FIRST TESTS OF A RE-ACCELERATED BEAM AT HEIDELBERG ION-BEAM THERAPY CENTRE (HIT)

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Abstract

In the active raster scanning method performed at HIT since 2009, tumours are irradiated slice-by-slice by changing the extraction energy. The synchrotron provides a library of 255 different extraction energy levels per ion type, according to the aimed penetration depth. So far, a new synchrotron cycle is started for each iso energy slice resulting in a non-optimal duty cycle.

In order to reduce treatment time and to increase the number of patients treated per day, synchrotron cycles with several extraction flattops on different energy levels are planned. After completing one iso energy slice, remaining particles will be re-accelerated to the adjacent level. As a first test a new data supply model generating patterns for power supplies and RF devices with two different extraction flattops has been implemented recently.

The properties of the re-accelerated beam are now under detailed examination. The re-accelerated beam was successfully extracted and guided to the experimental area. Ionisation chambers along the beam line clearly show two spills on two different extraction flattops. The desired change of beam energy has been verified by range measurements in a water column.

INTRODUCTION

About 4400 patients have been irradiated at Heidelberg Ion-Beam Therapy Centre (HIT) between Nov. 2009 and May 2017 with carbon ions and protons. Helium and oxygen ions are available for research purposes.

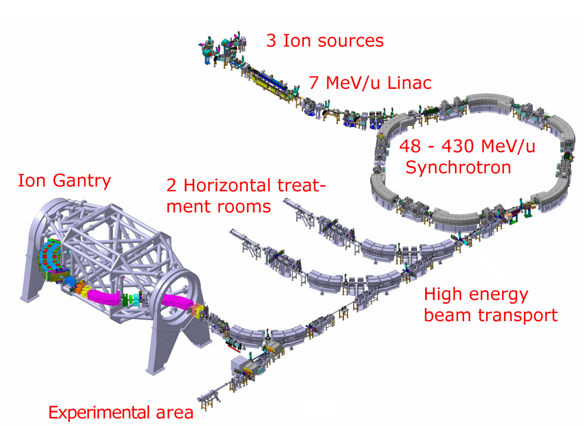

Figure 1: HIT accelerator complex. The synchrotron based accelerator can deliver 4 different types of ions to 3 treatment rooms and one experimental room in therapy quality.

Current Operation Mode

The synchrotron based accelerator (Fig. 1, [1]) optimally fulfils the requirements of the active raster-scanning method [2]. In this method the tumour is irradiated slice by slice. The penetration depth of the ions is controlled by their initial energy. A wide range of beam parameters can be provided by the accelerator complex, including 255 energy levels per ion type. Particles are spilled out of the synchrotron by transverse RF knock-out extraction.

Up to now, each synchrotron cycle can provide only one specific energy, see Fig. 2 top. During injection and acceleration as well as dump and preparation phases no beam is extracted from the synchrotron. The patient does not receive dose in these phases, hence the total treatment time is longer than desired.

The average irradiation time for each iso energy slice is 1.5 s, an extraction time up to 5 s is possible. Therefore, the amount of particles available in the synchrotron usually exceeds the number of particles required for the current iso energy slice. Accelerated particles not needed for the completion of the actual slice are dumped at the end of the extraction period.

Future Multi Energy Operation Mode

For several reasons the duration of stay for patients inside the treatment room should be as short as possible:

- Higher dose conformity due to less intra-fractional organ motion.
- Enhancing the patient comfort as patients are fixed on the treatment table.
- More treatments per day possible.

In order to reduce the total treatment time it is desirable to shorten the phases without beam extraction. *Multi energy operation* is a possible future mode of operating the synchrotron which is currently investigated at HIT. Instead of dumping remaining particles at the end of the extraction phase they will be accelerated or decelerated to the next energy level, see Fig. 2 bottom. In a typical treatment plan adjacent iso energy slices have a distance of a few mm only, corresponding to an energy difference of $\leq$ 4 MeV/u. In such an irradiation scheme several iso energy slices can be irradiated with short interruptions only. Phases without beam availability at the treatment place will be drastically reduced. This paper shows first measurements of a re-accelerated beam at HIT.

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ISBN 978-3-95450-182-3

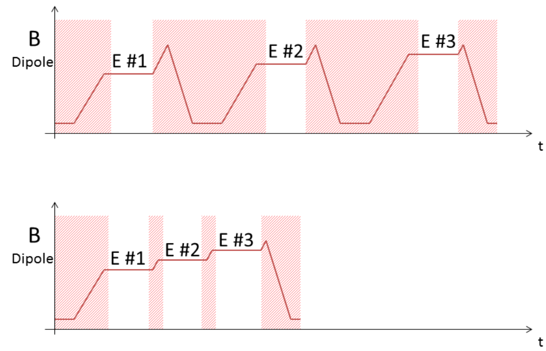

Figure 2: Synchrotron dipole current in old and new synchrotron operation mode, schematically. Phases without beam availability at the treatment room are shown in red. Top: In the present irradiation scheme each synchrotron cycle can provide one extraction energy (E#1, 2, 3...) only. Bottom: The goal of the new and currently investigated *Multi Energy Operation Mode* is to irradiate several consecutive iso energy slices with very short interruptions.

Evaluation of Benefit

Estimations regarding the time reduction have already been presented in [3]. The benefit and requirements have now been analysed again in detail using the data of more than 1000 patients treated at HIT in a period of 18 months [4]. It was assumed that re-acceleration can take place in 100 – 500 ms, which is a rather conservative estimate [5]. Possibly occurring particle losses due to re-acceleration of a transversally blown up beam have been estimated to the range of 0 – 50 %. Simulating the multi energy operation with these assumptions the following scenario can be expected:

- Number of synchrotron cycles required for the irradiation of one field[1]: 6 ± 2.
- Number of extraction phases that can be realised per synchrotron cycle: 6 ± 2.
- Estimated reduction of irradiation time: 48 – 66 %.

These numbers show, that a huge reduction of treatment time of ≈ 50 % or more compared to the current status is possible[2]. In average six normal synchrotron cycles can be replaced by one multi energy cycle. For an individual patient these numbers strongly depend on the size of the tumour. Sometimes one cycle will even be enough to irradiate the whole tumour.

New Data Supply Model

For this project the HIT data supply model for all synchrotron and HEBT-devices has been modified. Two arbitrary extraction energies per cycle are now possible in a test environment. Both, beam re-acceleration or deceleration between the two energy levels have been defined. A detailed description of the new data supply model is given in [6] in these proceedings.

[1] One field means the irradiation of the patient from one direction or one angle. Typically the total dose is spread up in 2 or 3, rarely up to 5 fields. All fields are covered in each treatment session.

[2] Treatment time means the time from the beginning of the first spill to the end of the last spill of one field.

RESULTS

The re-accelerated beam has been successfully guided to the experimental cave. This was done for both ions used for therapy at HIT, protons and carbon ions. In the following subsections measurements of the re-accelerated carbon beam in the synchrotron, high energy beam line and the isocentre are presented.

Beam Current in Synchrotron

The different phases of acceleration and extraction can be observed in Fig. 3. The plot shows the synchrotron beam current measured with a DCCT. The energy difference was chosen very large for the generation of this plot to make the second acceleration stage clearly visible. This is not a typical therapy case.

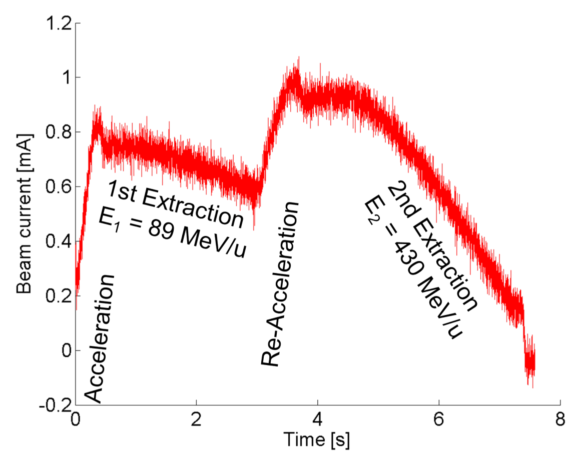

Figure 3: Beam current in the synchrotron measured by a DCCT for a carbon spill in the new multi energy operation mode. First acceleration to: E_1 = 89 MeV/u. Second energy level: E_2 = 430 MeV/u. The beam current rises in the first standard acceleration phase as well as during re-acceleration and decreases in the phases for slow extraction.

Spill-structure Measurements

An example of the spill-structure on two different energy levels is shown in Fig. 4. This data of a carbon beam was taken with the first ionisation chamber in the high energy beam transport (HEBT) line after the synchrotron. The first 2 s have been extracted at E_1 = 352 MeV/u. In the phase between the two parts of the spill the re-acceleration of the remaining particles takes place. The number of particles spilled out in this phase has been successfully reduced by appropriate settings of tune, sextupole strength and amplitude of the synchrotron cavity. The second part of the spill

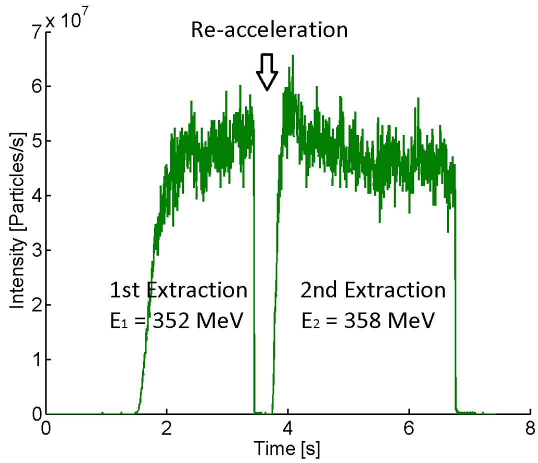

Figure 4: Carbon spill on two different energy-levels in the HEBT-line. Measured with ionisation chamber immediately after the synchrotron. First part of spill: $E_1 = 352\,\mathrm{MeV/u}$. Second part of spill: $E_2 = 358\,\mathrm{MeV/u}$. Re-acceleration takes place between the two parts of the spill.

has an energy of $E_2 = 358\,\mathrm{MeV/u}$. The active spill control [7] implemented at HIT has been deactivated in this measurement.

Range Verification

A range-measurement has been performed to verify the change of the beam energy. The measurement of the ion range has been carried out with a PTW-Peakfinder water-column [8]. This device permits a relative measurement of ionisation events in two ionisation chambers as a function of depth in water.

Figure 5 clearly shows two different depth dose curves[3]. In one series of multi energy carbon spills the depth dose profile has been measured in the first part of the spill (blue circles). The second depth dose profile for the energy level E_2 has been recorded accordingly (red circles). The chosen energy levels had a difference of $6\,\mathrm{MeV/u}$. Furthermore, both curves are identical to the reference measurement performed without the multi energy operation mode (indicated by blue and red crosses). The successful re-acceleration to the desired energy level has thus been proven!

CONCLUSION AND OUTLOOK

The general feasibility of re-accelerating a beam in the HIT synchrotron has been shown for carbon ions and protons. Transverse blow-up due to RF knock-out extraction does not necessarily lead to significant beam losses in a subsequent re-acceleration phase.

The tests will be extended to a larger number of energy levels to cover the whole spectrum of beam parameters. In parallel to this experimental stage the HIT control system will be modified to allow more than two extraction energies.

[3] The position of the peaks does not correspond to the real penetration depth in water due to additional measurement equipment between nozzle and water column.

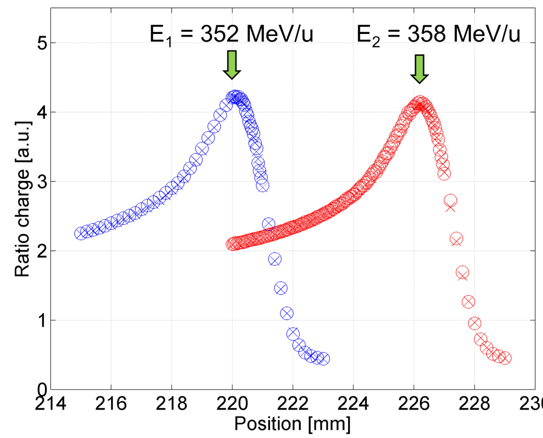

Figure 5: Depth dose curves (*Bragg-Peaks*) measured with ionisation chambers in a water column for two different energy levels. X-Axis: Range in mm. Y-Axis: Peak-plateau ratio of ionisation. Red: Carbon beam at $358\,\mathrm{MeV/u}$. Blue: Carbon beam at $352\,\mathrm{MeV/u}$. Crosses: Reference measurement for single energy operation scheme. Dots: Measurement for multi energy operation mode, both energies available within one synchrotron cycle. The resulting Bragg-peaks are identical for both scenarios.

The final goal is the implementation of a control system that allows to generate patient-specific patterns for all synchrotron devices according to the individual treatment plan.

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