# ADVANCED CONCEPTS FOR PARTICLE-THERAPY ACCELERATORS*

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*Abstract*

Presently in Europe the first generation of particle-therapy accelerators is being put into operation. The paper presents potential enhancements for next generations still based on existing layouts and design studies. The focus lies on using molecular hydrogen ions in combination with carbon ions. Identical charge-to-mass ratio is expected to simplify the accelerator chain. An optimized version of a gantry is presented. Its design is driven by an analysis of effects of mechanical misalignments on the beam-position accuracy.

## INTRODUCTION

The recent trend in the design of dedicated hospital-based ion-therapy facilities is a combination of low-LET and high-LET treatment modalities, LET = Linear Energy Transfer. Typically, the low-LET and high-LET treatments are accomplished by protons and carbon ions, respectively. Hospital-based compact facilities are equipped with a single accelerator accelerating protons and carbon ions. This approach requires a relatively large span of working parameters of the accelerator components and complicates optimization of the machine parameters for both particle species simultaneously. Due to the high magnetic rigidity of carbon ions, synchrotrons are used in the existing proton/carbon therapy facilities. In this paper, an option for acceleration of molecular hydrogen $(H_2)^{1+}$ beam instead of protons is discussed and its consequences for accelerator design are analysed.

## MOTIVATION

Combination of protons and carbon ions in the same synchrotron means from the accelerator point-of-view combining low-rigidity and high-rigidity particles. The low-rigidity region extends from 1.13 Tm (proton range of 3 cm in water) to 2.26 Tm (proton range of 30 cm in water) whereas the high-rigidity region extends from 3.1 Tm (carbon range of 3 cm in water) to 6.6 Tm (carbon range of 30 cm in water). However, there is a possibility to accelerate beams of molecular hydrogen ions instead of protons. $(H_2)^{1+}$ ions or $(H_3)^{1+}$ ions have two-times and three-times higher rigidities compared to protons, respectively. It means the low-rigidity region of protons can be shifted towards the high-rigidity region of carbon ions. This shrinks the magnetic rigidity interval that must be handled by the machine. The beam rigidity regions for different particles are shown in Fig. 1 (after [1]).

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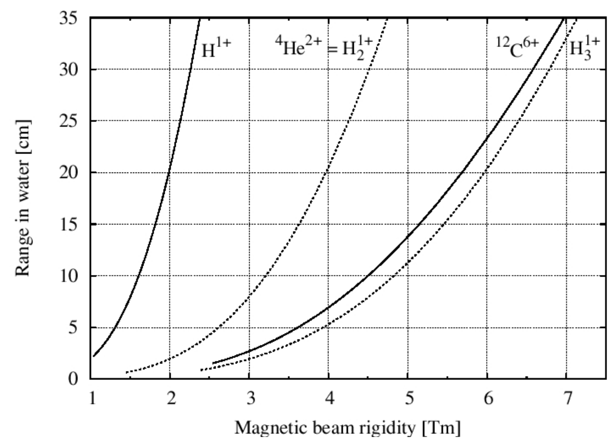


Figure 1: Penetration range as a function of the beam rigidity. Dotted lines – molecular hydrogen ions stripped into protons before entering the patient.

## ACCELERATOR LAYOUT

Using of molecular hydrogen ions instead of protons would lead to accelerating particles with identical charge-to-mass ratio. A corresponding accelerator concept was proposed in [1] and is schematically shown in Fig. 2.

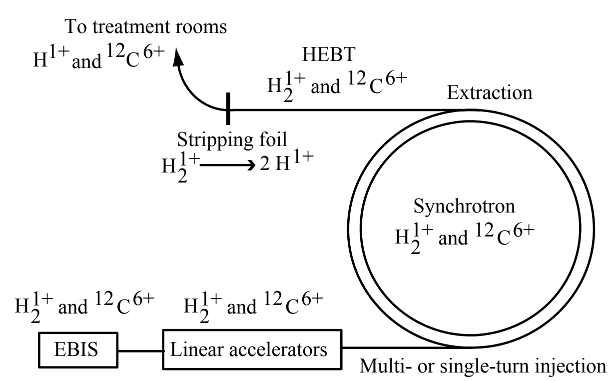


Figure 2: A novel concept of a dual-species proton/carbon medical accelerator based on acceleration of molecular hydrogen ions.

## INJECTION CHAIN

For the injection scheme there is only one major boundary condition, namely the injection to the synchrotron. In practice, two basic designs exist. In Japan, the injection chain was based on an Alvarez structure [2], whereas European designs preferred an RFQ and IH-linac combination optimized for $C^{4+}$ ions. Recently, HIMAC has also adopted this combination [3]. In our study, we discuss an injector for the accelerator layout shown in Fig. 2. The injection chain of the Heidelberg ion therapy accelerator [4] will serve as a reference.

### The Same Charge-to-Mass Ratio

The first assessment is dedicated to the dual species mode that delivers particles of the same charge-to-mass ratio at the injection energy of 7 MeV/u. In combination with an ion source that can produce both beams with sufficient intensity, there are some major possibilities for simplifying the injector.

The first implication would be the transfer line from the source to the RFQ. The same charge-to-mass ratio reduces the length of this line. The space charge of the $H_2^+$ beam is lower compared to the proton beam. In addition, matching to the RFQ is easier for particles with the same charge-to-mass ratio. Taking into account the lower space charge, the shape of the RFQ electrodes can be optimized for acceleration efficiency. As a rough estimation, the length of the RFQ can be shortened by 10 – 15% at the entrance energy 8 keV/u and exit energy 300 keV.

The better acceleration efficiency of the IH-linac due to higher charge-to-mass ratio and also stronger focusing of the quadrupole lenses, which are included in certain drift tubes, generally imply a shorter linac. However, there is one major bottle-neck for the length of the linac. When the frequency is fixed for the whole IH-linac system, it is the velocity of the synchronous particle that defines the drift tube and gap structure. The drift tubes at 300 keV/u are already short compared to the apertures. The ratio of the length-to-diameter is around 0.8 already. At higher acceleration efficiency and higher frequency, the drift tubes would become too short for reliable acceleration. To overcome the problem, the entrance energy could be increased. This would lead to an increased length of the RFQ, which compensates the gain in shortening the overall length.

The medium energy beam line (MEBT) is designed at 7 MeV/u in order to achieve a proper stripping efficiency for $C^{4+}$ ions. Skipping the stripper foil due to direct injection of $C^{6+}$ would enable to lower the injection energy. The main purpose of the de-buncher is to properly prepare the beam for injection. A longitudinal kick in the de-buncher cavity and a rather long drift space result in half the momentum spread at injection. Since the MEBT is already designed for $C^{6+}$ after the stripper, there is no optimization potential except for lowering the injection energy.

### Lowering the Injection Energy

Obviously most potential for higher compactness of the linac lies in lowering the injection energy. Fig. 3 shows a simulation study of the IH-linac. Injection energy of 5MeV/u instead of 7MeV/u leads to a shrinking of the linac-tank from roughly 4m to almost 3m.

The effect could even be higher at MEBT. With a total length of currently 15.5 m, the length of the line could be reduced to 13.3 m. All together, lowering the injection energy to 5 MeV/u would lead to a compactness of the linac system of about 70 % compared to the state-of-the art designs.

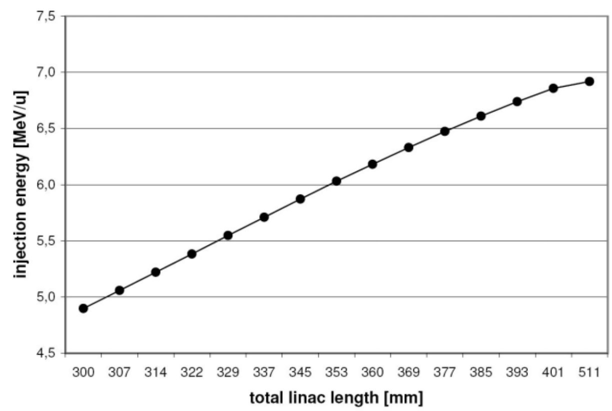


Figure 3: IH-linac length as a function of the injection energy into the synchrotron (based on simulations).

A significantly shorter linac would be possible with a completely new design, considering a new layout, probably without RFQ, and other frequency ranges. Two boundary conditions have to be set to design and optimize such a system: (1) the injection scheme to the ring and (2) availability of an ion source capable of producing sufficient current and small emittance beam.

## GANTRY OPTIMIZATION

In radiotherapy with photons, electrons and protons, gantries are common practice and offer geometric flexibility. Considering gantries for carbon ions the effort rises considerably due to the higher magnetic rigidity. The latter is about three times higher for carbon ions in comparison to protons for equivalent penetration ranges, see Fig. 1. This leads to larger magnets and increased overall dimensions while the same accuracy specifications should be met.

Although the first prototype of an ion gantry will be put into operation soon in the Heidelberg HIT-facility, there is still room for systematic and critical review of existing gantry concepts and for some optimization.

### Beam-Transport Error Analysis

In preparation of the MedAustron design study [5] a beam-line layout of an isocentric gantry has been studied. This beam-line features a maximum beam rigidity of 6.6 Tm and parallel scanning. It consists of three conventional dipoles, seven quadrupoles and two scanning magnets.

Due to the enormous weights and dimensions of the dipole magnets and the size of the mechanical structure deformations can never be avoided. This distortion also implies a deformed beam-line, i.e. a significant contribution to magnet misalignments. A beam-transport error analysis provides data for the implication concerning the resulting beam position alteration at the isocentre. These calculations show that individual beam-line elements have different sensitivity to mechanical displacements concerning the beam position at the isocentre. This sensitivity depends on:

- the type of element (dipole or quadrupole),
- the nature of displacement (shift or tilt),
- the direction of displacement (lateral or longitudinal),
- the position of the element within the beam-line.

With this knowledge one can identify more and less critical displacements for individual beam-line elements concerning their effect on the beam position, as it is shown in Fig 4. It shows that dipole tilts and quadrupole shifts, especially the magnets distant to the rotation axis, lead to the largest beam displacements at the isocentre.

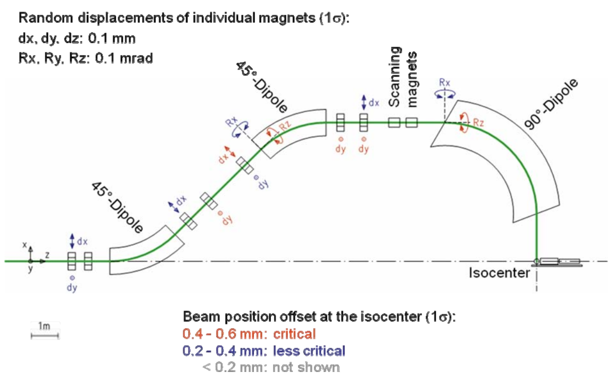


Figure 4: Ion gantry beam-line layout and its implication on random mechanical displacement of individual beam-line elements concerning the beam-position accuracy at the isocentre (after [2]).

### *Mechanical Layout*

Over the past the gantry designs were dominated by beam-optics. The support structure was designed as a last step with equal alignment tolerances for all beam-line elements. A novel strategy now is to transfer beam-optical and mechanical design into a mutually iterative procedure taking into account individual alignment tolerances for different elements and types of misalignments.

Our ambition is the development of a new ion gantry design based on the knowledge gained from ion optical error analyses. The resulting gantry should have less structural weight and improved beam position accuracy. Therefore the critical displacements responsible for the largest impact on the beam position were determined and a mechanical structure with focus on preventing these critical deformations can be developed. In contrast to these stiff regions the structure can be weaker to uncritical displacements. The final result will be a fitted gantry structure customized to high beam position accuracy.

A possible solution is a three rings concept shown in Fig. 5. In contrast to a typical state-of-the-art barrel design the gantry rests on three supports. The mechanical structure is setup such way that critical dipole rotations are minimized. This was achieved by changing the support principle – the mechanical structure supports the largest loads in their centres of gravity.

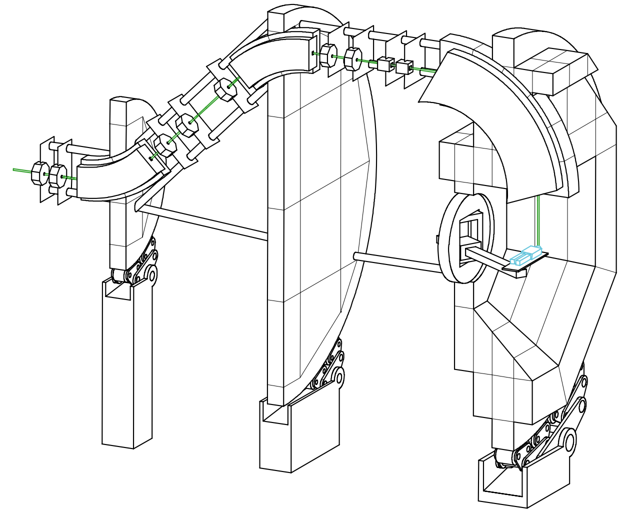

Figure 5: Sectional view of a new ion gantry design – the three rings concept proposed in [2].

## CONCLUSIONS

The paper demonstrated potential improvements resulting from accelerating of molecular hydrogen ions and fully-stripped carbon ions in proton/carbon therapy facilities. Deeper studies on the component-level are necessary to get more accurate quantitative evaluation. A specific ion gantry design based on the presented design-philosophy is currently in progress.

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