STATUS OF THE ION SOURCE AND RFQ TEST BENCH AT THE HEIDELBERG ION BEAM THERAPY CENTRE

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Abstract

The possibility of cancer treatment with proton and carbon beams provides HIT (Heidelberg Ion Beam Therapy Centre) with an exceptional feature and gives it a unique position in Europe. In the future, the variety of available ions will be extended towards helium and oxygen. To allow fast switching between three of these ion species an additional ion-source / spectrometer combination will be installed in the LEBT. For comprehensive tests of the new components a dedicated test bench including a beam emittance analyser has been set up at the HIT facility. It opens up the opportunity to perform detailed investigations of the improved ECR ion source with its enhanced extraction system and the redesigned RFQ of the HIT injector. Parallel to the measurements, the beam optical model of the assembly could be refined to better reproduce the beam diagnostic results. Since August 2010 the test bench has been in operation in different configurations. Behind the RFQ a beamline comprising a phase-probe-based time-of-flight system and beam current measurement devices is set up. The aim is to determine the RFQ working point and to validate the optimisations in terms of particle transmission.

INTRODUCTION

Since the inauguration of the Heidelberg Ion Beam Therapy Centre (HIT) in November 2009 almost 500 cancer patients have been treated with carbon ions (90%) and protons (10%). Switching between these two ion species from pulse to pulse is feasible due to the existence of two independent ECR ion sources. However, for changing to a third ion like helium or oxygen one ion source would have to be shut down and restarted being a time-consuming procedure. As there is an increasing interest in extending clinical protocols to the use of helium ions [1] the low energy beam transport system (LEBT) will be complemented by another ECR ion source making also helium ions available within seconds. First preparations have already taken place during the last shutdown by replacing the old analyser magnet by the new one containing a transit tube and a zero field trim coil.

Based on the experience of five years commissioning and operation the new ion source beamline contains some optimisations [2, 3, 4] that are validated on a dedicated test bench which is in operation since August 2010. During the last test bench activities we have measured beam emittances in both transverse planes behind the analysing magnet with a slit grid assembly. The results obtained so far suggest that we have succeeded in increasing the beam brightness which will bring us closer to the goal of higher beam intensities for the upcoming clinical applications.

TEST BENCH SETUP

The data presented in this paper have been acquired with the following setup (Fig. 1): ECR ion source with extraction system (einzel lens), horizontal/vertical pair of steerer, 90° double focusing analyser dipole, beam diagnostics chamber with profile grid and Faraday cup, AC-transformer, emittance measuring system (slit/grid) and Faraday cup. The emittance measurement analyser is a loan of GSI Darmstadt and consists, amongst the data acquisition electronics and software, of two chambers, the first one housing the slits, the second one the profile grids. It is capable to measure the horizontal as well as the vertical beam emittance. The test bench has its own control system and database and is remotely operable from the accelerator control room.

Without a magnetic focusing element between source and analyser dipole the plasma lens (extraction aperture) can be placed in the focus of the dipole making the most important difference to the existing (long) LEBT with a solenoid generating a beam focus in this section.

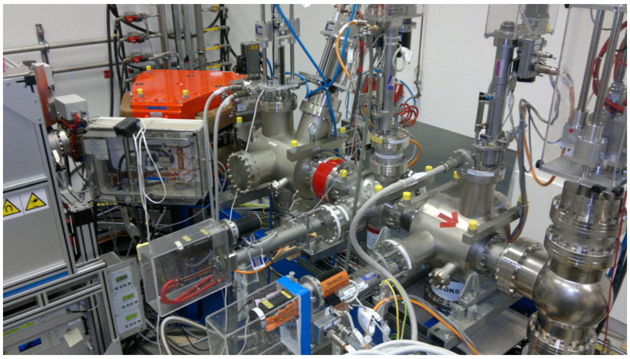

Figure 1: Test bench setup: ion source (left), steerer, analyser dipole (orange), diagnostic chamber, DC-transformer (red), emittance measurement device and Faraday cup.

BEAM EMITTANCE MEASUREMENTS

During our measurement activities we compared two different ion source extraction systems with respect to their influence on the beam emittance. One is a three electrode system consisting of a cone-shaped puller electrode and two tube electrodes. The second extraction system (four

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electrode system) differs by an additional insertion and provides an accel-decel configuration. We investigated five (molecular) ion species (see Tab. 1). Independent on the extraction system the carbon beam emittance of the short LEBT under test is significantly (approx. factor 2) smaller than the one measured for the long LEBT at RFQ injection during the commissioning, the ion currents being comparable. For all ions except for carbon we observed a further reduction of the beam emittance using the four electrode system. With respect to carbon operation further optimisations of the extraction system may be necessary and other operating gases than the used CO_2 are under test [5]. For future operation the reduced emittances imply a better transmission through the RFQ and hence higher particle rates in the treatment rooms.

Table 1: Measured rms beam emittances with and without (in brackets) decel electrode

Ion Species	Current μA	Emittance / (π mm mrad) Horizontal	Vertical
H_2^+	927 (902)	133 (147)	124 (160)
H_3^+	1490 (779)	65 (85)	77 (103)
He^{2+}	746 (577)	64 (65)	64 (72)
O^{6+}	188 (165)	74 (102)	53 (86)
C^{4+}	166 (206)	98 (67)	110 (92)

SIMULATIONS

The TURTLE [6] model of the test bench has been adapted to the current setup. As input we have generated a particle distribution of 15 000 particles which features a concave triangular correlation in the momentum subspace (Fig. 2). This shape imitates the loss lines in the hexapole magnetic field in an ECR plasma. As a new degree of freedom the peak momentum can now be chosen independently for x and y by a scale factor so that we can start the simulation with different beam emittances in the horizontal and vertical plane. The einzel lens, though in this example only slightly excited, has been modeled based on an analytic formula. As an example we compare the emittance measurement of a 8 keV/u, 950 μA $^4He^{2+}$ beam with our second order simulation.

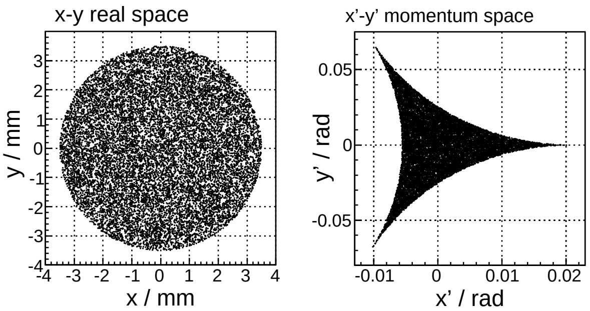
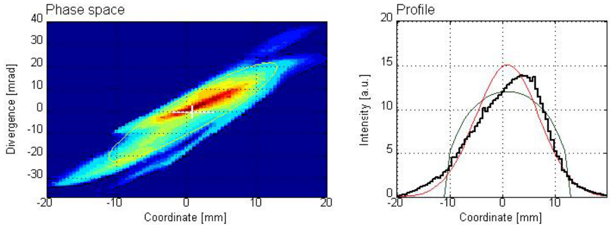
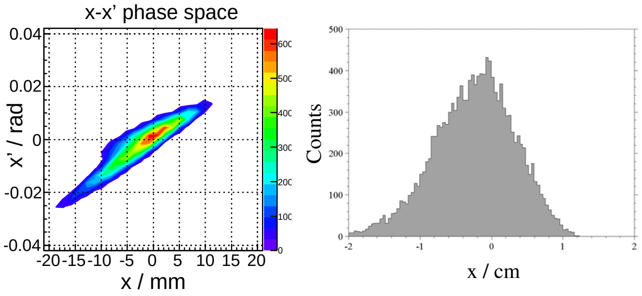


Figure 2: Input particle distribution at the plasma lens (ion source extraction aperture) consisting of 15 000 particles. All other 2D subspaces are uncorrelated.



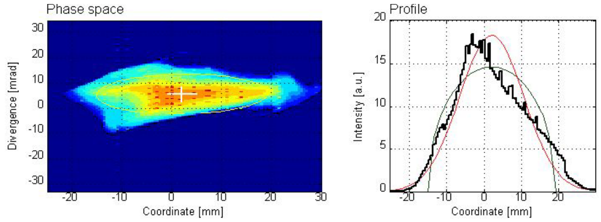
(a) Measurement.



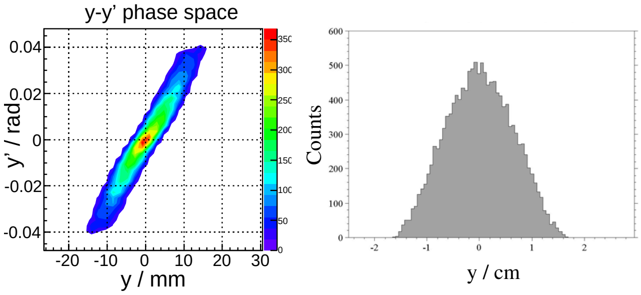
(b) Simulation.

Figure 3: Measured (a) and simulated (b) **horizontal** beam emittance (left) and corresponding beam profile (right) behind the analyser magnet.

As shown in Fig. 3 a good agreement between measurement and simulation can be achieved in the horizontal phase space assuming a ratio between vertical and horizontal peak momentum of four. This indicates that there is a strong asymmetry in the transverse emittances of the extracted beam. Caused by the momentum correlation the beam develops a tail at negative positions and angles. In the beam profile this transforms into a slowly rising left edge and a rapidly falling right edge. This phase space pattern can also be found in the simulation showing even quantitatively satisfying agreement. It cannot be seen using a simple, uncorrelated momentum space.



(a) Measurement.



(b) Simulation.

Figure 4: Measured (a) and simulated (b) **vertical** beam emittance (left) and corresponding beam profile (right) behind the analyser magnet.

The vertical phase space (Fig. 4) cannot be reproduced by the simulation with the same good quality as the horizontal one. In the calculation the phase space orientation of the simulated beam is tilted versus the real beam and the profile barely reaches the width of the measured beam. It has to be mentioned that the vertical phase space orientation is very sensitive to the fringe field integral K of the dipole. E.g. the beam is convergent with the default value $K = 0.5$ whereas at $K = 0.3$, the value determined for our dipole, it is divergent. The exact modelling of the fringe field and the edge focusing is therefore the crucial point which has to be improved to yield more realistic results in the vertical plane. However, the projection of the phase space gives a beam profile which is comparable to the measured one due to its triangular shape.

RFQ TEST BENCH

The final stage of the test bench will contain the LEBT, including quadrupole triplet, macro pulse chopper and solenoid, and the RFQ with a dedicated test beamline at the high energy end of approx. 1 m length. The setup complies the following diagnostic components (see Fig. 5):

- three phase probes
- an AC transformer
- a viewing target
- alternatively a profile grid or a pepper pot screen with mirror and CCD-camera
- a Faraday cup

The RFQ tank has an integrated rebuncher whose voltage has to be set via the conductor length of the second drift tube. This can be done via a set of several voltage scans (beam energy as a function of the RFQ voltage) at different heights of the drift tube support [7]. This will provide us with the right support height and working point (set voltage) of the RFQ. The energy determination will be done by a time-of-flight (ToF) measurement using the three phase probes. The ToF itself will be calculated from the cross correlation function of the phase probe signals.

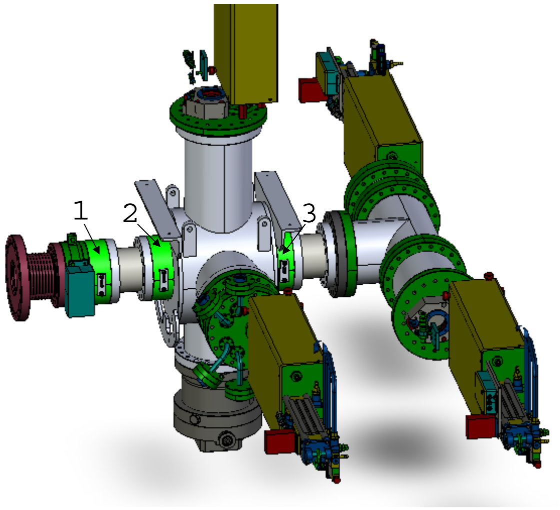


Figure 5: RFQ test bench setup. The three phase probes for time-of-flight measurements are numbered.

The transmission of the RFQ can be measured with the AC transformer. This information is important as the RFQ realises an enhanced electrode design and a refined alignment compared to the one used in the LINAC. The sockets of the beam diagnostics chamber in the drift space between the second and third phase probe may be equipped, depending on demands, with different devices. From top a viewing screen may be inserted. For the residual flange one has the choice between a profile grid or a pepper pot which, together with the mirror / camera combination in the end chamber, will enable us to perform emittance measurements. There will be the possibility to add the intertank section (a quadrupole doublet / steerer combination) between RFQ and the diagnostics elements for further investigations.

OUTLOOK

The next test bench configuration is currently installed and will contain the LEBT up to the solenoid. After completion of the RFQ input beam analysis, foreseen for autumn 2011, the measurements including the RFQ will take place. In winter shutdown 2011/2012 the LEBT of the main facility will be modified, which will enable us to set up the third ion source while the machine is running. With a third ion species at call and increased beam intensities we will make an important step towards more efficiency and higher patient numbers.

ACKNOWLEDGEMENTS

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