FRONT-TO-END SIMULATION OF THE INJECTOR LINAC FOR THE HEIDELBERG ION BEAM THERAPY CENTRE

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Abstract

The injector linac of the Heidelberg ion beam therapy centre is currently in the commissioning phase. Its main components are two electron cyclotron resonance ion sources (ECRIS), a radio frequency quadrupole accelerator (RFQ) and an interdigital H-type drift tube linac (IH-DTL). It will be able to accelerate beams of hydrogen-, helium-, carbon- and oxygen-ions up to a specific energy of 7 MeV per nucleon. This contribution focuses on the beam dynamics simulation of the transport lines and the accelerating structures. Three dedicated tools have been employed: MIRKO for the beam transport, RFQmed for the particle dynamics along the RFQ and LORASR for the acceleration in the IH-DTL. Between the different beam dynamics codes interfaces have been implemented and a front-to-end simulation has been performed. The work will enable us to investigate the behaviour of the machine in a theoretical model during the forthcoming operating.

INTRODUCTION

Radiotherapy with heavy ions is an upcoming cancer treatment method with to date unachieved precision. It associates higher control rates particularly for radiation resistent tumor species with reduced adverse effects compared to conventional photon therapy.

The accelerator beam lines and structures of the **H**eidelberg **I**on Beam **T**herapy Centre (HIT [1]) have been designed under the leadership of the GSI Darmstadt with contributions of the IAP Frankfurt (RFQ, IH-DTL). Currently the accelerator is under construction and the commissioning of the injector LINAC has already begun [2]. When the patient treatment starts end of 2007, HIT will be the first medical heavy ion accelerator in Europe. The success of the design is largely based on the simulation tools developed at the collaborating institutes during the past. They have been made available to the operating crew. The aim of this work is to join them to a front-to-end tool, which will allow us to perform beam dynamics calculation from the source to the foil stripper taking advantage of the excellence of each programme.

FRONT-TO-END SIMULATION

The HIT linac [3] is equipped with two identical ECR ion sources operated in the DC-mode. Besides the design ion ${}^{12}C^{4+}$ it is intended to generate the (partly molecular) ions ${}^{1}H^{1+}$, ${}^{1}H_2^{1+}$, ${}^{1}H_3^{1+}$, ${}^{3}He^{1+}$ and ${}^{16}O^{6+}$ with these sources. The simulations presented here have been performed for the design mass-to-charge ration of $A/q = 3$. From the emittance measurements during the acceptance tests of the ion sources we know that in case of the ${}^{12}C^{4+}$-beam 100% of the intensity is covered by an ellipse of 180 πmm·mrad which is even better than specified. So it is reasonable to take this value as input for our simulations starting at the double waist in the extraction system ($\alpha_x = \alpha_y = 0$) and assuming a round beam ($\beta_x = \beta_y = 0.1$ mm / mrad). The initial particle distribution consisting of 1000 particles was generated internally with the MIRKO programme.

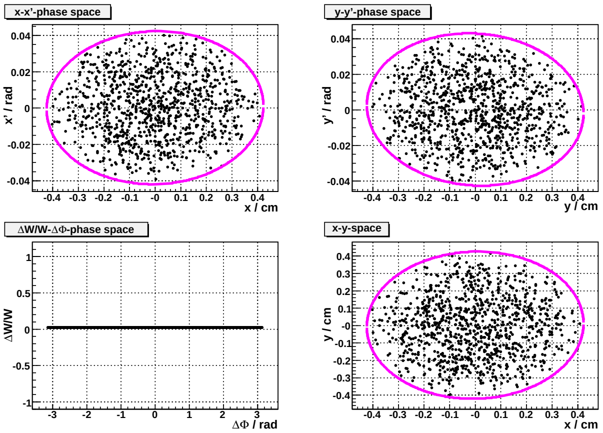

Figure 1: Input particle distribution as generated with the MIRKO programme.

Table 1: Initial Twiss-parameters (6-rms-values) corresponding to the particle distribution of fig. 1.

plane	α	β mm / mrad	ε πmm·mrad
x-x'	0.0225	0.100	178
y-y'	-0.0559	0.099	181

From the Source to the RFQ

The low energy beam transport system (LEBT) serves for separation of the desired ion species and beam matching to the acceptance of the RFQ. It consists of two identical branches angled by 60°. As can be seen from the envelope plot of fig. 2 each branch is provided with a solenoid, a quadrupole singulet, a 90° double focusing dipole spec-

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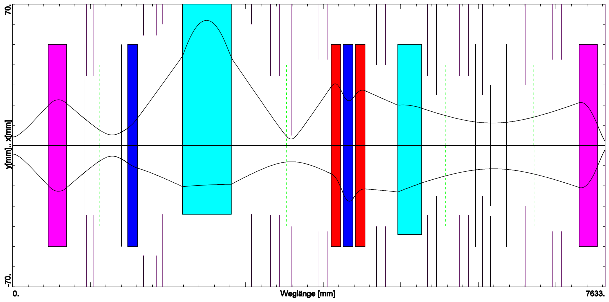

Figure 2: Horizontal (top) and vertical (bottom) beam envelopes in the LEBT calculated with MIRKO. Pink: solenoids, red/blue: focusing/defocusing quadrupoles, turquoise: dipoles.

trometer and a quadrupole triplet. A ±30° switching magnet combines the two branches into a straight section. A macropulse chopper cuts out pulses of 300 μs length from the DC-beam. Another solenoid serves for final focussing into the RFQ.

The tool applied for the simulation of the LEBT is MIRKO, a matrix code written by B. J. Franczak from GSI Darmstadt [4]. It is especially suited for calculation, screen display and (interactive) modification of ion optical settings of accelerators and beam lines. It is possible to generate time-dependent phase space plots (useful for synchrotrons) and 3D beamline displays. The input file can be exported in MAD-, WinAgile- and Transport-format. The programme is integrated in the control system and will be used as online-tool.

The output distribution (see fig. 3) is written in an external ASCII-file and reformatted into the RFQmed input file. For the data acquisition and the file I/O-procedures a script has been programmed using the ROOT libraries [5].

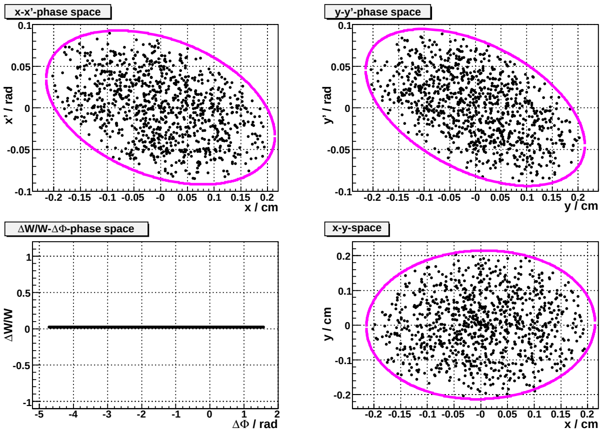

Figure 3: Particle distribution at the exit of the LEBT as simulated with MIRKO.

Along the RFQ

The first RF-accelerator of the HIT-LINAC is a four-rod-type RFQ designed at the IAP Frankfurt [6]. The resonance structure consisting of a ground plate, 16 stems and four electrodes is housed in a 1390 mm long cylindrical vacuum tank. A two gap rebuncher required for the longitudinal matching has been integrated in the RFQ-tank.

For the simulation of the RFQ-structure the programme RFQmed [7], a derivative of the particle tracking code Parmteq [8], is used. The present version is designed for the transformation of a particle distribution through the HIT-RFQ electrode design. It is able to include transport elements like drifts, bunchers or magnetic quadrupoles. The user may choose between predefined distribution types and can enter the initial Twiss parameters. For the simulation presented here we imported the previously generated particle file as input.

In the output graphics (fig. 4) the particle trajectories projected on the transverse and longitudinal planes are plotted versus the z-axis. The different sections of the RFQ (radial matcher, shaper, gentle buncher, accelerator) can be well distinguished. The simulation ends in the centre of the first rebuncher drift tube. Transverse as well as longitudinal particle losses lead to a transmission of 95.1%.

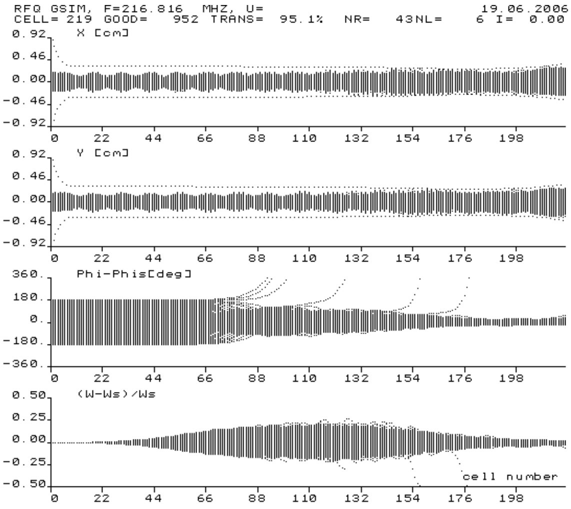

Figure 4: Graphical output of the RFQmed programme. Top down: x-z-, y-z-, $\Delta\varphi$-z-, ΔW/W-z-plane (z-axis in units cell number).

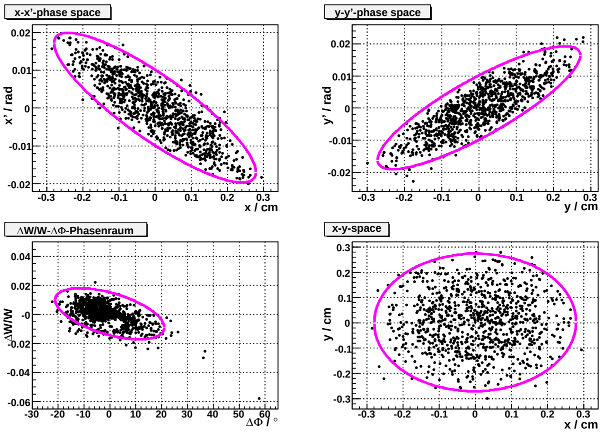

Figure 5: Particle distribution in the centre of the first rebuncher drift tube as simulated with RFQmed.

Along the IH Drift Tube Linac

The second accelerator stage is an interdigital H-type drift tube linac (IH-DTL) [9]. It is an implementation of the combined 0° synchronous particle dynamics (KONUS) [10]. The 56 gaps are divided into four sections separated by internal quadrupole triplets. The structure with a total length of 3.77 m accelerates the ions to an end energy of 7 MeV/u.

The beam dynamics along the IH-DTL including the rebuncher integrated in the RFQ and the matching section between the two tanks is calculated with the programme LORASR [11]. It is based on a 6 dimensional ray tracing method including space charge effects. The field in the accelerating gaps is calculated with a parametrised electric field approximation.

The initial particle distribution can either be entered in terms of ellipse half axes or be explicitly defined in the input file. The latter was the case in the simulations we performed after transforming the data in a similar way as described before. The transverse beam envelopes are displayed in fig. 6. The DFD-O-FDF-O focusing scheme can be clearly seen. The simulations finishes at the foil stripper position with the particle distribution of fig. 7.

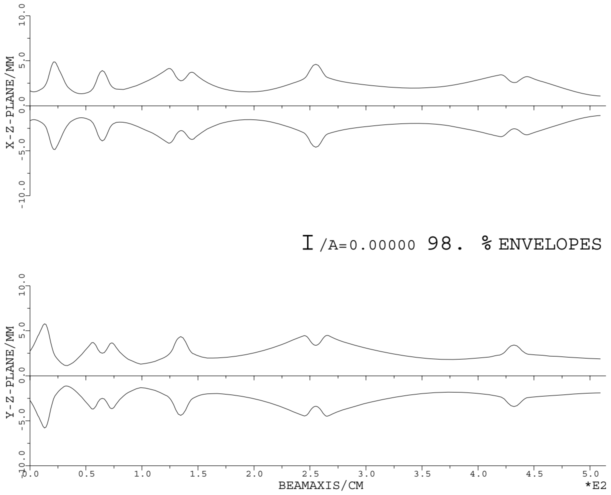

Figure 6: Graphical output of the LORASR programme: horizontal (top) and vertical (bottom) beam envelopes.

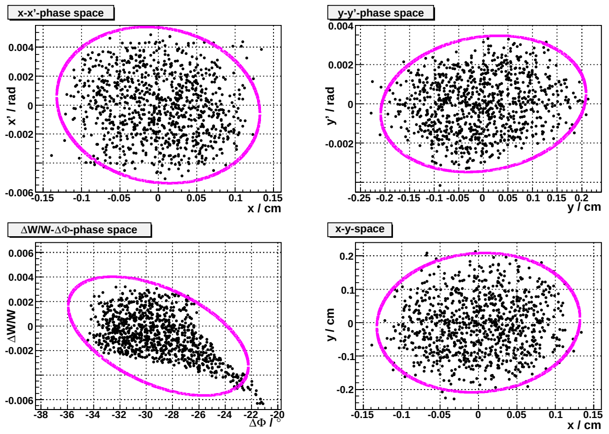

Figure 7: LORASR particle distribution at the foil stripper.

Table 2: Twiss-parameters (6-rms-values) at the foil stripper corresponding to the particle distribution of fig. 7.

plane	α	β mm / mrad ns / (keV/u)	ε πmm·mrad (keV/u)·ns
x-x'	-0.112	0.247	7.073
y-y'	0.150	0.608	7.166
z-z'	-0.585	$2.495 \cdot 10^{-4}$	2.568

Conclusion

We have implemented interfaces between the beam dynamics programmes MIRKO, RFQmed and LORASR which enables us to transform initially defined particle ensembles through the injector LINAC of the Heidelberg Ion Beam Therapy Centre. One of the next steps will be to match the input particle distribution to data either based on data of the ongoing commissioning or on simulation results of the ion source extraction system. Furthermore the influence of the foil stripper on the ion beam has to be taken into account. This will enable us to include the middle energy beam transport (MEBT) connecting the LINAC with the synchrotron into our simulation. Last but not least an automation of the application flow has to be achieved.

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