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DESIGN OF A HELIUM ION LINEAR ACCELERATOR FOR INJECTION IN A PARTICLE THERAPY SYNCHROTRON AND PARALLEL PRODUCTION OF RADIOISOTOPES*

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Abstract

Interest in helium ions for cancer therapy is growing, motivated by their superior conformality as compared to protons or carbon. Clinical trials are starting, using beams produced by large carbon synchrotrons. To exploit the potential of this new ion, a compact synchrotron is being designed to accelerate helium and protons at treatment energies, for about half the size of a carbon machine. The helium linac is designed to operate at a higher duty cycle than the one required for synchrotron injection. Beam pulses can be sent to target-producing radioisotopes, in particular alpha emitters to be used for targeted alpha therapy of cancer.

The 352 MHz linac is made of 3 sections. To increase the efficiency with respect to a standard Drift Tube Linac (DTL), the first section from 1 to 5 MeV/u is made of a Quasi-Alvarez DTL, a structure combining high efficiency and smooth beam optics. Only this section is powered when injecting helium ions into the synchrotron. The second and third sections of the DTL type have energies of 7.1 MeV/u, the threshold for the production of ^{211}At, the most widely used alpha emitter, and 10 MeV/u, for the production of other radioisotopes.

INTRODUCTION

Helium ions can be effectively used for production of several radioisotope species of medical interest, in particular those used for Targeted Alpha Therapy (TAT). This technique involves linking alpha-emitting radioisotopes to a carrier that is injected and absorbed by cancerous cells, thus delivering an intense and localized radiation dose. Investigations of the usage of TAT on tumors such as prostate cancer, neuroendocrine tumors, or brain cancers are progressing, with several ongoing clinical trials [1].

In parallel, there is a renewed interest in directly using helium ions for cancer treatment, related to their better conformality compared to protons or carbon ions [2]. Treatment of deep-seated tumors at beam energy of 250 MeV/u can be realized after acceleration in a compact synchrotron of the He^{2+} beam provided by a linac injector [3, 4].

To satisfy both requirements above, the design of a linear accelerator that can inject helium ions into a therapy synchrotron and produce in parallel a wide range of therapeutic radioisotopes is presented in this paper. Modifying the synchrotron injector linac with the addition of two accelerating tanks and dimensioning cooling system and power supplies for operation at higher duty cycle can provide with minor investment an effective system for radioisotope production. Operation at 50 Hz repetition frequency with pulse length of 2 ms (10 % duty cycle) can provide enough radioisotope doses as required by a medium-size hospital [5]. One linac pulse out of 50 will go to the synchrotron that operates at 1Hz repetition frequency.

The layout of the complete facility for helium ion therapy and production of radioisotopes is presented in Fig. 1 [4]. After the linac, a magnet allows choosing the beam destination between the radioisotope production target and the synchrotron.

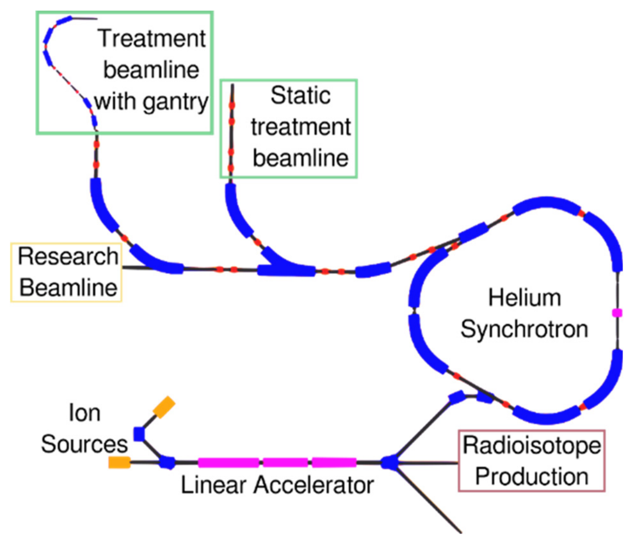

Figure 1: Layout of compact cancer therapy facility [4].

LINAC DESIGN

The linac as synchrotron injector must deliver 5 mA of He^{2+} ions at the energy of 5 MeV/u, as required for multi-turn injection [4]. For production of ^{211}At, the most promising alpha emitter for TAT [6], the linac has to provide an additional acceleration up to 7.1 MeV/u. An additional section to 10 MeV/u allows production of other radioisotopes like ^{47}Sc, ^{67}Cu and ^{123}I [7-9].

The proposed linac is made of three cavities, all at 352 MHz frequency. The first structure is a Quasi-Alvarez Drift Tube Linac (QA-DTL) [10]. This structure has been selected since it presents a higher shunt impedance compared to a conventional DTL, and for light ions has comparable shunt impedance to IH-DTL structures with cleaner beam optics [11]. The QA-DTL is followed by two

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cavities of Alvarez DTL-type with output energies (He^{2+} ions) of 7.1 MeV/u and 10 MeV/u. Input energy to the QA-DTL is 1 MeV/u, corresponding to the output energy of an RFQ at 176 MHz of about 1.6 m length operating with 98% transmission [12].

The schematic layout of the linac is shown in Fig. 2. Since multiturn injection in the synchrotron at relatively high intensity requires a careful control of the longitudinal beam parameters, two short RF cavities have been included in the design: an Energy Ramping Cavity (ERC) providing a fast ramping of beam energy for longitudinal painting, and a Debunching cavity to minimise energy spread. The ERC follows immediately the QA-DTL and is placed at the entrance of the DTL1 cavity, while the debunching cavity is placed at the entrance of the DTL2 cavity.

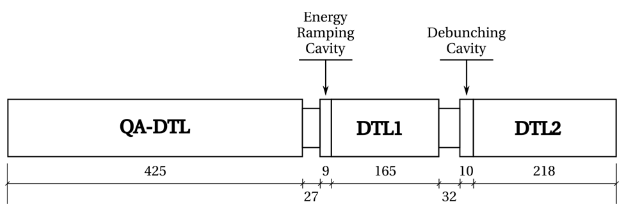

Figure 2: Linac layout (distances in cm).

Both ERC and Debunching cavities are realised by physically separating with a copper wall the first cells of DTL1 and DTL2, feeding them separately using small RF solid-state amplifiers. When the linac is used as a synchrotron injector, ERC and Debuncher are fed while the DTL tanks are off. For radioisotope production, all RF units are on, to provide maximum acceleration. The distance between the ERC and the Debuncher, and their respective neighbouring cavities, is $3\beta\lambda$.

RF AND BEAM OPTICS DESIGN

The RF design of the three cavities has been done using the Superfish code [13]. A 3D model of QA-DTL is shown in Fig. 3. For the 1 MeV/u injection energy, the length of the first QA-DTL drift tube is sufficient for housing the first Permanent Magnet Quadrupole (PMQ).

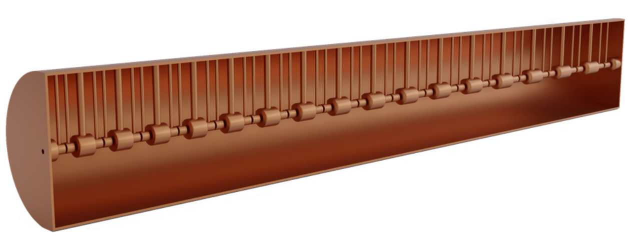

Figure 3: 3D view of the QA-DTL.

The main RF parameters for each of the three cavities are reported in Table 1. An average axial acceleration field of 3.1 MV/m has been selected for the DTL-type cavities. This value has been adopted for the Linac4, DTL at CERN as the one giving the best compromise between manufacturing and RF power cost for 352 MHz DTL-type structures [14]. The average axial acceleration field for the Quasi Alvarez type cavity is slightly higher, at 3.5 MV/m, corresponding to 1.8 times the Kilpatrick limit [15].

Table 1: Main RF Parameters

Cavity	QA-DTL	DTL1*/ ERC**	DTL2* / DEB**	
Length	4.25	1.74	2.28	m
Input energy	1	5	7.1	MeV/u
Output energy	5	7.1	10	MeV/u
Max. surface field	1.8	1.3	1.3	Kp
Synch. phase	-35 to -24	-24	-24	deg
Eff. shunt impedance	60.12	59.14	56.18	MΩ/m
RF Power **	535	35	38	kW
RF Power *		235	300	kW
Avg. axial el. field	3.5	3.1	3.1	MV/m
No. of cells	17	18	20	-

* Linac used for radioisotope production
** Linac used as synchrotron injector

Beam optics have been analysed with the TraceWin codes [16]. The beam parameters at the end of the linac section before injection into the therapy synchrotron are presented in Table 2.

Table 2: Beam Parameters at Synchrotron Injection

Parameter	Value	Unit
Output energy	5	MeV/u
Energy ramping	±0.1	MeV/u
Beam current	5	mA
In./Out. trans. emit. (xx') *	0.25 / 0.264	π.mm.mrad
In./Out. trans. emit. (yy') *	0.25 / 0.261	π.mm.mrad
In./Out. long. emit. *	0.394 / 0.403	π.deg.MeV
Energy spread	±0.37	%
Transmission	100	%

* Emittances are rms normalized

For synchrotron injection, the beam energy can be modulated for ±0.1MeV/u along the pulse using the energy ramping cavity, for a change of synchronous phase of ±57°.

For radioisotopes production, the linac can provide Helium ions at 7.1 MeV/u or 10 MeV/u. Beam parameters on target for the two energies are given in Table 3.

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Table 3: Beam Parameters for Radioisotope Production

Output energy	7.1	10	MeV/u
Beam current	5		mA
In./Out. trans. emit. (xx')*	0.25 / 0.263	0.25 / 0.261	π.mm. mrad
In./Out. trans. emit. (yy')*	0.25 / 0.262	0.25 / 0.263	π.mm. mrad
In./Out. long. emit. *	0.394 / 0.402	0.394 / 0.433	π.deg. MeV
Energy spread	±1.23	±0.98	%
Transmission	100		%

* Emittances are rms normalized

Beam phase space in transversal (horizontal and vertical) and longitudinal planes after the first cavity (before energy ramping and debunching cavities) is shown in Fig. 4.

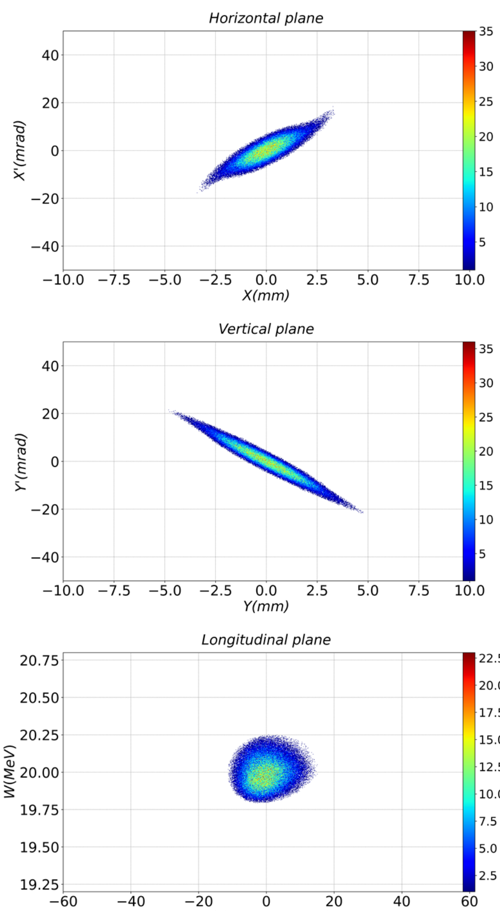

Figure 4: (Top) horizontal; (middle) vertical; (bottom) longitudinal, phase space at the end of the QA-DTL.

The beam has been then transported through the energy ramping and debunching cavities, for three values of the RF phase in energy ramping cavity, corresponding to minimum and maximum energy, and zero-crossing phase. The resulting longitudinal emittances and energy spread are presented in Fig. 5.

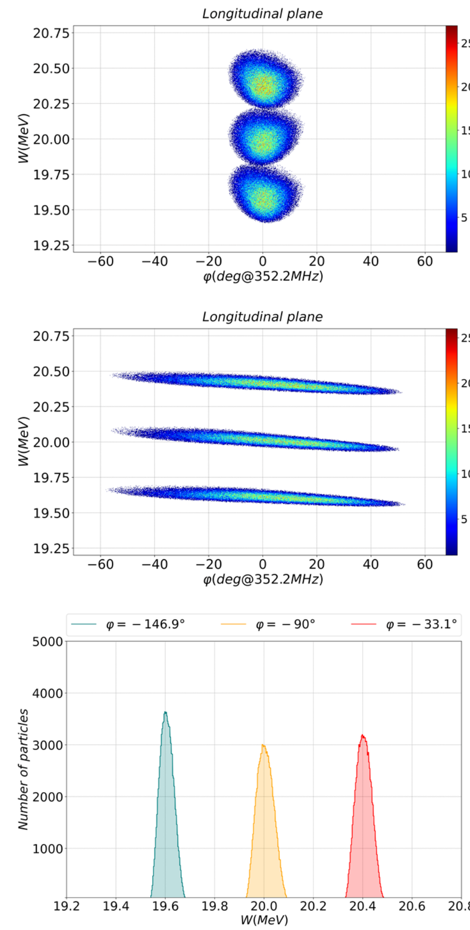

Figure 5: Longitudinal phase space (top) after energy ramping cavity and (middle) at linac exit; (bottom) energy spread at linac exit; for three limit settings of the energy ramping cavity RF phase (-57°, 0°, +57°).

CONCLUSION

A 4.25 m long 352 MHz QA-DTL tank followed by energy ramping and debunching cavities constitutes an efficient injector for a Helium ion synchrotron for cancer therapy. With the addition of two DTL-type tanks of 1.7 m and 2.3 m, respectively, the linac can be used for production of ^{211}At and other radioisotopes for cancer imaging and therapy. For radioisotope production, all RF cavities have to be designed for 10% duty cycle, a value achievable using a standard mechanical design like in [14].

This linac design represents a cost-effective way to combine, in a single accelerator centre connected to a hospital, research and treatment programmes based on the use of light ions and of advanced radioisotopes, paving the way as well for exploring new treatments based on the combination of both. The Advanced Particle Therapy Centre in the Baltic States, a major initiative joining the three Baltic States for the construction of a new regional facility for research and therapy of cancer, has adopted this linac design for its baseline layout [17].

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