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ALVAREZ DRIFT TUBE LINAC FOR MEDICAL APPLICATIONS IN THE FRAMEWORK OF HITRIPLUS PROJECT*

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Abstract

A first beam dynamics and RF design of an Alvarez-type drift tube linac (DTL) has been defined in the framework of the EU project, HITRIplus. It is meant primarily as a carbon ($^{12}C^{4+}$) and helium ($^{4}He^{2+}$) ion injector of a compact synchrotron for patient treatment. As a second implementation, helium particle acceleration with a higher duty cycle (10%) enables radioisotope production. The 352.2 MHz structure efficiently accelerates ion species with A/q=3 and 2, in the energy range from 1 to 5 MeV/u and for a beam current up to ~0.5 mA. The design extends to a full length of ~6.4 meters. Permanent magnet quadrupoles are utilized all along the DTL for focusing both ion beams. This paper presents a first-phase analysis towards a realistic DTL design capable of providing full beam transmission and minimum overall emittance increase for both A/q values.

INTRODUCTION

In Europe, cancer therapy with high energy proton and heavy ion beams was introduced almost 20 years ago. To develop tools for improved therapy with ions heavier than protons, a consortium of organizations from across Europe has initiated the EU-funded project, HITRIplus [1]. One of the HITRIplus goals is to investigate compact and cost-effective accelerator designs for future facilities, to make this treatment option more accessible to a wider range of patients.

The basic HITRIplus accelerator complex is made of a synchrotron, equipped with normal-conducting or superconducting magnets, accelerating up to 10^{10} carbon ions per pulse at the final energy of 430 MeV/u, and other ions at comparable intensities. Injection in the synchrotron is provided by a linear accelerator (linac) accelerating $^{12}C^{4+}$ (A/q=3) ions to 5 MeV/u. After the linac, the ions are stripped and injected in the synchrotron over several turns. The basic HITRIplus configuration includes the option of accelerating $^{4}He^{2+}$ (A/q=2) and protons (A/q=1) at lower voltages in the main linac tank. These ions can then either be injected in the synchrotron or accelerated to higher energy in additional linac tanks, to be sent to a target for production of radioisotopes for clinical and experimental use for imaging and therapy. The main radioisotope of interest is ^{211}At that is considered propitious for combined therapy and diagnostics (theragnostics). ^{211}At production requires an energy threshold < 28.4 MeV to avoid co-production of the unwanted ^{210}At [2].

The HITRIplus project is focused on exploring alternative options to the standard IH (Interdigital H) based injector at 217 MHz that is currently used by the four European carbon ion therapy facilities [3] and has a significant impact on both the cost and performance of the overall facility.

One of the teams involved in the HITRIplus project has recently developed an improved version of the 217 MHz IH injector [4]. However, the project is also exploring other options, such as DTL accelerators operating at 352 MHz, which may offer advantages in terms of beam quality, smaller dimensions and cost.

The considered alternative designs could take advantage of existing klystron designs [5], which offer a competitive cost per installed RF power.

Among the different options at 352 MHz, a standard DTL, equipped with modern permanent magnet quadrupoles, is a viable option due to its excellent beam optics, despite its relatively high construction cost and RF power consumption. The tanks for acceleration of isotopes are designed for acceleration of helium (A/q=2) from 5 MeV/u, and at this charge-to-mass ratio and energy level, the DTL is the optimal structure for providing adequate beam transport.

For the first tank up to 5 MeV/u at A/q=3, several options are available, such as Interdigital-H or Quasi-Alvarez [6]. However, using a standard Alvarez DTL for this section will enable the use of the same design as the A/q=2 part, standardizing the accelerating structures and reducing production costs, while providing excellent beam optics.

Although the DTL requires higher RF power than other solutions, this will be offset by the lower cost per Watt of the klystron solution, using typical 352 MHz klystrons that can reach 2.8 MW power in pulsed mode.

Figure 1 shows the DTL-based configuration of the HITRIplus injector.

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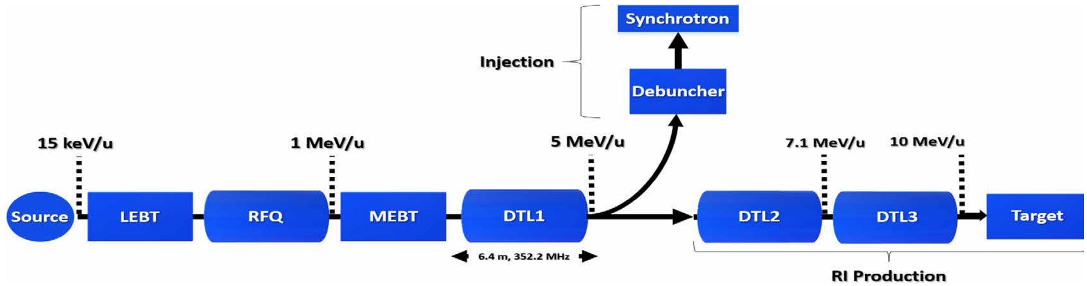

Figure 1: HITRIplus linac layout for double use. DTL2, 3 will follow the Alvarez-DTL1 reaching higher-energy ion acceleration aimed for radioisotope production.

An ECR source will produce the carbon ion beam. AISHa source by INFN-LNS [7] is used as a reference. It can provide the high beam brightness required by the HITRIplus synchrotron design. After a Low Energy Beam Transport (LEBT), the beam is matched into a Radio Frequency Quadrupole (RFQ). From there, a Medium Energy Beam Transport (MEBT) line will match the beam to the first Drift Tube Linac tank (DTL1). A second ECR source, not shown in Fig. 1, is envisaged to generate the helium beam with beam parameters referenced to a commercial ion source [8].

The ECR ion source exit energy is 15 keV/u; the RFQ's exit energy is 1 MeV/u. Prior to beam injection into the synchrotron, the ions must be entirely stripped to $^{12}C^{6+}$. To facilitate the stripping procedure and increase its efficiency > ~95% [9], the DTL1 output energy is selected at 5 MeV/u, a value that is also sufficient for injection into the synchrotron with a linac operation of 0.1% duty cycle (d.c.).

DTL1 can also accelerate $^{4}He^{2+}$ (A/q=2), and protons (A/q=1) with 10% d.c. DTL2 and DTL3 (Fig. 1) will allow for energies of 7.1 and 10 MeV/u respectively, directing the beam to the target system for medical radioisotope production.

DTL DESIGN

The DTL1 geometry, acceleration and power efficiency parameters, as well as the matching and characteristics of beam evolution inside the structure, were computed using GenDTL and Tracewin software [10].

Table 1 provides the main parameters of the DTL1 for acceleration of A/q = 3, 2, after the RFQ.

Table 1: Main parameters of the DTL1

Ion	$^{12}C^{4+}$	$^{4}He^{2+}$
Frequency [MHz]	352.2	
Peak Current [mA]	0.6	0.5
Input Energy [MeV/u]	1	
Output Energy [MeV/u]	5	
A/q	3	2
Pulse Length [ms]	1	
Repetition Rate [Hz]	1	100
Duty Cycle [%]	0.1	10
Length [m]	6.4	

The DTL1 mechanical design will be similar to CERN Linac4. Novel permanent magnet quadrupoles (PMQs) can be housed inside smaller drift tubes with stems, shortening the DTL length. DTL1 will operate at 1 Hz with 1 ms pulse length for injection. Repetition rate can be increased to 100 Hz for radioisotope (RI) production.

Electromagnetic Design:

The energy ranges from 1 to 5 MeV/u for a 0.5 and 0.6 mA current for the two beams. The E_{peak} along the structure varies in the comfortable range of 1.5÷1.8 E_{Kilp}. The structure consists of 104 cells, reaching a total of ~6.4 m length.

The maximum surface electric field of the first cell is located on the drift nose at a radius (R) equal to 13.5 mm (1.5Kilp = 27.9 MV/m) from the beam axis. At the same point the PMQ fringe field (B' = 58.5 T/m) is ~0.2 T, Fig.2.

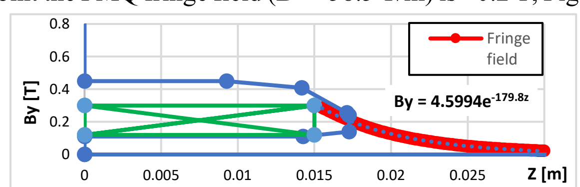

Figure 2: Rapid decrease in the magnetic fringe field of the 1st DT cell at R = 13.5 mm along the beam axis.

Figure 2 demonstrates the rapid PMQ fringe field drop, which minimizes the risk of breakdown effects in a drift tube (considering the ratio of electric field to axial magnetic field at the surface according to the Moretti criterion [11]). The design incorporates a 10% margin beyond the Moretti criterion, which is shown in Fig. 3, to reduce the risk of electric breakdown in the presence of magnetic fields [12].

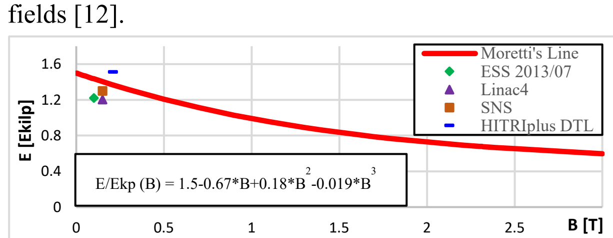

Figure 3: Max. surface E-field of DTL1 1st cell vs PMQ fringe field within 10% margin of Moretti's limit.

The DTL1 geometry parameters were established to accommodate PMQs and stems, increase the axial electric field concentration, minimize multipactor effects, and avoid high field intensity values at drift tube edges.

The DTL1 maximum RF peak power requirement together with a 25% engineering and 20% low-level RF (LLRF) margins is ~1.65 MW.

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Table 2 summarises several figures of merit of the DTL1.

Table 2: Figures of Merit of the DTL1

Parameter	Value
Average ZTT [MΩ/m]	31.5
Total Power [kW]	1,077.3
Q Factor	39,217

Beam Dynamics

DTL1's beam dynamics philosophy aims for maximum transmission with minimal emittance growth in all planes to prepare the beam for injection into the synchrotron.

The focusing scheme is based on permanent magnet quadrupoles for transverse focusing, included in each drift tube with a max gradient <63 T/m. Electromagnets may also be used prior to DTL1 to adjust beam matching.

The design of a novel PMQ able to reach high gradient values, evolution of the Linac4 PMQ model, is feasible and its basic parameters are presented in Table 3 [13].

Table 3: Main PMQ parameters of the DTL1

Aperture Diameter [mm]	24
Magnetic Length [mm]	28
Gradient [T/m]	≥70
Integrated Gradient [T]	≥1.96

The main material is Samarium Cobalt, as it is more stable at very high temperature values and more radiation resistant (density plot shown in Fig. 4).

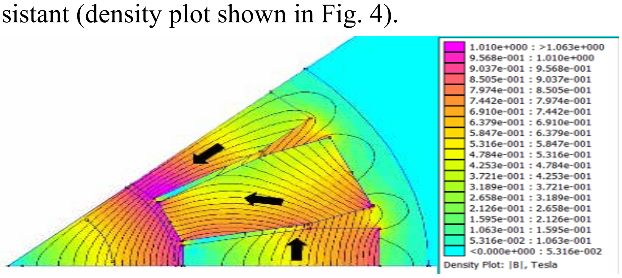

Figure 4: A portion of the novel PMQ design based on Linac4 PMQ —Halbach array with 16 PM blocks —with the density plot bar.

Table 4 provides the DTL1 beam dynamics input parameters together with the outcome studied for a 6D ellipse, 3σ cut Gaussian distribution.

Table 4: Beam Dynamics Specifications for DTL1

A/q	3	2
Focusing Lattice	FFFFDDDD	
Synchronous Phase [∘]	-35~-30	
Input Trans. $\varepsilon_{norm,\,RMS}$ [π mm mrad]	0.25 (ε_x, ε_y)	0.30 (ε_x ε_y)
Input Long. $\varepsilon_{norm,\,RMS}$ [π mm mrad]	0.113 (ε_z)	
Output Trans. $\varepsilon_{norm,\,RMS}$ [π mm mrad]	0.25 (ε_x, ε_y)	0.30 (ε_x ε_y)
Output Long. $\varepsilon_{norm,\,RMS}$ [π mm mrad]	0.121 (ε_z)	0.129 (ε_z)
Emittance Growth [%]	~0 ($\Delta\varepsilon_{x,y}$) 7 ($\Delta\varepsilon_z$)	~0 ($\Delta\varepsilon_{x,y}$) 14 ($\Delta\varepsilon_z$)
Transmission [%]	100	100

A 7% and 14% longitudinal emittance growth has been estimated for A/q = 3 and 2 respectively, with no emittance growth in the horizontal and vertical planes.

The results of the particles density for A/q = 3 and 2 in the X-Z plane are illustrated in Fig. 5.

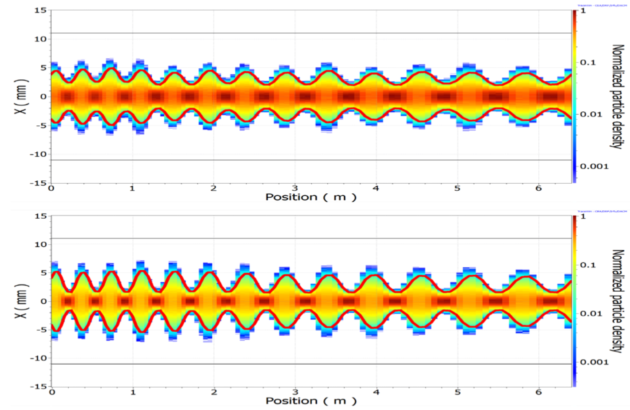

Figure 5: Particles density of a 3σ cut Gaussian distribution in X along the DTL1 for A/q = 3 (top) and A/q = 2 (bottom). The red lines include 99% of the beam particles.

The phase spaces at the end of the DTL1 in X-X′ and Y-Y′ of both A/q=3, 2 are shown in Fig.6.

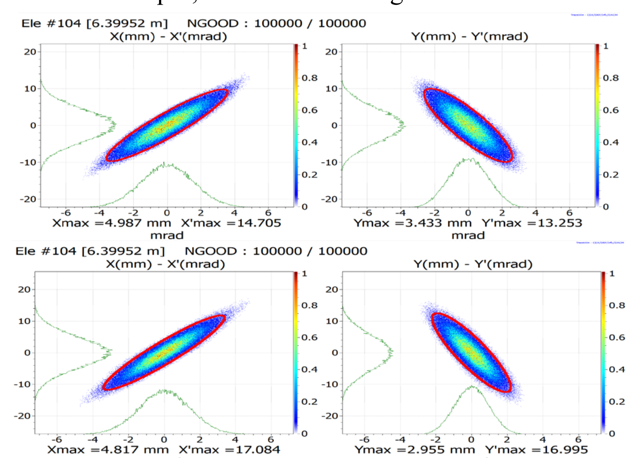

Figure 6: Phase spaces for A/q = 3 in X-X′ and Y-Y′ (top) and A/q = 2 (bottom). The red lines include 95% of the beam emittance.

Hoffman diagrams show no space charge effects at these low currents, leaving only the RF longitudinal term as the defocusing parameter [14]. The DTL1 design avoids parametric instabilities and minimizes emittance increase to maintain stable operation within desired limits.

CONCLUSION

This study has determined that an Alvarez DTL is a viable option for the first tank (DTL1) of the HITRIplus linac. The addition of DTL2 and DTL3, using the same mechanical design as DTL1, will provide the HITRIplus linac with both requirements (injection, RI production). DTL1 has zero transverse emittance growth for both $^{12}C^{4+}$ and $^{4}He^{2+}$ and a length of only ~6 m. Its maximum RF peak power is <1.7 MW, well within the capabilities of a single 352 MHz klystron.

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