: Left: The quadrupole field distribution within drift tubes. Right: phase sequence along particle trajectory, blue balls represent particles, red lines represent RF voltage along axis.

maintain stable. This dynamic process is characterized by a carefully tailored phase sequence:

-30° (Acceleration Phase): At the center of the main accelerating gap, the particle is accelerated while simultaneously experiencing the necessary stable longitudinal movement.

+30° (Focusing Phase): At the pole tip center, the RF phase advances by 60°, where the quadrupole field provides transverse focusing.

0° (Drift Phase): The particle travel into a relatively field-free drift section, allowing for natural envelope evolution without strong external RF perturbations.

150° (Transition Phase): Upon arriving at the next accelerating gap, the RF phase reaches 150°. Matched with the inherent $\pi(180°)$ phase shift of the TE110 mode between adjacent cells, the effective synchronous phase resets to -30° for the continuous acceleration cycle.

TRANSVERSE BEAM DYNAMICS AND LATTICE EVALUATION

To establish the baseline parameters for the RFI linac, beam dynamics were modeled using the TraceWin code [4]. To efficiently assess the theoretical viability of various configurations, the RF focusing fields were initially approximated using electrostatic quadrupole lenses. Particles are accelerated from 1 MeV to about 6 MeV using 'drift-kick' model.

Lattice Configurations Analyzed

The arrangement of focusing (F) and defocusing (D) elements dictates the required field gradients and beam quality. We investigated three distinct periodic sequences: $FDFD/FFDD/FFFDDD$. To thoroughly evaluate beam envelope stability, the zero-current transverse phase advance per period (σ_0) was parametrically scanned across 20°, 40°, 60° and 80°. This sweep allows us to get focus strength requirement with different periodic sequences.

Simulation Results

The simulations revealed a profound physics-engineering trade-off between optimal beam quality and practical electric field limits:

FDFD Lattice: Exhibits the most stable transport with 100% transmission and minimal emittance growth (1%-3%). However, its rapid alternating focusing demands unfeasibly high tip voltages (100-550 kV).

FFDD Lattice: Reduces the required tip voltages to a manageable 60-170 kV. However, the extended focusing period increases envelope oscillations, leading to a significant 18% beam loss at weak focusing ($\sigma_0 = 20°$).

FFFDDD Lattice: Requires the lowest tip voltages (43-89 kV), effectively minimizing RF breakdown risks. Conversely, severe envelope modulation causes beam losses at intermediate phase advances (30° – 50°) and an emittance growth of up to 7%.

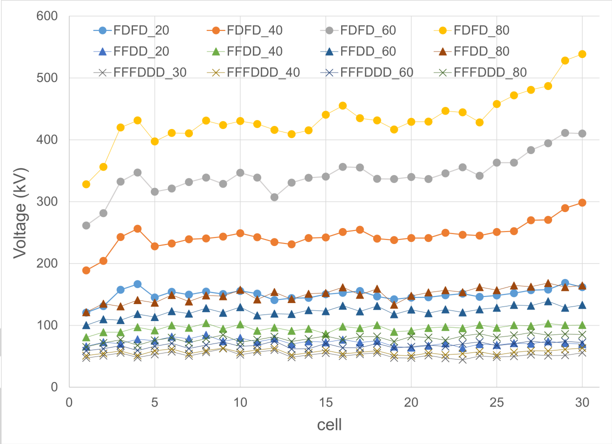

Figure 3: Optimized volatege used in different periodic sequence.

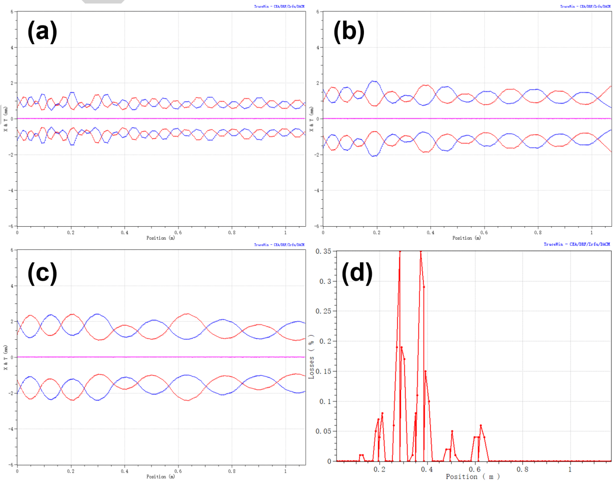

Figure 4: envelope with (a)FDFD, (b)FFDD, (c)FFFDDD, (d)shows the particle loss under FFFDDD and $\sigma_0 = 40°$.

Lattice Selection Strategy

Ultimately, while the FDFD lattice is dynamically optimal, the FFFDDD lattice offers a more practical engineering alternative. Its drawbacks can be mitigated by operating at higher phase advances ($\sigma_0 \geq 60^\circ$), which provide stronger focusing, shrink the transverse envelope, and effectively eliminate beam loss.

To translate TraceWin's theoretical voltages into practical RF fields, a 3D electromagnetic model was built in CST Microwave Studio [5]. An electrostatic calibration mapped the conceptual tip voltage (V) to the actual electric field (E). This mapping revealed that FDFD requires intense fields (3.5-19.4 MV/m), whereas FFFDDD operates safely at much lower fields (1.4-3.5 MV/m).

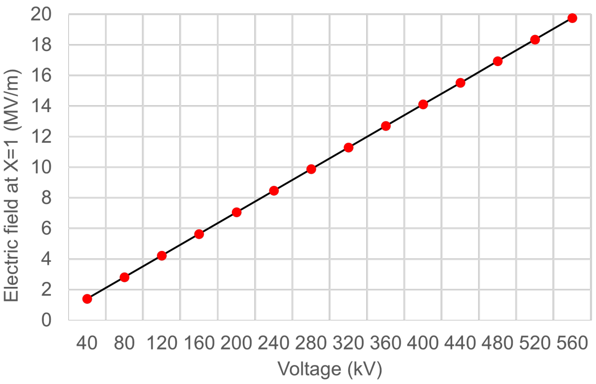

Figure 5: Electric field at $X = 1$ with different tip voltage.

ELECTROMAGNETIC DESIGN OF THE RFI DRIFT TUBE

The performance of the RFI drift tube is dictated by its complex geometry, as shown in Fig.6 characterized by the outer radius (R_t), cavity width (T), tip radius (R_e), support rod angle (α), and fine rod spacing (ΔS).

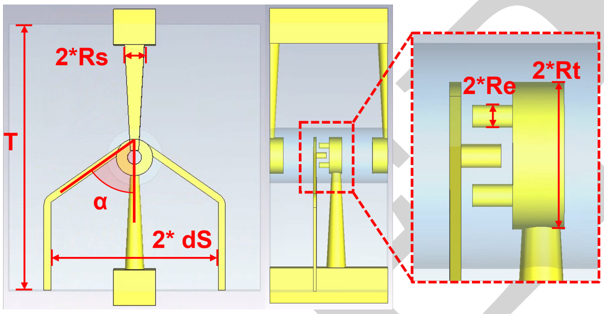

Figure 6: Key parameters of RFI drift tube linac.

To achieve the precise focusing fields required without compromising RF efficiency, a parametric sweep of α and ΔS was performed as shown in Fig. 7. The analysis demonstrated that the field strength is highly sensitive to the rod configuration. By fine-tuning ΔS to a range between 50 mm and 60 mm, the cavity reliably produced an electric field perfectly aligned with the 1.4-3.5 MV/m requirement of the FFFDDD lattice. The fundamental RF properties of the single cell were evaluated, yielding excellent results: $Q_0 = 10059, R_s = 259\,\mathrm{M\Omega/m}$. Subsequently, the required focusing strength can be adjusted by fine-tuning the support rod angle in each cell.

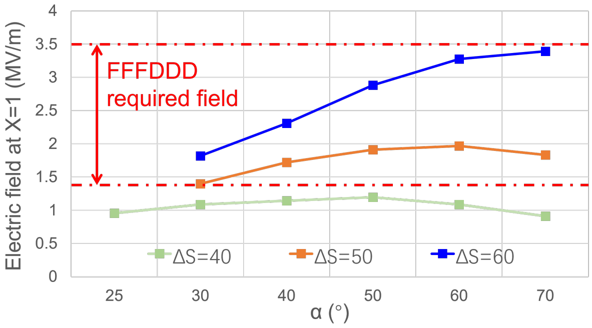

Figure 7: Electric field at X=1 under parametric sweep of α and ΔS.

The single-cell field map with $\Delta S = 60$ mm and $\alpha = 50^\circ$ was imported into TraceWin. At the exit, the beam's Twiss parameter α reaches 0.0827, demonstrating that the beam transforms from a defocused to a focused state in the X-direction as shown in Fig. 8.

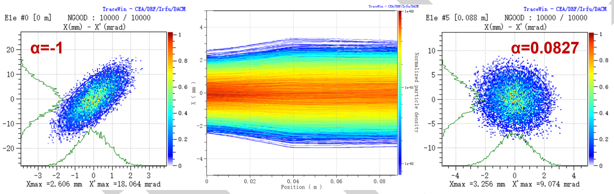

Figure 8: Evolution of the phase space distribution and envelope from the entrance to the exit of a single cell.

SUMMARY

This paper validates the design and optimization of a Radio-Frequency Integrated (RFI) H-mode drift tube linac. By utilizing the RF field for transverse focusing, the design circumvents the mechanical complexities of internal magnets while permitting operation at a stable -30° synchronous phase. Through rigorous lattice comparisons, we mapped the trade-offs between beam transmission and required voltage gradients. Based on the coupled CST and TraceWin simulations of the single accelerating cell, the transverse focusing lattice and its key 3D geometric parameters have been preliminarily established. The method presented herein provide a reliable framework for the future development of highly efficient, compact ion accelerators. Currently, the global physics design of the full multi-cell cavity is underway.

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