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COMPARISON OF 352 MHZ LINAC STRUCTURES FOR INJECTION INTO AN ION THERAPY ACCELERATOR*

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Abstract

In the frame of ongoing initiatives for the design of a new generation of synchrotron-based accelerators for cancer therapy with ion beams, an analysis of linac designs has been started, to address a critical element with a strong impact on the performance and cost of the accelerator. The goal is to identify alternatives at lower cost and a similar or possibly smaller footprint than the standard 217 MHz injector presently used in all carbon therapy facilities in Europe. As an additional feature, a new linac design can be tailored to produce radioisotopes for treatment and diagnostics in parallel with operation as a synchrotron injector. In this paper, the attractive option of moving to 352 MHz frequency is analyzed, to a profit of reliable mechanical designs already developed for protons and of the cost savings that can be obtained using Radiofrequency (RF) power sources klystrons with a much lower cost per Watt than tubes or solid-state units. The paper is presenting a Quasi-Alvarez Drift Tube Linac (QA-DTL) version of an injector linac for carbon ions at q/A=1/3 and compare it with Inter-Digital H-Mode DTL (IH-DTL) designs. The option of a Separated-tank IH-DTL structure (S-IH-DTL) is also discussed, along with a standard IH-DTL, both at 352 MHz. Finally, a DTL design at 352 MHz for the injection of fully stripped helium ions into the synchrotron is presented.

INTRODUCTION

The HITRIplus EU Project aims at integrating and propelling biophysics and medical research on cancer treatment with heavy ion beams, and at developing new accelerator designs to increase access to ion therapy [1]. The reference particles for HITRIplus are carbon ions since their higher relative biological effectiveness compared to lighter ions makes them more effective in treating radioresistant cancers with respect to both X-ray and proton therapy [2].

The reference HITRIplus accelerator design aims at treatment with up to 10^{10} C^{4+} ions per cycle at 430 MeV/u maximum energy, delivered from a conventional or superconducting synchrotron [1]. To respect this requirement, the linac injector must produce up to 600 μA of C^{4+} ions, which are stripped before injection into the synchrotron ring. As an additional option, the linac should provide a 7 MeV/u beam of He^{2+} particles for radioisotope production (e.g., 211-Astatine) [3], accelerated in the same linac structure operated at a voltage that is 2/3 than what used for C^{4+} ions.

This paper develops several designs of linac structures operating at 352 MHz frequency. They could represent a tangible alternative to the standard linac design at 217 MHz based on IH structures that is presently used in the four European carbon therapy centers [4-6]. The proposed designs are then analyzed and compared. The first 352 MHz structure is a Quasi-Alvarez (QA-DTL) [7]. A complete RF and beam optics design is presented and discussed. A standard Interdigital-H (IH) DTL is then analyzed with respect to its RF properties, without a full beam optics design, and finally, the RF design with detailed beam dynamics analysis of a Separated-tank IH structure (S-IH-DTL) is presented. All structures cover the energy range from 0.7 MeV/u corresponding to the output energy of the RFQ to 5 MeV/u which is the energy required for injection into the synchrotron. These structures follow an RFQ presently under design that covers the range 15-700 keV/u in 2.35 m [8].

QA-DTL DESIGN

The QA-DTL is a modified Alvarez DTL with only one drift tube (DT) out of three containing a quadrupole. Since not all DTs in the QA-DTL structure contain magnets, their radial and longitudinal dimensions are reduced thus increasing the achievable effective shunt impedance [9, 10].

Magnet arrangement is FO…ODO…O, where F represents the beam focusing in the X plane and defocusing in the Y plane; O represents drifting space – neither focusing nor defocusing in both X and Y planes; D represents the beam defocusing in the X plane and focusing in Y plane. The length of the drift tubes containing magnets (in this case Permanent Magnet Quadrupoles, PMQ) is $2\beta\lambda$, where $\beta\lambda$ represents the distance which the particle of velocity β travels in one RF period. The distance between gaps around DTs containing magnet is $n\beta\lambda$, where n is the periodicity factor, $\{n \in \mathbb{N} | n \geq 1\}$. The periodicity factor n needs to be chosen carefully, as a trade-off between beam transmission and gradient of magnets. The QA-DTL structure is most efficient when the periodicity factor is set to n=2 [9, 10]. Hence, the considered QA-DTL structure contains a set of superperiods with n=2 (Fig. 1).

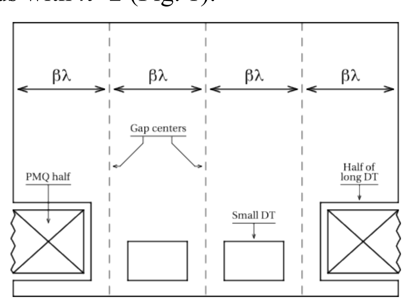

Figure 1: Scheme of a QA-DTL cell.

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After checking that the selected input energy allows sufficient space for the PMQ in the first long drift tube, an average axial acceleration field of 3.5 MV/m was selected, taking the same value of the CERN Linac4 that had been optimized for minimum RF and structure cost [11]. The QA-DTL was then designed using the Superfish set of codes [12]. Its main parameters are reported in Table 1.

Table 1: RF and Beam Optics Parameters for QA-DTL

Ion	C^{4+}	He^{2+}	
Length	5.1		m
Output energy	60	20	MeV
Maximum surf. field	1.8	1.2	Kp
Synchronous phase	-35 to -24.5		deg
No. of superperiods	22		
Power dissipation	626	278	kW
Beam current	0.6	0.5	mA
Input transv. norm. Emittance [rms]	0.25	0.30	π.mm. mrad
Output transv. norm. Emittance [rms]	0.28	0.32	π.mm. mrad
Input long. norm. Emittance [rms]	1.2	0.5	π.deg. MeV
Output long. norm. Emittance [rms]	1.1	0.6	π.deg. MeV
Transmission	100	100	%

In Table 1, Kp represents a unit that describes Kilpatrick criterion. That is, it defines the limit of maximum E field achievable before occurrence of RF breakdown. The beam optics has been calculated with TraceWin [13], for a bore radius of 7.5 mm. Transverse beam envelopes along first 7 superperiods of the QA-DTL tank are shown in Figure 2.

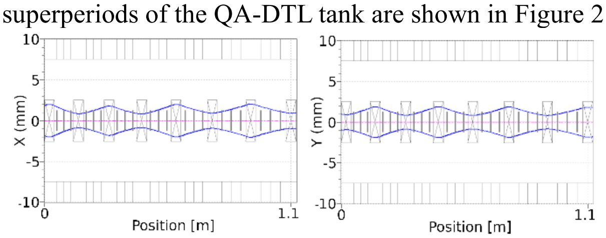

Figure 2: Envelopes in first 7 superperiods of QA-DTL.

Transverse and longitudinal phase space of C^{4+} ions at both input (0.7 MeV/u) and output (5 MeV/u) energies are presented in Figure 3.

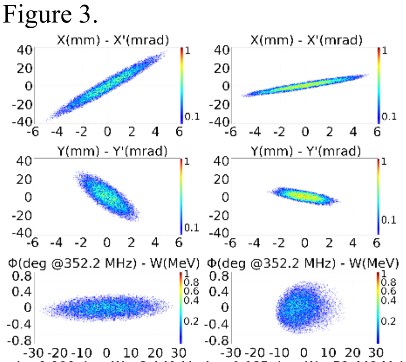

Figure 3: Phase space of C^{4+} at input and output.

Similarly, the transport of He^{2+} ions has been simulated in the structure. Its transverse and longitudinal phase space at both input and output energies are presented in Figure 4. Transmission for both particles is 100%.

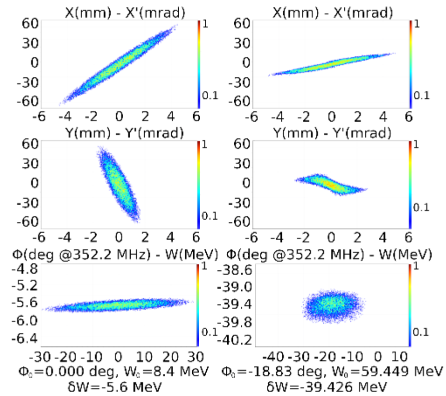

Figure 4: Phase space of He^{2+} at input and output.

H-MODE DTL DESIGN

As next step, the design of a 352 MHz standard IH structure has been tested, similar to a 217 MHz configuration already developed for the HITRIplus project [14]. The total estimated RF power is 417 kW, without considering the space for triplets, to be compared to 340 kW in [14]. The conclusion is that at the higher frequency, the efficiency is too low to justify the usage of the complex KONUS dynamics required for long IH structures.

An alternative to IH-DTL with lower efficiency but clean FODO optics is the Separated-IH (S-IH-DTL), made of short IH tanks with quadrupoles in between. A preliminary analysis of this configuration indicates that the optimum number of gaps per tank is 5, providing a good compromise between RF efficiency and beam optics. The tank radius can be changed after each series of 5 gaps, further increasing efficiency. As an example, the shape and electric field distribution of the first S-IH-DTL tank calculated with the CST code [15] is shown in Figure 5.

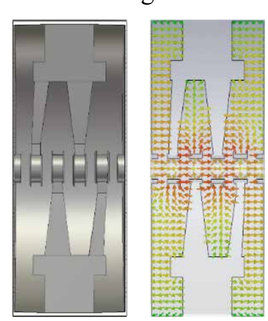
Figure 5: Shape and field distribution of the first tank.

Two transverse focusing schemes were considered, quadrupole doublets and quadrupole triplets, in both cases using PMQ's with gradients limited to <120 T/m. Transverse beam envelopes along the first 5 cells of the S-IH-DTL structure with a doublet focusing system are shown in Figure 6, while Figure 7 shows the envelopes of same cells with triplet focusing. Doublet focusing is preferred since it leads to a shorter length (5.9 m, compared to 8 m with

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triplets), with similar transverse beam dimensions. The phase space plots for C^{4+} are reported in Figure 8. The helium beam was also transported through the S-IH-DTL.

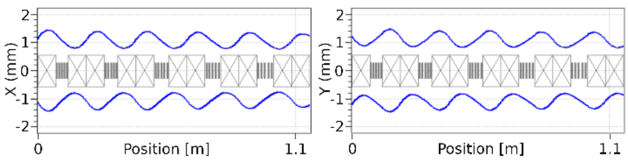

Figure 6: Beam envelopes along first 5 cells of the S-IH-DTL structure, designed with a doublet focusing system.

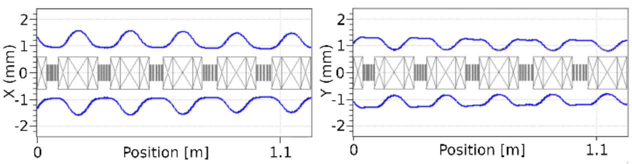

Figure 7: Beam envelopes along first 5 cells of the S-IH-DTL structure, designed with a triplet focusing system.

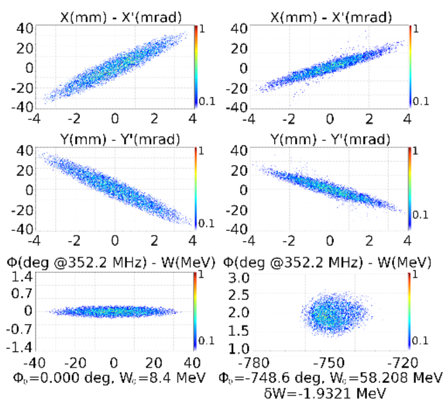

Figure 8: Phase space for C^{4+} at input and output.

The main parameters at the input and output of S-IH-DTL are shown in Table 2.

Table 2: RF and Beam Optics Parameters for S-IH-DTL

Ion	**C^{4+}**	**He^{2+}**	
Full length	5.9 (doublets)		m
RF structure length	3.8		m
Output energy	60	20	MeV
Maximum surf. field	2.1	1.4	Kp
Synchronous phase	-24.0		deg
Number of tanks	26		
Power dissipation	614	273	kW
Beam current	0.6	0.5	mA
Input transv. norm. Emittance [rms]	0.25	0.3	π.mm. mrad
Output transv. norm. emittance [rms]	0.31	0.36	π.mm. mrad
Input long. norm. emittance [rms]	1.2	0.5	π.deg. MeV
Output long. norm. emittance [rms]	2.3	0.7	π.deg. MeV

COMPARISON OF STRUCTURES

Table 3 shows a comparison of the main parameters for QA-DTL and S-IH-DTL. QA-DTL can use a single klystron as RF power source, while S-IH-DTL will use small Solid-State (SS) units, one per IH tank.

Table 3: Comparison Between QA-DTL and S-IH-DTL

Structure	**QA-DTL**	**S-IH-DTL**	
Length	5.1	5.9	m
Total RF Power	626	614	kW
No. of quadrupoles	23	52	
RF system	klystron	SS	

From the point of view of cost, the QA-DTL is expected to present some advantages with respect to S-IH-DTL. The QA-DTL RF power is only slightly higher than for S-IH-DTL, and single tank allows using a klystron with a lower cost per Watt than solid-state. That is, the cost per Watt of klystron is expected to be roughly 2 times less than the cost per Watt of solid-state amplifiers. While the cost per meter of S-IH-DTL structure is expected to be lower than QA-DTL because of smaller dimensions and less stringent alignment tolerances, this is somehow offset by the larger number of quadrupoles. In terms of beam performance, the QA-DTL presents a lower transverse emittance growth than S-IH-DTL although for the latter there are still margins for optimization of the inter-tank spacings.

For the linac section above 5 MeV/u two more tanks were designed, both of standard Alvarez DTL type. The first is designed to accelerate He^{2+} ions up to 7 MeV/u for radioisotope production, and the other to take H^{+} ions at 7 MeV/u and bring them to 10 MeV/u. The parameters of both tanks are shown in Table 4.

Table 4: RF Parameters for the DTL Section

	DTL 1	**DTL 2**	
Reference ion	He^{2+}	H^{+}	
Length	1.53	1.12	m
Input energy	5	7	MeV/u
Output energy	7	10	MeV/u
Synchronous phase	-35 to -24.5		deg
No. of cells per tank	18	10	
Power dissipation	181	147	kW
Axial electric field	3.1	3.1	MV/m
Beam current	0.5	5	mA

CONCLUSIONS

The 352 MHz frequency is an attractive option for the HITRIplus injector. Two options have been developed for the initial section, bringing different ions to 5 MeV/u, with some advantages in terms of cost expected for a QA-DTL. Both options take more space and require a higher RF power than the 217 MHz version presented in [14], yet they can provide certain cost savings coming from the configuration of the RF system. The main advantage of the higher frequency is indeed in the higher energy section, in

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particular in case of the shorter low-power tank required for protons.

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