DEVELOPMENT OF A 7 MEV/U, 217 MHZ CARBON INJECTOR LINAC FOR THERAPY FACILITIES

B. Schlitt, G. Hutter, B. Langenbeck, C. Mühle, W. Vinzenz, GSI, Darmstadt, Germany
A. Bechtold, Y. Lu, S. Minaev, U. Ratzinger, A. Schempp, R. Tiede, IAP, Frankfurt am Main

Abstract

A clinical synchrotron facility for cancer therapy using energetic proton and ion beams (C, He and O) has been designed at GSI and will be built at the Radiologische Universitätsklinik in Heidelberg, Germany. The actual development status of major injector linac parts and of its rf system is reported. An 1:2 scaled cold model of the IH-type drift tube linac has been built for rf tuning of the structure. First results are presented. Two prototypes of the linac quadrupole magnets are currently built at GSI.

1 INTRODUCTION

A dedicated clinical cancer therapy facility has been designed at GSI and will be built at the Radiologische Universitätsklinik in Heidelberg, Germany [1][2]. The facility is designed to treat more than 1000 patients per year using the intensity controlled rasterscan method, which was developed at GSI and has been successfully applied with carbon ion beams to more than 140 patients since December 1997 within the GSI therapy project [3].

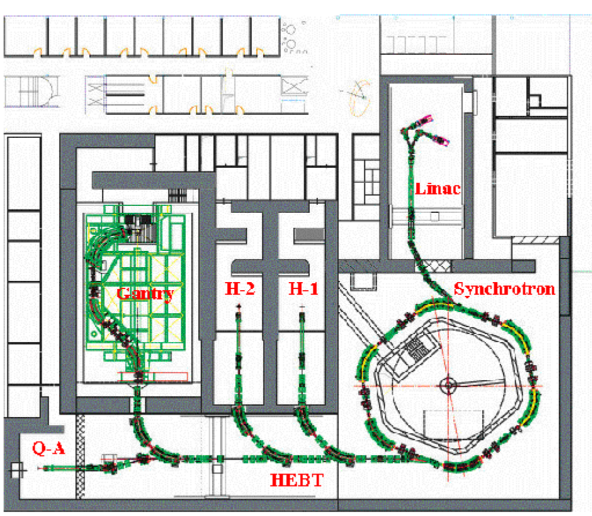

Figure 1: Layout of the accelerator complex to be built at the Radiologische Universitätsklinik in Heidelberg.

The layout of the first underground floor of the facility, housing the accelerator complex and the treatment places, is shown in Fig. 1. The facility consists of a 7 MeV/u injector linac, a compact synchrotron and three treatment areas (two fixed horizontal beam lines, one isocentric ion gantry) as well as of a quality assurance (Q-A) place for R&D activities. Some key parameters are listed in Table 1.

Table 1: Selection of beam parameters required at the treatment places (upper part) and major linac parameters.

Ion species	p, $^{3}He^{2+}$, $^{12}C^{6+}$, $^{16}O^{8+}$
Ion energies	48 – 430 MeV/u
Max. beam intensities	1×10^{9} $^{12}C^{6+}$ ions/spill
	4×10^{10} protons/spill
Beam contaminations	< 1%
Major linac parameters:	
Ion species and required ion source currents	H_3^{+}: 440 μA, $^{3}He^{+}$: 320 μA
	$^{12}C^{4+}$: 130 μA, $^{16}O^{6+}$: 100 μA
Final beam energy	7 MeV/u
Operating frequency	216.816 MHz
RF pulse length	≤ 500 μs @ PRF ≤ 10 Hz

The accelerator chain and the beam lines of the complete facility are well designed and all components are subject of a current call for tenders. The construction of the building will start early in 2003. Installation and commissioning of the accelerator are scheduled for 2004/2005. First patient treatments are planned for 2006.

The layout of the injector linac (Fig. 2) [4] and preceding studies including beam dynamics simulations of the 400 keV/u RFQ and the 21 MV IH-type drift tube linac have been presented in earlier publications [4][5][6][7]. The actual development status of major linac parts is reported in the following.

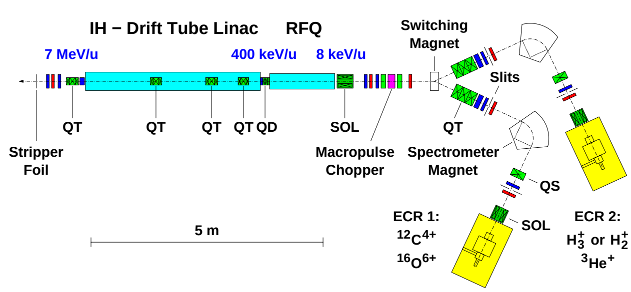

Figure 2: Schematic drawing of the injector linac. SOL ≡ solenoid magnet; QS, QD, QT ≡ magnetic quadrupole singlet, doublet, triplet.

2 ION SOURCES

The commercial 14.5 GHz permanent magnet ECR ion source SUPERNANOGAN from PANTECHNIK has been significantly improved by the manufacturer. High-voltage problems occurring during first tests [4] have been solved and the source could be operated successfully at extraction voltages of up to 30 kV [9]. A very small

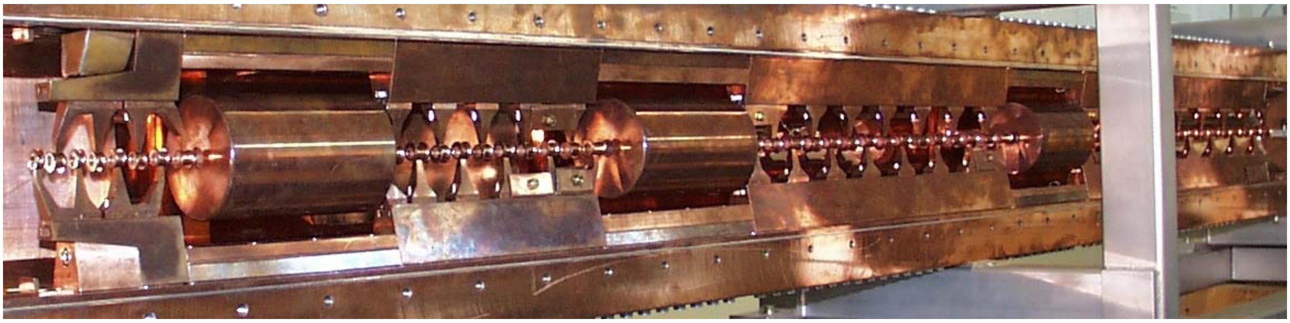

Figure 4: 1:2 scaled rf model of the IH-type drift tube structure (one tank shell and end flanges removed). The three large drift tubes are dummies for the internal magnetic quadrupole triplet lenses. The length of the model structure is about 1847 mm.

variation of the analyzed ion beam current of about 1 % has been measured over eight hours.

3 RF STRUCTURES AND INTERTANK MATCHING SECTION

The components of the 1.4 m long RFQ have been manufactured recently. Assembling and alignment is in progress at the Institut für Angewandte Physik (IAP), Universität Frankfurt am Main [8]. RF tuning is scheduled for the end of this year.

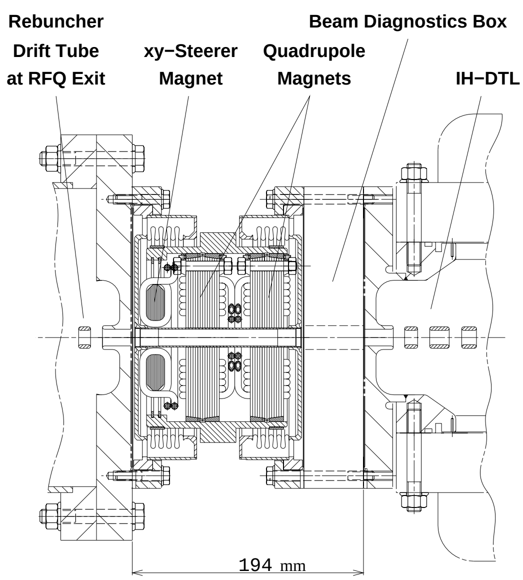

Figure 3: Design of the intertank matching section.

For matching the beam from the RFQ to the IH-DTL a very compact system has been designed (Fig. 3). For longitudinal matching two drift tubes are integrated into the RFQ tank [7][8]. The RFQ is followed by a pair of short steerer magnets and by a magnetic quadrupole doublet. The quadrupole magnets are identical to the shortest quadrupoles designed for the IH-DTL (see section 4). The subsequent beam diagnostics box with a length of only 80 mm contains a segmented ring aperture, an AC beam transformer and a capacitive phase probe. The fabrication of the diagnostics box is in progress and first functioning tests are planned for October this year.

For the rf tuning of the IH structure an 1:2 scaled cold model has been fabricated (Fig. 4). The tuning of the structure is in progress. Because of the large ratio of the structure length to the inner diameter of the cavity of about 10, the coupling of the four drift tube sections (separated by three integrated magnetic quadrupole triplet lenses) is comparatively small and has to be investigated in detail. Due to the large increase of the ion velocity along the structure, the period length is increasing from 21 mm at the low energy end to about 84 mm at the high energy end for the real structure. This causes an extreme reduction of the capacitance per unit length along the structure. For compensation several methods are applied at the same time: Four different drift tube types with inner diameters of 12, 14 and 16 mm are used; the ratio of the drift tube length to the period length is varied along the structure; the undercuts at the girder ends are optimized to tune the voltage distribution especially at the tank ends; the capacitance between the girders and the lens housing is optimized individually for each lens; the cavity cross-sectional area is reduced at the low energy sections in order to increase the local resonant frequency.

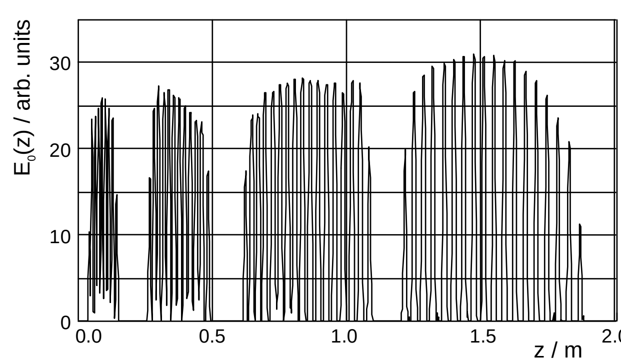

Figure 5: Measured electric field distribution along the axis of the IH-DTL model structure (preliminary).

An already encouraging result of a bead-pull measurement is presented in Fig. 5. An almost flat electric field distribution along the axis has been achieved. A further reduction of the electric field along the fourth section will be achieved by increasing the gap length along this section. The resonant frequency of 431.6 MHz is clearly separated from the next higher mode by about 3.5 MHz.

4 LINAC QUADRUPOLE MAGNETS

Since the operating frequency of the DTL is at least twice the frequency of IH-type DTLs with integrated magnetic quadrupole triplet lenses constructed so far, new compact quadrupole magnets had to be developed (Table 2). Due to the small inner diameter of the DTL the internal focusing magnets must have a rather small diameter as well, in order to provide a sufficient coupling between the drift tube sections separated by the triplet lenses. A ratio of the lens diameter to the inner tank diameter of about 0.4 can be achieved with the new magnet design. This is only slightly larger than the value of roughly 0.3 for current IH-type ion linacs with much bigger diameters (like the 108 MHz IH structure at the GSI High Charge State injector (HLI), or the 101 MHz IH structure of CERN Linac 3). Furthermore, to ensure a sufficient phase stability, the drift length along the lenses must be reduced to a minimum. A mean triplet length of only about 250 mm can be achieved (see Table 2).

Table 2: Key parameters of the linac quadrupole magnets and the internal triplet lenses. The maximum field levels are given for the design ion ($^{12}C^{4+}$).

Drift tube length (triplet)	237 – 264	mm
Drift tube outer diameter	146	mm
Magnet aperture diameter	20	mm
Core outer diameter	130	mm
Core length	42 / 49 / 67 / 81 / 97	mm
Core material	VACOFLUX 50	
Sheet thickness	0.35	mm
Number of turns per pole	5	
Excitation current	≤ 1050	A
Field gradient $\boldsymbol{B'}$	≤ 110	T/m
max $\{\boldsymbol{B'} \times \boldsymbol{L}_{\text{eff}}\}$	5.2 – 10.4	T
$\boldsymbol{B}$ on pole surface	≤ 1.1	T
$\boldsymbol{B}$ in the yoke	≤ 1.85	T
$\boldsymbol{B}$ at pole secant	≤ 2.25	T

In total, 14 quadrupole magnets are required for the intertank doublet, the three integrated triplet lenses and the triplet following the IH tank. Five magnet types with different length but with identical cross sections have been designed. 2D and 3D OPERA simulations were performed. Due to the compact size of the magnets significant differences occurred between 2D and 3D simulations. The required field gradients of up to 110 T/m result in magnetic flux densities of ≤ 1.1 T on the pole surface, and of up to almost 1.9 T in the yoke. The high field levels are achieved by using a 50 % iron-cobalt alloy with a very small sheet thickness of 0.35 mm, providing superior magnetic properties. Two prototype magnets of the most critical quadrupoles (42 mm and 81 mm core length) are currently built at GSI. The coils and the sheets have been fabricated, the manufacturing of the cores is in progress. First measurements of the magnet properties are scheduled for September this year.

5 LINAC RF SYSTEM

The 216.8 MHz rf system has to feed three resonant accelerating structures (RFQ, IH-DTL and a small debuncher cavity installed in the synchrotron injection beam line). Pulsed operation with an rf pulse length of ≤ 500 µs and with a repetition frequency of ≤ 10 Hz is planned. The rf peak power consumption is estimated to about 1.0 – 1.1 MW (IH-DTL), 100 kW (RFQ) and below 1 kW (debuncher), respectively. Three separate amplifier chains are planned. A powerful modular solid state preamplifier with an output power around 8 kW is foreseen for the RFQ and for the IH-DTL, respectively. The same model with a reduced number of modules should be used for the debuncher. A 120 kW tube stage will be used as the final stage for the RFQ and as a driver stage for the 1.4 MW final stage for the IH-DTL.

A cavity amplifier for the 1.4 MW final stage is under construction at BERTRONIX, Munich, Germany. It is designed for grounded-grid operation either with the EIMAC 8973 tetrode from CPI or with the TH 526 B from THALES Electron Devices. An adapter set is being constructed in order to operate the system with either of the two tubes. For high power tests of this cavity amplifier an existing test setup at GSI will be modified. First high power tests are scheduled for April 2003. For the 120 kW stage different tetrodes are under discussion. A TH 571 B with the corresponding cavity amplifier from THALES Electron Devices will be applied at the GSI test setup.

6 ACKNOWLEDGEMENTS

The fruitful cooperation of J. Janik in the design of the linac quadrupole magnets is greatly acknowledged.

7 REFERENCES

[1] H. Eickhoff, D. Böhne, Th. Haberer, B. Schlitt, P. Spiller, J. Debus and A. Dolinskii, *Proc. EPAC 2000, Vienna*, p. 2512, and references therein.
[2] H. Eickhoff et al., *Proc. EPAC 2002, Paris*, p. 2730.
[3] D. Schulz-Ertner et al., Int. J. Radiation Oncology Biol. Phys. **53**(1) (2002), 36.
[4] B. Schlitt, A. Bechtold, U. Ratzinger and A. Schempp, *Proc. Linac 2000, Monterey*, p. 226.
[5] B. Schlitt and U. Ratzinger, *Proc. EPAC 98, Stockholm*, p. 2377.
[6] S. Minaev, U. Ratzinger and B. Schlitt, *Proc. PAC 1999, New York*, p. 2485.
[7] A. Bechtold, U. Ratzinger, A. Schempp and B. Schlitt, *Proc. PAC 2001, Chicago*, p. 2485.
[8] A. Bechtold, C.P. Welsch, U. Ratzinger, A. Schempp and B. Schlitt, *this conference*.
[9] S. Kantas, PANTECHNIK S.A., Caen, France, private communication.