A TEST BENCH FOR THE HEIDELBERG ION BEAM THERAPY CENTRE

R. Cee*, E. Feldmeier, M. Galonska, T. Haberer, J. Mosthaf, A. Peters, S. Scheloske, T. Winkelmann
Heidelberger Ionenstrahl-Therapiezentrum, D-69120 Heidelberg, Germany

Abstract

The Heidelberg Ion Beam Therapy Centre (HIT) is the only medical facility in Europe for cancer treatment with protons and carbon ions. To broaden the range of available ion species towards helium, the low energy beam transport (LEBT) will be extended by a third ion source and the associated spectrometer section. Following a novel ion optical approach the LEBT branch has been redesigned. A dedicated test bench will be used to commission and validate the new design prior to its integration into the medical accelerator. In its final stage the test bench will comprise an ECR ion source, a LEBT and an RFQ with diagnostics line. It opens up the unique opportunity to perform comprehensive investigations not only of the ion source but also of other devices like the RFQ which have been optimised in the frame of the LINAC upgrade. Here, particular emphasis will be placed on the new design of the analyser dipole and the macro pulse chopper. Furthermore results of beam optical simulations and first measurement results will be presented.

INTRODUCTION

Since November 2009 about 170 cancer patients have been treated at the Heidelberg Ion Beam Therapy Centre (HIT) with carbon ions (98%) and protons (2%). Two ion sources of the ECR type allow a fast switching between these two ion species. For other ions like oxygen and helium the ion sources have to undergo a time-consuming shutdown and start-up process. As there is an increasing interest in the treatment with helium ions, especially for paediatric tumours, the low energy beam transport (LEBT) will be extended by another ion source which will also make helium ions permanently available. Based on the experience gained within four years of commissioning and operation we took this opportunity to not just copy the existing design but, where possible, to improve it. The major modifications affect the LEBT section between ion source and analyser dipole [1], the dipole itself, the macro pulse chopper and the RFQ [2]. All these optimisations should finally yield a higher beam brilliance and thus increased intensities for the upcoming clinical applications.

The objective of the test bench is to validate the new developments. In its current stage (Fig. 1) the setup comprises the ion source (supplier PANTECHNIK S.A.), the analyser dipole (supplier Sigmaphi S.A.) and a diagnostics section with profile grid and Faraday cup. It will further on be extended by a complete LEBT consisting of a quadrupole triplet, steerers, a chopper and a solenoid and will be complemented by an RFQ.

* rainer.cee@med.uni-heidelberg.de

Figure 1: Current test bench setup with ion source (left), analyser dipole (centre) and beam diagnostic chamber (right; with slit, profile grid and Faraday cup).

ANALYSER DIPOLE

The current LEBT consists of two ion source branches which are merged by a 30° switching magnet into the LINAC section. The new LEBT branch will be mounted in alignment with the left branch in the way shown in Fig. 2.

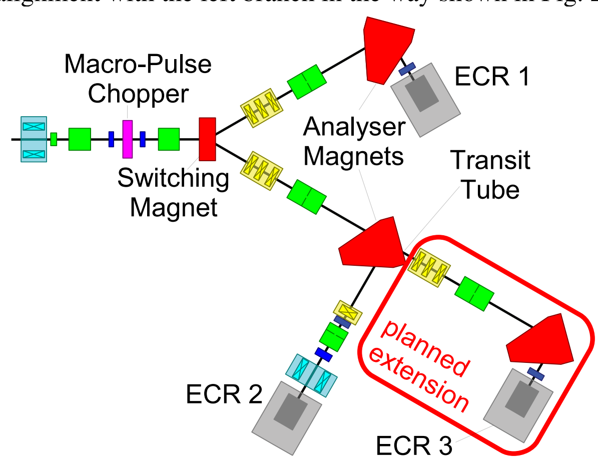

Figure 2: Existing LEBT with planned extension.

As a consequence the existing double focusing analyser dipole has to be replaced and will be used for the third ion source. The major modifications of the new dipole compared to the old design are the transit tube, the trim coil (zero field coil) and an optimised pole face curvature. The transit tube implies an additional opening in the yoke. It arises from the fact that the beam from the third ion source has to traverse the dipole of the second source to be transported to the switching magnet. As the beam should not experience any deviations due to remanence fields the new analyser had to be equipped with a trim coil which will be excited by a dedicated power supply. The main parameters of the trim coil are summarised in Tab. 1. There is one trim coil moulded with each main coil (upper and lower). The expected excitation current has been estimated from measured remanence fields. The overdimensioning arises from manufacturing reasons.

Table 1: Trim Coil Specifications

Parameter	Value
No. of coils	2
Windings per coil	50
Expected excitation current	0.5 A
Max. excitation current	6.0 A

The entry and exit pole faces of the dipole yoke are curved. This shape generates hexapole field components which compensate the intrinsic geometric aberrations of the magnet. We performed higher order optimisations that showed best suppression of the geometric aberrations for a curvature radius of approx. 1.1 m, which differs from the old dipole design specifying a radius of 1.25 m.

MACRO-PULSE CHOPPER

In routine operation the macro pulse chopper is used for the formation of short beam pulses ($\sim$100 μs @ 5 Hz) from the DC beam of the ion source. Beam dumping is achieved by deflection within an electric field of a plate capacitor. At beam request, the capacitor plates unload quickly ($\leq$1 μs), so that the beam passes the chopper unaffected. During operation it was observed that the voltage needed to achieve the desired deflection angle could not be reached in the case of the hydrogen beam. Further investigations showed that the H_2^+ beam, due to its relatively large dimensions at the chopper position, hits the negative chopper plate driving the power supply into its current limitation.

Taking this into account we increased the chamber size from 155 mm diameter (DN CF 160) to 200 mm (DN CF 200) which allows to increase the distance between the two plates to 100 mm (see Tab. 2 and Fig. 3). The loss in effective field can be easily compensated by adapting the voltage resulting in a utilisation of the power supply of $\approx$50 % leaving a convenient reserve. To be able to integrate the new chopper without alterations of the existing beam line we added a reduction flange on each side. In order to conserve the longitudinal dimension the plate length had to be reduced by 10 mm. The chopper has been tested during power supply commissioning and will be used the first time during the final stage of the test bench with RFQ operation.

Table 2: Macro-pulse Chopper Specifications

Parameter	Old design (DN 160 CF)	New design (DN 200 CF)
Plate length	120.0 mm	110.0 mm
Plate width	70.0 mm	90.0 mm
Plate distance	60.0 mm	100.0 mm

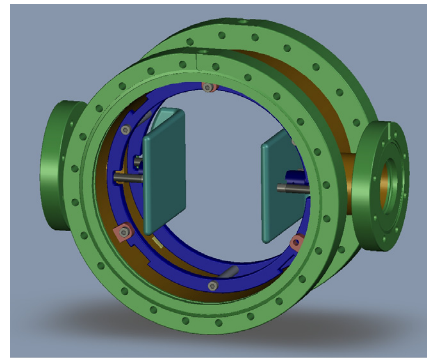

Figure 3: 3D model of the new macro-pulse chopper.

SIMULATIONS

A beam line model for the test bench has been set up with the simulation code TURTLE in the version of PSI, Villigen (Graphic Turtle Framework [3]). This ray-tracing programme provides the most important features for our application, namely import/export of particle distributions in ASCII-format, simulation of einzel lenses and support of second order effects such as curved magnet pole faces.

Input Particle Distribution

With respect to the input particle distribution we followed a new approach. Since the design of the HIT LEBT considerable progress in the simulation of ECR ion sources has been achieved. Based on the results e.g. in Ref. [4] we generated a particle distribution which features a correlation in the momentum space with a concave triangular shape (Fig. 4), the free parameter being the angle at the peak of the loss cone. This shape is typical for ECR sources and can be explained by the loss lines of the hexapole field in the plasma chamber. The spatial distribution in the plasma chambers transforms into a momentum distribution at the plasma lens, the origin of our simulation. The real space has been filled uniformly within the extraction aperture ($r = 3.5$ mm) with 10 000 monoenergetic particles.

Although this approach cannot achieve the accuracy of sophisticated ion source simulations we claim that it will lead to much more reasonable results than uncorrelated distributions being used in former works [5].

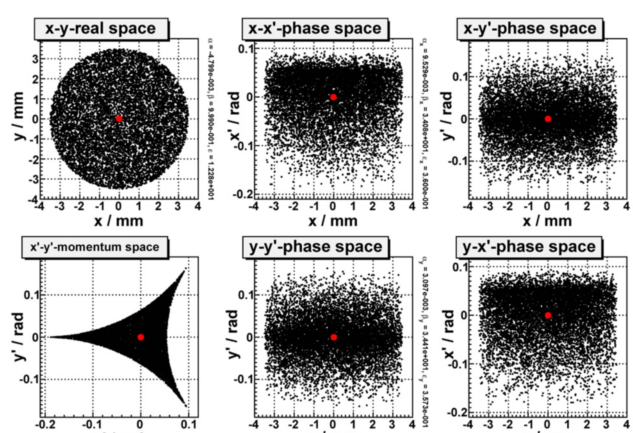

Figure 4: Particle distribution at the plasma lens of the ion source. The centre of mass is marked with a red dot.

Einzel Lens

The new extraction system of the ion source consists of three tubes (diameter 70 mm, gap length 10 mm) connected to individual power supplies [1]. It can therefore be operated as einzel lens and is the only variable focusing element between source and analyser dipole. The potential distribution on the axis of the einzel lens was calculated by extension of an approximate formula for tube lenses from Ref. [6] which is applicable if the tubes have equal inner diameters. As the simulation tool cannot process an analytical formula we discretised the curve according to the red step function in Fig. 5.

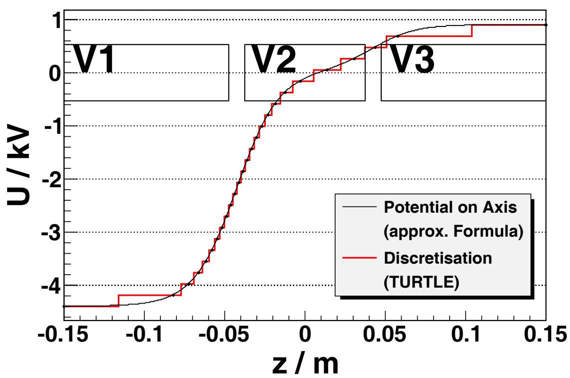

Figure 5: Potential on the axis of the einzel lens. The tube voltages have been chosen according to the operating parameters for ^{4}He (V1 = -4.4 kV, V2 = 25.0 V, V3 = 0.9 kV).

Results

The simulation starts at the plasma lens and ends at the position of the profile grid in the diagnostics chamber behind the dipole (see Fig.1). The output correlations are dominated by the fact that the beam has passed a horizontal waist behind the double focusing dipole whereas it is still convergent in the vertical plane (Fig. 6). In real space the originally round beam is deformed towards a rectangular shape. The momentum space conserves its general shape but is inverted in x'. The sharp edges from the input distribution are blurred and second order distortions appear. Setting the maximum angle at the cone peaks to 200 mrad, corresponding to a 4-rms-emittance of $\simeq$360 πmm mrad, yields best agreement between the measured and simulated ^{4}He profiles which can be interpreted as a prediction for the ^{4}He emittance. For the remaining quantitative differences in Fig. 7 we hold the following issues responsible:

- the field between plasma lens and puller electrode (V1 in Fig. 5) was not taken into account
- space charge calculation is not supported by the simulation code

STATUS AND OUTLOOK

The test bench is remotely operable and commissioning has begun with ^{4}He. As one of the next tasks we will perform comparative emittance measurements with a slit-grid and a pepper-pot system for different ion species. This will provide the opportunity to find the source settings yielding the best beam quality. By comparison of phase space plots we will also be able to validate and refine our simulation methods. In 2011 the test bench will be extended up to the RFQ for a performance check and rebuncher investigations. The integration into the running facility is foreseen for the winter 2011/12.

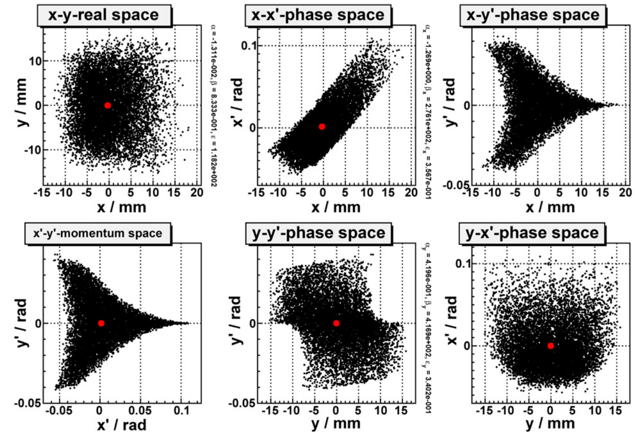

Figure 6: Particle distribution at the position of the profile grid.

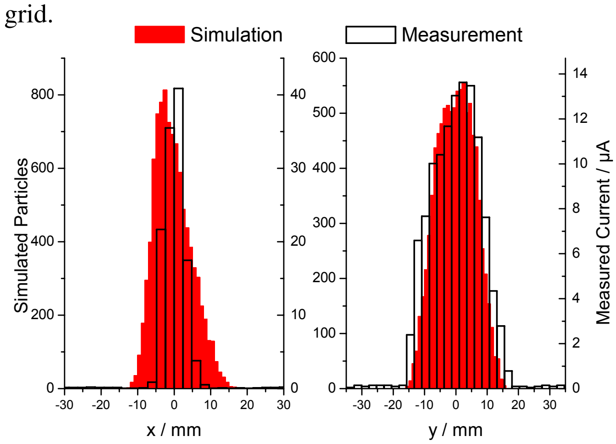

Figure 7: Simulated and measured beam profiles at the position of the profile grid.

REFERENCES

[1] T. Winkelmann et al., "Long-term Operation Experience with two ECR Ion Sources and Planned Extensions at HIT", ECRIS'10, Grenoble, France, August 2010, TUPOT016.

[2] R. Cee et al., "Intensity Upgrade Programme for the HIT Injector", EPAC'08, Genoa, Italy, July 2008, TUPP113, pp. 1788–1790, `http://www.JACoW.org`.

[3] PSI Graphic Turtle Framework by U. Rohrer based on a CERN-SLAC-FERMILAB version by K.L. Brown et al.

[4] P. Spädtke, "The Physics of Ion Beam Extraction from an Electron Resonance Ion Source", IEEE Trans. Plasma Sci., Vol. 36, No. 4, August 2008, pp. 1569–1573.

[5] R. Cee et al., "Front-to-end Simulation of the Injector Linac for the Heidelberg Ion Beam Therapy Center", EPAC'06, Edinburgh, Scotland, June 2006, WEPCH017, pp. 1957–1959.

[6] F. Ollendorff, "Elektronik des Einzelelektrons", Springer, Wien, 1955.