DESIGN OF A CARBON INJECTOR FOR A MEDICAL ACCELERATOR COMPLEX

B. Schlitt, U. Ratzinger, GSI, Darmstadt, Germany

Abstract

A design study of a 7 MeV/u $^{12}C^{4+}$ injector LINAC for a synchrotron for light-ion tumour therapy is presented. The injector consists of a 14.5 GHz ECR ion source, a LEBT line, a 216 MHz RFQ structure of 1.2 m length for acceleration from 6 keV/u to 300 keV/u and a subsequent 216 MHz IH drift tube LINAC of 4.0 m length for acceleration to 7 MeV/u. The IH structure consists of four drift tube sections applying the KONUS beam dynamics (*Kombinierte Null Grad Struktur*).

1 INTRODUCTION

The treatment of deeply sited tumours using energetic proton and / or light ion beams meets a strongly growing interest since the last decades and, most recently, the first patients were treated in Europe with light ion beams at GSI [1]. While HIMAC in Japan and Loma Linda in USA are the only dedicated clinical facilities in operation, so far, most of the running hadrontherapy projects are located at nuclear research institutes where the capacity is limited to a small number of patients. Hence, additional hospital based accelerator complexes consisting of synchrotrons or cyclotrons are planned, under construction or already under commissioning all around the world [2]. In Europe, improved accelerator designs are discussed, for instance, for the TERA / PIMMS [2, 3], MED-AUSTRON and GSI / Heidelberg projects. Within these projects the design of a carbon LINAC used as an injector for a clinical synchrotron is investigated at GSI.

The most important demands on a medical machine installed in a hospital environment are high reliability as well as stable and reproducible beam parameters. Additionally, compactness, reduced operating and maintenance requirements, low investment and running costs of the machine count, while the flexibility required usually at research facilities is not needed. For the injector LINAC, a very small duty cycle of about 0.1 % is sufficient, reducing the cooling requirements very much. The operating frequency of 216 MHz allows to find a quite compact LINAC design. In our present layout (Fig. 1, Tables 1 – 3), the complete injector has a length of about 10 m, including an ECR ion source, a Low Energy Beam Transport line (LEBT), an RFQ and an IH-DTL. After acceleration of $^{12}C^{4+}$ ions delivered by the ion source to 7 MeV/u in the LINAC, the ions are completely stripped in a carbon foil stripper before injection into the synchrotron.

Table 1: Output beam parameters of the designed carbon injector LINAC.

Design ion	$^{12}C^{4+}$
Ion species to synchrotron	$^{12}C^{6+}$ (after stripping)
Beam energy	7 MeV/u
Pulse current after stripper	≈ 100 eμA C^{6+} [a]
Beam pulse	≤ 200 μs, ≤ 5 Hz
Duty cycle	≈ 0.1 %
Norm. beam emittance	$\leq 0.6\ \pi$ mm mrad
Momentum spread	$\pm 1.5 \times 10^{-3}$, incl. stripper foil
Total LINAC length	≈ 10 m [b]

[a] depending on source version and current
[b] incl. ion source and up to stripper foil

2 ECR ION SOURCE

To provide very stable beam currents without any pronounced time structures as well as high beam quality an Electron Cyclotron Resonance Ion Source (ECRIS) is selected. The maximum beam intensities discussed for a therapy synchrotron are about 10^9 C^{6+} ions per spill at the patient [2]. Assuming a multi-turn injection scheme using 15 turns at 7 MeV/u, a bunch train of about 25 μs length delivered by the LINAC is injected into the synchrotron. Taking into account beam losses in the synchrotron injection line, the synchrotron and the high energy beam line, this corresponds to a LINAC output current of about 100 eμA C^{6+}. Considering further beam losses in the LEBT, the LINAC and the stripper foil, a C^{4+} current of about 130 eμA extracted out of the ion source is required. To fulfill this demand, the SUPERNANOGUN type ECR source [4] developed at GANIL is well suited for the carbon injector. This is a high performance ECRIS with the magnetic field provided exclusively by FeNdB permanent magnets. The required beam intensity can be delivered in a stable DC operating mode and with normalized beam emittances below 0.4 π mm mrad [5]. The source may be operated preferably at 14.5 GHz. An extraction voltage of 18 kV corresponding to a beam energy of 6 keV/u is selected in the design presented here (Table 2). To optimize beam quality and current as well as to minimize losses in the extraction system and in the LEBT, a three electrode extraction system is planned.

Alternatively, a single turn injection scheme has been discussed for the PIMMS design [3]. Source currents of several hundred eμA up to almost 1 emA C^{4+} are required

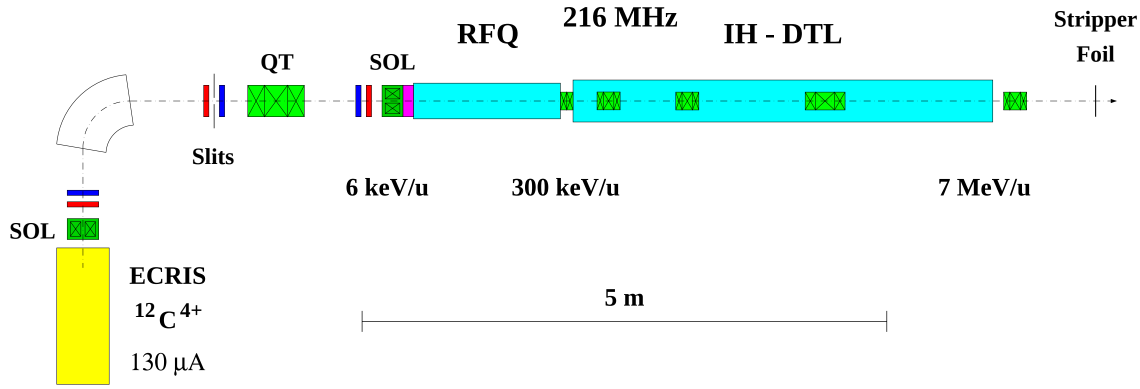

Figure 1: Schematic drawing of the designed carbon injector LINAC.

in this case. Such large currents might be provided by the HYPERNANOGUN model (ECR4-M type, larger plasma chamber, electrical coils) or by an ECRIS using superconducting magnet technology.

3 LOW ENERGY BEAM TRANSPORT

The ion beam extracted out of the ECRIS is focused by a solenoid magnet into a 90° spectrometer dipole followed by an image slit. The theoretical mass resolving power of the system is about 300. This is sufficient to separate the desired $^{12}C^{4+}$ ions from other charge states and from several other light ions. Behind of the image slit, the beam is transformed by a magnetic quadrupole triplet to a circular symmetry at the subsequent solenoid magnet which finally is focusing into a small matched waist at the beginning of the RFQ electrodes. A pair of chopper plates for macro-pulse formation will be placed in between the solenoid lens and the RFQ. For beam diagnostics, profile grids and Faraday cups are planned behind of the extraction solenoid of the ion source, at the image slit and in front of the second solenoid magnet (Fig. 1).

Table 2: Parameters of the designed carbon injector.

ECR ion source:	
Model	SUPERNANOGUN [4]
Magnets	fully FeNdB permanent magnet source
Operating frequency	14.5 GHz
Extraction voltage	18 kV
Source current (DC)	$\geq$ 130 eμA C^{4+}
Norm. beam emittance	$<$ 0.4 π mm mrad
RFQ:	
Components	one tank, 4-rod structure
Input energy	6 keV/u
Output energy	300 keV/u
Operating frequency	216 MHz
RF peak power requir.	100 kW
RF pulse length	300 μs, 5 Hz
Electrode peak voltage	70 kV
Electrode length	$\approx$ 1.2 m
Aperture radius	$\approx$ 3.6 – 2.7 mm
Acceptance, transv., norm.	$\approx$ 1 π mm mrad
Transmission	$\geq$ 0.9
Tank diameter	$\approx$ 0.3 m
Vacuum pressure	$\leq 10^{-7}$ mbar
Intertank matching:	
Longitudinal	2 drift tubes inside RFQ tank [6]
Transverse	1 magn. quad. doublet

Table 3: Parameters of the designed carbon injector (cont.).

IH drift tube LINAC:	
Components	one tank, 58 gaps, 3 magn. quad. triplets
Input energy	300 keV/u
Output energy	7 MeV/u
Operating frequency	216 MHz
RF peak power requir.	1 MW
RF pulse length	300 μs, 5 Hz
Max. eff. gap voltage V_0T	$\leq$ 450 kV
Max. on axis field E_0	$\leq$ 18 MV/m
Drift tube aperture diam.	10 – 16 mm
Lens aperture diam.	$\leq$ 20 mm
Acceptance, transv., norm.	$\approx$ 0.8 π mm mrad
Acceptance, long.	$\approx$ 1.5 π keV/u $\times$ ns
Transmission	$\geq$ 0.9
Emittance blow up	$\leq$ 1.2, 1.3 (transv., long.)
Tank length	4.0 m
Tank diameter	$\approx$ 0.35 m
Vacuum pressure	$\leq 10^{-7}$ mbar
Stripper section:	
Components	1 magn. quad. triplet, 50 μg/cm^2 carbon foil
Beam diam. on foil	$\approx$ 2 mm
Emittance growth, transv.	$\geq$ 5 %
Momentum degradation	$\pm 5 \times 10^{-4}$ add. in $\Delta p/p$
Transmission	$\approx$ 0.75

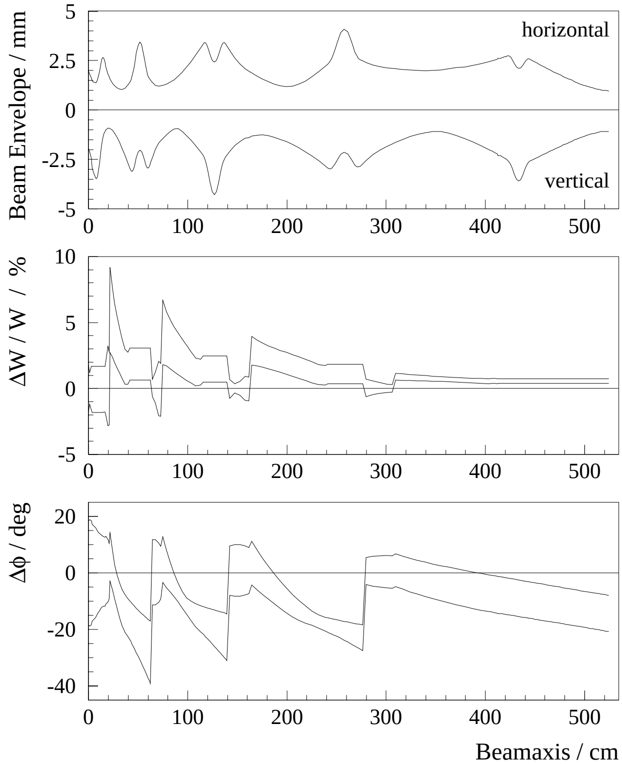

Figure 2: 98 % beam envelopes within the IH-DTL, including the intertank beam-matching section and up to the stripper foil (compare to Fig. 1). The IH cavity begins at an axial coordinate of about 17 cm and ends at about 414 cm. For longitudinal beam matching two drift tubes integrated in the RFQ cavity are included in the simulations.

4 RFQ AND INTERTANK MATCHING

A four-rod RFQ structure of 1.2 m length with an electrode voltage of 70 kV and operated at the same rf frequency of 216 MHz as applied to the IH-DTL is designed for acceleration from 6 keV/u to 300 keV/u by the Institut für Angewandte Physik (IAP), Universität Frankfurt (Table 2). The rf power required is about 100 kW. The aperture radius of 3.6 mm in the beam shaping section of the RFQ provides a normalized acceptance of about 1 π mm mrad.

For matching the output beam parameters of the RFQ to the values required for injection into the IH-DTL a very compact scheme is proposed in order to simplify operation and to increase the reliability of the machine. For longitudinal beam matching two schemes are under discussion:

- Integration of two drift tubes at the exit of the RFQ resonator [6] and negative synchronous phase around $-35°$ in the first IH-DTL gaps.
- Minimization of the drift in front of the IH-DTL and providing the longitudinal matching exclusively at the DTL entrance.

For transverse matching a short magnetic quadrupole doublet of about 14 cm in length placed in between the RFQ and the IH tank is required. Furthermore, an xy-steerer immediately behind of the RFQ would be desirable.

5 IH DTL

The 216 MHz IH drift tube LINAC (Table 3) designed for acceleration from 0.3 MeV/u to 7 MeV/u is subdivided into four KONUS sections which are housed in the same cavity of about 4 m in length and 35 cm in diameter. The subsequent magnetic quadrupole triplet focuses the beam onto the stripper foil placed about 1 m behind of the IH tank (Fig. 1). The rf power required by the DTL is about 1 MW. Each KONUS section consists of a short re-bunching unit (2 to 4 gaps applying $\phi_s = -35°$), a $0°$ synchronous particle section for effective acceleration (8 to 14 gaps) and a subsequent magnetic quadrupole triplet for transverse focusing (*Combined* $0°$ *Synchronous Particle Structure* [7]). The particle dynamics has been simulated using the LORASR computer code [7] and is presented in Fig. 2. The simulations start at the end of the RFQ electrodes and include the complete beam matching between RFQ and IH-DTL. The beam emittances at the exit of the RFQ assumed in our simulations are about 0.4 π mm mrad at 2 mm beam diameter in both transverse phase planes and about 1 π keV/u $\times$ ns in the longitudinal plane. The transverse beam diameters within the IH structure are below 6 mm along the drift tube sections and below 10 mm within the quadrupole magnets. This allows small drift tube diameters of about 10 mm for the first gaps and up to about 16 mm along the last drift tube section. The maximum effective on axis gap voltage along the 58 gaps is 450 kV resulting in an maximum on axis field of about 18 MV/m. The generated averaged effective voltage gain (including the length required for quadrupole magnets) is about 5 MV/m. An 1:2 scaled rf model for optimization of the rf properties of the IH cavity is designed at present.

6 ACKNOWLEDGEMENTS

We would like to thank A. Schempp and A. Bechthold (IAP, Frankfurt) for fruitful cooperation. The cooperation of L. Dahl (GSI) in the LEBT design is greatly acknowledged.

7 REFERENCES

[1] G. Kraft, these proceedings.

[2] U. Amaldi, in: *Proc. LINAC'96, Geneva, 1996*, p. 605, and in: *Proc. EPAC 96, Sitges (Barcelona), 1996*, p. 244.

[3] Ph. Bryant, these proceedings.

[4] P. Sortais et al., Rev. Sci. Instrum. **69**, 656 (1998).

[5] P. Sortais et al., in: *Proc. 13th Int. Workshop on ECR Ion Sources, Texas A&M University, 1997*, p. 83.

[6] U. Ratzinger et al., in: *Proc. LINAC'94, Tsukuba, 1994*, p. 275.

[7] U. Ratzinger, in: *Proc. IEEE Part. Accel. Conf., San Francisco, 1991*, p. 567.